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

**Obiettivo scientifico:**

studiare la dinamica di gas quantistici di atomi ultrafreddi al fine di modellizzare interazioni e meccanismi fondamentali alla base della fisica delle alte energie, focalizzandosi sui processi di rilassamento in teorie di campo e di eccitazioni topologiche.

**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).

# Genesi della proposta: FISH

- “WHAT NEXT” 2015 → 2021,

  studio sperimentale di fisica fondamentale con approcci innovativi.

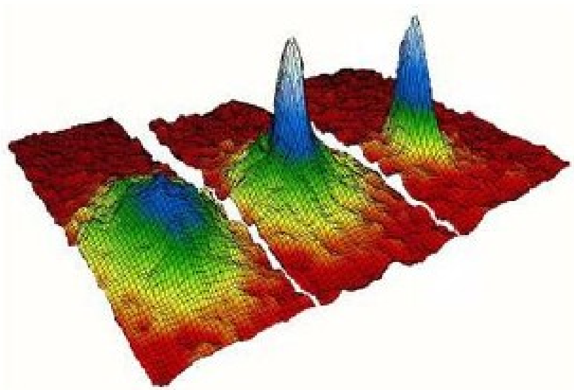
- Obiettivo: simulazione quantistica di interazioni fondamentali su piattaforma di gas atomici ultrafreddi;
- Approccio innovativo: impiego di gas superfluidi di spin con accoppiamento coerente

  → simulazione equazione Sine-Gordon,

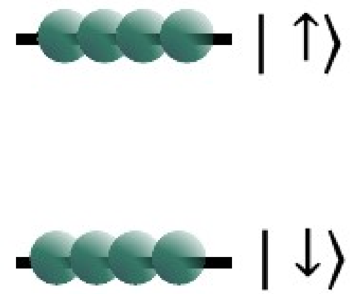
  → ingegnerizzazione di potenziali per teorie di campo;
- Innovazione tecnologica: produrre e studiare gas ultrafreddi in regime di stabilità estrema di campo magnetico;


- G. Colzi et al., Phys. Rev. A 93, 023421 (2016)
- T. Bienaimé et al., Phys. Rev. A 94, 063652 (2016)
- E. Fava et al,. Phys. Rev. Lett. 120, 170401 (2018)
- G. Colzi et al., Phys. Rev. A 97, 053625 (2018)
- A. Farolfi et al., Rev. Sci. Instr. 90, 115114 (2019)
- A. Farolfi et al., Phys. Rev. Lett. 125, 030401 (2020)
- A. Farolfi et al., Phys. Rev. A 104, 023326 (2021)
- A. Farolfi et al., Nature Physics 17, 1359 (2021)
- R. Cominotti et al., Phys. Rev. Lett. 128, 210401 (2022)

# the experimental platform

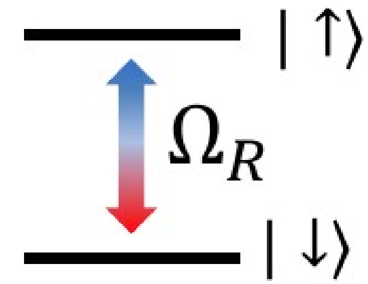


Bose-Einstein Condensate




Spin Mixture

+




Coherent Coupling

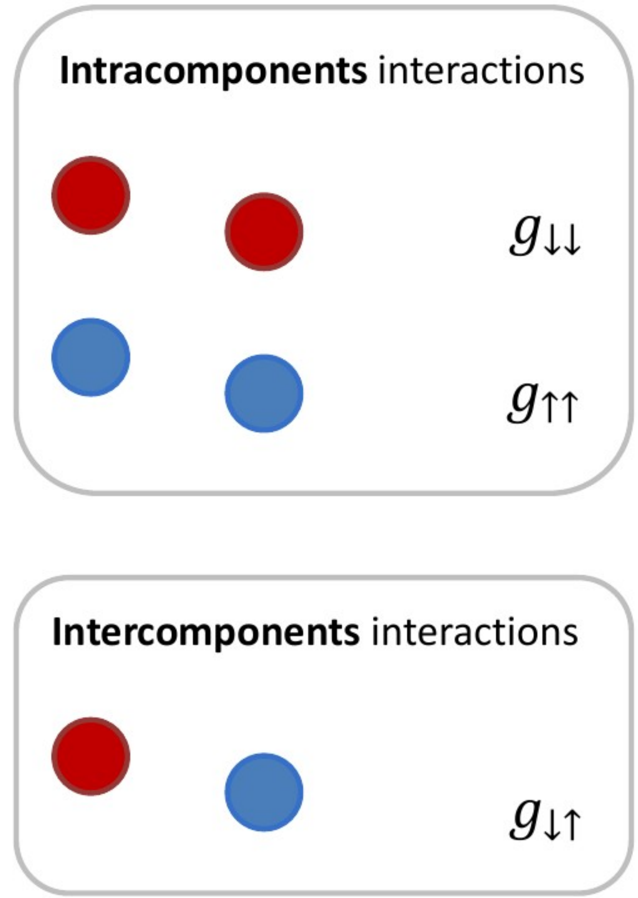
# from one component to spin mixtures

- U(1)xU(1) symmetry

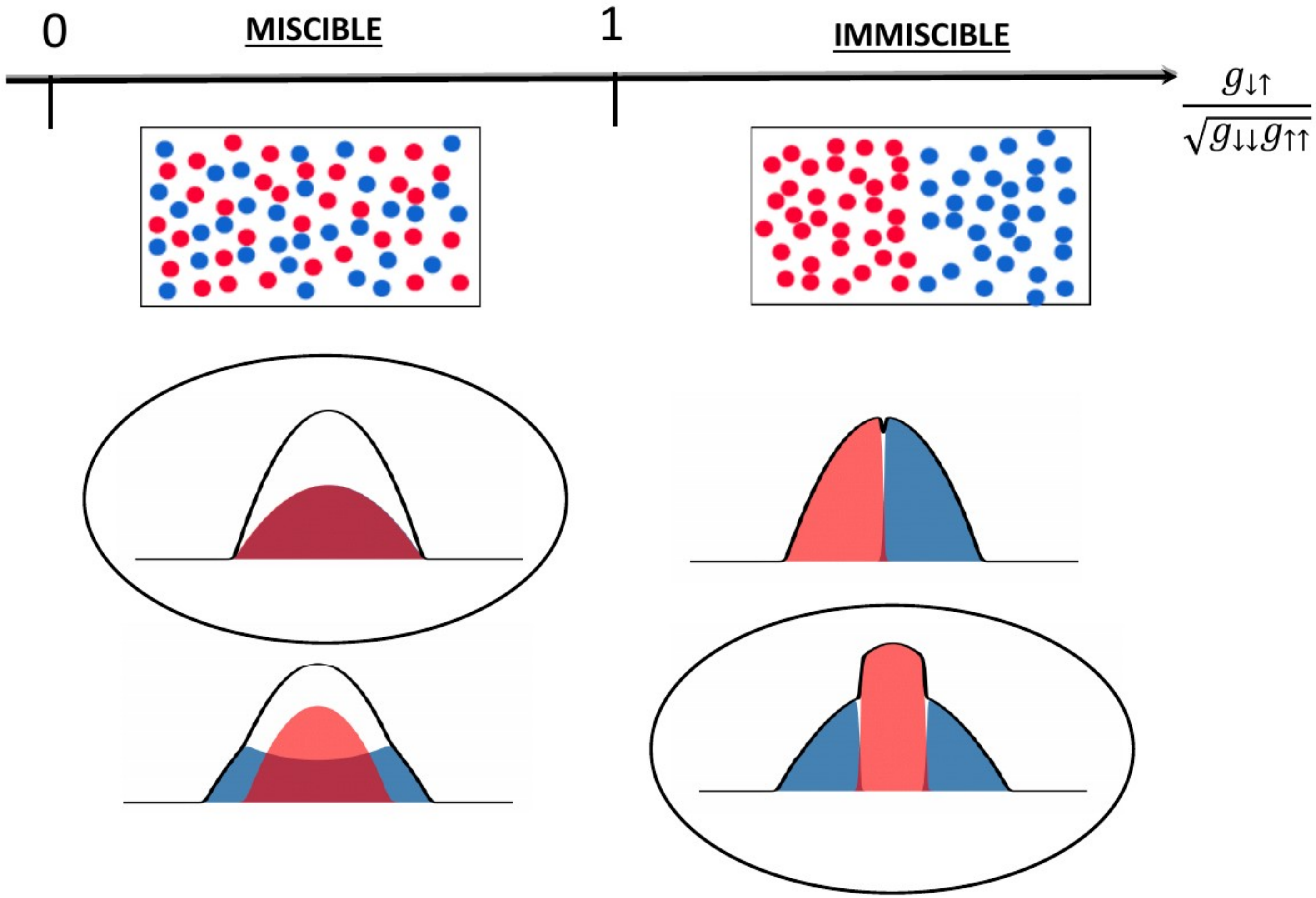
- Three interaction parameters $g_{ij} = \frac{4\pi\hbar^2 a_{ij}}{m}$

$$i\hbar\partial_t\psi_\downarrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\downarrow\downarrow}|\psi_\downarrow|^2 + g_{\downarrow\uparrow}|\psi_\uparrow|^2\right]\psi_\downarrow$$

$$i\hbar\partial_t\psi_\uparrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\uparrow\uparrow}|\psi_\uparrow|^2 + g_{\downarrow\uparrow}|\psi_\downarrow|^2\right]\psi_\uparrow$$



## from one component to spin mixtures




$g_{\downarrow\downarrow} = g_{\uparrow\uparrow} = g$

Buoyancy condition for $g_{\downarrow\downarrow} \neq g_{\uparrow\uparrow}$

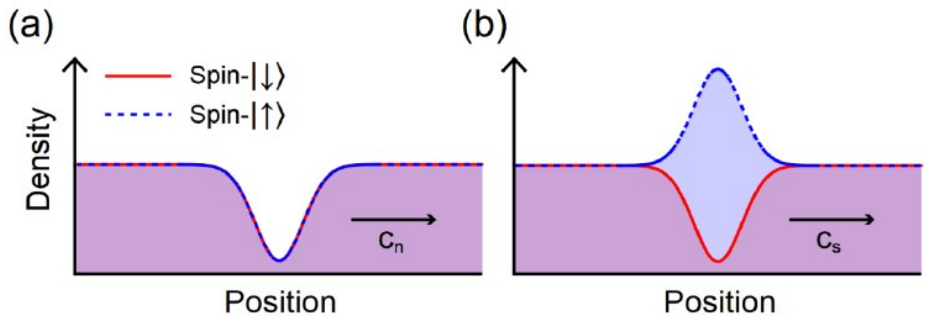
# miscible mixture, Ω=0: elementary excitations

Density

$$d(\vec{r}) = n_\uparrow(\vec{r}) + n_\downarrow(\vec{r})$$

Spin

$$s(\vec{r}) = n_\uparrow(\vec{r}) - n_\downarrow(\vec{r})$$

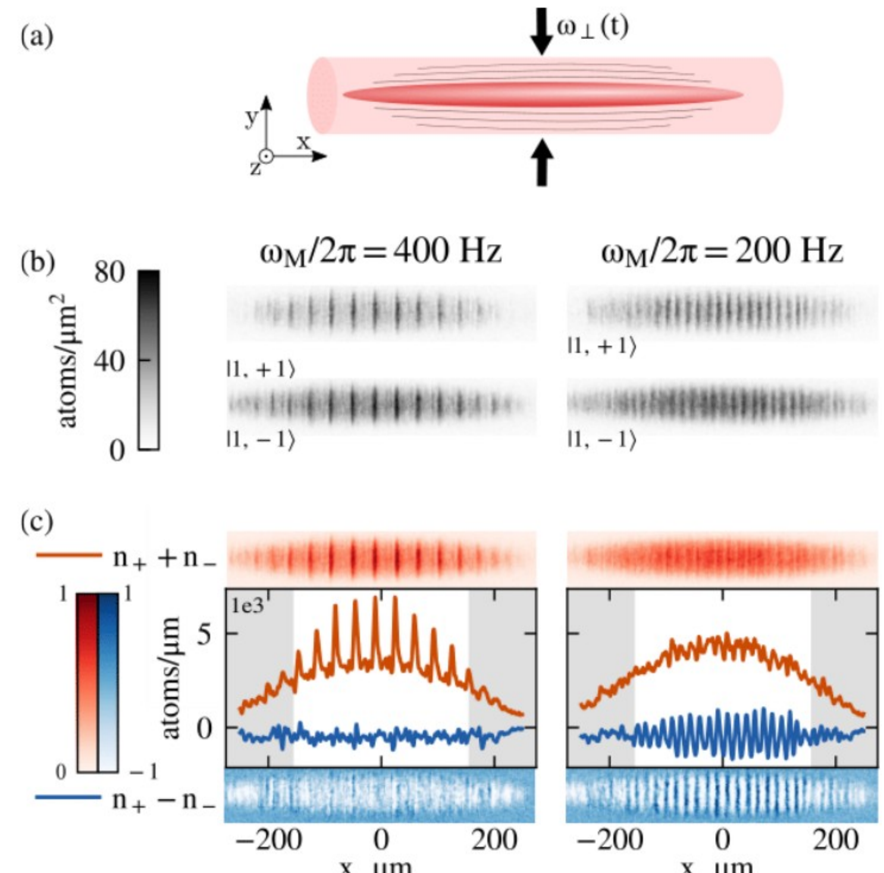



$$c_d = \frac{(g + g_{\downarrow\uparrow})n}{2m} \gg c_s = \frac{(g - g_{\downarrow\uparrow})n}{2m}$$

R. Cominotti et al., Phys. Rev. Lett. **128**, 210401 (2022)

**Faraday spectroscopy** to measure the **dispersion relations** of the normal modes:

$$\omega_{d,s}(k) = \sqrt{\frac{\hbar k^2}{2m}\left(\frac{\hbar k^2}{2m} + \frac{2mc_{d,s}^2}{\hbar}\right)}$$

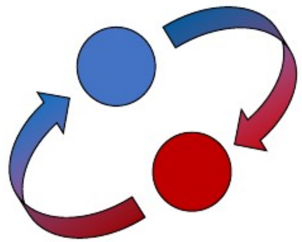


# … to Rabi-coupled spin mixtures

- U(1) symmetry

$$i\hbar\partial_t\psi_\downarrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\downarrow\downarrow}|\psi_\downarrow|^2 + g_{\downarrow\uparrow}|\psi_\uparrow|^2\right]\psi_\downarrow - \frac{\hbar\Omega_R}{2}\psi_\uparrow$$

$$i\hbar\partial_t\psi_\uparrow = \left[-\frac{\hbar^2}{2m}\nabla^2 + V + g_{\uparrow\uparrow}|\psi_\uparrow|^2 + g_{\downarrow\uparrow}|\psi_\downarrow|^2\right]\psi_\uparrow - \frac{\hbar\Omega_R}{2}\psi_\downarrow$$



$N_1$ and $N_2$ not independently conserved

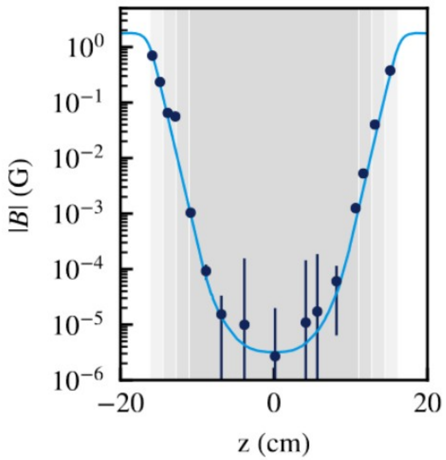
$$\delta g = \frac{g_{\downarrow\downarrow} + g_{\uparrow\uparrow}}{2} - g_{\uparrow\downarrow}$$

→ Set the relevant energy scale

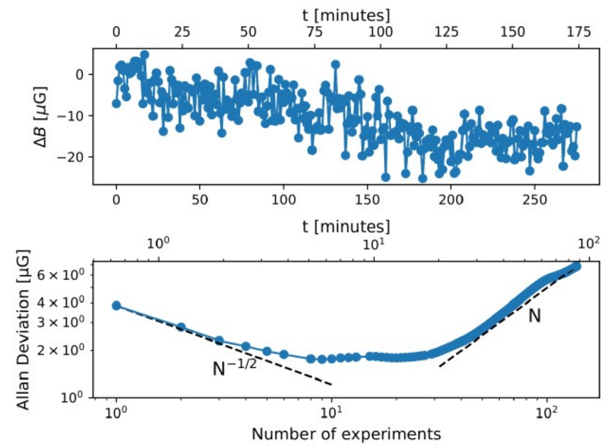
| Energy scale | $\mu_B \delta B$ | $\ll \hbar\Omega_R$ | $< \lvert\delta g\rvert\, n$ |
|---|---|---|---|
| Temperature | | | $15 \div 60$ nK |
| Frequency | 10 Hz | $100 \div 600$ Hz | $300 \div 1200$ Hz |
| Magnetic field | 5 μG | $50 \div 100$ μG | |

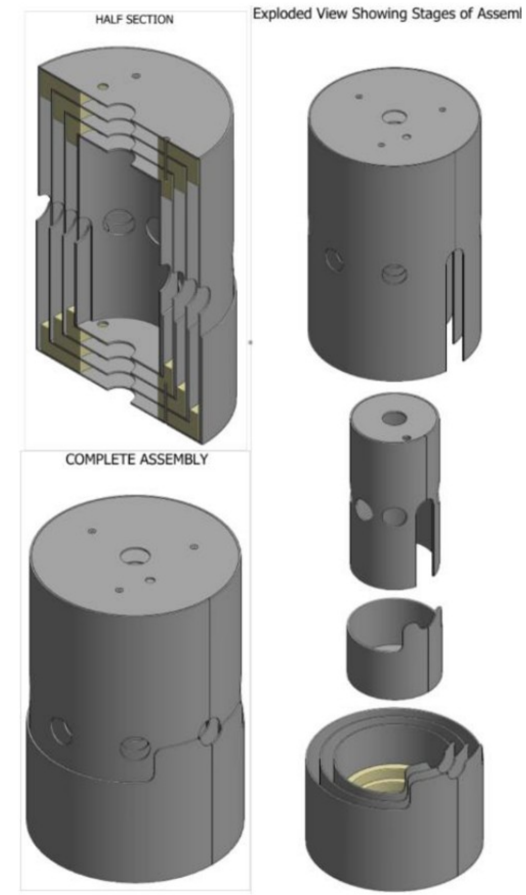
# … in a magnetically shielded environment

Fluctuation attenuation: $10^5$




B field stability: a few μG over an hour




| Energy scale | $\mu_B \delta B$ | $\ll \hbar\Omega_R$ | $< \lvert\delta g\rvert\, n$ |
|---|---|---|---|
| Temperature | | | $15 \div 60$ nK |
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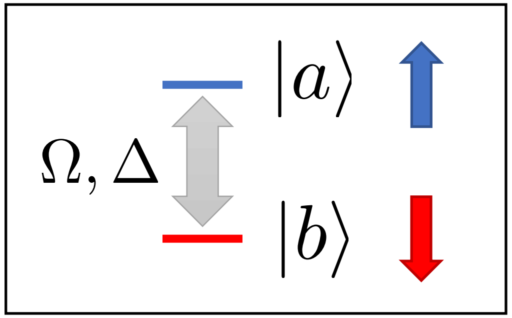
A. Farolfi, D. Trypogeorgos, G. Colzi, E. Fava, G. Lamporesi, GF
Rev. Scient. Instr. **90**, 115114 (2019)

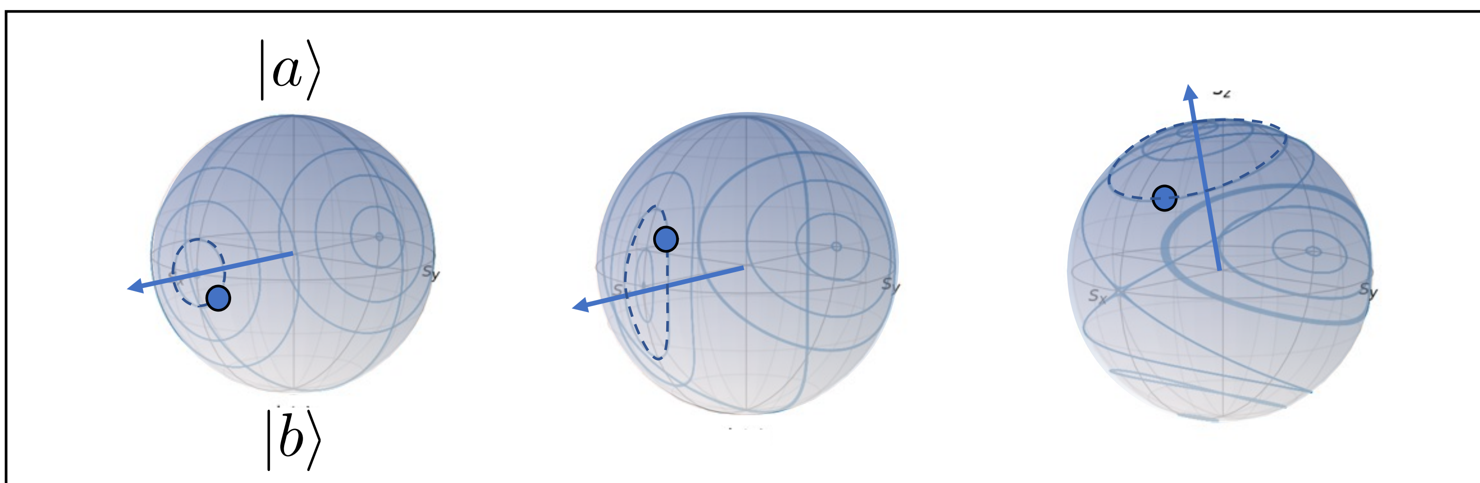
# immiscible mixture




$$i\hbar\frac{\partial}{\partial t}\psi_a = \left(-\frac{\hbar^2}{2m}\nabla^2 + V + g_a|\psi_a|^2 + g_{ab}|\psi_b|^2\right)\psi_a - \frac{\hbar\Omega}{2}\psi_b$$
$$i\hbar\frac{\partial}{\partial t}\psi_b = \left(-\frac{\hbar^2}{2m}\nabla^2 + V + g_b|\psi_b|^2 + g_{ab}|\psi_a|^2 - \hbar\Delta\right)\psi_b - \frac{\hbar\Omega^*}{2}\psi_a$$

Competition between **spin interactions** and **coupling**

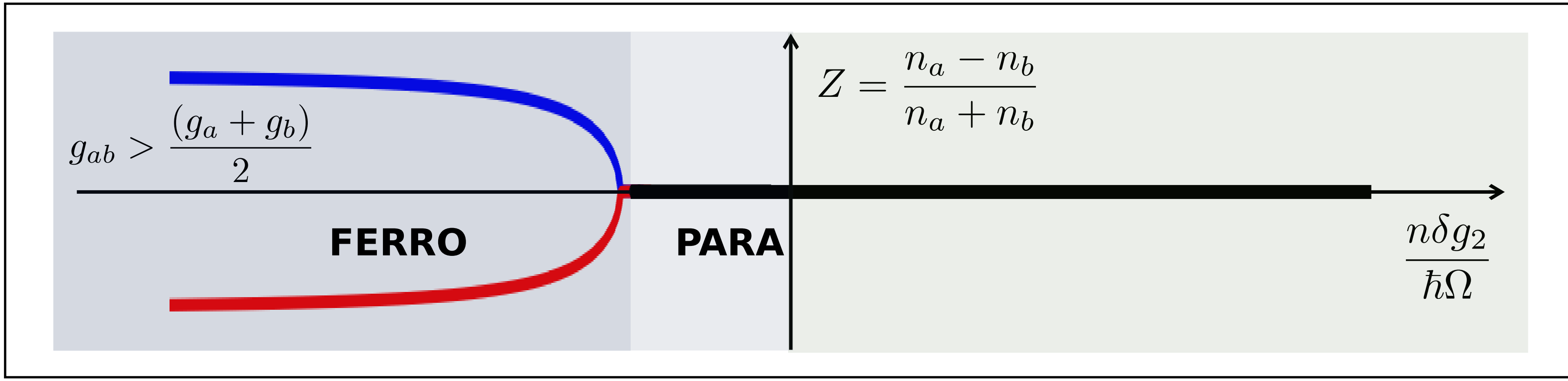
$$\mathbf{W}_{\text{eff}} = \left(\Omega, 0, \Delta - \frac{n\delta g_1}{\hbar} - \frac{n\delta g_2 Z}{\hbar}\right)$$

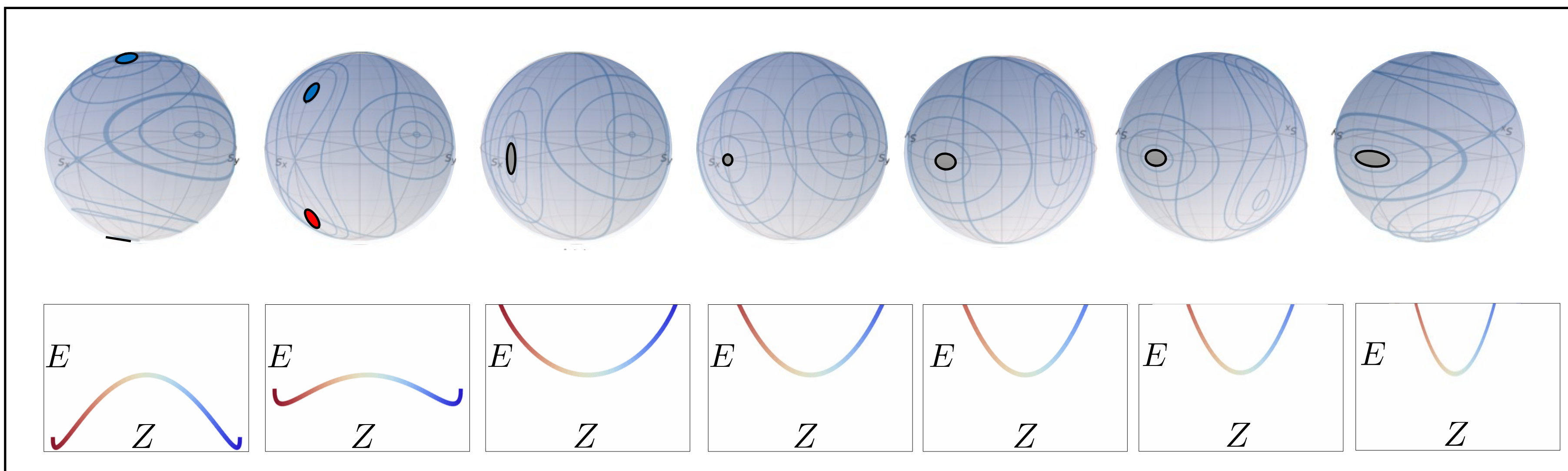



Coherent-coupling dominated ⟷ Spin-interaction dominated

## immiscible mixture

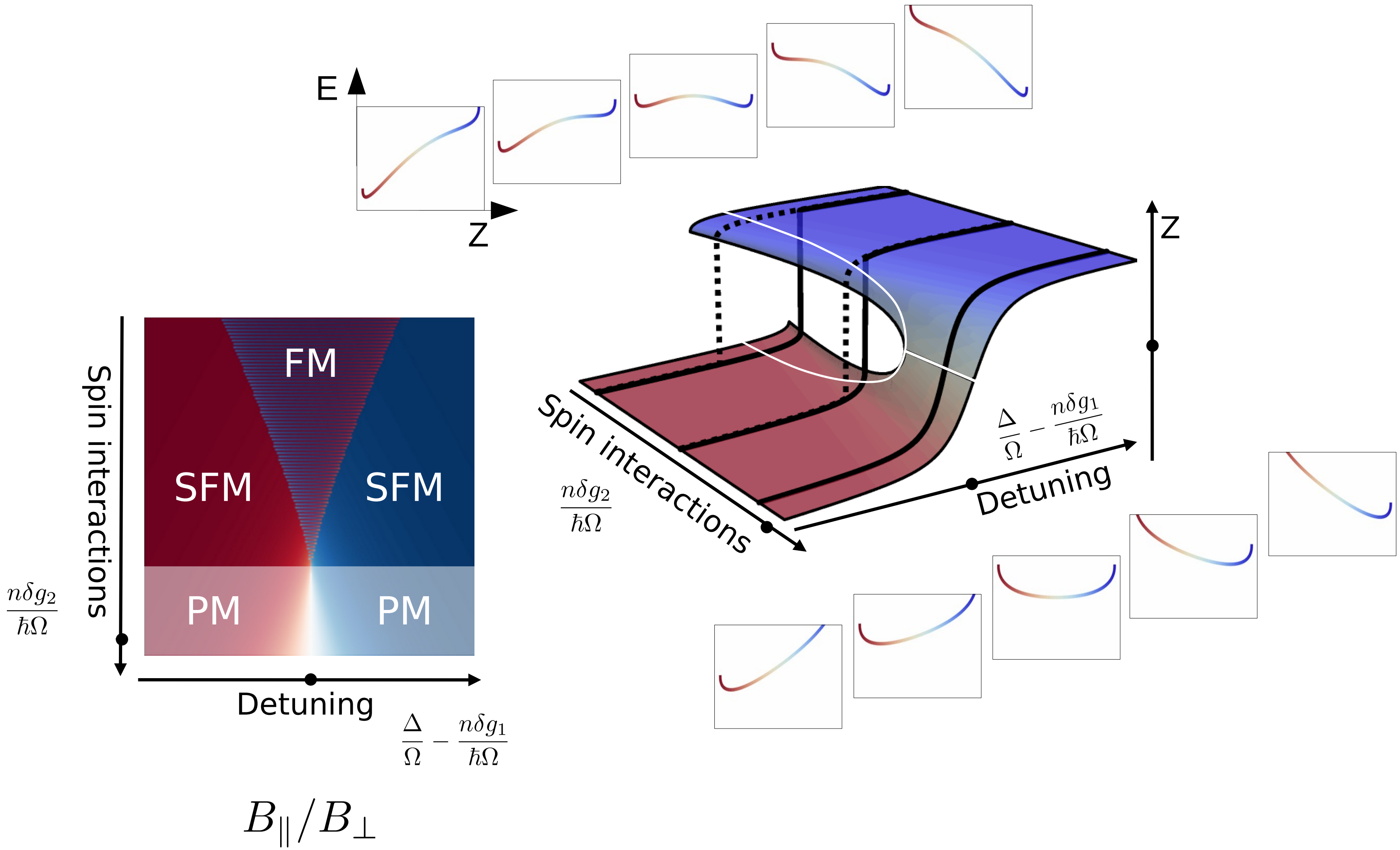
Ground state ***BIFURCATION***



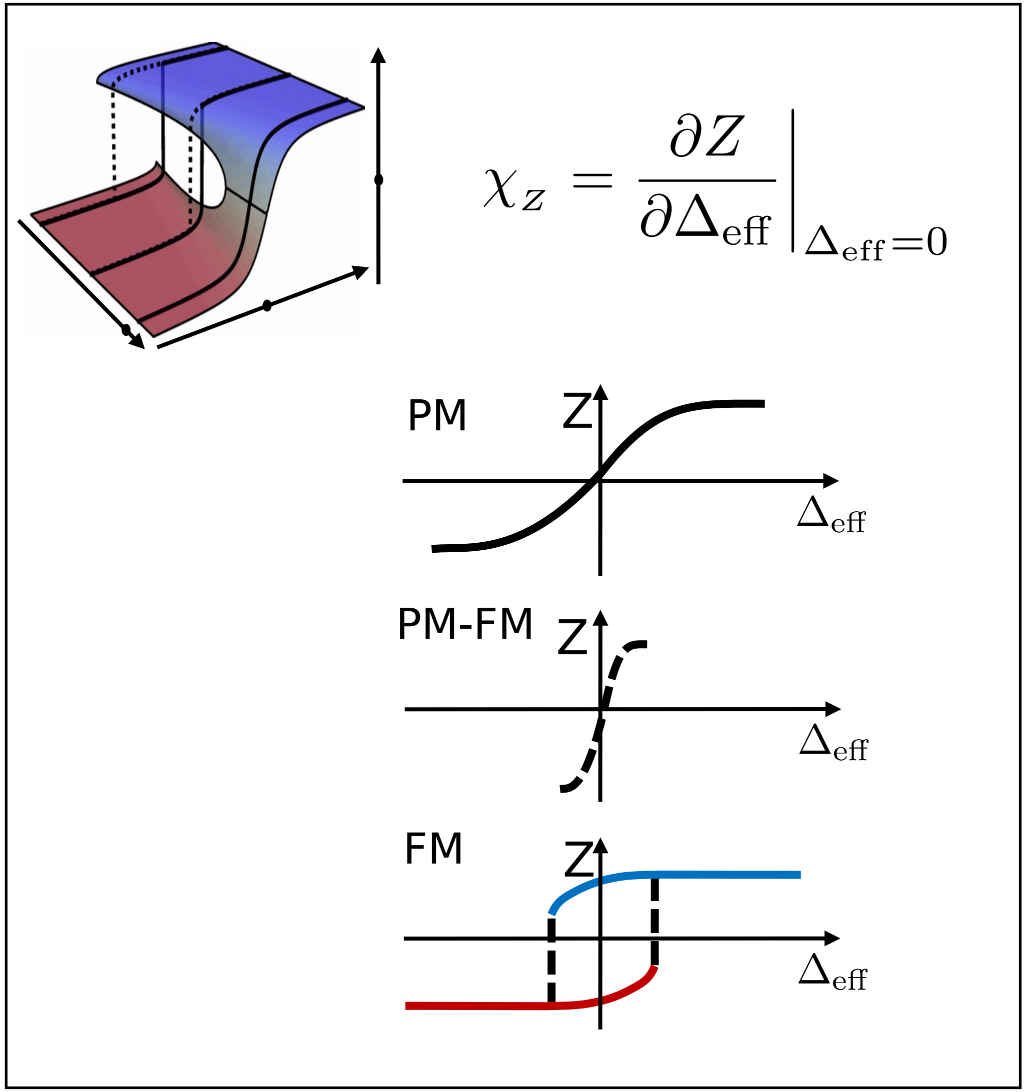

$$E(Z,\phi) \propto (n\delta g_1 - \hbar\Delta)\, Z + \frac{n\delta g_2}{2} Z^2 - \hbar\Omega\sqrt{1-Z^2}\cos\phi$$

# complete phase diagram of GS

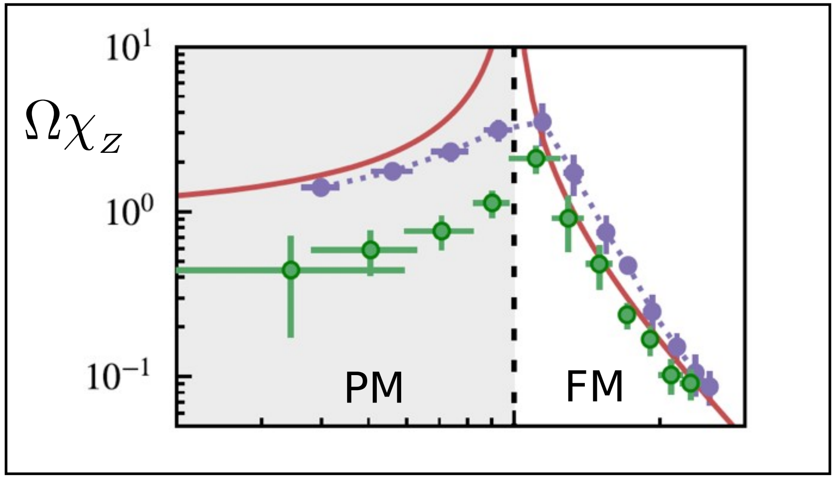



$$E(Z,\phi) \propto (n\delta g_1 - \hbar\Delta)\, Z + \frac{n\delta g_2}{2} Z^2 - \hbar\Omega\sqrt{1-Z^2}\cos\phi$$

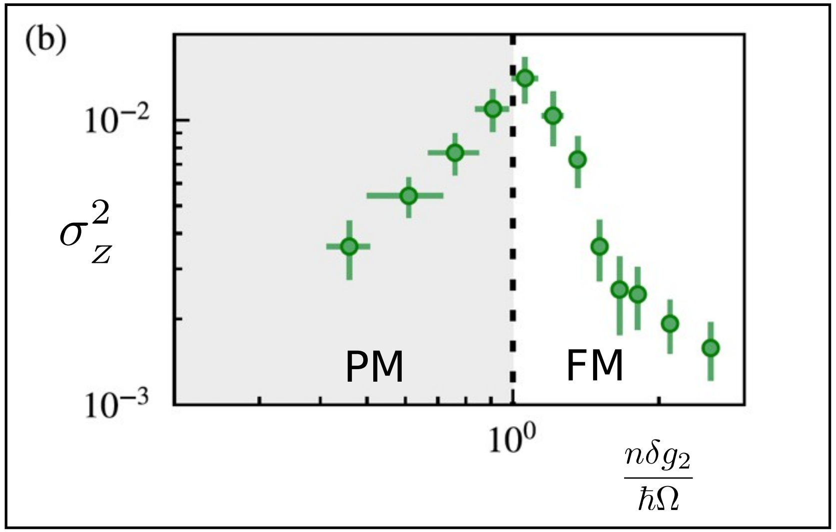
# key magnetic properties




***MAGNETIC SUSCEPTIBILITY***

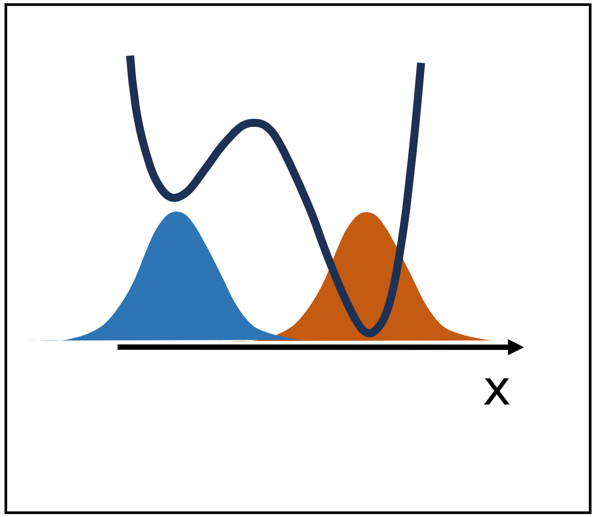



***FLUCTUATIONS OF THE MAGNETIZATION***




R. Cominotti *et al.*, PRX 13, 021037 (2023)

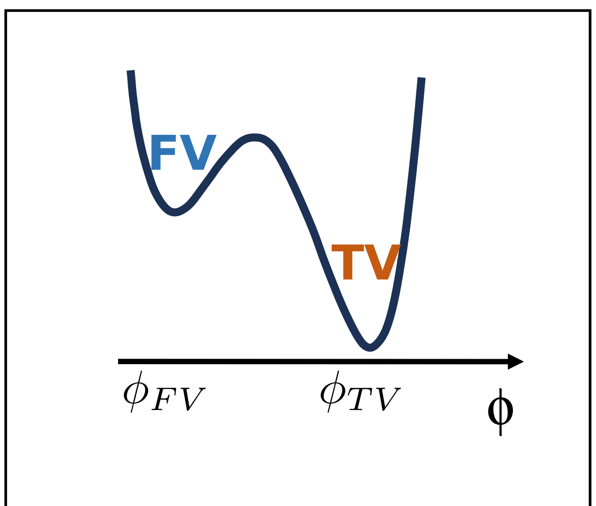
# false vacuum decay




**Single particle**

Nonuniform external potential

Single particle tunneling — *Wavefunction overlap*



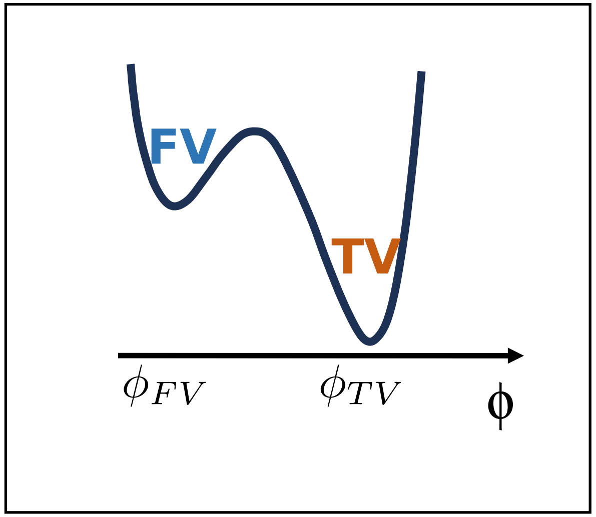

**Many-body quantum system with internal degrees of freedom**

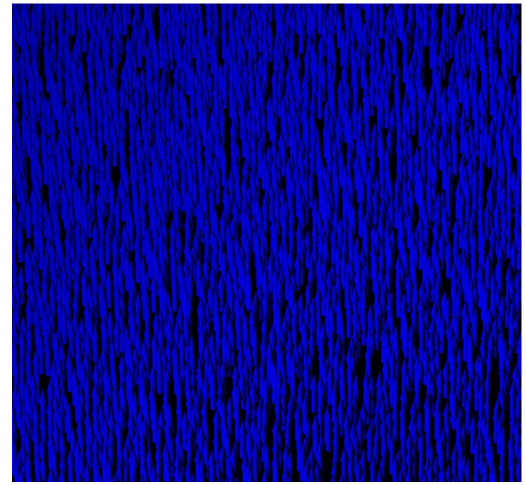
**Quantum field**

Nontrivial **energy landscape** (field internal state and orbital origin)

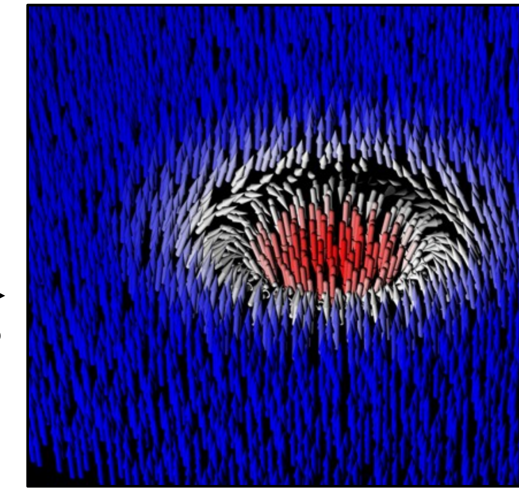
Macroscopic tunneling — *Fluctuation-driven*

# false vacuum decay

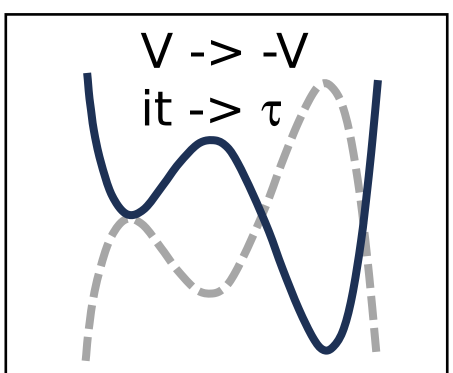


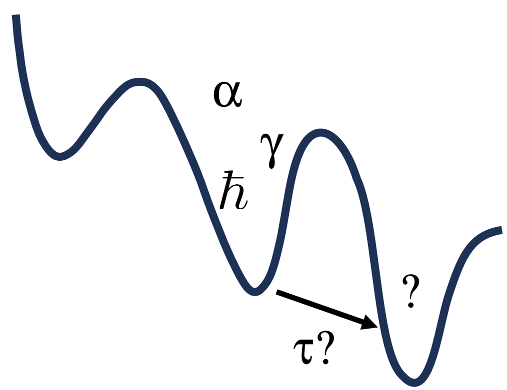



Timescale?

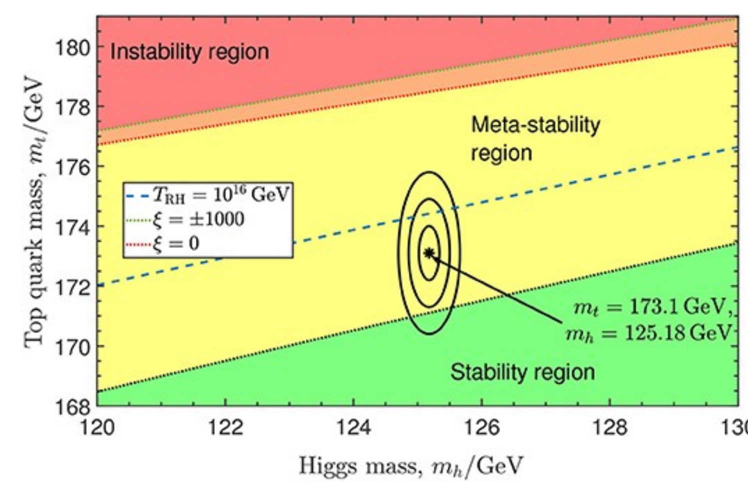


Applied to cosmological problems (Big bang , stability of universe)



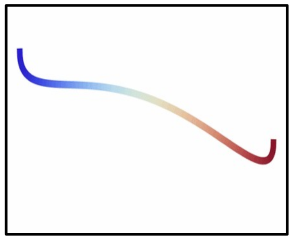

Dramatic change of physics laws



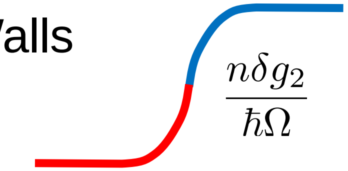

S.R. Coleman, Phys. Rev. D **15**, 2929 (1977)

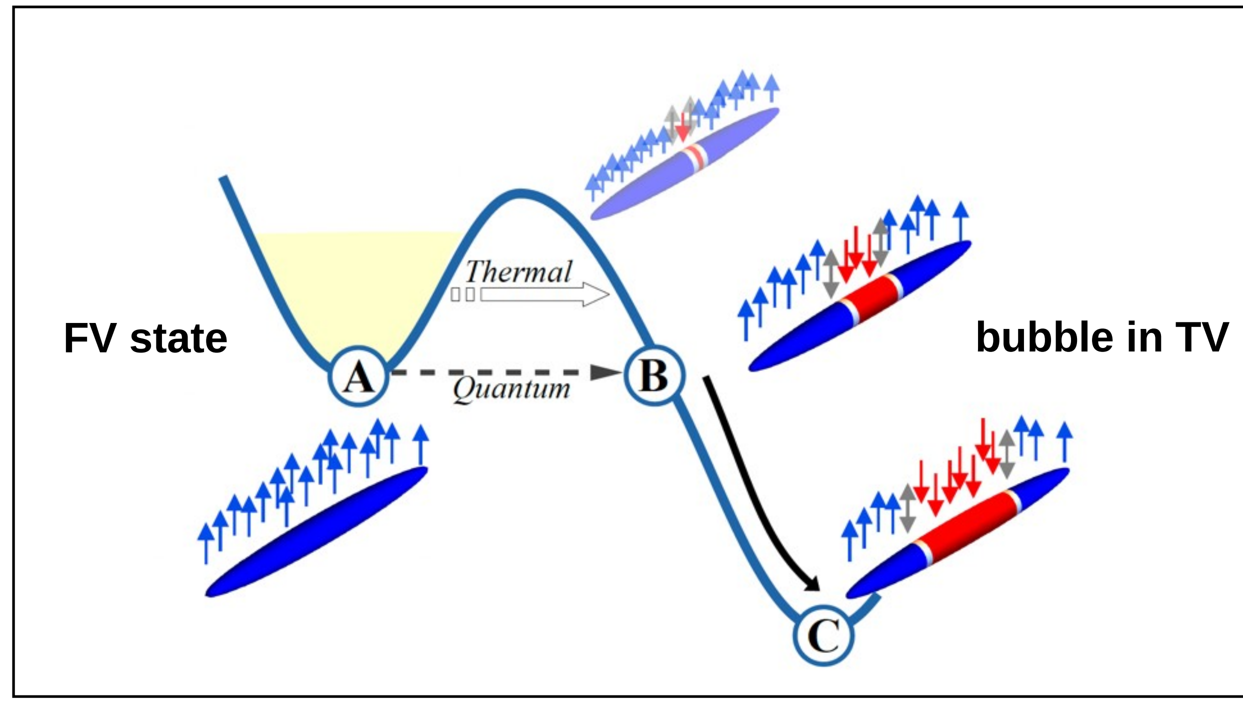
# nucleation of true vacuum bubble

Mean-field energy landscape



+ Kinetic energy cost for the Domain Walls




$k_B T$

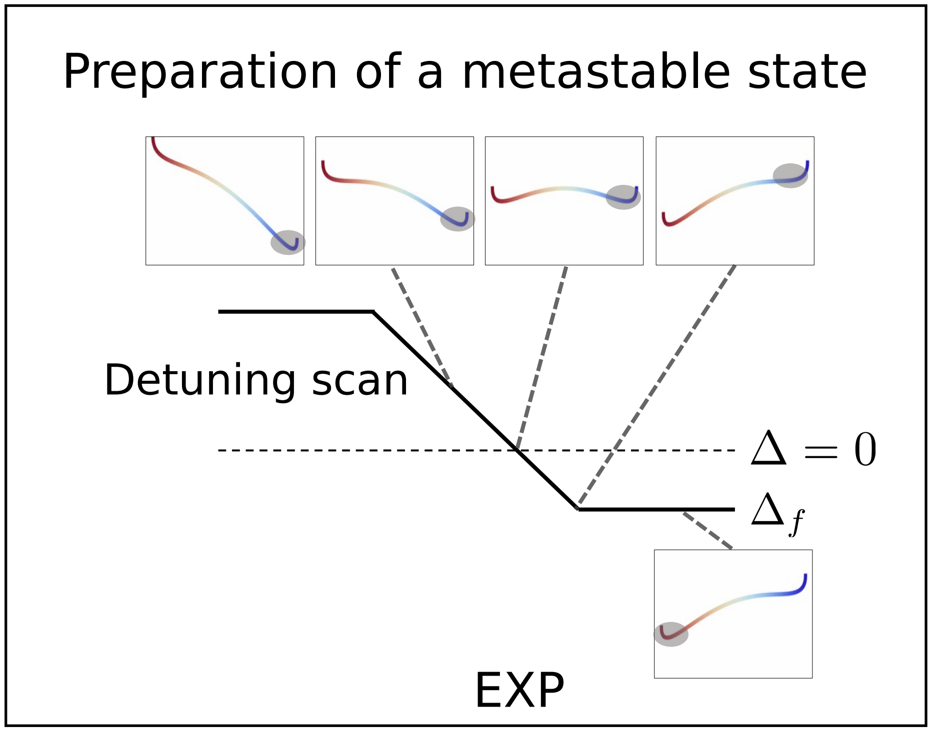
Thermal fluctuations

$n|\delta g_2|$

Quantum fluctuations

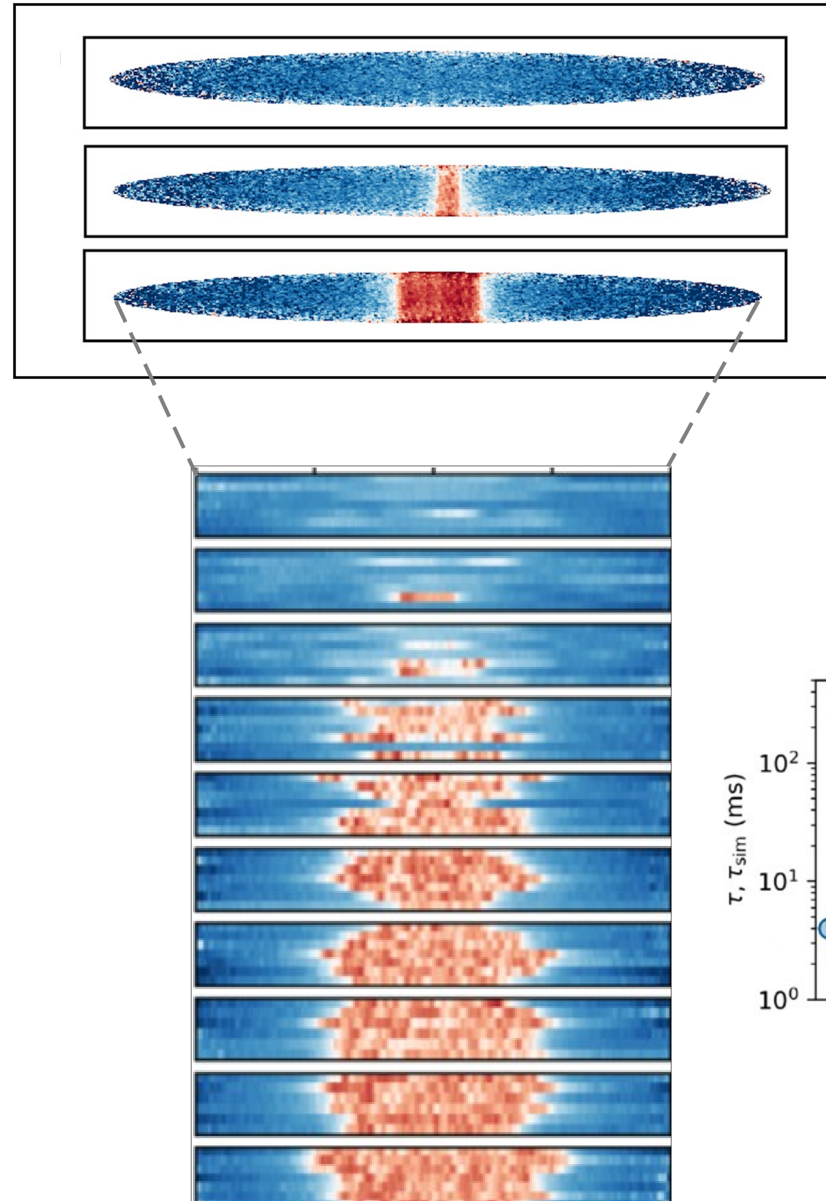
- **Many-body barrier** (NOT external potential)
- **Macroscopic tunneling** of the field (NOT single particle tunneling)
- **Thermal fluctuations** drive the tunneling

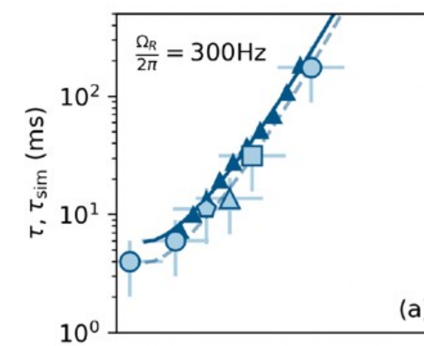
# false vacuum decay



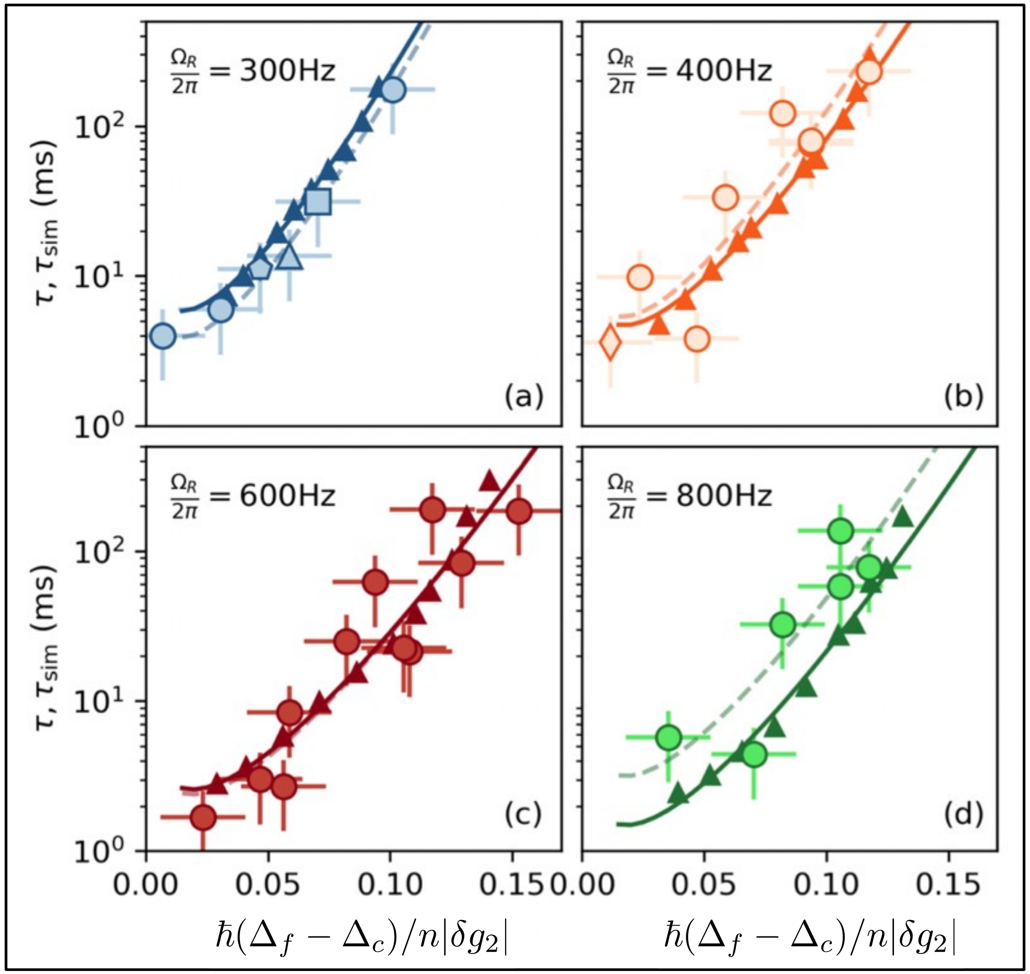

A. Zenesini et al., Nat. Phys. 20, 558 (2024)

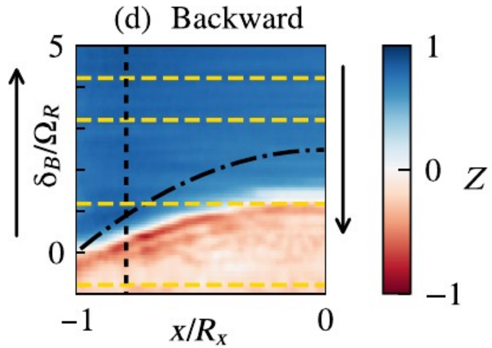
EXPERIMENT





# scaling of the bubble nucleation time




Comparison between

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

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

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

Large range on τ (2 – 200 ms)

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

# Stato attuale e obiettivi

**Dove siamo**

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

**Obiettivi**

- Estendere al caso 2D, validae simulazioni numeriche (non esistono modelli analitici).
- Intrappolamento in potenziale omogeneo 1D e 2D → nucleazione simultanea di più bolle.
- Studio di eccitazioni topologiche generate a seguito della fusione di bolle.

# Milestones TIFPA

**Milestones 2025**

- Implementazione del setup ottico per la manipolazione coerente dei gradi di liberta' di spin con risoluzione spaziale.
- Decadimento di falso vuoto a temperatura finita, gas 1 dimensionale.

**Milestones successive**

- Studio della dinamica di crescita e di interazione tra domini di magnetizzazione.
- Studio di eccitazioni topologiche generate a seguito della fusione di domini di magnetizzazione.
- Realizzazione di una trappola ottica omogenea 1D.
- Realizzazione di una trappola ottica 2D.
- Decadimento di falso vuoto in sistemi 1D omogenei.
- Decadimento di falso vuoto in sistemi 2D omogenei.

# Milestones Firenze

**Milestones 2025**

- Implementazione del setup ottico per la manipolazione coerente dei gradi di liberta' di spin con risoluzione spaziale.
- Decadimento di falso vuoto a temperatura finita, gas 1 dimensionale.

**Milestones successive**

- Coefficienti di mutual friction tra vortici in funzione della temperatura,
- Coefficienti di mutual friction in funzione dello sbilanciamento in popolazione di spin,
- Studio dell’interazione vortici-suono,
- Studio dell’interazione vortici-suono in funzione della temperatura.

# Ricercatori coinvolti

**TIFPA:**

| | | |
|---|---|---|
| Gabriele Ferrari | prof UNITN | 50% |
| Giacomo Lamporesi | staff CNR-INO | 30% |
| Alessandro Zenesini | staff CNR-INO | 30% |
| Iacopo Carusotto | staff CNR-INO | 20% |
| Alessio Recati | staff CNR-INO | 20% |
| Cosetta Baroni | postdoc CNR-INO | 50% |
| Riccardo Cominotti | postdoc CNR-INO | 50% |
| Chiara Rogora | dottoranda UniTN | 50% |
| Diego Andreoni | dottorando UniTN | 50% |
| | **Totale: 9 pesone,** | **3.5 FTE** |

**Firenze:**

| | | |
|---|---|---|
| Giacomo Roati, PI | staff CNR-INO | 30% |
| Giulia Del Pace | RTDA UniFI | 50% |
| Marcia Frometa | assegnista CNR-INO | 50% |
| Diego Hernandez Rajkov | dottorando LENS | 50% |
| Nicola Grani | dottorando UniFI | 50% |
| | **Totale: 5 pesone,** | **2.3 FTE** |

# Richieste 2025

| | |
|---|---|
| • Manutenzione e trasporti: riparazione sorgenti laser HP | 30.5k€ |
| • Consumo:<br>- alimentatori di corrente bipolari alta stabilità<br>- fibre ottiche PM luce visibile<br>- fibre ottiche PCF alta potenza IR<br>- amplificatori e minuteria microonda<br>- adattatore di impedenza microonda | 61k€ |
| • Missioni: collaborazione + nazionali + internazionali | 15k€ (TIFPA + FI) |
| • Pubblicazioni open access: | 9k€ (TIFPA + FI) |