# Hyperbolic exciton-polaritons in monolayer black phosphorus

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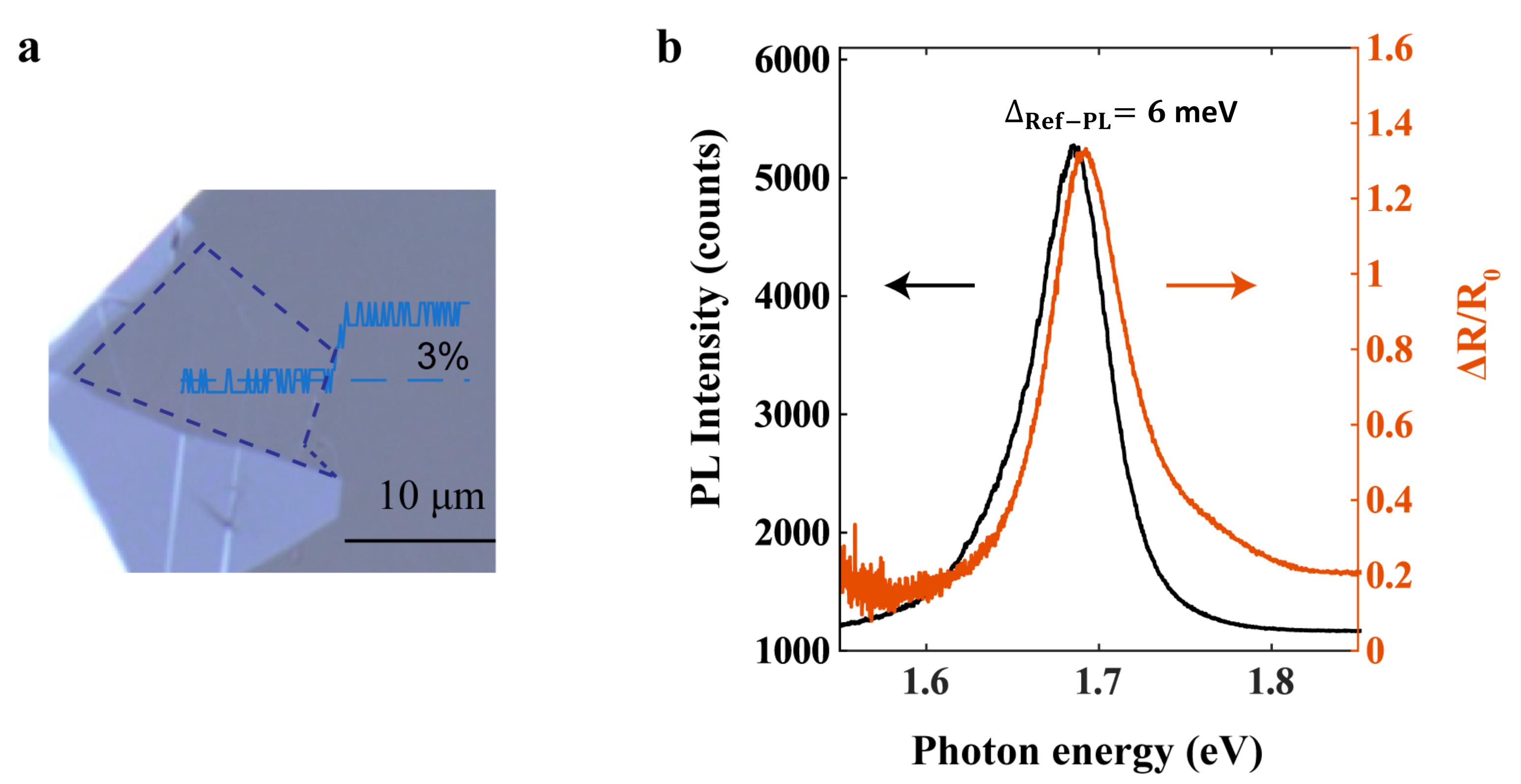
## Introduction

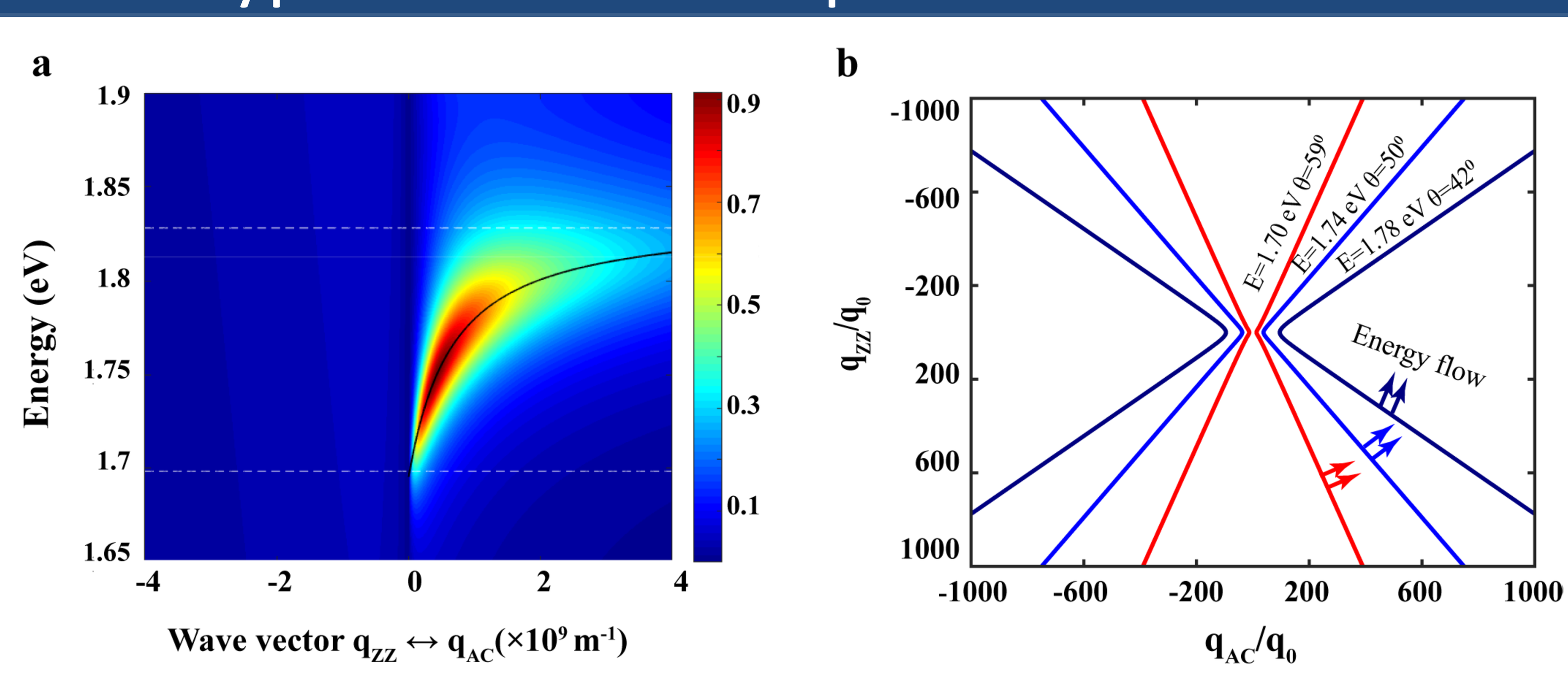
Two-dimensional (2D) materials provide rich platforms for 2D polaritons. In particular, some hyperbolic polaritons have been found to exist naturally, such as phonon-polaritons in $MoO_3$ and plasmon-polaritons in $WTe_2$. These materials exhibit strong in-plane anisotropy. Black phosphorus (BP) shows anisotropic band structure, making it a potential candidate for hyperbolic material. The tunable hyperbolic plasmon-polaritons in BP have been theoretically predicted. However, up to date, there is no experimental verification for such plasmon-polaritons in BP. All aforementioned 2D polaritons are based on either phonons or plasmons. Here, we experimentally demonstrate 2D natural hyperbolic exciton-polaritons in high quality monolayer BP, by fully determining the anisotropic dielectric function (optical conductivity) through optical spectroscopy. We also suggest that the propagating hyperbolic exciton-polariton in BP is highly tunable.

## High quality monolayer BP




- $\Delta_{\mathrm{Ref-PL}} = 6$ meV, the energy difference between reflection and photoluminescence (PL) imply the high quality of the monolayer BP.

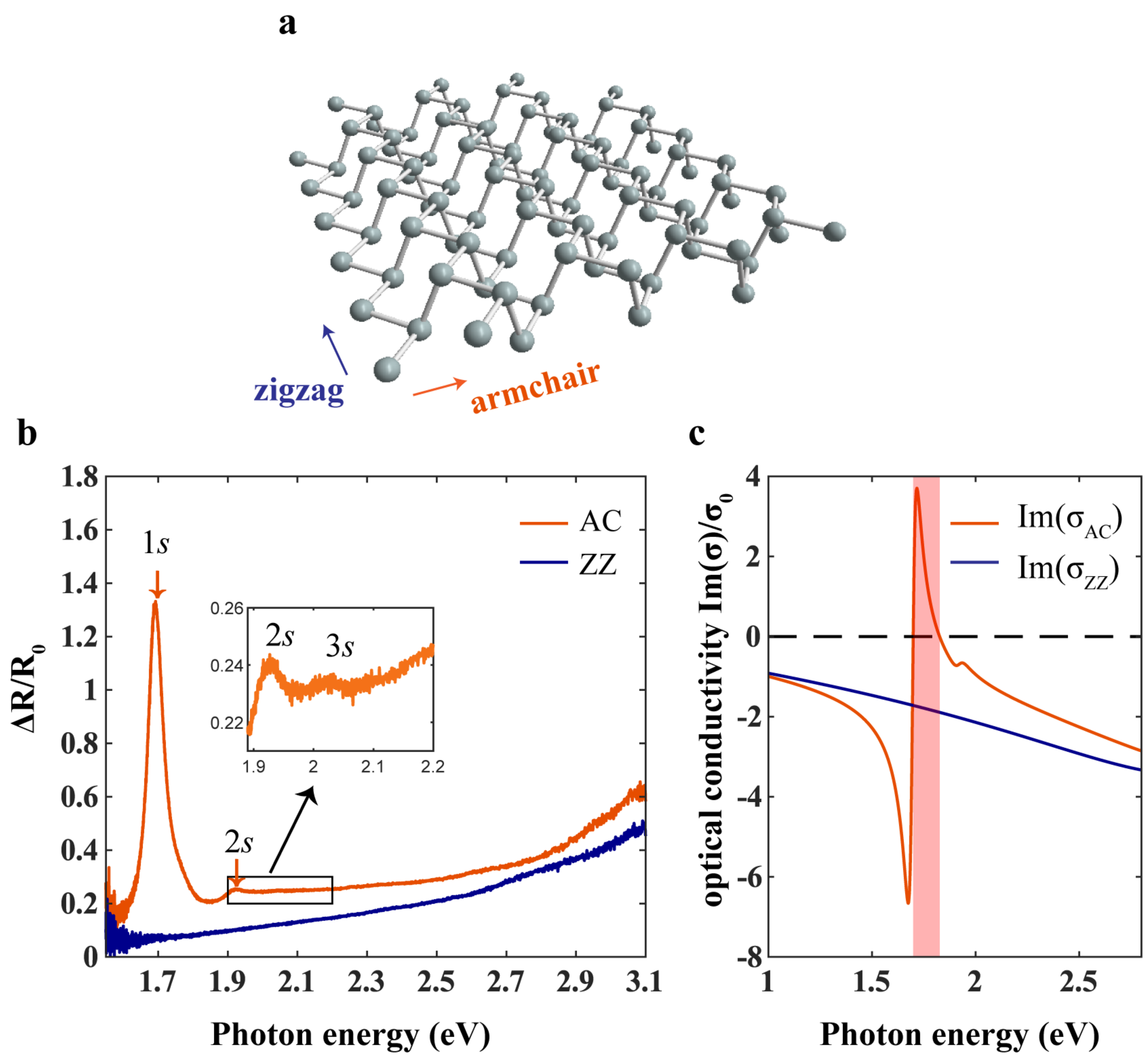
## Hyperbolic exciton-polariton modes




$$\varepsilon(\boldsymbol{q},\omega) = \varepsilon_{\mathrm{env}} + \frac{i(\sigma_{\mathrm{AC}}cos^2\theta + \sigma_{\mathrm{ZZ}}sin^2\theta)}{\varepsilon_0\omega}\frac{\boldsymbol{q}}{2}$$

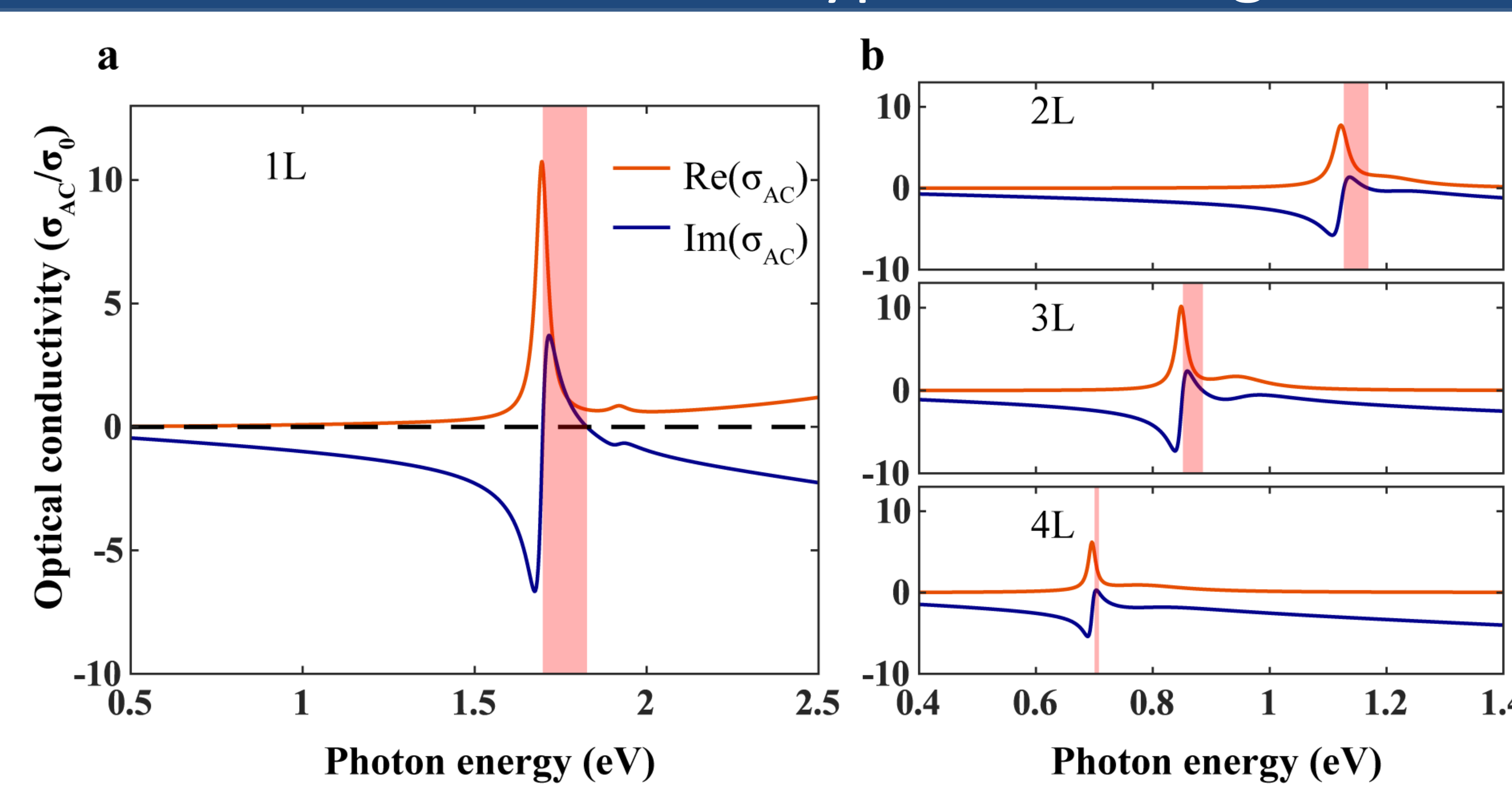
- The exciton-polariton modes exist only along AC direction.
- The hyperbolic exciton-polaritons show large wave vectors and ray-like propagation directions.

## Anisotropic optical conductivity




- $E_{2s} - E_{1s} = 230$ meV, the exciton binding energy is ~**452 meV**.
- $\mathrm{Im}(\sigma_{\mathrm{AC}}) \cdot \mathrm{Im}(\sigma_{\mathrm{ZZ}}) < 0$, indicating a regime supporting in-plane exciton-polaritons.

## Thickness tunable hyperbolic range




- $\mathrm{Im}(\sigma_{\mathrm{AC}}) \cdot \mathrm{Im}(\sigma_{\mathrm{ZZ}}) < 0$ regime (pink area) becomes narrower, and the onset shifts from visible to the near-infrared range, when the thickness increases from 1-layer to 4-layer.

## Summary

- The exciton binding energy of monolayer BP is ~**452 meV**.
- BP is a natural system to host tunable in-plane propagating hyperbolic exciton-polaritons.

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