Luciano Girardello Memorial

Milano Bicocca --16 January 2023

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- **Luciano has been my master thesis and PhD advisor (in Bicocca from 2004)**
- **Mentor for physics and science**
- **Luciano has been inspirational for a generation of "young" physicists**
- **We all remember his fascinating (and very soft) QFT lectures**
- **Many quotes of him that we still remember:**

  "No emotional comments", "Non danno premi Nobel a caso", ...

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- **Grateful to Luciano for his guiding and mentoring, Luciano guided me to supersymmetry and supergravity**
- **Passion for dynamical SUSY breaking**
- **Luciano: "Look at this paper (ISS '06), it is very interesting"**
- **Last years of scientific publications of Luciano with Antonio Amariti, Davide Forcella, Massimo Siani, Gabriele Tartaglino-Mazzucchelli ...**

The role of impurities in cosmological first order phase transitions

Alberto Mariotti

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Based on arXiv:2203.16450 (Phys. Rev. Lett. 129 (2022) 26, 261303)
with Simone Blasi

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Why cosmological first order PT?

★*Probe of Early Universe cosmology*

★*In the Standard Model, QCD and EW PT are not first order*

First Order Phase Transition would be signal of BSM physics

- ✳ *First order EW PT can lead to electroweak baryogenesis* → New physics in Higgs sector
- ✳ *New first order PT in dark matter sectors*
- ✳ *FOPT are powerful sources of stochastic GW signal*

FOPT proceeds through bubble formation

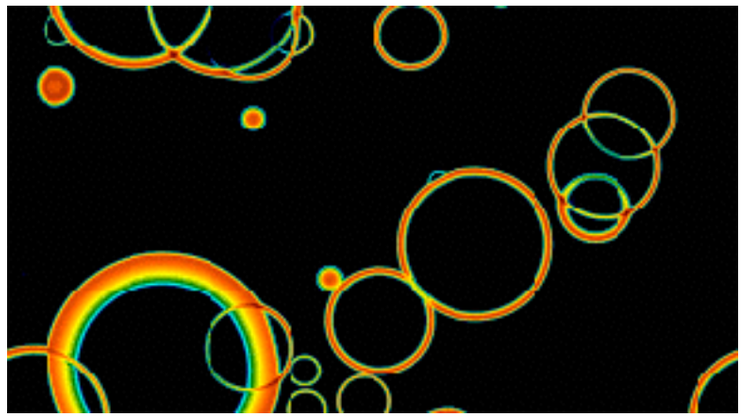


fig. from arXiv:1705.01783 D. Weir

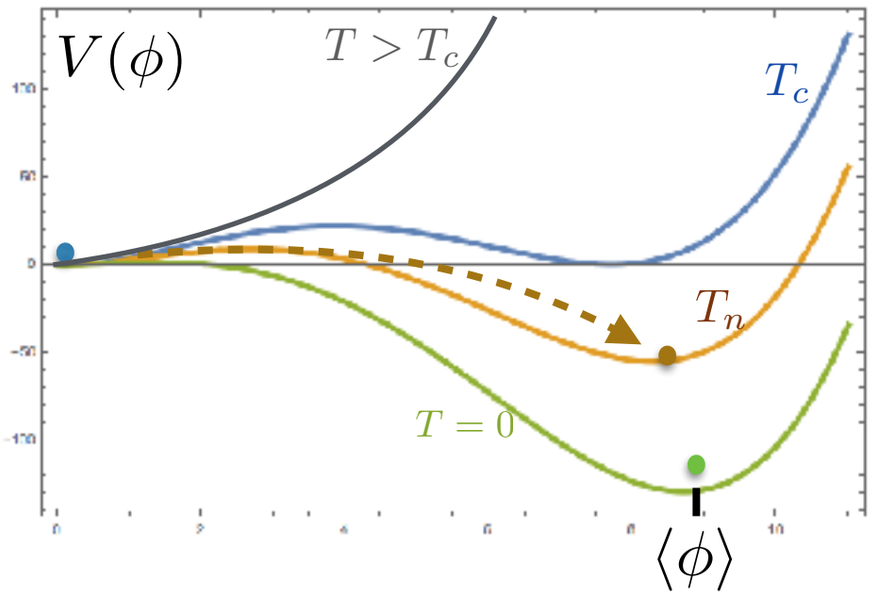
Target for current and future GW experiments

- ✦ *Ligo Virgo Kagra*
- ✦ *NANOGrav*
- ✦ *LISA*
- ✦ *Einstein Telescope*
- ✦ *Cosmic explorer*

First order phase transition

★***First Order Phase transition (FOPT) proceeds with bubble nucleation***

★***Nucleation condition in homogeneous Universe***



✳ ***Phase transition described by effective potential***

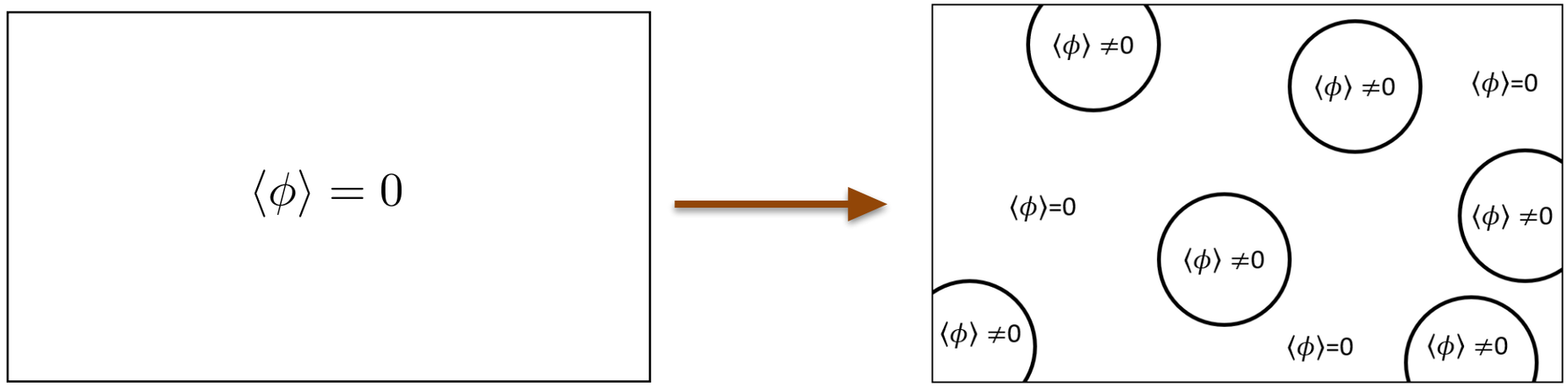
✳ ***Thermal fluctuation induces nucleation of bubbles***

✳ ***Nucleation rate/volume set by O(3) bounce action***

$$\gamma_V(T) \sim T^4 e^{-S_3(T)/T}$$

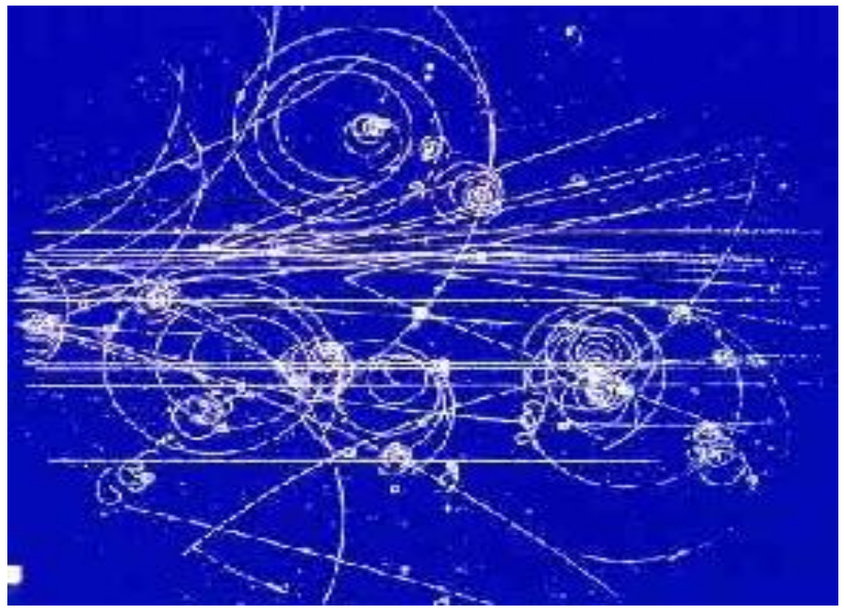
✳ ***Nucleation condition sets nucleation temperature*** $\gamma_V(T_n) \sim H(T_n)^4$

Homogeneous Universe in false vacuum



... however ... impurities

★***Impurities drastically modify the nucleation process***

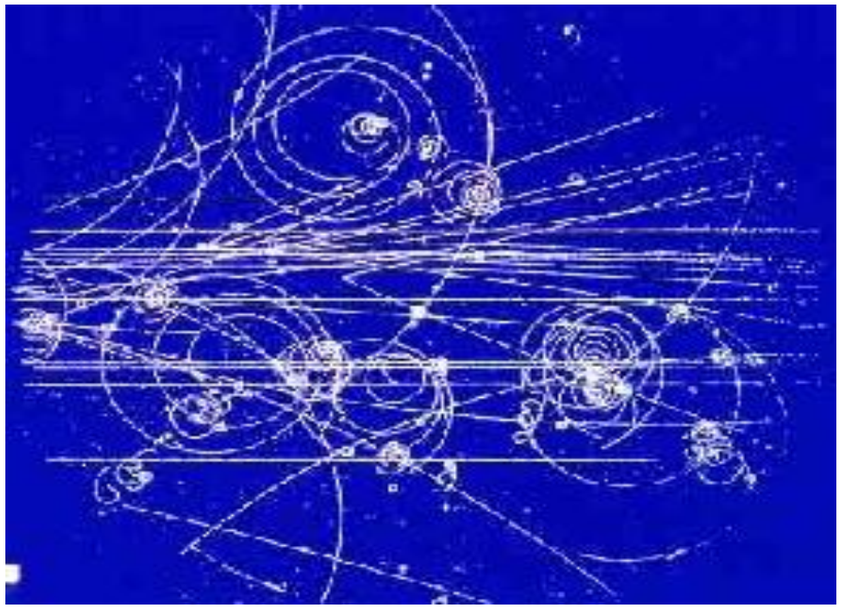


... however ... impurities

★*Impurities drastically modify the nucleation process*

... also in cosmological phase transitions ...

- ✳ "Monopole and Vortex dissociation and decay of the false vacuum" *Steinhardt 1981*
- ✳ "Impurities in the Early Universe" *Hosotani 1982*
- ✳ "Cosmic separation of phases" *Witten 1984*
- ✳ "Phase transitions induced by cosmic strings" *Yajnik 1986*



★*The nature of impurities for cosmological PT*

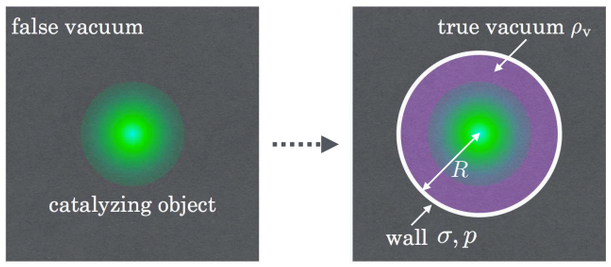
✳ **High energy collisions**

E.g. Affleck, De Luccia '79, --- Selivanov,Voloshin '85, --- Kuznetsov, Tinyakov '97 --- Strumia '23

✳ **Compact objects like BH, gravitational effects**

E.g. Hiscock '87, -- Gregory, Moss, Withers '14, -- Grinstein, Murphy '15, -- El-Menoufi, Huber, Manuel '20, Balkin et al '21, Strumia '22

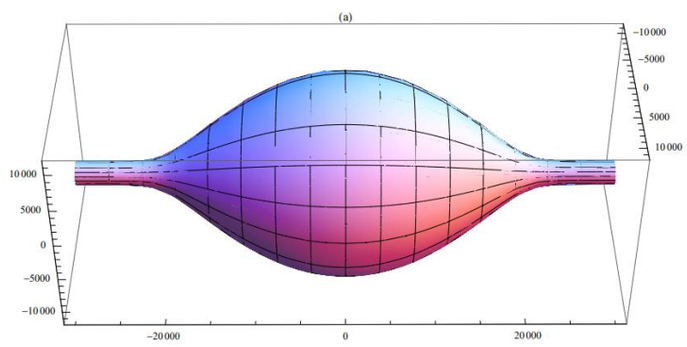
Fig. from Oshita et al.1808.01382



✳ ***Topological defects*** **(strings, monopoles ...)**

E.g. Steinhardt '81, Hosotani '82, Witten '84, Yajnik '86, Preskill Vilenkin '92, --- Kumar et at '10, -- Agrawal, Nee '22

Fig. from Lee et al.1310.3005



Why Topological defects as impurities

★***What is the origin of the topological defects?***

★***Remnants of PT depending on vacuum manifold topology*** ***[Zel'dovich et al. '74, Kibble '76]***

Defect	Dimension	Homotopy
Domain walls	2	$\pi_0(M)$
Strings	1	$\pi_1(M)$
Monopoles	Point-like	$\pi_2(M)$

Their dynamics can source gravitational waves

★***They can be present if EW symmetry breaking is final step of a multi-step breaking of larger symmetry group***

Typical in unified theories

Can the EW phase transition occur through impurities?

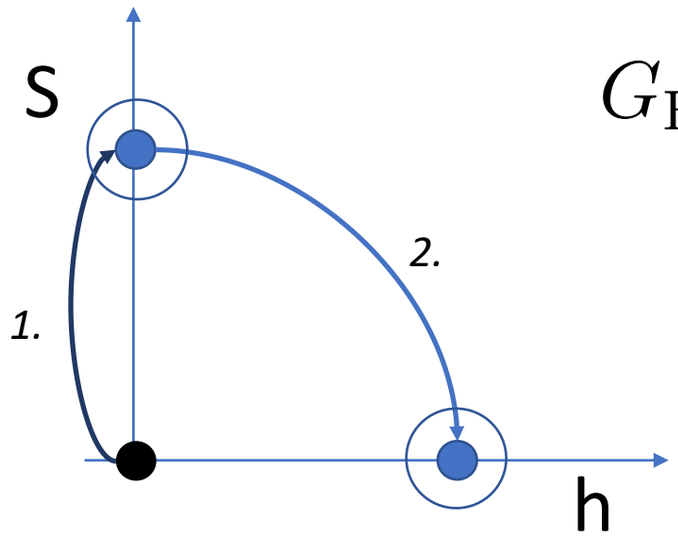
Minimal realization of seeded EW via topological defects?

Blasi, AM 2203.16450

Simplest model for EW FOPT

★***Higgs (h) plus Singlet S with a*** $\mathbb{Z}_2 : S \to -S$

★***The electroweak phase transition occurs in two steps***



$$G_{\rm EW} \times \mathbb{Z}_2 \xrightarrow[\textbf{1.}]{} G_{\rm EW} \xrightarrow[\textbf{2.}]{} U(1)_{\rm em} \times \mathbb{Z}_2$$

★***Many pheno studies on Higgs Singlet EWPT***

- ✳ **Simplest new physics scenario with strong EW FOPT**
  [Espinosa, Konstandin, Riva 1107.5441]
- ✳ **Minimal mechanism for EW baryogenesis**
  [Espinosa, Gripaios, Konstandin, Riva 1110.2876]
- ✳ **Benchmark for gravitational wave signals**
  [Caprini et al 1512.06239]
- ✳ **Singlet is challenging to detect at colliders**
  [Curtin, Meade, Yu 1409.0005]

✦ ***Order 1000 papers on this model in last 10 years***

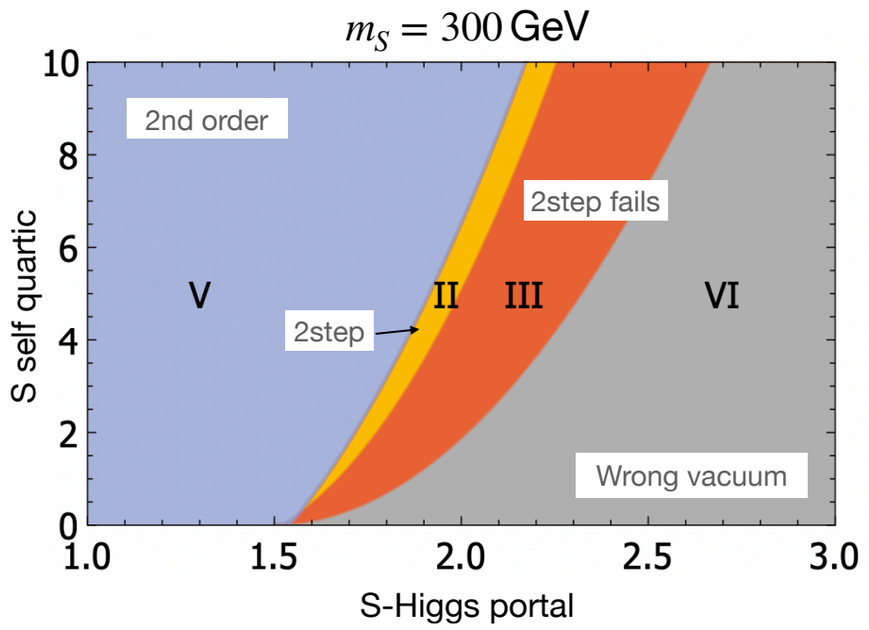
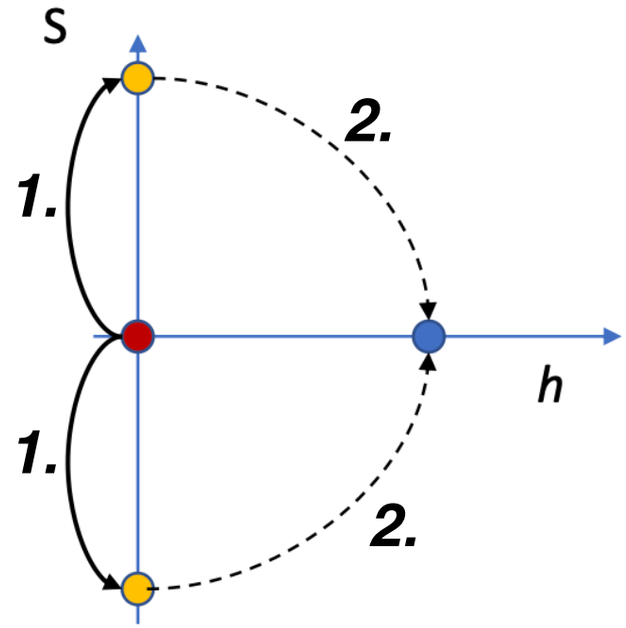


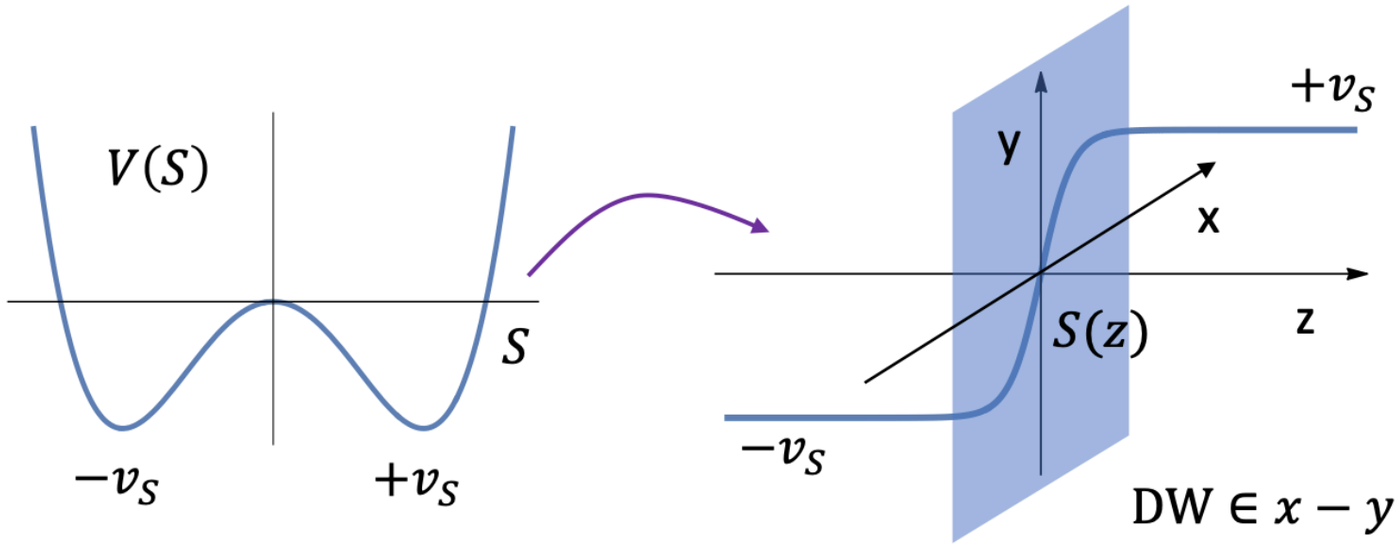
Fig. adapted from Kurup, Perelstein [1704.03381] PRD

... but ...

★***Domain walls are formed in first step!***

- ✳ **Disconnected vacuum manifold after first step**
- ✳ **Walls are formed at boundaries between different domains**





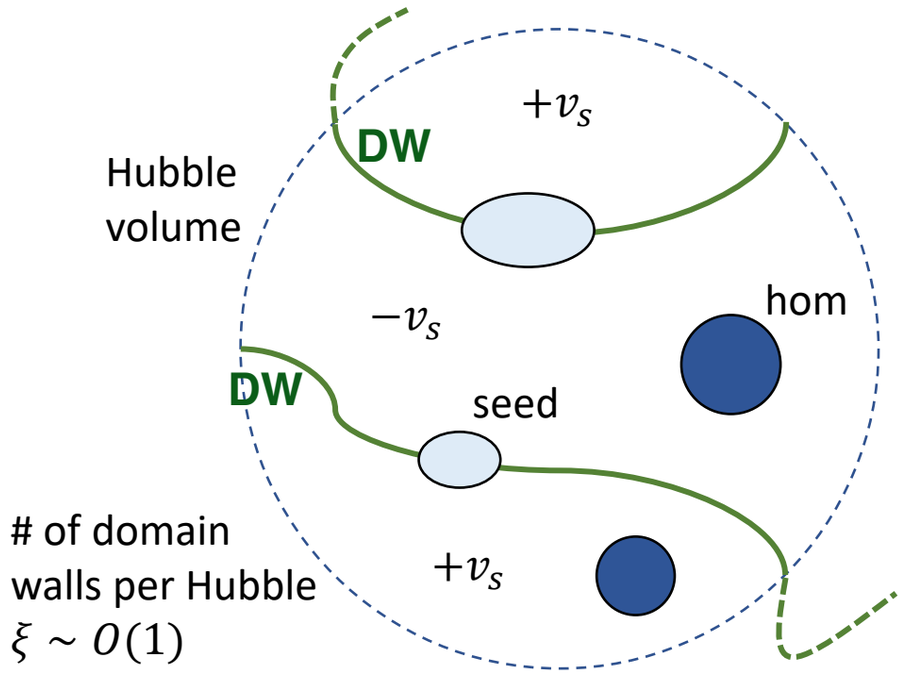
★***They can act as seed for the second step of the PT, when EW symmetry is broken***

Minimal realization of seeded EW phase transition

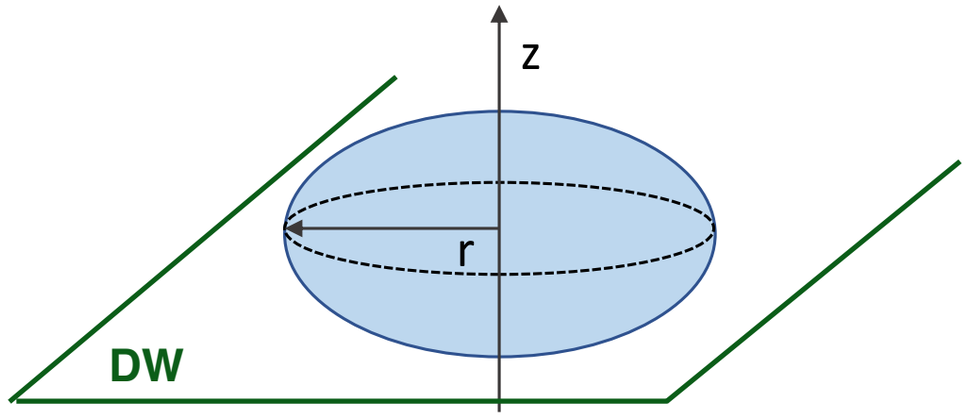
Seeded vs homogeneous nucleation

Blasi, AM 2203.16450

★*Nucleation probability enhanced at the DW location*



Geometry of seeded critical bubble



O(2) symmetry on the DW plane

✳ ***Nucleation rate/surface set by O(2) bounce action***

$$\gamma_S \sim T^3 e^{-S_2/T}$$

✳ ***Seeded nucleation condition***

$$\xi \gamma_S \sim H^3$$

Seeded vs homogeneous nucleation

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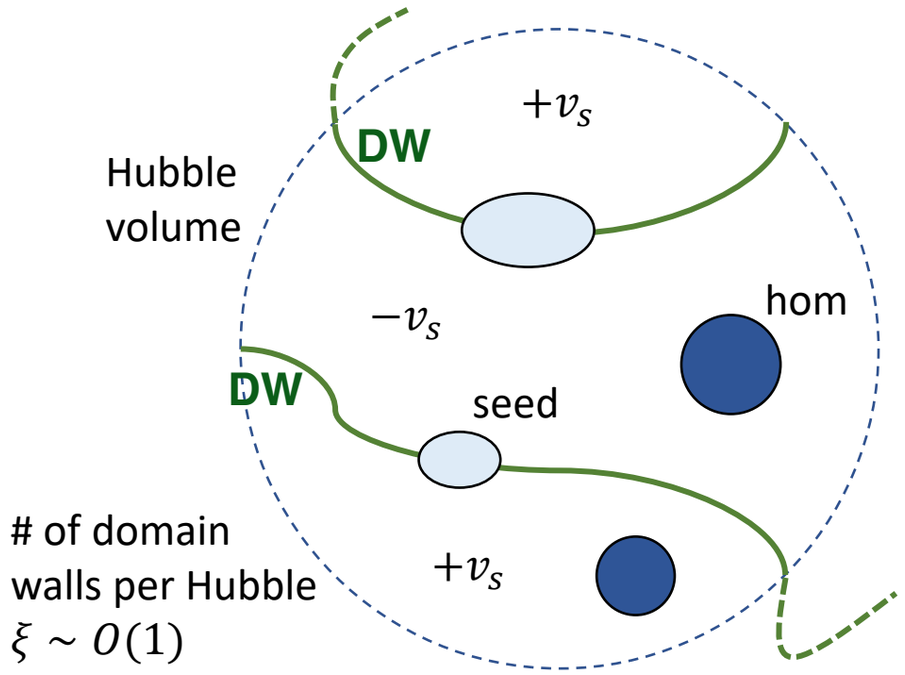

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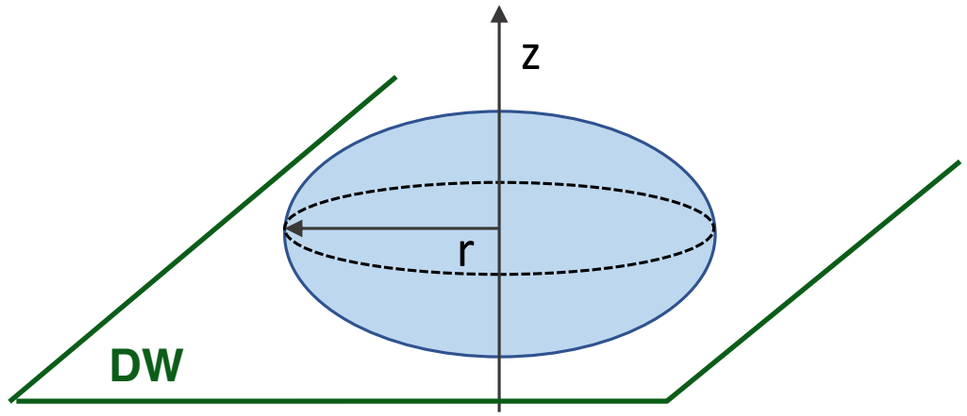

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✦ **Bounce action for the O(2) symmetric seeded bubble**

✦ ***How to compute it?***

Thin wall approximation

Blasi, AM 2203.16450

★Thin wall approximation to estimate energy of critical bubble

As in Homogeneous PT

Gain of eating DW inside bubble

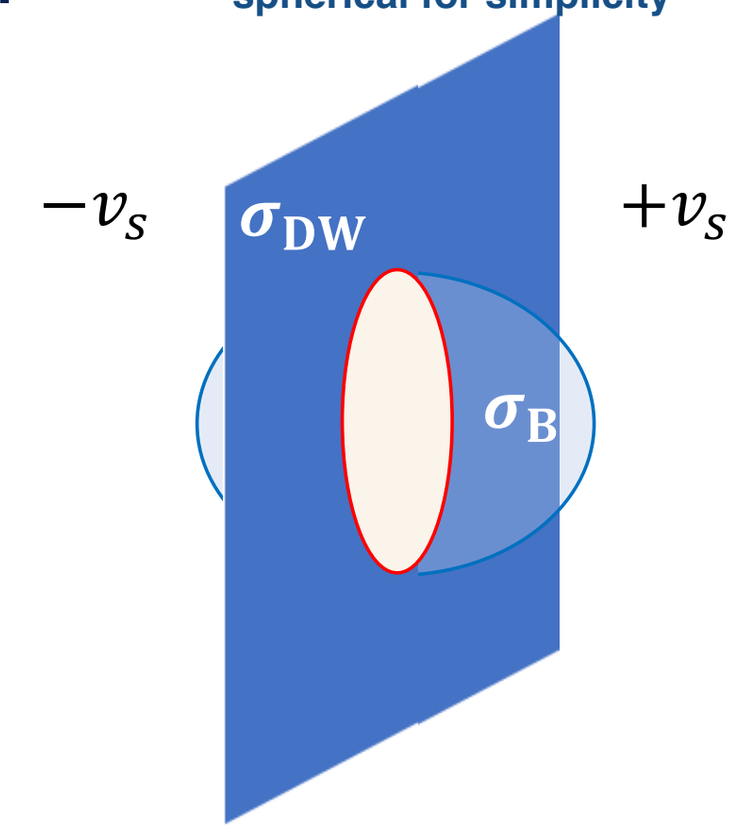
$$E(R) \simeq 4\pi R^2 \sigma_B - \frac{4}{3}\pi R^3 \Delta V - \pi R^2 \sigma_{\rm DW}$$

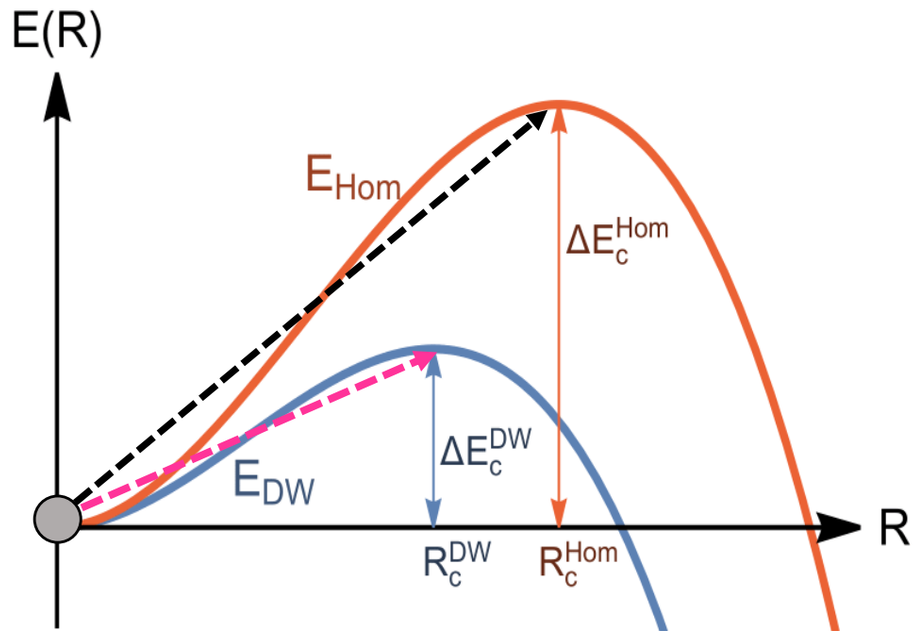
Surface tension of the bubble

Potential energy difference

Tension of the DW

Assume bubble on DW O(3) spherical for simplicity





★*Domain walls catalyze phase transition*

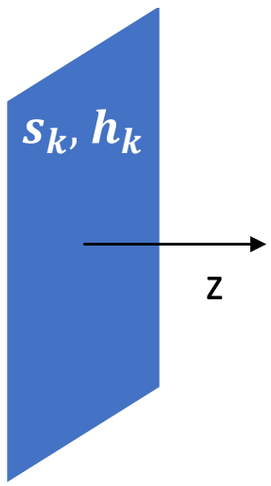
$$\text{Rate} \sim e^{-\Delta E/T}$$

Kaluza Klein reduction method

Blasi, AM 2203.16450

★Study 3-dimensional theory on the domain wall

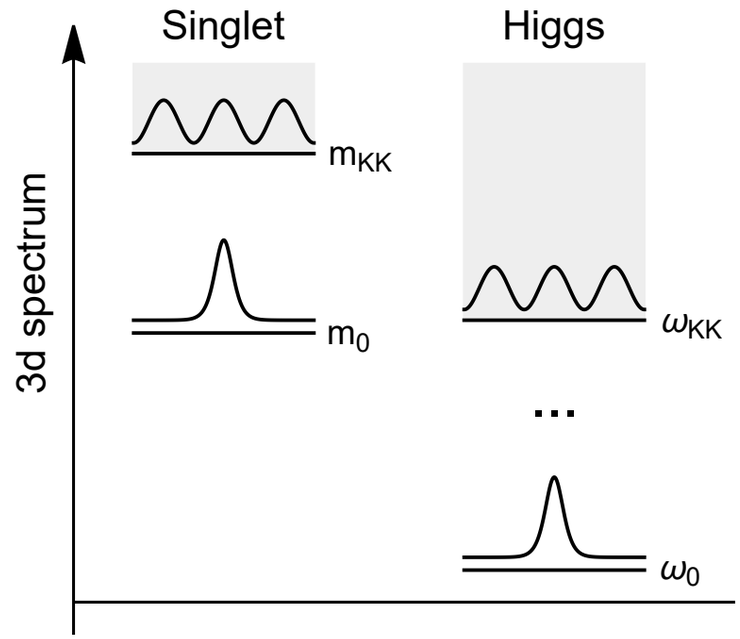
- ✳ KK spectrum contains massive localized states gapped to a continuum
- ✳ Bound states correspond to localized profiles in the z-direction
- ✳ Scattering states correspond to continuum



$$S = S_{\mathrm{DW}}(z) + \sum_k s_k(x_\mu)\sigma_k(z)$$

$$h = \sum_k h_k(x_\mu)\phi_k(z)$$

$$x_\mu = t, x, y$$



✦ *Metastability of DW controlled by the 3d h mass*

$\omega_0^2(T) < 0$ **Classical instability of DW**

$\omega_0^2(T) > 0$ **Classically stable DW**
Seeded Tunnelling at T<Tc

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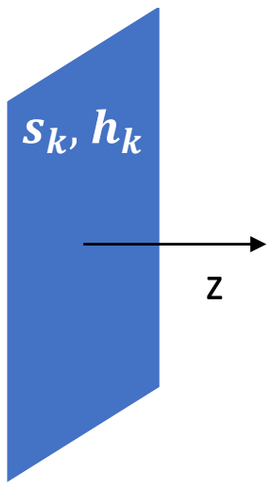

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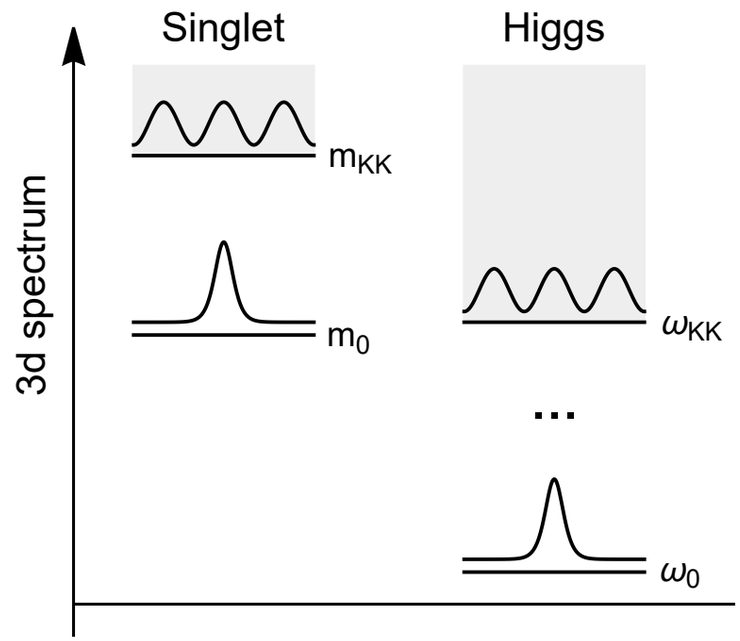

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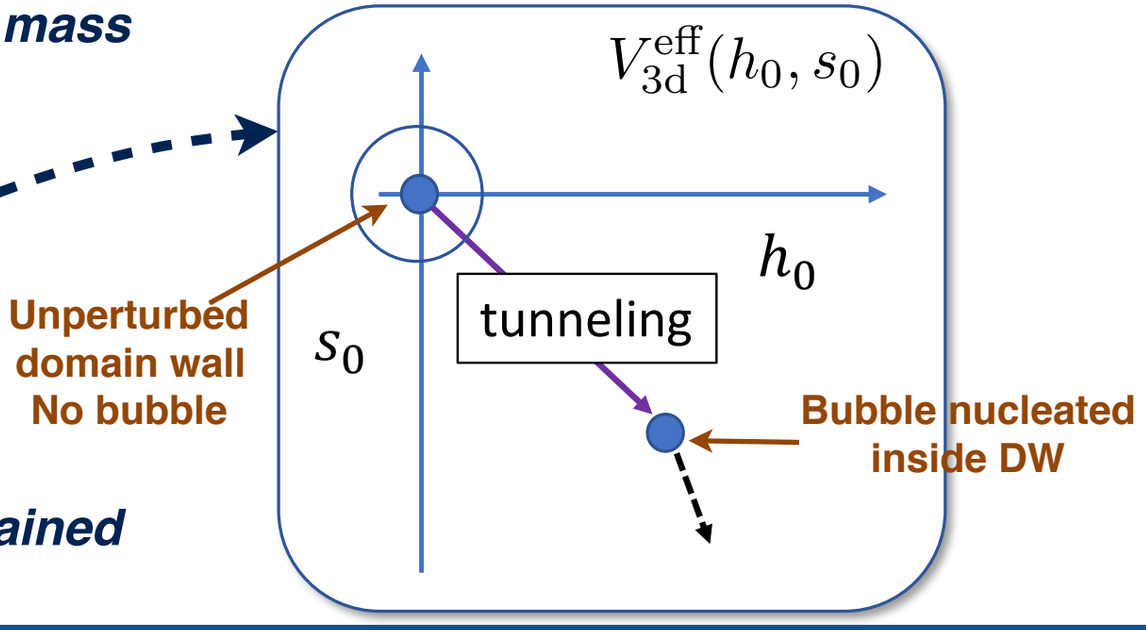
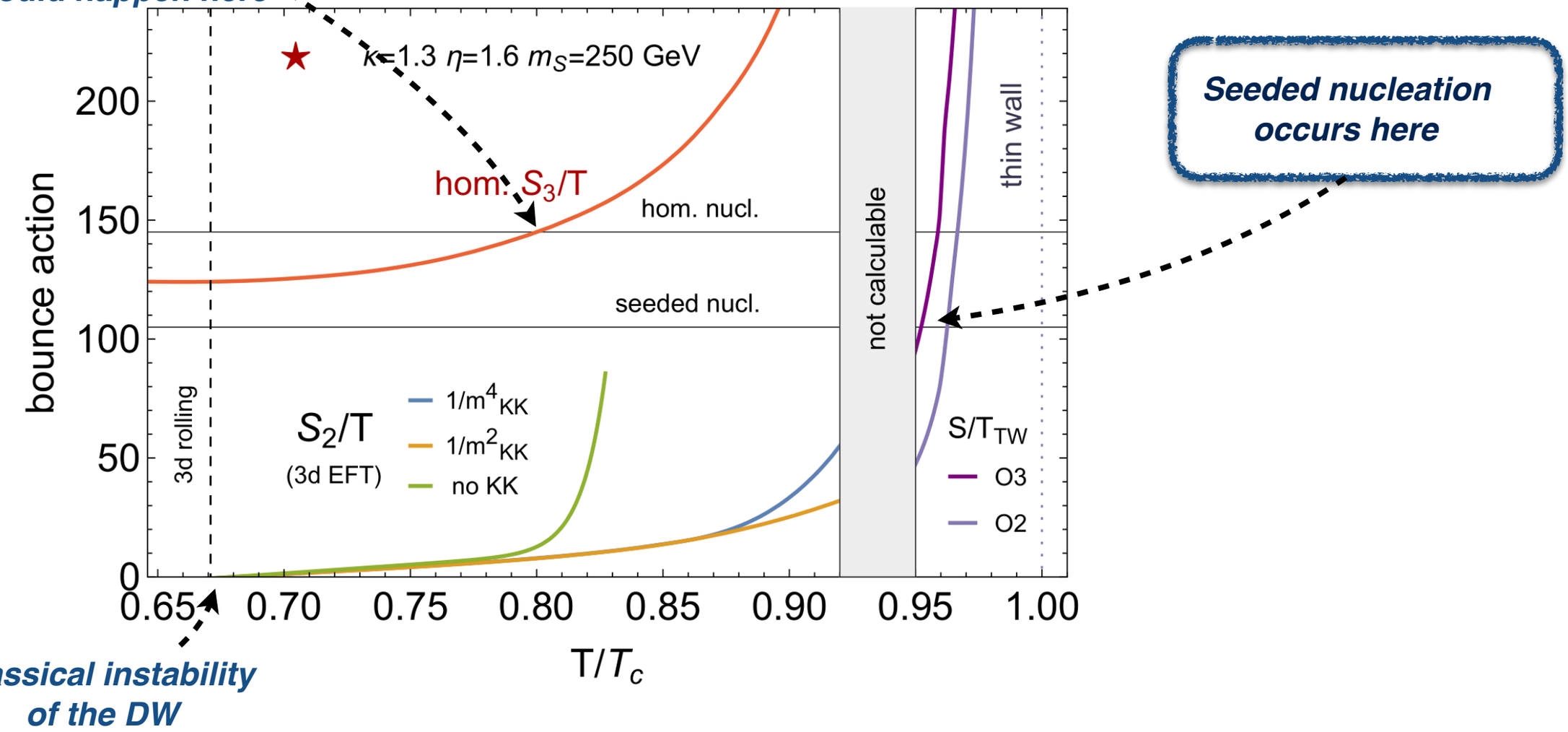


✦ *The O(2) seeded bubble profile can be obtained*

Blasi, AM 2203.16450

Bounce action

Homogeneous nucleation would happen here



Seeded nucleation occurs here

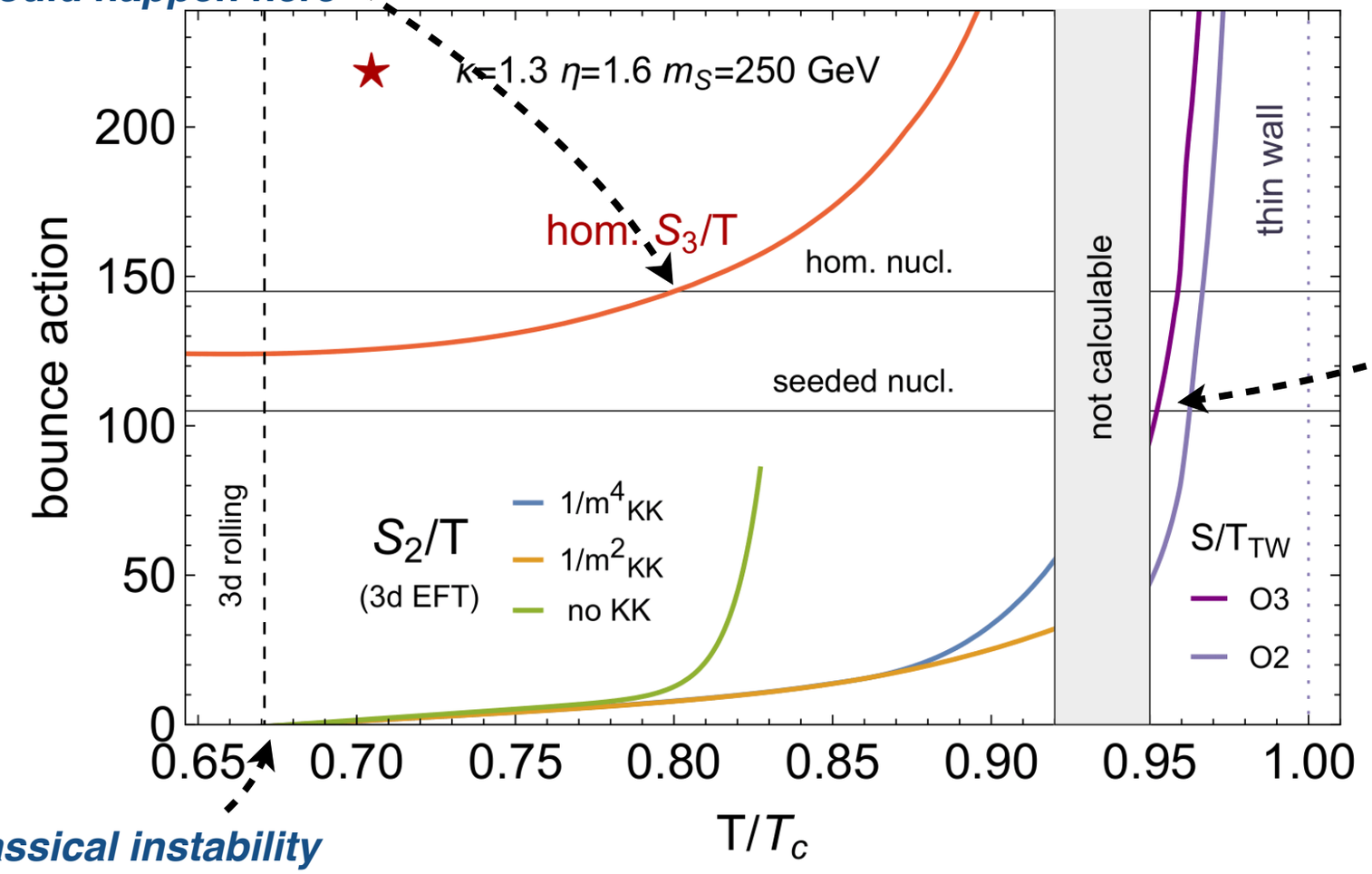
Classical instability of the DW

★***PT via nucleation on the DW always dominates***

Bounce action

Blasi, AM 2203.16450

Homogeneous nucleation would happen here



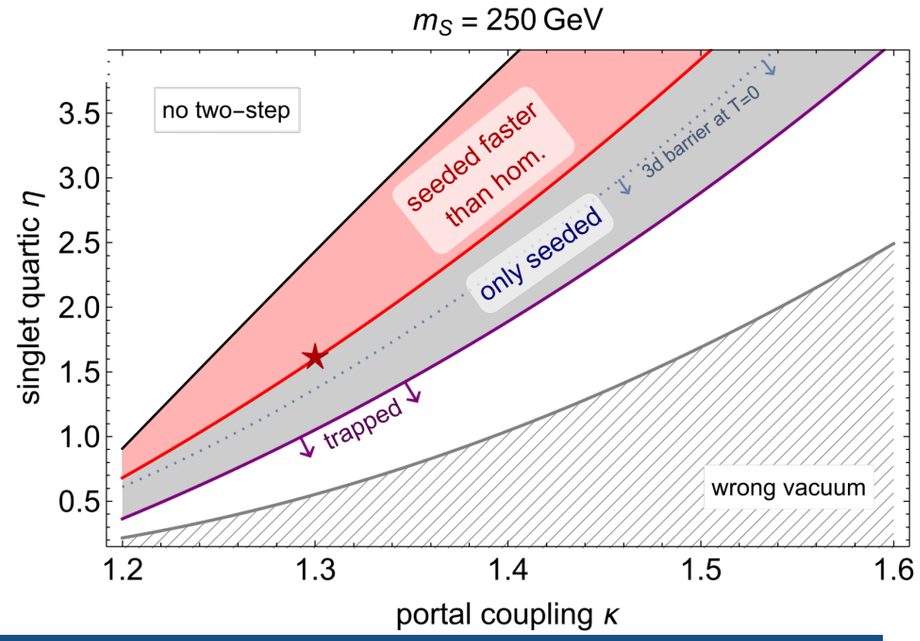
Classical instability of the DW

Seeded nucleation occurs here

★PT via nucleation on the DW always dominates

★Completely new phenomenology of EW PT

★Strong impact on parameter space

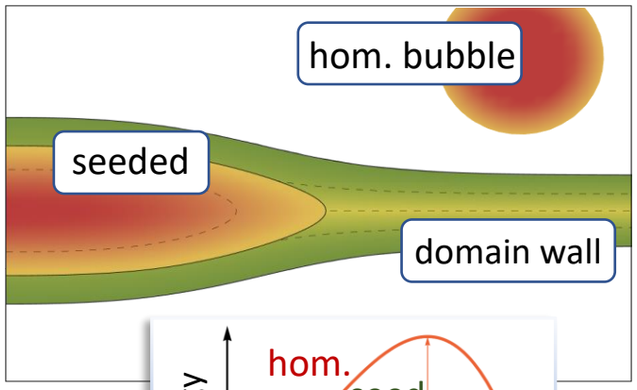


Conclusions

★*Impurities (topological defects) play a role in cosmological PT*

★*Topological defects emerge in multi-step phase transitions*

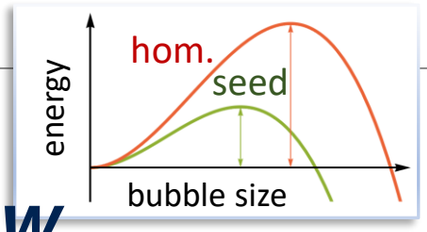
➡ *The EW phase transition can be seeded by topological defects*



★*Minimal realization with DW in Higgs Singlet model*

★*It can impact several well-known models*

✳ E.g. Other Minimal extensions of Higgs sector, 2HDM, ...



★*Phenomenological implications for baryogenesis and GW*

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✳ ***Thanks to Luciano for his legacy***