Gravitational Waves from colliding bubbles in cold hidden sectors

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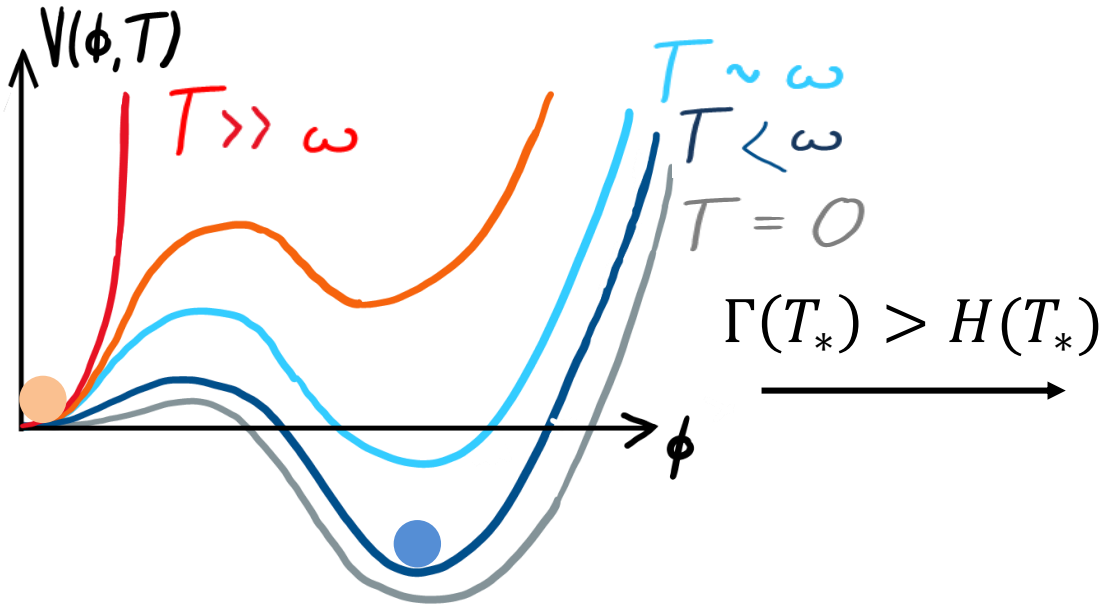
arviX:1901.110381

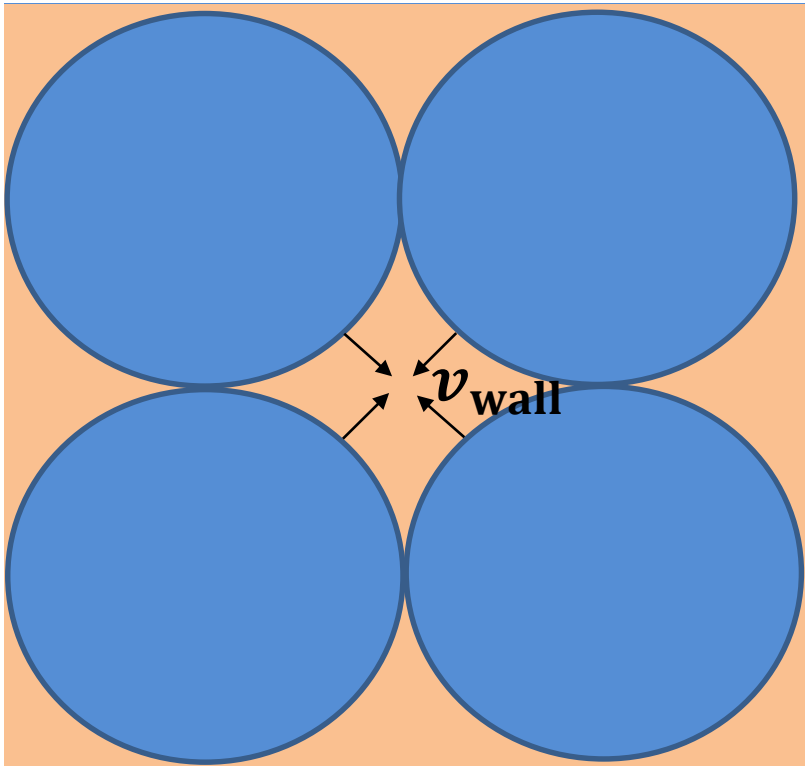
European Research Council

Established by the European Commission

➢ Overview of Gravitational Waves from phase transitions

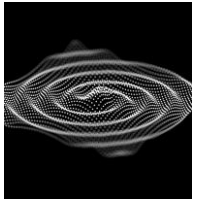


$$\Gamma(T_*) > H(T_*)$$



➢ Overview of Gravitational Waves from phase transitions

Gravitational Wave Sources



Bubble wall collisions

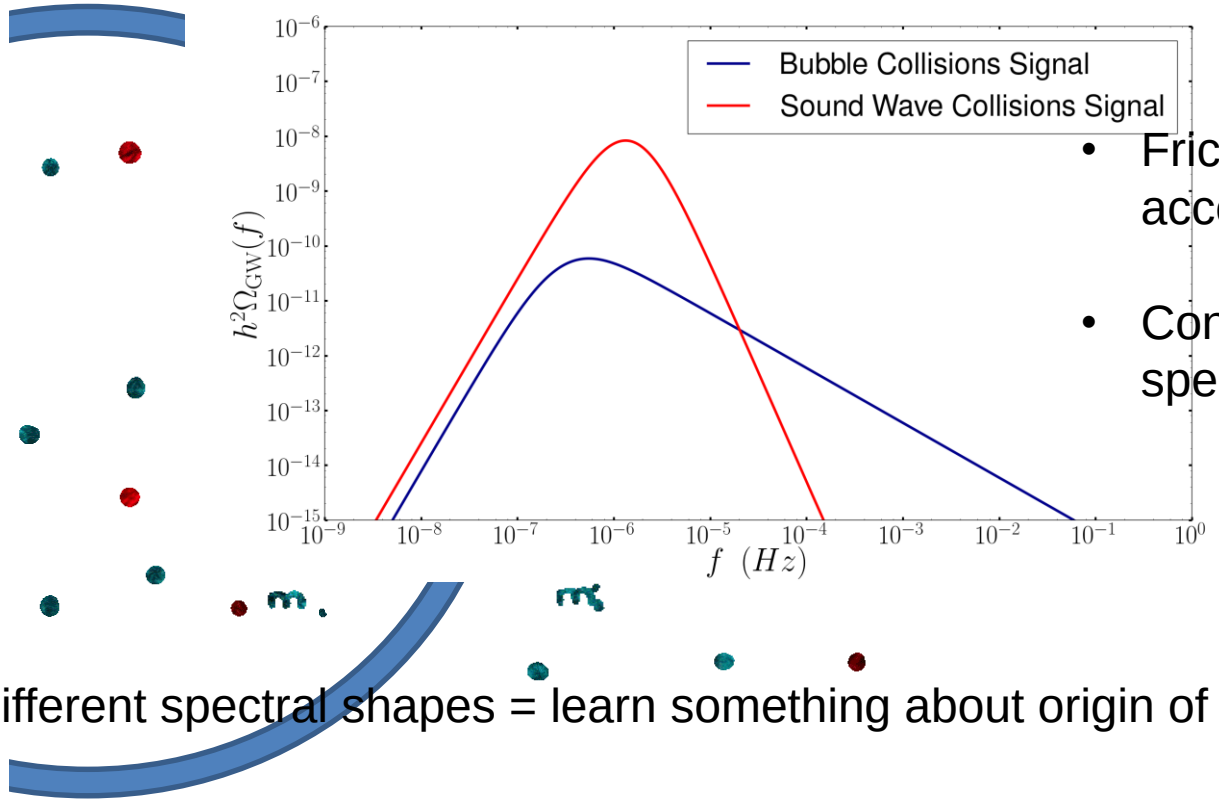
Acoustic sounds waves in plasma

(Turbulent flows in plasma)

Friction in plasma controls which source dominates!

1) Overview of Gravitational Waves from phase transitions

Bubble wall dynamics



- Friction determines if wall is accelerating at collision
- Controls shape of GW spectrum

Different spectral shapes = learn something about origin of signal?

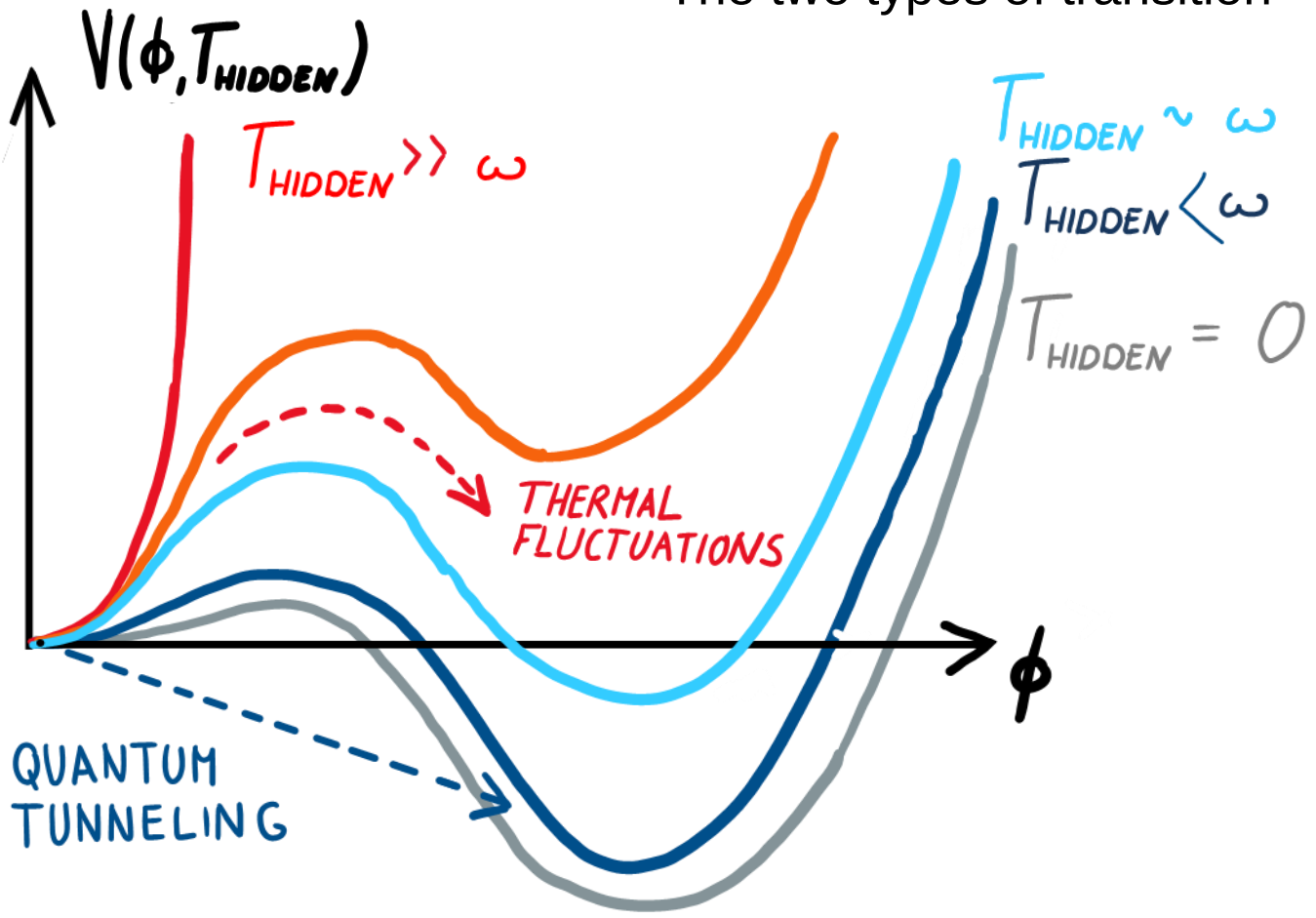
2) Cold hidden sectors

What are Cold Hidden Sectors?

- Gauge group weakly coupled to Standard Model
- Interact with SM via gravity as normal
- Temperature ratio $\epsilon = \frac{T_{hid}}{T_{vis}}$ generated at early times
- Can be generated from e.g. differing inflaton decay rates into two sectors

2) Cold hidden sectors

The two types of transition



Thermal transition

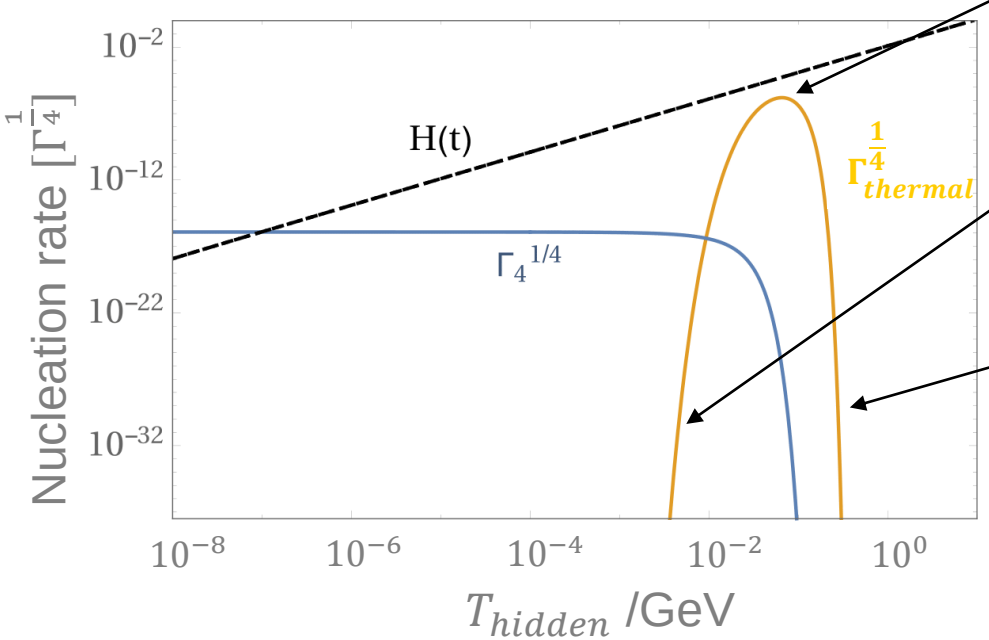
- Happens when $\Gamma_{thermal}(t) \sim H(t)$

Tunneling transition

- Happens when $\Gamma_{tunneling}(t) \sim H(t)$

2) Phase transitions

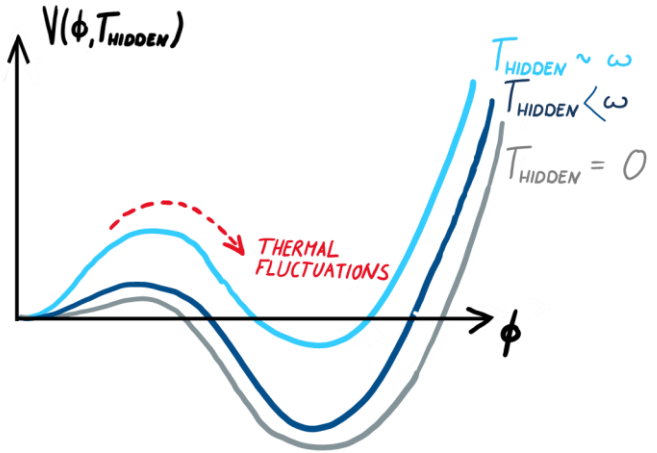
The two types of transition: concrete example



Sweet spot for thermal fluctuations

Thermal fluctuations are very small

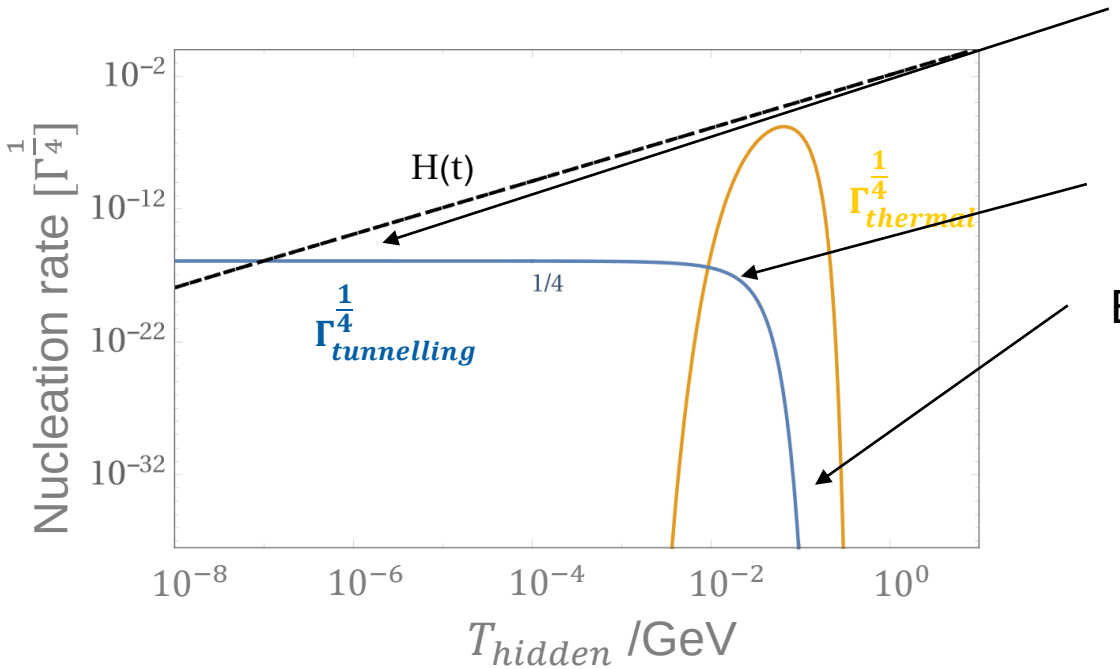
Barrier is very high



2) Phase transitions

The two types of transition: concrete example

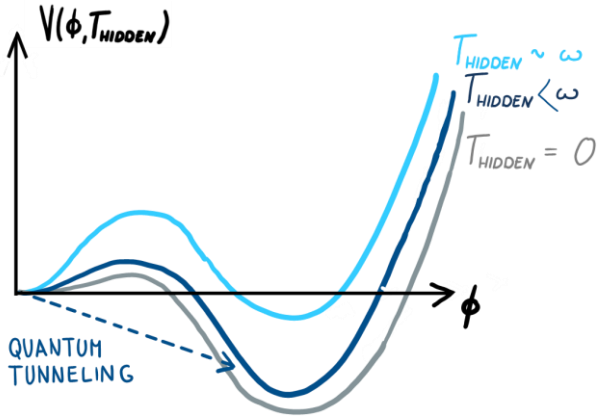
Case 1: $\frac{T_{hidden}}{T_{visible}} \ll 1$



Tunnelling nucleation rate stays constant

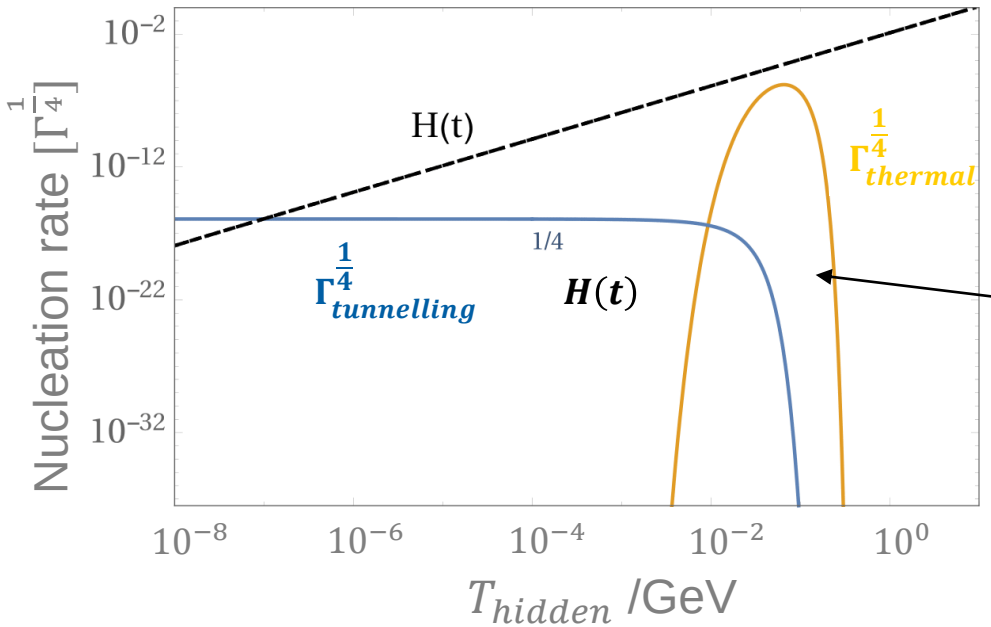
Barrier close to $T_{hidden} = 0$ form

Barrier height very high



2) Phase transitions

Case 2: $\epsilon = \frac{T_{hidden}}{T_{visible}} \ll 1$?

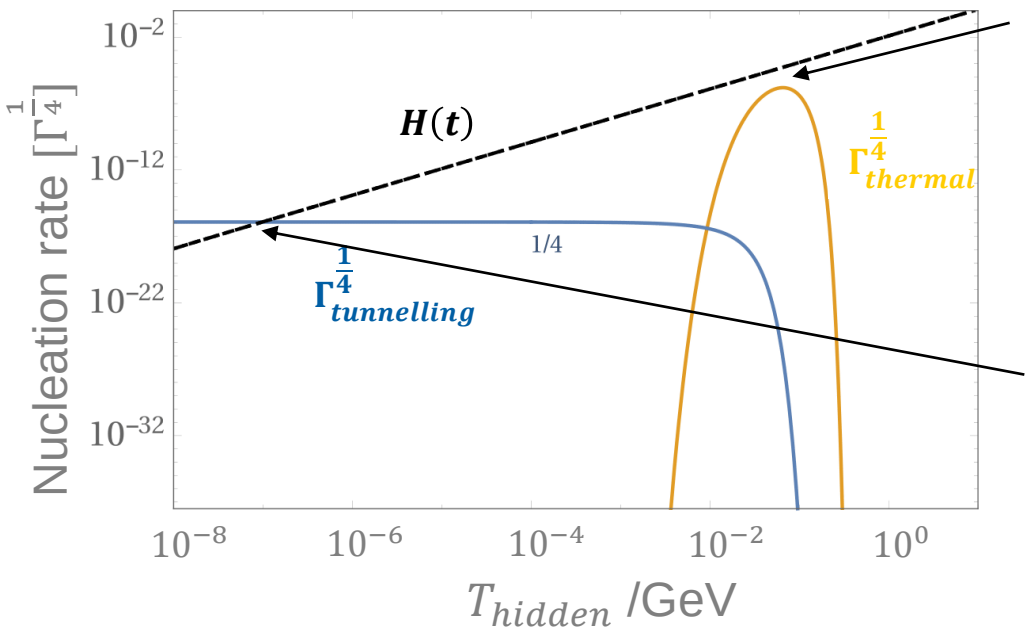


Thermal transition takes place when hidden plasma is hot

Hot plasma → High friction→ Sound wave signal

2) Phase transitions

Case 2: $\epsilon = \frac{T_{hidden}}{T_{visible}} \ll 1$



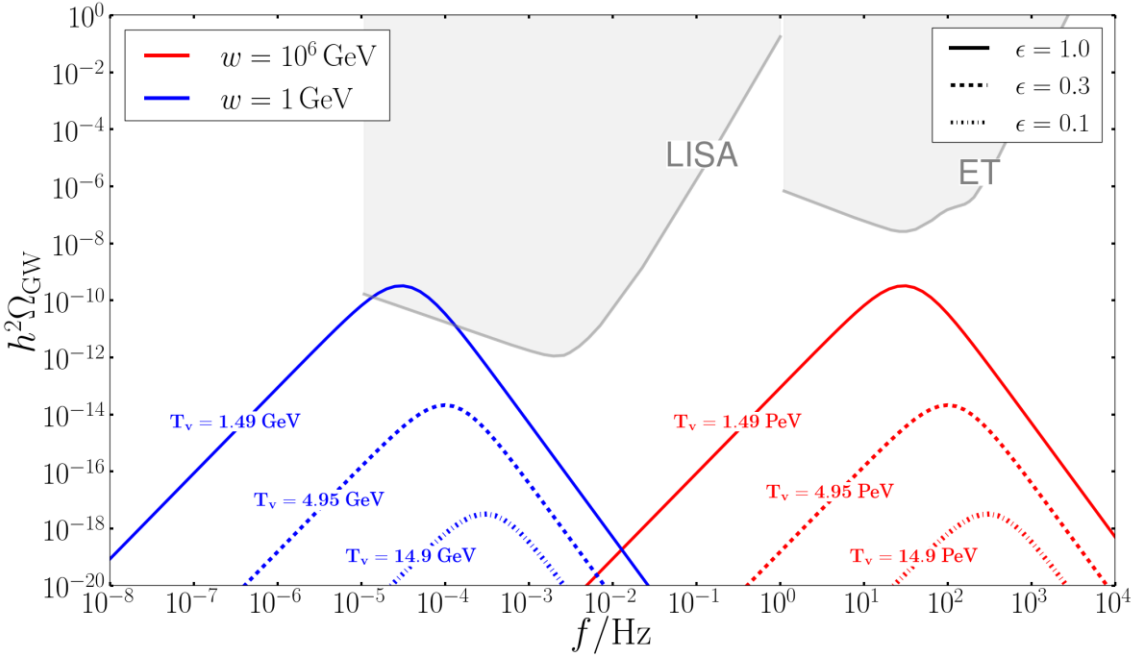
Thermal transition window missed

Tunnelling transition happens later when hidden plasma is cold

Cold plasma → Low wall friction → Bubble collision signal?

4) Gravitational Waves

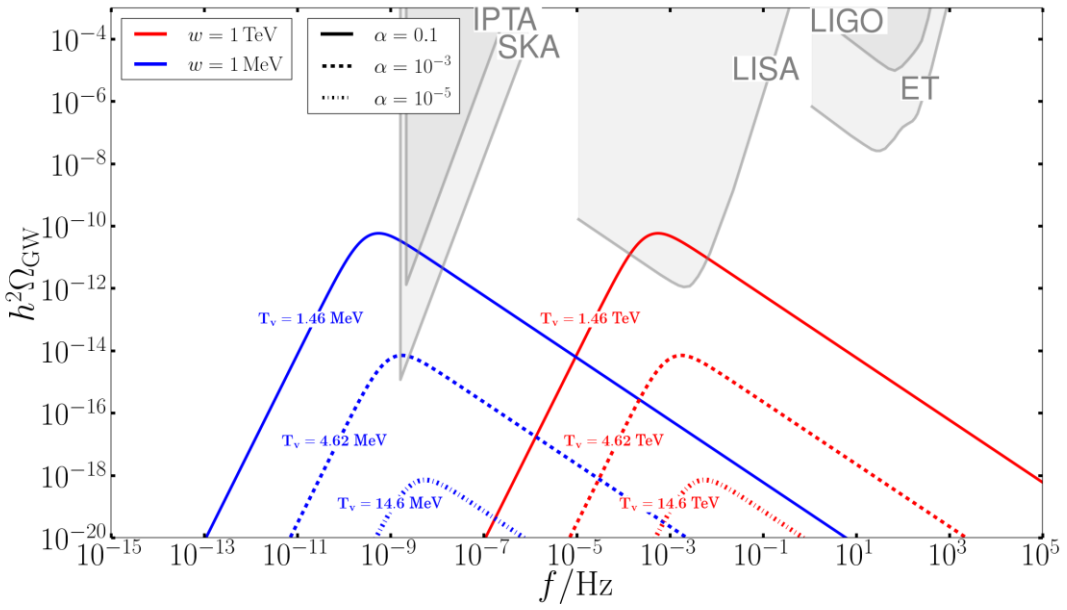
A thermal phase transition



- Decreasing $\epsilon = \frac{T_{hidden}}{T_{visible}}$ heavily suppresses signal
- Sound Wave dominated signal

4) Gravitational Waves

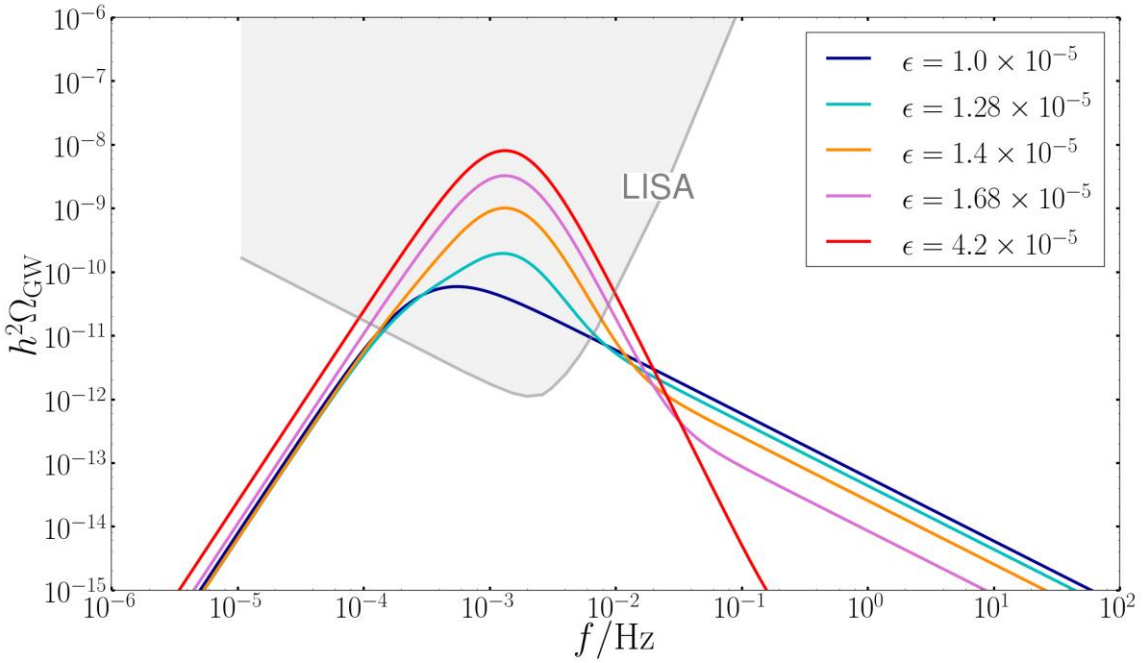
A tunnelling phase transition



- $\epsilon = \frac{T_{hidden}}{T_{visible}} \ll 1$ and you still get an observable signal
- Pure bubble collision signal as friction negligible

4) Gravitational Waves

From collision to sound wave dominated signal



- Decreasing $\epsilon = \frac{T_{hidden}}{T_{visible}}$ decreases friction on bubble wall
- Sound wave → bubble collision
- Could LISA be used to look for cold hidden sectors?

5) Summary

- Bubbles can accelerate without friction when you have a phase transition in a very cold hidden sector

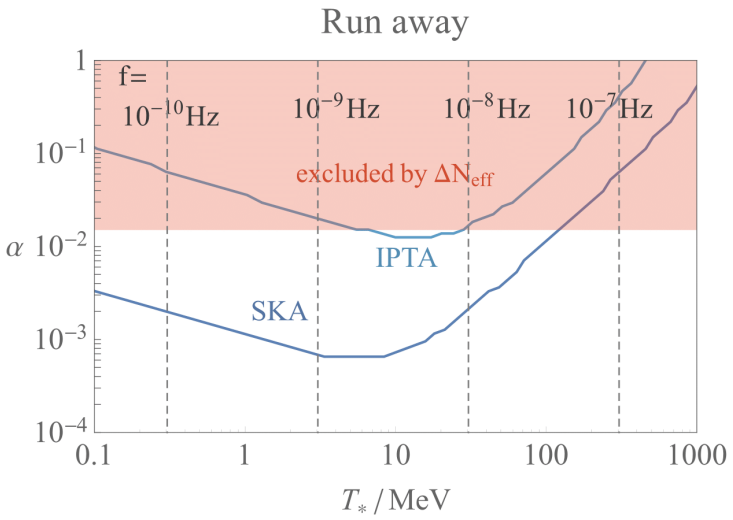
- Observing a bubble collision GW signal could be a smoking gun signature of a tunnelling phase transition in a very cold hidden sector

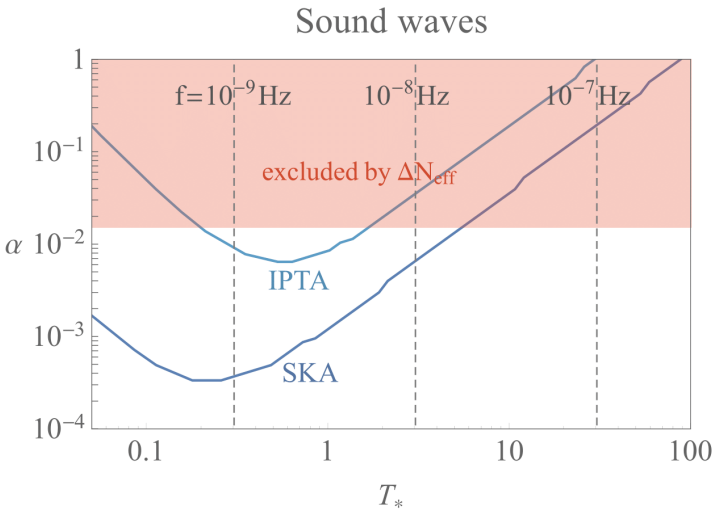
Thanks for listening!

Appendix

4) Gravitational Waves

Detecting a signal at a frequency ruled out by BBN





- PT cannot happen $T_* \leq 10$ MeV due to BBN constraints
- Detecting a signal in this region could be a signature of a cold hidden sector

1) What is a cold hidden sector

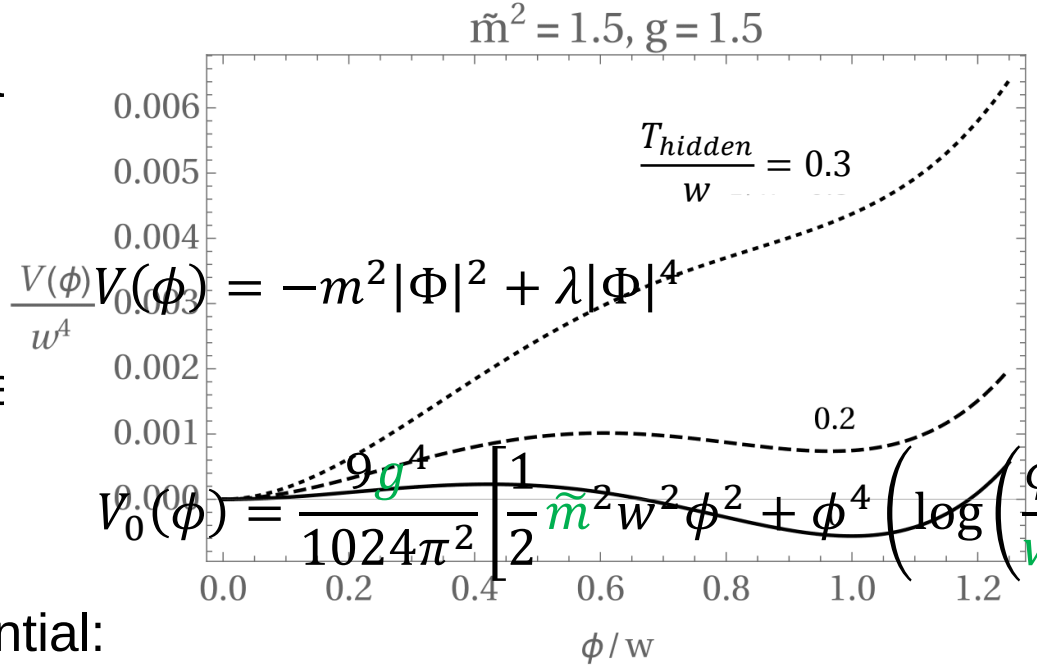
An example hidden sector

- SU(2) gauge grou
- Tree level potenti

$$V(\phi) = -m^2|\Phi|^2 + \lambda|\Phi|^4$$

- With 1 -loop corre

$$V_0(\phi) = \frac{9g^4}{1024\pi^2}\left[\frac{1}{2}\tilde{m}^2 w^2\phi^2 + \phi^4\left(\log\left(\frac{\phi^2}{w^2}\right) - \frac{(2+\tilde{m}^2)}{4}\right)\right]$$



- Full thermal potential:

$$V(\phi, T_{hidden}) = V_0(\phi) + V_{T_{hidden}}(\phi, T_{hidden})$$

We consider parts of the parameter space where there is a barrier at zero temperature!

1) What is a cold hidden sector

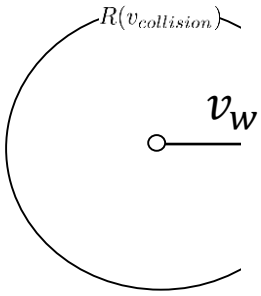
What is a hidden sector?

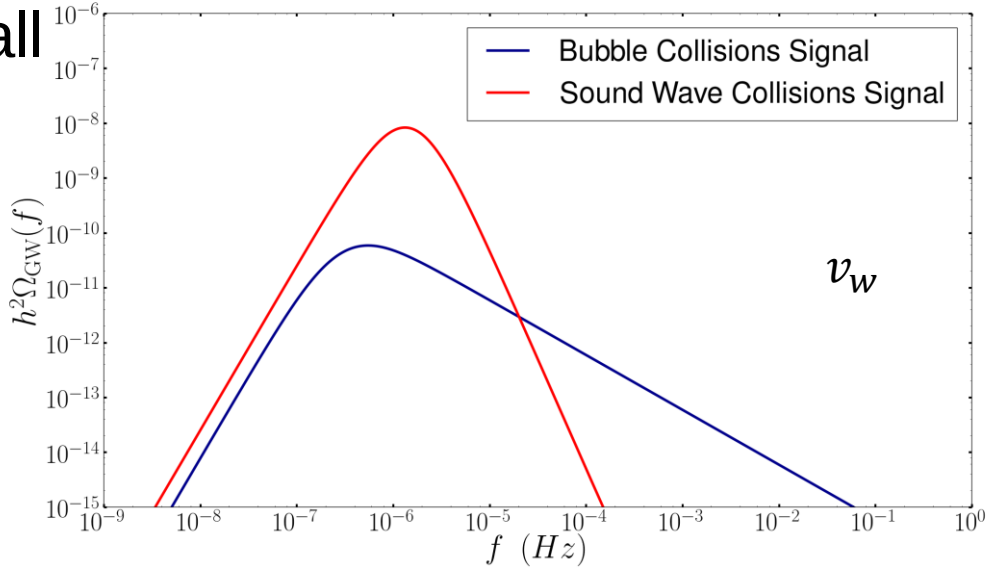
- Interact with SM via gravity as normal
- SM (e.g. visible sector) drives expansion of universe
- Can provide dark matter candidates

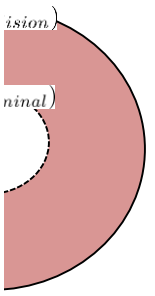
3) Bubble wall dynamics

Runaway bubble walls

Runaway wall







- Energy stored into plasma via friction

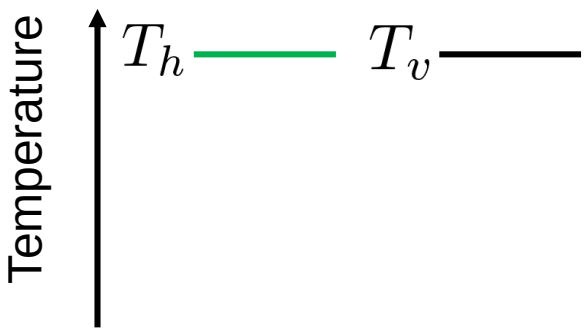
- Bubble wall dominated GW signal
- Sound wave dominated GW signal

Different spectral shapes = learn something about origin of signal?

3) Bubble wall dynamics

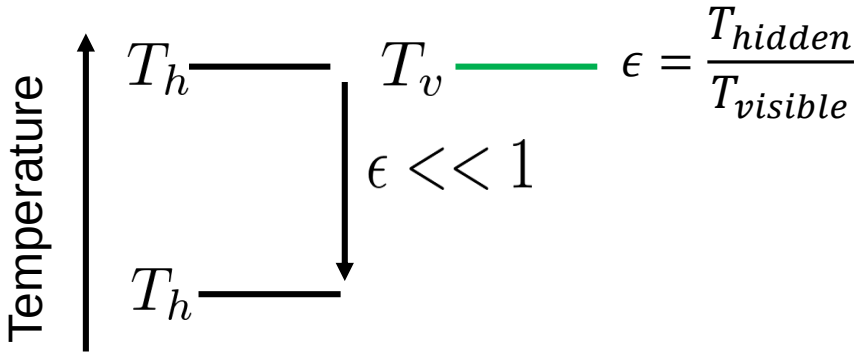
Are runaway walls possible?

Thermal Transition with $T_{hidden} \approx T_{visible}$



- Friction fixed by T_{hidden}
- Runaway walls unlikely in a thermal transition!

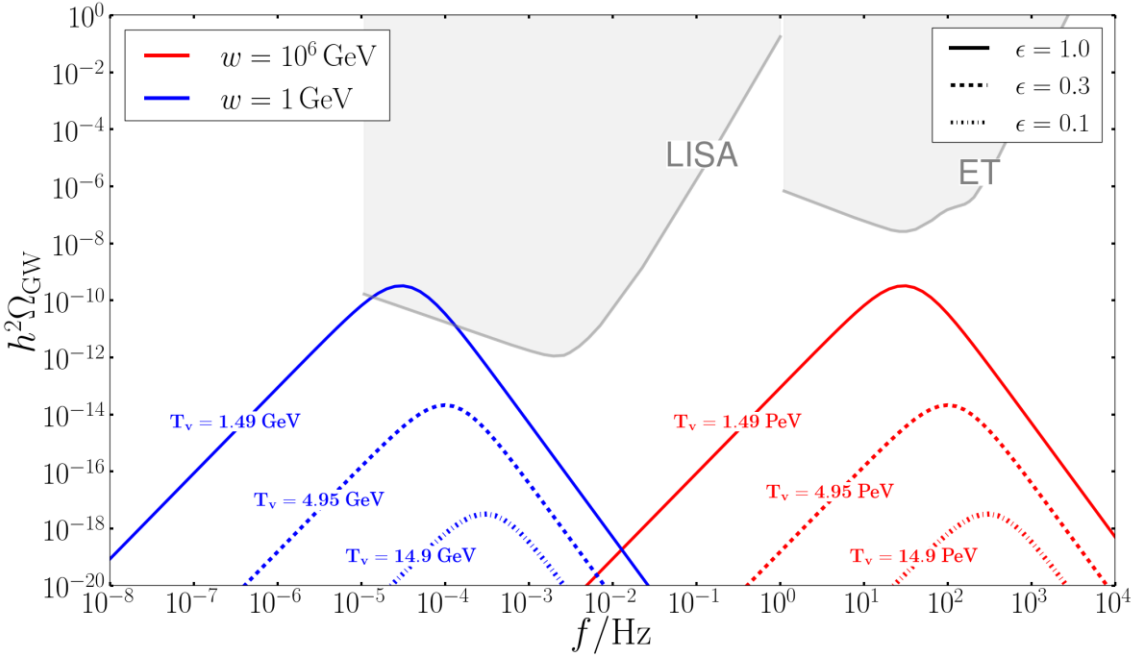
Tunnelling Transition with $T_{hidden} << T_{visible}$



- Hidden sector can be arbitrarily cold
- Low friction means runaway walls possible!

4) Gravitational Waves

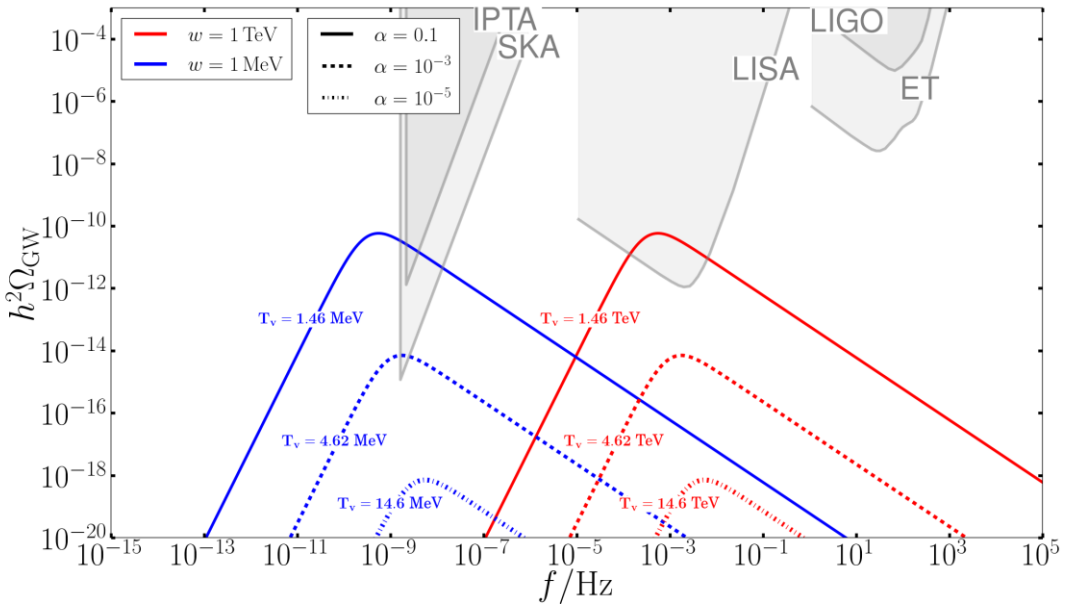
A thermal phase transition



- Decreasing $\epsilon = \frac{T_{hidden}}{T_{visible}}$ heavily suppresses signal
- Sound Wave dominated signal

4) Gravitational Waves

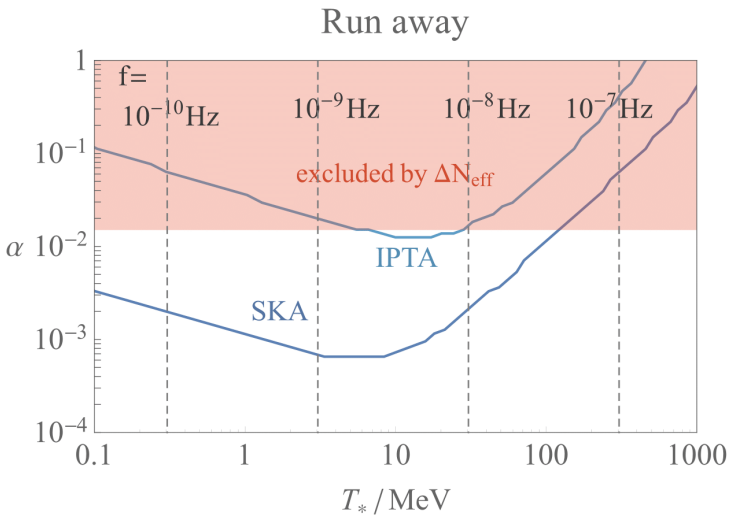
A tunnelling phase transition

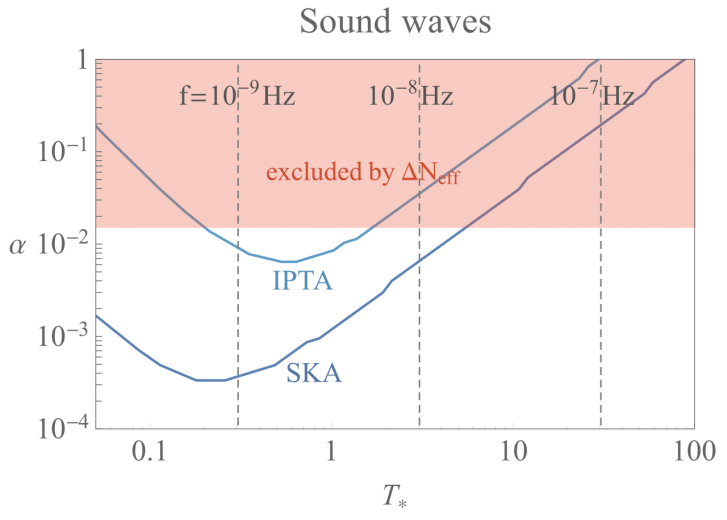


- $\epsilon = \frac{T_{hidden}}{T_{visible}} \ll 1$ and you still get an observable signal
- Pure bubble collision signal as friction negligible

4) Gravitational Waves

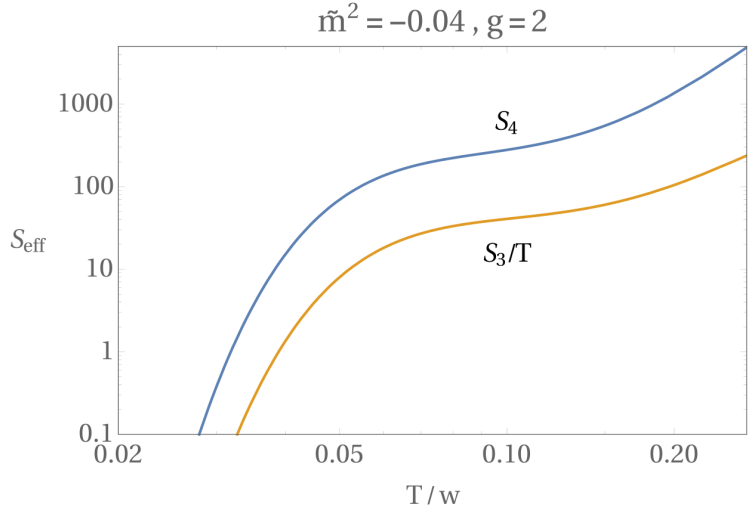
Detecting a signal at a frequency ruled out by BBN





- PT cannot happen $T_* \leq 10$ MeV due to BBN constraints
- Detecting a signal in this region could be a signature of a cold hidden sector

Appendix



5) Summary

- Runaway bubbles from a first order phase transition are generically possible in situations where you have a very cold hidden sector
- Observing a bubble collision dominated GW signal could provide a smoking gun signature of a tunnelling phase transition in a very cold hidden sector
- Further detection prospects: observing a GW signal in a frequency ruled out by BBN could indicate a thermal phase transition in a cold hidden sector

Thanks for listening!

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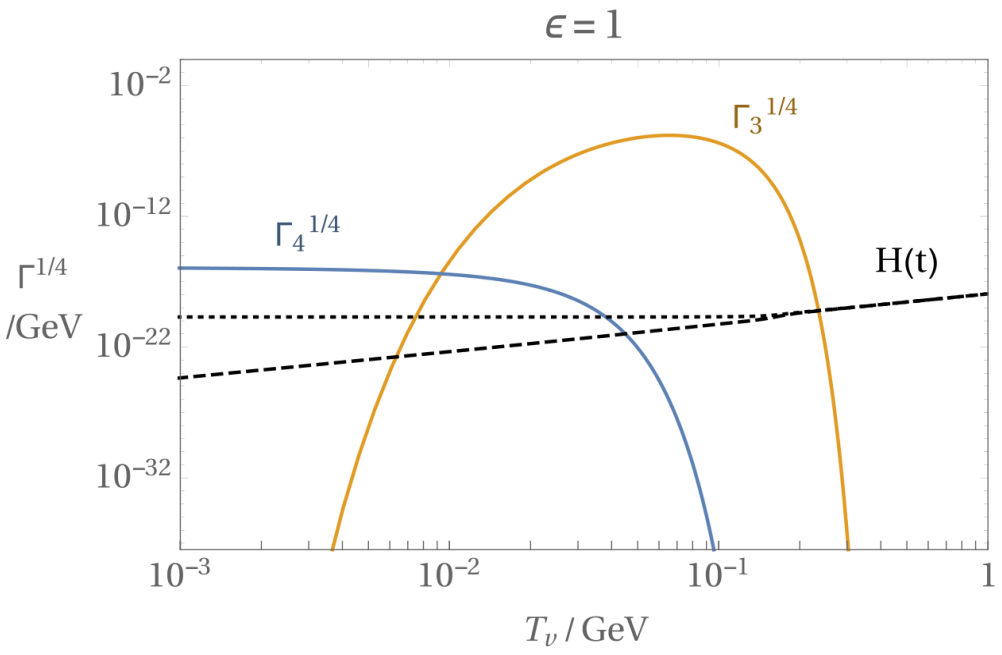
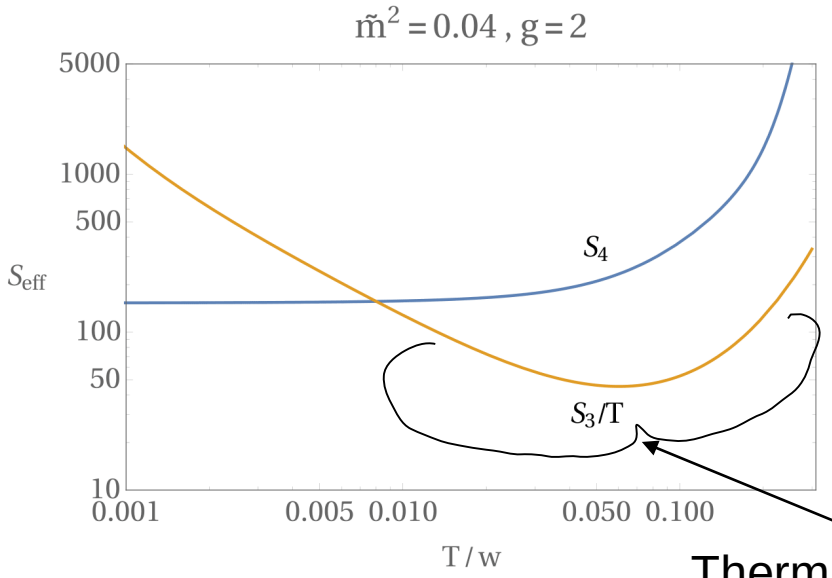

$\epsilon = 1$
10^{-2}
10^{-12}
10^{-22}
10^{-32}
$\Gamma^{1/4}$
/GeV
$\Gamma_3{}^{1/4}$
$\Gamma_4{}^{1/4}$
H(t)
10^{-3}
10^{-2}
10^{-1}
1
T_ν / GeV

Radial profile of hidden scalar field

Thermal Nucleation Rate vs Tunnelling Nucleation Rate

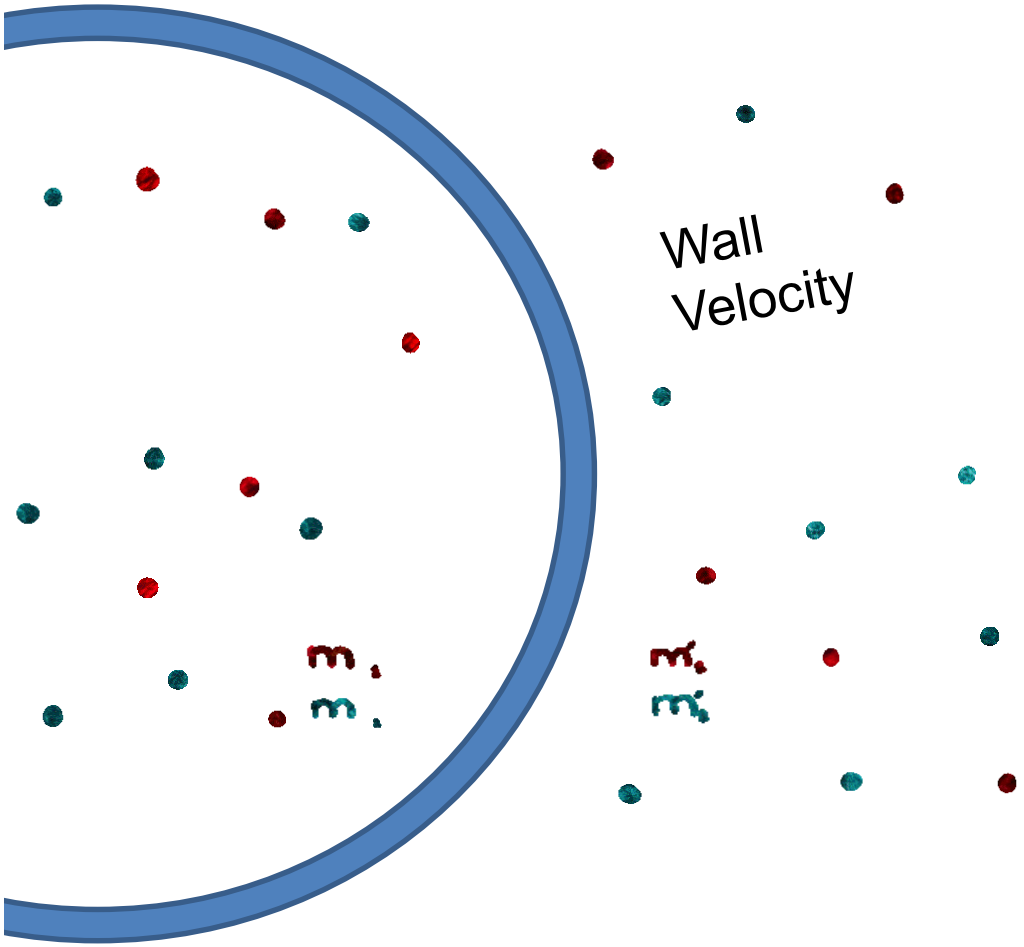


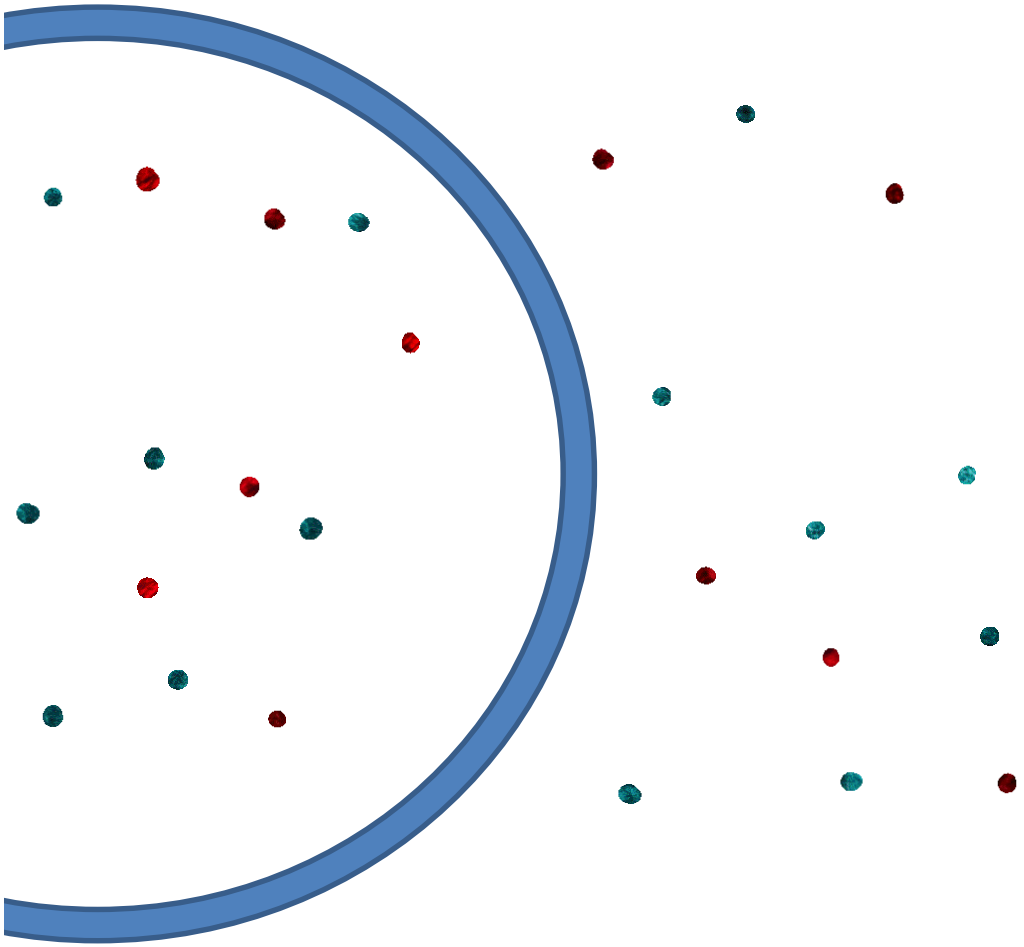
- Thermal transition favoured at high temperatures around T_h ~ w GeV.
- But thermal nucleation rate is suppressed at low temperatures as barrier height is no longer decreasing
- The lower the barrier the higher the tunneling bubble nucleation rate
- Tunnelling nucleation rate is temperature independent below T_h < w when it tunnels only through the zero temperature potential

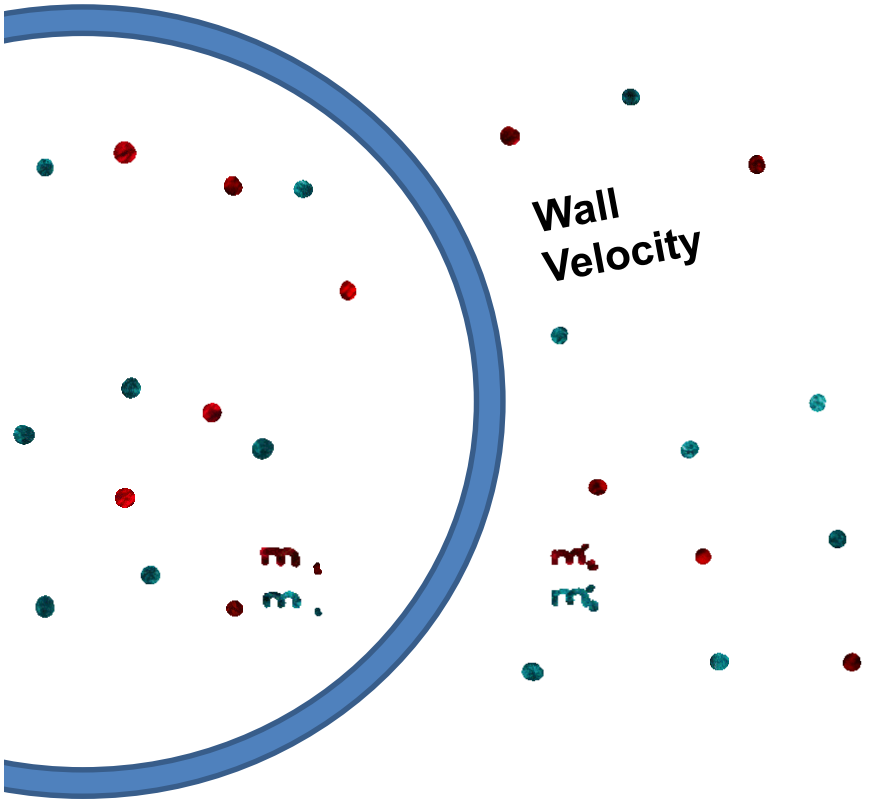
Thermal transition window

Key point:

-
- Tunnelling transitions can only happen at fixed visible sector temperature, as tunnelling nucleation rate is constant below T_h < w. Thus need to wait for Hubble rate which is based on visible sector temerature, to come down to match nucleation rate

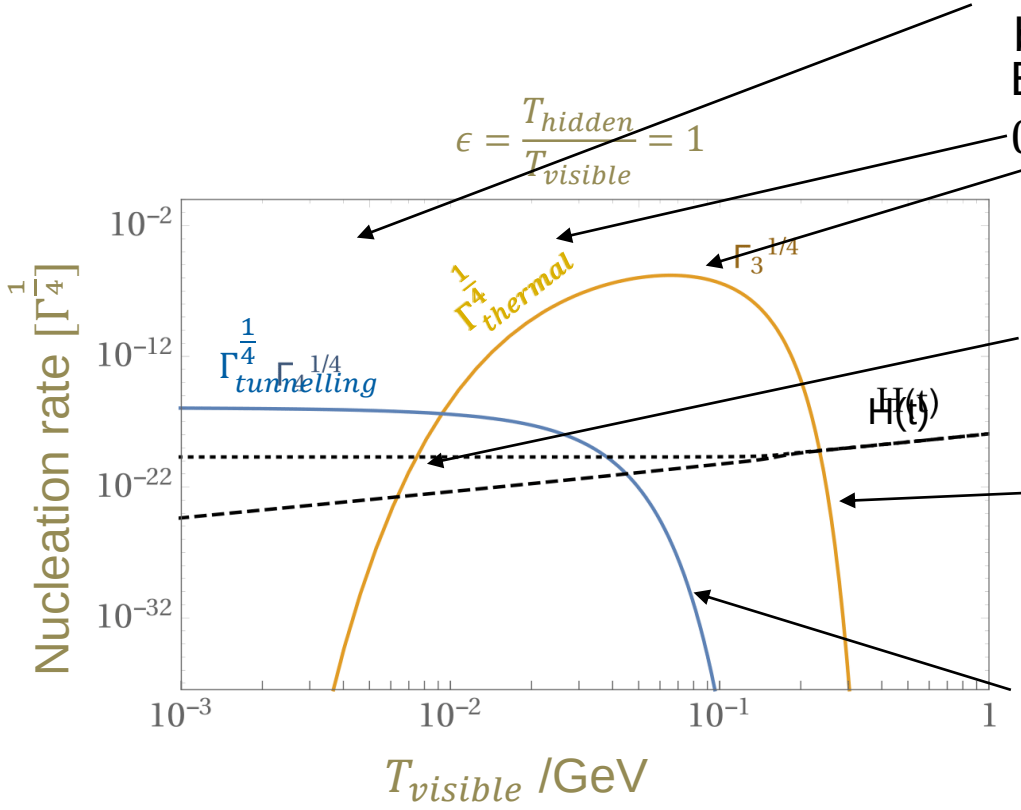

Wall
Velocity
m1
m2
m1'
m2'




Wall
Velocity
m_1
m_2
m_1
m_2

2) Phase transitions

Thermal transitions when $T_{hidden} = T_{visible}$



Tunnelling nucleation rate stays constant below $T_{hidden} \lesssim 0.02$ GeV

Barrier height stops changing much below 0.02 GeV

Sweet spot for thermal fluctuations

Not enough energy in hidden plasma for thermal fluctuations

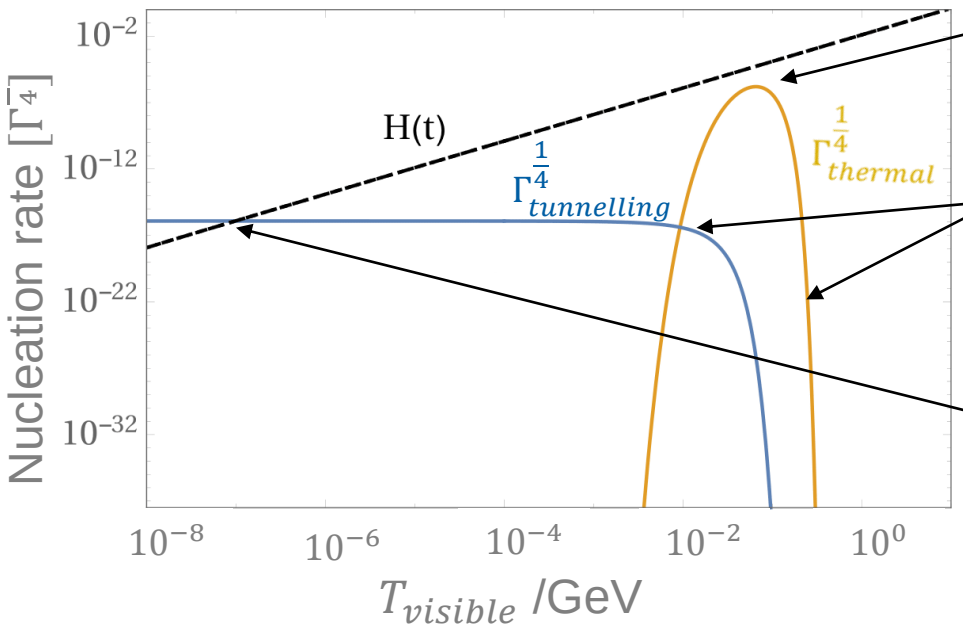
Barrier too high for thermal fluctuations

Tunnelling becomes easier with decreasing barrier height

Thermal phase transition takes place at **fixed** $T_{hidden} \approx 0.2$ GeV

2) Phase transitions

Tunnelling transitions when $T_{visible} \gg T_{hidden}$

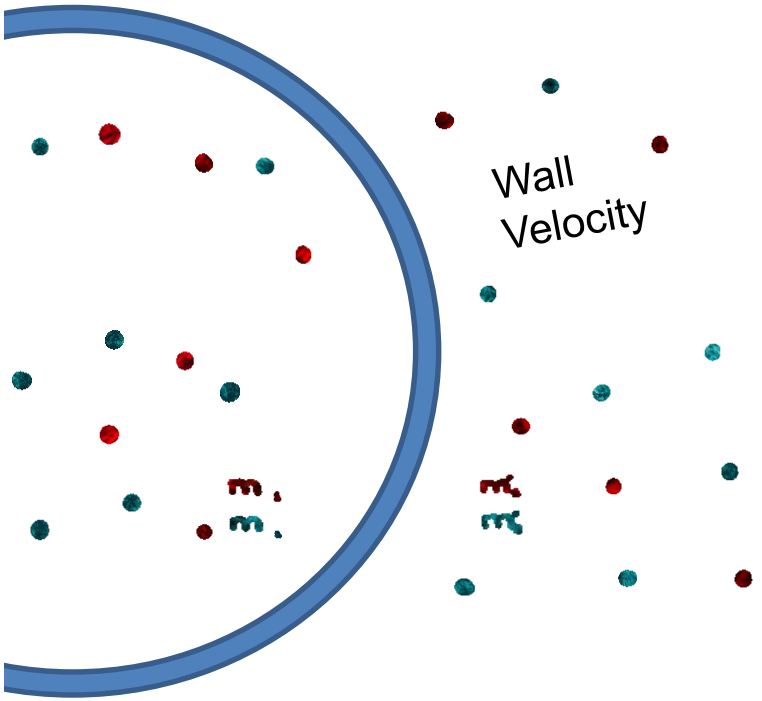


Hubble is too large so thermal transition window is missed

Nucleation rate of bubbles is happening at same T_{hidden} as previous case!

Tunnelling transition happens later at a **fixed $T_{visible}$**

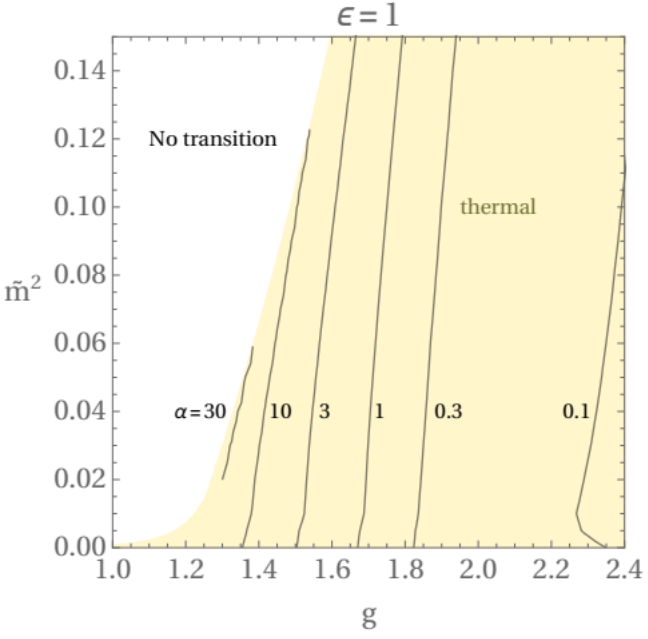
The wall velocity



- v_w - the bubble wall velocity at collision. Can be expressed as the

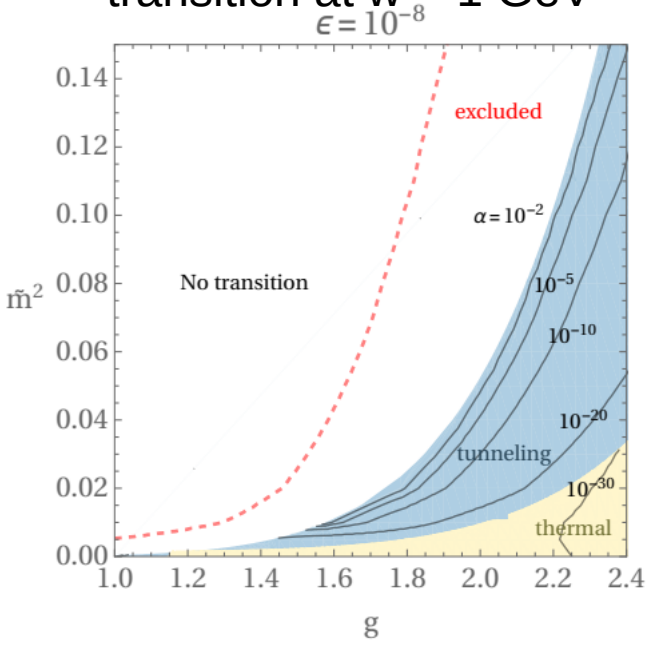
Transitions in hot & cold hidden sectors

Hot hidden sector transition at w=1 GeV



Thermal transition takes place!

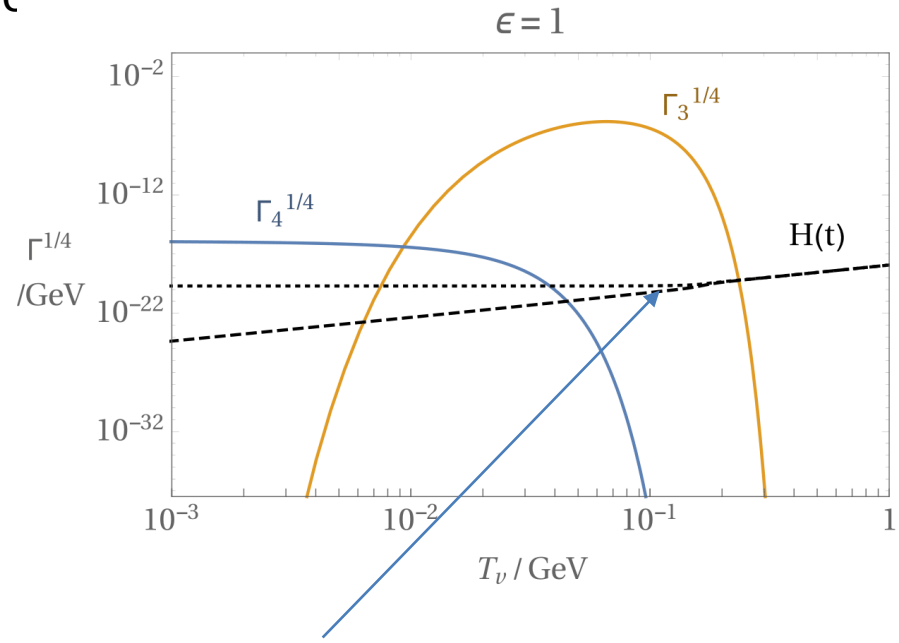
Cold hidden sector transition at w = 1 GeV



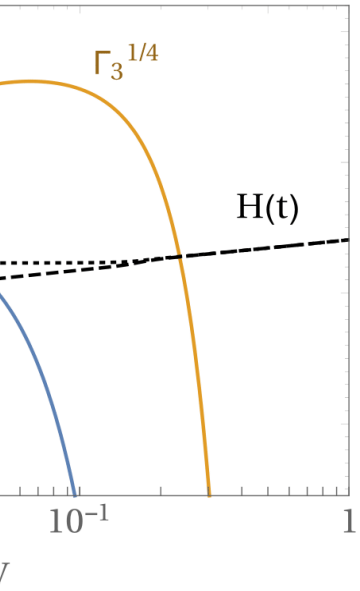
Thermal transition missed and tunneling transition takes place at later time!

Thermal transitions when both sectors are at similar temperatures

- Requires thermal nucleation rate > Hubble rate
- Happens at fixed *hidden sector temperature* T_h~ w
- In most scenarios thermal transitions are favoured



Temperature at which point at which hidden sector vacuum energy begins to dominate

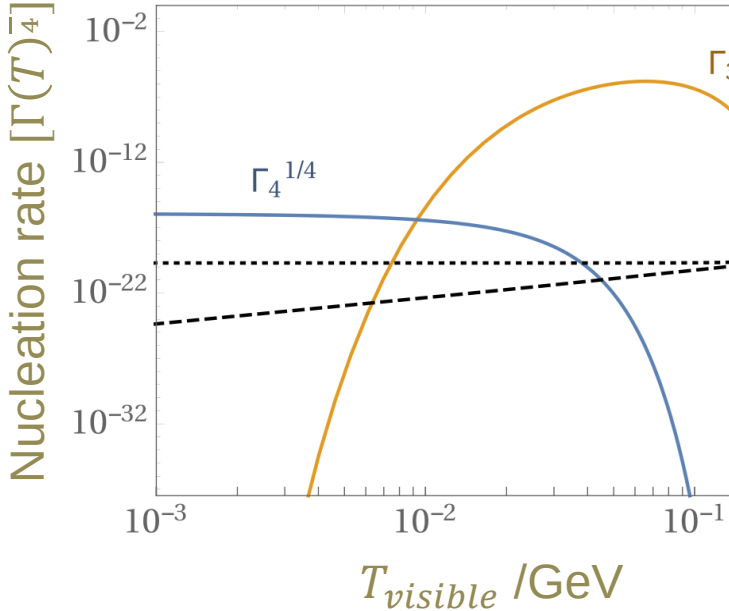


$\Gamma_{tunnel}^{\frac{1}{4}}$

$\epsilon = \frac{T_{hidden}}{T_{visible}} = 1$

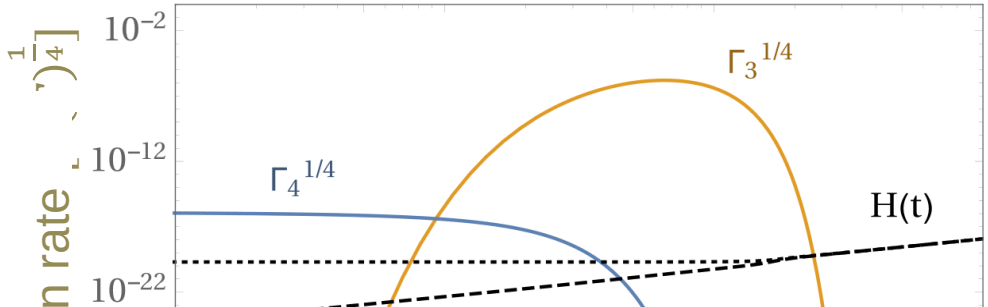
$\Gamma_{thermal}^{\frac{1}{4}}$

$\epsilon = \frac{T_{hidden}}{T_{visible}} = 1$

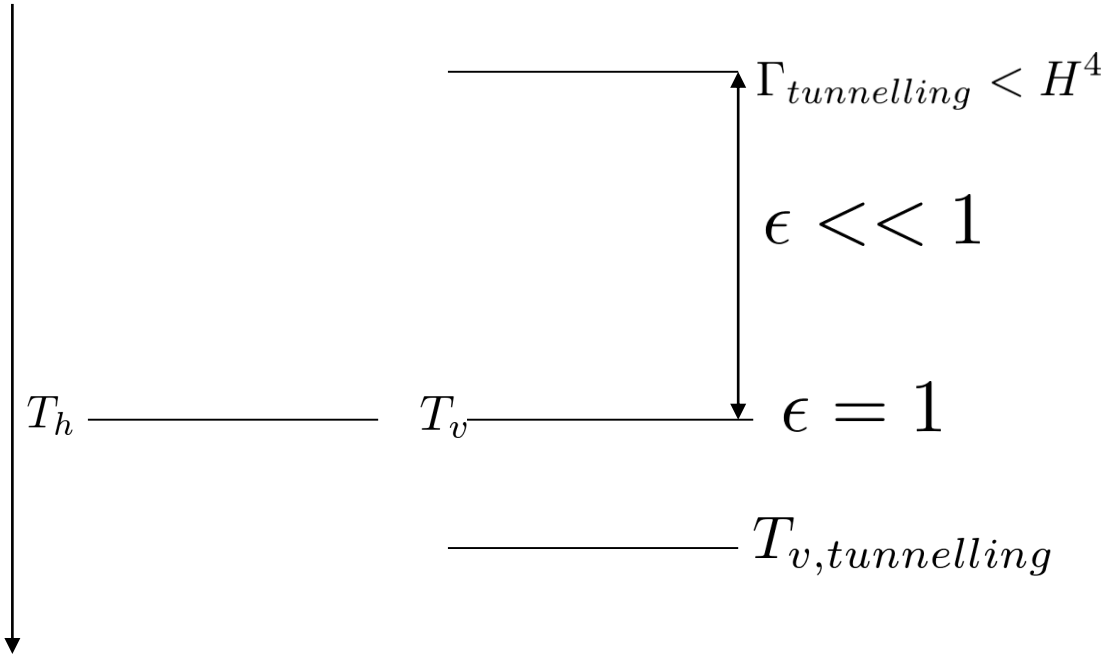


eV

$\epsilon = \frac{T_{hidden}}{T_{visible}} = 1$



Visualising cold hidden sectors



Friction on the bubble wall

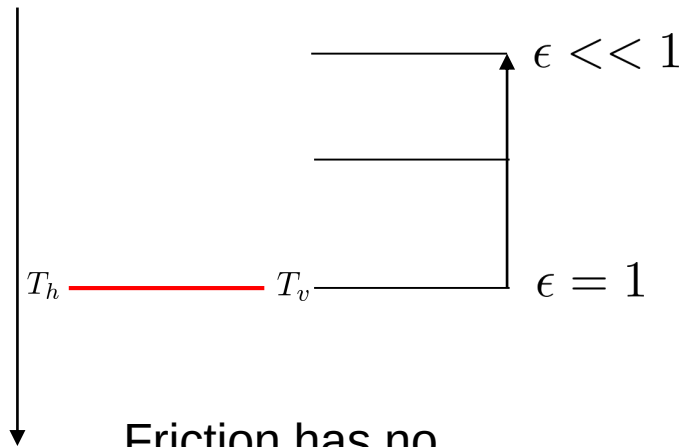
The wall velocity can be described by a differential equation: dv/dt = 1/sigma*gamma^3(rho_vac P_fr). P_fr depends on the hidden sector temperature.

- Thermal transition
- Thermal transition must happen at T_h ~ w
- Friction fixed at T_h ~ w
- Epsilon not a relevant parameter as decreasing it only serves to make visible sector hotter which has no effect on the friction
- Generally do no get runaway walls in thermal transitions

- Tunnelling transition
- Tunnelling transition happens at fixed visible sector temperature
- Can vary epsilon as we like
- Decreasing epsilon decreases the temperature of T_h relative to the fixed T_v
- Thus friction decreases and we go from GW sourced by sound waves to GW sourced by bubble collisions

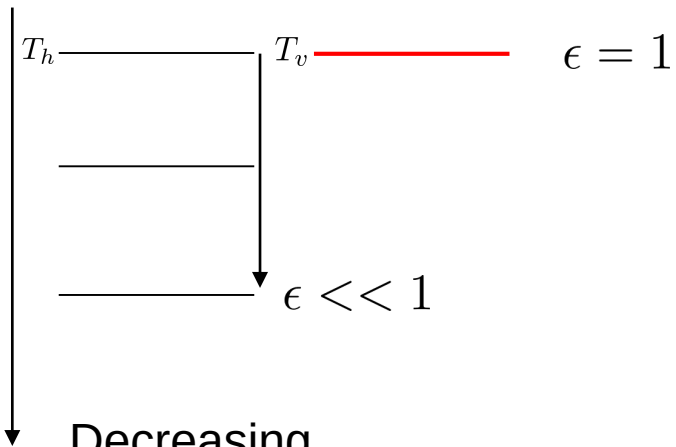
Visualising friction

Thermal Transition



Friction has no dependence on epsilon

Tunnelling Transition



Decreasing epsilon decreases friction

associated hi
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down. Vice-ve
diagram.

Two types of Transition

Tunnelling transition

- Quantum tunnelling through the barrier
- Happens when $\Gamma_{tunnel}(T_*) > H(T_*)$

Thermal Trans

- Thermal fluctuations
- Happens when Γ_{therm}

Plan of slides

1) Intro :
2) What is a first order PT & how does it take place….. Have one diagram or sequence of diagrams that summarises everything from beginning to end! Include example potential in diagram and chat about its dependence on temperature
3) What are the sources of GW (sound waves vs bubble collisions) & what are the key parameters that affect them (e.g. beta/H, alpha, wall velocity etc.)
4) Summarise literature/simulations of which signal dominates in most models? Can bubbles runaway and thus we get bubble collision signal dominating? I aim to show you that in a class of theories where you have a hidden sector that is cold relative to the visible sector you can get runaway walls and bubble collision signal (which has different spectral shape!

1) Hidden sectors and our Model:
2) Cold hidden sectors and how one generates temperature ratio. Briefly discuss cosmological constraints.
3) Set up hidden sector model, describe potential (nearly conformal) and particle content
4) Thermal PT's vs Tunnelling PT's
5) a) Tunneling action vs Thermal action (show plots) & describe gamma_s4 vs gamma_s3 (has to match Hubble)
6) c) KEY POINT: Thermal happens at T_h=w whilst tunnelling happens at a fixed value of T_v for any given point in parameter space
7) Tunnelling and thermal transitions in hot and cold hidden sectors (show contour plots). Missing the thermal transition when hidden sector is cold!

1) GW parameters and GW spectrum:
2) Beta/H_* for Tunnelling and thermal transitions in hot and cold hidden sectors
3) Describe alpha briefly
4) Runaway vs non-runaway walls (affects spectrum)
5) a) Frictional effects and showing diagram of when depositing of energy into plasma becomes efficient after gamma_terminal.
6) a) Friction & runaway in thermal transitions (show GW plot)
7) b) Friction & runaway in tunnelling transitions (show GW plot)
8) Summarise