Probing classically conformal B-L model with gravitational waves

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Based on arXiv:1604.05035 (by RJ & Masahiro Takimoto)

July 7th, 2016 SUSY @ Melbourne

Introduction & Conclusion

FIRST DECECTION OF GWS

- LIGO announcement @ 2016/2/11

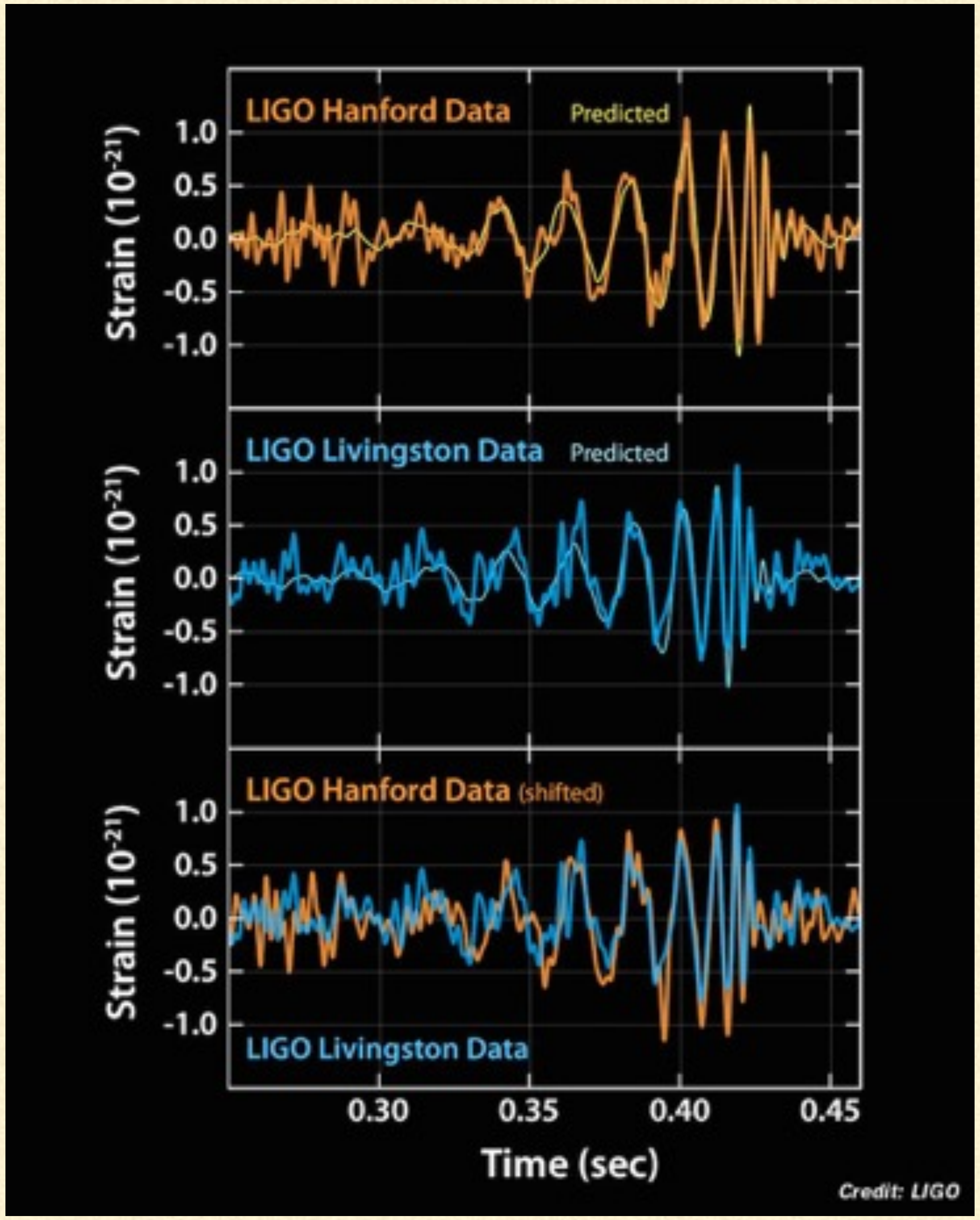
  - Black hole binary

    36M⊙ + 29M⊙ →62M⊙

    with 3.0M⊙ radiated in GWs

  - Frequency ~ 35 to 250 Hz

  - Significance > 5.1σ



FIRST DECECTION OF GWS

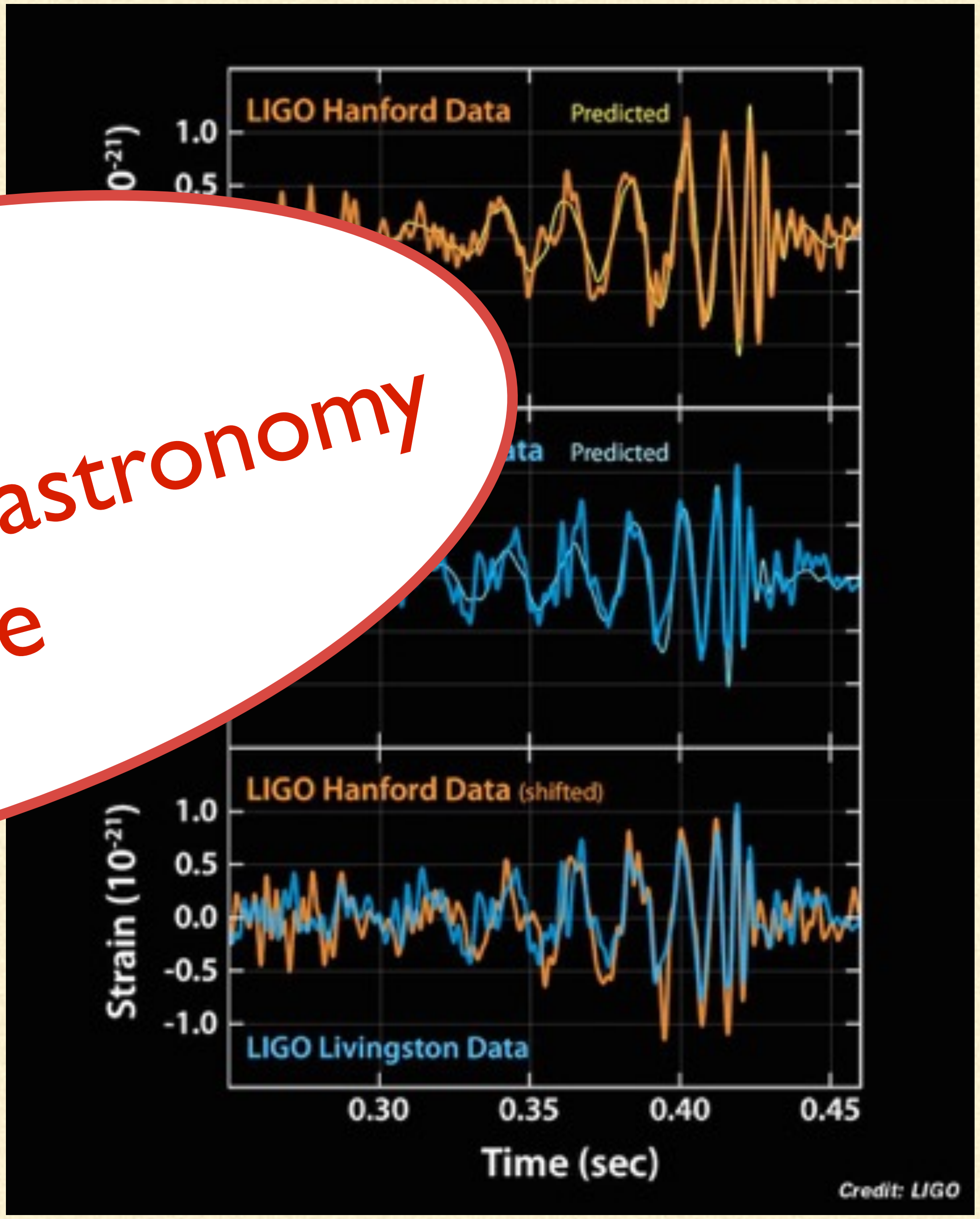
- LIGO announcement @ 2016/2/11
  - Black hole binary

    $36M_\odot + 29M_\odot \rightarrow 6$

    with $3.0M_\odot$ radia

  - Frequency ~ 35 t
  - Significance > 5.1σ

The era of
Gravitational wave astronomy
has come



FROM ASTRONOMY TO COSMOLOGY

- Next will come the era of gravitational-wave "cosmology"

  - Space interferometries (eLISA, BBO, DECIGO,...) are proposed

- What kind of high-energy physics can we search using GWs ?

  - Inflationary quantum fluctuations

  - Preheating

  - Cosmic strings, domain walls

  - First-order phase transition

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  - Preheating
  - Cosmic strings, domain walls
  - First-order phase transition

Candidates

- Electroweak symmetry breaking
- SUSY breaking
- PQ symmetry breaking
- GUT breaking ...

TAKE-HOME MESSAGE

- Question :

  What kind of particle physics

  leads to first-order phase transition with huge GW production ?

- Answer :

  A class of models with “classical conformal invariance”

  is one of such examples

TALK PLAN

0. Introduction

1. GW production in cosmic phase transition

2. GWs produced in classicaly conformal B-L model

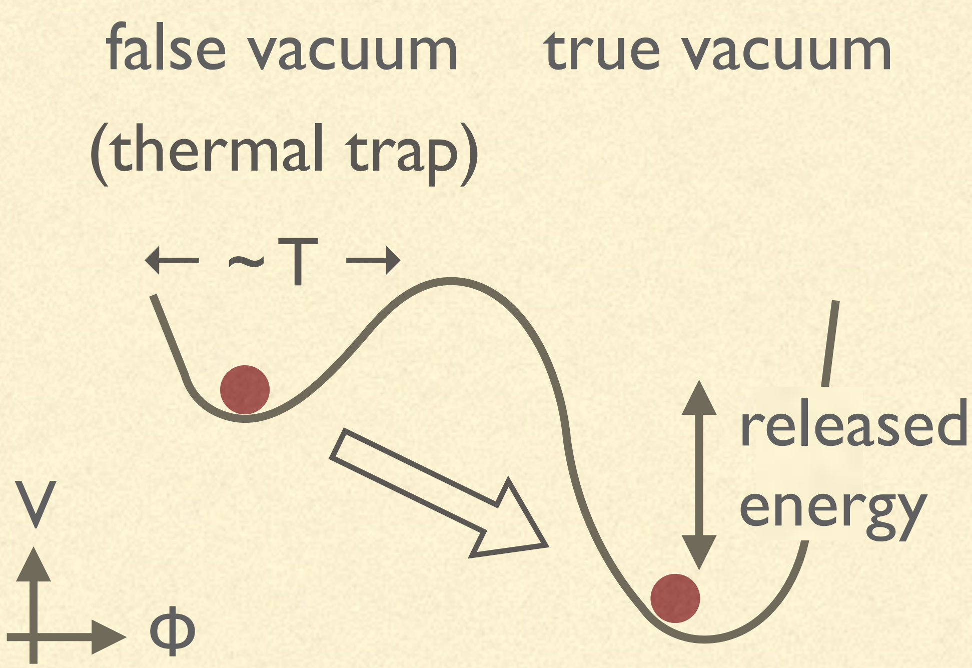
3. Summary

1. GW production in cosmic phase transition

GW PRODUCTION IN COSMIC PHASE TRANSITION

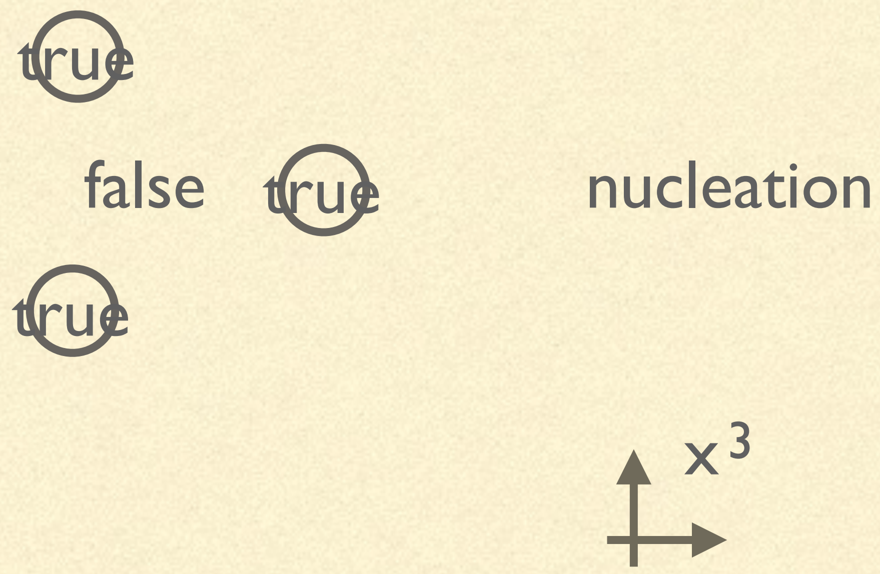
- Rough sketch of GW production in first order phase transition

- Field space



Quantum tunneling

- Position space



Bubble formation & GW production

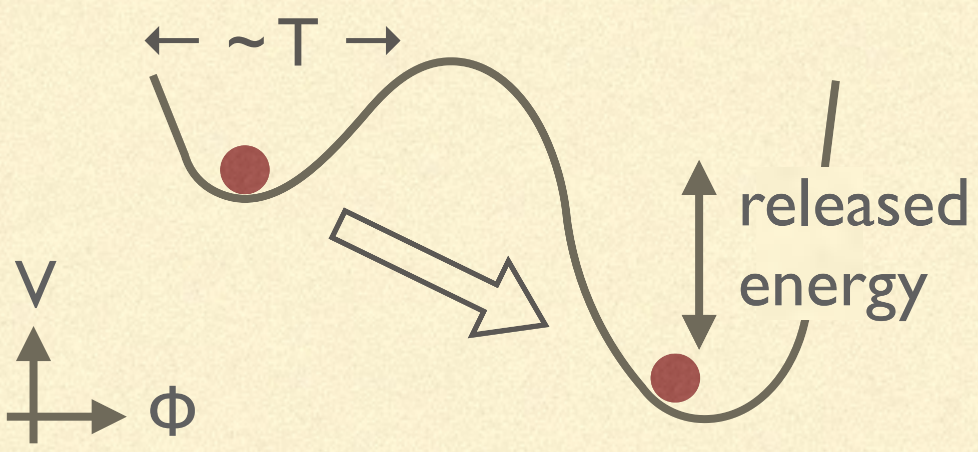
GW PRODUCTION IN COSMIC PHASE TRANSITION

- Rough sketch of GW production in first order phase transition

- Field space

false vacuum (thermal trap)

true vacuum



Quantum tunneling

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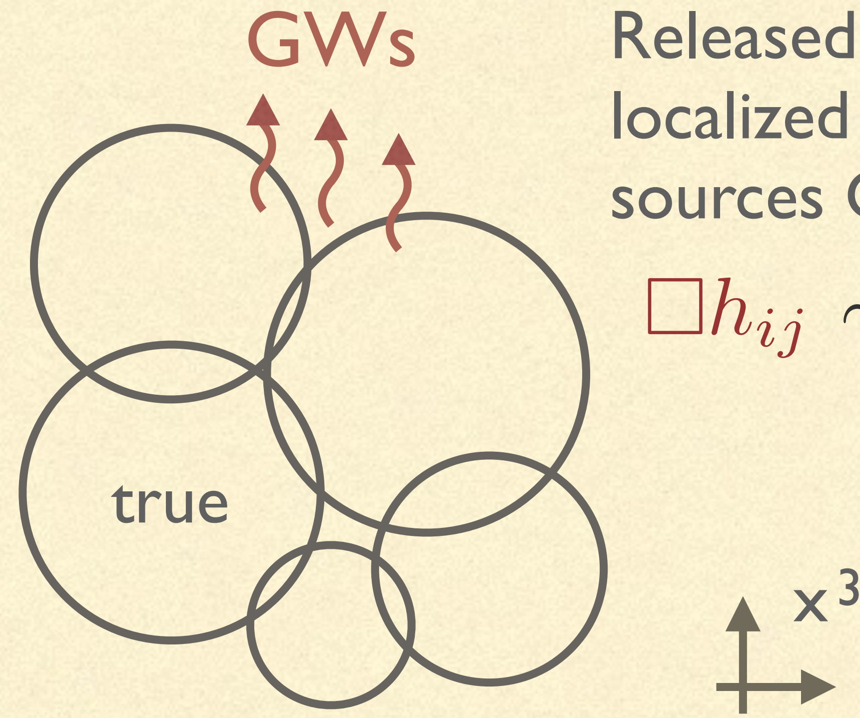


Released energy localized around walls sources GWs

$$\Box h_{ij} \sim G T_{ij}^{(\mathrm{wall})}$$

Bubble formation & GW production

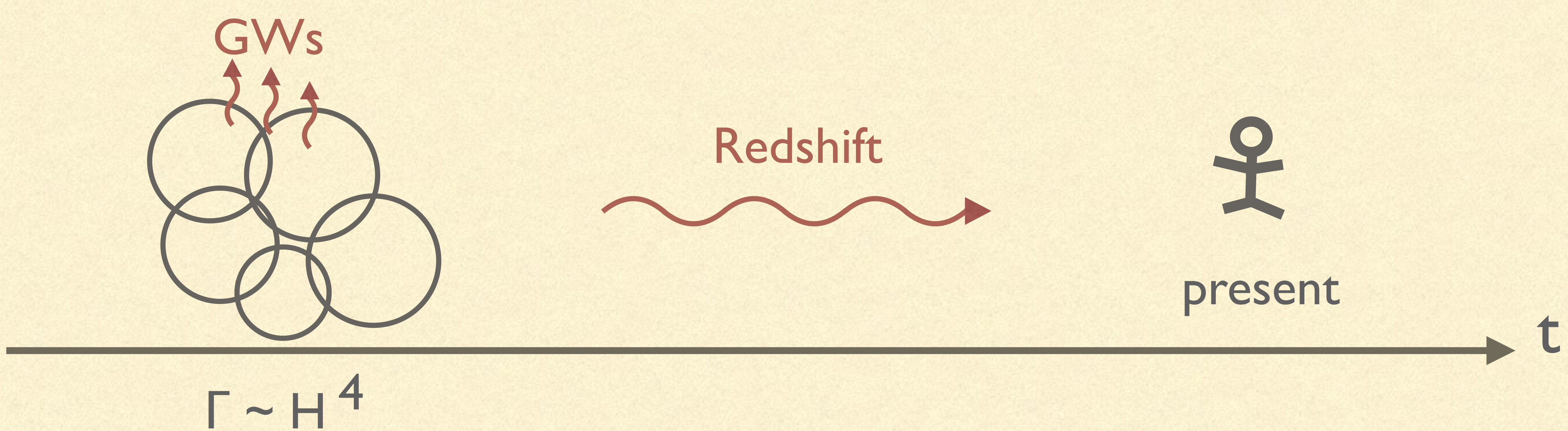
GW PRODUCTION IN COSMIC PHASE TRANSITION

- Rough sketch of GW evolution after production

  - Bubble formation & GW production occurs when $\Gamma \sim H^4$

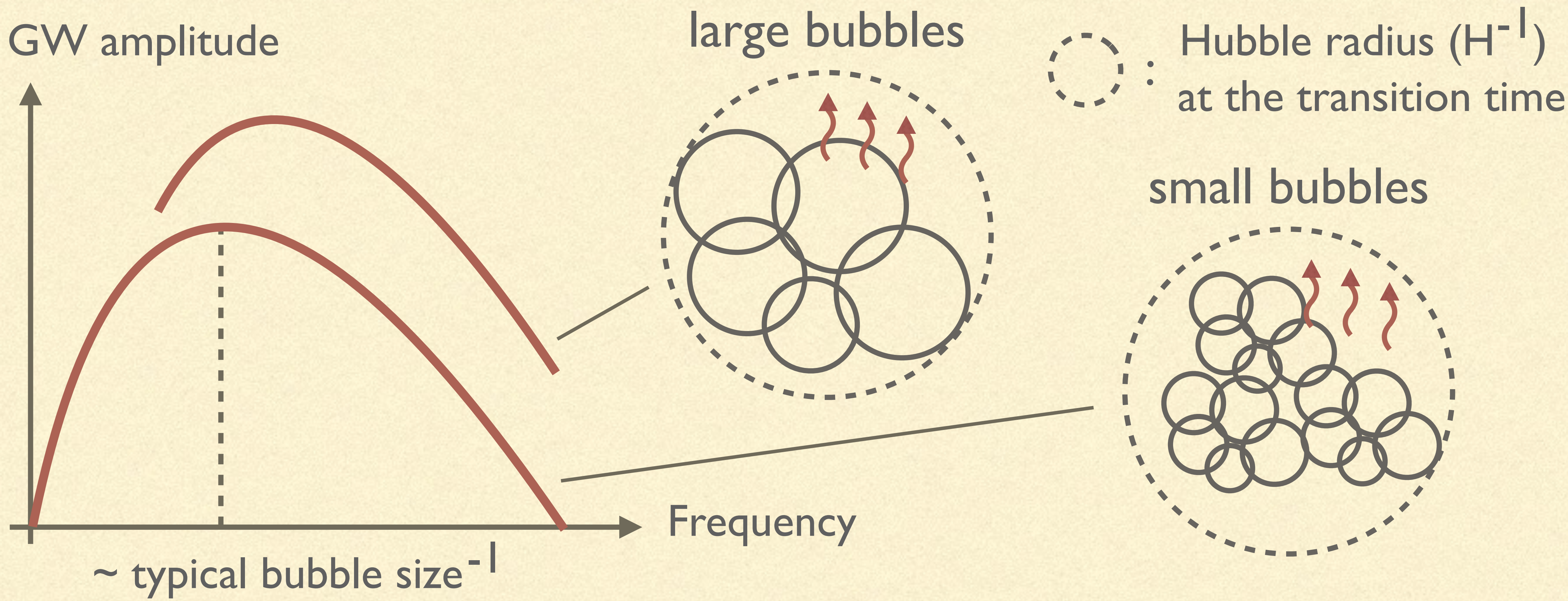
  (Γ : nucleation rate per unit time & vol. / H : Hubble parameter)

  - After produced, GWs evolve just by redshifting



GW PRODUCTION IN COSMIC PHASE TRANSITION

- Large bubbles is favored for GW production



- Larger bubbles → longer time from nucleation to collision → longer GW sourcing time

GW PRODUCTION IN COSMIC PHASE TRANSITION

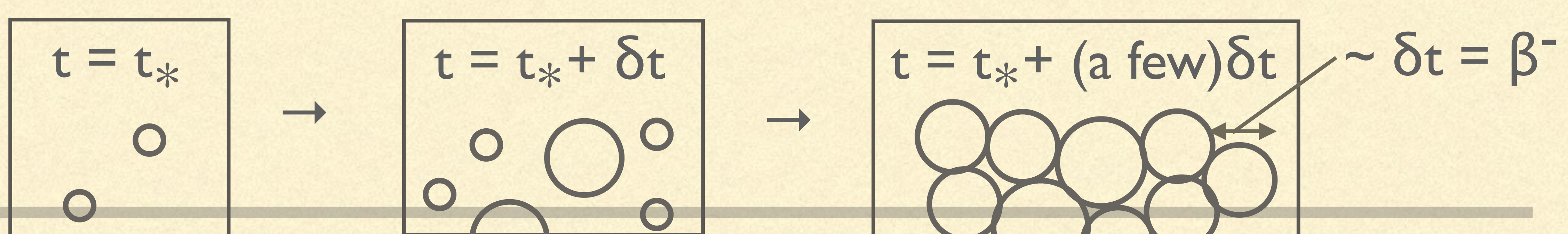
- What determines the typical bubble size ?

  - Taylor expansion of the nucleation rate Γ (per unit time & vol.)

$$\Gamma \underset{\text{around } t_*}{\overset{\text{Taylor exp.}}{\sim}} \Gamma_* \, e^{\beta(t - t_*)}$$

t_* : typical transition time (time when $\Gamma \sim H^4$)

  - Starting from t_* , bubbles can expand only for timescale $\delta t = \beta^{-1}$ since after that many bubbles start to nucleate here and there (Γ changes by orders of magnitude with timescale $\delta t = \beta^{-1}$)



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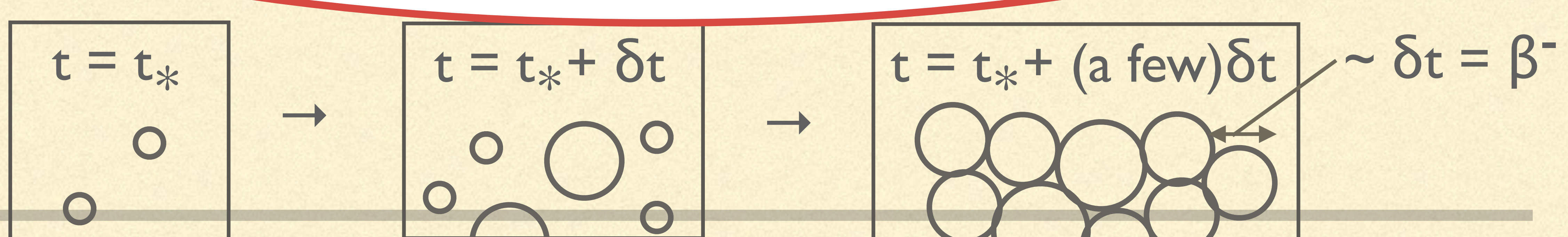
- Start … β^{-1}

(I

Slowly changing nucleation rate
(small β)
is favored for GW production



2. GW production in classically conformal B-L model

GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- What is "classically conformal" ?

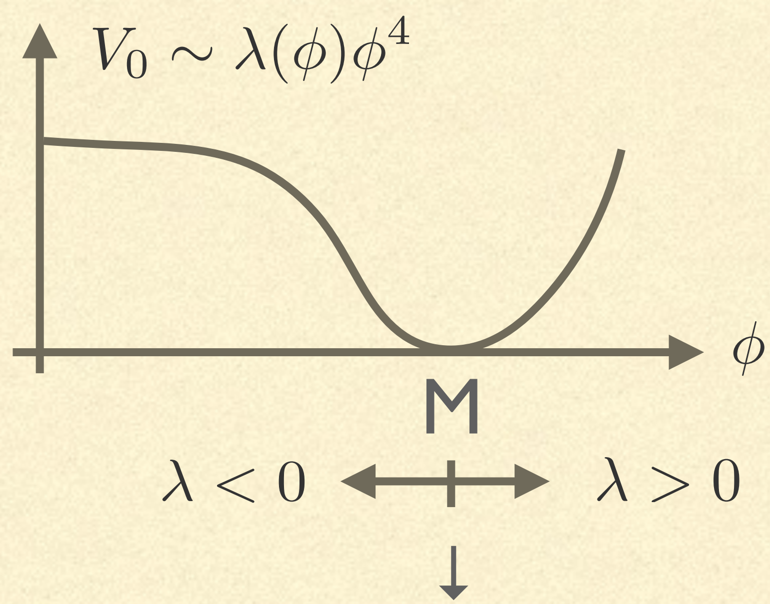
  - Classically no mass scale & its violation by quantum effect

    (Coleman-Weinberg mechanism)

- Motivation [Bardeen '95]

  - Naturalness problem

Rough sketch



$|\phi|^2|H|^2$ produces the EW scale

GW PRODUCTION
IN CLASSICALLY CONFORMAL B-L MODEL

- The model [Iso et. al., '09]

Gauge couping g_{B-L}
(equivalently, $\alpha_{B-L} = g_{B-L}^2/4\pi$)

- Gauge : $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$

- Matter :

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{B-L}$
q_L^i	**3**	**2**	+1/6	+1/3
u_R^i	**3**	**1**	+2/3	+1/3
d_R^i	**3**	**1**	-1/3	+1/3
l_L^i	**1**	**2**	+1/6	-1
e_R^i	**1**	**1**	-1	-1
ν_R^i	**1**	**1**	0	-1
H	**1**	**2**	-1/2	0
Φ	**1**	**1**	0	+2

GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

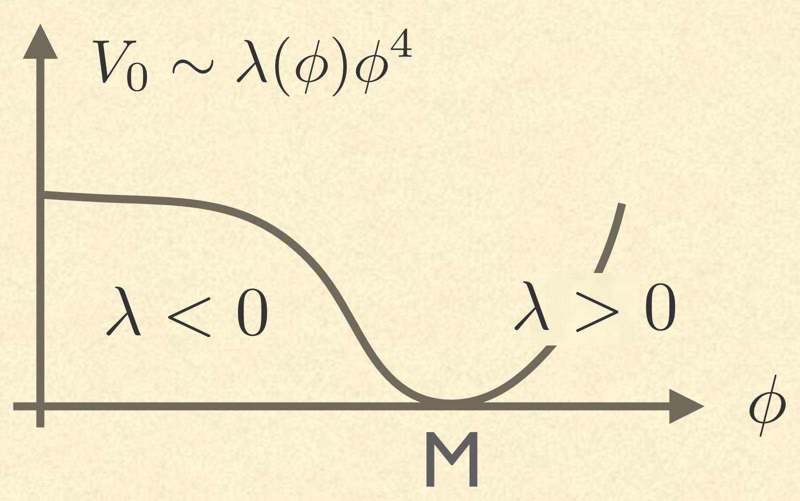
- Potential behavior (zero-temperature)

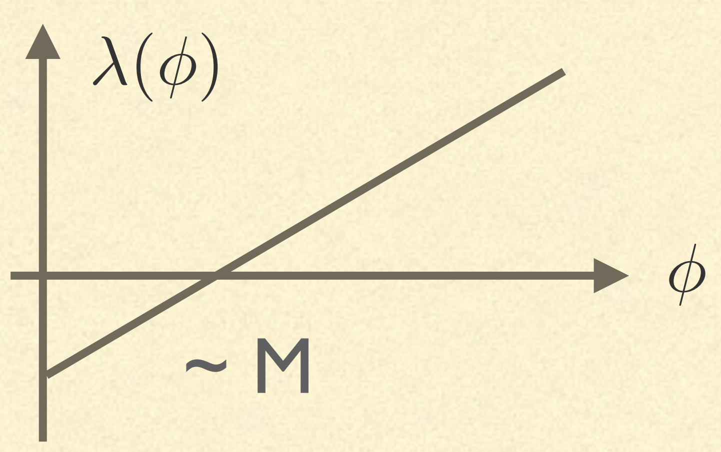
  - Zero-temperature potential

$$V_0 = \lambda_H |H|^4 + \boxed{\lambda |\Phi|^4} - \lambda' |\Phi|^2 |H|^2$$

+ no mass terms
("classically no-scale" assumption)

  - Scale is induced by the running of λ (determined by g_{B-L})

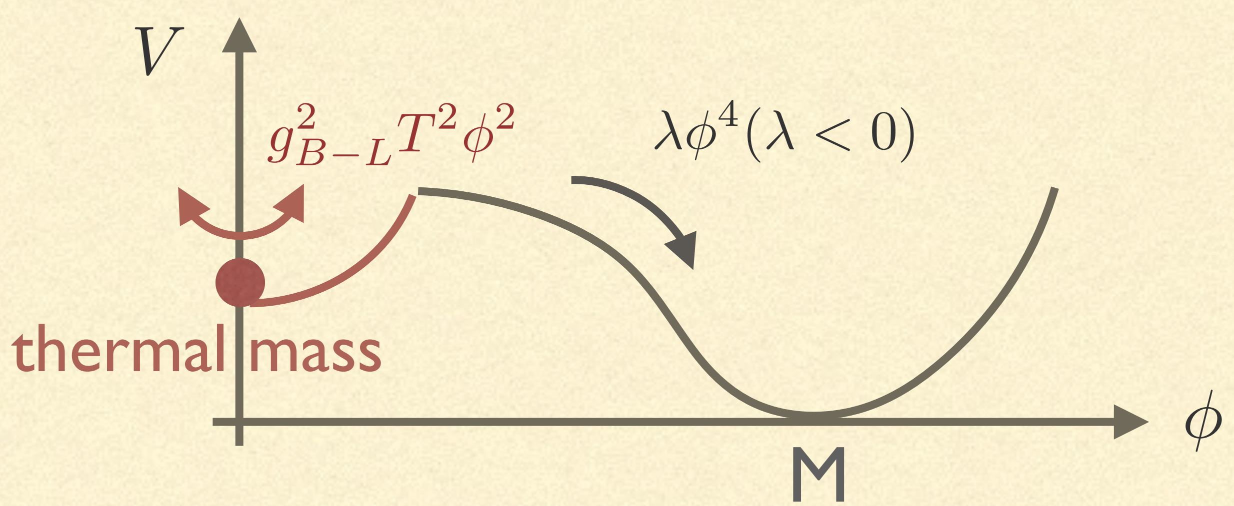




GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- Potential behavior (finite temperature)

  - Full effective potential $V \sim g_{B-L}^2 T^2 \phi^2 + \lambda(\max(T,\phi))\phi^4$



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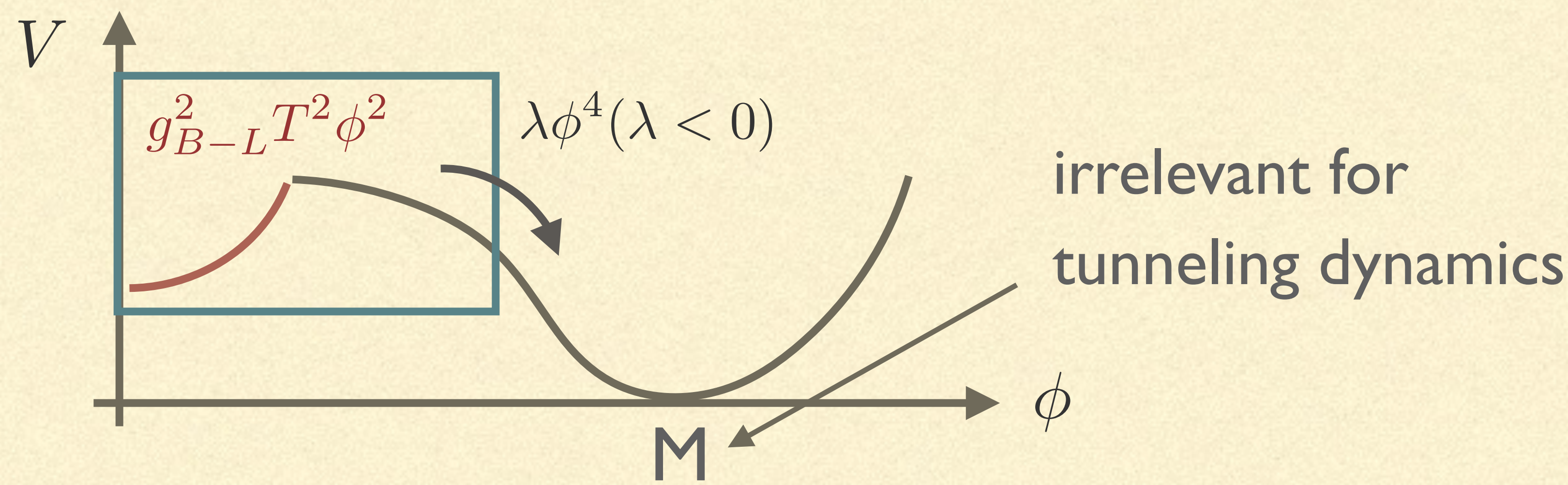
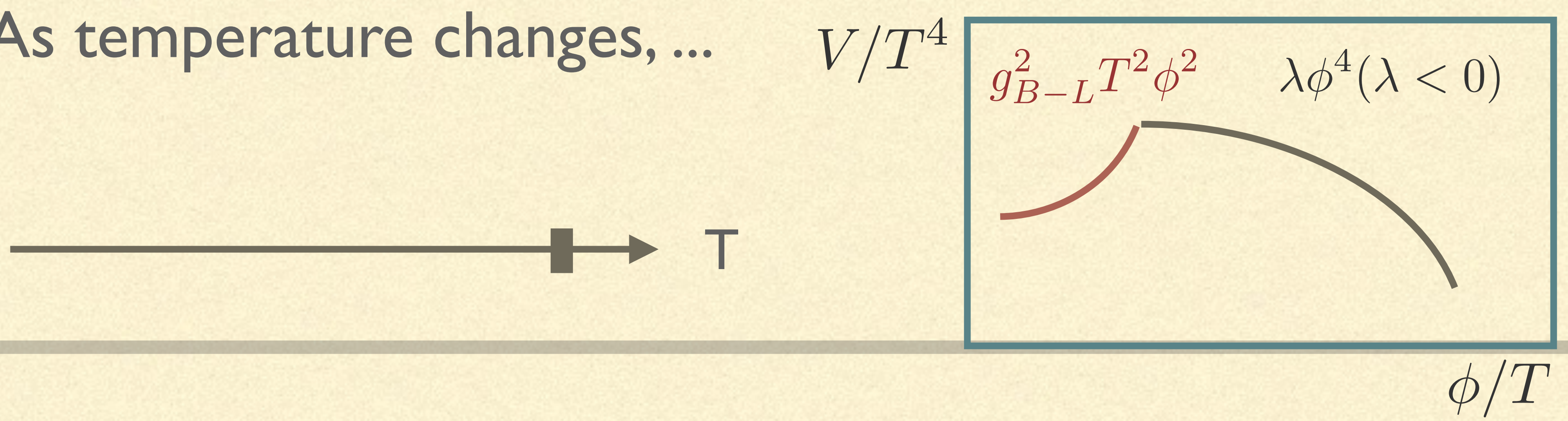


  - As temperature changes, ...



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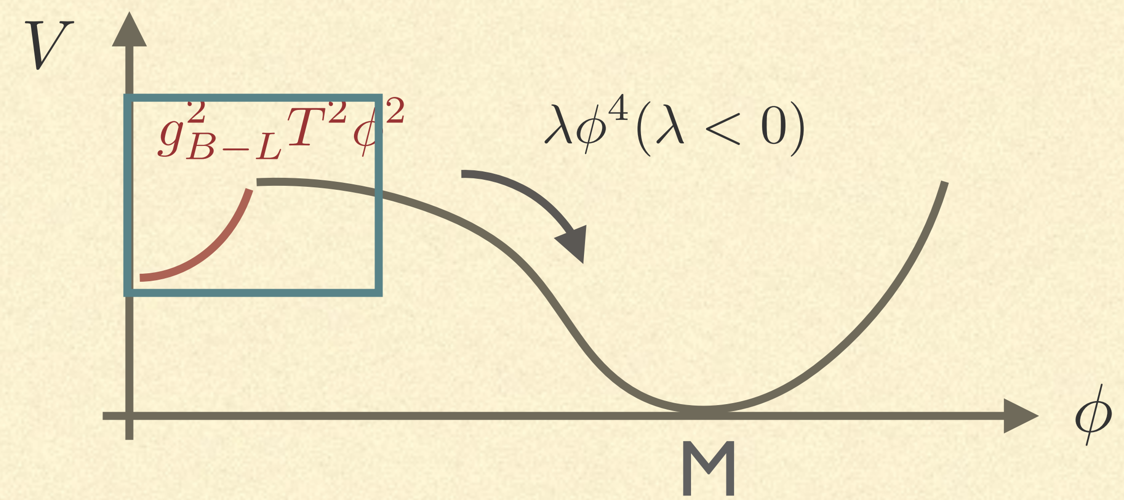

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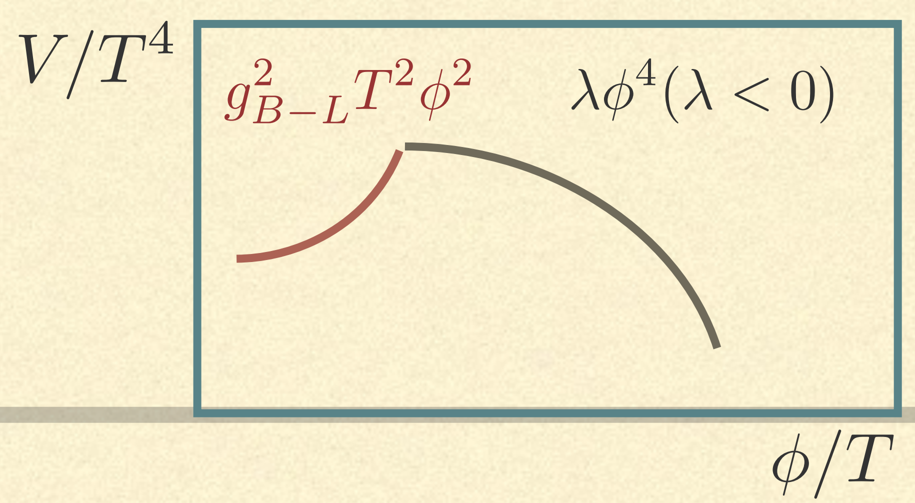

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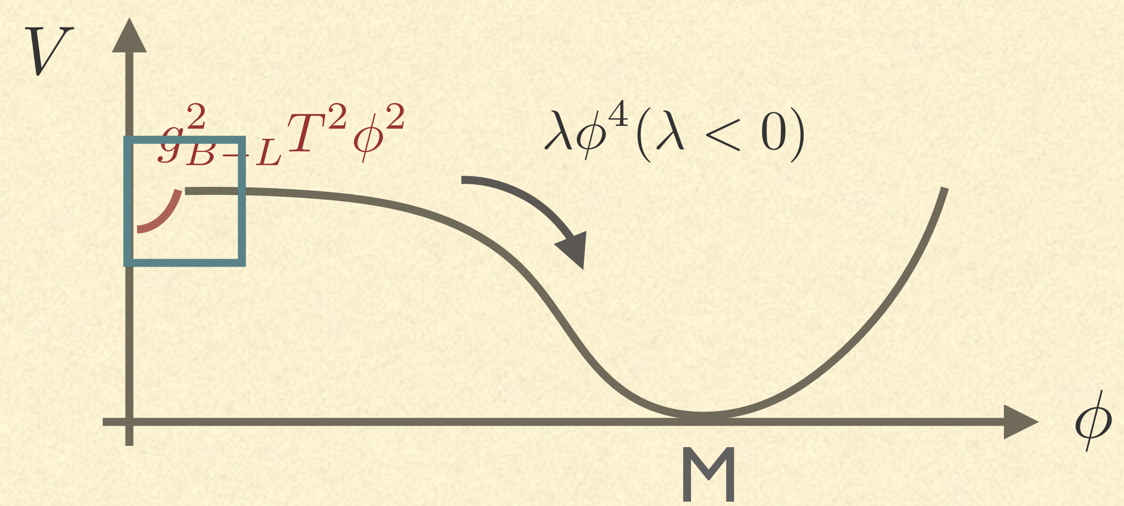

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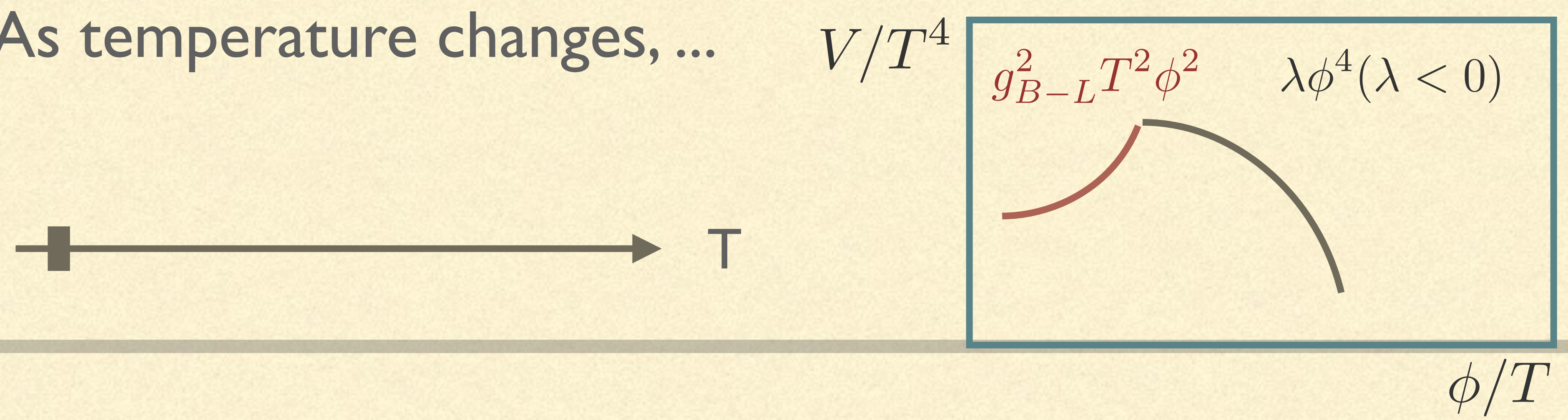

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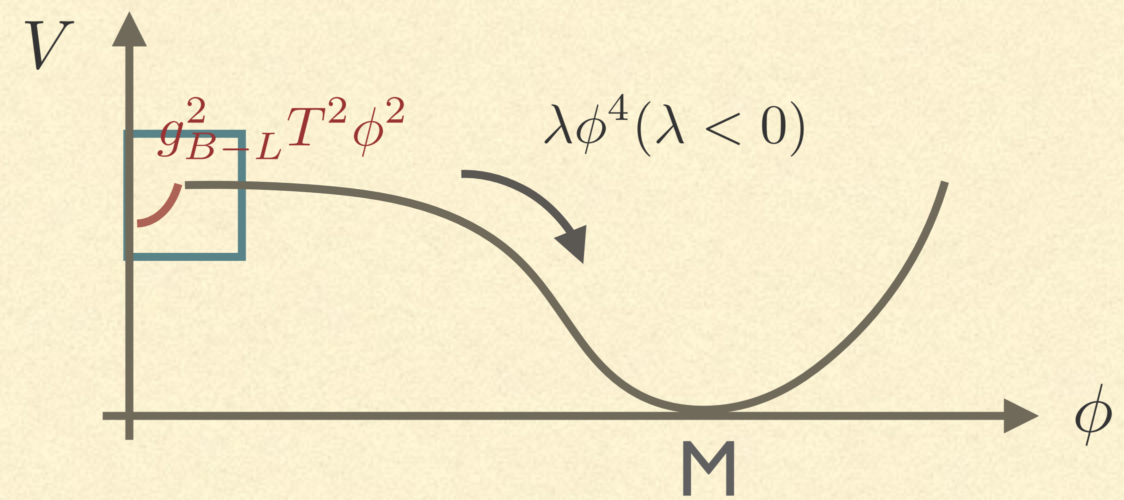
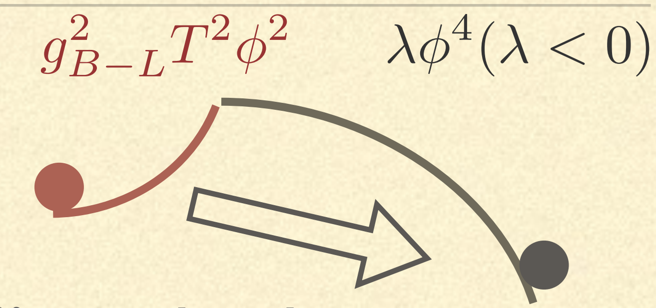


  - As temperature changes, ...

    potential structure at the origin slowly changes (~ beta function)

GW PRODUCTION
IN CLASSICALLY CONFORMAL B-L MODEL



- Nucleation rate Γ changes slowly

  - Nucleation rate is calculated with so-called "bounce" method

$$\Gamma \sim O(T^4)\, e^{-S_3/T}$$

dimensionless

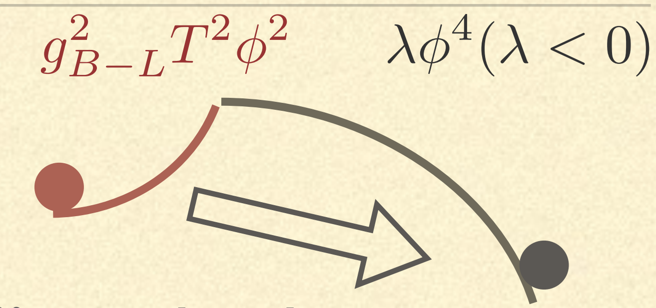
  - The only relevant mass scale (for transition) T cancels out in S_3/T :

$$S_3/T \sim 10\, \frac{g_{B-L}}{|\lambda|}$$

(for effective potential $V \sim g_{B-L}^2 T^2 \phi^2 + \lambda(\max(T,\phi))\phi^4$)

  - Nucleation rate Γ (equivalently S_3/T) changes slowly (with beta function)

GW PRODUCTION
IN CLASSICALLY CONFORMAL B-L MODEL



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$$\Gamma \sim O(T^4)\, e^{-S_3/T}$$ dimensionless

  - The only relevant ... cancels out in S_3/T :

One of the requirements
for huge GW production
is satisfied

  - Nucleation rate Γ (equivalently S_3/T) changes slowly (with beta function)

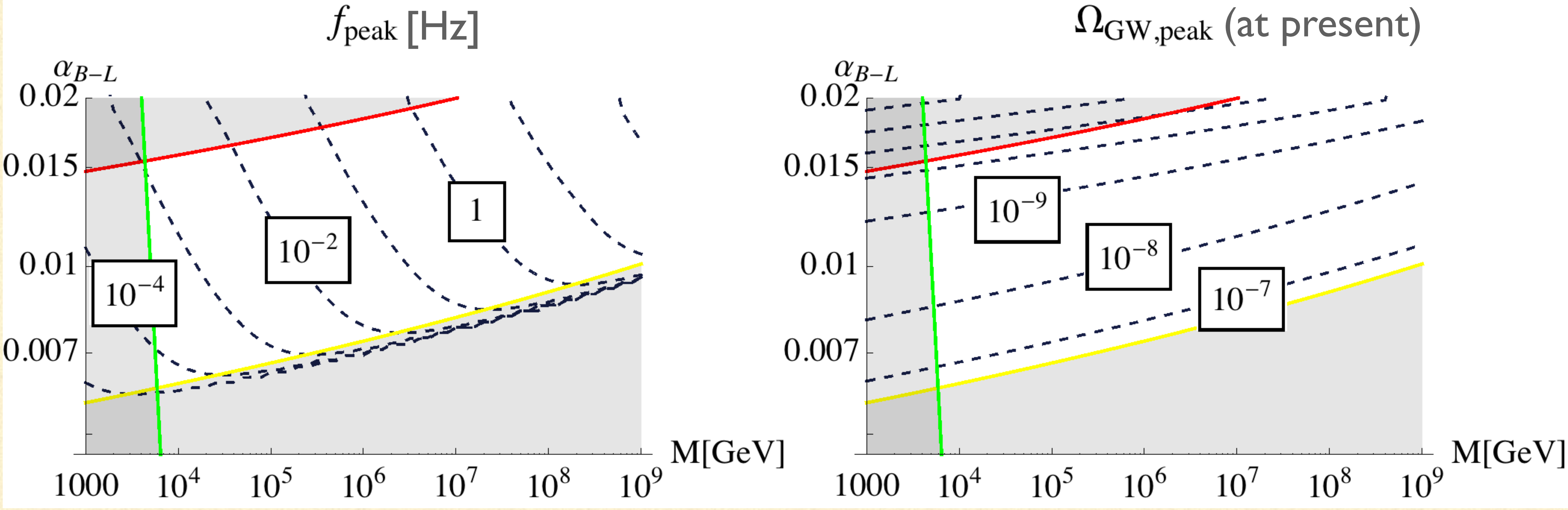
GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- Peak frequency & amplitude of the GW spectrum

$M \equiv \langle \phi \rangle$

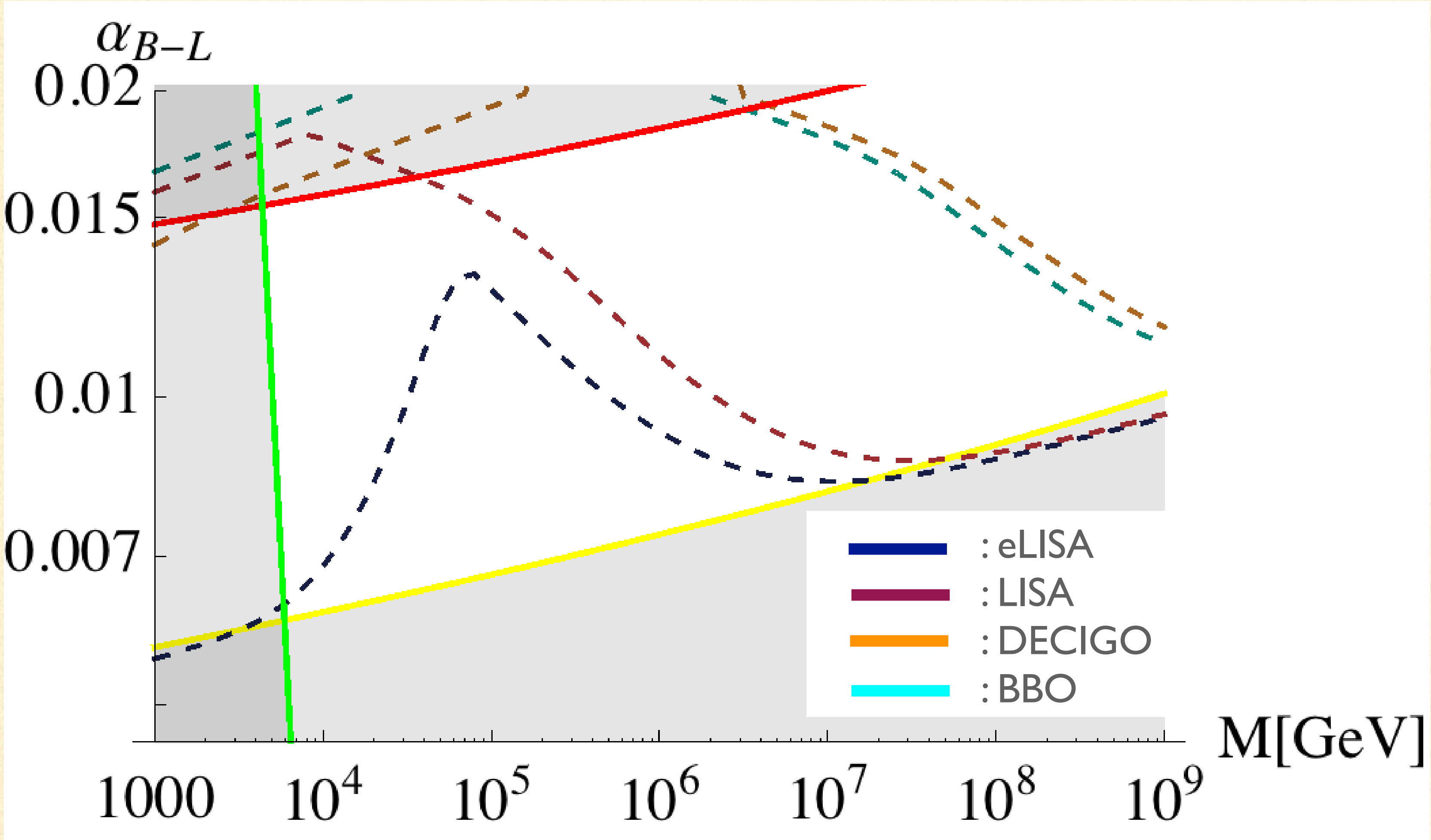
α_{B-L} : value at M

: Above this line → couplings hit Landau poles below Mp
: Below this line → successful PT does not occur
: Left to this line → excluded by Z' mass constraint



GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- Detectability in the future

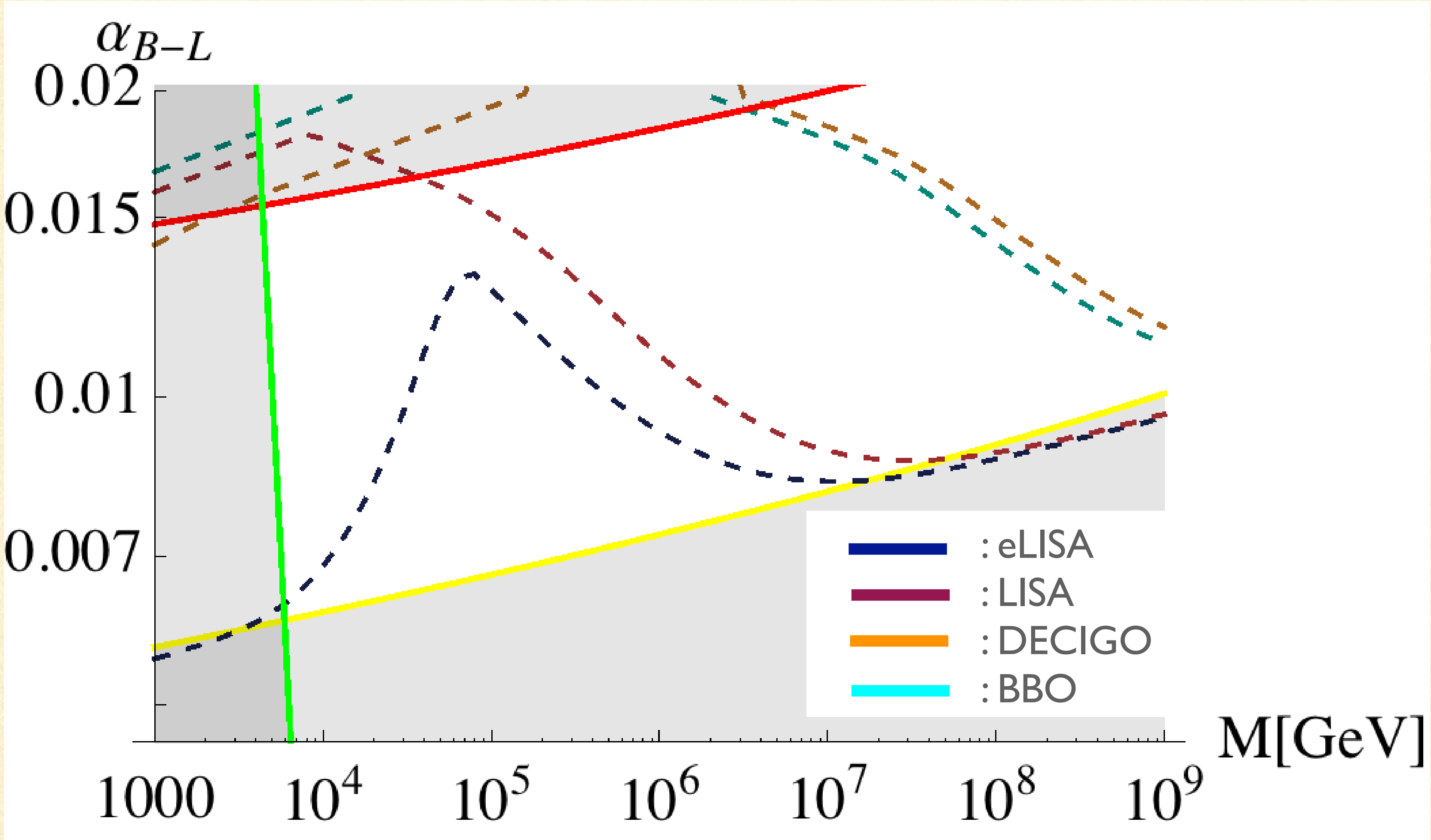


(Regions below dashed lines can be searched with future interferometer experiments)

GW PRODUCTION
IN C... ...DEL

A vast parameter region can be explored by future experiments

- Detectab...



(Regions below dashed lines can be searched with future interferometer experiments)

SUMMARY

- GWs can be a unique probe to cosmic first-order phase transition
- For huge GW prod., large bubbles is one of the requirements
- This requirement is satisfied in "classically conformal" models, and such models can be tested by future experiments

Key : "No mass scale" at the classical level guarantees
a slow change of nucleation rate (~ beta function),
large bubbles, and huge GW production

Backup

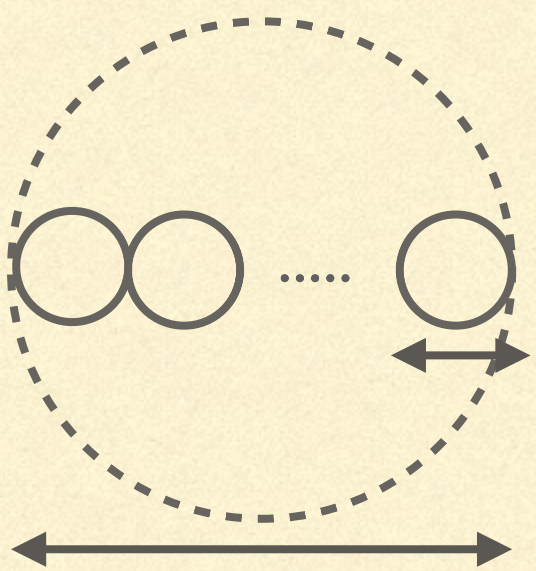
GW PRODUCTION IN COSMIC PHASE TRANSITION

- GW spectrum just after the transition

$$\Omega_{\rm GW}\big|_{\rm peak} \sim 10^{-2} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\rho_{\rm wall}}{\rho_{\rm rad} + \rho_{\rm wall}}\right)^2$$

(Number of bubbles)$^{1/3}$ in one Hubble patch

unity if walls are the dominant energy component



β^{-1} : typical bubble size

H_*^{-1} : size of the Hubble patch (around the transition time)

GW PRODUCTION IN COSMIC PHASE TRANSITION

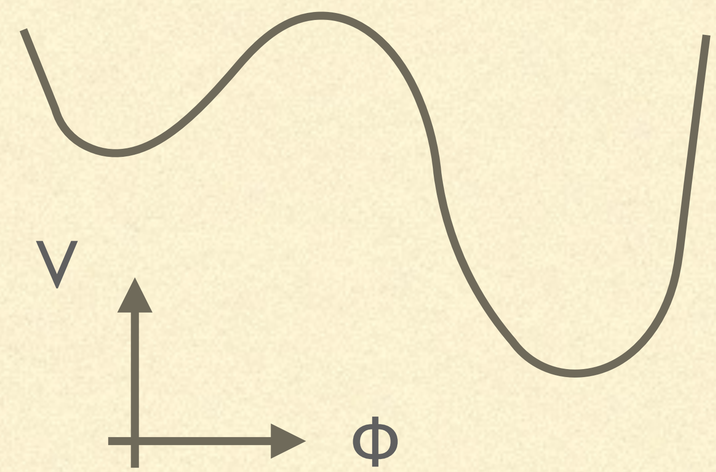
- Estimation of the transition rate

  - Bounce calculation

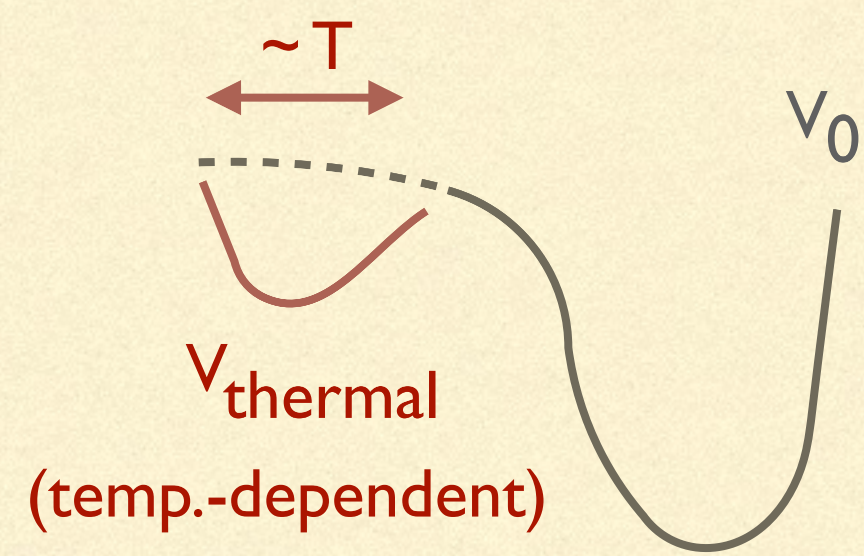
  $\Gamma \sim O(T^4)\, e^{-S_3/T}$ $\quad S_3 \sim \int d^3r \left(\frac{1}{2}\phi'(r)^2 + V(\phi)\right)$

  - Estimation of β

  $\Gamma \sim \Gamma_* \, e^{\beta(t - t_*)}$ $\quad \beta \simeq \frac{d(S_3/T)}{dt} \simeq H \frac{d(S_3/T)}{d \ln T}$



|| (in our setup)



GW PRODUCTION
IN CLASSICALLY CONFORMAL B-L MODEL

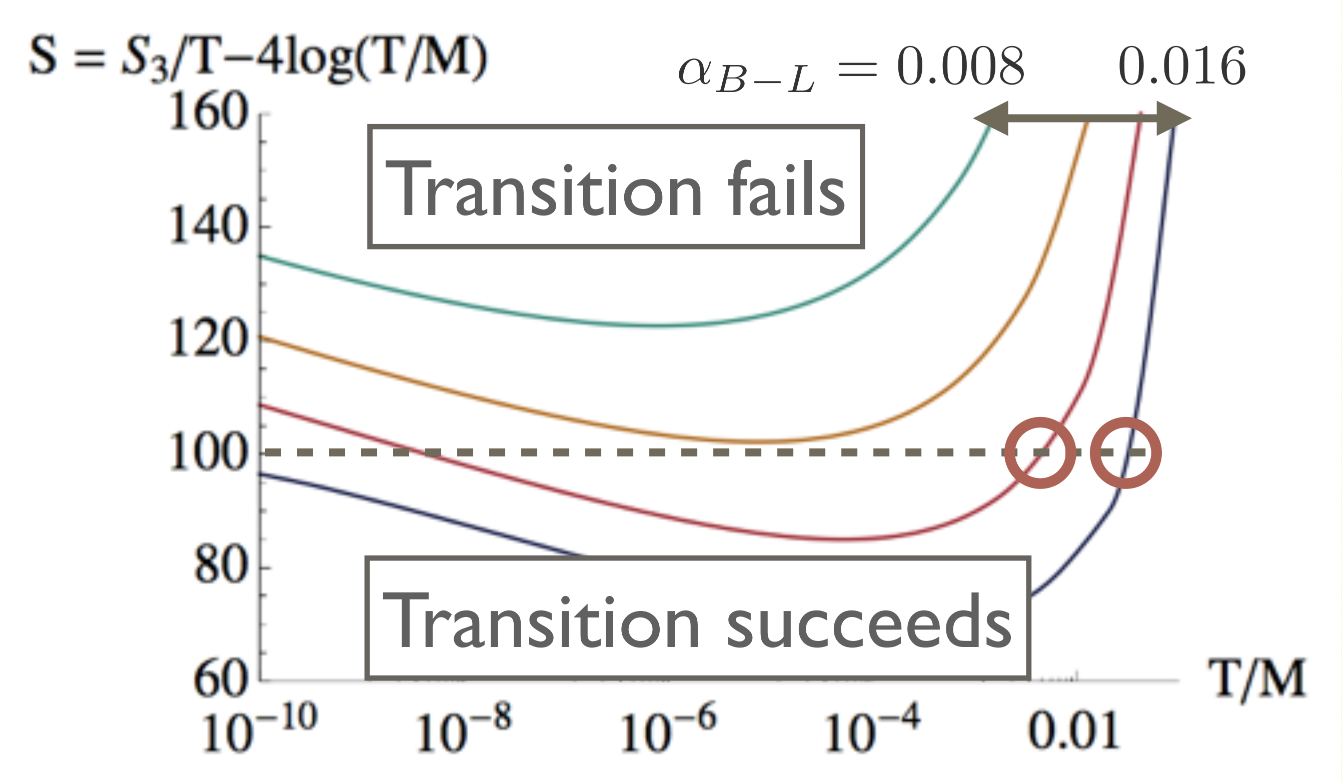
- By the way, phase transition occurs at all?

  - Phase transition needs $\Gamma H^4 \sim 1$ → $S \sim 100$

    $(\Gamma \sim \mathcal{O}(T^4) e^{-S_3/T} \sim M^4 e^{-S_3/T + 4\ln(T/M)} \equiv M^4 e^{-S})$

    For small α_{B-L},
    transition does not complete

    For large α_{B-L},
    transition typically occurs at
    $T/M\big|_{S\sim 100} \ll 1$ (○ →)
    → large α expected



GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- α & β

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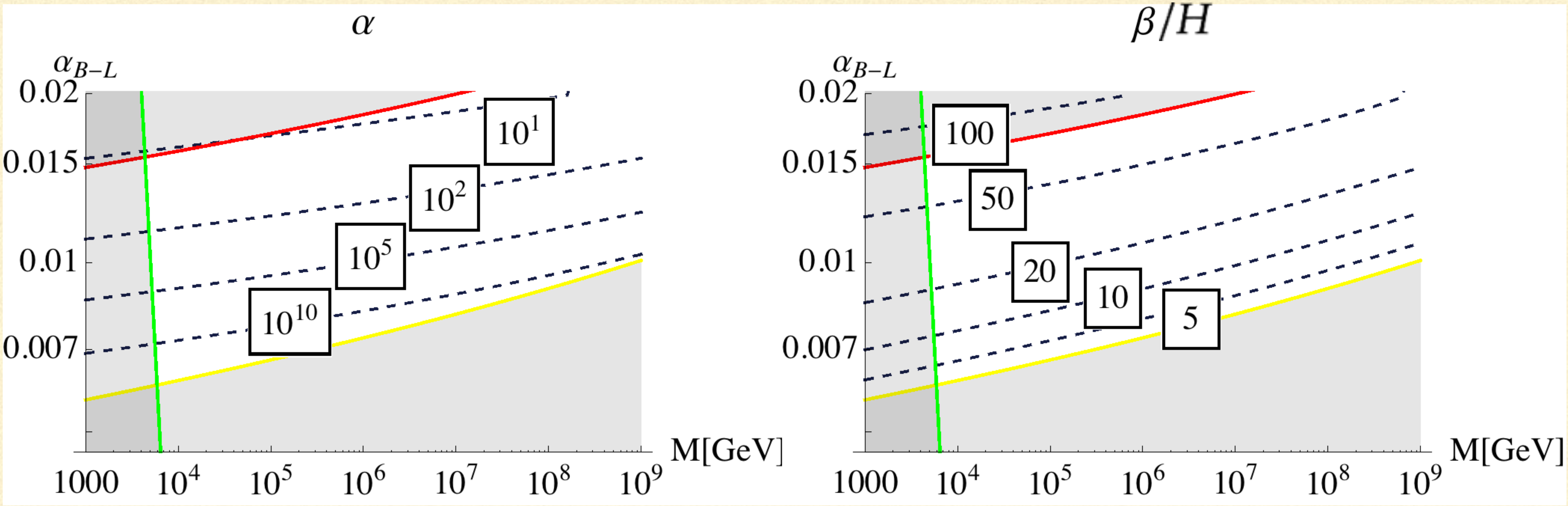
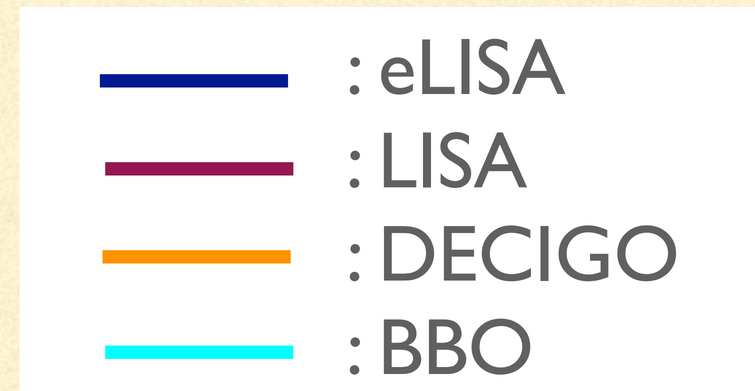
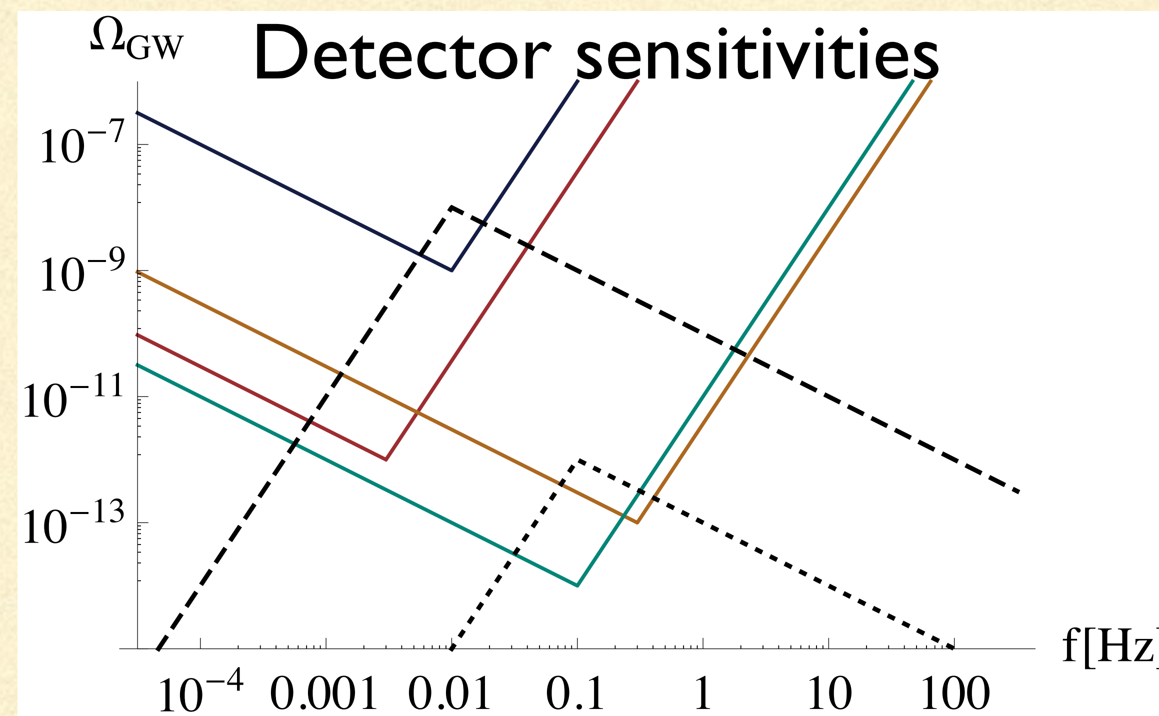


GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- Rough estimation of GW amplitude



- Present GW spectrum



~quadrupole factor ~radiation fraction today

$$h^2\Omega_{\rm GW,peak} \sim \mathcal{O}(10^{-2})\mathcal{O}(10^{-5})\left(\frac{\beta}{H_*}\right)^{-2}\left(\frac{\alpha}{1+\alpha}\right)^2$$

duration time

$$f_{\rm peak} \sim \frac{\beta}{H_*}\frac{T_*}{10^8{\rm GeV}}[{\rm Hz}]$$

cf. SM with $m_H \sim 10$ GeV $\rightarrow$ $\beta/H \sim \mathcal{O}(10^5),\ \alpha \sim \mathcal{O}(0.001)$