Liao *et al.* Reply: Trackable numerical models are usually of limited applicability, yet often valuable for elucidating important aspects of a physical system or process. For the complex physical process of photoemission from surfaces by intense bursts of radiation, model-intrinsic uncertainties and limited predictability are largely unavoidable in physically transparent models. We thus appreciate the Comment by Krasovskii and Kuzian (KK) [1] correctly pointing to the limited accuracy of our analysis and numerical example in Ref. [2].

While reduced-dimensionality models based on a simplified representation of the solid electronic structure remain valuable for revealing photoemission mechanisms and can reproduce dominant features in time-resolved spectra (cf. [2–4] and references therein), we agree with KK that there is a need for large-scale numerical photoemission calculations based on accurate three-dimensional electronic structure models of the solid, in order to better account for the complicated many-electron dynamics during streaked or interferometric photoemission from surfaces. However, numerically simple models remain beneficial for their physical transparency. At the same time, photoemission models based on the static *ab initio* band-structure calculations discussed in the Comment by KK have to weigh increased accuracy against (i) a loss of physical transparency, (ii) significant numerical expense, and (iii) remaining modeling deficits. These deficits importantly include the inability of static band-structure calculations to account for the transient distortion of the solid (valence) electronic structure by the incident intense laser pulse.

In their comment KK question our use in Ref. [2] of momentum-dependent effective masses in a reduced dimensionality model for describing photoemission from bulk matter in general, and our analysis of photoelectron transport in solids based on the reduced-mass concept and a reduced-dimensionality numerical illustration in particular. KK organize their critical discussion of our model in three cases. We first note that case (i) is irrelevant within our model, since the absence of "propagating waves" in direction normal to the surface prohibits photoemission. Our concept cannot be applied to this case. With regard to case (ii), we point out that outgoing final waves are specified by their momentum (vector), not energy. Should several propagating Block states with the same energy contribute, they must have different momenta, both inside [as shown in Fig. 1(a) of the Comment at 31.6 eV] and outside the solid, and thus do not contribute to the same outgoing wave. Such superpositions can be disentangled in time- and angle-resolved photoemission spectra. Indeed, measured time- and angle-resolved photoemission spectra from Ni surfaces have revealed a strong dependence of photoemission phases (time delays) on the emission angle at a given energy (see Fig. 4 in [5]). In case (iii), the damped amplitude of the evanescent wave does not directly influence the phase accumulation during propagation.

We would like to emphasize that time delay measurements in streaked or interferometric photoemission experiments have commonly been interpreted with reference to (the not directly observable) photoelectron transport in the solid target while, to our knowledge, photoelectron transport times have not been clearly related to the directly observable phase (difference) information. Equation (1) in Ref. [2] provides this missing link based on the decisively different effect of photoelectron energy-momentum dispersion on the active electron's phase and group velocity. For clarity this link is illustrated in Ref. [2] with a simple trackable numerical example in reduced dimensionality and based on an effective photoelectron mass that derives from an assumed parabolic dispersion relation. As KK admit in their Comment, "the concept of photoelectron phase and effective mass are plausible for one-dimensional models.". Clearly, the degree to which predictions from one-dimensional models and Eq. (1) in Ref. [2] are applicable to real (strong-field dressed three-dimensional solids) remains to be seen. Since one-dimensional numerical models have been applied with some success to model time-resolved photoemission from surfaces in the past ([3,4] and references therein) and in view of the arguments at the beginning of our Reply, we (i) disagree with the conclusion of KK that the concept of photoelectron phase and effective mass … are inapplicable to real solids" and (ii) find the statement by KK that for the "cases (i)—(iii) Eq. (1) becomes inapplicable" overstated and inappropriate.

Qing Liao, Wei Cao, Qingbin Zhang, Kai Liu, Feng Wang, Peixiang Lu and Uwe Thumm

Received 21 January 2021; accepted 28 January 2021; published 11 March 2021

DOI: 10.1103/PhysRevLett.126.109304

[1] E. E. Krasovskii and R. O. Kuzian, preceding Comment, Comment on Distinction of Electron Dispersion in Time-Resolved Photoemission Spectroscopy, Phys. Rev. Lett. **126**, 109303 (2021).

[2] Q. Liao, W. Cao, Q. Zhang, K. Liu, F. Wang, P. Lu, and U. Thumm, Distinction of Electron Dispersion in Time-Resolved Photoemission Spectroscopy, Phys. Rev. Lett. **125**, 043201 (2020).

[3] M. J. Ambrosio and U. Thumm, Spatiotemporal analysis of a final-state shape resonance in interferometric photoemission from Cu(111) surfaces, Phys. Rev. A **100**, 043412 (2019).

[4] Q. Liao and U. Thumm, Attosecond time-resolved streaked photoemission from Mg-covered W(110) surfaces, Phys. Rev. A **92**, 031401(R) (2015).

[5] Z. Tao, C. Chen, T. Szilvási, M. Keller, M. Mavrikakis, H. Kapteyn, and M. Murnane, Direct time-domain observation of attosecond final-state lifetimes in photoemission from solids, Science **353**, 62 (2016).

