# INTERACTING DARK ENERGY AS AN OPEN QUANTUM SYSTEM: PHENOMENOLOGY AND LATE-TIME COSMIC ACCELERATION

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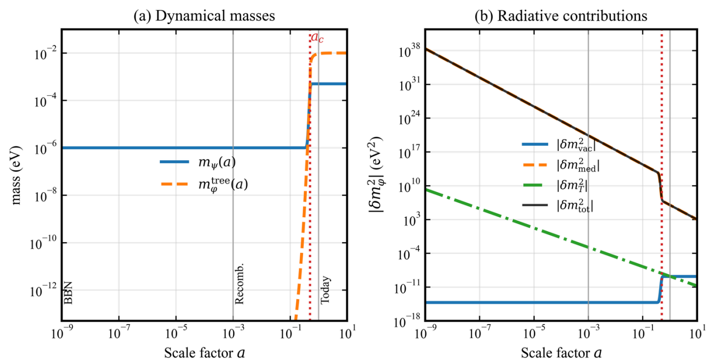
**Summary:** Persistent tensions in the Hubble constant $H_0$ and the growth amplitude $S_8$ motivate interacting dark-energy (IDE) scenarios beyond the minimal ΛCDM framework, where the dark sector is assumed to be non-interacting without symmetry protection. In effective field theory (EFT), a Yukawa coupling between an ultralight scalar dark energy (DE) field and fermionic dark matter (DM) is technically natural; however, when treated as a closed quantum system, such a coupling generically induces radiative instability and destabilizes the ultralight mass scale. We instead formulate the dark sector as an open quantum system: tracing over DM degrees of freedom yields Lindblad evolution for the scalar field, generating controlled, positive late-time dissipation consistent with complete positivity of the reduced dynamics. A density-triggered symmetry-breaking mechanism activates the interaction near the onset of cosmic acceleration, preserving early-time cosmology while providing a microphysically consistent origin for late-time IDE phenomenology.

## Radiative Instability in Closed EFT




In panel (a), the fermion mass remains nearly constant at early times, while the scalar mass undergoes a late-time transition at the critical epoch 'ac' triggered by density-dependent symmetry breaking. The scalar is effectively light during most of cosmic history and only acquires its stabilized curvature mass after activation. Panel (b) shows the vacuum, medium, and thermal radiative contributions to the scalar mass correction across cosmic time. Although individual contributions can be large in the early universe, their combined effect becomes strongly suppressed at late times. The transition at ac marks the onset of a weak-dissipation phase in which radiative corrections remain subdominant

## Observational Constraints & Survival Window

| Dataset | $\Omega_m$ | $H_0$ | $\sigma_8^0$ | $\beta_0$ | $a_c$ |
|---|---|---|---|---|---|
| SN+CC (Lindblad) | 0.286 ± 0.05 | 67.1 ± 1.4 | — | 0.005 ± 0.006 | — |
| RSD (Self-cons.) | 0.31 ± 0.10 | 70.2 ± 6.0 | 0.59 ± 0.01 | 0.063 ± 0.06 | 0.58 ± 0.33 |
| Joint (Full) | 0.292 ± 0.008 | 69.65 ± 0.60 | 0.784 ± 0.006 | 0.524 ± 0.004 | 0.467 ± 0.035 |

| Benchmark | $y$ | $m_\psi$ [eV] | $m_\varphi$ [eV] | $\Gamma_Q/H_0$ |
|---|---|---|---|---|
| (A) Weak, observable | $3\times10^{-16}$ | $10^9$ | $10^{-27}$ | $5.9\times10^{-3}$ |
| (B) Deep weak regime | $1\times10^{-17}$ | $10^9$ | $10^{-27}$ | $6.6\times10^{-6}$ |
| (C) Heavier scalar | $1\times10^{-15}$ | $10^9$ | $10^{-25}$ | $6.6\times10^{-4}$ |
| (D) Strong / excluded | $1\times10^{-12}$ | $10^9$ | $10^{-27}$ | $6.6\times10^{4}$ |

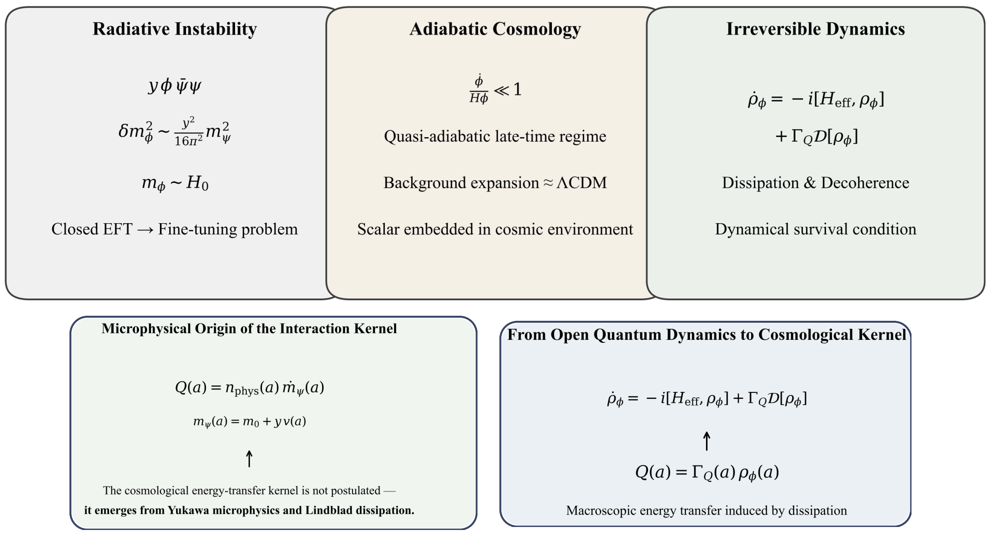
Tables summarize the phenomenology and microphysical consistency of the model:

- 68% constraints from SN+CC (background), RSD (growth), and joint analyses.
- Background data prefer weak, positive late-time dissipation.
- Growth data show suppressed structure formation.
- Joint analysis localizes a late activation epoch with nonzero coupling.
- Ultralight scalars with tiny Yukawa couplings yield $\Gamma(Q)/H_0 \ll 1$.
- Large couplings imply excessive dissipation and fall outside the open-system regime.

## Conclusion

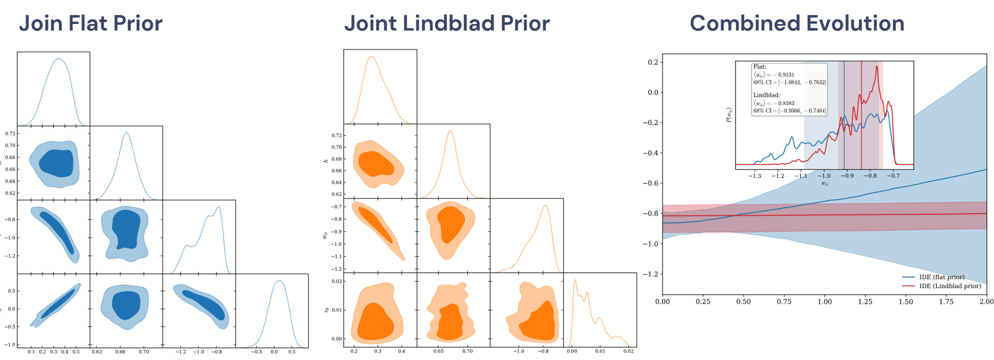
Radiative instability is not removed but reorganized: in the open-system regime, it **manifests as controlled, irreversible dissipation** rather than catastrophic mass renormalization. Within this framework, DE behaves as a late-time scalar condensate whose survival is dynamically regulated by its interaction with the DM bath. Our joint analysis localizes a late-time activation epoch ac≃0.47 and a nonzero coupling β0~O(0.5), while growth-only data favor a suppressed structure amplitude σ80≃0.59. The effective dissipation rate remains at the percent level ($\Gamma(Q)/H_0 \ll 1$), fully consistent with Lindblad positivity and background stability. Strongly dissipative or sign-changing phenomenological IDE models are excluded by both radiative consistency and data. Future studies can further constrain DM mass scales and interaction strengths, identifying the region in which **condensate coherence** is preserved while allowing percent-level late-time energy transfer consistent with cosmological observations.

## Open Quantum System Framework




These panels summarize the conceptual structure. The same interaction that generates loop corrections now also induces controlled dissipation and decoherence, providing a dynamical survival condition for the DE scalar. At the macroscopic level, this open-system evolution translates into a cosmological kernel Q(a) which emerges from the underlying microphysics and density-triggered mass evolution governed by the **Lindblad Master equation**,

$$\dot\rho_\phi = -i[H_{\rm eff}, \rho_\phi] + \Gamma_Q\left(L\rho_\phi L^\dagger - \tfrac{1}{2}\{L^\dagger L, \rho_\phi\}\right)$$




## Posterior Structure and Dynamical Evolution

- Corner plots compare a phenomenological flat prior with a Lindblad-consistent prior (SN+CC+RSD).
- The Lindblad prior sharpens constraints and reduces degeneracies.
- The combined evolution plot shows the redshift dependence of the effective interaction and reconstructed EoS.
- The coupling remains dynamically suppressed at early times.
- Activation occurs near the onset of cosmic acceleration.
- Shaded regions (68% credible intervals) confirm weak, positive late-time dissipation consistent with background data.

## References

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