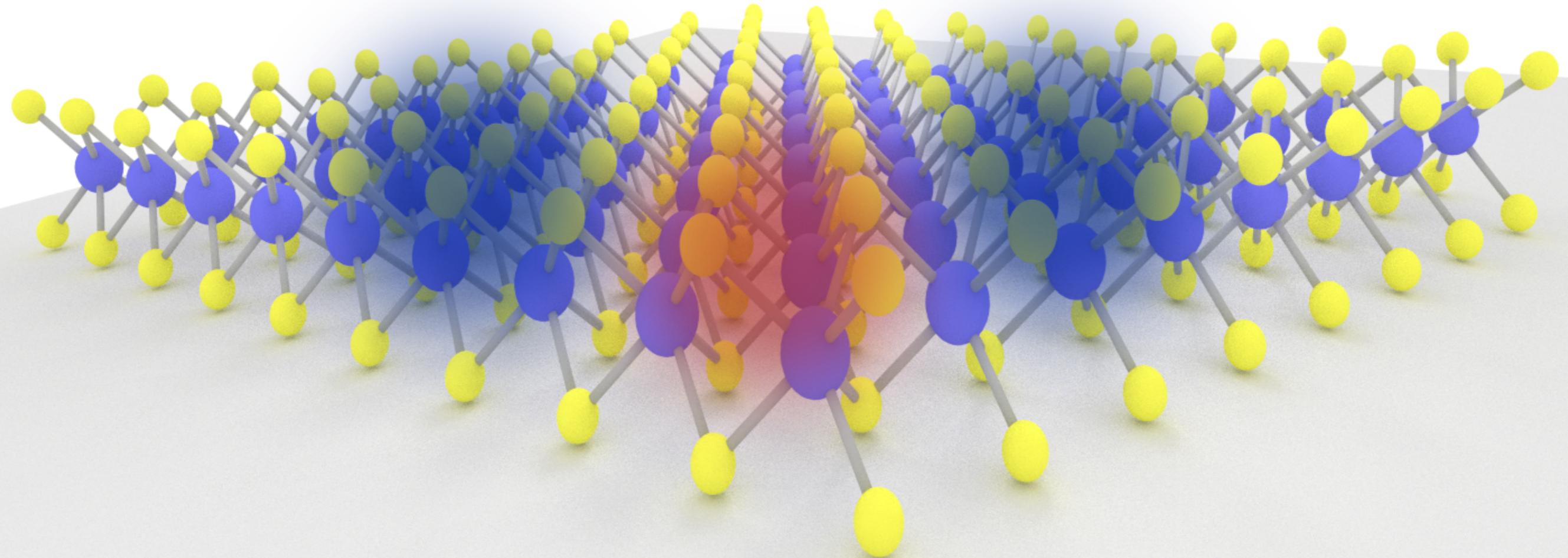


TMDCs: Fast relaxation, dark excitons and semi-dark triions

Mark Danovich

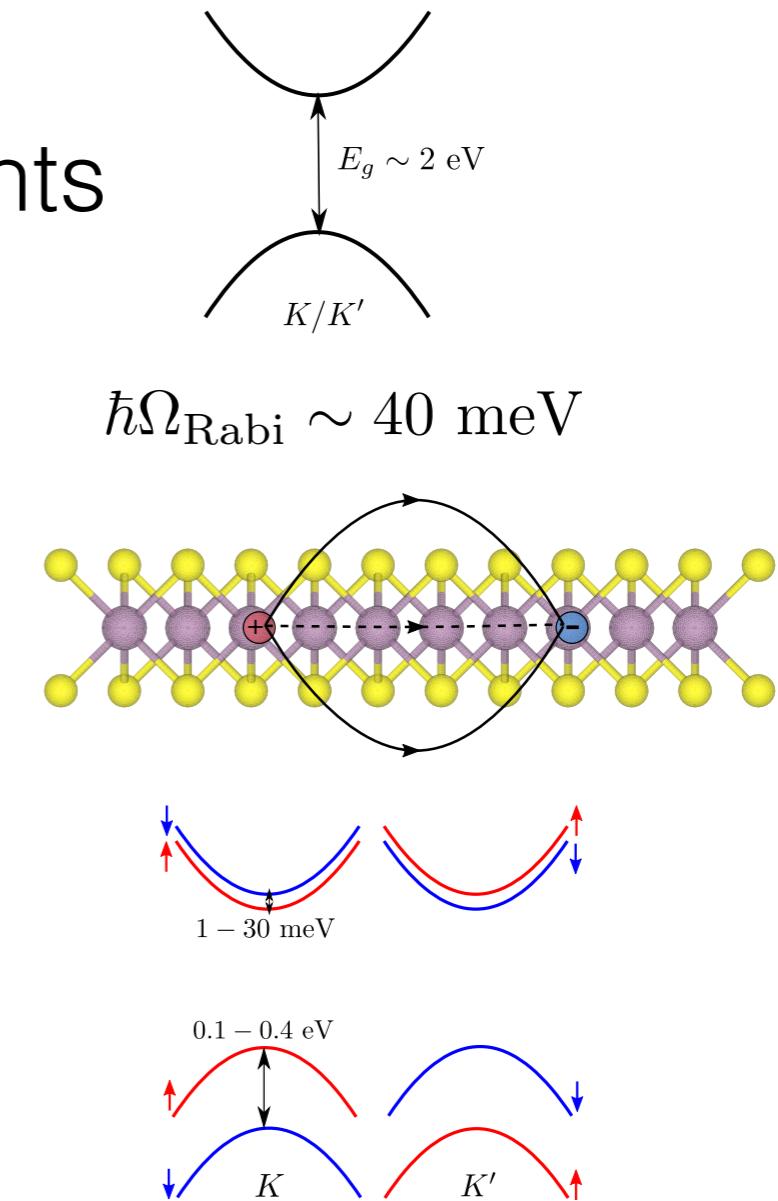
The University of Manchester



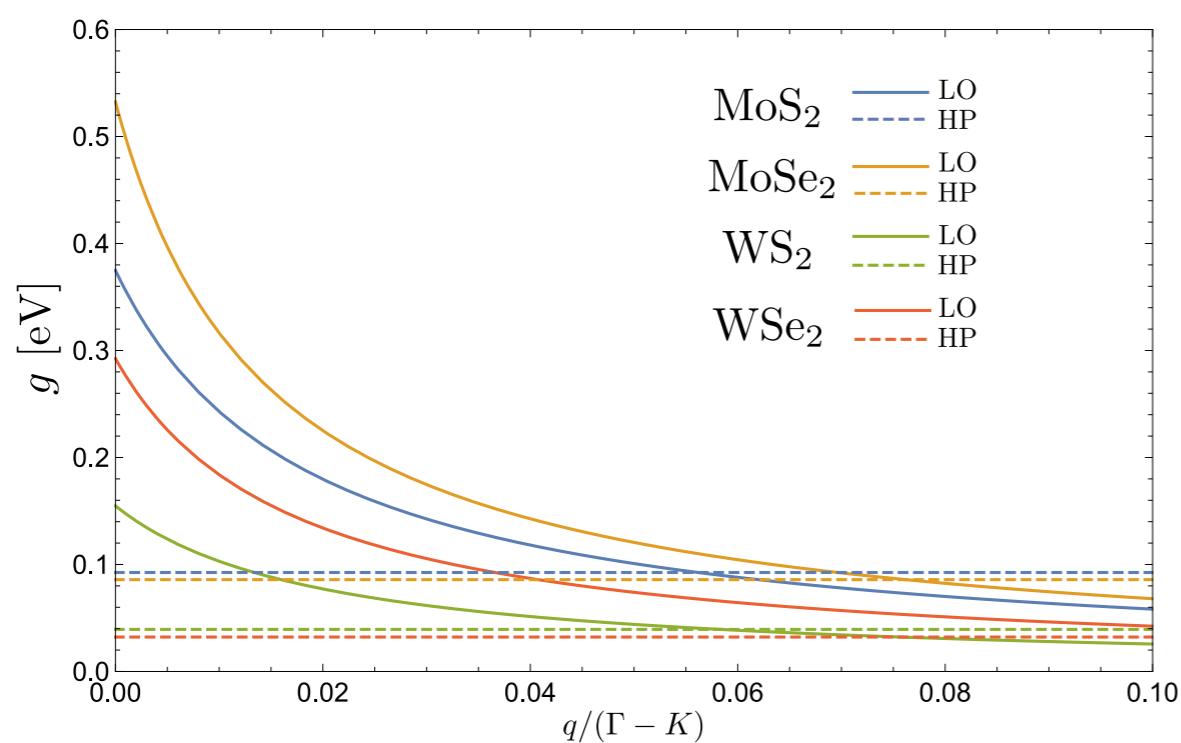
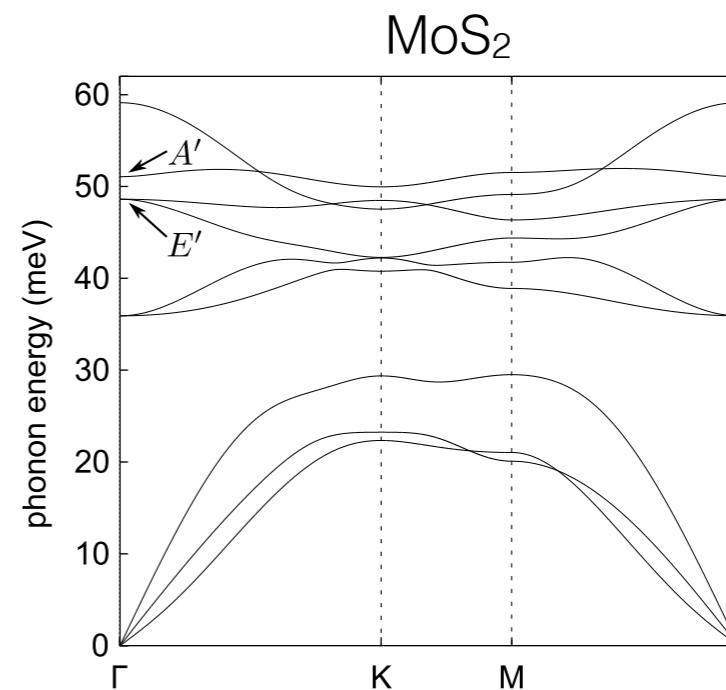
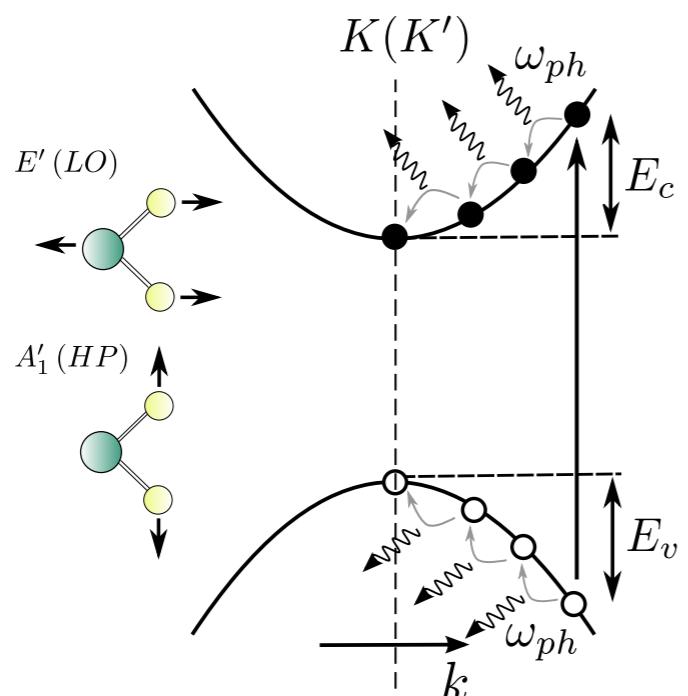
Cambridge, 17/02/17

TMDCs: Key features

- Direct band gap at the K/K' points
- Strong light-matter interaction
- Enhanced Coulomb interaction
- Strong spin-orbit coupling
- Lack of inversion symmetry



1. Fast relaxation of photo excited carriers

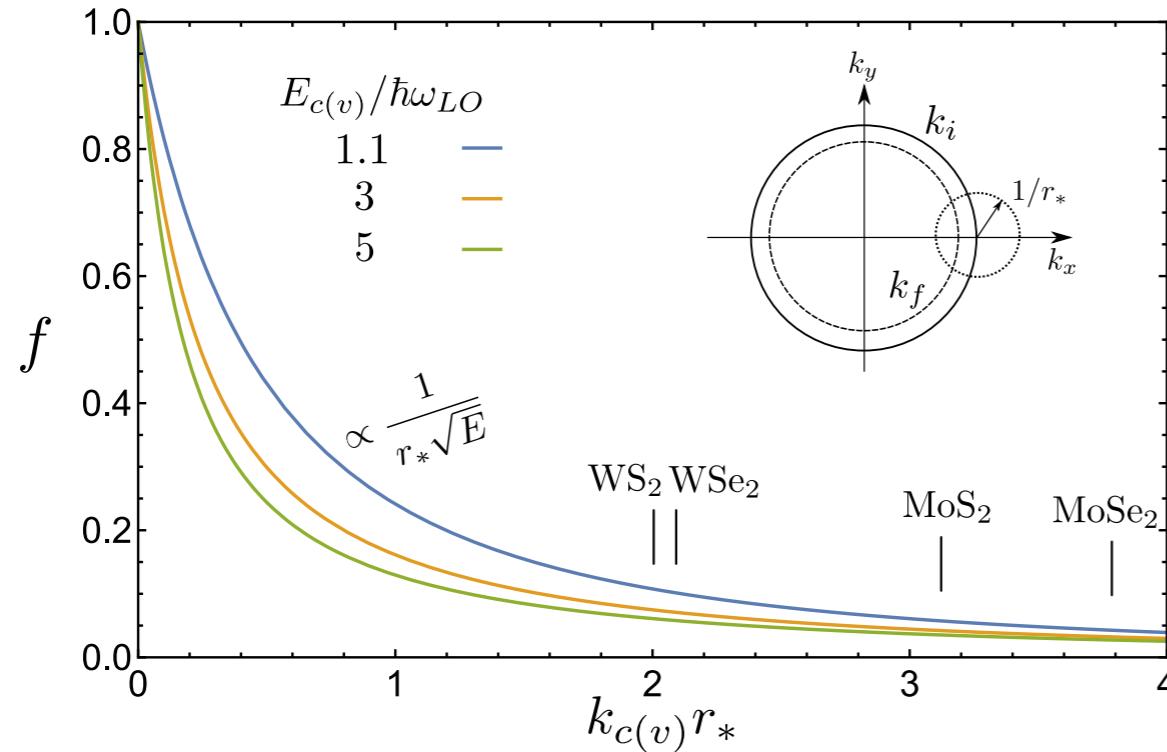


effective charge $\sim 0.5 - 1.8$

$$|g_{LO}| = \frac{1}{A} \sqrt{\frac{\hbar}{2M_r\omega_{LO}}} \frac{Ze^2}{1 + qr_*}$$

$$|g_{HP}| = \sqrt{\frac{\hbar}{2M\omega_{HP}}} D$$

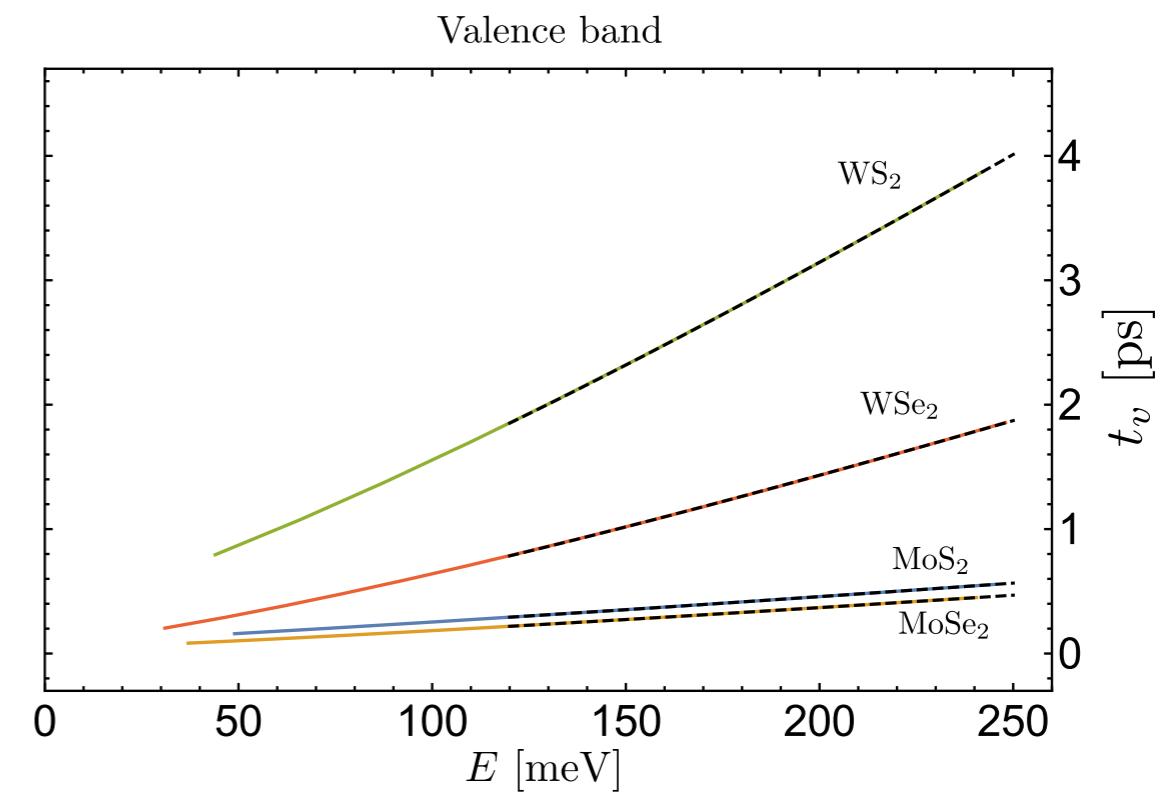
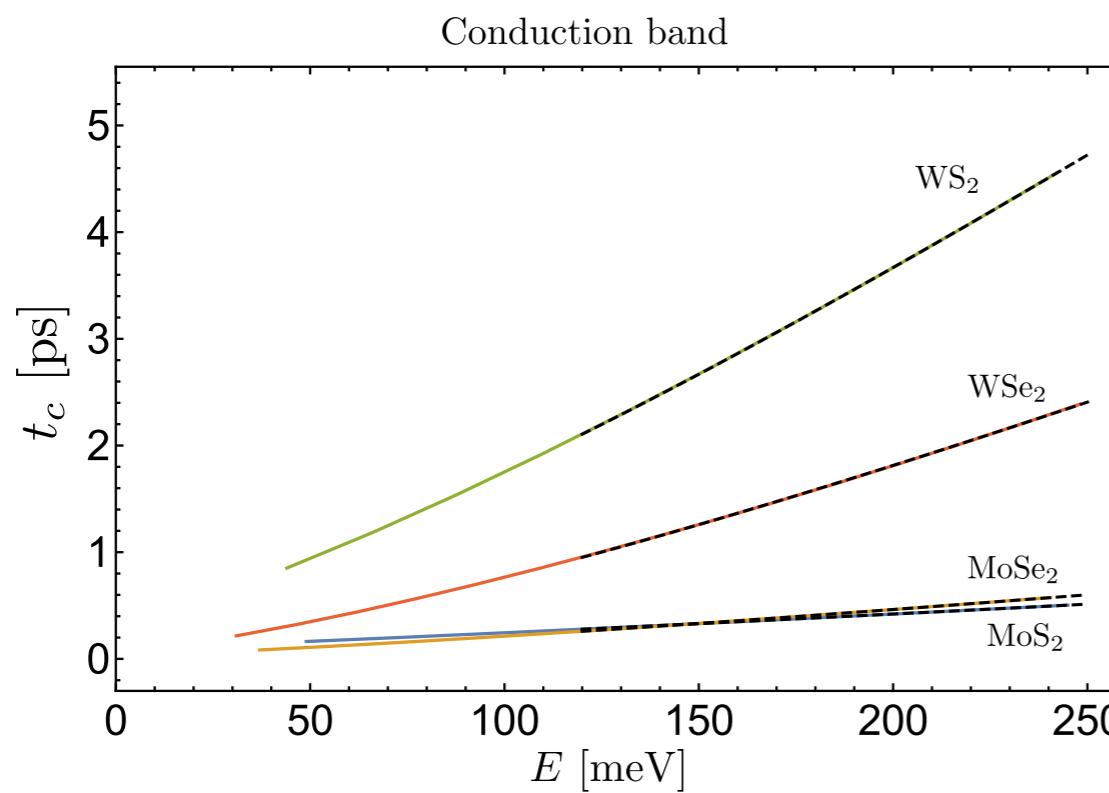
Scattering rates



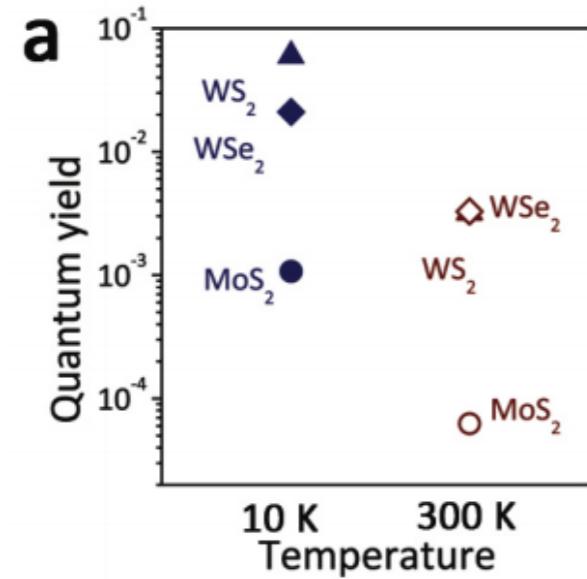
$$\tau_{LO}^{-1} = (10 - 300) \times f\left(\frac{E}{\hbar\omega_{LO}}, kr_*\right) \text{ ps}^{-1}$$

$$\tau_{HP}^{-1} \sim 0.5 - 7 \text{ ps}^{-1}$$

Cooling times

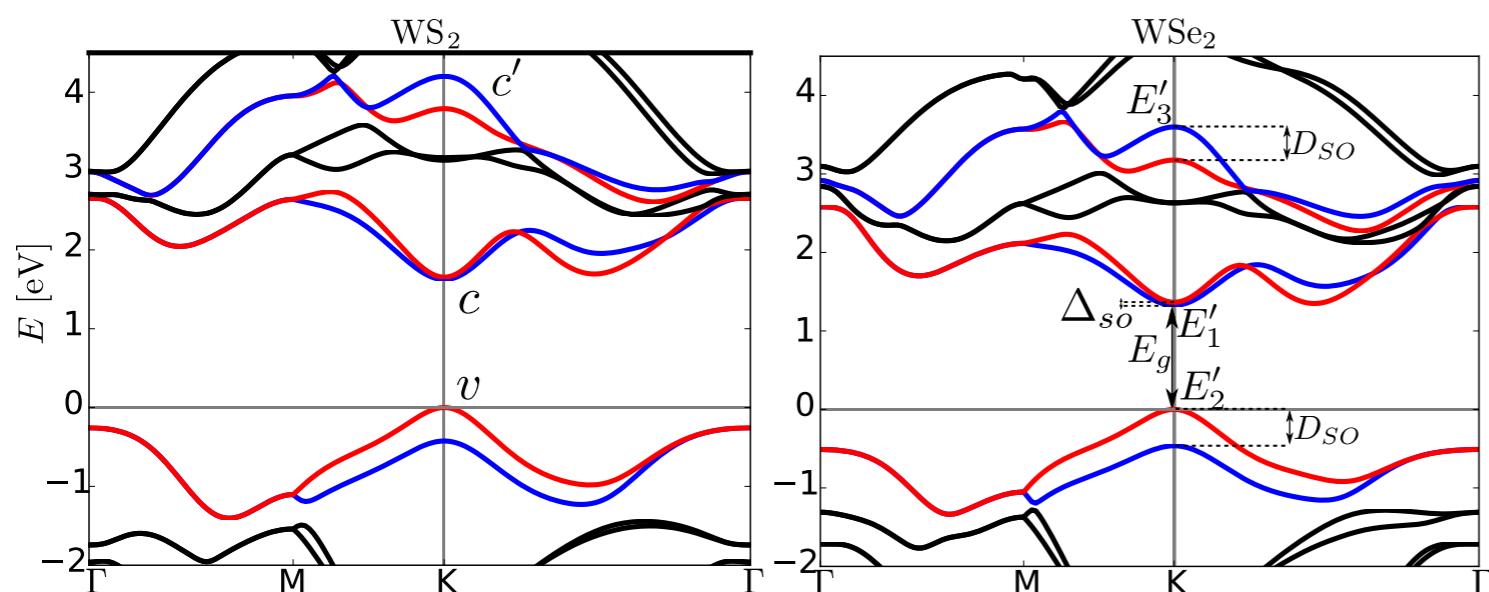


2. Auger recombination of dark excitons in WS₂ and WSe₂

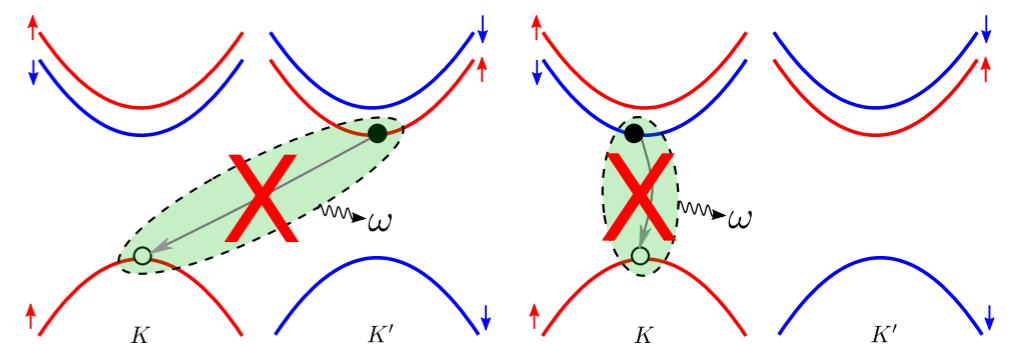


Low quantum yield -
Material specific process?

Nature Photonics, 9, 733-737, 2015

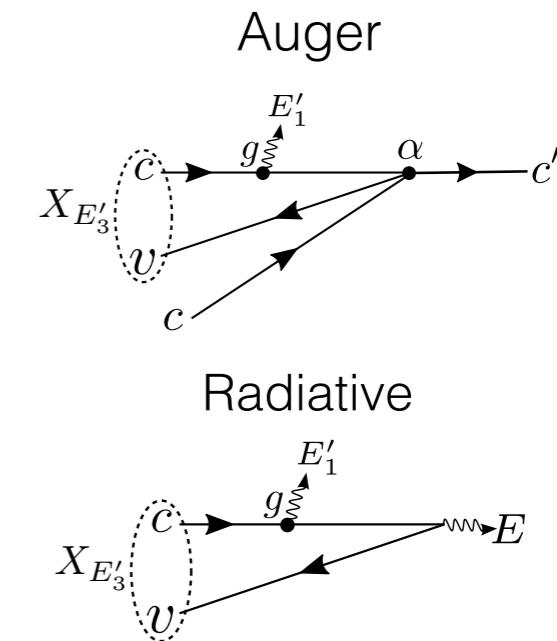
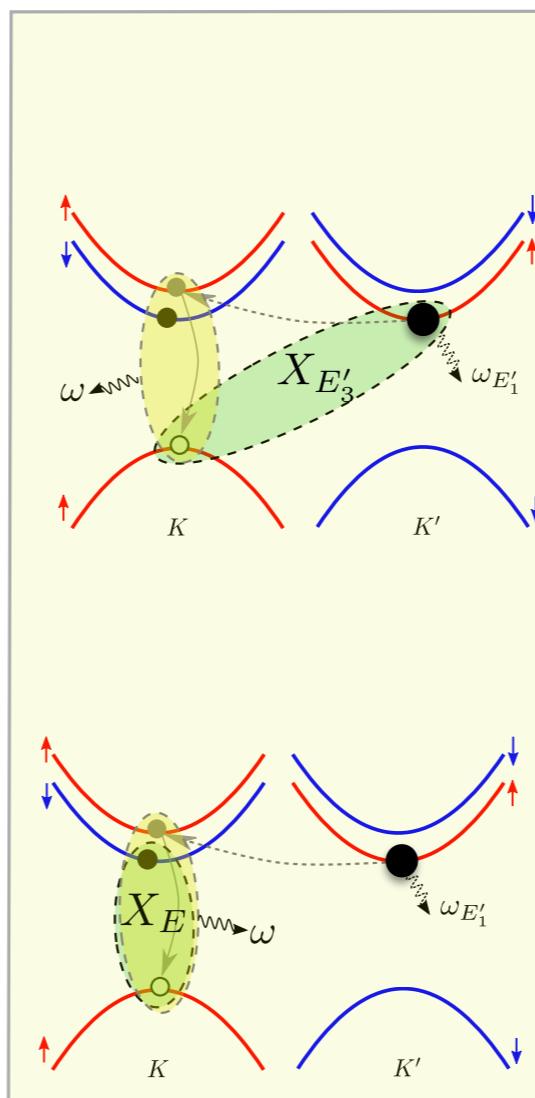
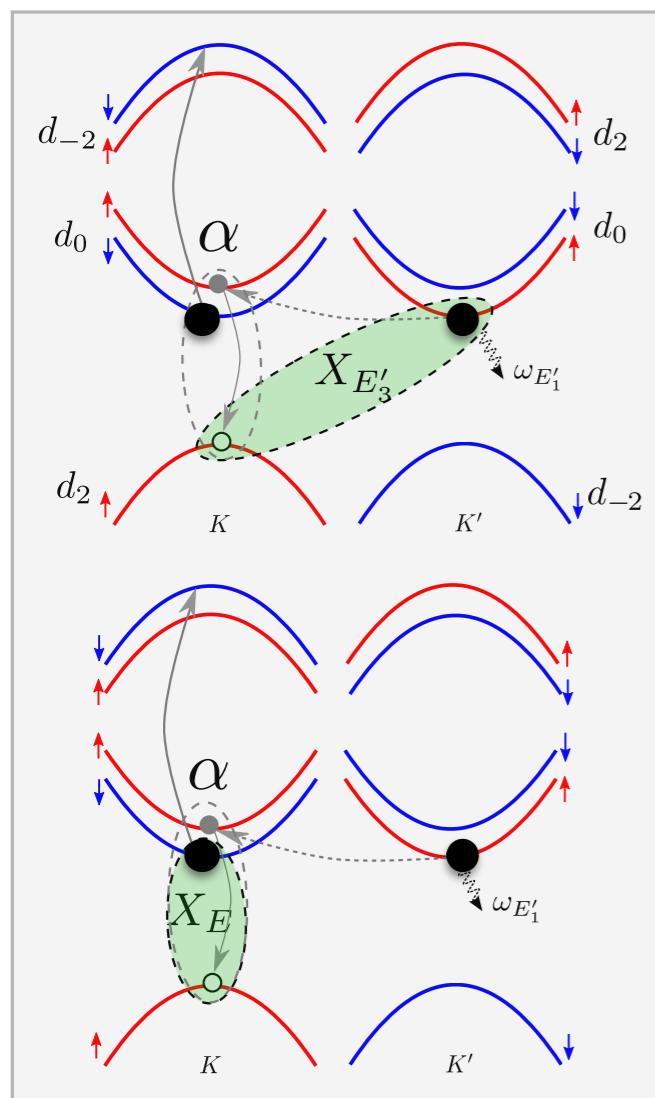


Dark ground state
excitons



Auger

Radiative



g - electron-phonon coupling

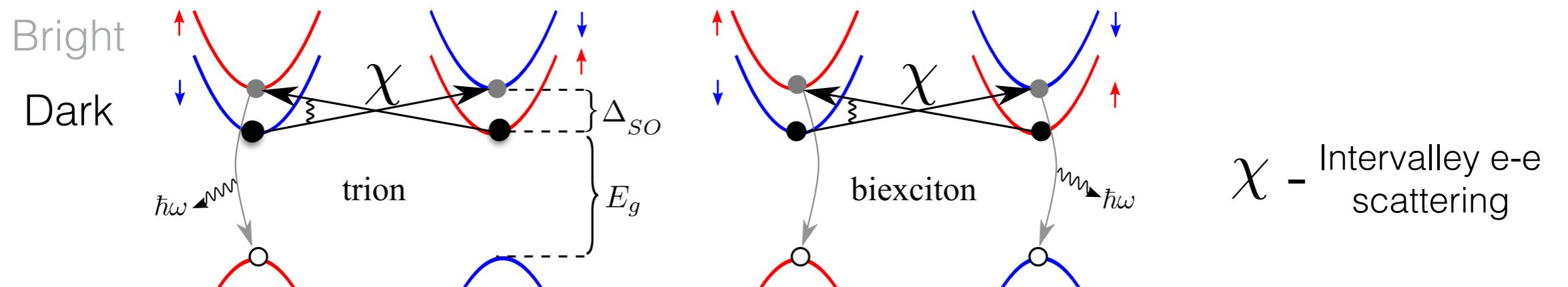
α - e-e intravalley-interband scattering

$$\tau_{Auger}^{-1} > \tau_{Radiative}^{-1} \rightarrow n_e > n_e^*$$

$$n_e^*(\text{WS}_2) \sim 10^{10} \text{ cm}^{-2}$$

$$n_e^*(\text{WSe}_2) \sim 4 \times 10^9 \text{ cm}^{-2}$$

3. Semi-dark trions and biexcitons



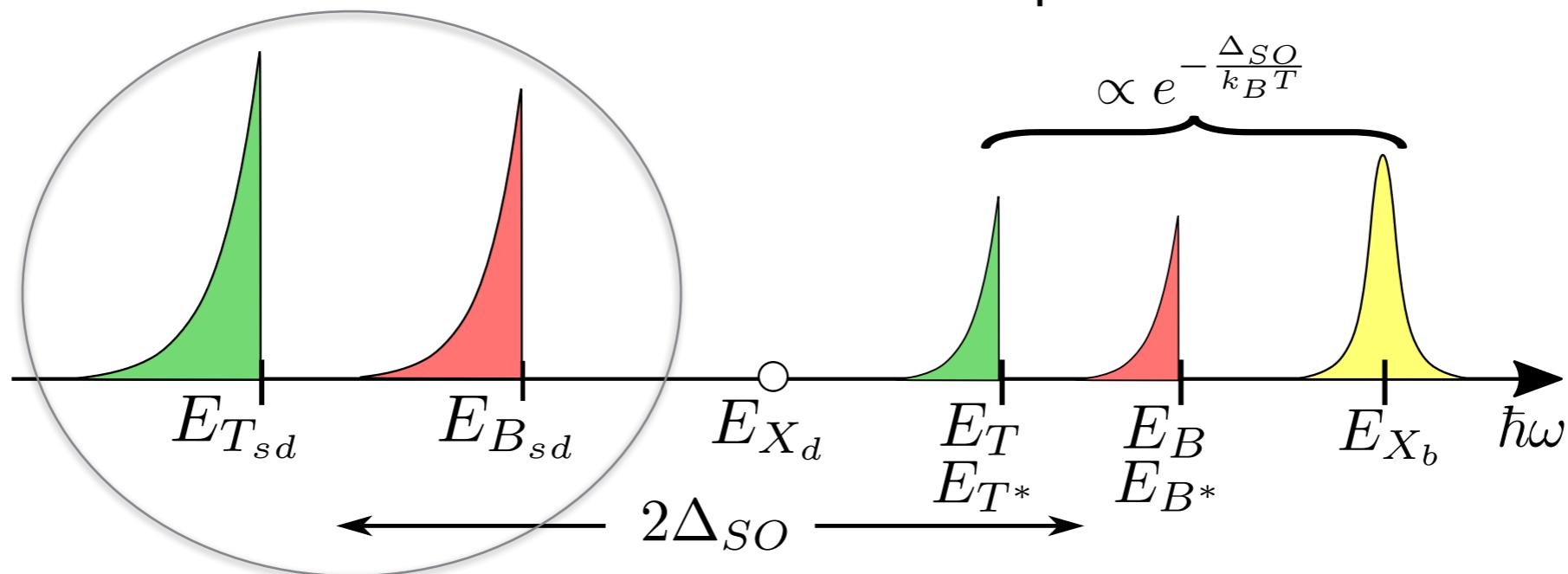
$$H = \begin{pmatrix} E_{bright} & \mu \\ \mu^* & E_{dark} \end{pmatrix} \rightarrow \tau^{-1} \approx \left(\frac{\mu}{2\Delta_{SO}} \right)^2 \eta \tau_X^{-1}$$

$$\mu \propto g_{ee}\chi$$

Radiative lifetimes

| | χ_{DFT} | χ_{TB} | μ_T [meV] | μ_B [meV] | τ_X [ps] | $\tau_{sd}(T)$ [ps] | $\tau_{sd}(B)$ [ps] |
|------------------|--------------|-------------|------------------|------------------|------------------|------------------------|------------------------|
| WS ₂ | 1.0 | 1.6 | 18 [29] | 13 [21] | 0.25 | 7.7 [3.9] | 10 [4.5] |
| WSe ₂ | 1.3 | 2.0 | 19 [30] | 14 [22] | 0.26 | 9.1 [4.7] | 12 [5.7] |

Photoluminescence spectrum



Summary

- Fast relaxation of carriers due to LO and HP phonons.
- Phonon assisted Auger process kills dark excitons in WX_2 .
- Dark trions in WX_2 are made bright by intervalley electron-electron scattering.