GRAVITATIONAL WAVE SIGNATURES OF REHEATING

Based on arXiv:2305.09712
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5/18/2023 The Mitchell Conference

Chronology of the Universe

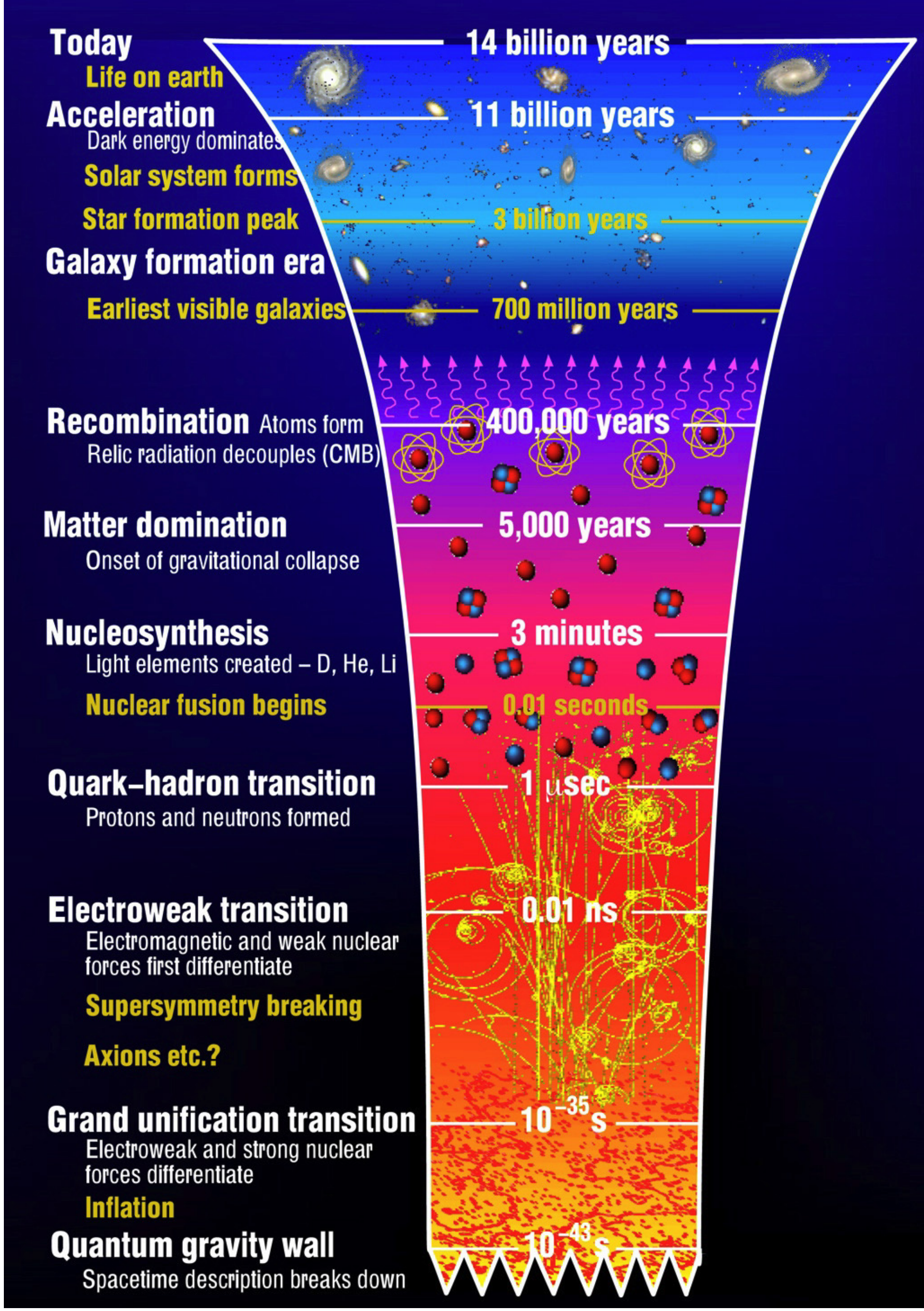

Image from https://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php

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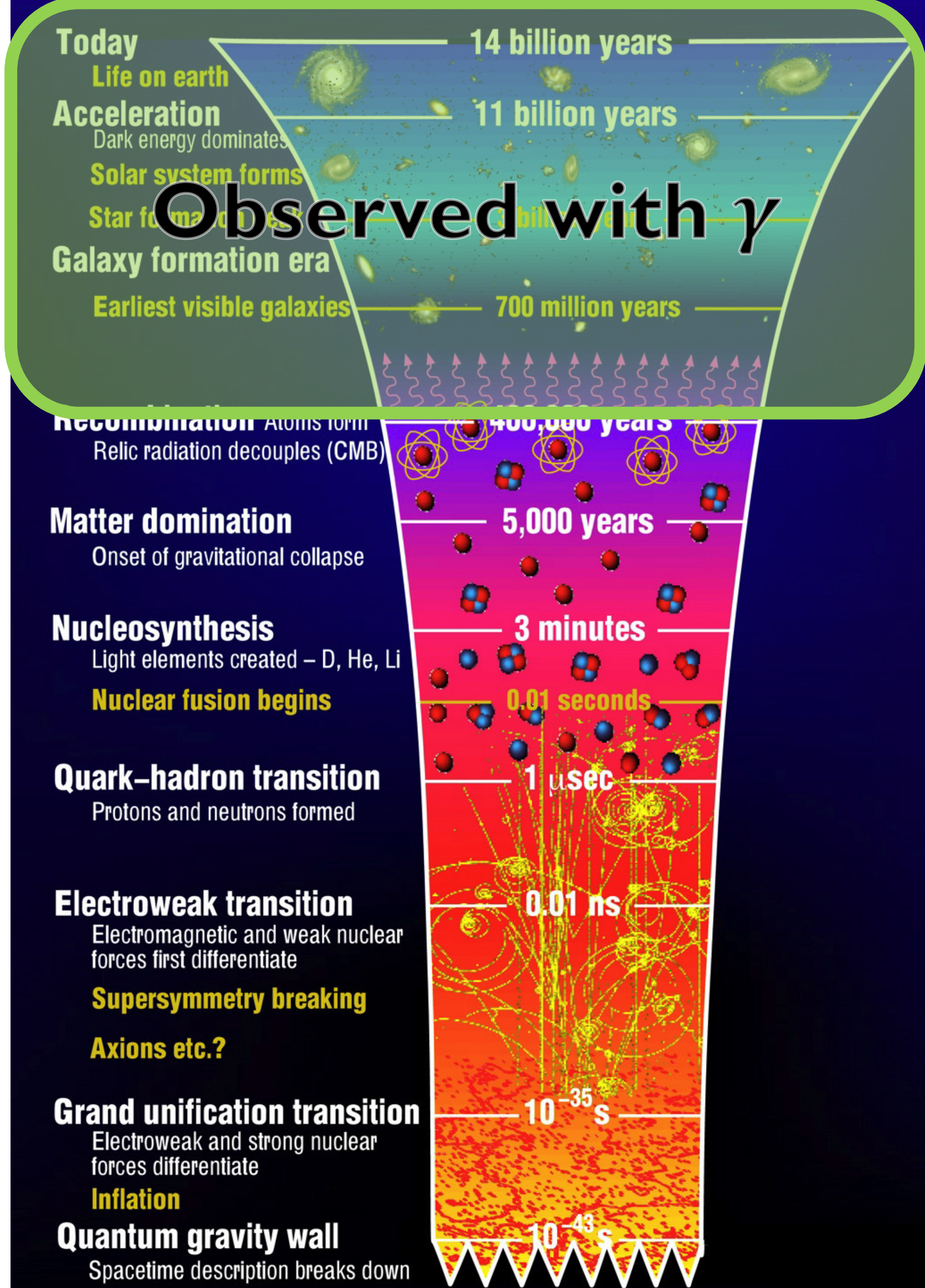

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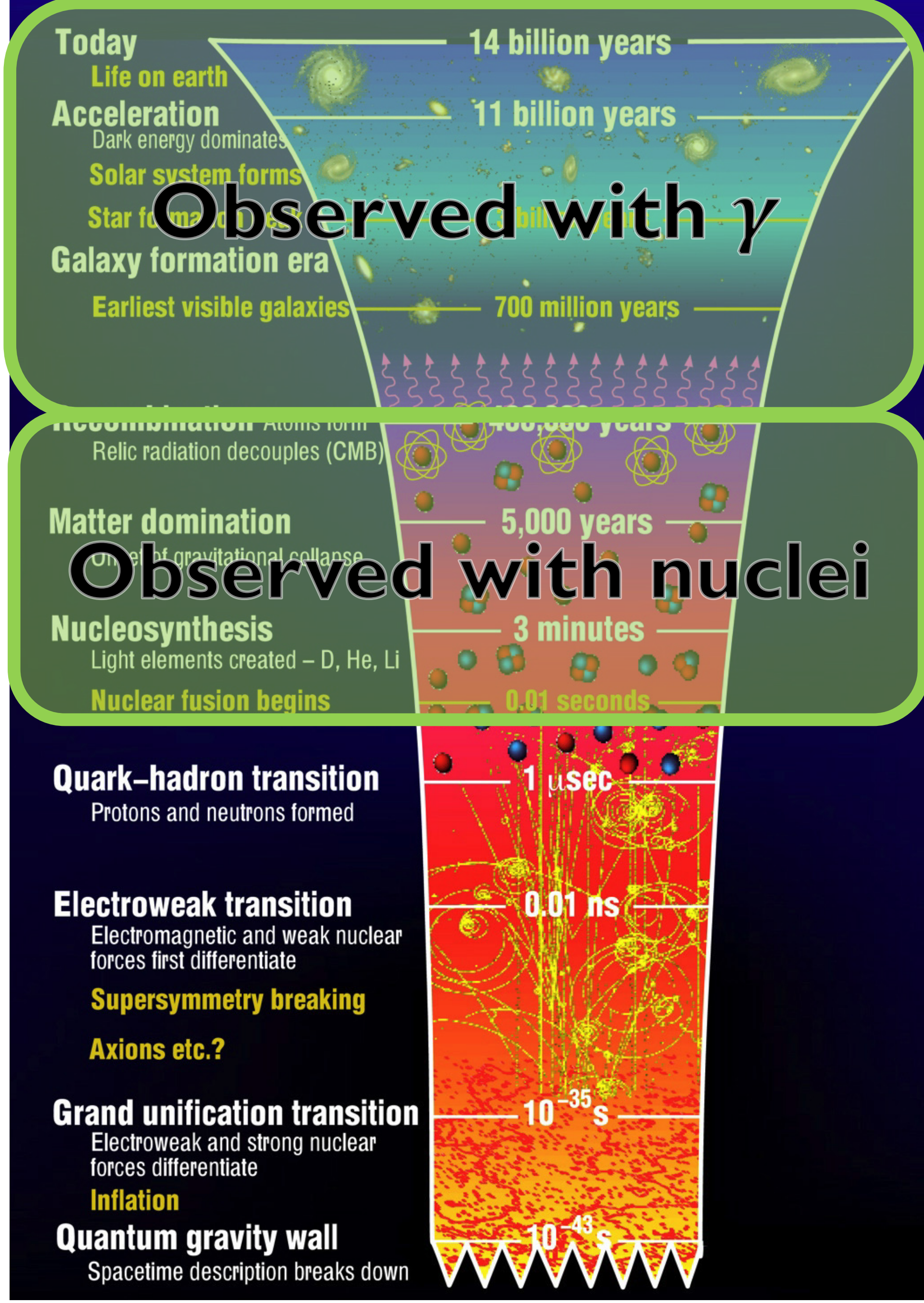

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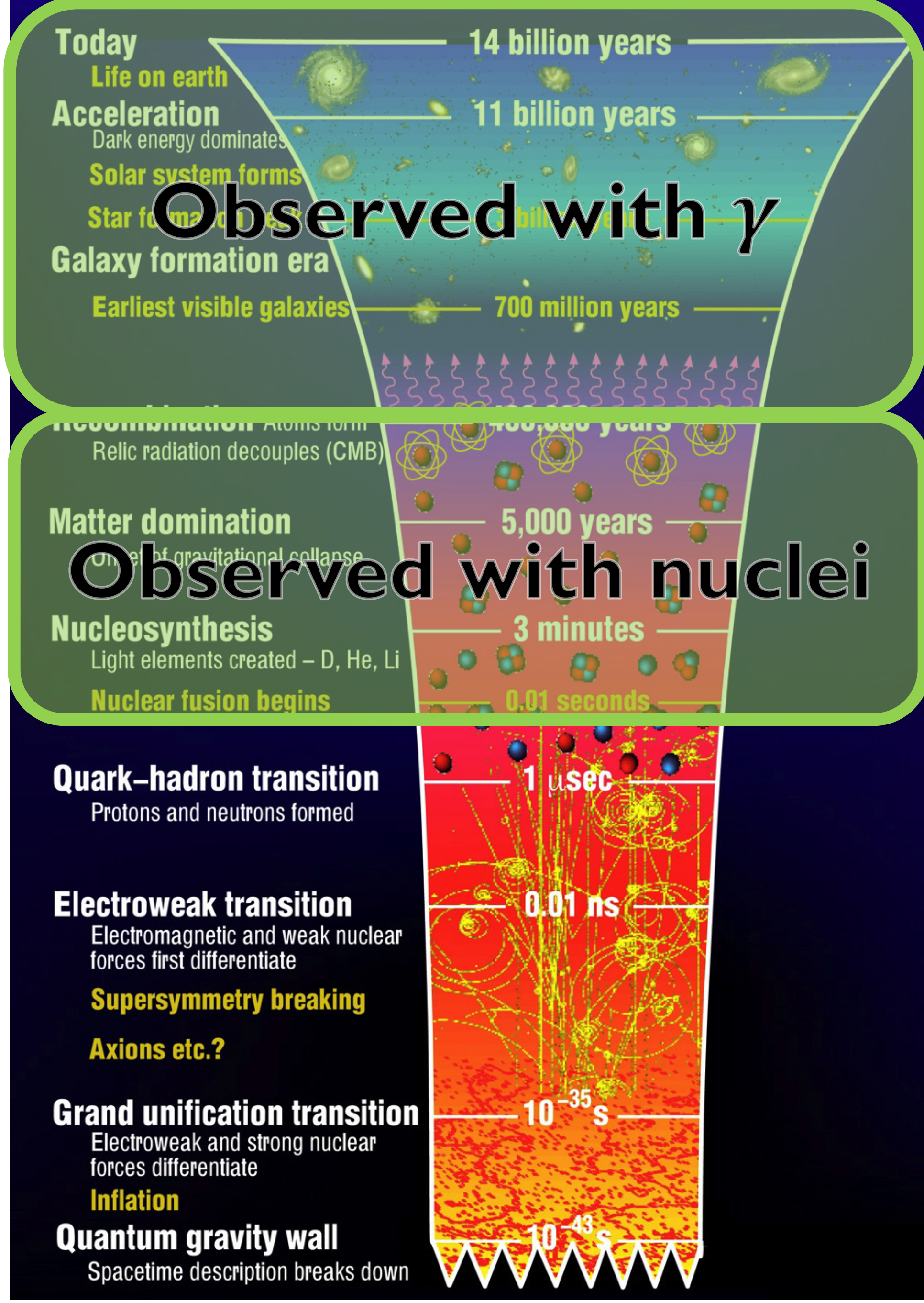
Chronology of the Universe

- We have observational data only after BBN



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Chronology of the Universe

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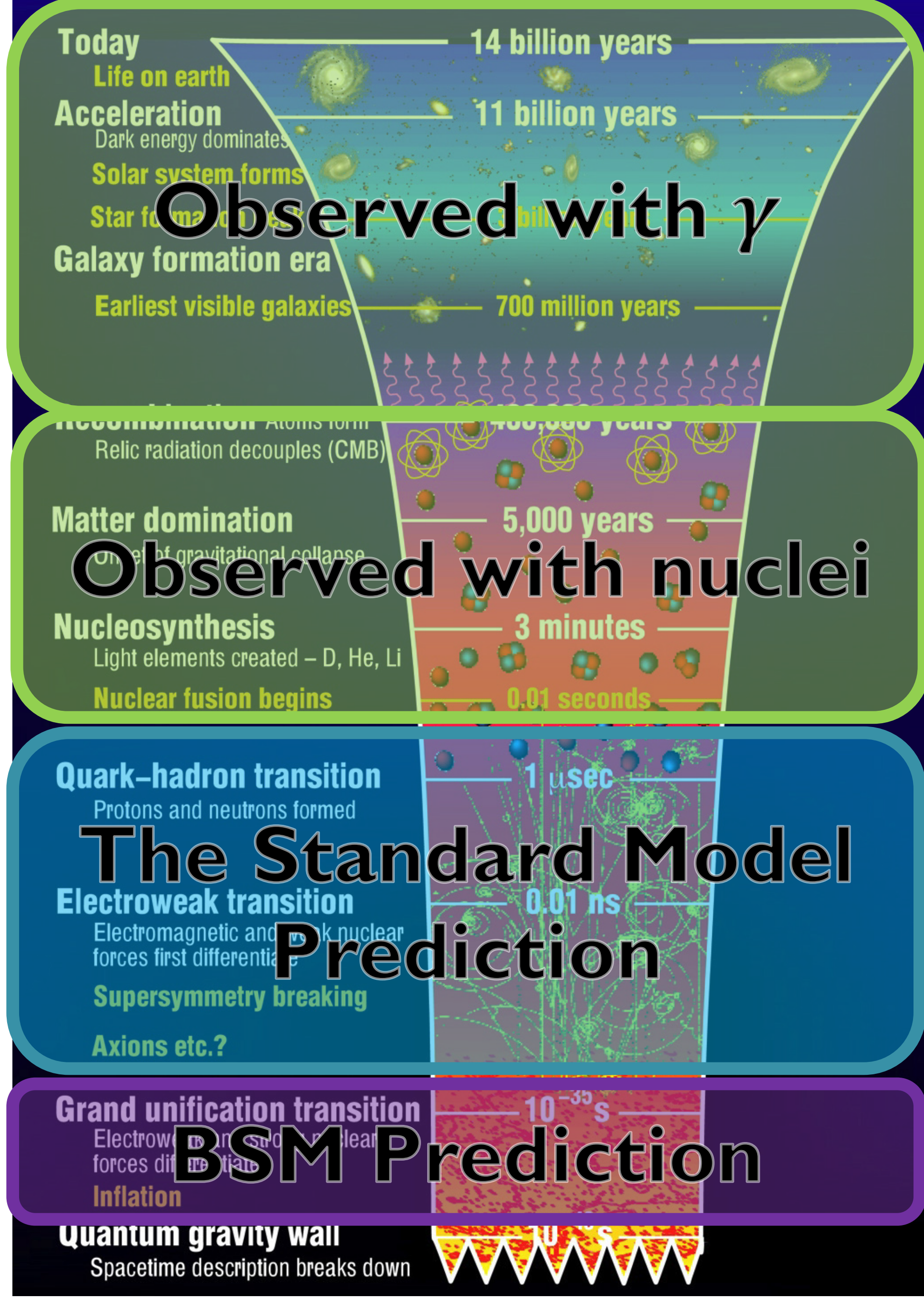

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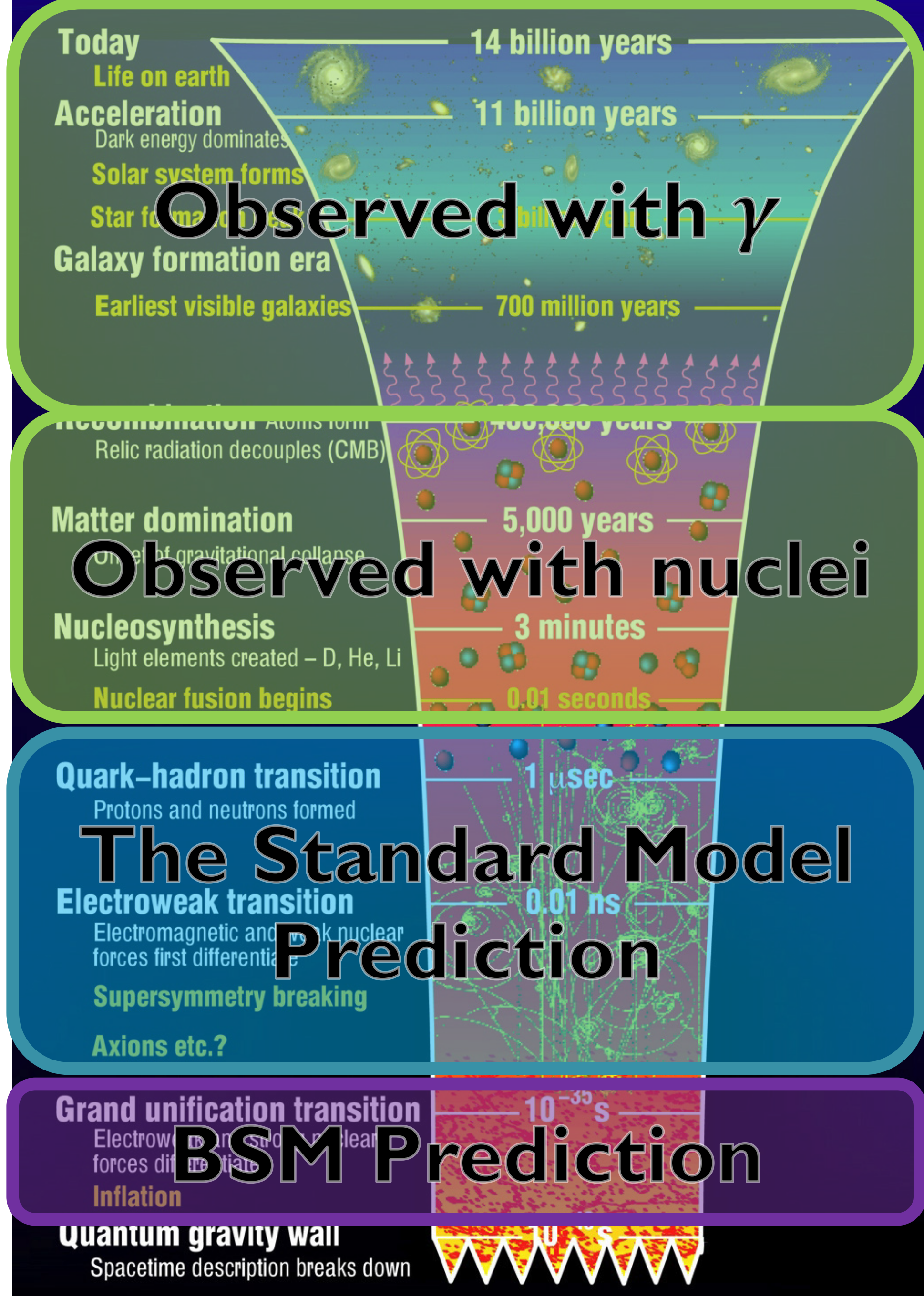
Chronology of the Universe

- We have observational data only after BBN
- How do we probe earlier Universe?



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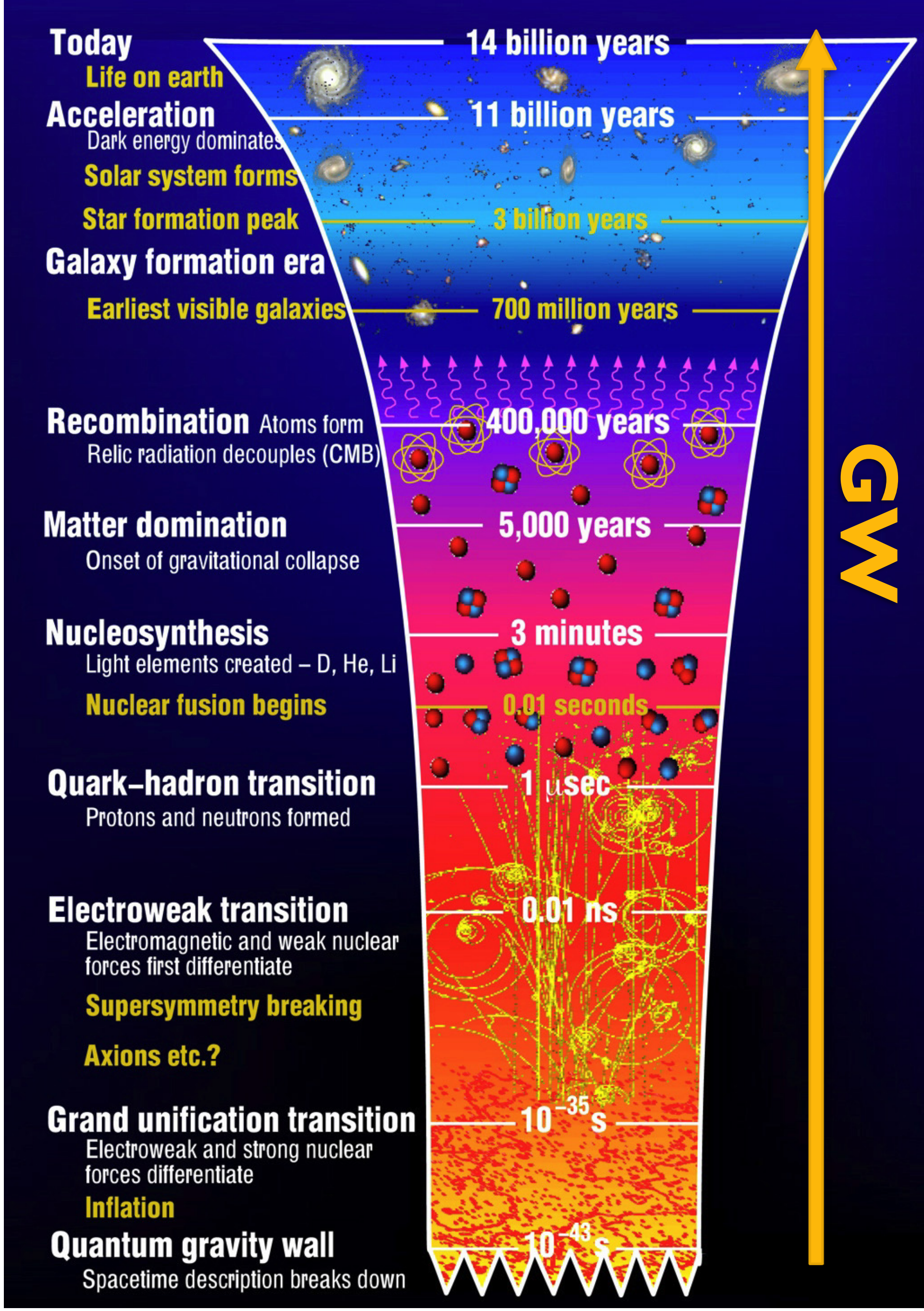
Gravitational Waves!

- Universe is transparent to GW for all time
- We can probe earlier time if GW are produced from some early-time events



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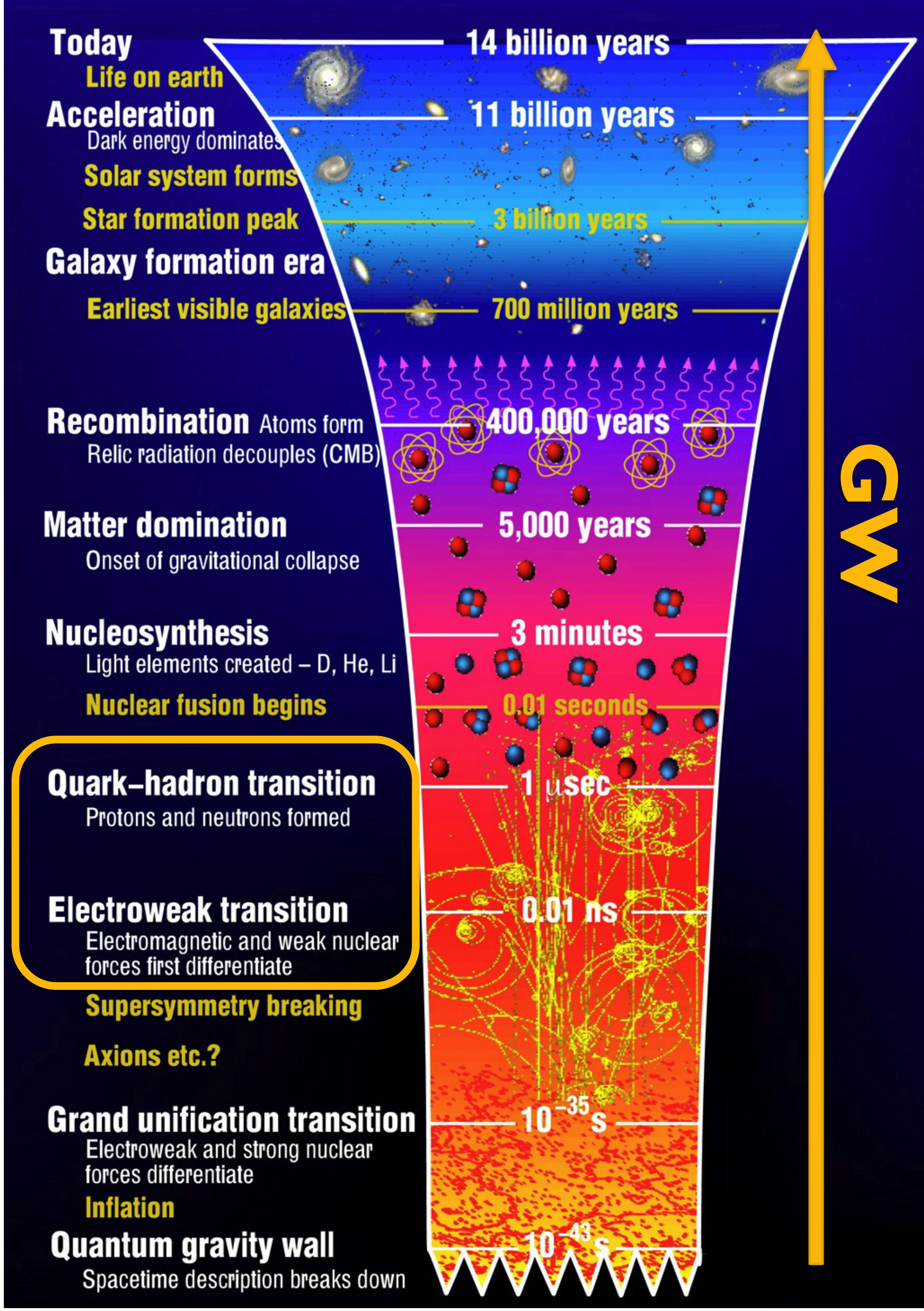
Gravitational Waves!

- Universe is transparent to GW for all time
- We can probe earlier time if GW are produced from some early-time events
- e.g. 1st order phase transitions



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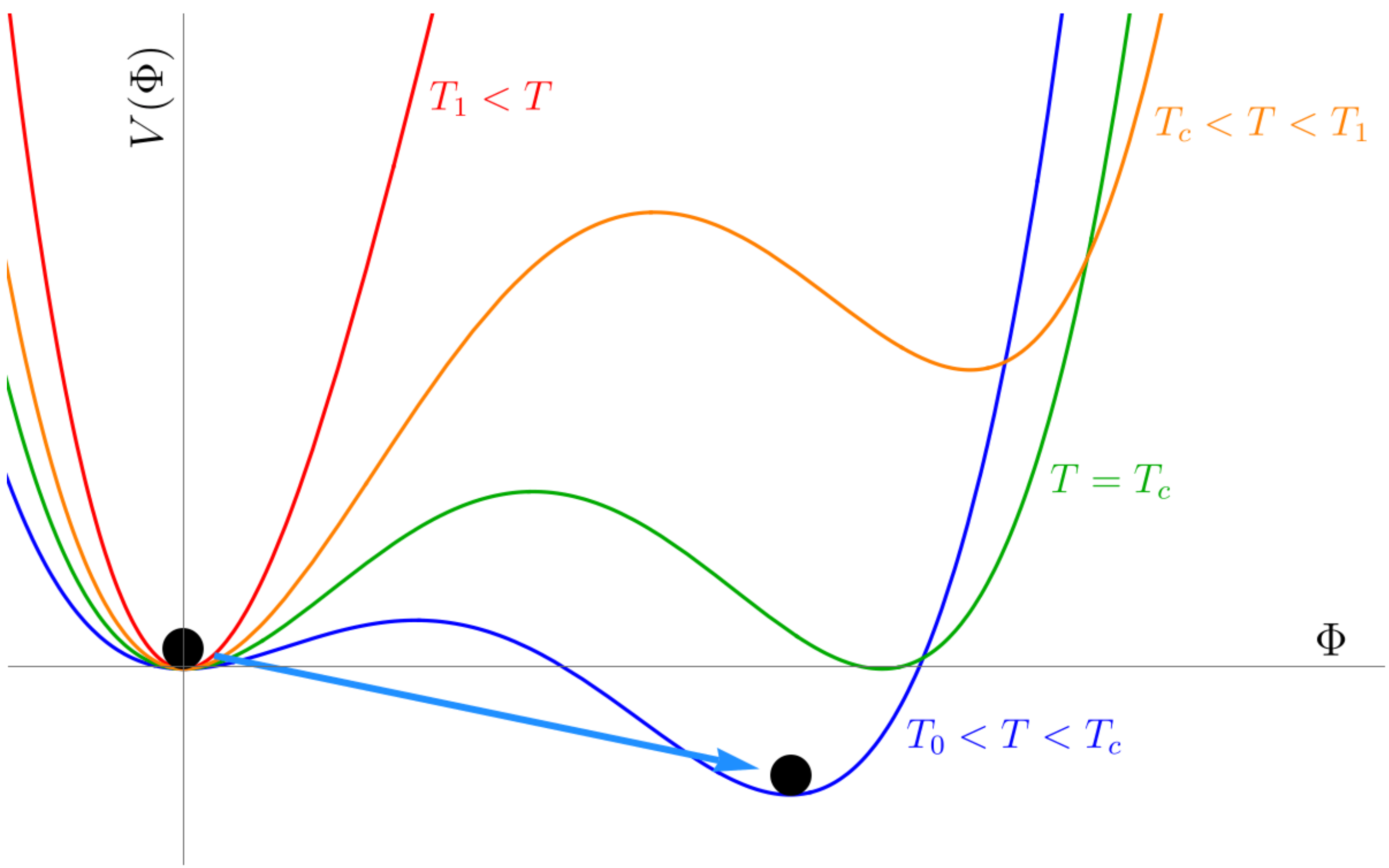
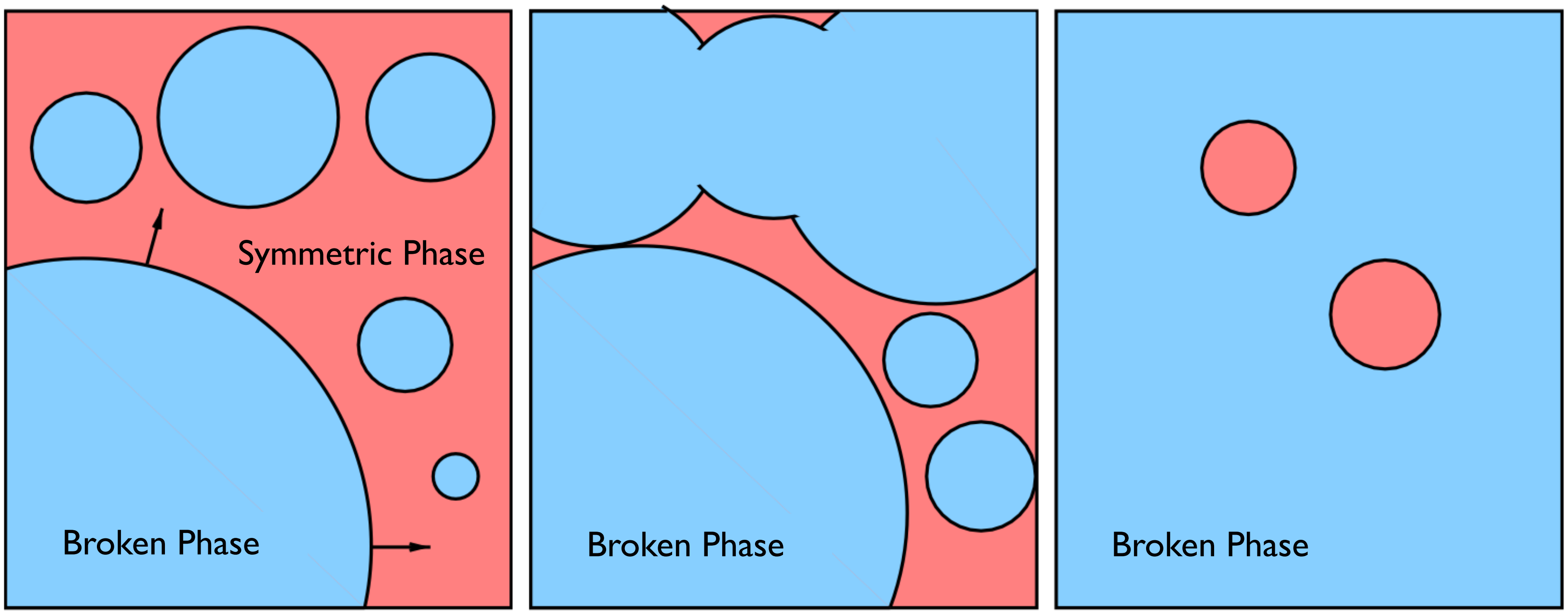
GW from 1st order PT



GW from 1st order PT



- GW are produced from bubble dynamics (bubble collisions, sound waves, and turbulences)

Image from arXiv:2008.09136

If we have a 1st order PT at T_c,

it must occur twice:

If we have a 1st order PT at T_c,

it must occur twice:

once during the reheating period

and once again during

the subsequent cooling period

Toy Model for Reheating

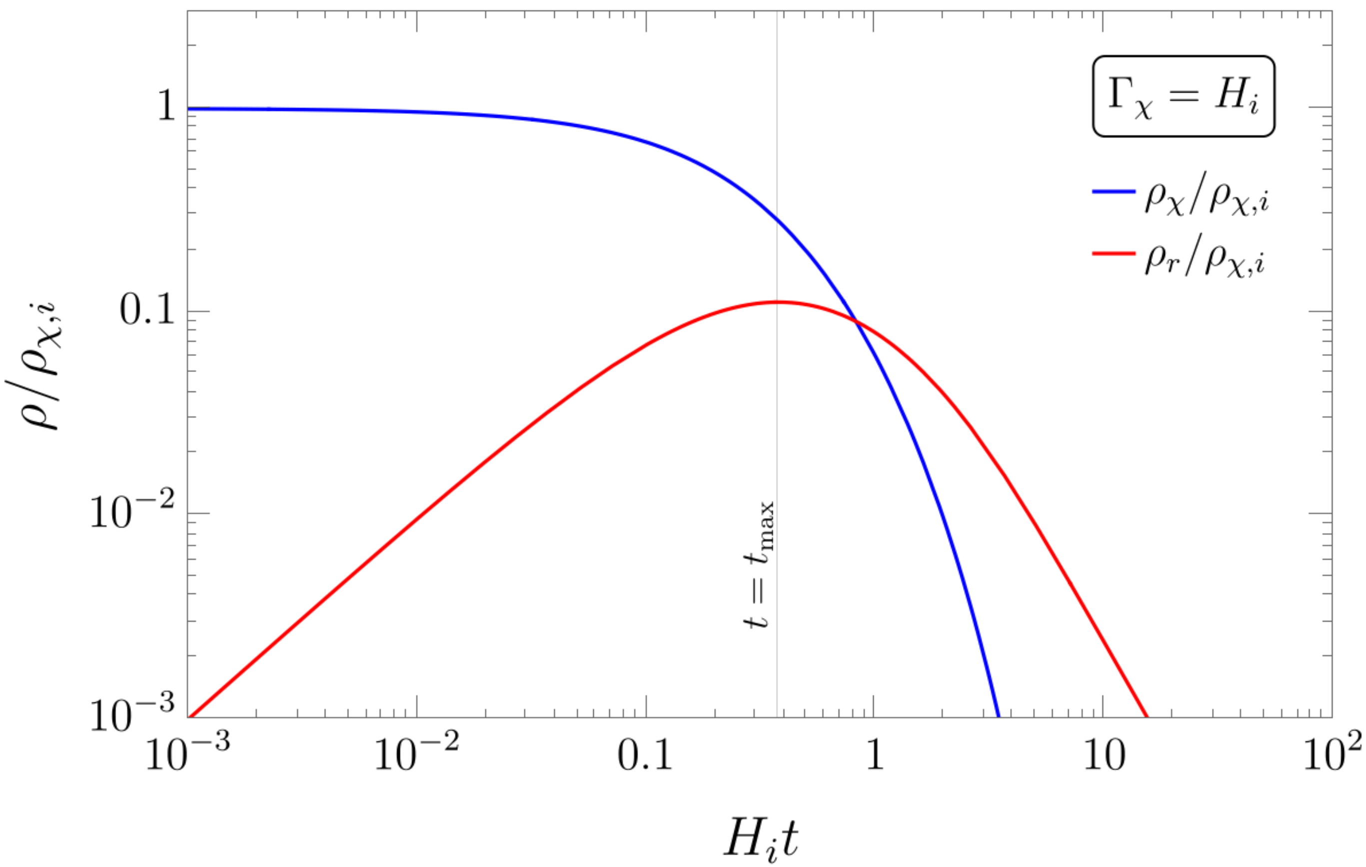
- A non-relativistic reheaton χ decays to a radiation r, which has 1st order phase transition

$$\dot{\rho}_\chi + 3H\rho_\chi = -\Gamma_\chi \rho_\chi$$

$$\dot{\rho}_r + 4H\rho_r = \Gamma_\chi \rho_\chi$$

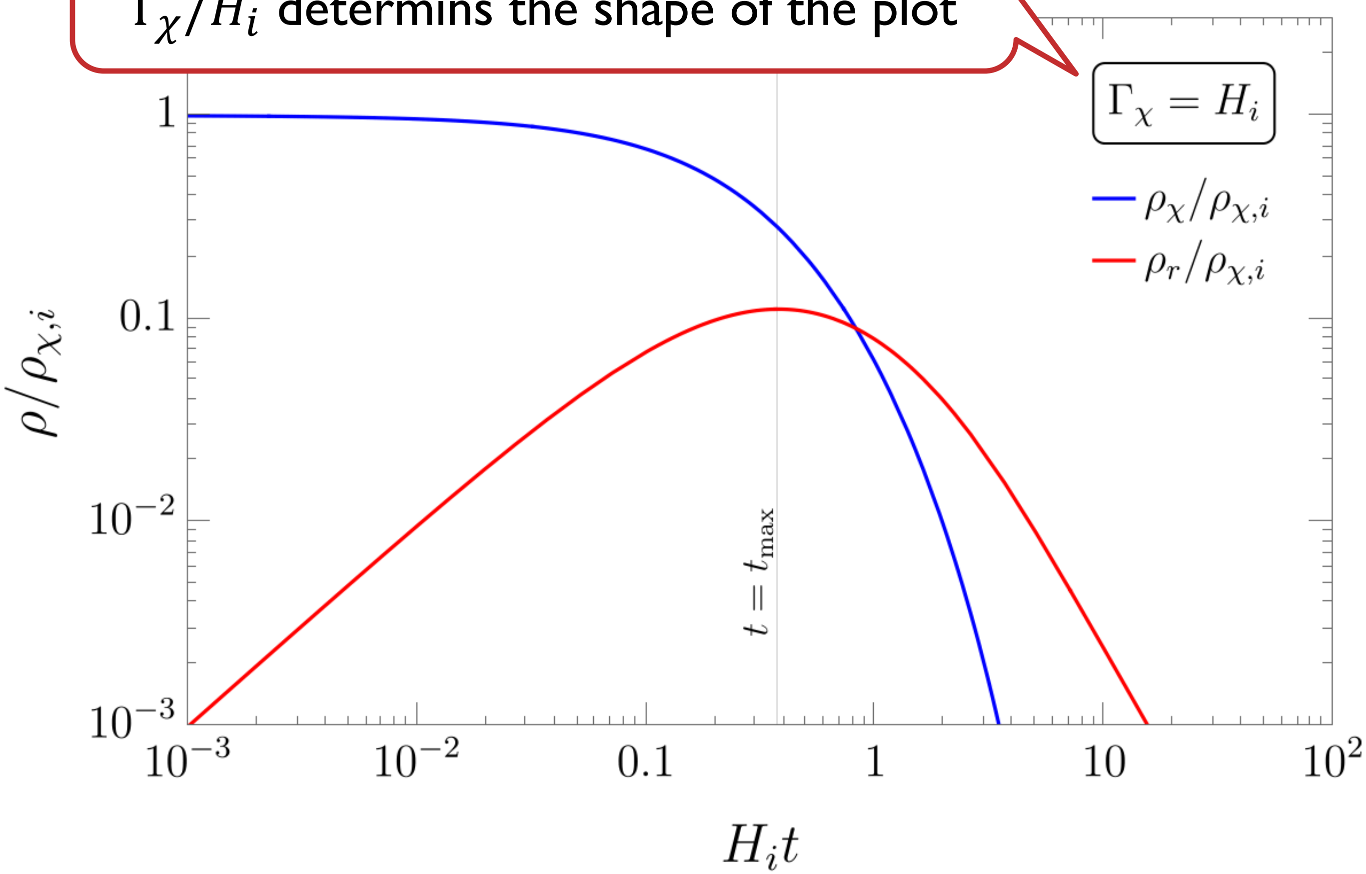
- Γ_χ is the reheaton decay rate
- Radiation r thermalizes with SM sector later
- χ can be an inflaton, but not necessarily

Temperature history during reheating



Temperature history during reheating

H_i is the Hubble at the time decay starts
Γ_χ / H_i determins the shape of the plot



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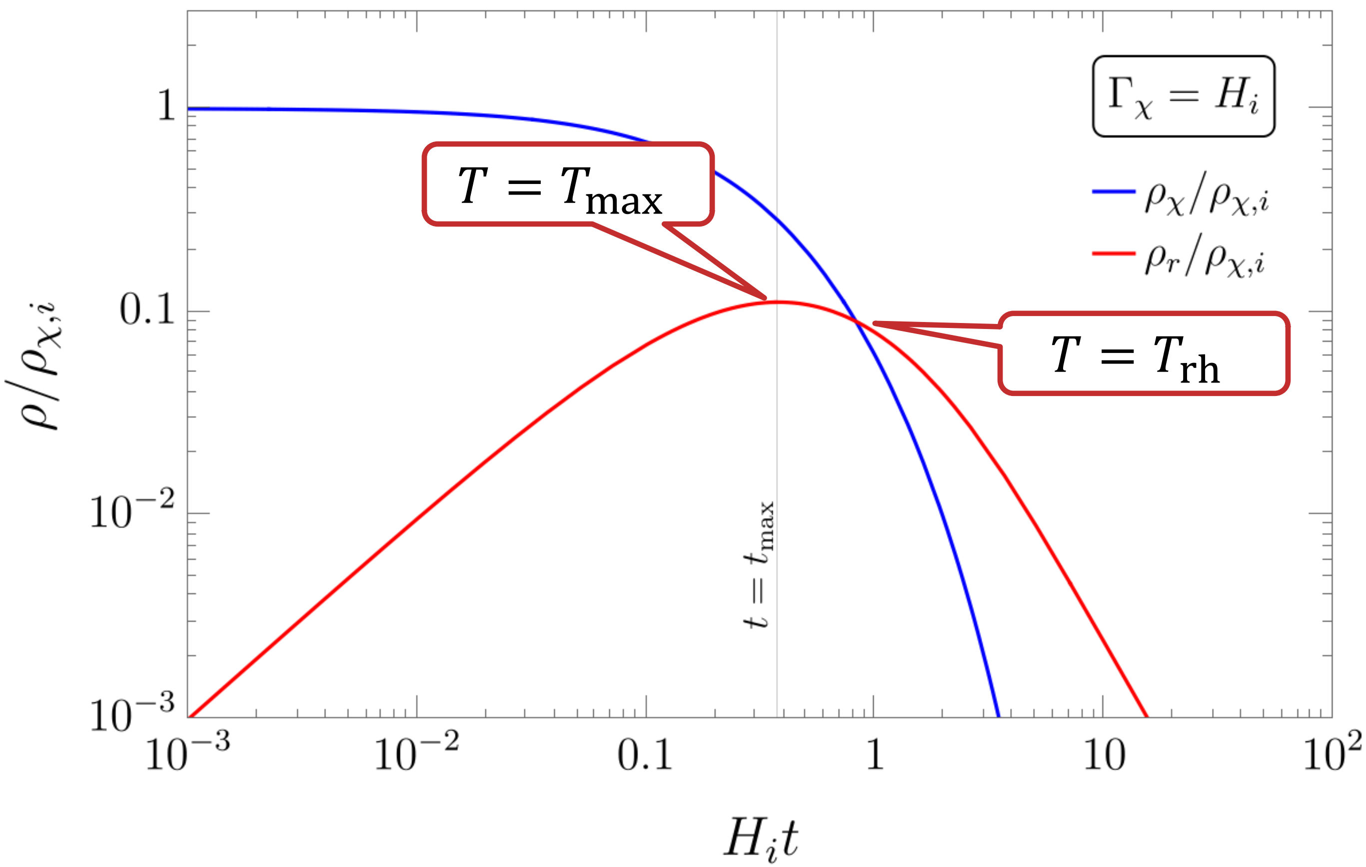

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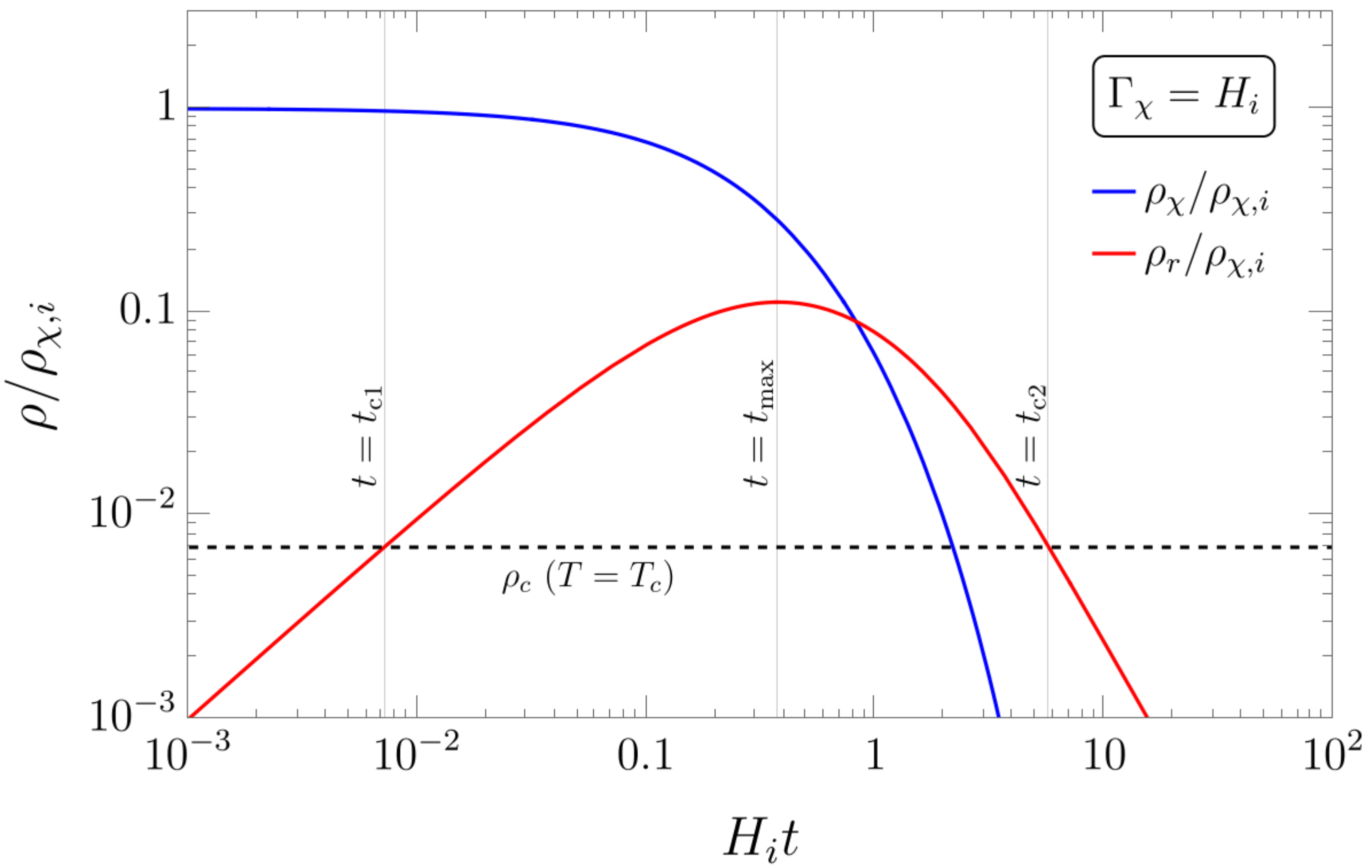

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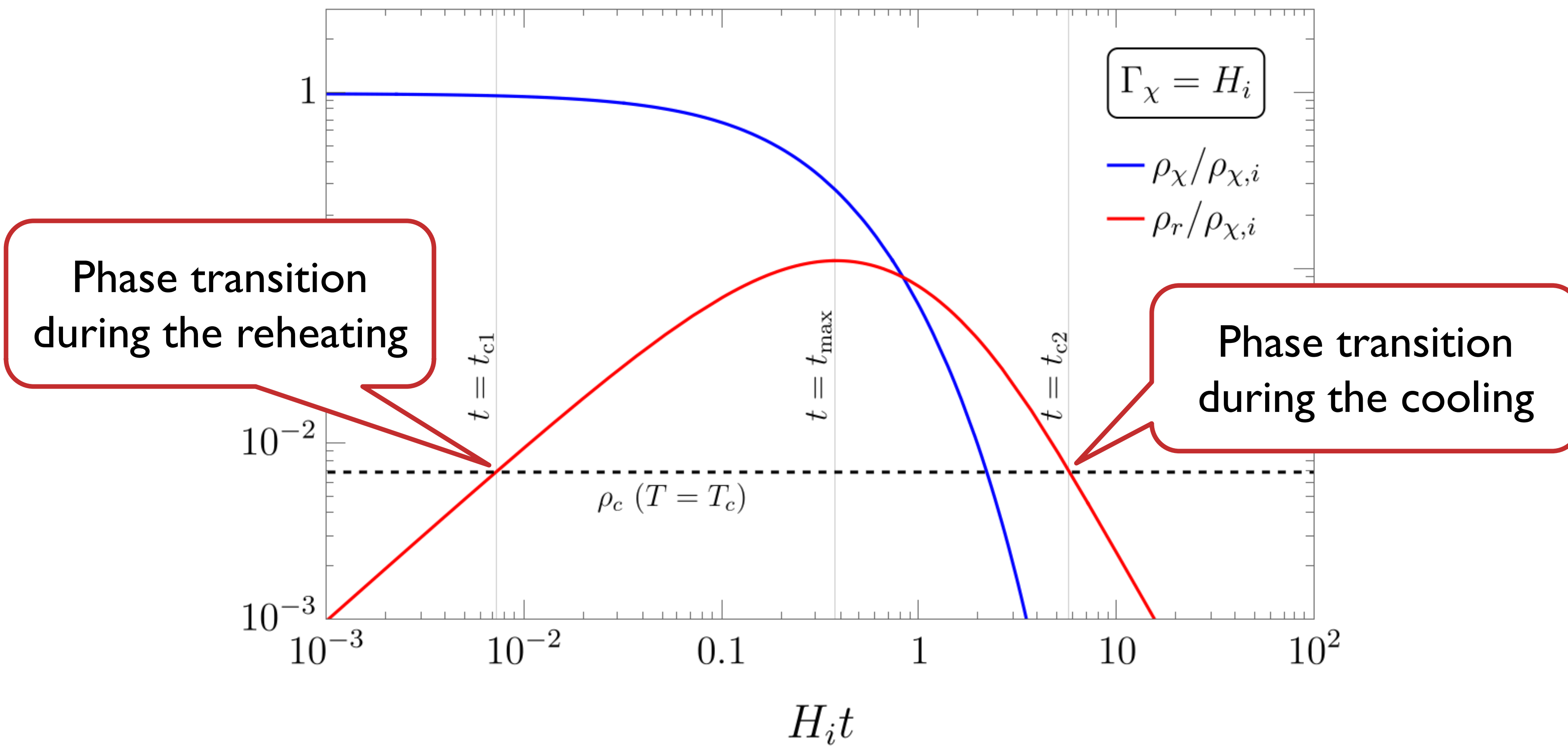
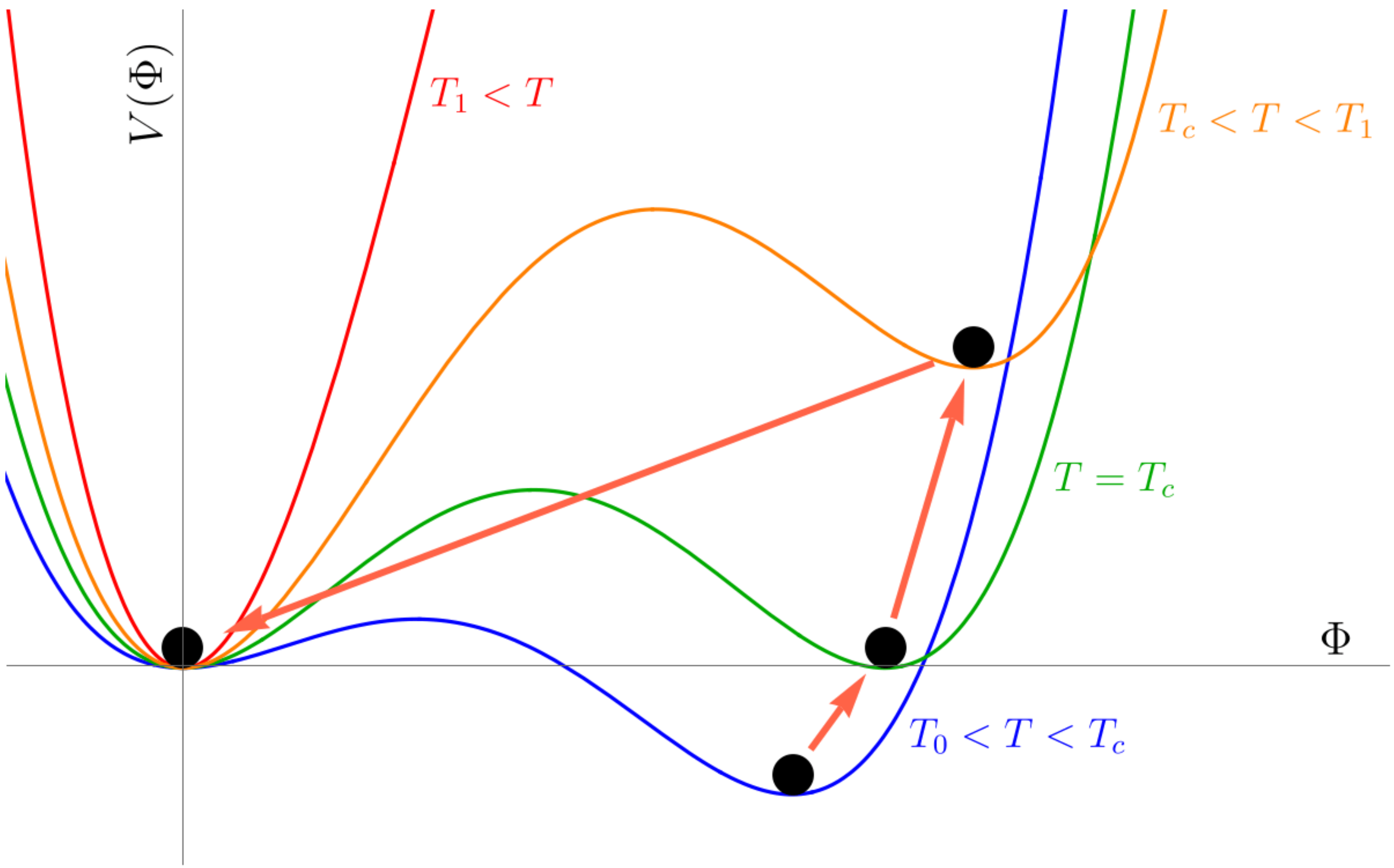
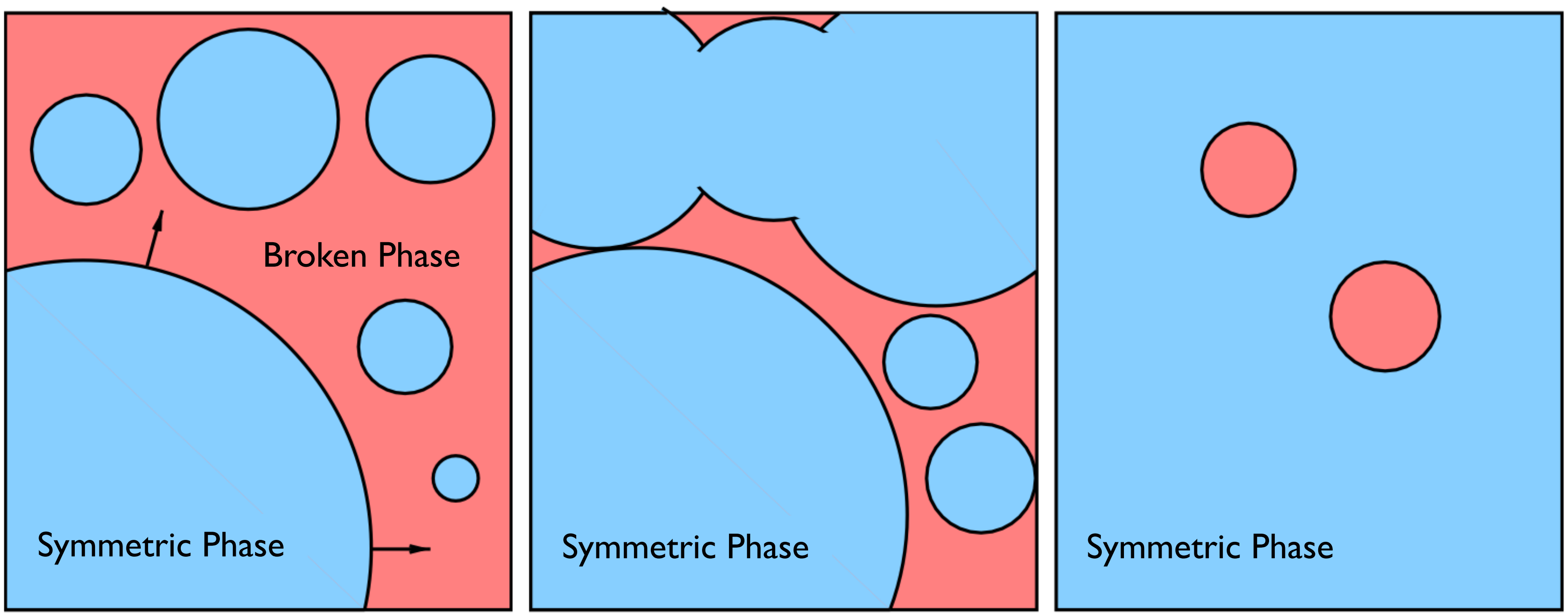


1st order PT during the reheating



GW from PT during the reheating



- GW are produced from the same way, but there're several differences

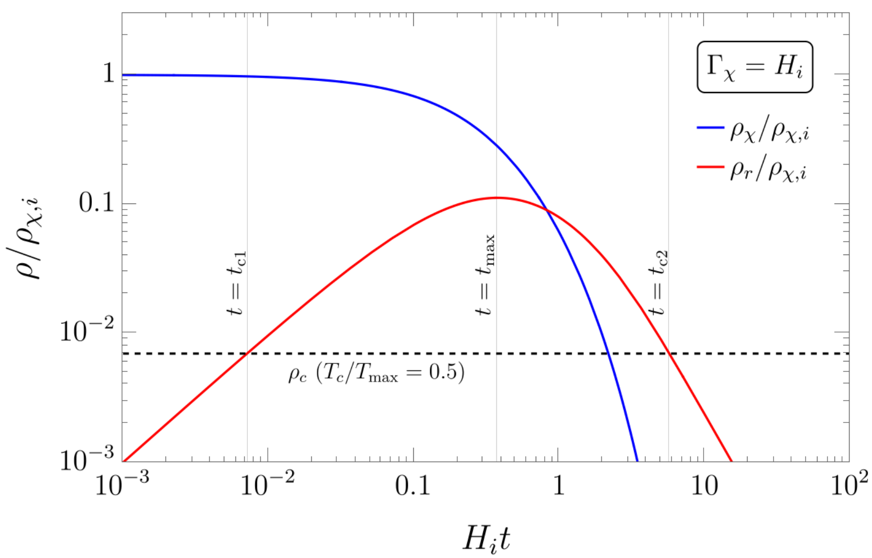
Image from arXiv:2008.09136

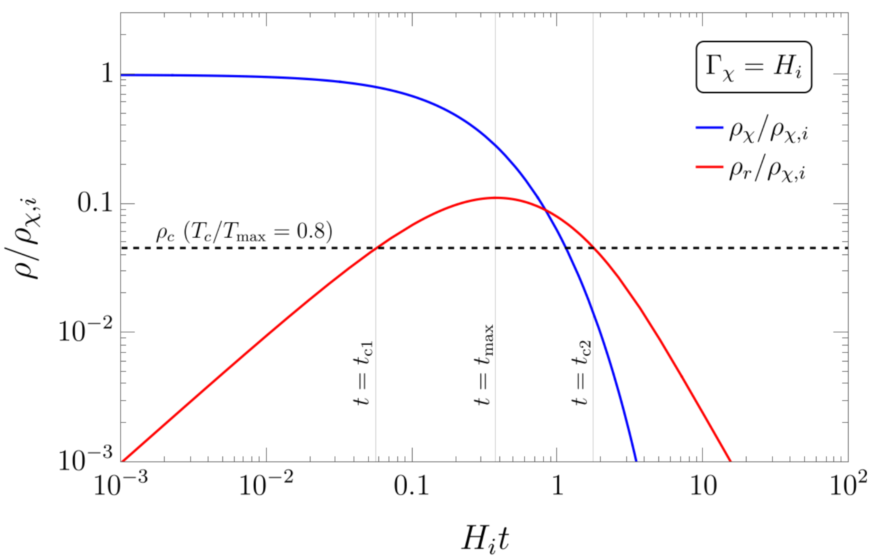
Heating PT and Cooling PT

- To distinguish, we define
  - hPT as phase transition during the reheating
  - hGW as gravitational waves from hPT
  - cPT as Phase transition during the cooling
  - cGW as gravitational waves from cPT

Difference between hGW and cGW

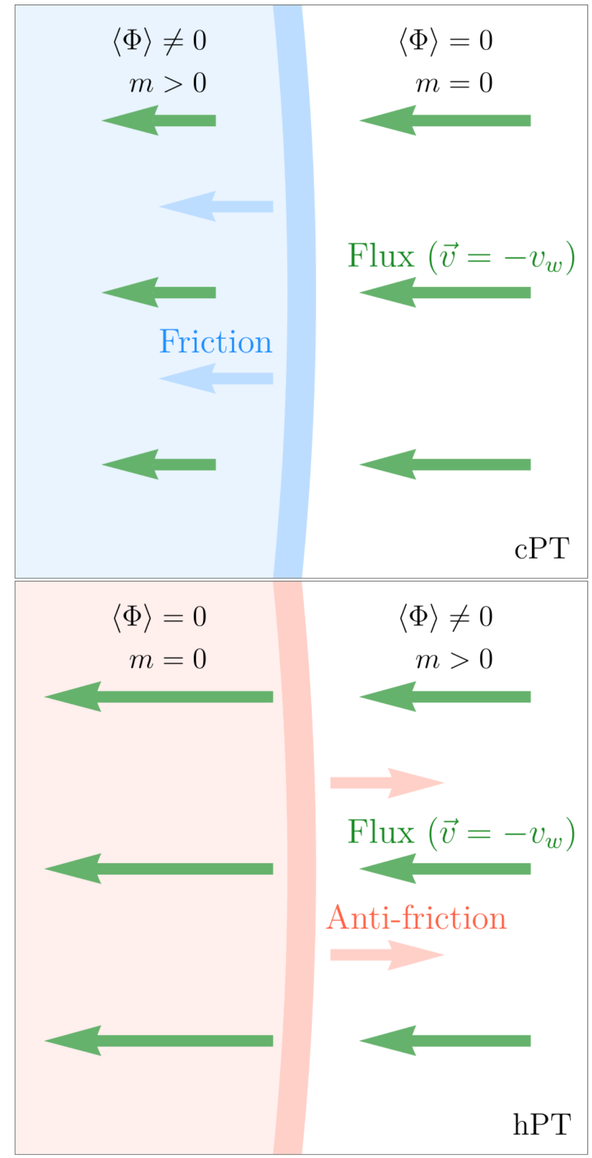
- hGW redshift more than cGW
  - hGW are produced early, and GW redshift $\propto a^{-4}$
  - This is why hGW is not considered normally
  - We can avoid this redshift factor by having $T_c \lesssim T_{\max}$





Difference between hGW and cGW

- Different bubble dynamics
  - The bubble wall in cPT feels friction, while the wall in hPT feels anti-friction
  - Thus, normally the wall speed in cPT ($v_{w,\mathrm{cPT}}$) saturates at a constant value, while $v_{w,\mathrm{hPT}}$ enters a runaway regime
  - The bubble wall in hPT gets energy from the radiation, which eventually converts to GW



Toy Model for PT

$$V(\Phi) = \frac{\mu^2}{2}(T - T_0)^2\Phi^2 + \frac{A}{3}T\Phi^3 + \frac{\lambda}{4!}\Phi^4$$

- Φ : A scalar in the radiation r that drives PT
- $\mu^2 = \frac{1}{12}\sum_i c_i N_i y_i^2$, $A = \frac{1}{4\pi}\sum_B N_B y_B^3$
- We define $\Delta \equiv \frac{4A^2}{3\lambda\mu^2}$, which controls physics of PT
- T_0 : Binodal temperature
- $T_c = T_0/\sqrt{1-\Delta}$: Critical temperature
- $T_1 = T_0\sqrt{8/(8-9\Delta)}$: Spinodal temperature

Free Parameters

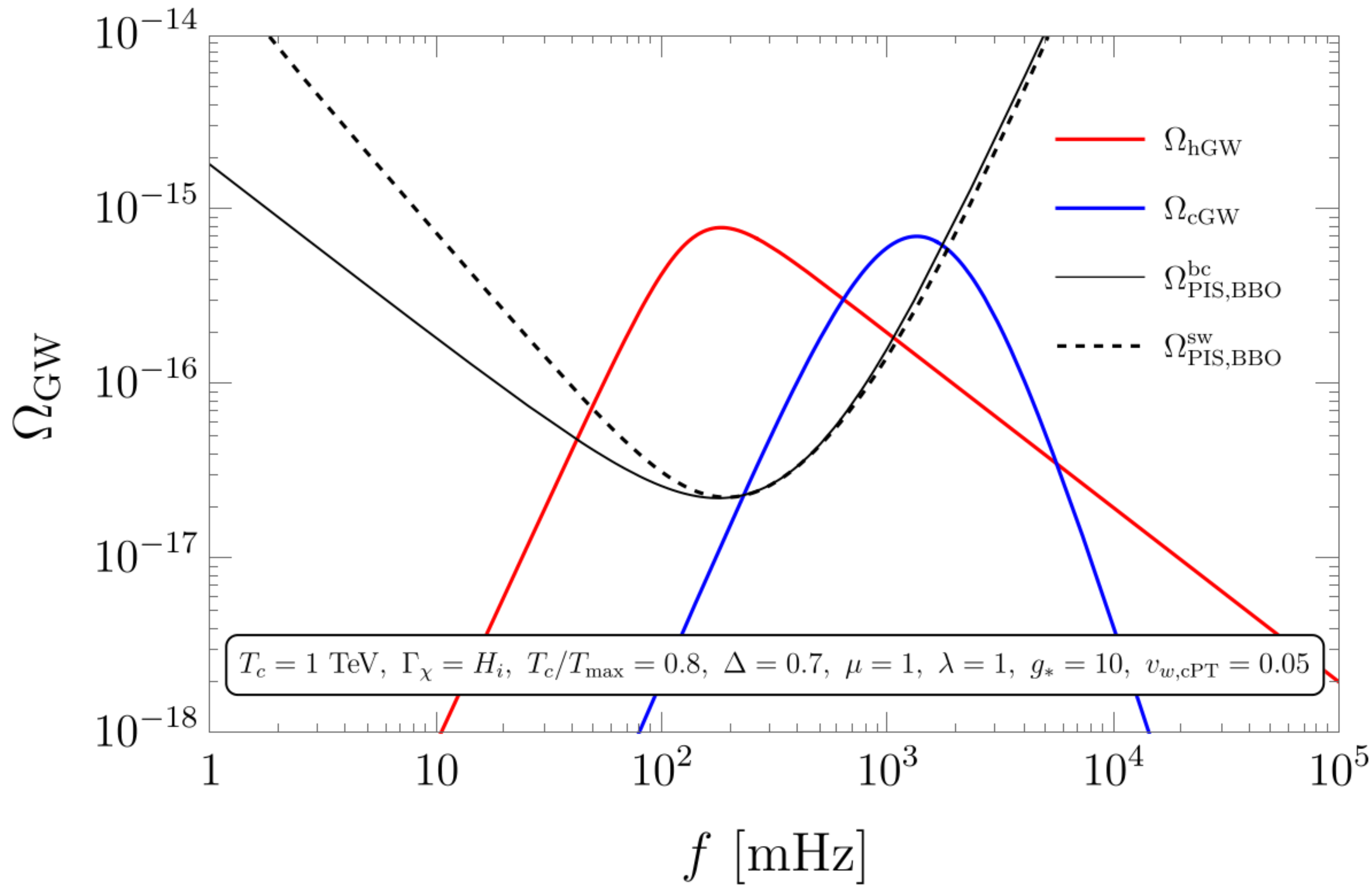
$$T_c, \quad \Gamma_\chi, \quad T_c/T_{\rm max}, \quad \{\mu, A, \lambda\}, \quad g_*, \quad v_{w,\rm cPT}$$

- We choose
  - $T_c \sim 1$ TeV
  - $\Gamma_\chi \sim H_i$
  - $\mu = \lambda = 1$
  - $g_* = 10$
  - $v_{w,\rm cPT} = 0.05$
- Vary $T_c/T_{\rm max}$ and $\Delta \equiv \dfrac{4A^2}{3\lambda\mu^2}$

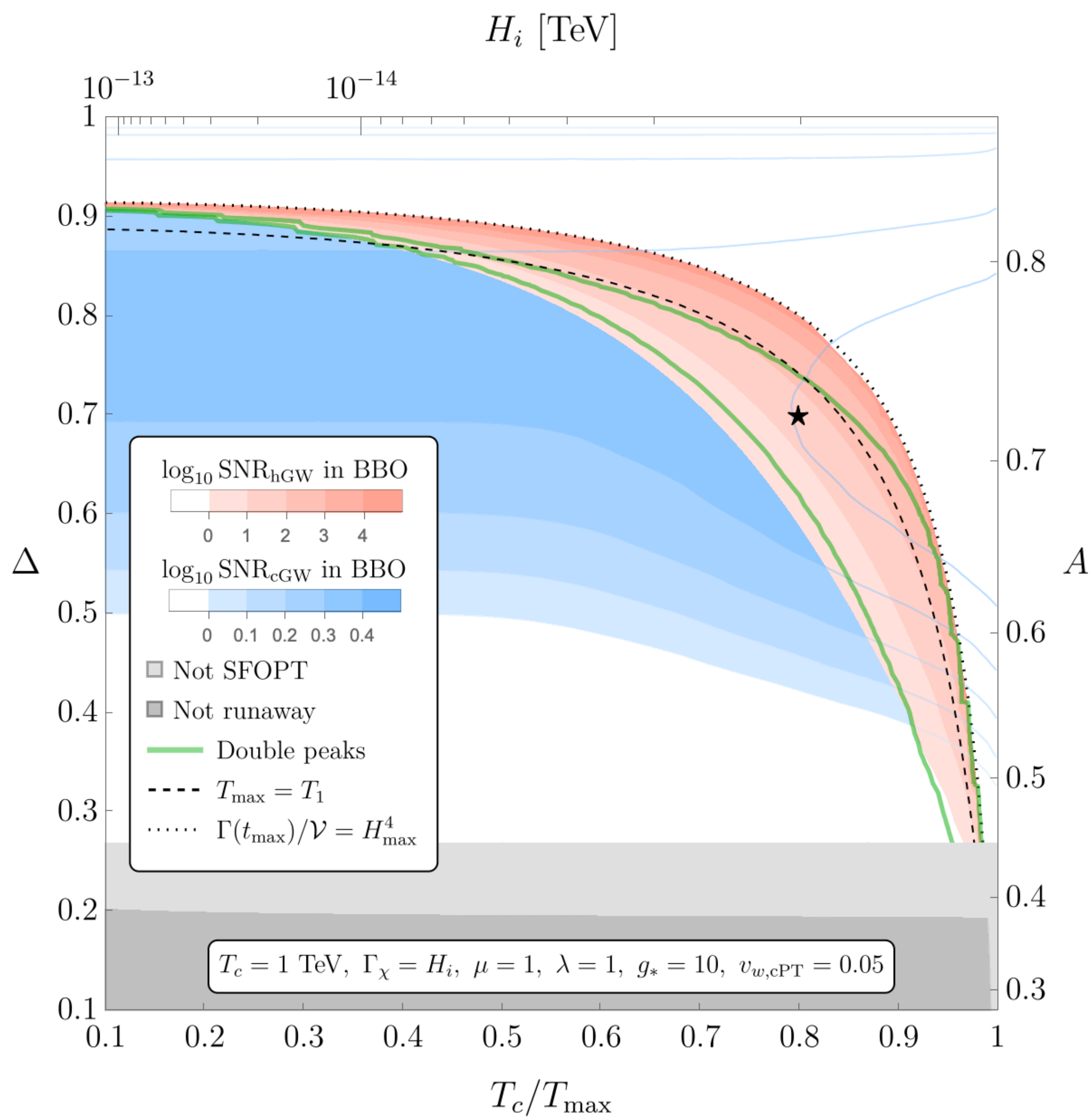
Gravitation Waves from PT

- The dominant contribution for hGW comes from bubble collisions as it's in the runaway regime
- The bubble wall for cPT has a constant wall velocity, thus sound waves dominates for cGW
- We calculate SNR in BBO by using $\Omega_{\rm PIS}$

Gravitation Waves from PT

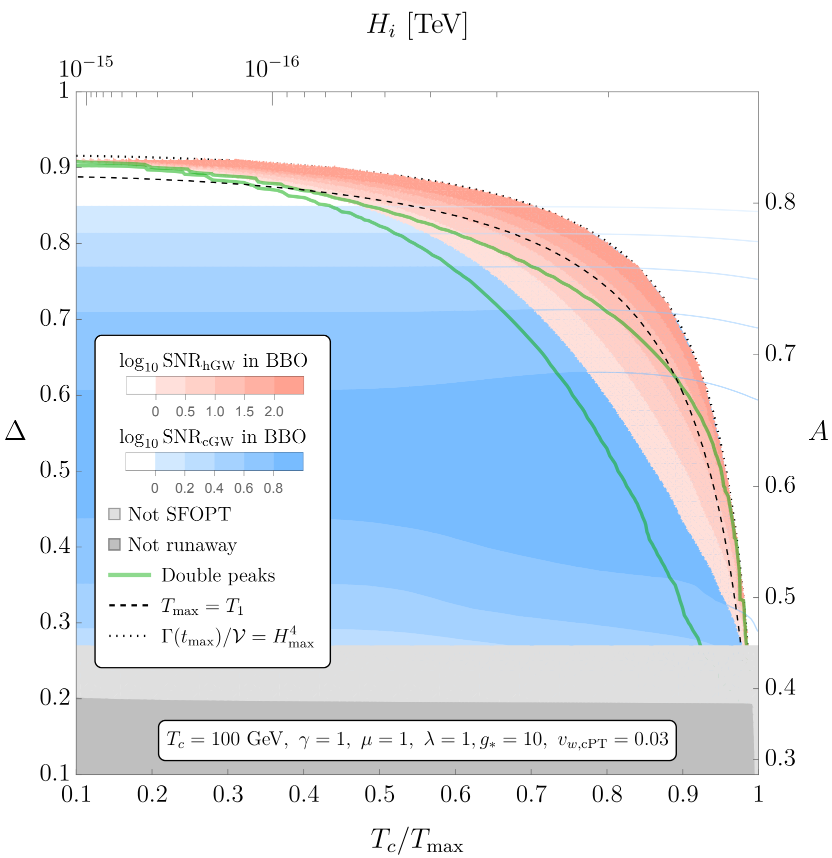


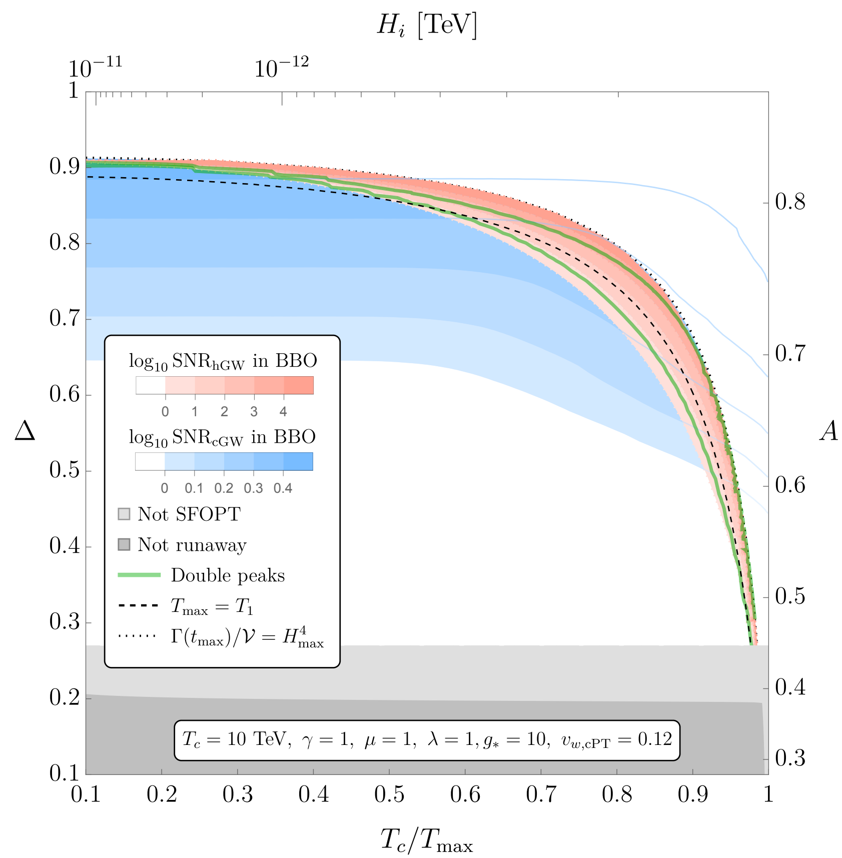
Results



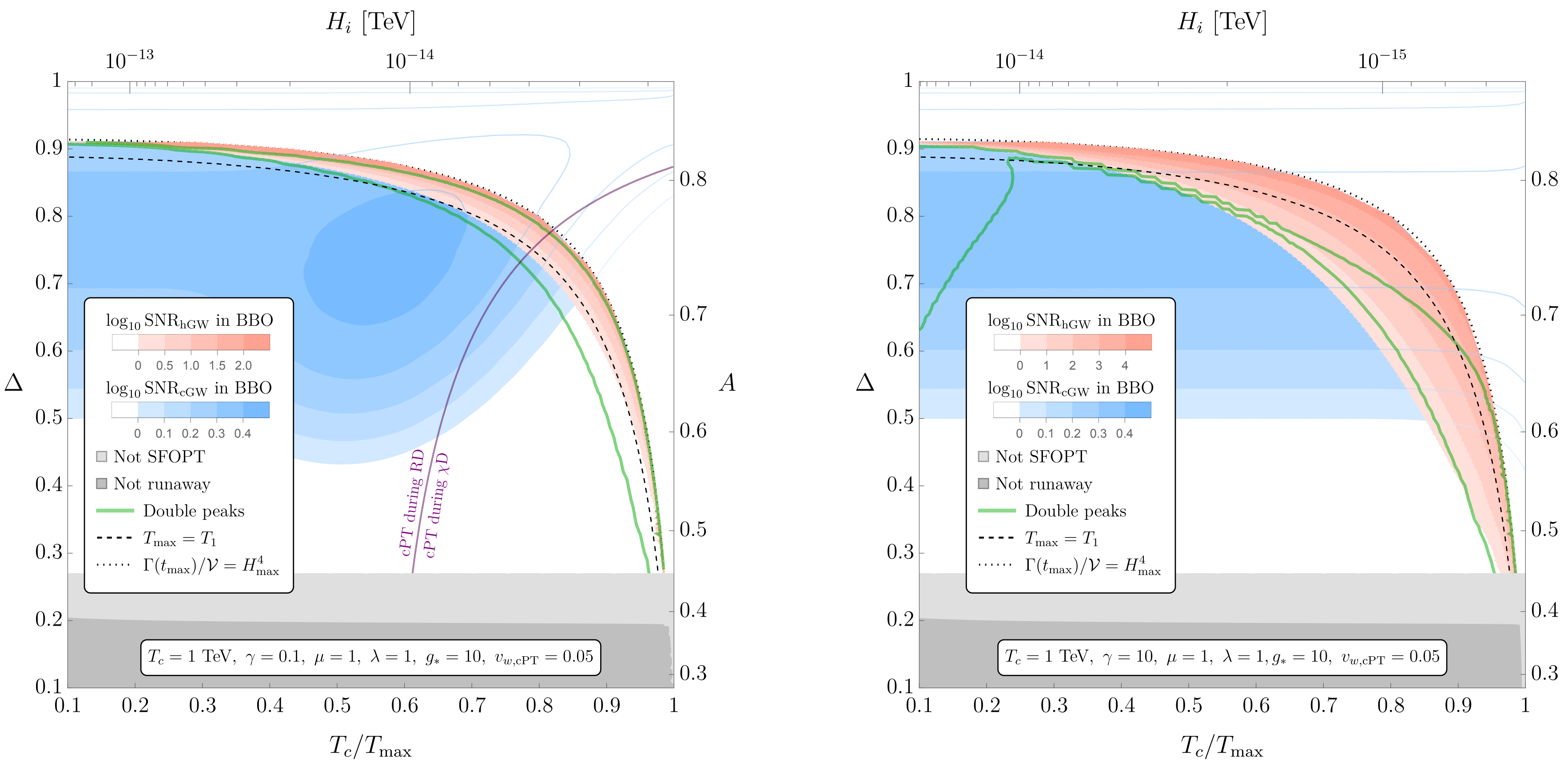
H_i [TeV]
10^{-13}
10^{-14}
Δ
A
$T_c/T_{\max}$
$\log_{10}$ SNR$_{\rm hGW}$ in BBO
0 1 2 3 4
$\log_{10}$ SNR$_{\rm cGW}$ in BBO
0 0.1 0.2 0.3 0.4
Not SFOPT
Not runaway
Double peaks
$T_{\max} = T_1$
$\Gamma(t_{\max})/\mathcal{V} = H_{\max}^4$
$T_c = 1$ TeV, $\Gamma_\chi = H_i$, $\mu = 1$, $\lambda = 1$, $g_* = 10$, $v_{w,\rm cPT} = 0.05$

Results: different T_c

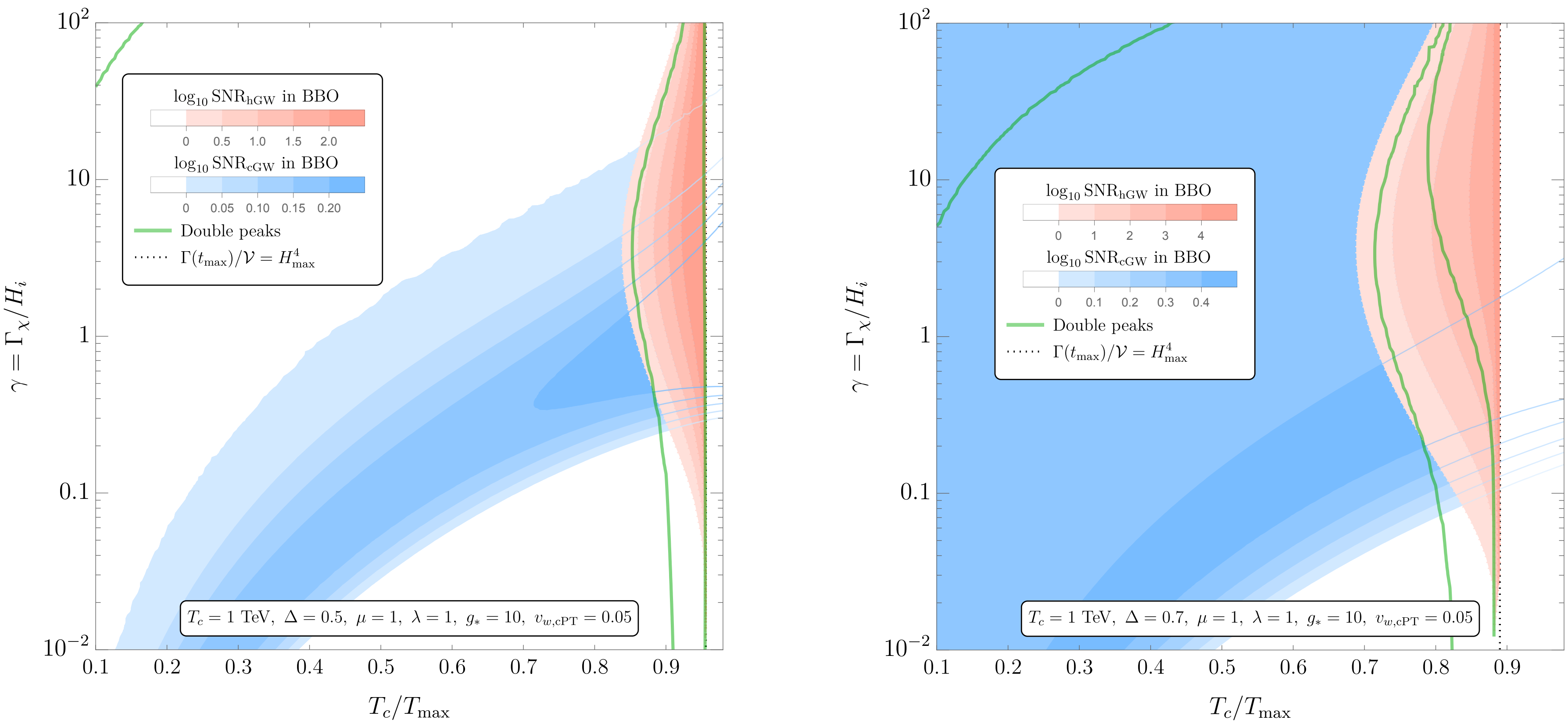




Results: different Γ_χ / H_i



Results: varying Γ_χ / H_i for fixed Δ



Conclusions

- 1st order phase transition may occur twice during the reheating and during the cooling

- If we can measure GW from both PTs, we can learn physics of reheating

- In this work, we study the properties of GW production during the reheating

THANK YOU

BACK UP

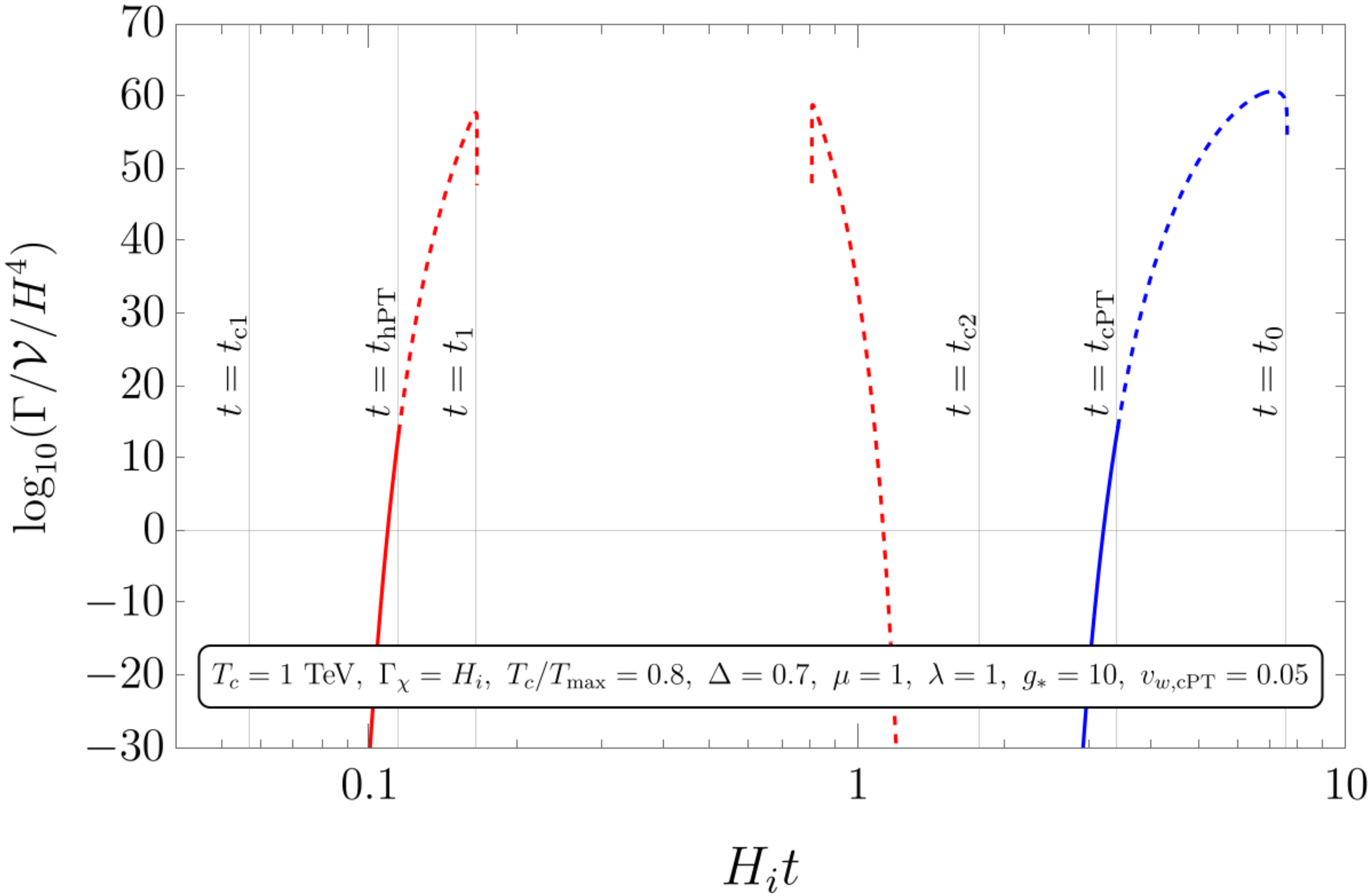
Bubble Nucleation Rate

$$\frac{\Gamma}{\mathcal{V}} \approx T^4 \left(\frac{S}{2\pi}\right)^{3/2} e^{-S}$$

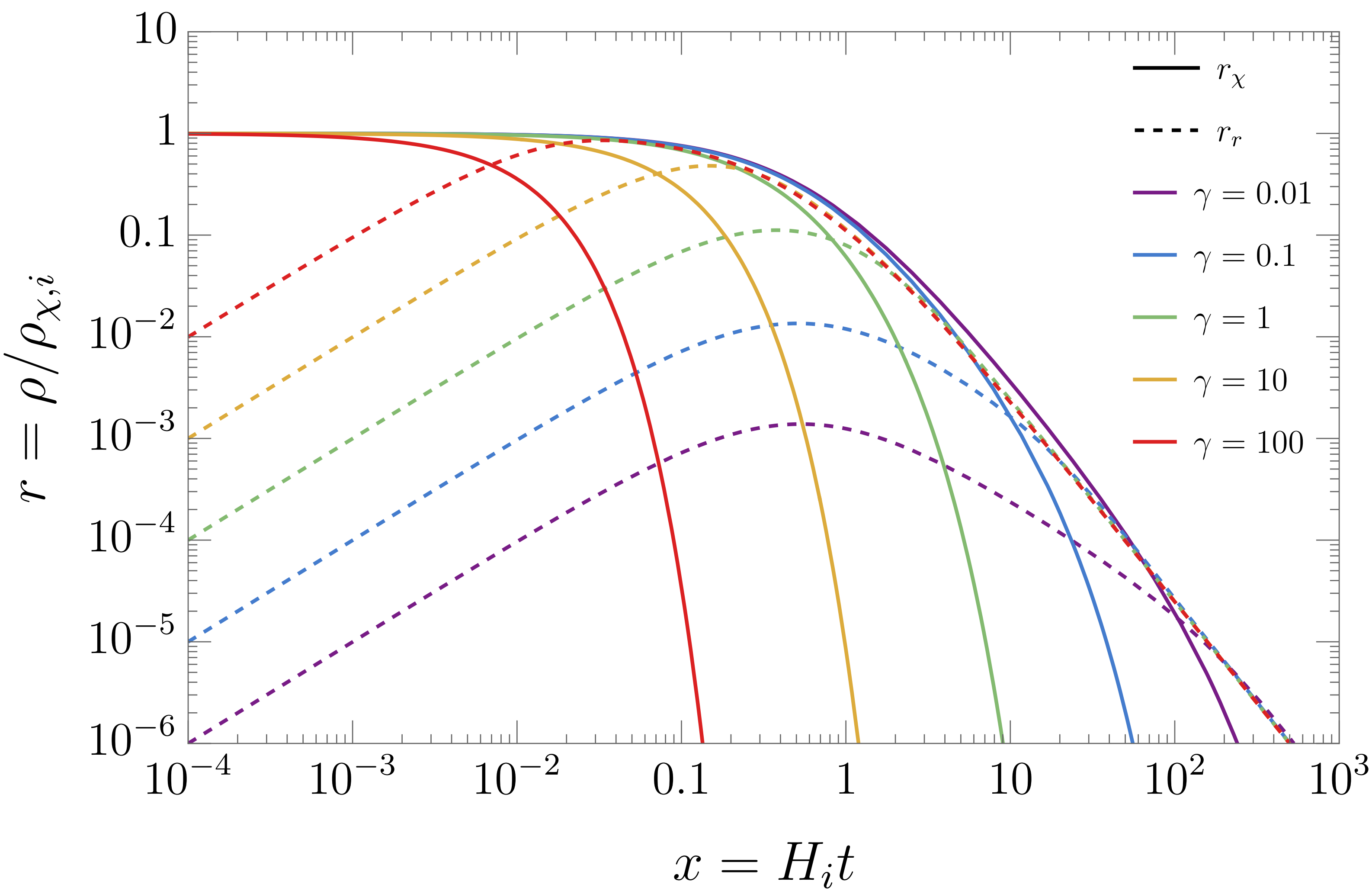
$$h(t) = \exp\left[-\int_{t_c}^{t} dt' \frac{\Gamma}{\mathcal{V}}(t') \frac{4\pi}{3} v_w^3 (t-t')^3\right]$$

- h is the fraction of the volume of the Universe found in the metastable phase
- Define t_{PT} at which $h(t_{PT}) = 1/e$

Bubble Nucleation Rate



Temperature history according to γ



Daisy, runaway, and κ_Φ