Probing classically conformal B-L model with gravitational waves

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

July 12th, 2016 PASCOS @ Qui Nhon

Introduction & Conclusion

FIRST DECECTION OF GWS

- LIGO announcement @ 2016/2/11

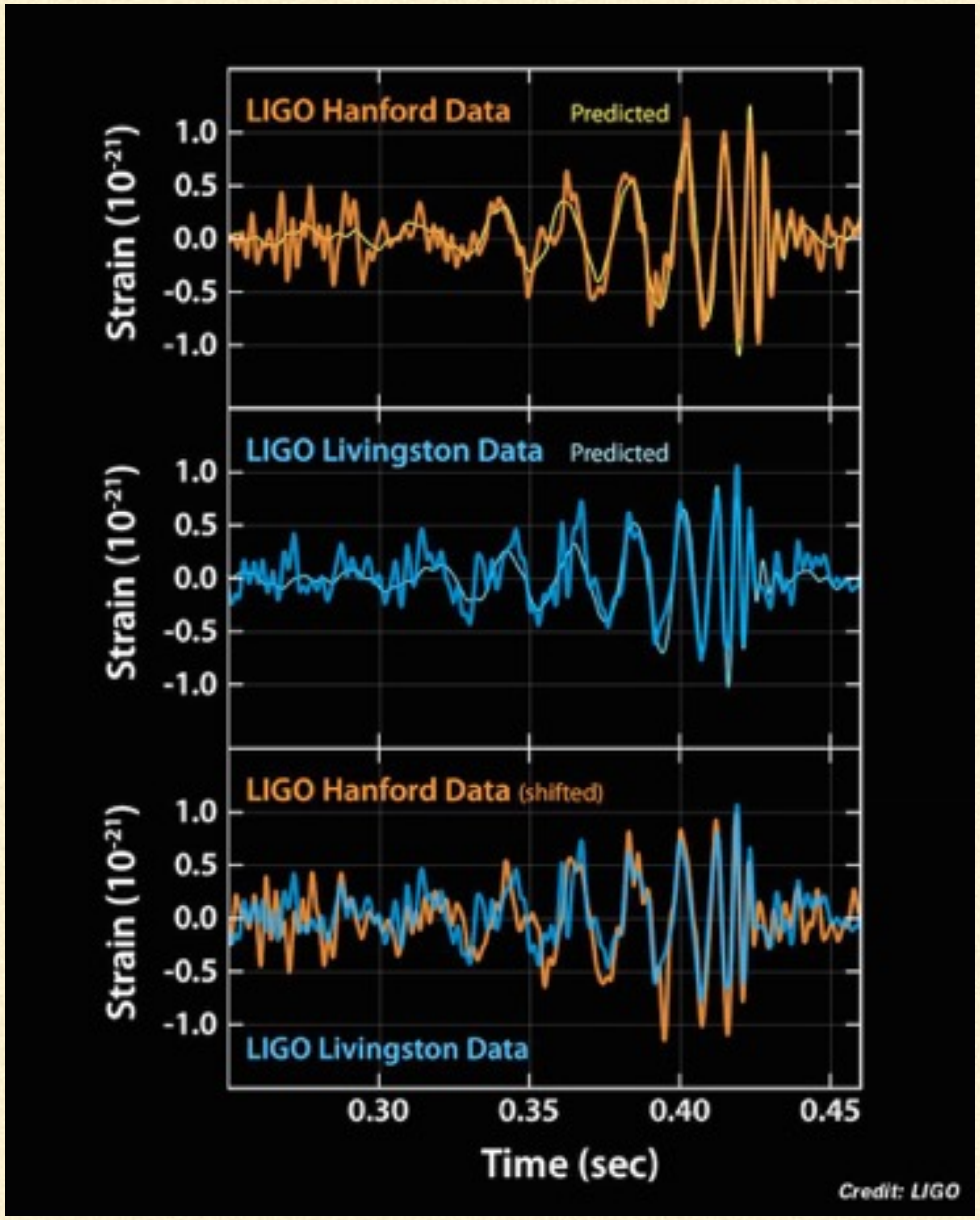
  - Black hole binary

    $36M_\odot + 29M_\odot \rightarrow 62M_\odot$

    with $3.0M_\odot$ radiated in GWs

  - Frequency ~ 35 to 250 Hz

  - Significance > 5.1σ



FIRST DECECTION OF GWS

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  - Black hole binary

    36M⊙ + 29M⊙

    with 3.0M⊙

  - Frequency

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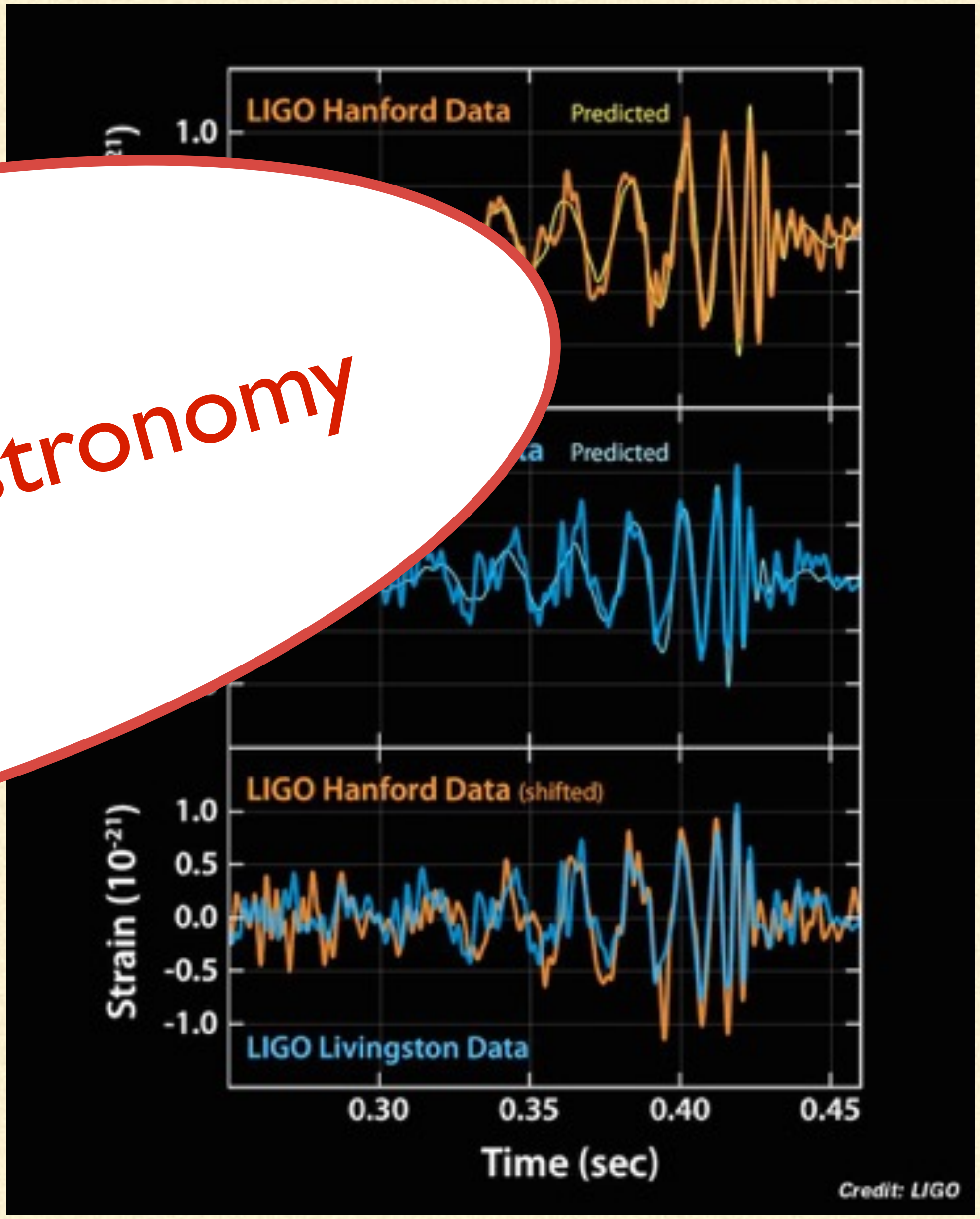
The era of
Gravitational-wave astronomy
has come



FROM ASTRONOMY TO COSMOLOGY

- Next will come Gravitational-wave "COSMOLOGY"

  - Space interferometers (LISA, BBO, DECIGO,...) are planned in the future

- What kind of cosmology can we search by GWs ?

  - Inflationary quantum fluctuations

  - Preheating

  - Cosmic strings, domain walls

  - First-order phase transition

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Many particle-physics candidates

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

TAKE-HOME MESSAGE

“Classical conformal” models

can lead to first-order PT

with large amount of gravitational waves

TAKE-HOME MESSAGE

<u>KEY</u>

Making BIG bubbles in the early universe

TALK PLAN

0. Introduction & Conclusion

1. GW production in cosmic phase transition (General)

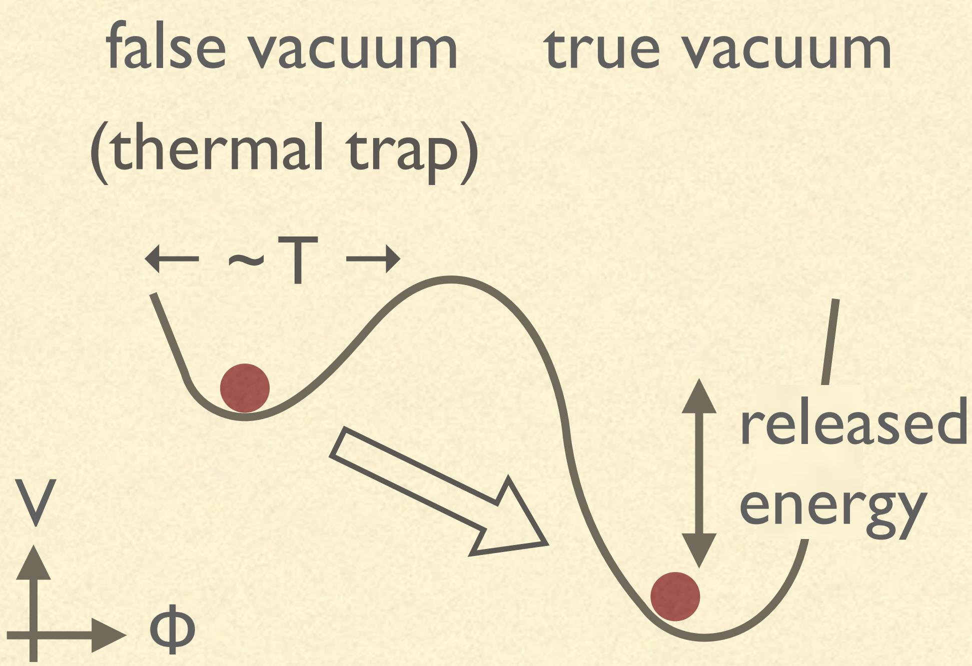
2. GWs produced in classicaly conformal B-L model (Model specific)

3. Conclusion

1. GW production in cosmic phase transition

ROUGH SKETCH

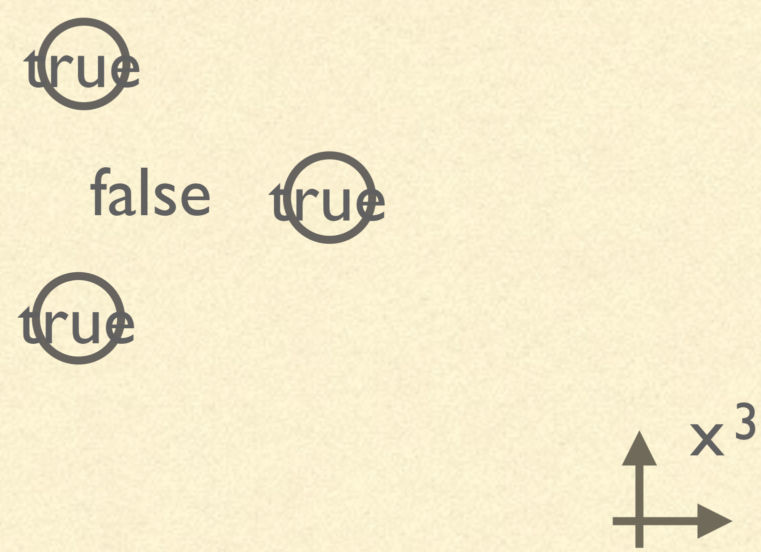
- Field space



Quantum tunneling

- Position space

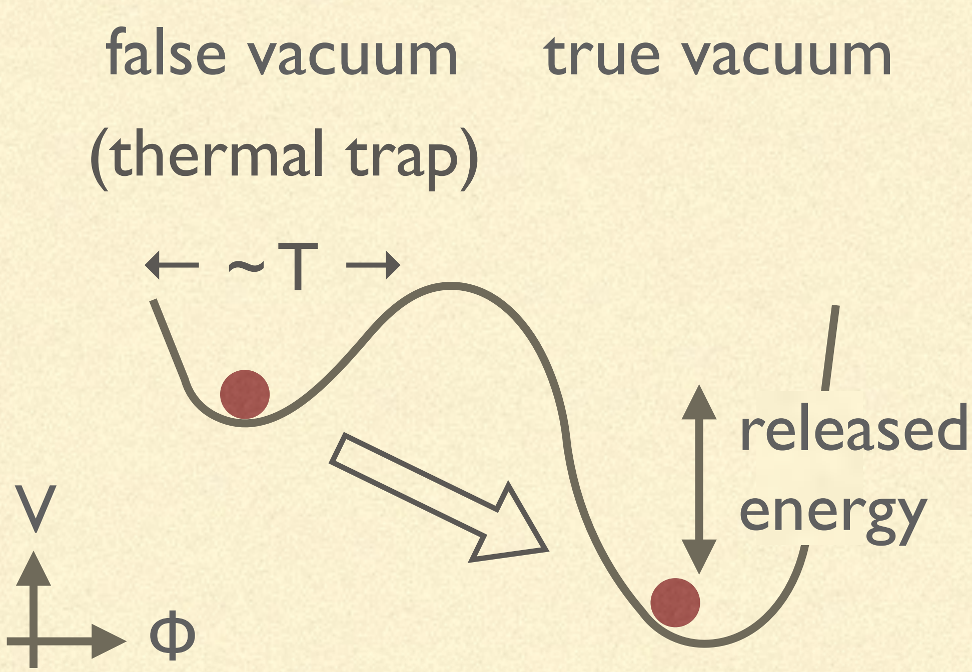
1. Bubbles nucleate



Bubble formation & GW production

ROUGH SKETCH

- Field space



Quantum tunneling

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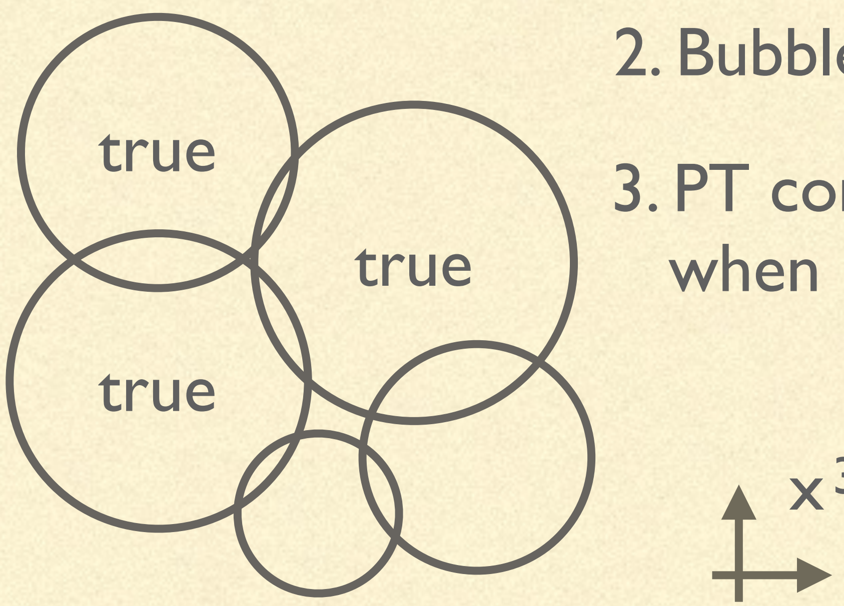

1. Bubbles nucleate
2. Bubbles expand
3. PT completes when bubbles collide

Bubble formation & GW production

ROUGH SKETCH

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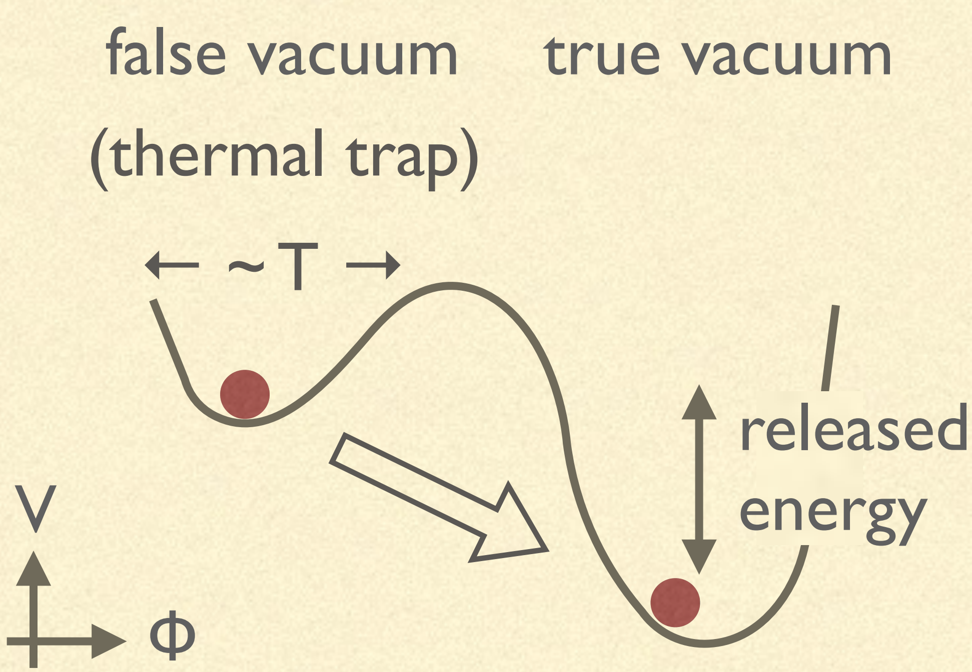

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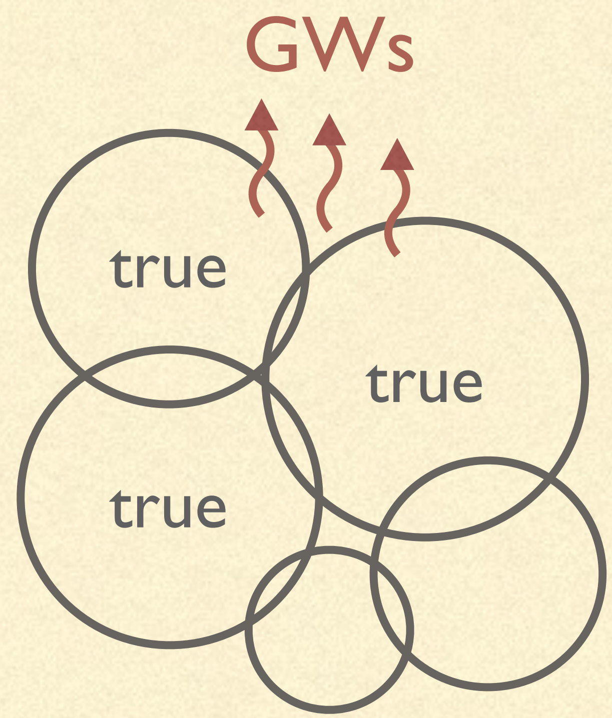
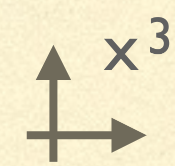


$\Box h_{ij} \sim G T_{ij}^{(\mathrm{wall})}$

Released energy localized around walls sources GWs



Bubble formation & GW production

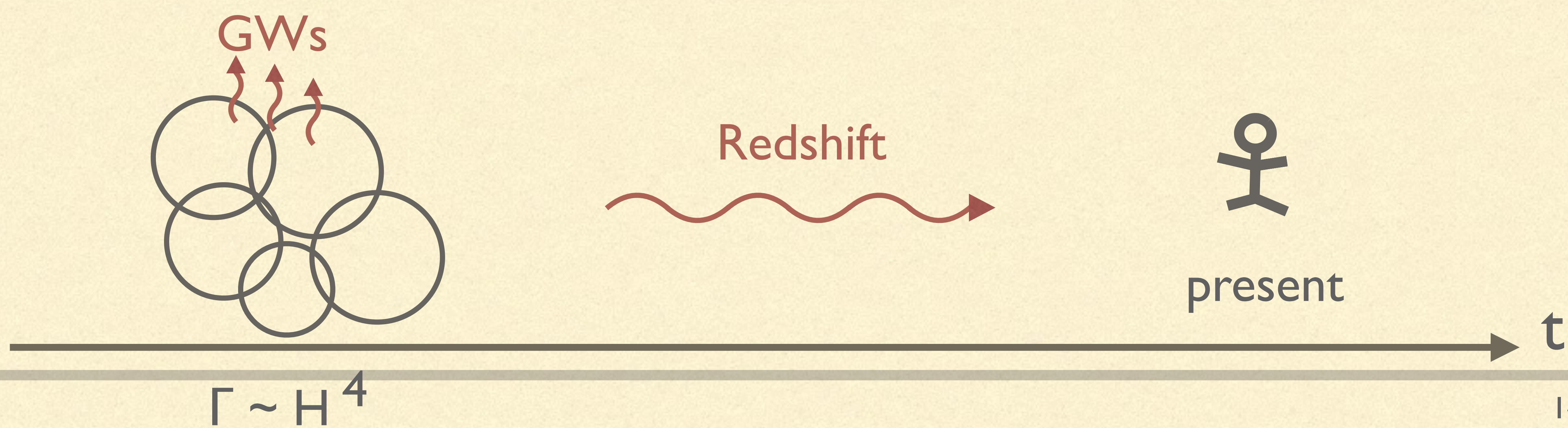
ROUGH SKETCH

- Bubble formation & GW prod. occurs and completes when...

$$\Gamma \sim H^4$$

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

- After produced, GWs evolve just by redshifting



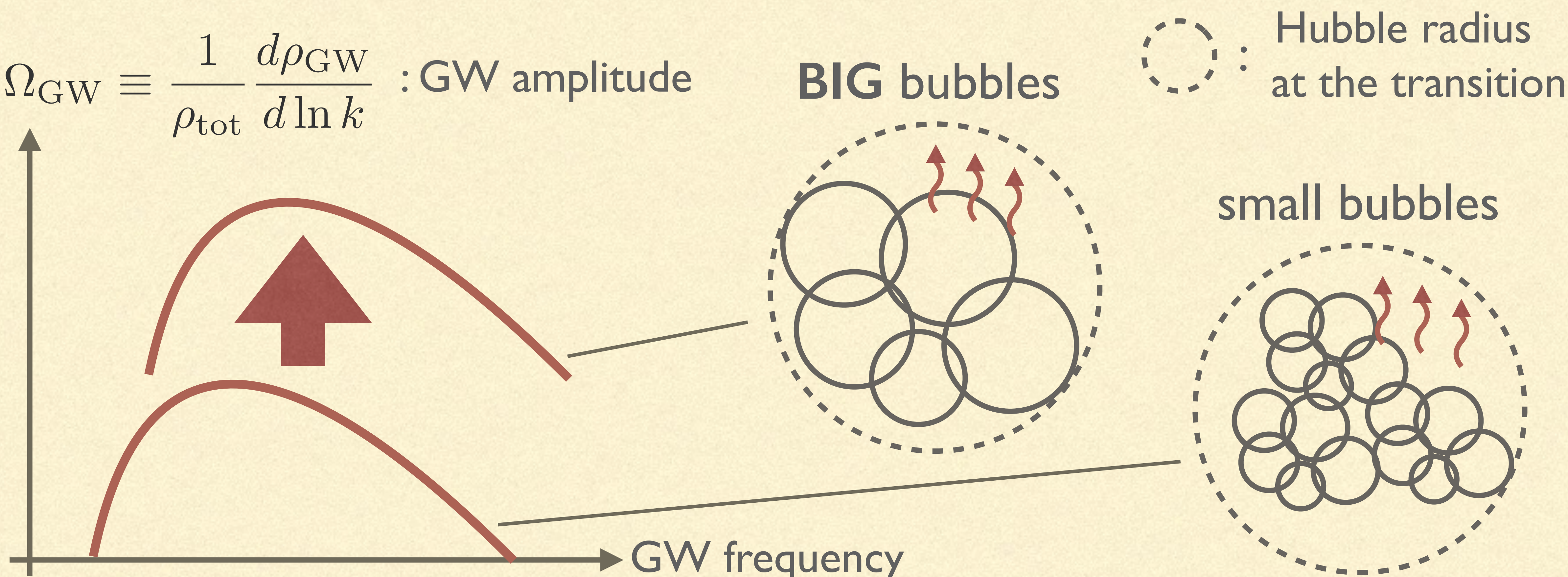
BIG bubbles produce LARGE GWs

- Why ?

BIG bubbles → LONG time from nucleation to PT completion

→ LONG time for GW sourcing

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_{\rm tot}} \frac{d\rho_{\rm GW}}{d\ln k}$$: GW amplitude



How to make BIG bubbles

- Typical bubble size ~ β^{-1}

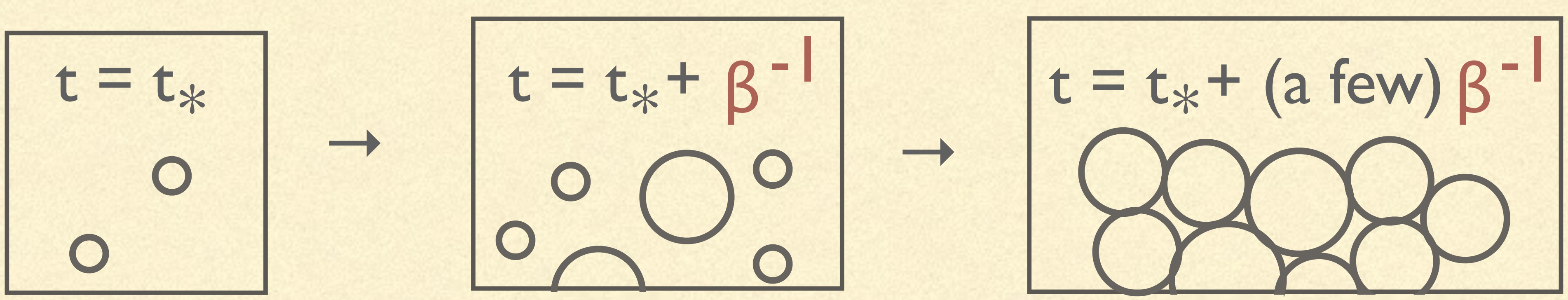
t_* : typical transition time (when $\Gamma \sim H^4$)

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

- Γ changes significantly with timescale β^{-1}

- Then, bubbles can expand only for $t_* \sim t_* +$ (a few) β^{-1}

(because many bubbles start to nucleate here and there after this time)



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- Γ changes si

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ne)

BIG bubbles

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SMALL β

||

SLOWLY changing nucleation rate

2. GW production in classically conformal B-L model

CLASSICALLY CONFORMAL

- What is "classically conformal" ?

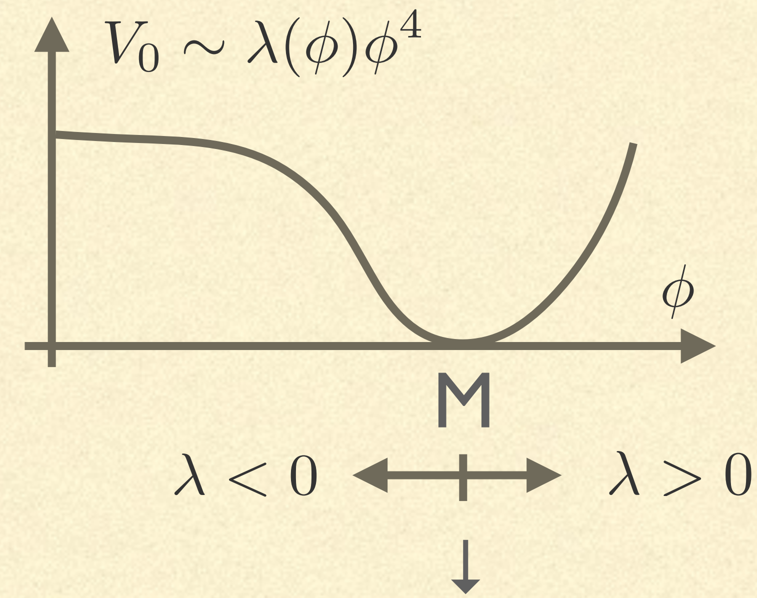
  - Classically no mass scale & violation of scale invariance by quantum effect

    (Coleman-Weinberg mechanism)

- Motivation [Bardeen '95]

  - Naturalness problem

<u>Rough sketch</u>



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

CLASSICALLY CONFORMAL B-L MODEL

- Gauge & matter content [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

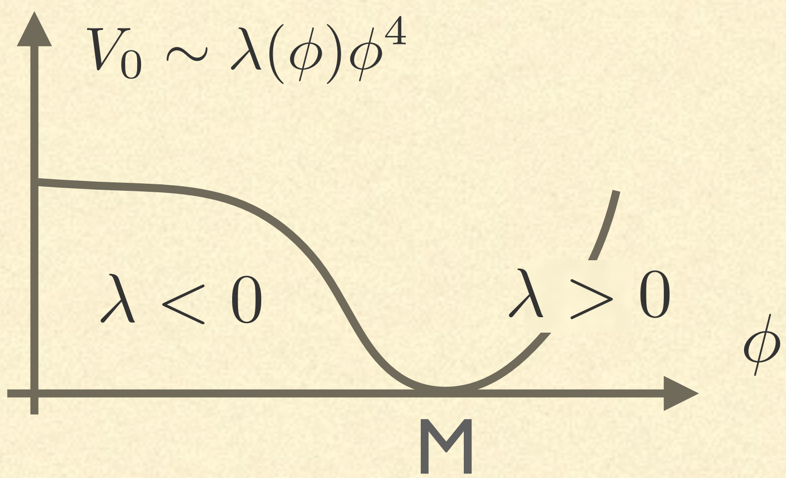
POTENTIAL BEHAVIOR

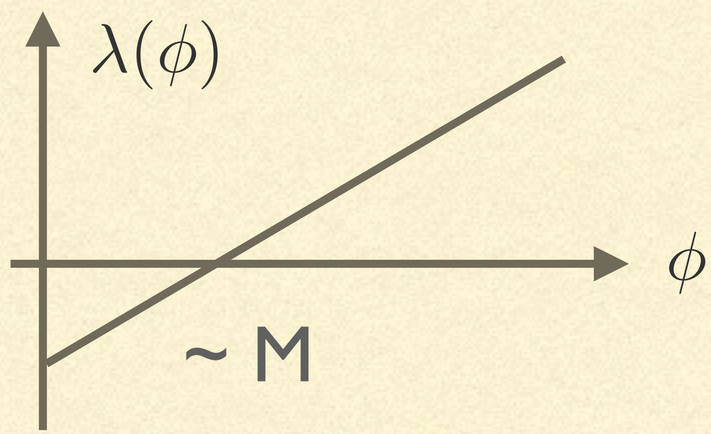
- Zero temperature potential

  - Quartic terms + No mass terms

$$V_{\text{tree}} = \lambda_H |H|^4 + \boxed{\lambda|\Phi|^4} - \lambda'|\Phi|^2|H|^2$$ + no mass terms ("classically no-scale" assumption)

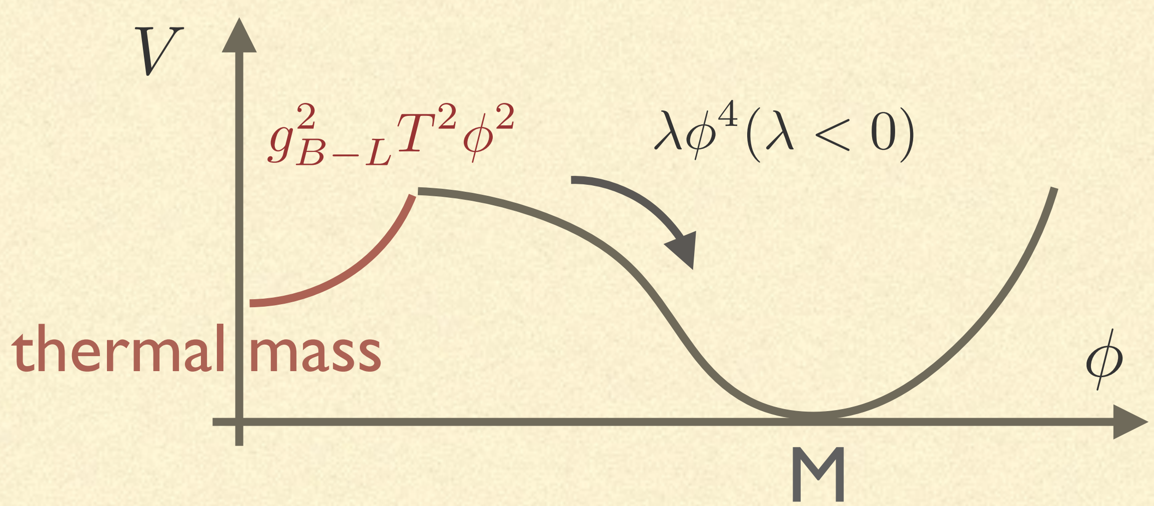
  - Scale is induced by the running of λ (determined by g_{B-L})





POTENTIAL BEHAVIOR

- Finite temperature potential
  - Thermal mass + Quartic $V \sim g_{B-L}^2 T^2 \phi^2 + \lambda(\max(T,\phi))\phi^4$

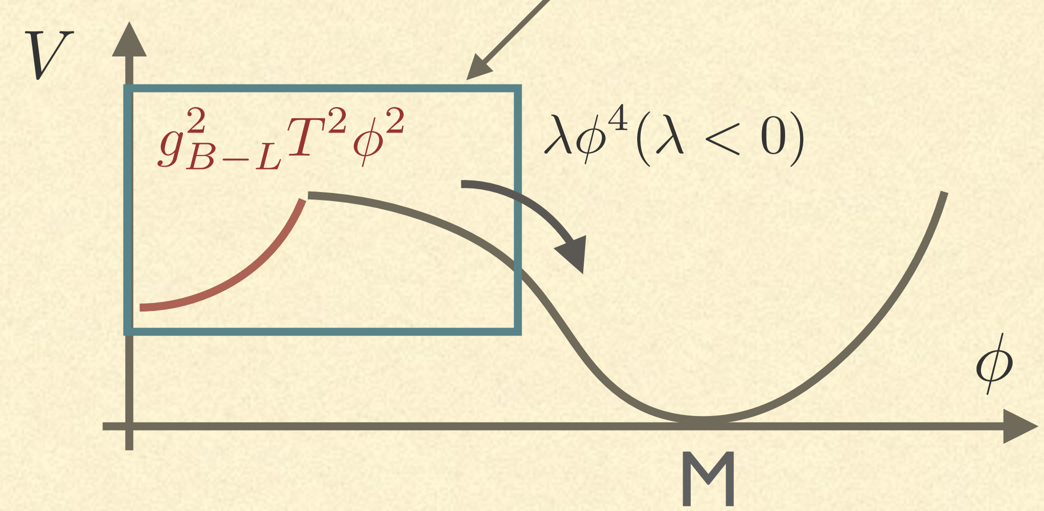


POTENTIAL BEHAVIOR

- Finite temperature potential

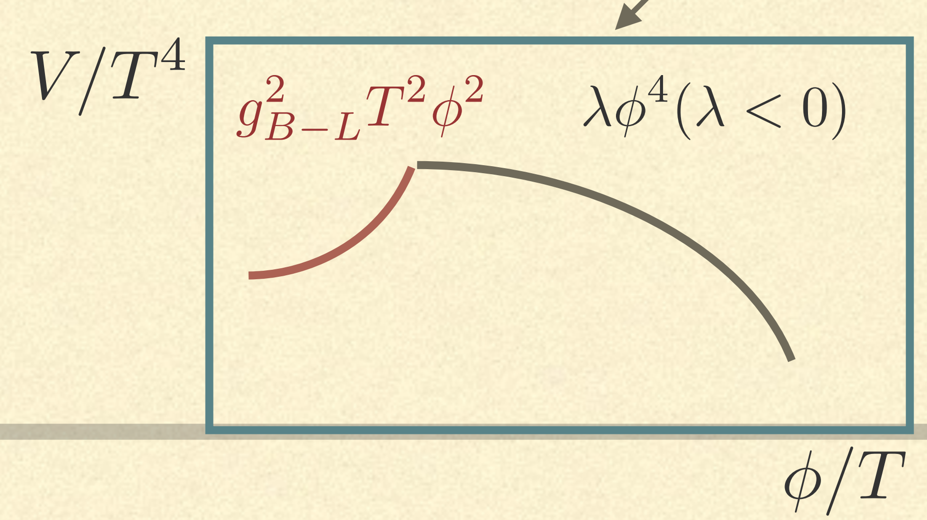
T is the only mass scale relevant to tunneling

- Thermal mass + Quartic $V \sim g_{B-L}^2 T^2 \phi^2 + \lambda(\max(T,\phi))\phi^4$



All dimensionful quantities normalized by T

- As temperature changes, ...



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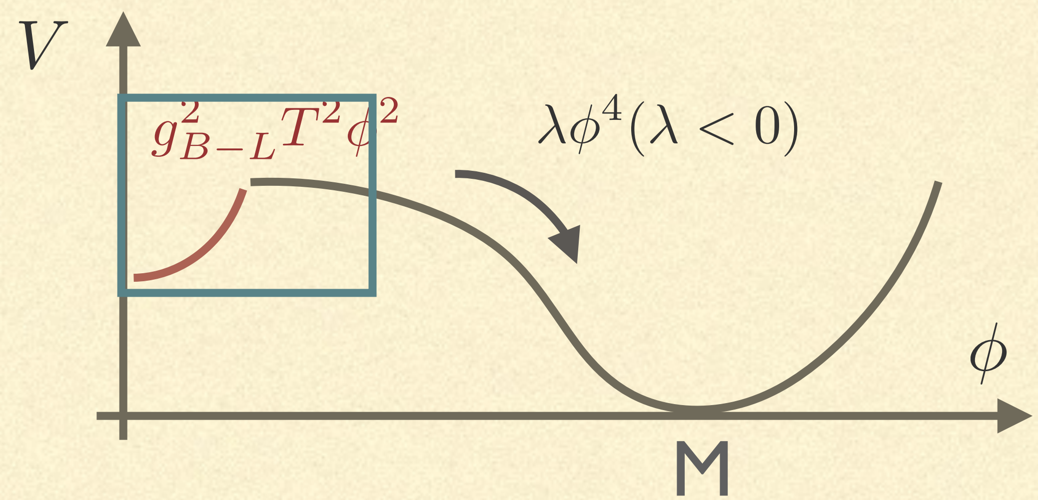

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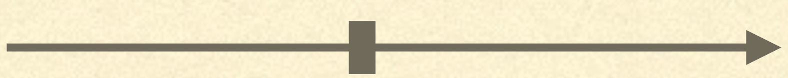

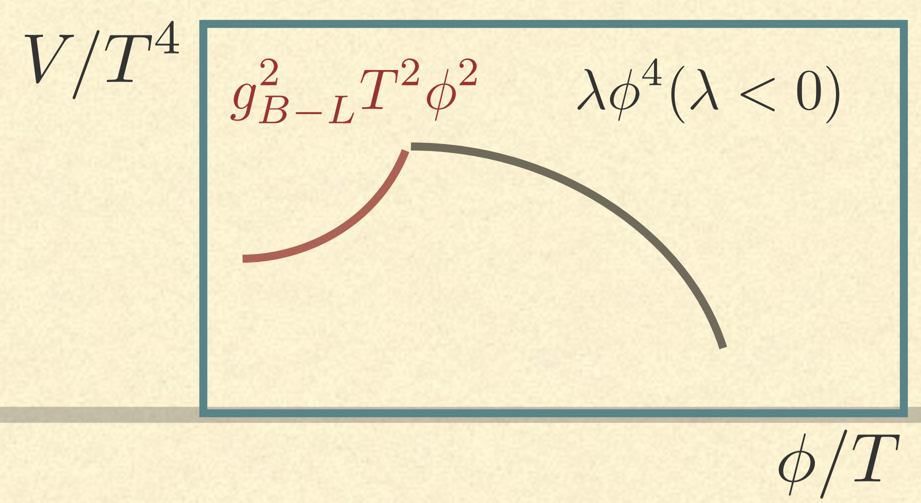

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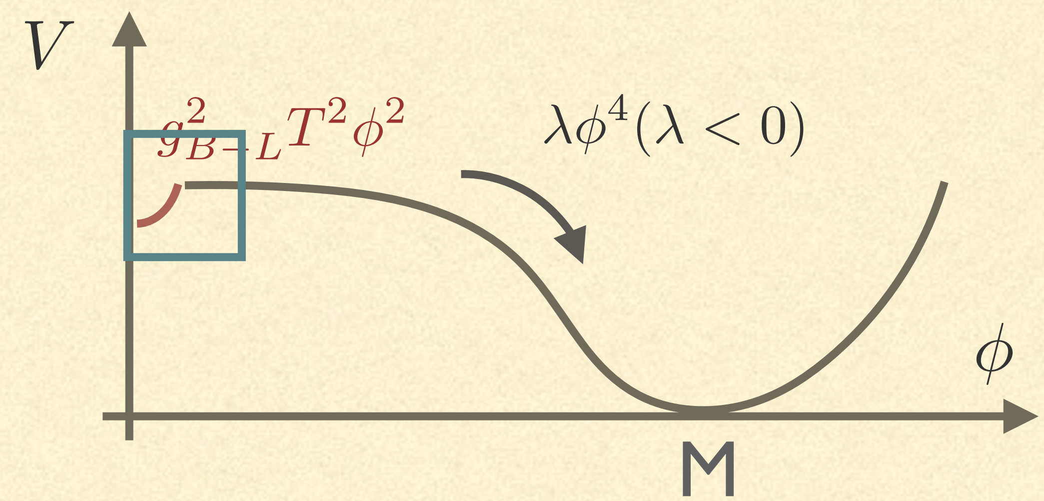

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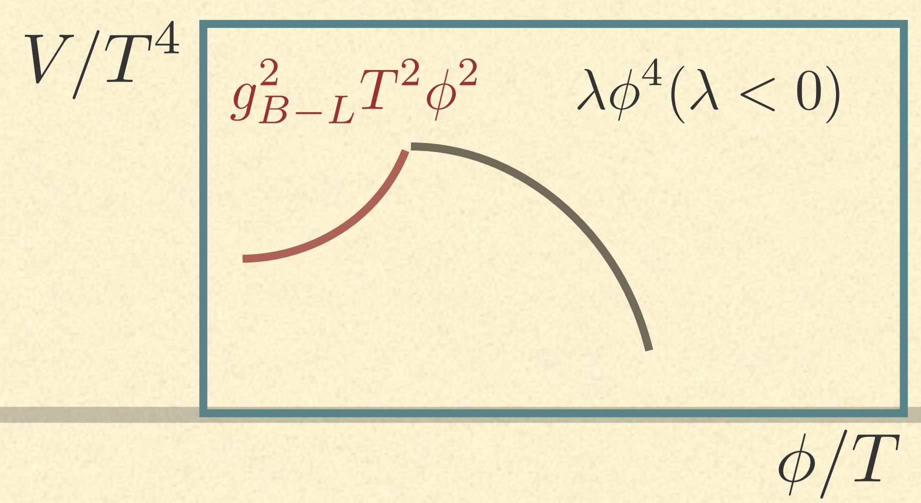

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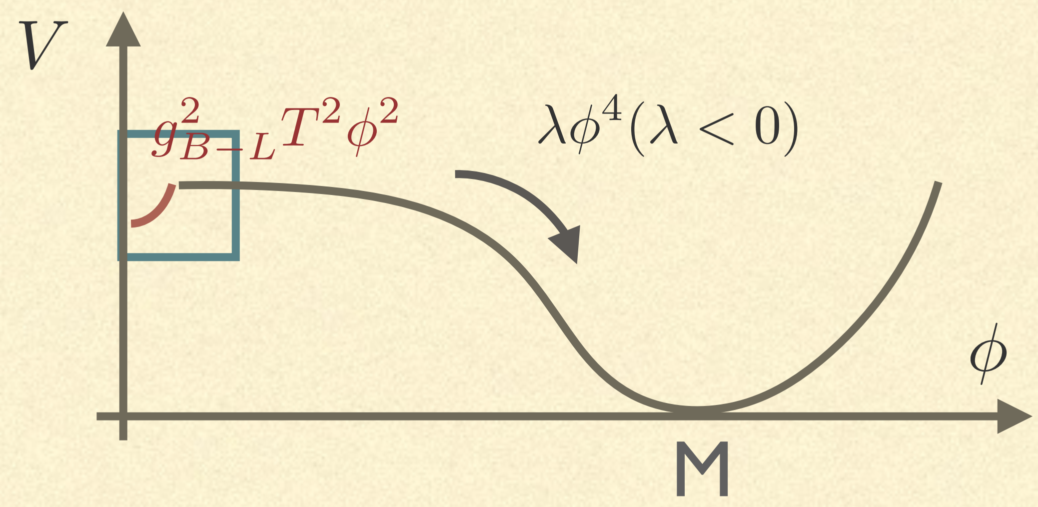
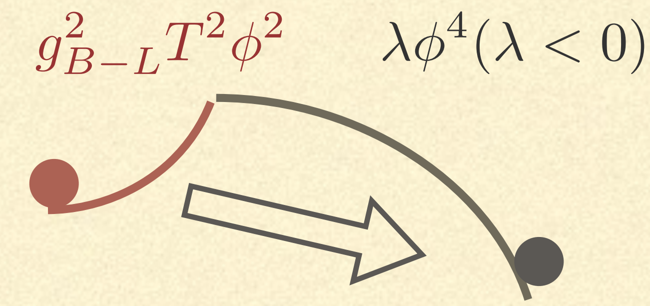


  - As temperature changes, ...

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

SLOWLY-CHANGING NUCLEATION RATE



- Nucleation rate is calculated with "bounce method"

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

dimensionless

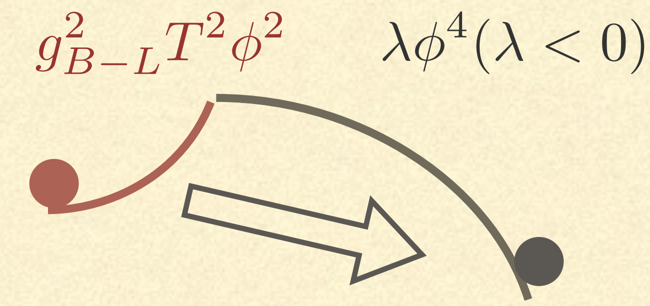
- S_3/T depends only on couplings (since it is dimensionless!)

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

Note : Usually does not hold since m/T (m : mass scale of the potential) enters

- Nucleation rate Γ changes SLOWLY (with beta function)

SLOWLY-CHANGING NUCLEATION RATE



- Nucleation rate is calculated with "bounce method"

SLOWLY changing nucleation rate

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BIG bubbles

||

LARGE GWs

- Nucleation rate Γ changes SLOWLY (with beta function)

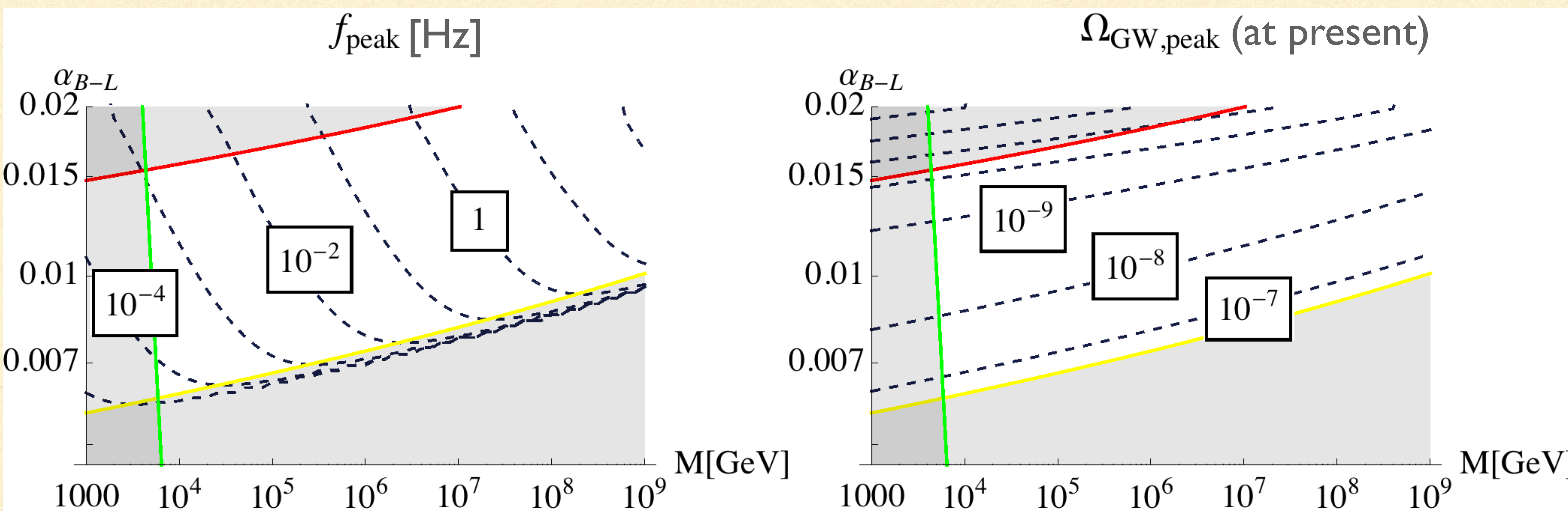
RESULT : LARGE GWS

- Peak frequency & amplitude of the GW spectrum

$M \equiv \langle \phi \rangle$

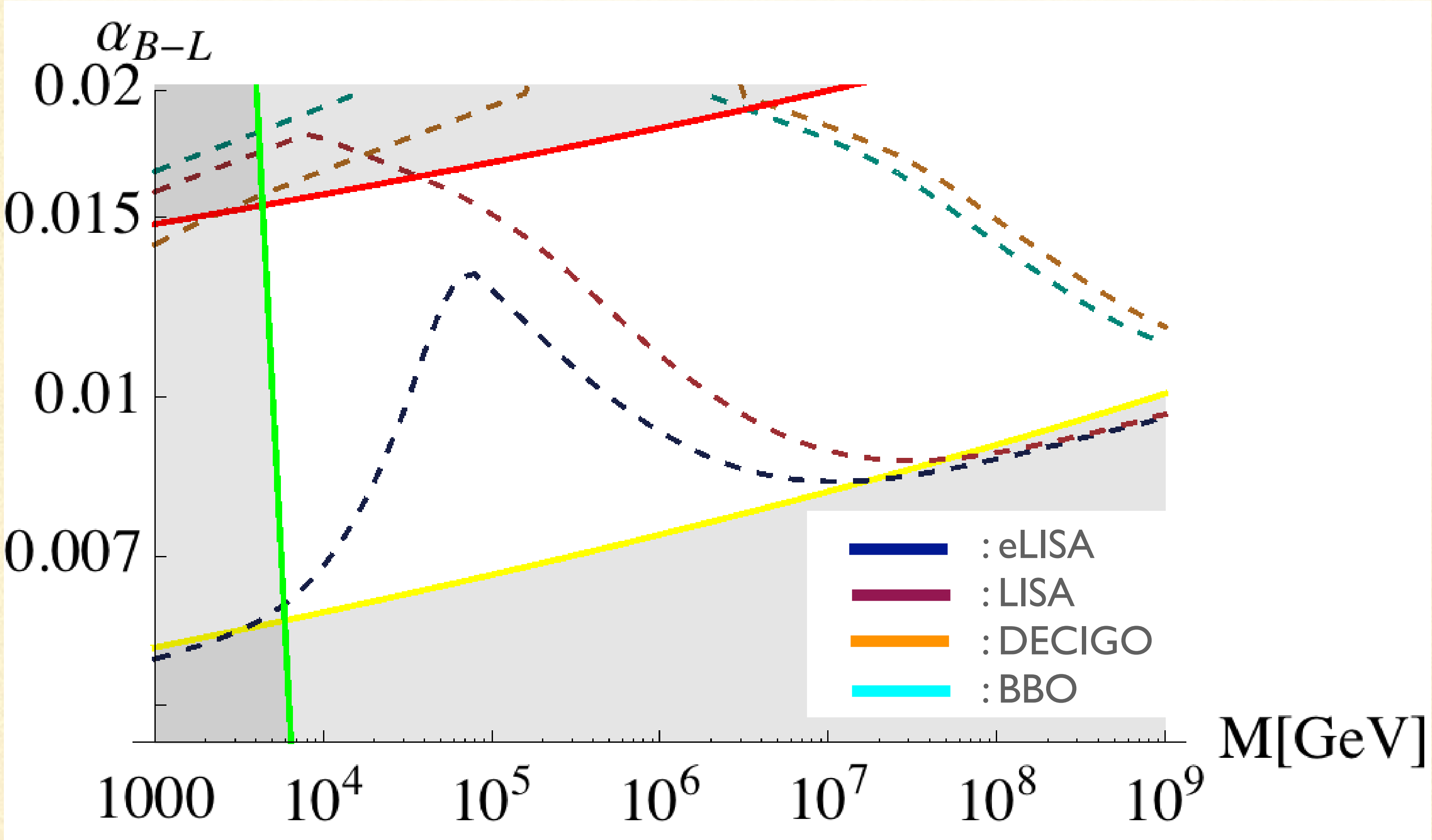
α_{B-L} : Gauge coupling at scale M

: Above this → Landau poles below Mp
: Below this → Successful PT does not occur
: Left to this → Excluded by Z' mass constraint



RESULT : LARGE GWS

- Detectability in the future



(Regions below dashed lines are detectable)

CONCLUSION

- The era of GW cosmology will come
- Classically conformal models lead to PT with large GWs, and can be tested by future experiments

Key "No mass scale" at the classical level

→ SLOWLY changing nucleation rate (~ beta function),

→ BIG bubbles

→ LARGE GW amplitude

Backup

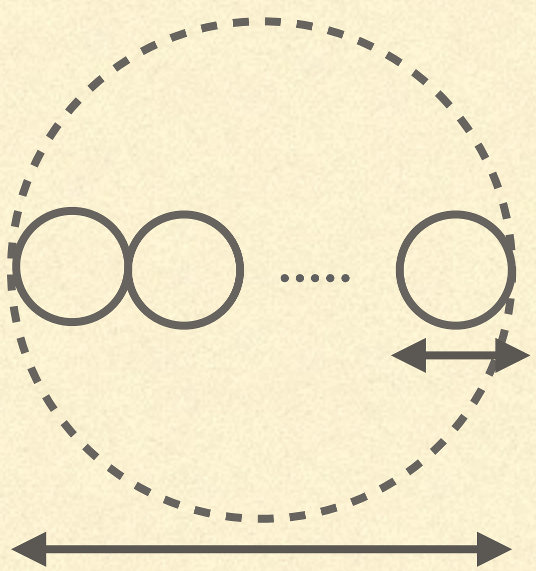
GW PRODUCTION IN COSMIC PHASE TRANSITION

- GW spectrum just after the transition

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

(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

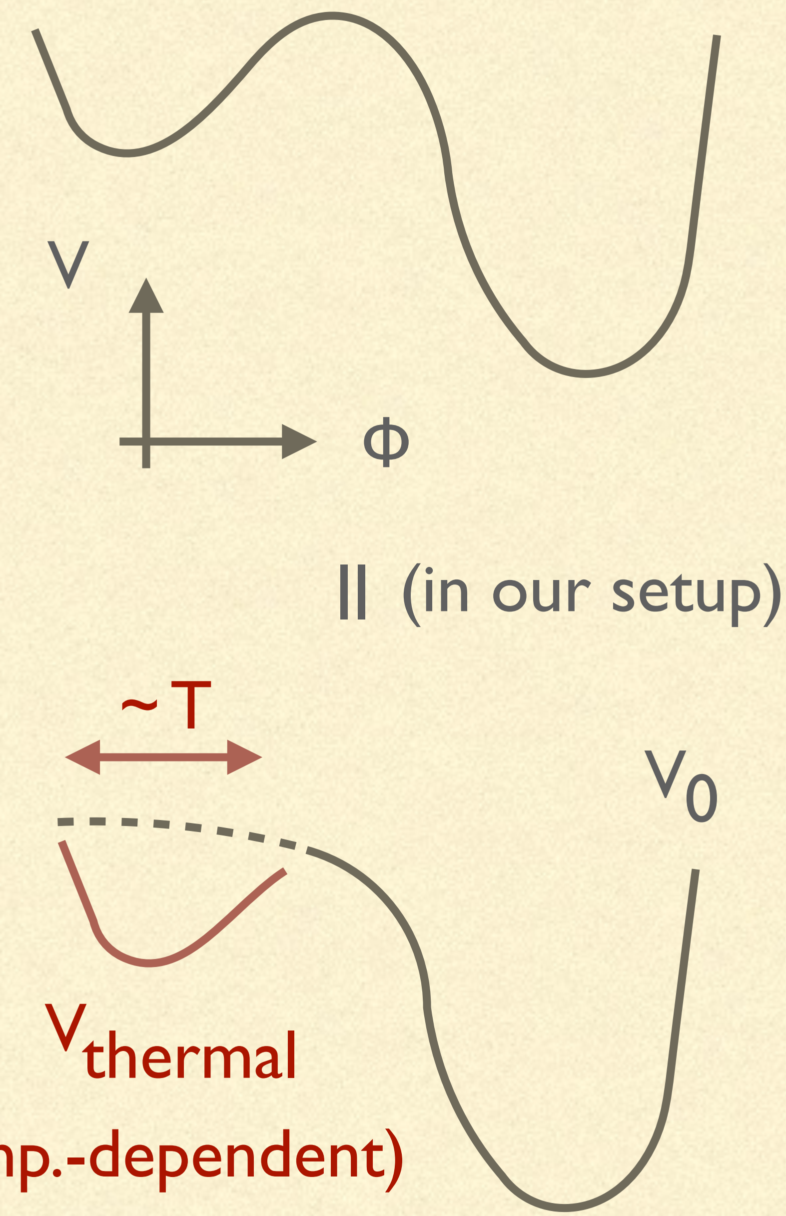
- Estimation of the transition rate

  - 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

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



GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

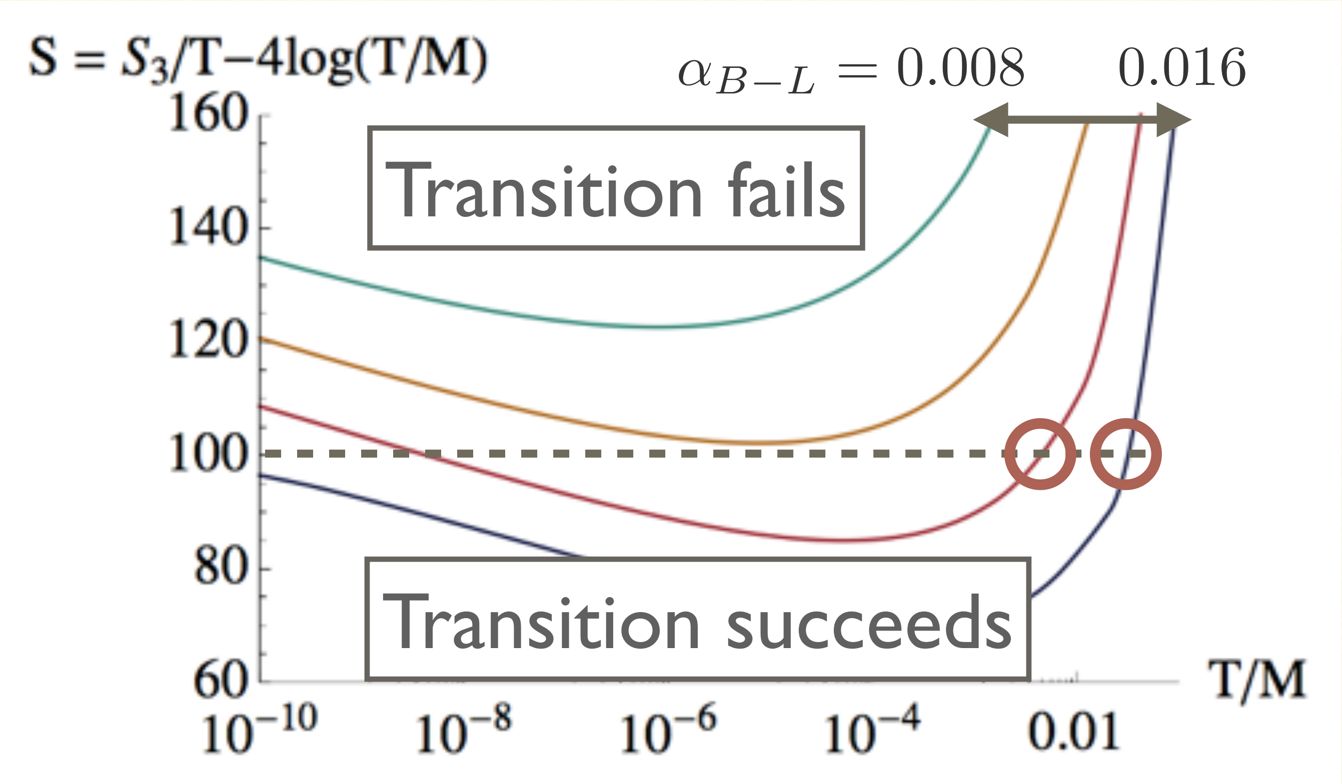
- By the way, phase transition occurs at all?

  - 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
    $T/M|_{S\sim 100} \ll 1$ (O →)
    → large α expected



GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- α & β

$M \equiv \langle \phi \rangle$

α_{B-L} : value at M

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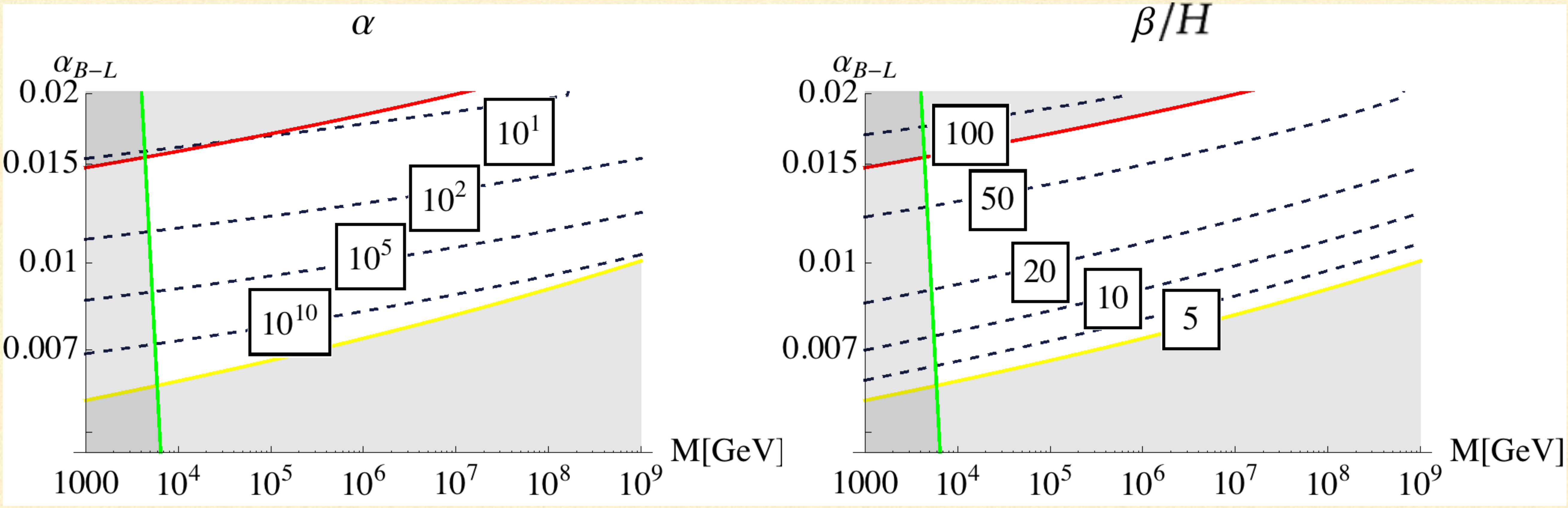


GW PRODUCTION IN CLASSICALLY CONFORMAL B-L MODEL

- Rough estimation of GW amplitude

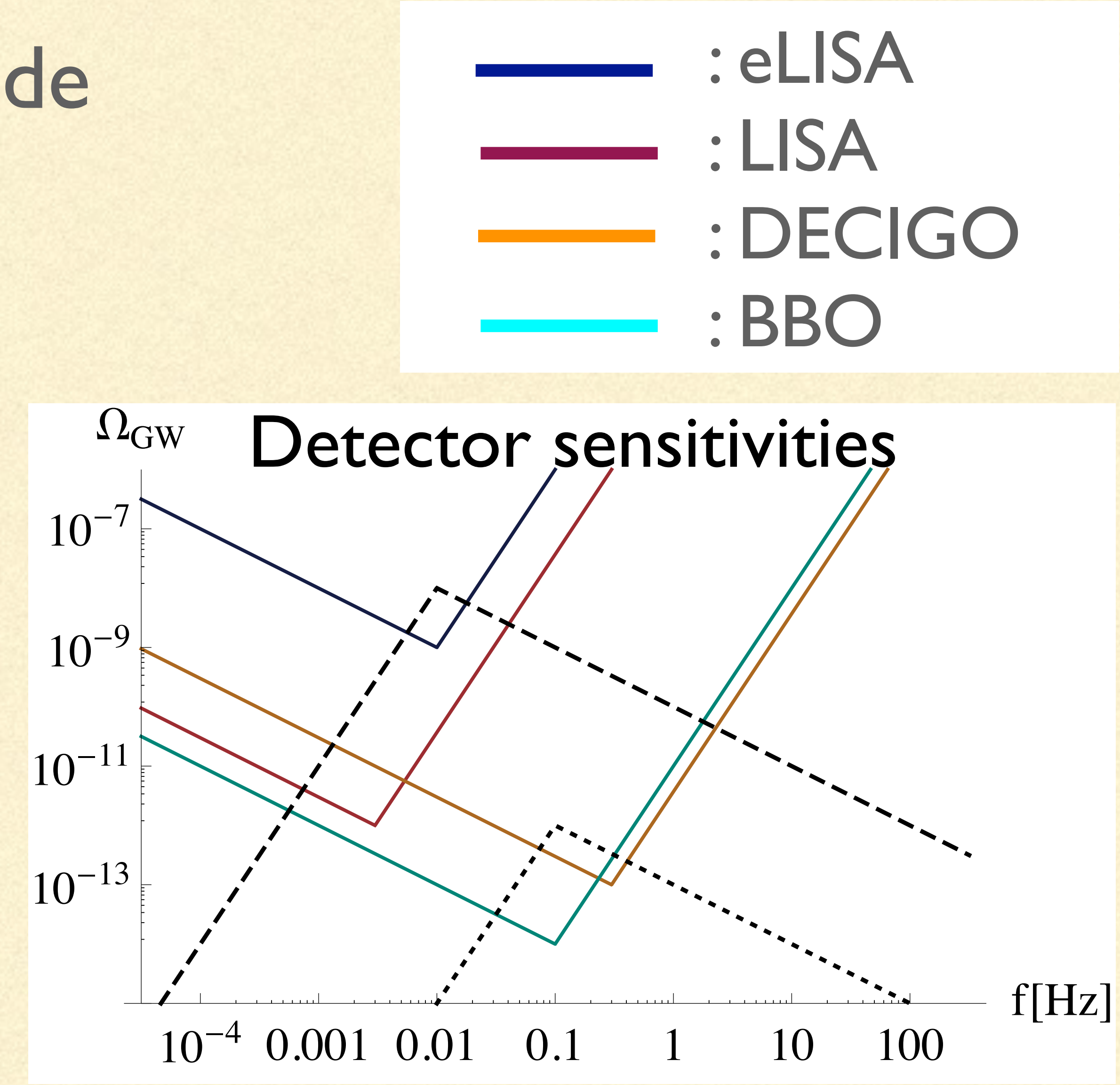
  - Present GW spectrum

~quadrupole factor ~radiation fraction today

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

duration time

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



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