Modulation of Attosecond Beating in Resonant Two-Photon Ionization

Control of Ultrafast Quantum Phenomena
May 21st, Nordita, Stockholm, Sweden, EU

Luca Argenti
Autonomous University of Madrid
Madrid, Spain, EU

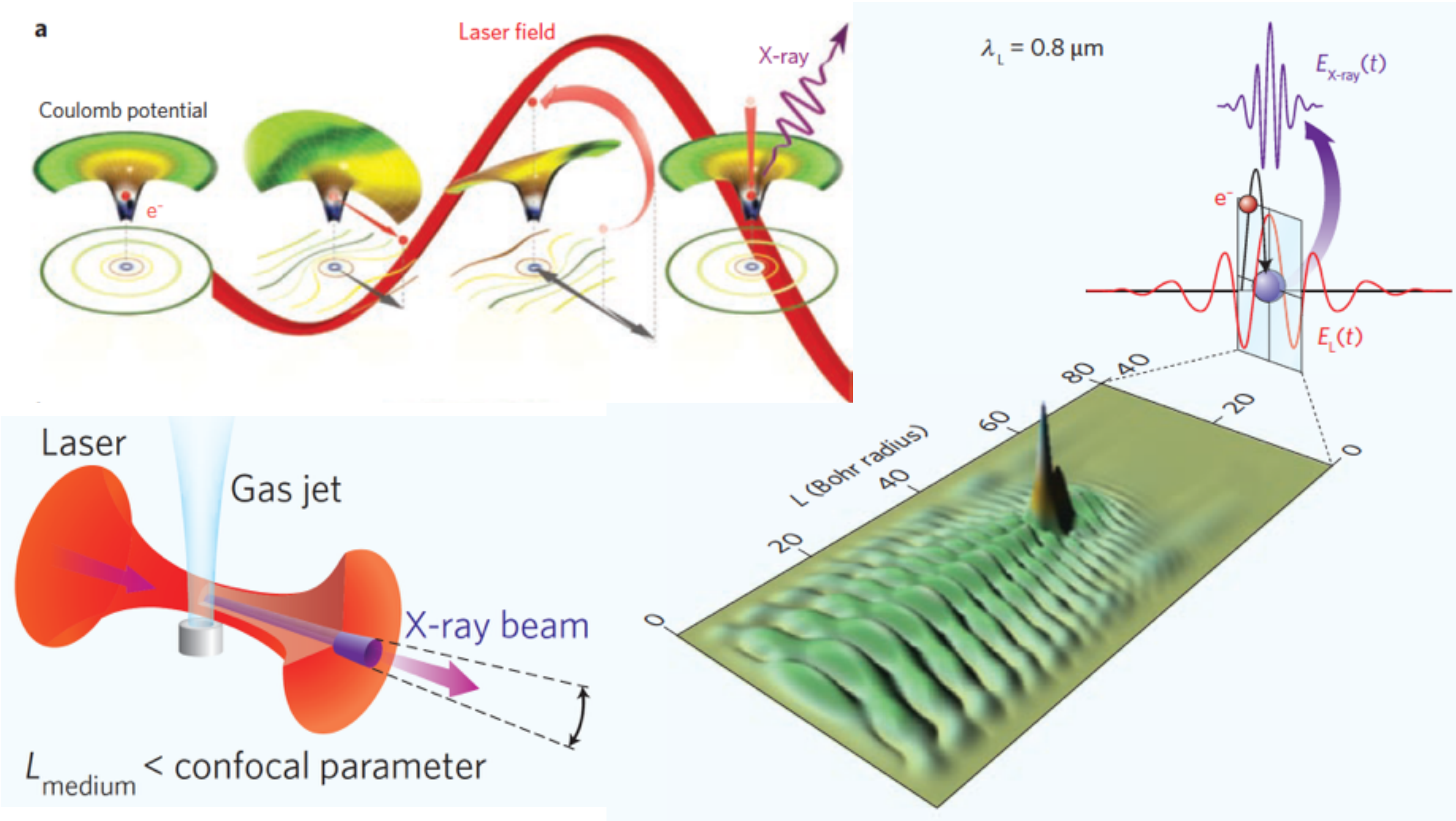
XChem
Lasers for Ultrafast Control

Outline

- Short reminder of RABITT spectroscopy
- Outline of the resonant two-photon finite-pulse model
- Extension to the multichannel case and comparison with experiment in argon
- Conclusions

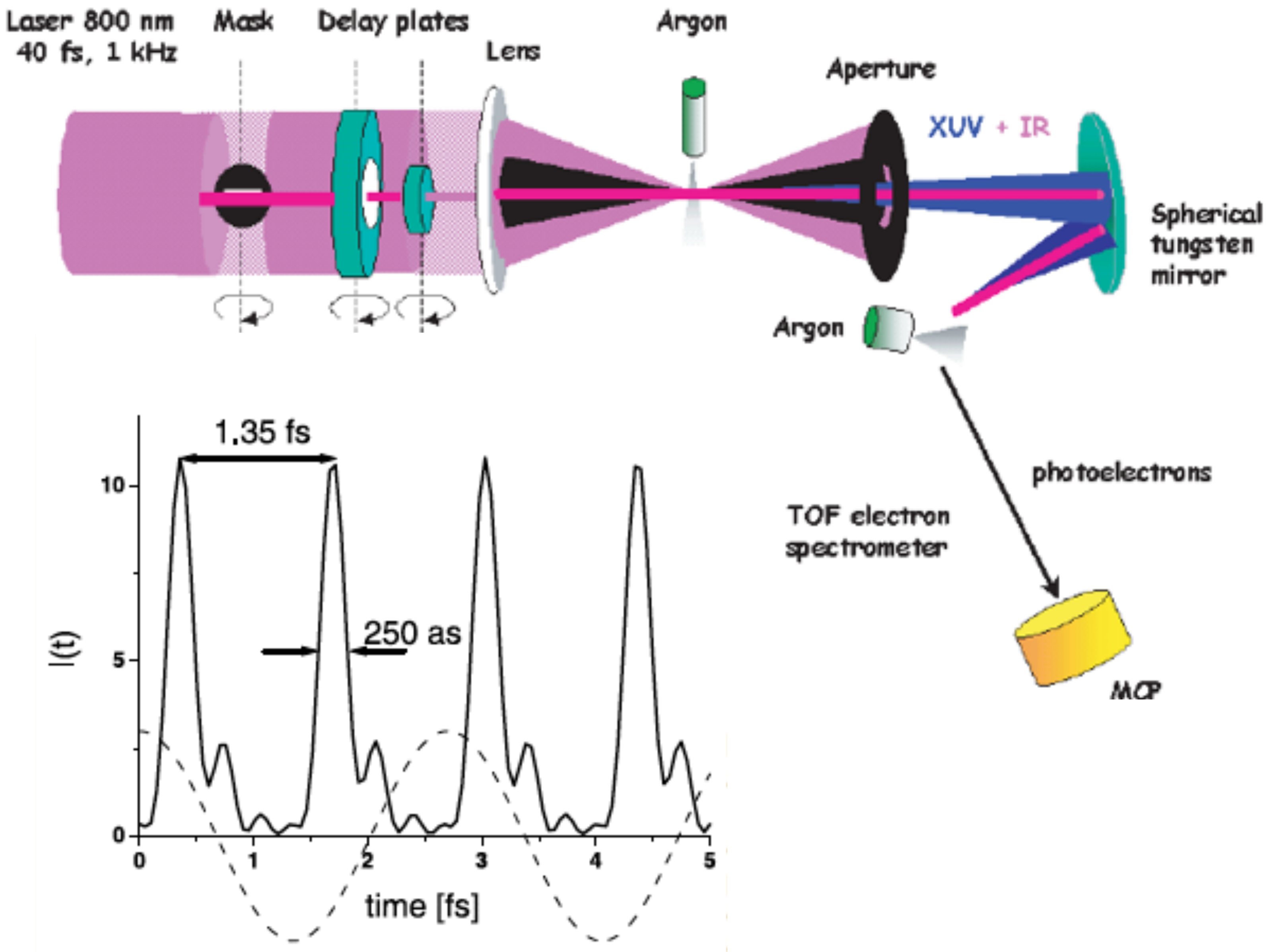
10:00

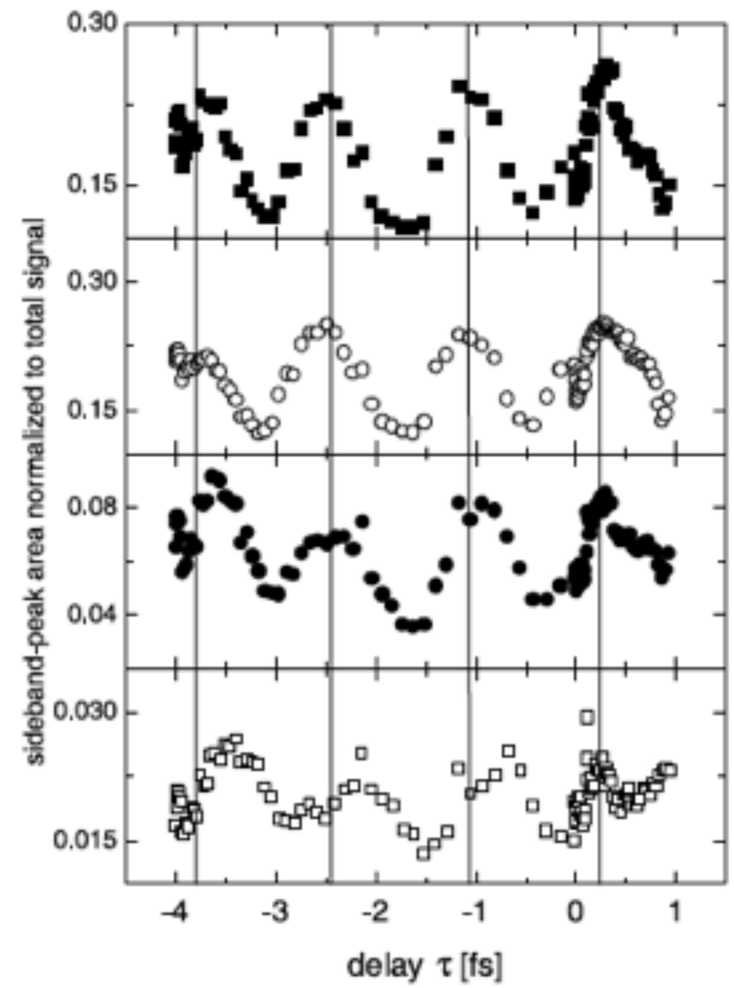
High Harmonic Generation



T. Popmintchev *et al.*, Nature Photonics **4**, 822 (2010)

Attosecond Pulse Trains

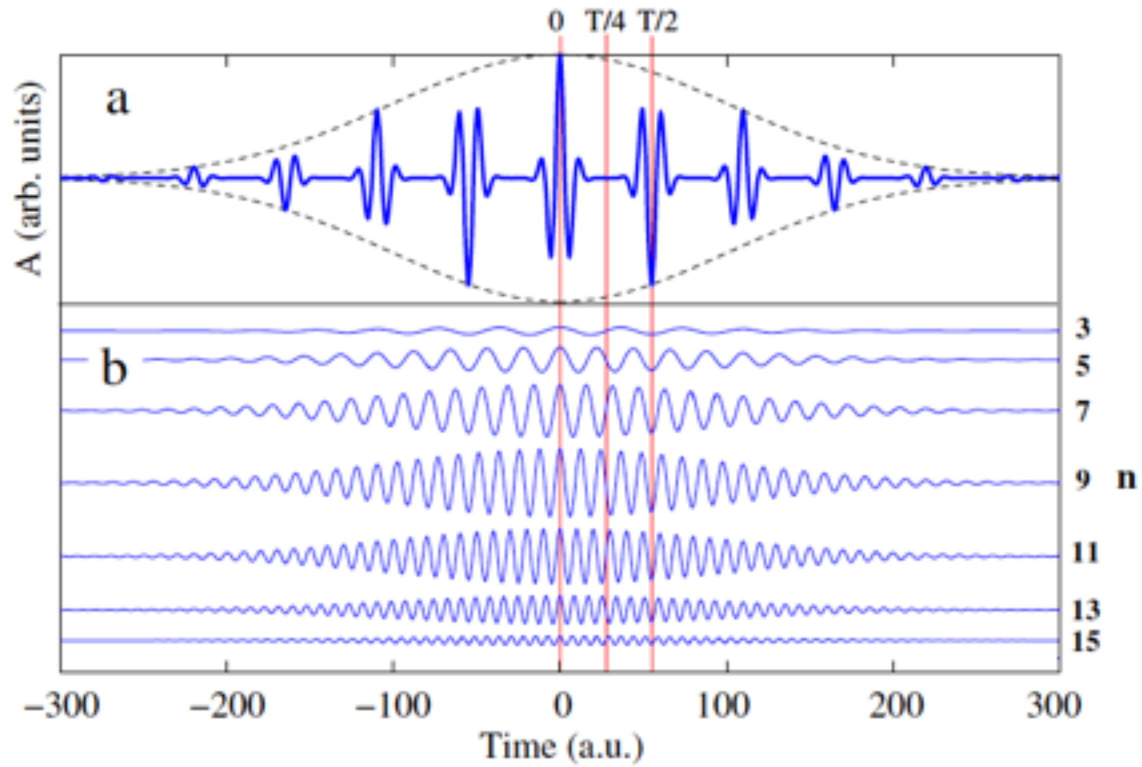


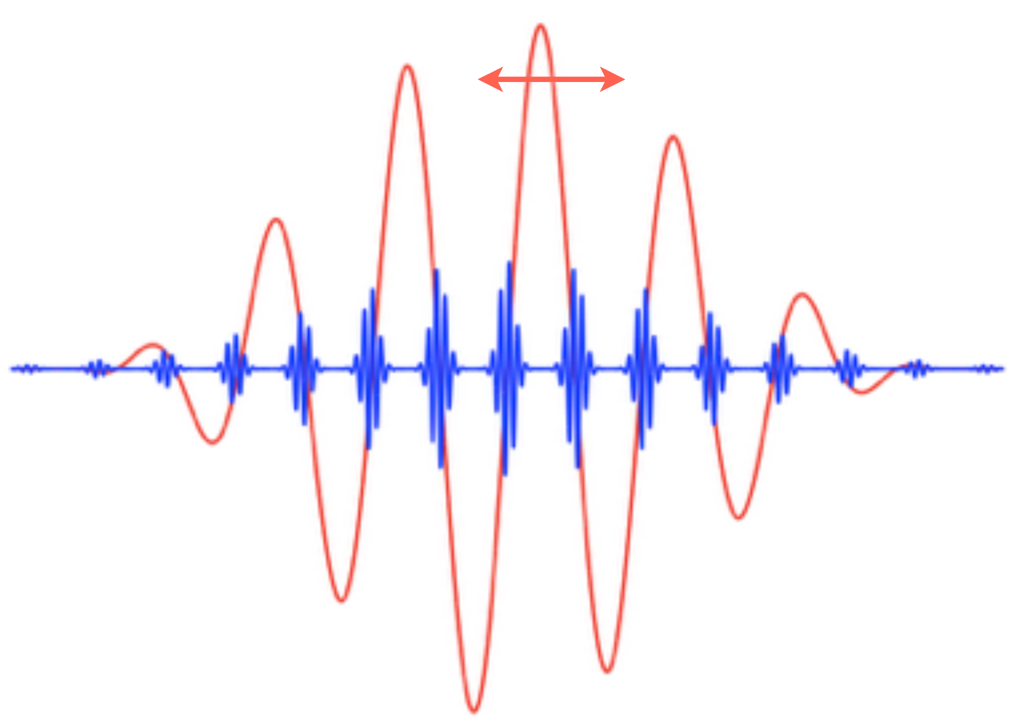


P. M. Paul *et al.*, Science **292**, 1689 (2001)

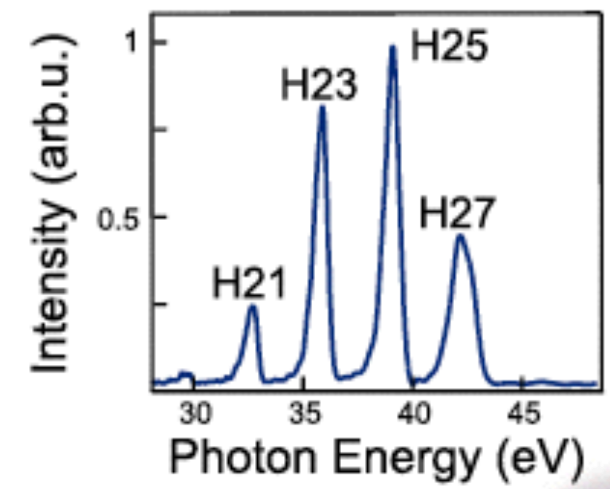
Reconstruction of Attosecond Beating By Two photon transitions (RABBIT)

$$\Delta\phi_{2n} \equiv \phi_{2n+1} - \phi_{2n-1}$$



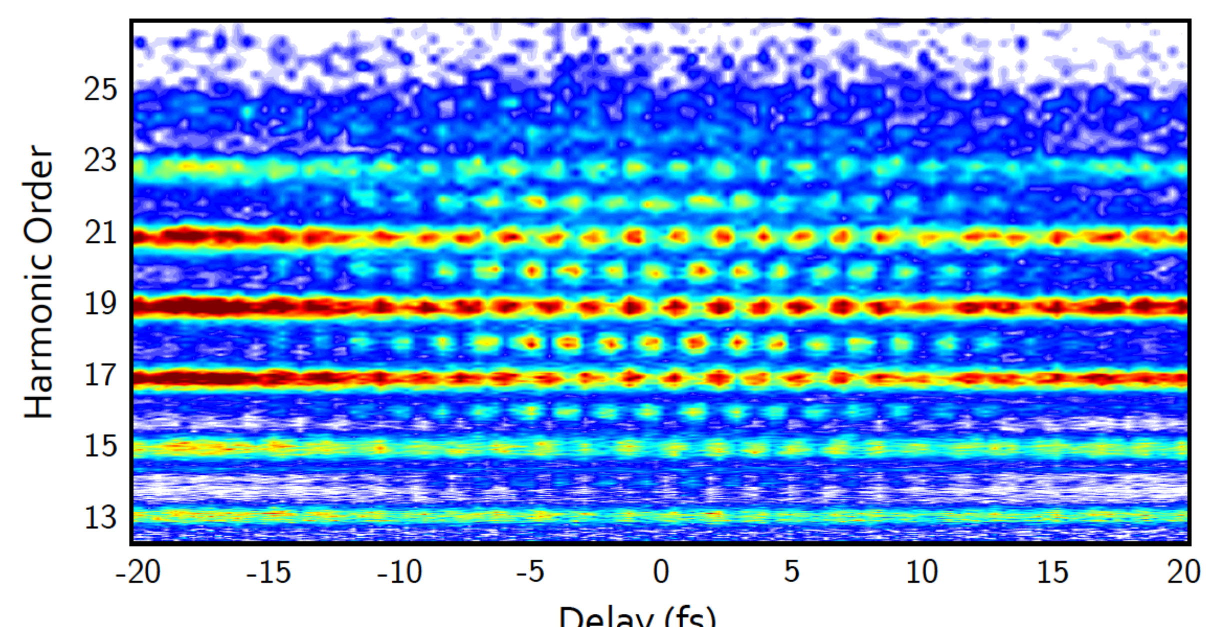


$A + \gamma_{Hn} \longrightarrow A^+ + e^-$



K. Klünder *et al.*, PRL **106**, 143002 (2011)

$A + \gamma_{Hn} \pm \gamma_{IR} \longrightarrow A^+ + e^-$

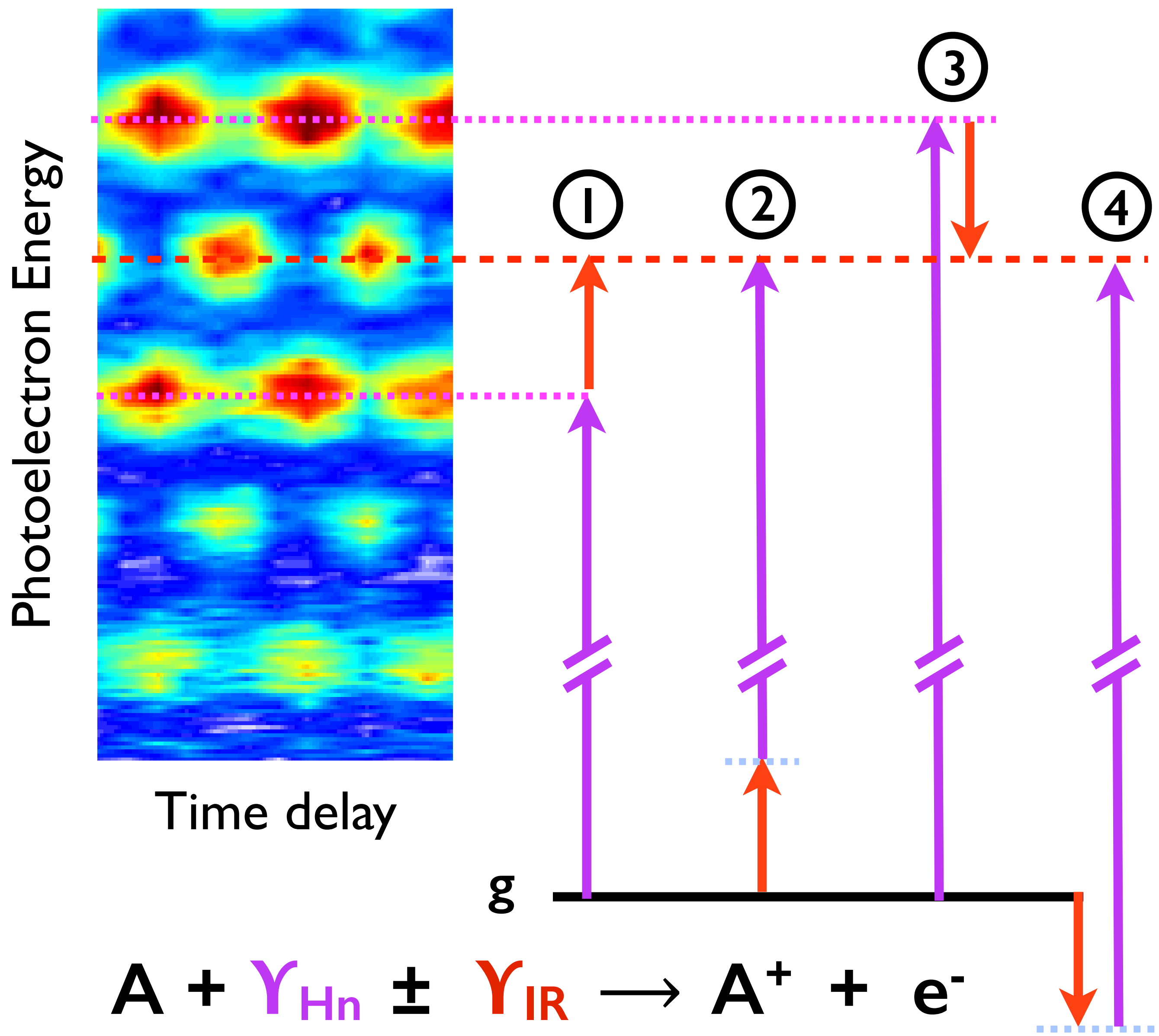


M. Swoboda, PhD Thesis, Lund (2010)

The principle of RABBIT

$$\Delta\mathcal{W}^{(2)}_{2n\omega} \propto |\mathcal{M}_{2n-1}\mathcal{M}_{2n+1}|\,\cos\left(\,2\,\omega_{\rm IR}\tau - \Delta\phi_{2n} - \Delta\varphi^{At}_{2n}\,\right)$$

$$\mathcal{M}_{2n\pm1} = \langle E|\,\mathcal{O}\left[G_0^+(\omega_g \mp \omega_{\rm IR}) + G_0^+(\omega_g + \omega_{2n\pm1})\right]\mathcal{O}\,|g\rangle$$



Resolvent

$$G_0^+(\omega) = (\omega - H_0 + i0^+)^{-1}$$

Harmonic Phase

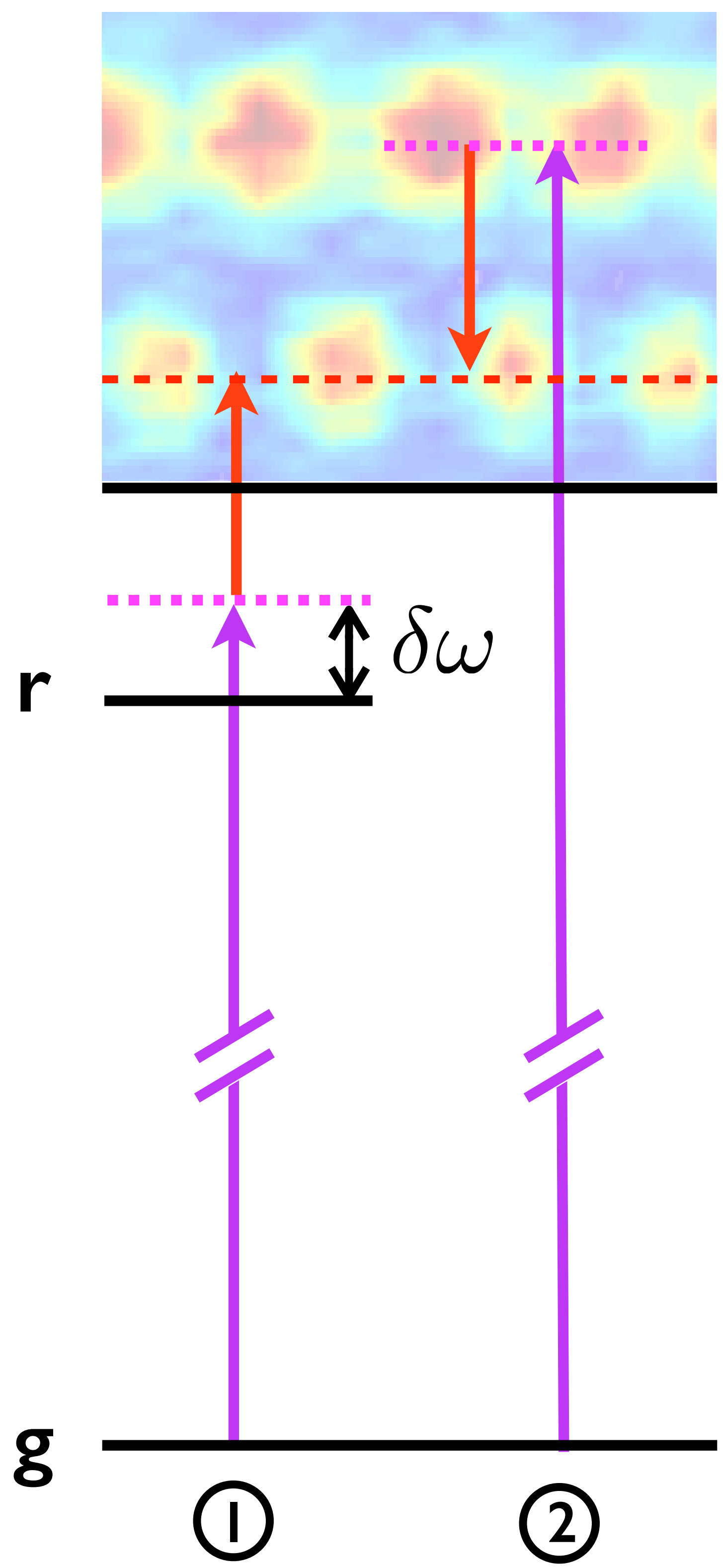
$$\Delta\phi_{2n} \equiv \phi_{2n+1} - \phi_{2n-1}$$

Atomic Phase

$$\varphi^{\rm At}_n = \arg\mathcal{M}_n$$

$$\Delta\varphi^{\rm At}_{2n} = \varphi^{\rm At}_{2n+1} - \varphi^{\rm At}_{2n-1}$$

What if one paths is resonant?

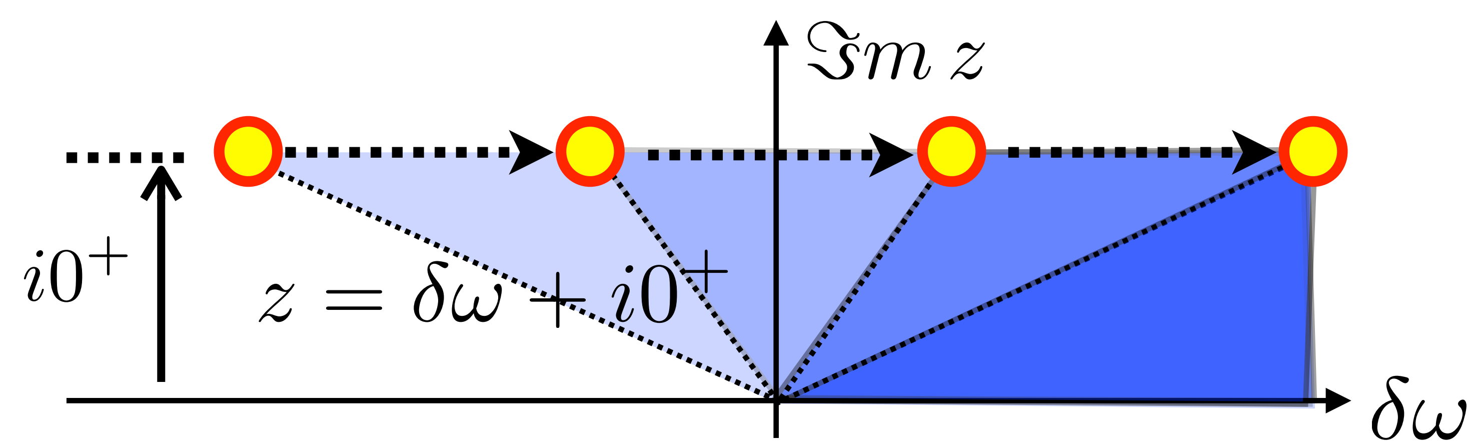


1 $\begin{cases} A + \gamma_{2n-1} \longrightarrow A^{*}\,(r) \\ A^{*}(r) + \gamma_{IR} \longrightarrow A^{+} + e^{-} \end{cases}$

2 $A + \gamma_{2n+1} \longrightarrow A^{+} + e^{-} + \gamma_{IR}$

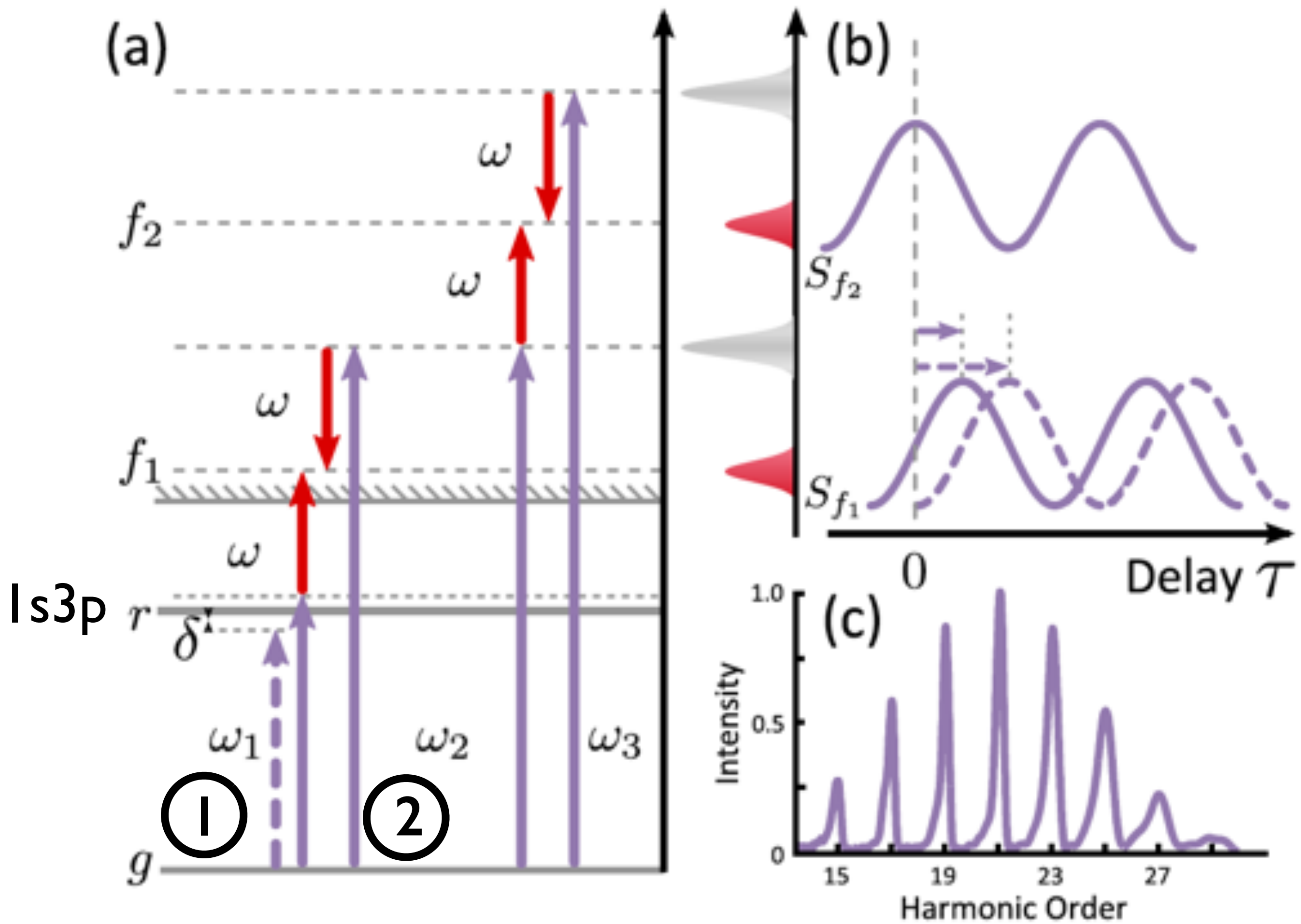
$$\mathcal{M}_{2n-1} \simeq \langle E|\, \mathcal{O}\, G_0^{+}(\omega_g + \omega_{2n-1})\, \mathcal{O}\, |g\rangle$$

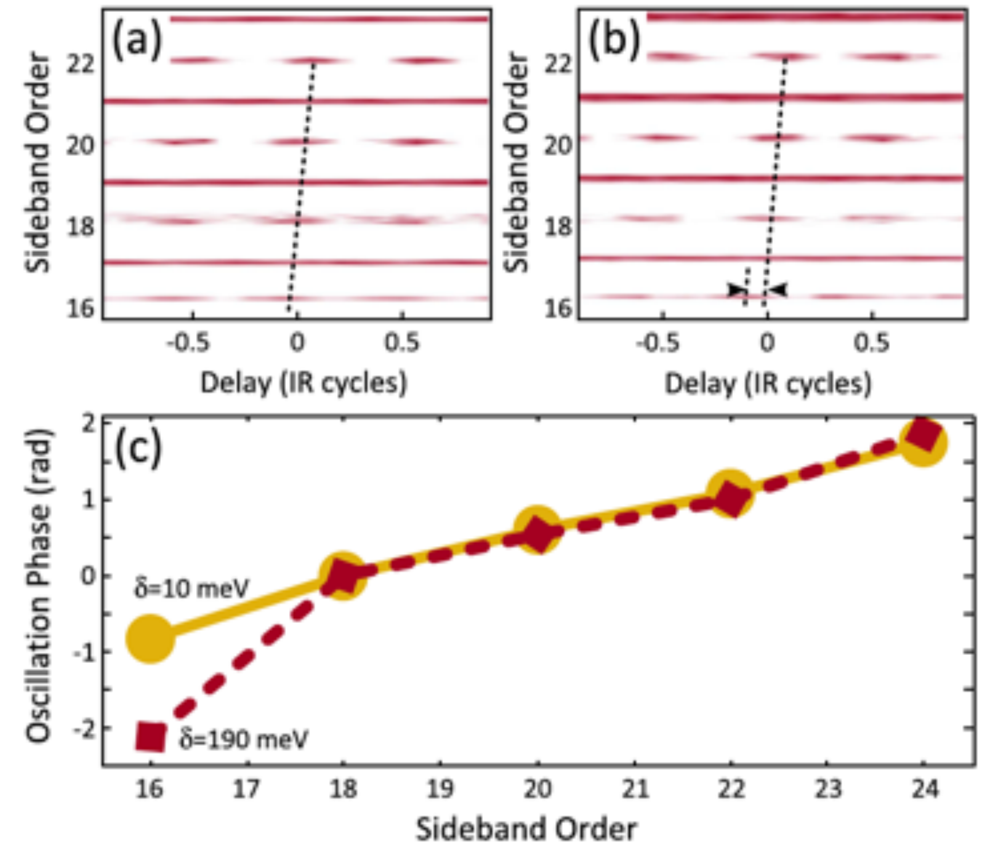
$$\simeq \frac{\mathcal{O}_{Er}\mathcal{O}_{rg}}{\delta\omega + i0^{+}} \qquad \varphi_n^{At} = \arg \mathcal{M}_n$$

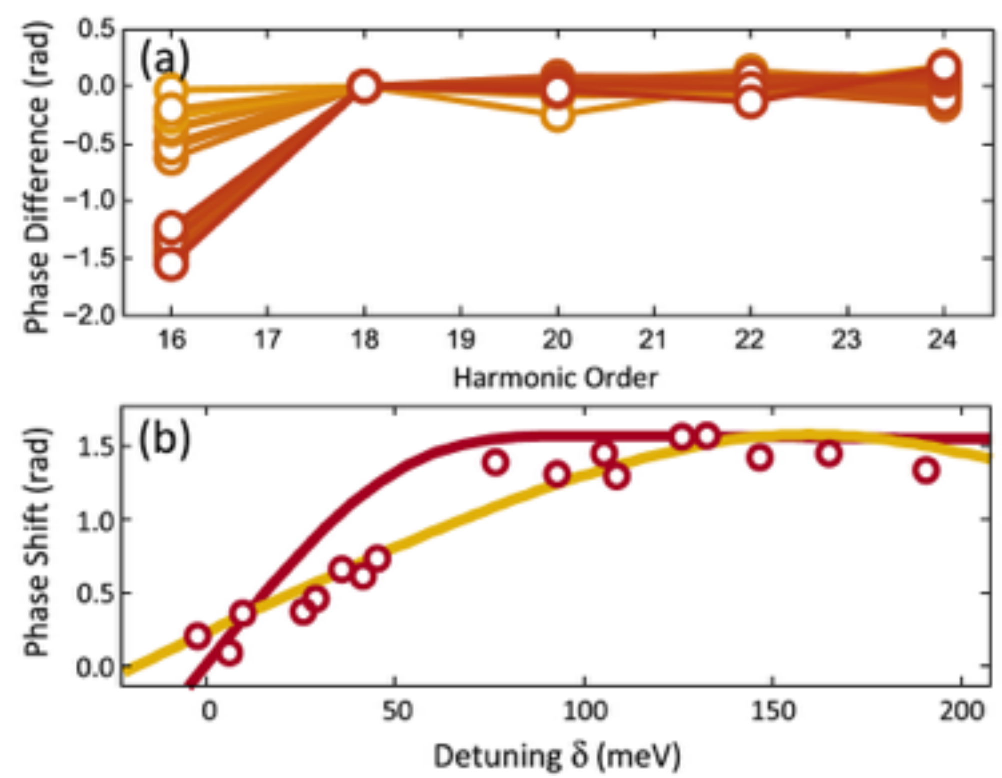


Traversing r, φ_n^{At} jumps up by π

RABBIT with a resonant bound state







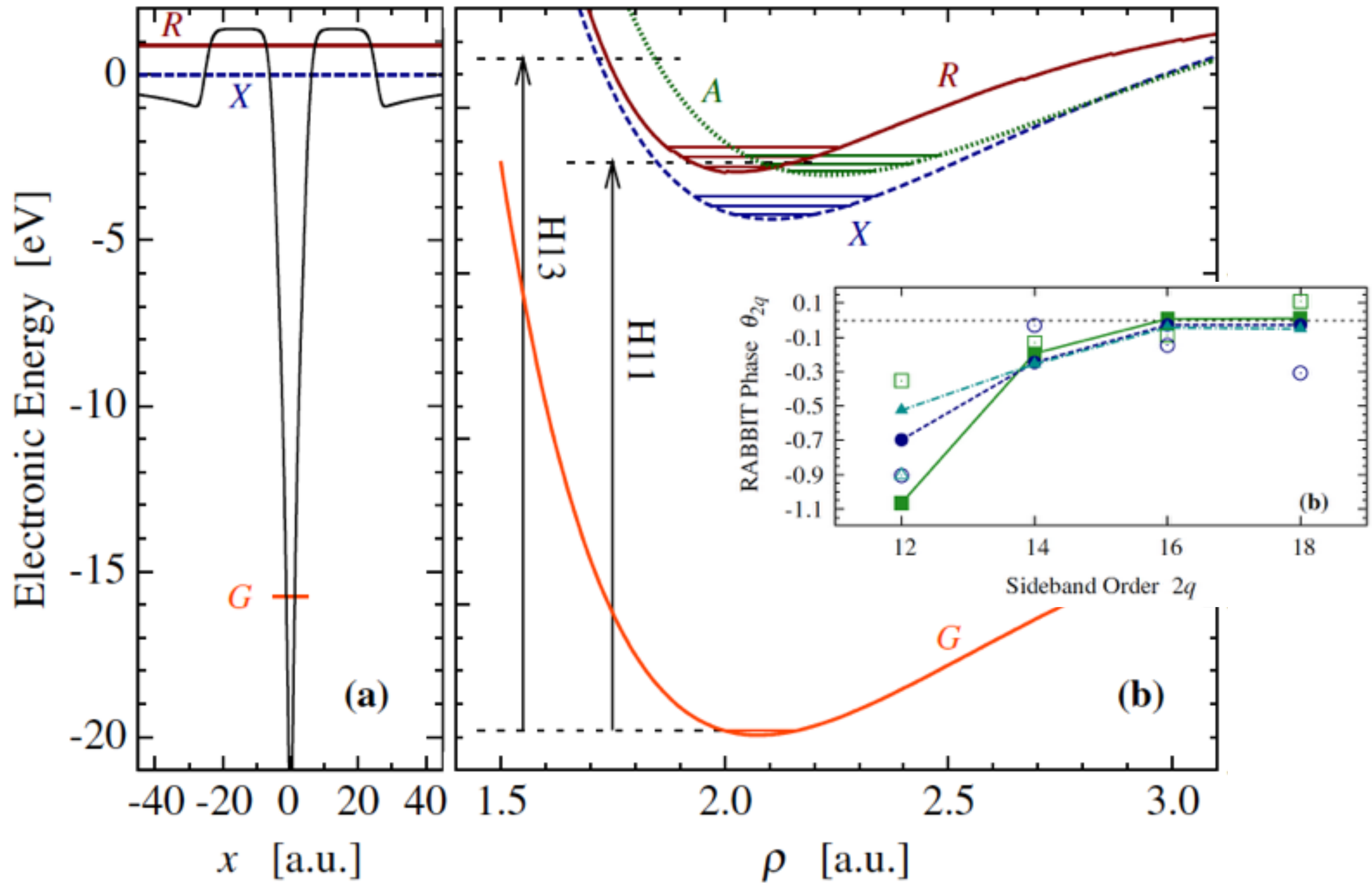
1 $\left\{ \begin{array}{l} \mathrm{He} + \gamma_{2n-1} \longrightarrow \mathrm{He}^{*}\,(1s3p) \\ \mathrm{He}^{*}(1s3p) + \gamma_{IR} \longrightarrow \mathrm{He}^{+} + e^{-} \end{array} \right.$

2 $\mathrm{He} + \gamma_{2n+1} \longrightarrow \mathrm{He}^{+} + e^{-} + \gamma_{IR}$

M. Swoboda *et al.*, PRL **104**, 103003 (2010)

RABBIT with a resonant autoionizing state

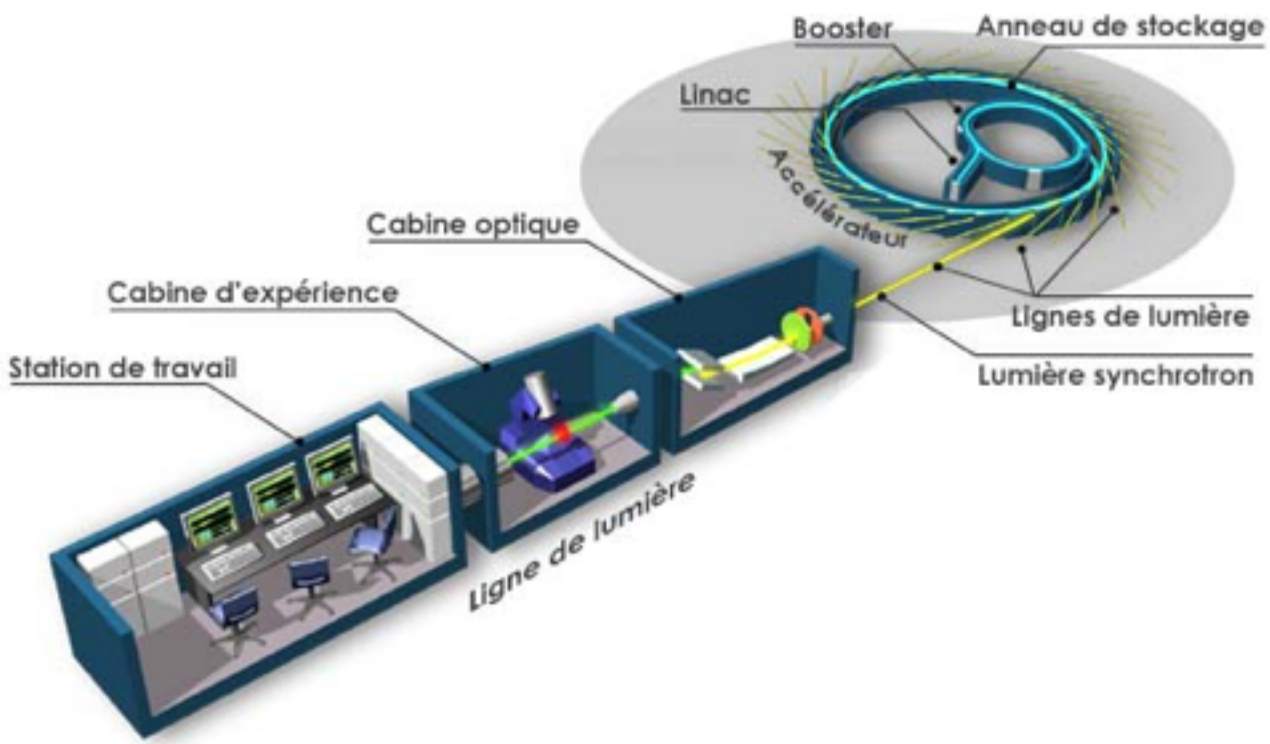
$N_2 + \gamma_{Hn} \pm \gamma_{IR} \longrightarrow N_2^+(X) + e^-$

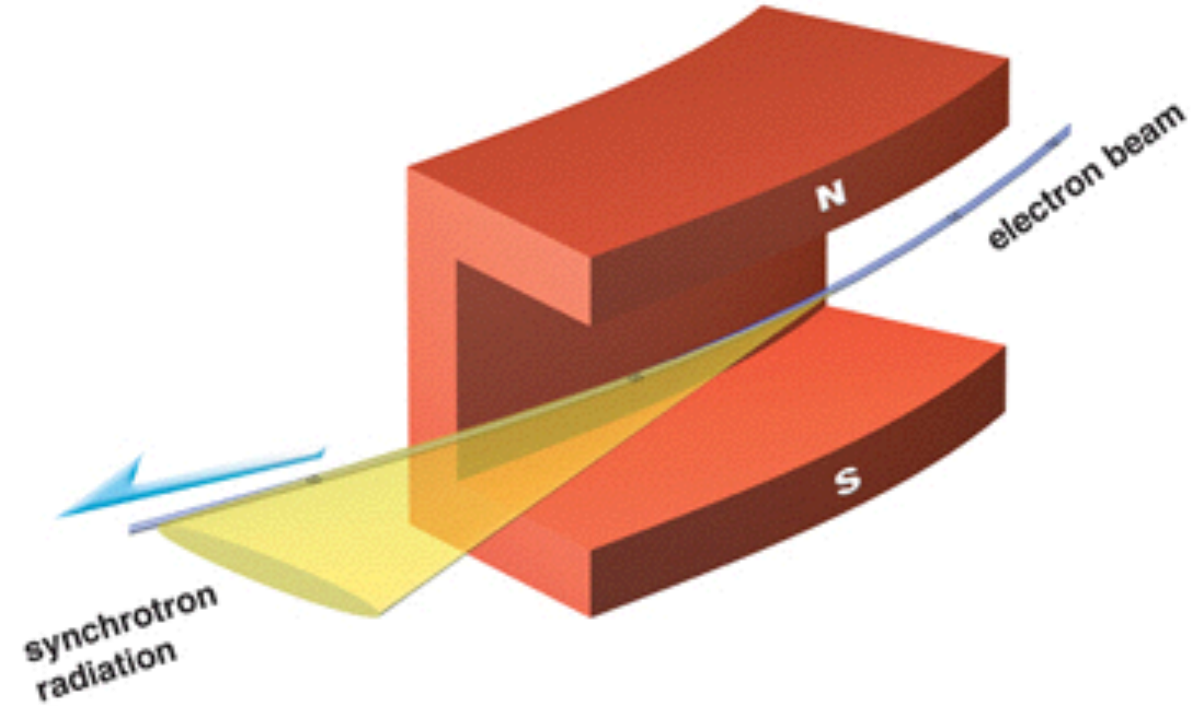


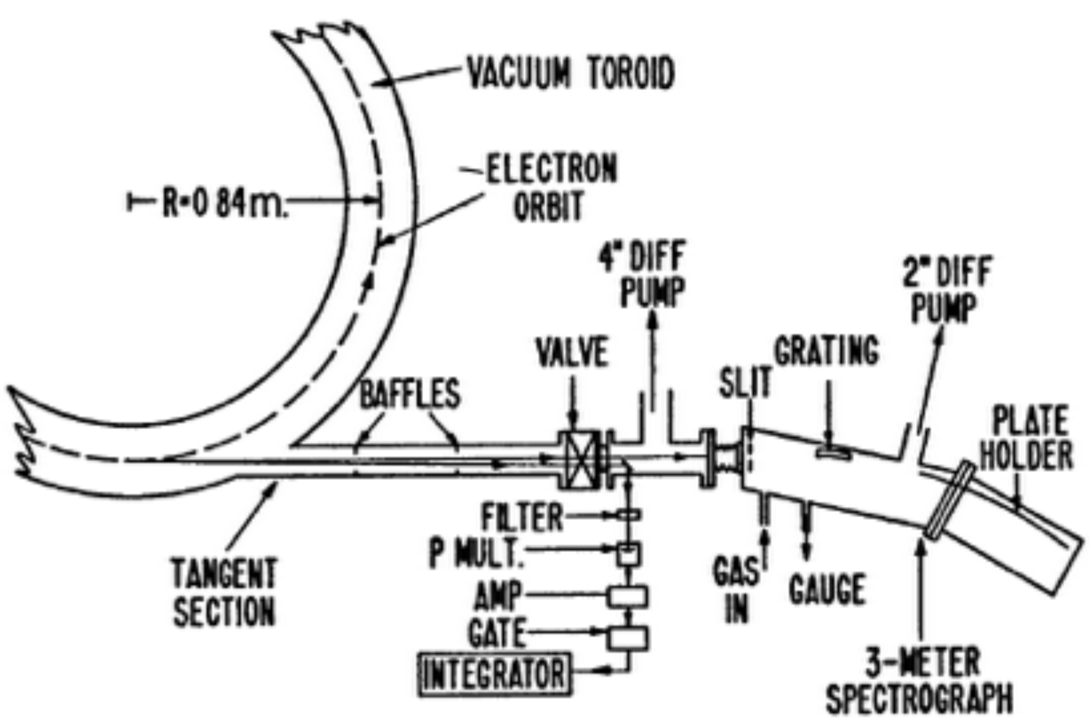
J. Caillat *et al.*, PRL **106**, 093002 (2011)

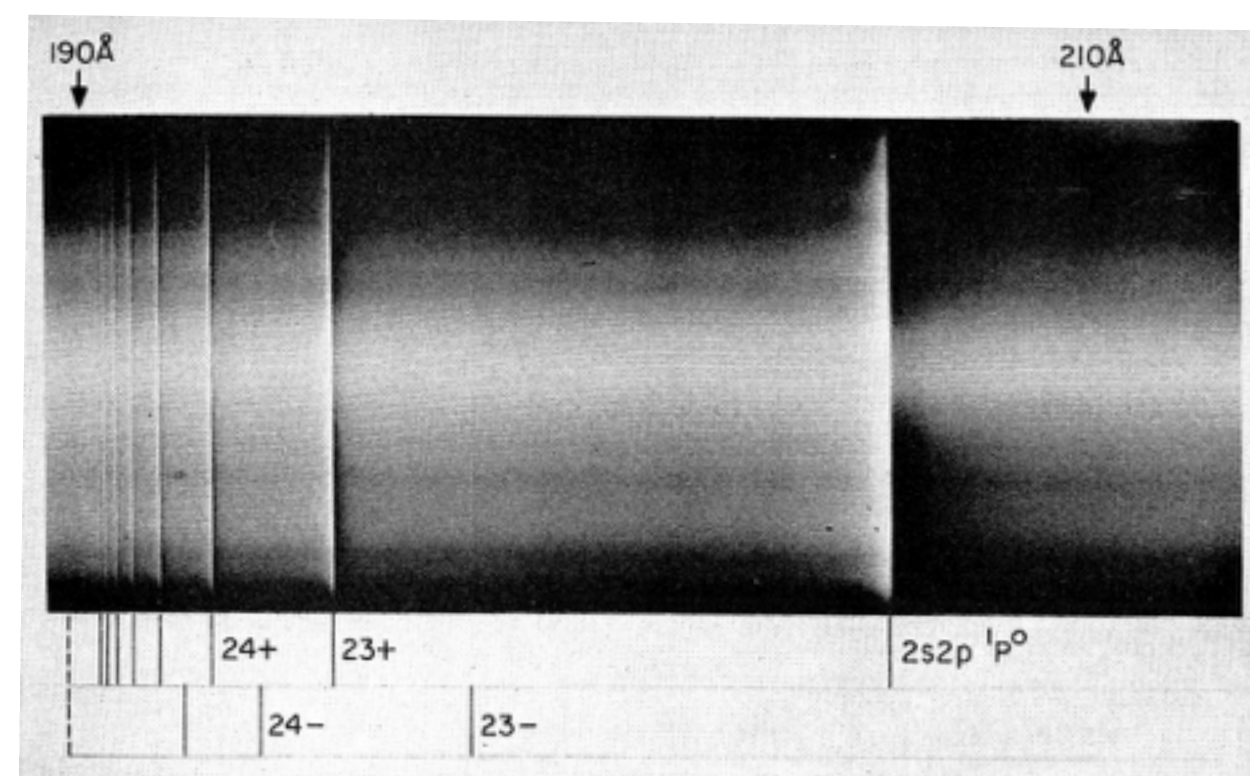
Resonant contribution still largely dominant

XUV absorption with synchrotron radiation









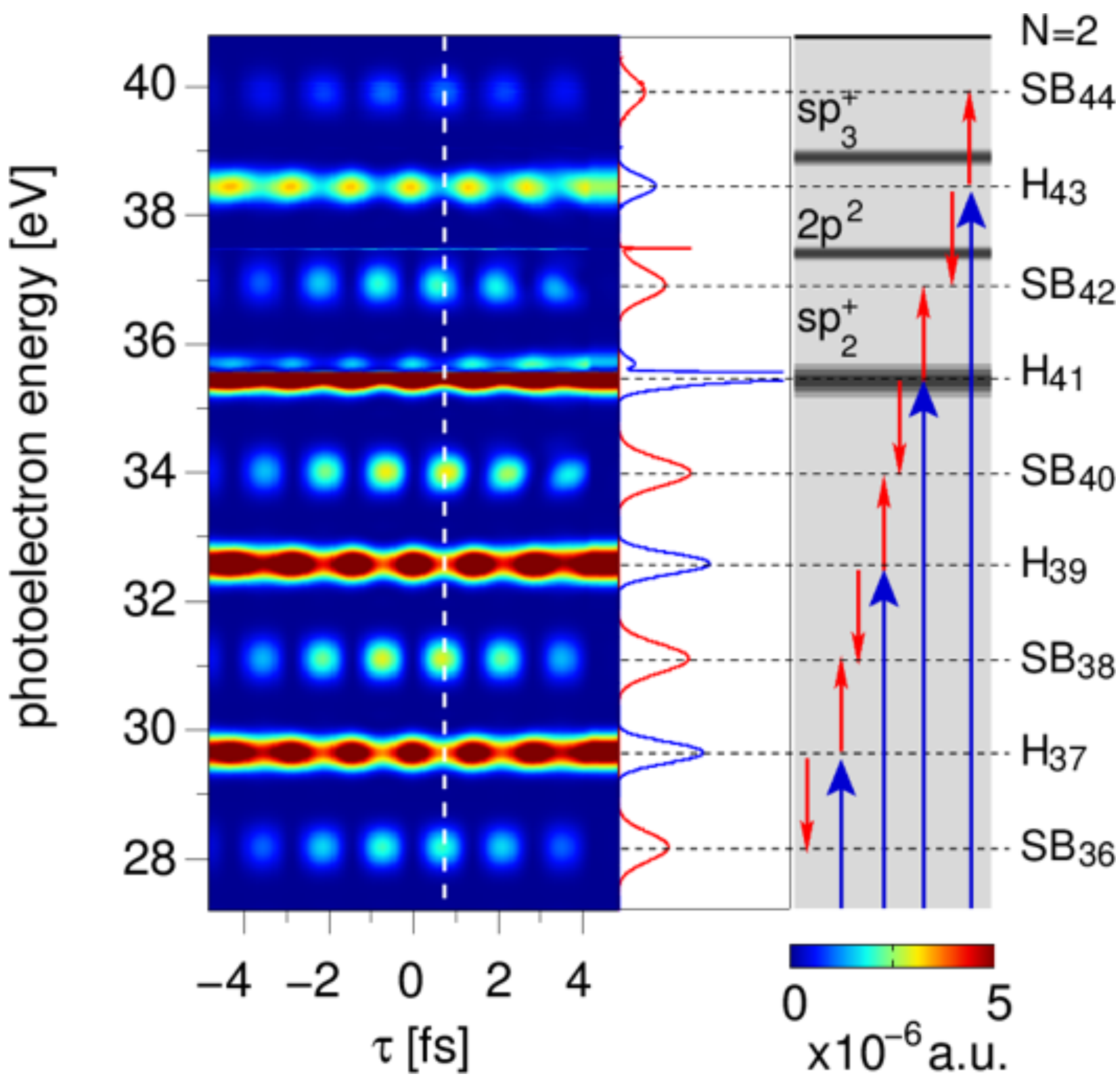
R P Madden, K Codling, Ast. Phys. J. **141**, 364 (1965)

$$\mathrm{He} + \gamma \rightarrow \mathrm{He}^{+}(1s) + e^{-}$$

RABITT with an intermediate autoionizing state

$$\mathrm{He} + \gamma_\omega \longrightarrow \mathrm{He}^+(1s) + e^- \qquad \mathrm{He}^+(1s) + e^- + \gamma \longrightarrow \mathrm{He}^+(1s) + e^-$$

$$\mathrm{He} + \gamma_\omega \longrightarrow \mathrm{He}^{**} \qquad \mathrm{He}^{**} + \gamma \longrightarrow \mathrm{He}^+(1s) + e^-$$



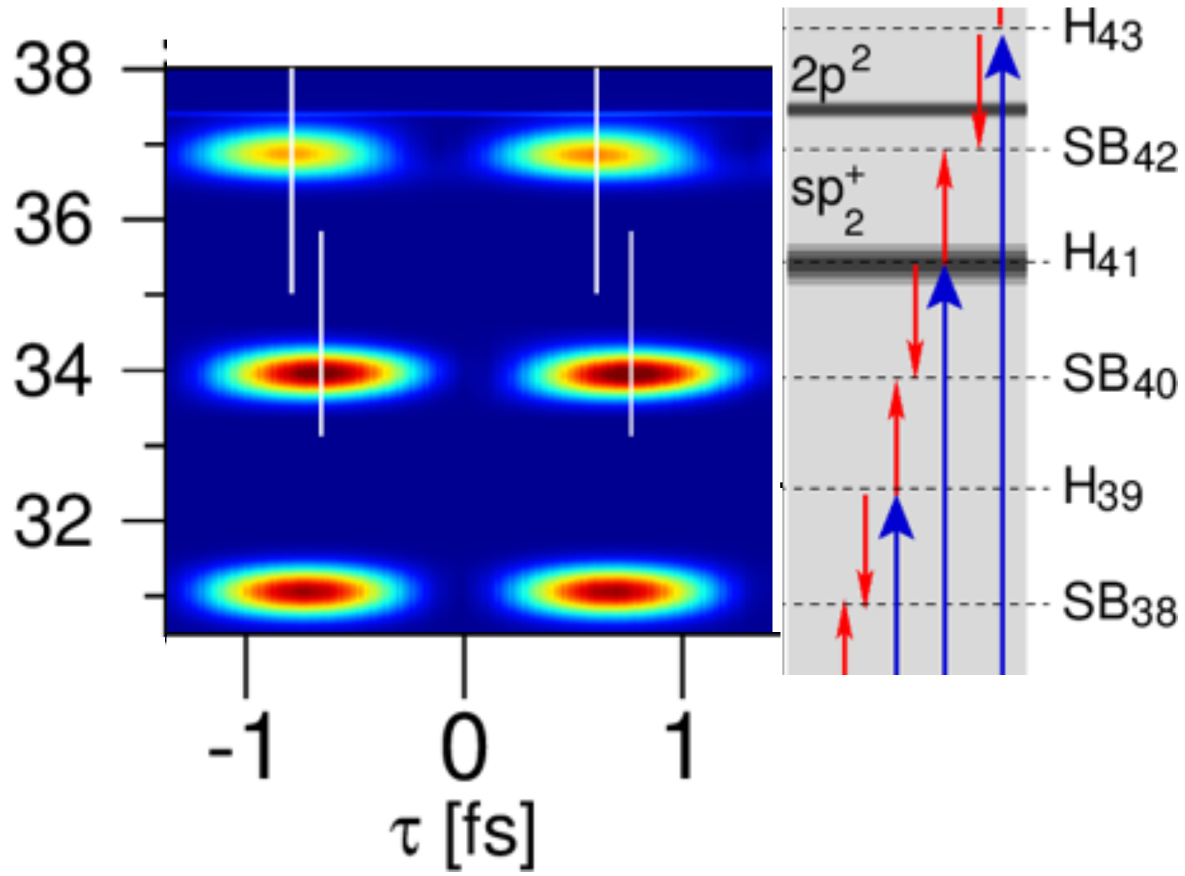
1. What should we expect when both the bound and the continuum part of an intermediate resonant state contribute to the transition?

2. How does a finite duration of the pulse, comparable with the resonance lifetime, affects the measurement?

3. How is the electron dynamics to be interpreted?

Sideband signal resonant RABBIT

$$I_{\rm SB}(E_f;\omega_{\rm IR},\tau) = \left|\mathcal{A}^+(\omega_{\rm IR},\tau)\right|^2 + \left|\mathcal{A}^-(\omega_{\rm IR},\tau)\right|^2 + 2\,\Re e\left[\mathcal{A}^{+*}(\omega_{\rm IR},\tau)\mathcal{A}^-(\omega_{\rm IR},\tau)\right]$$



Sideband signal resonant RABBIT

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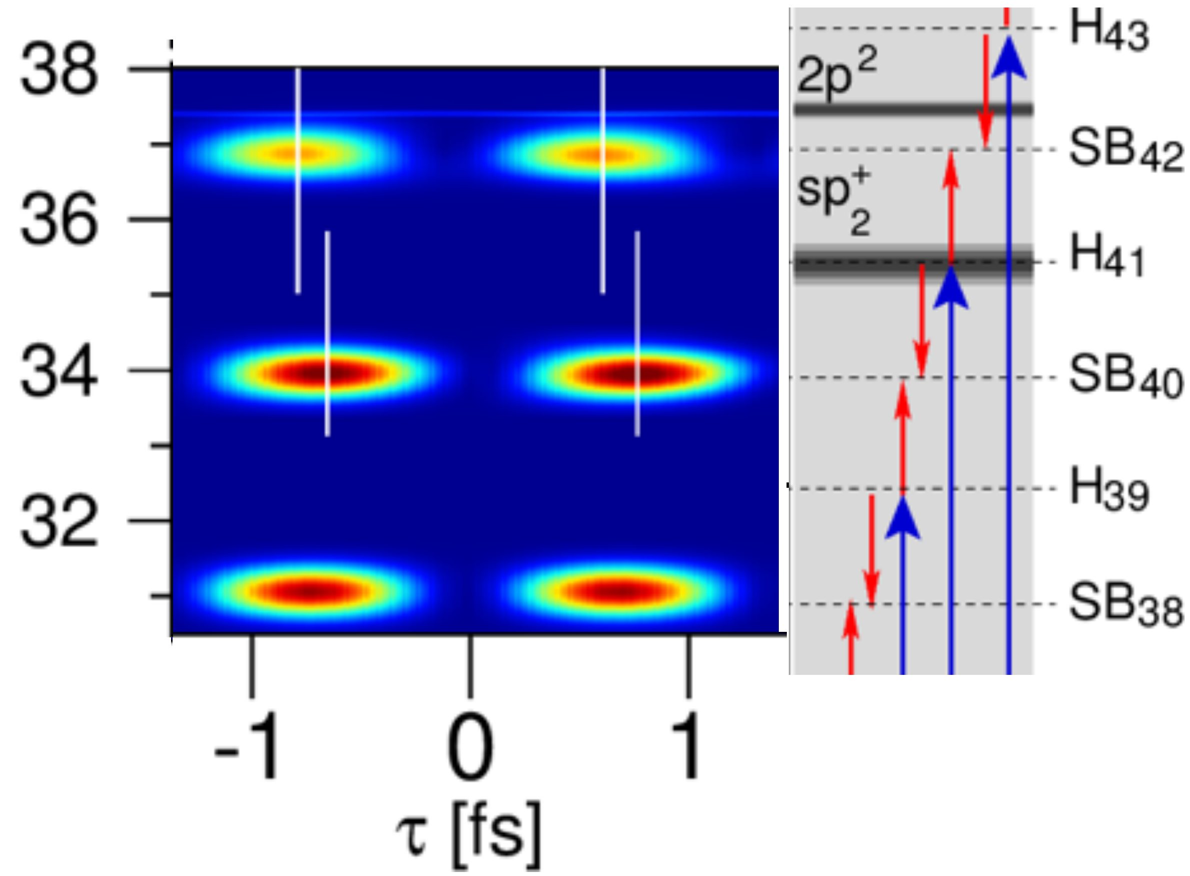
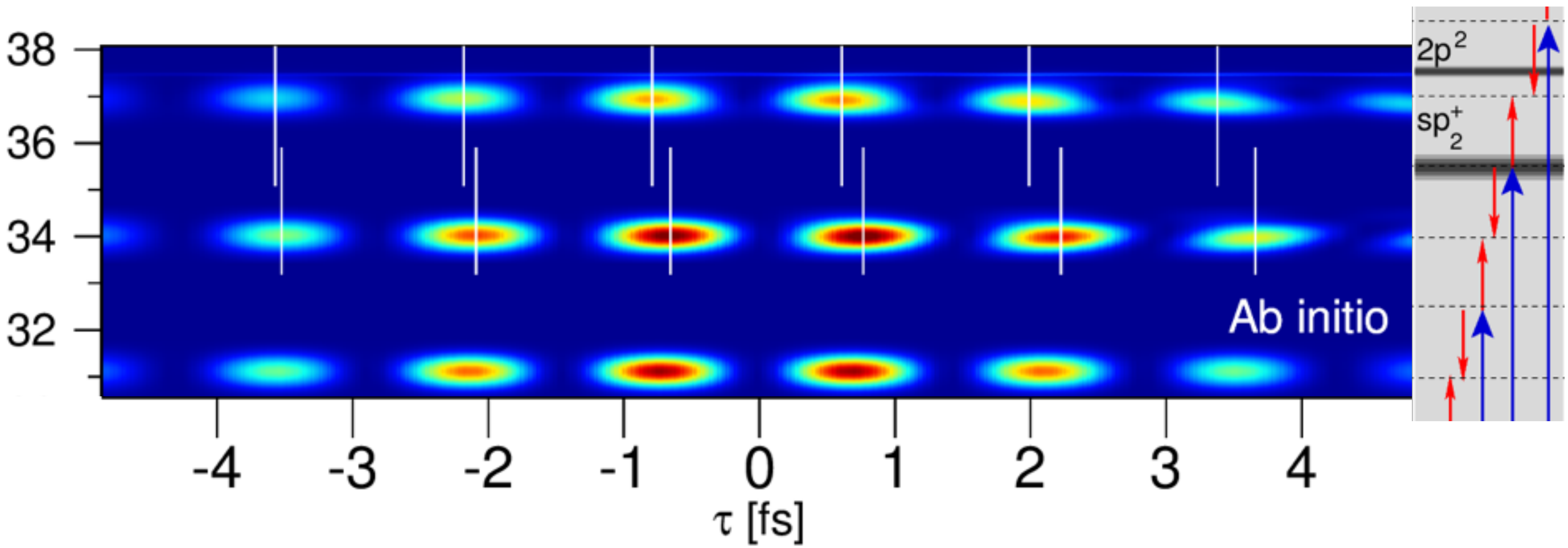


There certainly is a shift. Yet, something is not quite right …

Sideband signal resonant RABBIT

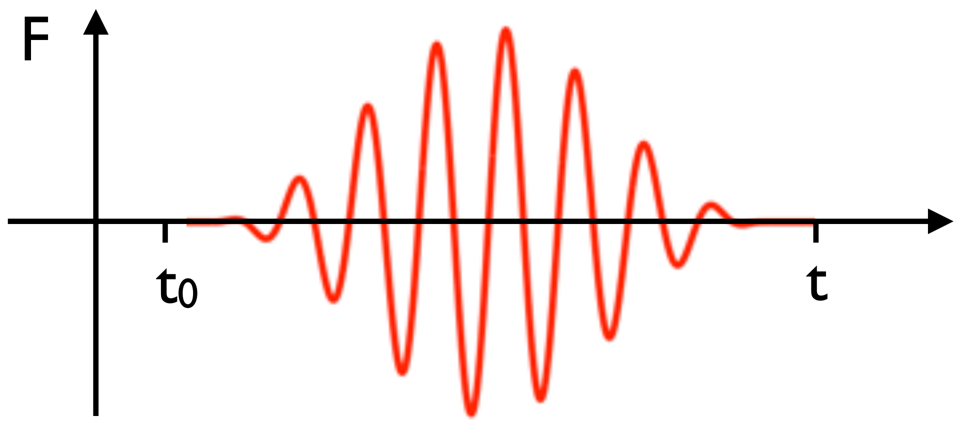
$$I_{\mathrm{SB}}(E_f;\omega_{\mathrm{IR}},\tau)=\left|\mathcal{A}^{+}(\omega_{\mathrm{IR}},\tau)\right|^2+\left|\mathcal{A}^{-}(\omega_{\mathrm{IR}},\tau)\right|^2+2\,\Re e\left[\mathcal{A}^{+*}(\omega_{\mathrm{IR}},\tau)\mathcal{A}^{-}(\omega_{\mathrm{IR}},\tau)\right]$$



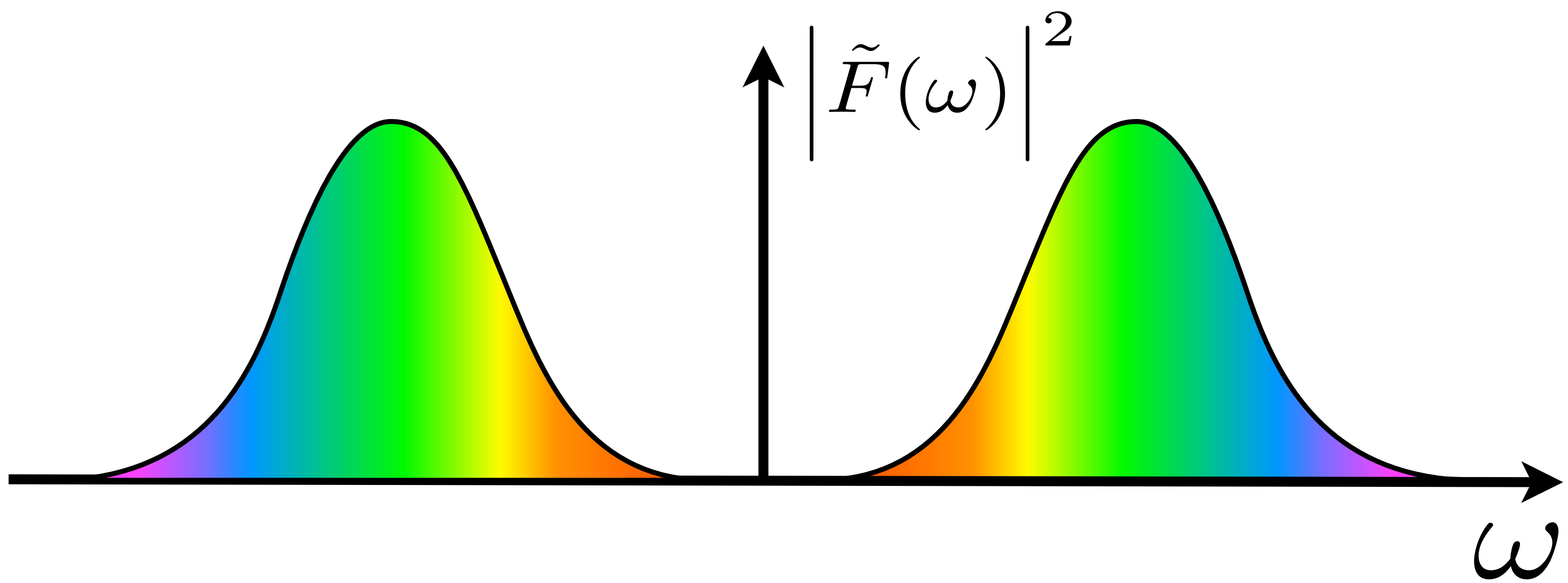
The "shift" increases with the time delay

The RABBIT frequency itself is altered

More than one way to skin a cat



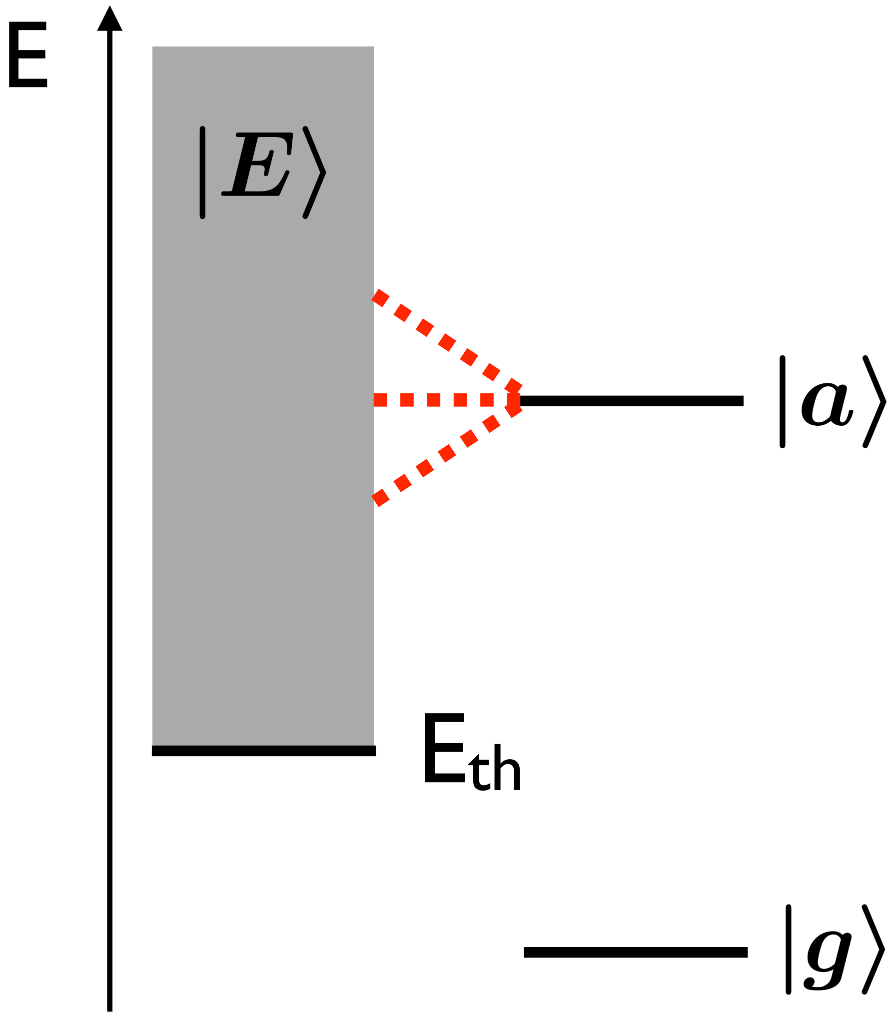
$$\boxed{\mathcal{A}_{fi}^{(2)} = -\int_{t_0}^{t} dt_1 \int_{t_0}^{t_1} dt_2 \, \langle f | H_I'(t_1) H_I'(t_2) | i \rangle}$$

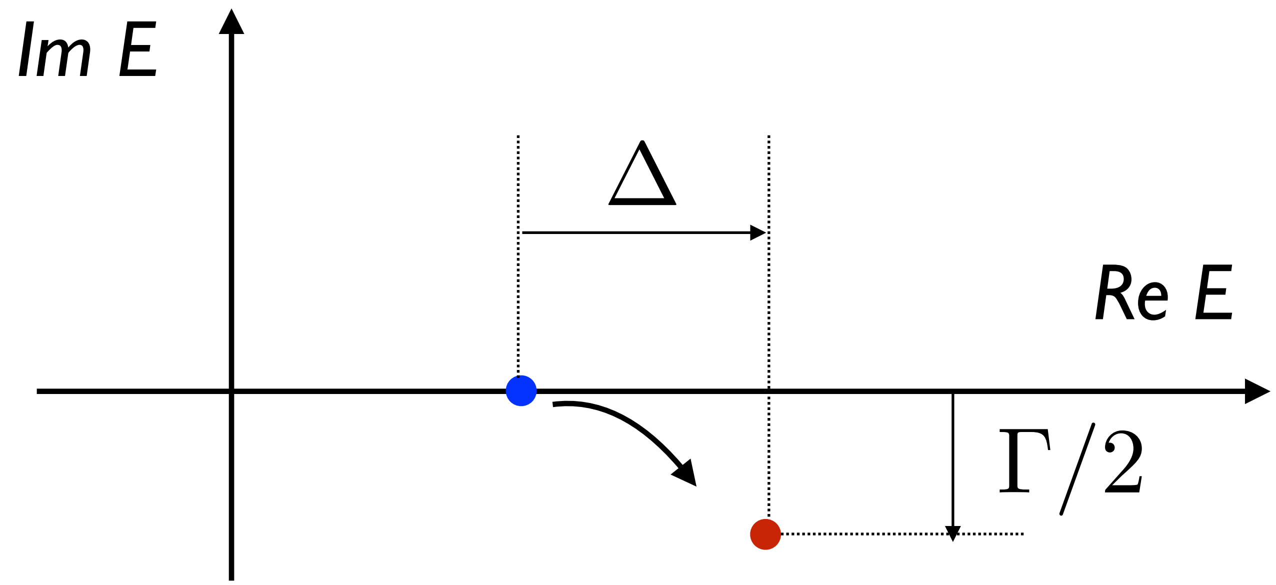


$$\boxed{\mathcal{A}_{fi}^{(2)} = -i \int d\omega \tilde{F}(\omega) \tilde{F}(-\omega_{fi} - \omega) \langle f | \mathcal{O} G_0^{+}(\omega_i - \omega) \mathcal{O} | i \rangle}$$

10:15

Fano recap





$$\tilde{E}_a(E) = E_a + \Delta(E) - i\,\Gamma(E)/2$$

$$\Delta(E) = P\int d\varepsilon\,\frac{V_{a\varepsilon}V_{\varepsilon a}}{E-\varepsilon} \qquad \Gamma(E) = 2\pi|V_{aE}|^2$$

$$|\Psi_E\rangle = |E\rangle + \left(|a\rangle + \int d\varepsilon\,|\varepsilon\rangle\,\frac{V_{\varepsilon a}}{E-\varepsilon+i0^+}\right)\frac{V_{aE}}{E-\tilde{E}_a(E)}$$

$$\epsilon(E) \equiv \frac{E-\bar{E}_a(E)}{\Gamma(E)/2} \qquad q \equiv \frac{\mathcal{O}_{g\tilde{a}}}{\pi V_{Ea}\mathcal{O}_{gE}} \qquad \langle g|\mathcal{O}|\psi_E\rangle = \mathcal{O}_{gE}\,\frac{\epsilon+q}{\epsilon+i}$$

Time-resolved resonant two-photon model

$$\mathcal{A}^{(2)}_{f\leftarrow i} = -\mathrm{i}\int_{-\infty}^{\infty} d\omega \tilde{A}(\omega_{fi}-\omega)\tilde{A}(\omega)\mathcal{M}_{fi}(\omega) \qquad \tilde{A}(\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} A(t)\, e^{i\omega t}\, dt$$

$$\mathcal{M}_{fi}(\omega) = \alpha^2 \langle \psi_{\beta E_f} | P_z G_0^+(\omega_i+\omega) P_z | \psi_i \rangle \qquad G_0^+(E) \equiv (E - H + i0^+)^{-1}$$

$$\mathcal{M}_{fi}(\omega) = \alpha^2 \sum\!\!\!\!\!\!\int d\varepsilon \frac{\langle \psi_{E_f \ell m} | P_z | \psi_{\varepsilon 10} \rangle \langle \psi_{\varepsilon 10} | P_z | \psi_i \rangle}{\omega_i + \omega - \varepsilon + \mathrm{i}0^+}$$

$$|\psi_E\rangle = |E\rangle + |a\rangle \frac{V_{aE}}{E-\tilde{E}_a} + \int d\varepsilon |\varepsilon\rangle \frac{V_{\varepsilon a}}{E-\varepsilon+i0^+}\frac{V_{aE}}{E-\tilde{E}_a}$$

H **D** **M**

$$\mathcal{M}_{f\leftarrow i}(\omega) = \sum_{\alpha,\beta,\gamma\in\{D,M,H\}} \mathcal{M}_{\gamma\leftarrow\beta\leftarrow\alpha\leftarrow i}(\omega) + \sum_{\gamma\in\{D,M,H\}} \mathcal{M}_{\gamma\leftarrow B\leftarrow i}(\omega)$$

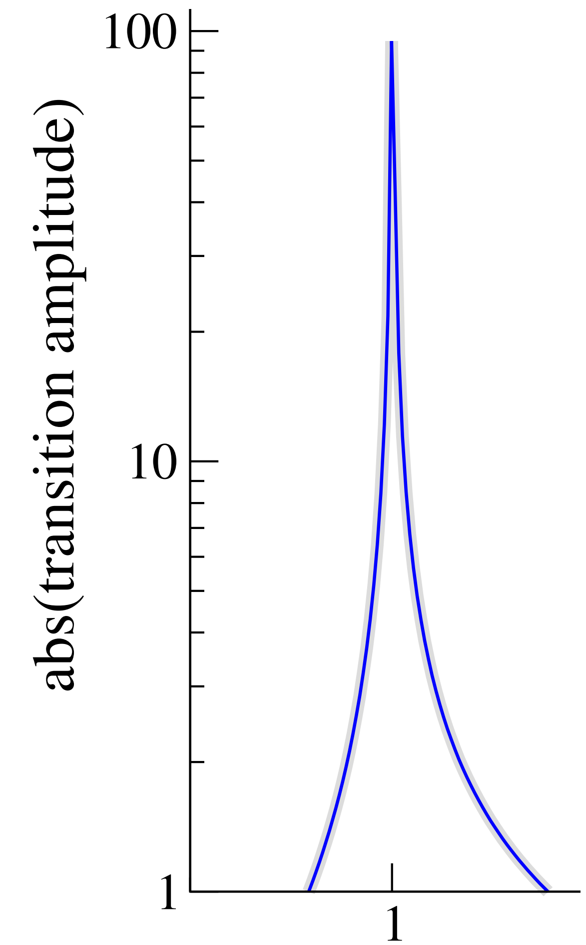
Á. Jiménez Galán, L. Argenti, F. Martín, PRL **113**, 263001 (2014)

Time-resolved resonant two-photon model

$$\sum_\alpha \mathcal{M}_{H\leftarrow M\dashleftarrow\alpha\leftarrow g}(\omega) = \int d\varepsilon \frac{\langle E_f|\mathcal{O}|\psi_{\varepsilon,M}\rangle \mathcal{O}_{\varepsilon g}}{E_g+\omega-\varepsilon+i0^+}\frac{\epsilon+q}{\epsilon-i}$$

$$\langle E_f|\mathcal{O}|\psi_{\varepsilon,M}\rangle = \int d\varepsilon' \langle E_f|\mathcal{O}|\varepsilon'\rangle \frac{V_{\varepsilon' a}}{\varepsilon-\varepsilon'+i0^+}\frac{V_{a\varepsilon}}{\varepsilon-\tilde{E}_a}$$

$$\langle E_f|\mathcal{O}|\varepsilon'\rangle \approx \bar{\mathcal{O}}_{fE}\delta(\varepsilon'-E_f)$$



$$\frac{1}{a-b+\mathrm{i}0^+}\frac{1}{b-c+\mathrm{i}0^+} = \frac{1}{a-c+\mathrm{i}0^+}\left[\frac{1}{a-b+\mathrm{i}0^+}+\frac{1}{b-c+\mathrm{i}0^+}\right]$$

$$\cancel{P\int d\varepsilon \frac{\mathcal{O}_{\varepsilon g}}{\varepsilon-E_f}} - \cancel{P\int d\varepsilon \frac{\mathcal{O}_{\varepsilon g}}{\varepsilon-(E_g+\omega)}} - i\pi\mathcal{O}_{E_f g} - i\pi\mathcal{O}_{E_g+\omega,g}$$

Á. Jiménez Galán, L. Argenti, F. Martín, PRL **113**, 263001 (2014)

C. Marante, L. Argenti and F. Martín, Phys. Rev. A **90**, 012506 (2014)

Time-resolved resonant two-photon model

$$\mathcal{A}^{(2)}_{f\leftarrow i} = -\mathrm{i}\int_{-\infty}^{\infty} d\omega \tilde{A}(\omega_{fi}-\omega)\tilde{A}(\omega)\mathcal{M}_{fi}(\omega)$$

$$A(t) = A_0 \mathrm{e}^{-\frac{1}{2}\sigma^2(t-t_0)^2}\cos[\omega_0(t-t_0)+\phi]$$

$$A(t,\tau) = A_{\mathrm{APT}}(t) \ + \ A_{\mathrm{IR}}(t;\tau), \qquad A_{\mathrm{APT}}(t) = \sum_n A_{\mathrm{H}_{2n+1}}(t)$$

$$\boxed{\mathcal{A}^{(2),\pm}_{f_H\leftarrow i} = \mathcal{F}(\tau)\ \left[w(z_f^{\pm}) + (\beta_{Ea}-\epsilon_{fa}^{-1})\,(q_a'-i)\,w(z_a^{\pm})\right]}$$

$$z_a^{\pm} = \frac{\sigma_t}{\sqrt{2}}(\tilde{\omega}^{\pm}-\omega_{\tilde{a}i}) \qquad \tilde{\omega}^{\pm} = \omega_{\mathrm{H}_{2n\pm1}} + \frac{\delta_f}{\sigma_t^2\sigma_{\mathrm{IR}}^2} - i\frac{\tau}{\sigma_t^2} \qquad \delta_f = E_f - E_{\mathrm{SB}_{2n}}$$

$$z_f^{\pm} = \frac{\sigma_t}{\sqrt{2}}(\tilde{\omega}^{\pm}-\omega_{fi}) \qquad w(z) = e^{-z^2}\left(1+\frac{2i}{\sqrt{\pi}}\int_0^z e^{t^2}dt\right)$$

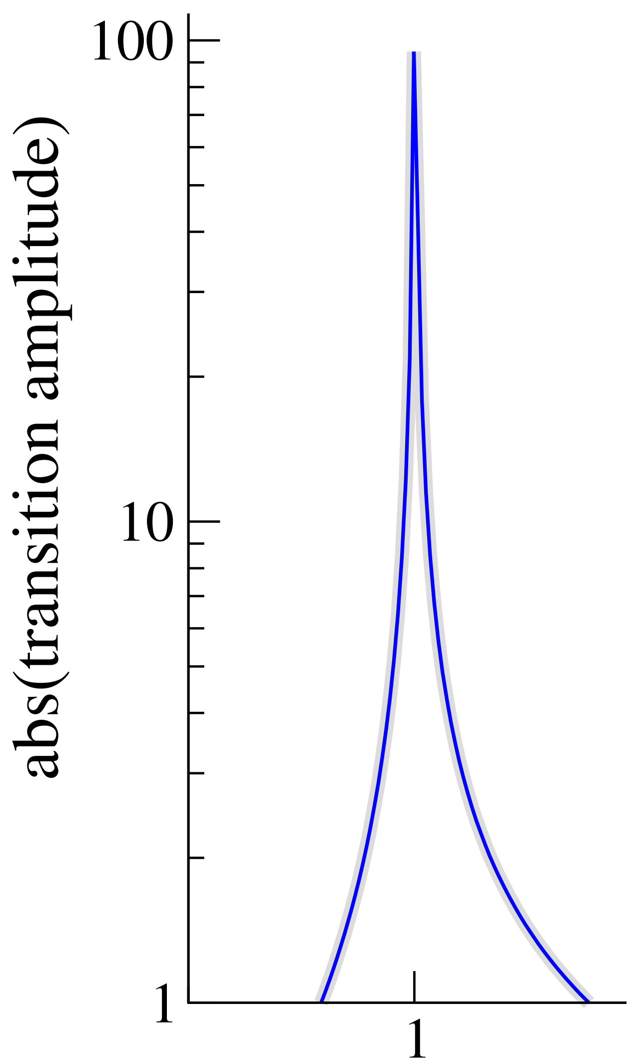
Faddeeva function

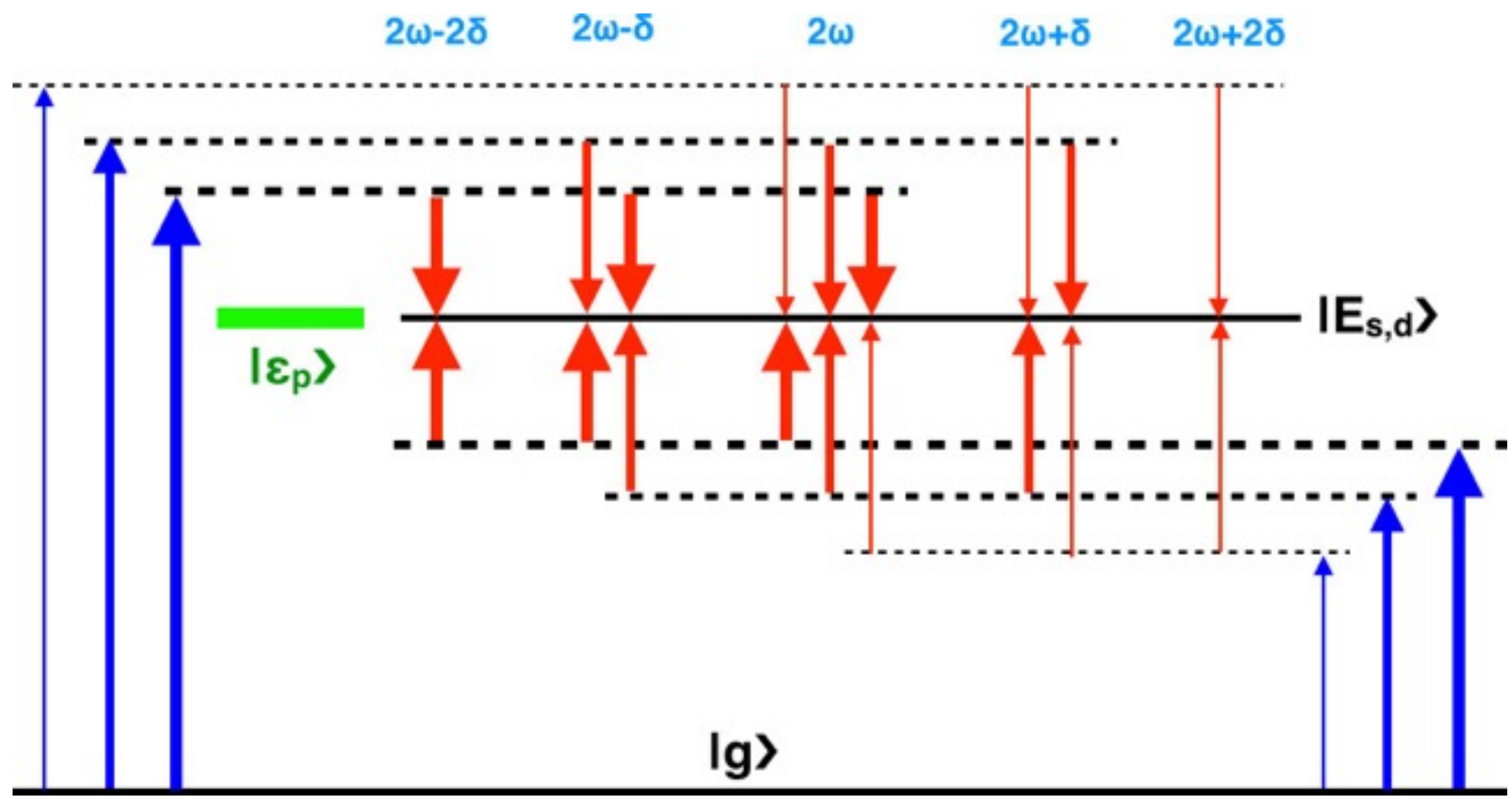
$$\beta_{Ea} = \sqrt{\frac{\pi\Gamma}{2}\frac{\mathcal{O}_{Ea}}{\bar{\mathcal{O}}_E}}$$

Á. Jiménez Galán, L. Argenti, F. Martín, PRL **113**, 263001 (2014)

Non-resonant RABBIT *red-shift*

$$\langle E_s|\mathcal{O}G_0^+(E_g+\omega_{2n\pm1})\mathcal{O}|g\rangle \simeq \pm\frac{1}{\omega_{\rm IR}}\left(\int_{E_s-\delta}^{E_s+\delta} d\epsilon\,\langle E_s|\mathcal{O}|\epsilon_p\rangle\right)\langle E_p|\mathcal{O}|g\rangle$$





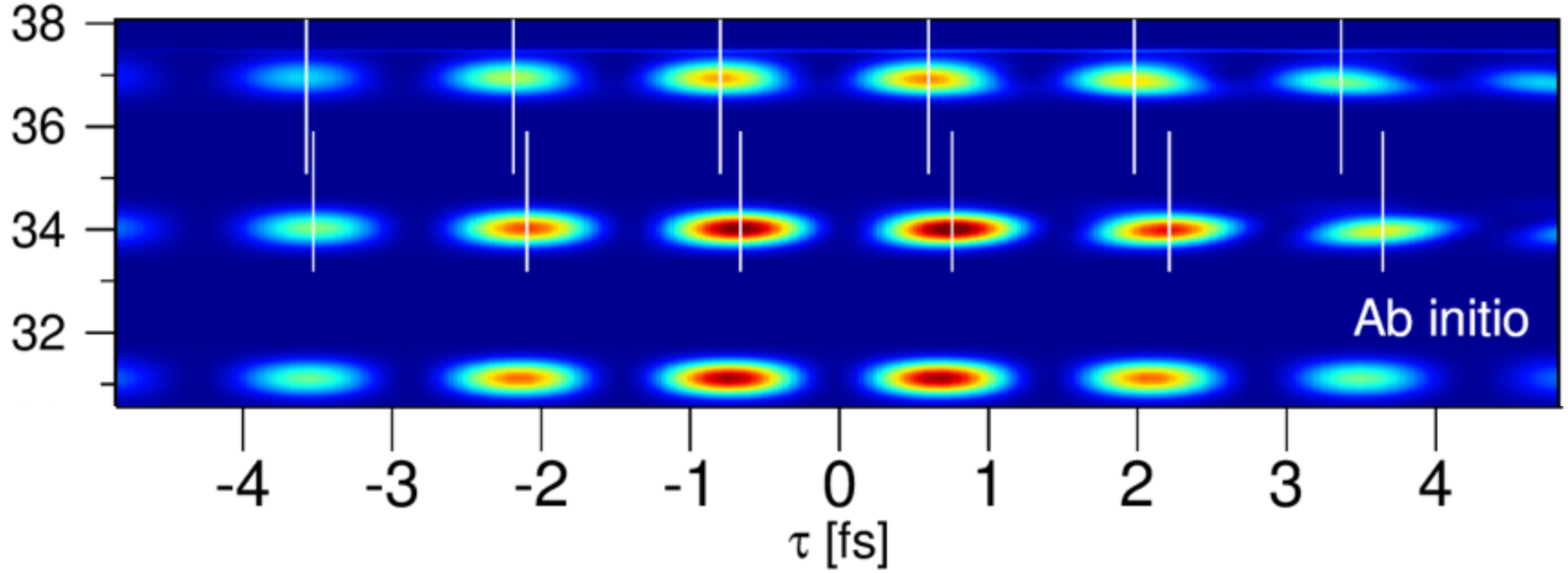
Approx. the same for all sidebands

Á. Jiménez Galán, F. Martín, L. Argenti, *manuscript in preparation* (2015)

C. Marante, L. Argenti and F. Martín, Phys. Rev. A **90**, 012506 (2014)

Sideband signal resonant RABBIT

$$I_{\rm SB}(E_f;\omega_{\rm IR},\tau) = \left|\mathcal{A}^{+}(\omega_{\rm IR},\tau)\right|^2 + \left|\mathcal{A}^{-}(\omega_{\rm IR},\tau)\right|^2 + 2\,\Re e\left[\mathcal{A}^{+*}(\omega_{\rm IR},\tau)\mathcal{A}^{-}(\omega_{\rm IR},\tau)\right]$$



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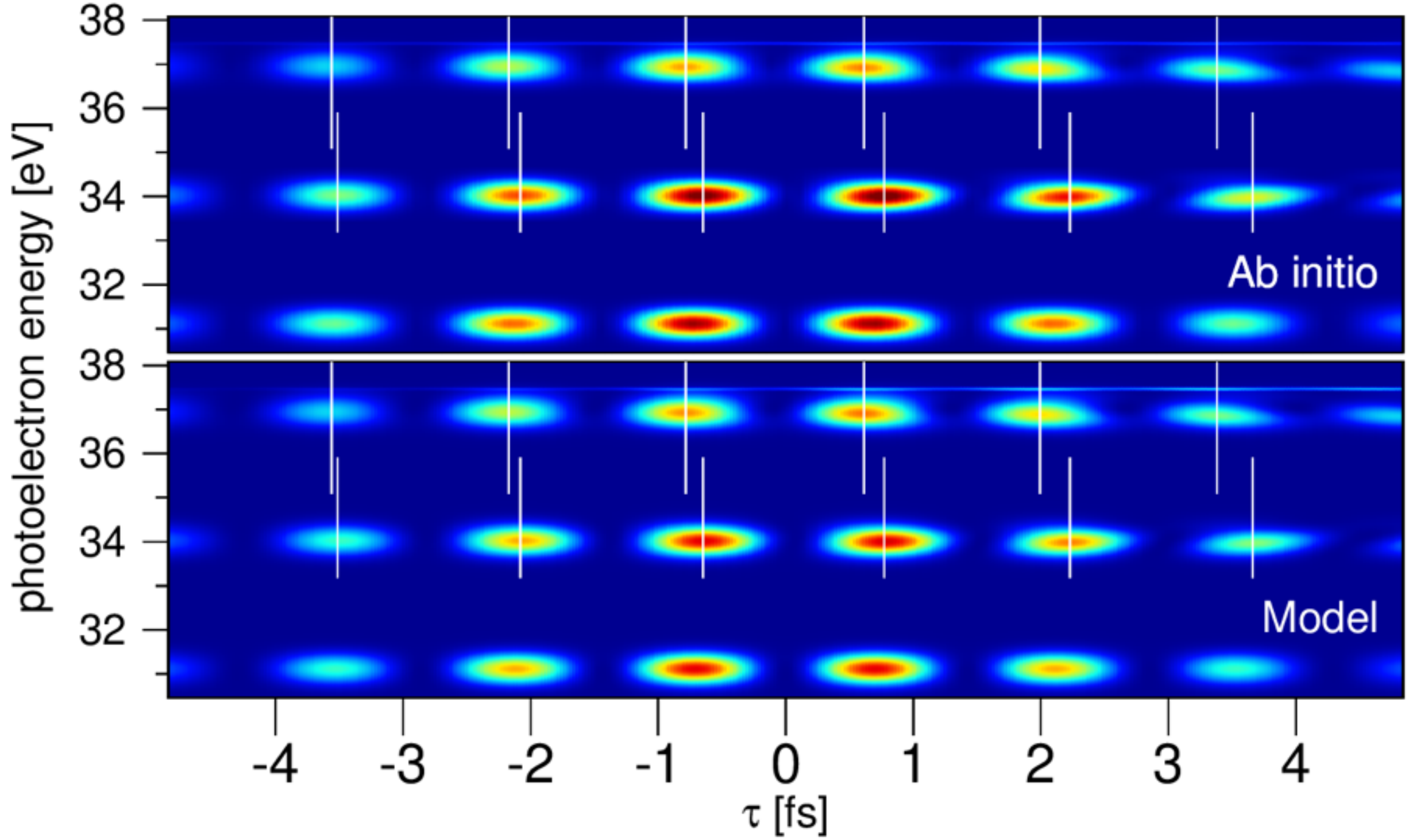

Á. Jiménez Galán, L. Argenti, F. Martín, PRL **113**, 263001 (2014)

Resonant phase-shift of sideband beating

$$\langle E|\mathcal{O}G_0^+(E_g+\omega_{\rm XUV})\mathcal{O}|g\rangle \simeq \frac{\langle E|\mathcal{O}|a\rangle\langle a|\mathcal{O}|g\rangle}{\omega_{\rm XUV}-E_{ag}+i\Gamma_a/2}+\mathcal{M}_{\rm dir}(E)$$

Resonant phase-shift of sideband beating

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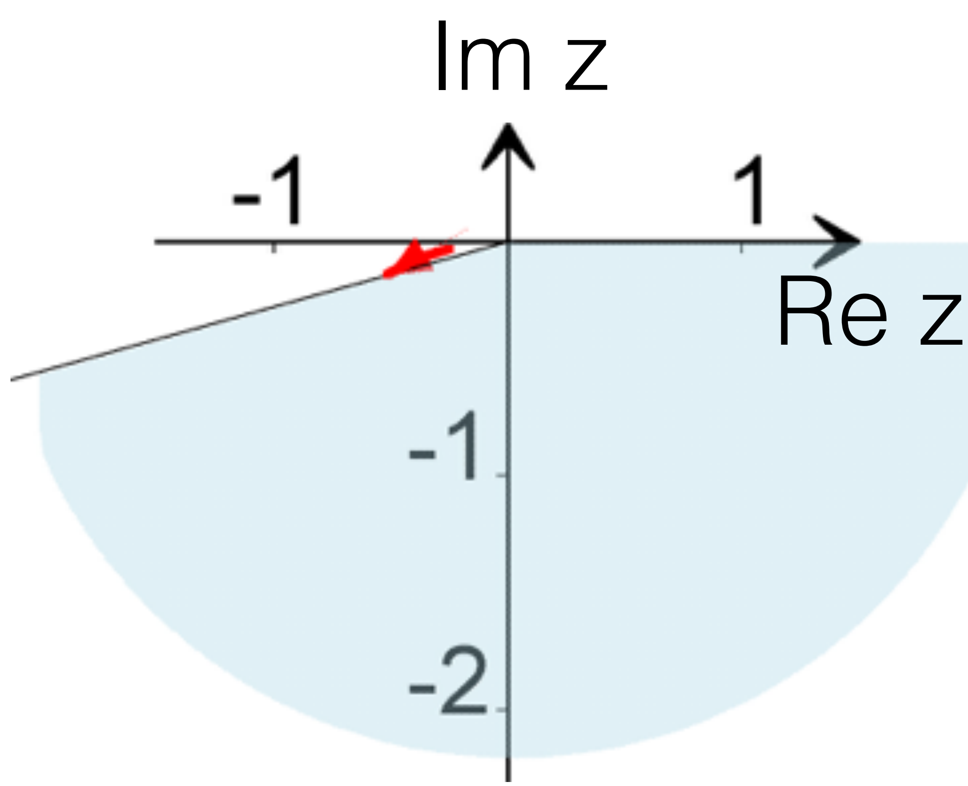

As the laser frequency crosses the resonance, the transition amplitude describes a circle in the complex plane, centered at -iΓ_a with radius Γ_a

$$\left|\frac{1}{x-z}-\frac{i}{2z_I}\right|^2 = \frac{1}{(2z_I)^2}$$

Resonant phase-shift of sideband beating

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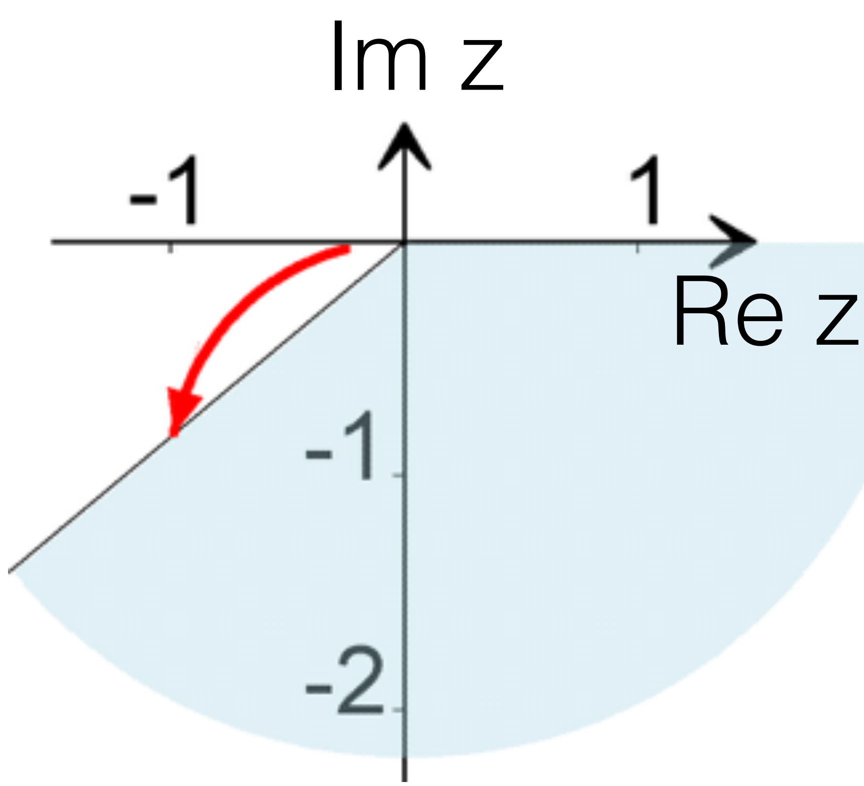
$$\frac{1}{x-z}$$



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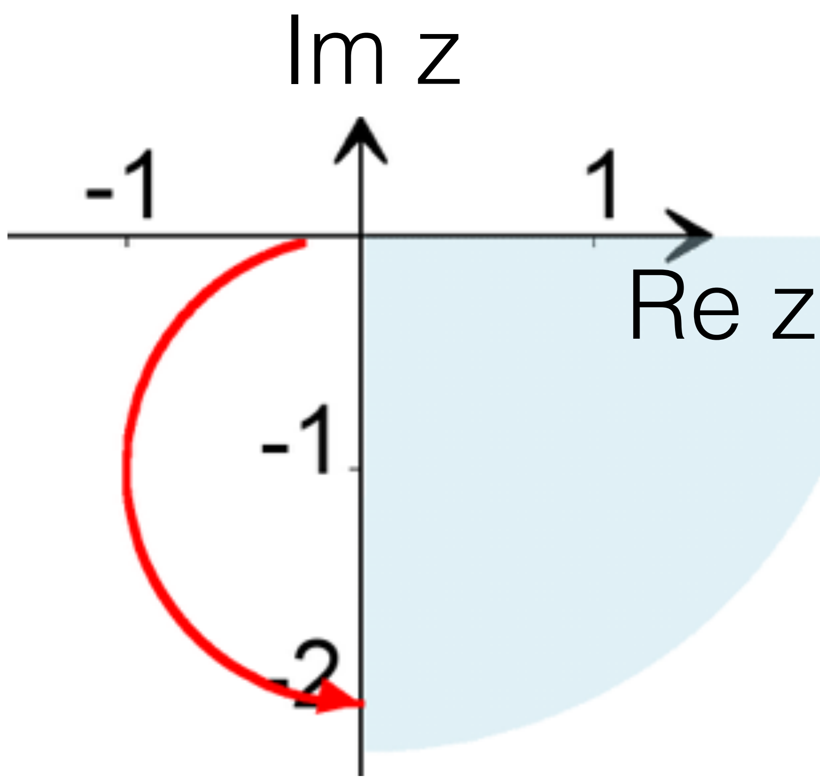

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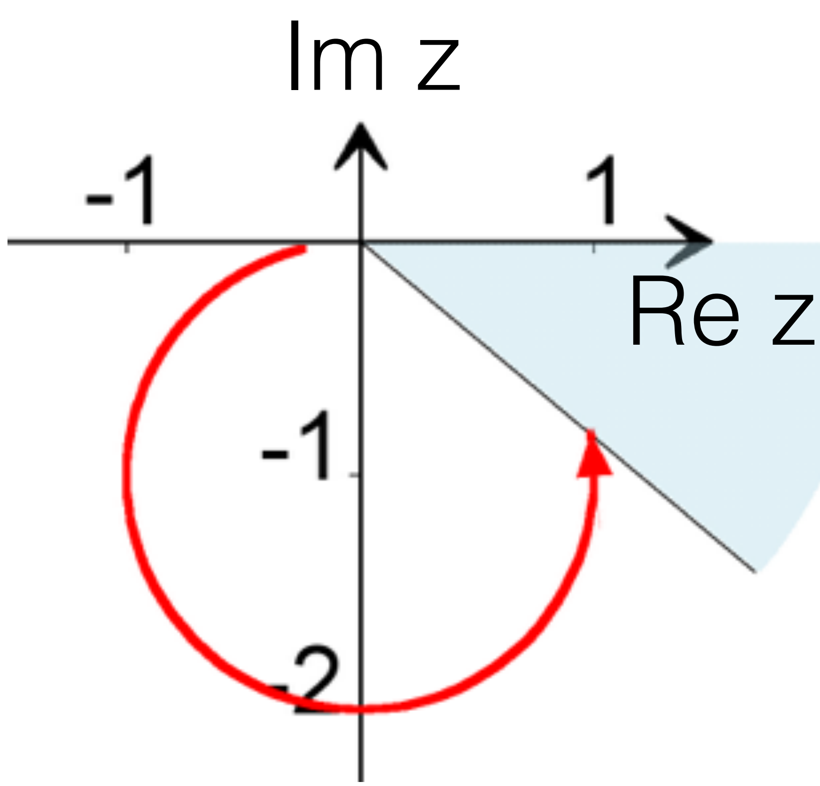
Resonant phase-shift of sideband beating

$$\langle E|\mathcal{O}G_0^+(E_g+\omega_{\mathrm{XUV}})\mathcal{O}|g\rangle \simeq \frac{\langle E|\mathcal{O}|a\rangle\langle a|\mathcal{O}|g\rangle}{\omega_{\mathrm{XUV}}-E_{ag}+i\Gamma_a/2} \qquad \frac{1}{x-z}$$



As the laser frequency crosses the resonance, the transition amplitude describes a circle in the complex plane, centered at -iΓ_a with radius Γ_a

$$\left|\frac{1}{x-z}-\frac{i}{2z_I}\right|^2=\frac{1}{(2z_I)^2}$$

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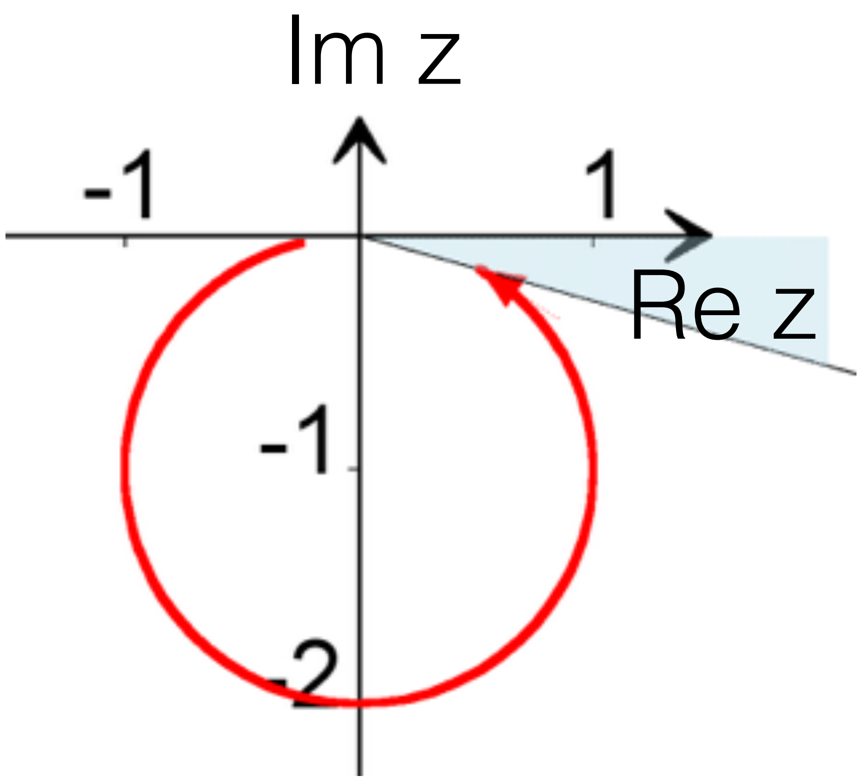

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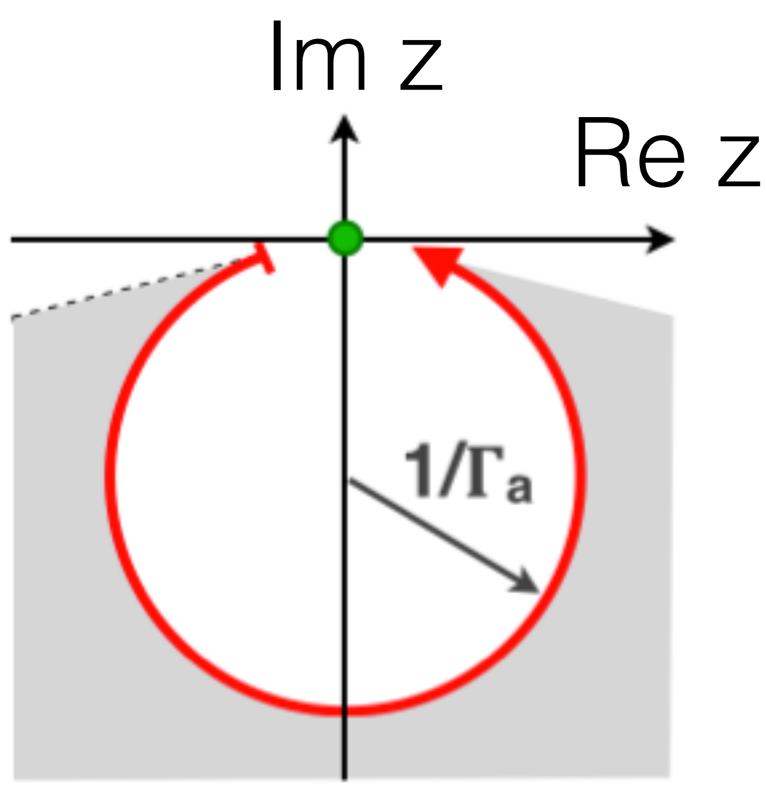
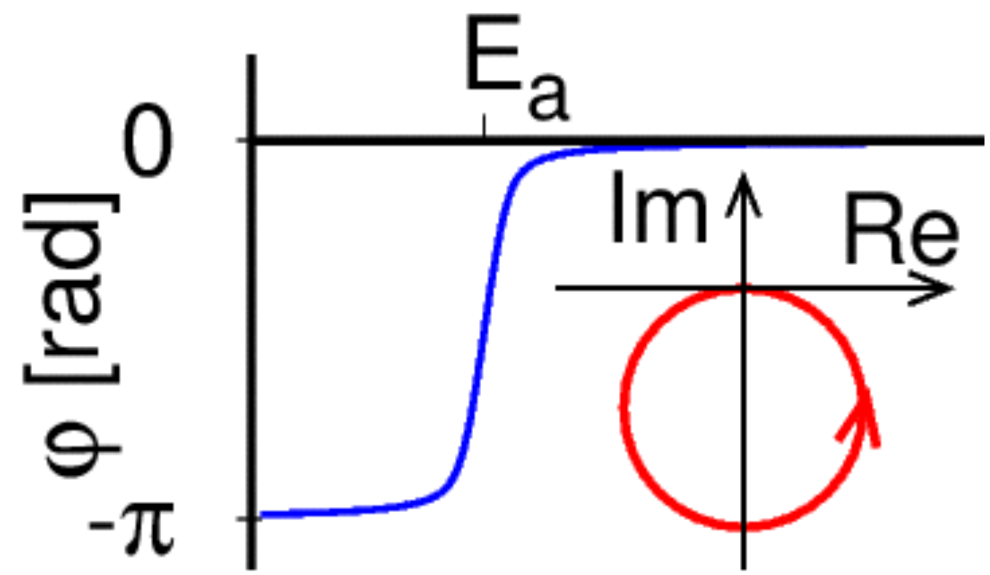
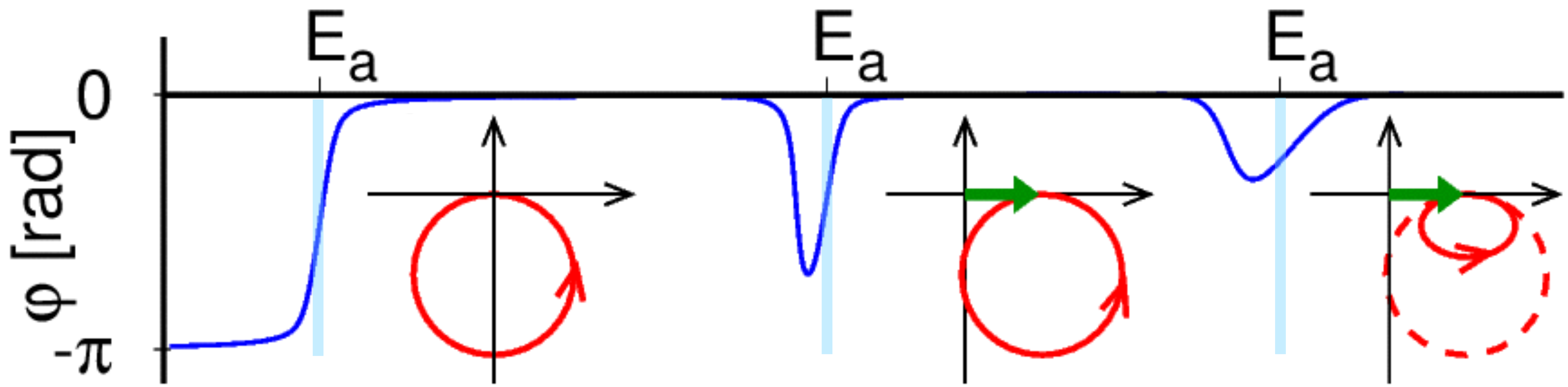




$$\varphi(x) = \arg\left(\frac{1}{x-z}\right) = \arctan\left(\frac{x-z_R}{|z_I|}\right) - \frac{\pi}{2}$$

Resonant phase-shift of sideband beating

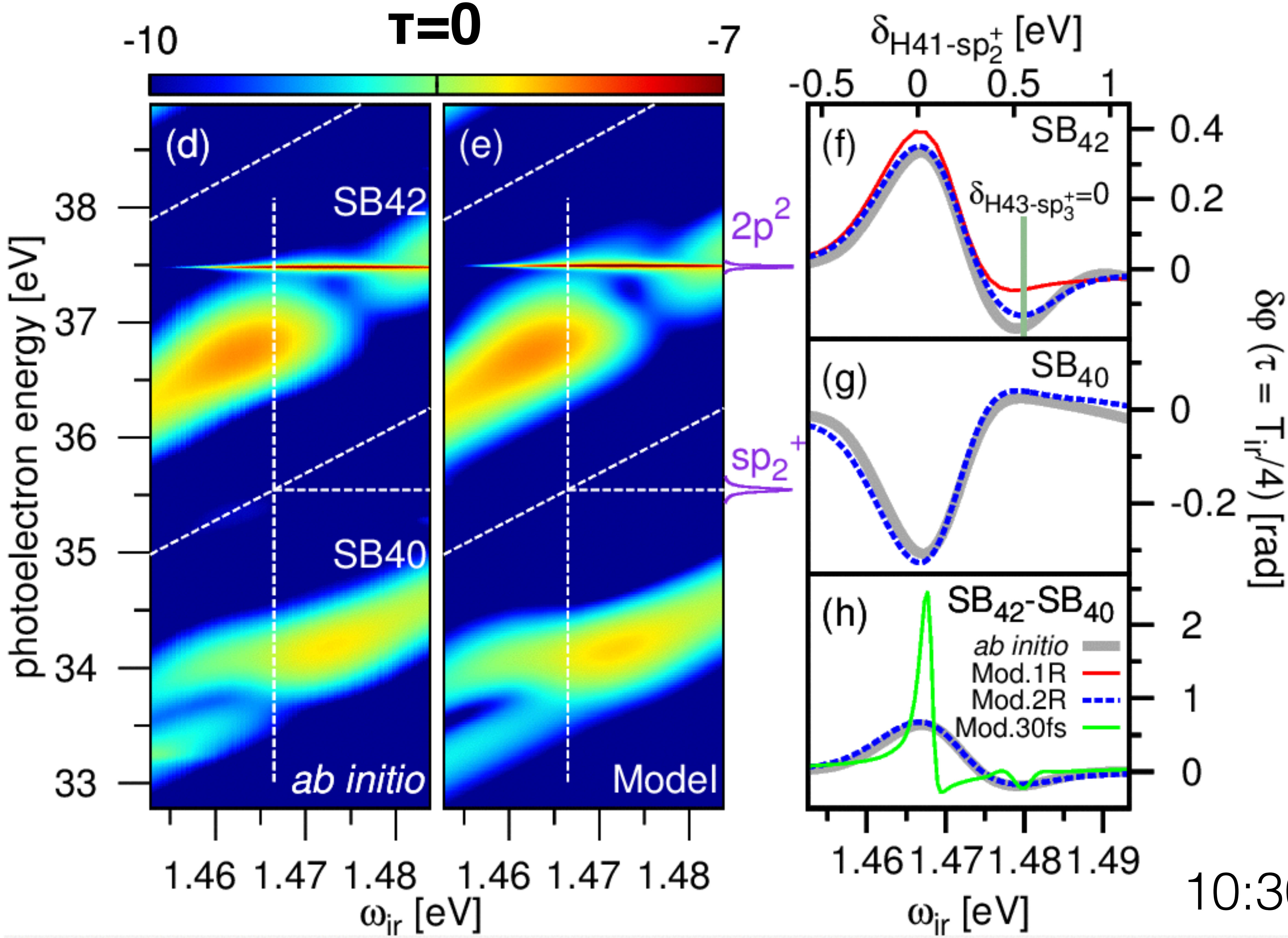
$$\langle E|\mathcal{O}G_0^+(E_g+\omega_{\text{XUV}})\mathcal{O}|g\rangle \simeq \frac{\langle E|\mathcal{O}|a\rangle\langle a|\mathcal{O}|g\rangle}{\omega_{\text{XUV}}-E_{ag}+i\Gamma_a/2}+\mathcal{M}_{\text{dir}}(E)$$



$$\delta\varphi(\omega_{\text{IR}},\tau) = -\arg\left\{w^*(z_f^-)\left[B\,w(z_a^+)-w(z_f^+)\right]\right\}$$

$$B=[\beta_{Ea}-2^{-1}\Gamma_a/(E_f-E_a)](i-q_a')$$

Apparent phase modulation

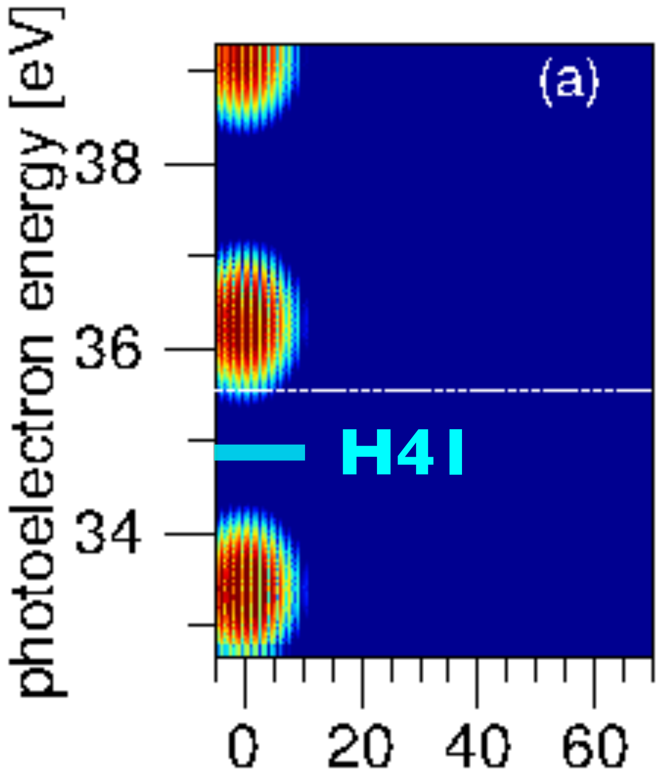


10:30

Top secret

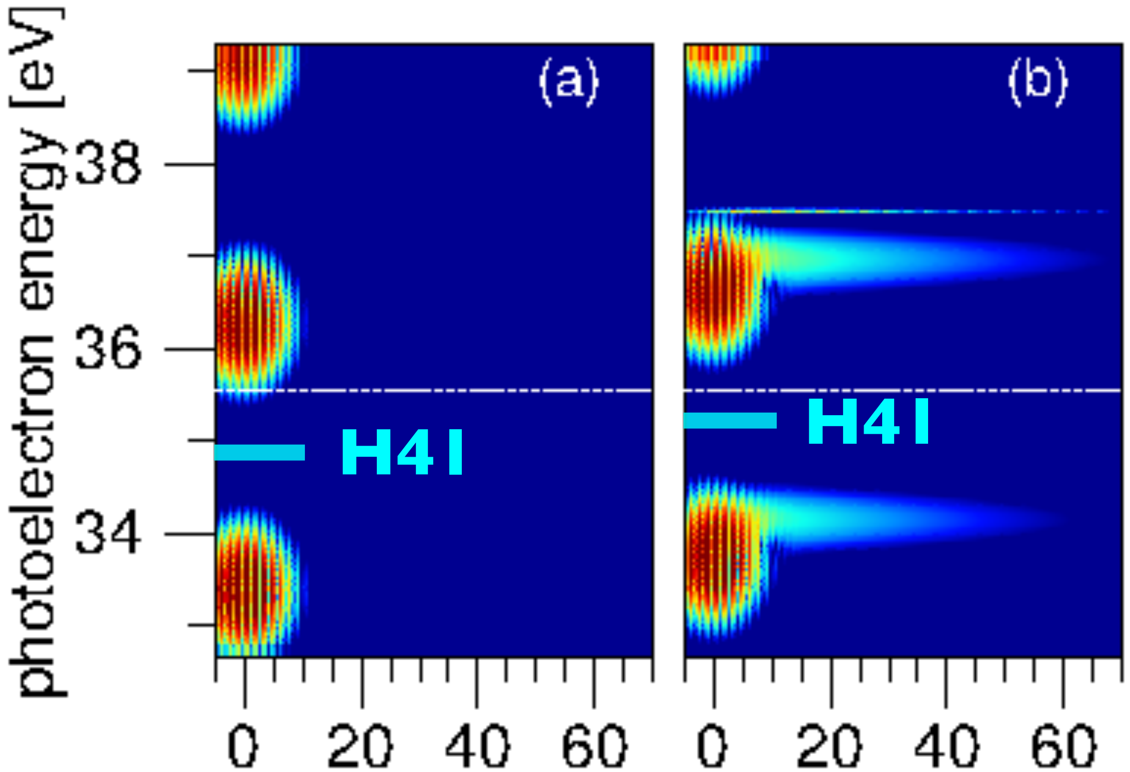
Us from Madrid, plus other people, *work in preparation* (2015)

Resonant Sidebands



Álvaro, Fernando and I, *work in preparation* (2015)

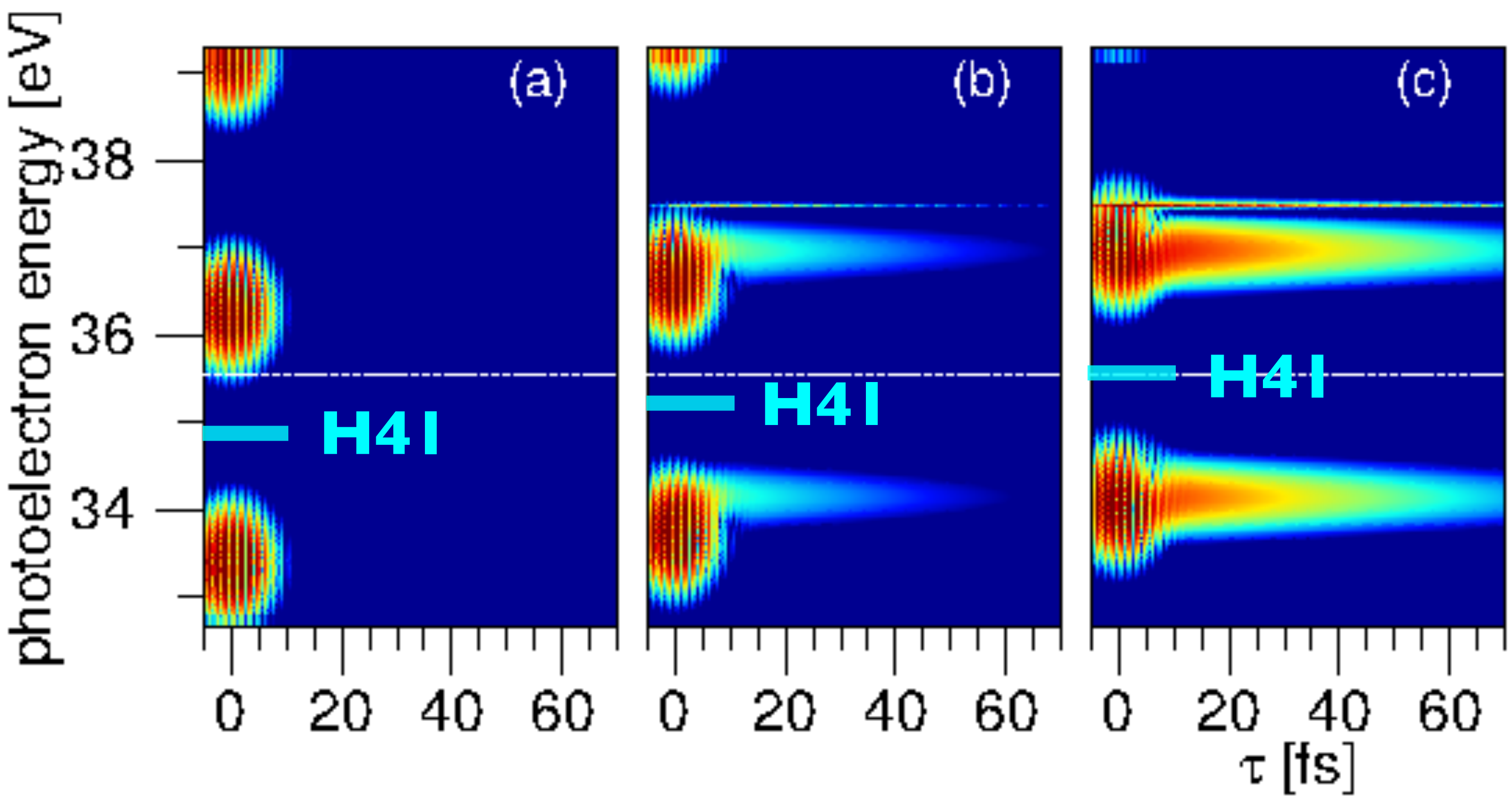
Resonant Sidebands



1. Close to resonance, exponentially decaying SB appears

Álvaro, Fernando and I, *work in preparation* (2015)

Resonant Sidebands



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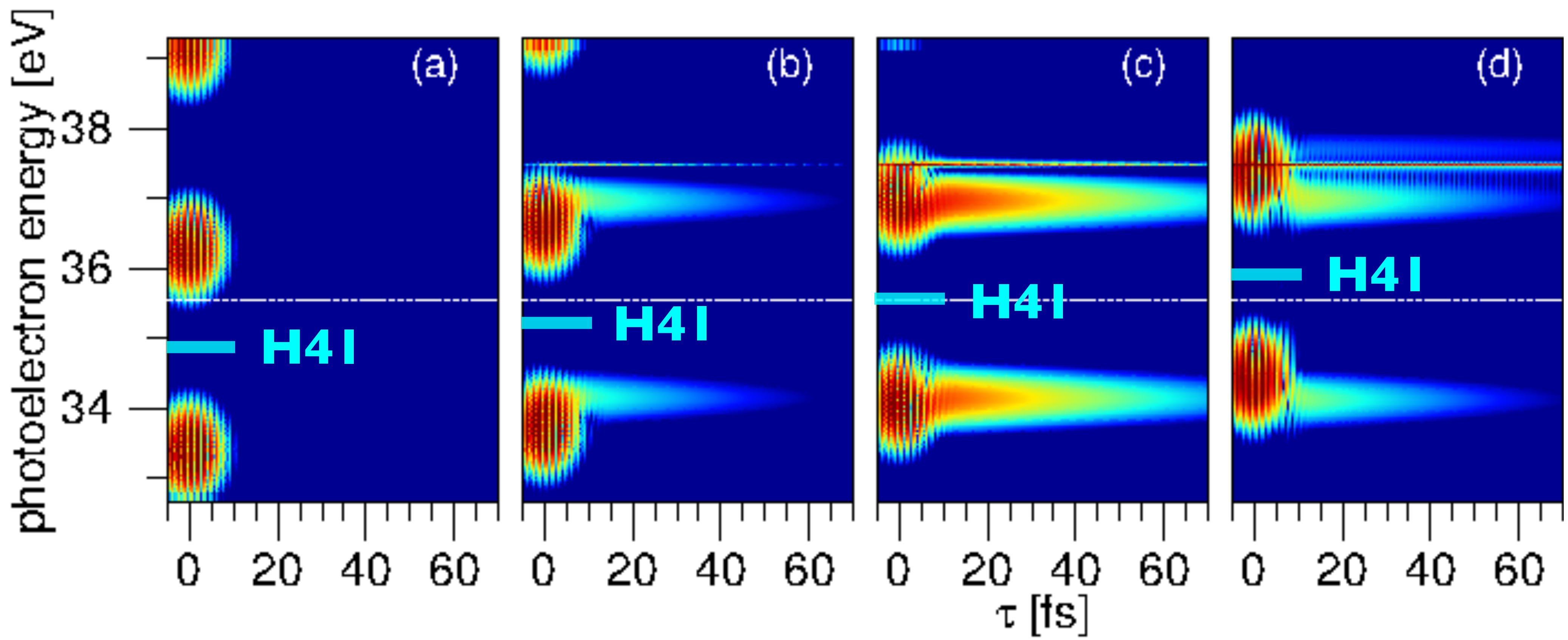
Resonant Sidebands

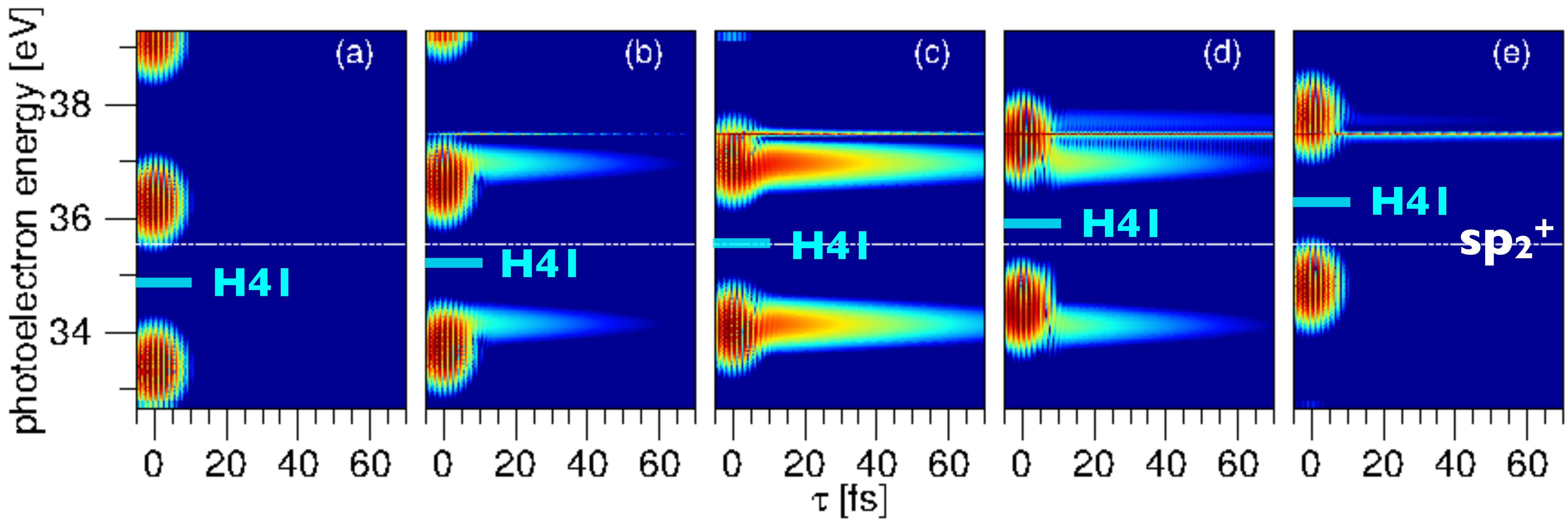


1. Close to resonance, exponentially decaying SB appears

2. If sidebands from two resonances overlap, beating persists

Álvaro, Fernando and I, *work in preparation* (2015)

Resonant Sidebands



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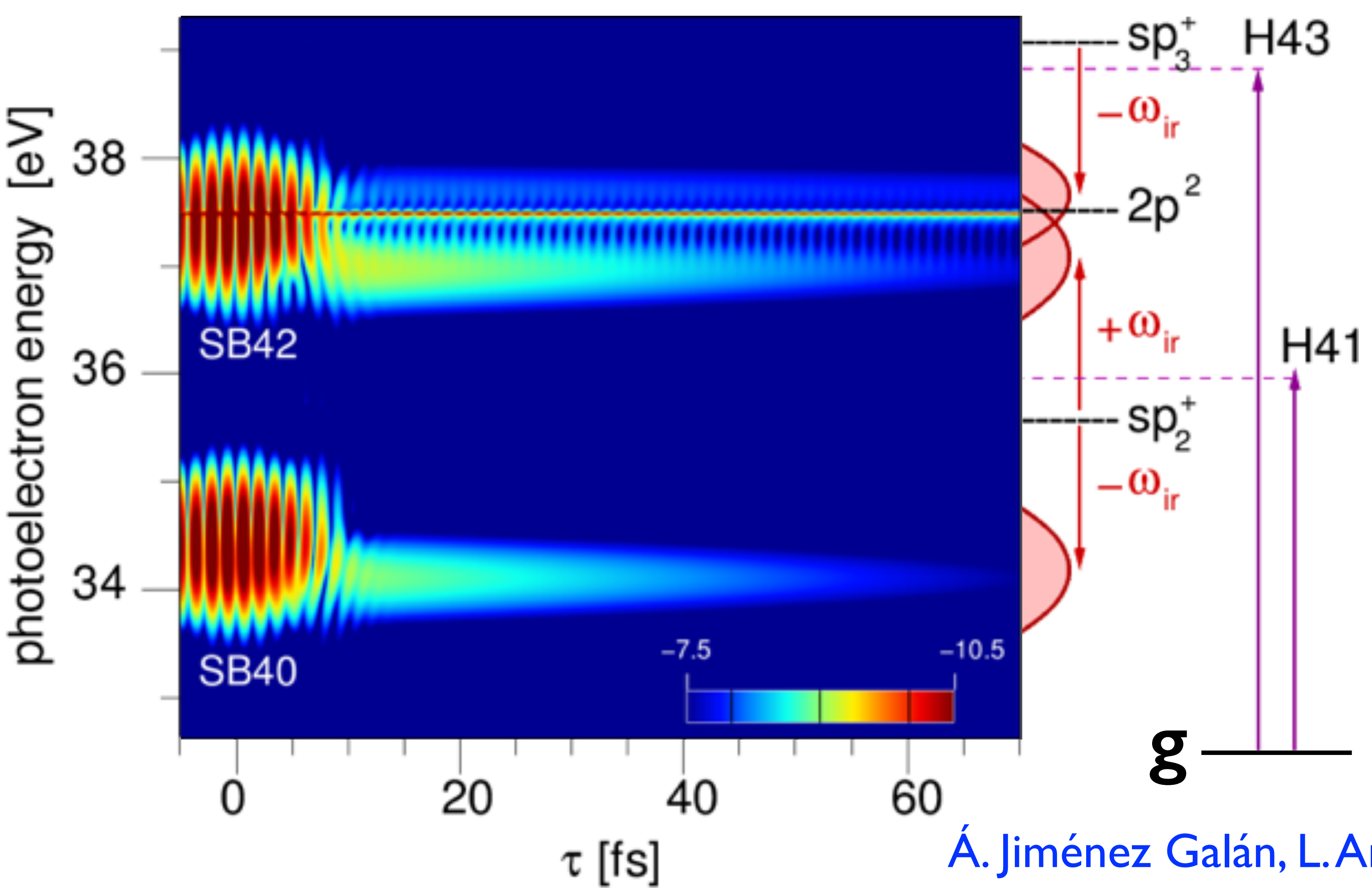
Álvaro, Fernando and I, *work in preparation* (2015)

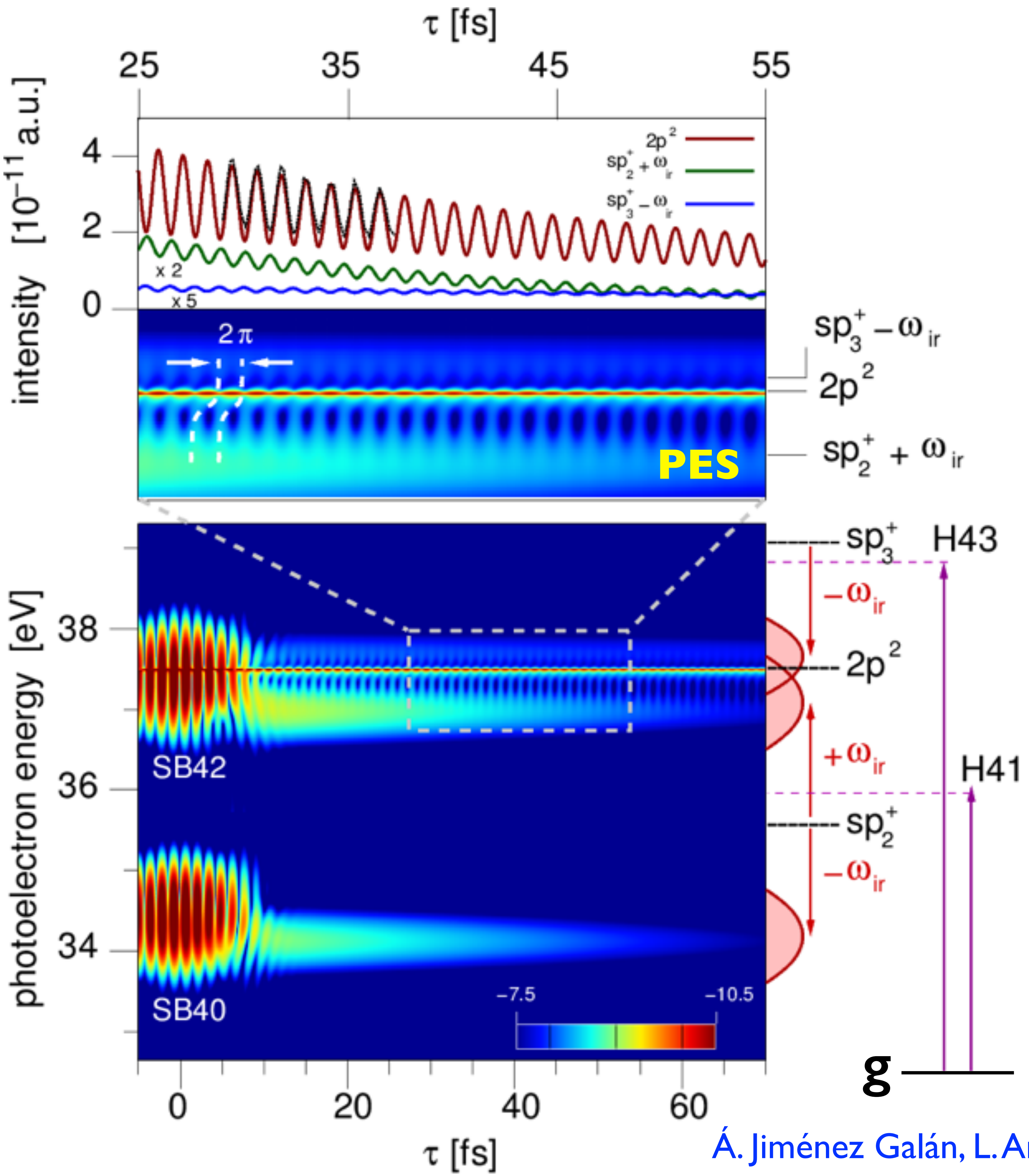
Separated pump-probe

1. sideband beating persists beyond PP overlap

2. change of phase and frequency wrt to “normal” RABBIT



Á. Jiménez Galán, L. Argenti, F. Martín, PRL **113**, 263001 (2014)



Separated pump-probe

1. sideband beating persists beyond PP overlap

2. change of phase and frequency wrt to “normal” RABBIT

3. complex q parameter for final resonance

4. Inversion of Fano profile

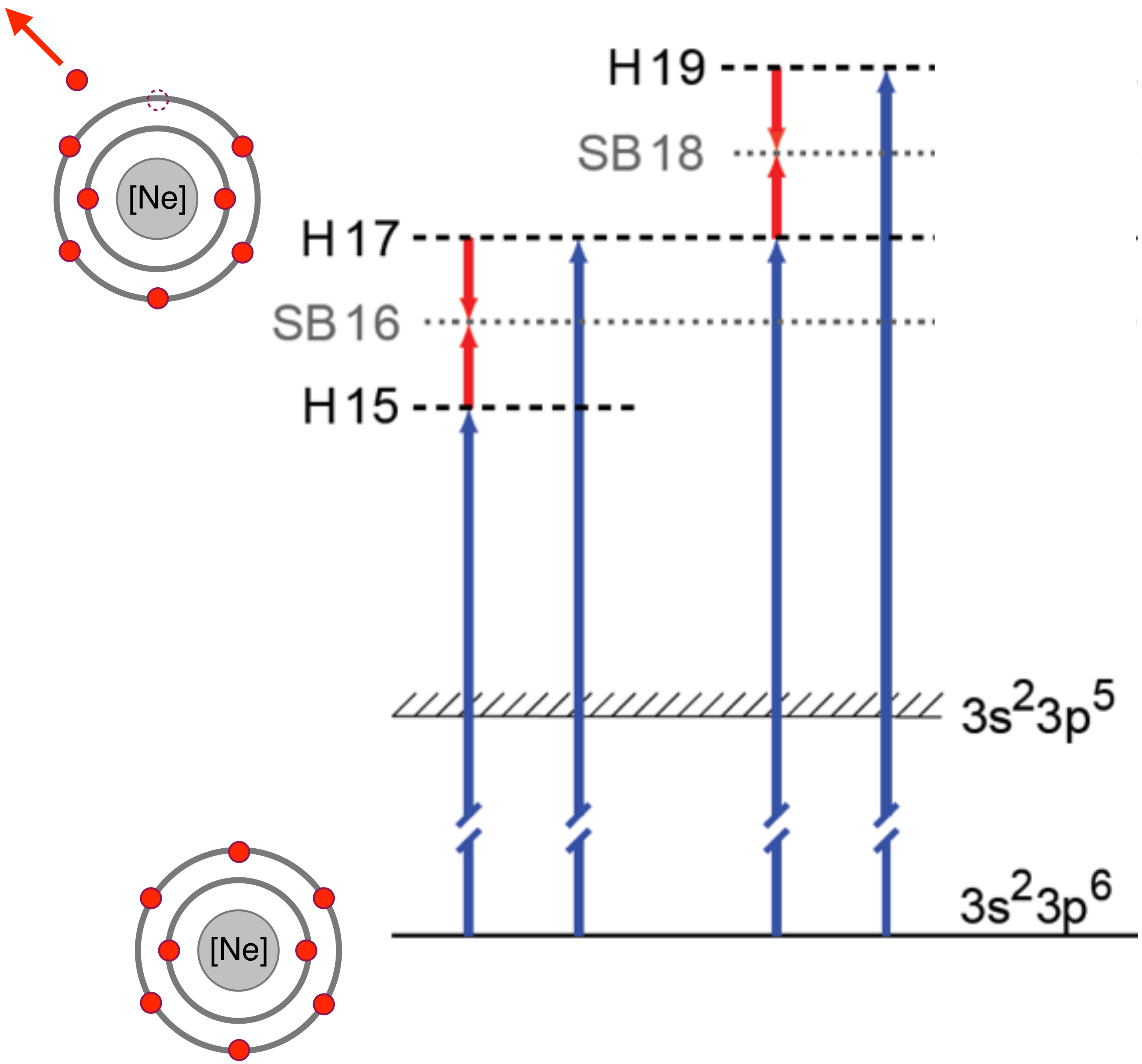
10:35

Á. Jiménez Galán, L. Argenti, F. Martín, PRL **113**, 263001 (2014)

Resonant RABITT ionization of Argon

$$\mathrm{Ar} + \gamma \rightarrow \mathrm{Ar}^+ + e^-$$

$$\mathrm{Ar}^+ + e^- \pm \gamma \rightarrow \mathrm{Ar}^+ + e^-$$



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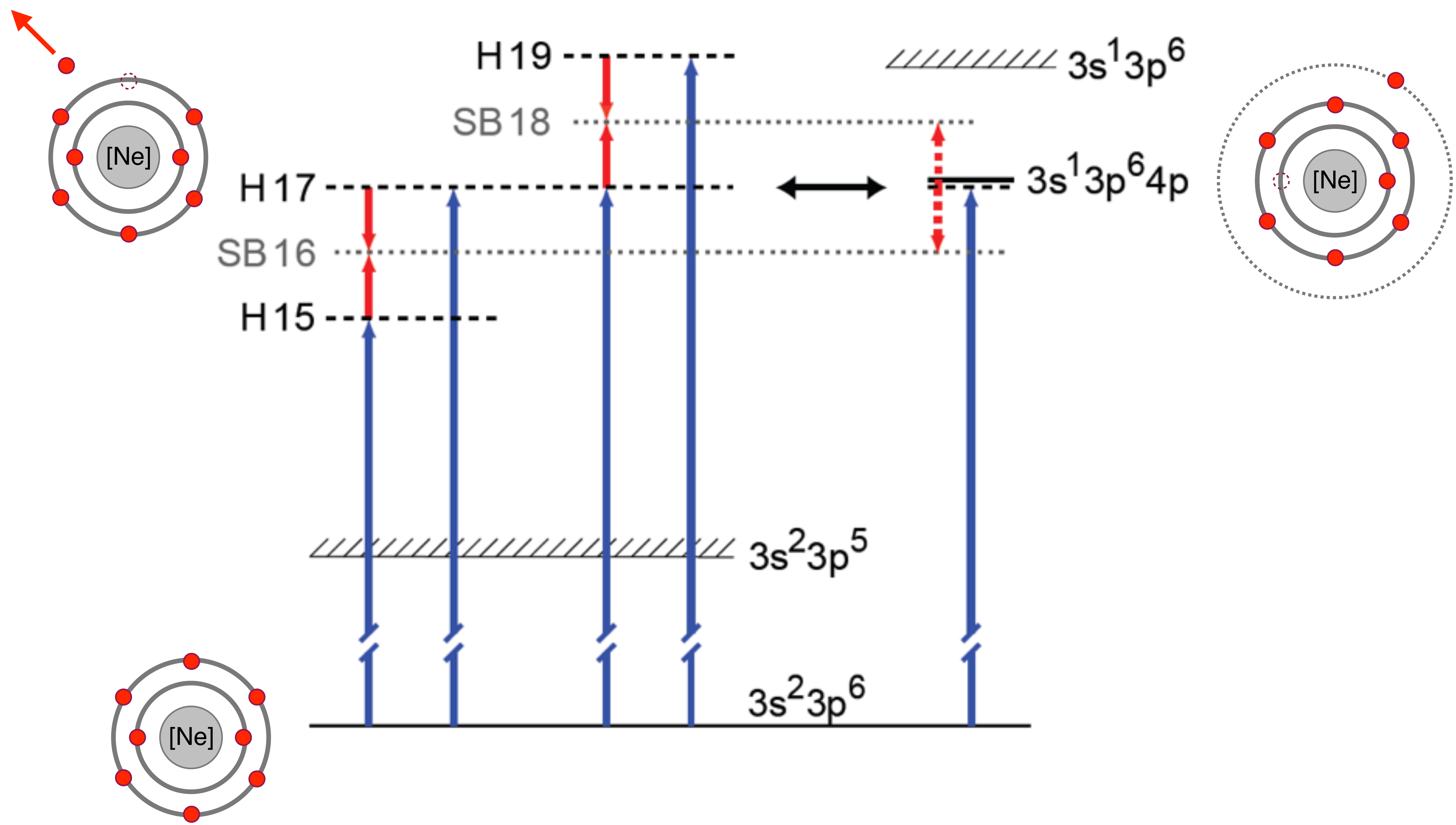
M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

Resonant RABITT ionization of Argon

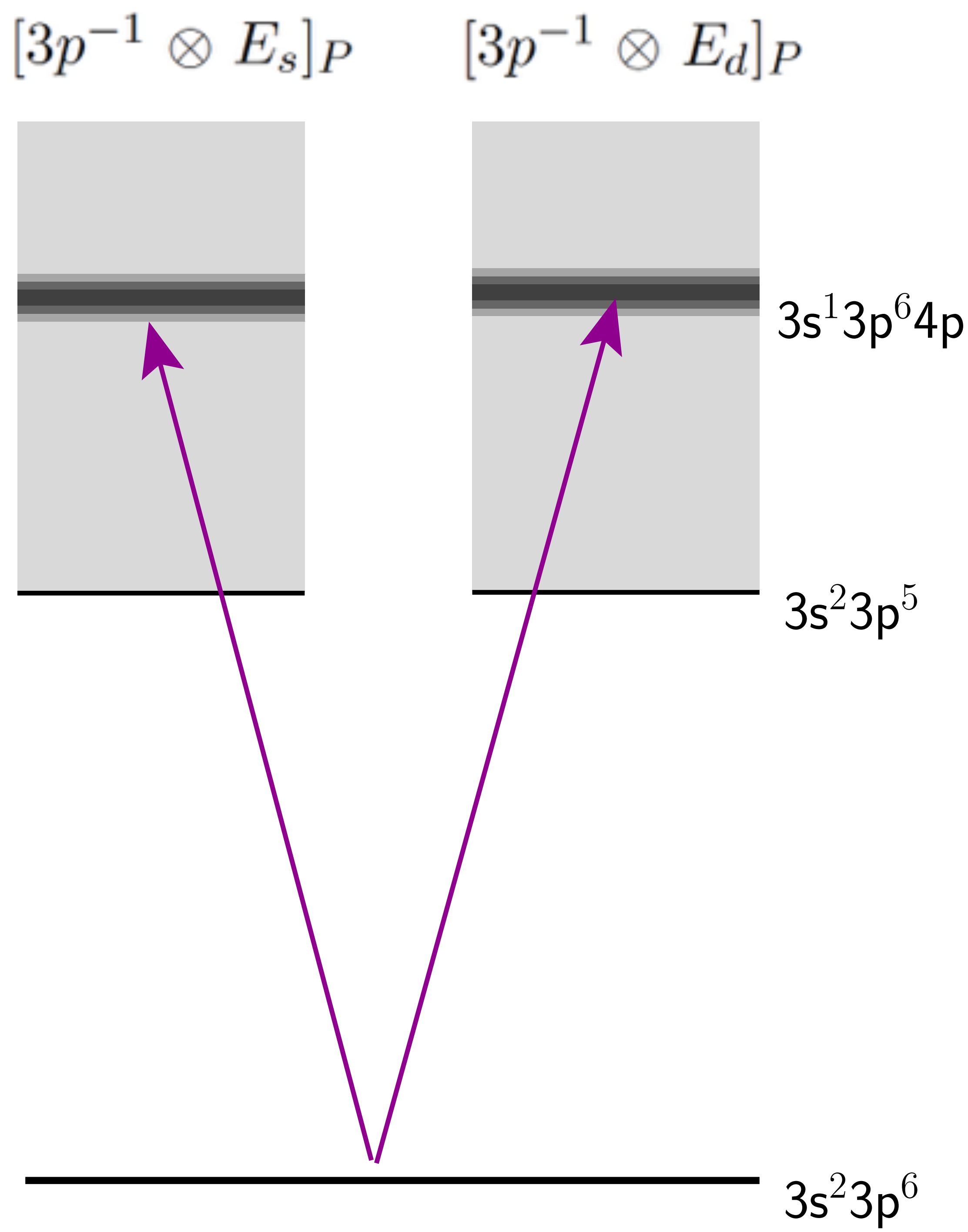
$$\mathrm{Ar} + {\color{blue}\gamma} \rightarrow \mathrm{Ar}^{+} + e^{-} \qquad \mathrm{Ar} + {\color{blue}\gamma} \rightarrow \mathrm{Ar}^{*}(3s^{-1}4p)$$

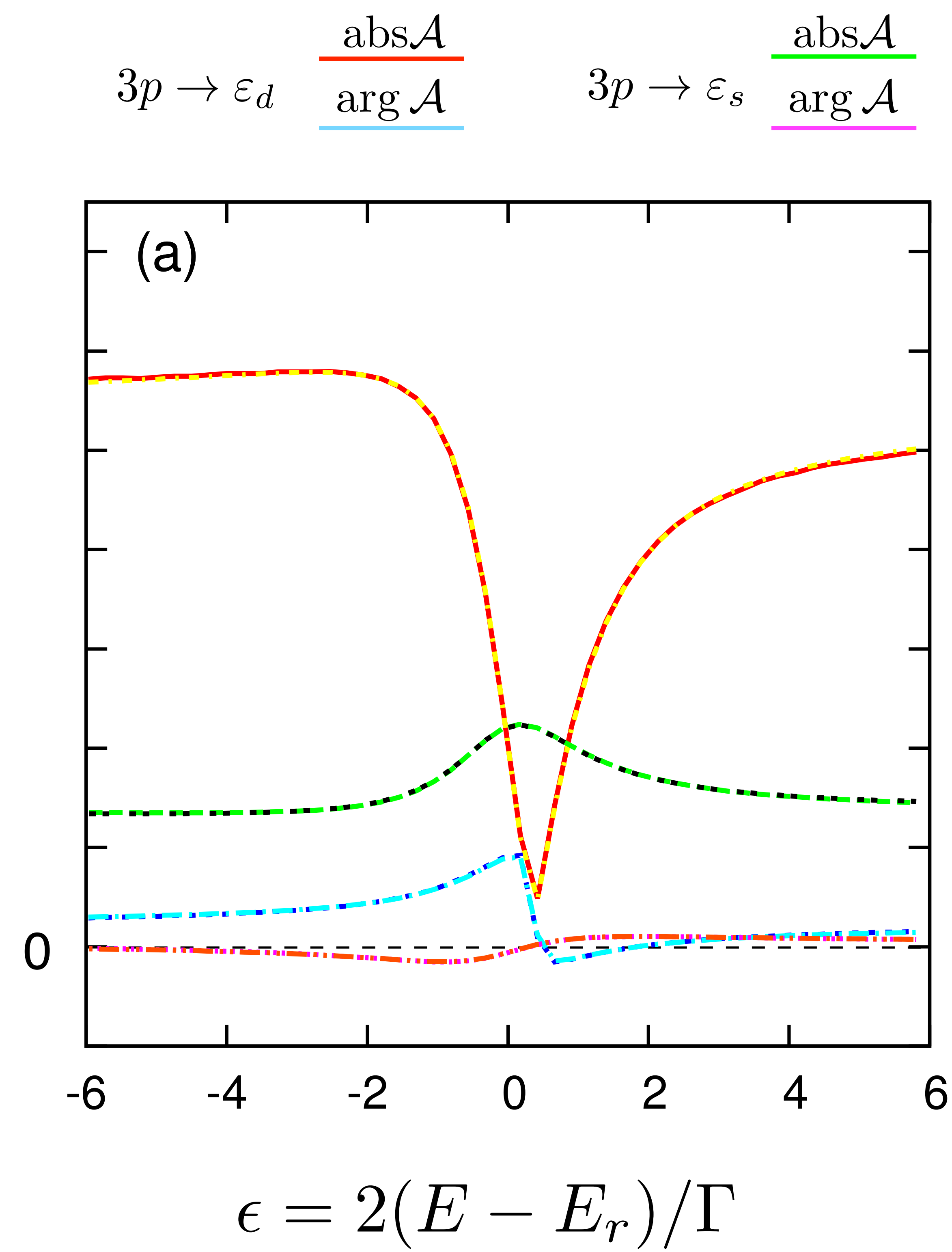
$$\mathrm{Ar}^{+} + e^{-} \pm {\color{red}\gamma} \rightarrow \mathrm{Ar}^{+} + e^{-} \qquad \mathrm{Ar}^{*}(3s^{-1}4p) \pm {\color{red}\gamma} \rightarrow \mathrm{Ar}^{+} + e^{-}$$



M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

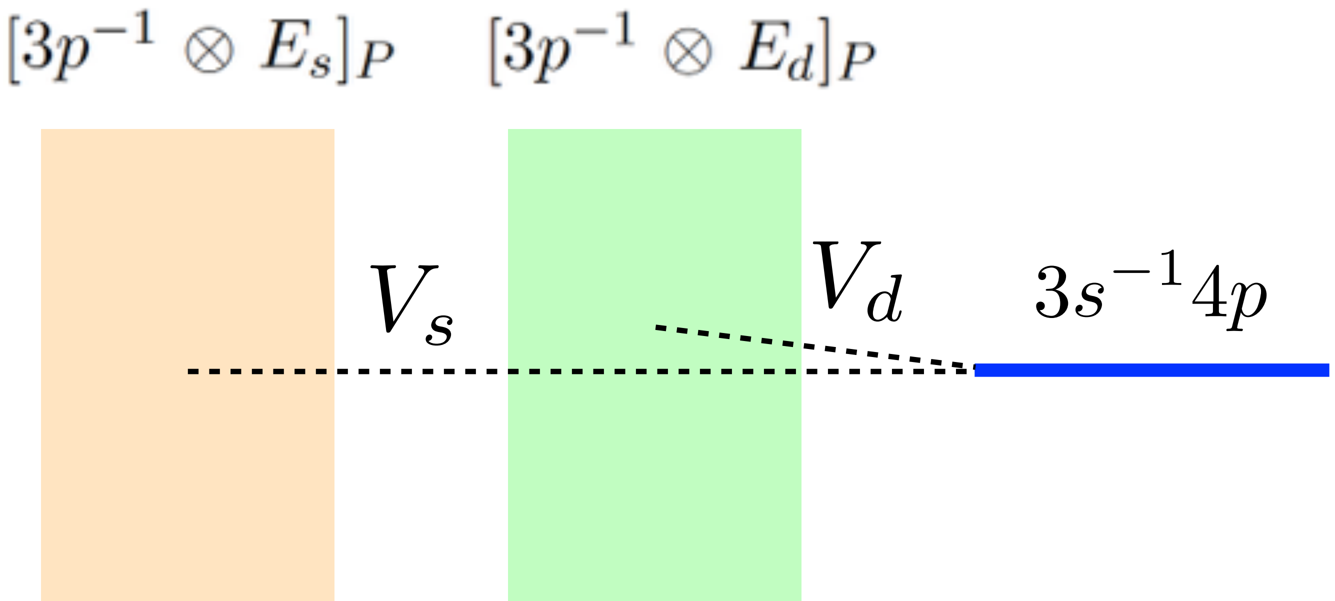
Intermediate multichannel-resonant states





T. Carette *et al.*, PRA **87**, 023420 (2013)

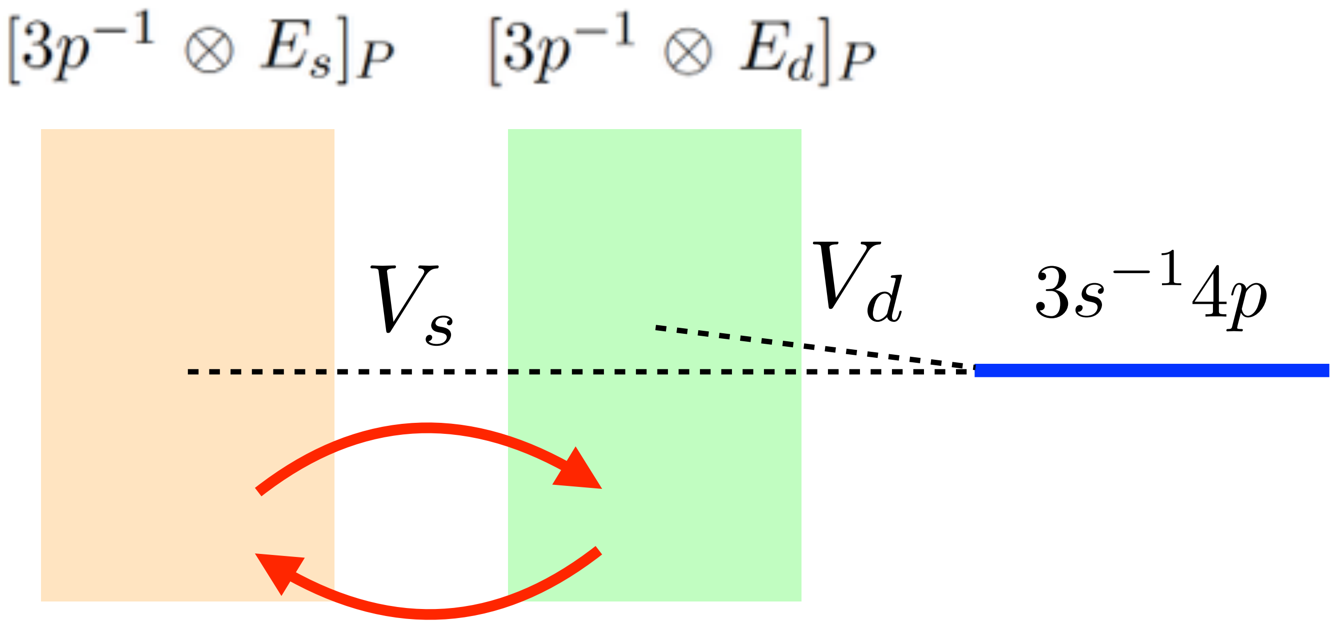
Intermediate multichannel-resonant states



$$V_\ell = \langle \varphi_{[3p^{-1} \otimes \varepsilon_\ell]_P} | H | 3s^{-1}4p \rangle$$

$$V = \sqrt{V_s^2 + V_d^2}$$

Intermediate multichannel-resonant states



$$V_\ell = \langle \varphi_{[3p^{-1} \otimes \varepsilon_\ell]_P} | H | 3s^{-1}4p \rangle$$

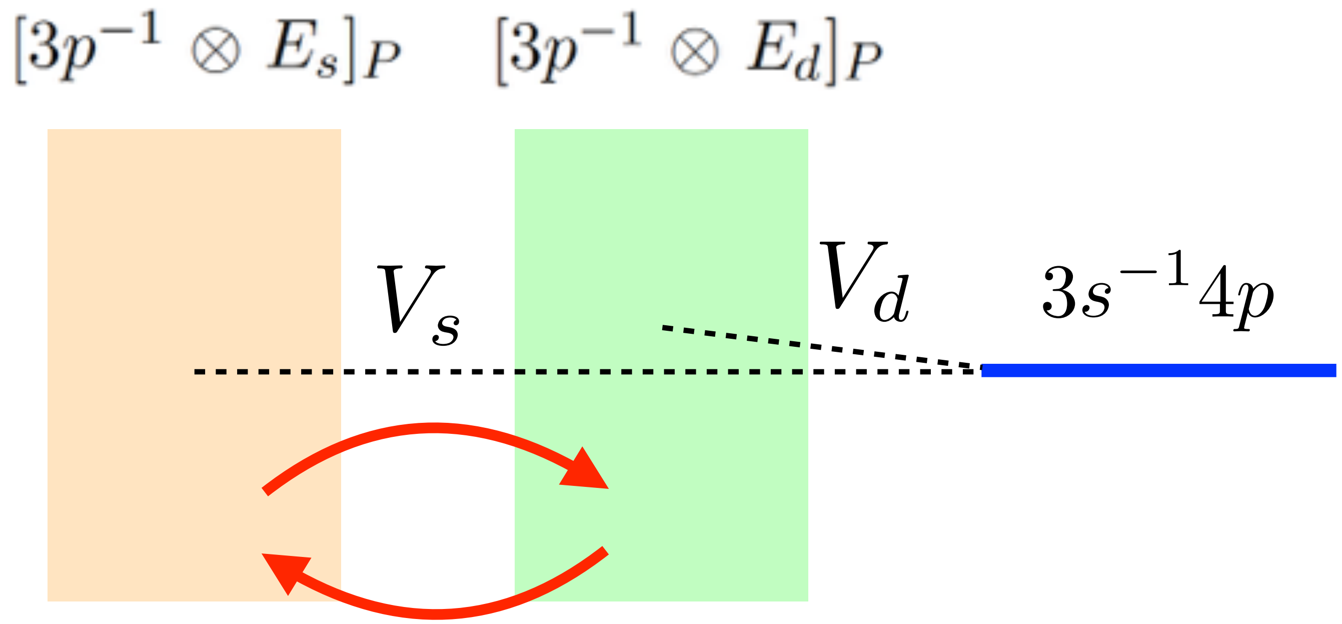
$$V = \sqrt{V_s^2 + V_d^2}$$

$$|\varphi_D\rangle = |\varphi_{[3p^{-1} \otimes \varepsilon_s]_P}\rangle \, V_d/V - |\varphi_{[3p^{-1} \otimes \varepsilon_d]_P}\rangle \, V_s/V$$

$$|\varphi_R\rangle = |\varphi_{[3p^{-1} \otimes \varepsilon_s]_P}\rangle \, V_s/V + |\varphi_{[3p^{-1} \otimes \varepsilon_d]_P}\rangle \, V_d/V$$

Unitary Transf.

Intermediate multichannel-resonant states



$$V_\ell = \langle \varphi_{[3p^{-1} \otimes \varepsilon_\ell]_P} | H | 3s^{-1}4p \rangle$$

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$$|\varphi_D\rangle = |\varphi_{[3p^{-1} \otimes \varepsilon_s]_P}\rangle\, V_d/V - |\varphi_{[3p^{-1} \otimes \varepsilon_d]_P}\rangle\, V_s/V$$

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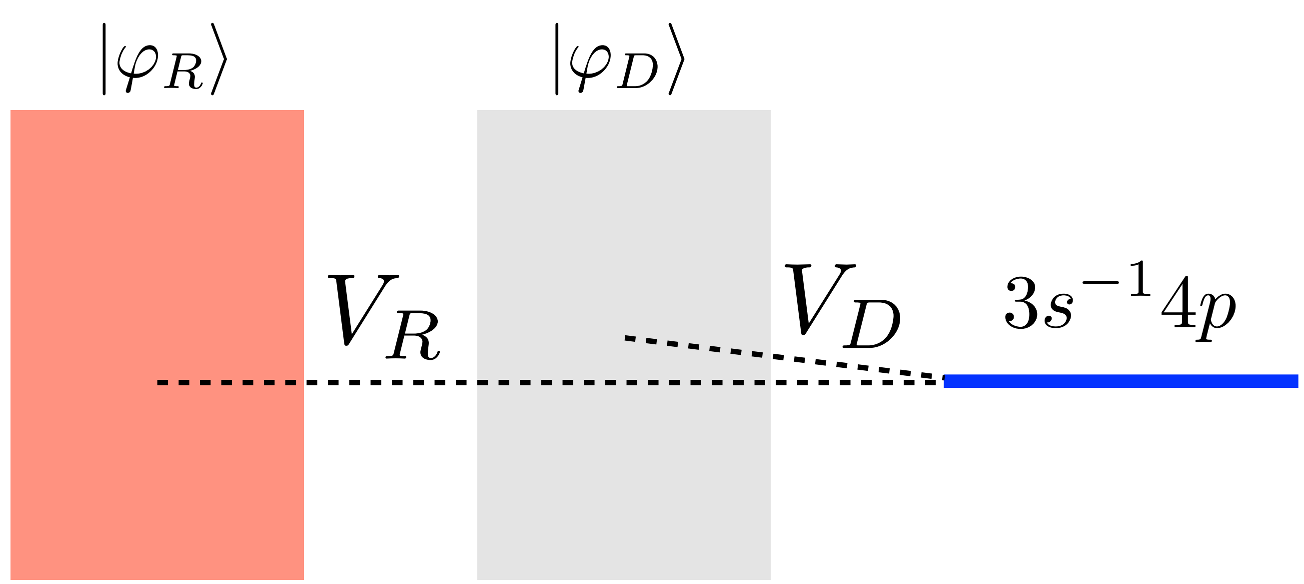
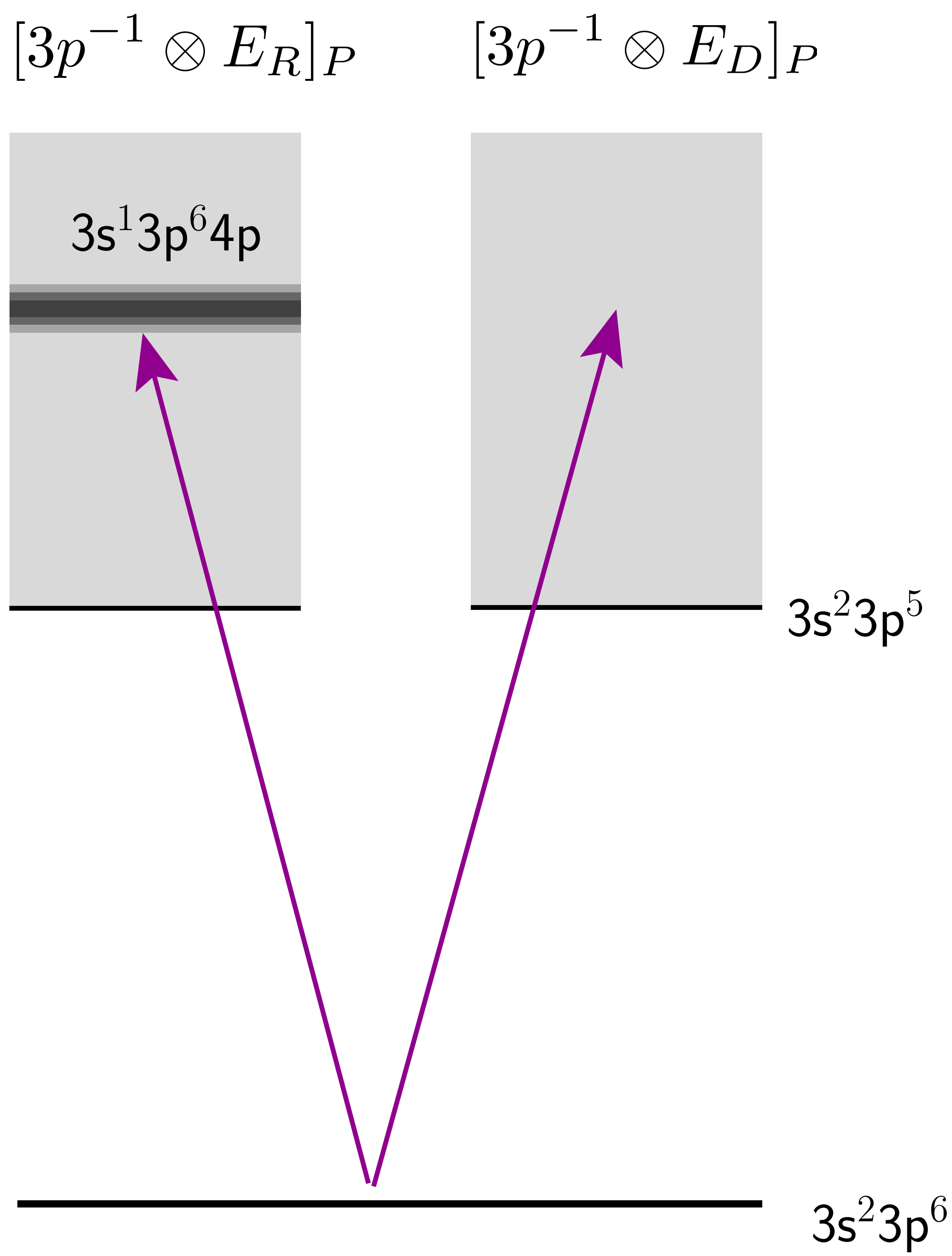
Unitary Transf.

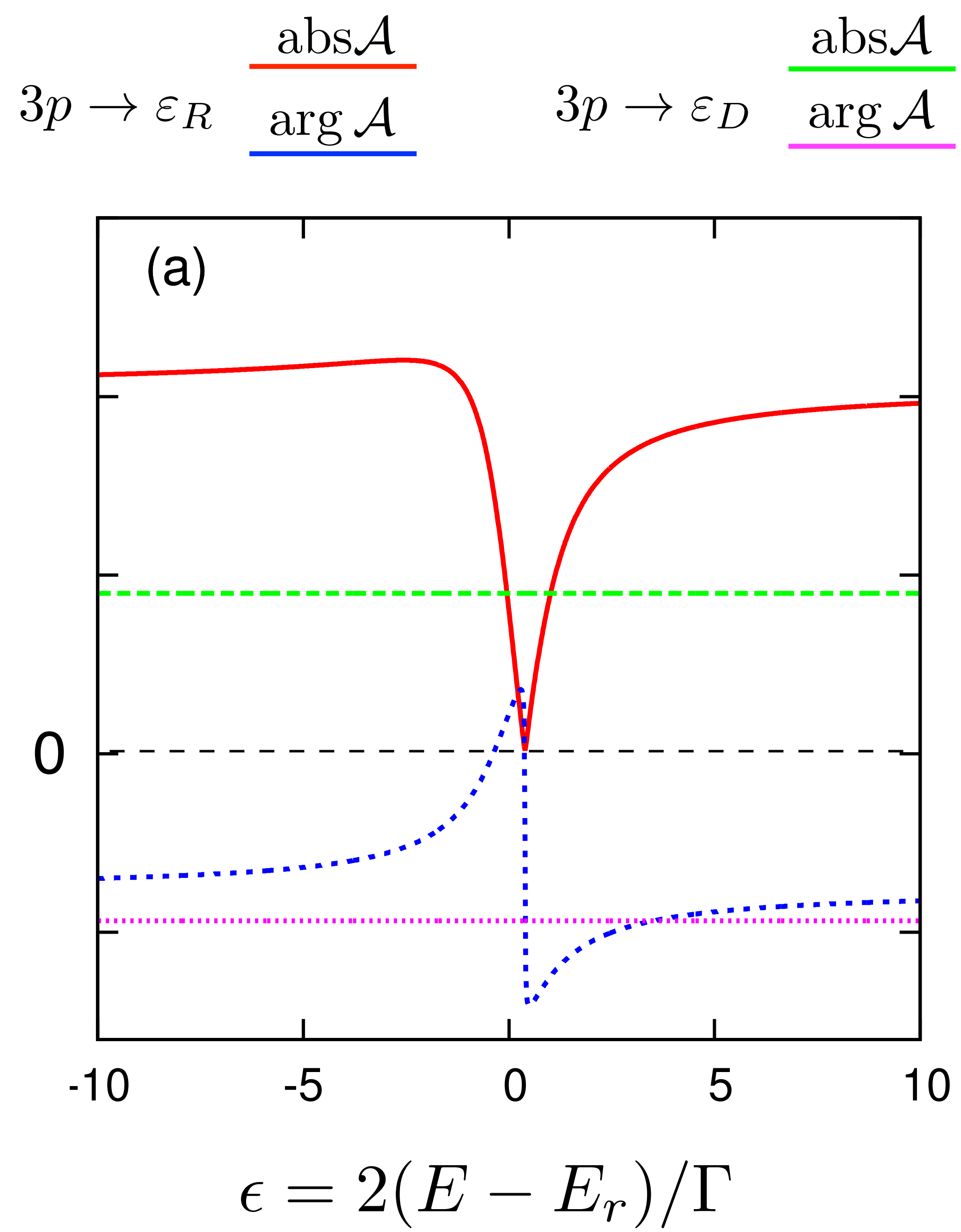


$$V_R = \langle \varphi_R | H | 3s^{-1}4p \rangle = V$$

$$V_D = \langle \varphi_D | H | 3s^{-1}4p \rangle = 0$$

Decoupling of intermediate multichannel-resonant states

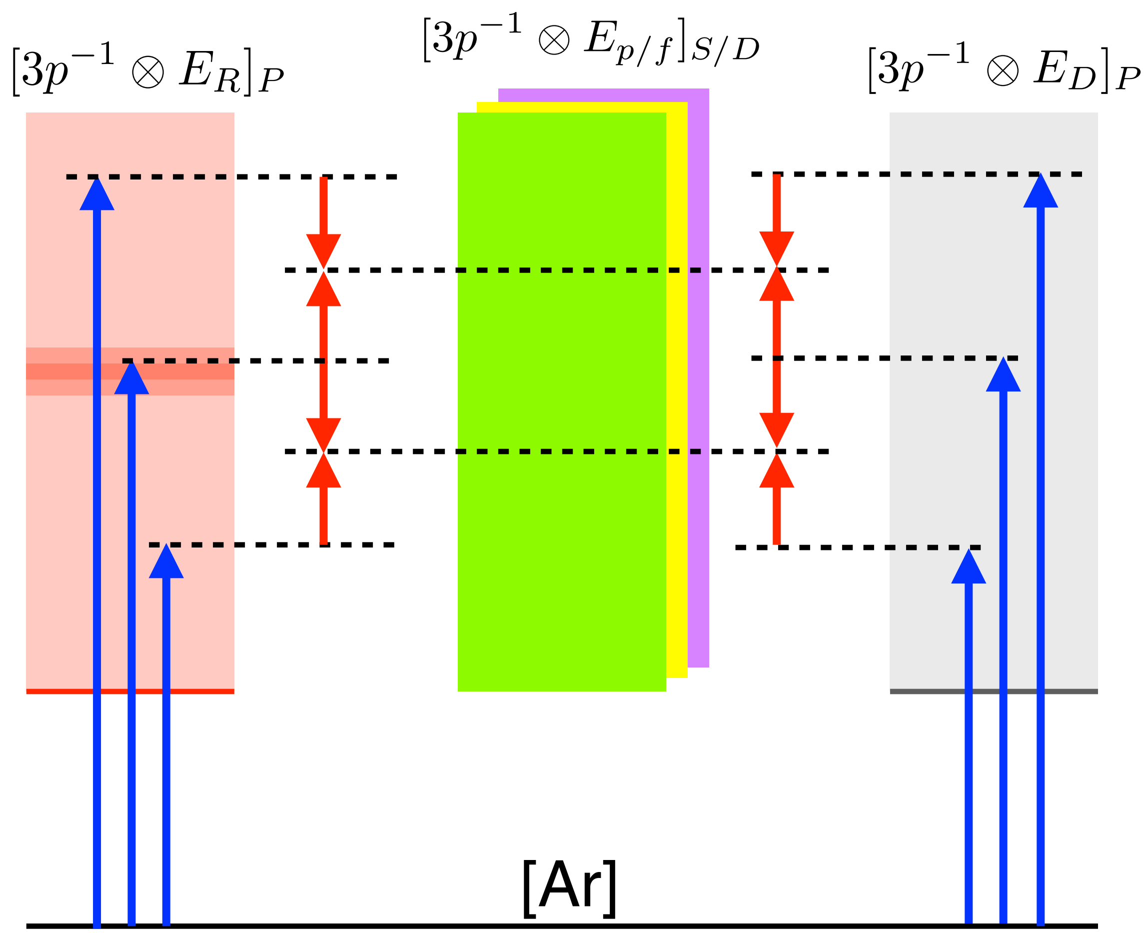




$$|\Psi^{^1P^o}_{R,E}\rangle = |\Psi^{^1P^o(-)}_{s,E}\rangle C_{s,R} + |\Psi^{^1P^o(-)}_{d,E}\rangle C_{d,R},$$

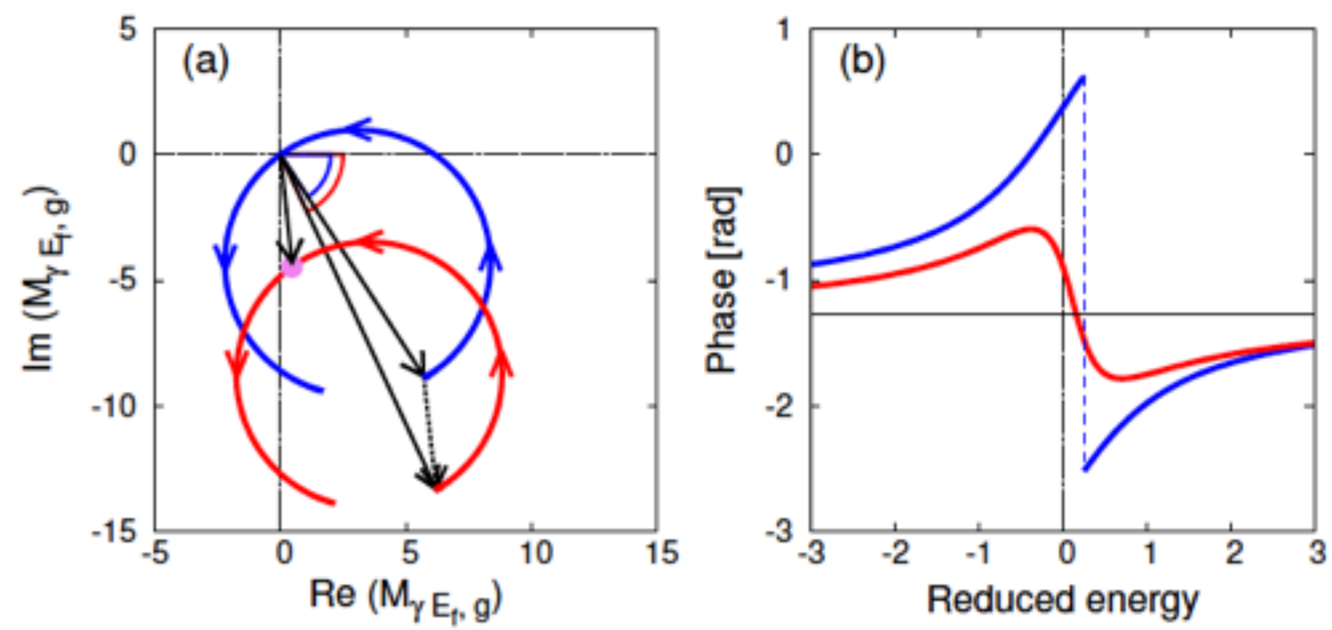
$$|\Psi^{^1P^o}_{D,E}\rangle = |\Psi^{^1P^o(-)}_{s,E}\rangle C_{s,D} + |\Psi^{^1P^o(-)}_{d,E}\rangle C_{d,D}.$$

Decoupling of intermediate multichannel-resonant states



$$\mathrm{Ar} + \gamma \rightarrow \mathrm{Ar}^+ + e^-$$

$$\mathrm{Ar}^+ + e^- \pm \gamma \rightarrow \mathrm{Ar}^+ + e^-$$



$$\mathcal{A}^{\pm}_{2n,\,\beta\leftarrow g} = \mathcal{A}^{\pm}_{2n,\,\beta\leftarrow D\leftarrow g} + \mathcal{A}^{\pm}_{2n,\,\beta\leftarrow R\leftarrow g}$$

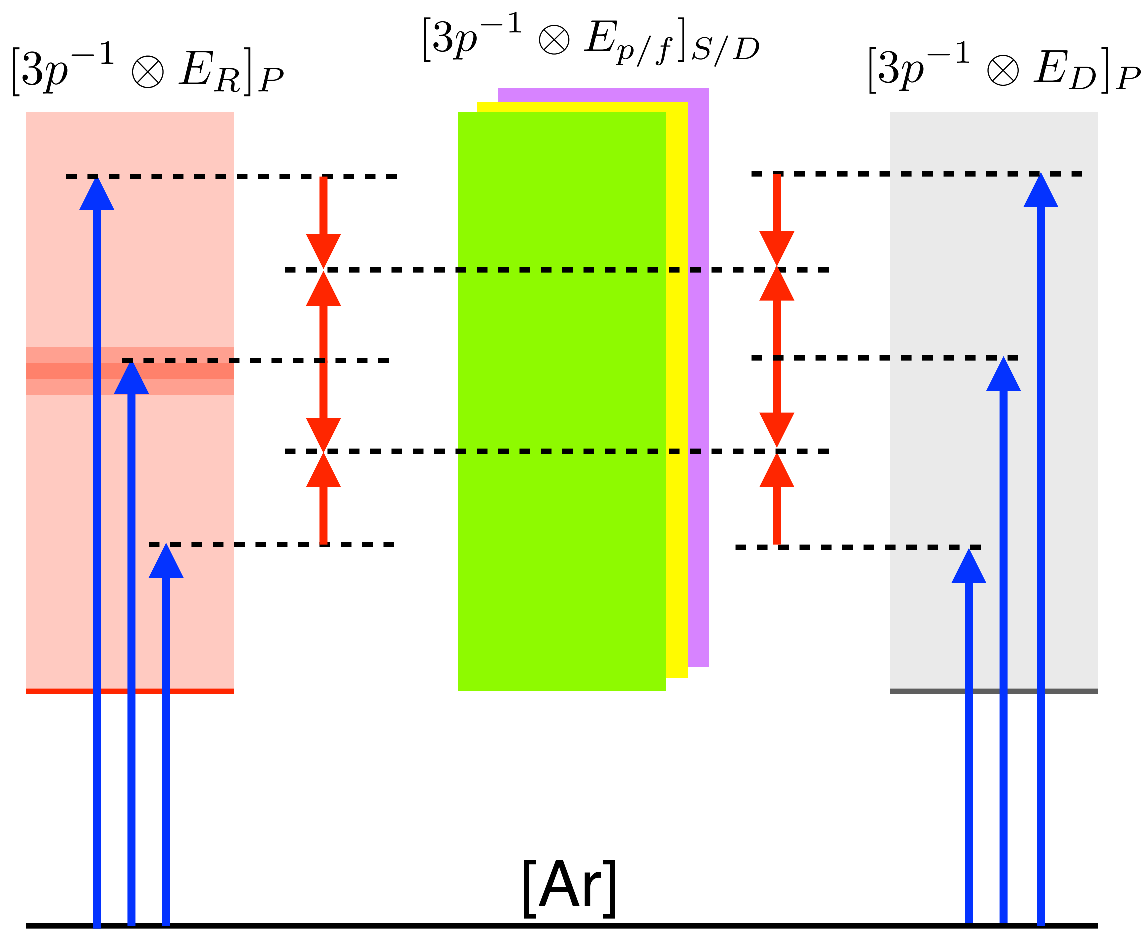
$$M_{\gamma E_f, g} = M^{(1)}_{\gamma E_f, g} \frac{q+\epsilon}{\epsilon + i} + M^{(2)}_{\gamma E_f, g}$$

$$\mathcal{A}^{\pm}_{2n,\,\beta\leftarrow D\leftarrow g} = e^{\mp i\omega_{\mathrm{IR}}\tau} \mathcal{F}_D(\tau)\ \ w(z_f^{\pm})$$

$$\mathcal{A}^{\pm}_{2n,\,\beta\leftarrow R\leftarrow g} = e^{\mp i\omega_{\mathrm{IR}}\tau} \mathcal{F}_R(\tau) \left[w(z_f^{\pm}) + (\beta_{Ea} - \epsilon_{fa}^{-1})(q_R - i) w(z_a^{\pm}) \right]$$

M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

Decoupling of intermediate multichannel-resonant states



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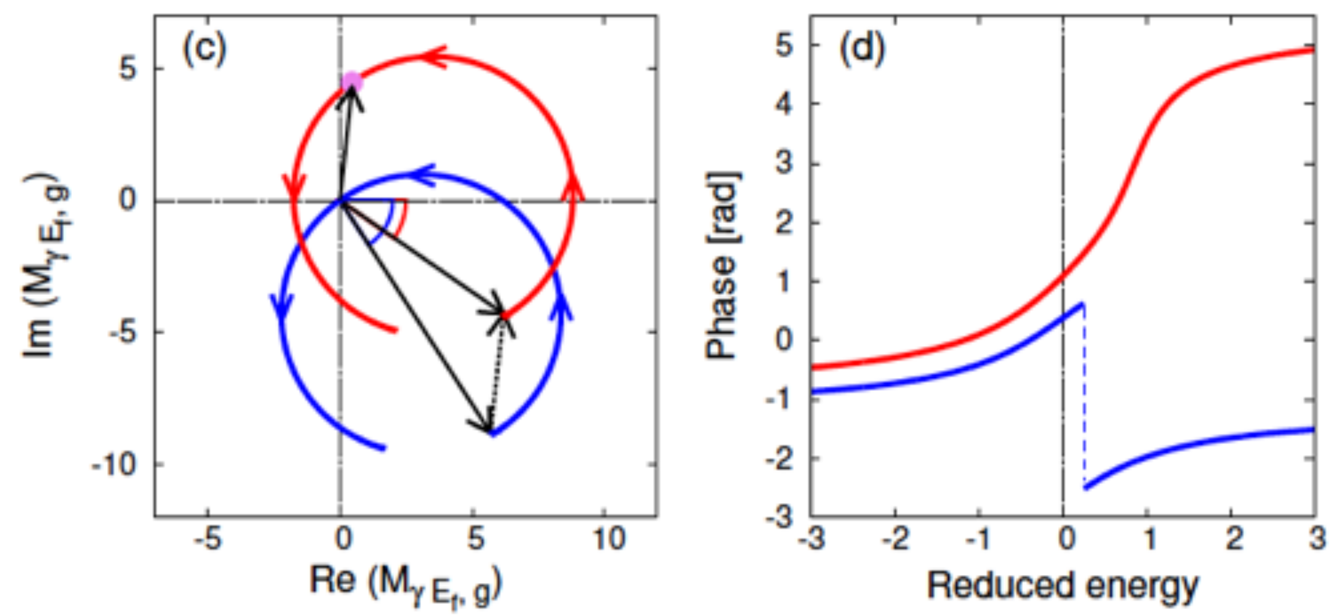

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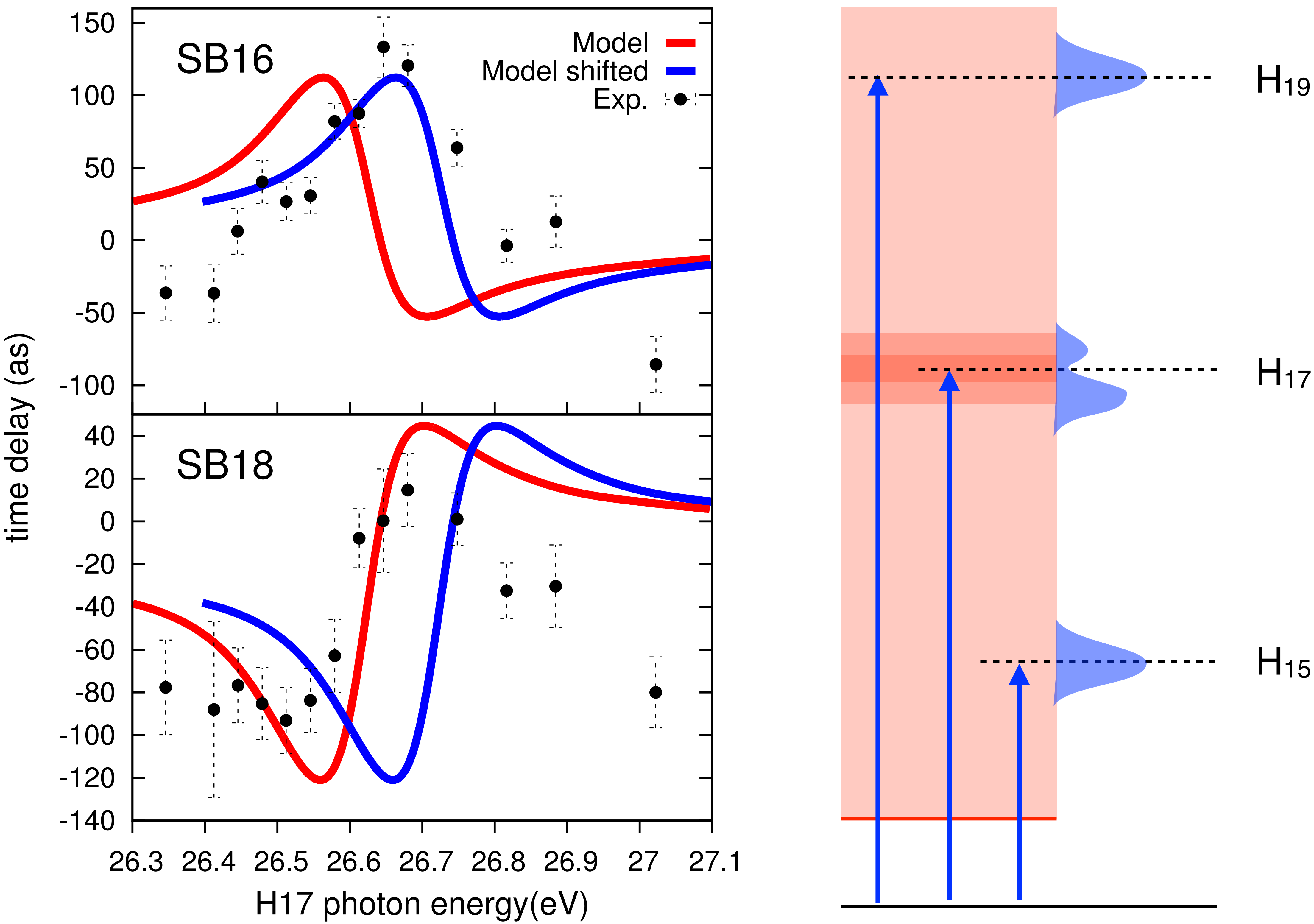
M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

Prediction Total Sideband Signal

$$I_{2n}(\tau) = I_{2n,\,[3p^{-1}\otimes E_p]_S\leftarrow g}(\tau) + I_{2n,\,[3p^{-1}\otimes E_p]_D\leftarrow g}(\tau) + I_{2n,\,[3p^{-1}\otimes E_f]_D\leftarrow g}(\tau)$$



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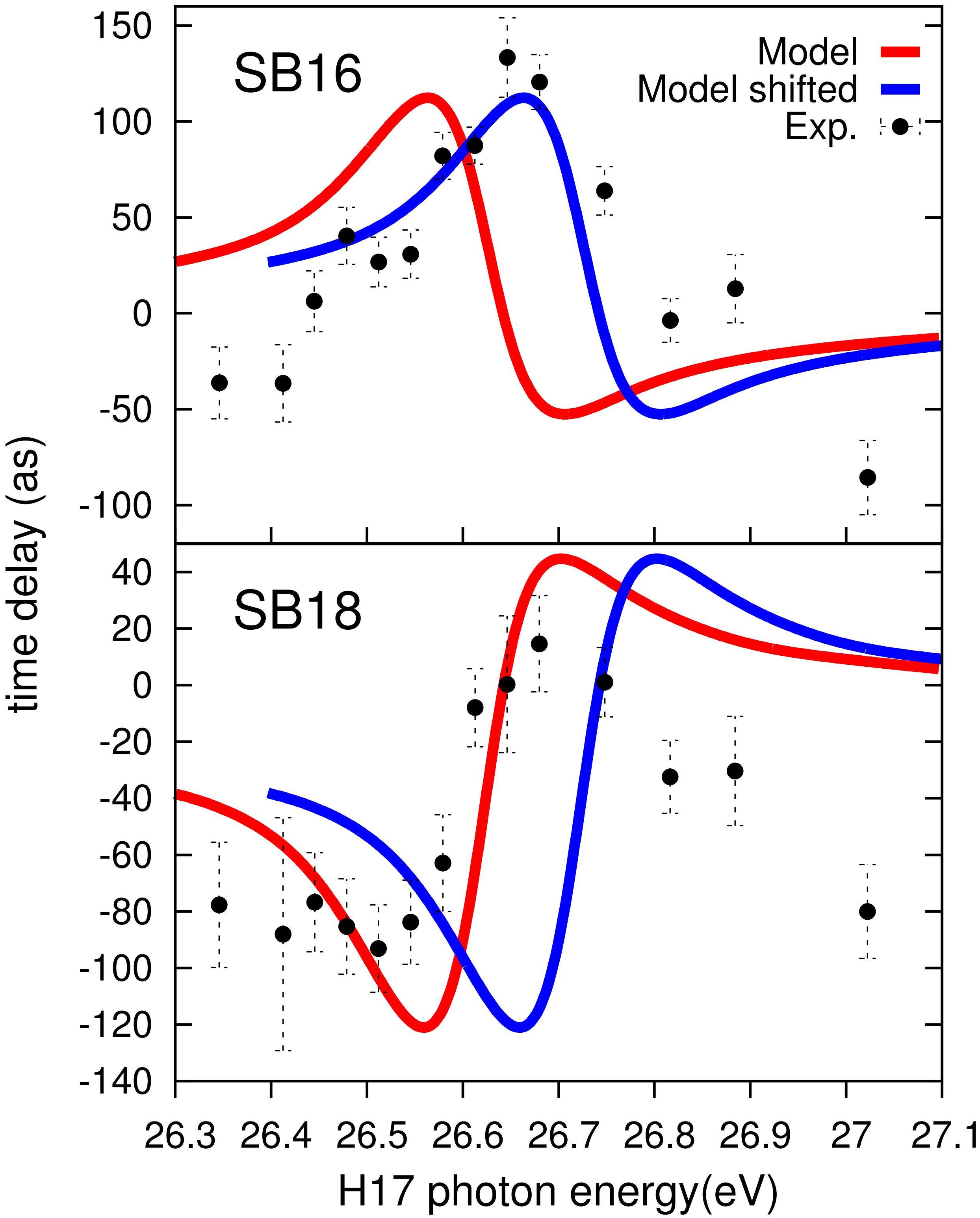

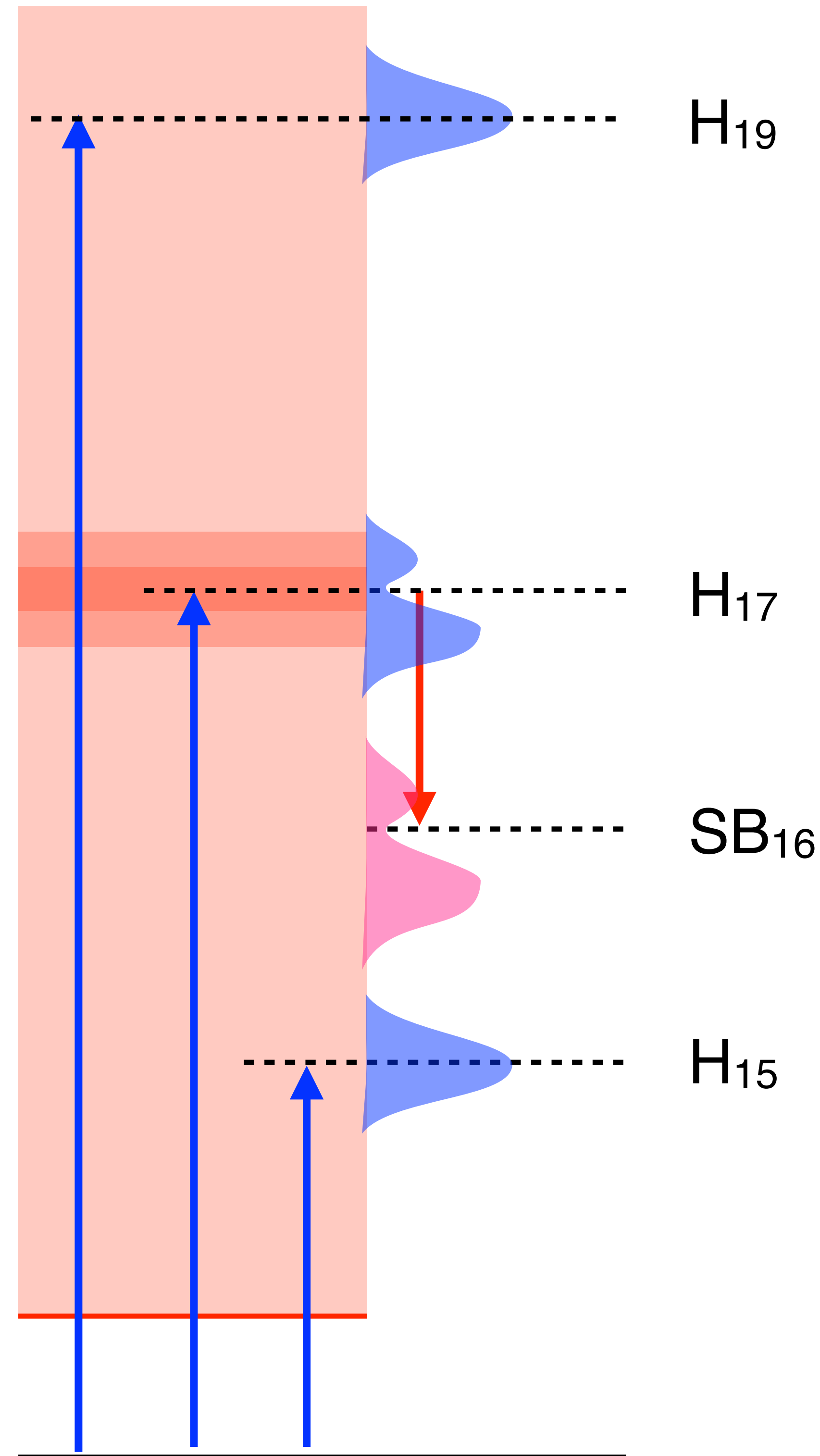

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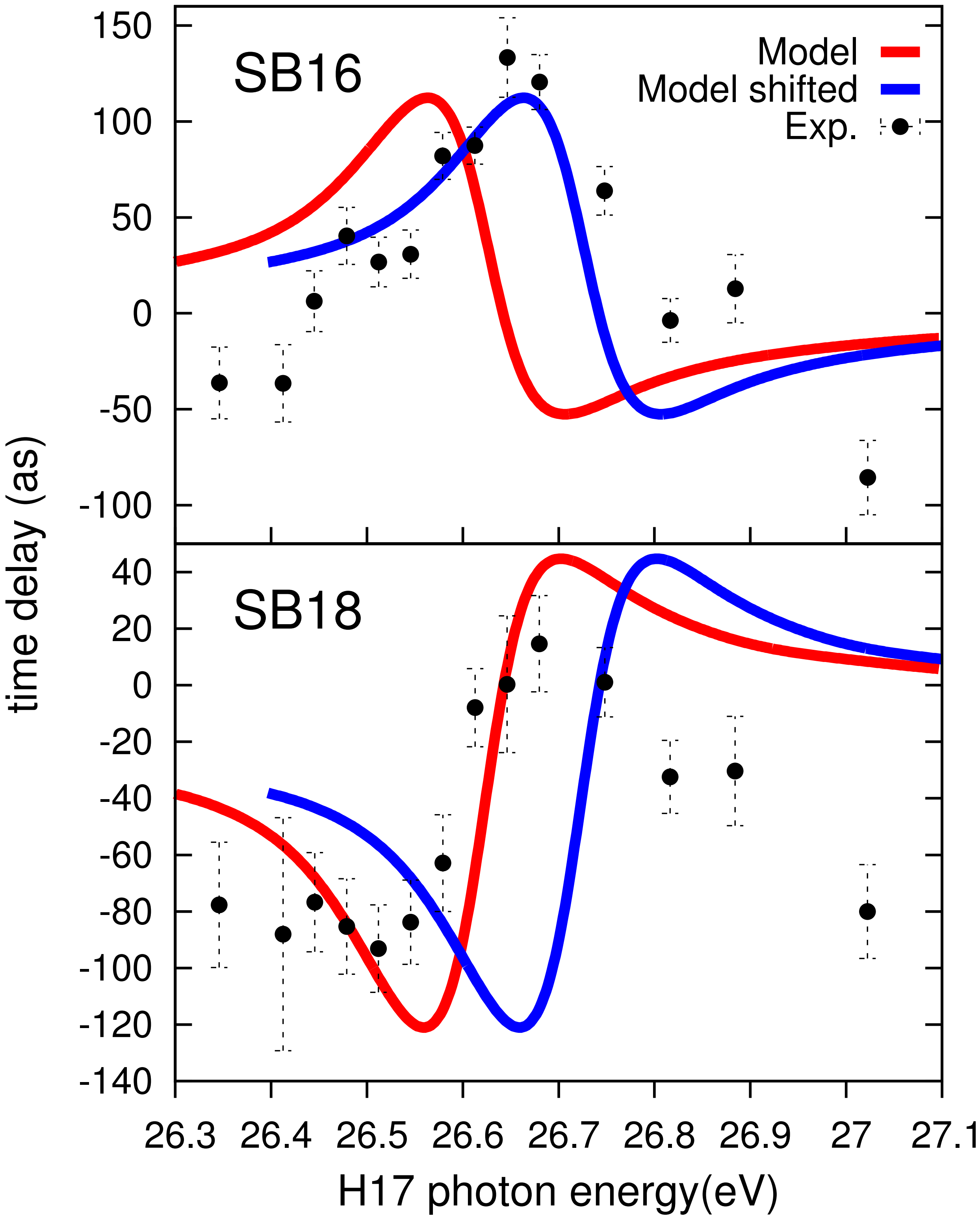

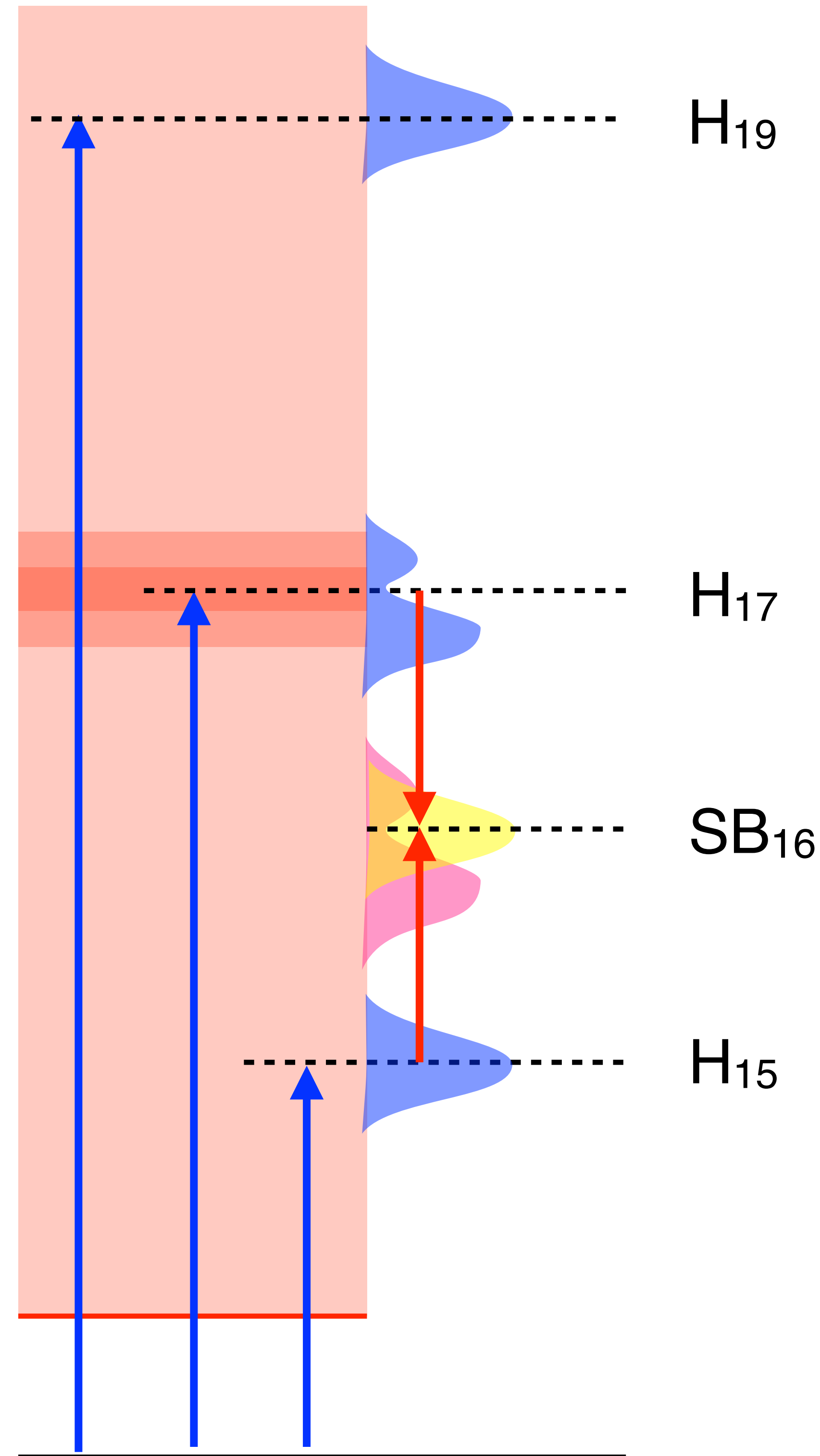

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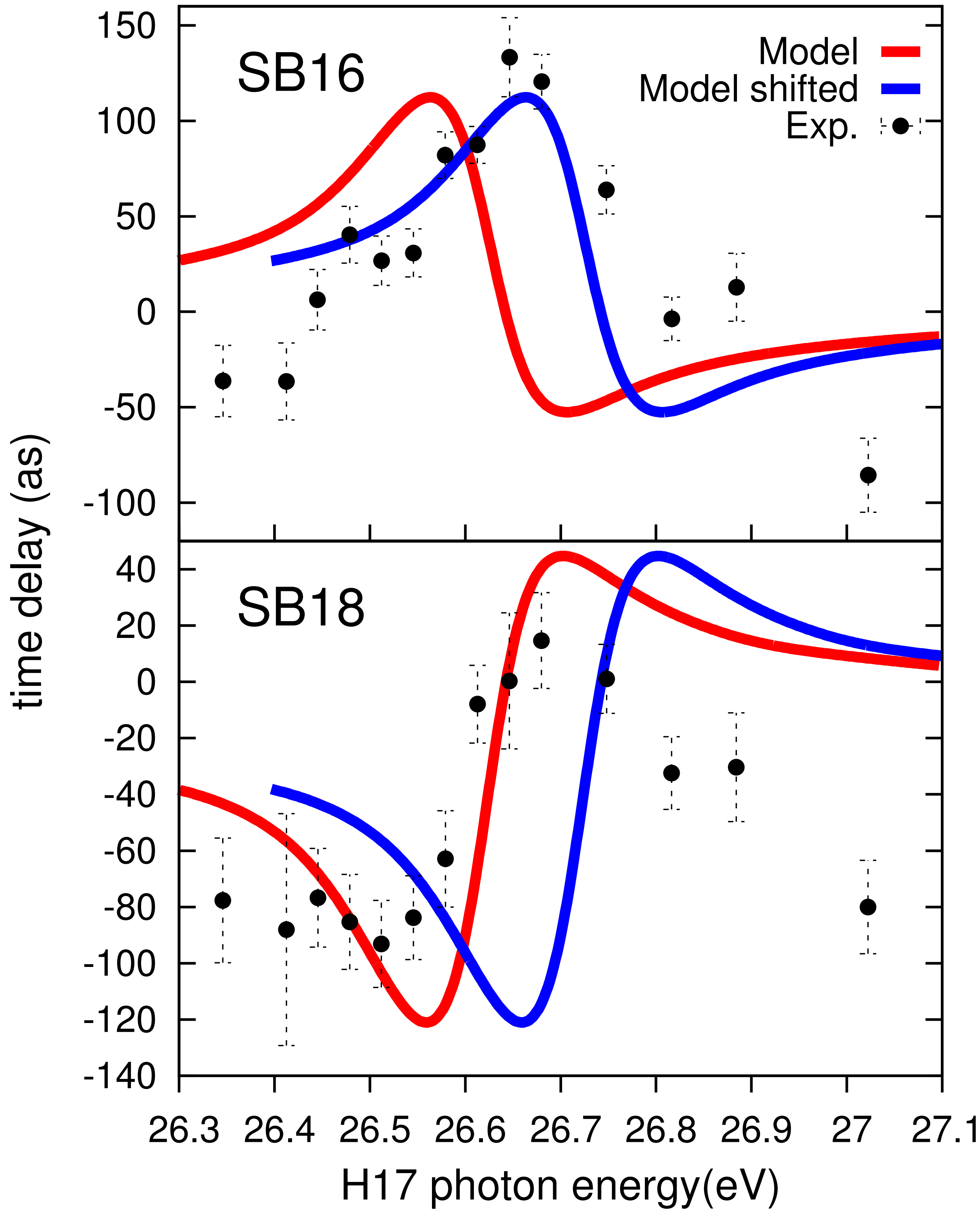

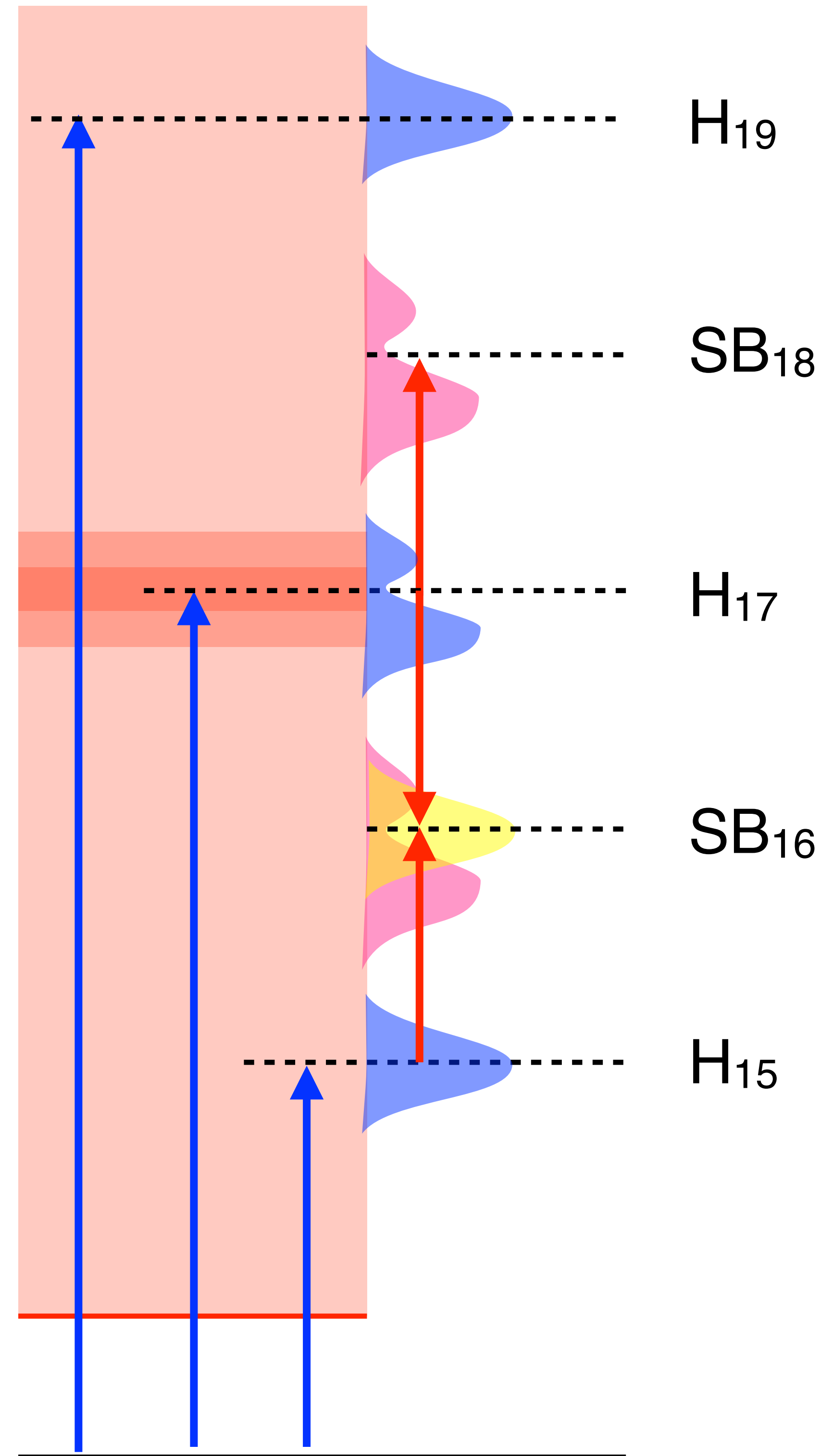

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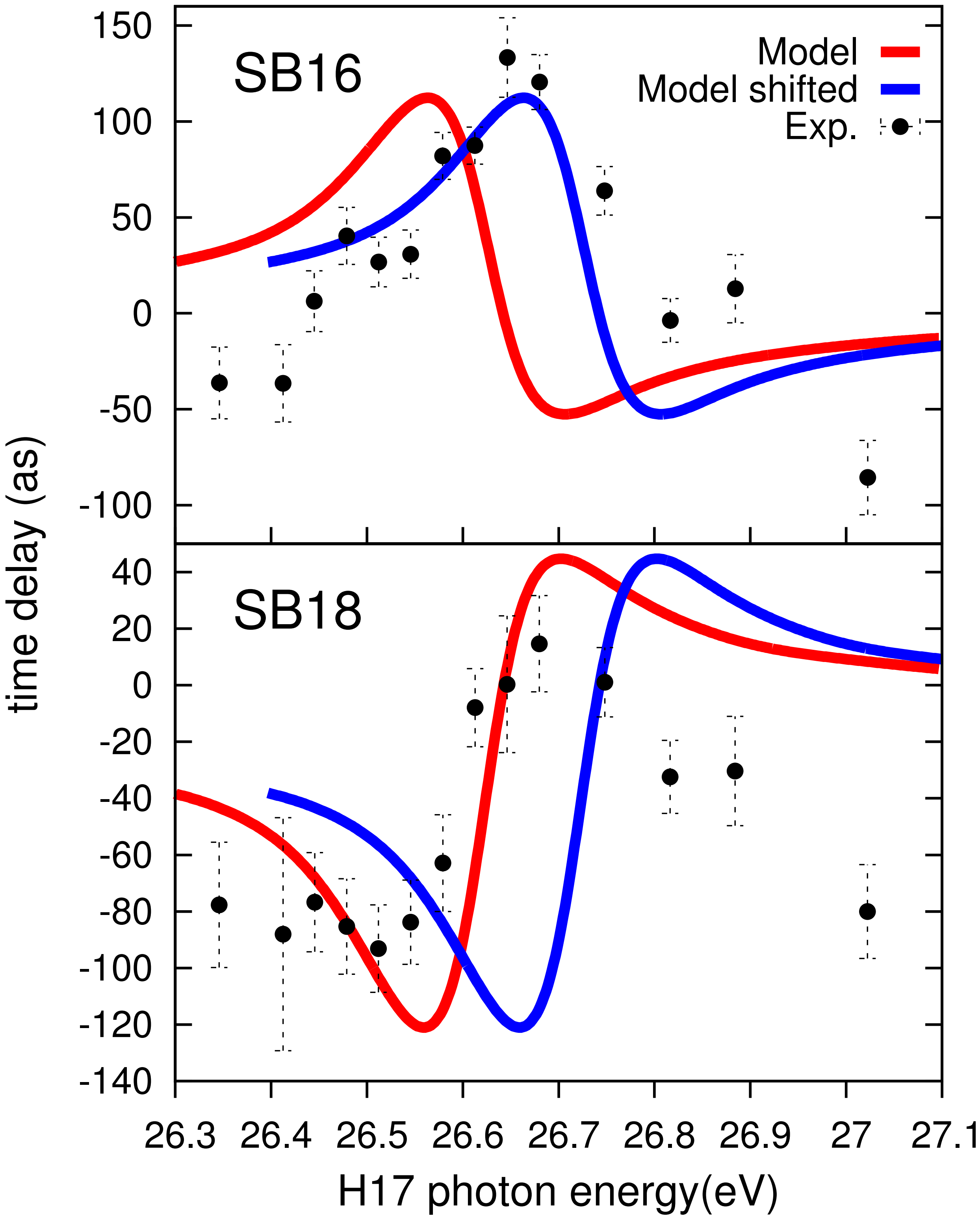

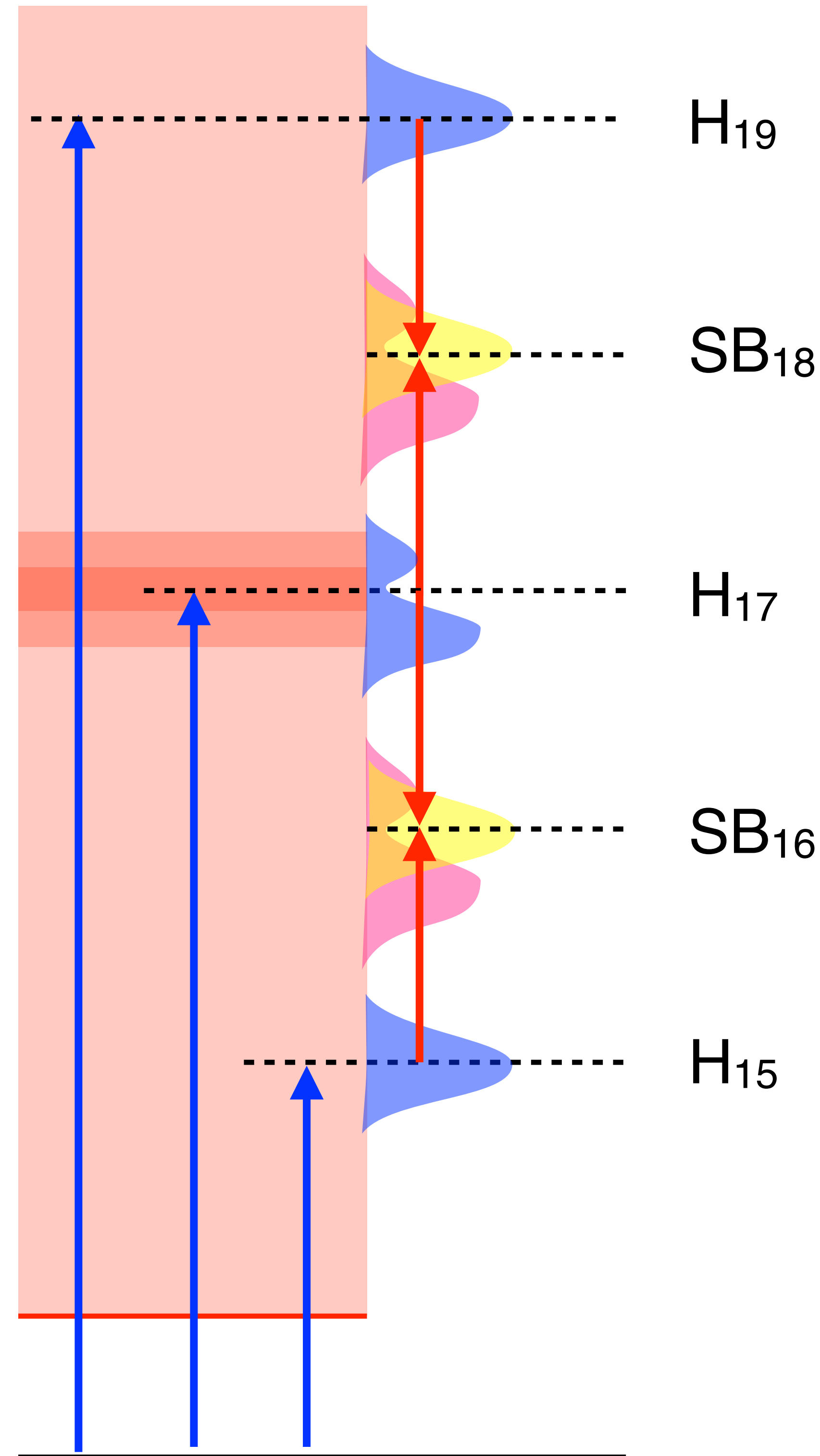

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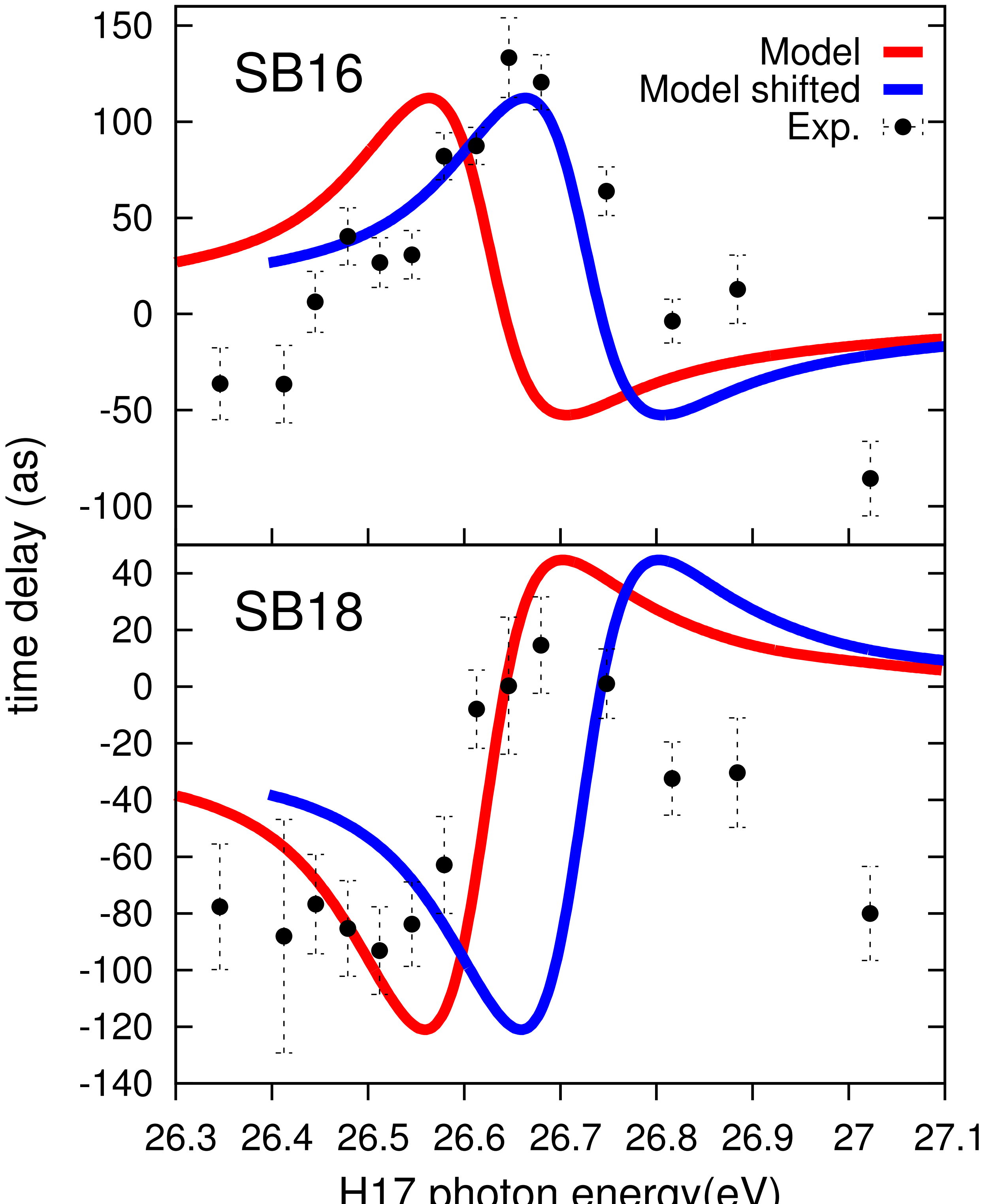

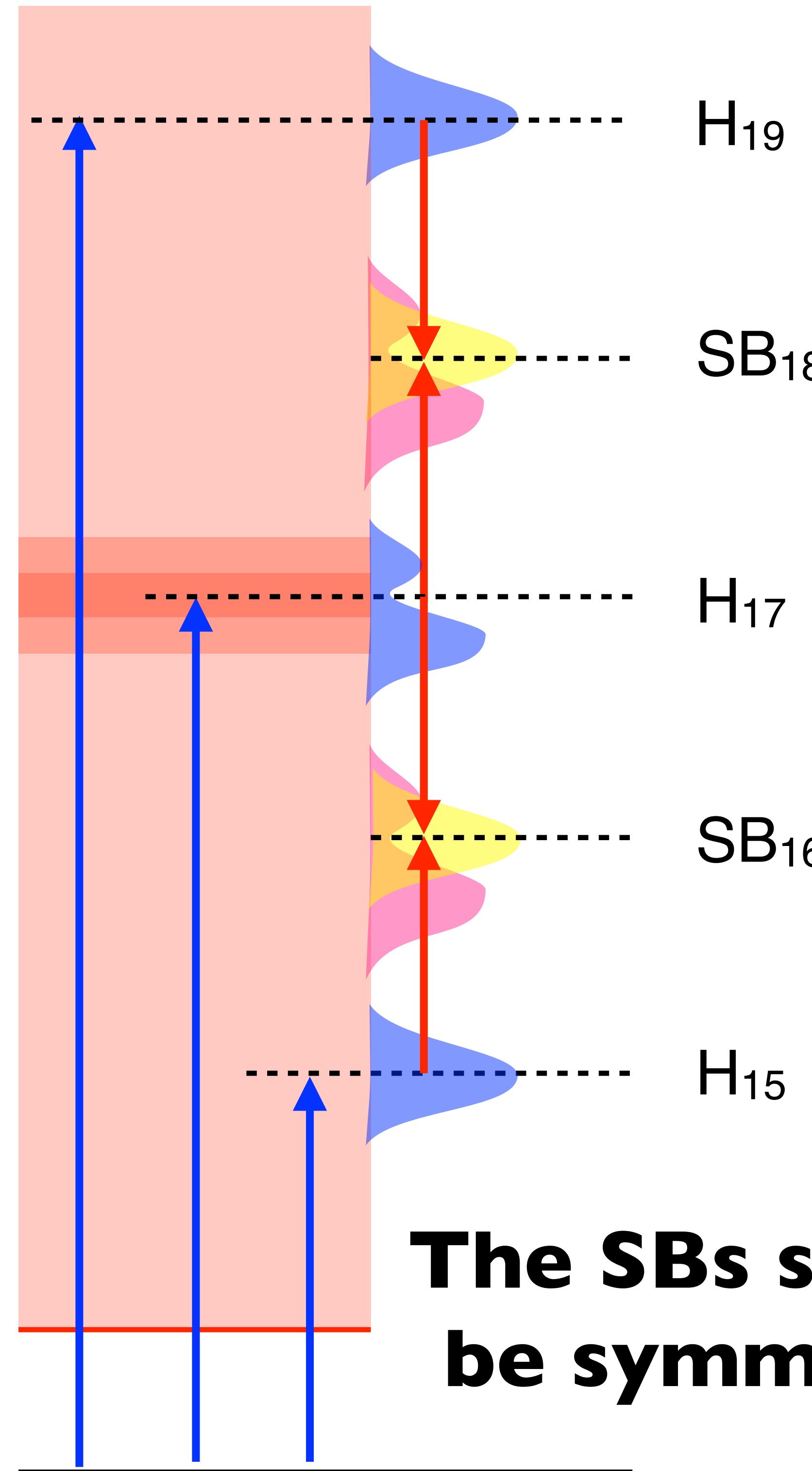

The SBs should be symmetric

M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

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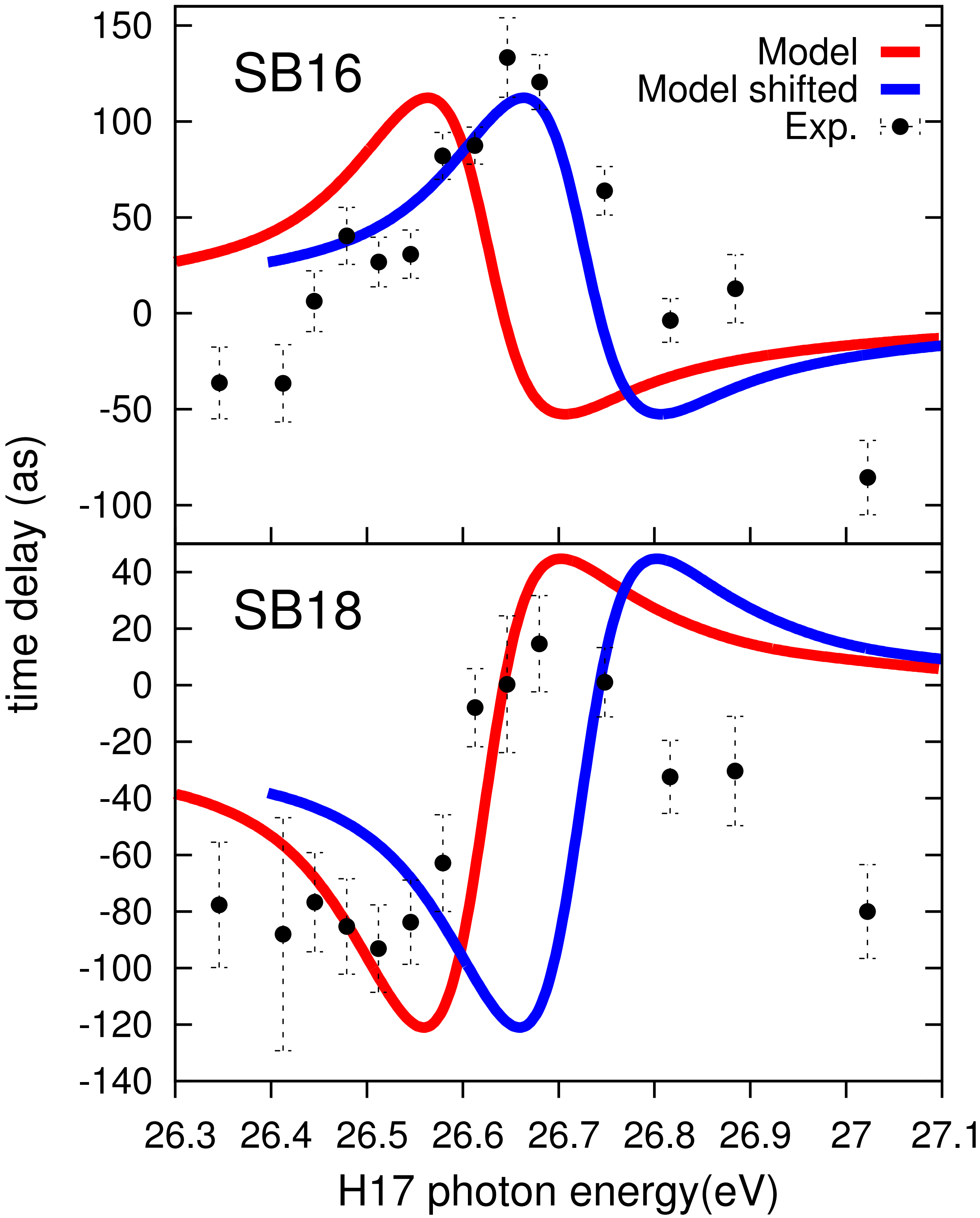

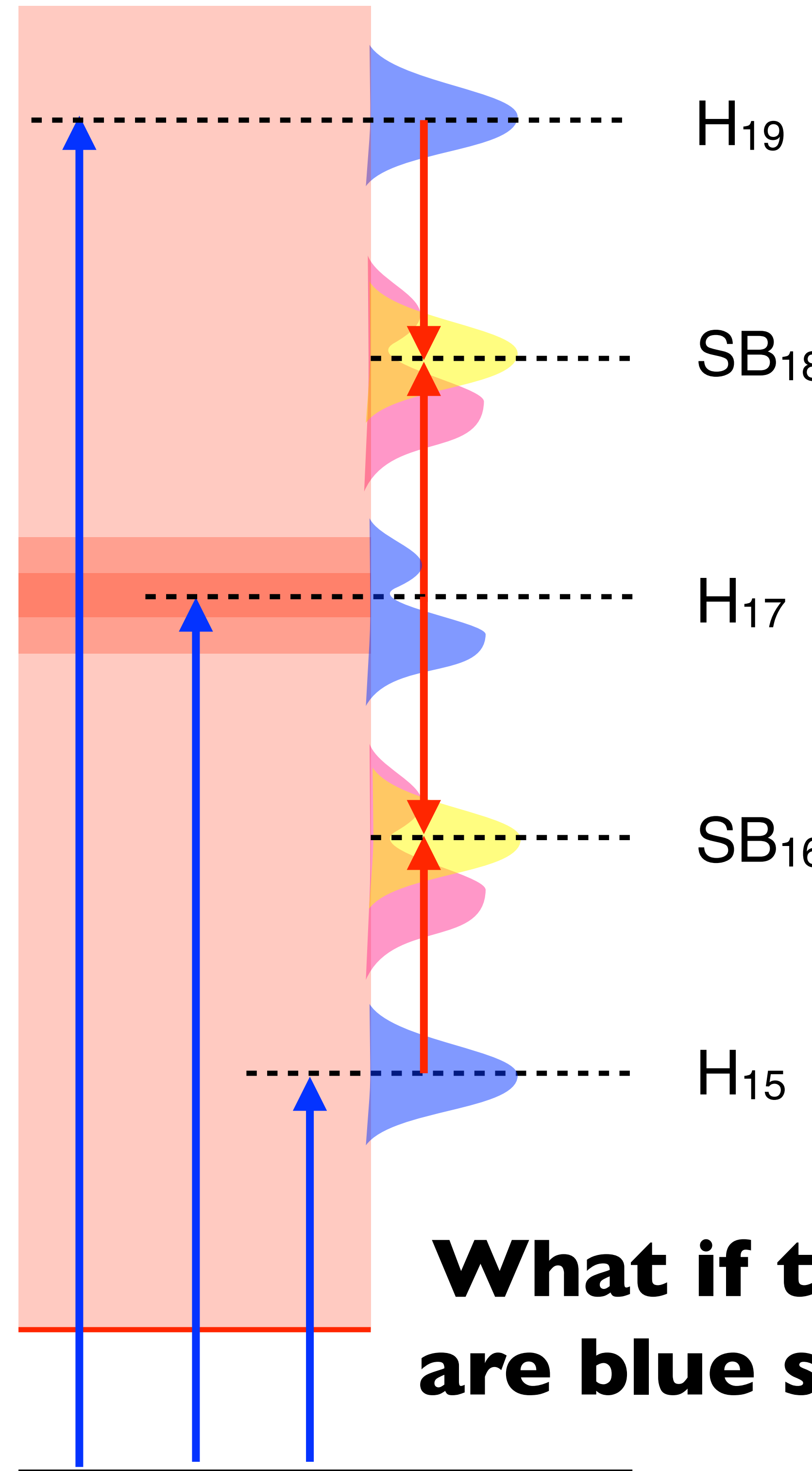

What if the HH are blue shifted?

M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

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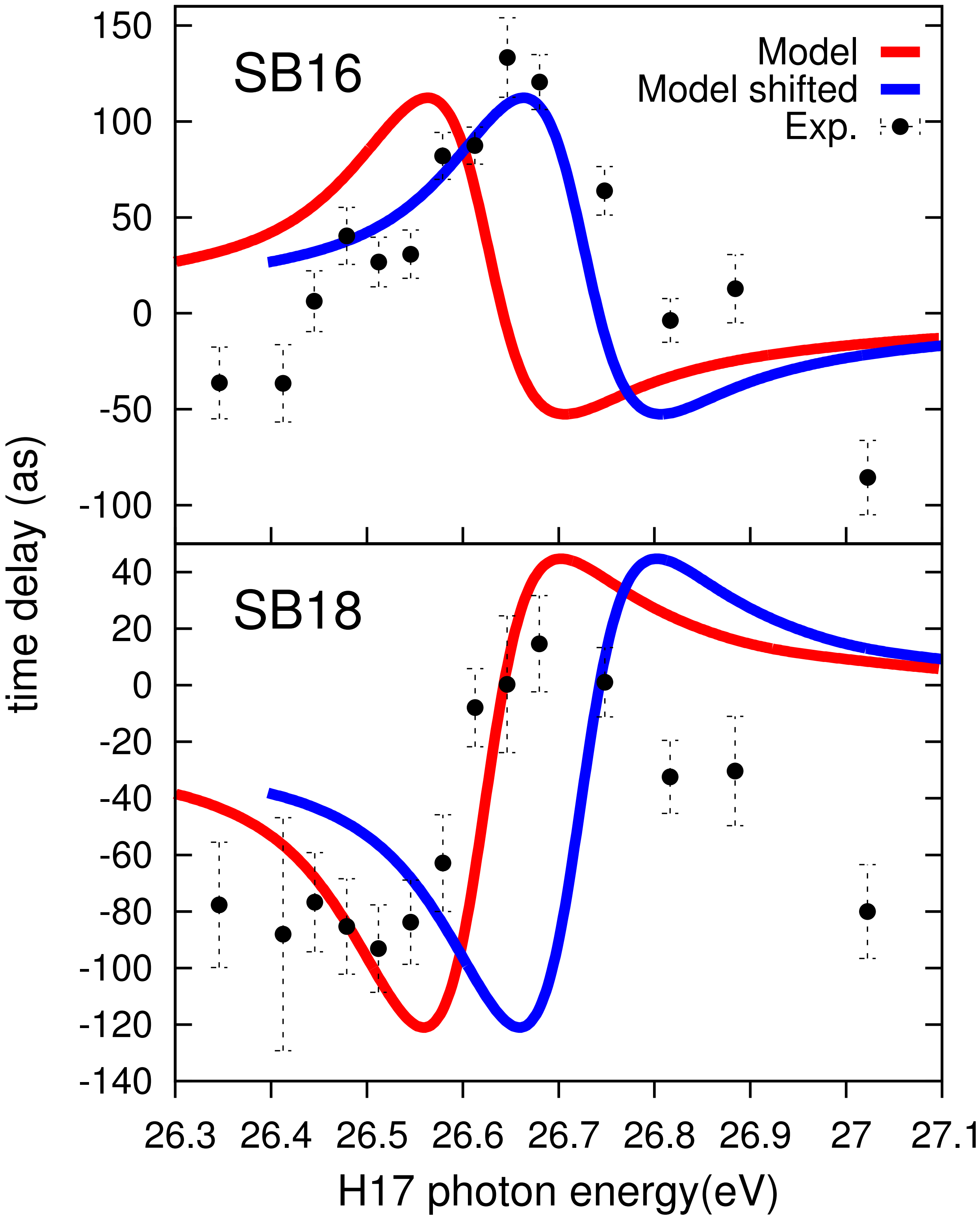

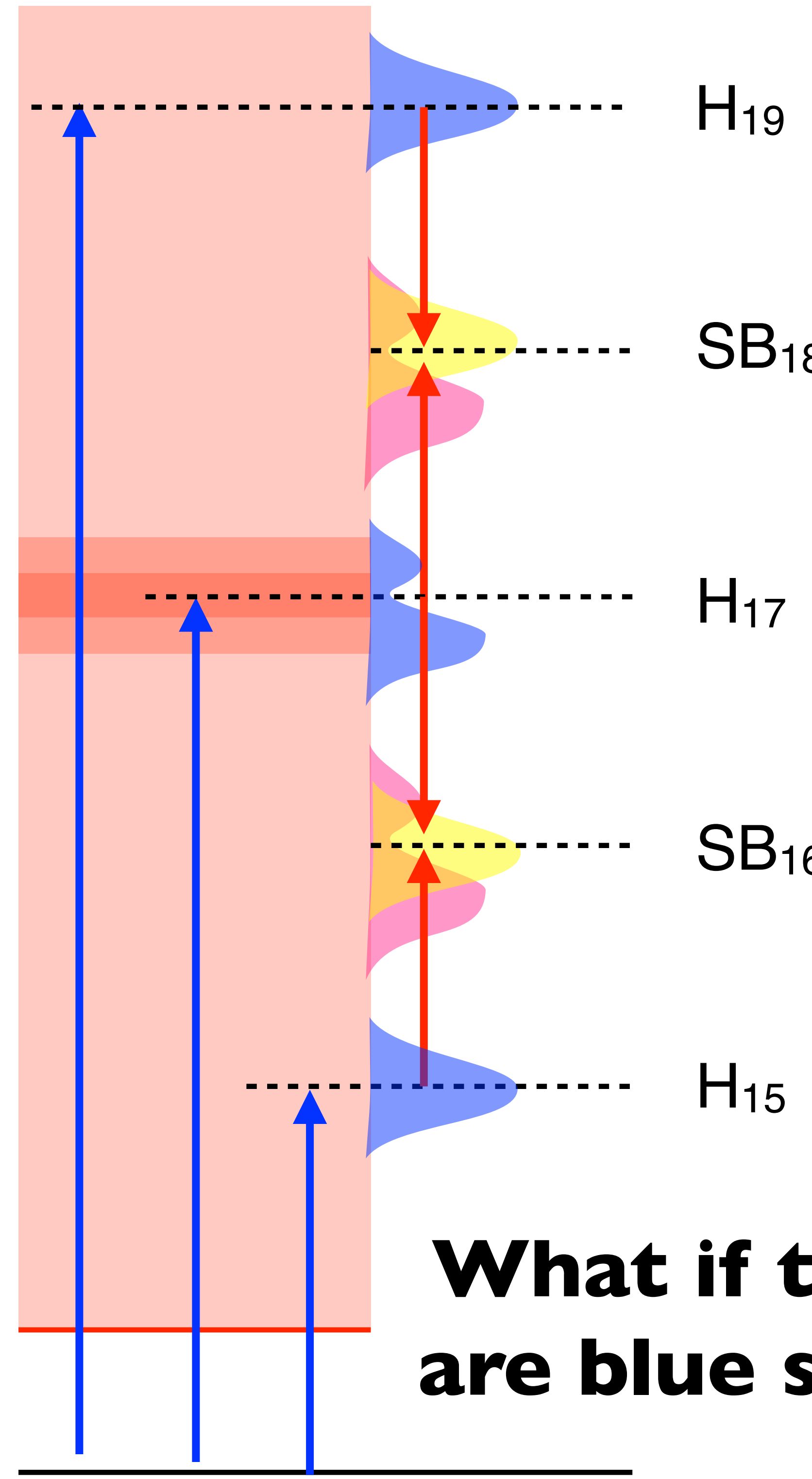

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Prediction Total Sideband Signal

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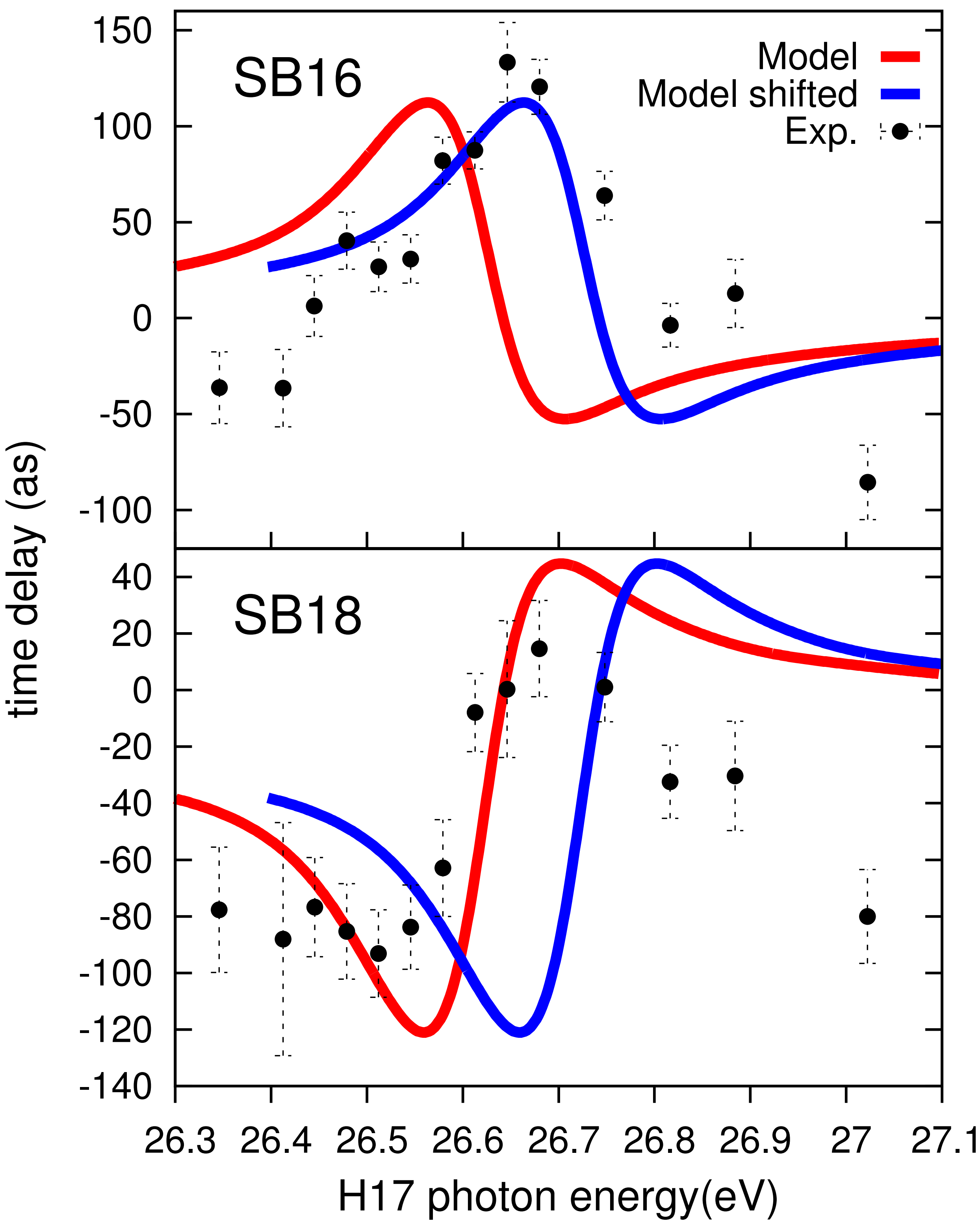

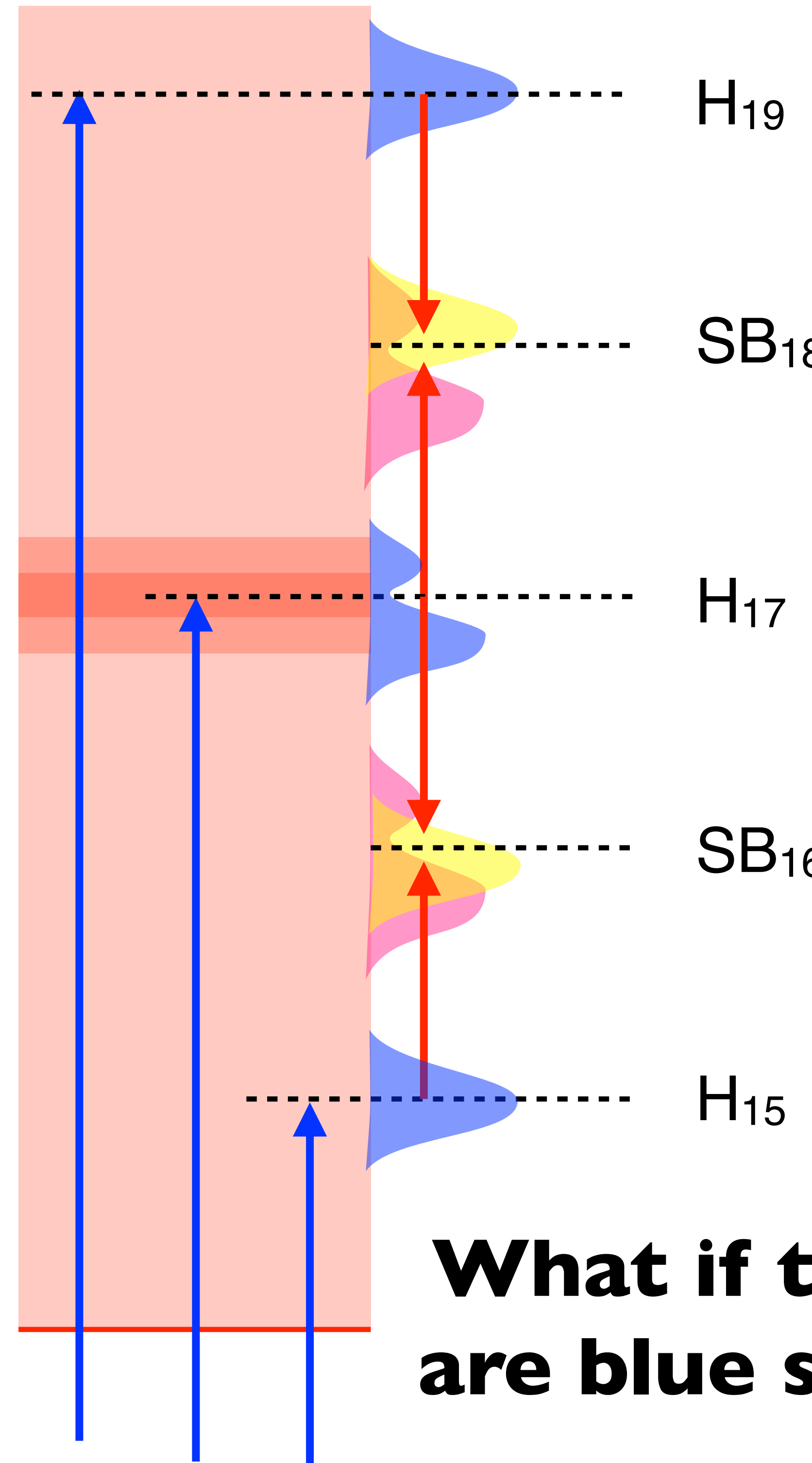

What if the HH are blue shifted?

M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

Prediction Total Sideband Signal

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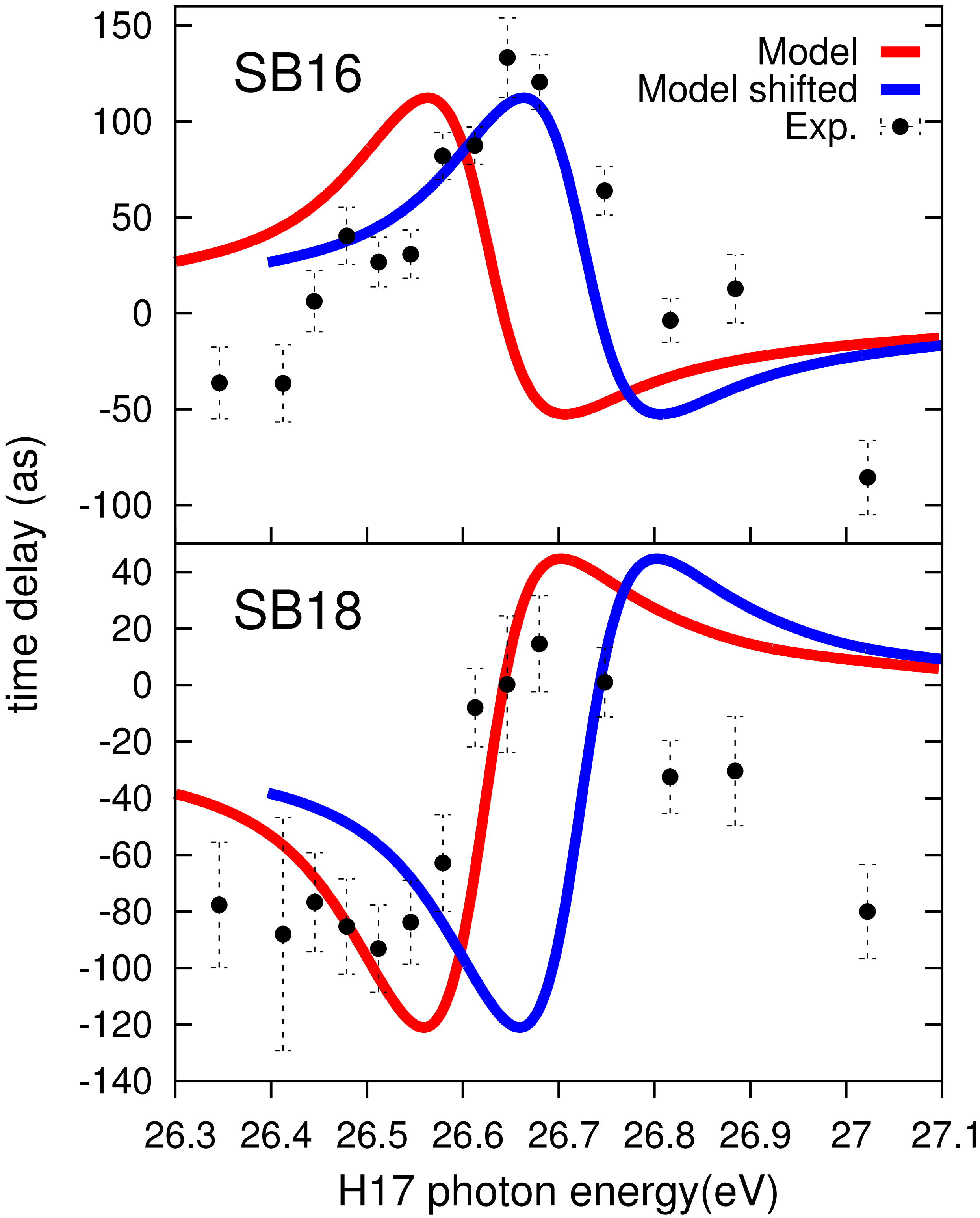

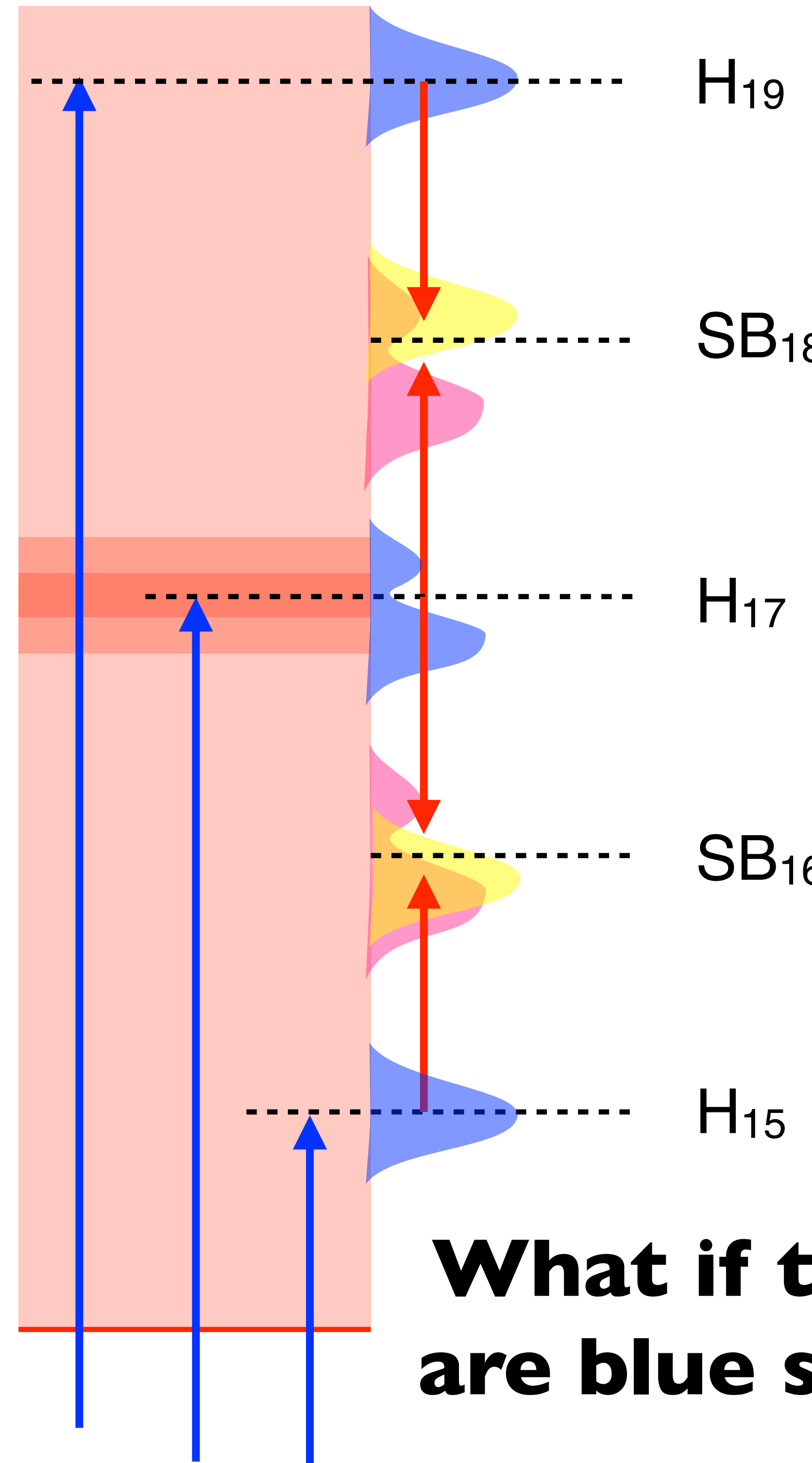

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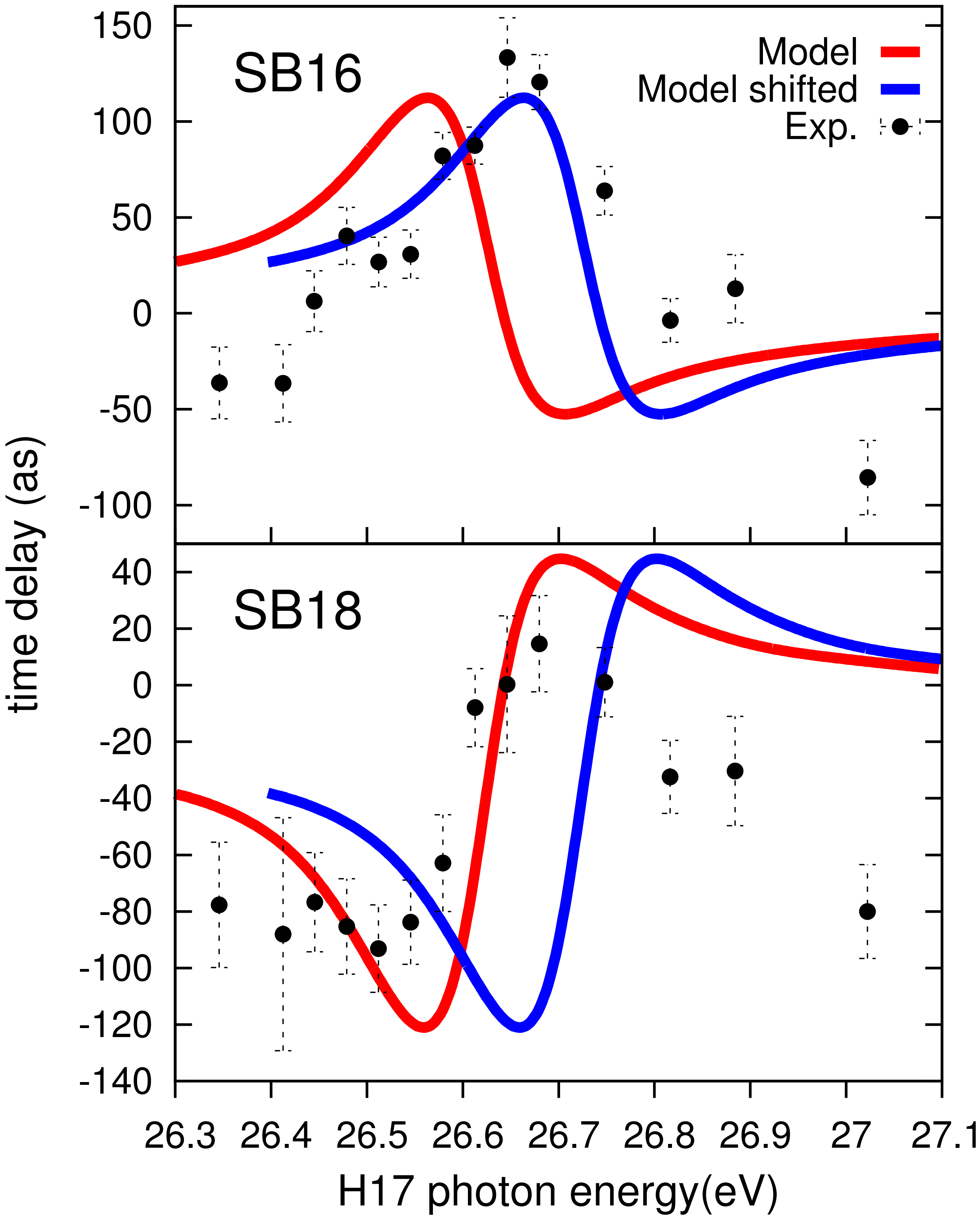

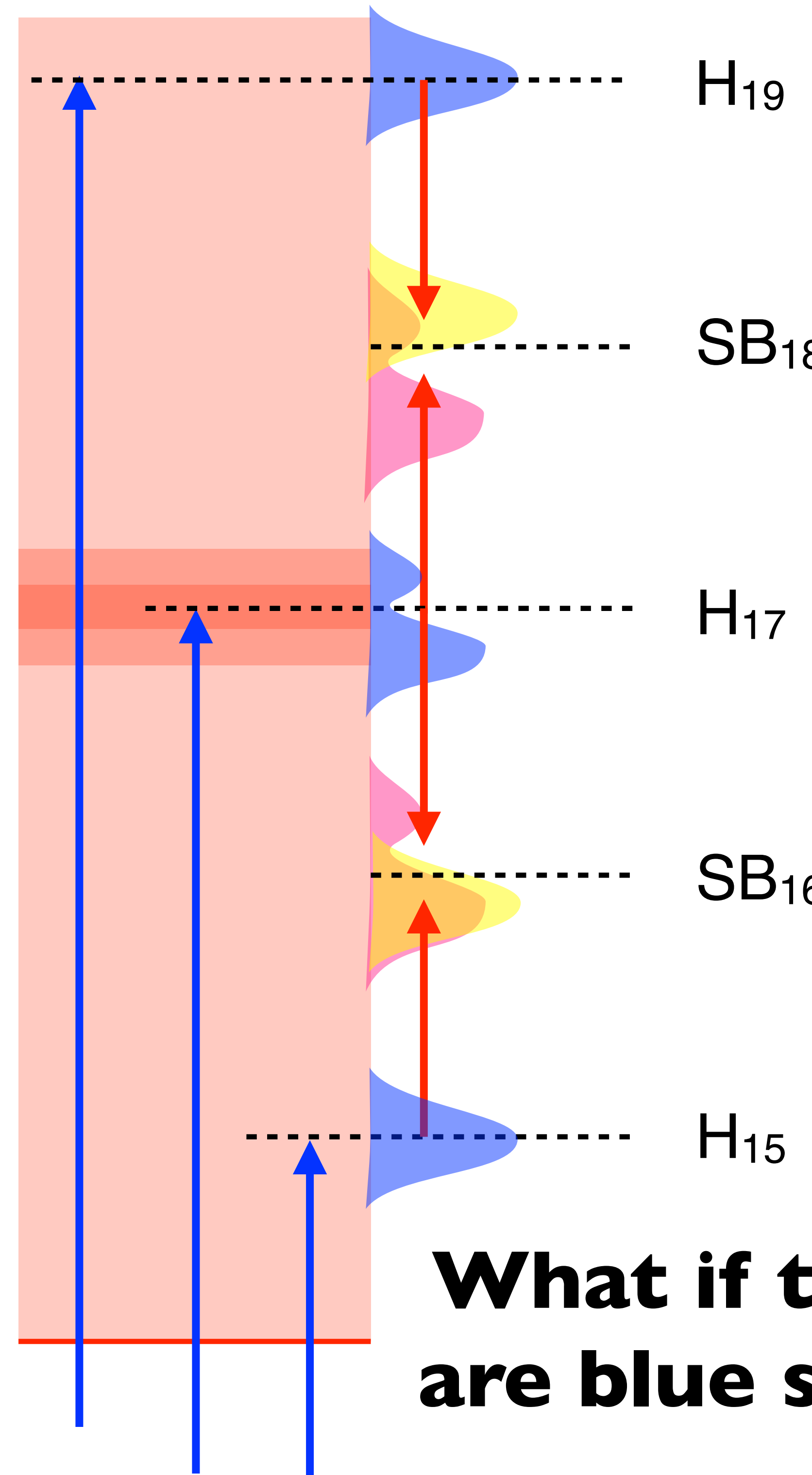

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Prediction Total Sideband Signal

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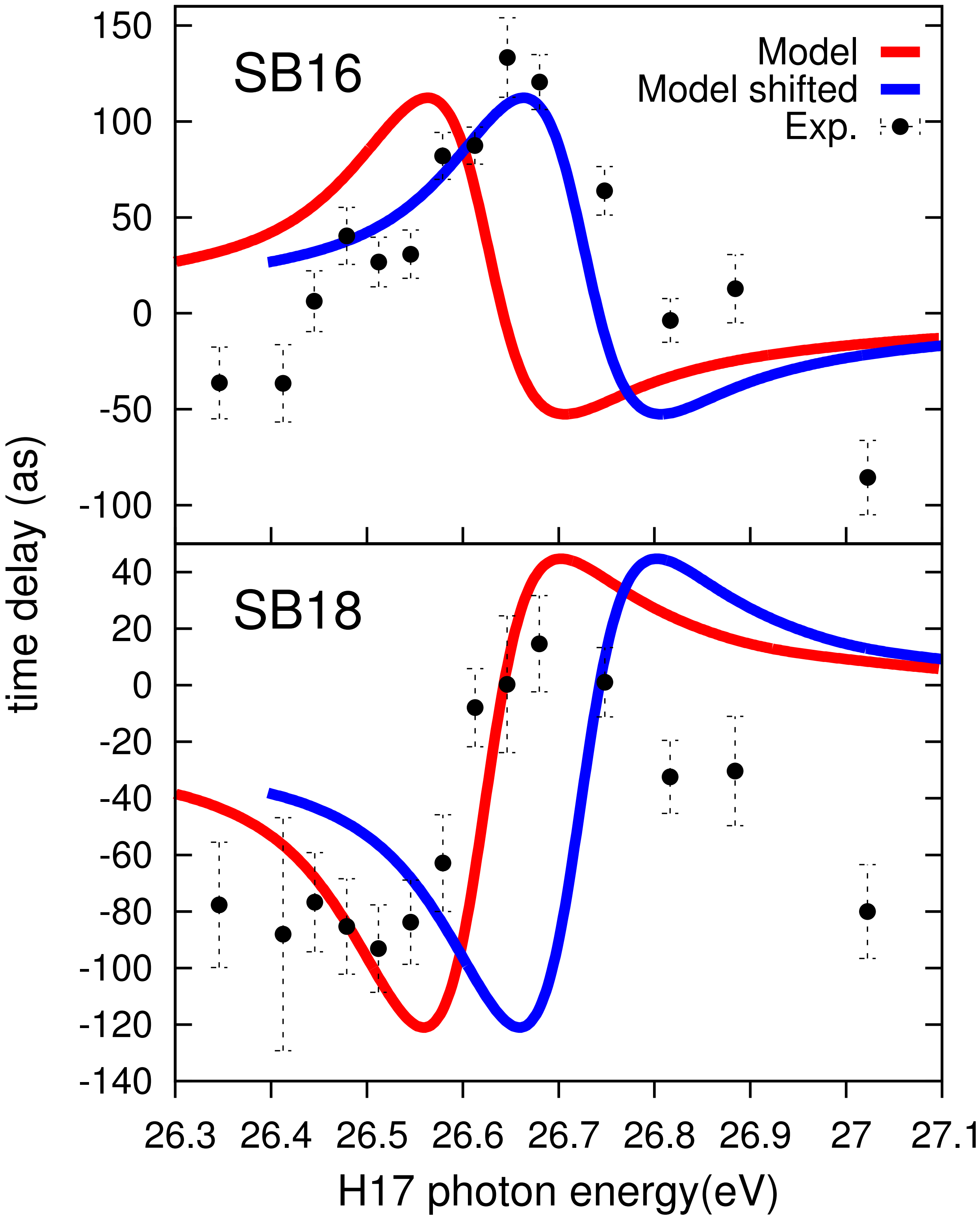
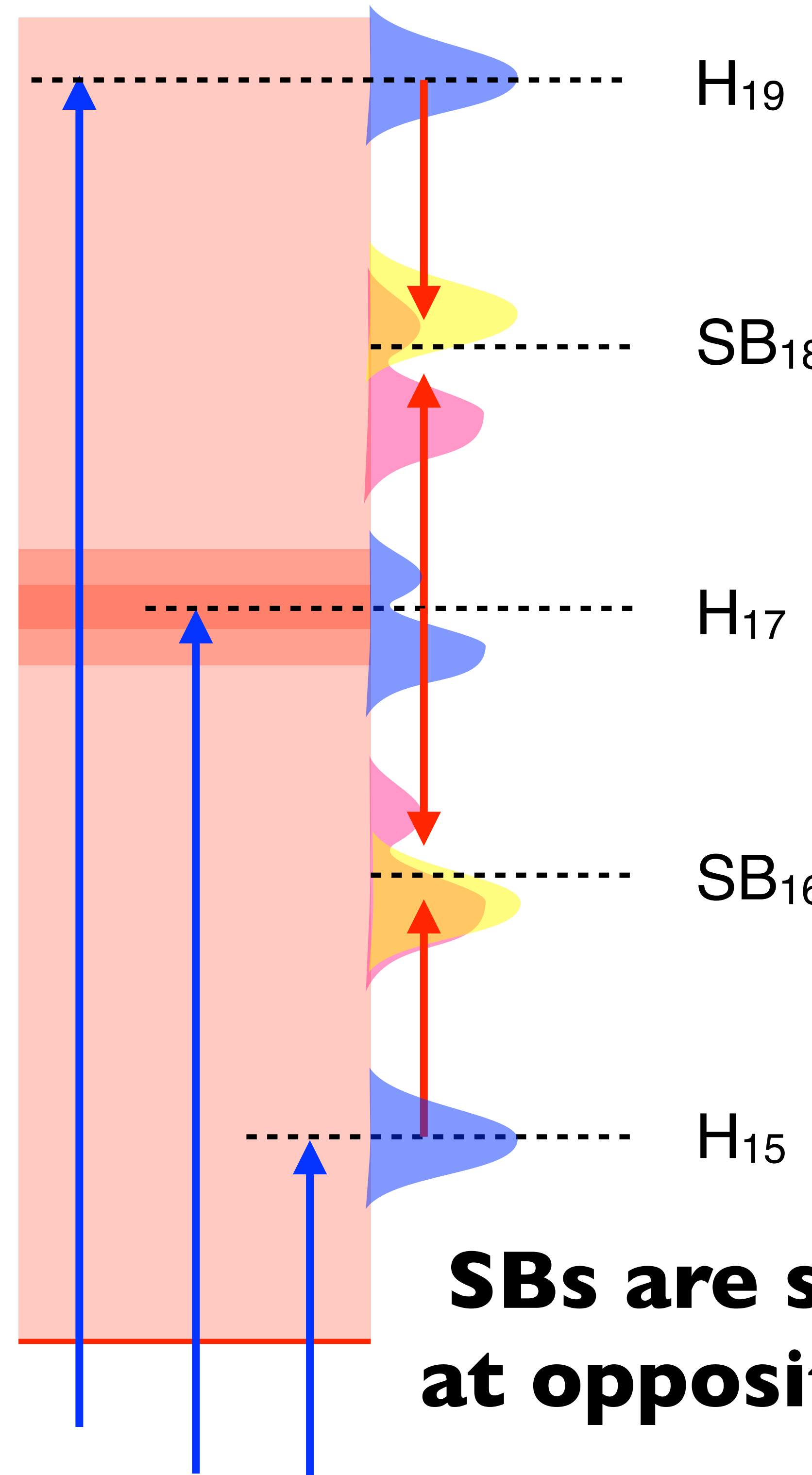
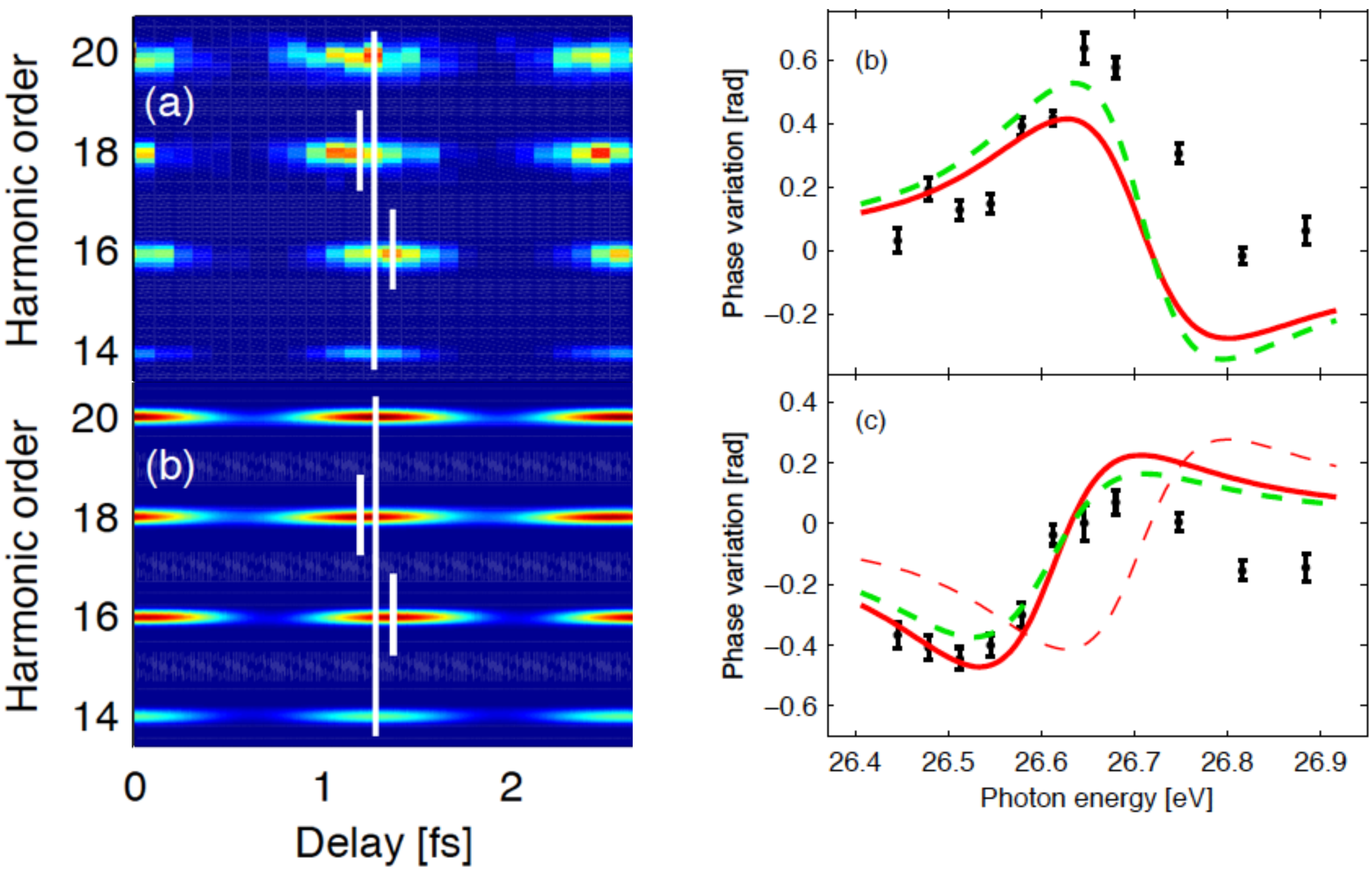




SBs are shifted at opposite dirs.

M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

Predictions Accounting for Blue Shift



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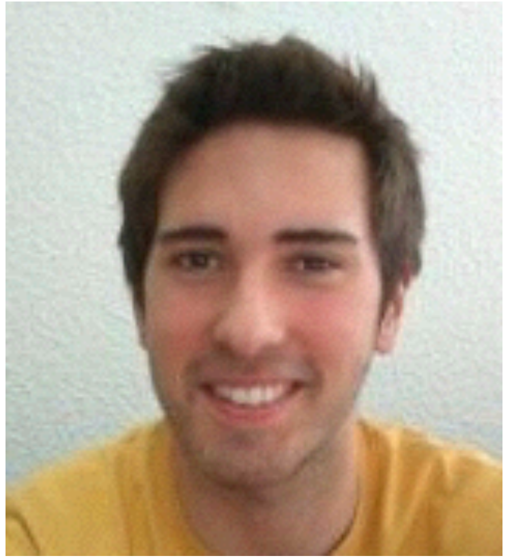
M. Kotur *et al.*, arXiv:1505.02024 [physics.atom-ph] (2015)

Conclusion

A two-photon finite-pulse resonant model has been both necessary and sufficient to explain the phenomenology predicted numerically or observed experimentally so far.

The interpretation of the dynamics in terms of wavepackets is probably still viable but it cannot rely solely on stationary descriptions.



Credit

Álvaro Jiménez Galán
Fernando Martín
Alfred Maquet
Eva Lindroth
Markus Dahlström

Anne L'Huillier
Marija Kotur
Diego Guénot
David Kroon
Mathieu Gisselbrecht
…

XCHEM code

Carlos Marante
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Thank you!