Ripples in spacetime from broken SUSY

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Based on arXiv:2011.13949 (JHEP)
with Nathaniel Craig, Noam Levi and Diego Redigolo

Durham University IPPP
20 May 2021

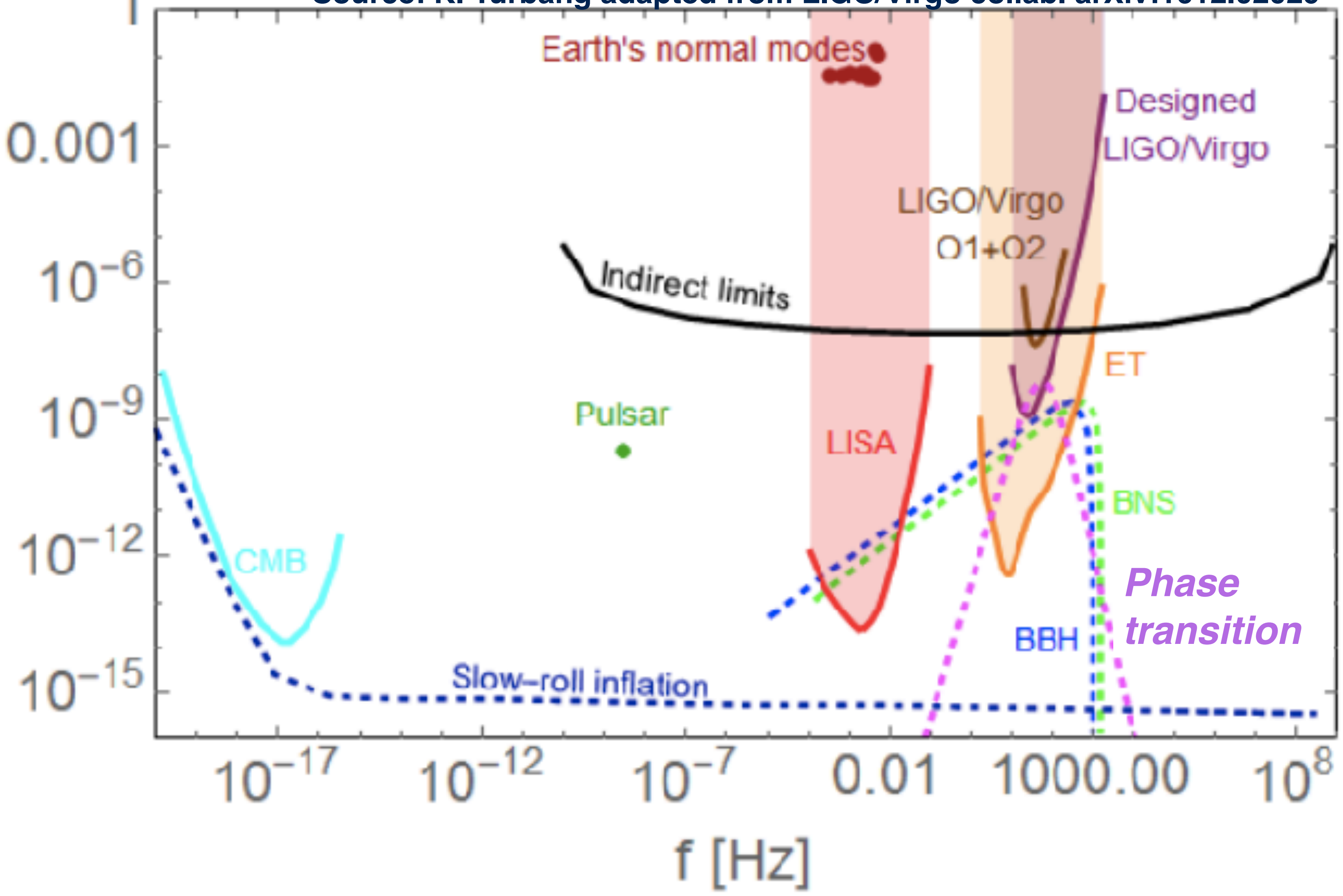
Stochastic Background of GW

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

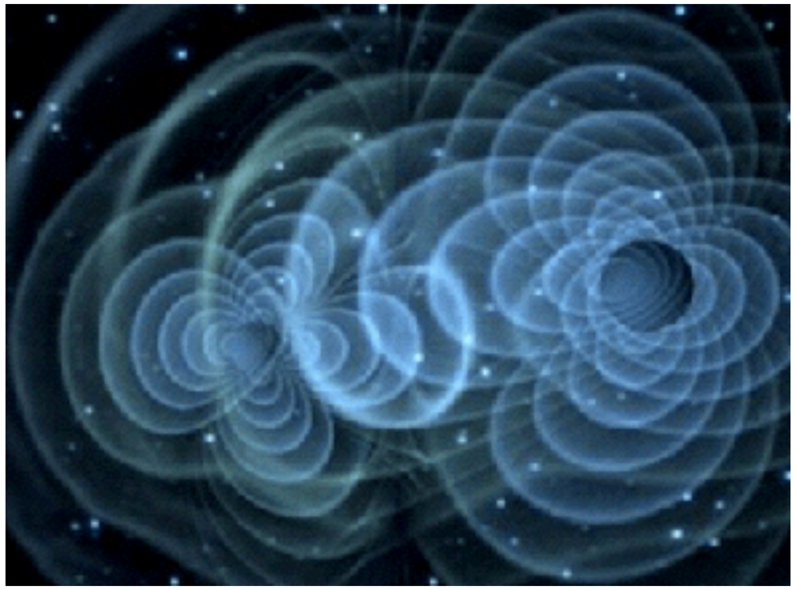
- ✴ Superposition of unresolvable sources

BBH **BNS**

- ✴ Predictable after LIGO/Virgo observations

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

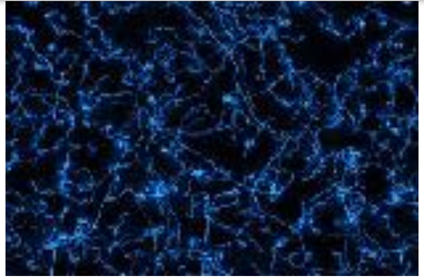
! Most likely measured in next few years !



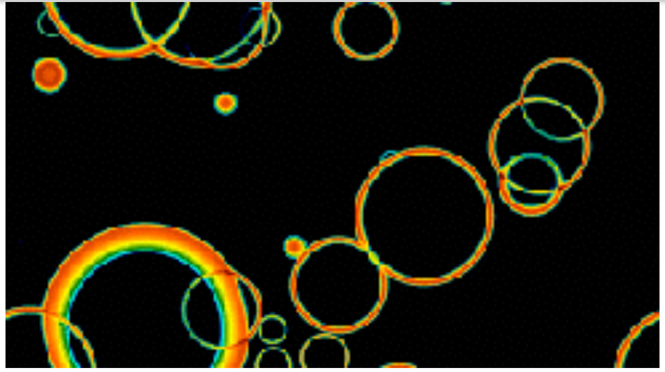
★Cosmological SGWB

- ✴ Generated by energetic events during cosmological evolution

Cosmic strings



First Order Phase Transitions



arXiv: 1705.01783 D. Weir

Inflation

Explore Universe earlier than CMB!

Stochastic Background of GW

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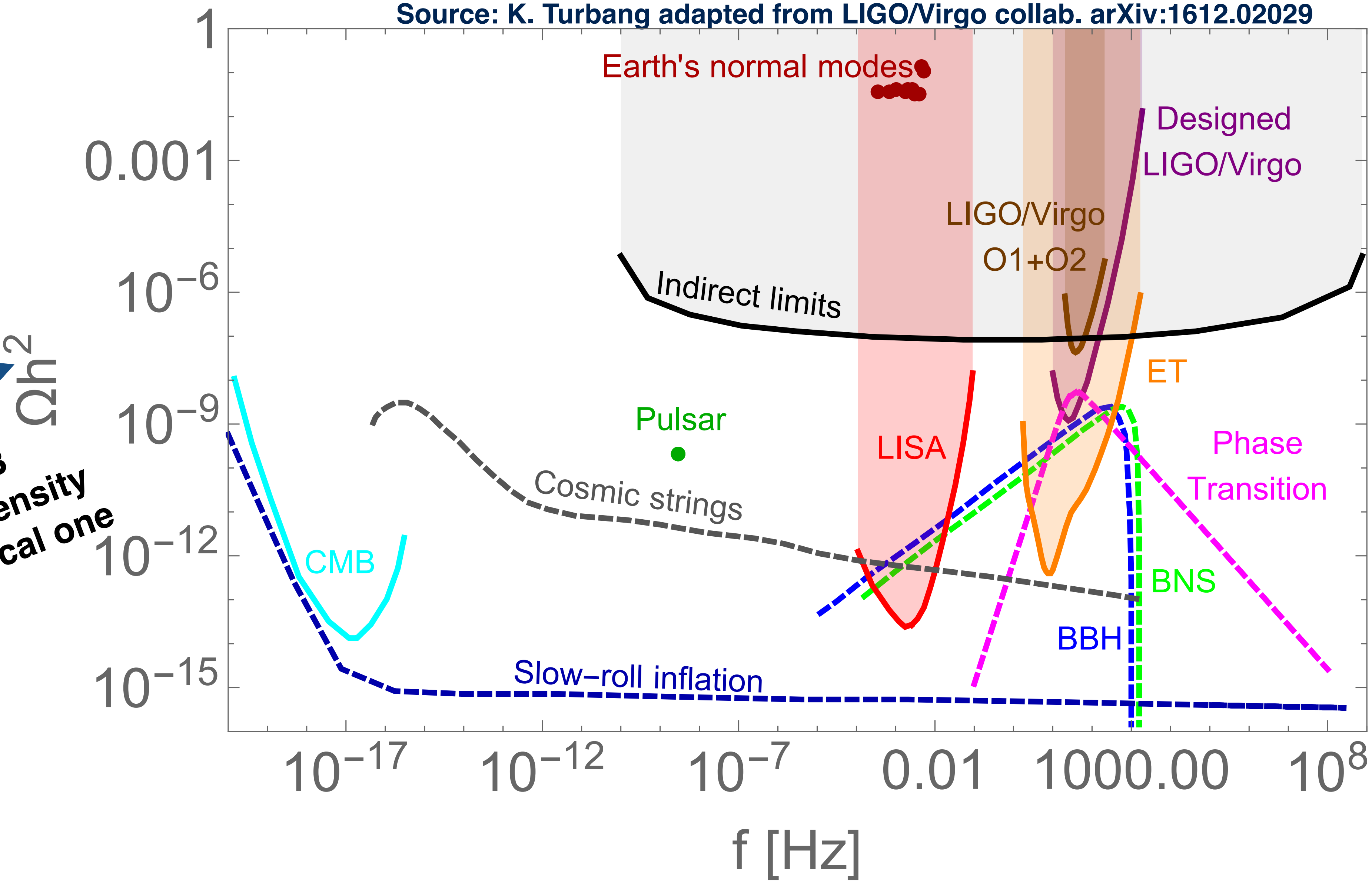


SGWB energy density over critical one

Experimental probes

★CMB, Pulsar timing arrays (NANOgrav)

★Interferometers (LIGO/Virgo, LISA, ET, CE, BBO ....)

LIGO/Virgo arXiv:2101.12130

Note: Astrophysical SGWB and cosmological SGWB will superimpose

First order phase transitions

First order phase transitions

✦Discontinuos Transition between symmetric to non-symmetric phase (order parameter)

✦Characterized by bubble formations

✦*Bubbles can source GW*

★*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

FOPT is signal of BSM physics

★*In Beyond the Standard Model*

Modify EW or QCD phase transition

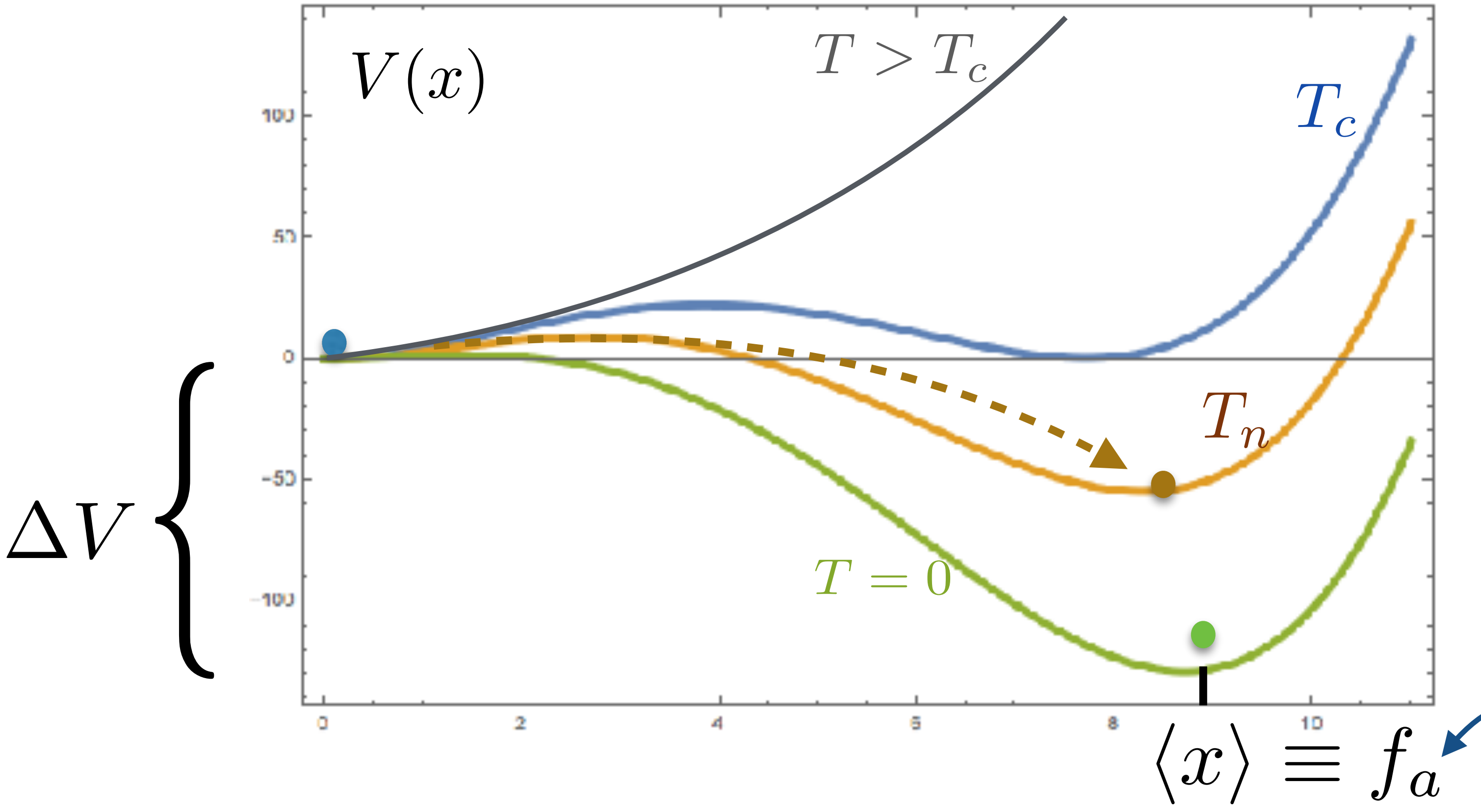
New symmetries which undergo PT

PT in dark sectors

First order phase transitions

Described in terms of potential evolution with temperature

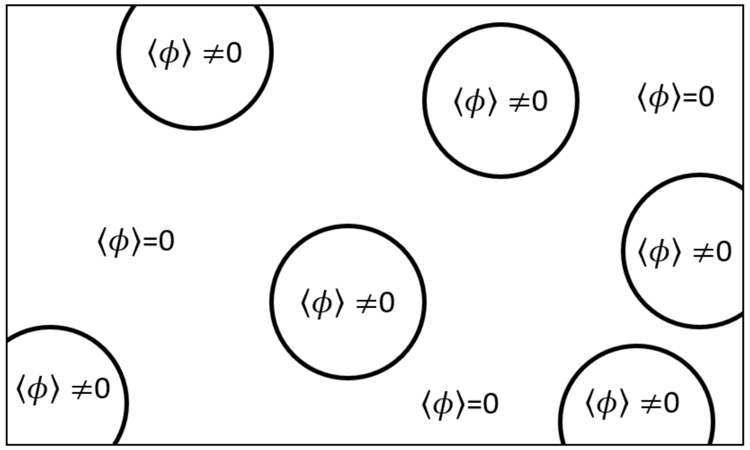
Transition from metastable minimum to symmetry breaking vacuum



Order parameter for symmetry breaking

T_c ***minima are degenerate***

T_n ***nucleation to symmetry breaking vacuum occurs through formation of bubbles of the true vacuum***



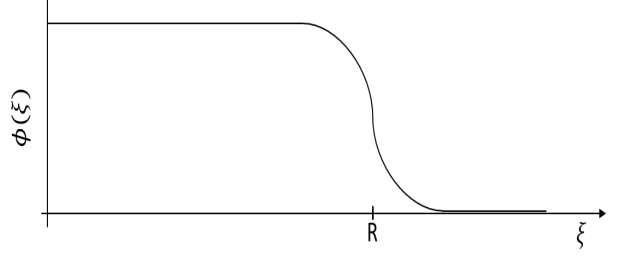
Bounce action

- ***Transition rate controlled by bounce action***

$$S_3(T) = 4\pi \int dr\, r^2 \left(\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V(\phi, T) \right)$$

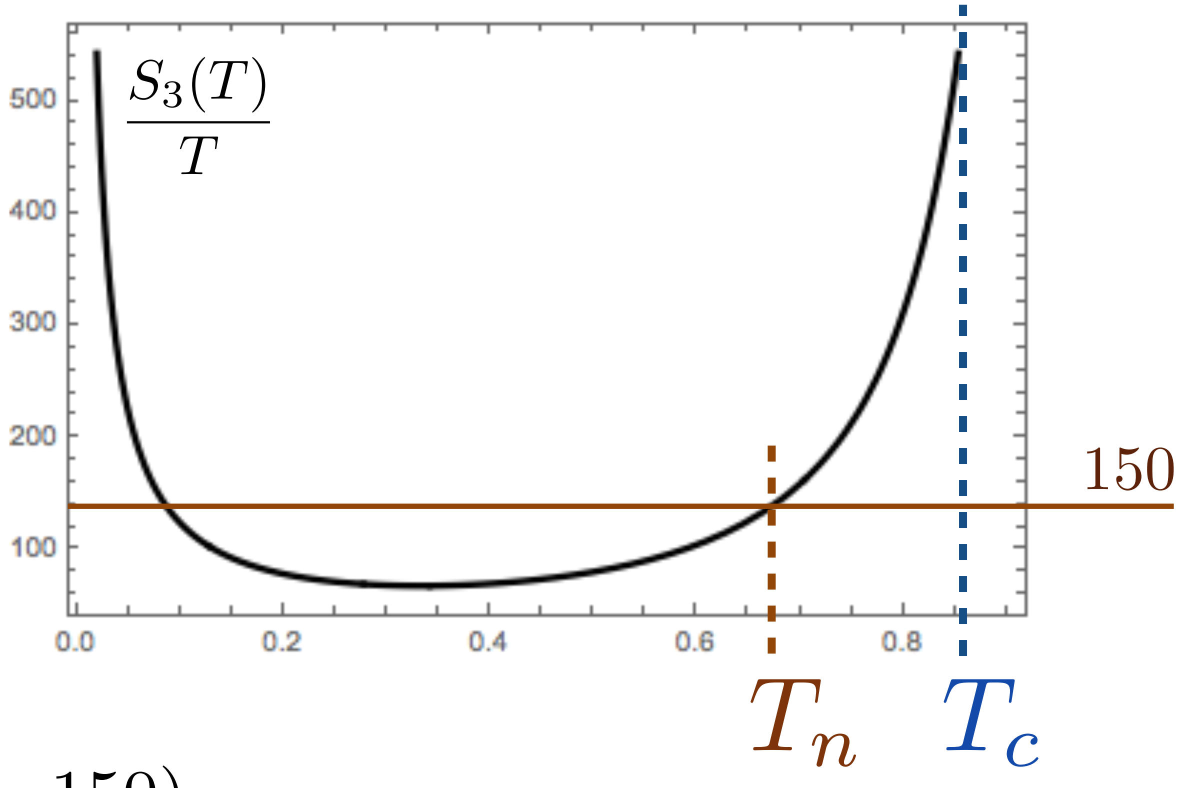
$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$$

Evaluated on Bubble profile



- ***Nucleation happens at T such that***

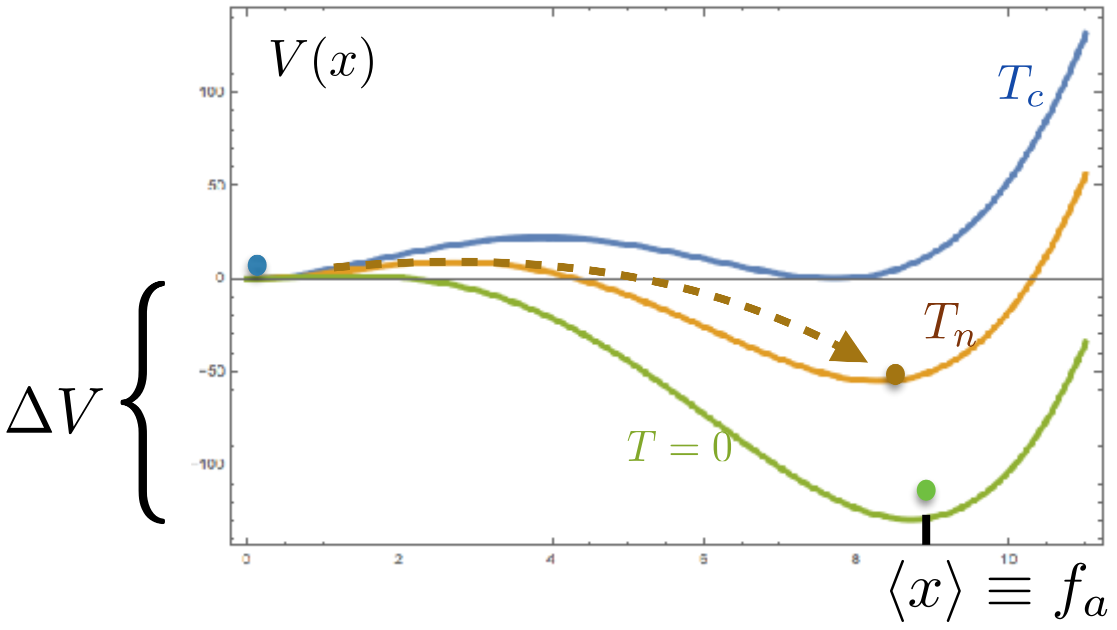
$$\Gamma(T_n) \simeq H(T_n)^4$$

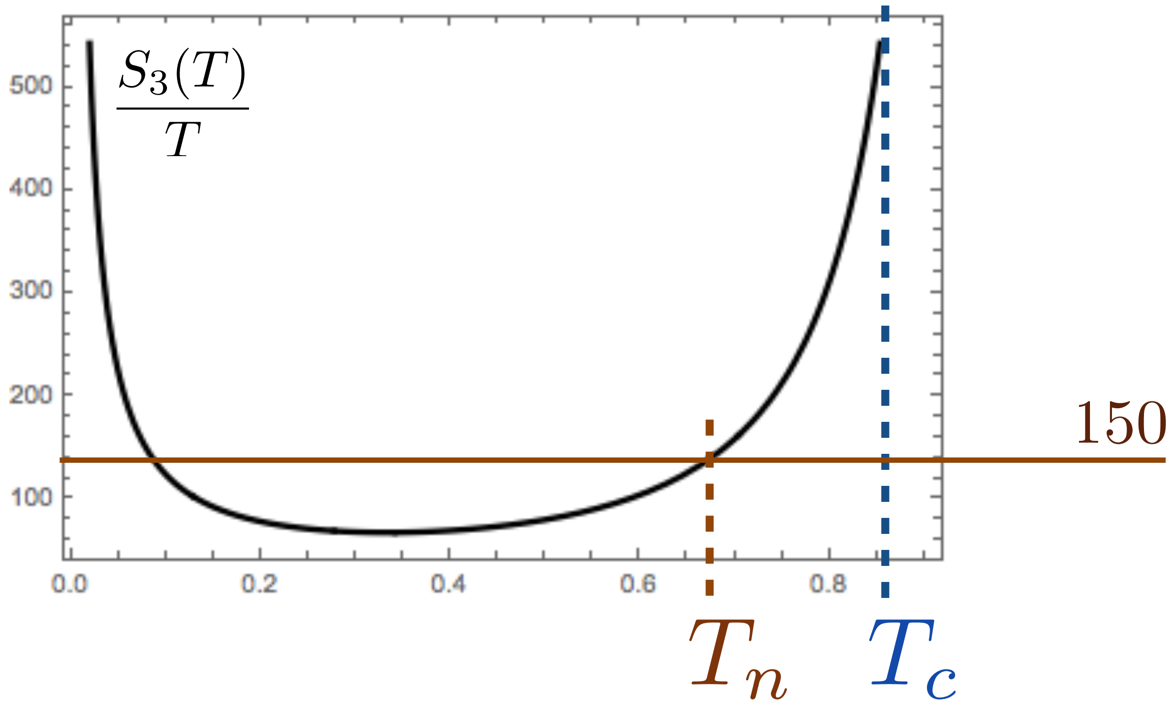


Approximate condition for nucleation in RD

$$\left.\frac{S_3(T)}{T}\right|_{T=T_n} \simeq 4 \log \frac{M_{\rm Pl}}{T_n} \simeq \mathcal{C} \sim O(100-150)$$

First order Phase Transition





✦Parameters controlling PT properties and SGWB

Energy released during phase transition

$$\boxed{\alpha(T_n)} = \frac{30}{\pi^2 g_*(T_n) T_n^4}\left(\Delta V(T_n) - T_n \left.\frac{d\Delta V(T_n)}{dT}\right|_{T=T_n}\right)$$

Inverse time-scale of the phase transition

$$\boxed{\beta_H(T_n)} \overset{\text{def}}{=} \frac{\beta(T_n)}{H(T_n)} = T_n \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_n}$$

Bubble dynamics in cosmic plasma

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 correct GW signal

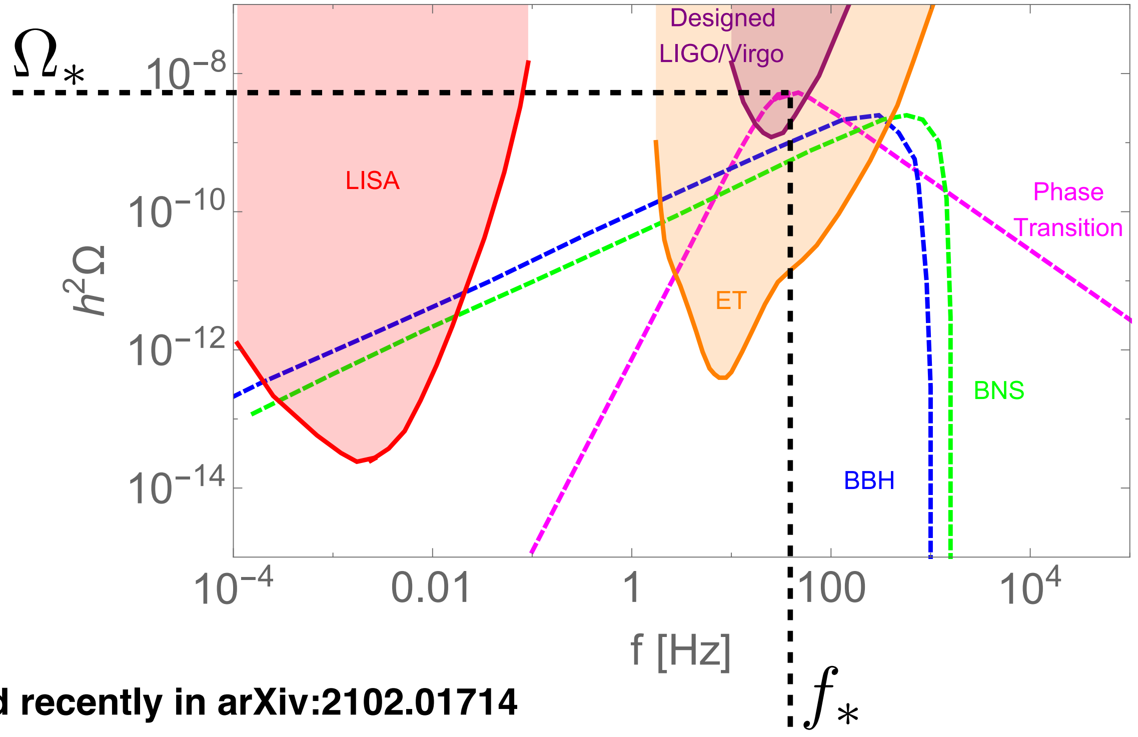
- **Bubble wall velocity/acceleration**
- **Correct estimation of friction in plasma**
- **Energy budget determines production mechanism**
- **Hydrodynamic simulations**

Bodeker Moore '17
Höche, Kozaczuk, Long, Turner, Wang '20
Azatov, Vanvlasselaer '20
Balaji, Spannowsky, Tamarit '20
Hindmarsh, Huber, Rummukainen, Weir '13
Ellis, Lewicki, No, Vaskonen '19

GW signal is broken power law

$$h^2\Omega(f) = \Omega_* \left(\frac{f}{f_*}\right)^{a_1}\left(1+\left(\frac{f}{f_*}\right)^{\Delta}\right)^{(a_2-a_1)/\Delta}$$

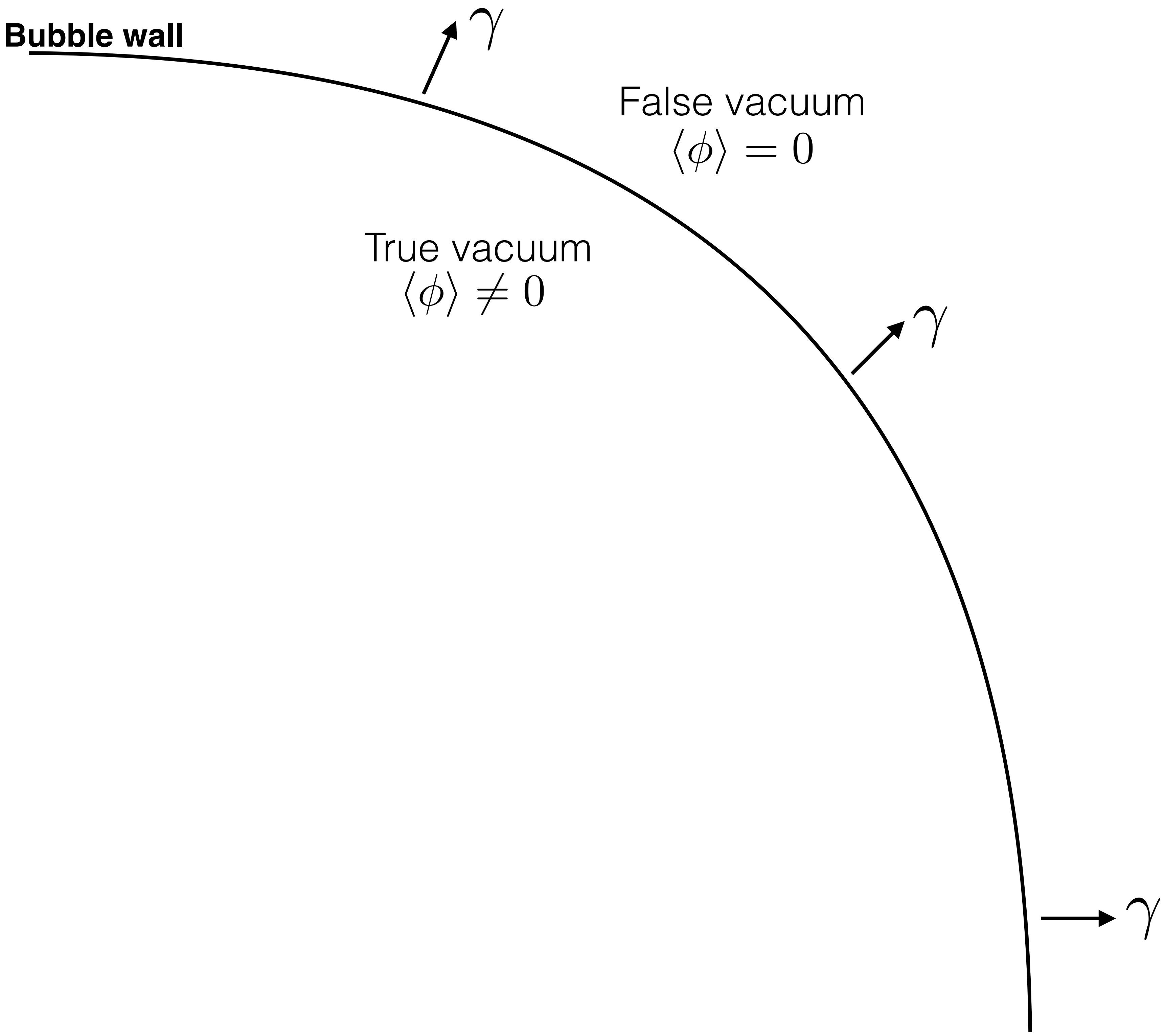
constants $a_1, a_2, \Delta, f_*, \Omega_*$



See e.g. LISA W.G. arXiv:1910.13125, O3 data of LIGO/Virgo analysed recently in arXiv:2102.01714

Bubble friction

Can be computed knowing spectrum in false and true vacuum



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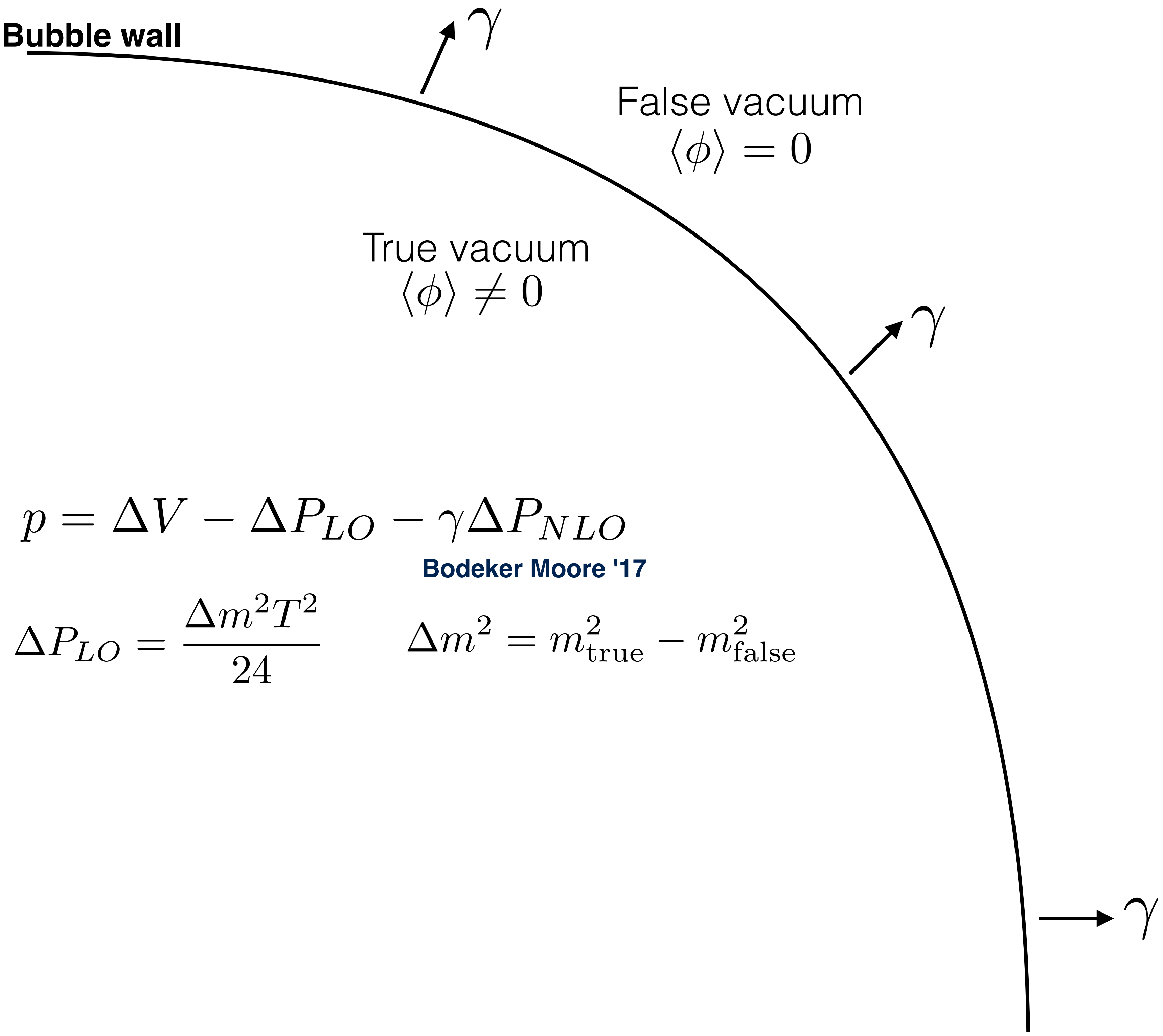

Bubble wall

γ

False vacuum
$\langle\phi\rangle = 0$

True vacuum
$\langle\phi\rangle \neq 0$

γ

γ

$$p = \Delta V - \Delta P_{LO} - \gamma \Delta P_{NLO}$$

Bodeker Moore '17

$$\Delta P_{LO} = \frac{\Delta m^2 T^2}{24} \qquad \Delta m^2 = m^2_{\rm true} - m^2_{\rm false}$$

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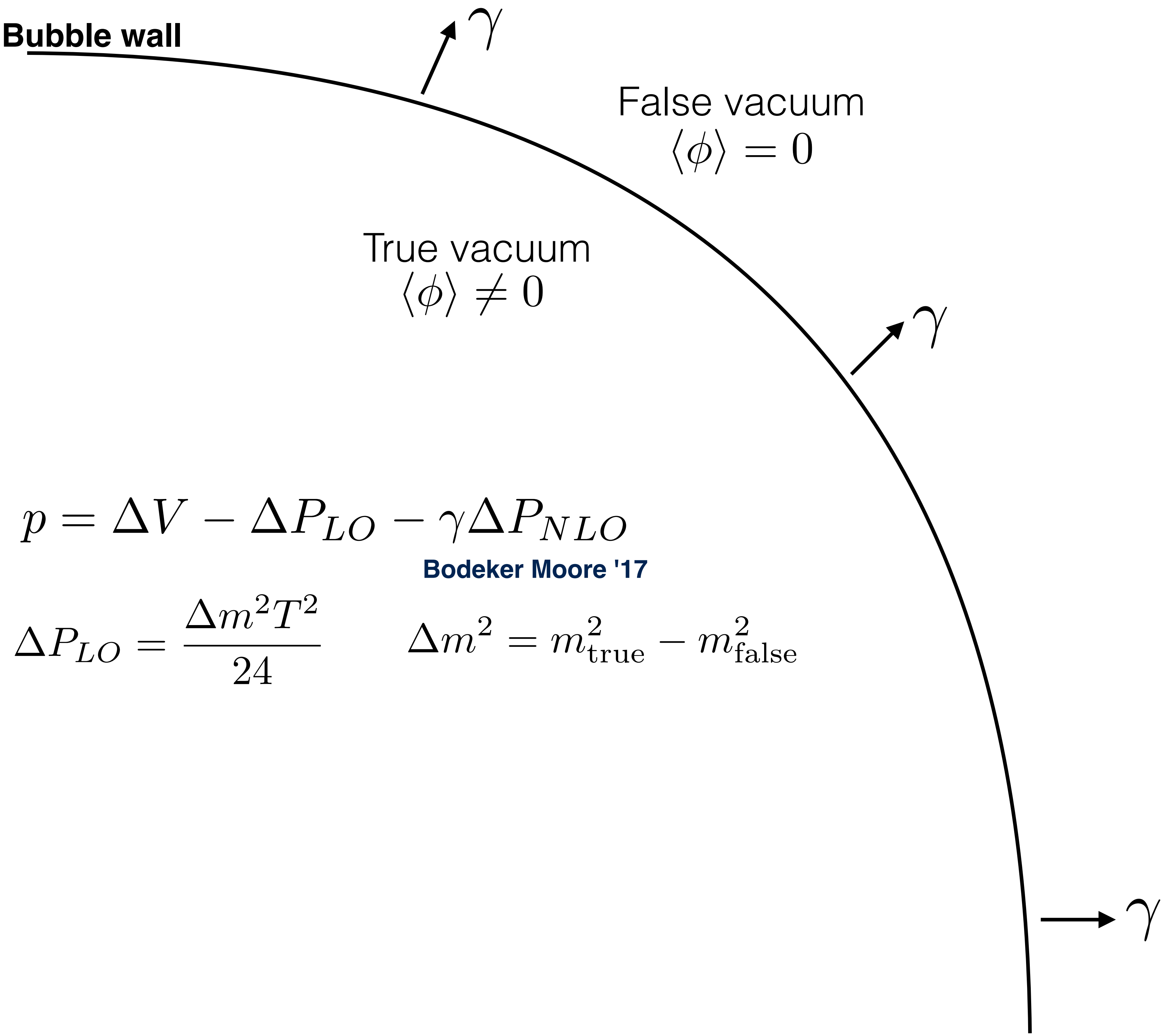

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$$\Delta P_{LO} = \frac{\Delta m^2 T^2}{24} \qquad \Delta m^2 = m^2_{\rm true} - m^2_{\rm false}$$

Conditions for friction

$$T \gtrsim m_{\rm false}$$
$$\gamma T \gtrsim m_{\rm true}$$

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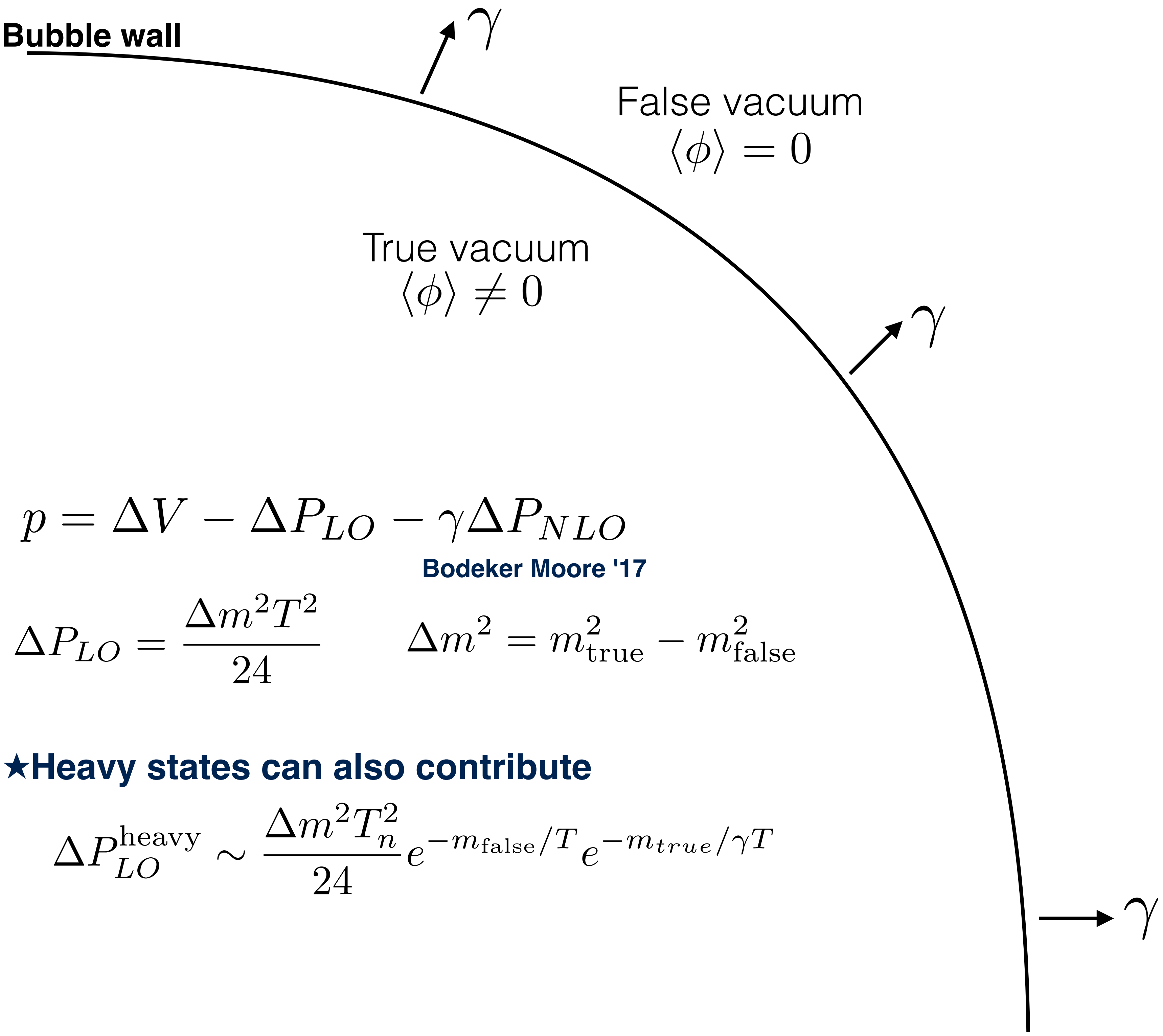

$$p = \Delta V - \Delta P_{LO} - \gamma \Delta P_{NLO}$$

Bodeker Moore '17

$$\Delta P_{LO} = \frac{\Delta m^2 T^2}{24} \qquad \Delta m^2 = m^2_{\rm true} - m^2_{\rm false}$$

★Heavy states can also contribute

$$\Delta P_{LO}^{\rm heavy} \sim \frac{\Delta m^2 T_n^2}{24} e^{-m_{\rm false}/T} e^{-m_{true}/\gamma T}$$

Conditions for friction

$$T \gtrsim m_{\rm false}$$
$$\gamma T \gtrsim m_{\rm true}$$

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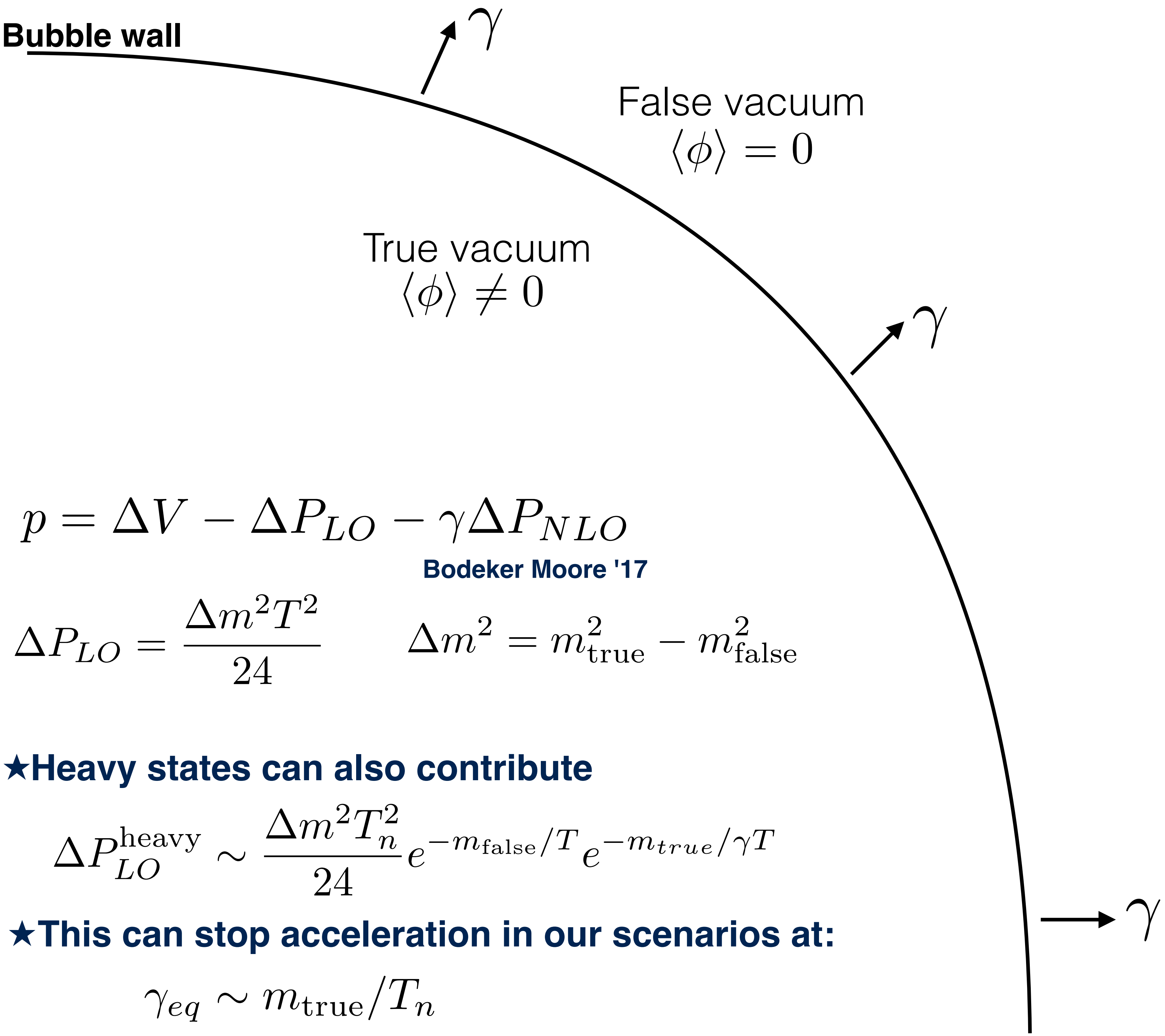
Bubble friction

Can be computed knowing spectrum in false and true vacuum



Conditions for friction

$$T \gtrsim m_{\text{false}}$$
$$\gamma T \gtrsim m_{\text{true}}$$

$$p = \Delta V - \Delta P_{LO} - \gamma \Delta P_{NLO}$$

Bodeker Moore '17

$$\Delta P_{LO} = \frac{\Delta m^2 T^2}{24} \qquad \Delta m^2 = m^2_{\text{true}} - m^2_{\text{false}}$$

★Heavy states can also contribute

$$\Delta P^{\text{heavy}}_{LO} \sim \frac{\Delta m^2 T_n^2}{24} e^{-m_{\text{false}}/T} e^{-m_{true}/\gamma T}$$

★This can stop acceleration in our scenarios at:

$$\gamma_{eq} \sim m_{\text{true}}/T_n$$

Bodeker Moore '17
Höche, Kozaczuk, Long, Turner, Wang '20
Azatov, Vanvlasselaer '20

Sound Waves contribution

- **If friction is significant dominant production mechanism is sound waves**

Sound Waves contribution

SGWB amplitude

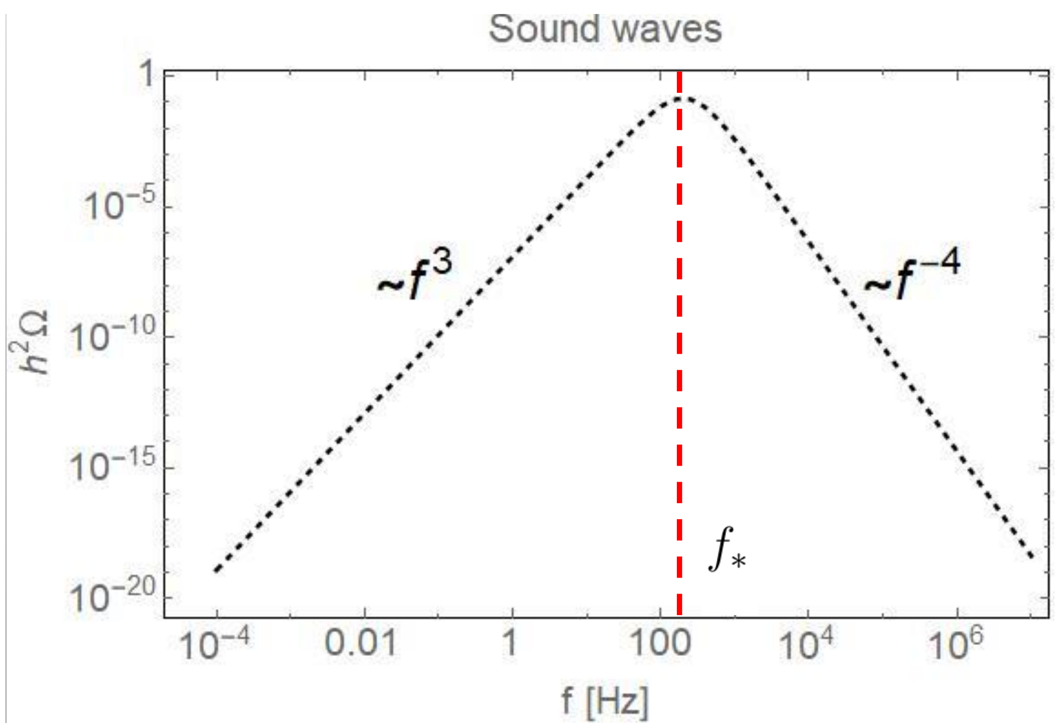
$$\Omega_* \sim \frac{1}{\beta_H}\left(\frac{\kappa_{sw}\alpha}{1+\alpha}\right)^2$$

Efficiency factor between 0 and 1.

Precise number depends on simulation

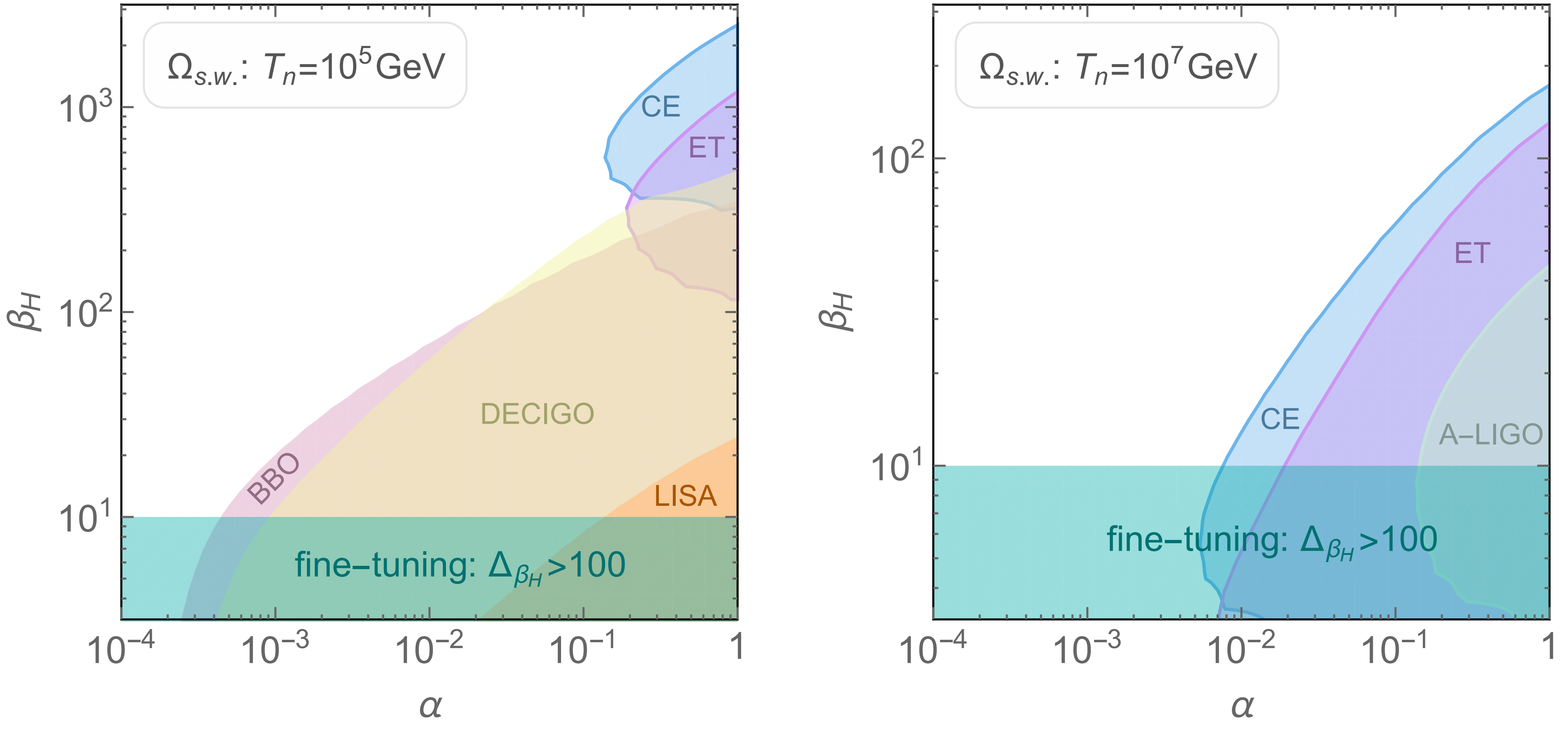
Peak frequency

$$f_* \sim 10\ \text{Hz}\left(\frac{\beta_H}{100}\right)\left(\frac{T_n}{10^7\text{GeV}}\right)$$



Detectability and beta tuning

Model independent Experimental reach on SGWB from PT



Detectability and beta tuning

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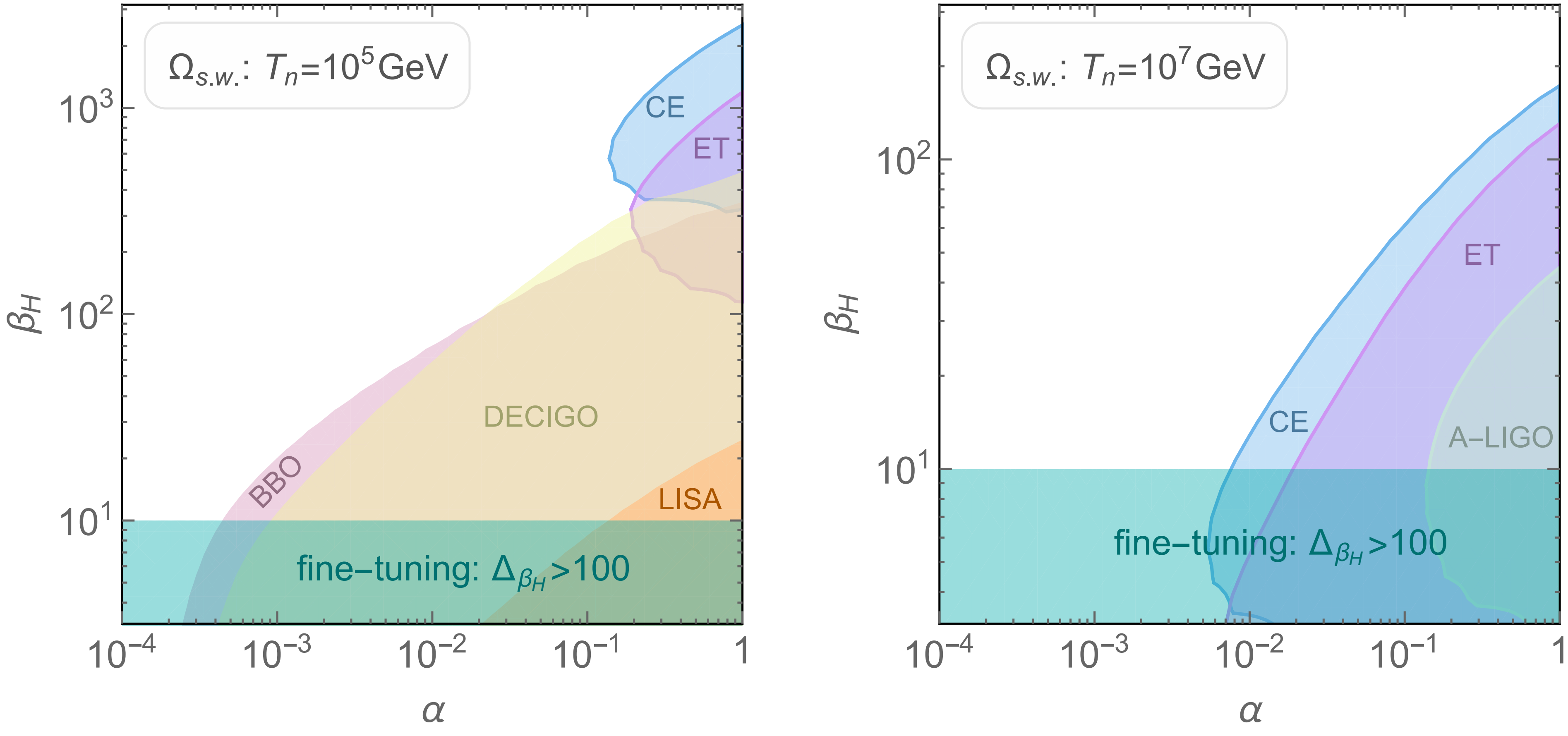


Using Nucleation Condition one can show that

$$\beta_H(T_n) \simeq S_3'(T_n) - \mathcal{C} \sim O(100-150)$$

Unless fine-tuning to have cancellation

One can quantify and compute the tuning to get a small β_H

$$\Delta_{\beta_H} \equiv \mathrm{Max}_{\{p_i\}} \left| \frac{d\log\beta_H}{d\log p_i} \right|$$

Tuning measure a la Giudice-Barbieri

FOPT in BSM theories

Can FOPT occur in BSM theories?

Many BSM theories includes spontaneously broken new symmetries
Perfect playground for generating SBGW

Grojean, Servant: arXiv:hep-ph/0607107

Probe of BSM physics up to 10^8 GeV

With planned interferometers

Which kind of BSM can we explore?

- ✦ *Dark Matter Sectors*
- ✦ *Sectors solving the Strong CP problem*
- ✦ *Sector addressing flavour hierarchies*
- ✦ *Force unification models*

What about SUSY?

Craig: arXiv:0902.1990

(Vintage) SUSY in 2021

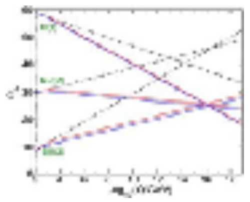
Negative results in LHC and DM experiments challenge BSM physics

Similar argument applies to SUSY and other BSM scenarios

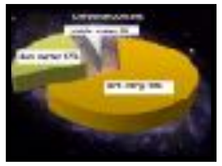
Is there a Desert above the TeV scale?

Why SUSY?

- ***Address*** hierarchy problem and naturalness (little fine-tuning)
- Included in unified description



- Dark matter candidate (LSP)



- Admit a low energy SM limit (including also ***SM-like BEH boson***)

SUSY beyond TeV could be tested in GW?

SUSY breaking and R-symmetry

Scheme of SUSY breaking

Visible sector

Standard Model of particle physics

Mediation

Hidden sector

~~**SUSY**~~ $\sqrt{F}$

SUSY breaking scale

$$V = F^2$$

Vacuum Energy

Q: can it exhibit a phase transition?

SUSY breaking and R-symmetry

Scheme of SUSY breaking

Visible sector

Standard Model of particle physics

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Hidden sector

~~**SUSY**~~ $\sqrt{F}$

SUSY breaking scale

$$V = F^2$$

Vacuum Energy

Q: can it exhibit a phase transition?

Actually it is expected!

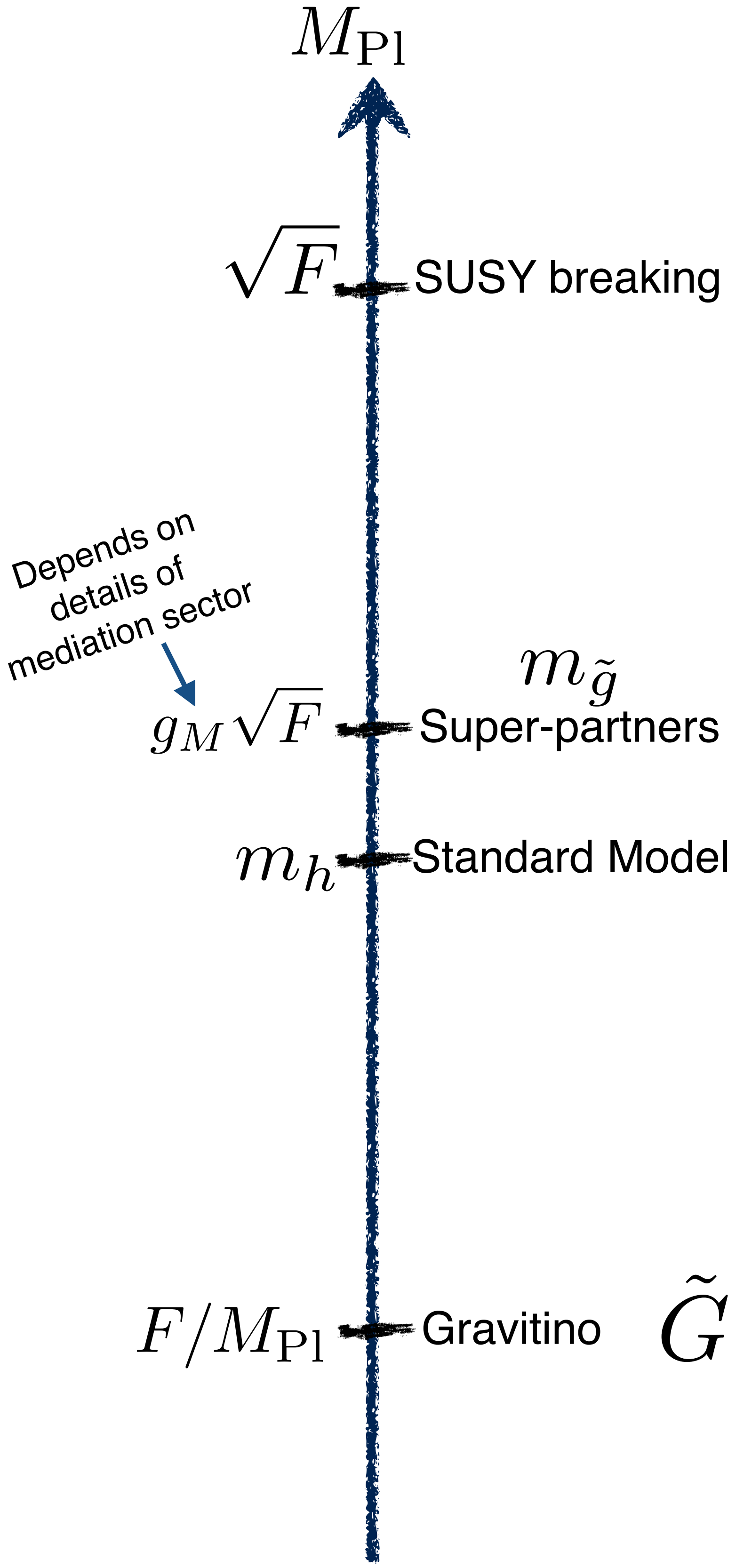
Spontaneous SUSY breaking ↔ ***(Spontaneously broken) R-symmetry***

Nelson Seiberg '93

Needed for gaugino masses

!!! If R symmetry breaking PT is first order it can deliver GW signals !!!

SUSY scales



$M_{\rm Pl}$

$\sqrt{F}$ SUSY breaking

Depends on details of mediation sector

$m_{\tilde{g}}$

$g_M\sqrt{F}$ Super-partners

m_h Standard Model

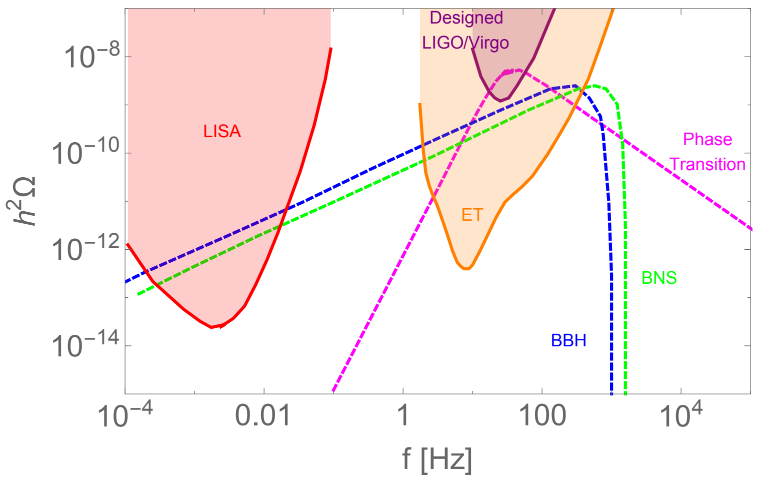
$F/M_{\rm Pl}$ Gravitino $\tilde{G}$

$$T_{re} \gtrsim \sqrt{F}$$

SUSY breaking sector must be reheated and undergoes PT at $T_* \sim \sqrt{F}$

$$f^{\rm GW}_{\rm peak} \sim 10\,{\rm Hz}\left(\frac{T_*}{10^7\,{\rm GeV}}\right)$$

GW frequency peak correlates with SUSY breaking scale



Low Energy SUSY breaking

Gravitino is the LSP

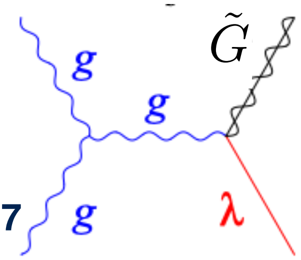
Gravitino cosmology shapes the parameter space

Gravitino problem

$$T_{re} \gtrsim \sqrt{F}$$

Universal gravitino Lagrangian

$$\mathcal{L}_{\tilde{G}} \supset \frac{1}{F}\partial^\mu \tilde{G} J_\mu \quad \cdots\cdots\blacktriangleright$$



Rychkov, Strumia '07

Gravitino production in the plasma enhanced if it is light

$$Y_{3/2} \sim C_{UV} \frac{T m_{\tilde{g}}^2}{m_{3/2}^2 M_{\rm Pl}}$$

Typically leads to Gravitino overabundance for large T_{re}

Two ways out in LESB

Ultra light Gravitino

Thermal

Warm DM constraints

$$m_{3/2} < 16 \text{ eV}\,, \; \sqrt{F} \lesssim 260 \text{ TeV}$$

Collider bounds $\sqrt{F} \gtrsim \text{TeV}$

Model building challenges to get superpartners out of LHC

Heavy Gravitino DM

Non Thermal

$$m_{3/2} \simeq \frac{F_0}{M_{\rm Pl}}$$

$$\kappa = F/F_0 \lesssim 10^{-2} \left(\frac{\sqrt{F}}{10^7 \text{GeV}}\right)^{1/2} \left(\frac{0.1}{g_M}\right)$$

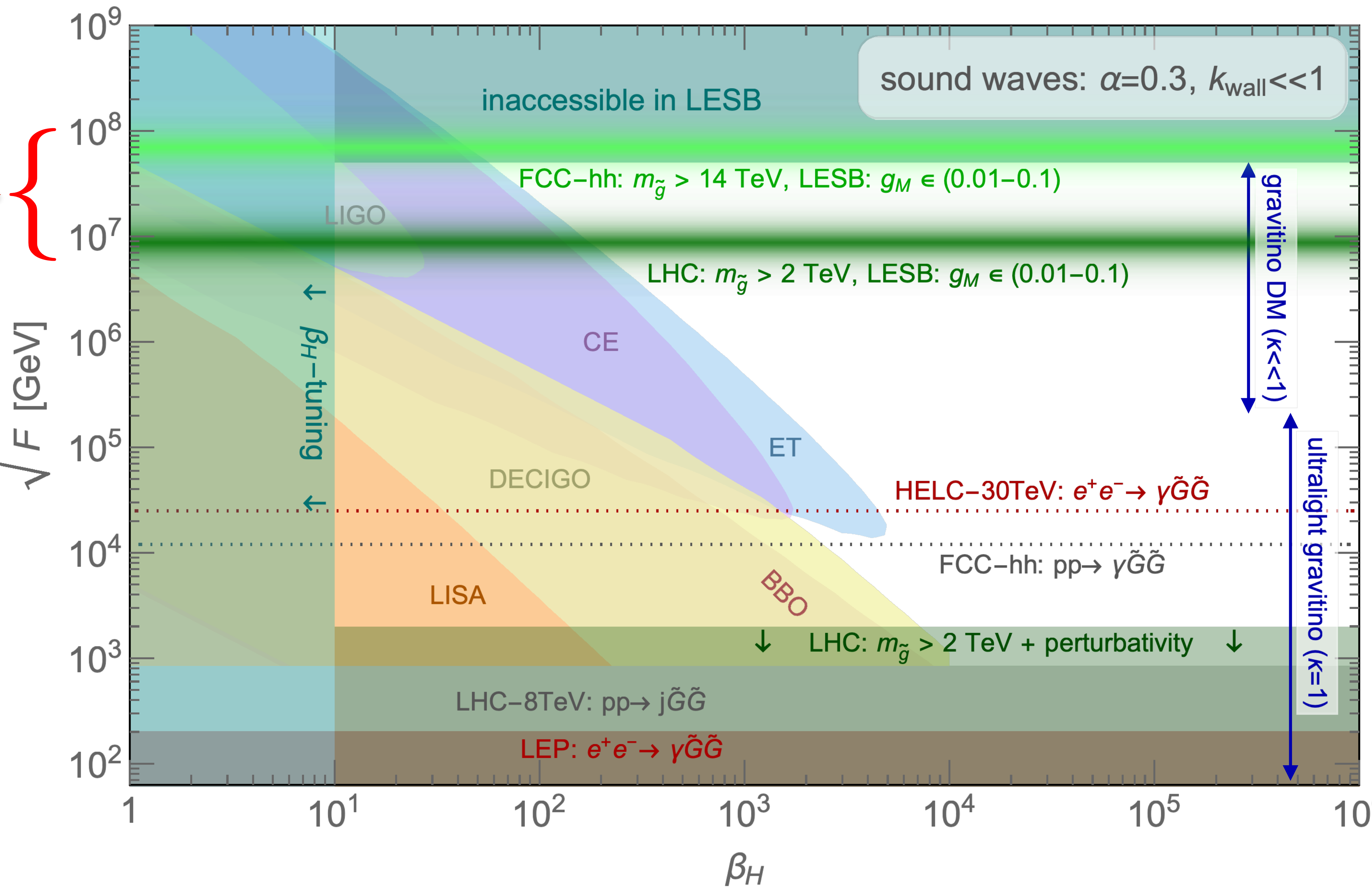
Viable DM candidate in window

$$10^5 \text{ GeV} < \sqrt{F} < 10^8 \text{ GeV}$$

Hall, Ruderman,Volansky arXiv:1302.2620

How we discover LESB

SUSY breaking sector First Order Phase Transition at $T_* \simeq \sqrt{F}$



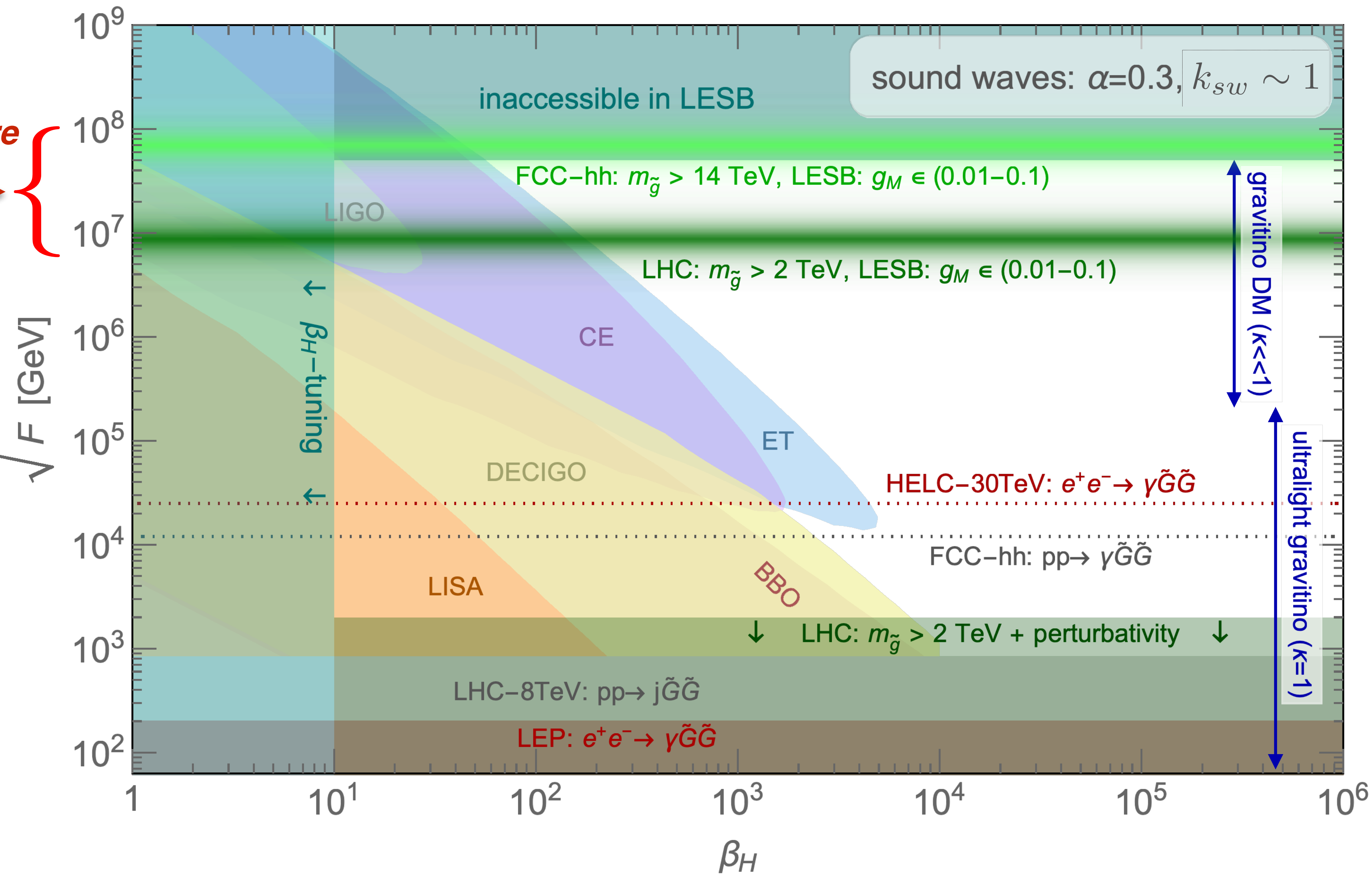
SUSY br. scale

SBGW at high frequency ↔ ***SUSY at reach for FCC***

How we discover LESB

SUSY breaking sector First Order Phase Transition at $T_* \simeq \sqrt{F}$

Here live the hidden sectors that we explore



SUSY br. scale

SBGW at high frequency ⟷ ***SUSY at reach for FCC***

Hidden sector class

SUSY and R breaking in the same chiral superfield

Goldstino

$$X = \frac{x}{\sqrt{2}} e^{2ia/f_a} + \sqrt{2}\theta\tilde{G} + \theta^2 F$$

Pseudo-modulus

SUSY breaking

R-charges: $R[x] = 2\,,\ R[\tilde{G}] = 1\,,\ R[F] = 0$

✦ ***R-symmetry breaking occurs along x***

$$\langle x \rangle \equiv f_a$$

R-breaking scale

In typical models

$$f_a \gtrsim \sqrt{F}$$

SUSY theorems: x is a pseudo-flat direction

Komargodski and Shih '09

We study EFT and PT along x direction in SUSY br models

PseudoModulus PT

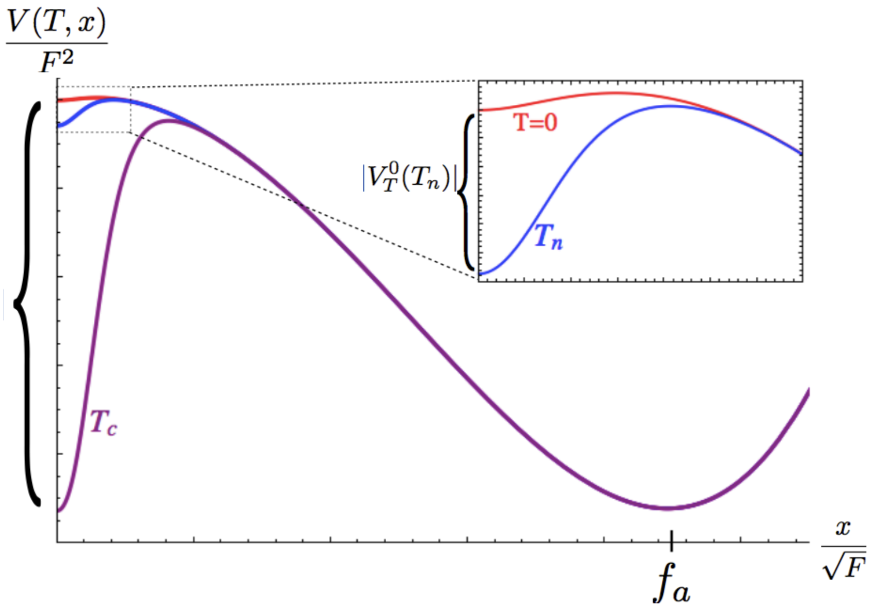
Now I focus on SUSY breaking sector dynamics

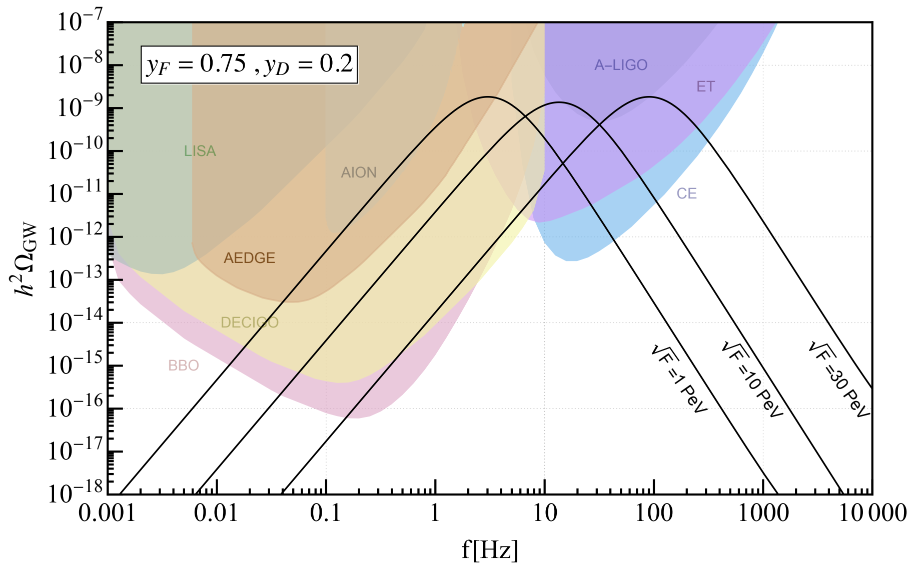
$$X = \frac{x}{\sqrt{2}} e^{2ia/f_a} + \sqrt{2}\theta\tilde{G} + \theta^2 F$$

Pseudo-modulus

★*How is R-symmetry breaking PT along pseudomodulus?*

★*What are properties of typical potential?*



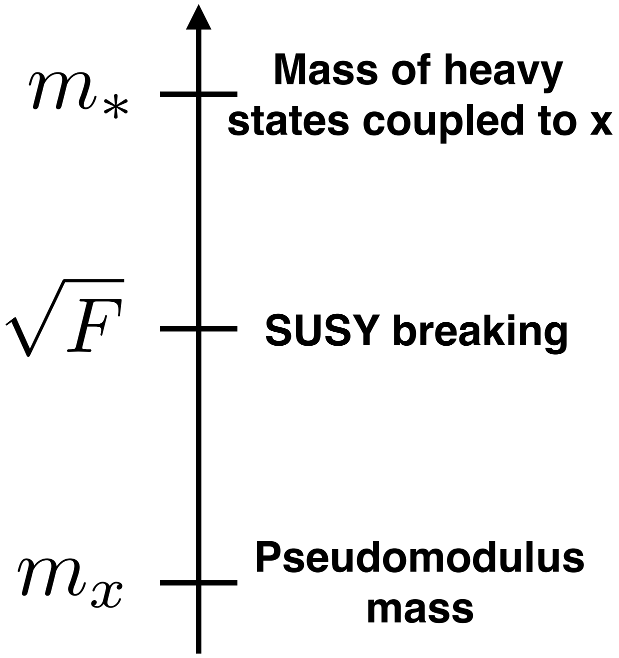


★*What are conditions to get GW signal?*

★*How it compares with known scenarios? (EW PT, supercooling ...)*

Pseudomodulus EFT

EFT scales



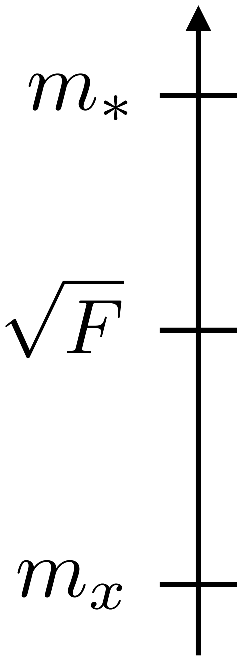
m_* Mass of heavy states coupled to x

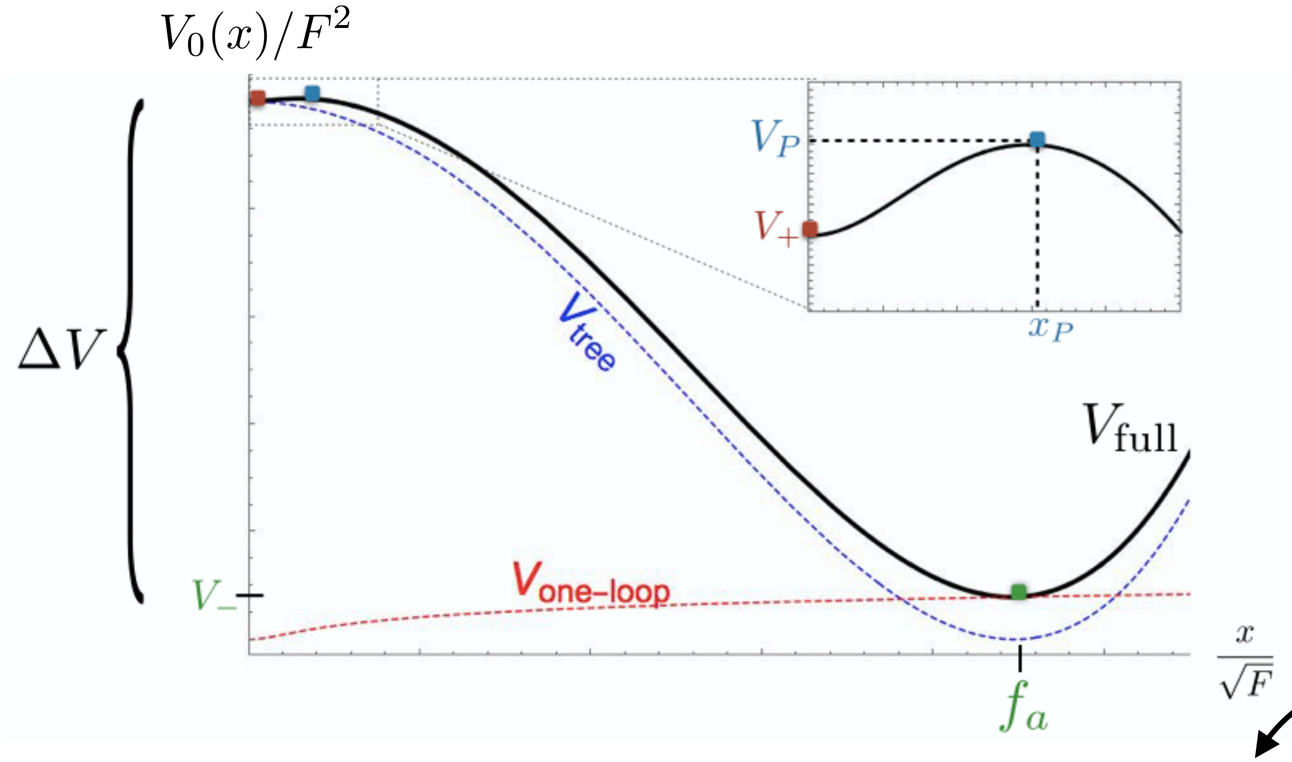
$\sqrt{F}$ SUSY breaking

m_x Pseudomodulus mass

Pseudomodulus toy model

EFT scales





$$V_0(x) = \kappa_D^2 \left(F - \epsilon_{\not R}\, x^2\right)^2 + \frac{\lambda^2}{32\pi^2}|F|^2 \log\left(\frac{\lambda^2 x^2 + m_*^2}{m_*^2}\right)$$

SUSY Mass of heavy states coupled to x

$\kappa_D = 1$

Single scale SUSY breaking

Tree level explicit R-breaking

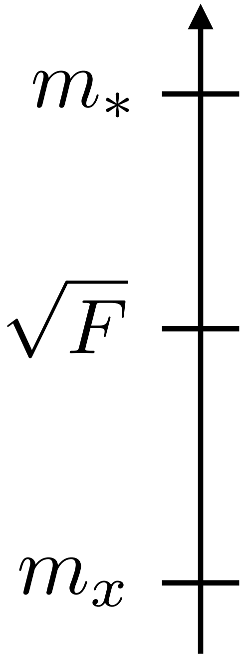
Pure log at x -> infinity

$$\Delta V = (\kappa_D F)^2 \qquad \langle x \rangle_{\rm true} = f_a = \sqrt{\frac{F}{\epsilon_{\not R}}}$$

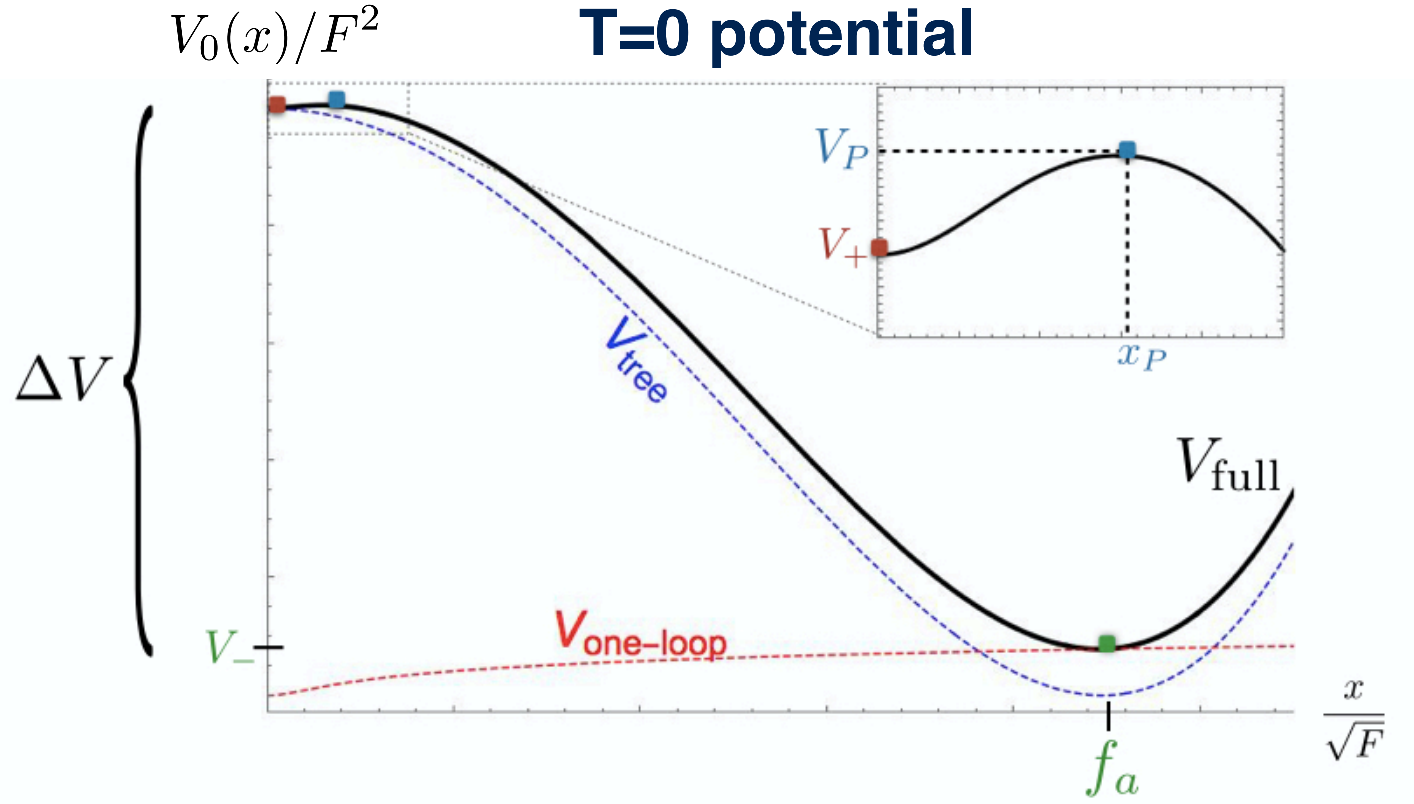
Flatness of the potential $\epsilon_{\not R} < 1/\sqrt{\kappa_D}$

Pseudomodulus potential at T=0

EFT scales

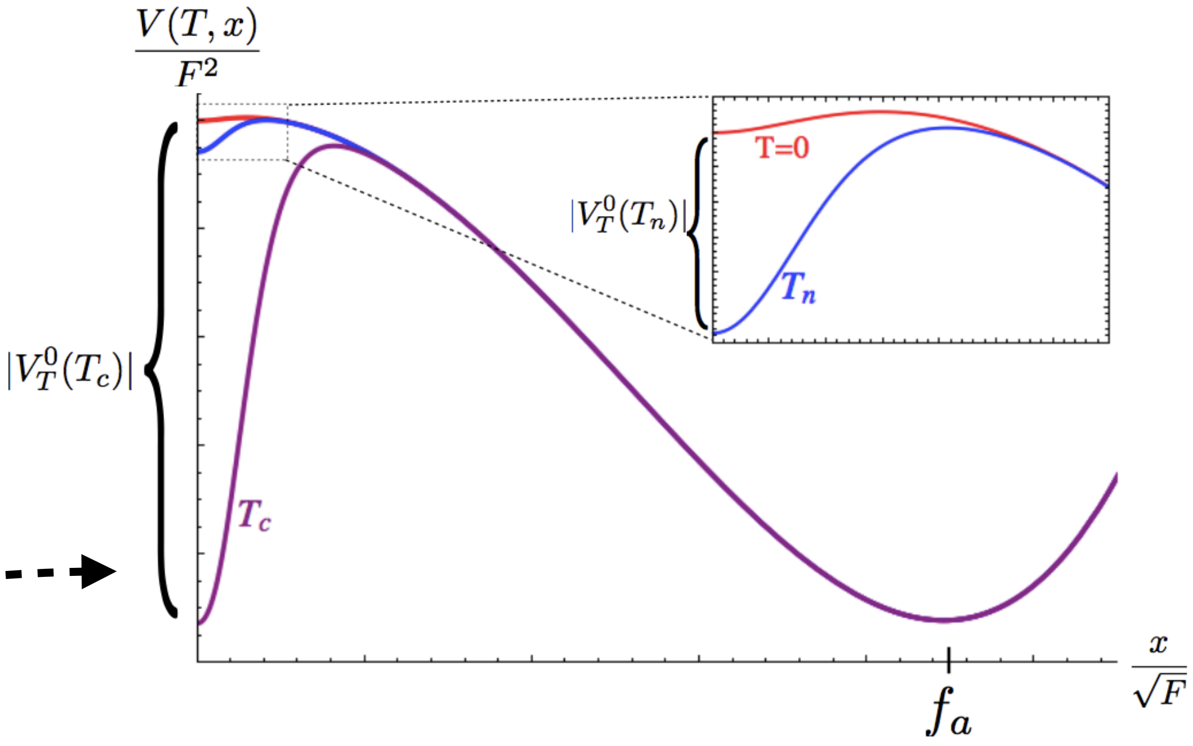


T=0 potential



- ✳ ***Mass of x parametrically smaller than heavy states*** $m_x \sim \frac{\lambda^2}{16\pi^2}\frac{F}{m_*}$ ← Heavy states mass
- ✳ ***Loop corrections asymptotes to a ~log for large x (special of SUSY)***
- ✦ ***The potential is flat*** $f_a^4 \gg \Delta V$
- ✳ ***Barrier is small*** $\frac{V_P}{\Delta V} \simeq \frac{\lambda_{\rm eff}^2}{16\pi^2}$

Pseudomodulus potential at finite T



- ✦**Flatness of potential** ⟷ **low T expansion of VT applies**
- ✦**We expect** $T_n \sim \sqrt{F} \lesssim m_*$

$$V_T(x) \simeq -T^4 \left(\sqrt{\frac{\lambda^2 x^2 + m_*^2}{(2\pi T)^2}}\right)^{3/2} e^{-\sqrt{\frac{\lambda^2 x^2 + m_*^2}{T^2}}}$$

Low T expansion

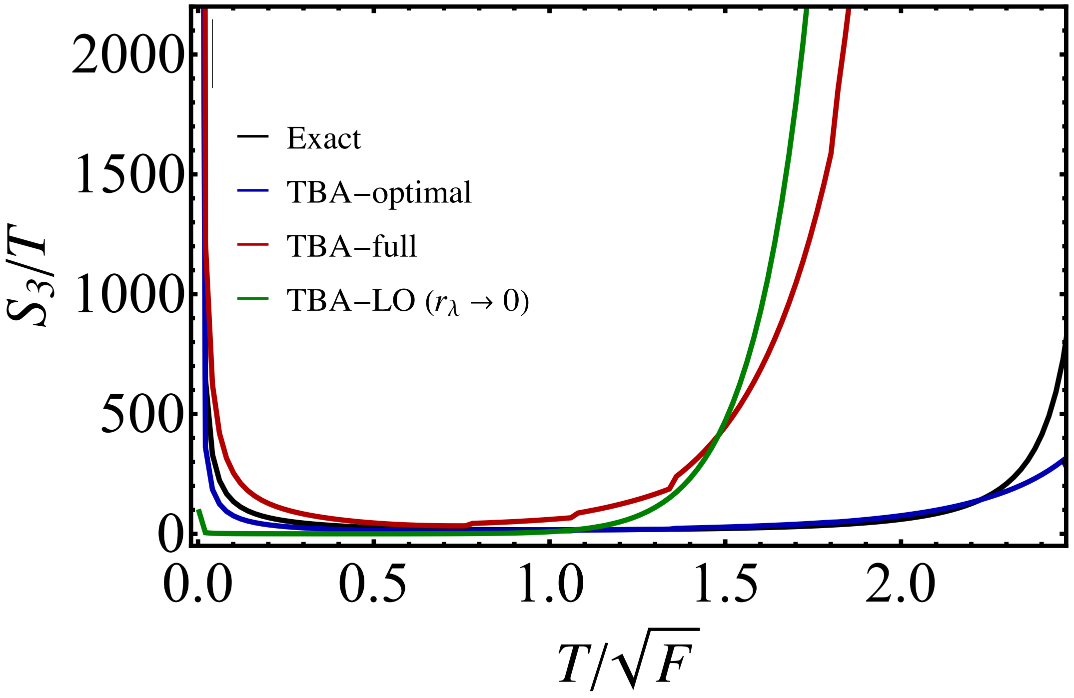
✳ ***Main effect of thermal corrections is to pull down the origin***

✳ ***In non-SUSY theories this could happen only with fine-tuning***

SUSY protects the flat direction but is broken by thermal corrections

Pseudomodulus bounce action

Triangular barrier approximation (TBA) works quite well



- ✦ *Full analytic treatment: expand TBA for flat potential + small barrier*

$$\frac{S_3}{T} \simeq \frac{144\sqrt{2}\pi}{5T}\,\frac{(V_P - V_T^0)^{5/2} f_a^3}{(\Delta V)^3}$$

Height of the peak of the potential barrier

Independent on the position of the peak at this order

- ✦ *Thermal dependences encoded in low-T* $V_T^0 \sim T^{5/2}\left(\frac{m_*}{T}\right)^{3/2} e^{-\frac{m_*}{T}}$

- ✦ *Remarkable difference with:*

$S_3/T \sim T^a$ ✦ *Standard high-T PT (as modified EW)*

$S_3/T \sim 1/\log{(m/T)}$ ✦ *Supercooling*

GW observables: analytics

✦ *Nucleation temperature (by further expanding in small V_P)*

$$T_n \simeq T_n^0 \left(1 - \frac{7}{\mathcal{C}^{2/5}} \frac{V_P}{m_*^4} \left(\frac{T_n^0}{m_*}\right)^{3/5} \left(\frac{f_a m_*^3}{\Delta V}\right)^{6/5}\right)$$

Reduce Tn by increasing barrier or increasing distance in field space

$T_n^0 \sim m_*/2$

✦ *Duration of phase transition*

$$\beta_H = \ldots \dashrightarrow \Delta_{\beta_H} \gtrsim 4\left(\frac{100}{\beta_H}\right)$$

To get small beta tuning is unavoidable

✦ *Energy released*

$$\alpha = \frac{30}{g_*(T_n)\pi^2}\left(\frac{\kappa_D F}{T_n^2}\right)^2 \sim 10^{-2}\kappa_D^2 \left(\frac{F}{m_*^2}\right)^2 \left(\frac{230}{g_*(T_n)}\right)$$

By taking $T_n \sim m_*/2$

Two scales of SUSY breaking are needed to get sizeable alpha

Our analytics are confirmed by numerical analysis in full models

A working model

O'Raifeartaigh model is the minimal model to break SUSY spontaneously

$$W = -FX + \lambda X \Phi_1 \tilde{\Phi}_2 + m(\Phi_1 \tilde{\Phi}_1 + \Phi_2 \tilde{\Phi}_2)$$

- ★***It does not break R-symmetry (vacuum is at X=0)***
- ★***We deform it to get R-symmetry breaking and another SUSY breaking scale***

Vaknin arXiv:1402.5851

- ★***We have then to study thermal properties***
- ★***First we study thermal properties of O'Raifeartaigh***
- ★***Then we proceed with the deformation and its thermal evolution***

The OR phase diagram

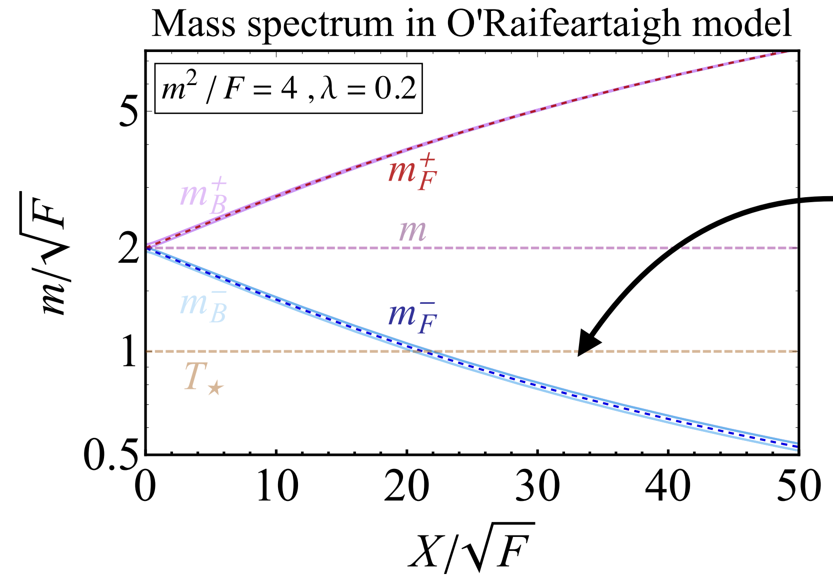
See also A. Katz 2009

$$W = -FX + \lambda X \Phi_1 \tilde{\Phi}_2 + m(\Phi_1 \tilde{\Phi}_1 + \Phi_2 \tilde{\Phi}_2)$$

One-loop T=0 vacuum is at X=0

We consider vector-like O'Raifeartaigh model

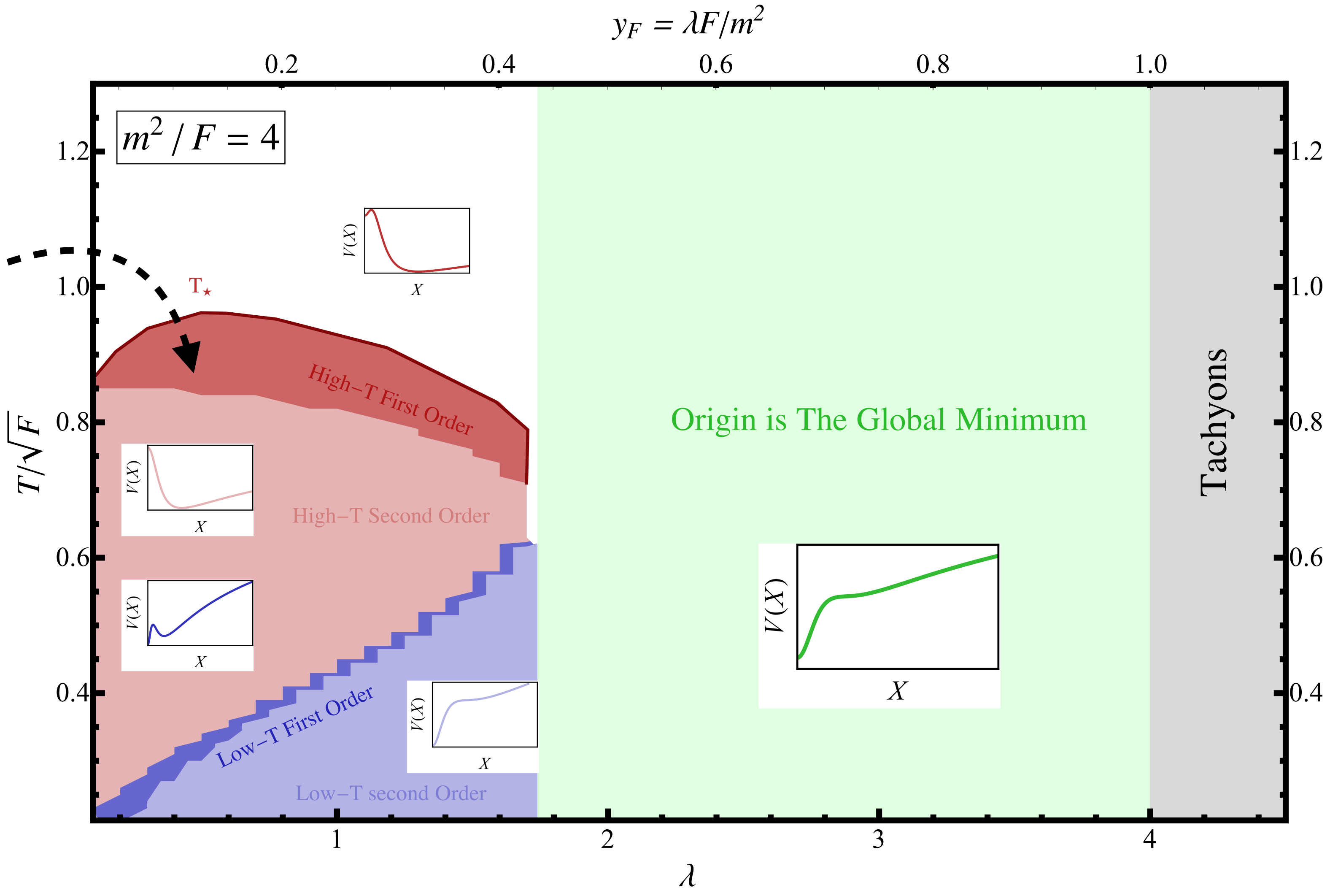
	X	Φ_1	$\tilde{\Phi}_1$	Φ_2	$\tilde{\Phi}_2$
$U(1)_R$	2	0	2	2	0
$U(1)_D$	0	1	-1	1	-1


Mass spectrum in O'Raifeartaigh model

There are eigenvalues decreasing for increasing X

Competition between one-loop and thermal corrections generate local minimum in a temperature range

$$x_\star \simeq \frac{2\sqrt{2}\pi T}{\lambda y_F} \quad , \quad T_\star \sim 0.23\sqrt{y_F}m$$



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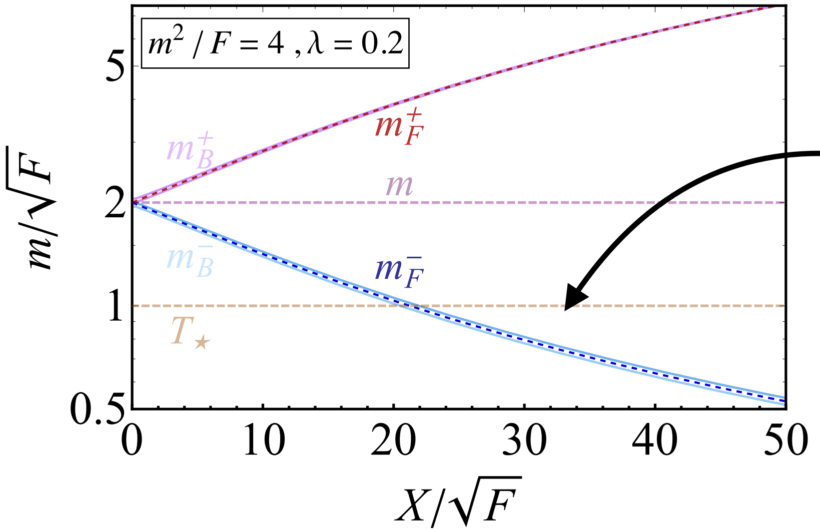
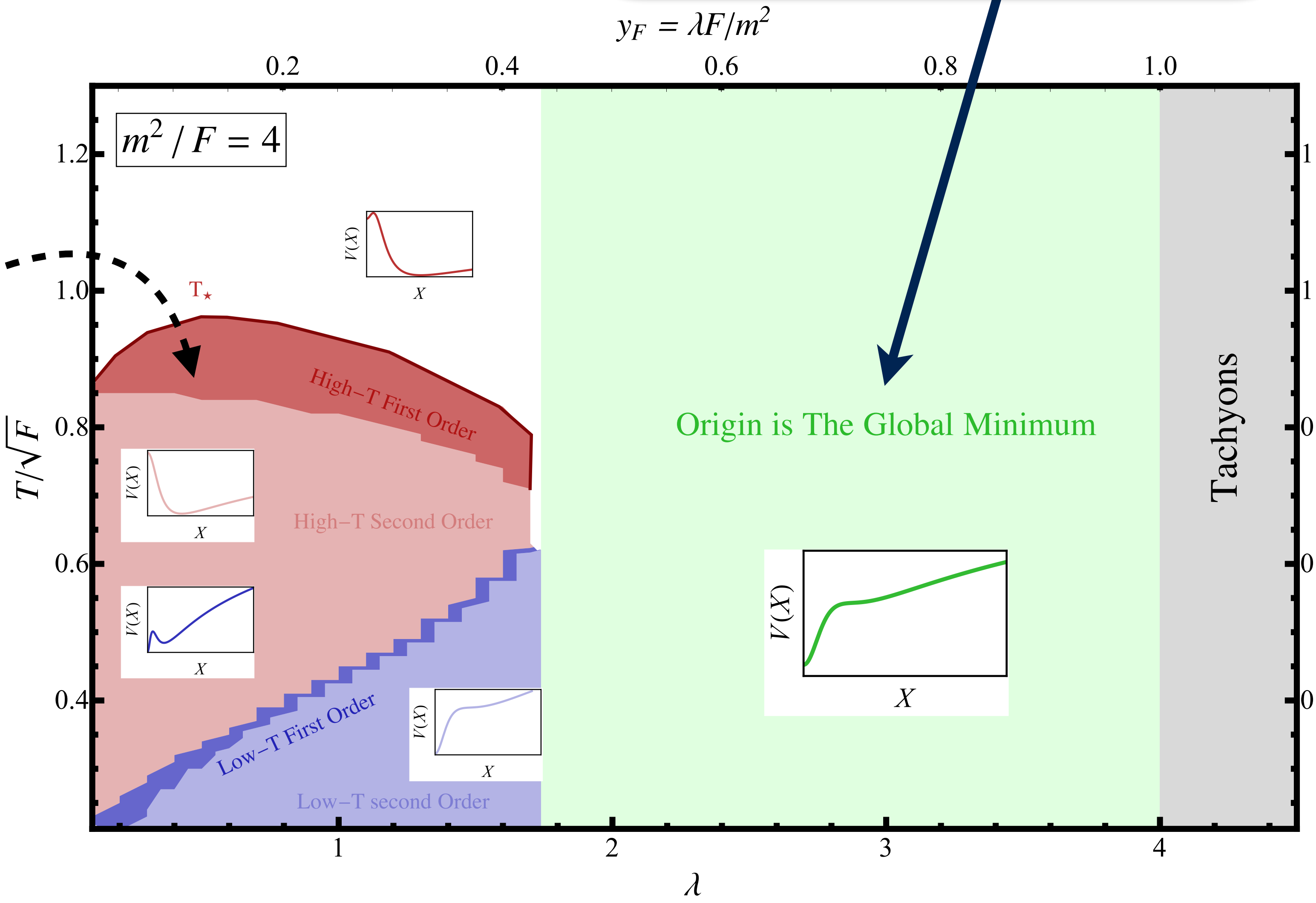


There are eigenvalues decreasing for increasing X

We focus on this regime for simplicity



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A full model of LESB

Same chiral field content than O'Raifeartaigh model

$$W = -FX + \lambda X \Phi_1 \tilde{\Phi}_2 + m(\Phi_1 \tilde{\Phi}_1 + \Phi_2 \tilde{\Phi}_2)$$

	X	Φ_1	$\tilde{\Phi}_1$	Φ_2	$\tilde{\Phi}_2$
$\mathrm{U}(1)_R$	2	0	2	2	0
$\mathrm{U}(1)_D$	0	1	-1	1	-1

Flavour symmetry is gauged and a Fayet-Iliopoulos term is added

$$\dashrightarrow \quad +\frac{g^2}{2}\left(\frac{D}{g} + |\phi_1|^2 - |\tilde{\phi}_1|^2 + |\phi_2|^2 - |\tilde{\phi}_2|^2\right)^2$$

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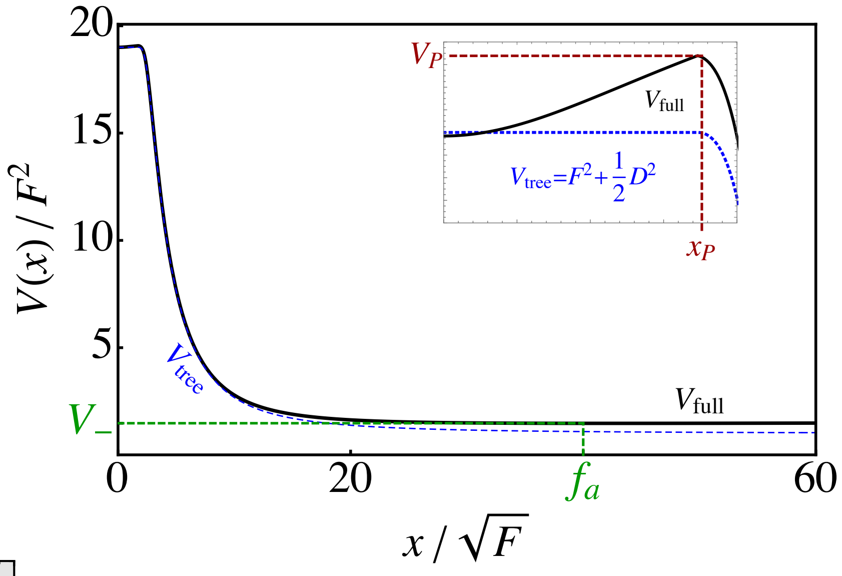
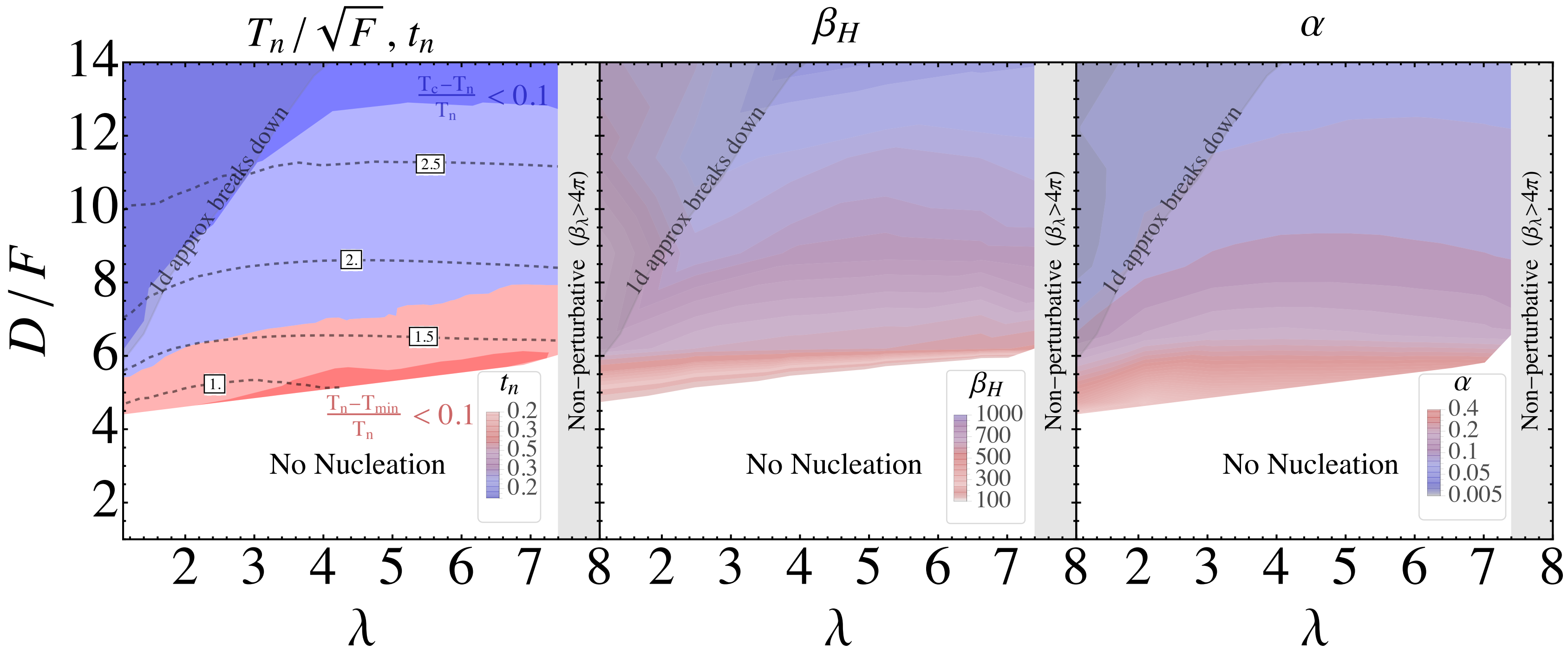
Flat potential with local minimum



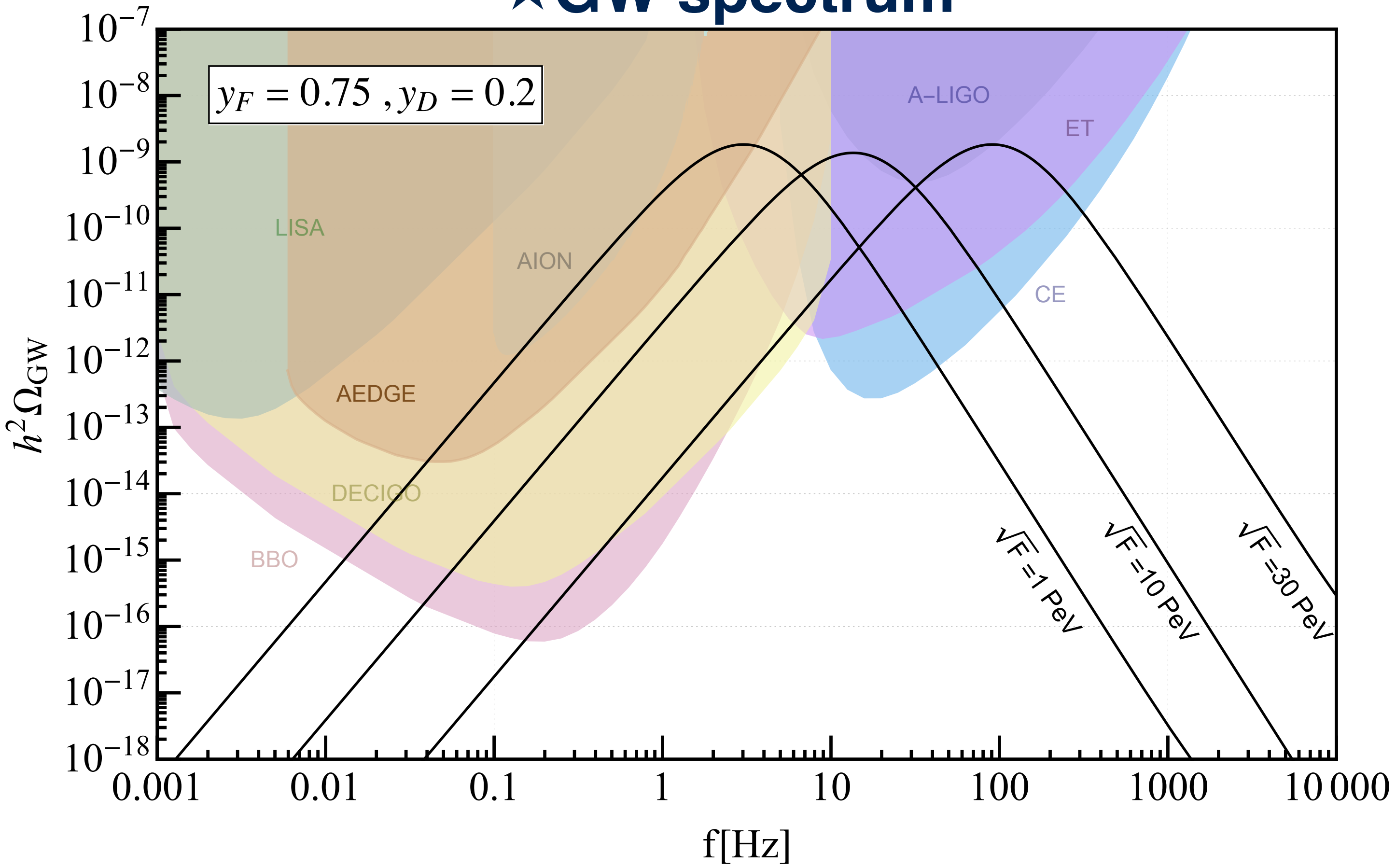


PT parameters

Numerics employed, but low-T approximation and TBA cross-checked

A full model of LESB

★GW spectrum



- ✳ *Simplest O'Raifeartaigh model*
- ✳ *Gauge non-anomalous U(1) + D-term*

SUSY and spontaneous R-breaking

First Order Phase Transition associated to SUSY and R-symmetry breaking

★Prediction for Superpartner spectrum

Add messenger in 5+bar5

$$SU(6) \supset U(1)_D \times SU(5) \qquad \mathcal{M}_{\rm mess} = \begin{pmatrix} \frac{\lambda f_a}{\sqrt{2}} & m \\ m & 0 \end{pmatrix}$$

$$m_{\tilde g} \simeq 2\ \text{TeV} \left(\frac{F}{30\ \text{PeV}}\right)^{1/2} \left(\frac{y_F}{0.75}\right)^3 \left(\frac{F}{2.5D}\right)^{1/2} \left(\frac{\lambda}{4}\right) \left(\frac{g}{0.4}\right)$$

Gaugino screening is unavoidable

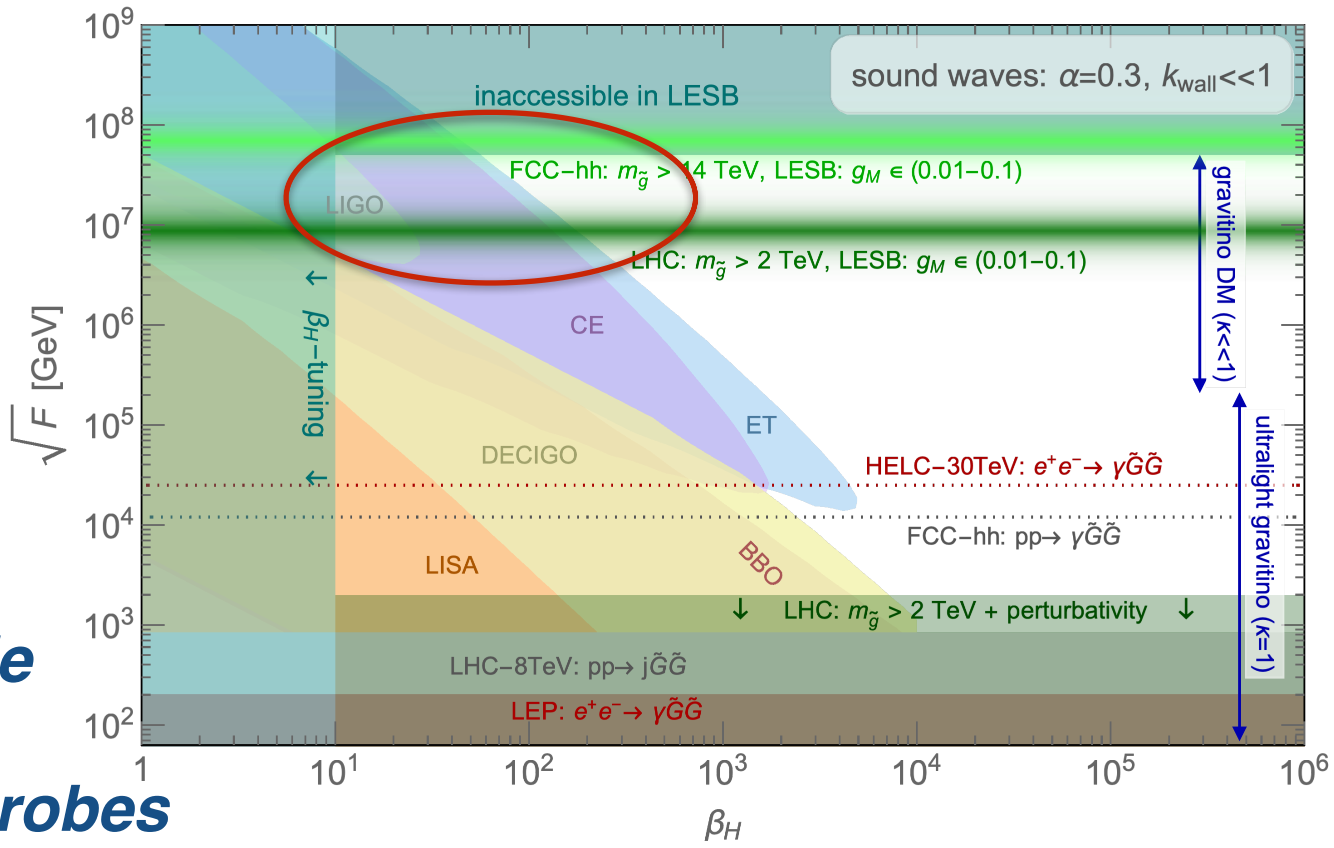
A signal of SGWB at O(100) Hz correlates to gluino at reach of FCC-hh

Conclusions

✦*SBGW from PT provides probe of BSM theories at high energy*

✦*SUSY breaking hidden sector contains naturally R-symmetry PT*

→ *Can deliver SBGW*



✦*SBGW frequency point to SUSY br scale*

✦*Interesting interplay with other SUSY probes*

✦*Novel features in 1st order PT (low-T ...)*

SBGW can be the first sign of SUSY (breaking)!

Can provide hints for future colliders