Time dependent dynamics of nuclear many-body states

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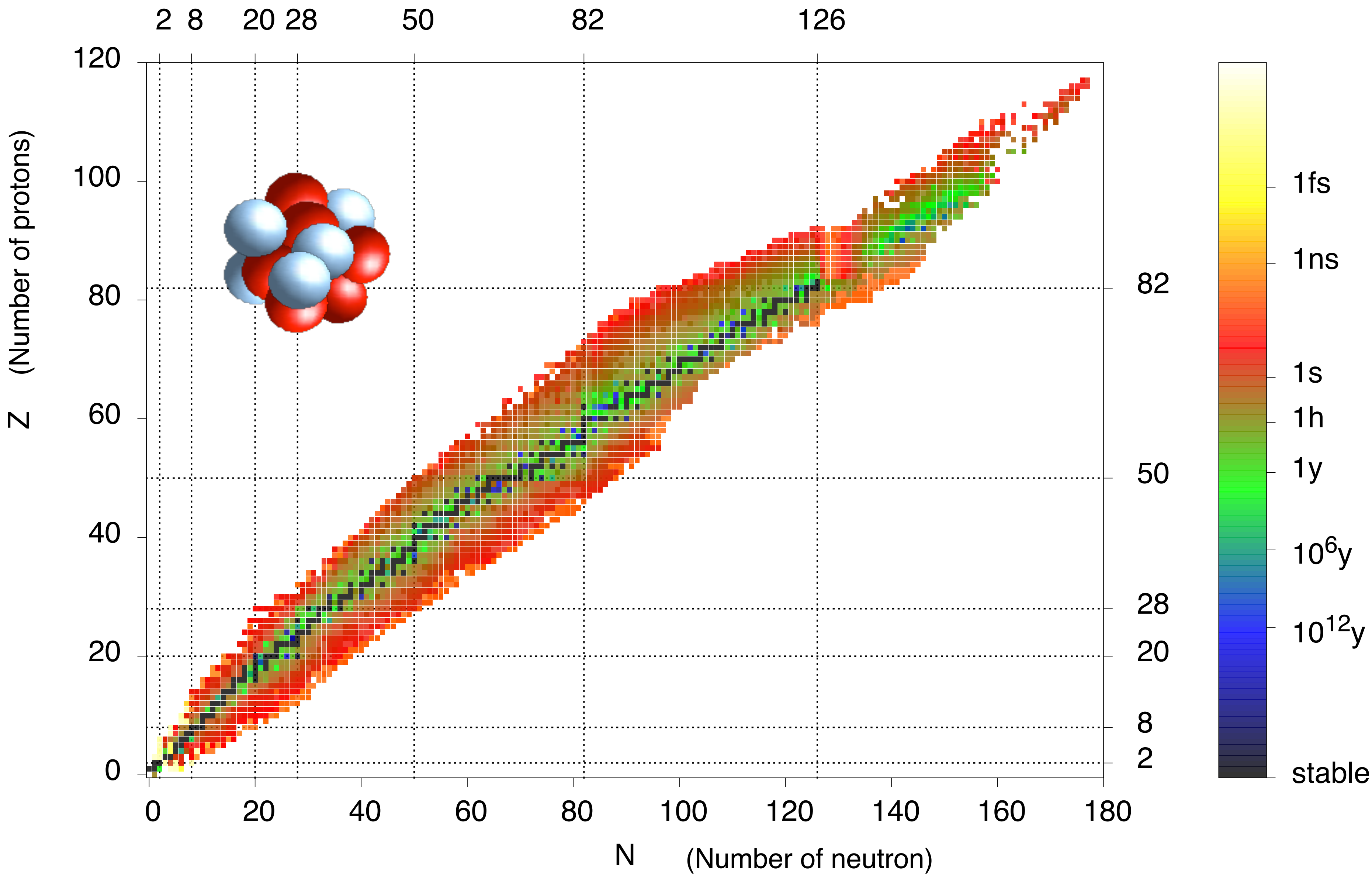
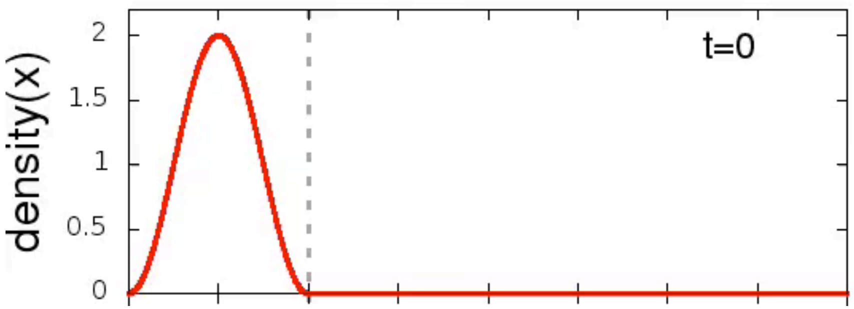
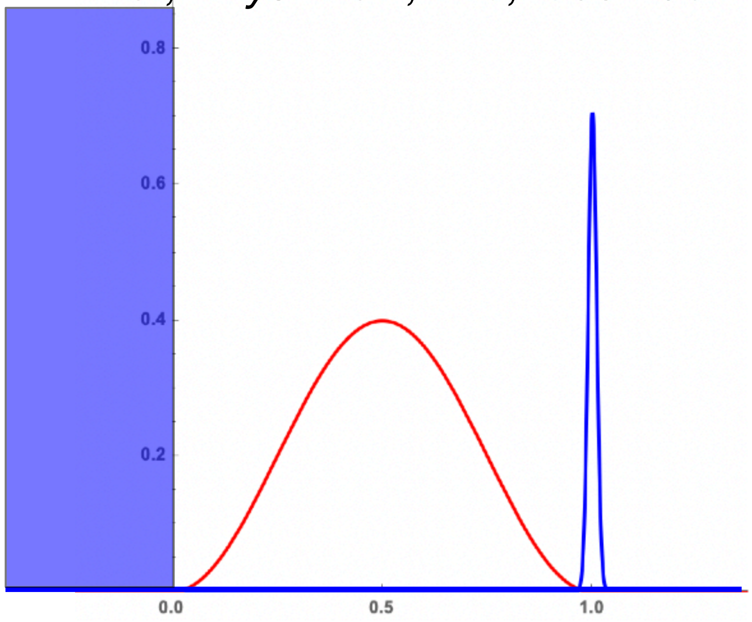
Atomic nucleus and open quantum system

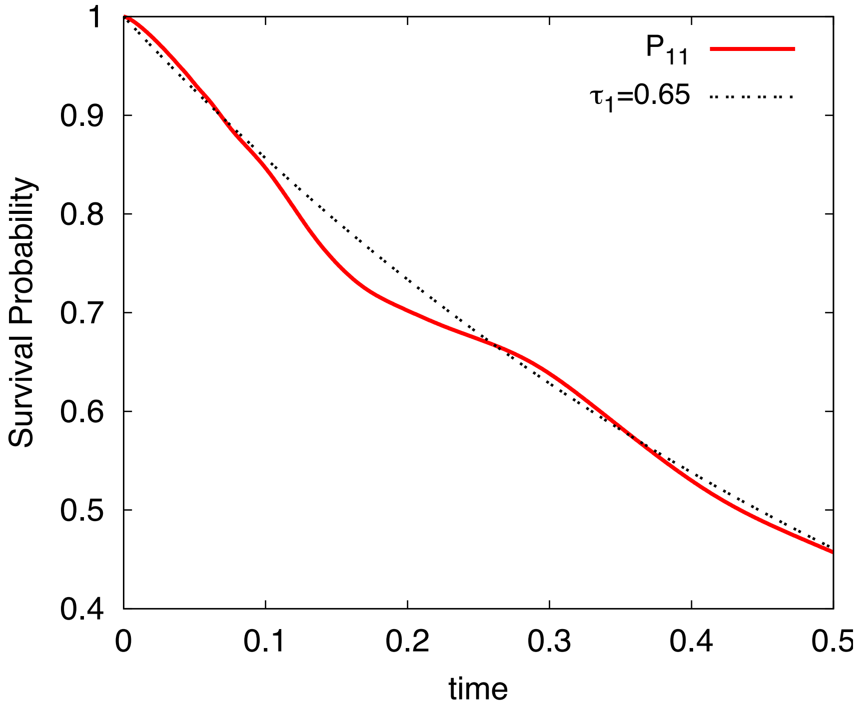


Time dependence of decay

Winter, Phys. Rev., ***123****,1503 1961.*







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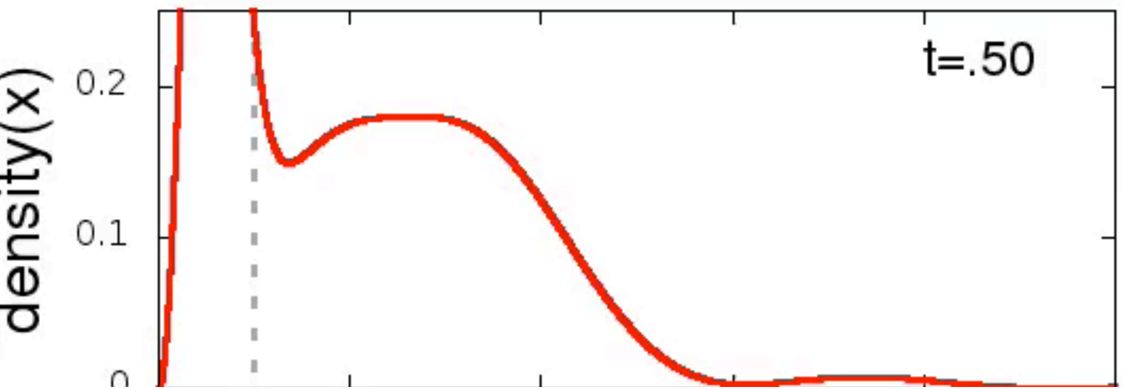
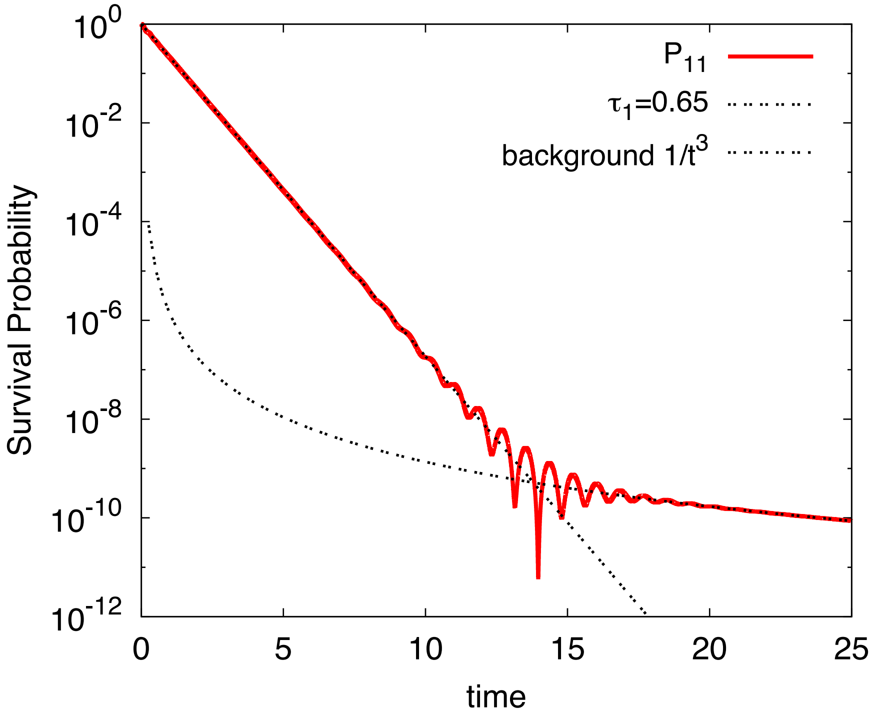
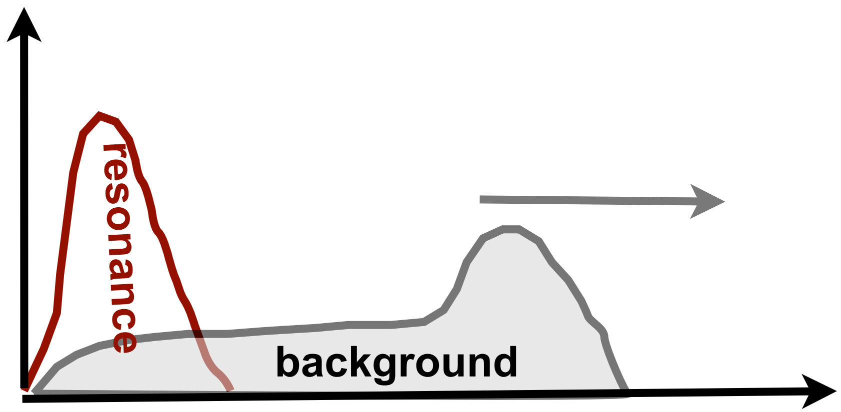
Winter's model: Dynamics at remote times





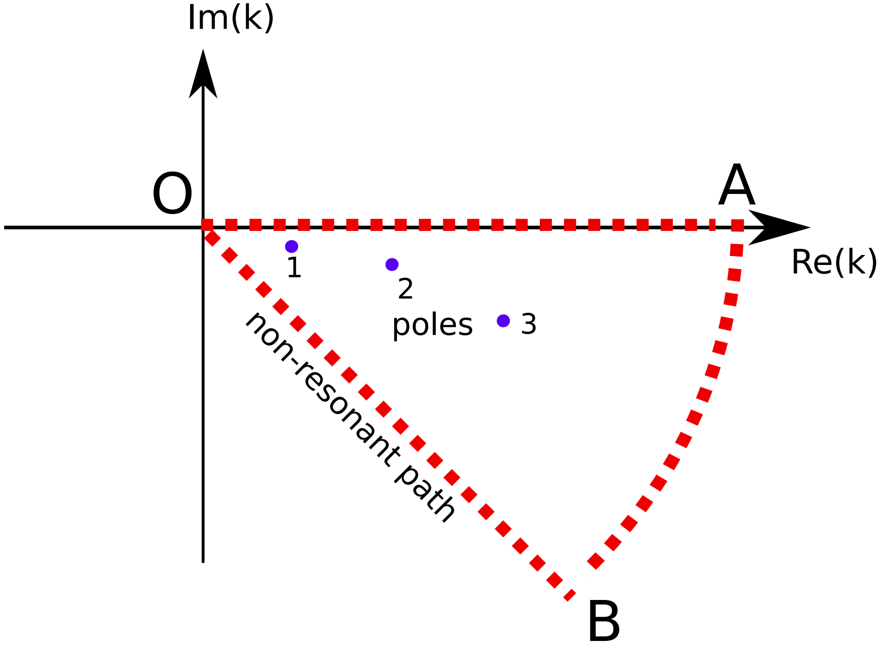


Internal dynamics in decaying system
Winter's model

$$M_{nn'}(t) = \langle n | e^{-iHt} | n' \rangle = \int_0^\infty e^{-ik^2 t} \langle n | k \rangle \langle k | n' \rangle dk \,.$$

$$M_{nn'}(t) = \sum_{k_r} M_{nn'}^{(r)} e^{-ik_r^2 t} + M_{nn'}^{(NR)}(t) \qquad M_{nn'}^{(r)}(t) = -\,2\pi i \,\mathrm{Res}(k_r)$$

$$M_{nn'}^{(NR)}(t) = \frac{1+i}{\pi^{5/2}\sqrt{2}} (1+G)^2 \frac{1}{nn'} \frac{1}{t^{3/2}} \,.$$



Internal dynamics in decaying system
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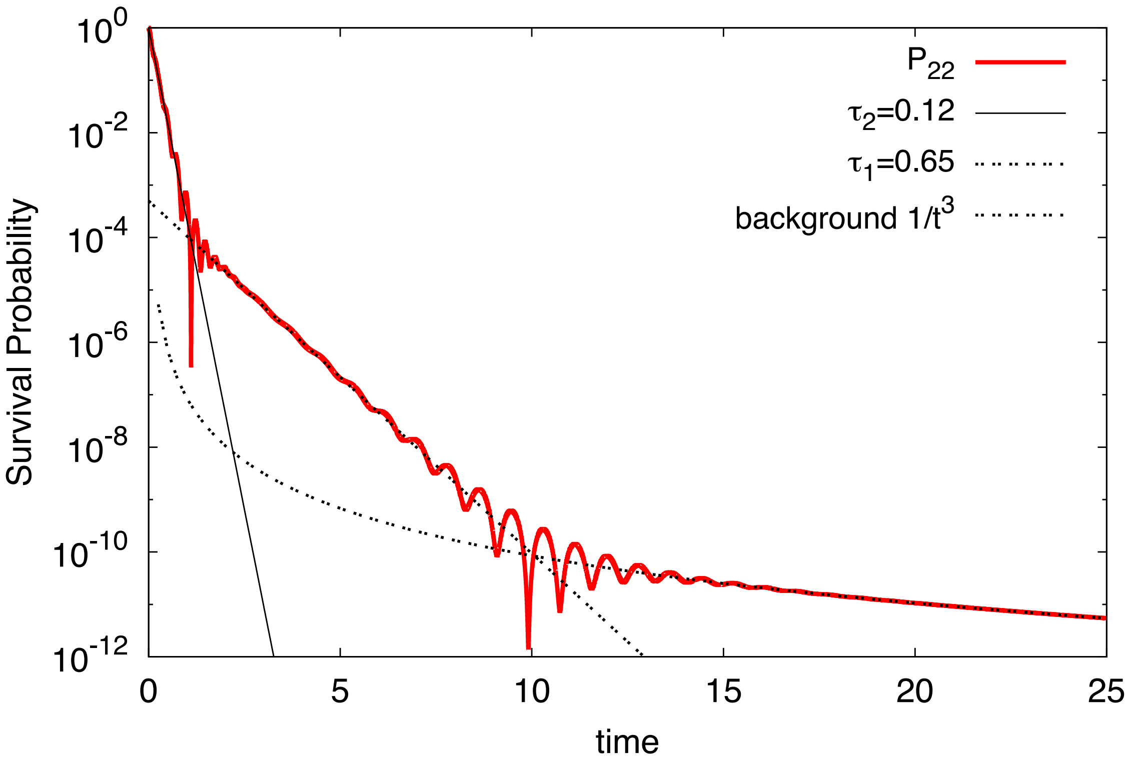

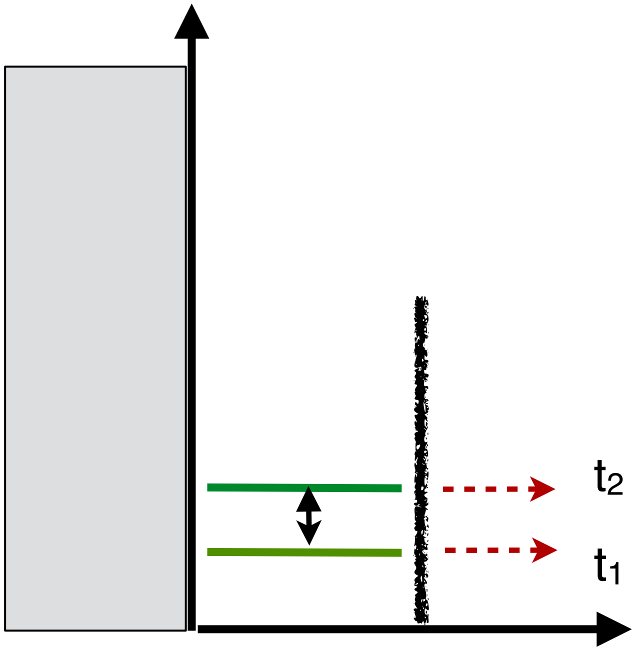

M. Peshkin, A. Volya, and V. Zelevinsky, "Non-exponential and oscillatory decays in quantum mechanics," *EPL*, vol. 107, no. 4, p. 40001, 2014.

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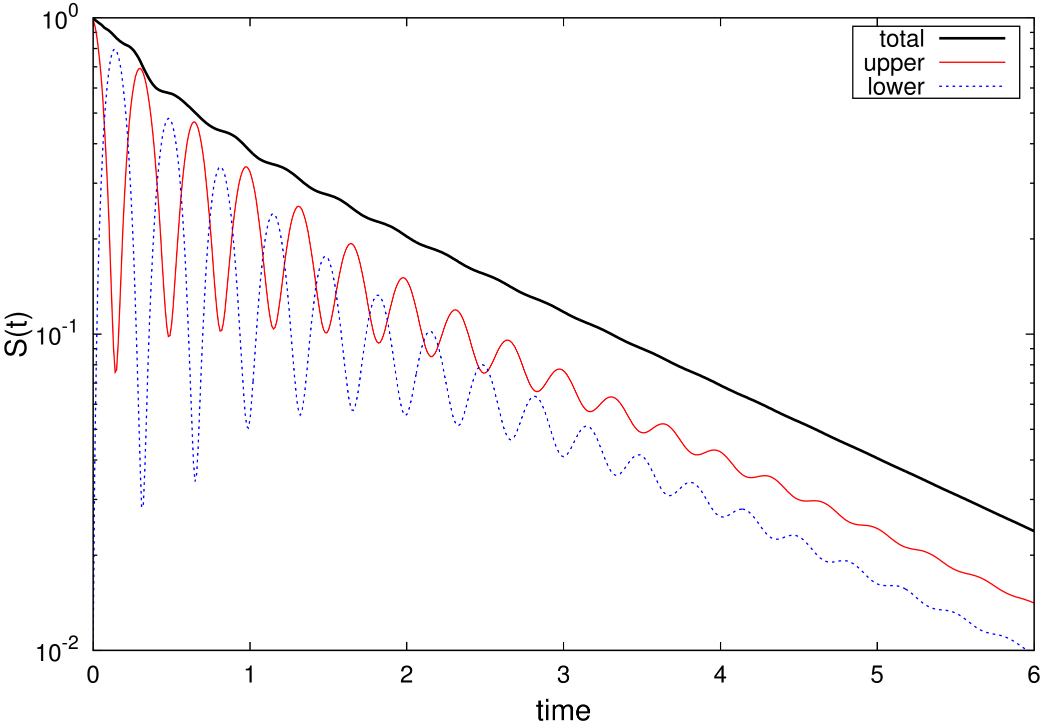
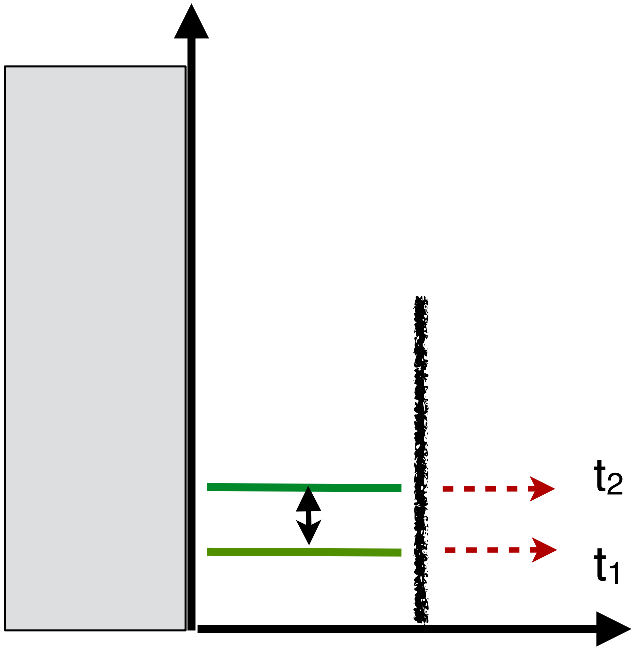




M. Peshkin, A. Volya, and V. Zelevinsky, "Non-exponential and oscillatory decays in quantum mechanics," *EPL*, vol. 107, no. 4, p. 40001, 2014.

Time-dependent
Continuum Shell Model Approach

- Expand Using evolution operator in Chebyshev polynomials

$$\exp(-iHt) = \sum_{n=0}^{\infty} (-i)^n (2-\delta_{n0}) J_n(t) T_n(H)$$

- Chebyshev polynomial $T_n[\cos(\theta)] = \cos(n\theta)$
- Use iterative relation and matrix-vector multiplication to generate

$$|\lambda_n\rangle = T_n(H)|\lambda\rangle$$

$$|\lambda_0\rangle = |\lambda\rangle, \quad |\lambda_1\rangle = H|\lambda\rangle \quad |\lambda_{n+1}\rangle = 2H|\lambda_n\rangle - |\lambda_{n-1}\rangle$$

$$\langle\lambda'|T_{n+m}(H)|\lambda\rangle = 2\langle\lambda'_m|\lambda_n\rangle - \langle\lambda'|\lambda_{n-m}\rangle, \quad n \geqslant m$$

- Use FFT to find return to energy representation

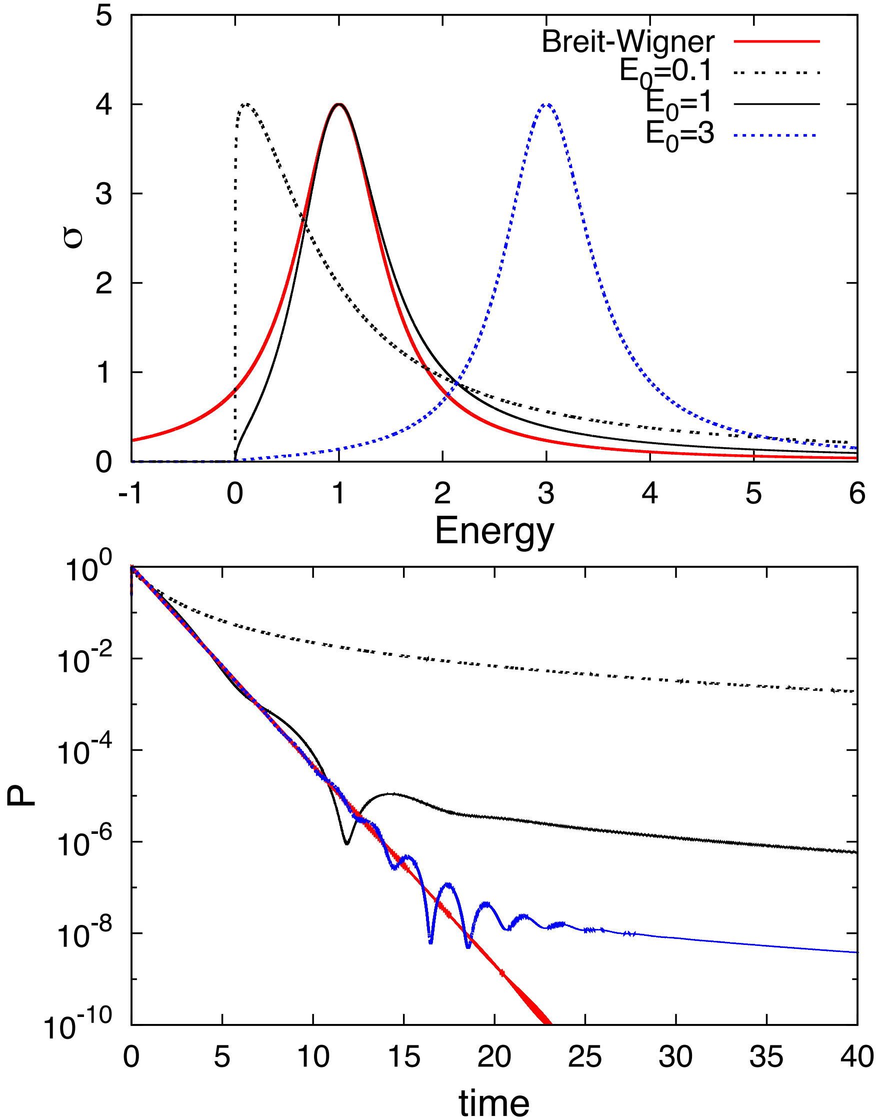
A. Volya, Phys. Rev. C 79, 044308 (2009).

Probing the Non-exponential Decay Regime in Open Quantum Systems

- Broad threshold resonance (^{9}N,^{9}He)
  - Pronounced non-exponentiality
  - Very short half-life
- Three-body decay (^{6}Be, ^{13}Li, ^{16}Be)
  - Nucleon-nucleon correlations
  - Energy dependence
- Overlapping resonances (^{13}C, ^{13}N)
  - Interference, pronounced non-exponentiallity
  - Superradiance

S. M. Wang, W. Nazarewicz, A. Volya, and Y. G. Ma, "Probing the Non-exponential Decay Regime in Open Quantum Systems." arXiv, Nov. 21, 2022. doi: 10.48550/arXiv.2211.11619.

Time-dependent picture

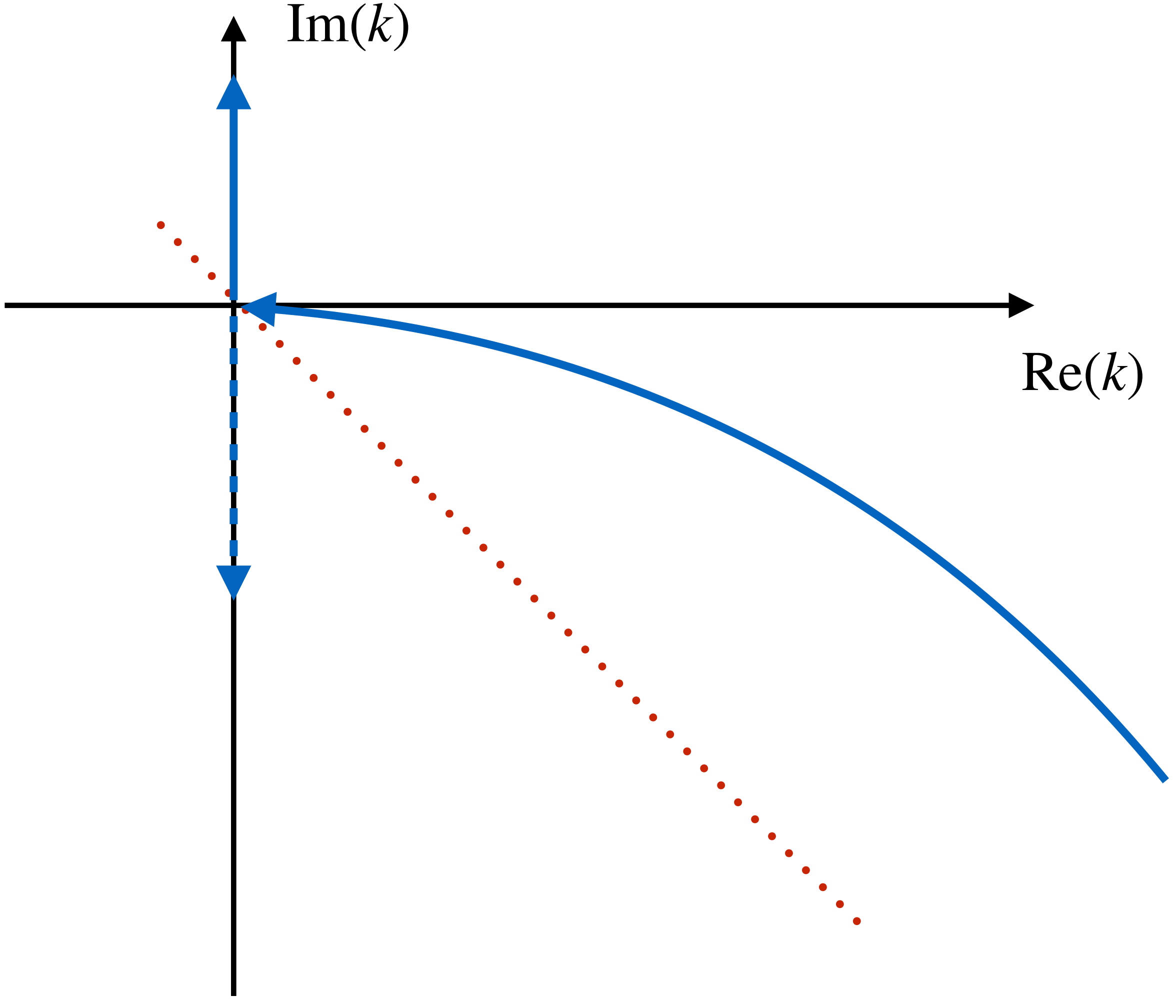


$$\mathcal{G} = \frac{1}{E - E_o + i/2\,\Gamma(E)}$$

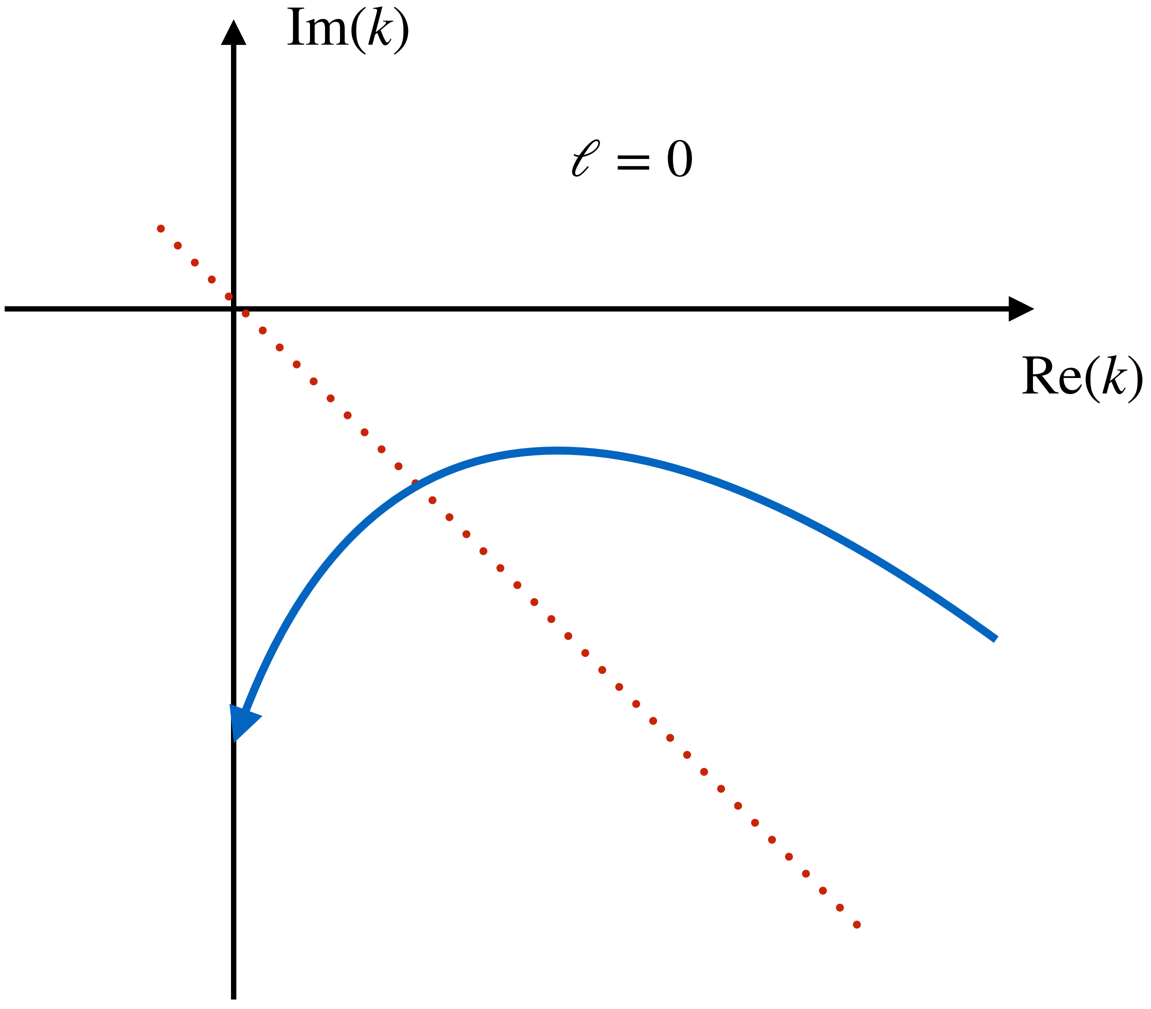
$$\Gamma(E) \propto \sqrt{E}$$

Power-law remote decay rate!

Resonance to bound state pole dynamics



Resonance to bound state pole dynamics



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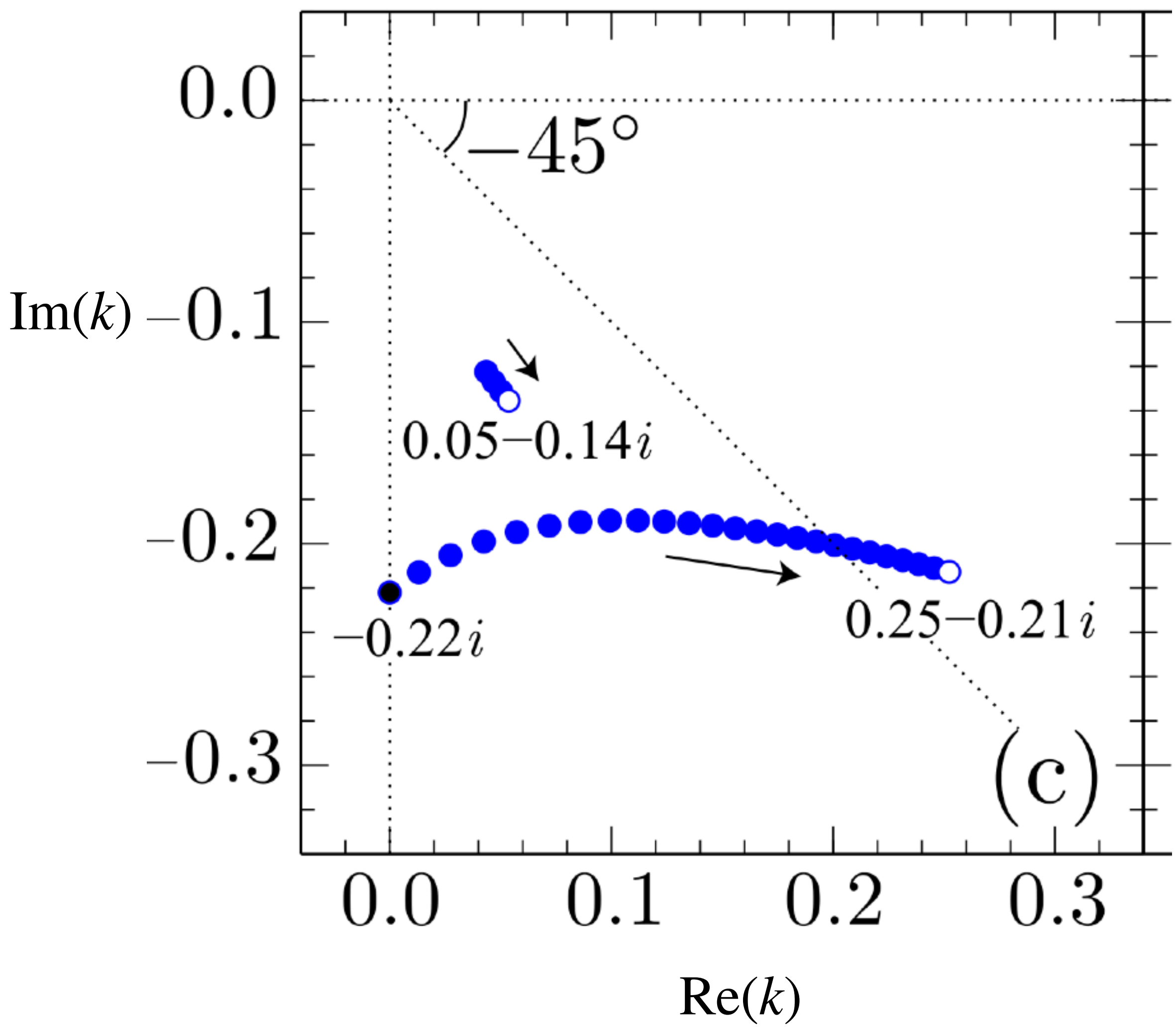

S. M. Wang, et.al Phys. Rev. C **99**, 054302 (2019)

n+^{9}Li p+^{9}C

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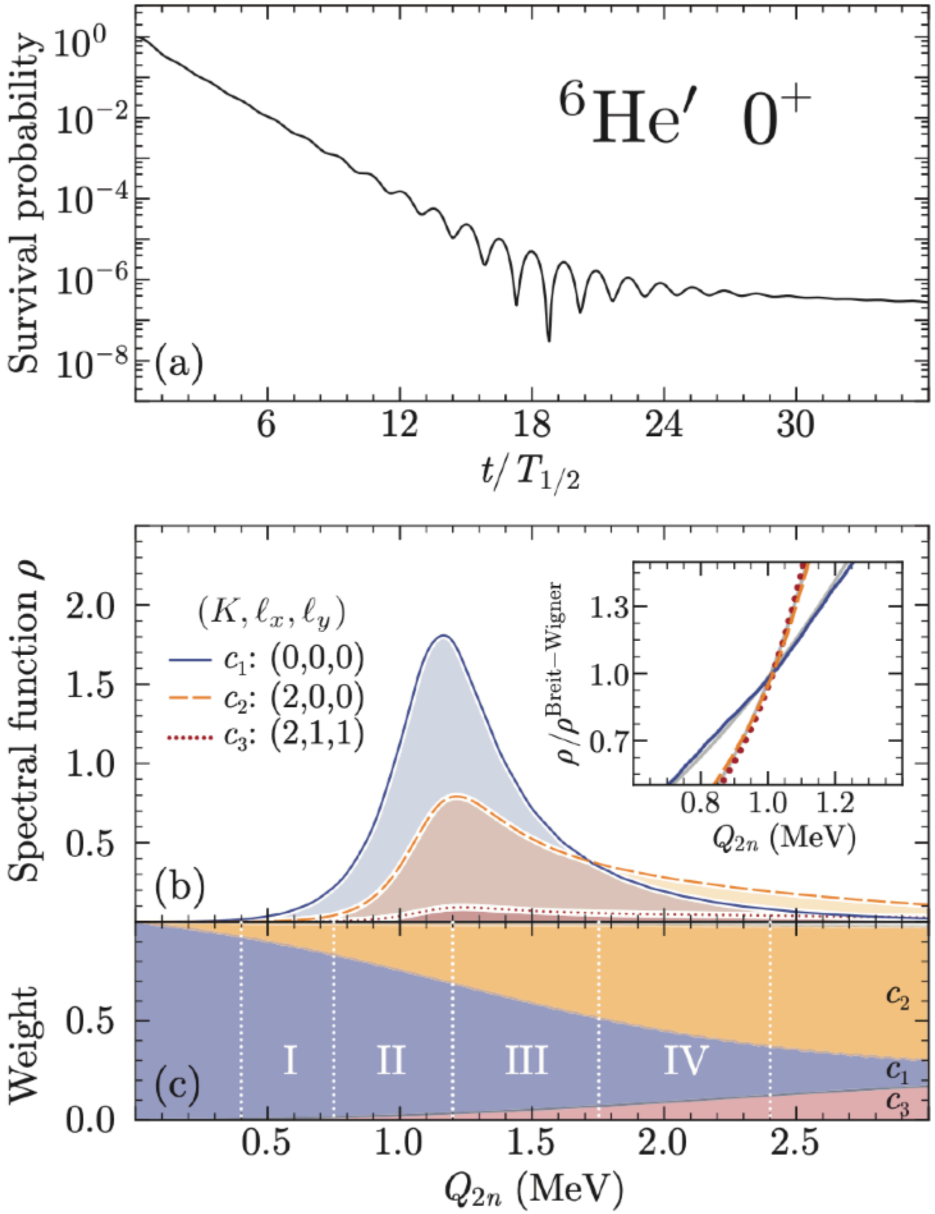
Time-dependent picture
Two-neutron decay



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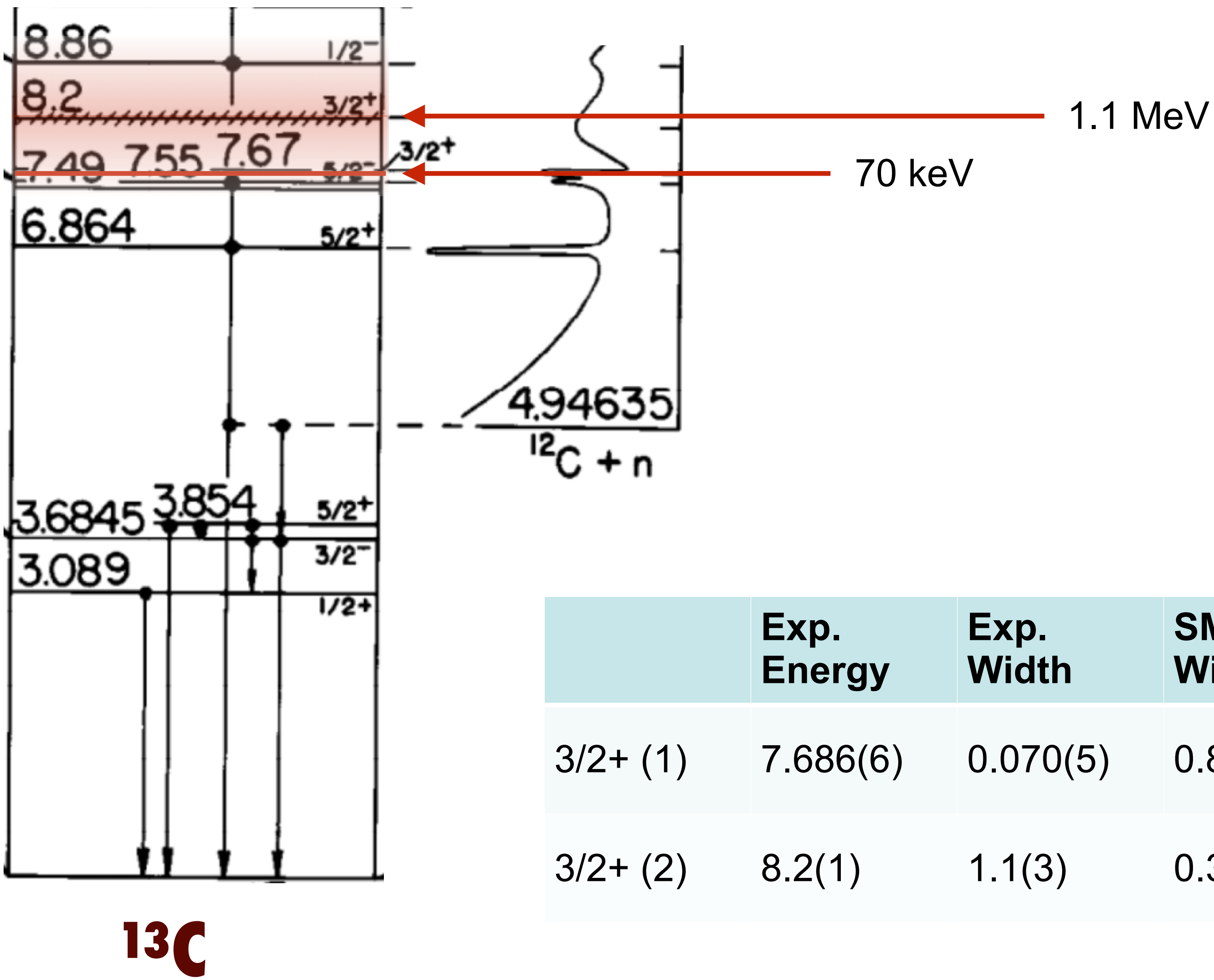
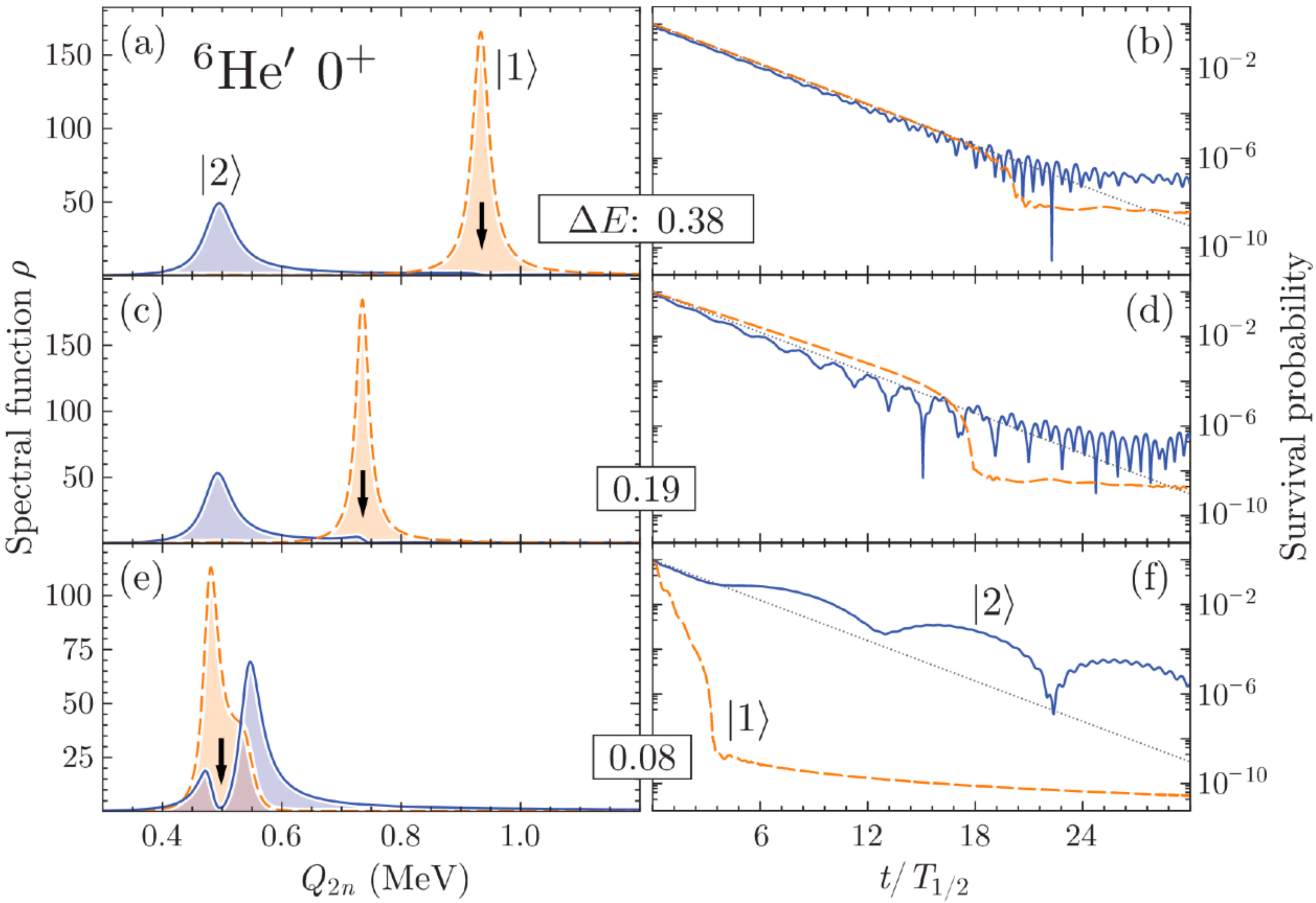
Superradiance in ^{13}C



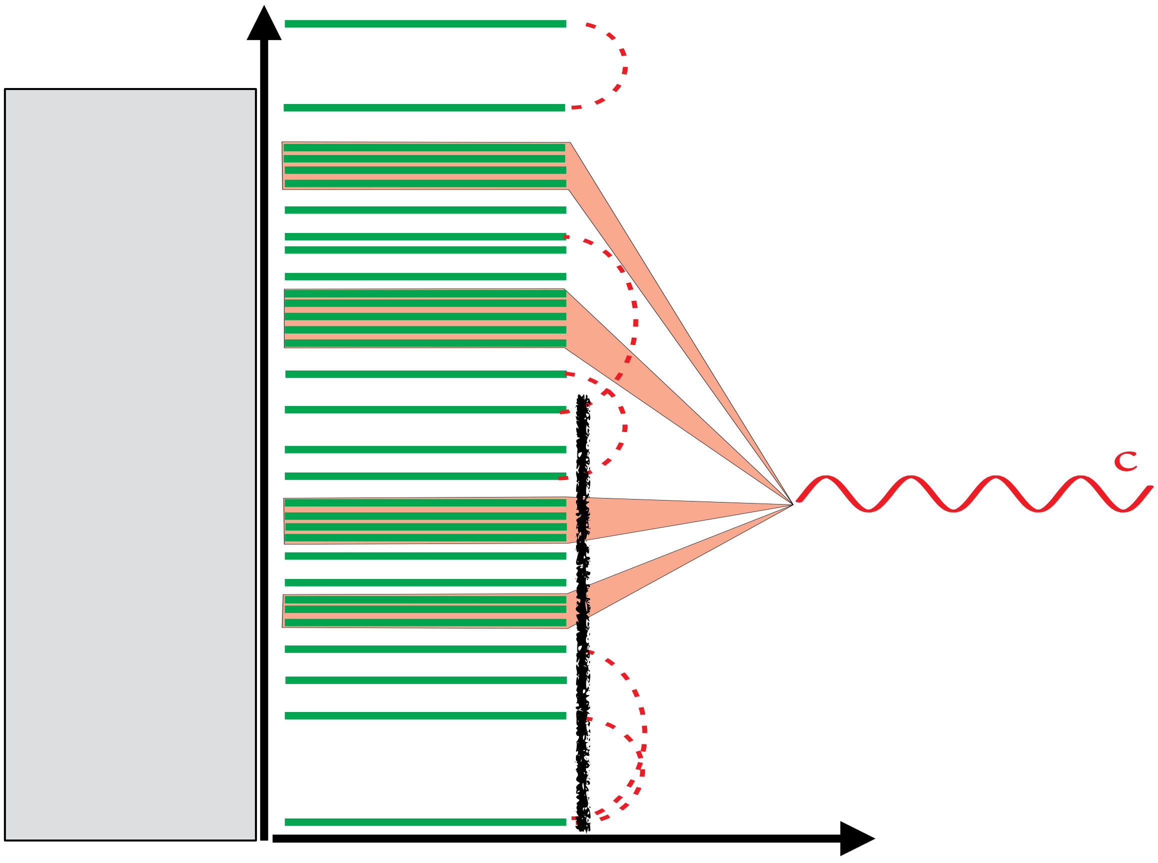
	Exp. Energy	Exp. Width	SM. Width	CSM Width
3/2+ (1)	7.686(6)	0.070(5)	0.858	0.098
3/2+ (2)	8.2(1)	1.1(3)	0.342	1.031

Example of interference between resonances



S. M. Wang, W. Nazarewicz, A. Volya, and Y. G. Ma, "Probing the Non-exponential Decay Regime in Open Quantum Systems." arXiv, Nov. 21, 2022. doi: 10.48550/arXiv.2211.11619.

Coupling via continuum



Universal law of relaxation

$$Q_a(t) = \langle \Psi_a(t) | \hat{Q} | \Psi_a(t) \rangle \,.$$

$$f_{a'a}(t) = \langle a' | e^{-i\hat{H}t} | a \rangle \,,$$

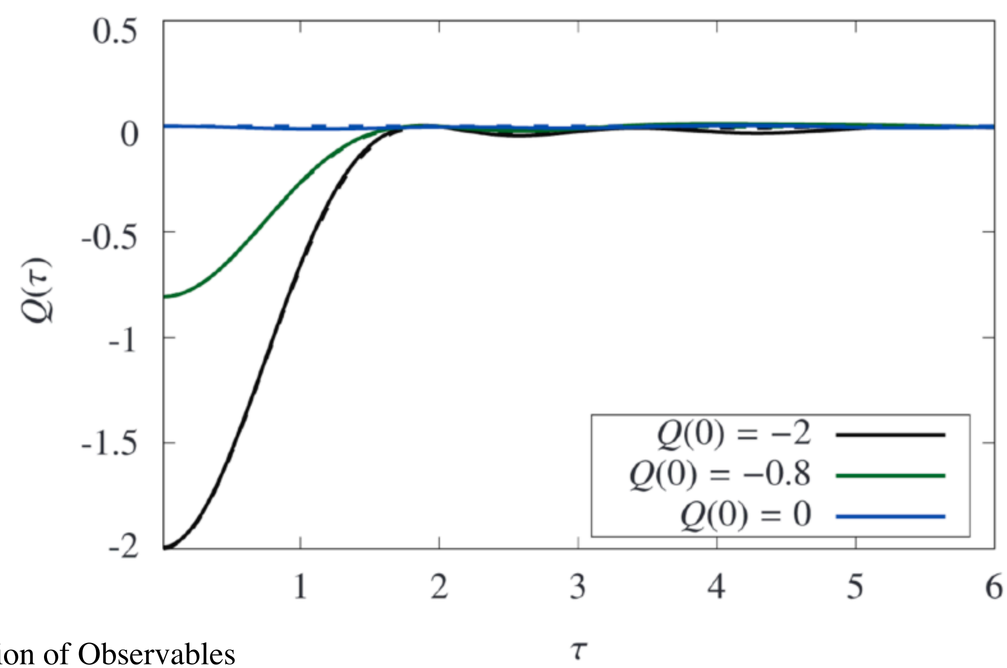
$$f_{aa'}(0) = \delta_{aa'} \,, \quad f_{aa'}(t) = f_{a'a}(-t),$$

$$\overline{f_{aa'}(t)} = \sum_n e^{-iE_n t} \overline{\langle a | n \rangle \langle n | a' \rangle} = \delta_{aa'} f(t),$$

$$Q(t) = Q(0) \, | f(t) |^2$$

Under the above assumptions of full randomness, the function $f(t)$ is universal

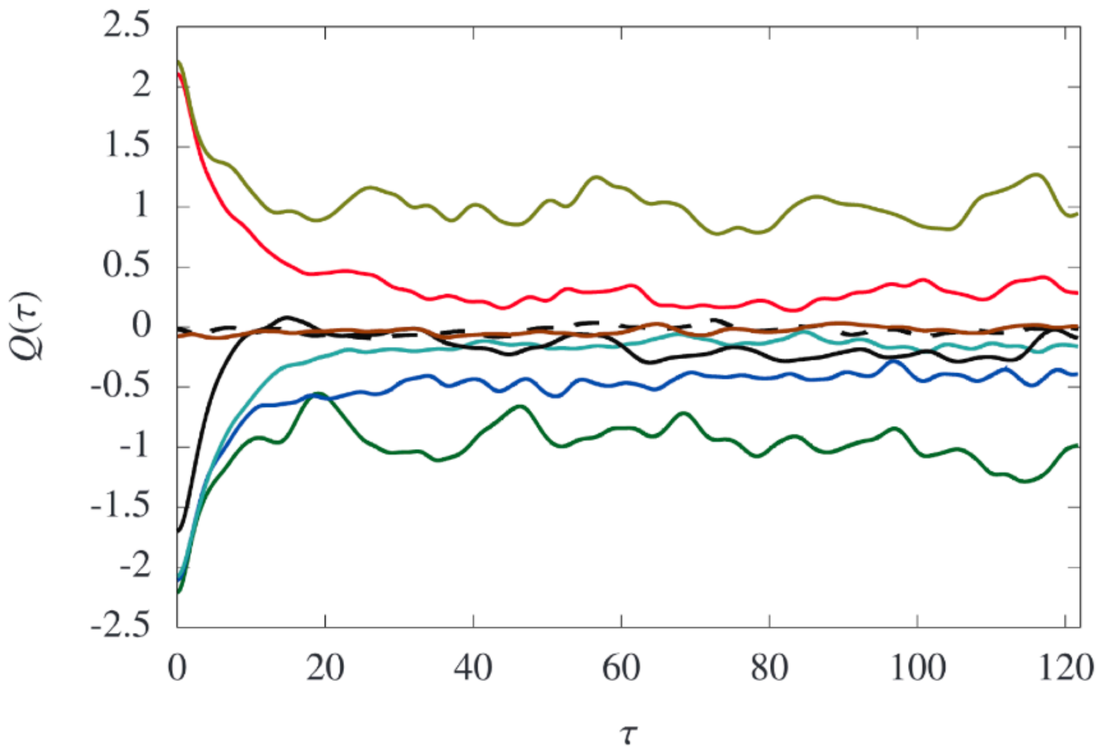
$$f(\tau) = \frac{1}{\tau} J_1(2\tau),$$



A. Volya and V. Zelevinsky, Time-Dependent Relaxation of Observables in Complex Quantum Systems, J. Phys. Complex. **1**, 025007 (2020).

Realistic shell model

Realistic sd shell model
USDB Hamiltonian
Realistic quadrupole moment
Spreading width ~10 MeV

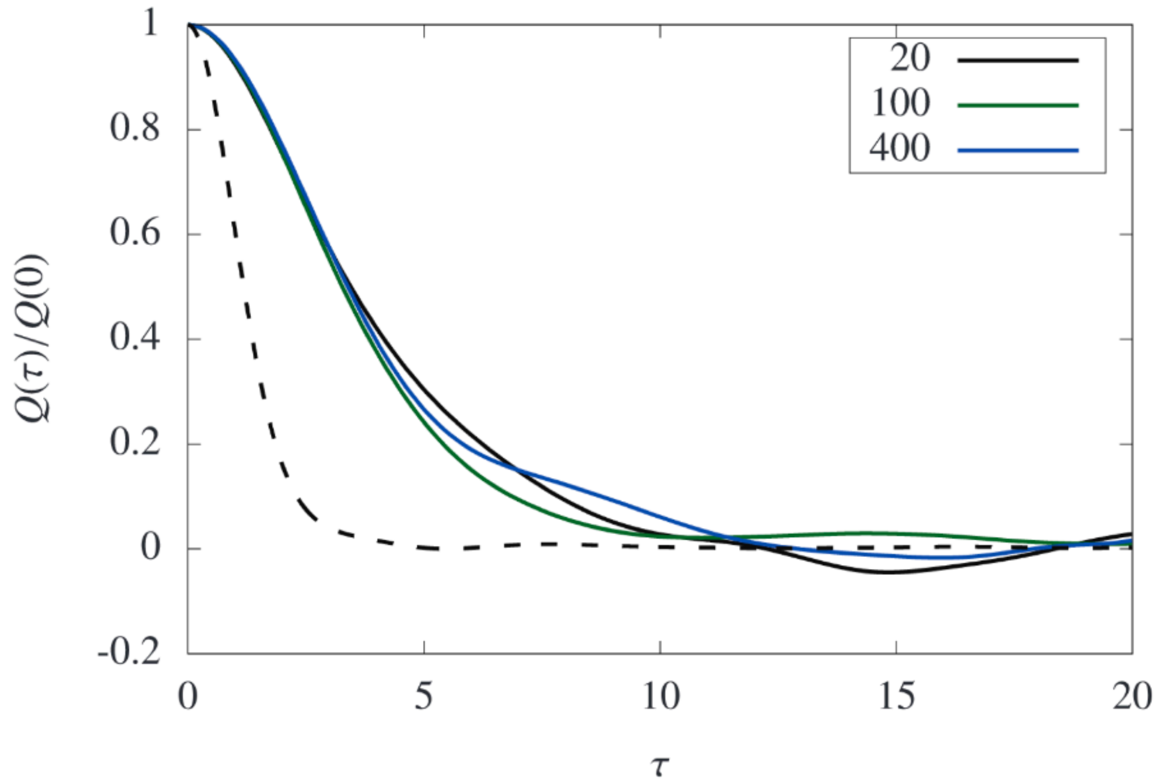


- Most states thermalize at zero
- Extreme states retain their average quadrupole moment
- Giant resonances
- Scars in chaotic dynamics

A. Volya and V. Zelevinsky, Time-Dependent Relaxation of Observables in Complex Quantum Systems, J. Phys. Complex. **1**, 025007 (2020).

Relaxation in realistic systems

Realistic sd shell model
USDB Hamiltonian
Realistic quadrupole moment
Spreading width ~10 MeV



Relaxation times in realistic systems is significantly longer.
Extended lifetime of perturbation

A. Volya and V. Zelevinsky, Time-Dependent Relaxation of Observables in Complex Quantum Systems, J. Phys. Complex. **1**, 025007 (2020). [1]

K. Ma, A. Volya, and K. Yang, *Eigenstate Thermalization and Disappearance of Quantum Many-Body Scar States in Weakly Interacting Fermion Systems*, Phys. Rev. B **106**, 214313 (2022).

Conclusions

- Discussion of dynamics becomes central to exotic nuclear systems on the verge of stability.
- Exponential decay is not exact and is a result of delicate approximations.
- Poles of the scattering matrix differentiate the types of dynamics.
- The initial state (of real energy) matters, as do the reaction mechanism and memory effect.
- Experimental studies of correlations can be used to probe the state and its time evolution.
- There is strong competition between internal relaxation and decay.

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