# New probes of a light dark sector in vacuum birefringence tests

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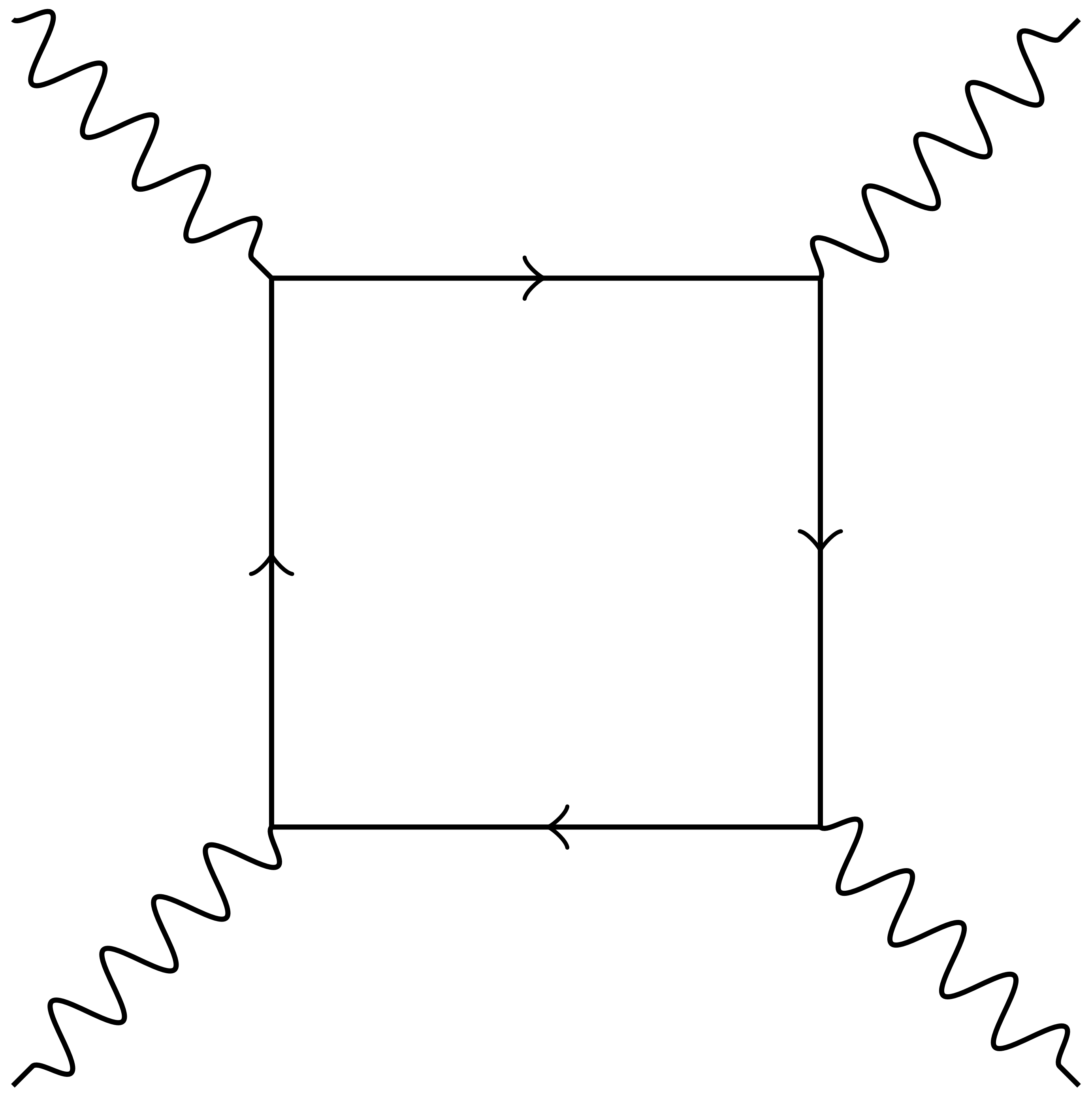
# Euler-Heisenberg Term

- There are still a few Standard Model operators left to probe!
- Leading non-linear interaction of SM E&M is encoded in the Euler-Heisenberg Lagrangian

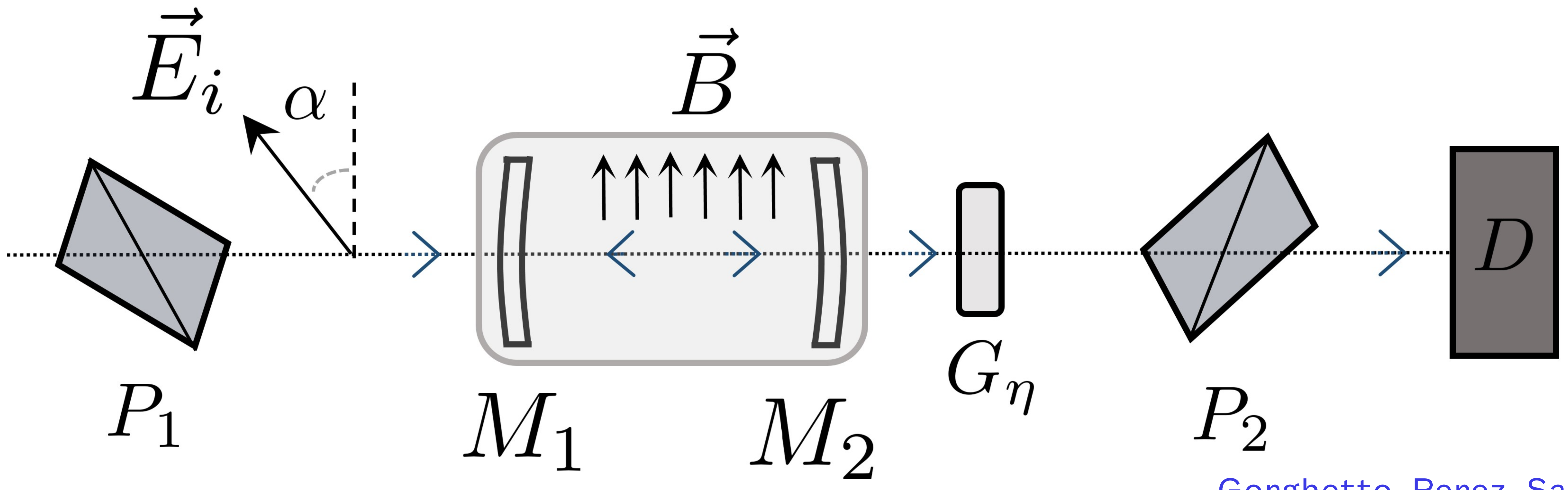
$$\mathscr{L} \supset \frac{2\alpha^2}{45m_e^4}\left[(\mathbf{E}^2 - \mathbf{B}^2)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2\right]$$

- This is the low energy manifestation of light-by-light scattering



# PVLAS

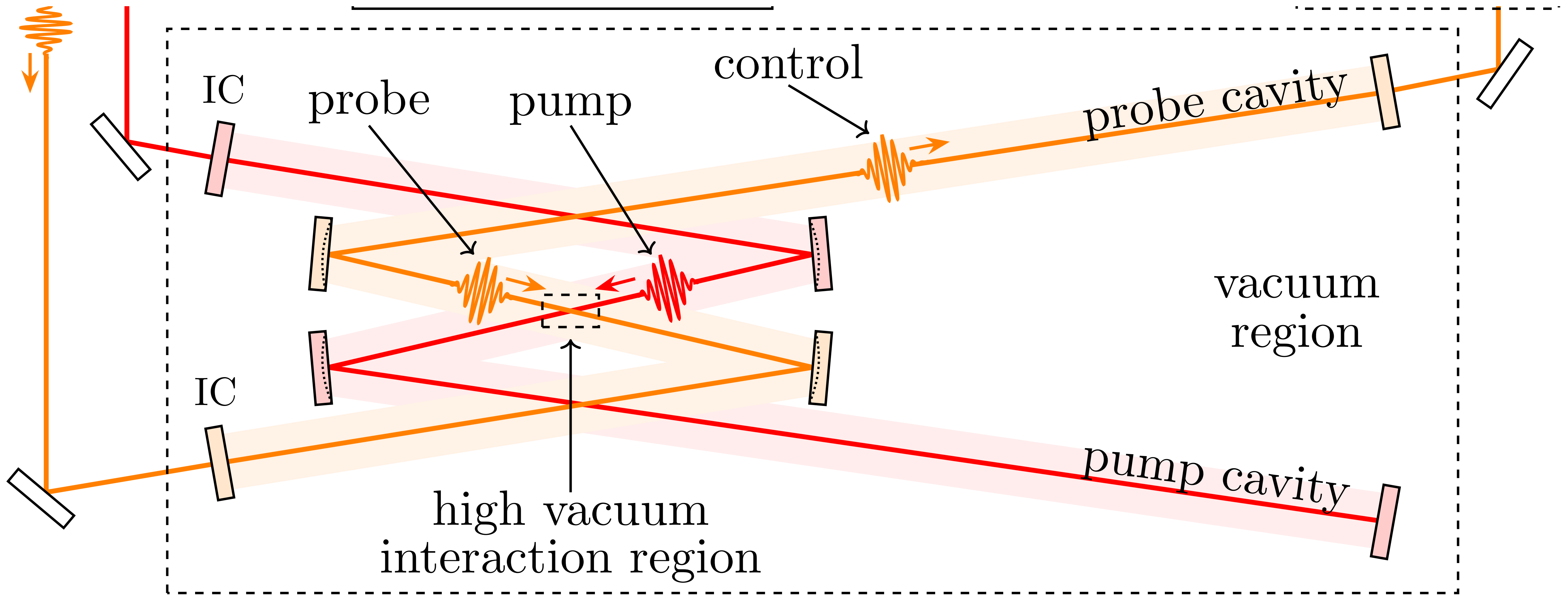
- One approach: bounce photon back and forth through magnetic field to (hopefully) accumulate changes to the polarization of the photon, which can be measured at the end
- Polarizzazione del Vuoto con LASer did exactly this search
- Current version: CP violation cancels between forward and backward trajectory




Gorghetto, Perez, Savoray, Soreq: 2103.06298

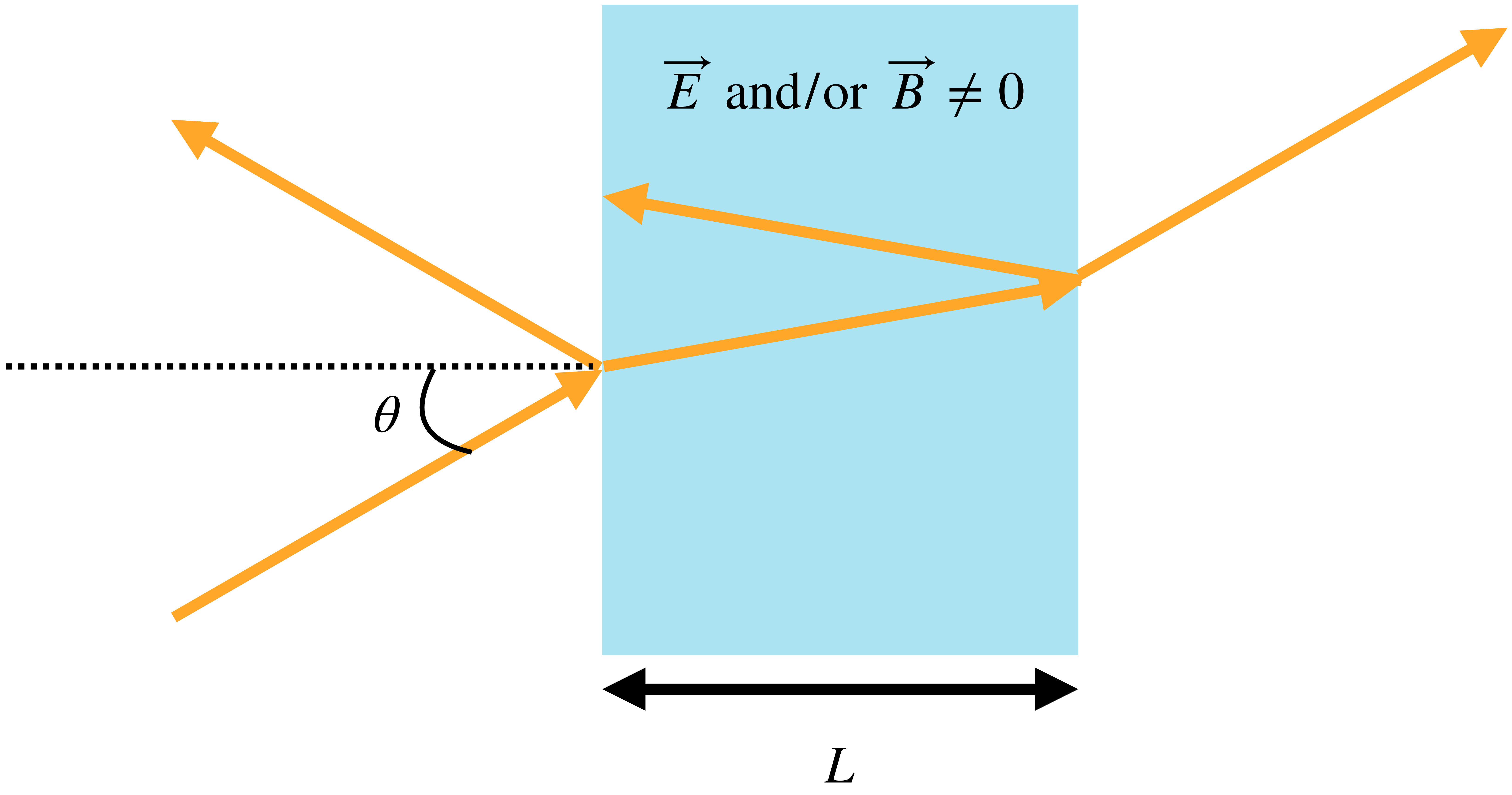
# A New Proposal

- Bullis, Jentshura, Yost propose a light on light “collider”
- Expectation of very low systematic uncertainties, so added statistics can get high sensitivity
- Configuration prevents loss of CP-violation sensitivity over many round trips
- Current design is aimed at measuring the Euler-Heisenberg term




Bullis, Jentschura, Yost: PRR 7 (2025) 2, 023026

# Simplified, Universal Picture

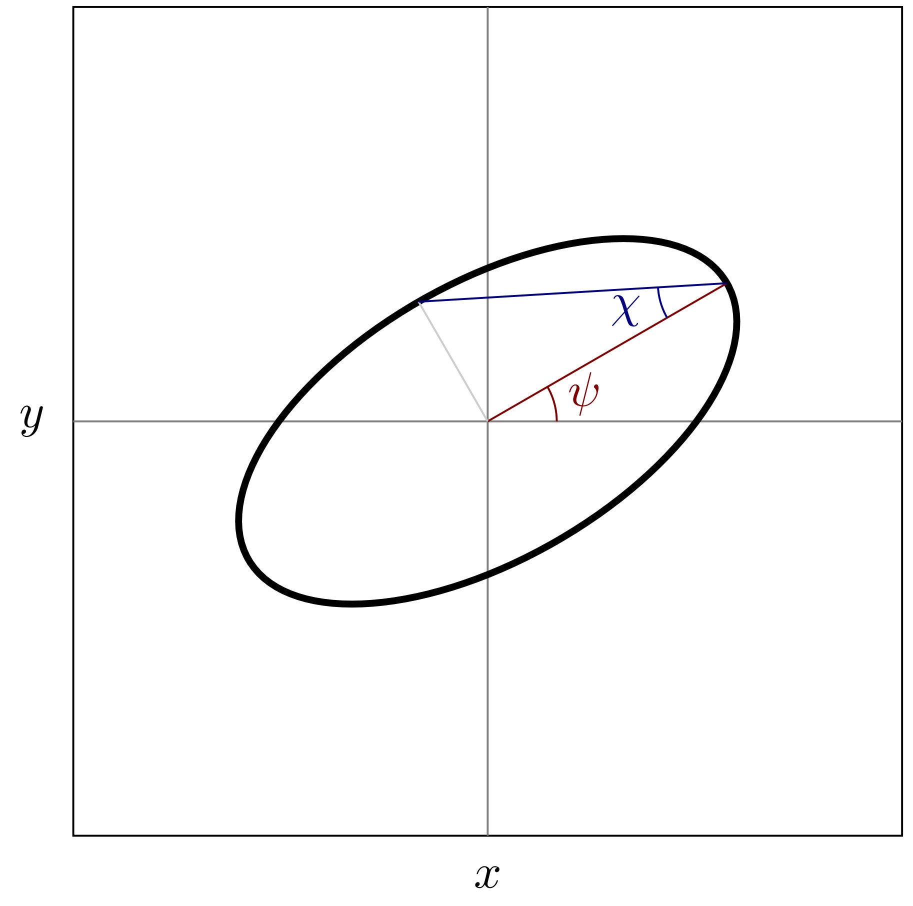


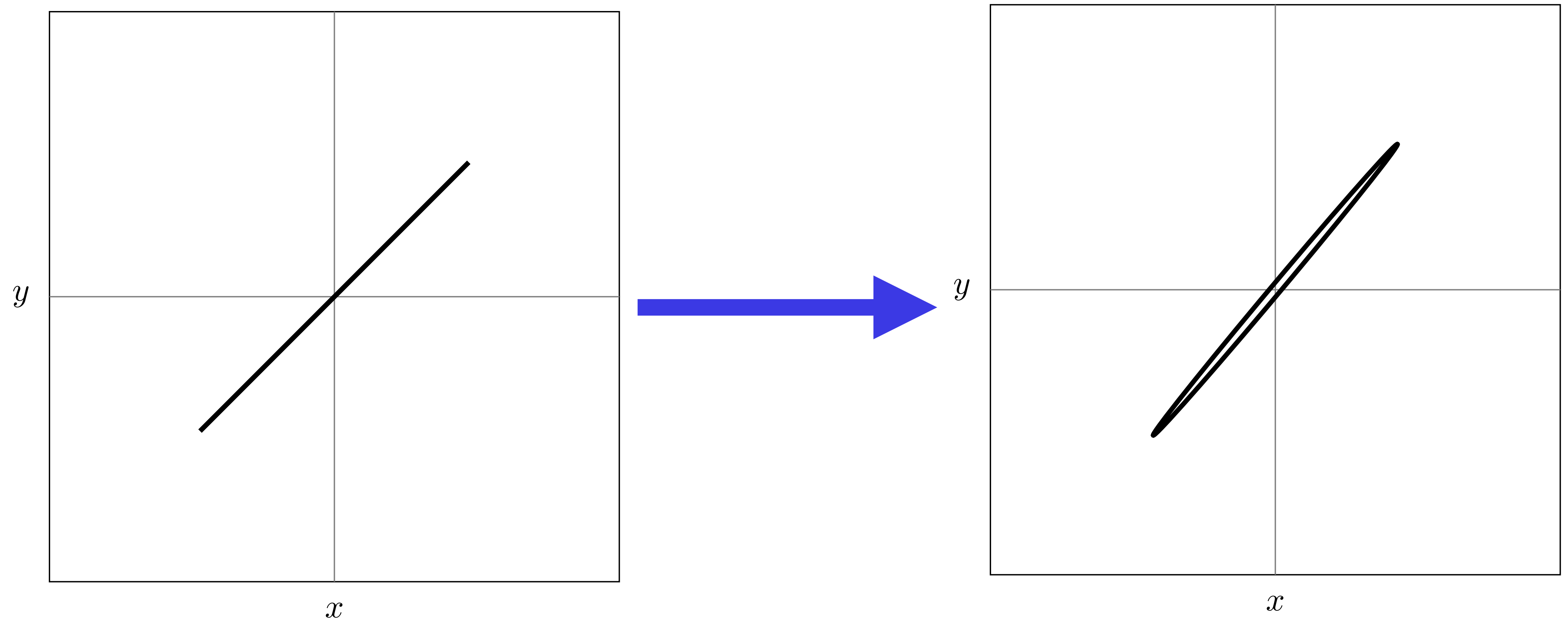
# Side-by-side Comparison

| Parameter | PVLAS | BJY |
| --- | --- | --- |
| **B (T)** | 2.5 | 365 |
| **L (m)** | 0.82 | 0.0003 |
| **$\lambda$ (nm)** | 1064 | 1070 |
| **N** | 400,000 | 10,000 |
| **$\theta$ (º)** | 0 | 70 |

# Parameterizing the Polarization

- Project the electric field into a plane orthogonal to motion
- Electric field rotates around an ellipse
- Linear polarization is a line, circular polarization is a circle
- Start with linear polarization
- Region of polarization-dependent index of refraction causes ellipse to tilt and puff out

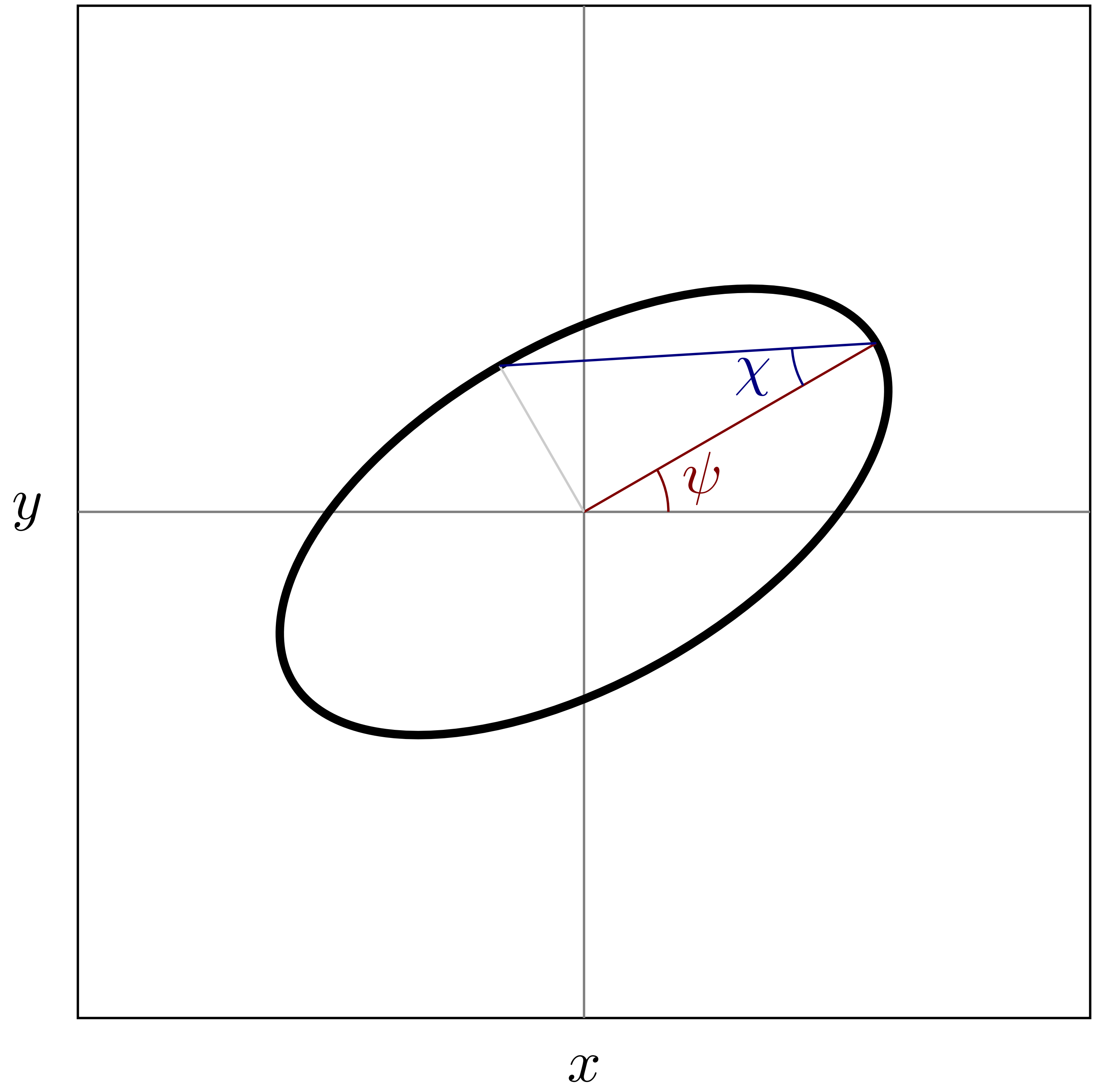


# The Goal for the Calculation

- Two polarizations projected onto **Jones vector** $J$
- Optical element corresponds to a **Jones matrix** $M$
  That is: $J' = MJ$
- Construct the **Stokes parameters**:
  $I = J^\dagger J, \qquad Q = J^\dagger \sigma^3 J, \qquad U = J^\dagger \sigma^1 J, \qquad V = J^\dagger \sigma^2 J$
- Finally, the **rotation** $\psi$ and **ellipticity** $\chi$ are

$$\tan 2\psi = \frac{U}{Q}, \qquad \tan 2\chi = \frac{V}{\sqrt{U^2 + Q^2}}$$



# Expected Sensitivity

- Best PVLAS run measured

$$\Delta\psi = -9.4 \times 10^{-11} \pm 6.7 \times 10^{-10}, \qquad \chi = -6.9 \times 10^{-11} \pm 4.9 \times 10^{-10}$$

- Bullis, Jenstschura, Yost (BJY) expect sensitivity of $10^{-10}$ in 10 minutes of integration time
- Can this be improved with more statistics? Yes!
- Systematic effects due to birefringence drift off the mirrors, thermal noise, stray light expected to by manageable
- An improvement of sensitivity by a factor of 10,000 is not unreasonable with extra work on the power and longer integration time, so we consider another benchmark of $10^{-14}$

# BSM Models

- A primary goal of PVLAS is to search for axion-like particles
- More generally, a model with scalar and pseudo-scalar couplings can be probed

$$\mathscr{L} \supset d_1 \phi \mathscr{F} + d_2 \phi \mathscr{G}, \qquad \mathscr{F} = \frac{1}{4} F^{\mu\nu} F_{\mu\nu}, \qquad \mathscr{G} = \frac{1}{4} \widetilde{F}^{\mu\nu} F_{\mu\nu}$$

- Both couplings non-zero implies CP violation
- Interested in probing a general combination of the couplings
- Greatest sensitivity for masses $m \lesssim \omega$

# Effective Theories

- Can also consider a "model-independent" EFT approach
- Three light-by-light operators can be introduced

$$\mathscr{L} \supset c_1 \mathscr{F}^2 + c_2 \mathscr{G}^2 + 2 c_3 \mathscr{F} \mathscr{G}$$

- First two terms are non-zero in the SM due to Euler-Heisenberg
- Last term is again a measure of CP violation
- For heavy axions, we can integrate out to get

$$c_1 = d_1^2, \qquad c_2 = d_2^2, \qquad c_3 = d_1 d_2$$

# Equations of Motion

- Interested in the coherent, forward effect, so linearize in the "probe" photon field with a background "pump" field
  - Pump is the background B for PVLAS or the other pump EM wave for BJY
- Then, Maxwell's equations can be written in the usual form for a field in a medium

$$\partial_\mu d^{\mu\nu} = 0, \qquad \partial_\mu \tilde{f}^{\mu\nu} = 0, \qquad d^{\mu\nu} = f^{\mu\nu} + d_1 \phi F^{\mu\nu} + d_2 \phi \widetilde{F}^{\mu\nu}$$

- Convention: lower case is the probe, upper case is the background
- Similar result of the scalar EOM (assuming negligible self-interaction for simplicity):

$$\partial_\mu \psi^\mu + m^2 \phi = 0, \qquad \psi^\mu = \partial^\mu \phi - (d_1 F^{\mu\nu} + d_2 \widetilde{F}^{\mu\nu}) a_\nu$$

# Dispersion Relation

- A matrix dispersion relation can be derived from the ansatz $a_\mu = a_{\mu,0}e^{-ik\cdot x}$, $\phi = \phi_0 e^{-ik\cdot x}$

$$\omega^2 - k^2 + \begin{pmatrix} & & id_1\sqrt{-(Fk)^2} \\ & & id_2\sqrt{-(\widetilde{F}k)^2} \\ -id_1\sqrt{-(Fk)^2} & -id_2\sqrt{-(\widetilde{F}k)^2} & -m^2 \end{pmatrix} = 0$$

- Work in a basis of $a \propto F \cdot k \equiv Fk$, $a \propto \widetilde{F} \cdot k \equiv \widetilde{F}k$, and $\phi$
- Avoid approximations here: see the next slide

# Expand in a small correction?

- System has multiple scales of interest: $m, \sqrt{d_1^2 + d_2^2} B_0, \omega$
- Naive small parameter is

$$\frac{(d_1^2 + d_2^2) B_0^2}{m^2}$$

- Clearly not small to arbitrarily small $M$, so need to be careful at small $m$
- For the plots: calculate everything to all orders numerically

# Modes

- Regime 1 — expanding in $\sqrt{d_1^2 + d_2^2}\omega B_0 \ll m^2$ (for BJY):

$$k_1 = \omega, \qquad k_{2,3} = \omega\left(1 \pm \frac{2}{M^2}(d_1^2 + d_2^2)B_0^2 \sin^4(\theta/2)\right)$$

- Regime 2 — Expanding in $m^2 \ll \sqrt{d_1^2 + d_2^2}\omega B_0 \ll \omega^2$

$$k_1 = \omega, \qquad k_{2,3} = \omega \pm \sqrt{d_1^2 + d_2^2}B_0 \sin^2(\theta/2)$$

- Mass-dependence in the sensitivity should flatten out at small mass
- Stronger difference at larger magnetic field (i.e. in BJY compared to PVLAS)

# Interface Conditions

- With the definitions we've made, it's easy to integrate the EOM across the interface to get the "usual" Maxwell conditions plus a somewhat modified scalar interface condition here

$$n \cdot (D_{\text{out}} - D_{\text{in}}) = 0, \qquad n \cdot (\widetilde{F}_{\text{out}} - \widetilde{F}_{\text{in}}) = 0, \qquad n \cdot (\psi_{\text{out}} - \psi_{\text{in}}) = 0, \qquad \phi_{\text{out}} - \phi_{\text{in}} = 0$$

- $n$ is just the normal four-vector to the interface
- Gives the usual interface behavior: reflection and refraction with Snell's law
- Seemingly higher order effect, but makes some difference here when $m$ is not neglected

# Jones Matrix

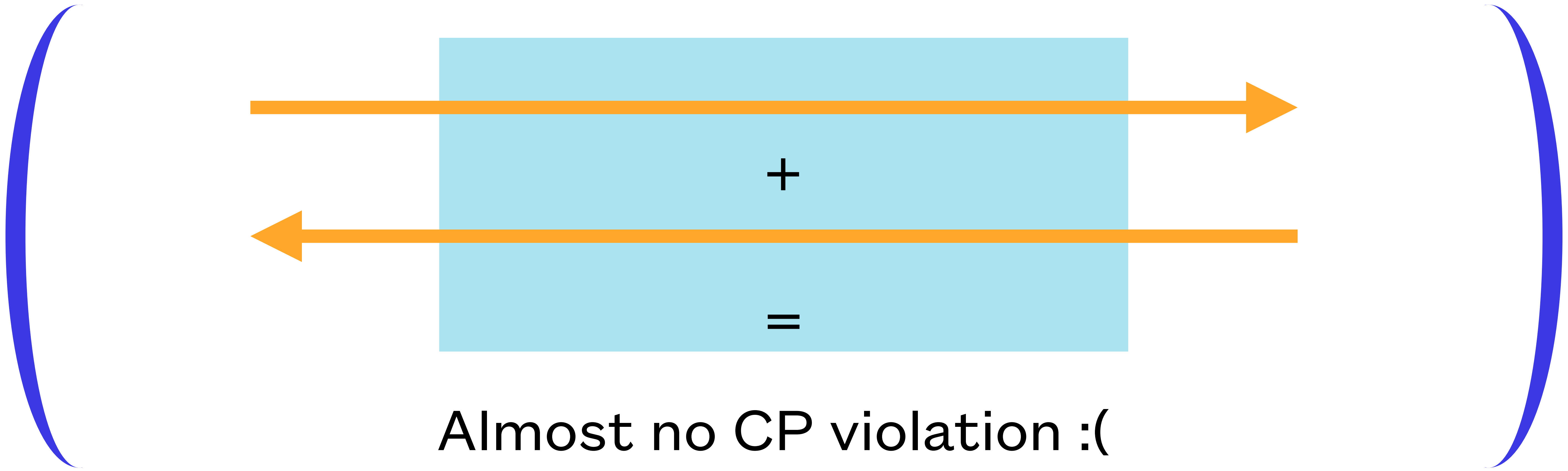
- Reminder: characterize the effect on a given polarization vector by the Jones matrix
- Full form is a bit of a mess due to the interface conditions, but there are a few key take aways
- The leading effect due to the wavenumber shift is order $d_1^2 + d_2^2$ for intermediate mass

$$\text{(overall phase)} \times \text{diag}(e^{i(k_1-\omega)L}, e^{i(k_2-\omega)L}, e^{i(k_3-\omega)L})$$

- For $m \neq 0$, non-trivial effects combine from change in the basis vectors and the interface conditions that can give effects at order $\sqrt{d_1^2 + d_2^2}$ at each interface and cannot be neglected
- Relevant for regime 1!

# Effect of Round Trips

- For PVLAS as currently run: each round trip cancels out CP-violating effect if $d_1, d_2 \neq 0$
- Basically going through the magnetic field in the opposite direction cancels out the effect
- Proposal in Gorghetto, Perez, Savoray, Soreq: 2103.06298 to avoid this issue
- The BJY setup avoid this issue entirely, as the beams can easily be collided always with the same orientation, leading to an additive CP-violation effect



# Rotation and Ellipticity

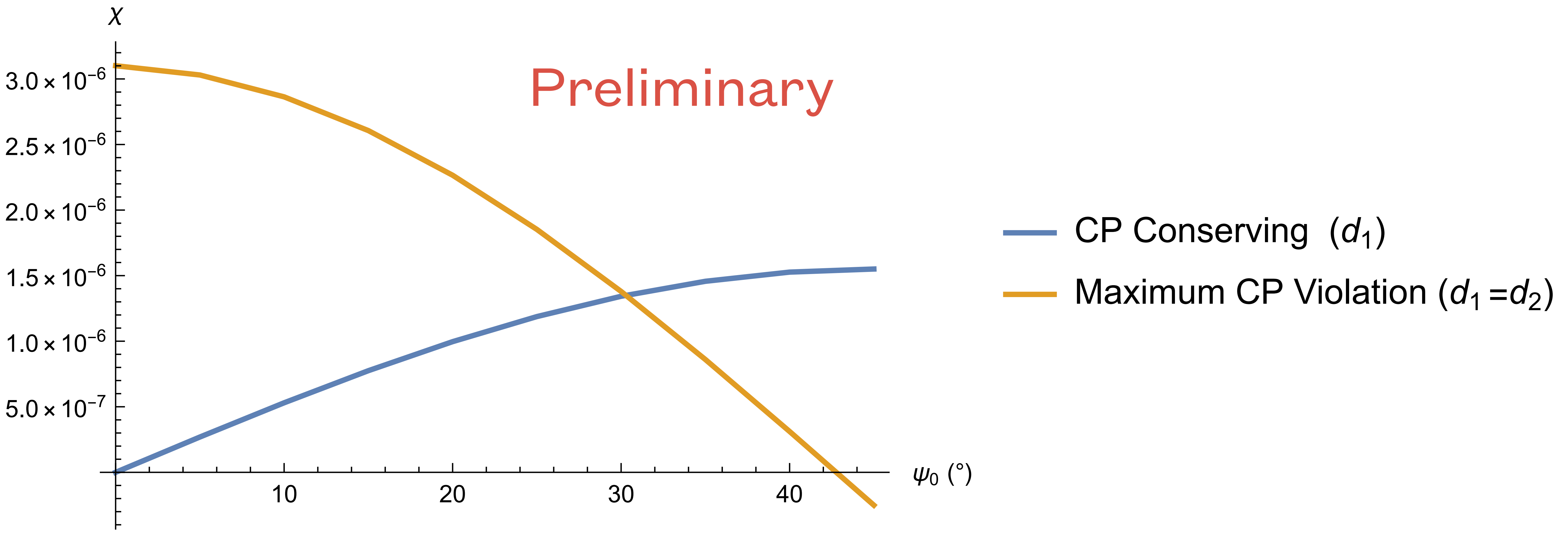
- Again, the results with the full interface conditions are a bit of a mess…
- In region 1, we can the leading result for the ellipticity is really due to the index of refraction directly and we can calculate:

$$\chi \sim \frac{1}{m^4} 2 N B_0^2 d^2 \omega^2 \sin^4(\theta/2) \sin[m^2 L/(2\omega)] \sin[2(\delta - \psi_0)], \qquad d^2 = d_1^2 + d_2^2, \qquad \tan\delta = d_2/d_1$$

- Key features:
  - Order $d^2$: linear contribution vanishes, which is a big contributor to complications here
  - If $\delta = n\pi/2$, i.e. any CP conserving model, $\chi$ vanishes at $\psi_0 = 0$

# CP Violation Signal

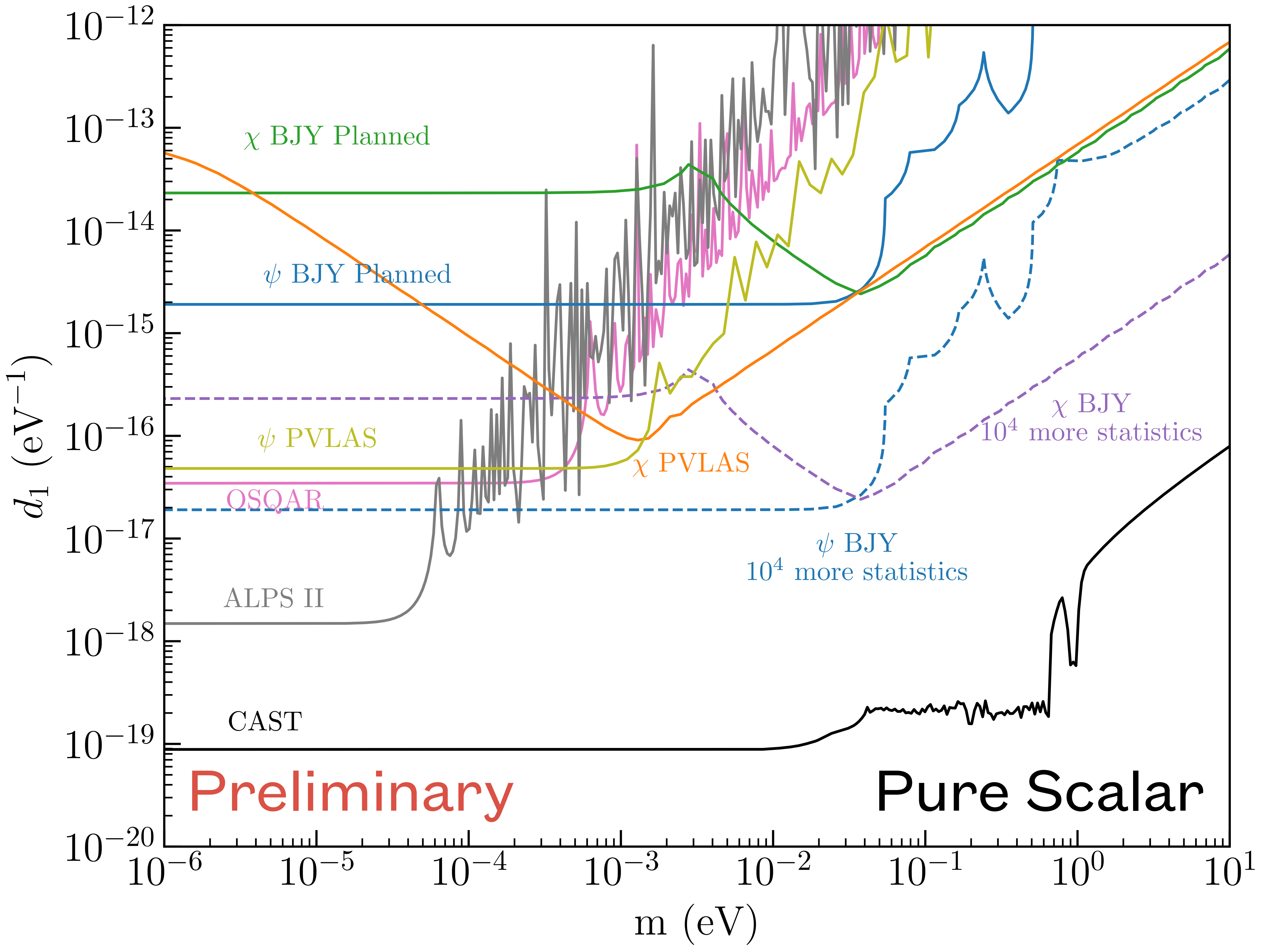
- Polarization of the incident beam has a strong effect on the BSM reach
- To look for Euler-Heisenberg: optimal to polarize at $45°$ with respect to the scattering plane
- For a maximal CP-violating set of interactions, the peak signal shifts to a polarization aligned with or orthogonal to the scattering plane (distorted by the expected Euler-Heisenberg term)

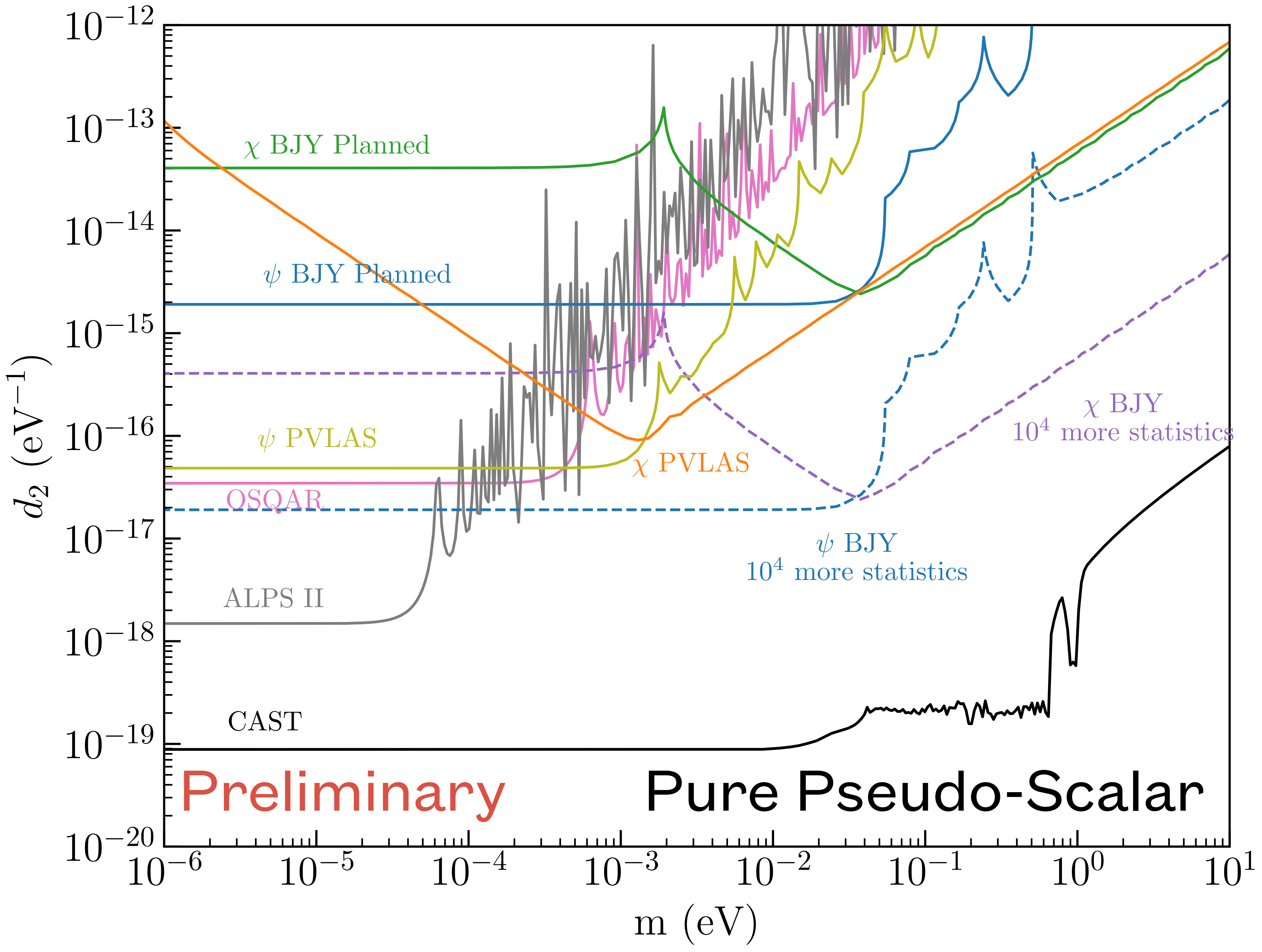


# Other Experiments

- OSQAR and ALPS-II: light-shining-through-walls experiments
  - Not directly sensitive to CP-violation
  - Bounds weaken for masses large enough that the frequency difference becomes of order the inverse length of the magnetic field region
- CAST: axion haloscope
  - Solar-produced scalars/axions can then interact in the telescope
  - Strong bounds, but somewhat sensitive to solar modeling
- ACME: electron electric dipole moment, strong bounds on the CPV case

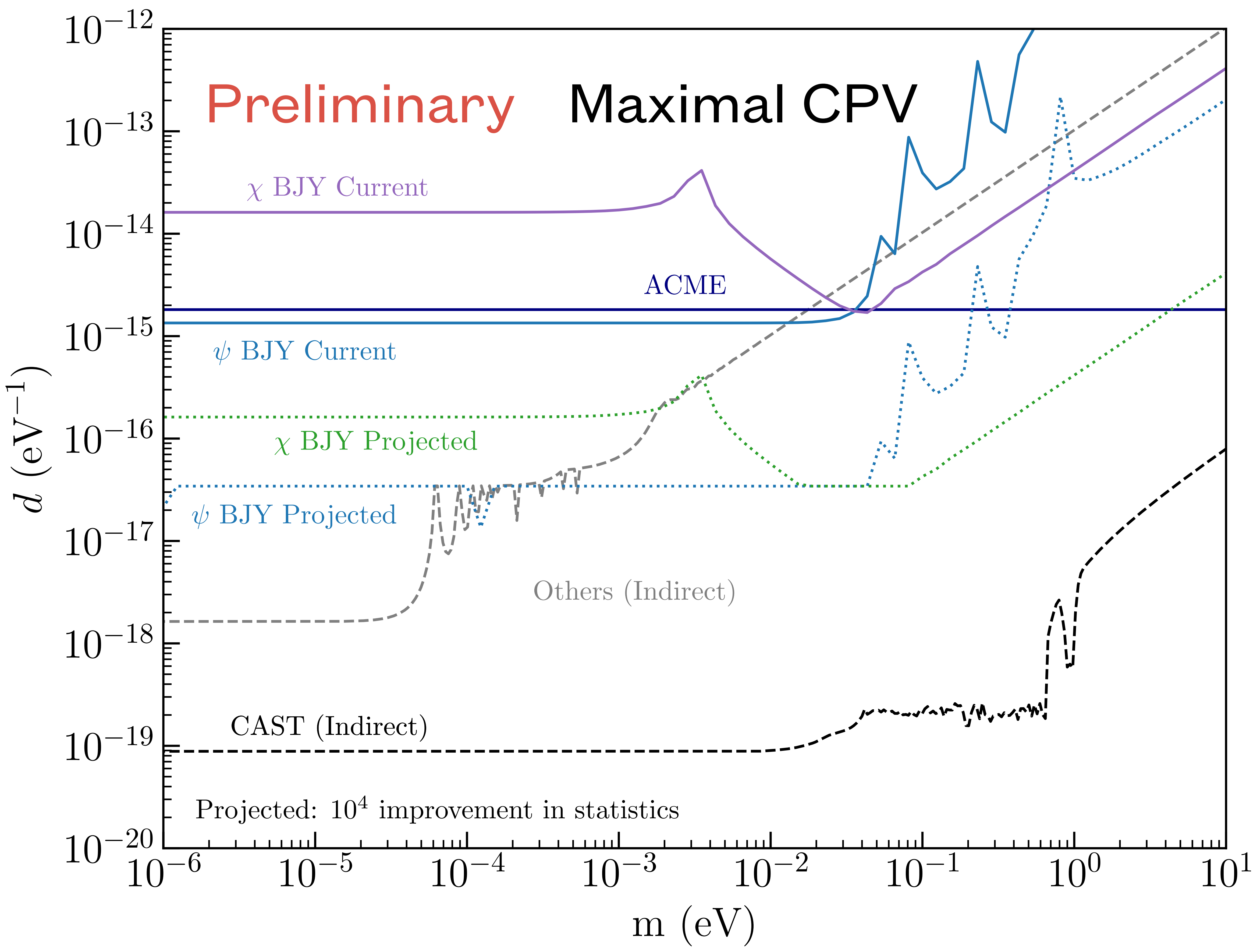
# Projected Sensitivity



# CP Violation Sensitivity

- Upshot is CAST bounds are very strong
- But the BJY setup can be systematically improved & provides a complementary test
- By measuring at different initial polarizations, CPV can be measured
- Can exceed the sensitivity of electron EDM and other direct probes



# Outlook

- The Euler-Heisenberg light-by-light interaction has not been directly measured in the Standard Model, but near or a bit below the level of that interaction, there could be new terms
- Atomic physicists at CSU are currently building a scalable experiment to detect birefringence in photon-photon crossings
- The setup to CP-violation by default and can generally get leading terrestrial bounds with sufficient statistics
- Long term goal: see if sensitivity to models not nominally excluded by CAST can be achieved