Domain walls as seeds in cosmological phase transitions

Alberto Mariotti

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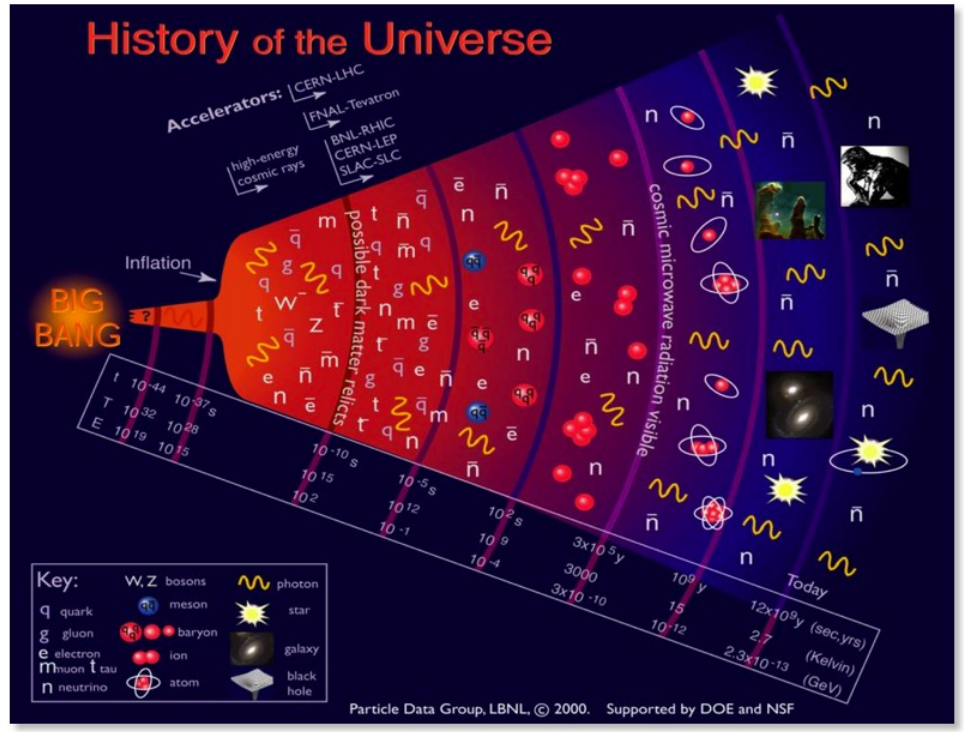
Based on arXiv:2203.16450 (PRL) with S. Blasi and on arXiv:2312.06749 with P. Agrawal, S.Blasi and M. Nee

BIG&C Meeting

IFAE Barcelona — 22 January 2024

Early Universe Cosmology

★*How looks Universe before its first second?*

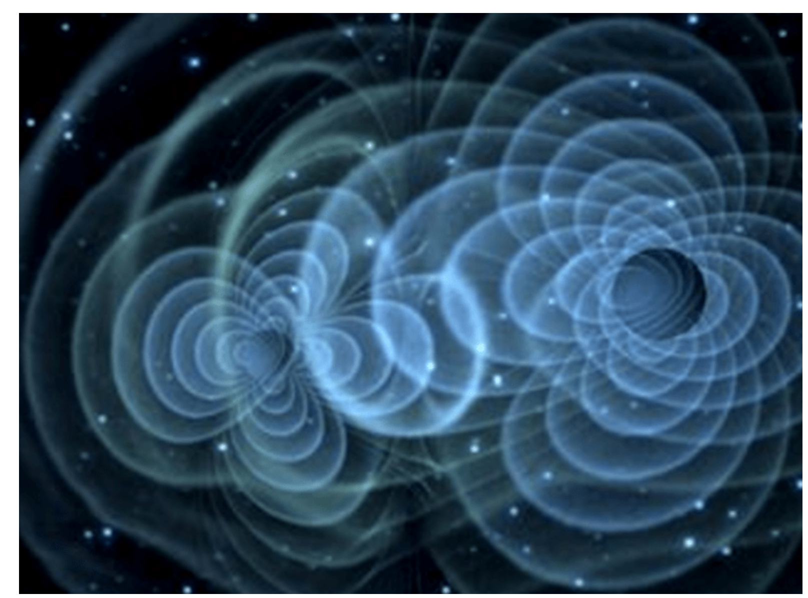


Background of Gravitational waves can probe early universe cosmology

Inflation

Cosmic strings

First Order Phase Transitions

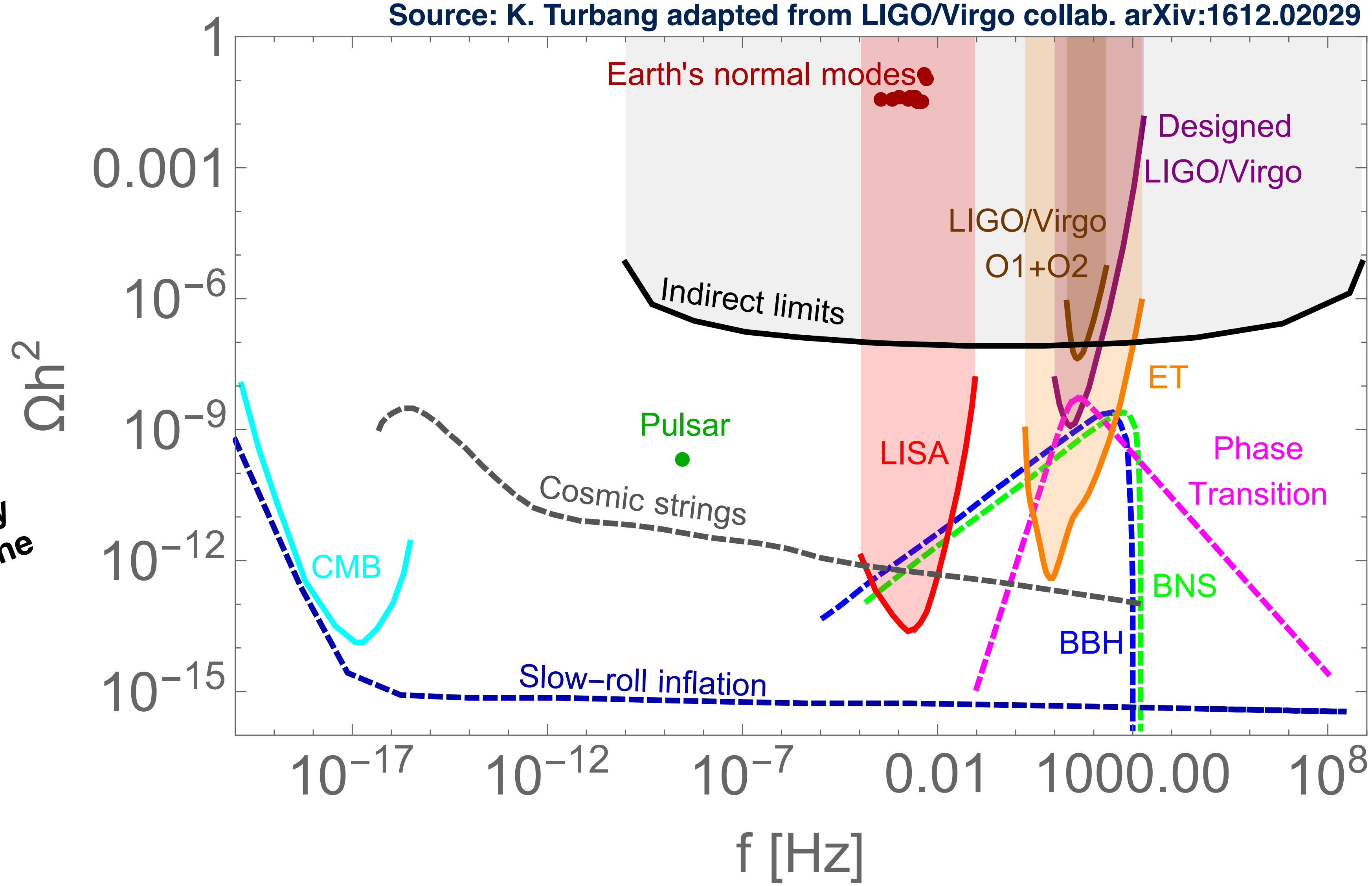


Stochastic Background of GW

WHAT IS IT? *Looks like noise, detected by cross-correlation*
Allen Romano gr-qc/9710117

Analog of CMB but for GW

Source: K. Turbang adapted from LIGO/Virgo collab. arXiv:1612.02029



SGWB energy density over critical one

AstroPhysical SGWB ⟷ **Cosmological SGWB**

Experimental probes

Stochastic Background of GW

★AstroPhysical SGWB

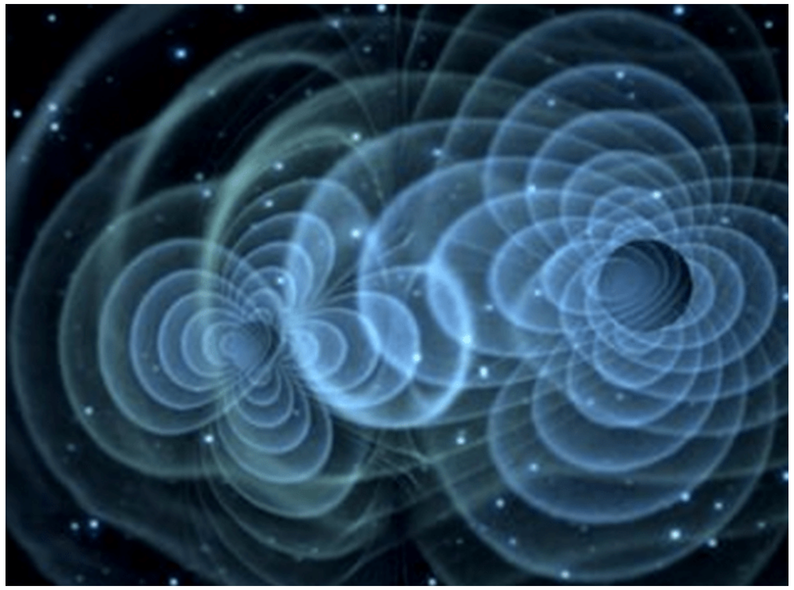
- ✳ Superposition of unresolvable sources

  BBH   BNS

- ✳ Predictable after LIGO/Virgo observations

  LIGO/Virgo Phys.Rev.D 100 (2019)

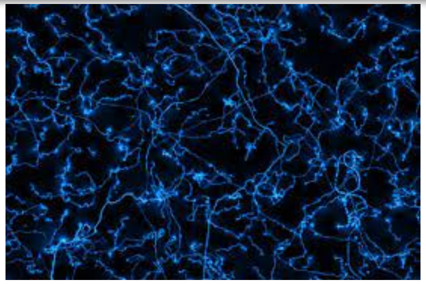
! Most likely measured in next few years !



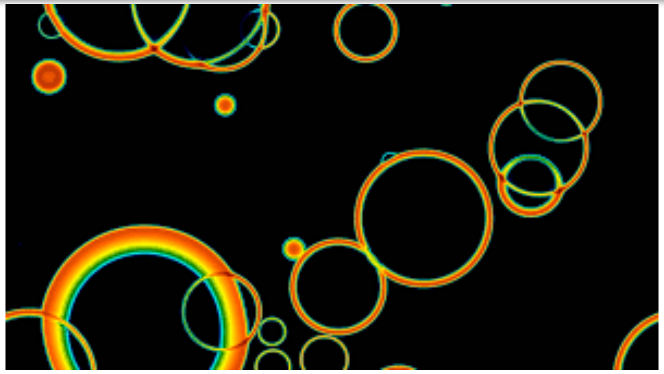
★Cosmological SGWB

- ✳ Generated by energetic events during cosmological evolution

Cosmic strings



First Order Phase Transitions



arXiv: 1705.01783 D. Weir

Inflation

Explore Universe earlier than CMB!

Cosmological phase transitions

★*Consider Universe with high reheating temperature*
★*Consider spontaneously broken symmetry*

ϕ : order parameter of a symmetry

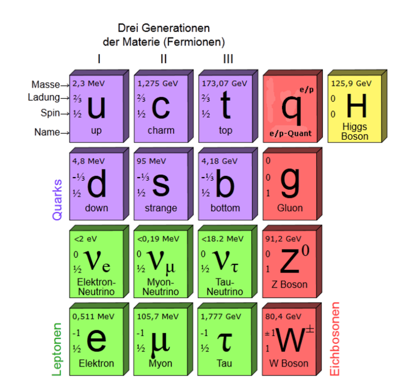
High-T ——— T_c ——— ***Low-T*** → $1/T$

$\langle\phi\rangle = 0$ ... T_c ... $\langle\phi\rangle \neq 0$

Phase transition during the cooling of the Universe at critical temperature $\sim T_c$

★***Phase transitions***
- ✳First order: discontinuos change of order parameter
- ✳Second order: smooth change of order parameter

★*In the Standard Model*



✳QCD Phase Transition (T ~ GeV)? In SM No first order

✳EW Phase Transition (T~ 100 GeV)? In SM No first order

(If very light Higgs it could have been strongly first order)
'81 Witten

Why cosmological first order PT?

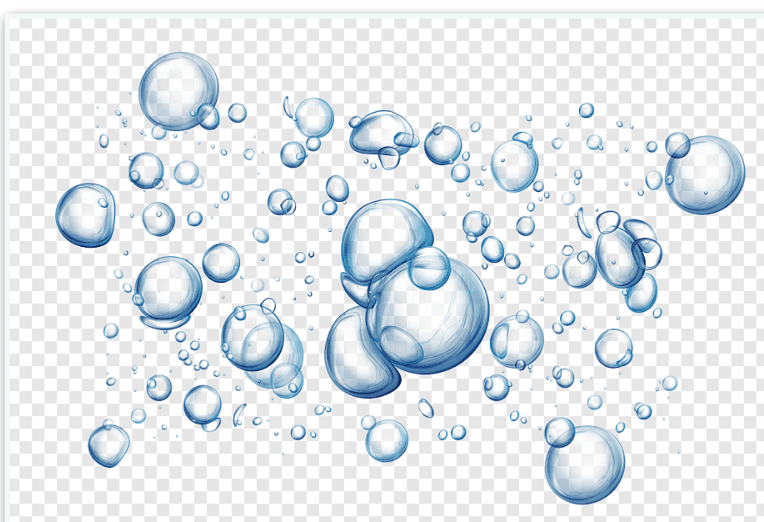
★*Probe of Early Universe cosmology*

★*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



Target for current and future GW experiments

LIGO VIRGO KAGRA

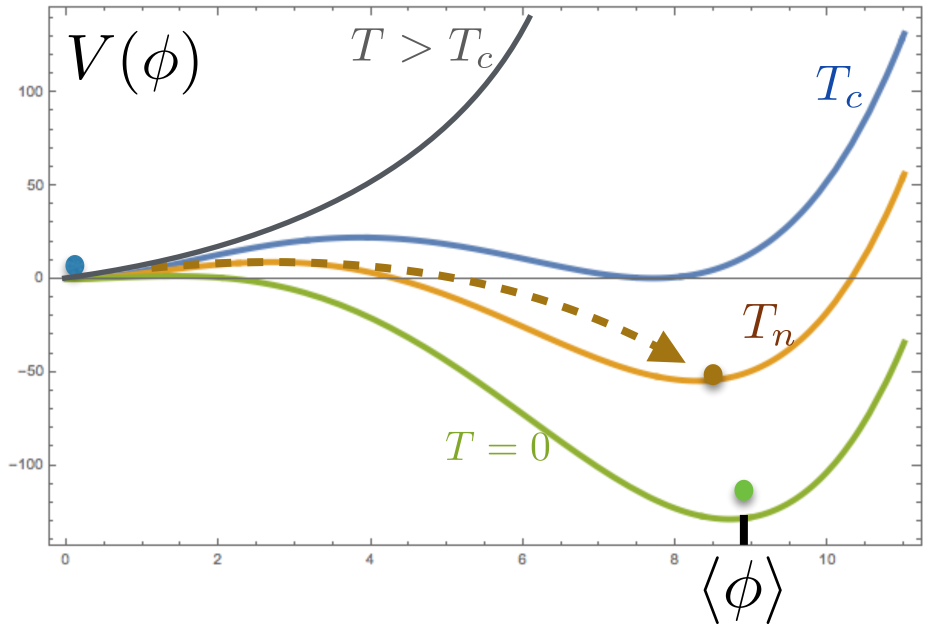
- *Ligo Virgo Kagra*
- *NANOGrav, PPTA, EPTA*
- *LISA*
- *Einstein Telescope*
- *Cosmic explorer*

ET EINSTEIN TELESCOPE

First order phase transition

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

★ *Nucleation condition in homogeneous Universe*



✳ *Phase transition described by effective potential*

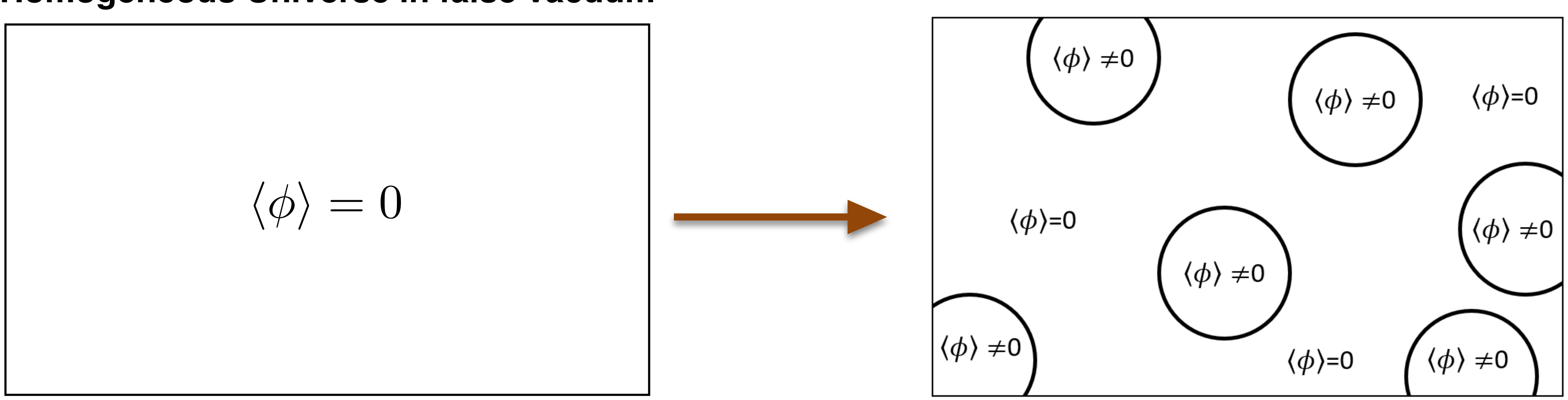
✳ *Thermal fluctuation induces nucleation of bubbles*

✳ *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



Basics of first order phase transitions

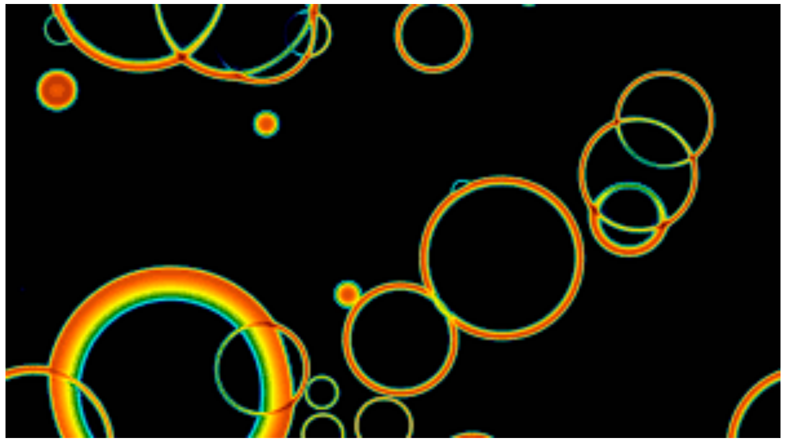
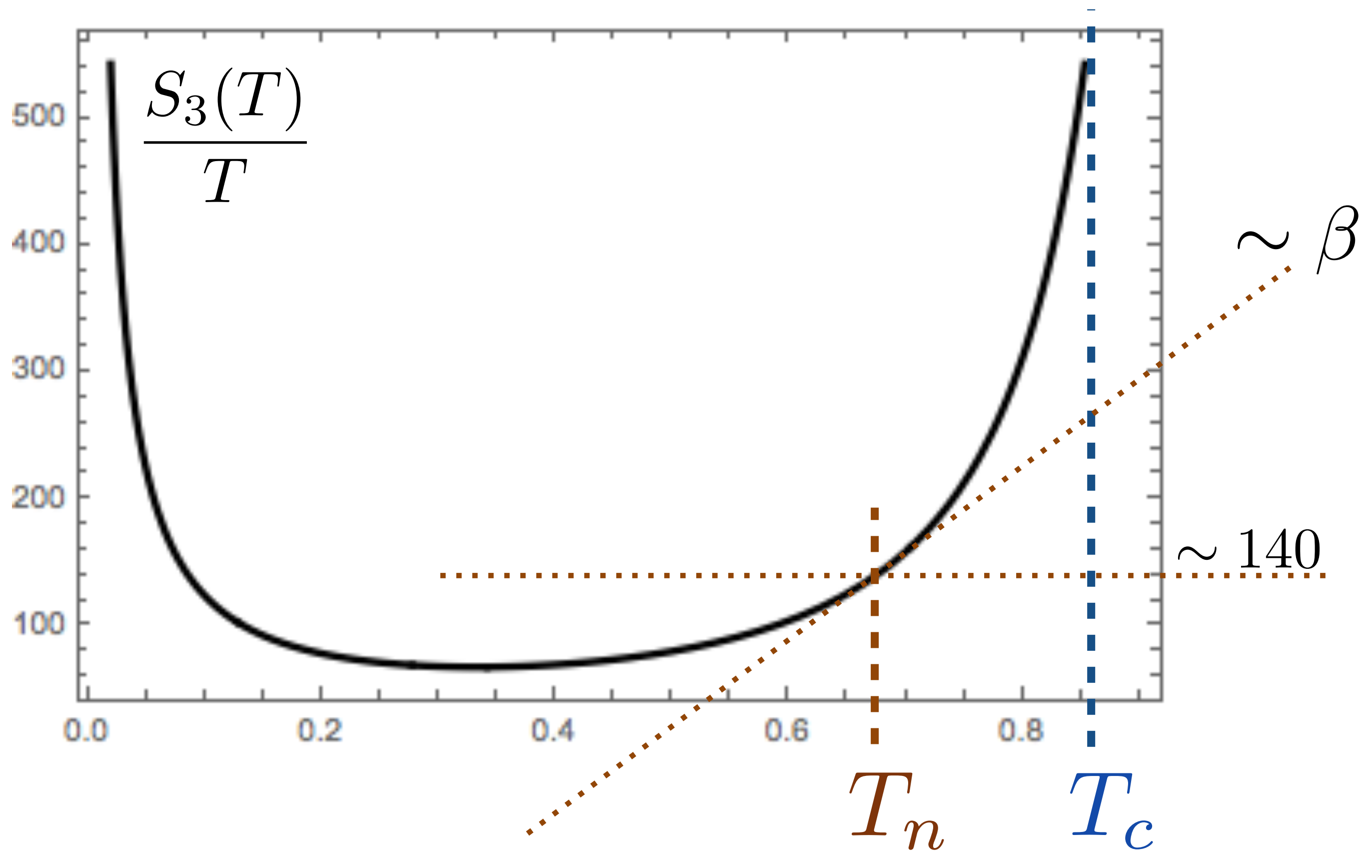


fig. from arXiv:1705.01783 D. Weir

✦ ***Nucleation rate controlled by the bounce action***

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



★Parameters describing PT properties

$$\alpha_* \simeq \frac{\Delta V}{\rho_{rad}}\Big|_{T_*}$$ Latent heat

$$\frac{\beta}{H_*} = T\frac{d}{dT}\frac{S_3}{T}\Big|_{T_*}$$ Time-scale

SGWB from FOPT

3 mechanisms to generate SBGW from FOPT

- ✦ *Bubble collisions*
- ✦ *Sound Waves in the plasma*
- ✦ *Turbulence*

Which dominates depends on PT properties

Many subtleties in computation of GW signal (bubble velocity, friction, …)

★*GW signal is broken power law*

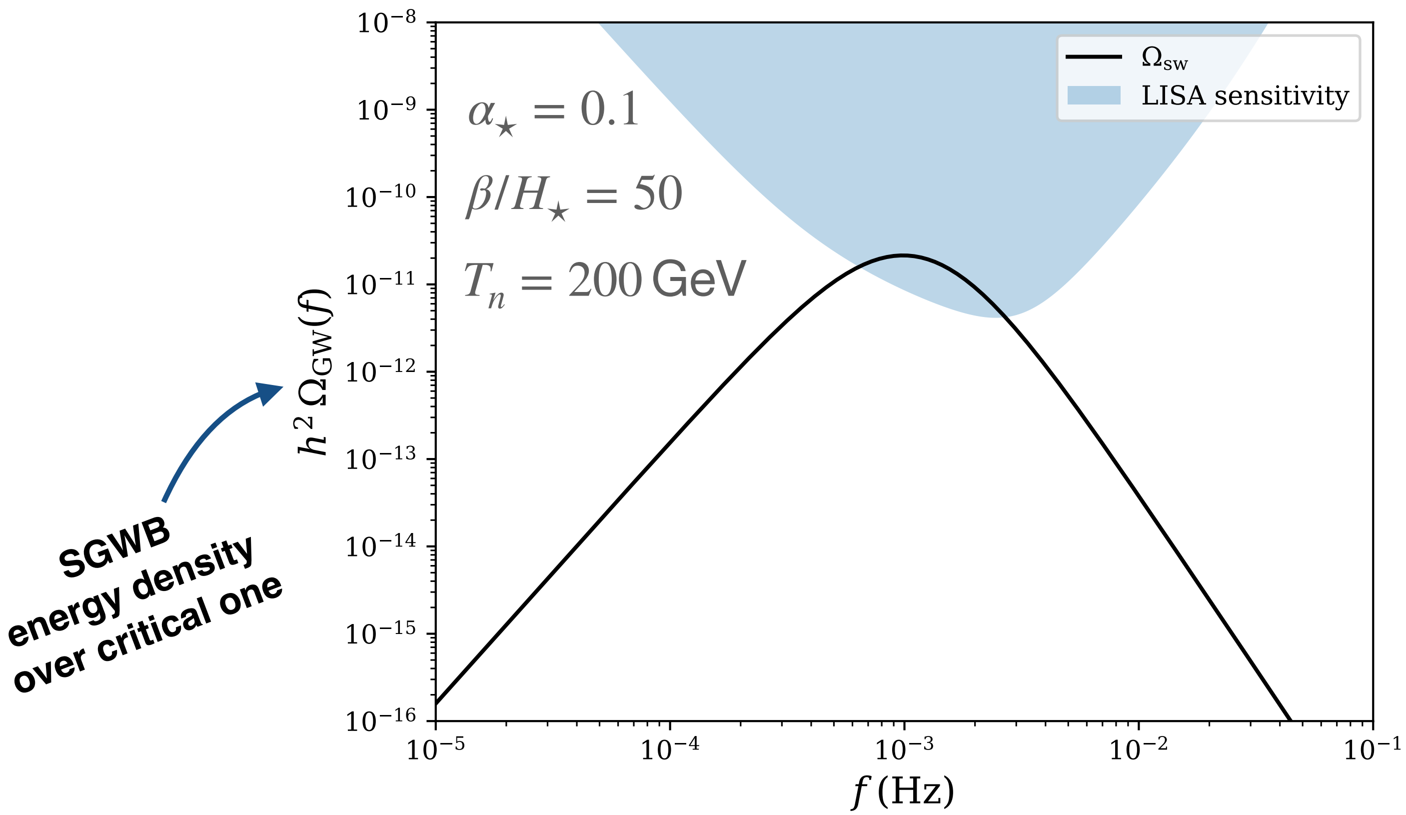


Fig. from LISA cosmology working group

Ex: Spectrum from sound waves

$$f_{peak} \sim 10^{-3}\,\mathrm{Hz}\left(\frac{\beta/H_*}{100}\right)\left(\frac{T_n}{100\,\mathrm{GeV}}\right)$$

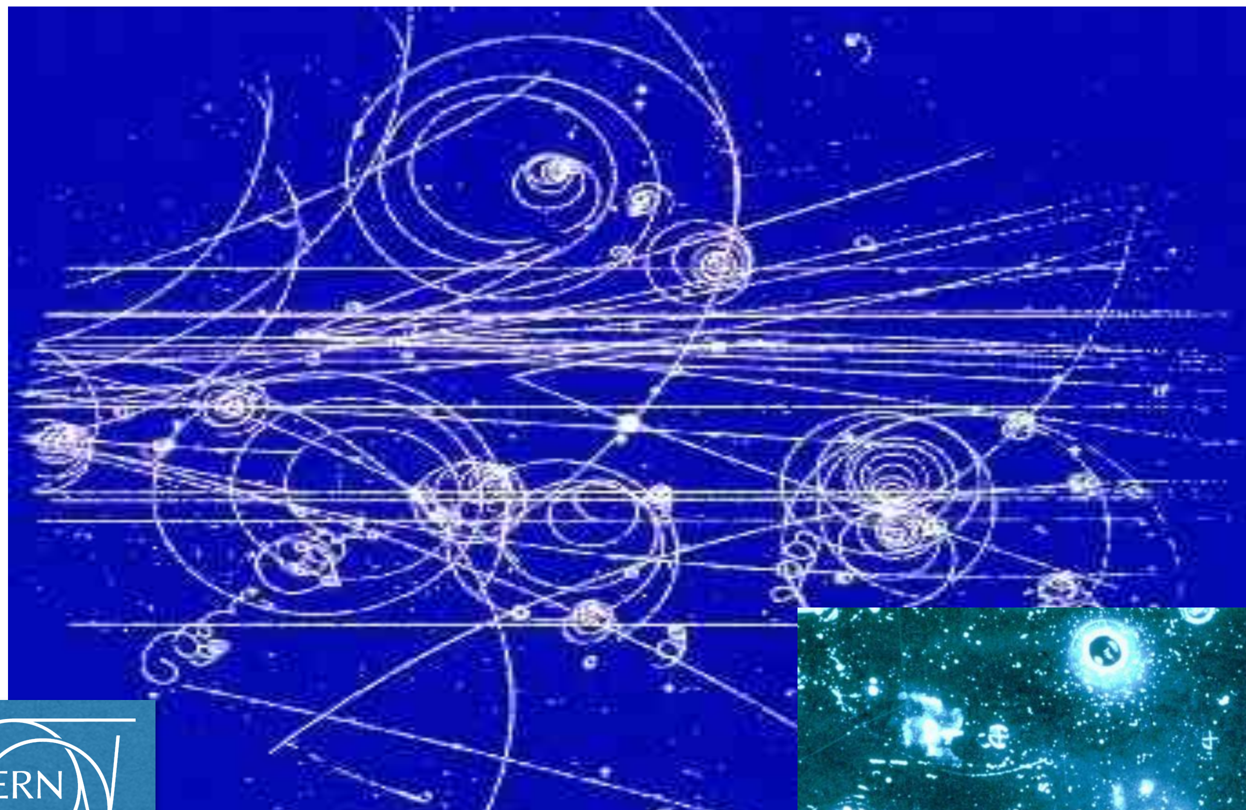
$$h^2\Omega_{\rm GW}^{peak} \sim 10^{-8}\left(\frac{100}{\beta/H_*}\right)(k_{sw}\alpha_*)^2$$

Efficiency factor between 0 and 1

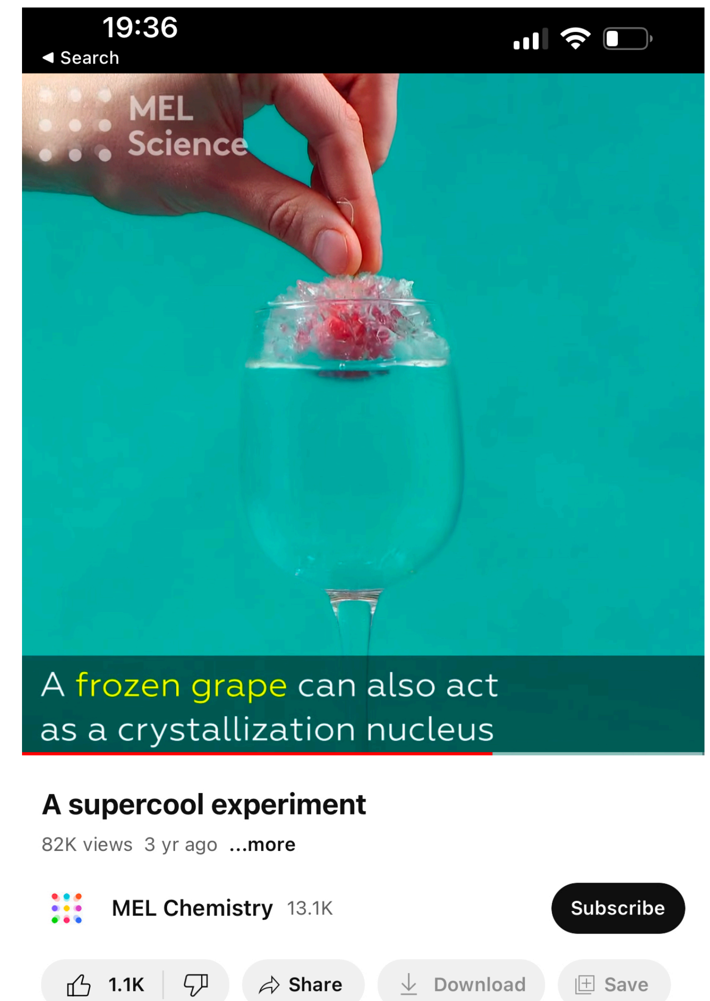
... however ... impurities

★*Impurities drastically modify the nucleation process*

Bubble chamber



Supercool water



... however ... impurities

★Impurities can play a role also in cosmological phase transitions

MONOPOLE AND VORTEX DISSOCIATION AND DECAY OF THE FALSE VACUUM

Paul Joseph STEINHARDT

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Received 17 February 1981

"**If monopole** (or vortex) **solutions exist** for a metastable or false vacuum, **a finite density of monopoles** (or vortices) **can act as impurity sites that trigger inhomogeneous nucleation** and decay of the false vacuum."

Impurities in the early universe

Yutaka Hosotani

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 1 November 1982)

"Now one has to ask the following question: **Is the early universe really sufficiently pure in order for supercooling to take place**? The aim of this paper is to show that in most cases the early universe is very pure. […] In this paper we consider **ordinary particles as impurities**."

Cosmic separation of phases

Edward Witten*

Institute for Advanced Study, Princeton, New Jersey 08540

(Received 9 April 1984)

"In particle physics it is often assumed that phase transitions are nucleated by thermal fluctuations. In practice, […] except in very pure, homogeneous samples, **phase transitions are often nucleated by various forms of impurities and inhomogeneities of nonthermal origin**."

"What if the transition was nucleated by impurities? In this case **the mean spacing between bubbles has nothing to do with free energies** of nucleation and is simply the spacing between the relevant impurities. "

Impurities in cosmological PT

★*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, Jinno et at. '23

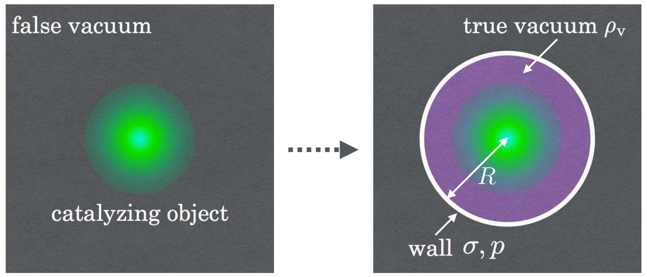


Fig. from Oshita et al.1808.01382

- ✳ ***Topological defects* (strings, monopoles ...)** E.g. Steinhardt '81, Hosotani '82, Witten '84, Yajnik '86, Preskill Vilenkin '92, --- Kumar et at '10, -- Agrawal, Nee '22

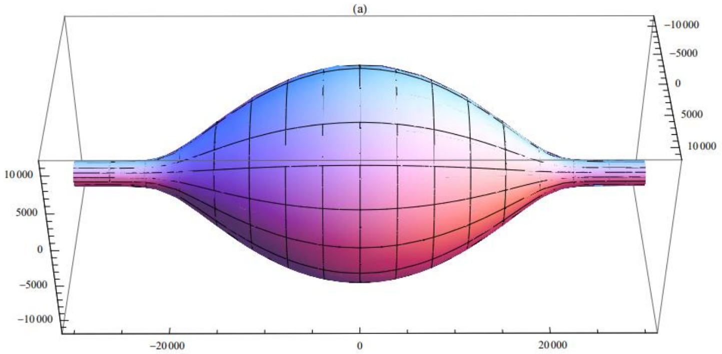


Fig. from Lee et al.1310.3005

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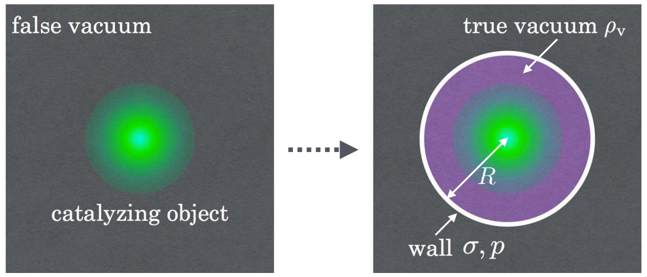

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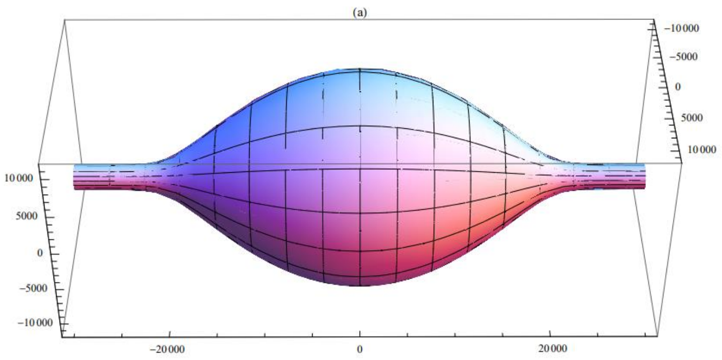


Fig. from Lee et al.1310.3005

★In rest of the talk:

EW phase transition can occur through impurities (Domain Walls) in minimal BSM scenarios

Blasi, Mariotti '22; Agrawal, Blasi, Mariotti, Nee '23

Why Topological defects as impurities

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

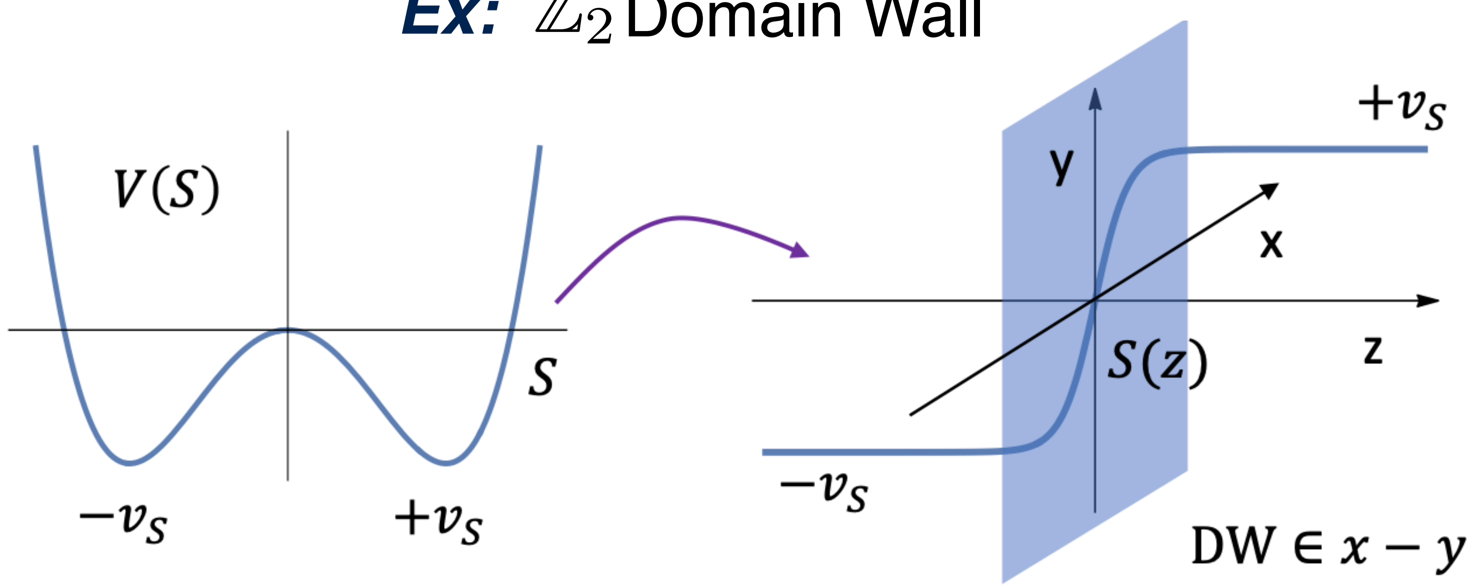
★*Remnants of PT depending on vacuum manifold topology* [Zel'dovich et al. '74, Kibble '76]

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

★*Classical solutions to the EoM*

Ex: $\mathbb{Z}_2$ Domain Wall



DW Tension

$\sigma_{\rm DW} \sim v_s^3$

Roles of cosmological defects

Topological defects impact cosmology in many directions:

Eg: Superconducting Strings

Witten '81

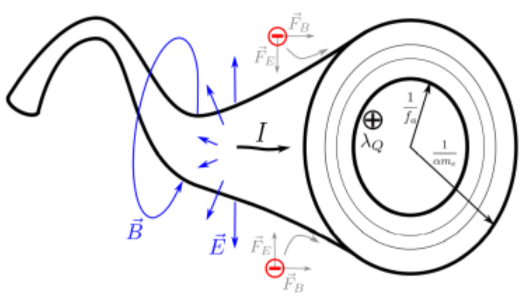


Fig. from Agrawal et. al 2010.15848

- ✳ **Sources of gravitational waves** *A.Vilenkin and E.P.S.Shellard, Cambridge University Press*
- ✳ **Contribute to dark matter** *Hiramatsu et al. '12 Gorghetto et al. '18,*
- ✳ **Link to primordial black holes** *Ferrer et. al '18 Pujolas et. al '22*
- ✳ **Induce baryogenesis** *Rubakov '82, Cline et at. '99, Daido et al '15*
- ✳ **Also observable effects on late time** *Ferreira et al. '23*

⋮

Topological defects as seeds in EW phase transition

★**Topological defects are present if EW symmetry breaking is final step of a multi-step breaking of larger symmetry group**

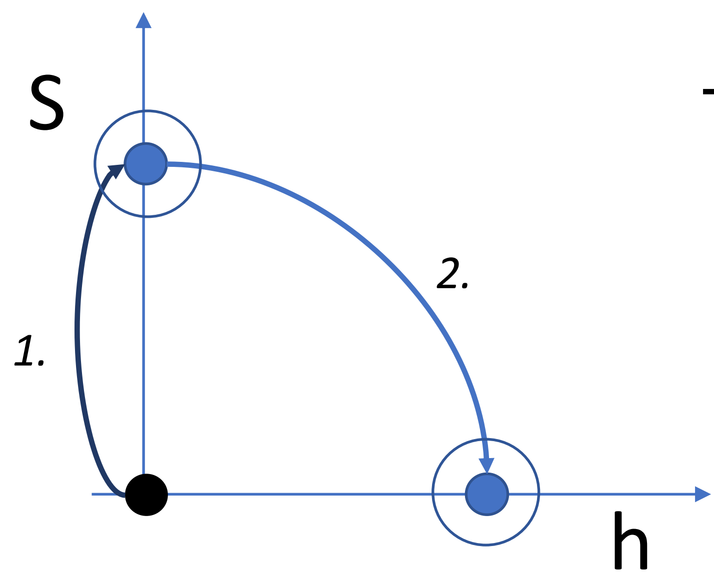
Typical in unified theories

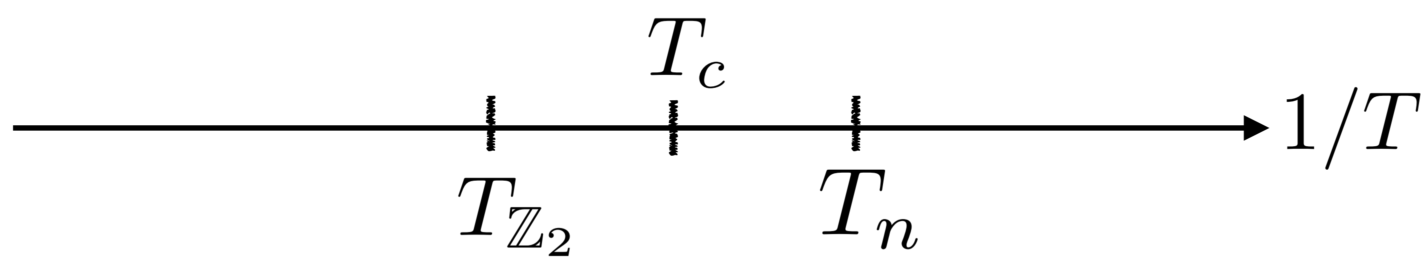
Simplest model for EW FOPT

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

$$V(h,S) = -\mu_h^2|\mathcal{H}|^2 + \lambda|\mathcal{H}|^4 - \frac{\mu_s^2}{2}S^2 + \frac{\eta}{4}S^4 + \kappa|\mathcal{H}|^2 S^2$$

★ ***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 O(1000) papers on this model in last 10 years***

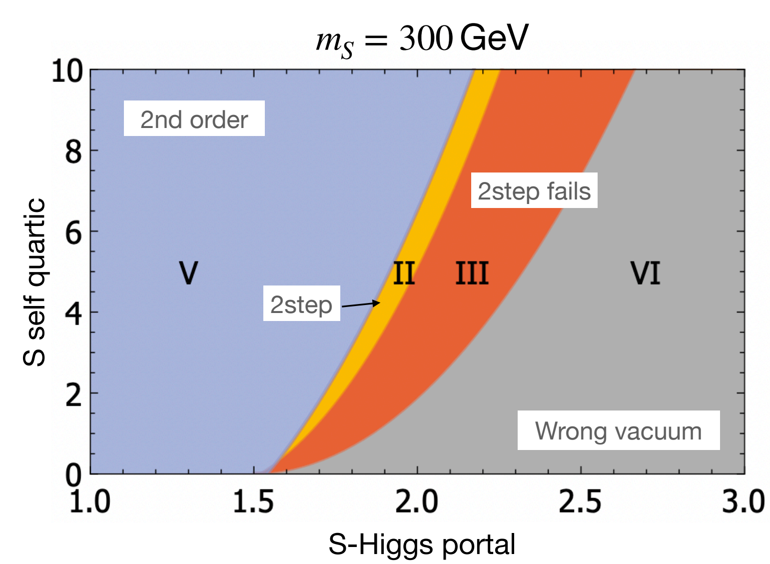


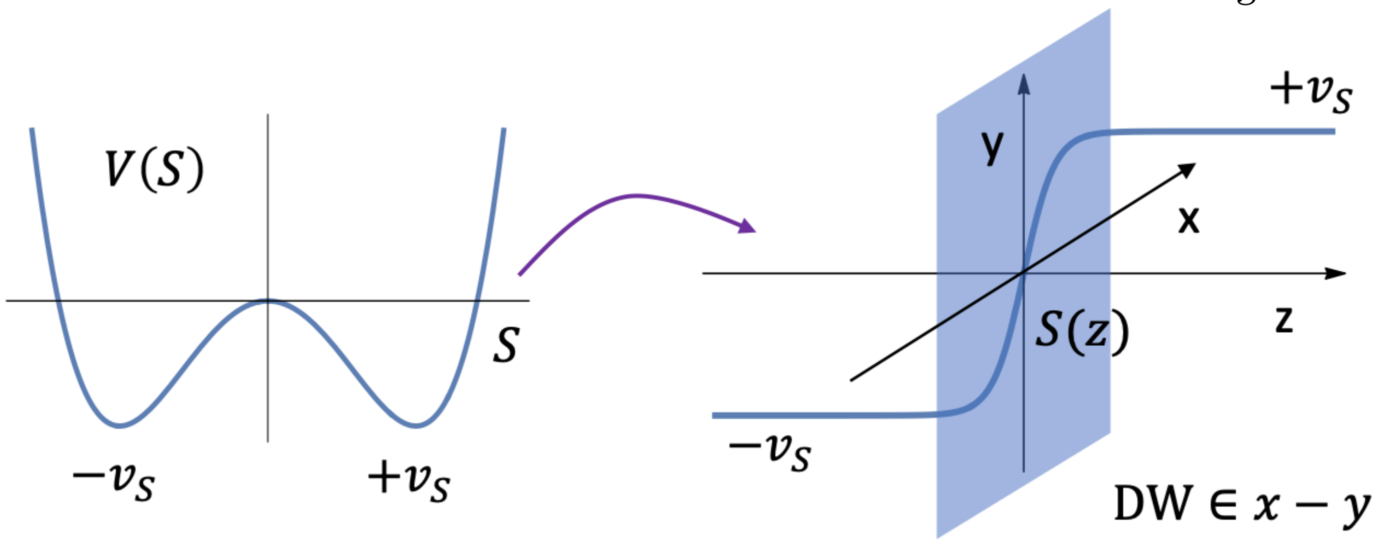
Fig. adapted from Kurup, Perelstein [1704.03381] PRD

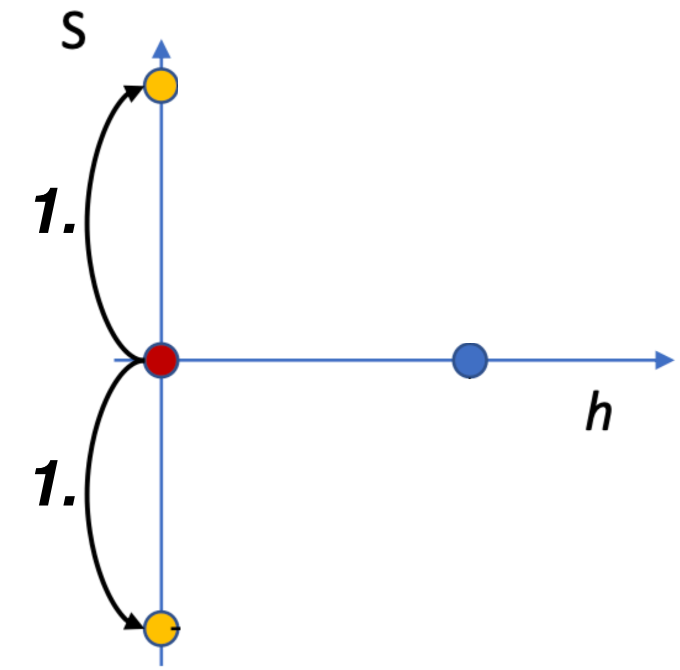
… but Domain Walls …

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

- ✳ **Disconnected vacuum manifold after first step**
- ✳ **Walls are formed at boundaries between different domains** $T_{\rm formation} \sim T_{\mathbb{Z}_2}$

DW Tension $\sigma_{\rm DW} \sim v_s^3$





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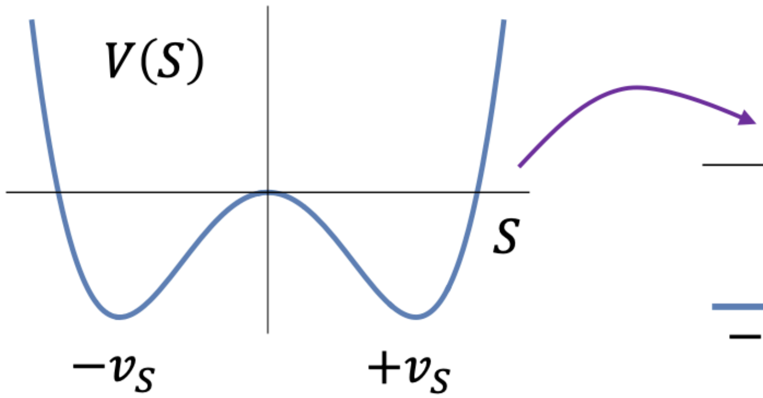
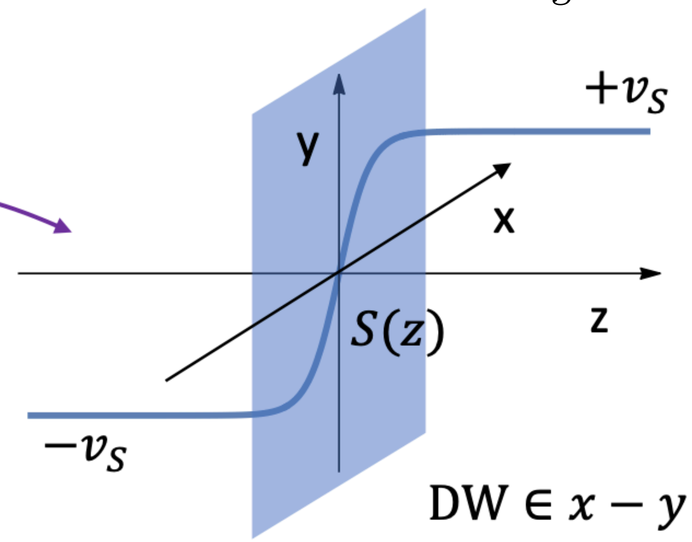
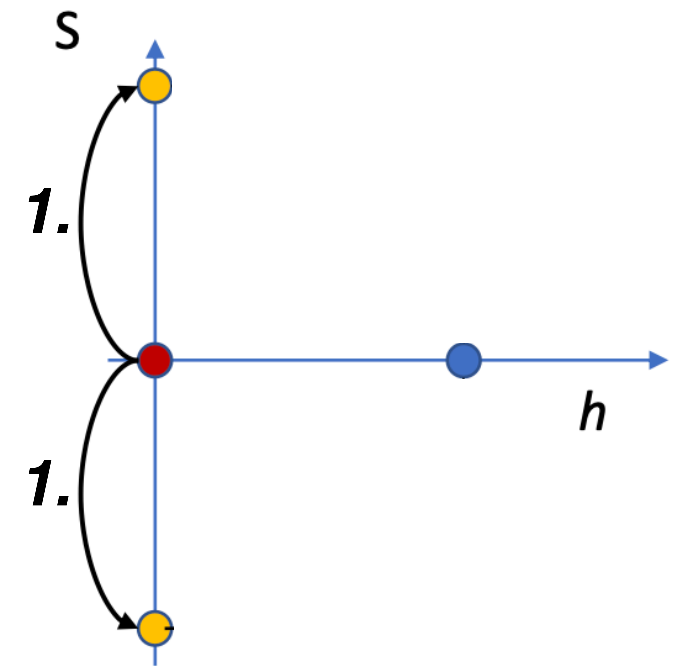






They impact the mechanism of the EW phase transitions

Blasi, AM 2203.16450

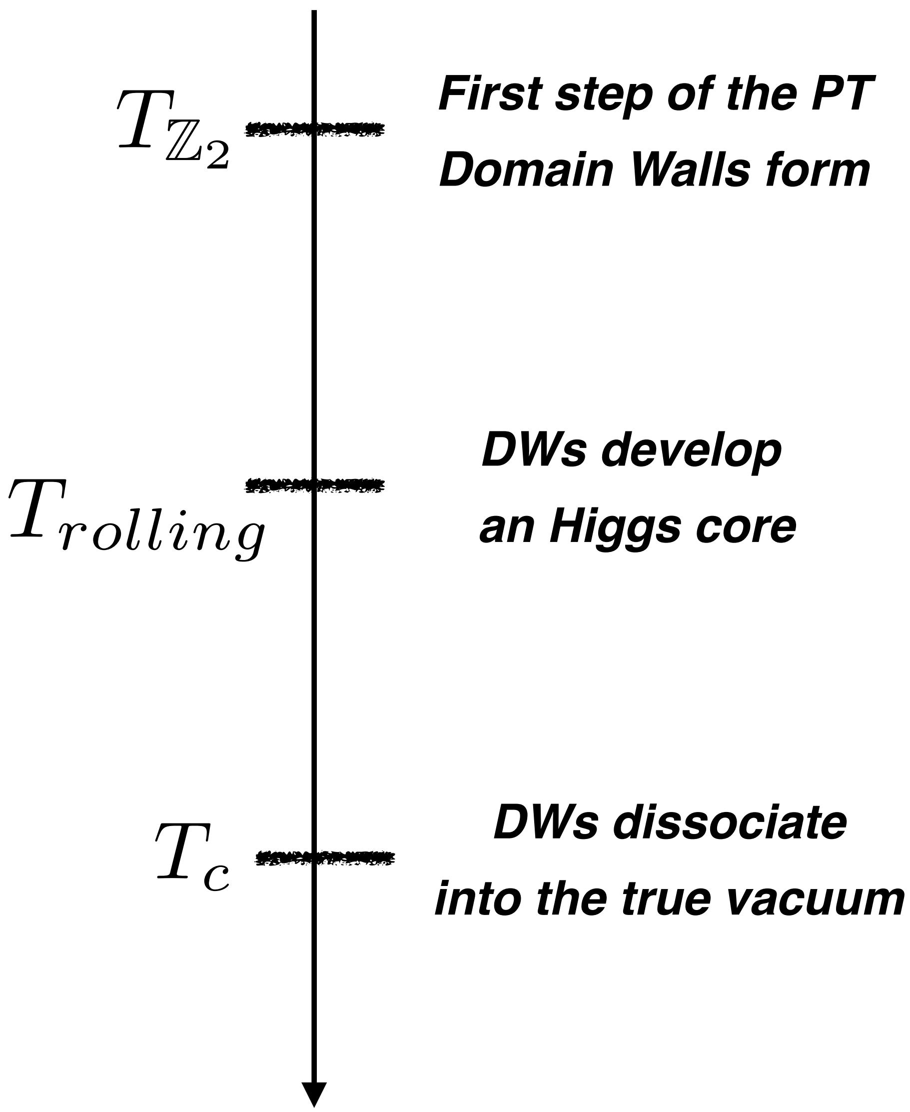
Rolling | **Seeded tunneling**

The rolling (classical instability)

Blasi, AM 2203.16450

★Domain walls can become classically unstable while the Universe cools down

★Developing a region of the true vacuum in their interior, and then dissociate



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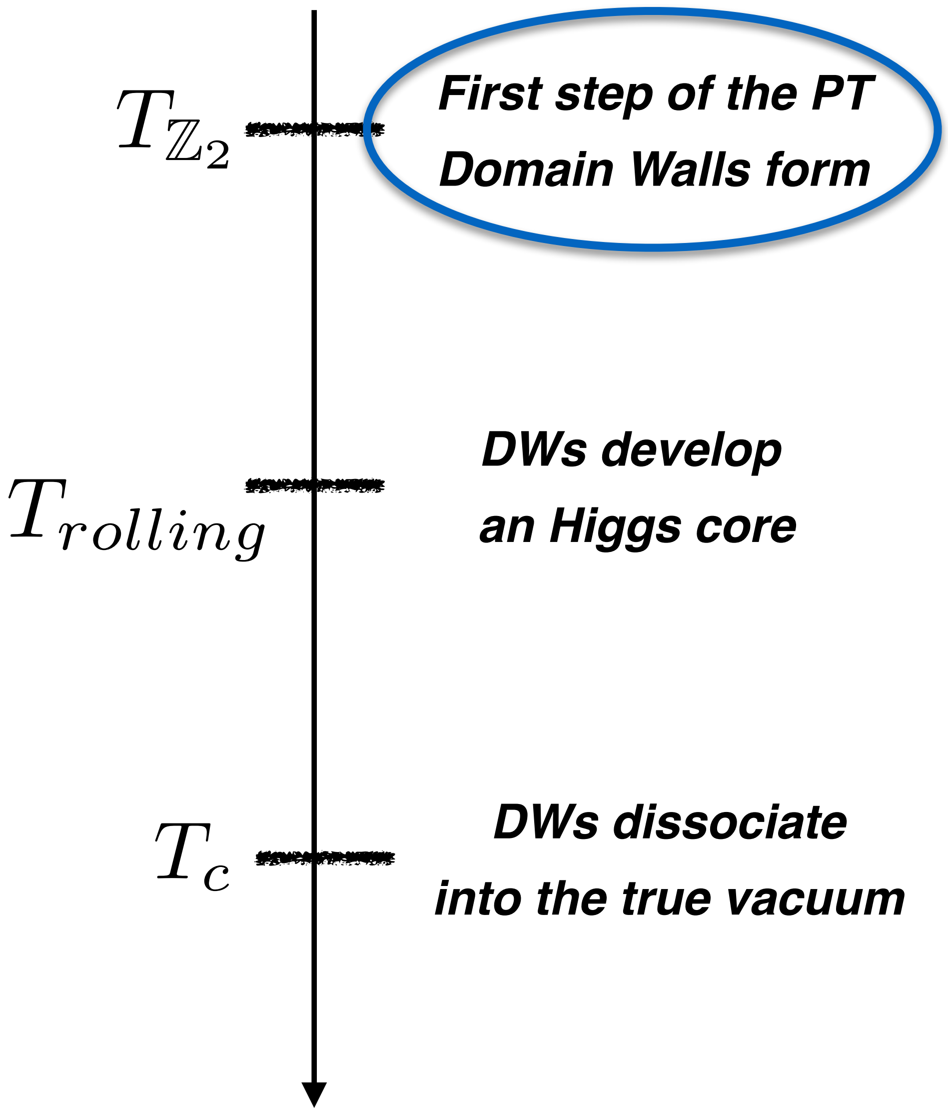

Steinhardt '81: Same phenomena for monopoles

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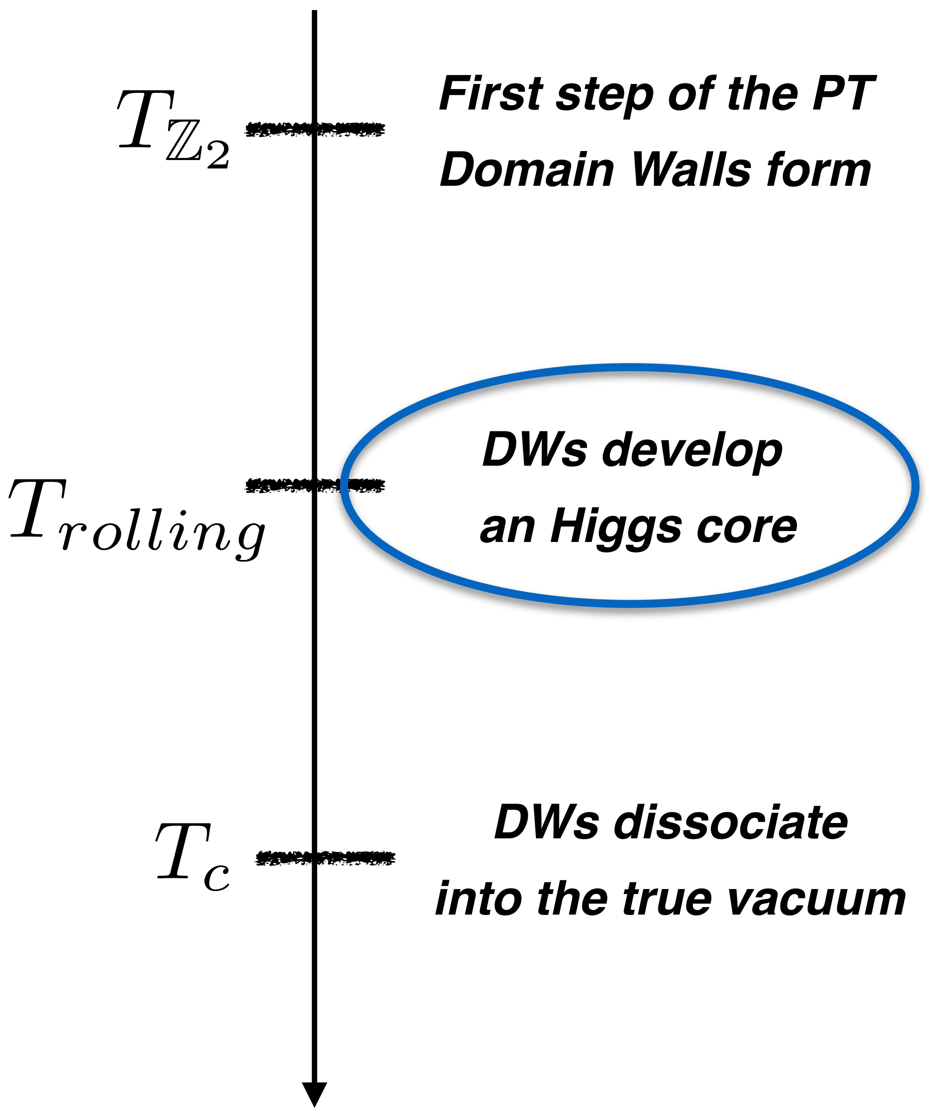

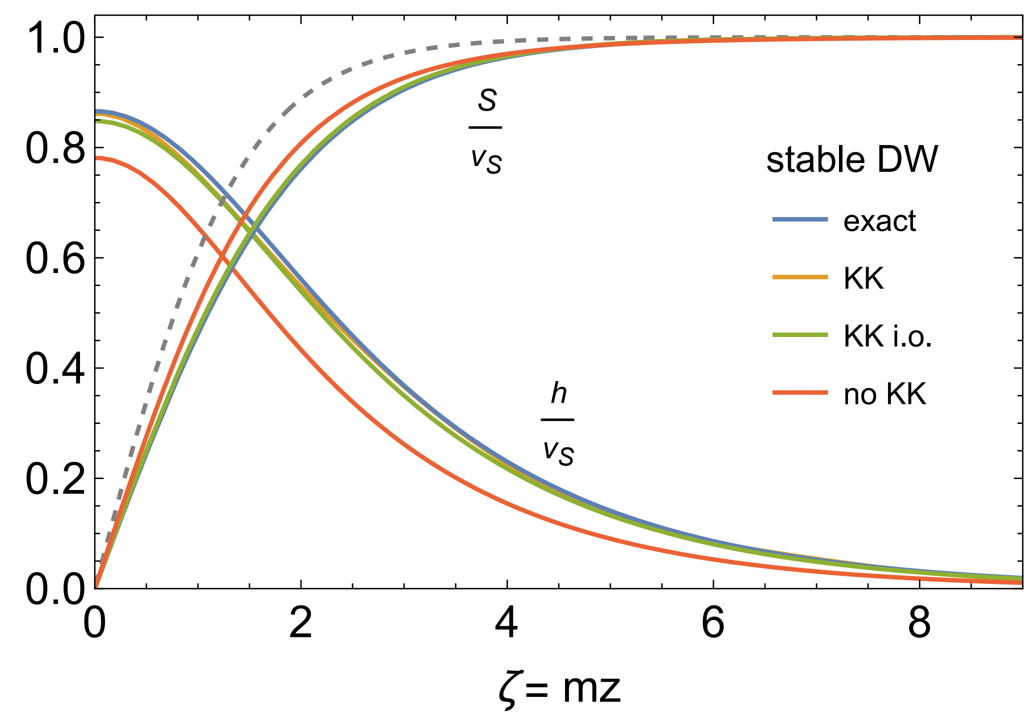

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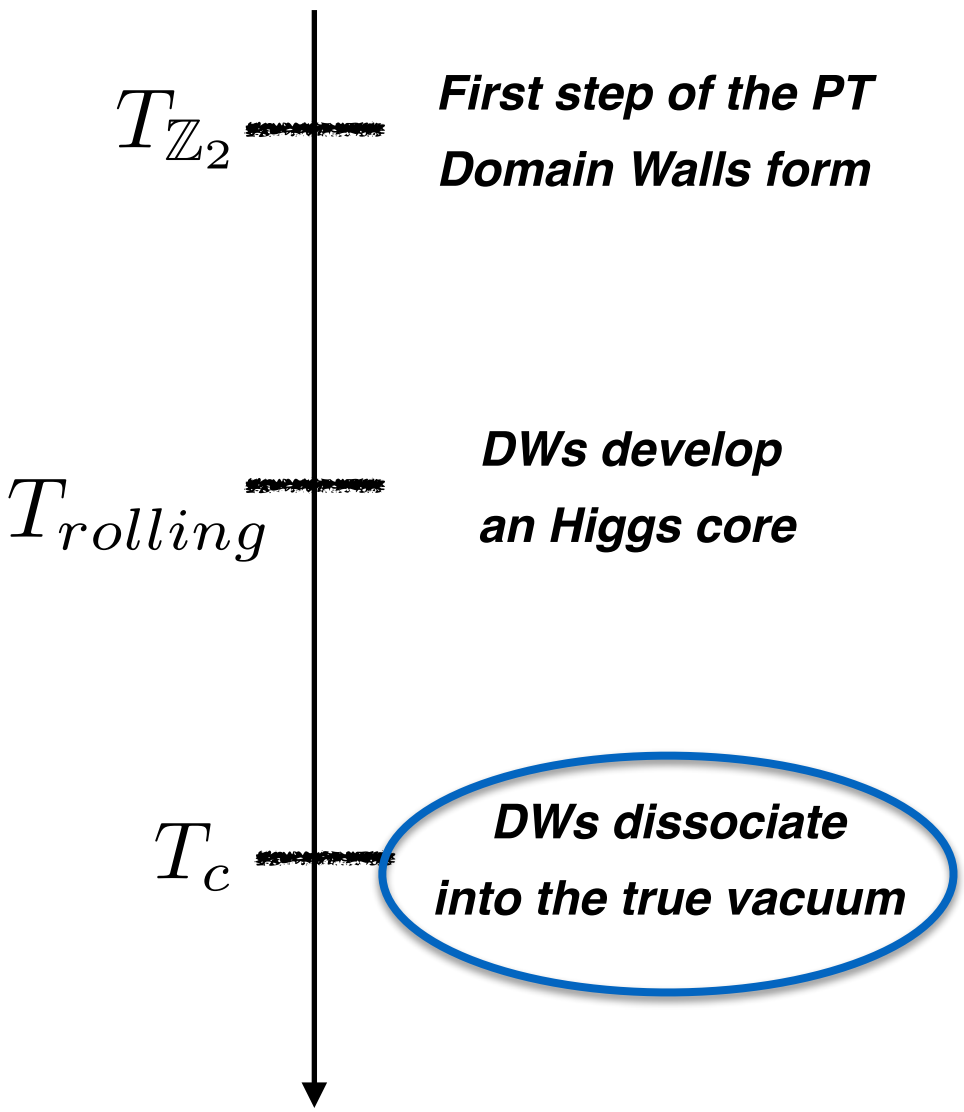
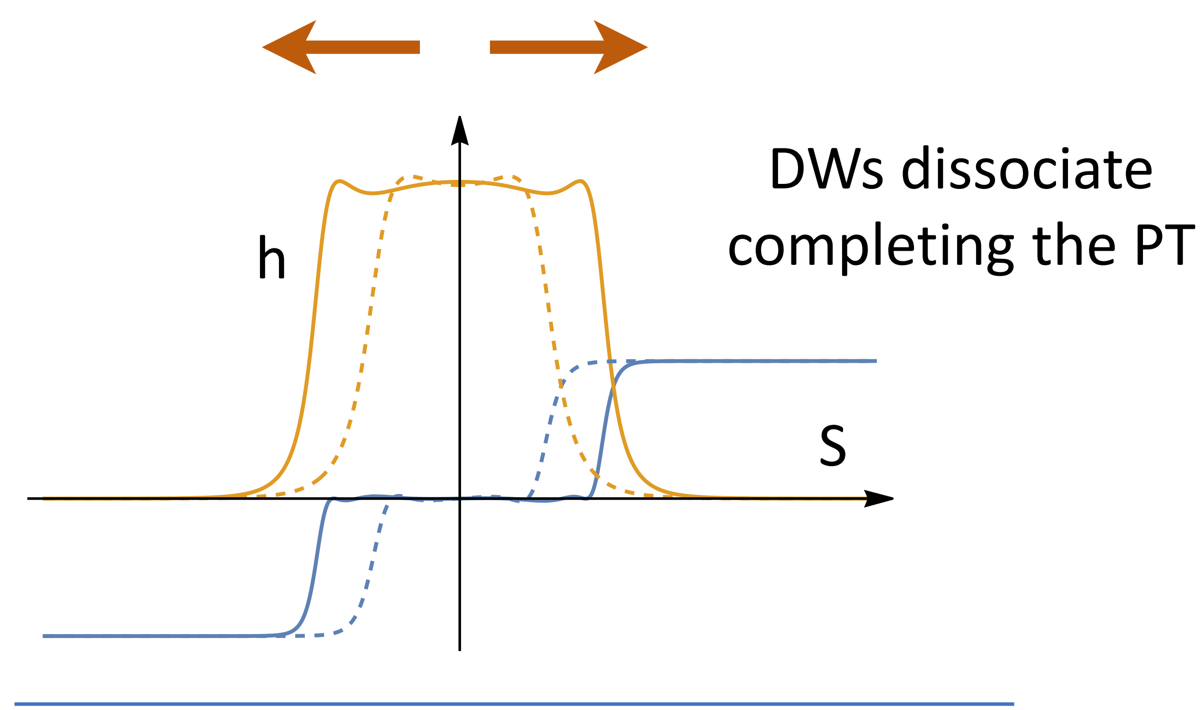




Higgs core gains energy by expanding

Figure from Simone

Steinhardt '81: Same phenomena for monopoles

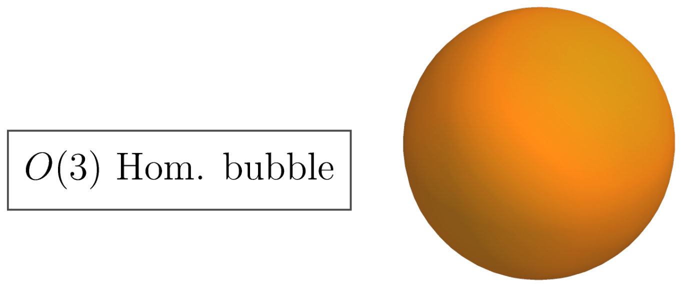
Seeded vs homogeneous nucleation

Blasi, AM 2203.16450
Agrawal, Blasi, Nee, AM '23

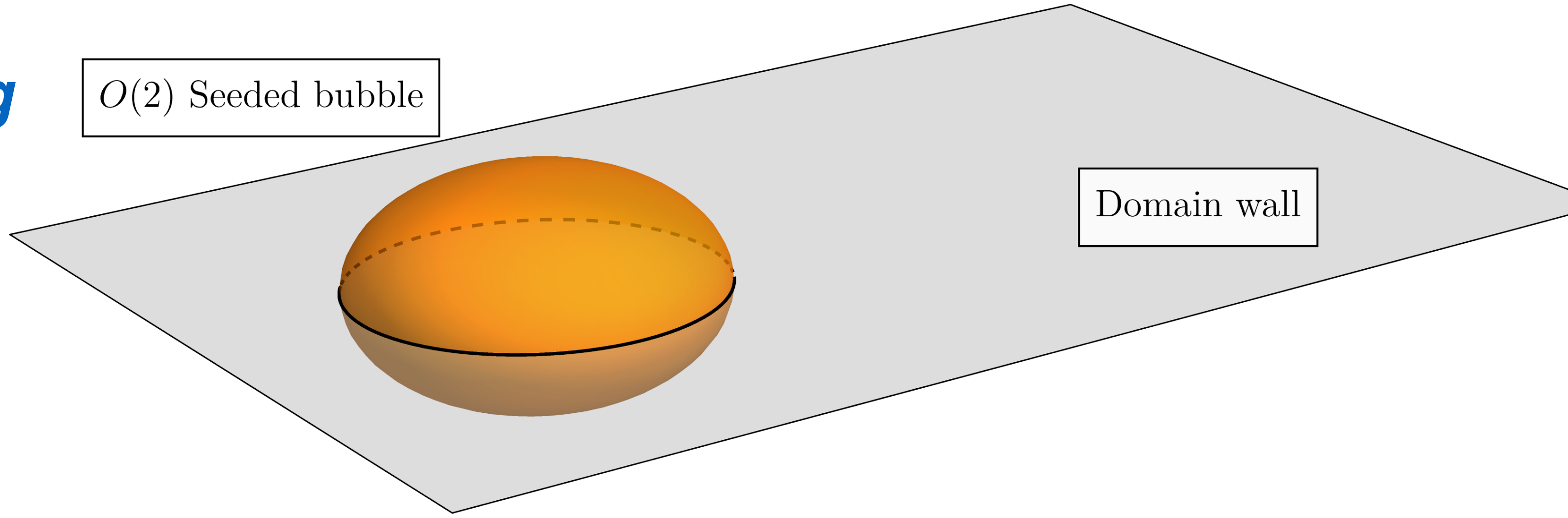
★If classically stable, Domain wall can act as seeds for the EW phase transition

★*Tunneling can occur in two competing processes*

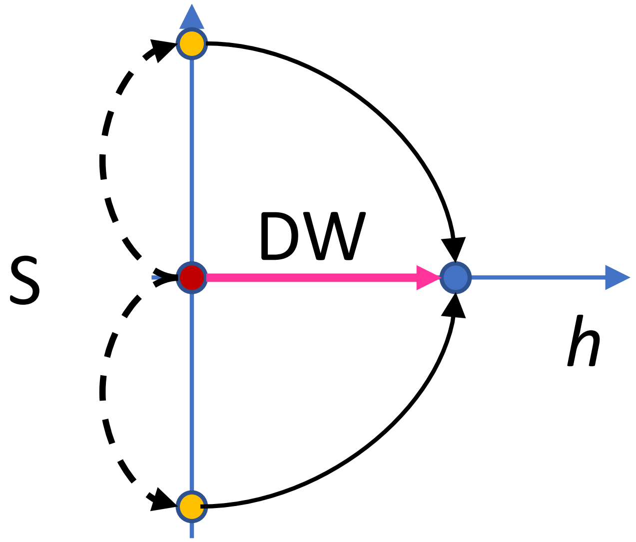
★*Far from the DW: homogeneus tunneling*



★*On the DW: seeded tunneling*



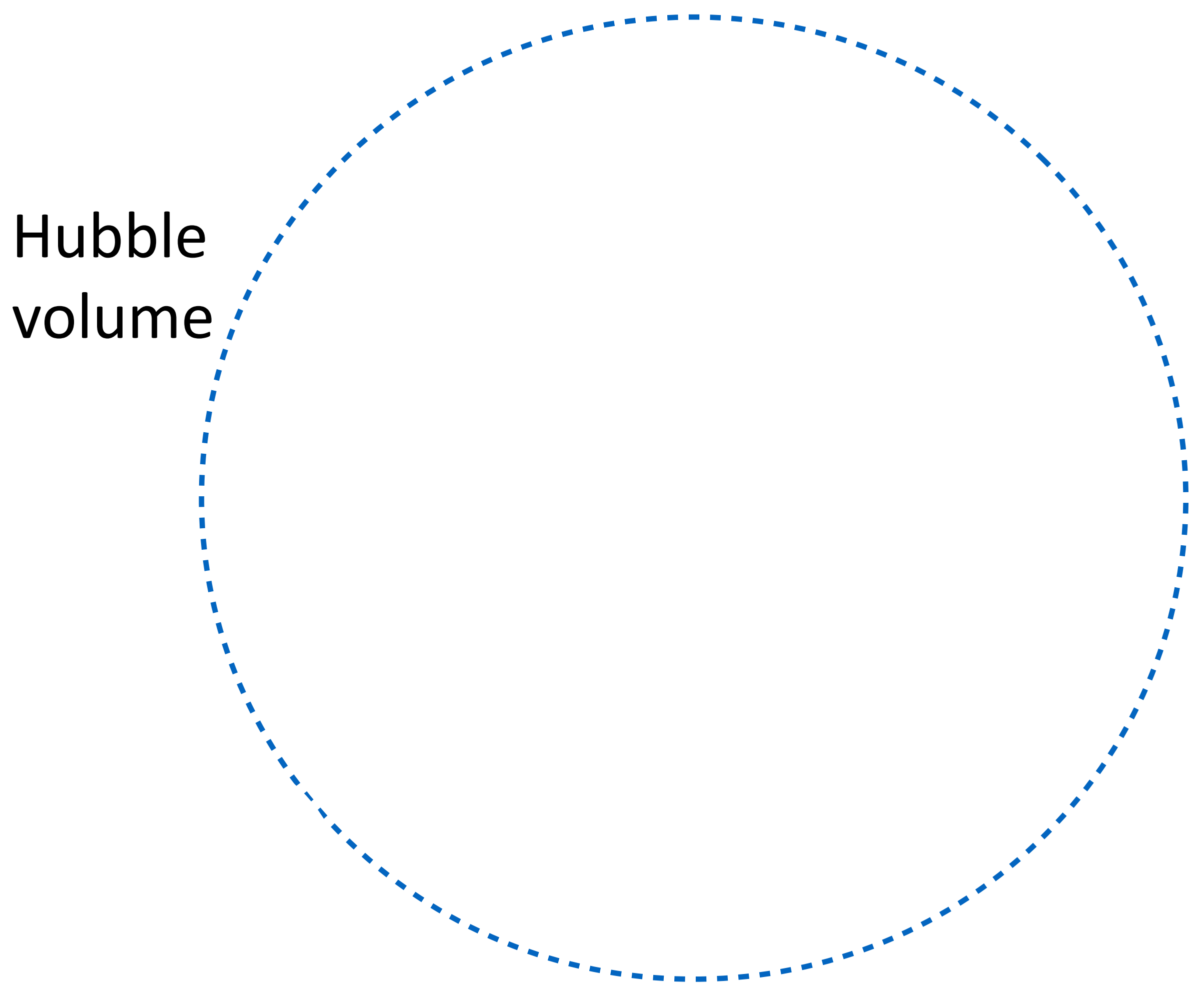
Field space trajectories

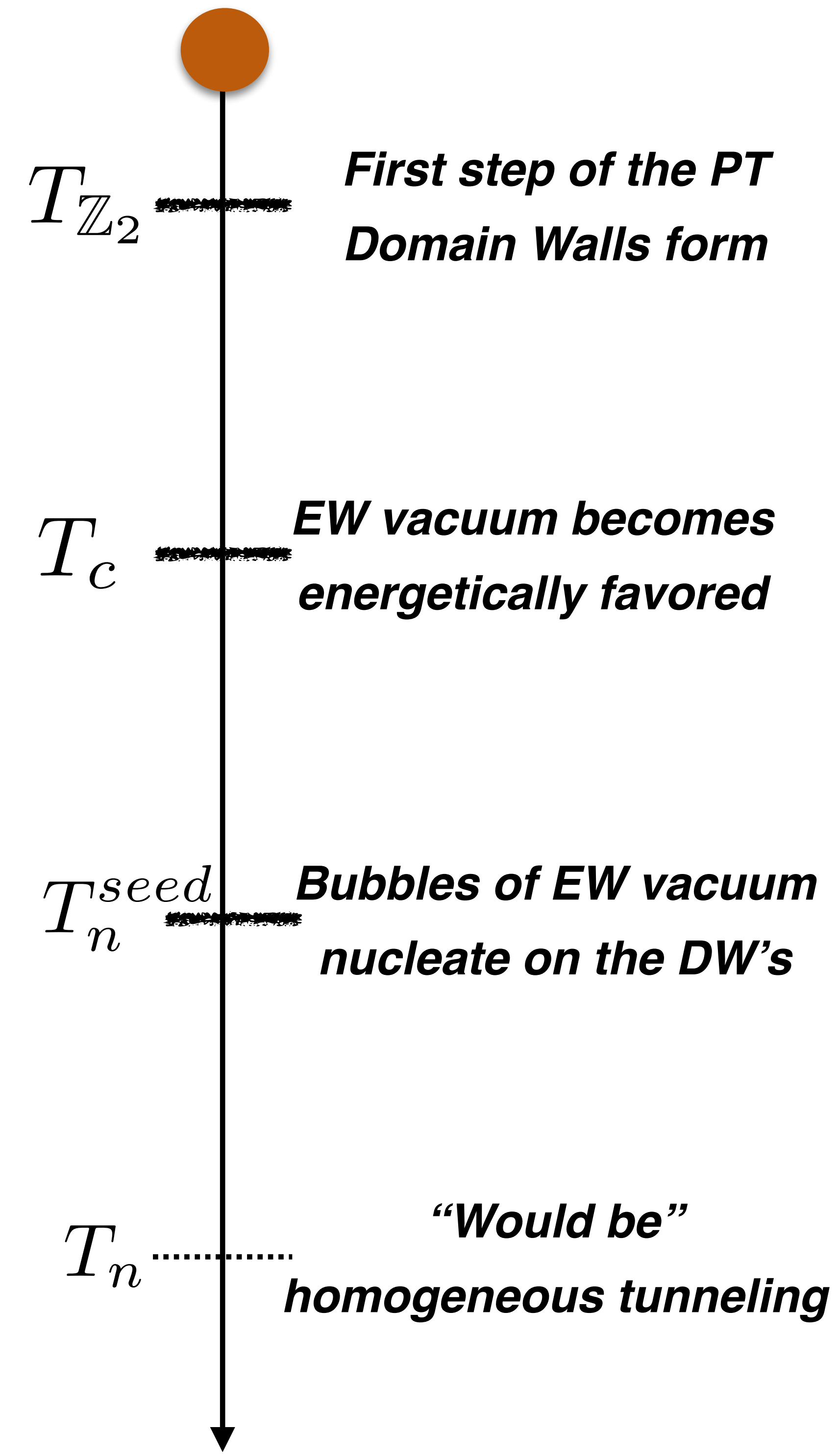


✳ *The field space trajectories differ in the two cases*

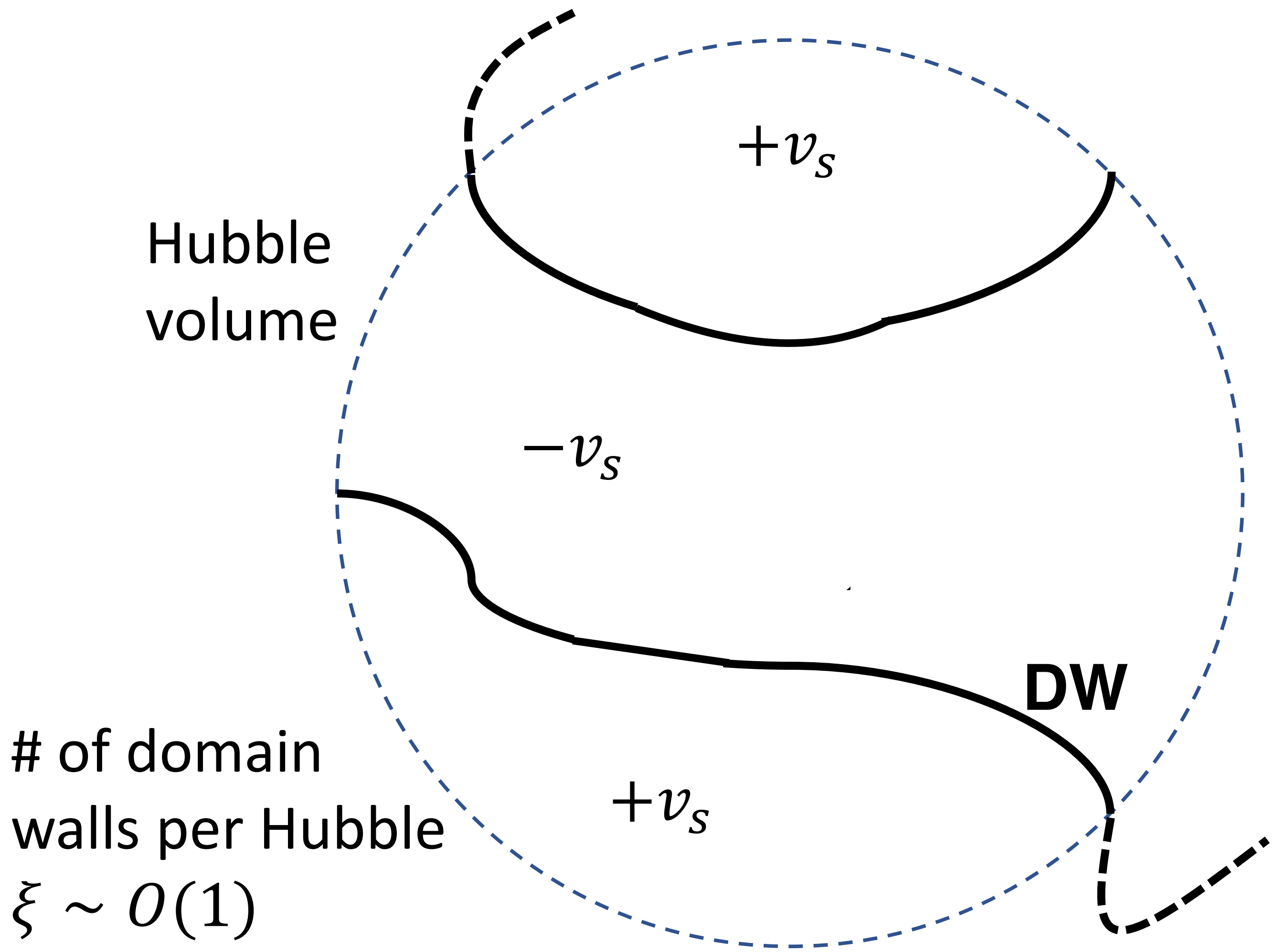
Cosmological history of Seeded vs homogeneous PT

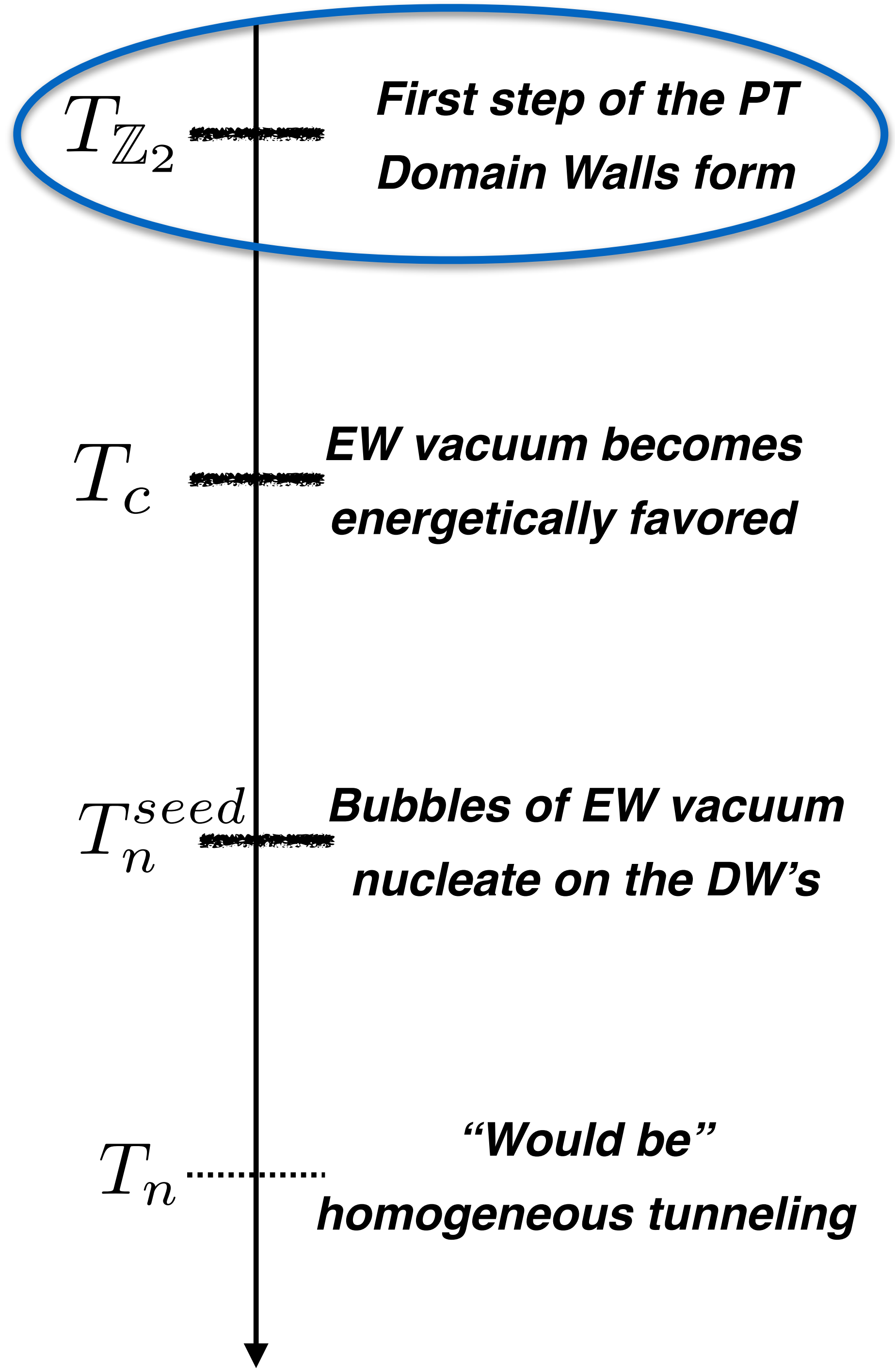
High - T





Cosmological history of Seeded vs homogeneous PT





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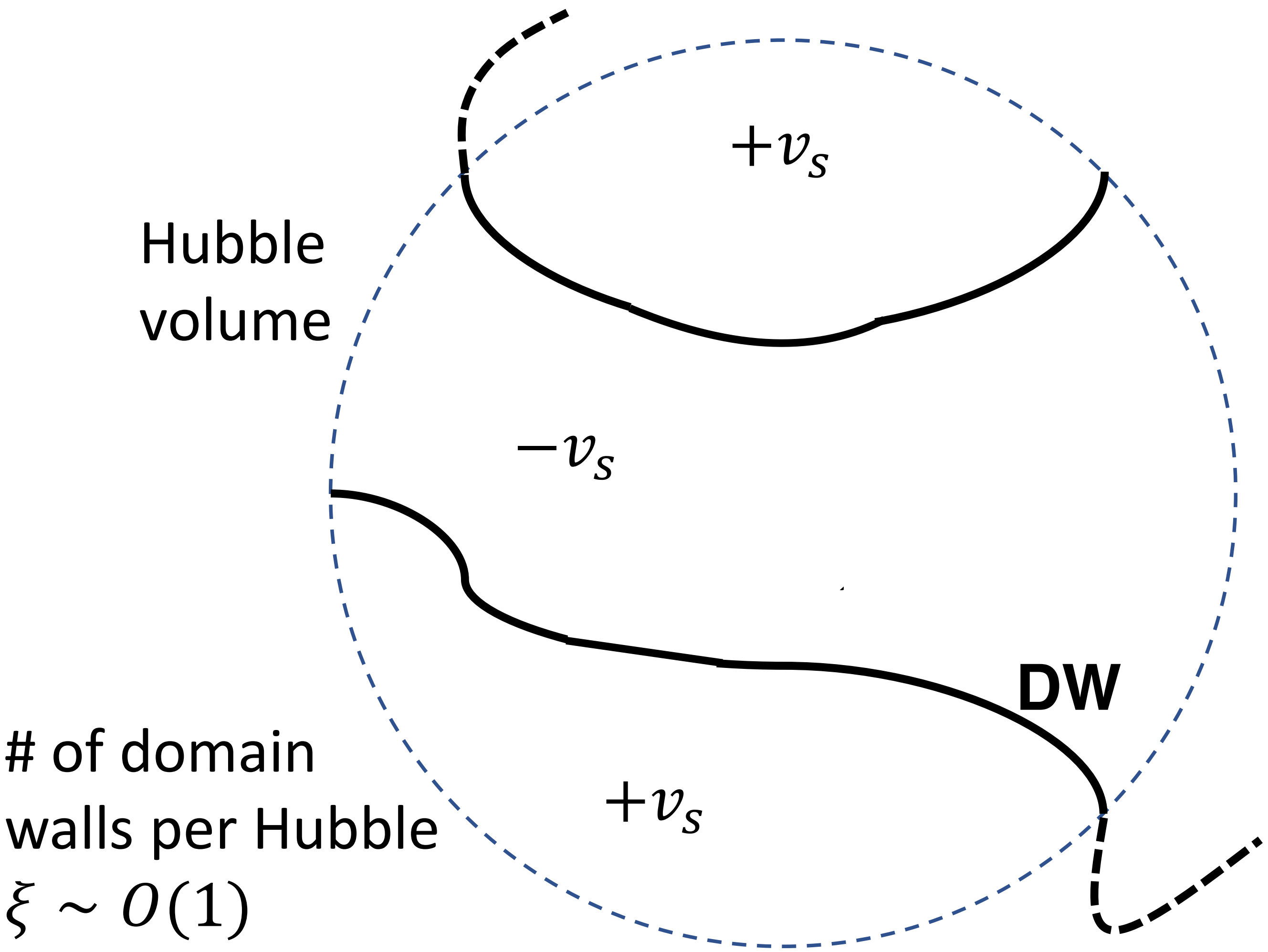
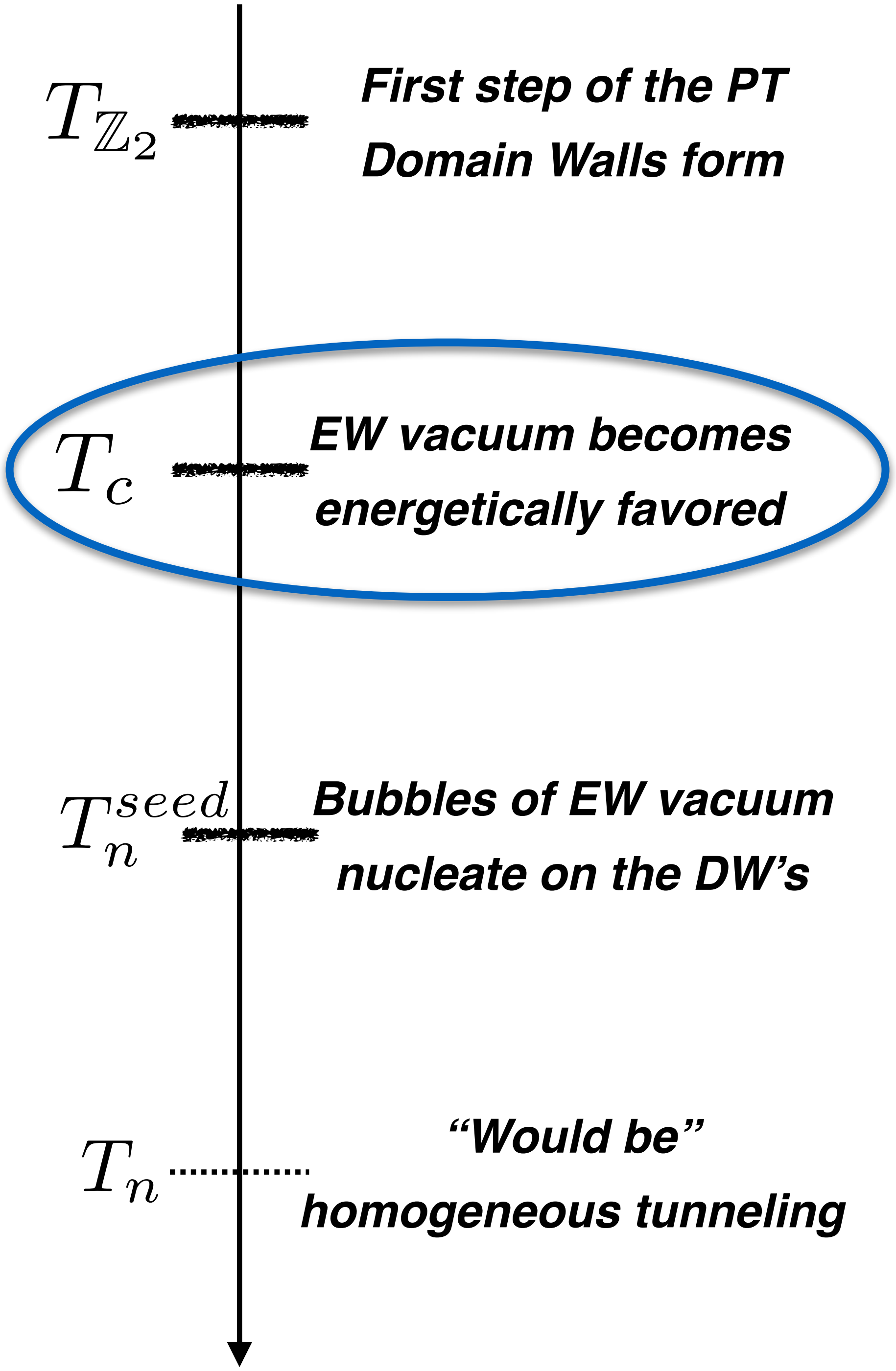
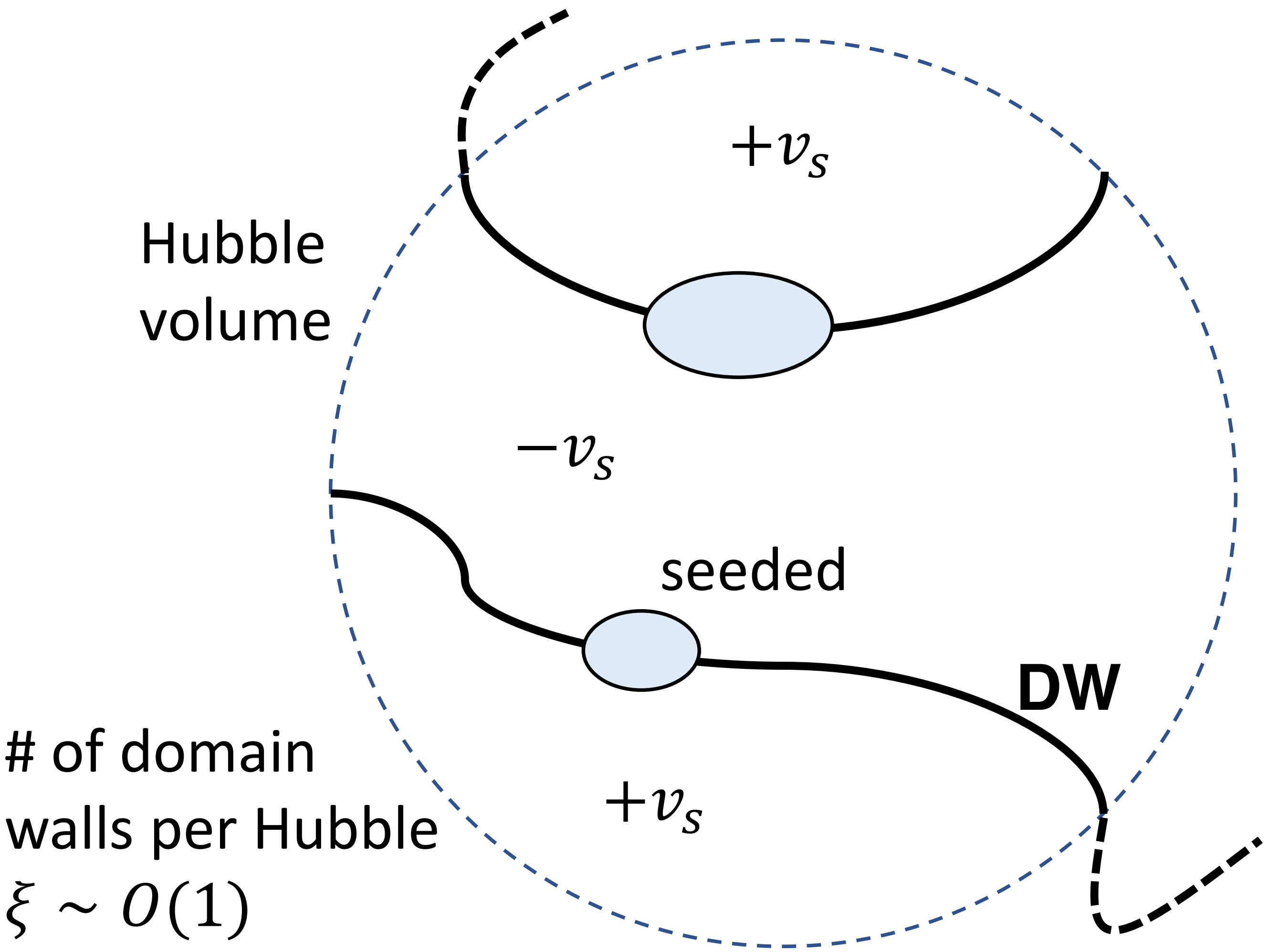
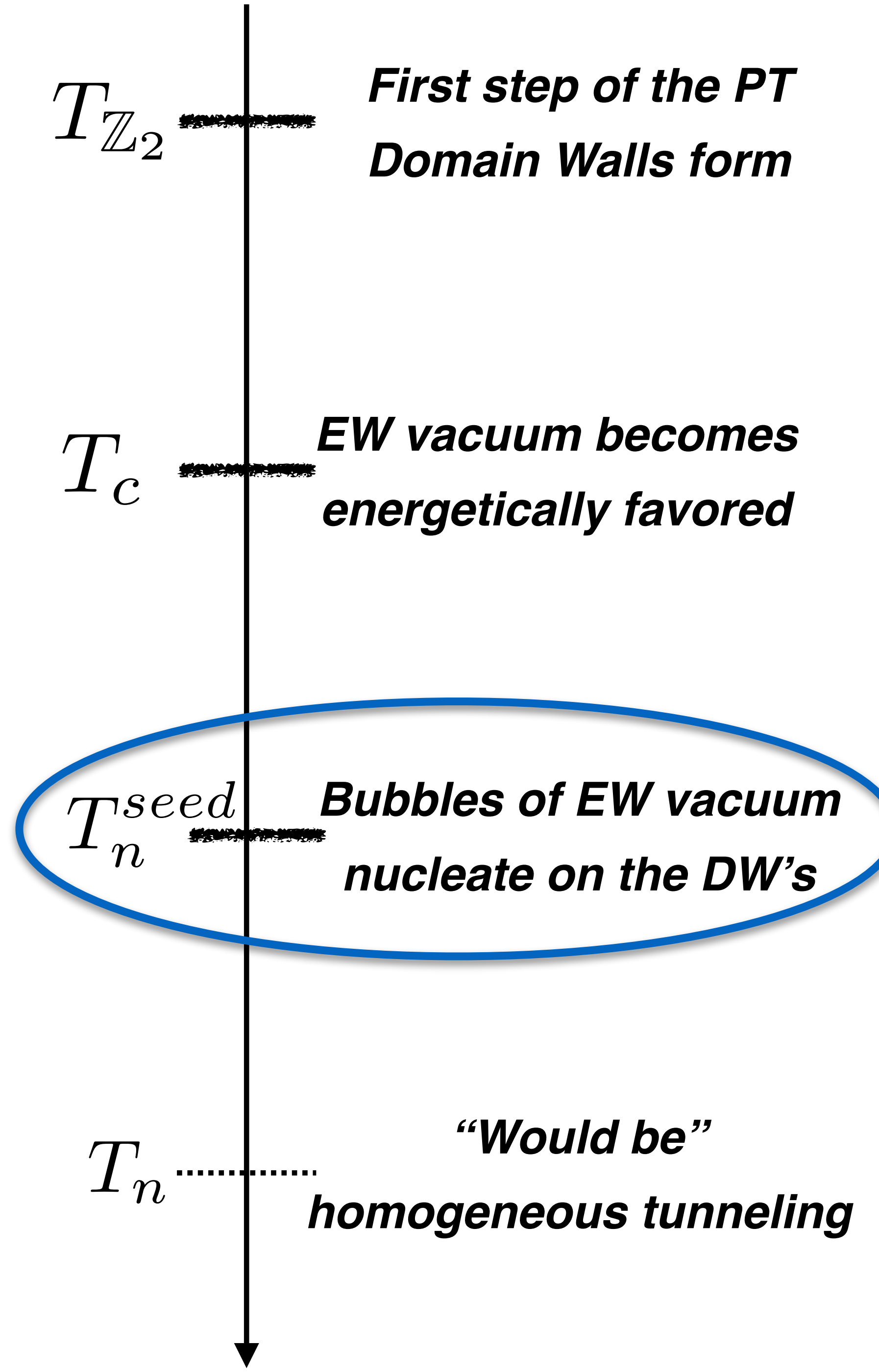




Cosmological history of Seeded vs homogeneous PT

Nucleation probability is enhanced around the impurities (DW) in the early Universe





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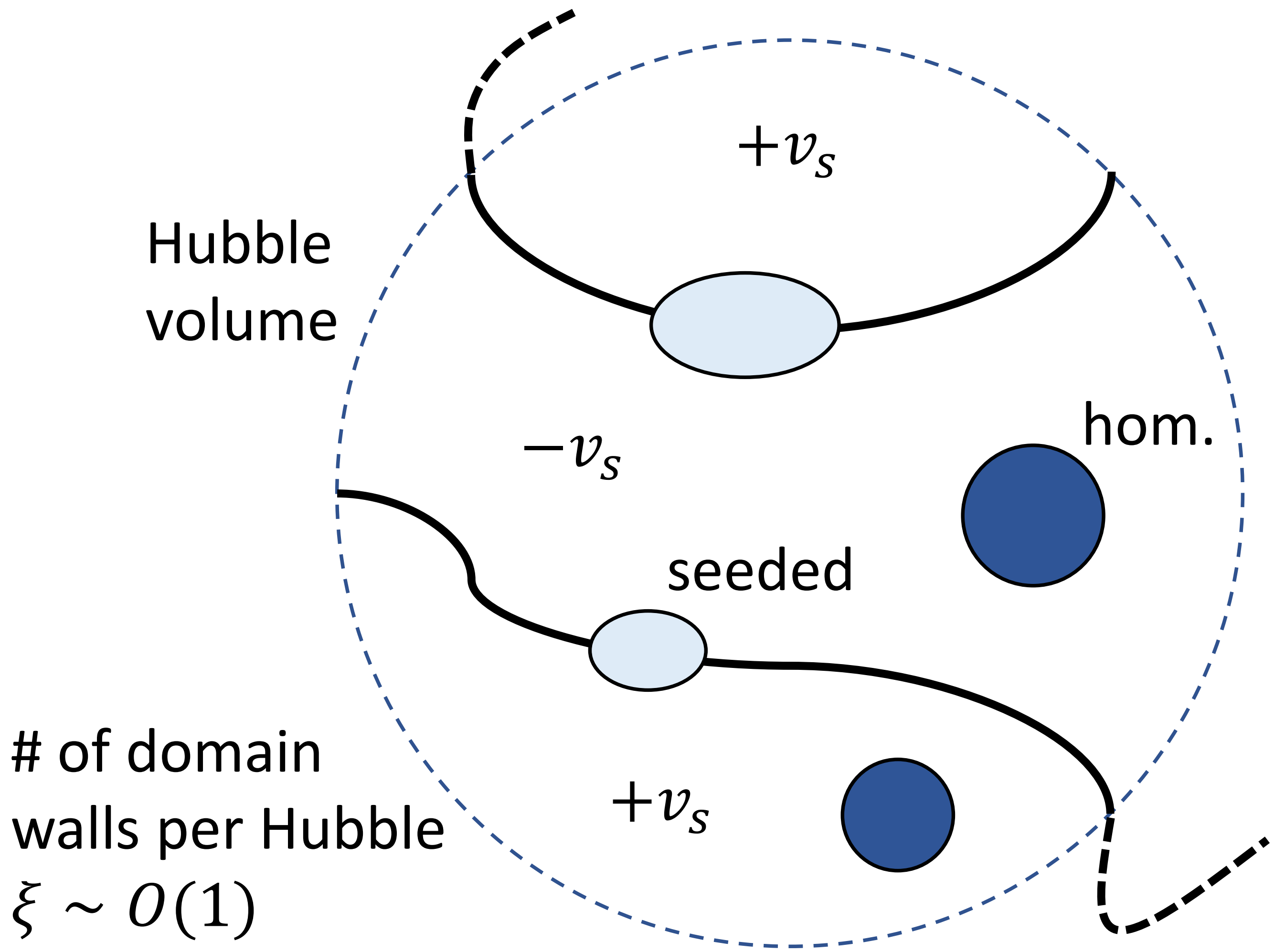
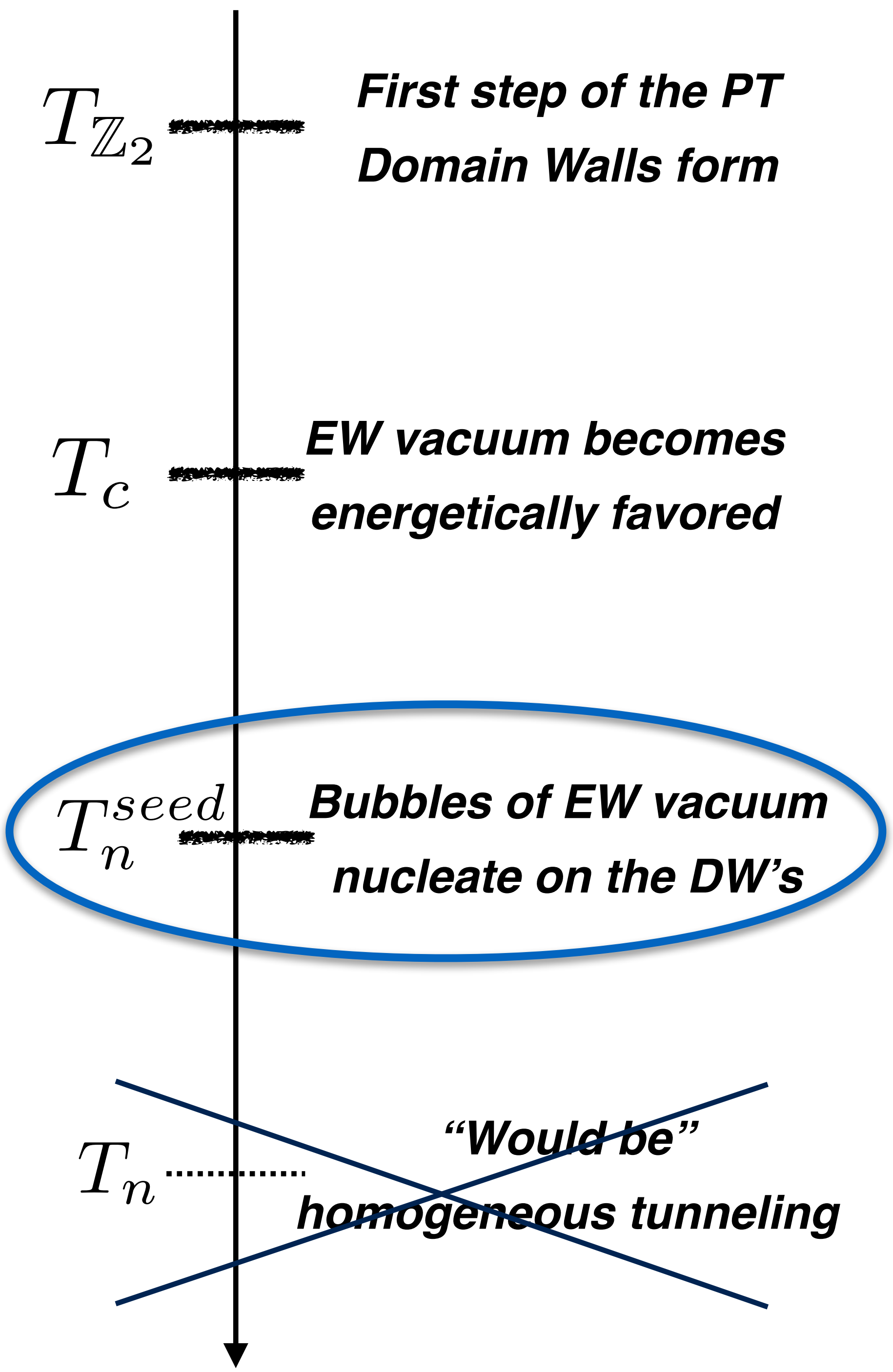
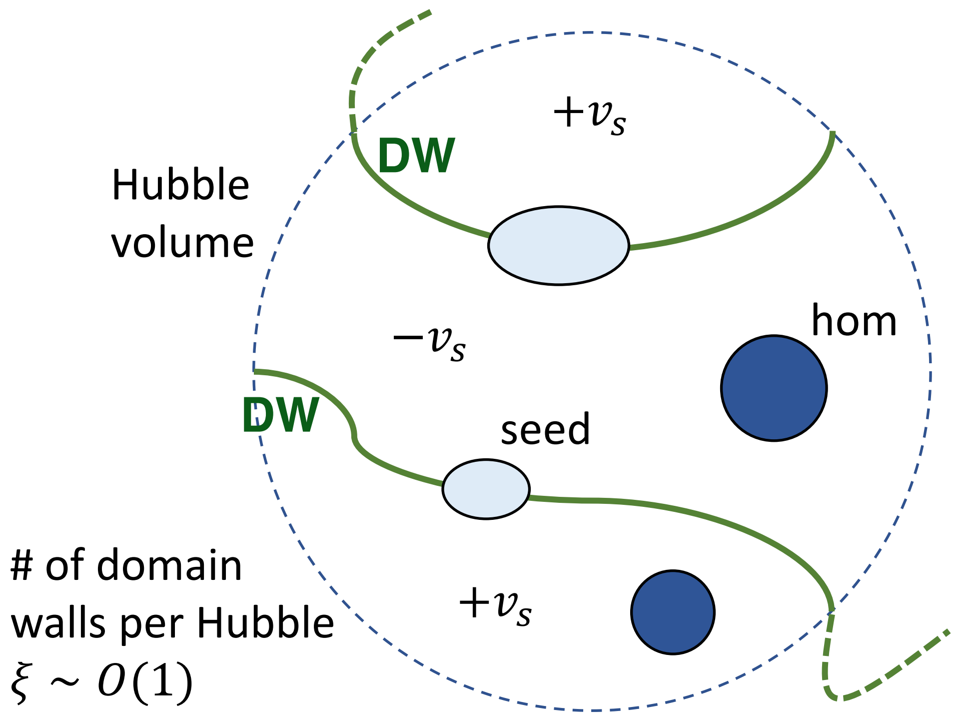




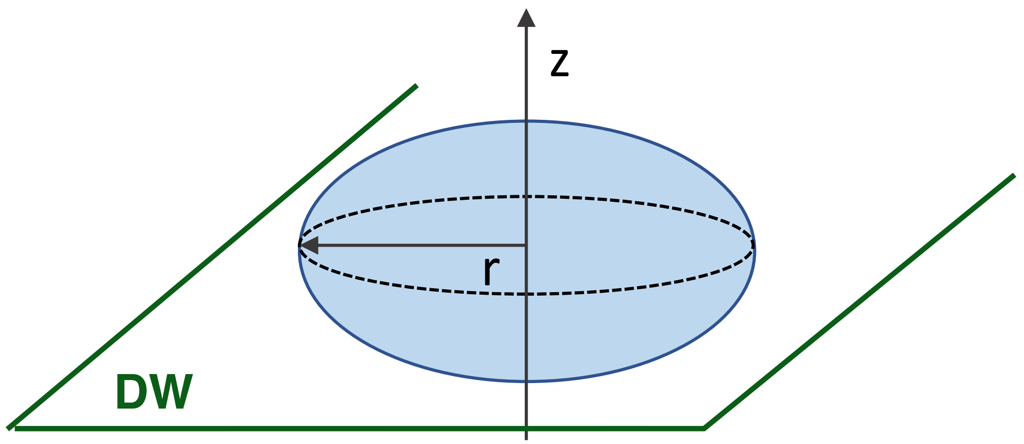
How to characterize and compute the seeded tunneling?

Seeded vs homogeneous nucleation

★ ***Look for nucleation probability 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***

$$\gamma_S(T_n^{seed}) \sim \frac{1}{\xi} H^3(T_n^{seed})$$

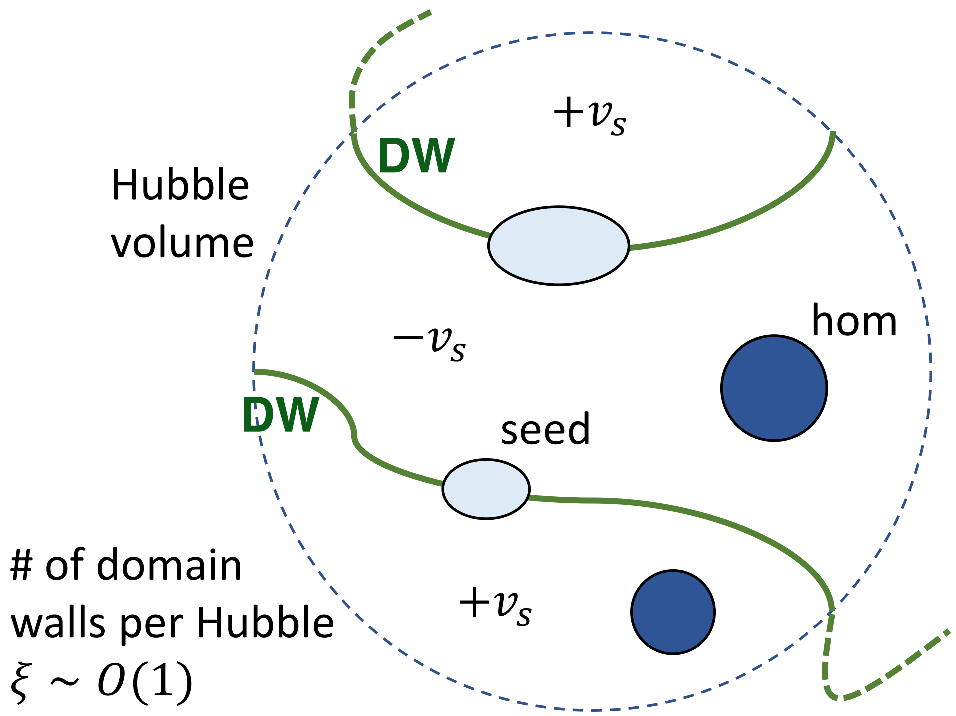
Remind for comparison homogeneous tunneling

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

Nucleation: $\gamma_V(T_n) \sim H(T_n)^4$

Seeded vs homogeneous nucleation

★ ***Look for nucleation probability at the DW location***



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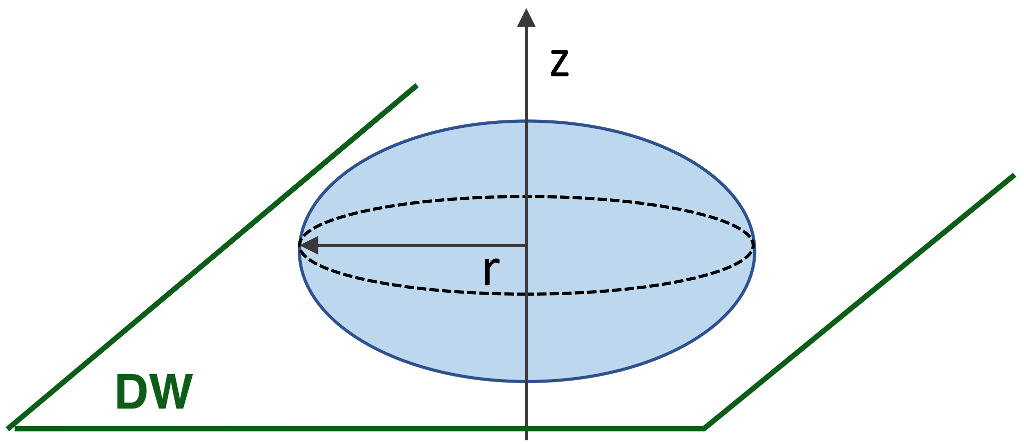

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✦ **Bounce action for the O(2) symmetric seeded bubble**

✦ ***How to compute it?***

Thin wall approximation

★**Thin wall approximation to estimate energy of critical bubble**

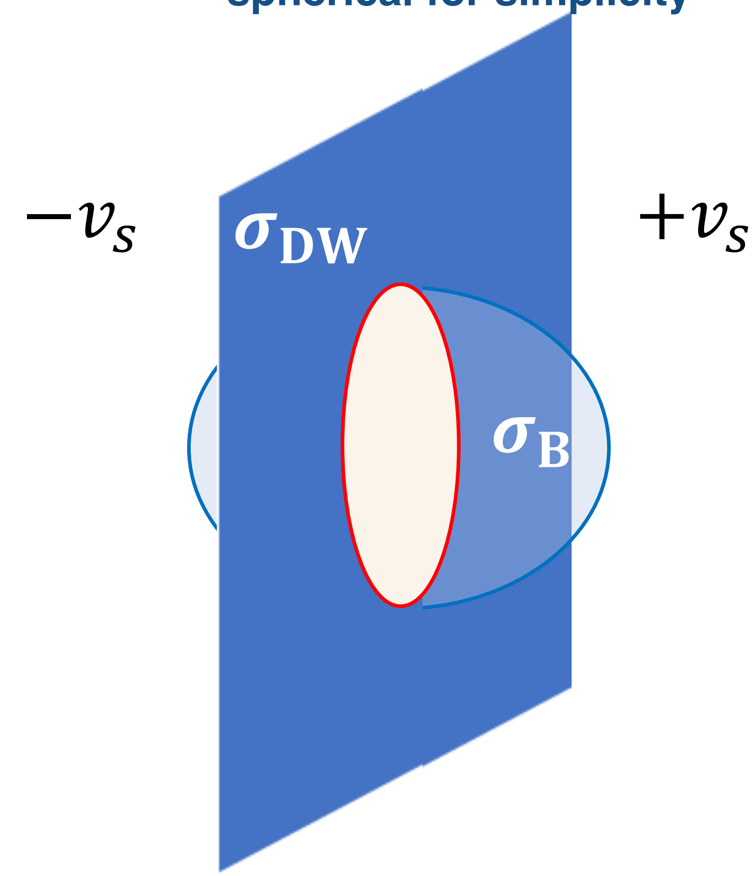
As in Homogeneous PT

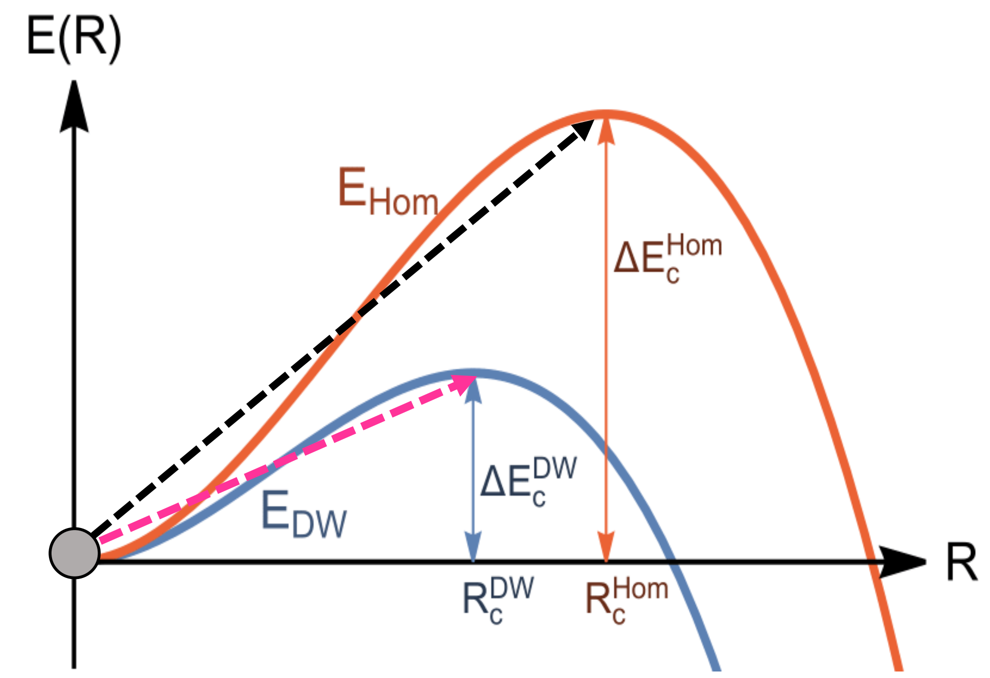
$$E(R) \simeq 4\pi R^2 \sigma_B - \frac{4}{3}\pi R^3 \Delta V - \pi R^2 \sigma_{\rm DW}$$

Surface tension of the bubble (σ_B) — **Potential energy difference** (ΔV) — **Tension of the DW** ($\sigma_{\rm DW}$)

Gain of eating DW inside bubble

Assume bubble on DW O(3) spherical for simplicity





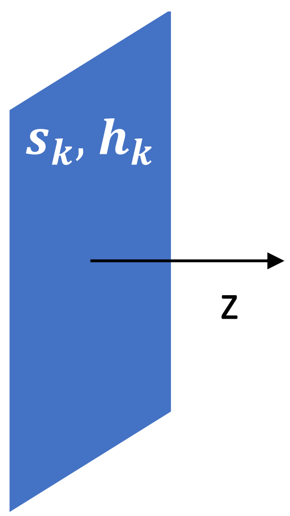
★***Domain walls catalyze phase transition***

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

Kaluza Klein reduction method

★Study 3-dimensional theory on the domain wall

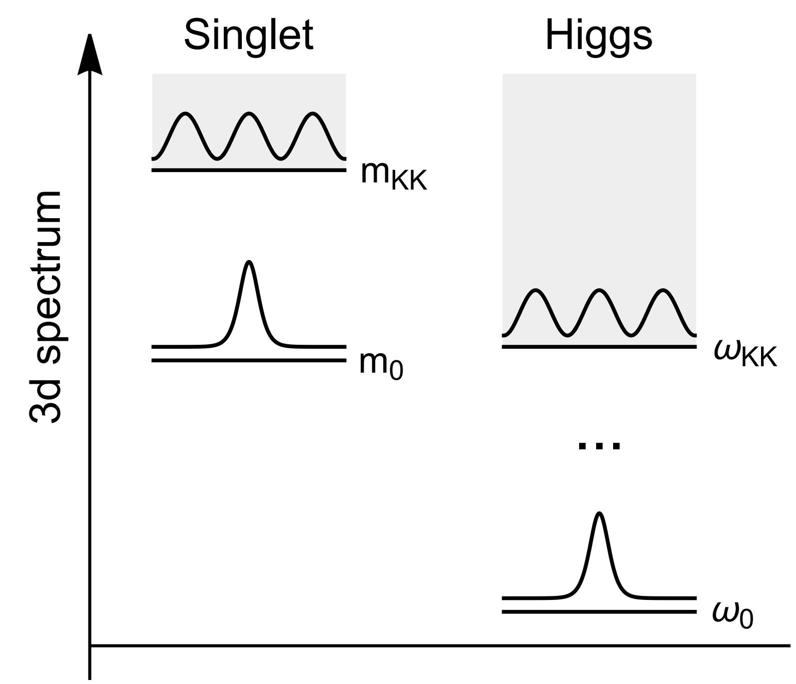
- ✳ KK spectrum contains massive localized states gapped to a continuum
- ✳ Bound states correspond to localized profiles in the z-direction
- ✳ Scattering states correspond to continuum



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

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

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



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

$\omega_0^2(T) < 0$ **Classical instability of DW** ◂- - - - - -▸ ***The "rolling"***

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

Kaluza Klein reduction method

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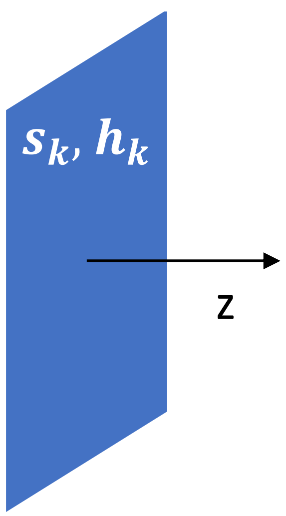

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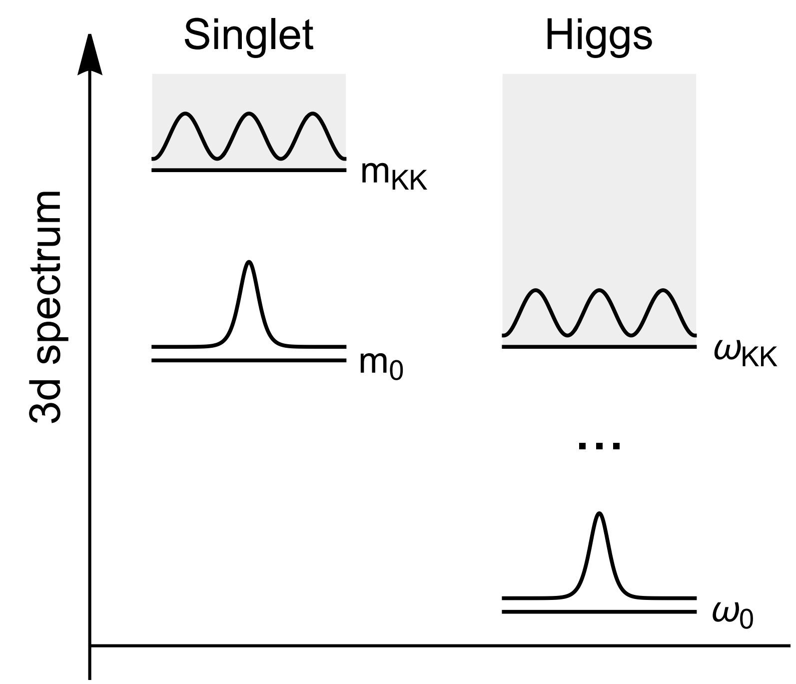

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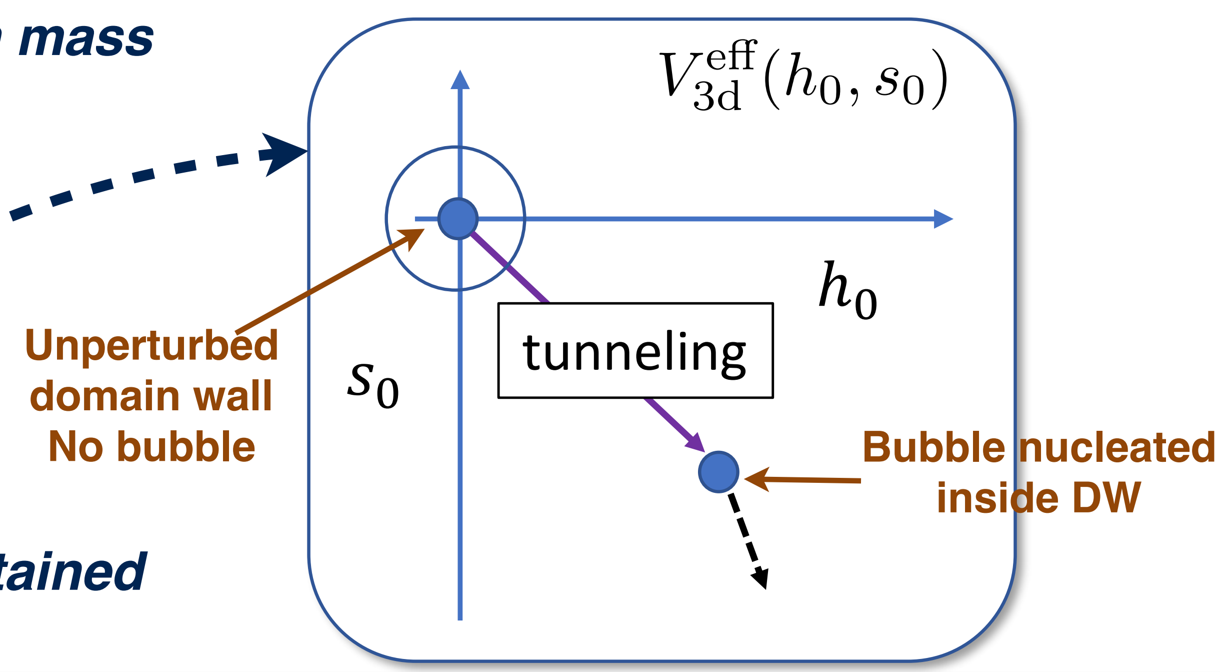


✦ ***The O(2) seeded bubble profile can be obtained***

Agrawal, Blasi, Nee, AM '23

Numerics: mountain pass algorithm

★Numerical solving for the PDE's is a non trivial task

- *Reduced symmetry (only O(2))*
- *Bounce action is a saddle point*

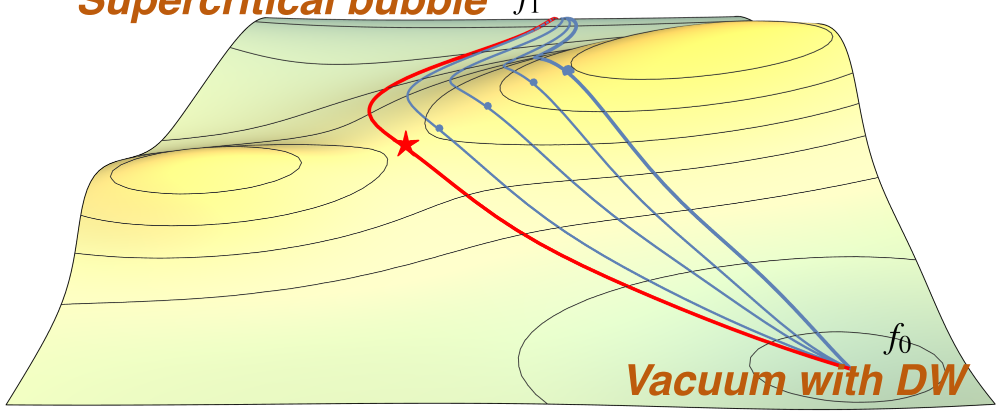


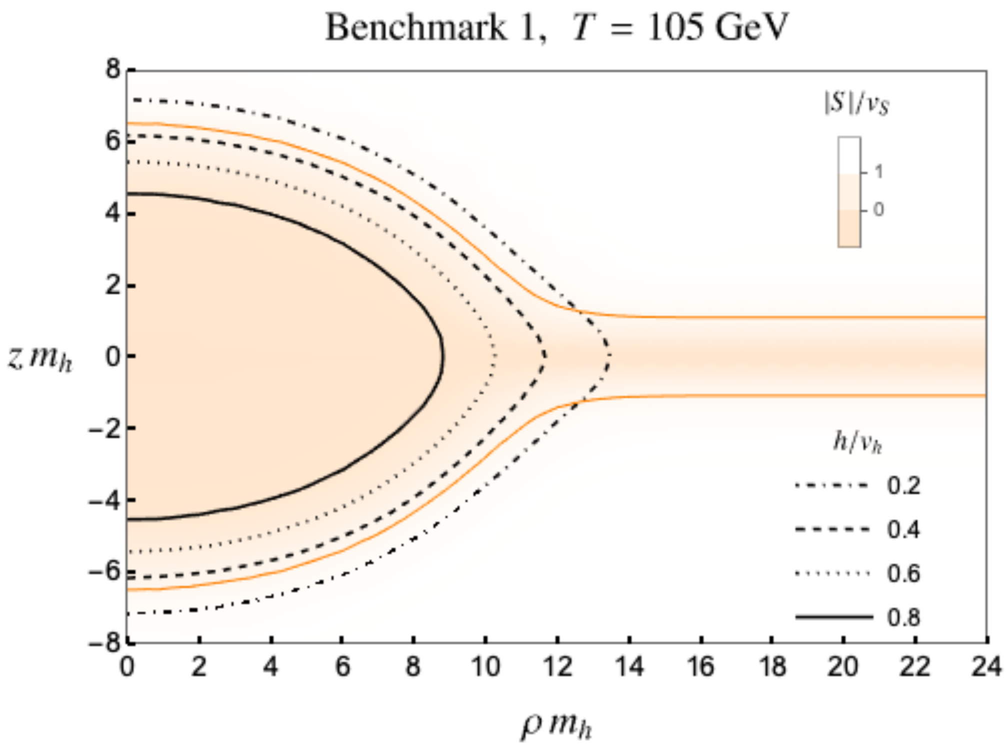
Figure from: Agrawal, Nee '22 SciPost

✦Employ a numerical algorithm suitable to find saddles

Designed to find the "mountain pass" between two points

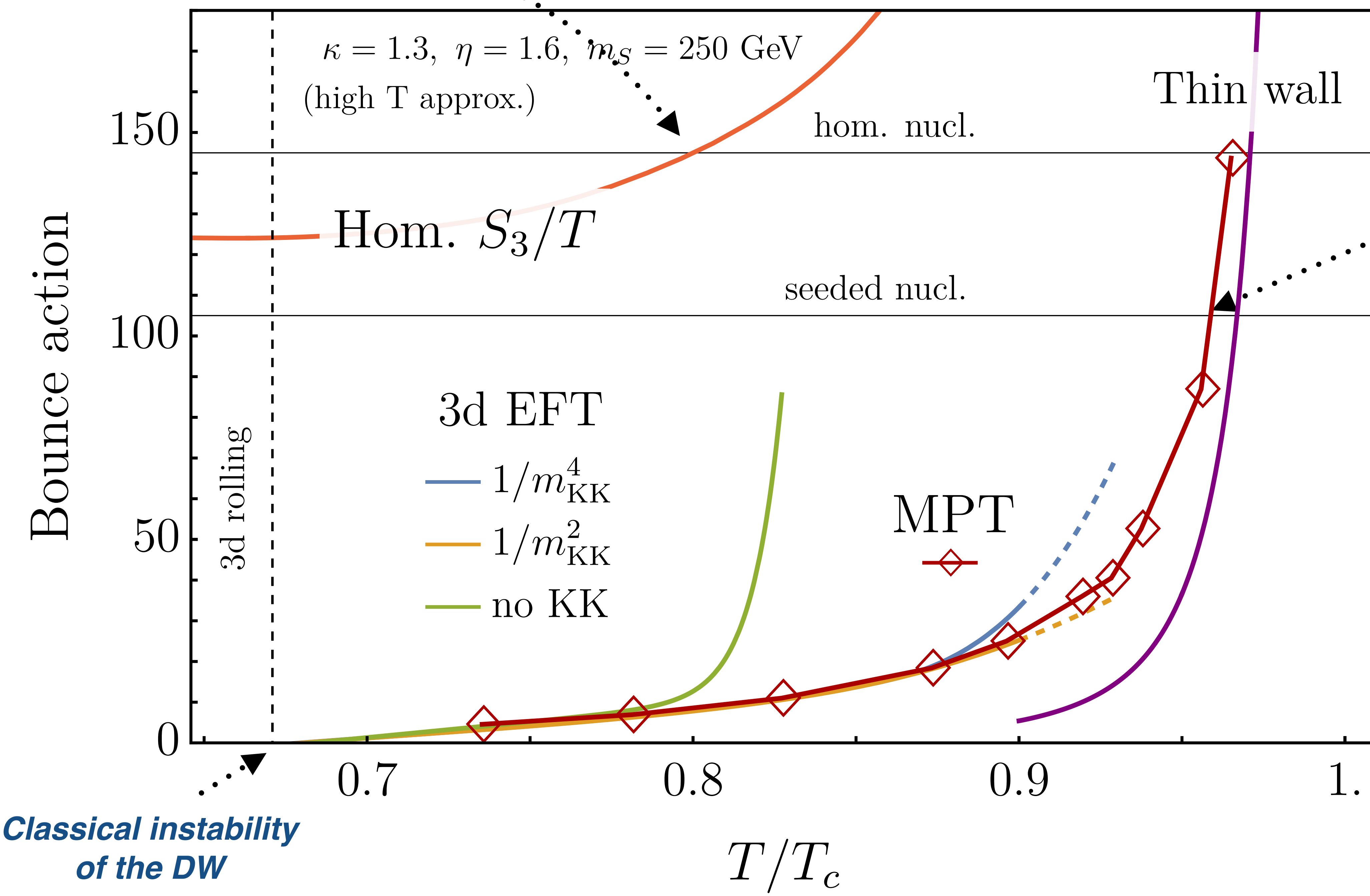
Agrawal, Nee '22 SciPost

Bubble profile and bounce action found for full thermal effective potential



Bounce action in 3 methods

Homogeneous nucleation would happen here



Seeded nucleation occurs here

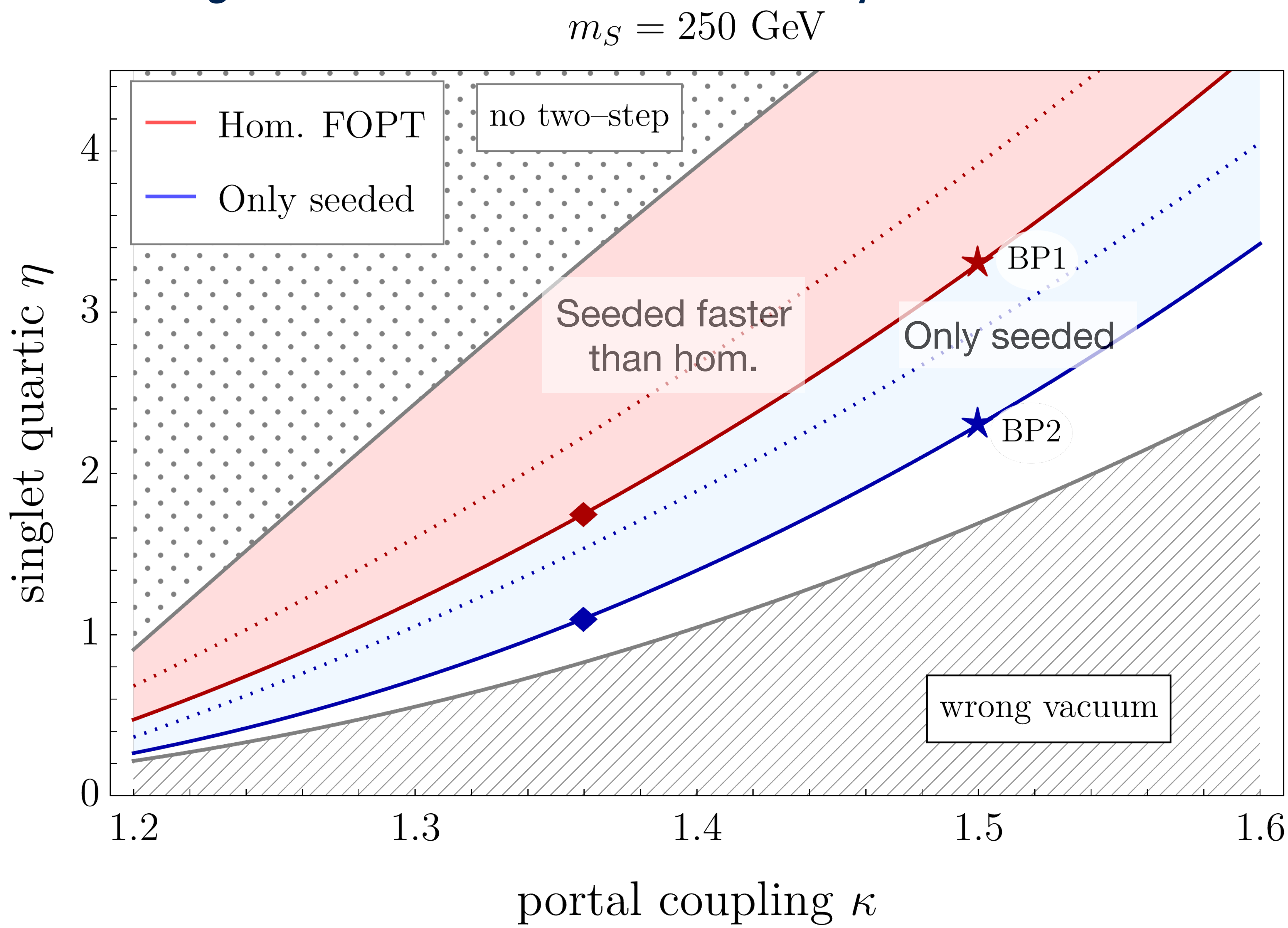
Classical instability of the DW

EW Phase transition seeded by the DW always dominates !

Impact on Higgs-Singlet parameter space

★***Seeded phase transition always faster than homogeneous PT***

★***New viable region in parameter space thanks to seeded PT***



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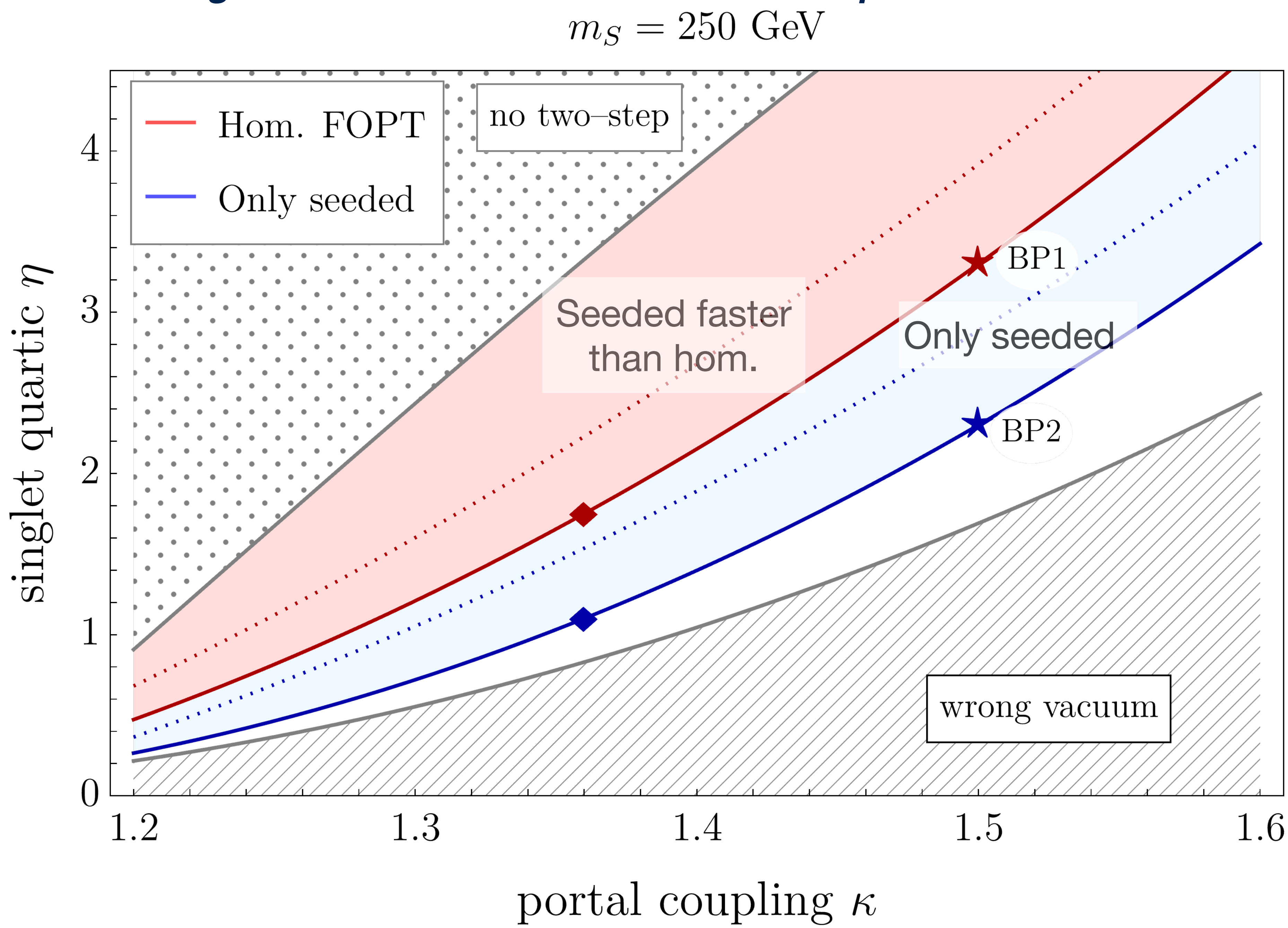
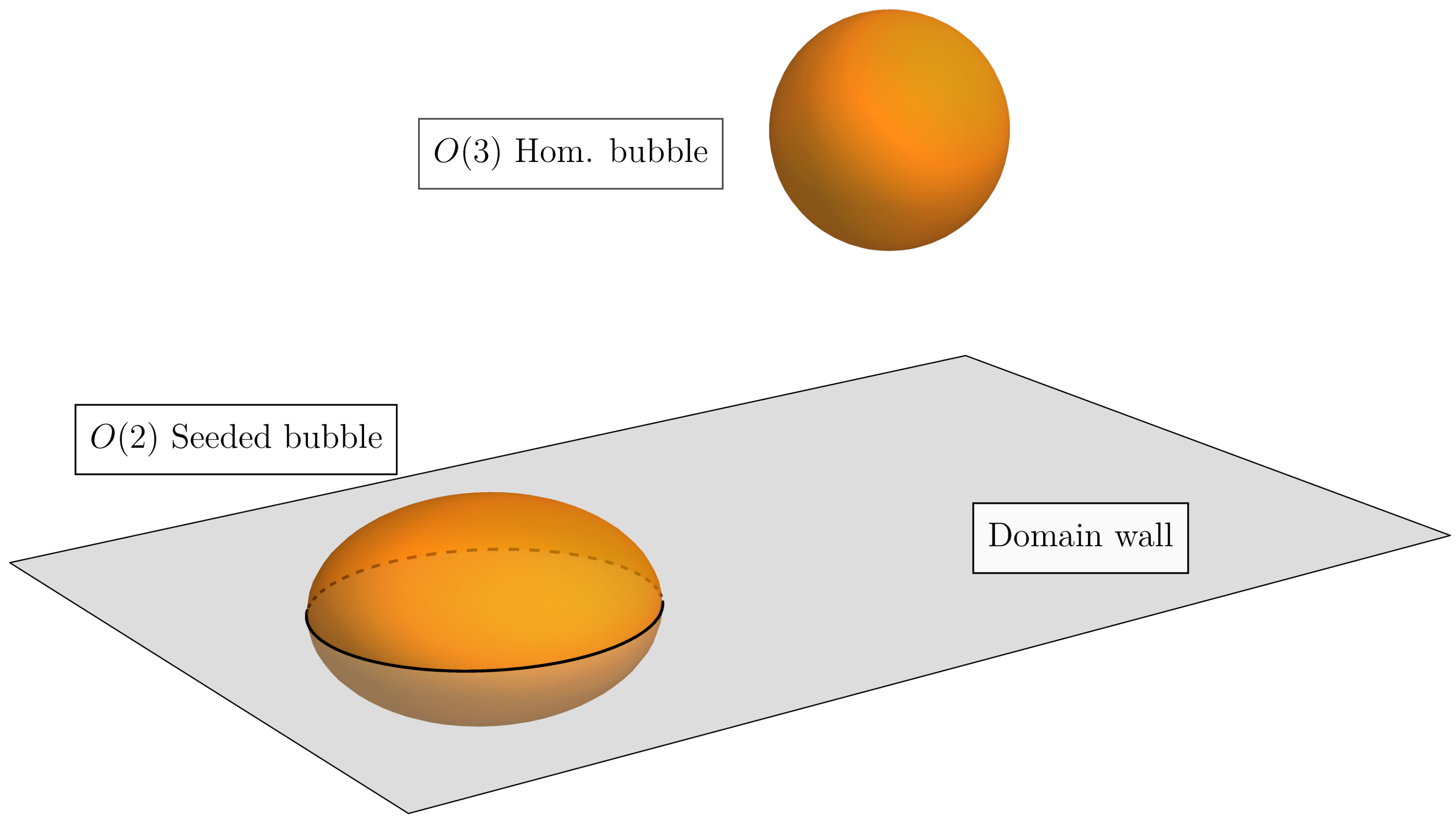


★***Certain quality of the Z2 symmetry is needed for DW to exist***

✳ **Z2 symmetry explicitly broken by Planck scale suppressed operator is allowed**

Agrawal, Blasi, Nee, AM '23

Properties of the seeded PT?

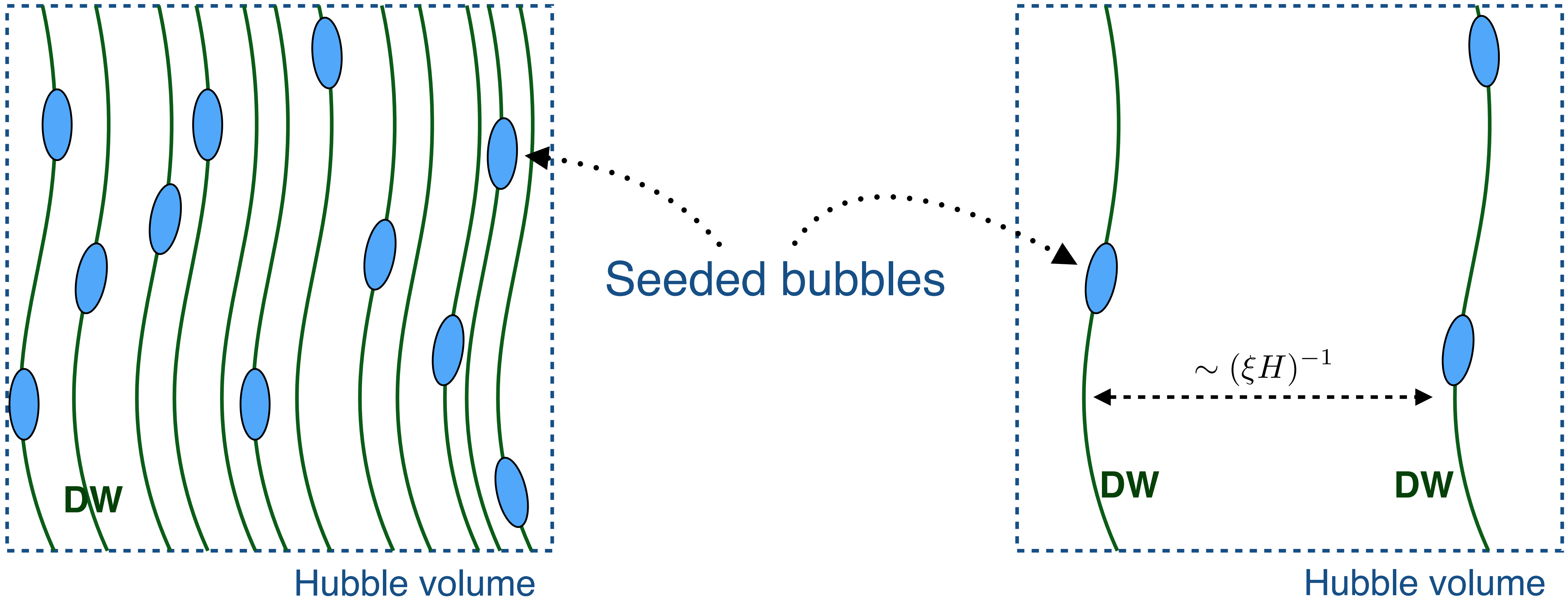


- ★*Criteria for the seeded phase transition to complete (percolation)*
- ★*Special features in latent heat and typical time scale?*
- ★*Special features in gravitational waves?*

See Blasi, Konstandin, Rubira, Stomberg '23 for GW from sound waves in seeded PT

Properties of the seeded PT?

Dense DW network | ***Sparse DW network***



Relevant time scale

$$\beta_{DW} = -\frac{dS_{DW}}{dt}\bigg|_{T_n}$$

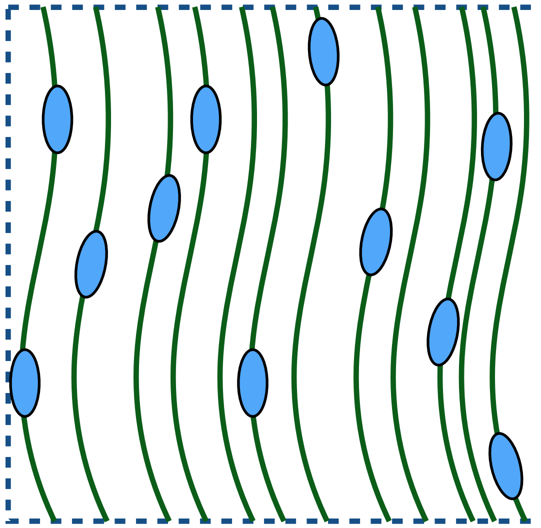
Relevant time scale

$$\beta_\xi = v_w \xi H\Big|_{T_n}$$

★ ***Generic network*** $\beta = \mathrm{Min}(\beta_{DW}, \beta_\xi)$

Properties of the seeded PT?

Dense DW network



Seeded PT features controlled by O(2) bounce

$$\beta_{DW} = -\frac{dS_{DW}}{dt}\Big|_{T_n}$$

★ ***Percolation temperature***

$$I(T_p) \simeq 0.34$$

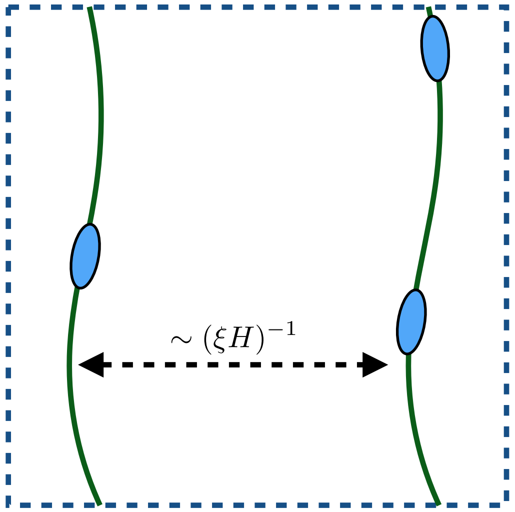
Usual expression for volume fraction in true vacuum

★ ***Bubble size at percolation***

$$R_{\rm p}^{\rm 3D} = -v_w (8\pi)^{1/3} \left(\frac{dB_{\rm DW}}{dt}\Big|_{T_{\rm p}} \right)^{-1}$$

Latent Heat and bubble size are different

Sparse DW network



Seeded PT features controlled by number of DW

$$\beta_\xi = v_w \xi H \Big|_{T_n}$$

★ ***Percolation temperature***

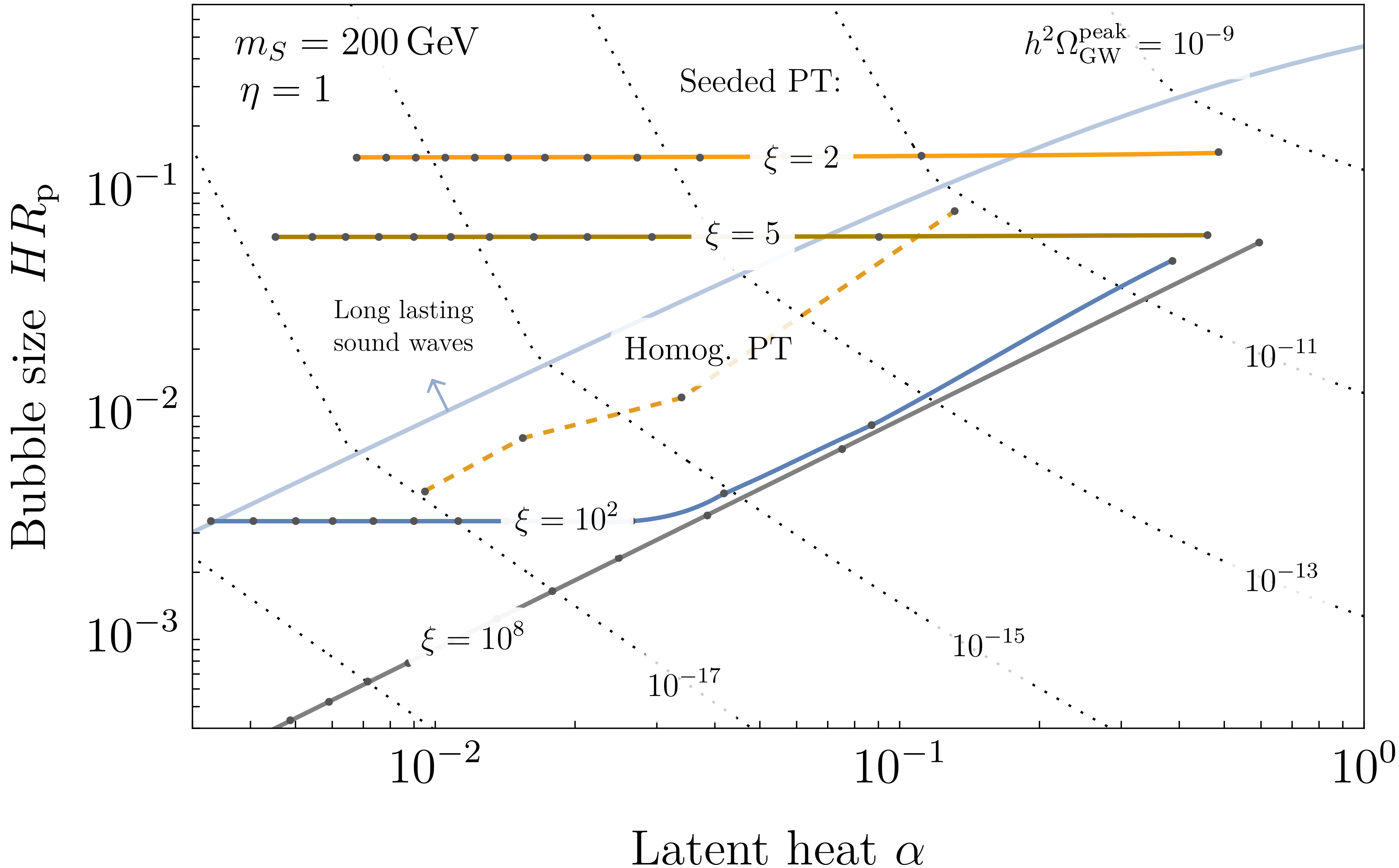
$$T_{\rm p}^\xi = \frac{1}{1 + \frac{n_c}{2\xi v_w}} T_{\rm n}$$

For monopoles: Guth-Weimberg '81

★ ***Bubble size at percolation***

$$R_p^\xi = \frac{n_c}{2\xi H} \left(1 + \frac{n_c}{2\xi v_w} \right)$$

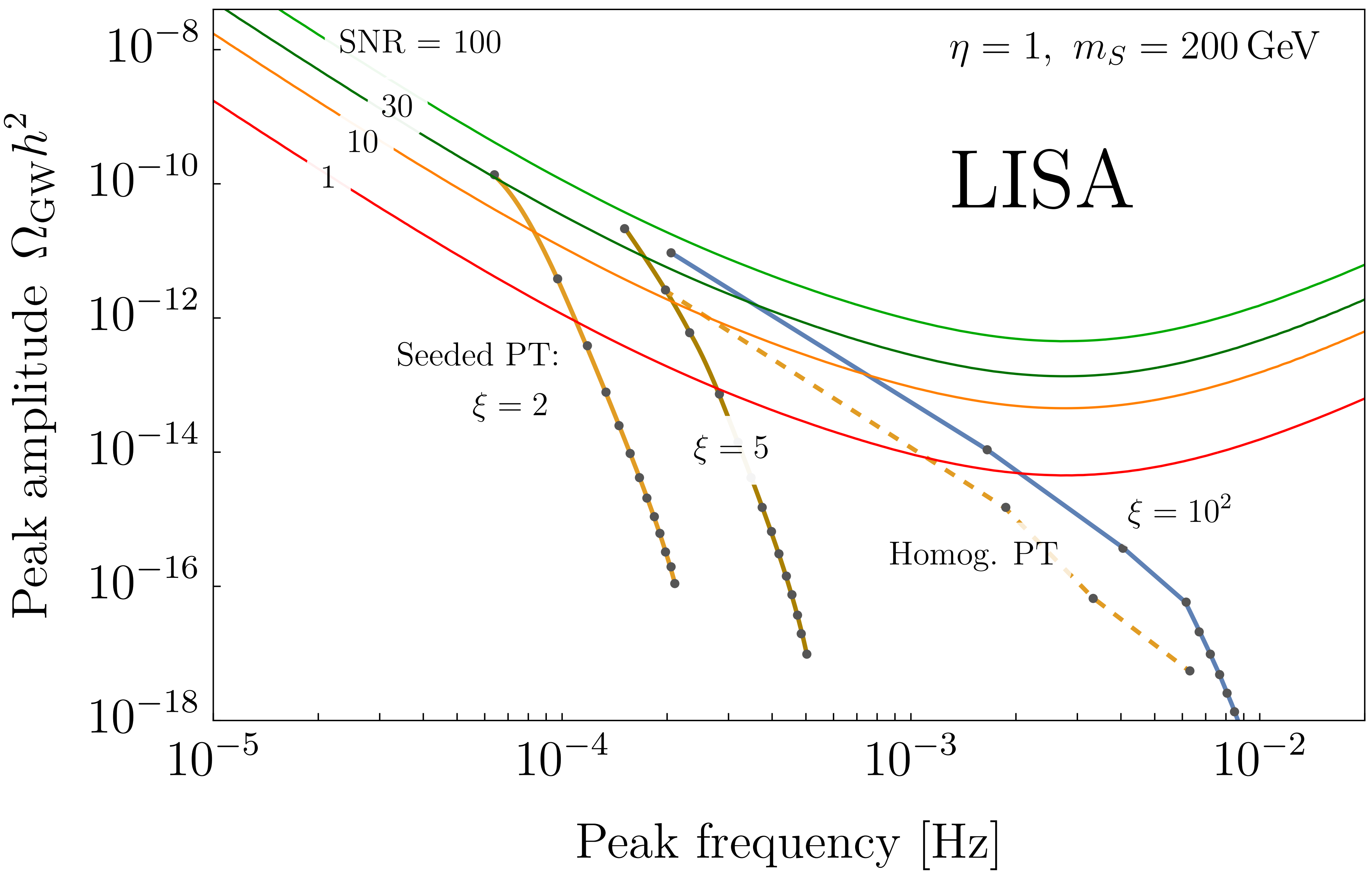
Bubble size and latent heat



★***Decorrelation between bubble size and latent heat***

Impact in GW spectrum

★***How GW signal from networks compare with homogeneos one***



Conclusions

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

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

→ *The EW PT can be catalyzed by topological defects*

★ *Minimal realization with DW in Higgs Singlet model (xSM)*

★ *It can impact several well-known models and expected signatures*

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

★ *Phenomenological implications for*

- *Gravitational wave spectrum*
- *Baryogenesis*
- *Primordial Black hole production*

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Thanks for the attention

Backup slide

★Percolation temperatures for homogeneous and seeded tunneling