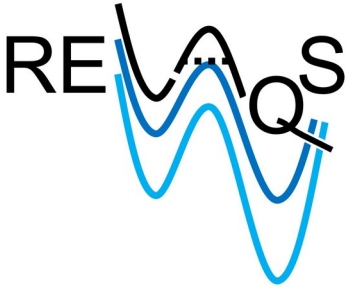
RelaQS: Relaxation by Quantum Simulation with ultracold atom-based experiments



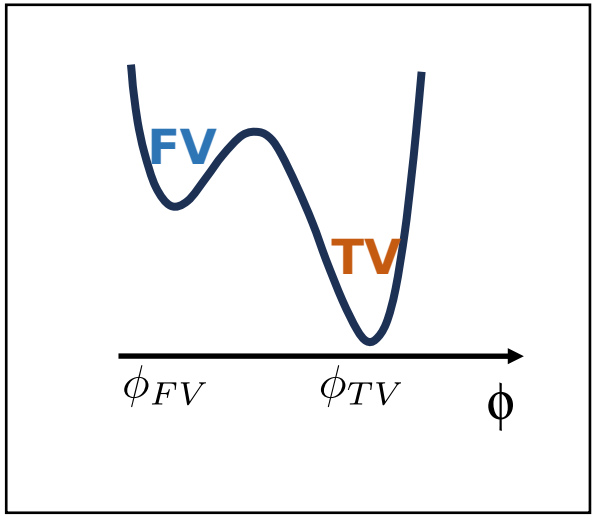
Obiettivo scientifico:

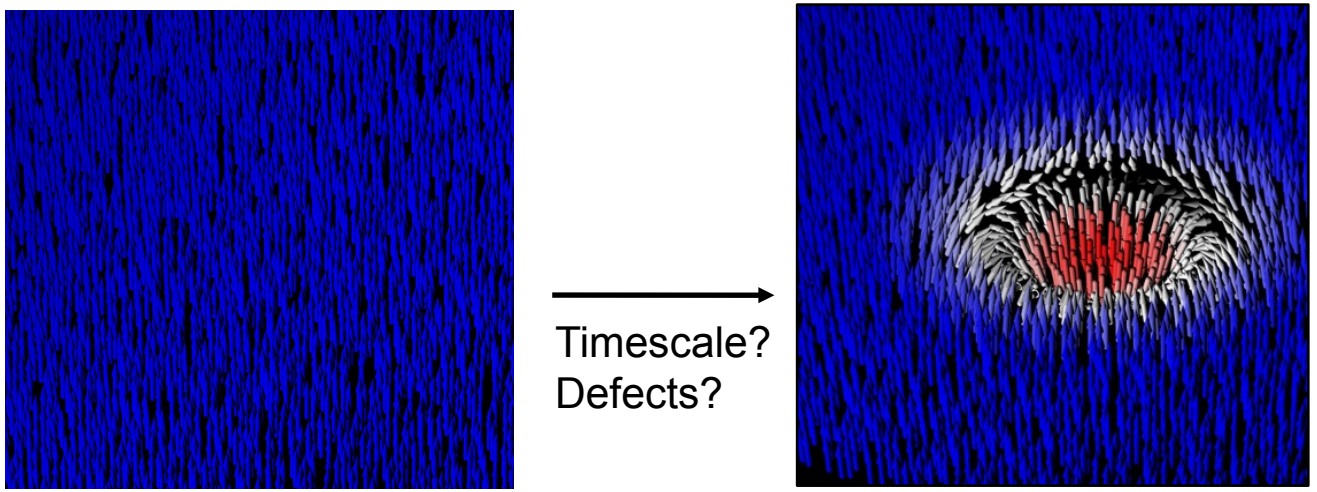
simulazione quantistica di meccanismi di rilassamento in teorie di campo e di eccitazioni topologiche di fermioni fortemente correlati su piattaforma di gas atomici ultrafreddi.

Articolazione:

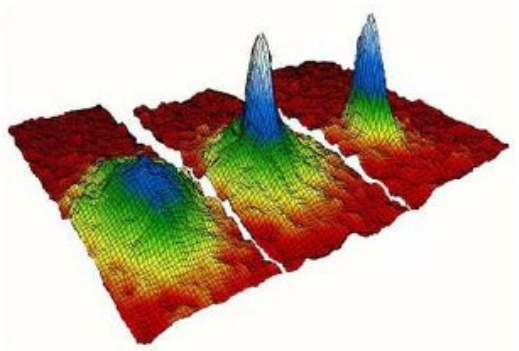
- TIFPA: ricreare ed osservare in laboratorio alcuni aspetti propri di teorie di campo e di materia fortemente correlata, come il meccanismo di decadimento di campi metastabili (processo noto come decadimento di falso vuoto),
- Firenze: studio della dinamica di rilassamento di eccitazioni topologiche (vortici quantizzati) in fermioni fortemente correlati (eg. glitches in stelle di neutroni).

false vacuum decay

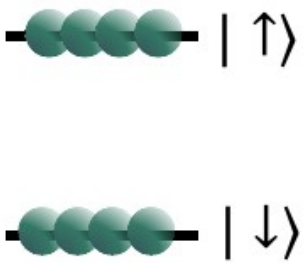




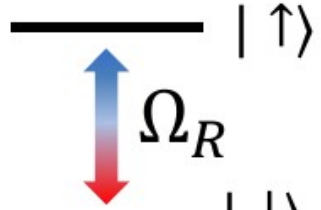
false vacuum decay



Bose-Einstein Condensate



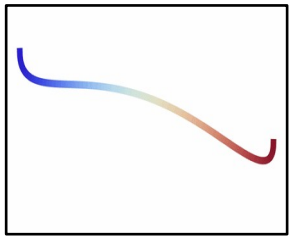
Spin Mixture



Coherent Coupling

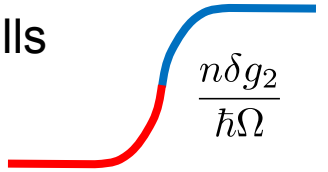
nucleation of true vacuum bubble

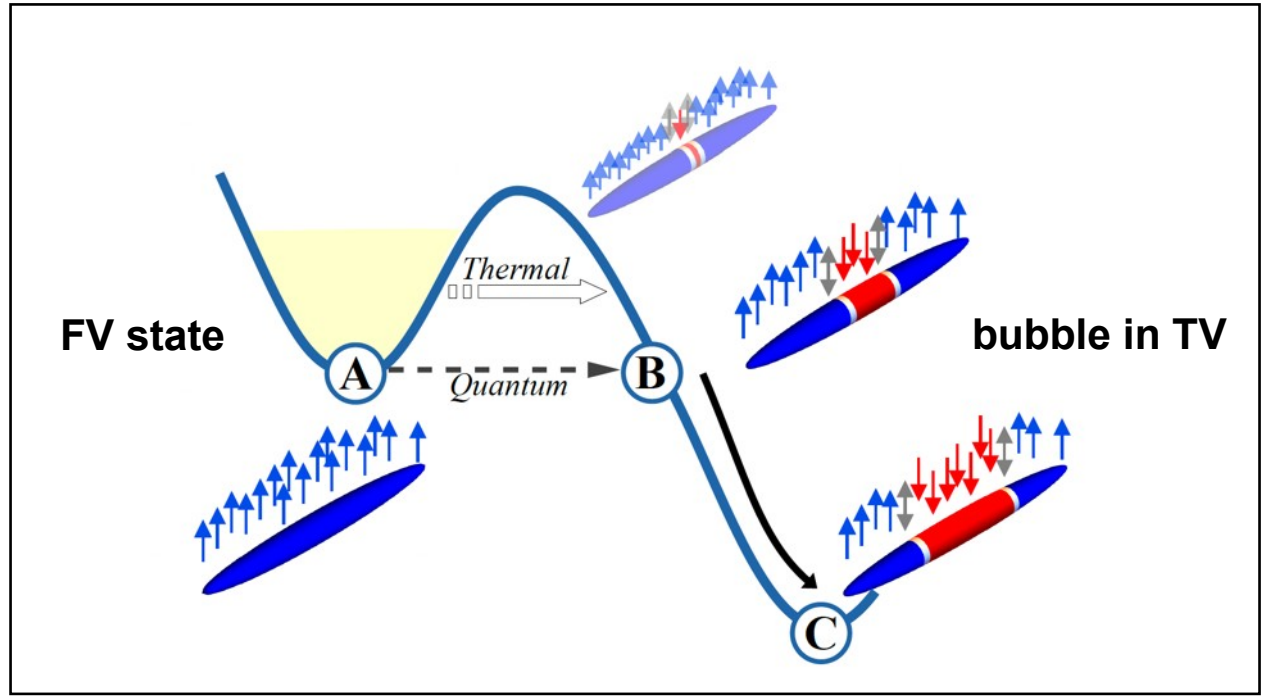
Mean-field energy landscape



+ Kinetic energy cost for the Domain Walls

$$E_{\text{kinetic}} \sim -\phi\,\nabla^2\phi$$





$n|\delta g_2|$

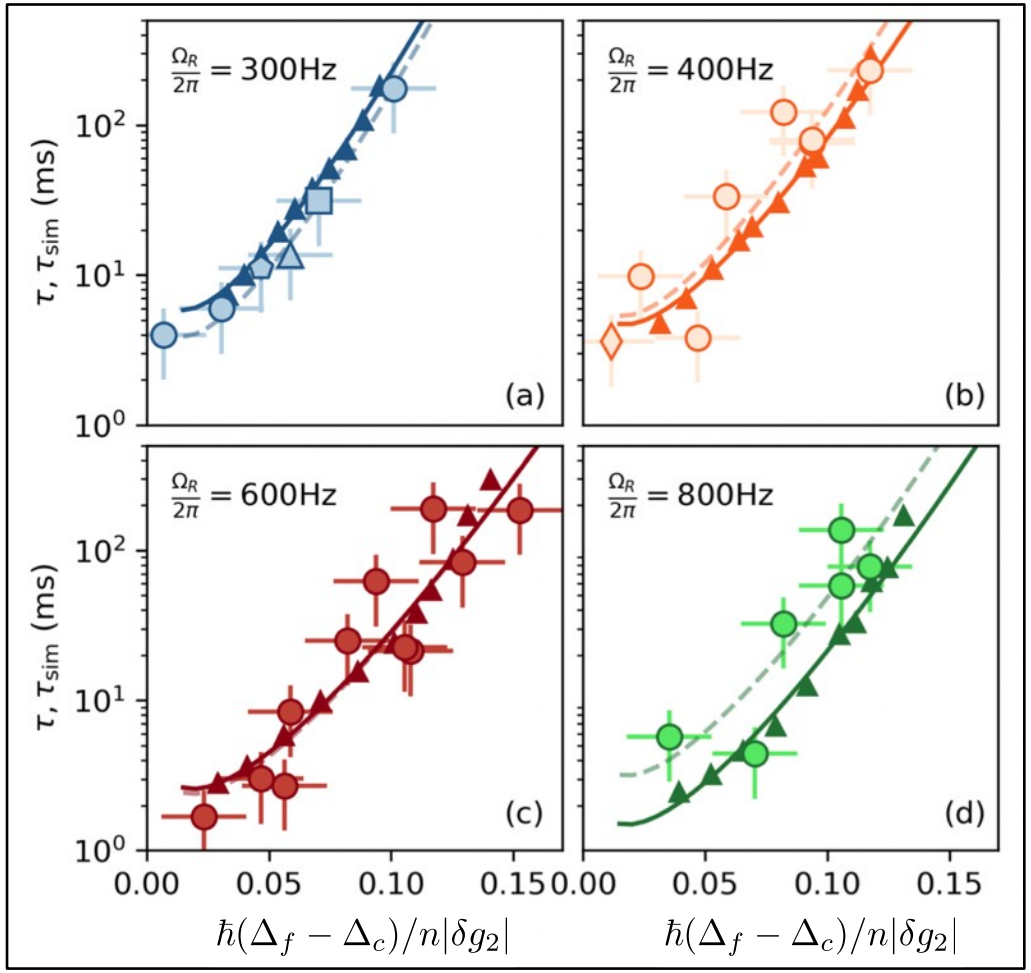
$k_B T$

Thermal fluctuations

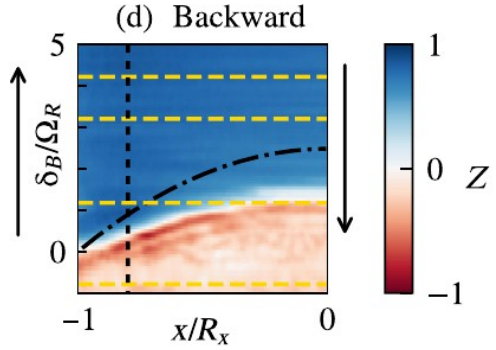
Quantum fluctuations

- **Many-body barrier** (NOT external potential)
- **Macroscopic tunneling** of the field (NOT single particle tunneling)
- **Thermal fluctuations** drive the tunneling

scaling of the bubble nucleation time



Large range on τ (2 – 200 ms)



Comparison between

- Experiment
- GPE simulations (with noise)
- Instanton theory

$$\tau = A(\beta E_c)^{-1/2}\ e^{\beta E_c}$$

$$\frac{E_c}{n|\delta g_2|} \propto \sqrt{\frac{\hbar^2 n}{2m|\delta g_2|}} \left(\frac{\hbar\Delta_f - \hbar\Delta_c}{n|\delta g_2|}\right)^{\frac{5}{4}} \left(\frac{\hbar\Omega}{n|\delta g_2|}\right)^{\frac{1}{6}} \left(\frac{\hbar|\Delta_c|}{n|\delta g_2|}\right)^{-\frac{1}{4}}$$

A. Zenesini et al., Nat. Phys. 20, 558 (2024)

Stato attuale e obiettivi

… un anno fa...

- prima osservazione sperimentale di decadimento di falso vuoto (FVD)
- prima verifica qualitativa dei tempi scala VS modello istantonico 1D (Coleman ‘77)

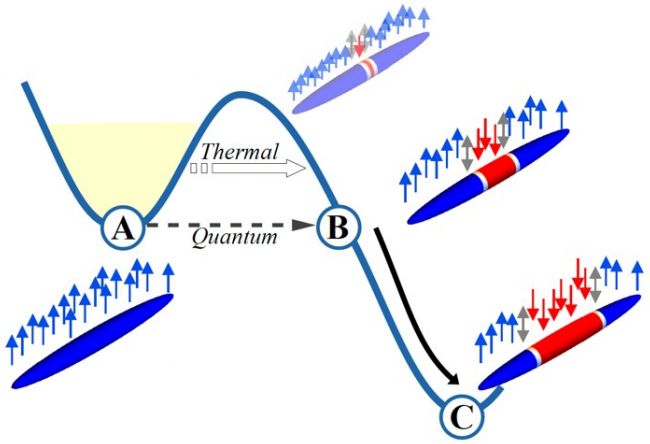
obiettivi 2025

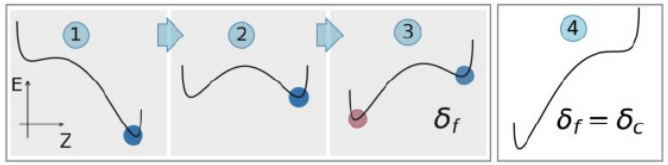
- studio effetti di temperatura sul decadimento di falso vuoto
- Intrappolamento in potenziale omogeneo 1D → osservazione nucleazione simultanea di più bolle

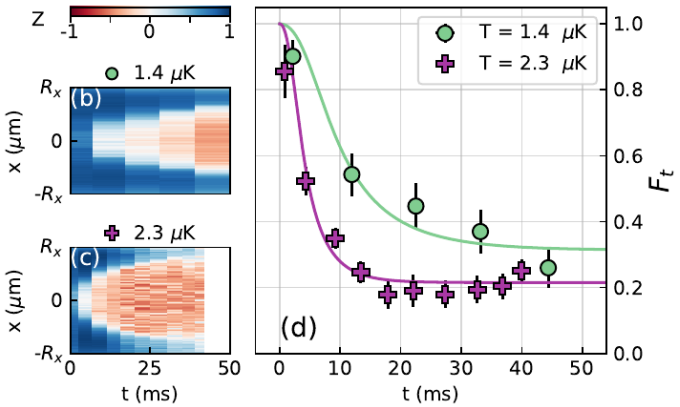
obiettivi 2026

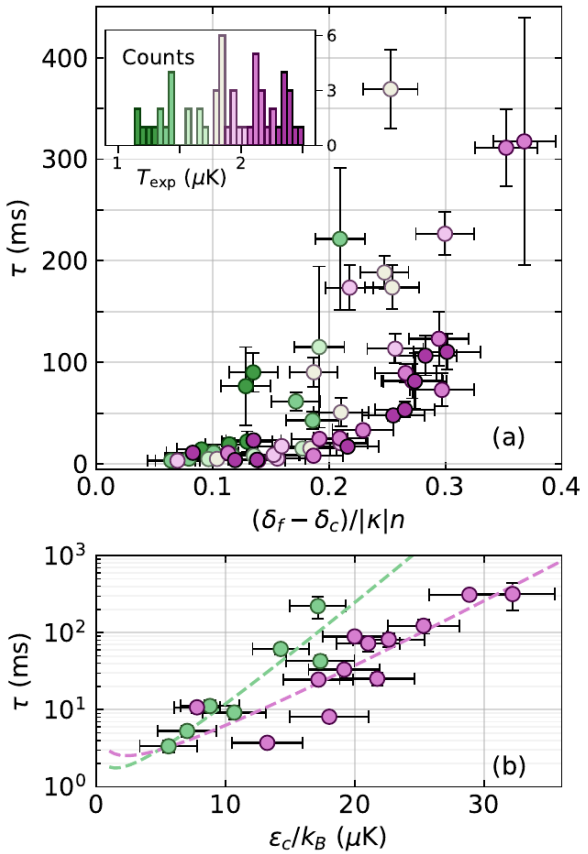
- Implementazione del setup ottico per la manipolazione coerente dei gradidi libertà di spin
- Studio della dinamica di crescita e di interazione tra bolle
- Osservazione di oscillone (precursore del decadimento, new entry!)

effetti di temperatura

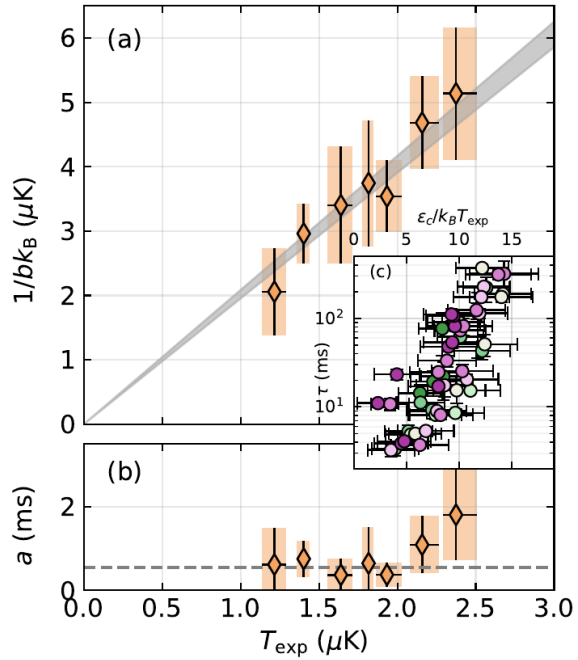








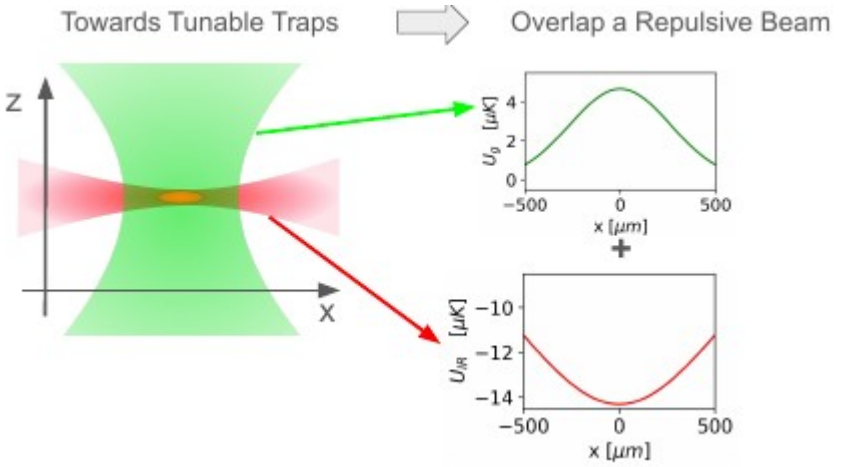
R. Cominotti et al.
arXiv:2504.03528

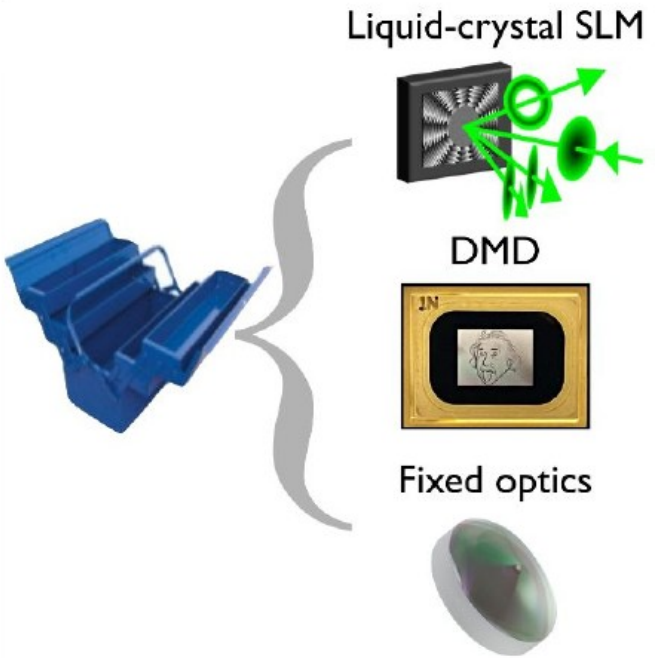


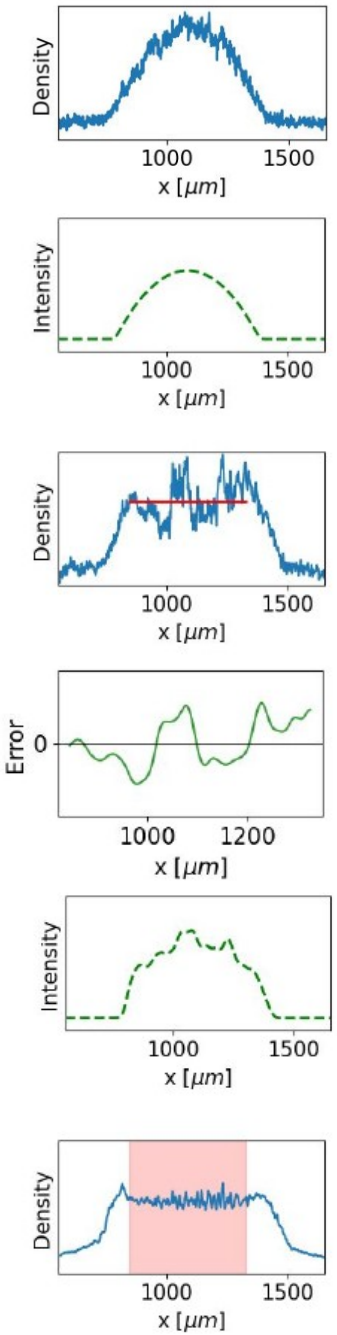
$$E_c = (\hbar|\kappa|n)(n_{1D}\xi)\left(\frac{\delta_f - \delta_c}{|\kappa|n}\right)^{\frac{5}{4}}\left(\frac{\delta_c}{|\kappa|n}\right)^{-\frac{1}{4}}\mathcal{G}$$

$$\ln(\tau) = b\,\varepsilon_c + \ln(a) - \frac{1}{2}\ln(b\,\varepsilon_c)$$

intrappolamento in potenziale omogeneo







Project Parabolic Intensity Profile

Acquire Density Profile

Compute Error Profile

Project new Intensity Profile

Convergence

Stato avanzamento

… un anno fa...

- prima osservazione sperimentale di decadimento di falso vuoto (FVD)
- prima verifica qualitativa dei tempi scala VS modello istantonico 1D (Coleman ‘77)

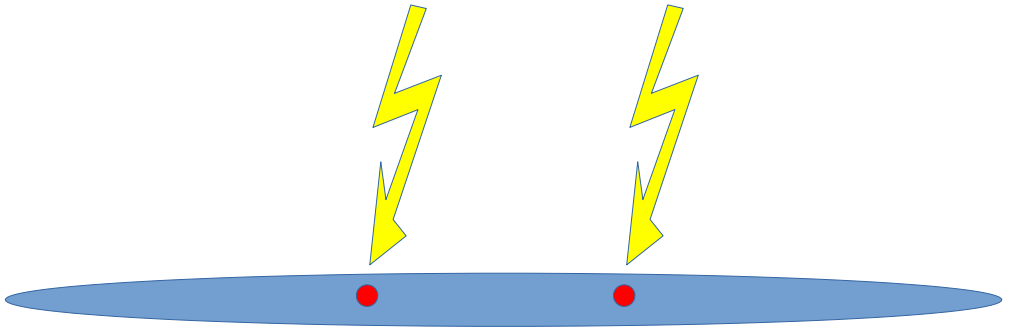
obiettivi 2025

- studio effetti di temperatura sul decadimento di falso vuoto ✓
- Intrappolamento in potenziale omogeneo 1D → in progress

rottura finestra da vuoto in primavera:
persi due mesi di misura!

attività 2026

Creation of oscillons and
deterministic nucleation of bubbles:



Bubble expansion and interaction dynamics:

Relaxation & generation of topological defects:

1 dimension

Stato fondi assegnati 2025

	k€ assegnati	k€ impegnati	
• missioni:	1	0	
• consumo:	45	30	
• trasporto:	5	1.5	
• manutenzione:	21	13	**8 k€ da restituire**

Ricercatori coinvolti

TIFPA:

Gabriele Ferrari	prof UNITN	50%
Francesco Pederiva	prof UNITN	20%
Giacomo Lamporesi	staff CNR-INO	30%
Alessandro Zenesini	staff CNR-INO	30%
Iacopo Carusotto	staff CNR-INO	20%
Alessio Recati	staff CNR-INO	20%
Chiara Rogora	dottoranda UniTN	50%
Diego Andreoni	dottorando UniTN	50%
Giacomo Guarda	dottorando UniTN	50%

Totale: 9 pesone, 3.2 FTE

Richieste 2026

- Consumo: 50 k€
  - alimentatori di corrente bipolari alta stabilità
  - fibre ottiche PM luce visibile
  - fibre ottiche PCF/hollow core alta potenza IR
  - ottiche per microscopio ad alta risoluzione
  - amplificaori e minuteria microonda
- Missioni: 1 k€
- Trasporto: 2 k€