Ripples in spacetime from broken SUSY

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Based on JHEP 02 (2021) 184

with Nathaniel Craig, Noam Levi and Diego Redigolo

MPI Heidelberg

7 February 2022

(Vintage) SUSY

Negative results in LHC and DM experiments challenge BSM physics

(Similar argument applies to SUSY and other BSM scenarios)

Naturalness of EW scale is into pressure

put aside EW scale mistery

Is there a Desert above the TeV scale?

(Vintage) SUSY

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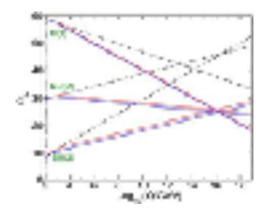
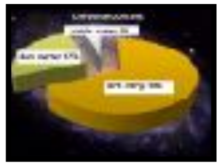
Why still SUSY beyond TeV?

- ***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?
Can SUSY reveals itself in GW?

SUSY breaking and R-symmetry

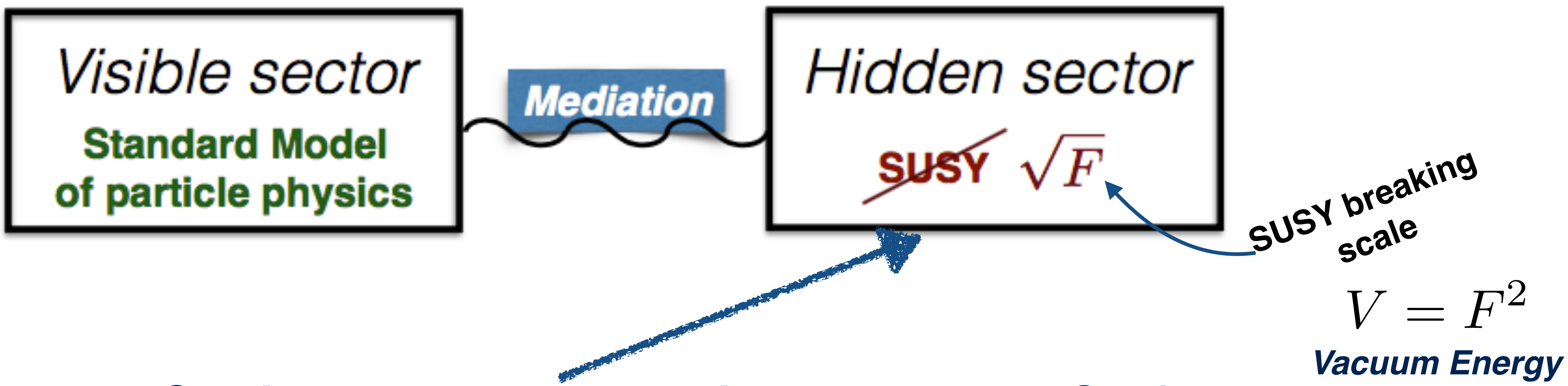
Scheme of SUSY breaking

$$V = F^2$$

Vacuum Energy

SUSY breaking and R-symmetry

Scheme of SUSY breaking



Q: Hidden sector dynamics can lead to GW?
Q: can it exhibit a phase transition (PT)?

SUSY breaking and R-symmetry

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Actually it is expected!

Spontaneous SUSY breaking ⟷ (Nelson Seiberg '93) *Existence of U(1) R-symmetry* ⟷ *Broken R-symmetry for gaugino masses*

SUSY breaking and R-symmetry

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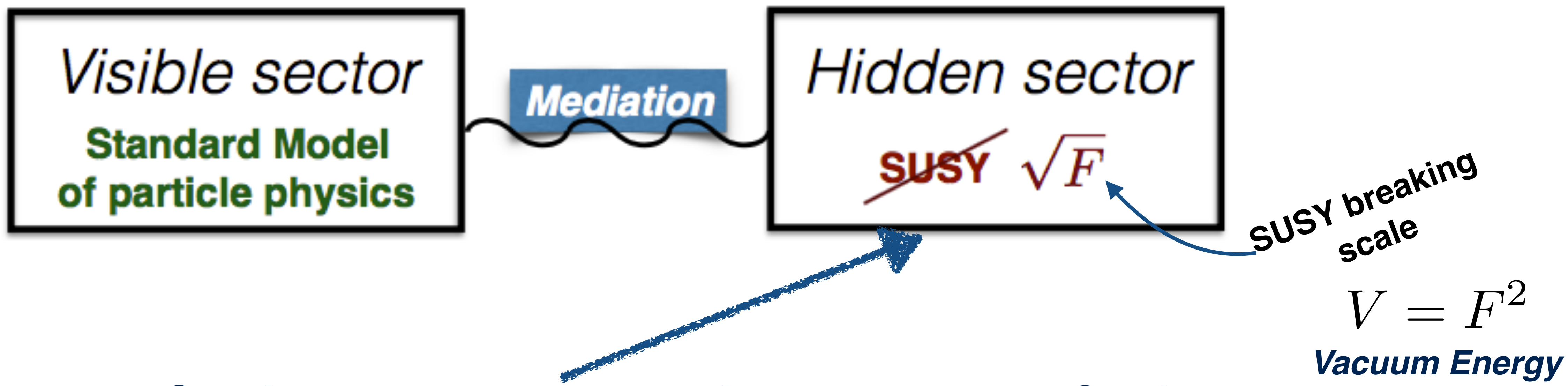

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!!! If R-symmetry breaking PT is first order it can deliver GW signals !!!

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Nelson Seiberg '93

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

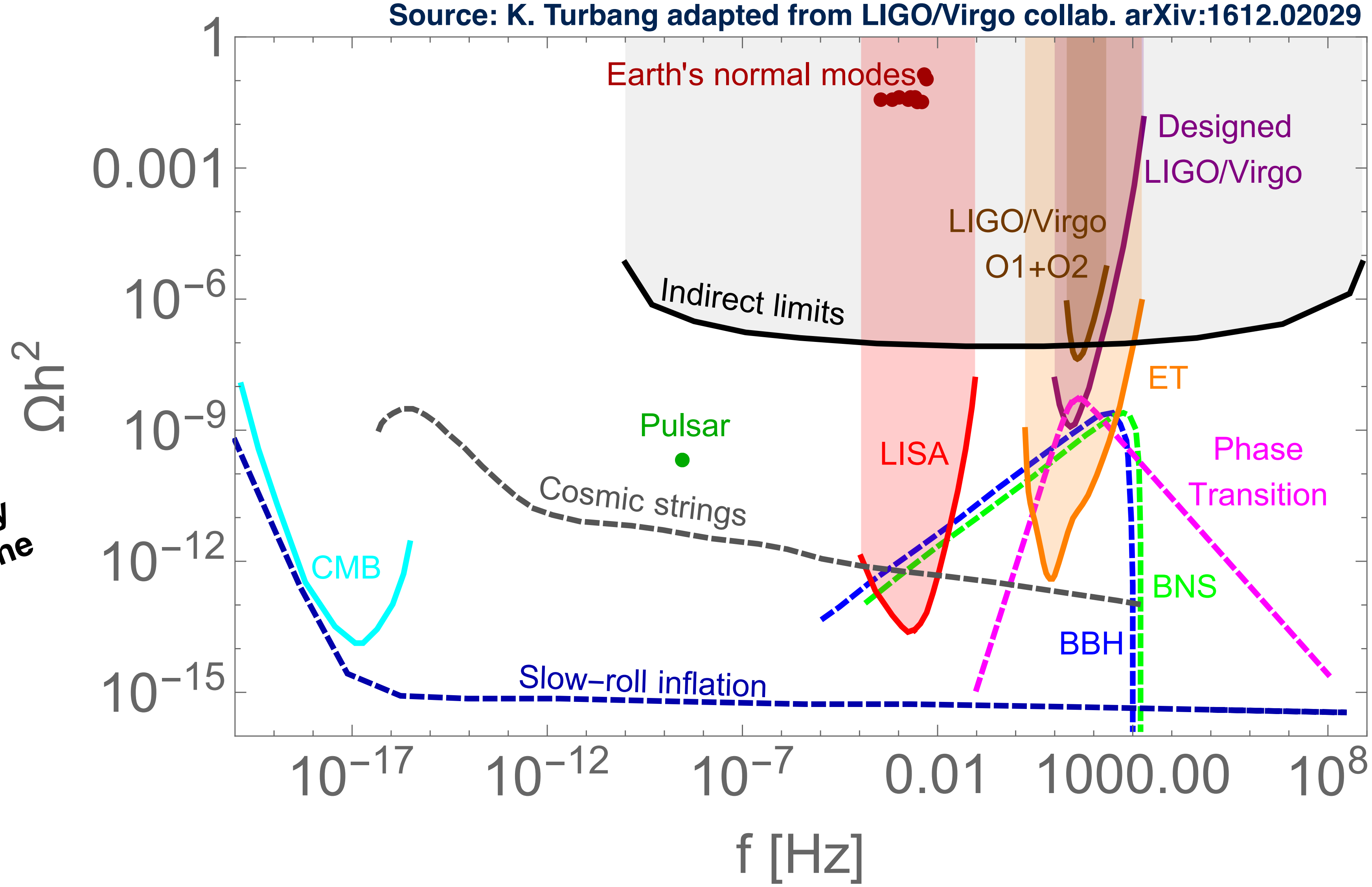
? Properties of the PT ? ***? How it correlates with sparticles ?***

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

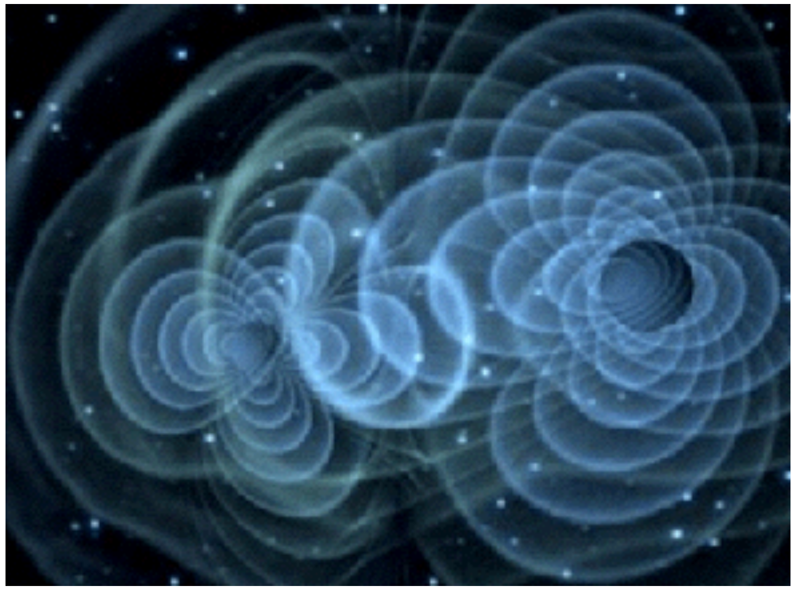
- Superposition of unresolvable sources

BBH **BNS**

- Predictable after LIGO/Virgo observations

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

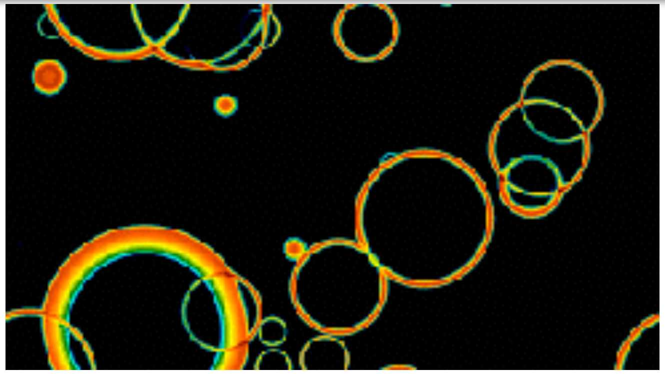
! Most likely measured in next few years !



★Cosmological SGWB

- Generated by energetic events during cosmological evolution

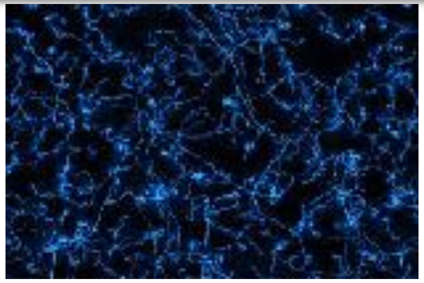
First Order Phase Transitions



arXiv: 1705.01783 D. Weir

Inflation

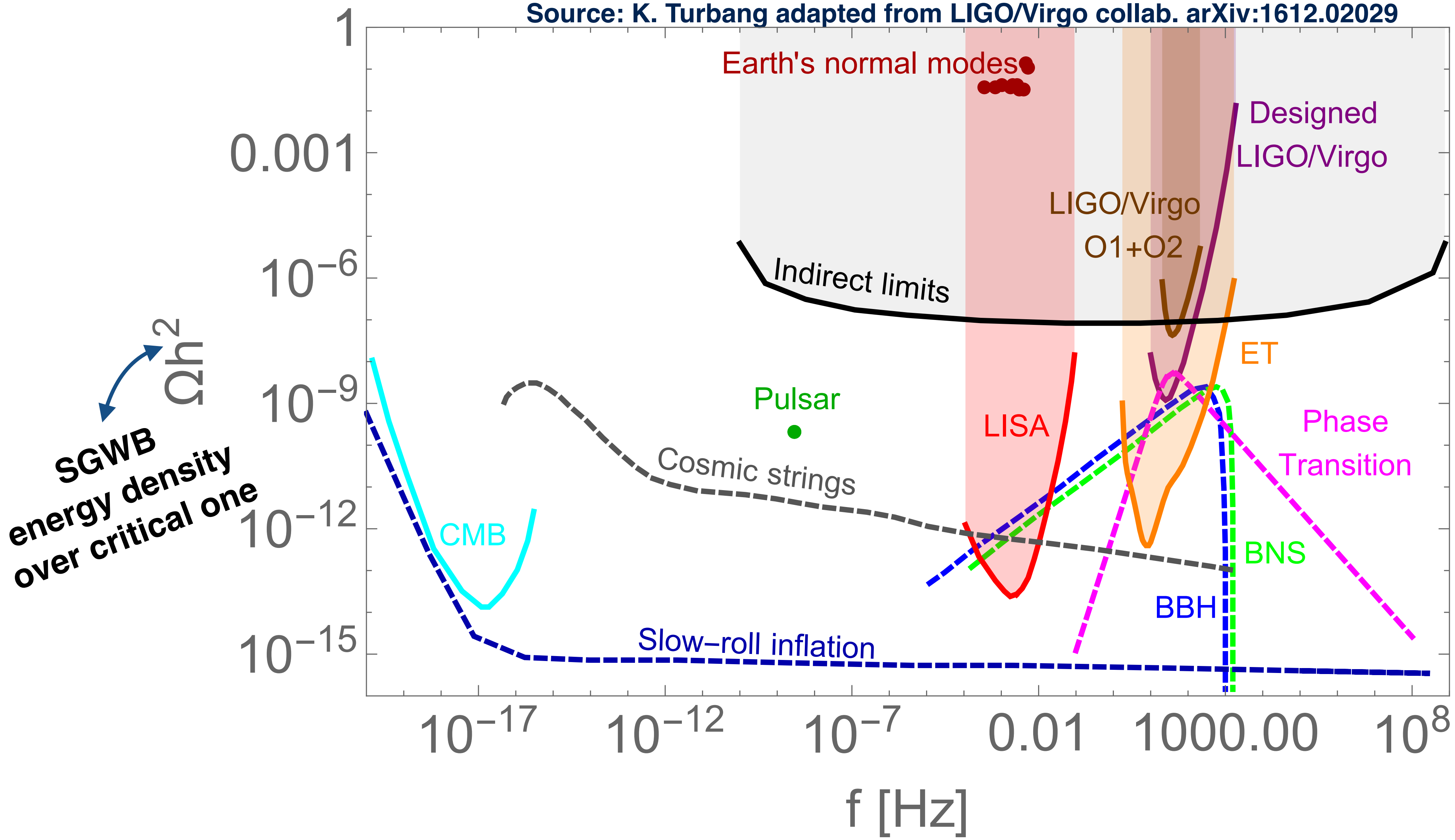
Cosmic strings



Explore Universe earlier than CMB!

Stochastic Background of GW

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



Experimental probes

★CMB, Pulsar timing arrays (NANOgrav)

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

LIGO/Virgo arXiv:2101.12130

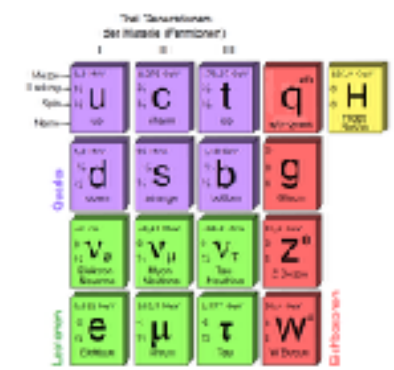
Note: Astrophysical SGWB and cosmological SGWB will superimpose

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

★*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

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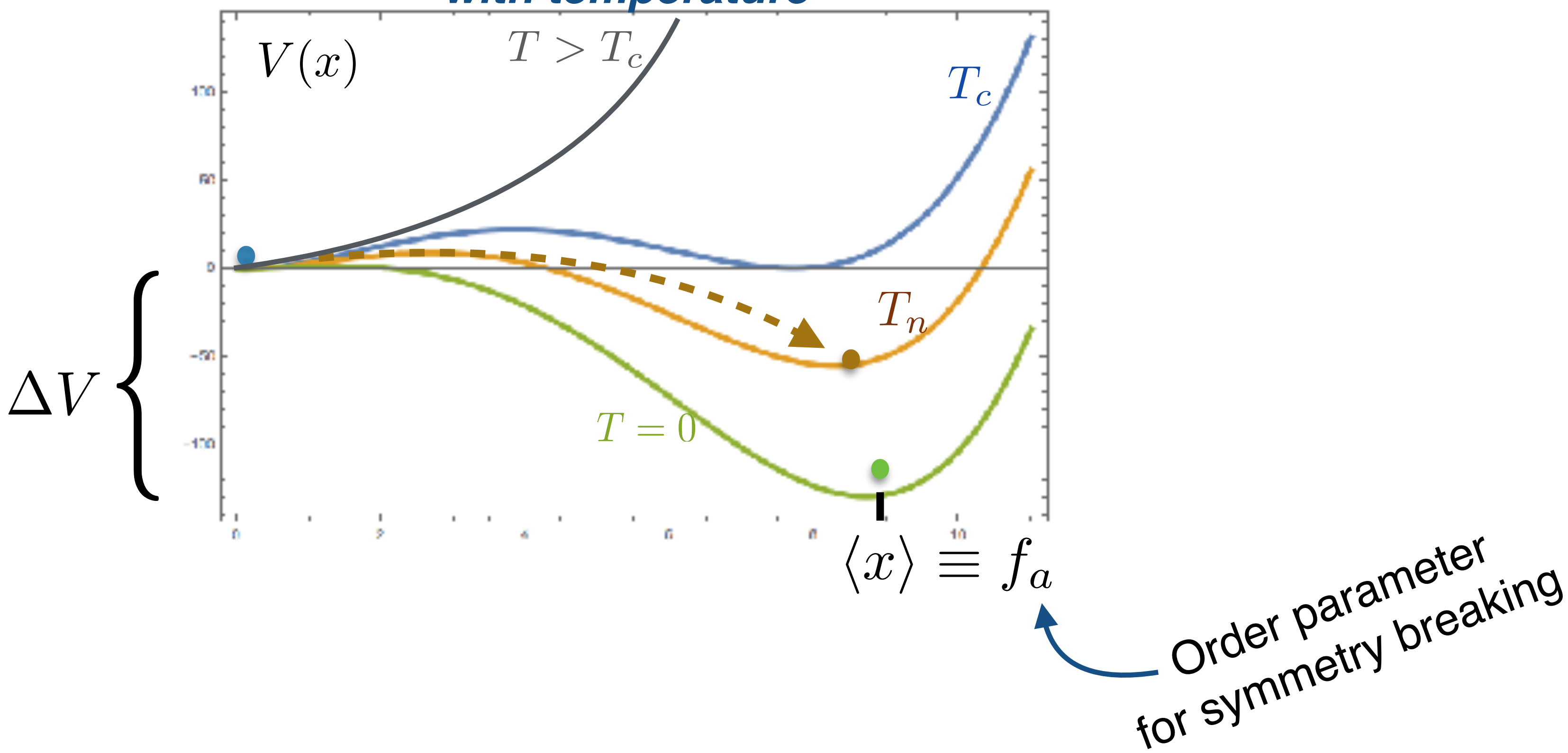
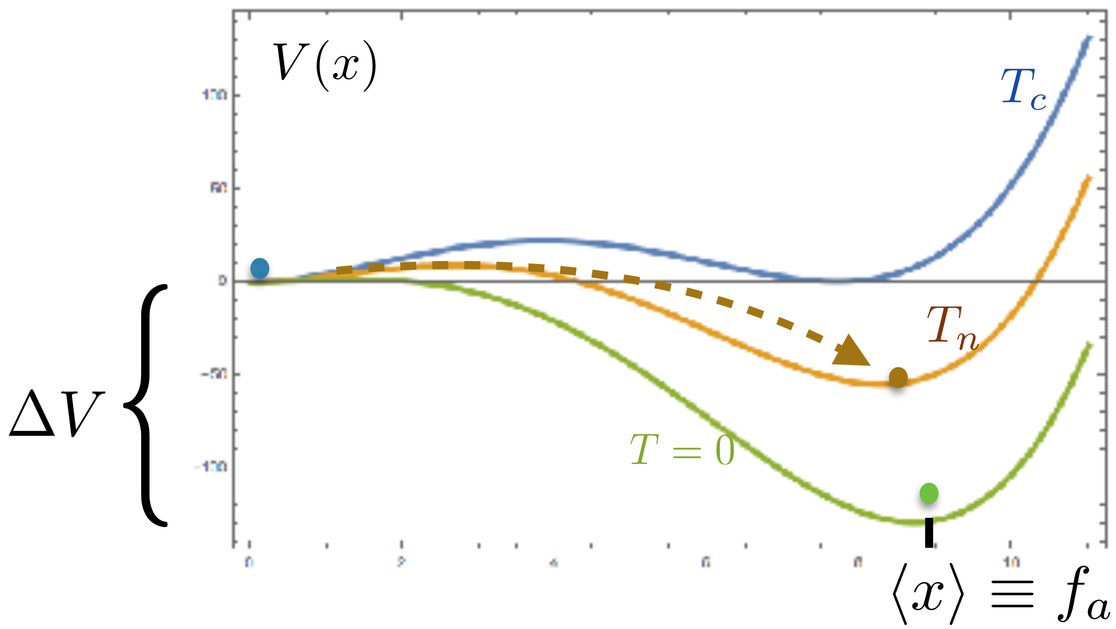
  SUSY br sector!

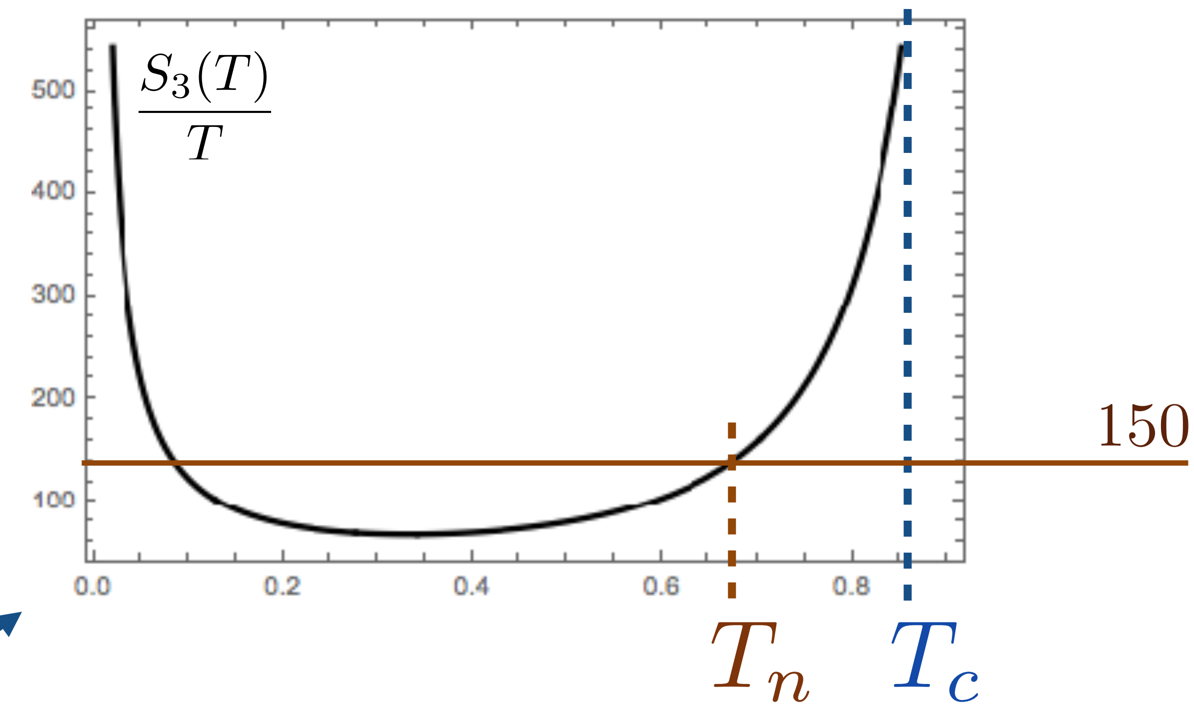
First order Phase Transition

Described in terms of potential evolution with temperature



First order Phase Transition





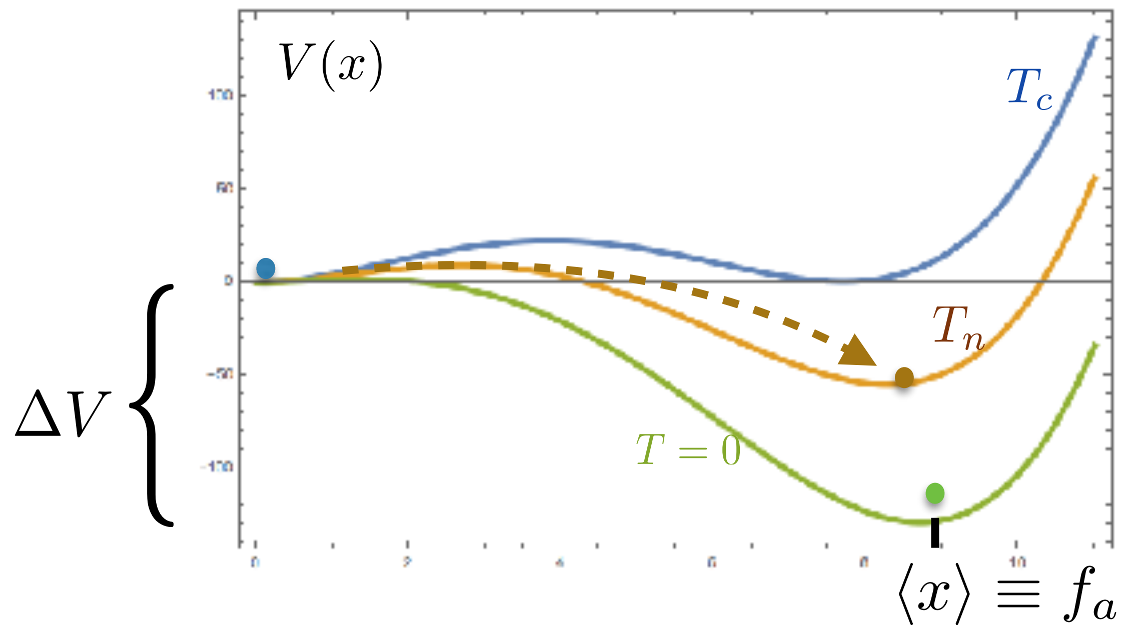
✦ ***Nucleation rate controlled by the bounce action***

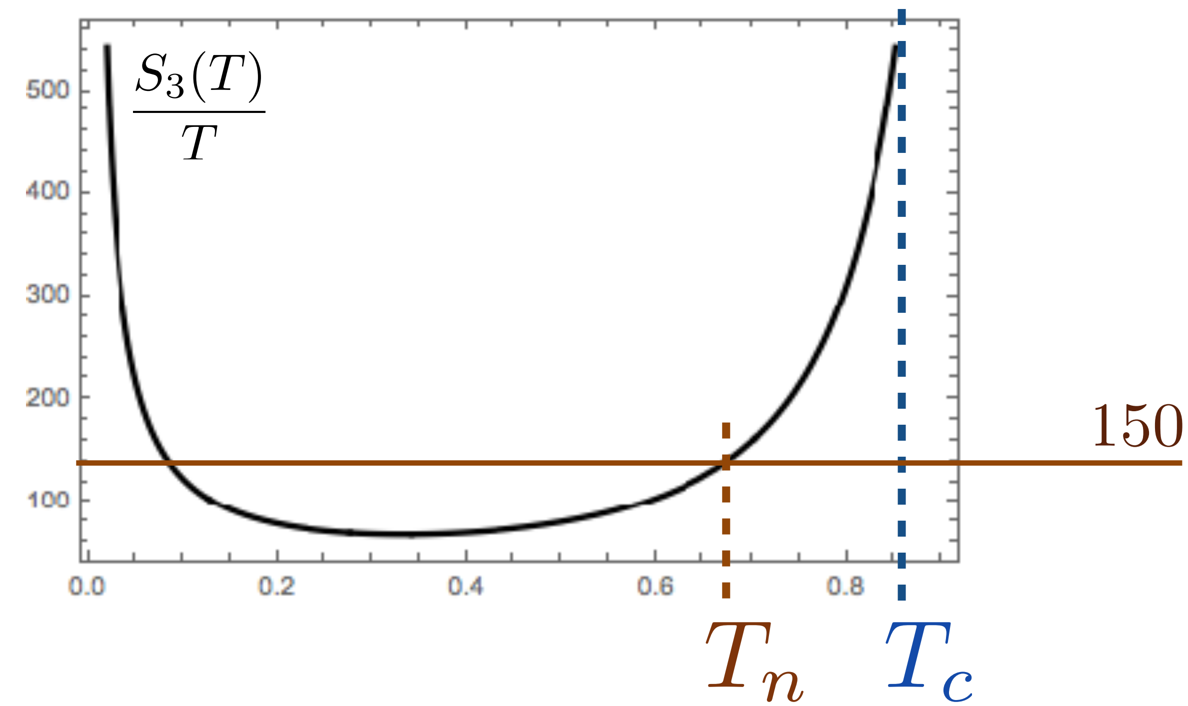
$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$$

Approximate condition for nucleation in RD

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

First order Phase Transition





✦ *Parameters controlling PT properties and SGWB*

Energy released during phase transition ⟷

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

Inverse time-scale of the phase transition ⟷

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

Bubble dynamics in cosmic plasma

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

E.g. Sound Waves contribution

- If friction is significant dominant production mechanism is sound waves

Sound Waves contribution

SGWB amplitude

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

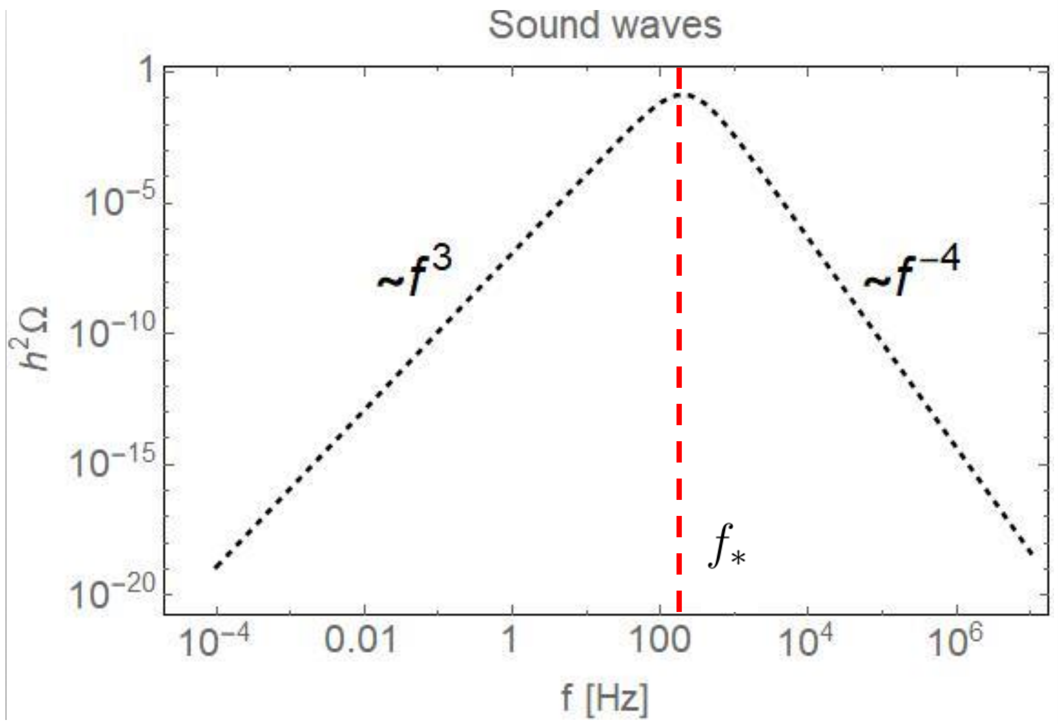
Efficiency factor between 0 and 1.

Precise number depends on simulation

Peak frequency

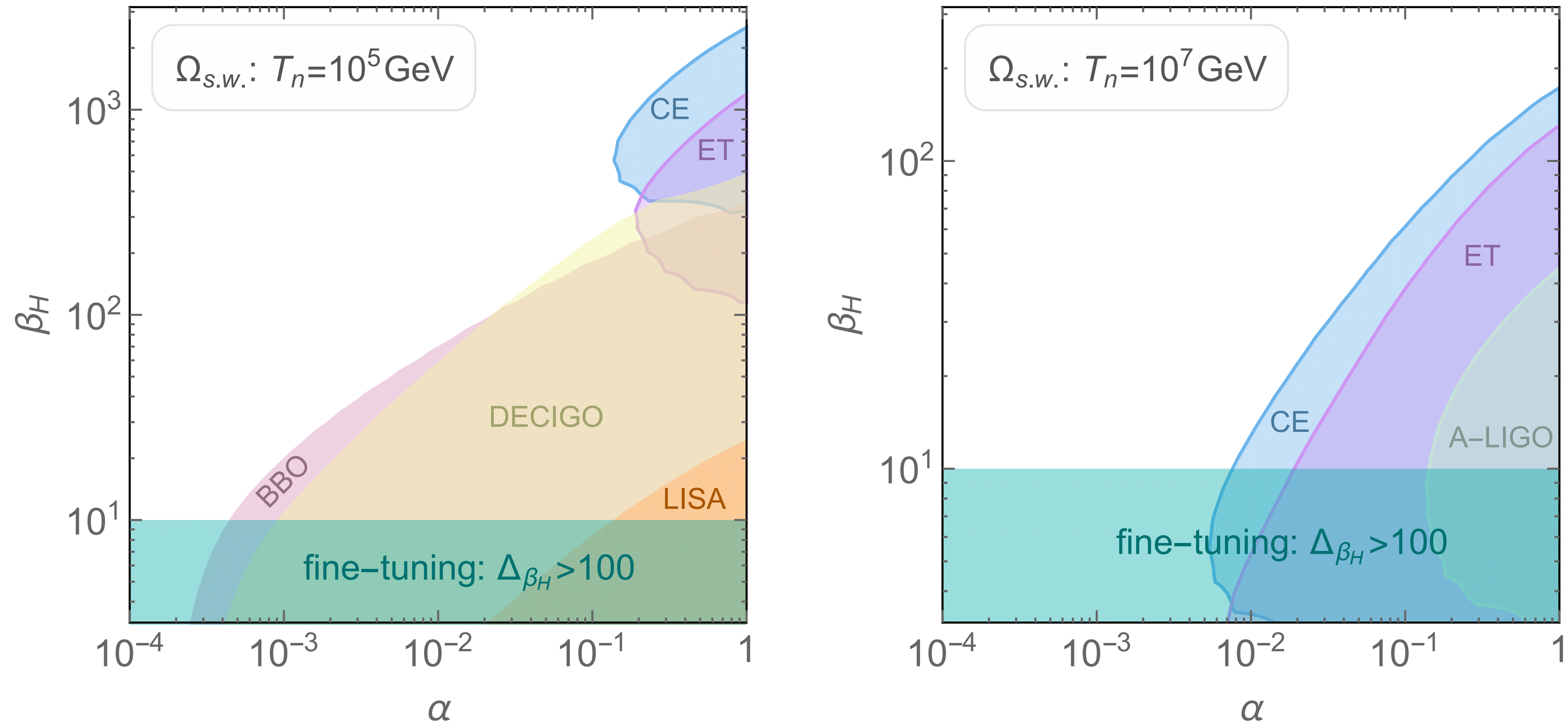
$$f_* \sim 10 \text{ Hz} \left(\frac{\beta_H}{100}\right)\left(\frac{T_n}{10^7 \text{GeV}}\right)$$

GW signal is broken power law



Detectability and beta tuning

Model independent Experimental reach on SGWB from PT



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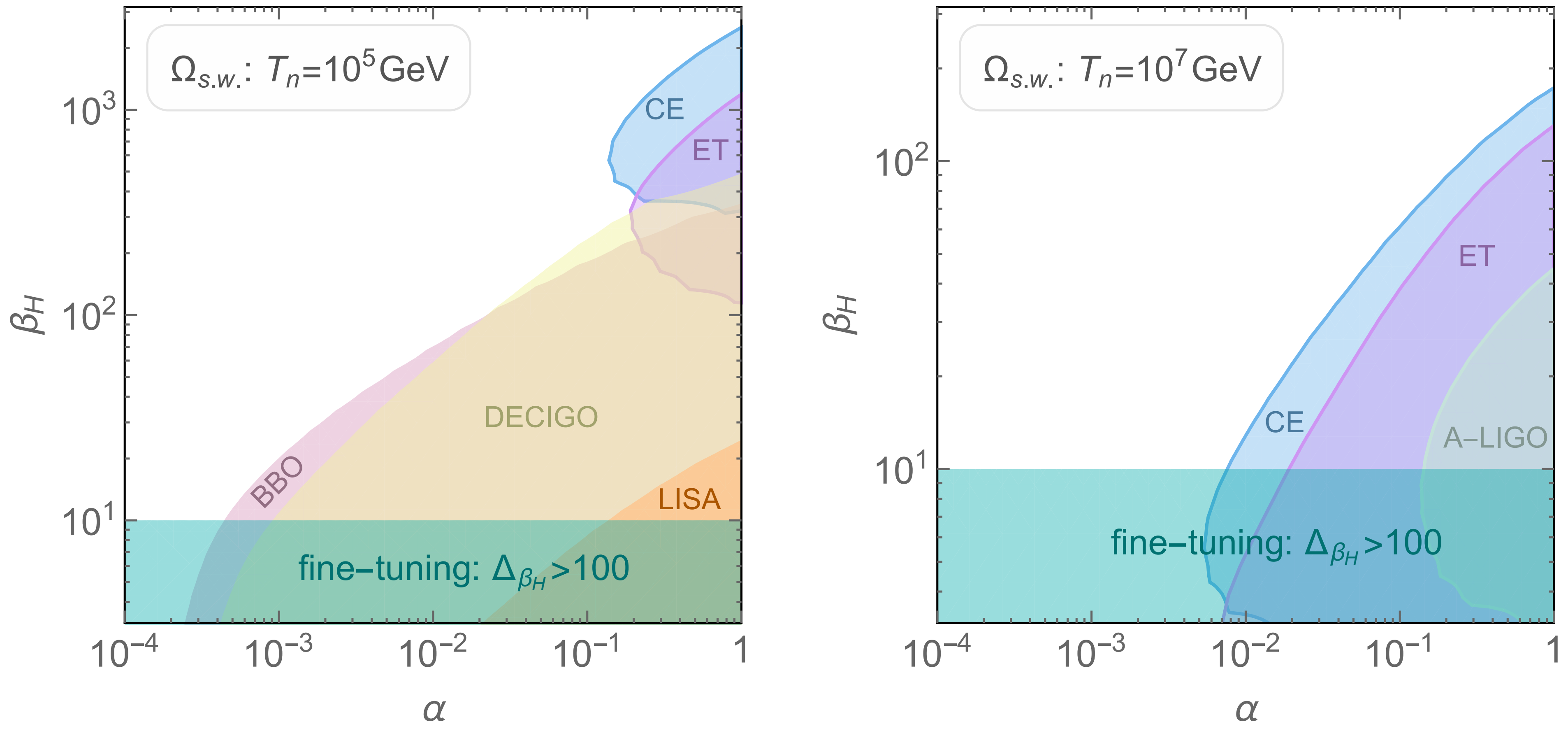


Using Nucleation Condition one can show that

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

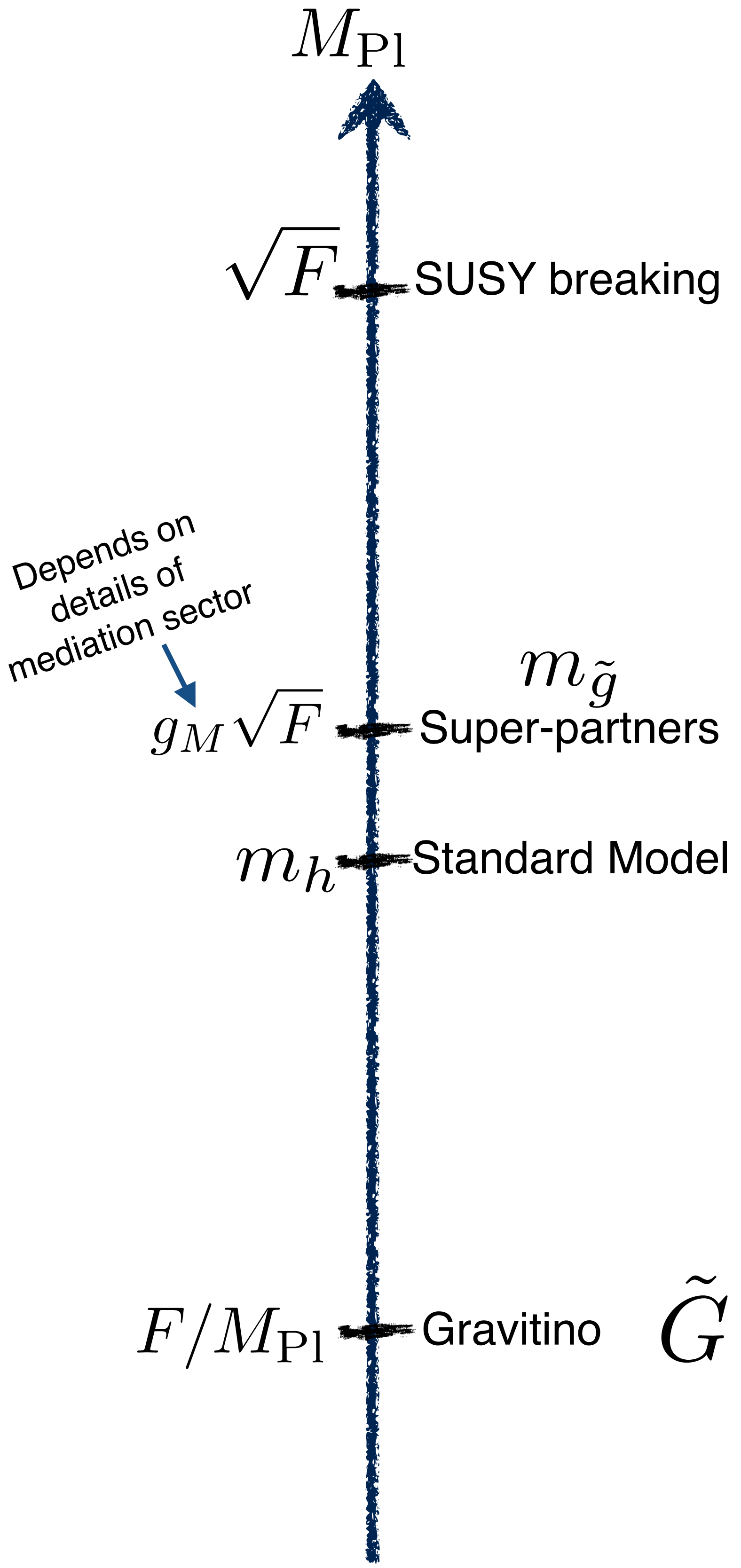
Unless fine-tuning to have cancellation

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

SUSY scales in Low Energy SUSY-breaking



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

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

SUSY scales in Low Energy SUSY-breaking

$M_{\rm Pl}$

$\sqrt{F}$ SUSY breaking

Depends on details of mediation sector

$g_M \sqrt{F}$ Super-partners $m_{\tilde{g}}$

m_h Standard Model

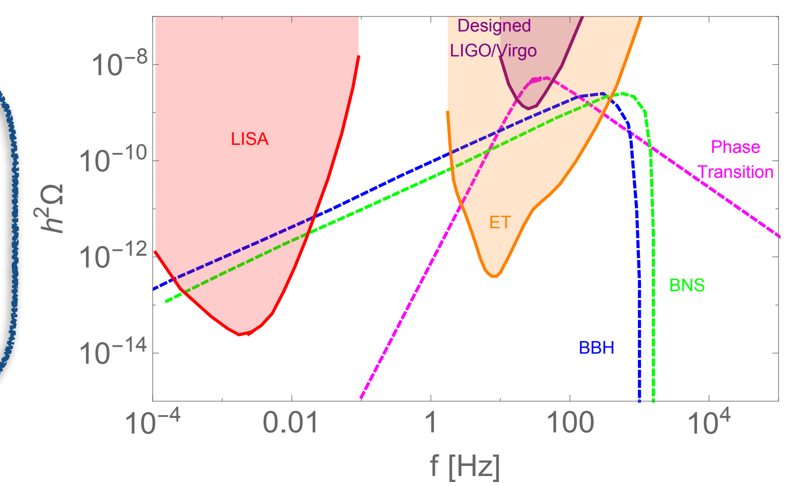
$F/M_{\rm Pl}$ Gravitino $\tilde{G}$

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

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



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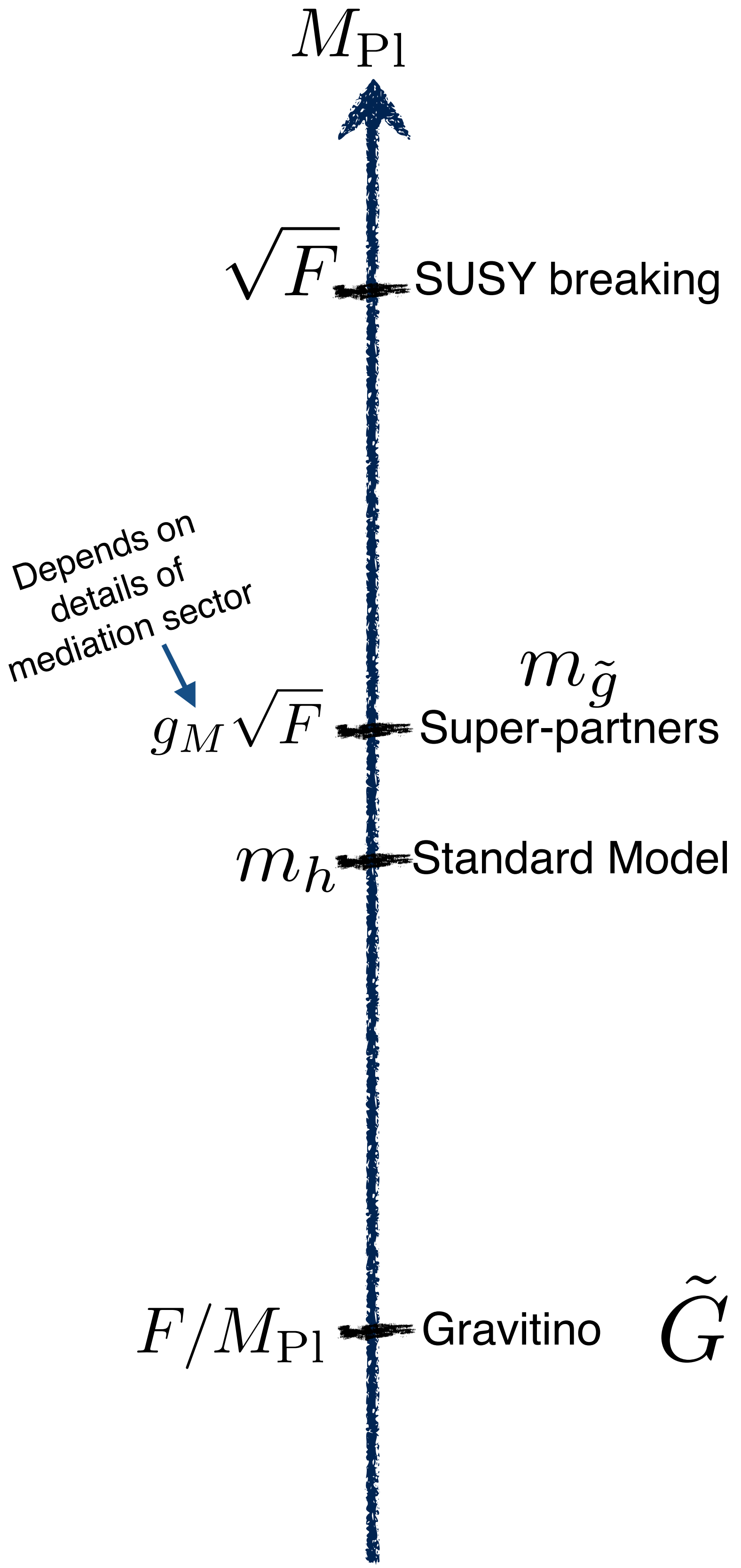

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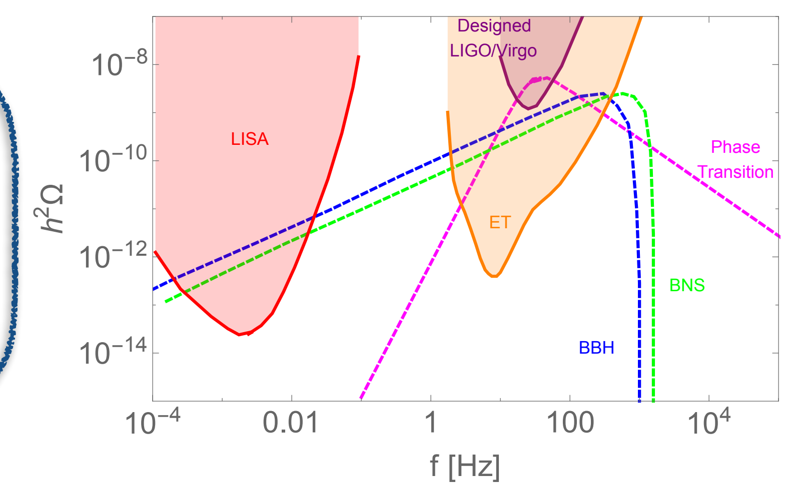


Low Energy SUSY breaking

Gravitino is the LSP

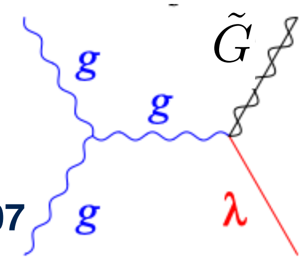
Gravitino cosmology shapes the parameter space

SUSY scales in Low Energy SUSY-breaking

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

Universal gravitino Lagrangian

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



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

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

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

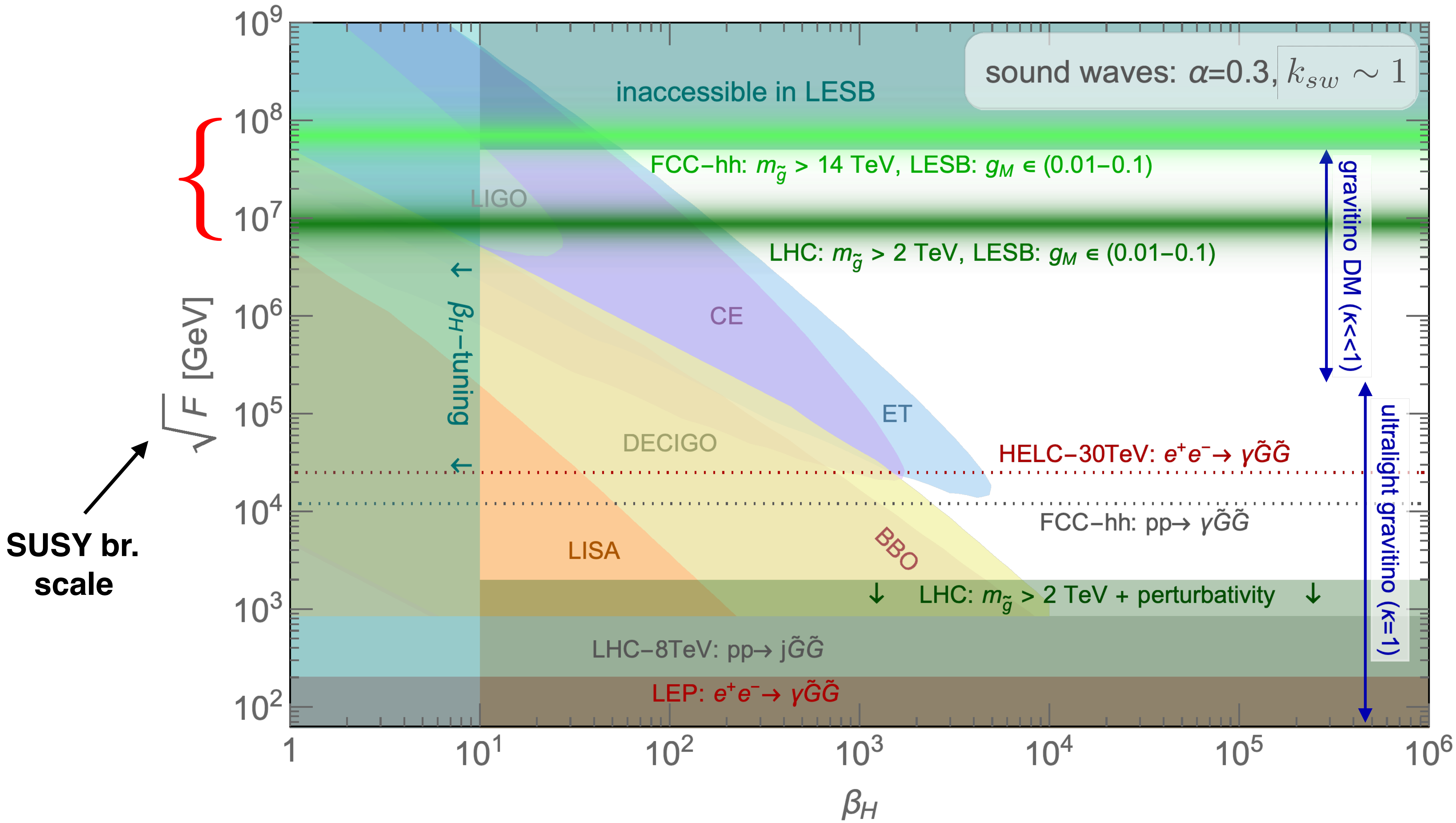
Viable DM candidate in window

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

Hall, Ruderman,Volansky arXiv:1302.2620

How we discover LESB

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



How we discover LESB

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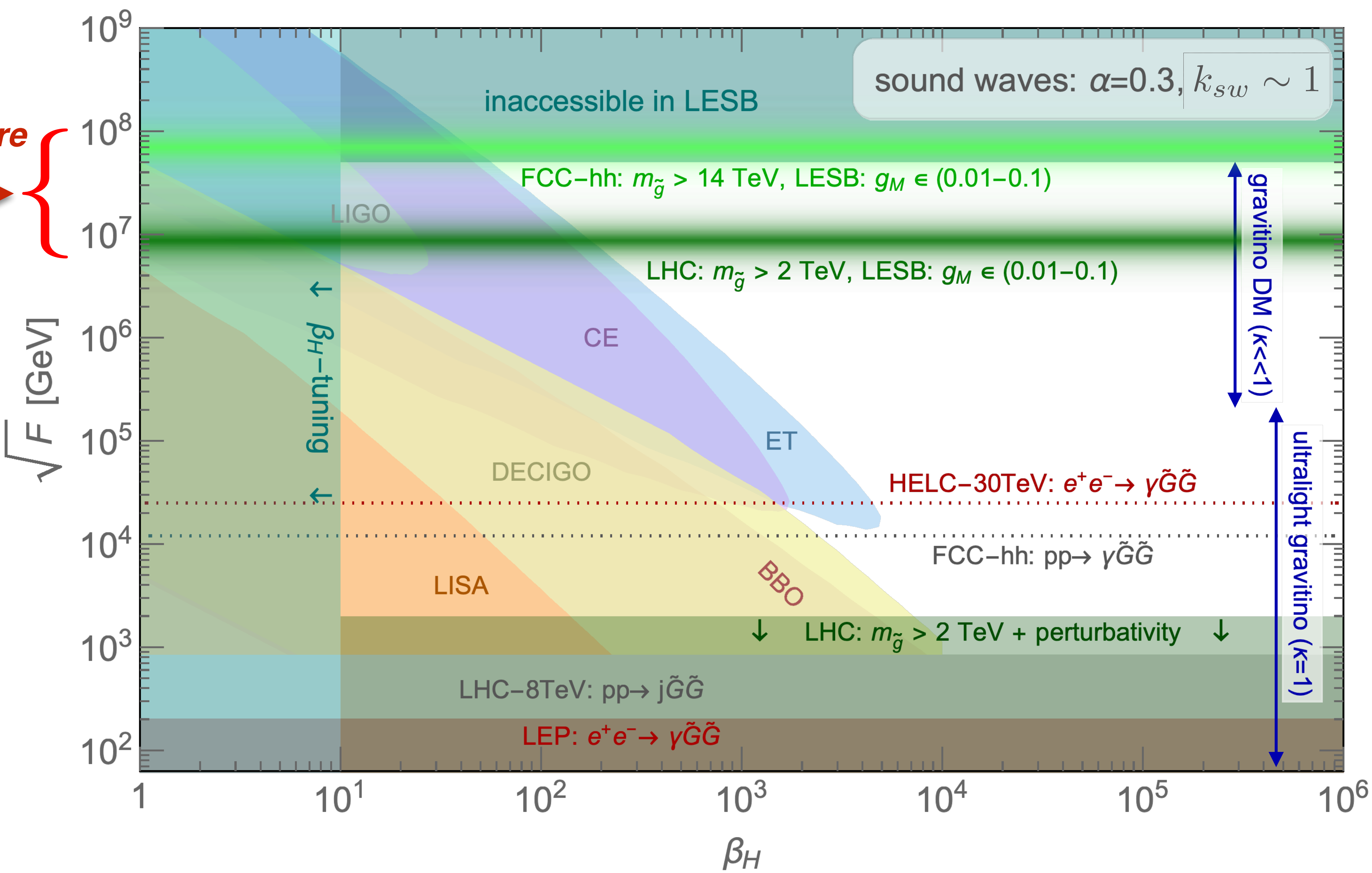
Here live the hidden sectors that we explore



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

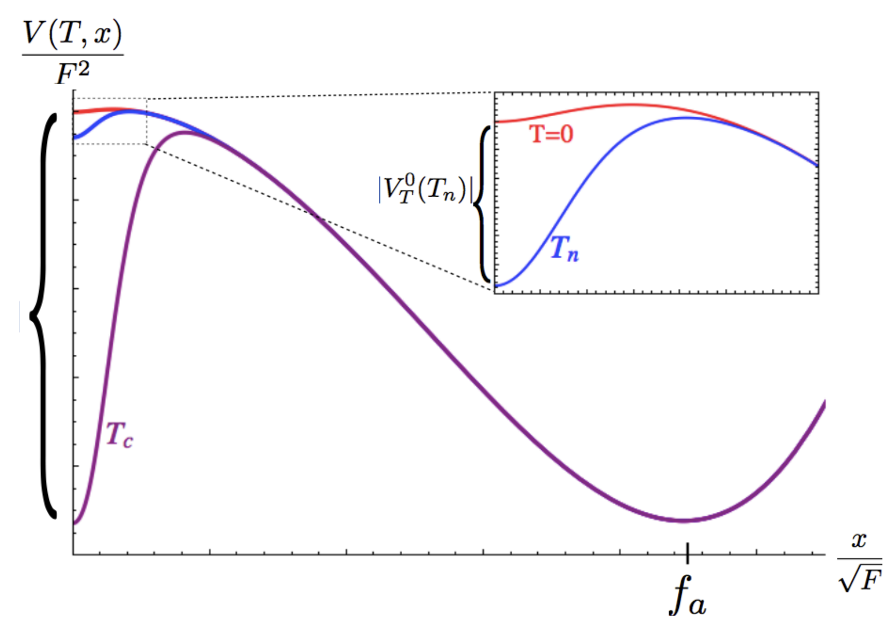
Now I focus on SUSY breaking sector dynamics

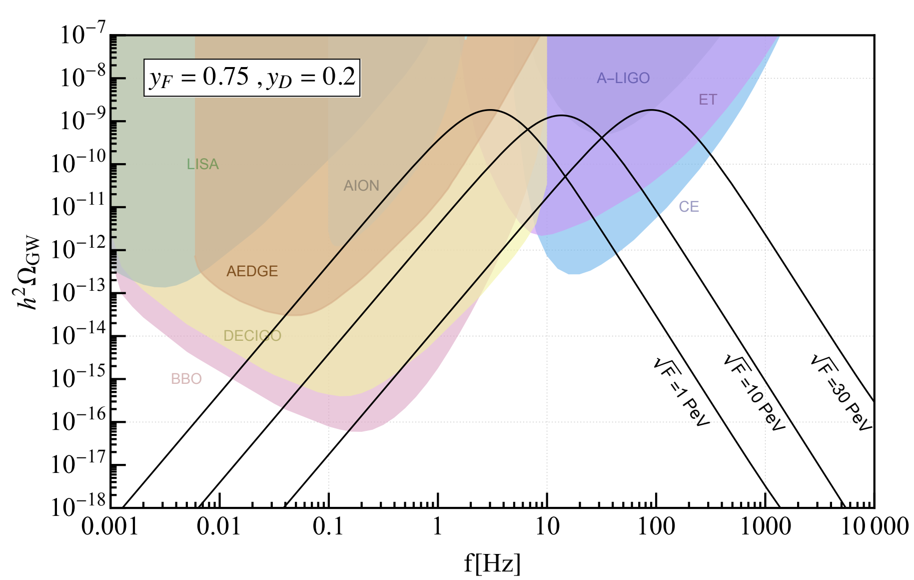
$$X = \frac{x}{\sqrt{2}} e^{2ia/f_a} + \sqrt{2}\theta\tilde{G} + \theta^2 F$$

Pseudo-modulus

★*Can R-symmetry breaking PT along pseudomodulus be first order?*

★*What are properties of scalar potential?*



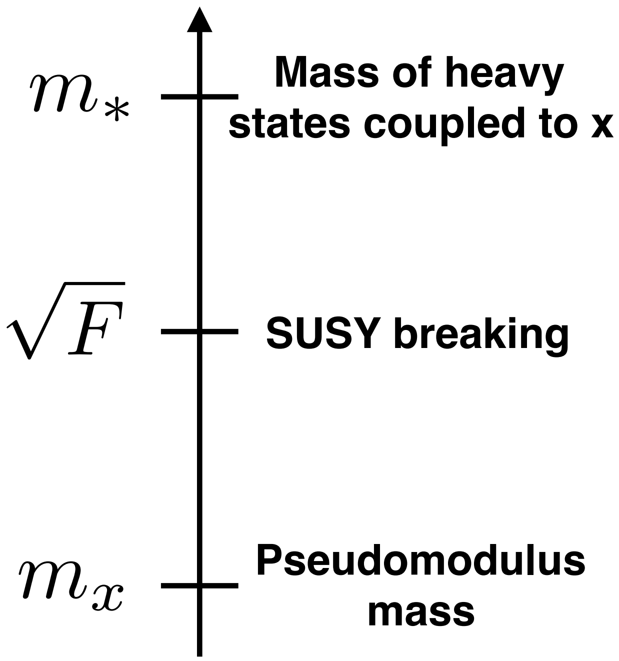


★*What are conditions to get strong GW signal?*

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

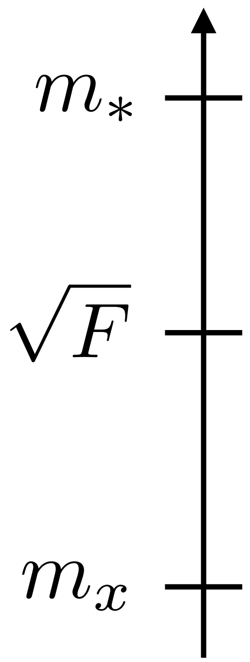
Pseudomodulus EFT

EFT scales

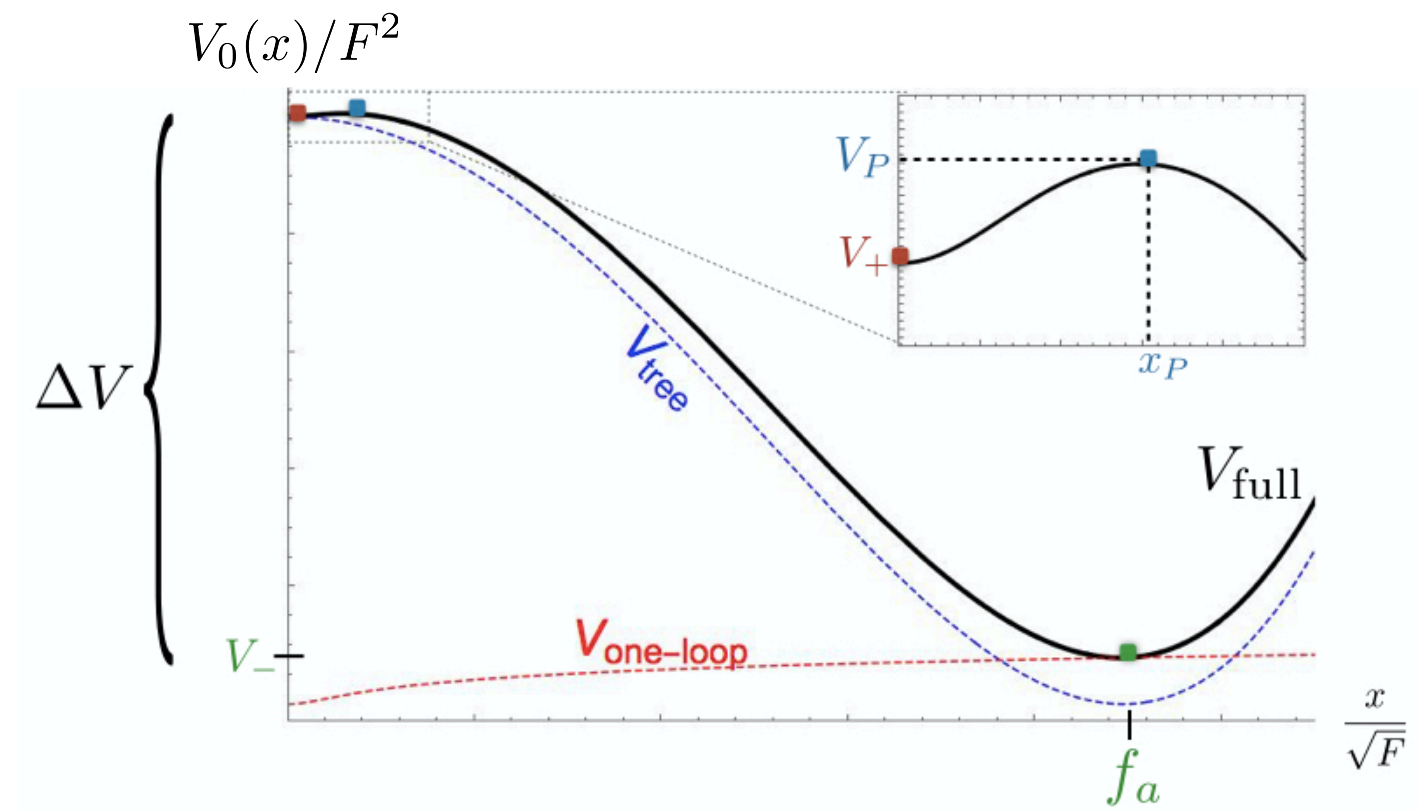


Pseudomodulus potential with FOPT

EFT scales



★ *What are properties of potential?*



✳ ***Combine flat tree level potential plus loop corrections***

→ ***Realize potentials exhibiting first order phase transition***

✳ ***Obtained by minimal deformation of basic O'Raifeartaigh models***

✓Marginal/Irrelevant R-breaking operators
✓Gauging of global symmetries

Intriligator Seiberg Shih '07
Witten '81

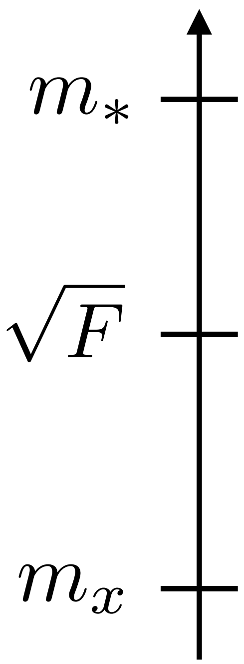
Basic properties

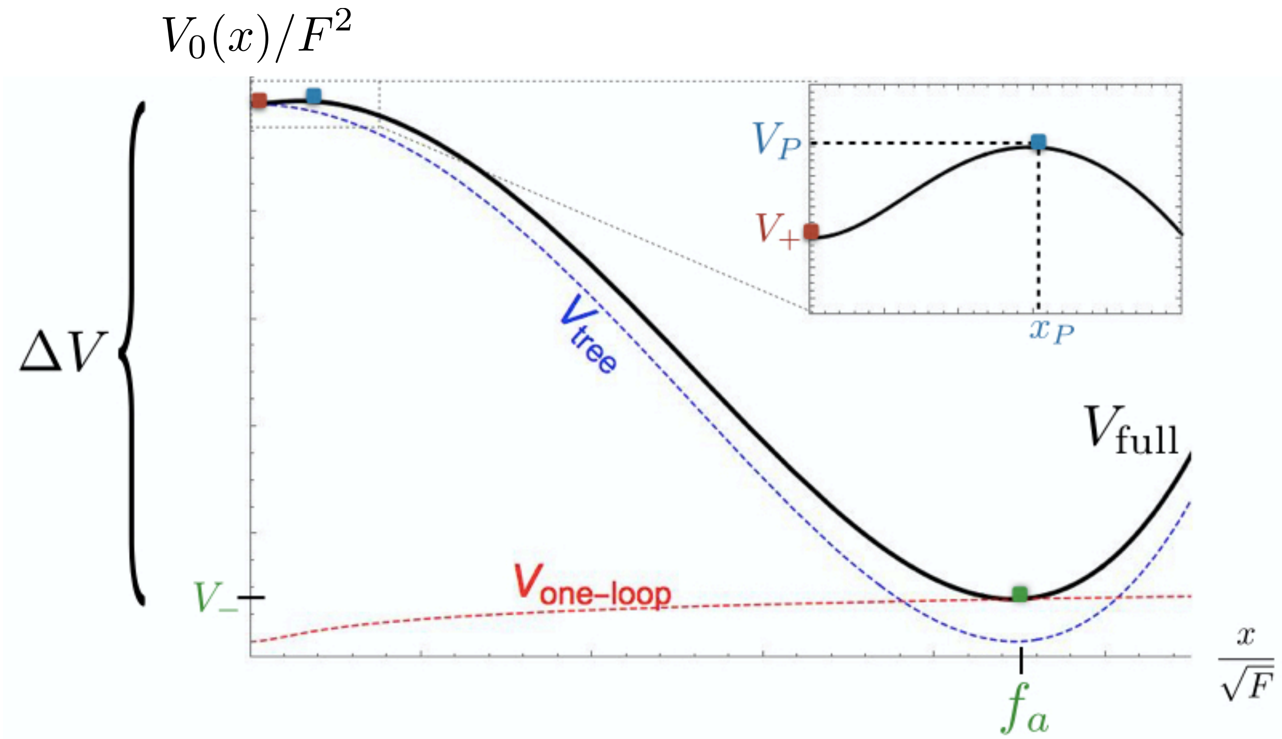
✳ ***Potential is flat*** $f_a^4 \gg \Delta V$

✳ ***Barrier is small*** $\frac{V_P}{\Delta V} \simeq \frac{\lambda_{\rm eff}^2}{16\pi^2}$

Pseudomodulus toy model

EFT scales





$$\Delta V = (\kappa_D F)^2$$

$$\langle x \rangle_{\text{true}} = f_a = \sqrt{\frac{F}{\epsilon_{\not R}}}$$

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

SUSY Mass of heavy states coupled to x

$\kappa_D = 1$
Single scale SUSY breaking

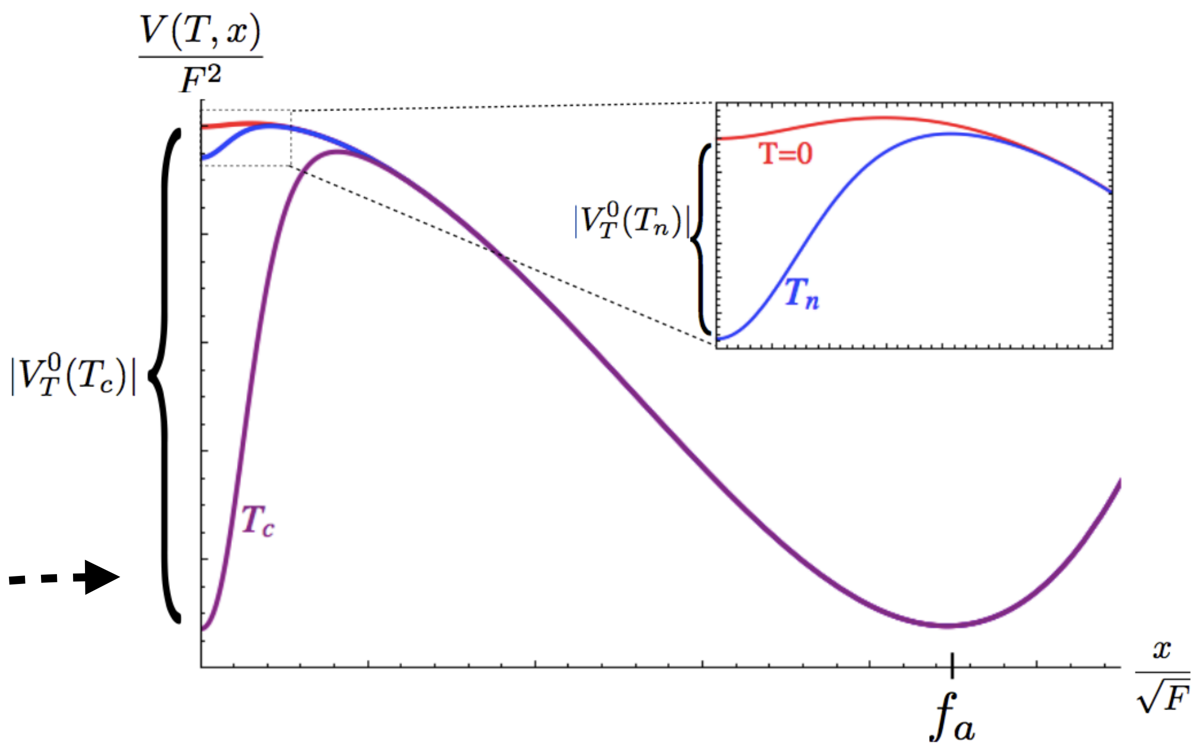
Tree level contribution

Pure log at x --> infinity

✳ ***Barrier is loop induced***

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

Pseudomodulus potential at finite T



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

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

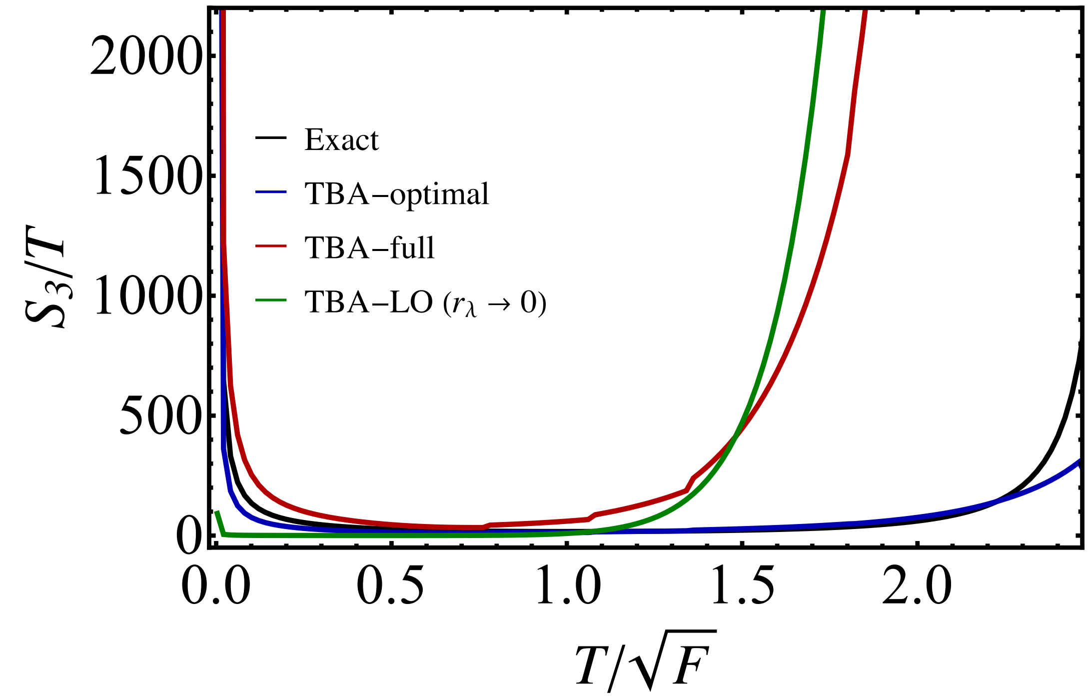
Low T expansion

- ***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* $V_T^0 \sim -T^{5/2} m_*^{3/2} e^{-\frac{m_*}{T}}$

✦ *Bounce action scales as:* $S_3/T \sim T^a e^{-m/T}$

✦ *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

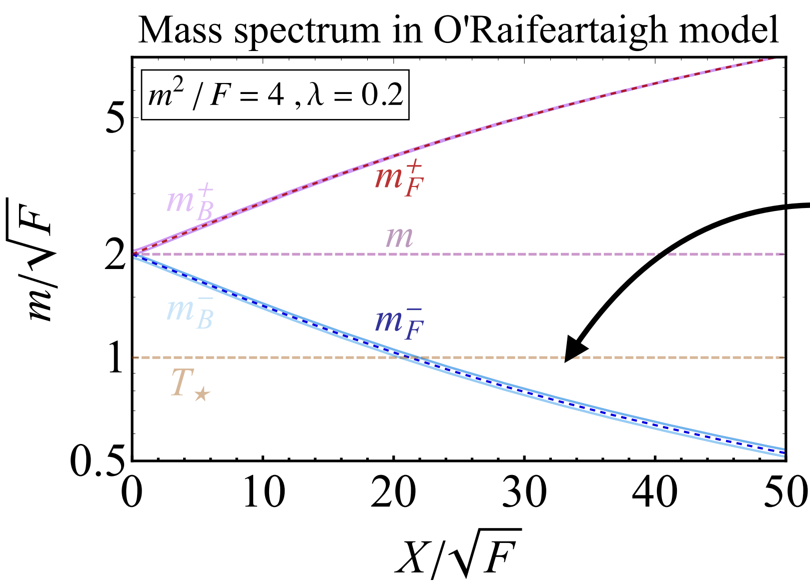
See also A. Katz 2009

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

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

We consider vector-like O'Raifeartaigh model

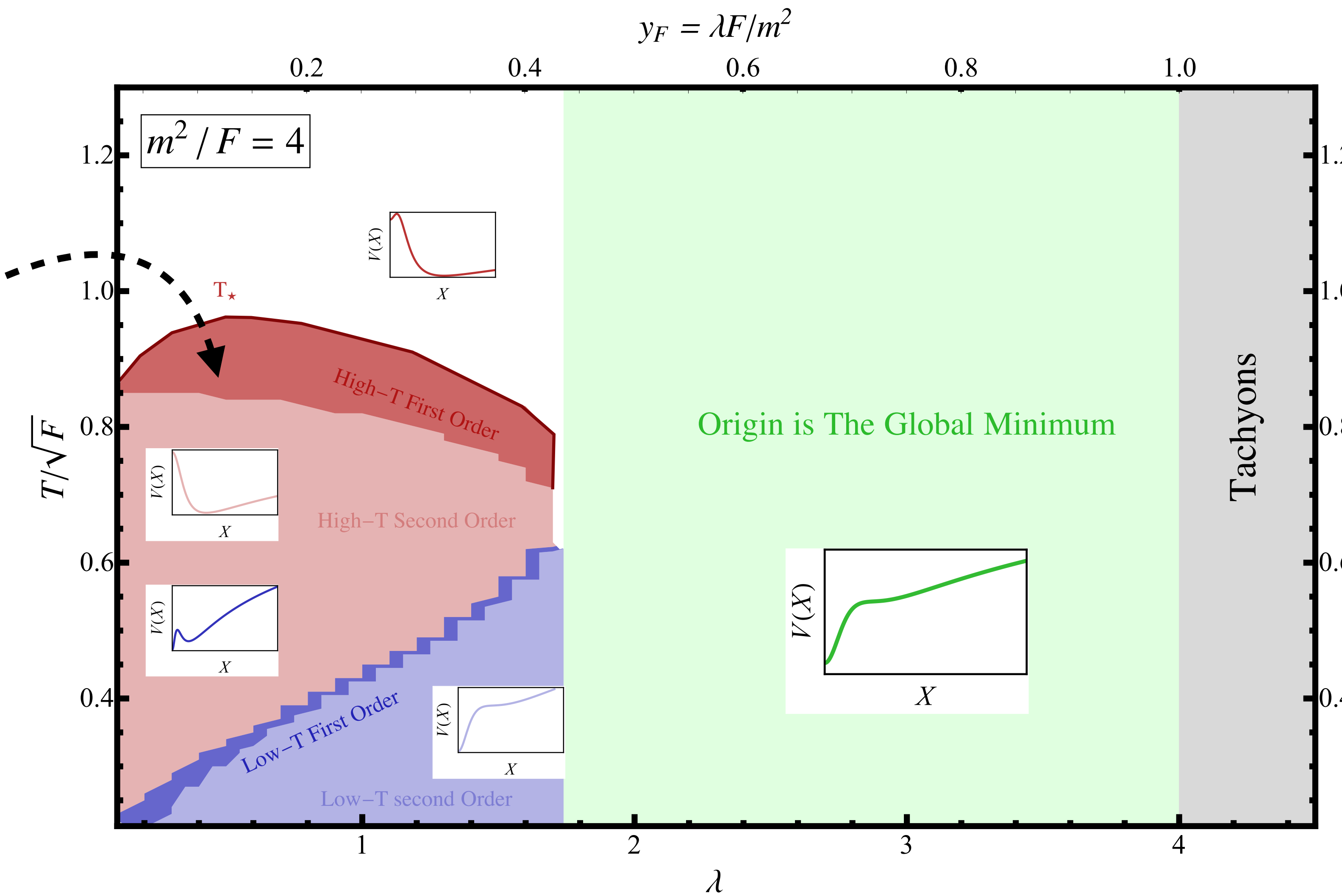
	X	Φ_1	$\tilde{\Phi}_1$	Φ_2	$\tilde{\Phi}_2$
$U(1)_R$	2	0	2	2	0
$U(1)_D$	0	1	-1	1	-1



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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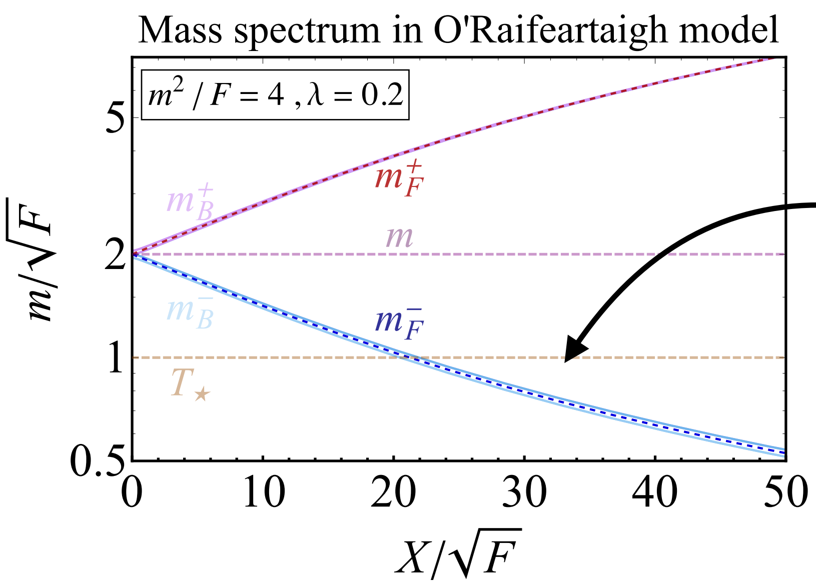

There are eigenvalues decreasing for increasing X

We focus on this regime for simplicity

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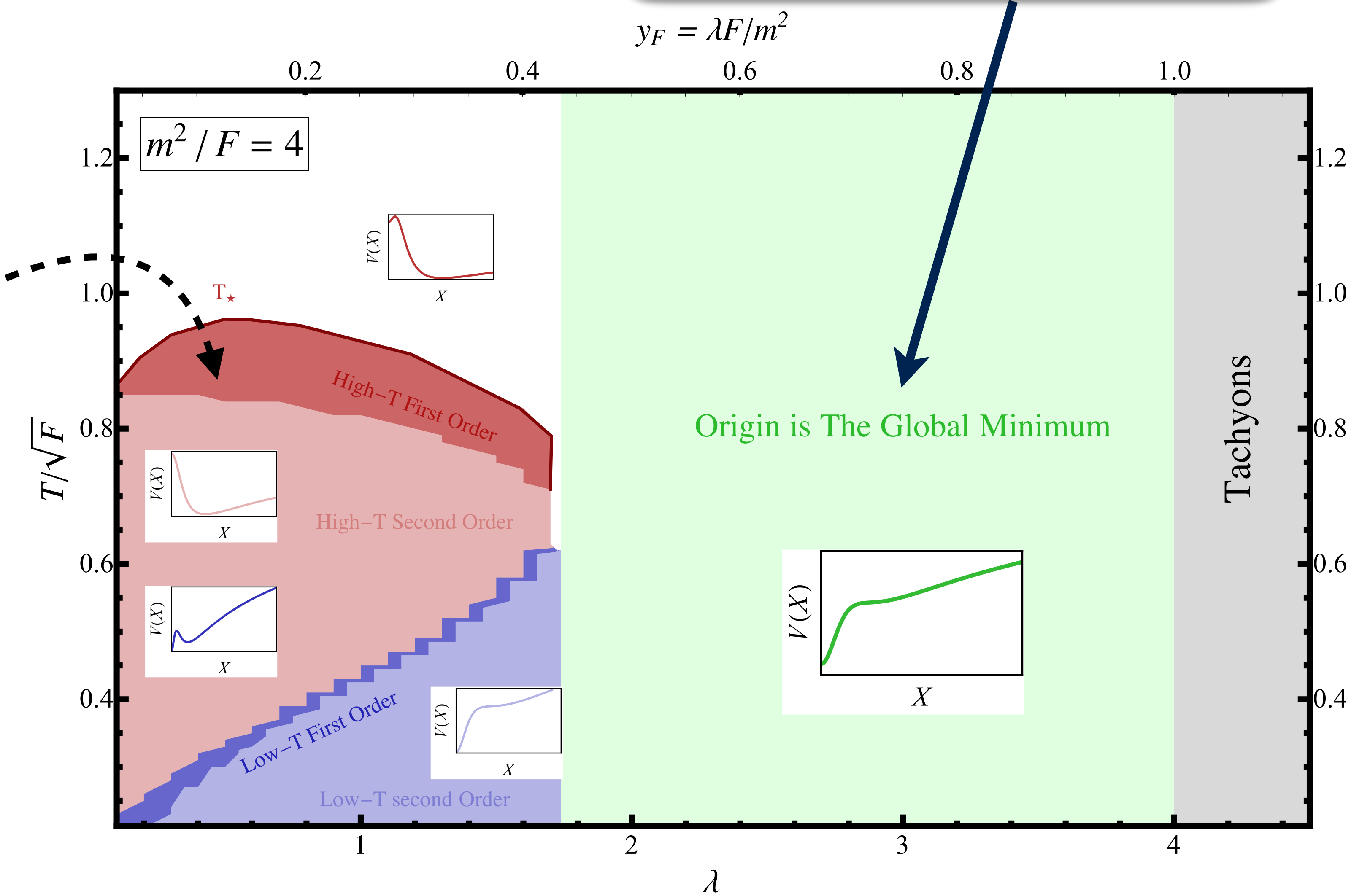

A full model of LESB

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
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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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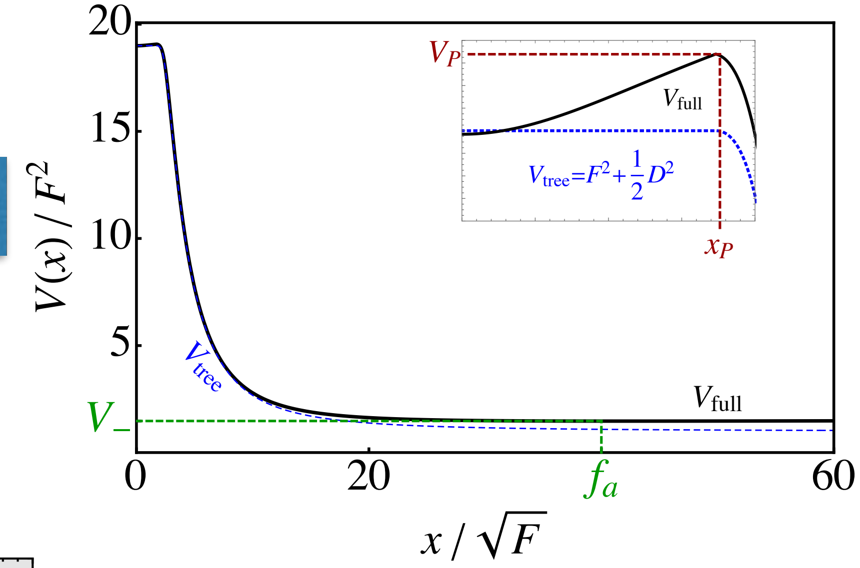
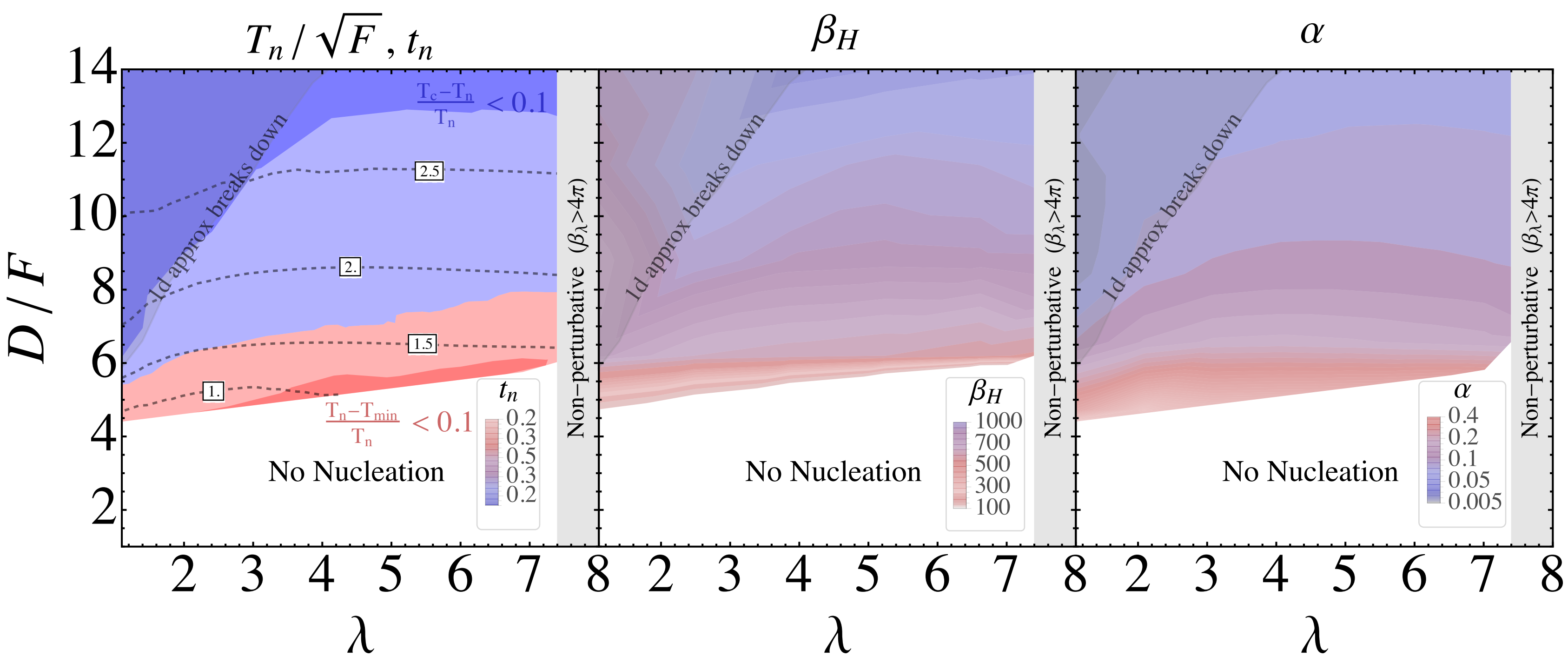
Flat potential with local minimum



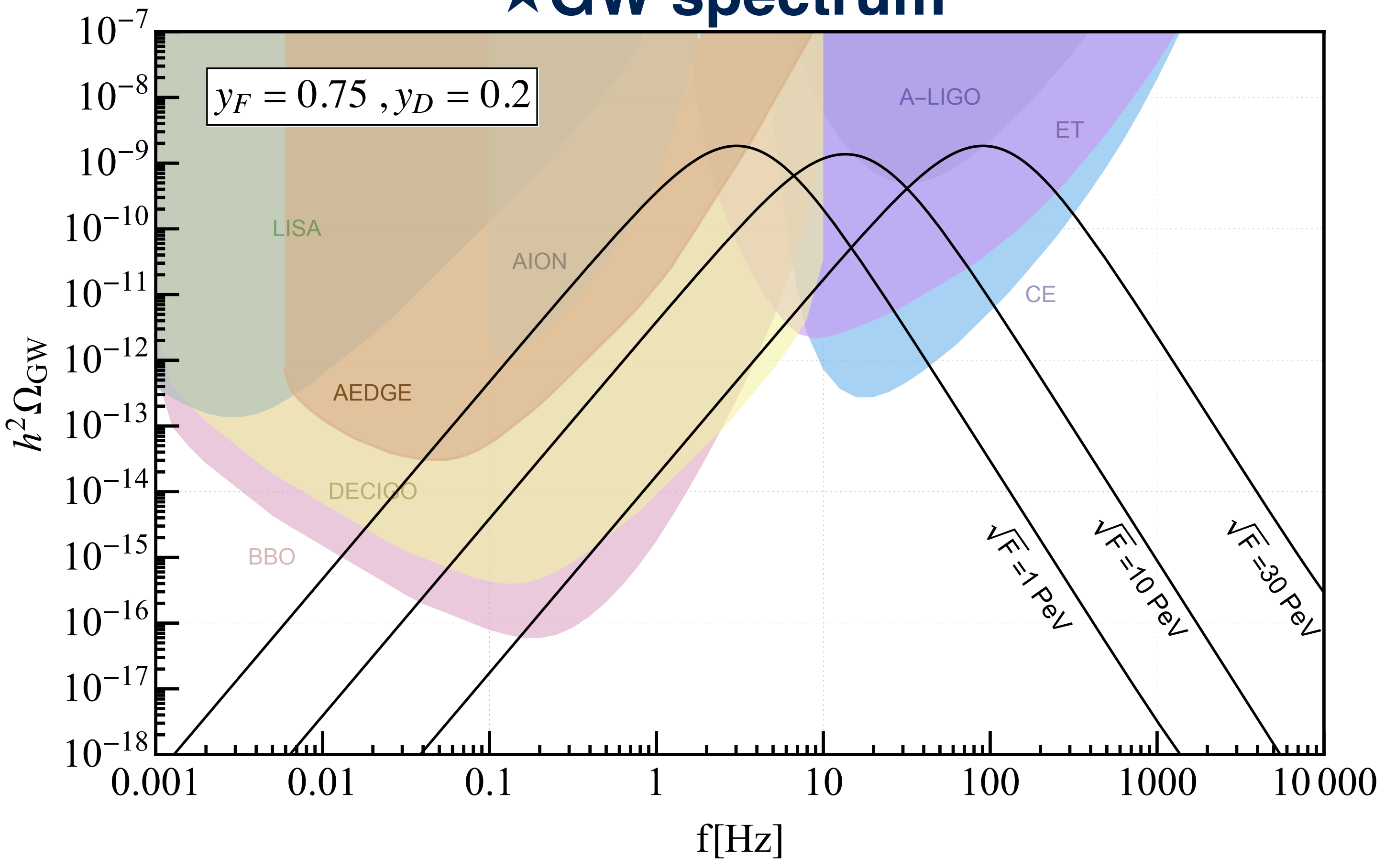


PT parameters

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

A full model of LESB

★GW spectrum



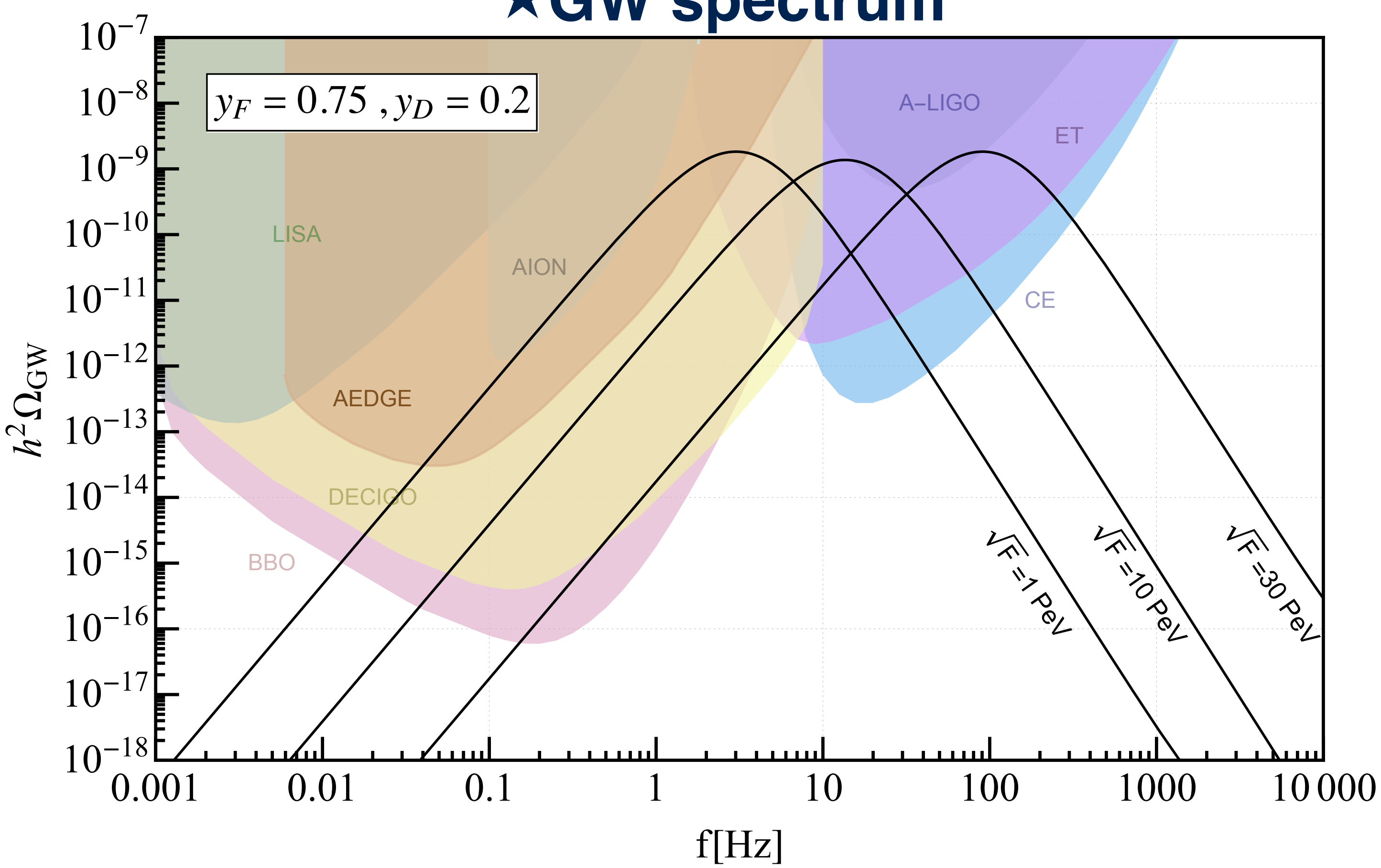
✳ ***Simplest O'Raifeartaigh model***
✳ ***Gauge non-anomalous U(1) + D-term***

SUSY and spontaneous R-breaking

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

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

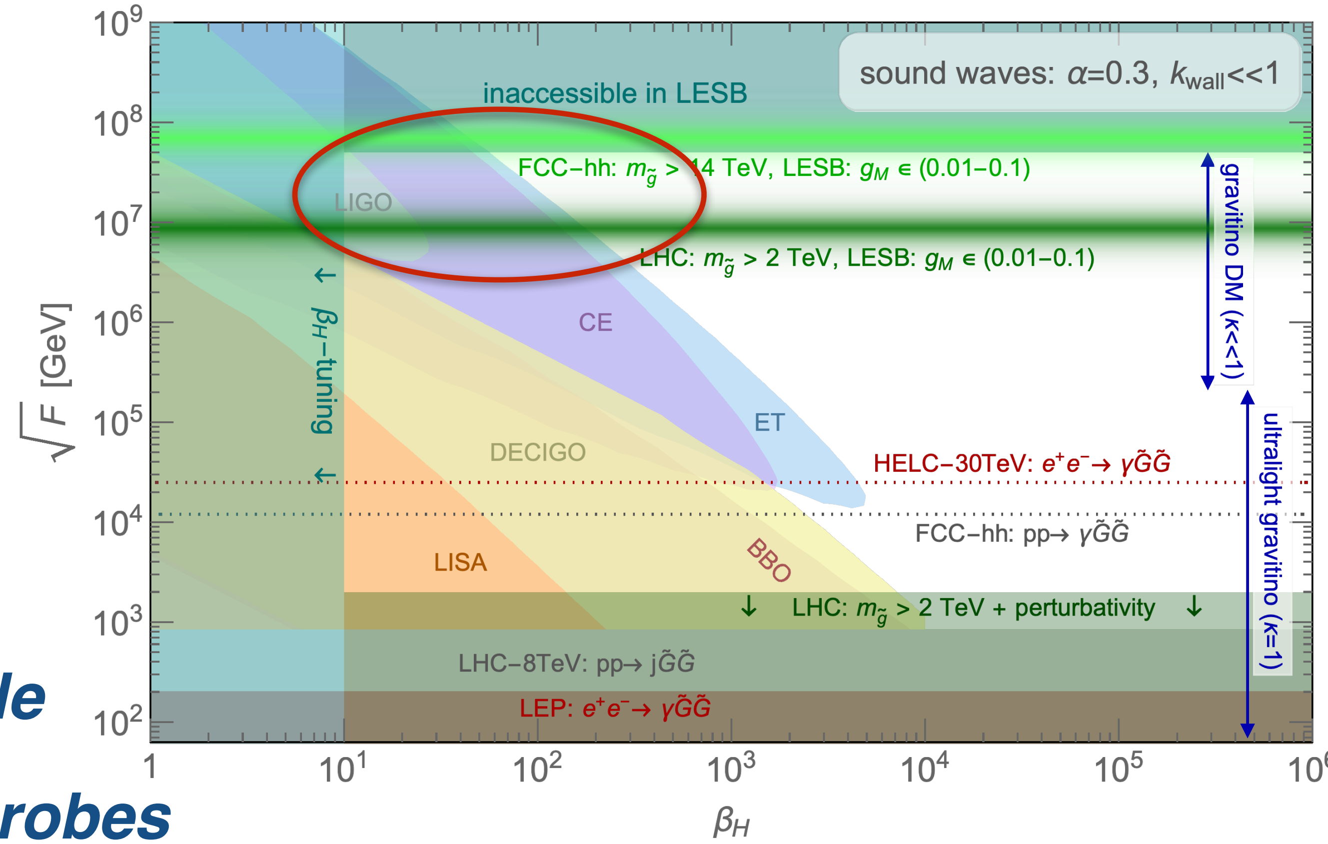
A signal of SGWB at O(100) Hz correlates to gluino at reach of FCC-hh

Conclusions

✦ **SUSY breaking hidden sectors can lead to R-symmetry FOPT**

→ **Can deliver SBGW**

- FOPT along the universal pseudomodulus direction
- Two scales of SUSY br needed for large SBGW
- Beta tuning in parameter space (as any other QFT)



✦ **SBGW frequency point to SUSY br scale**

✦ **Interesting interplay with other SUSY probes (future colliders)**

✦ **Novel features in SUSY breaking pseudomodulus 1st order PT low-T expansion**

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

Can provide hints for future colliders