高エネルギー相転移を重力波で探る

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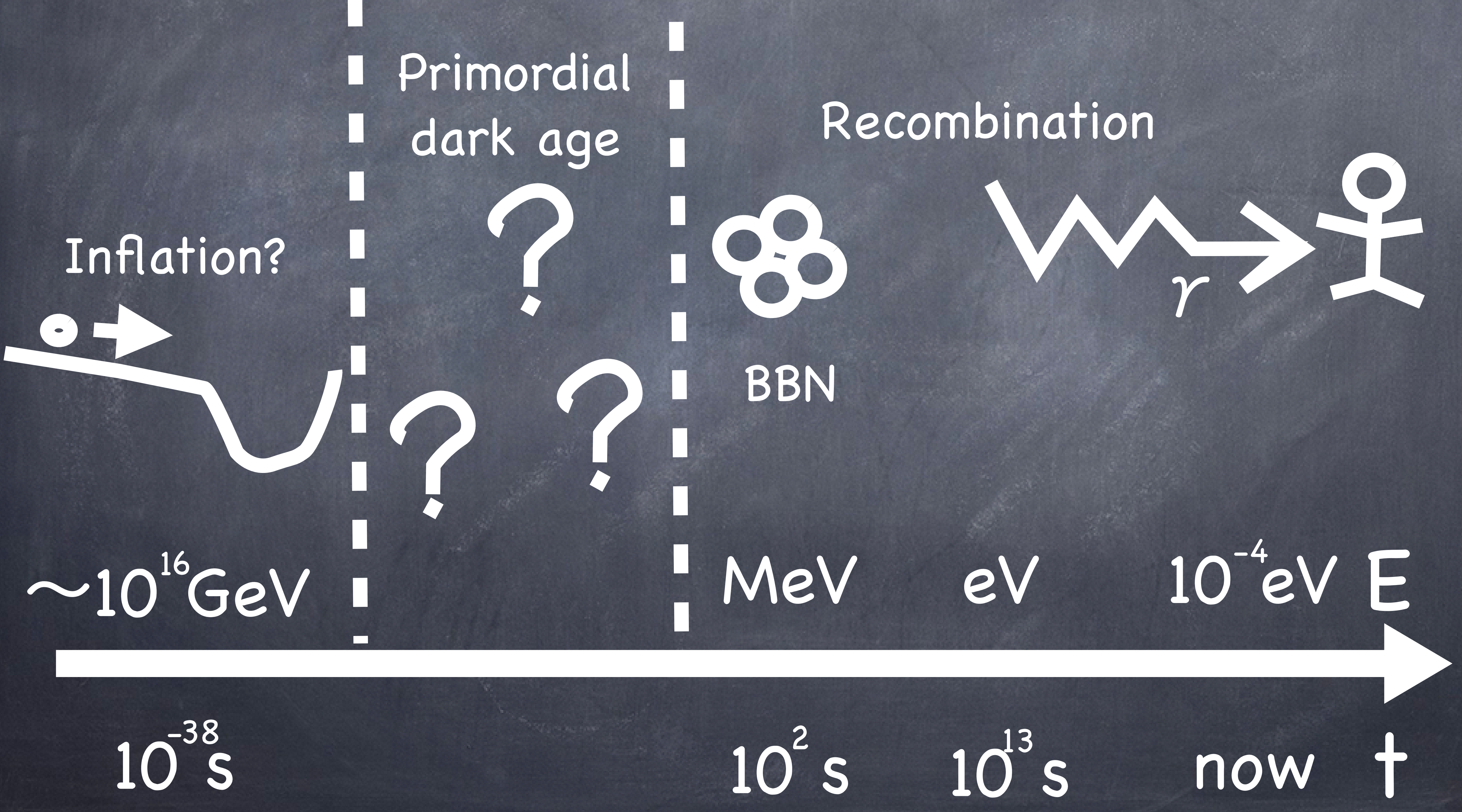
In collaboration with Takeo Moroi & Kazunori Nakayama

Based on arXiv:1307.3010

基研研究会　素粒子物理学の進展2013

Intro

What we know about the universe



What is in the "Primordial dark age"?

- Primordial dark age is a treasury of particle physics -

- Grand Unification
- (P)Reheating
- PQ symmetry breaking
- RH ν (Majoron?)
- SUSY breaking
- EW symmetry breaking
- QCD phase transition … and more

Outline

1. Introduction

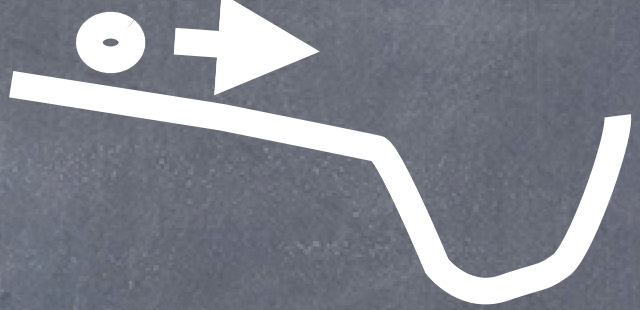
2. Properties of inflationary GWs
 - production and evolution -

3. Imprints of high-energy physics in GWs
 - example : SUSY PQ model -

4. Summary

Properties of Inflationary GWs

Inflation

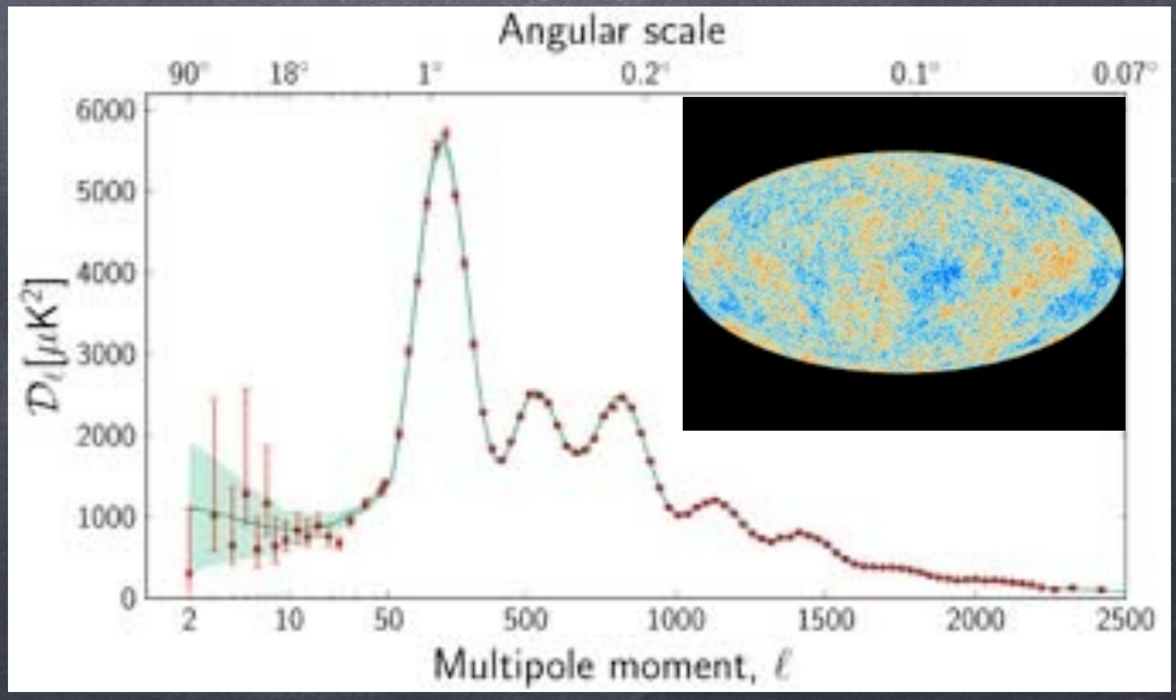


- Accelerating expansion of the universe
- Solution to

  horizon/flatness/monopole problem

- Explains the structure of the universe

  by quantum fluctuation



From Planck

Production of GWs during inflation

- Definition

$$ds^2 = -dt^2 + a^2(\delta_{ij} + h_{ij})dx^i dx^j \, , h_{ii} = h_{ij,j} = 0$$

- Action

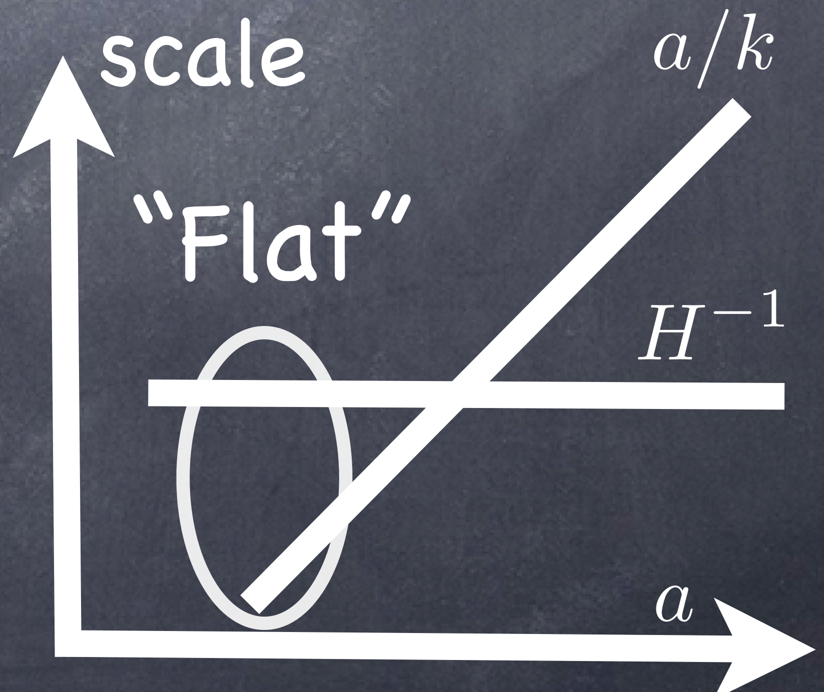
$$S_{\rm grav} = \frac{a^3}{32\pi G}\int \frac{d^3k}{(2\pi)^3}\left(\dot{h}_{ij}(t,\mathbf{k})\dot{h}_{ij}(t,-\mathbf{k}) - \frac{k^2}{a^2}h_{ij}(t,\mathbf{k})h_{ij}(t,-\mathbf{k})\right)$$

$\rightarrow$massless scalar field

- Production by quantum fluctuation

$$\Delta_h^2(k) = \left(\frac{k^3}{2\pi^2}\right)P_h(k) = 64\pi G\left(\frac{H_{\rm inf}}{2\pi}\right)^2$$

$$< h_{ij}(\mathbf{x})h_{ij}(\mathbf{x}') >= \int \frac{d^3k}{(2\pi)^3}e^{i\mathbf{k}(\mathbf{x}-\mathbf{x}')}P_h(k)$$



Production of GWs during inflation

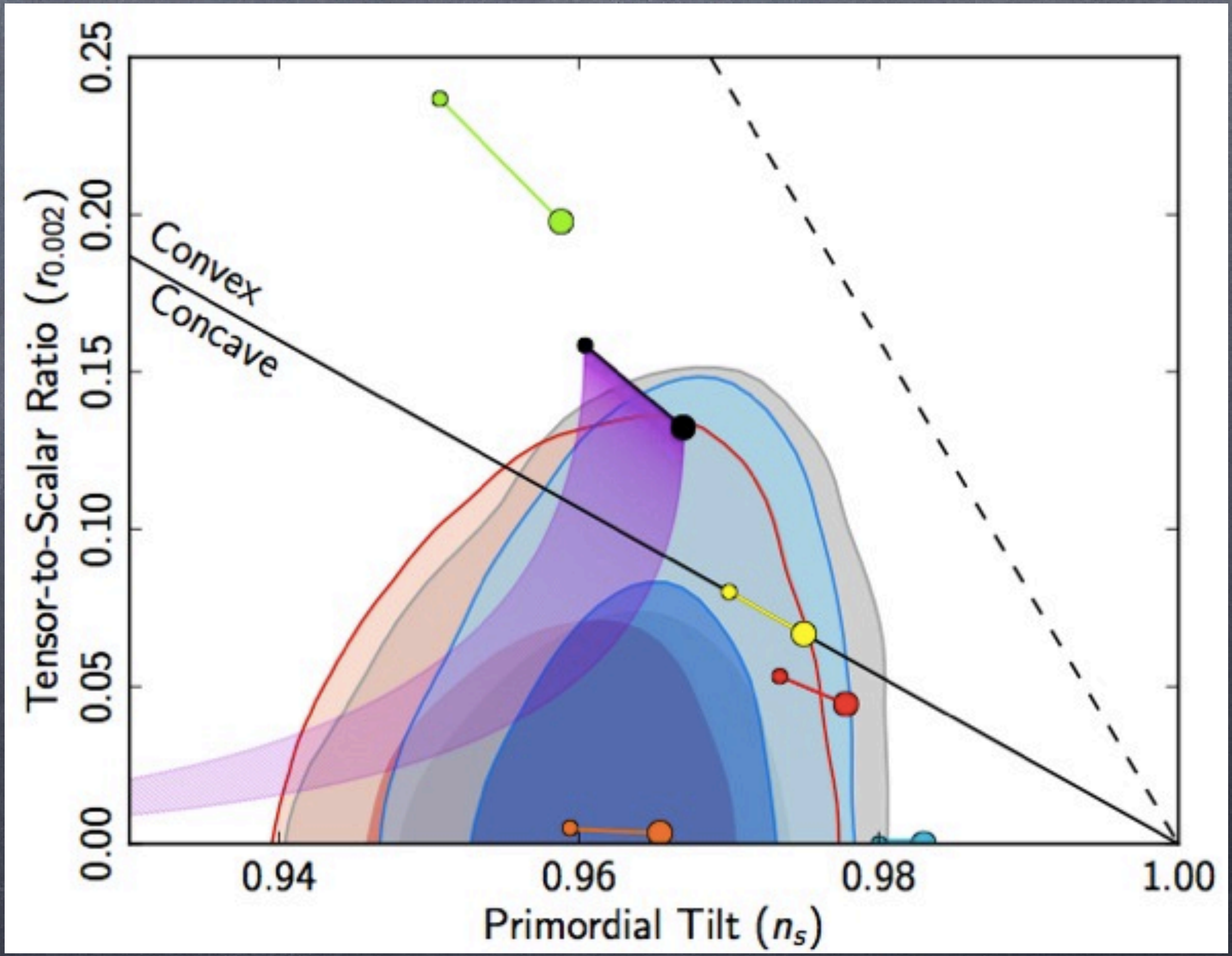
- Observational constraint

$$r \equiv \frac{\Delta_h^2}{\Delta_R^2} \lesssim 0.1$$

$$\Delta_R^2 = 2.22 \times 10^{-9}$$

$$\Delta_h^2(k) = 64\pi G \left(\frac{H_{\rm inf}}{2\pi}\right)^2$$

From Planck



Evolution of GWs

- The past is imprinted in GWs in 2 ways -

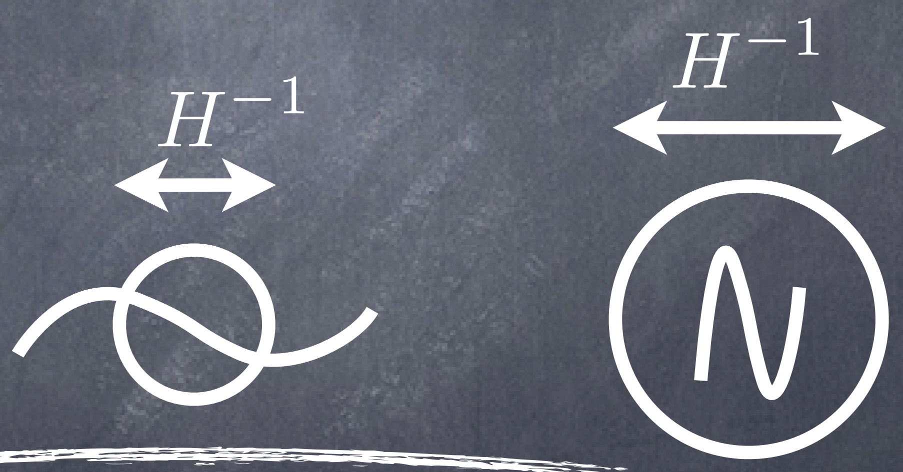
- Evolution equation

$$\ddot{h} + 3H\dot{h} + \frac{k^2}{a^2}h = 16\pi G\Pi\,, \quad T_{ij} = Pg_{ij} + \Pi_{ij}$$

Free-streaming particle

Background evolution

- Before/After horizon-in



Before ($k/a < H$) $\rightarrow h \simeq \mathrm{const}$

After ($k/a > H$) $\rightarrow < h^2 >_{\mathrm{osc}} \propto a^{-2} \quad (\rho_{\mathrm{GW}} \propto a^{-4})$

$\rightarrow$GWs behave as radiation after horizon-in

Evolution of GWs

- The effect of free-streaming particle = Back reaction at horizon-in -

- Anisotropic stress

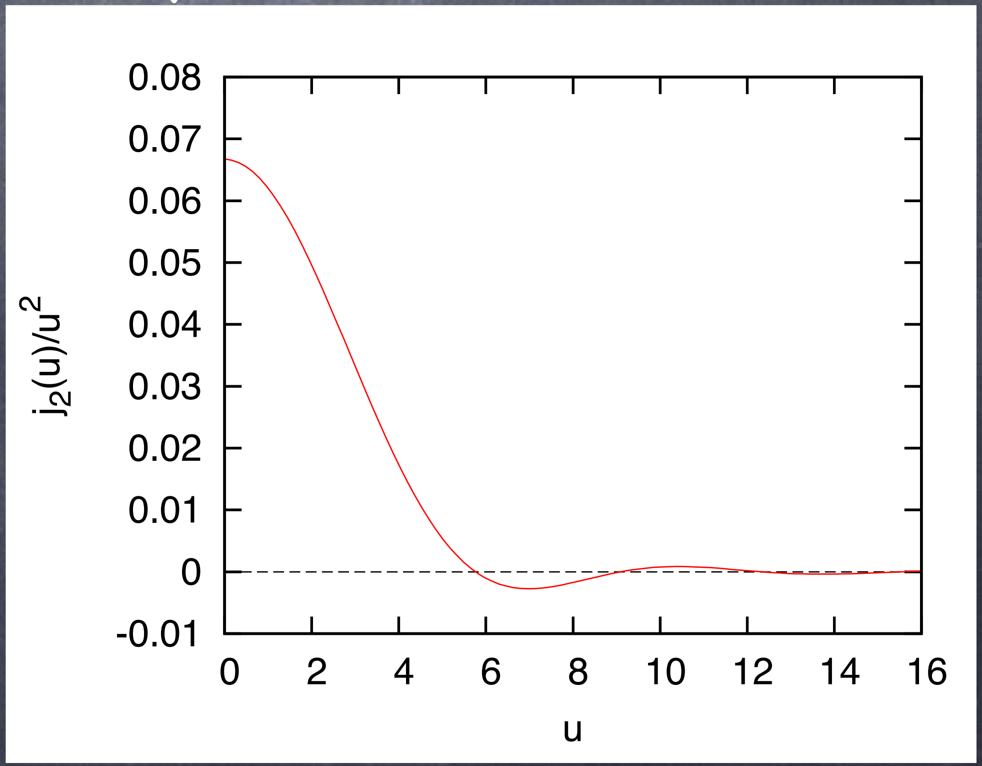
$$h'' + 2H_u h' + h$$
$$= -24\left[H_u^2 \frac{1}{a^4\rho_{\rm tot}}\right](u)\int_0^u du' \left[a^4\rho_X \frac{\partial h}{\partial u}\right](u')\frac{j_2(u-u')}{(u-u')^2}$$

RJ, T. Moroi, K. Nakayama arXiv:1208.0184

$$u = k\int_0^t \frac{dt'}{a(t')} \simeq \frac{k}{aH}, \quad H_u = \frac{1}{a}\frac{da}{du}, \quad X : \text{free} - \text{streaming particle}$$

$\rightarrow$ Free-streaming particle affects

GWs only at the horizon-in



Imprints of high-energy physics in GWs

Expected events

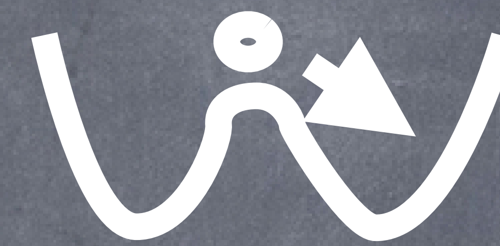
- Grand Unification
- (P)Reheating
- PQ symmetry breaking
- RH ν (Majoron?)
- SUSY breaking
- EW symmetry breaking
- QCD phase transition

$$\ddot{h} + 3H\dot{h} + \frac{k^2}{a^2}h = 16\pi G\Pi$$

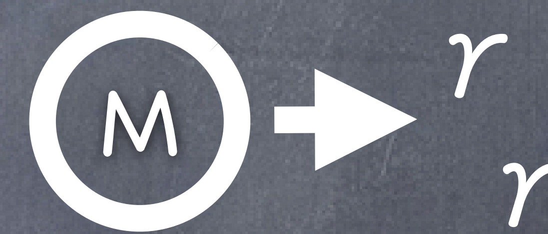
(blue) = background evolution

(red) = free-streaming particle

- Phase transition



  - Vacuum-energy domination
  - Decay into (free-streaming) radiation
- Entropy injection



  - Matter domination
  - Decay into (free-streaming) radiation
- Coherent oscillation

- Decouple of radiation

- Decay of free-streaming radiation

Effect of the events on GWs

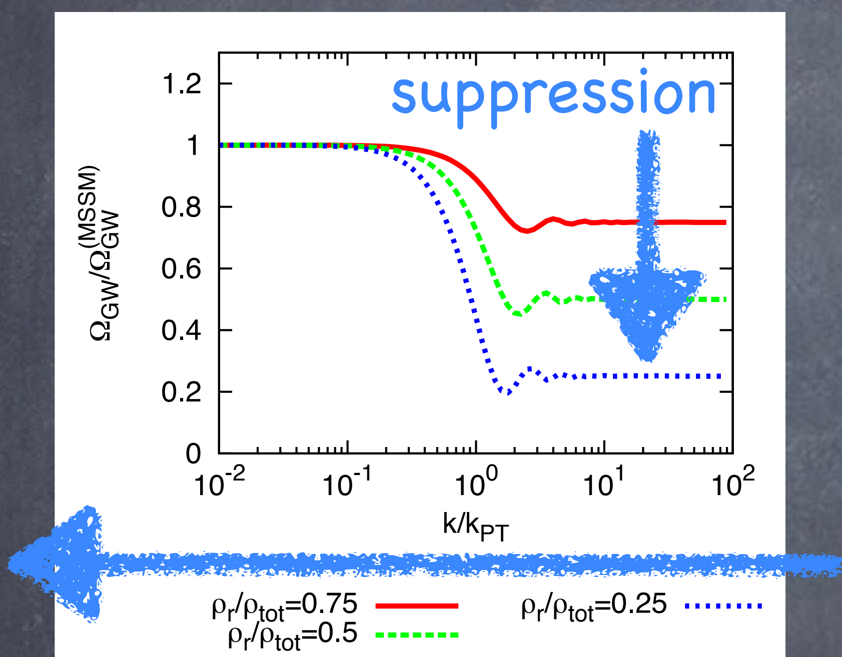
- Remember GWs are radiation inside the horizon -

- Vacuum-energy domination
  Matter domination, Coherent oscillation
  (& Decay into radiation)
  → Dilution of radiation
  = Dilution of GWs inside the horizon

- Free-streaming radiation
  → O(10)% decrease in $\rho_{\rm GW}$
  at the time of horizon-crossing,
  if free-streaming radiation exists

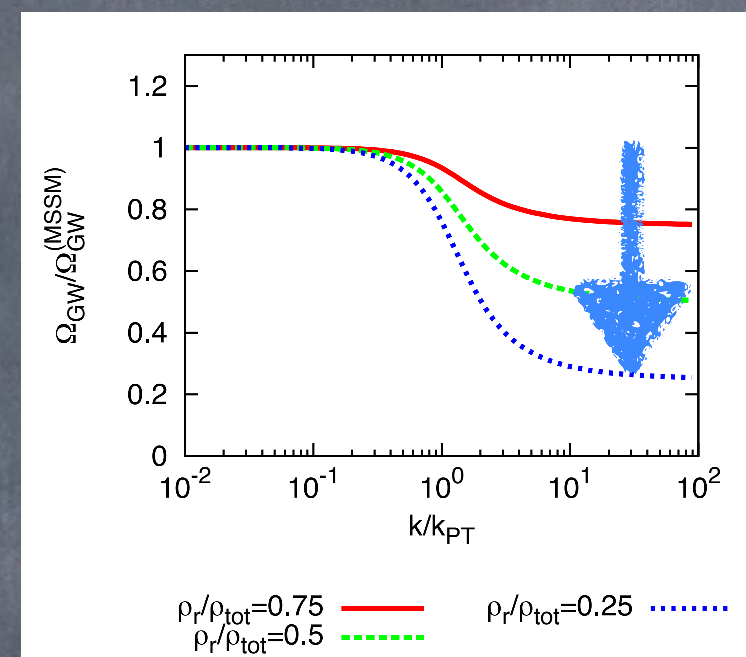
Illustration with simple examples

- Vacuum-energy domination

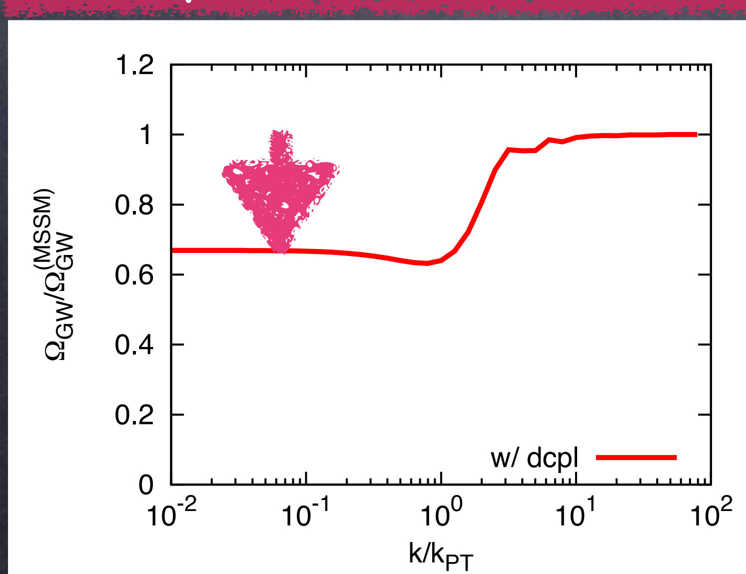


Time of horizon-in

- Matter domination, Coherent oscillation



- Decouple of radiation from thermal bath



$$\rho_{\rm GW}(t) = \frac{1}{32\pi G}\frac{1}{2} < \dot{h}_{ij}^2 + (\nabla h_{ij}/a)^2 >_{\rm ens} = \int d\ln k\ \rho_{\rm GW}(t,k)$$

$$\Omega_{\rm GW}(t,k) = \frac{\rho_{\rm GW}(t,k)}{\rho_c(t)}$$

Example -SUSY PQ-

- Model

$\Phi = <\Phi> e^{A}$ $\bar{\Phi} = <\bar{\Phi}> e^{-A}$

$$W = \lambda S(\Phi\bar{\Phi} - f^2) + y_1 \Phi Q_i \bar{Q}_i + y_2 \bar{\Phi} Q'_i \bar{Q}'_i \; (+\Phi H_u H_d)$$

	S	Φ	$\bar{\Phi}$	Q_i	$\bar{Q}_i$	Q'_i	$\bar{Q}'_i$
SU(3)	1	1	1	$\Box$	$\bar{\Box}$	$\Box$	$\bar{\Box}$
$U(1)_{PQ}$	0	α	$-\alpha$	$-\alpha$	0	α	0

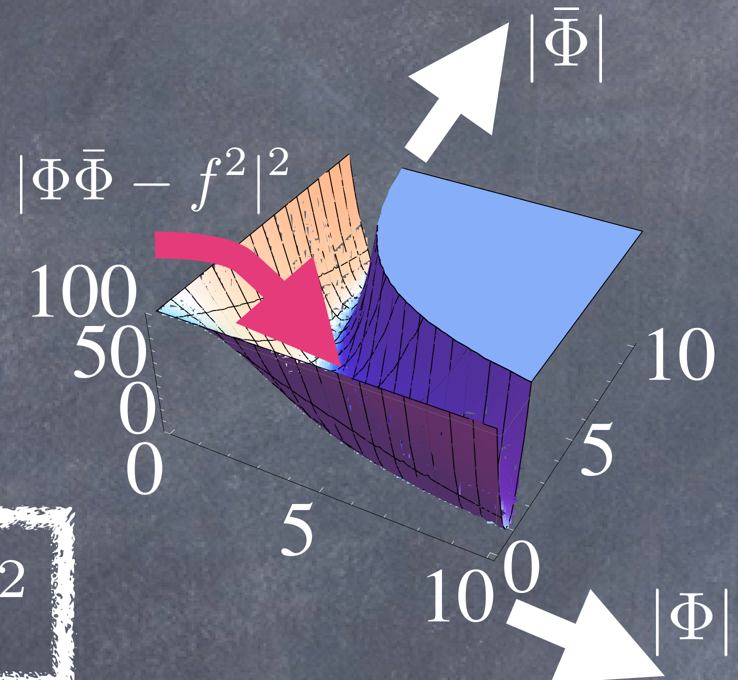
$$V(\Phi, \bar{\Phi}) = V_S + V_{\rm SB} + V_T + V_L$$

Example -SUSY PQ-

$$W = \lambda S(\Phi\bar{\Phi} - f^2) + y_1 \Phi Q_i \bar{Q}_i + y_2 \bar{\Phi} Q'_i \bar{Q}'_i$$

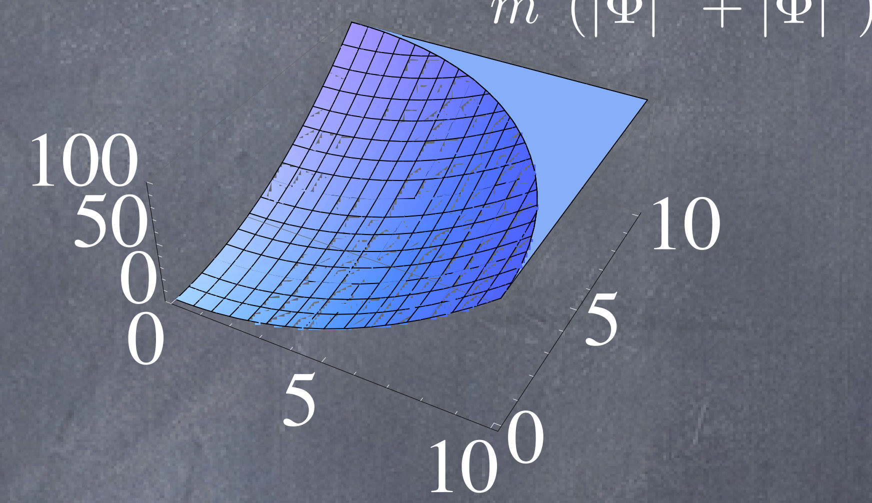
- Potential $V(\Phi, \bar{\Phi}) = V_S + V_{\rm SB} + V_T + V_L$

$V_S =$

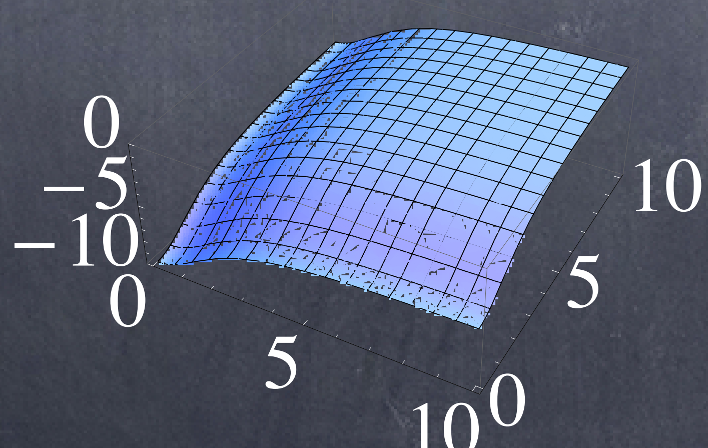


$\Phi\bar{\Phi} \simeq f^2$

$V_{\rm SB} =$

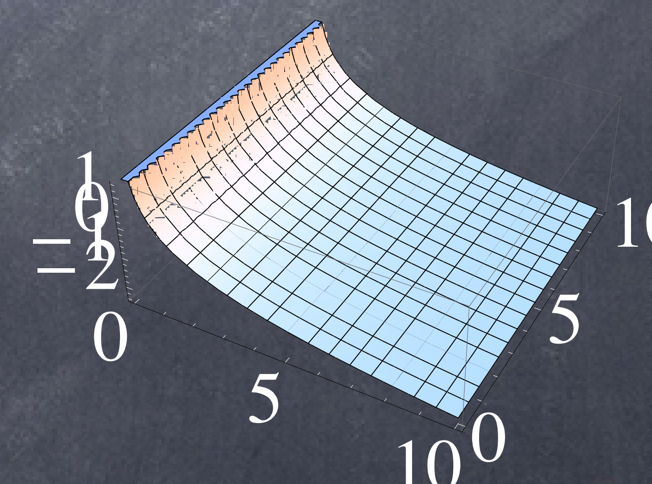


$V_T =$



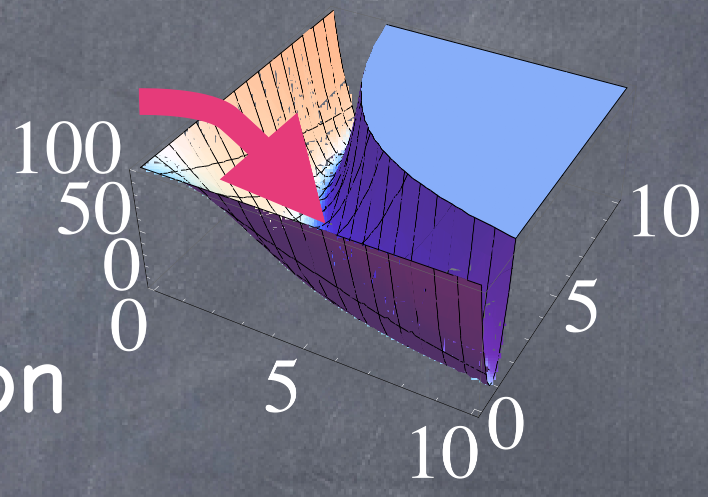
$\Phi = \bar{\Phi} = 0$ favored

$V_L =$



Example -SUSY PQ-

- Events in time sequence



1. Brief period of vacuum-energy domination

2. Phase transition & Decay into radiation (axion & saxion)

3. Decouple of axion & saxion from the thermal bath

(4. Saxion domination)

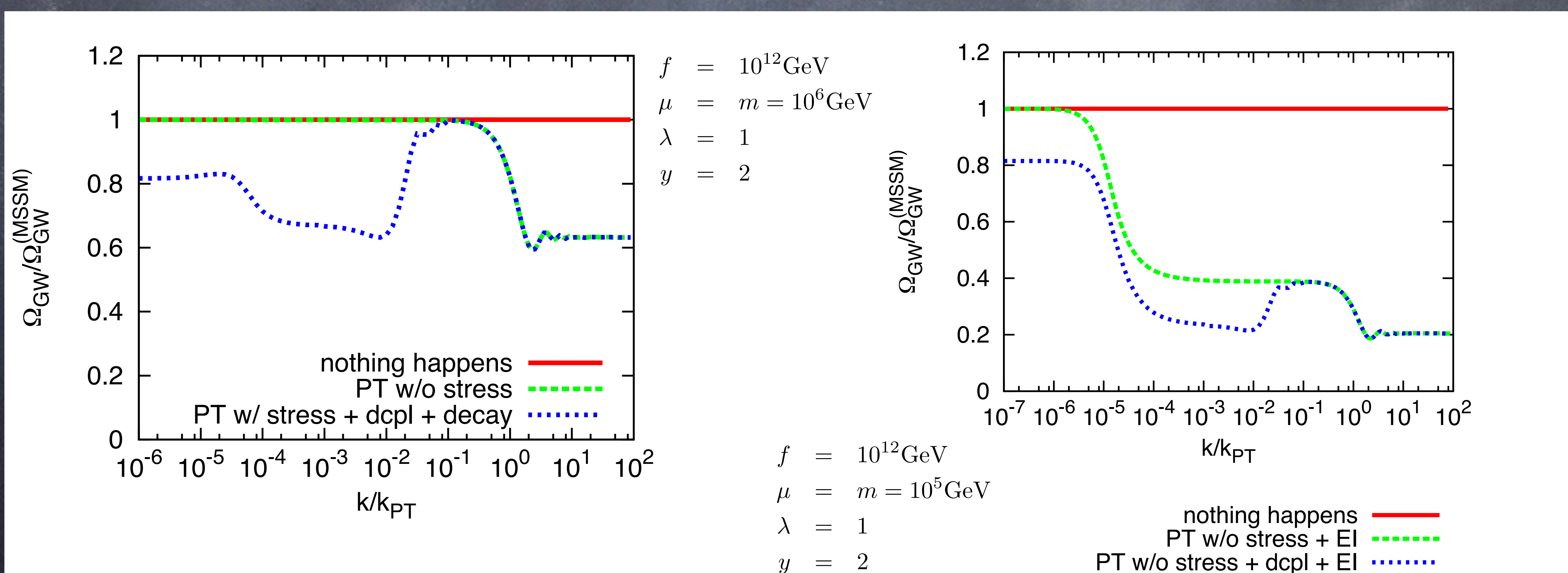
5. Decay of saxion into radiation (Higgs)

GW spectrum

- Energy density of GWs

$$\rho_{\rm GW}(t) = \frac{1}{32\pi G}\frac{1}{2} < \dot{h}_{ij}^2 + (\nabla h_{ij}/a)^2 >_{\rm ens} = \int d\ln k\, \rho_{\rm GW}(t,k)$$

$$\Omega_{\rm GW}(t,k) = \frac{\rho_{\rm GW}(t,k)}{\rho_c(t)}$$



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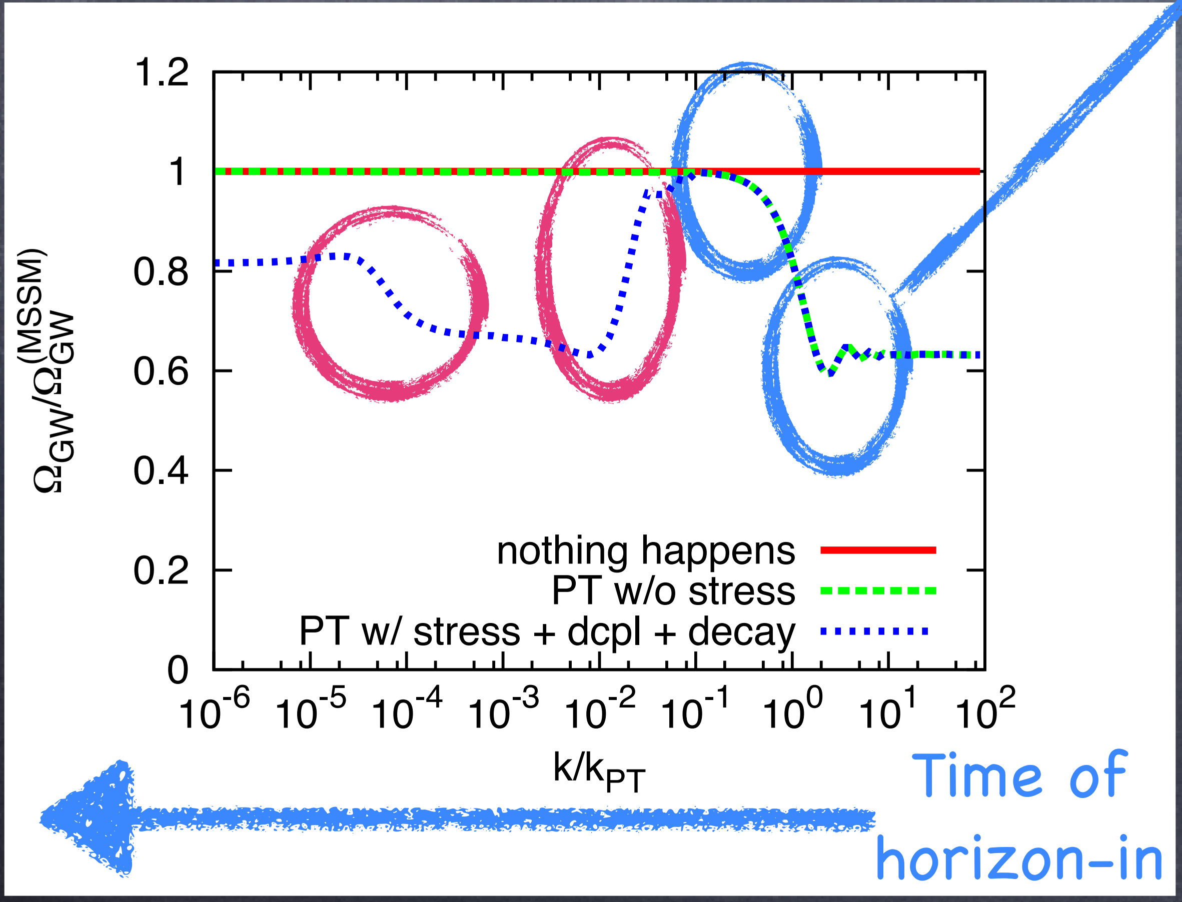
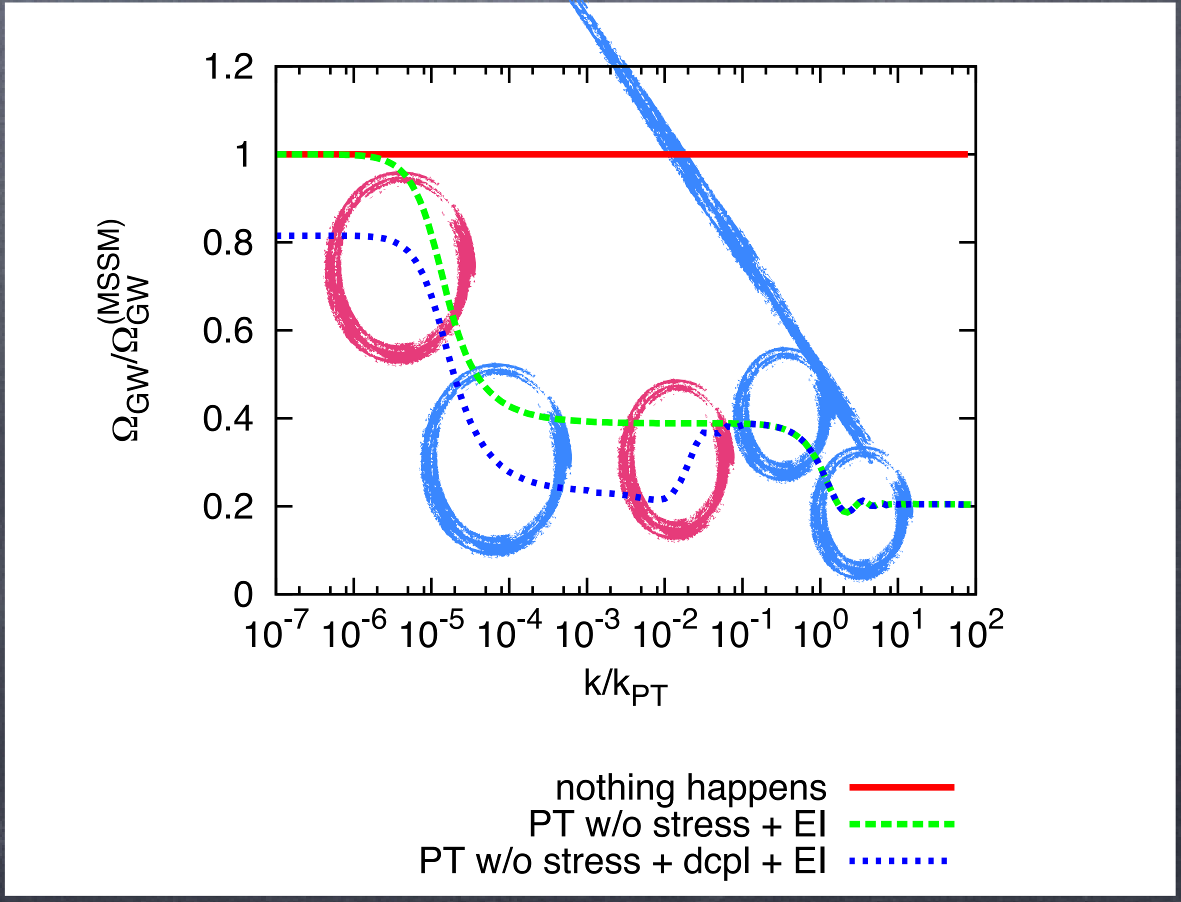
Vacuum-energy domination



Time of horizon-in



GW spectrum

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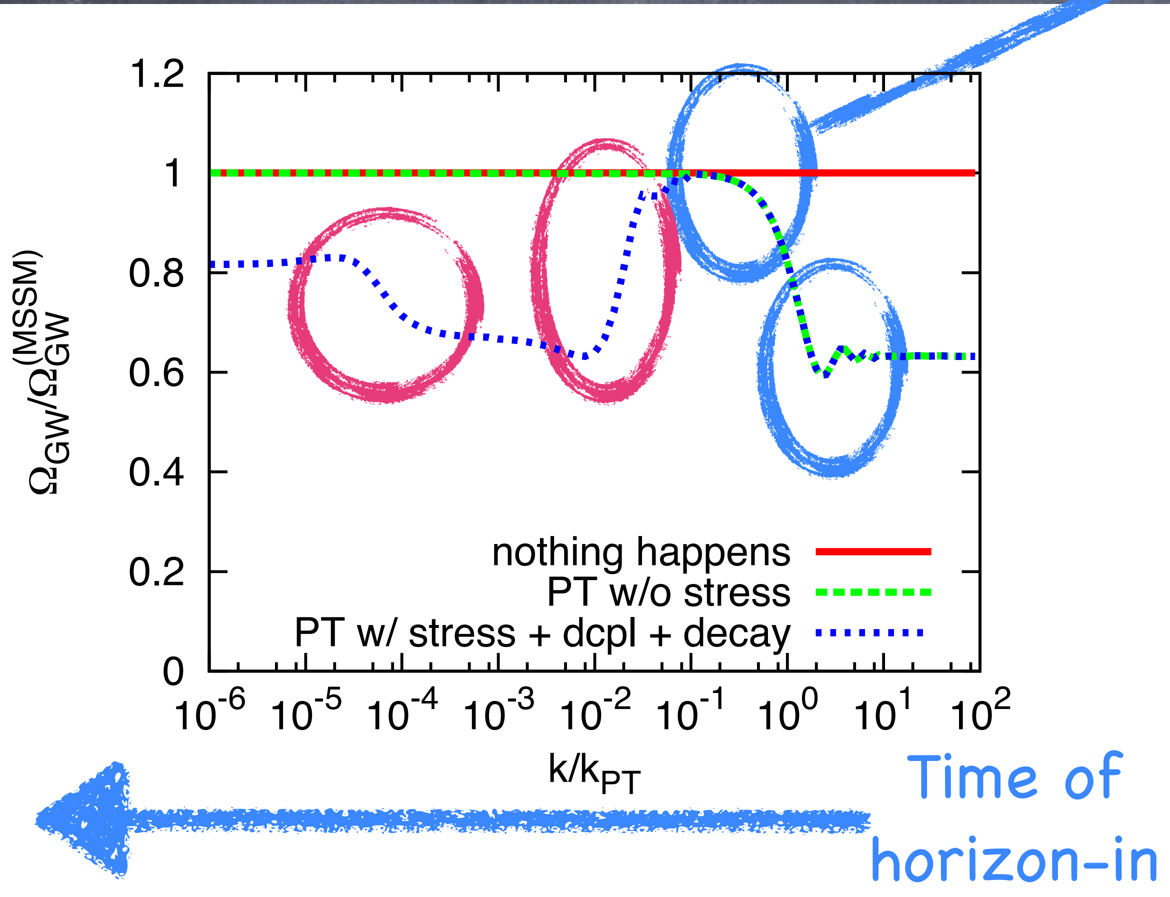
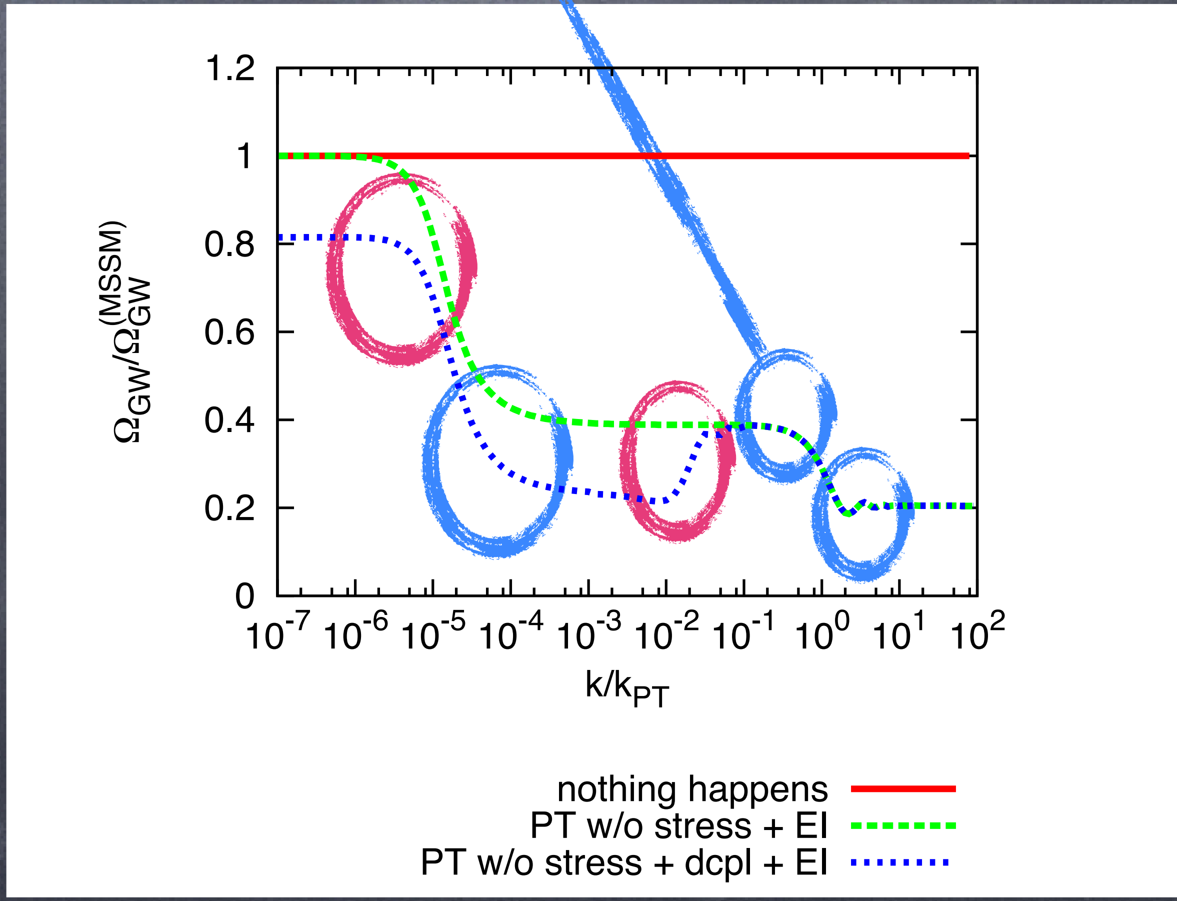
Phase transition & decay



Time of horizon-in



GW spectrum

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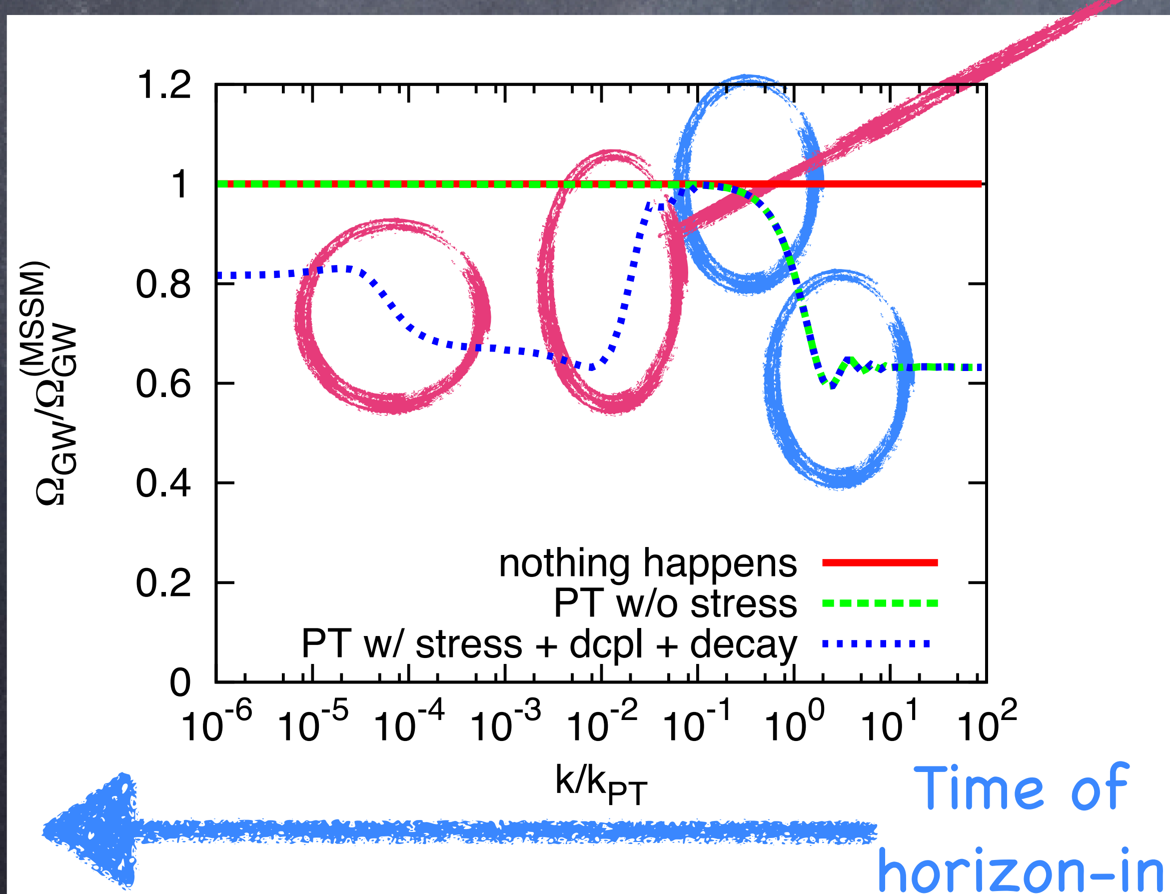
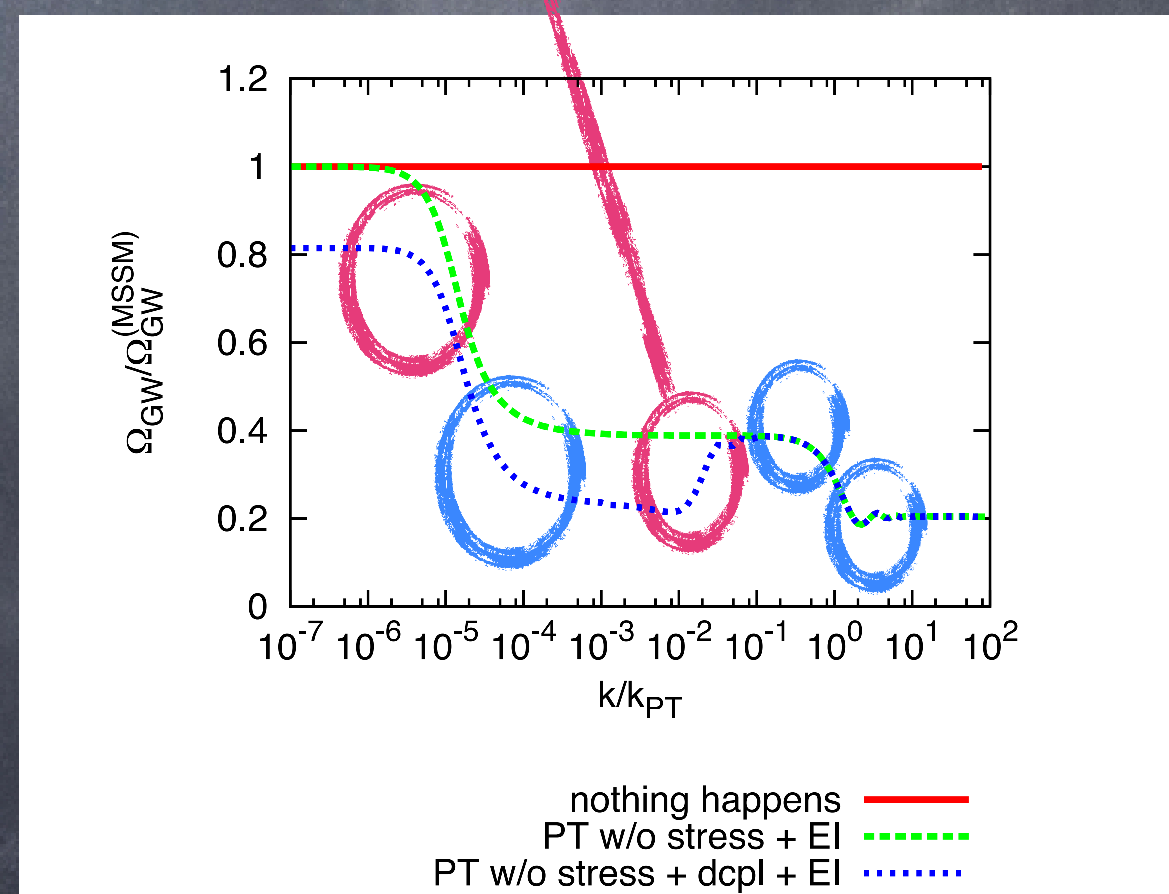
$$\Omega_{\rm GW}(t,k) = \frac{\rho_{\rm GW}(t,k)}{\rho_c(t)}$$

Decouple of axion & saxion





GW spectrum

- Energy density of GWs

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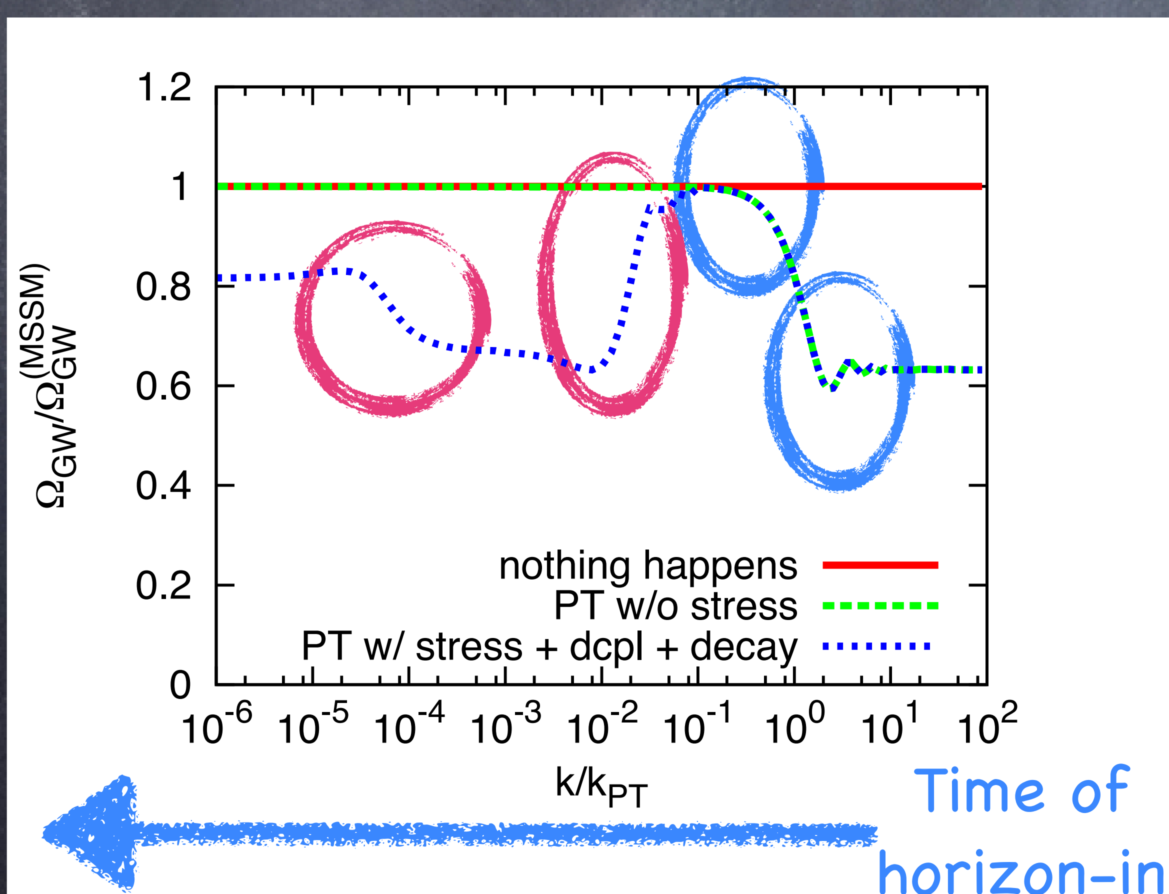

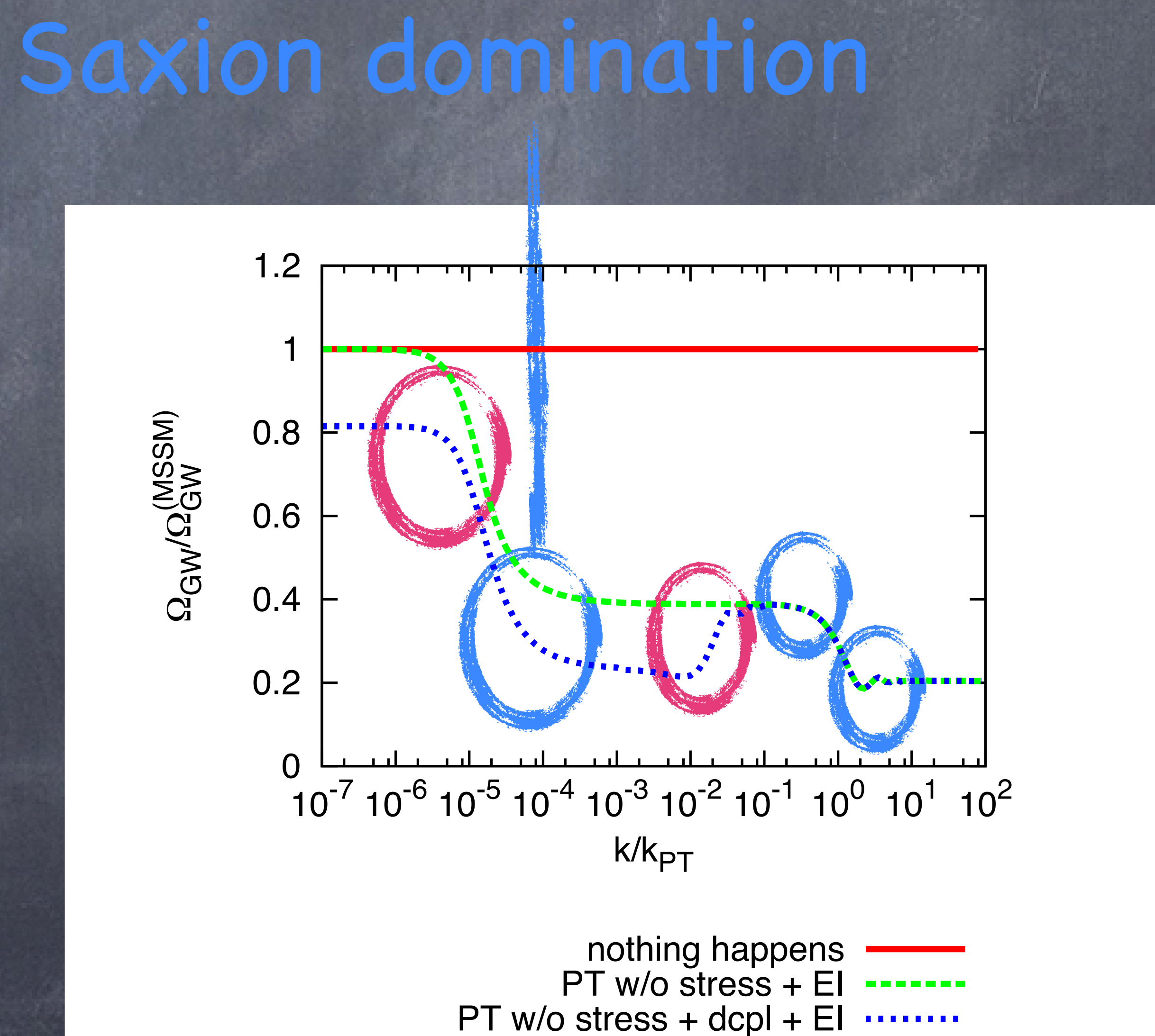

GW spectrum

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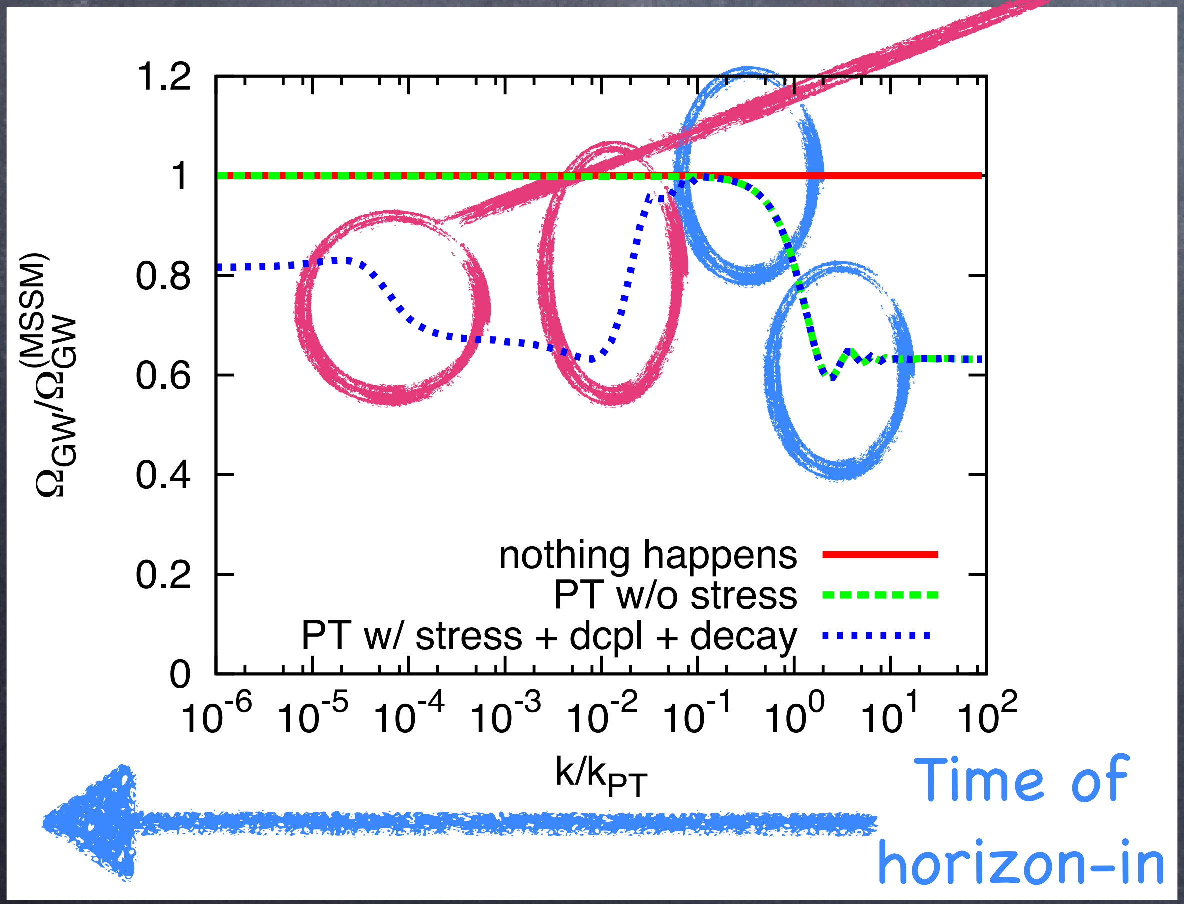
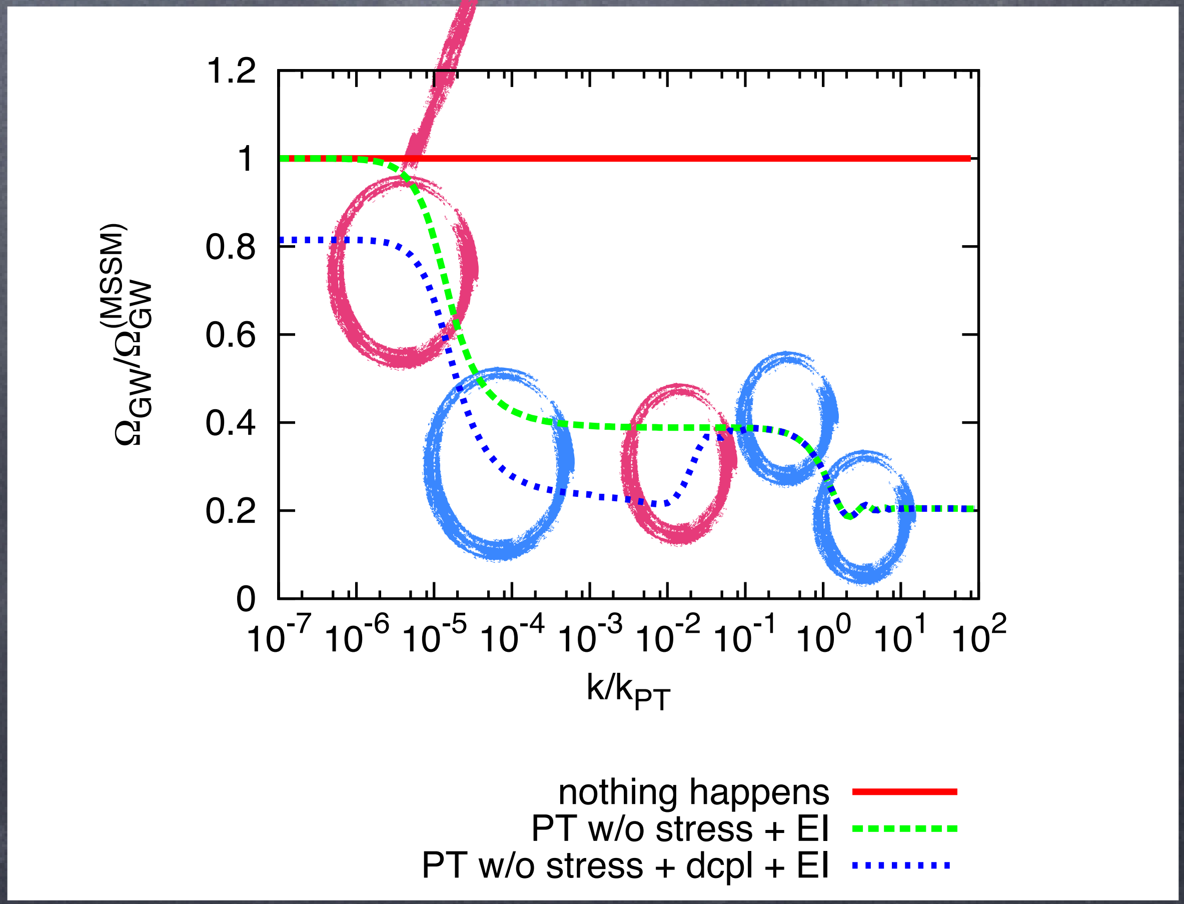
Decay of saxion



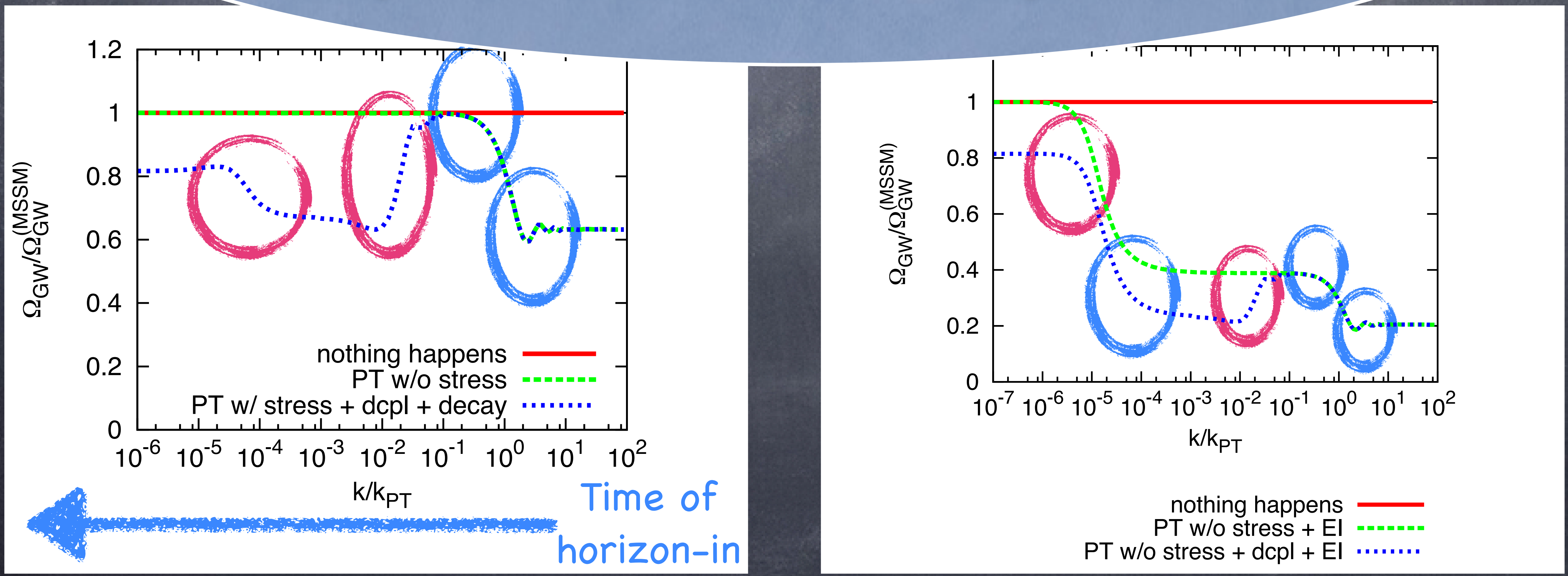


GW spectrum

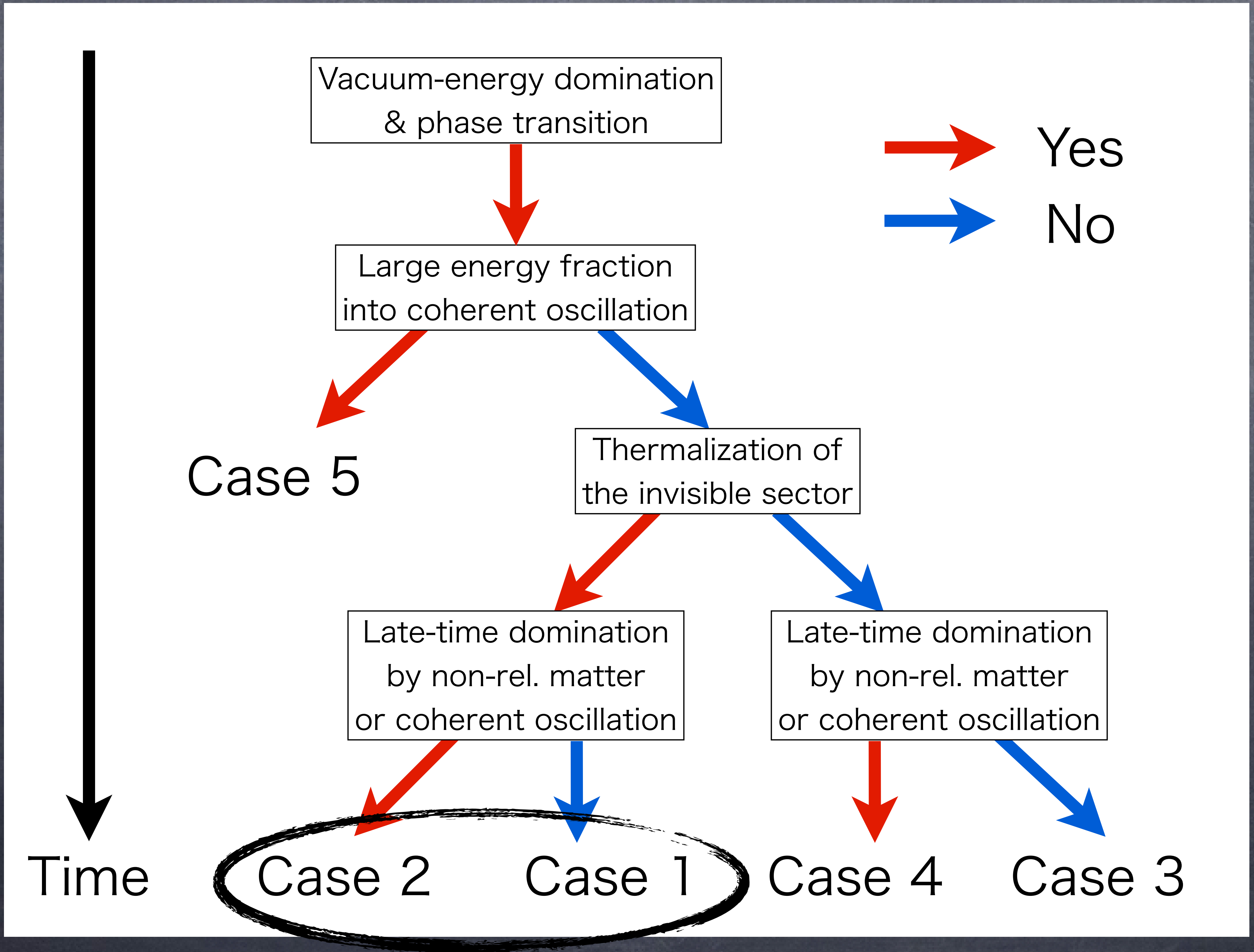
- Energy density of GWs

$\rho_{\rm GW}(t)$

Information on the background evolution & particles of the universe may be imprinted in the GW spectrum

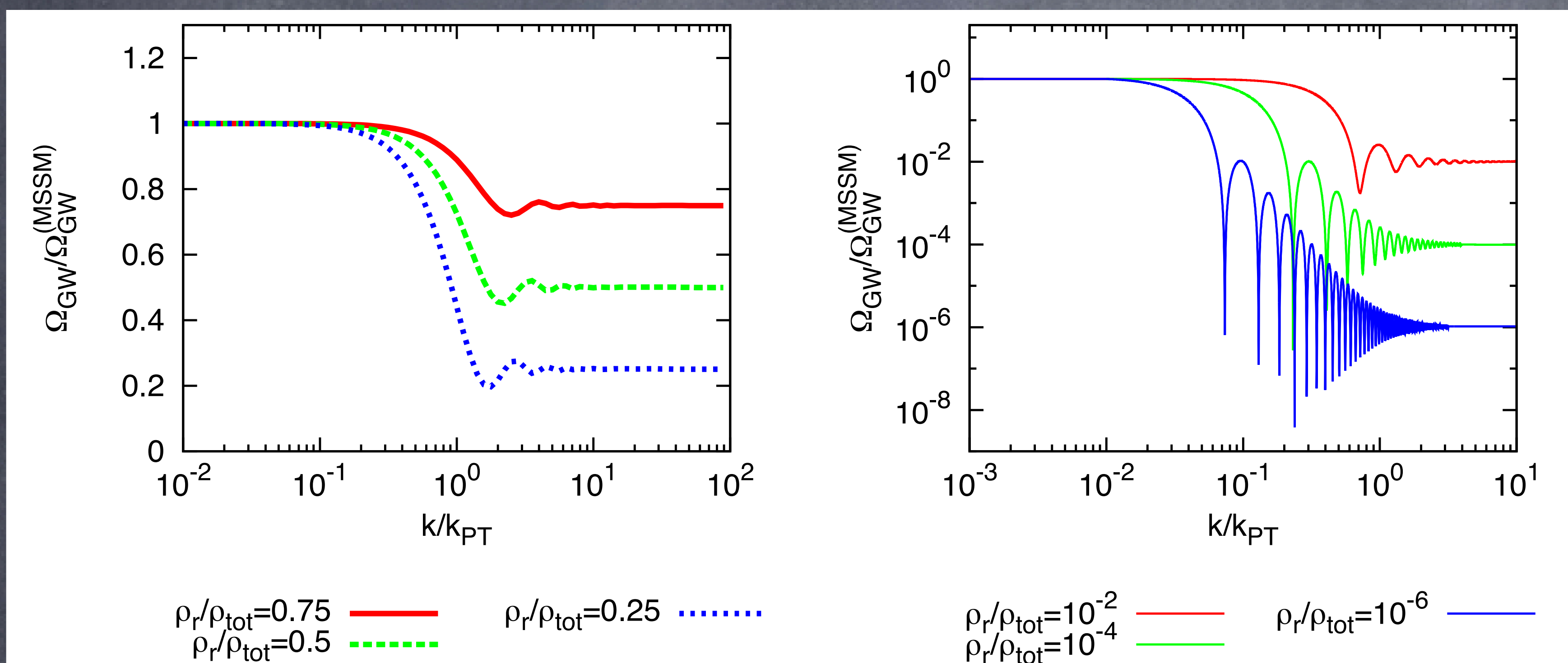


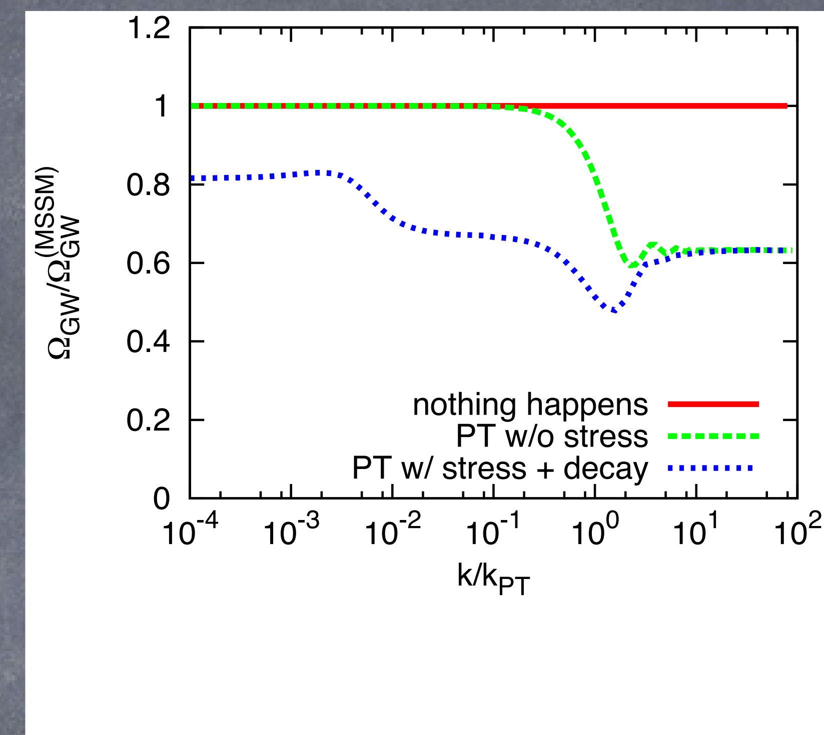
Cases discussed in the paper

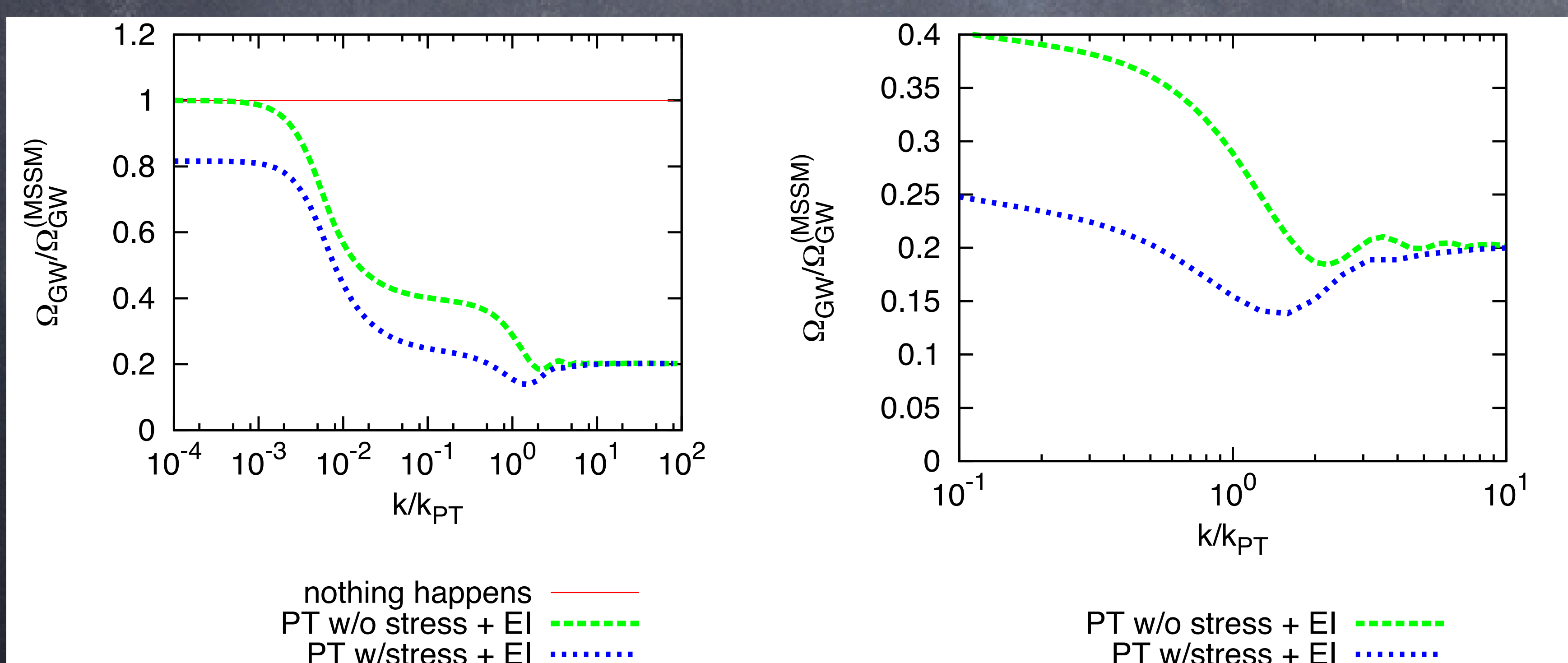


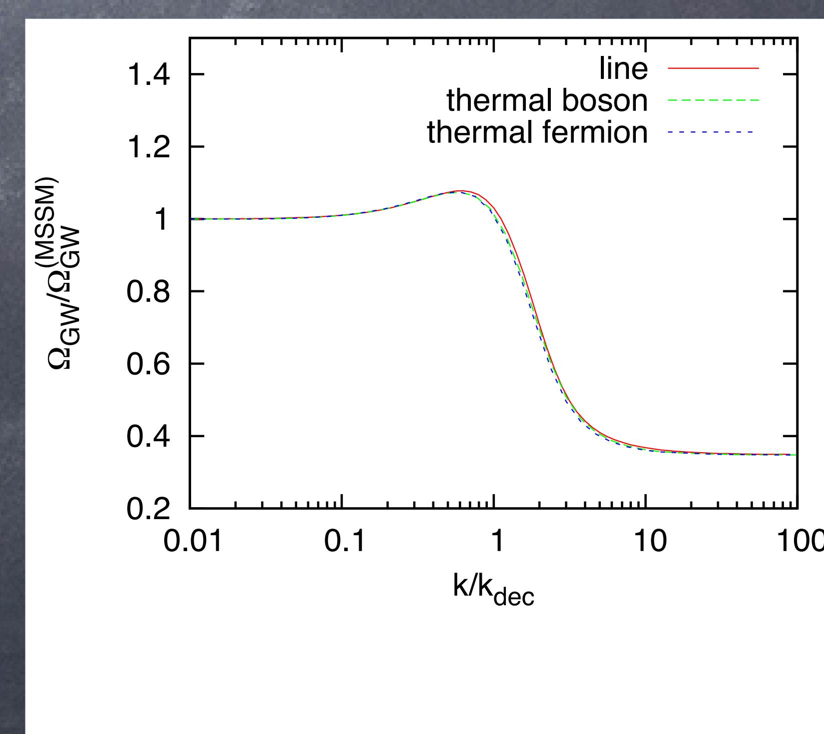
GW spectrum

- Other spectra









Asides

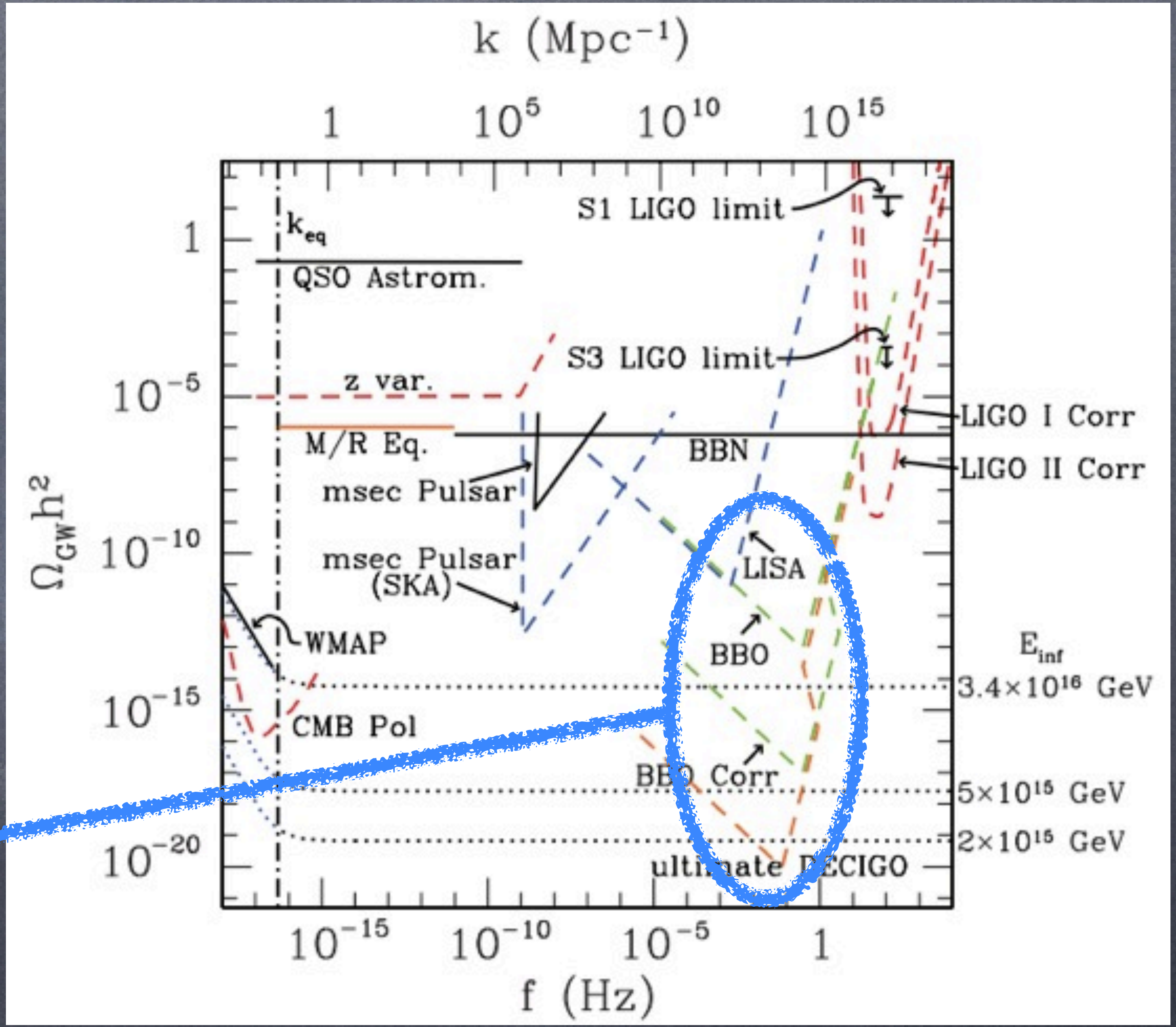
- GWs can probe various physics -

- EOS of neutron star
- Deviation from Einstein gravity
  - Massive gravity, Brans Dicke theory, ...
- "Ultra-high precision cosmology" arXiv:0906.3752
  - $H_0 \sim$ 0.1%, w_0&$w_a \sim$ 0.01&0.1
- Extra dimension
  - $h \propto D_L^{-(d-2)/2}$
- Probe to the "primordial dark age" and beyond
  - Inflation, (p)reheating, EOS of the universe, PT, cosmic strings

Observations

- CMB
  - B-mode
- msec Pulsar
  - SKA
- Ground-based interferometers
  - CLIO, TAMA, KAGRA LIGO, Virgo, ...
- Space interferometers
  - LISA, DECIGO, BBO

T.L.Smith et al. arXiv:0506421



$$\Omega_{\mathrm{GW}}(k) = O(1)\times 10^{-15}\left(\frac{k}{k_0}\right)^{n_t} r\,,\quad r \lesssim 0.1 \qquad f \simeq \frac{T}{10^8[\mathrm{GeV}]}[\mathrm{Hz}]$$

Observations

- Ground-based & Space interferometers

http://granite.phys.s.u-tokyo.ac.jp/ando/JGRG2010/jgrg10_ando_pub.pdf

Summary

Summary

- "Primordial dark age" is interesting
  from the viewpoint of particle physics
  (Especially from that of phase transitions)

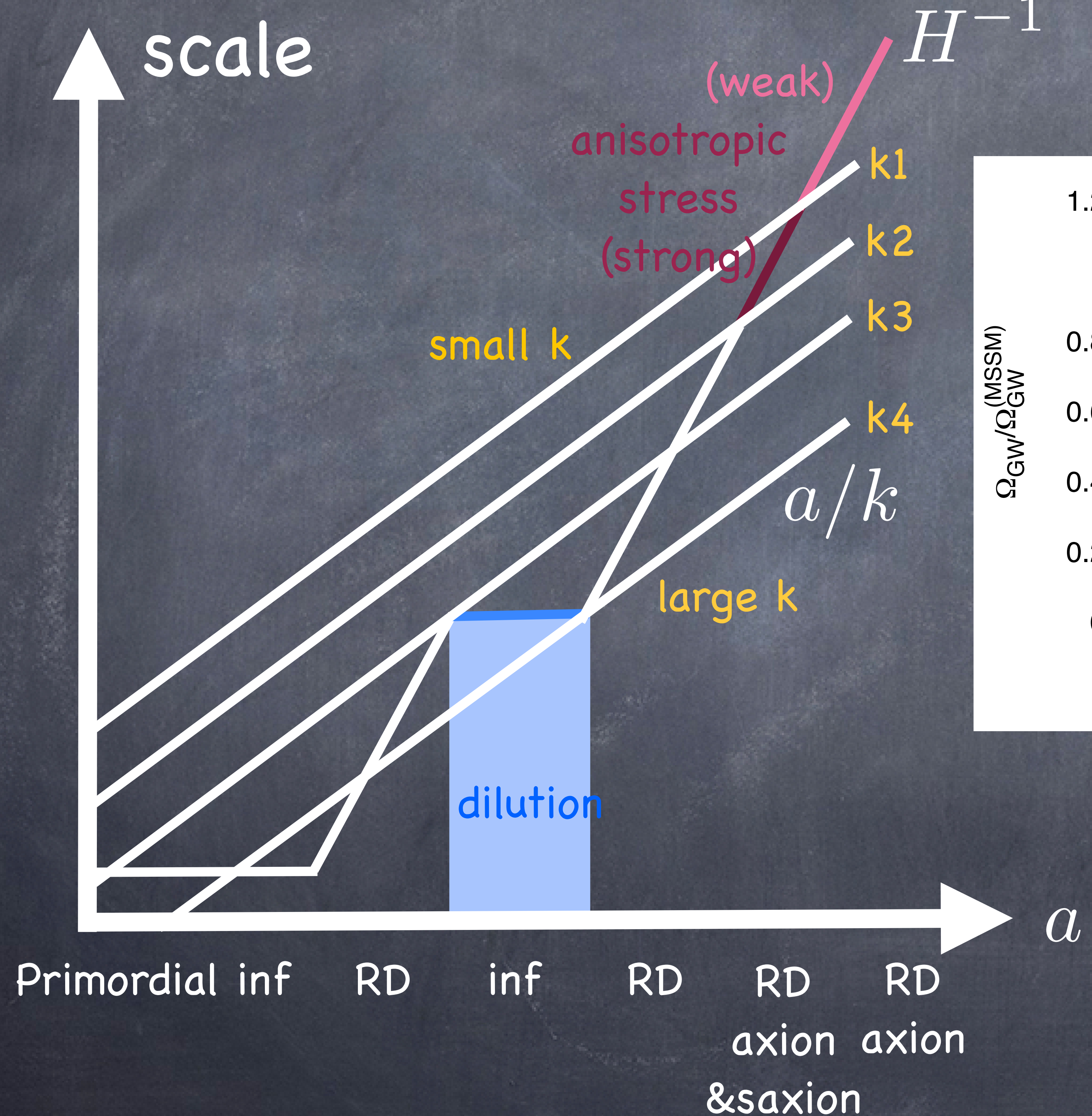
- Thermal "histories" of the age may be imprinted
  in the GW spectrum

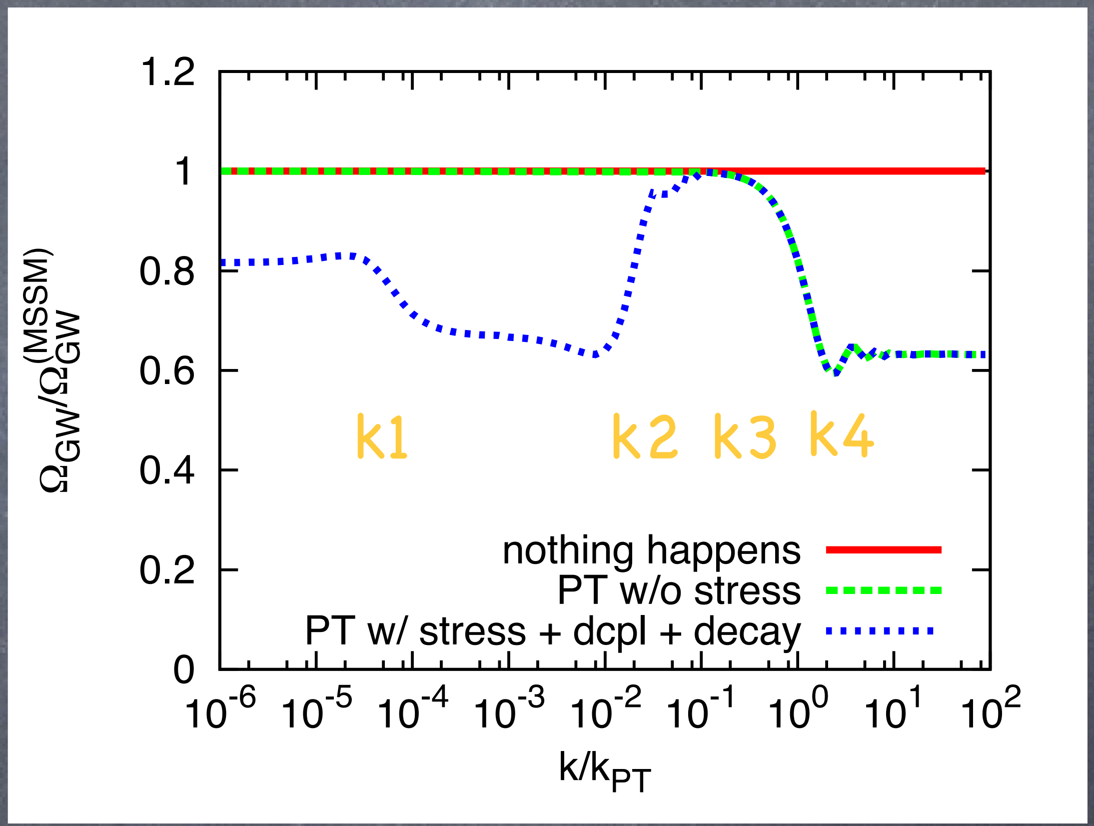
- GWs have the (unparalleled) potential to disclose the age
  in the (far) future

Thank you
for your attention

Backup

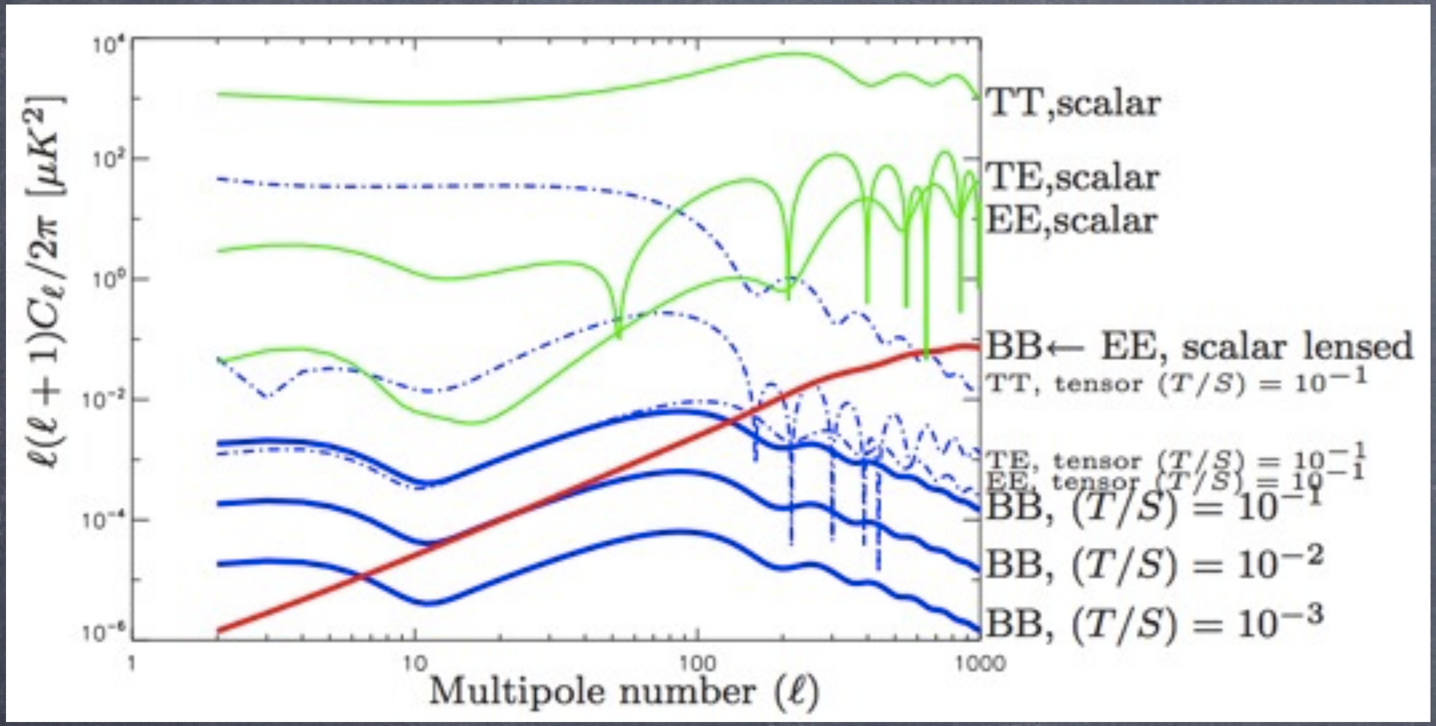
Detail of SUSY PQ model



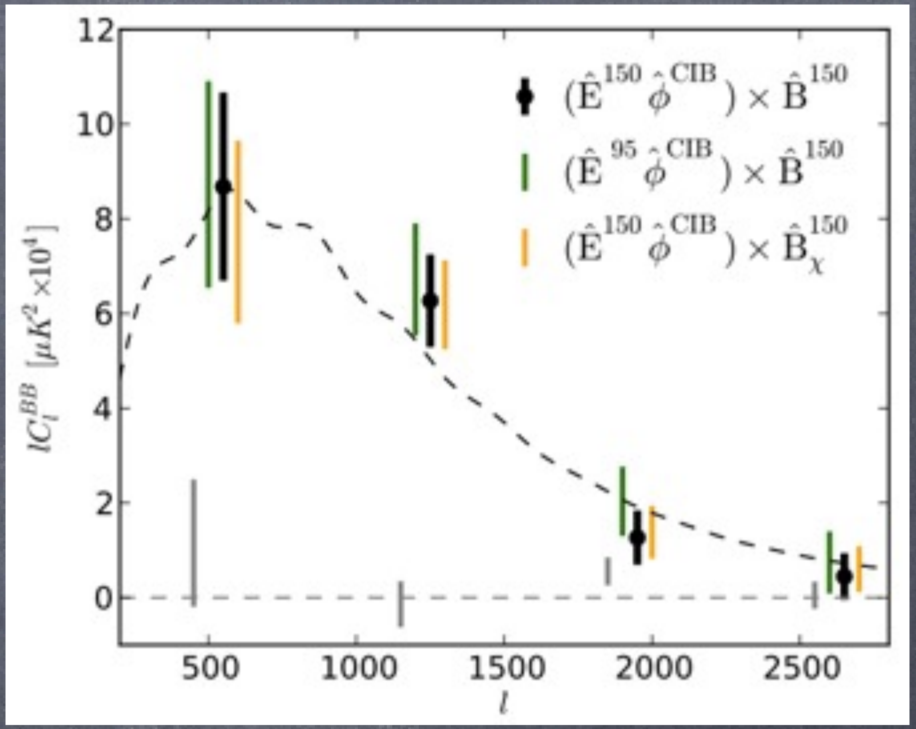


Observations

- CMB
  - B-mode



P.Bernardis et al. arXiv:0808.1881



D.Hanson et al. arXiv:1307.5830

Black : Cross-correlation btw.
SPT-observed B-mode &
B-mode inferred by cosmic
infrared background(500 μm)

Observations

- msec Pulsar

  Rotational period = msec

  GWs cause the signal to vary by O(10) ns

  e.g. GWs with 10^{-8} Hz

    The timing of the pulse changes by O(10) ns

    btw. August & February

Observations

- Ground-based interferometers

TAMA : Mitaka, Japan / 1st

CLIO : Kamioka, Japan / 1st

KAGRA : Kamioka, Japan / 2nd / 3km arms / Observation 2017-? / NS binary 10yr^{-1}

LIGO : Hanford & Louisiana, USA / 1st->2nd /

Virgo : Pisa, Italy / 3km arms / French-Italian / 1st->2nd

GEO600 : Hanover, Germany / 600m arms / 1st->2nd

Observations

- Space interferometers

  LISA : NASA, ESA

  (…"Funding shortage")

  DECIGO : Japan

  BBO (Big bang observer) : NASA

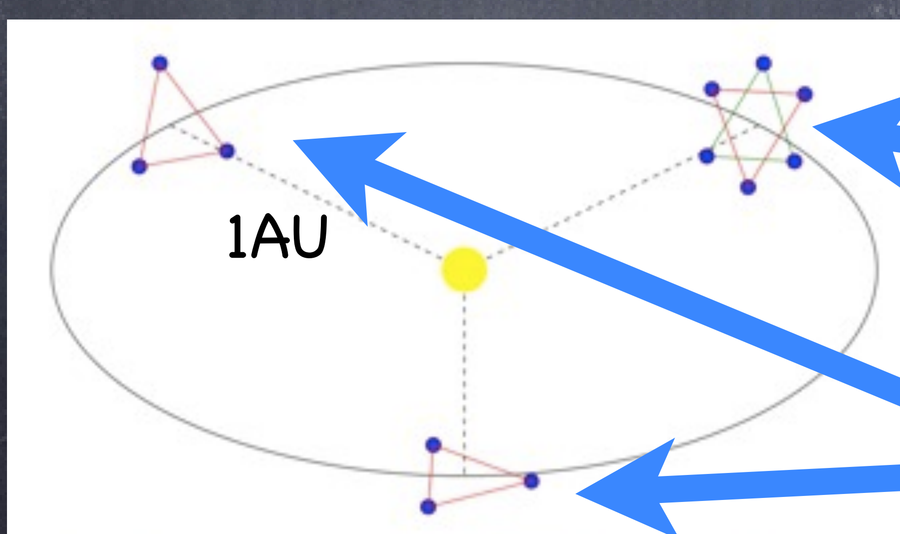
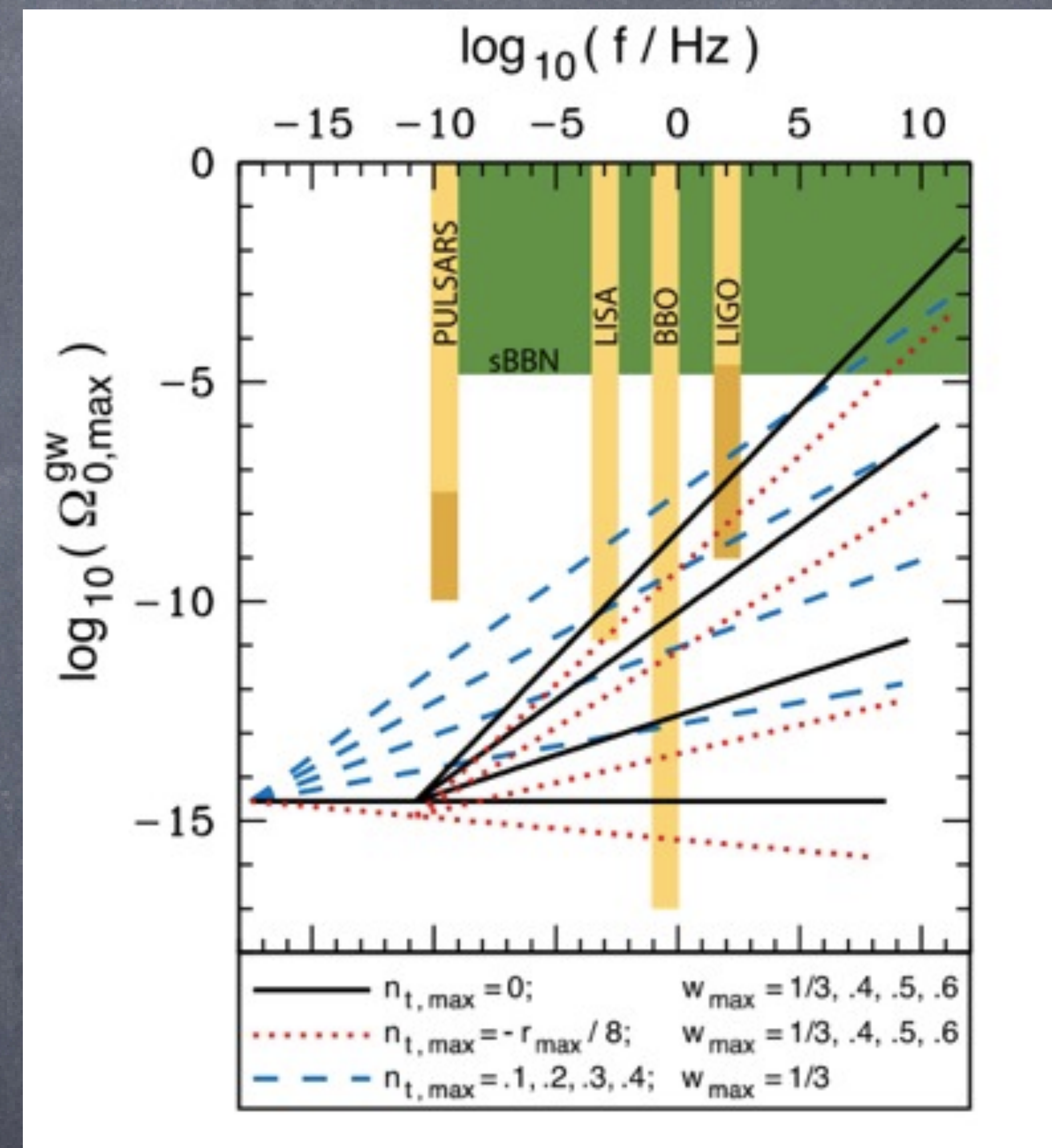


FIG. 1: The proposed orbital configuration of the Big Bang Observer.

Amplitude sensitivity

Direction sensitivity

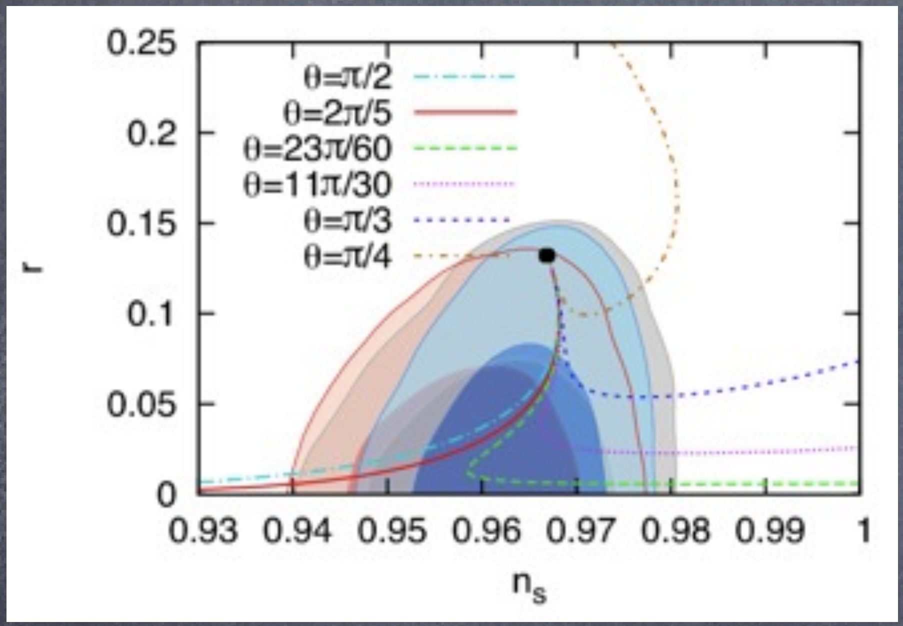
J.Crowder & N.J.Cornish arXiv:gr-qc/0506015



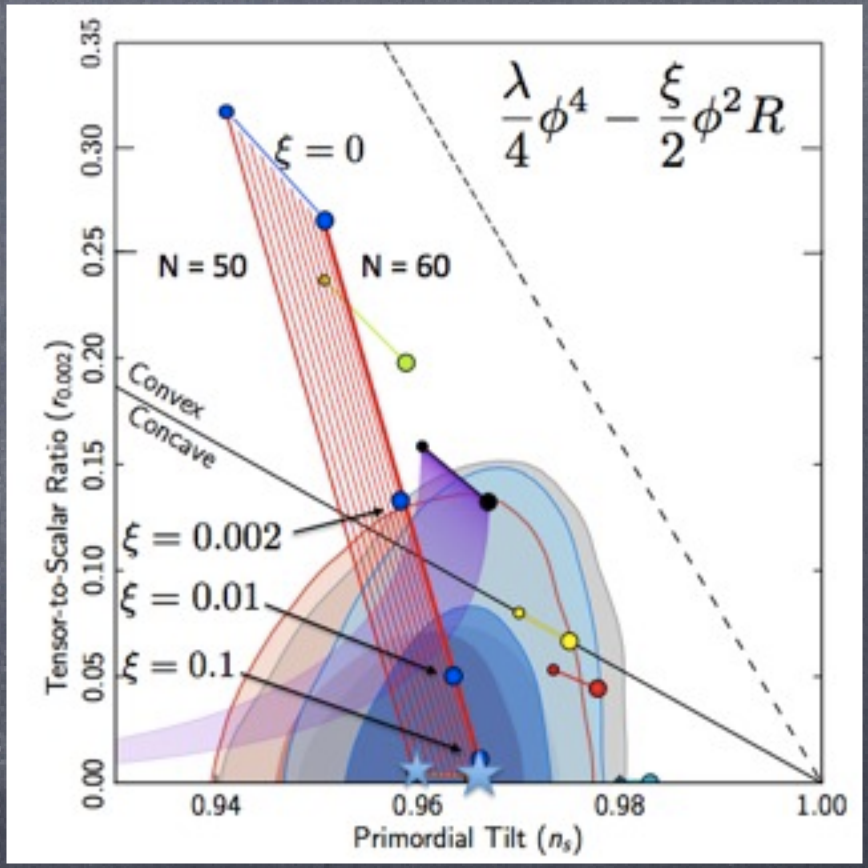
L.A.Boyle & A.Buonanno arXiv:0708.2279

Models for inflation

- Those predict (relatively) high tensor-to-scalar ratio
  - Polynomial inflation K.Nakayama et al. arXiv:1305.5099



  - Higgs inflation $r \sim 3 \times 10^{-3}$

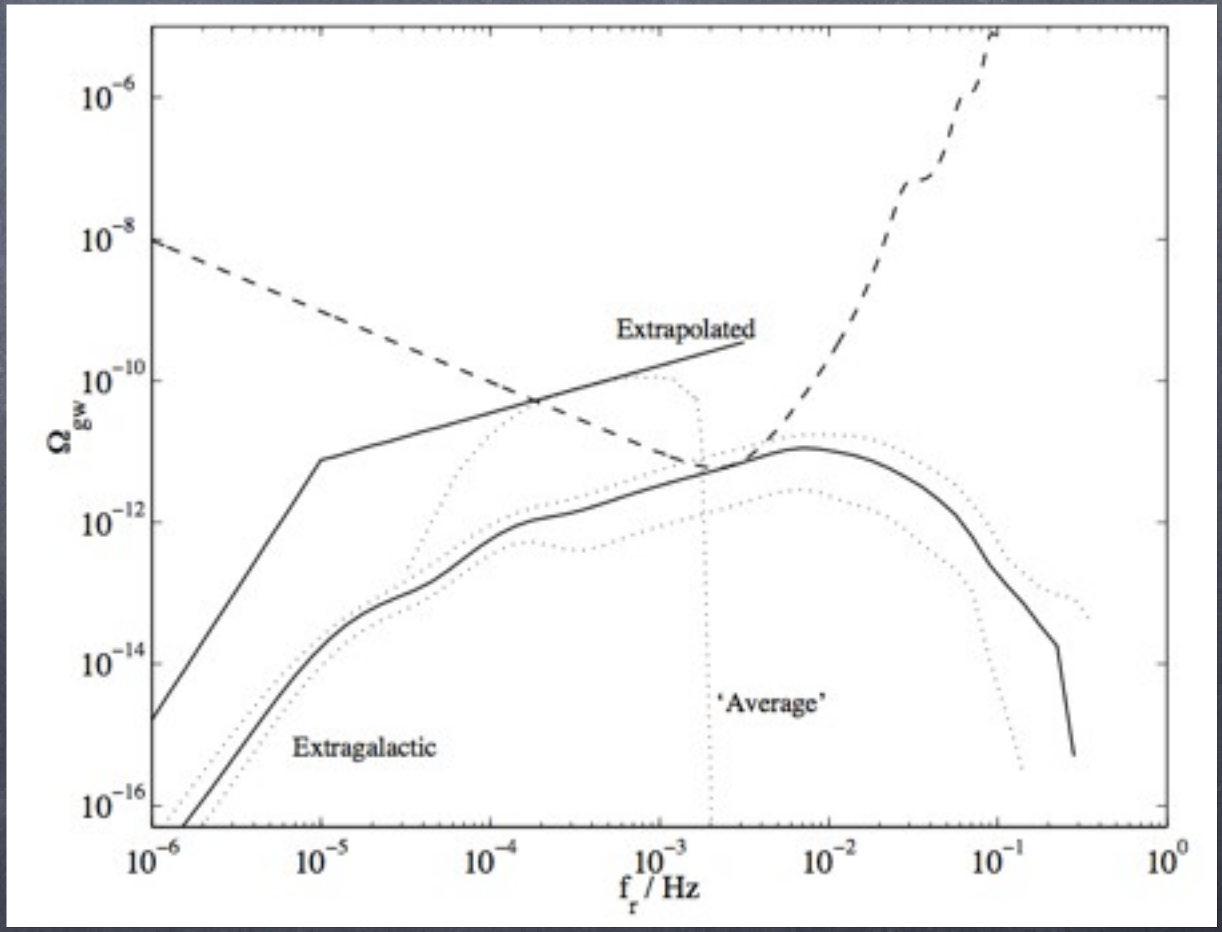


  - Canonical superconformal inflation R.Kallosh et al. arXiv:1306.3211

"Generalization of conformal & phi4 & Starobinsky in SUGRA framework"

Astrophysical foregrounds

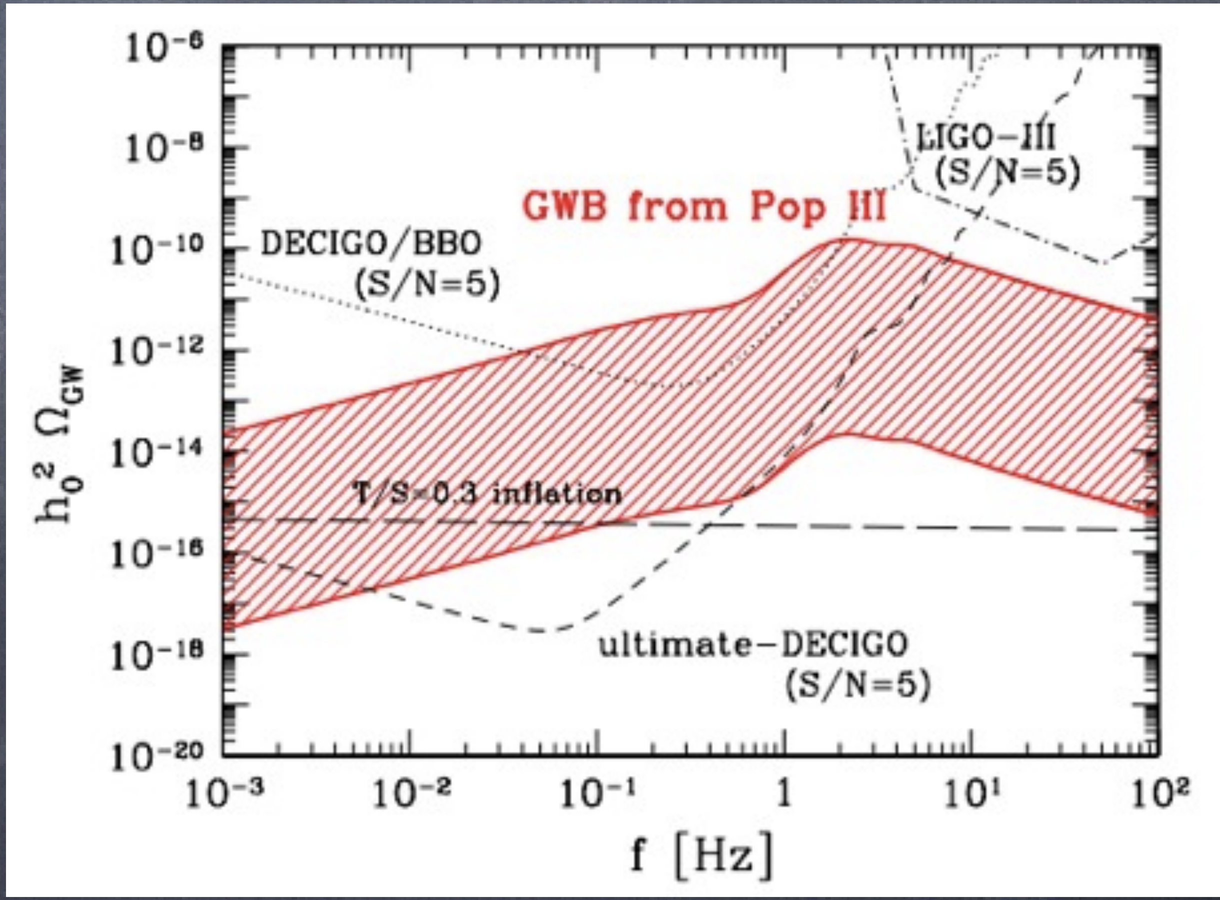
- White dwarf binary
  - Merger of 2 WDs generates GWs
  - Stochastic background
    - $\rightarrow$ Hard to remove
  - Rapid damp in > 0.01Hz,
    and vanishes at 0.25Hz



A.J.Farmer & E.S.Phinney arXiv:astro-ph/0304393

Astrophysical foregrounds

- Pop III stars
  - Collapse of first stars generates GWs
  - Star formation rate at early epoch is poorly-known
  - Removable



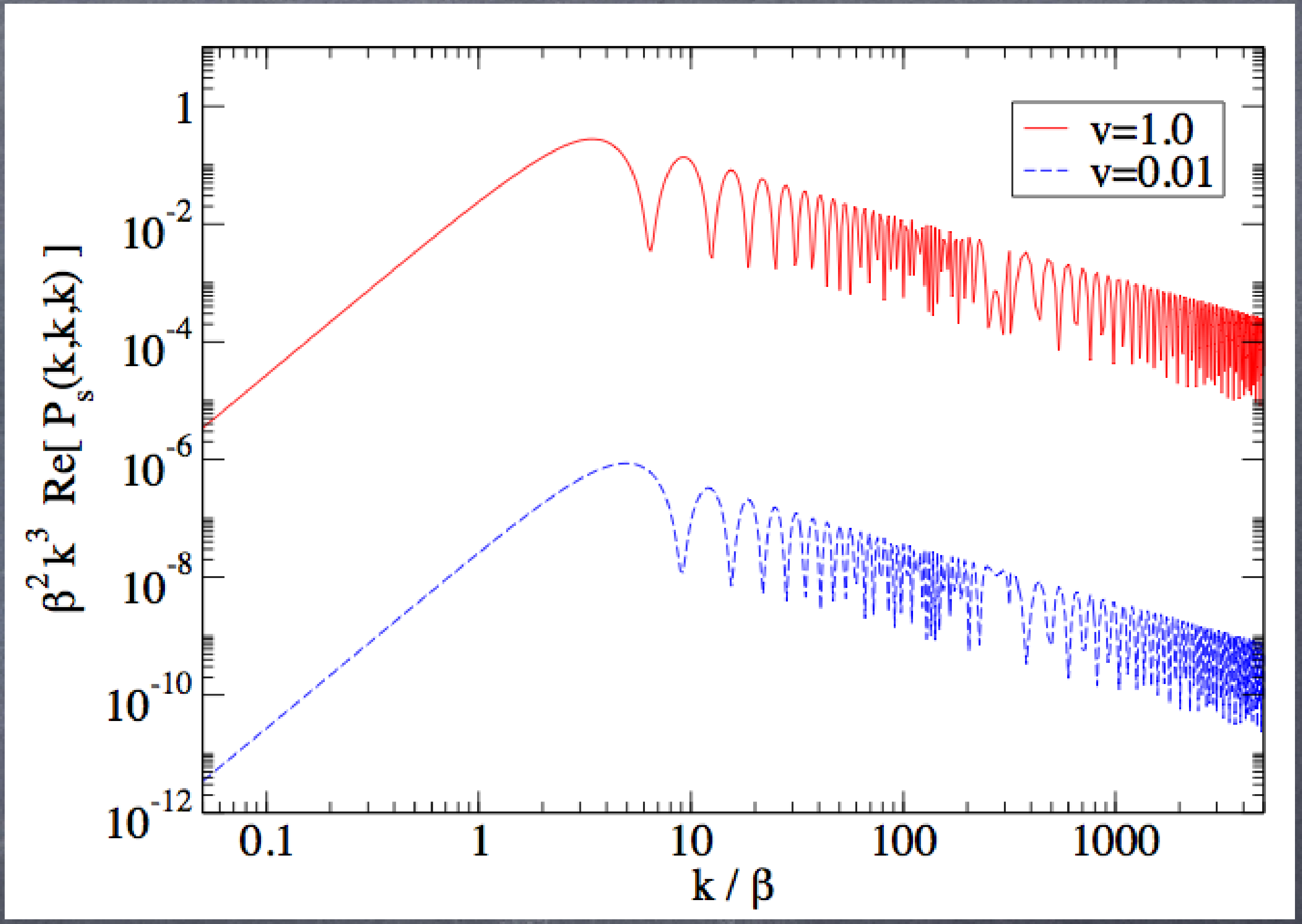
Y.Suwa et al. arXiv:0706.3495

Bubble collision

$$\Omega_{\rm GW} \sim 1\times10^{-5}\times\left(\frac{\rho_{\rm vac}}{\rho_{\rm tot}}\right)^2\left(\frac{k_{\rm PT}}{k_{\rm peak}}\right)^5$$

$$k_{\rm PT}\simeq10^{-2}k_{\rm peak}$$

$$\Omega_{\rm GW} \sim 1\times10^{-15}\times\left(\frac{\rho_{\rm vac}}{\rho_{\rm tot}}\right)^2$$



C.Caprini et al. arXiv:0901.1661