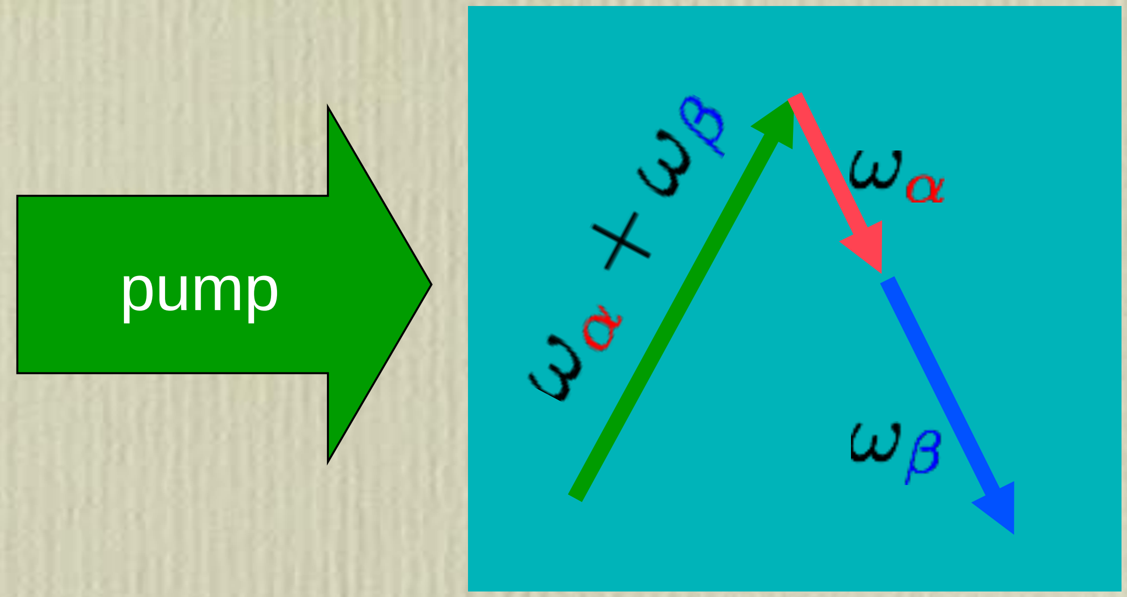
The correlations present in a separable state
turn out to be as efficient
as the correlations arising from entanglement
to boost the two-atom two-photon excitation

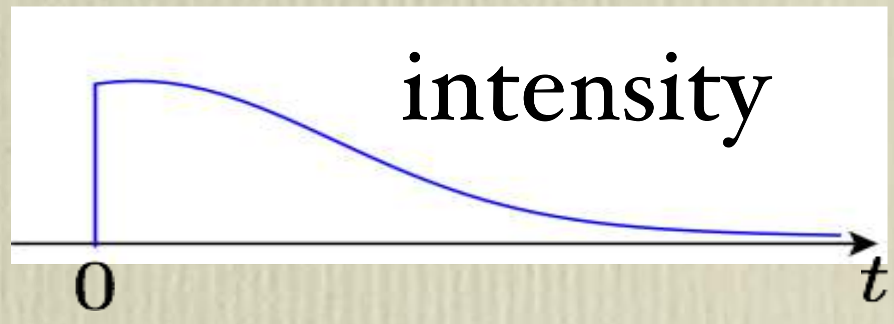
two-photon state
produced by parametric down-conversion:



same conclusion:
entangled pure state
and correlated separable mixed state
lead to the same enhancement and same resonant character
of the two-atom excitation

two-photon state pulse starting at a given time

t=0 $$|\Psi\rangle = \sum_{kq} c_{kq} |1:\omega_k; 1:\omega_q\rangle$$



with mean-field non-zero only for t>0

transition probability is the same, within a factor 2, for the pure entangled and for the mixed separable state

enhancement factor *R* with respect to uncorrelated photons:

$$R = \frac{|c(\omega_1,\omega_2)|^2 + |c(\omega_2,\omega_1)|^2}{\sum_{mn}\left[|c(\omega_1,\omega_n)c(\omega_m,\omega_2)|^2 + |c(\omega_2,\omega_n)c(\omega_m,\omega_1)|^2\right]}$$

superpositions of coherent states

$$|QMC\rangle = \sum_{kq} c(\omega_k, \omega_q)|\alpha : \omega_k; \alpha : \omega_q\rangle$$

QMC pure state is highly non-classical !

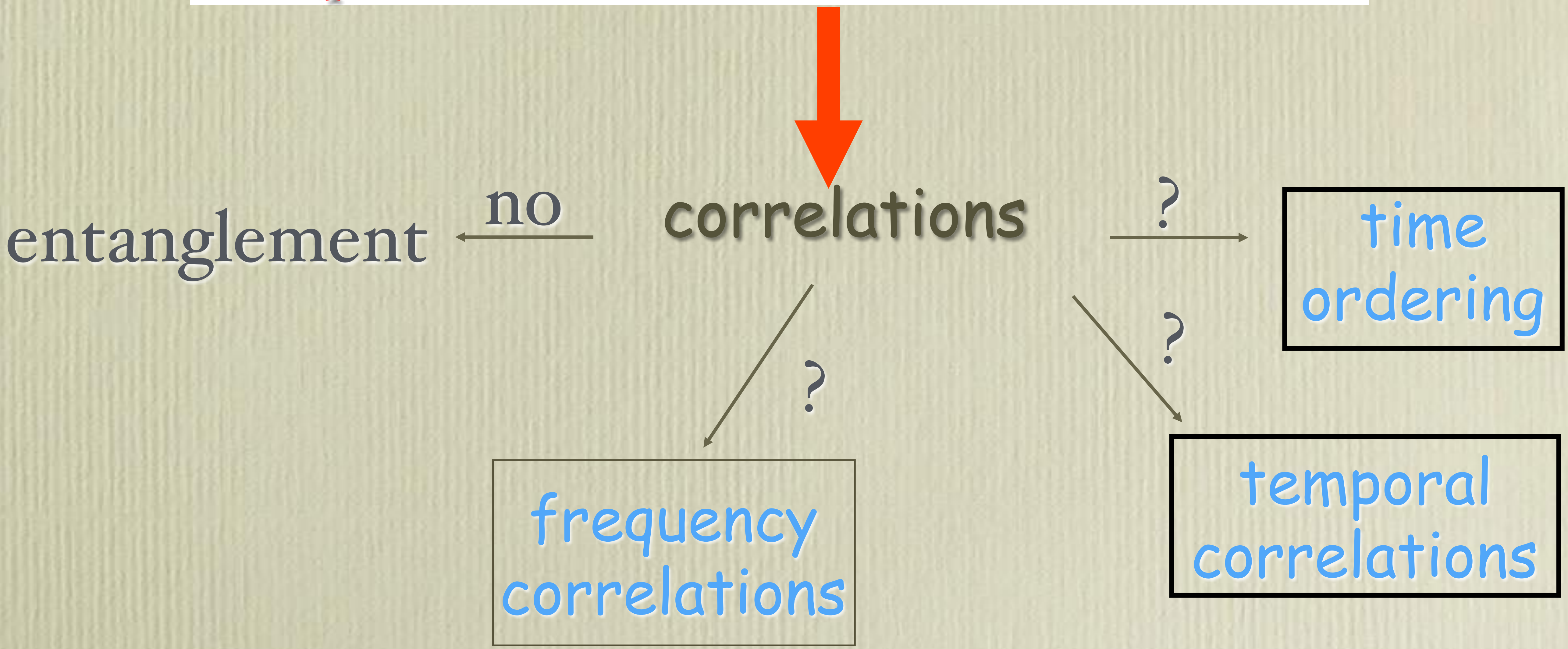
$$\rho_{CMC} = \sum_{kq} |c(\omega_k, \omega_q)|^2 |\alpha : \omega_k; \alpha : \omega_q\rangle\langle\alpha : \omega_k; \alpha : \omega_q|$$

QMC separable mixed state
can be produced by classical means !

$$P_{CMC} \simeq P_{QMC} \simeq |\alpha|^4 P(t)$$

transition probability greatly enhanced

What is the physical origin of the two-photon two-atom enhancement effect ?

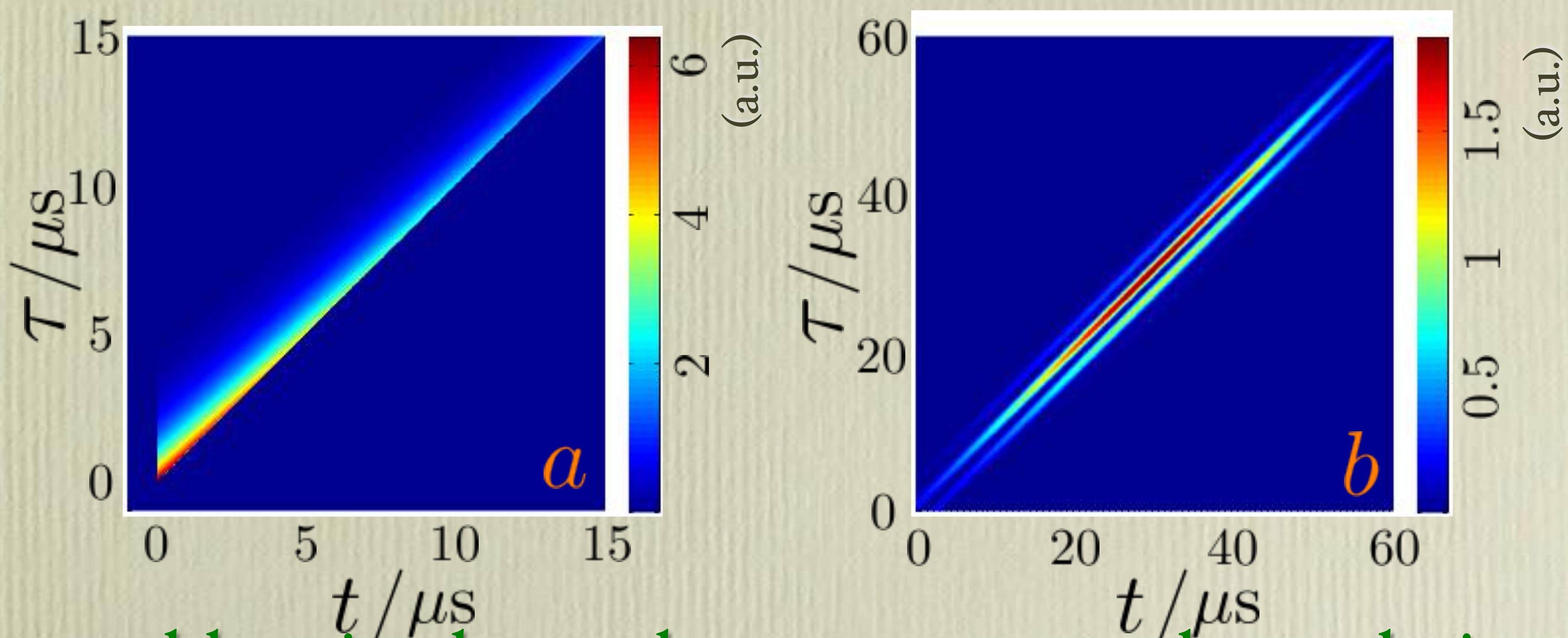


time ordering of the two-photons ?

two-time correlation function

pure cascade state
(time ordered photons)

pure SPDC state
(no time ordering)

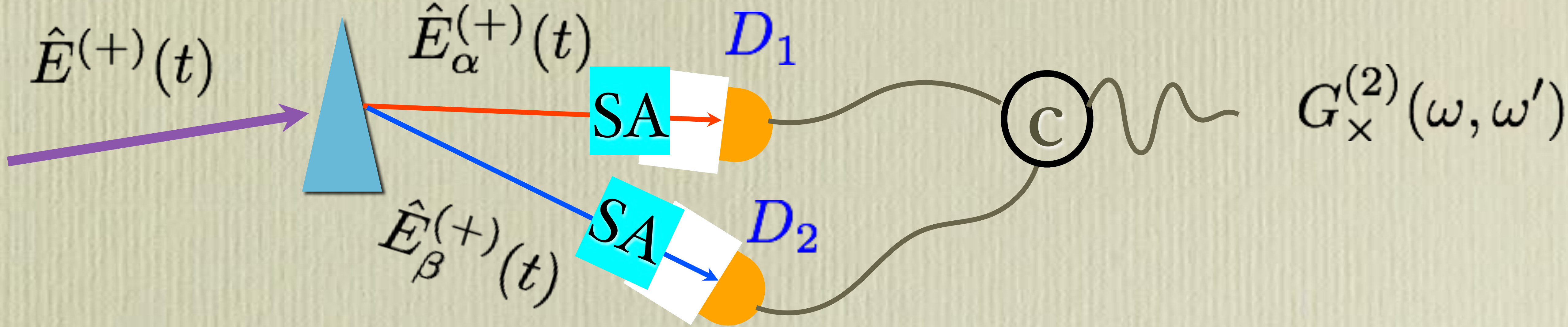


separable mixed state have no temporal correlation !

enhanced proba

time ordering is not at the origin of the effect

frequency correlations between the two-photons ?



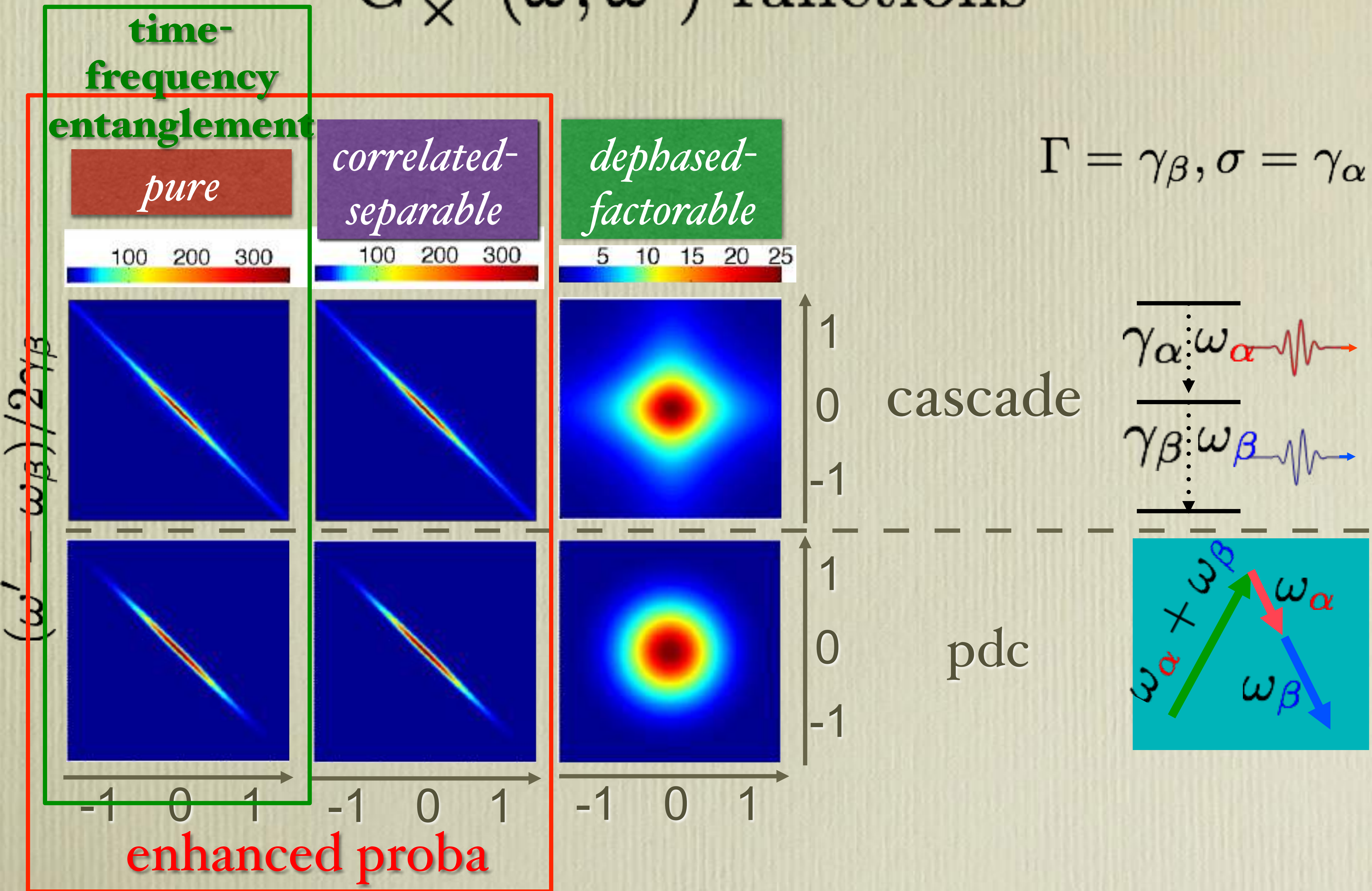
SA: spectral analysis

$$g_{\times}^{(2)}(\omega, \omega') = \frac{\langle \hat{\mathcal{E}}_{\alpha}^{(-)}(\omega) \hat{\mathcal{E}}_{\beta}^{(-)}(\omega') \hat{\mathcal{E}}_{\beta}^{(+)}(\omega') \hat{\mathcal{E}}_{\alpha}^{(+)}(\omega) \rangle}{\langle \hat{\mathcal{E}}_{\alpha}^{(-)}(\omega) \hat{\mathcal{E}}_{\alpha}^{(+)}(\omega) \rangle \langle \hat{\mathcal{E}}_{\beta}^{(-)}(\omega') \hat{\mathcal{E}}_{\beta}^{(+)}(\omega') \rangle}$$

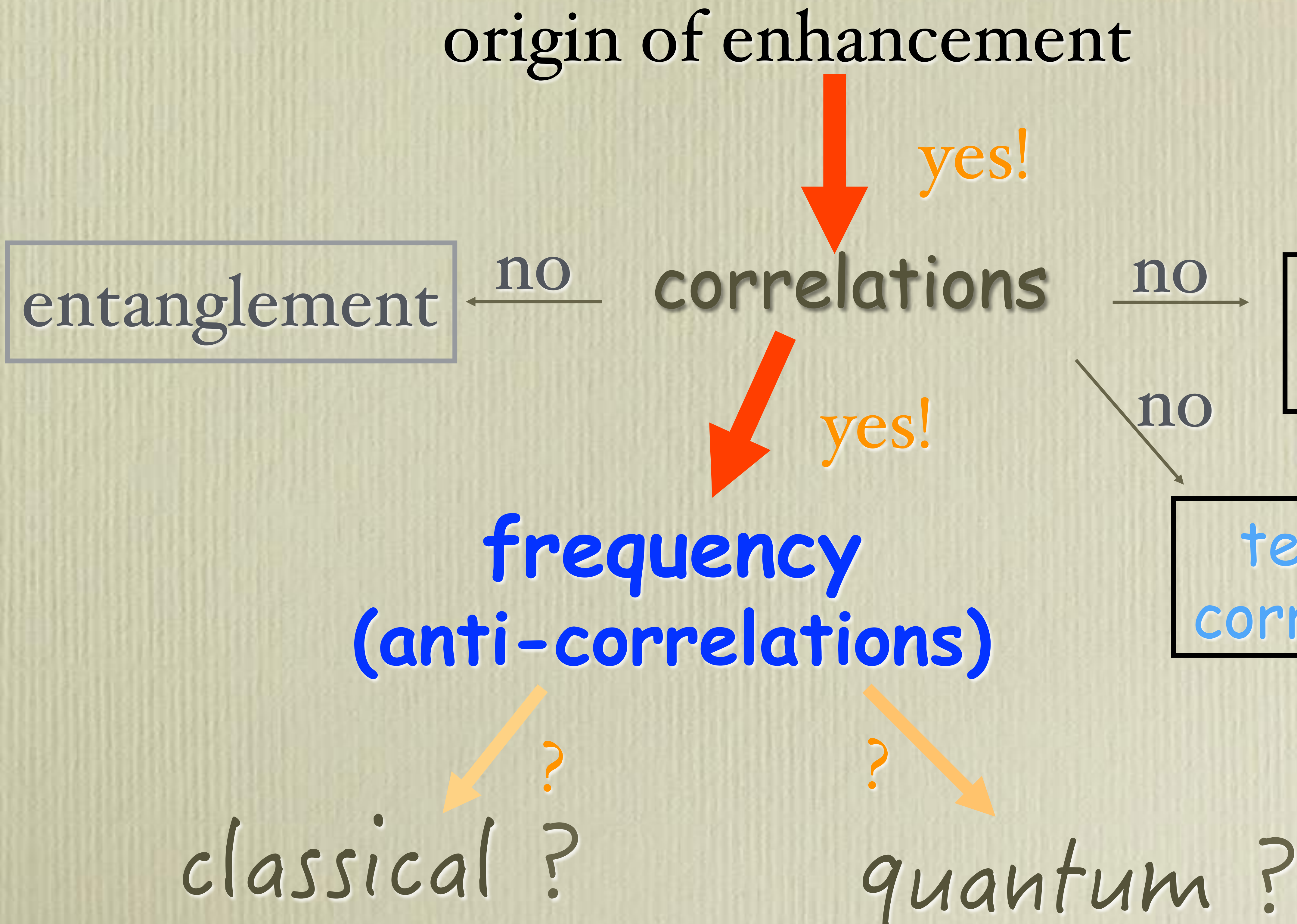
pure state and mixed state
have the same frequency correlation function

$G^{(2)}_{\times}(\omega, \omega')$ functions

$\Gamma = \gamma_\beta, \sigma = \gamma_\alpha$



The enhancement effect is due to
strong frequency anti-correlations in the two-photon state,
not time/frequency entanglement


origin of enhancement
yes!
entanglement
no
correlations
no
time ordering
yes!
no
frequency (anti-correlations)
temporal correlations
?
?
classical ?
quantum ?

Are the required frequency correlations of quantum origin ?

-no quantum discord in the state necessary

-when the cooperativity (Schmidt number) is high, the enhancement effect is big

- most light states used are not classical

except the separable mix of coherent states

$$\rho_{CMC} = \sum_{kq} |c(\omega_k, \omega_q)|^2 |\alpha : \omega_k; \alpha : \omega_q\rangle\langle\alpha : \omega_k; \alpha : \omega_q|$$

Conclusion

The frequency anti-correlations required for the two-photon two atom enhancement effect

-may be due to the presence of entanglement

-may be due to correlations not related to entanglement,

which can be either of quantum or classical origin