Superheavy Dark Matter Production from Symmetry Restoration First-Order Phase Transition During Inflation

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arXiv:2208.14857 [hep-ph]

Outline

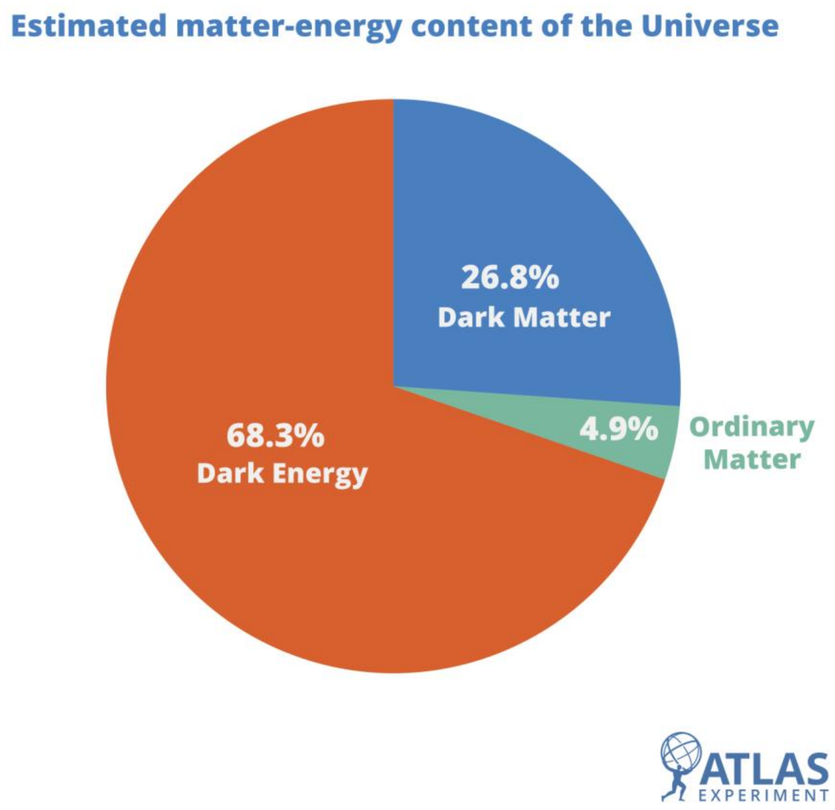
Superheavy Dark Matter

Symmetry Restoration First-Order Phase Transition During Inflation

Observational Signatures: Stochastic gravitational wave background

Conclusion and Outlook

Dark Matter



Most (85%) of the matter in our universe is made of dark matter

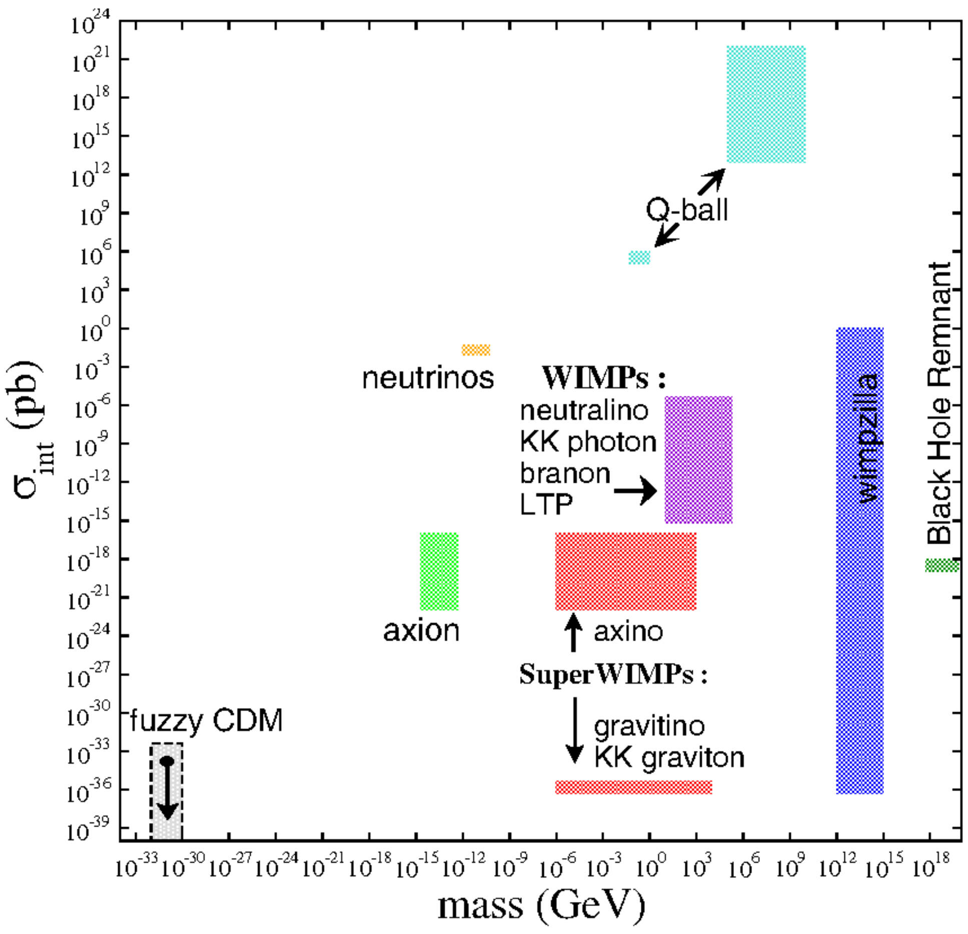
Does not interact with the electromagnetic field

Has huge influence on cosmology & large scale structure

We know its existence through its gravitational effects

ΛCDM **Cosmology**
68.3% Dark Energy
26.8% Dark Matter
4.9% Ordinary Matter

Dark Matter



Many dark matter candidates

Wide range of masses & cross sections

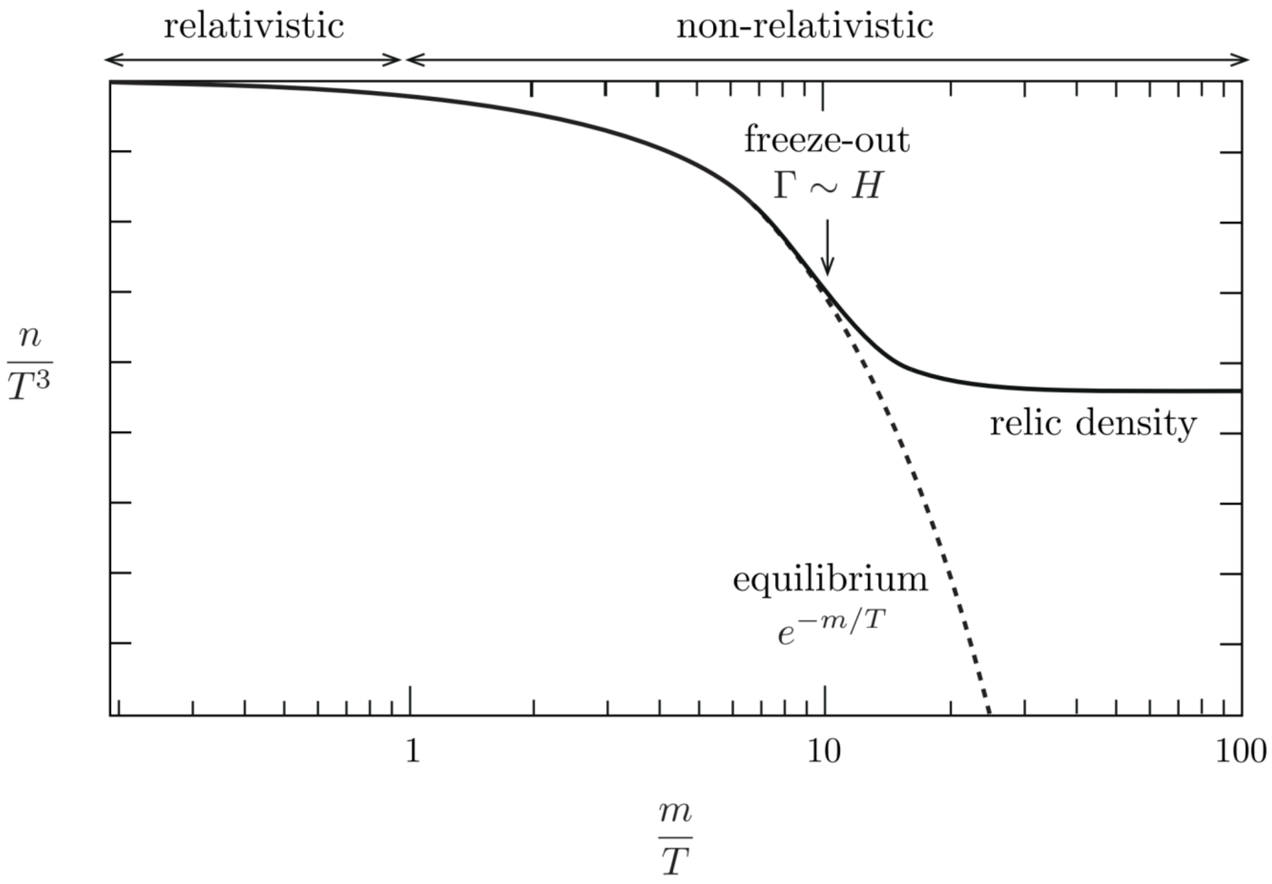
The nature of dark matter and its production mechanism remains unknown

Particle vs wave?

Most popular dark matter model
Weakly Interacting Massive Particles (WIMPs)

WIMPs are produced from the early universe through the freeze out mechanism

Freeze Out Mechanism

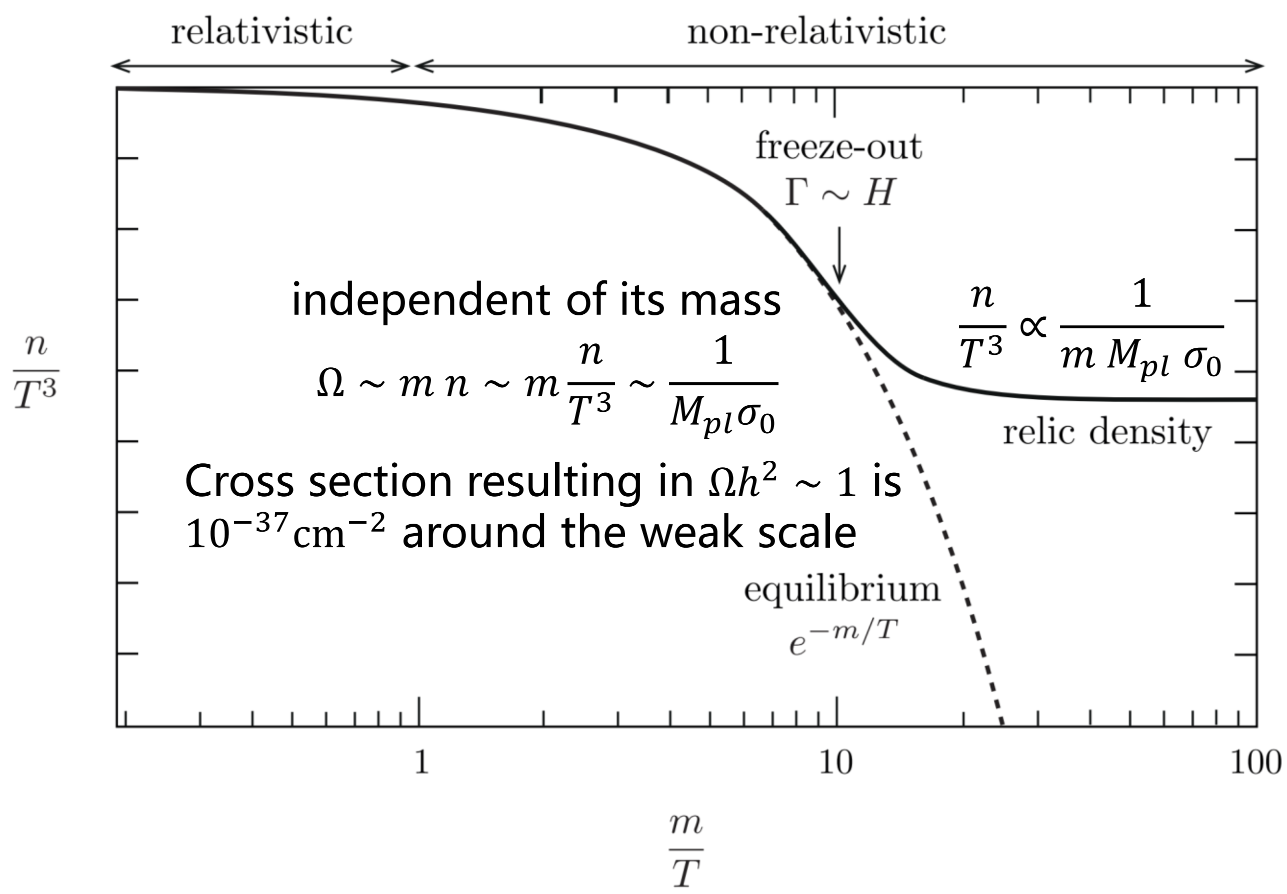


Daniel Baumann: Cosmology

The early universe was in local thermal equilibrium
$\Gamma > \mathrm{H}$ $t_{int} < t_H$ **(coupled)**

During expansion, the rate of expansion of the universe becomes larger than the rate of interaction particles fall out of thermal equilibrium
$\Gamma < \mathrm{H}$ $t_{int} > t_H$ **(decoupled)**

Freeze Out Mechanism

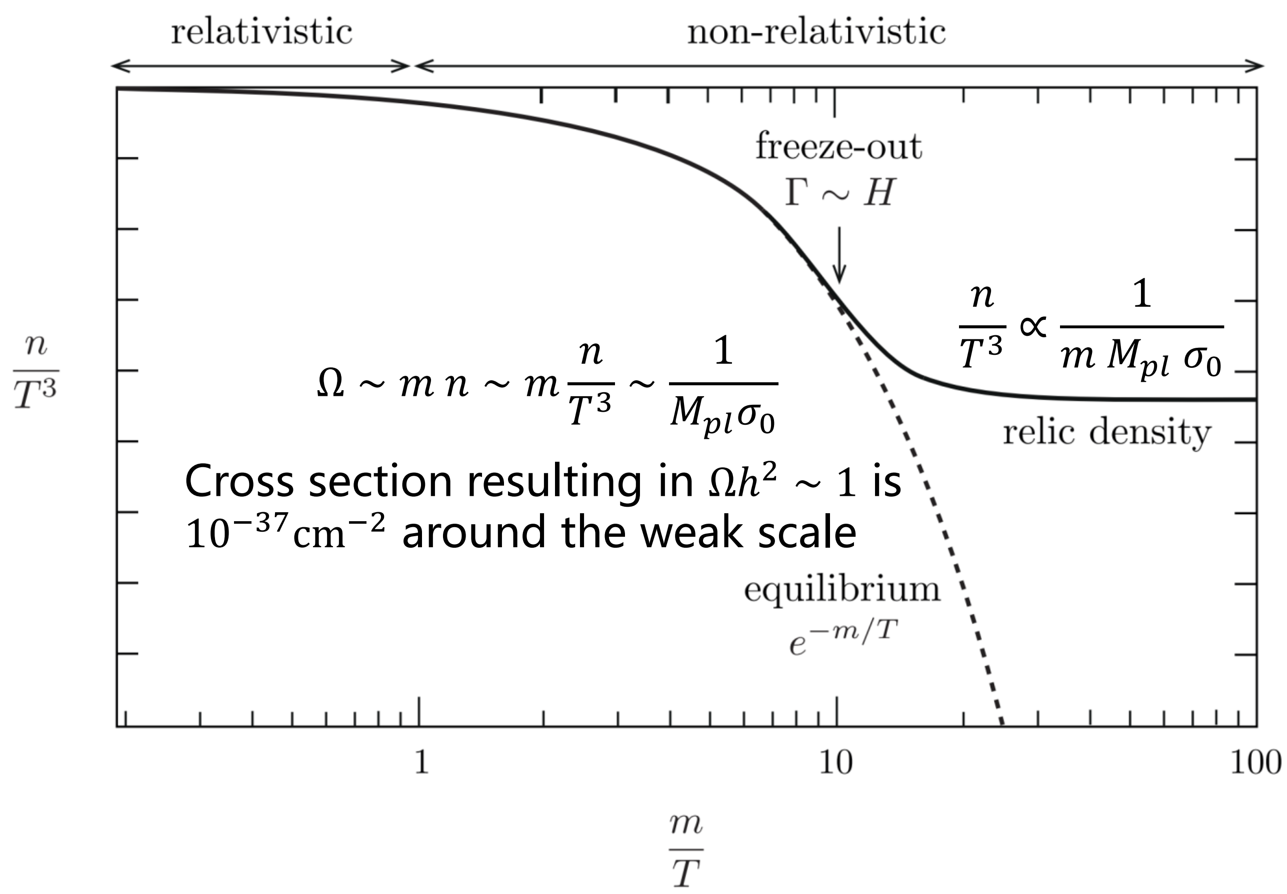


Daniel Baumann: Cosmology

At high temperatures, T >>m, the particle abundance tracks its equilibrium value

At low temperatures, T <<m, the particles freeze out and maintain a density that is much larger than the Boltzmann-suppressed equilibrium abundance

Freeze Out Mechanism



Cross section resulting in $\Omega h^2 \sim 1$ is $10^{-37}\mathrm{cm}^{-2}$ around the weak scale

$$\sigma_0 \propto \frac{1}{m^2}$$

Large m : Relic abundance is too large

A maximum mass for a thermal WIMP, which turns out to be $O(100)$ TeV

Mass cannot be too large

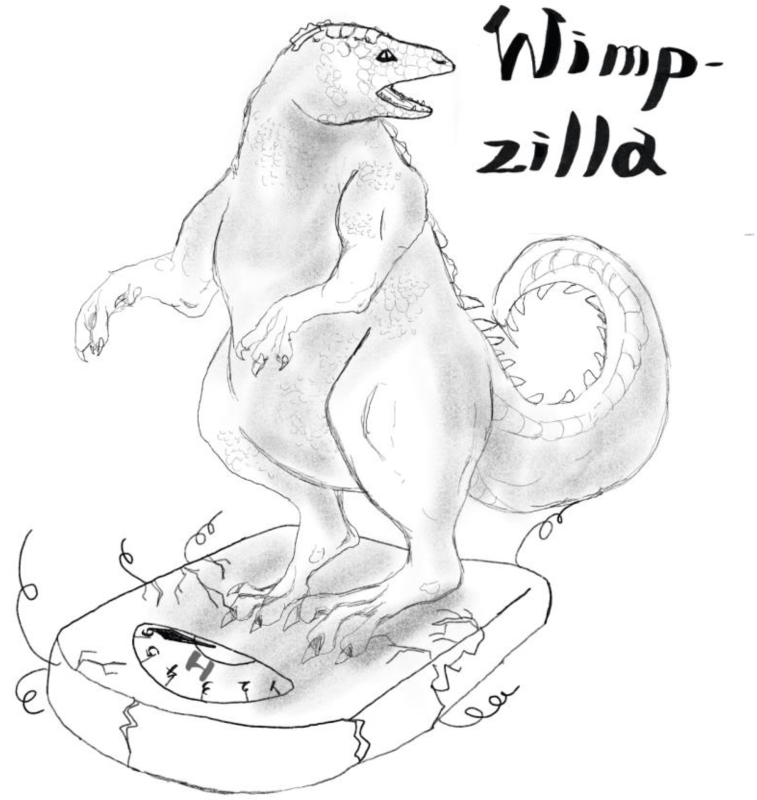
Mass ~ weak scale
Interaction with ordinary matter ~ weak scale

Thermal WIMPs

Superheavy Dark Matter

What about superheavy dark matter?

Non-thermal WIMPS!



Superheavy Dark Matter

arXiv:hep-ph/9810361v1 14 Oct 1998

WIMPZILLAS!

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Abstract. There are many reasons to believe the present mass density of the universe is dominated by a weakly interacting massive particle (WIMP), a fossil relic of the early universe. Theoretical ideas and experimental efforts have focused mostly on production and detection of *thermal* relics, with mass typically in the range a few GeV to a hundred GeV. Here, I will review scenarios for production of *nonthermal* dark matter. Since the masses of the nonthermal WIMPS are in the range 10^{12} to 10^{16} GeV, much larger than the mass of thermal wimpy WIMPS, they may be referred to as WIMPZILLAS. In searches for dark matter it may be well to remember that "size does matter."

Figure 7. Dark matter may be much more massive than usually assumed, much more massive than wimpy WIMPS, perhaps in the WIMPZILLA class.

Superheavy Dark Matter

Production Time

During inflation

At inflation to matter dominated/radiation dominated era

Production Rate

$m_\sigma \ll H$ $\quad n_\sigma \sim H$ **Ford 1987**

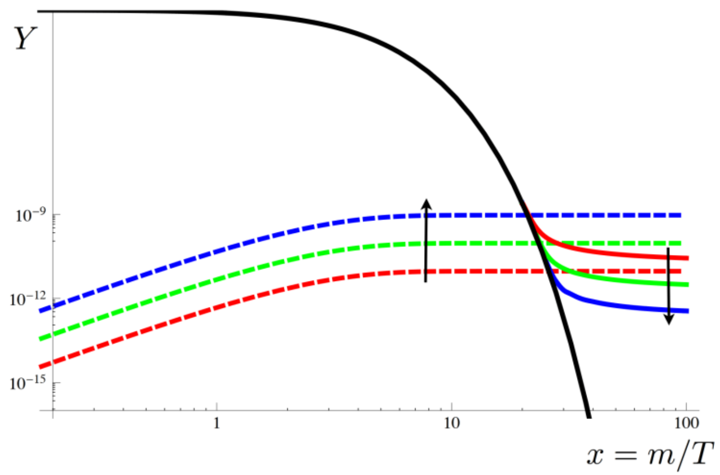
$m_\sigma \gg H$ $\quad n_\sigma \sim \exp(-\# m_X/H)$ **Chung 2003**

$n_\sigma \sim H$ **Ema, Nakayama, Tang 2018**

Production mechanism freeze in

Properties

Stable a lifetime much greater than the age of the universe
Non-thermal it must not have been in equilibrium when it froze out



Superheavy Dark Matter

Action

$$S_\sigma = -\int d^4x \sqrt{-g}[\frac{1}{2}\left(\partial_\mu \sigma\right)^2 + \frac{1}{2} m_\sigma^2 \sigma^2]$$

EOM

$$\ddot{\sigma} + 3H\dot{\sigma} - \frac{1}{a^2}\nabla^2\sigma + M_\sigma^2\sigma = 0$$

Quantization

$$\sigma = \int \frac{d^3k}{(2\pi)^3} e^{ik\cdot x} a^{-\frac{3}{2}}[f_k a_k + f_k^* a_{-k}^\dagger]$$

Superheavy Dark Matter

Each mode satisfies

$$\ddot{f}_k(t) + \omega_k^2 f_k(t) = 0$$

where

$$\omega_k^2 = \frac{k^2}{a^2} + H^2\mu^2 - \frac{3}{2}\dot{H} \qquad \mu \equiv \sqrt{\frac{m_\sigma^2}{H^2} - 9/4}$$

Mode function

The production rate is exponentially suppressed

$$f_k^{in}(t) = \sqrt{\frac{\pi}{4H}}\, e^{-\frac{\pi\mu}{2}} H_{i\mu}^{(1)}(-k\tau) \qquad f_k^{out}(t) = \frac{\left(\frac{2H}{k}\right)^{i\mu}\Gamma(1+i\mu)}{\sqrt{2H\mu}} J_{i\mu}(-k\tau)$$

$$f_k^{in}(t) = \alpha_k f_k^{out}(t) + \beta_k f_k^{out*}(t) \qquad N_\sigma = \int_0^\infty dk\, 2\pi k^2 |\beta|^2 \propto e^{-2\pi\mu}$$

Superheavy Dark Matter

Is there a more efficient superheavy dark matter production mechanism?

Yes

Symmetry restoration first order phase transition during inflation

Enough dark matter can be produced from large latent heat during first order phase transition

Outline

Superheavy Dark Matter

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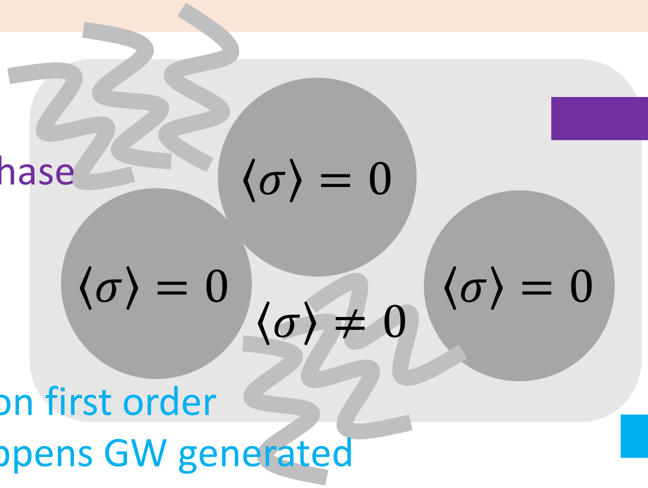
Observational Signatures

Conclusion and Outlook

Symmetry Restoration

Inflation begins
Symmetry broken phase

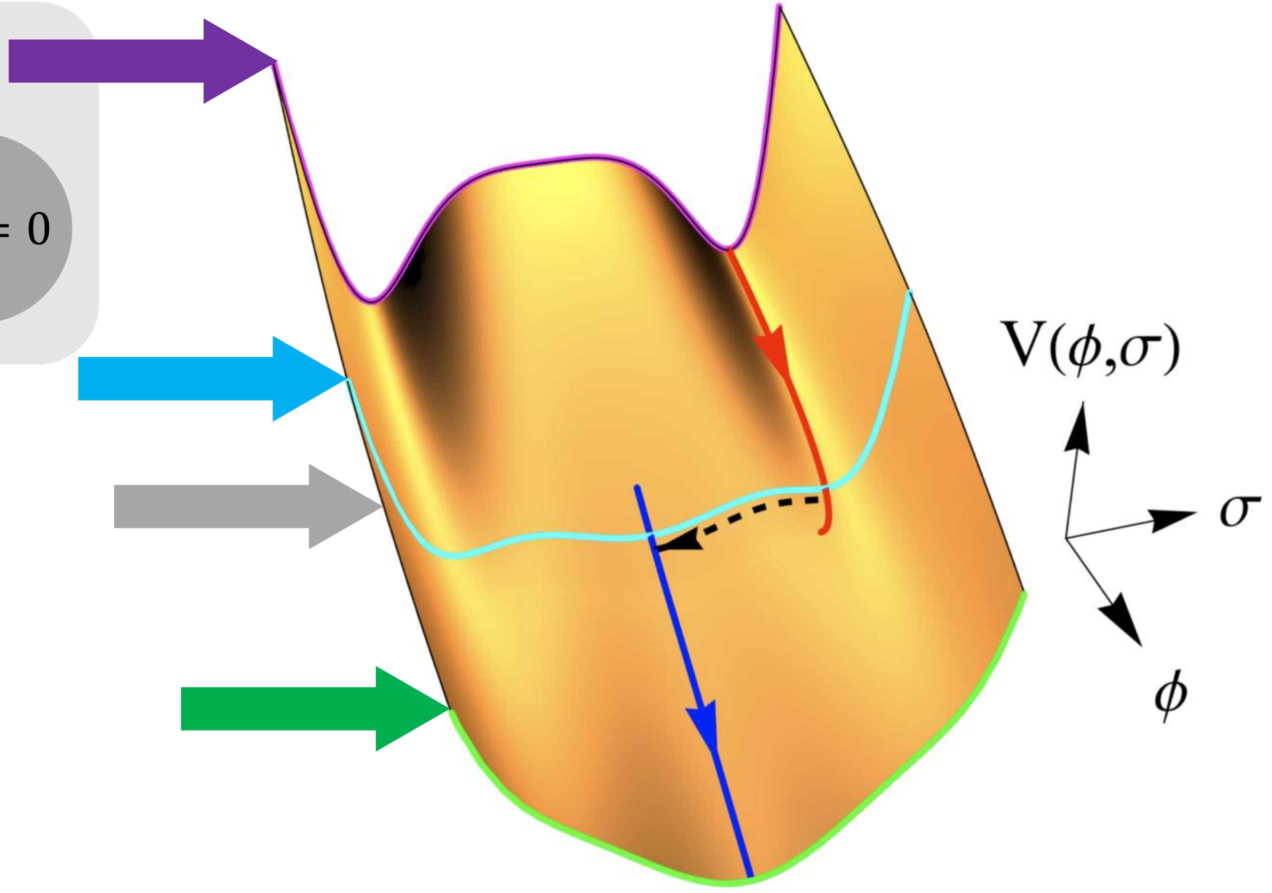


Symmetry restoration first order
phase transition happens GW generated

Dark matter is produced, relativistic

Dark matter becomes non-relativistic

Inflation ends
Symmetry restoration phase



Symmetry Restoration

During inflation, the inflaton field typically travels $\Delta\phi \sim N_e\sqrt{\epsilon}\, M_{pl}$

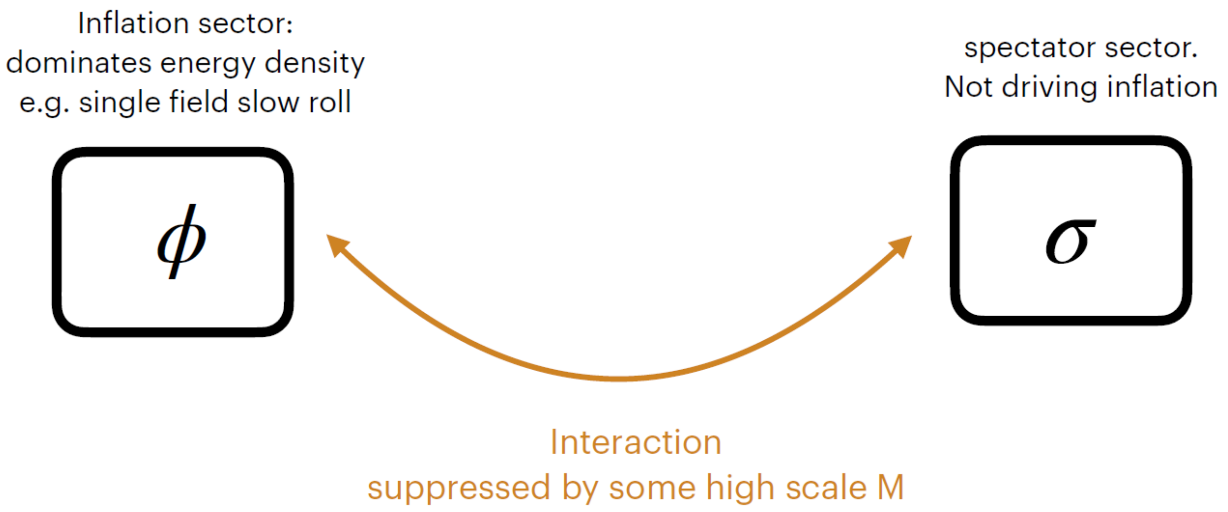
The change in the inflaton field value will induce the change in the effective potential in the σ sector

$$S \equiv \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}(\partial\sigma)^2 - U(\phi,\sigma)\right]$$

$$U(\phi,\sigma) \equiv V(\phi,\sigma) + V_{sr}(\phi)$$

$$V(\phi,\sigma) \equiv \frac{1}{2}\mu_{eff}^2(\phi)\sigma^2 + \frac{\lambda}{4}\sigma^4 + \frac{1}{8\Lambda^2}\sigma^6$$

$$\mu_{eff}^2(\phi) \equiv \mu^2 - c^2\phi^2$$



First Order Phase Transition

Typical mass scale of the σ particle is m_σ

$$\frac{\Gamma}{V_{phys}} = O(1) \times m_\sigma^4 e^{-S_4}$$

S_4 is the classical action of the bounce solution

β describes how fast the phase transition happens

$$\beta \equiv -\frac{dS_4}{dt} = O(100)\left|\frac{\dot{\phi}}{\phi - \frac{\mu^2}{c^2\phi}}\right|$$

Require that phase transition happens sufficiently fast so that inflation cannot tear the bubbles apart

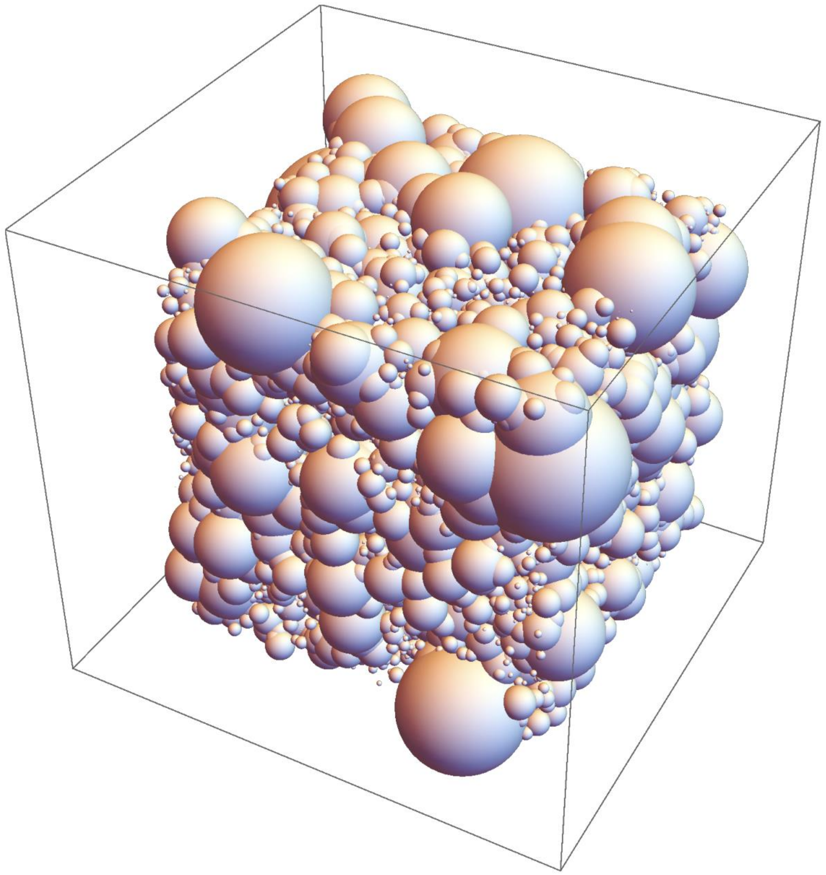
$$m_\sigma^4 \gg \beta^4$$

The energy density of the spectator sector is subdominant

$$m_\sigma^4 \sim V(\phi,\sigma) \ll V_{sr}(\phi) \sim M_{pl}^2 H^2$$

σ particles are formed in the Z_2 symmetric phase

σ particles are stable and can be the dark matter candidate



First Order Phase Transition

Latent heat $L \equiv \gamma_{PT} m_\sigma^4 \quad \gamma_{PT} \leq 0.6$

$$\gamma_{PT} m_\sigma^4 = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \sqrt{m_\sigma^2 + \mathbf{p}^2}\, e^{-\frac{\sqrt{m_\sigma^2+\mathbf{p}^2}}{T}}$$

Just after the phase transition ends

Highly relativistic $\gamma_{PT} \leq 0.6 \;\; \mathrm{T} = 1.2 m_\sigma \quad \bar{E} = 4 m_\sigma$

After a while

Marginal relativistic $\bar{E} = 2 m_\sigma \;\; \mathrm{T} = 0.48 m_\sigma \;\; \gamma_* \simeq 0.01$

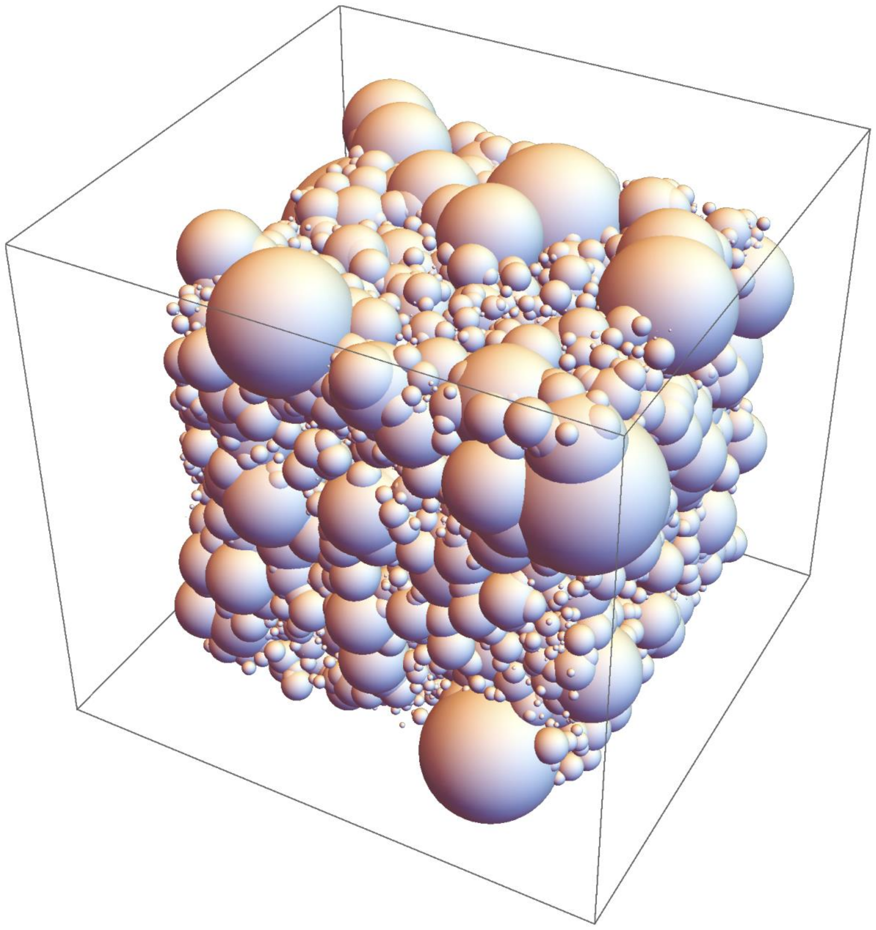
Dark matter relic abundance

$$\rho_{DM}^{(0)} = \Omega_\sigma \rho_0 = \frac{0.11923}{0.68^2} \left(3 M_p^2 H_0^2\right) \hbar^2 c^4 = \left(1.76 \times 10^{-12} \mathrm{GeV}\right)^4$$

The energy density of dark matter today

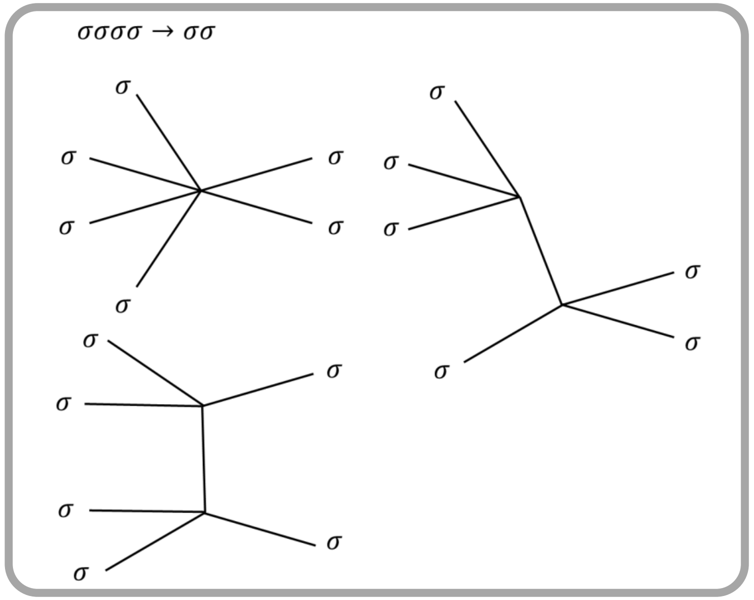
$$\rho_\sigma^{(0)} \sim \gamma_* \times m_\sigma^4 e^{-3\left(N_{today} + N_{PT} - \frac{1}{4} \ln(\gamma_{PT}/\gamma_*)\right)} \qquad \rho_\sigma^{(0)} = \rho_{DM}^{(0)}$$

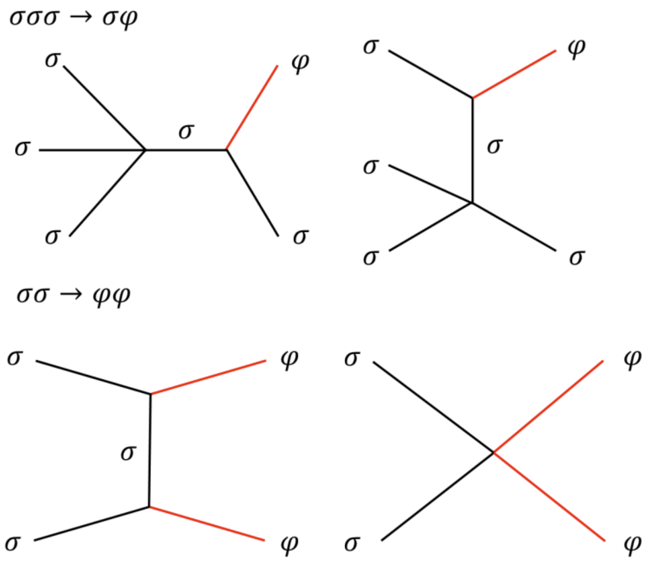
Typical parameter choice $H = 10^{12} \mathrm{GeV} \;\; N_{today} = 65 \;\; N_{PT} = 18$

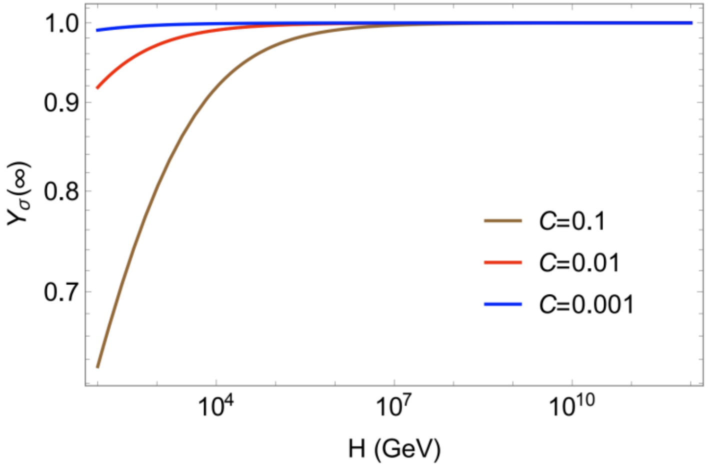


Dark Matter Decay Rate

Particle number decreases! Decay channels







$$Y_\sigma(t) = \frac{n_\sigma(t)a^3(t)}{n_\sigma(t_*)a^3(t_*)}$$

$$\frac{dY_\sigma}{dt} \sim C\,\frac{Y_\sigma^4 n_\sigma^3(t_*)}{m_\sigma^8} e^{-9H(t-t_*)} - \frac{Y_\sigma^4 n_\sigma^2(t_*)}{m_\sigma^3 M_{pl}^2} e^{-6H(t-t_*)} - \frac{Y_\sigma^2 n_\sigma(t_*)}{M_{pl}^4} e^{-3H(t-t_*)}$$

Most dominant contribution

Dark Matter Decay Rate

Dark matter decay is protected by global Z_2 symmetry via symmetry restoration first order phase transition

What about symmetry broken first order phase transition?

As long as there are Z_2 symmetry left, there are will be enough dark matter left after the phase transition

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Stochastic Gravitational Wave

Why do we want to study gravitational wave signals?

The universe is transparent to the gravitational wave, so it can give us information about the early universe that electromagnetic wave cannot give

What is stochastic gravitational wave background?

A stochastic background of GWs can be created by the superposition of a large number of independent sources

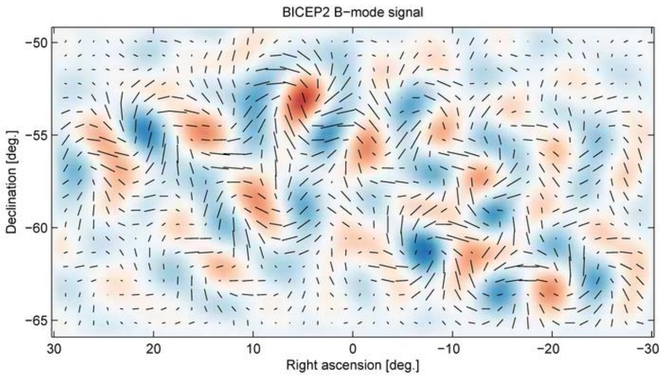
Analogous to the cosmic microwave background (CMB): electromagnetic (EM) record of the early universe

A **stochastic** background of GWs is very different from **transient** GWs (binary inspirals, burst events) or continuous periodic GWs (coming from pulsars). These other sources are sending GWs from **specific locations** in the sky

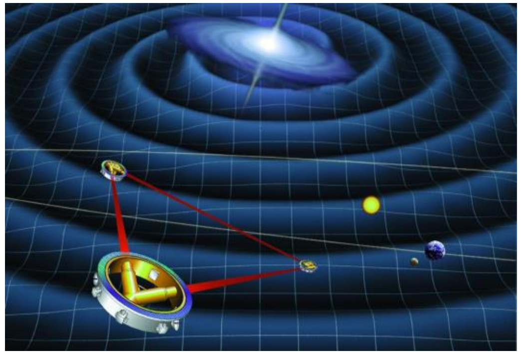
A stochastic background will be coming from **all directions**

Stochastic Gravitational Wave

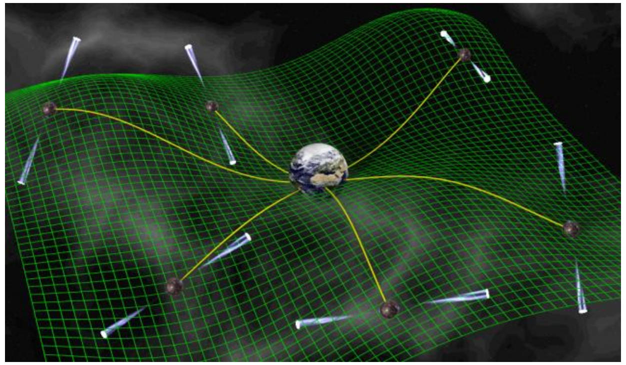
Very low frequency: CMB B mode



Middle frequency: LISA



Low frequency: Pulsar timing array



High frequency: LIGO, VIRGO

Stochastic Gravitational Wave

Sources that can generate stochastic gravitational wave

Inflation Quantum fluctuations of GW that went outside horizon and became classical

Cosmic strings one-dimensional topological defects

First order phase transitions GW from bubble nucleations

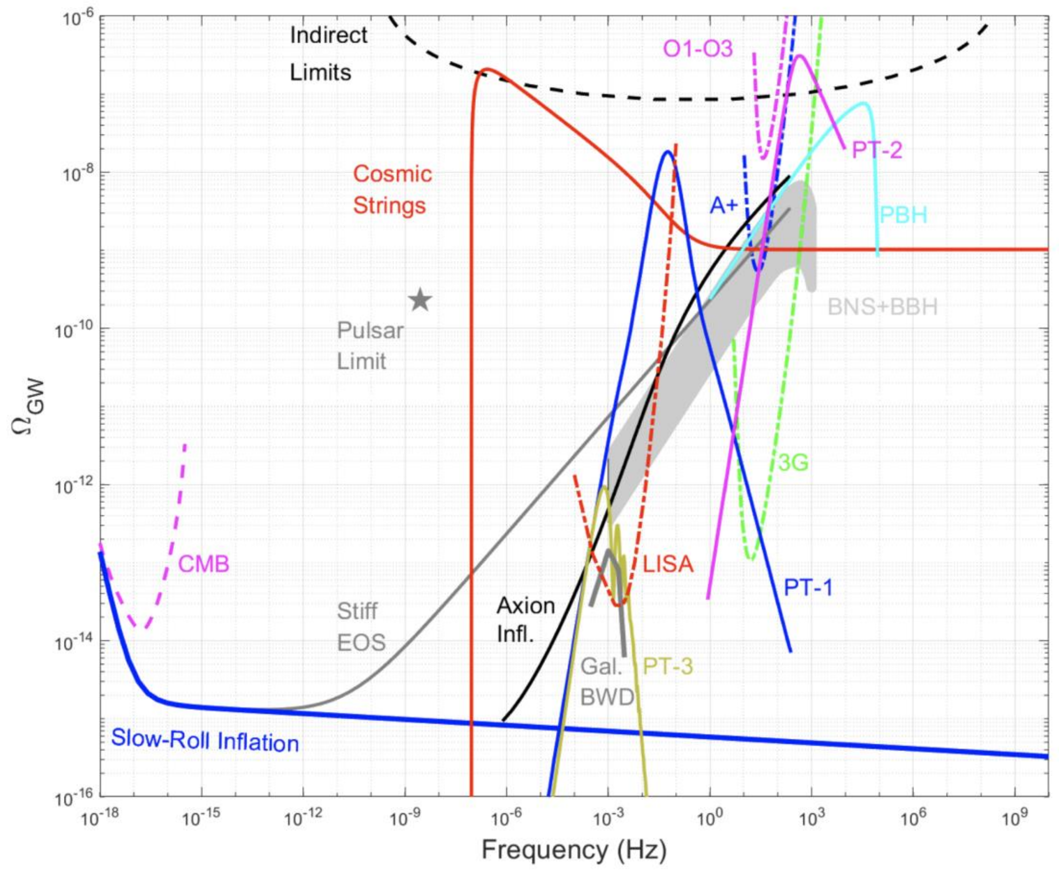
Pre big bang models an extension of the standard inflationary cosmology

Binary black holes GWs

Binary neutron stars GWs

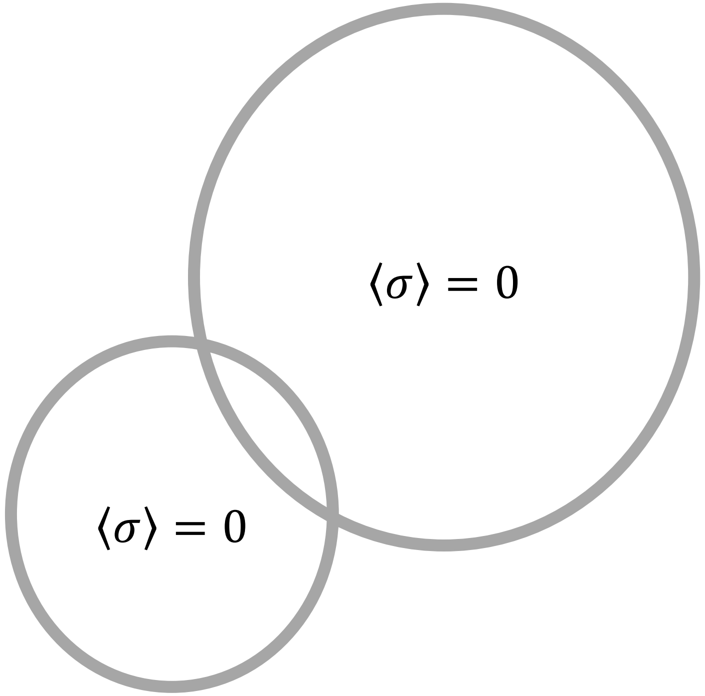
Supernovae if a supernova has some asymmetry, then GWs will be produced

Pulsar and magnetars Non-axisymmetric spinning neutron stars are expected to be a detectable source of GWs



Gravitational wave from first order phase transitions

Gravitational waves can be generated from bubble collisions



The stress-energy tensor in Fourier space

$$\frac{dE_{GW}}{d\omega d\Omega} = 2G\omega^2 \Lambda_{ij,lm}(\hat{\boldsymbol{k}}) T^*_{ij}(\hat{\boldsymbol{k}},\omega) T_{lm}(\hat{\boldsymbol{k}},\omega)$$

The projection tensor

Envelop approximation: assume that the overlap regions where the bubbles have expanded into one another do not contribute substantially to the gravitational radiation

$$T_{ij}(\hat{\boldsymbol{k}},\omega) = \frac{1}{2\pi}\int dt\, e^{i\omega t} \sum_n \int_{S_n} d\Omega \int dr\, r^2 e^{-i\omega\hat{\boldsymbol{k}}\cdot(\boldsymbol{x}_n + r\hat{\boldsymbol{x}})} T_{ij,n}(r,t)$$

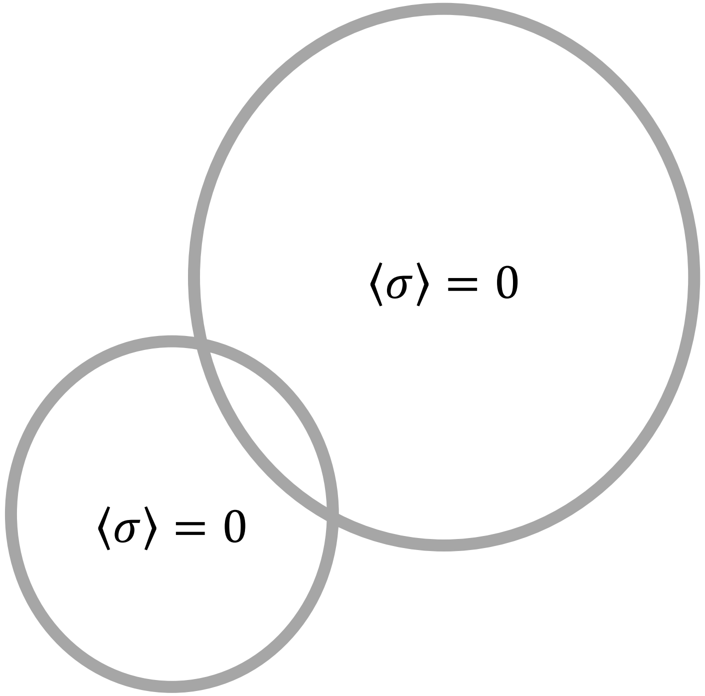
Thin-wall approximation: the wall of the bubble is thin compared to the bubble radius

$$4\pi\int dr\, r^2 e^{-i\omega\hat{\boldsymbol{k}}\cdot(\boldsymbol{x}_n + r\hat{\boldsymbol{x}})} T_{ij,n}(r,t) \simeq \frac{4\pi}{3} e^{-i\omega\hat{\boldsymbol{k}}\cdot(\boldsymbol{x}_n + r\hat{\boldsymbol{x}})} \hat{\boldsymbol{x}}_i \hat{\boldsymbol{x}}_j R_n^3 \kappa \rho_{vac}$$

How much of the vacuum energy is transformed into kinetic energy of the bulk fluid instead of reheating the plasma inside the bubble

Gravitational wave from first order phase transitions

Gravitational waves can be generated from bubble collisions



$$T_{ij}(\hat{\boldsymbol{k}},\omega) = \kappa \rho_{vac} v_b^3 C_{ij}(\hat{\boldsymbol{k}},\omega)$$

$$C_{ij}(\hat{\boldsymbol{k}},\omega) = \frac{1}{6\pi}\sum_n \int dt\, e^{i\omega(t-\hat{\boldsymbol{k}}\cdot\boldsymbol{x_n})}(t-t_n)^3 A_{n,ij}(\hat{\boldsymbol{k}},\omega)$$

$$A_{n,ij}(\hat{\boldsymbol{k}},\omega) = \int_{S_n} d\Omega\, e^{-i\omega v_b(t-t_n)\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{x}}}\hat{\boldsymbol{x}}_i\hat{\boldsymbol{x}}_j$$

Gravitational waves spectrum is

$$\Omega_{GW} = \omega\frac{dE_{GW}}{d\omega}\frac{1}{E_{tot}} = \kappa^2\left(\frac{H}{\beta}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2\Delta(\frac{\omega}{\beta}, v_b) \quad \alpha = \frac{\rho_{vac}}{\rho_{rad}}$$

$$\Omega_{GW*}(f_*) = \widetilde{\Omega}_{GW}\frac{(a+b)\,\tilde{f}_*^b f_*^a}{b\tilde{f}_*^{a+b}+af_*^{a+b}}$$

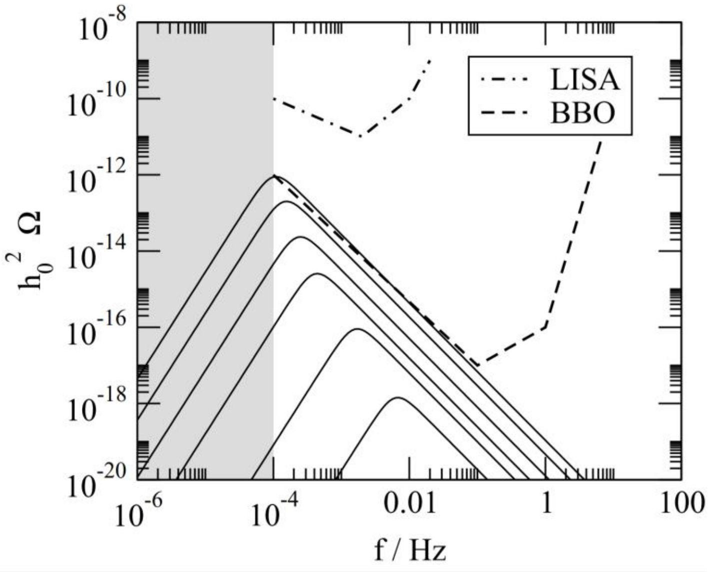
Hubble parameter is

$$H^2 = \frac{8\pi G\rho_{tot}}{3} = \frac{8\pi G(\rho_{vac}+\rho_{rad})}{3}$$

Gravitational wave from first order phase transitions

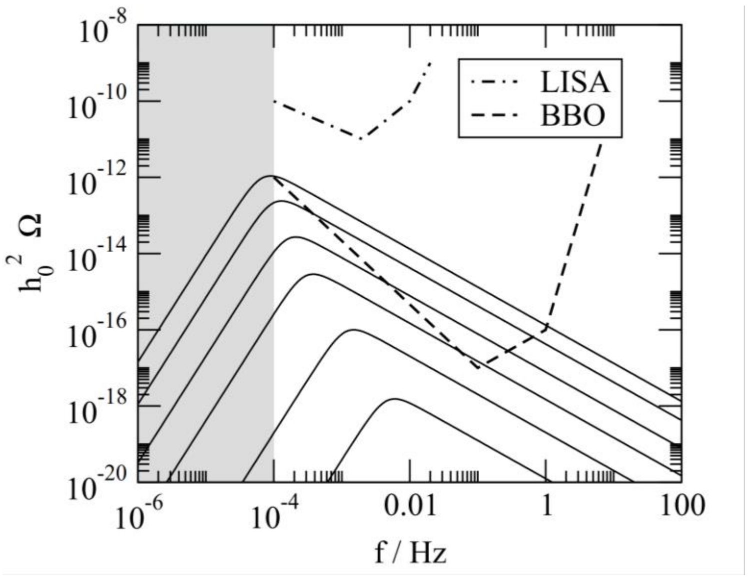
The UV spectrum decreases as $f^{-1.8}$

Arthur Kowsowsky, Michael S. Turner
PRD Volume 47, Number 10
Two bubbles



The IR spectrum rises as f^3
The UV spectrum decreases as f^{-1}

Stephan J. Huber, Thomas Konstandin
JCAP 0809:022,2008
More bubbles



Gravitational wave from first order phase transitions during inflation

The idea stems from old inflation. First order phase transition happen during inflation. The first order phase transition will produce bubbles. Bubbles will collide and thus generate gravitational waves.

Hongliang Jiang, Tao Liu, Sichun Sun, Yi Wang Physcs Letters B, Volume 765, Pages 339-343

First order phase transition at the beginning of inflation and its detectability at cosmic microwave background (CMB)

Yu-Tong Wang, Yong Cai, Yun-Song Piao Phys.Lett.B789(2019)191-196

First order phase transition during inflation and its detectability at gravitational wave interferometers, such as LISA and LIGO

Haipeng An, Kun-Feng Lyu, Lian-Tao Wang, Siyi Zhou Chin.Phys.C 46 (2022) 10, 101001

First order phase transition during inflation, its associated gravitational wave signal and how it can be distinguished from the first order phase transition after inflation

Haipeng An, Kun-Feng Lyu, Lian-Tao Wang, Siyi Zhou JHEP 06 (2022) 050

First order phase transition during inflation, its associated gravitational wave signal and how it can reflect the cosmological time evolution

How GW propagates in spacetime

The equation of motion of the transverse and traceless GW perturbation is

$$h_{ij}'' + \frac{2a'}{a} h_{ij}' - \nabla^2 h_{ij} = 16\pi G_N a^2 \sigma_{ij}$$

FRW metric $ds^2 = a^2(\tau)(-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j)$ During inflation $a(\tau) = -\frac{1}{H\tau}$

Typical time scale of the problem

1. The phase transition happens at conformal time τ_*
2. The duration of the phase transition is $\Delta_\tau \ll \tau_*$

Separate the problem into three regimes

1. IR $k < |\tau_*|^{-1}$
2. Intermediate $|\tau_*|^{-1} < k < \Delta_\tau^{-1}$

} ignore the details of the gravitational wave source, treat it as a delta function source $\widetilde{\sigma_{ij}} \sim \widetilde{T_{ij}^{(0)}} a^{-3}(\tau_*)\delta(\tau - \tau_*)$

Solution is $h \simeq -\frac{16\pi G_N H\tilde{T}\tau}{k}\left[\left(\frac{1}{k\tau} - \frac{1}{k\tau_*}\right)\cos k(\tau - \tau_*) + \left(1 + \frac{1}{k^2\tau\tau_*}\right)\sin k(\tau - \tau_*)\right] \to -\frac{16\pi G_N H\tilde{T}}{k^2}(\cos k\tau_* - \sin k\tau_* / k\tau_*)$

3. UV $k > \Delta_\tau^{-1}$ The details of bubble collision is essential

How GW propagates in spacetime

If inflation is connected to a radiation dominated universe immediately after inflation

$$h_k = h_k \frac{sink\tau}{k\tau}$$

The energy density of the gravitational wave has the form

$$\rho_{GW} \sim \frac{1}{a^2} \int \frac{d^3k}{(2\pi)^3} |h'(\tau)|^2$$

Deeply inside the horizon $k\tau \gg 1$

$$\frac{d\rho_{GW}}{d\,log\,k} \sim \frac{1}{k} \left(\cos k\tau_* - \frac{\sin k\tau_*}{k\tau_*} \right)^2$$

1. IR regime $k < |\tau_*|^{-1}$ $\quad \frac{d\rho_{GW}}{d\,log\,k} \sim k^3$ similar to GW signal from instantaneous source in radiation domination

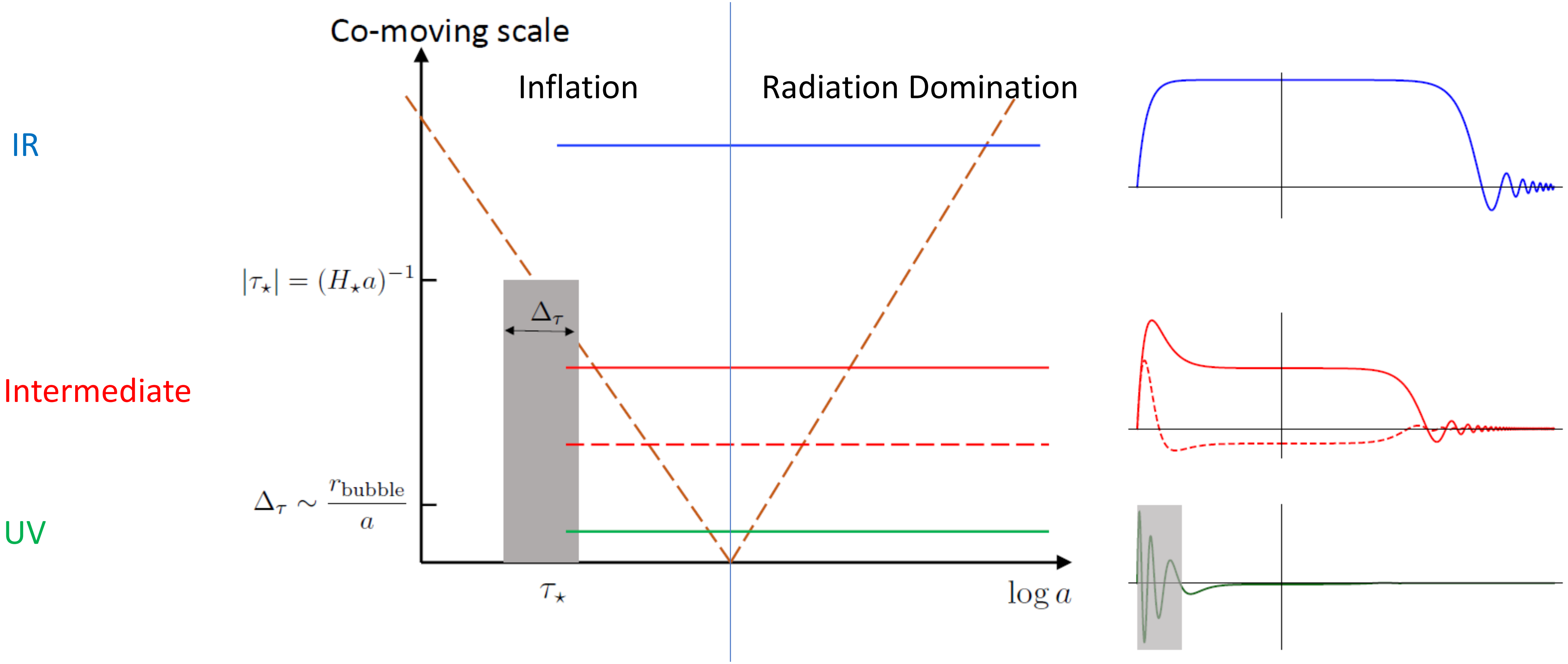
Rong-Gen Cai, Shi Pi, Misao Sasaki Phys. Rev. D 102, 083528 (2020)

C. Caprini, R. Durrer, T. Konstandin, and G. Servant, Phys. Rev. D 79, 083519 (2009)

2. Intermediate regime oscillation

3. UV regime $\frac{d\rho_{GW}}{d\,log\,k} \sim k^{-4} \frac{d\rho_{GW}^{flat}}{d\,log\,k_p}$

Gravitational wave from first order phase transitions during inflation



Gravitational wave from first order phase transitions during inflation

Final spectrum

$$\Omega_{GW}(k_{today}) = \Omega_R S(2\pi f_*) \left(\frac{L}{\rho_{\inf}}\right) \frac{d\rho_{GW}^{flat}}{L\, d\ln f_p} \qquad L = \gamma_{PT} m_\sigma^4\text{: Latent heat}$$

GW spectrum in flat space

$$\frac{d\rho_{GW}^{flat}}{L\, d\ln f_p} = \kappa^2 \left(\frac{L}{\rho_{\inf}}\right) \left(\frac{H}{\beta}\right)^2 \Delta(2\pi f_p) \qquad \Delta(2\pi f_p) = \tilde{\Delta} \times 3.8 \; \frac{\widetilde{k_p} k_p^{2.8}}{\widetilde{k_p}^{3.8} + 2.8\, k_p^{3.8}}$$

GW frequency

$$f_{today} = f_{PT}\, e^{-N_{PT} - N_{today}} \quad e^{-N_{today}} = \frac{T_{CMB}}{\left(\left(\frac{30}{g_*^{(R)}\pi^2}\right)\left(\frac{3H_r^2}{8\pi G_N}\right)\right)^{\frac{1}{4}}}$$

Due to the distortion from inflation, highest peak

$$f_*^{peak} \simeq \frac{H}{2\pi}$$

If σ particles constitute all the dark matter today $f_{today}^{peak} = \frac{1}{2\pi}\left(\frac{\gamma_{PT}}{\gamma_*}\right)^{\frac{1}{12}} \left(\frac{L}{\rho_{\inf}}\right)^{-\frac{1}{3}} \left(\frac{\Omega_{DM} H\, H_0^2}{Y_\sigma(\infty)}\right)^{1/3}$

Gravitational wave frequency

Low scale inflation
$H \sim 10^{-18} \sim 10^{-14} GeV$

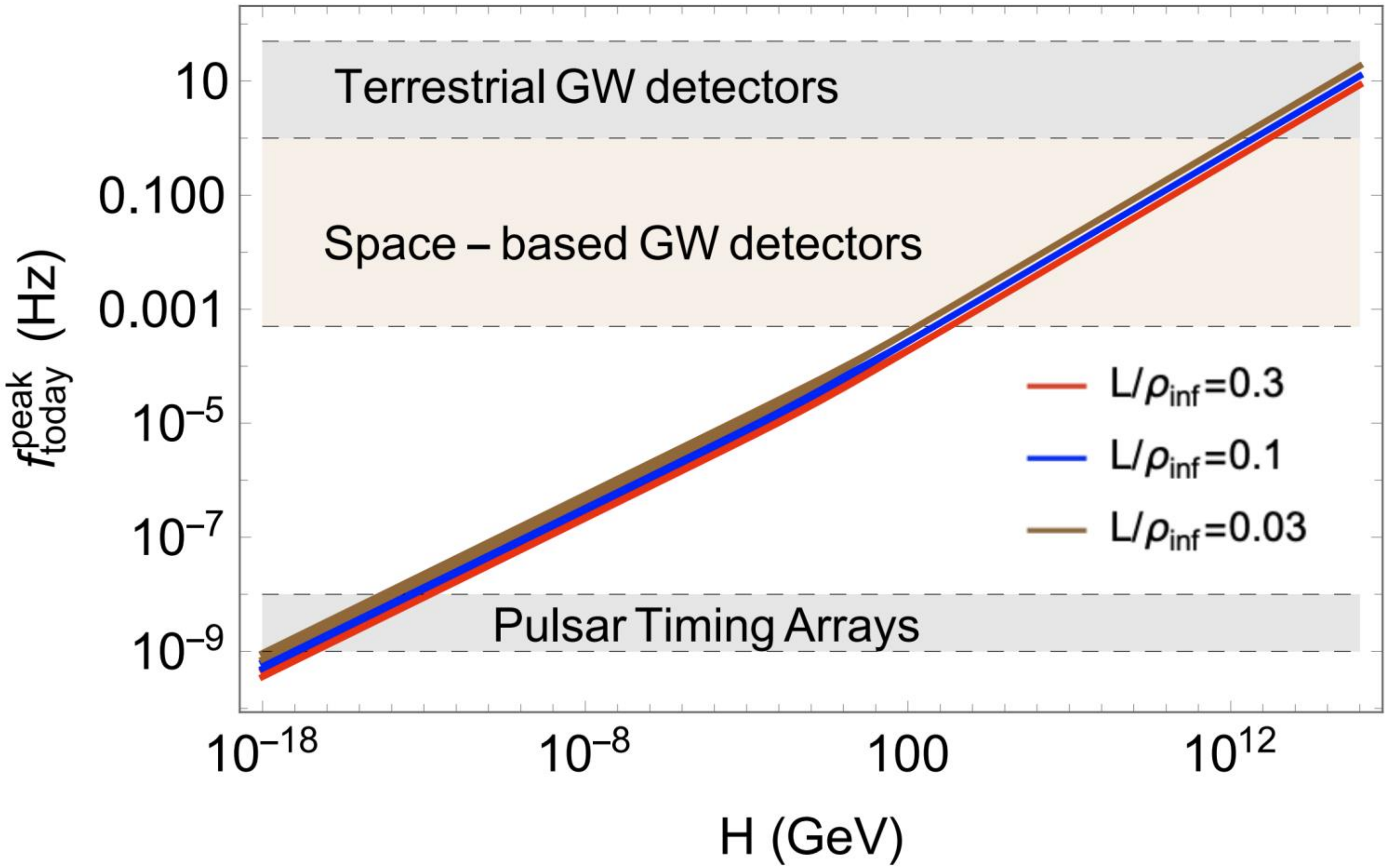
Signal may be detected by PTA

Low scale inflation
$H \sim 10^{2} \sim 10^{12} GeV$

Signal may be detected by Space-based GW detectors

High scale inflation
$H \sim 10^{12} \sim 10^{14} GeV$

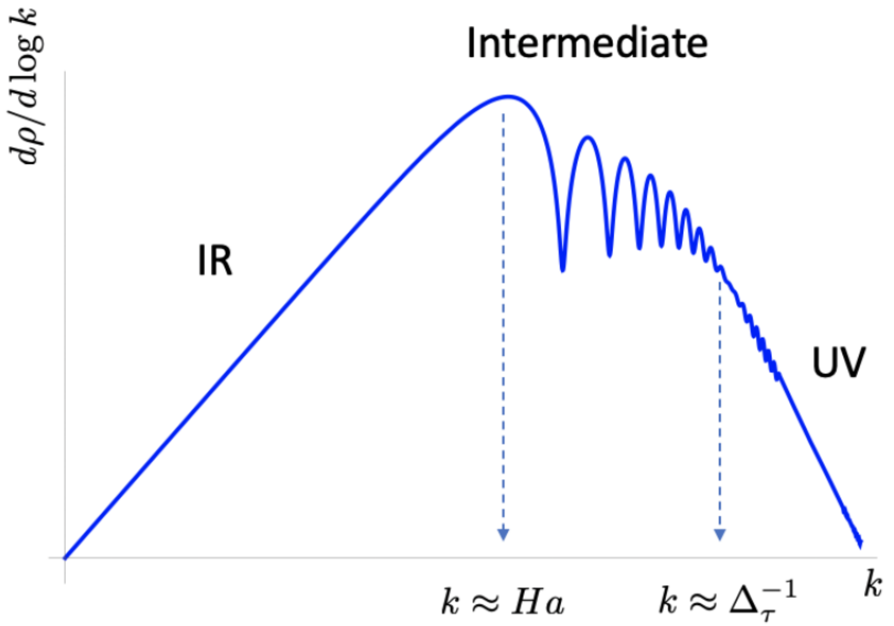
Signal may be detected by Terrestrial detectors



Gravitational wave signature

Tilt of different part of the gravitational wave spectrum will reflect different evolution history of the universe

		RD	MD	$t^{\tilde{p}}$
UV	dS	k^{-5}	k^{-7}	$k^{-3+2\frac{p}{\tilde{p}-1}}$
	t^p	$k^{-3+2\frac{p}{1-p}}$	$k^{-5+2\frac{p}{1-p}}$	$k^{-1+2\left(\frac{p}{1-p}+\frac{p}{\tilde{p}-1}\right)}$
Intermediate		RD	MD	$t^{\tilde{p}}$
	dS	k^{-1}	k^{-3}	$k^{1+2\frac{p}{\tilde{p}-1}}$
	t^p	$k^{1+2\frac{p}{1-p}}$	$k^{-1+2\frac{p}{1-p}}$	$k^{3+2\left(\frac{p}{1-p}+\frac{p}{\tilde{p}-1}\right)}$
IR		RD	MD	$t^{\tilde{p}}$
	dS	k^3	k^1	$k^{5+2\frac{p}{\tilde{p}-1}}$
	t^p	k^3	k^1	$k^{5+2\frac{p}{\tilde{p}-1}}$

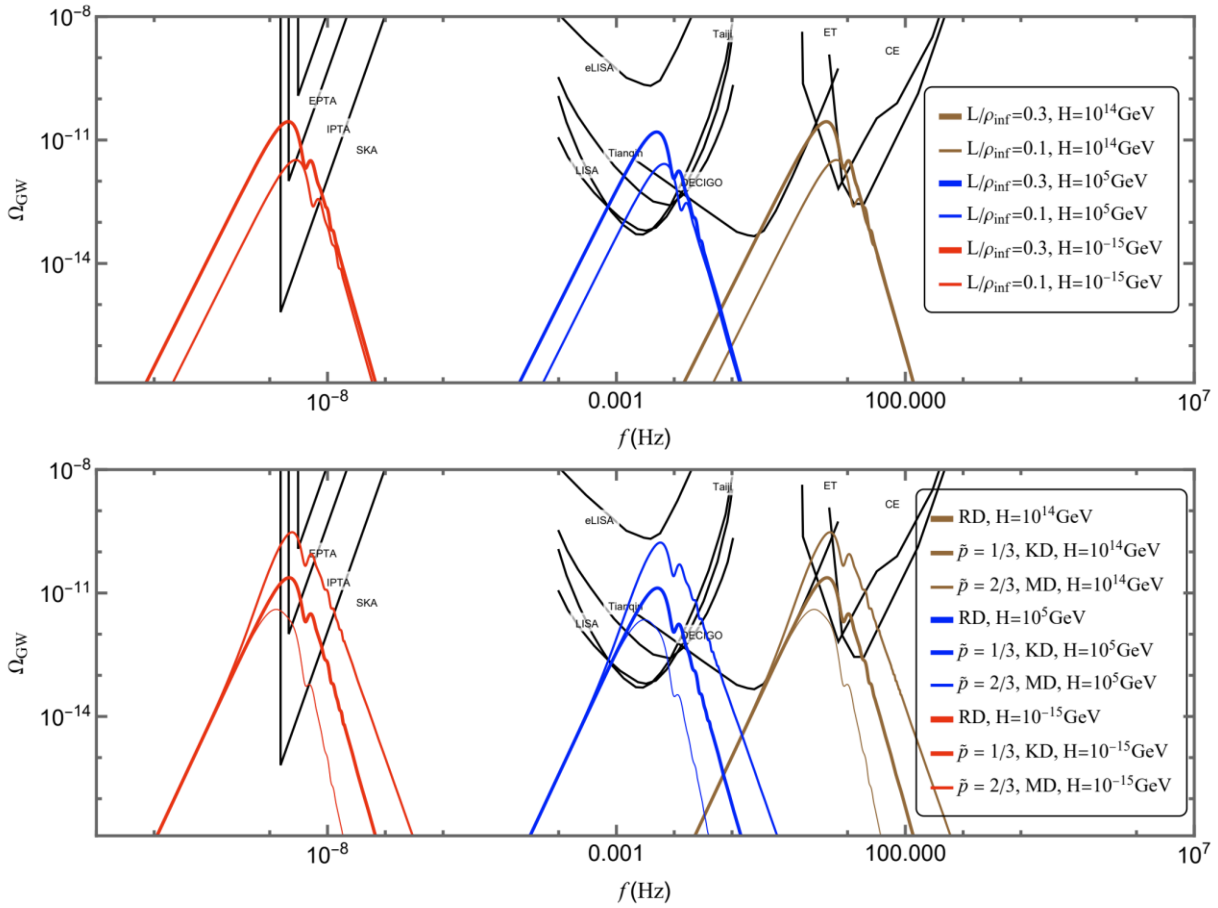


Gravitational wave signature

Magnitude of the signal is controlled by the latent heat released during first order phase transition

The frequency of the gravitational wave is linked to the Hubble parameter during inflation

The tilt of the UV part of the gravitational wave spectrum is determined by the evolution history of the universe



Power Spectrum

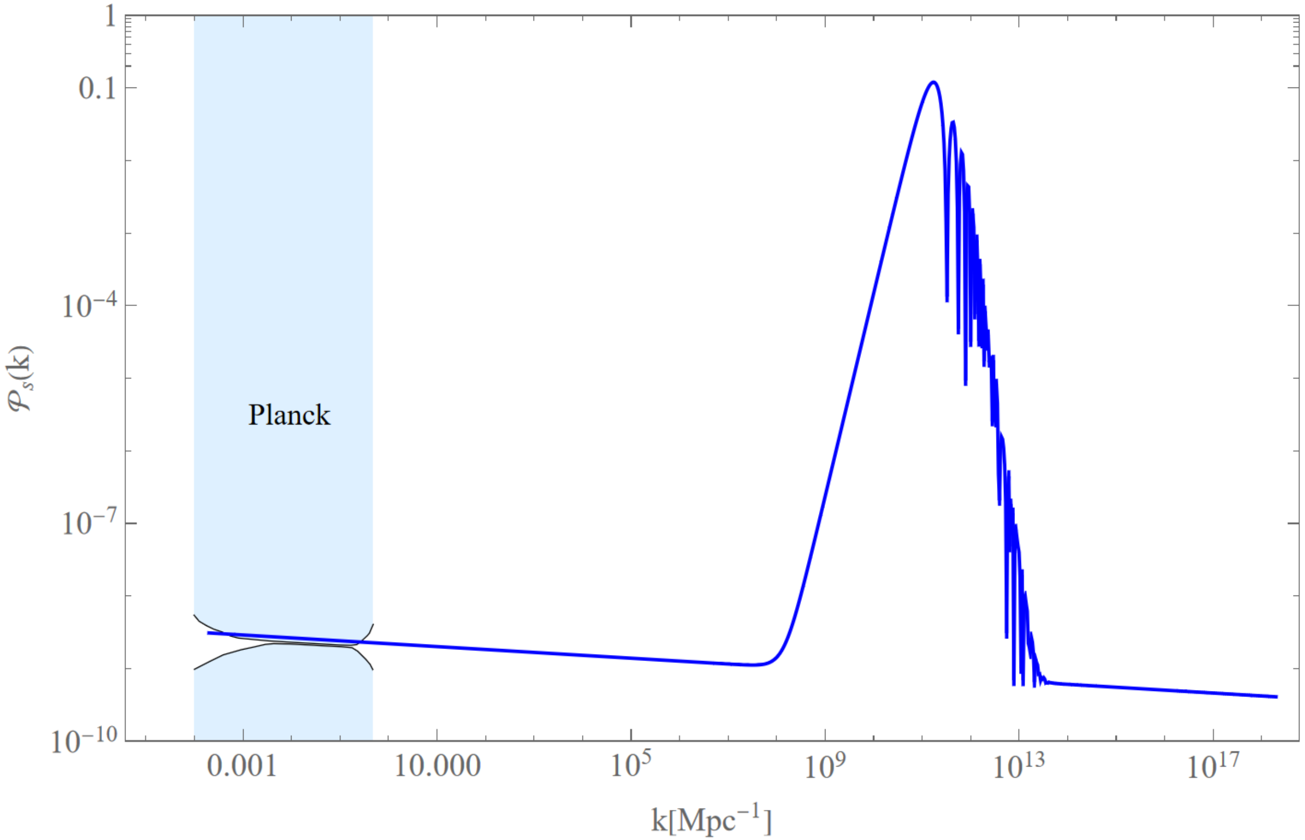
First order phase transition will also introduce peak in the primordial power spectrum

$$n_s = 0.96$$

$$\frac{L}{\rho_{\rm inf}} = 0.1$$

$$\beta = 9H$$

Phase transition happens at 25 e-folds before the end of inflation



Primordial black hole

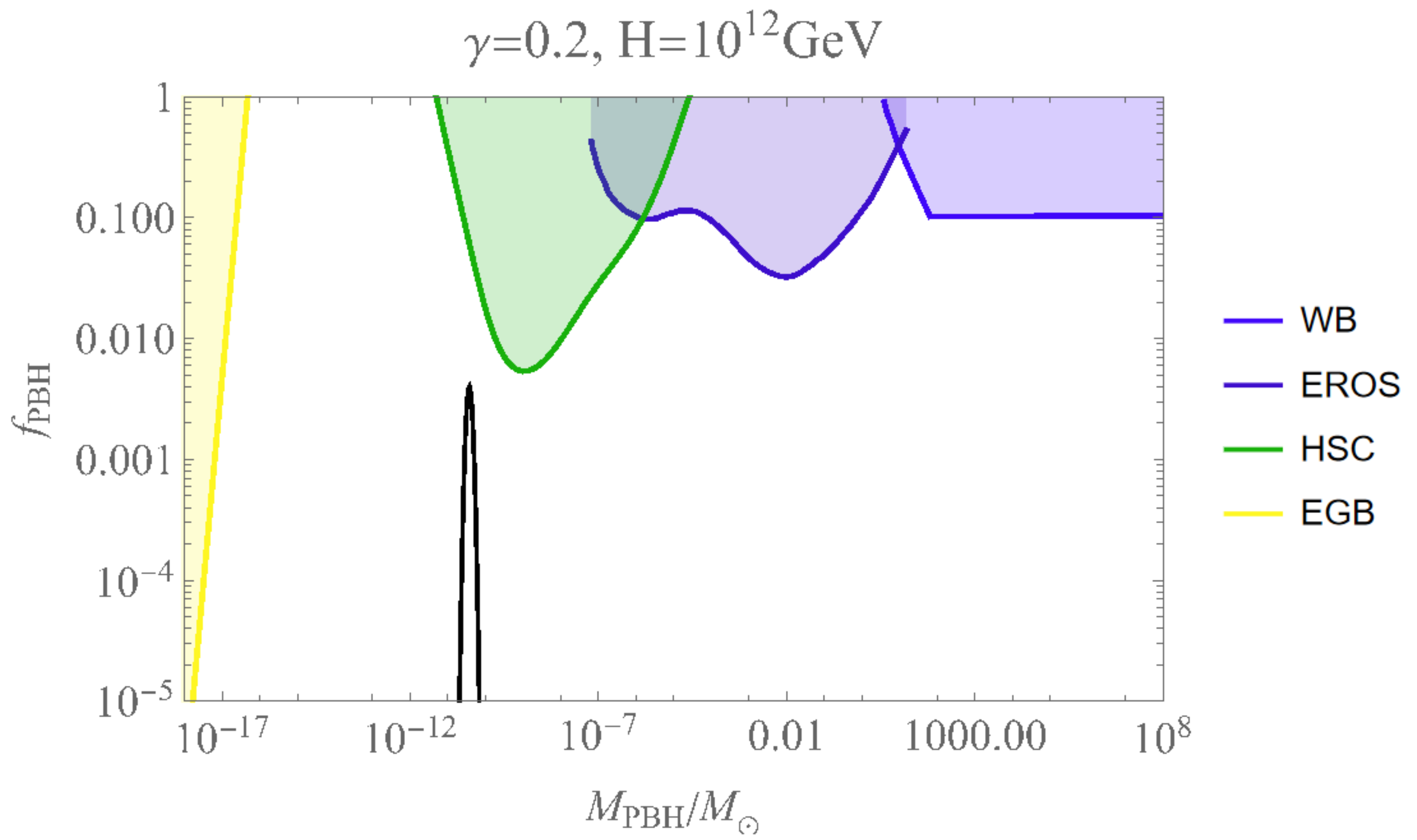
Large enhancement in the power spectrum will produce primordial black hole

$$n_s = 0.96$$

$$\frac{L}{\rho_{\rm inf}} = 0.1$$

$$\beta = 12\,H$$

Phase transition happens at 25 e-folds before the end of inflation



Outline

Superheavy Dark Matter

Symmetry Restoration First-Order Phase Transition During Inflation

Observational Signatures

Conclusion and Outlook

Conclusion and Outlook

Dark matter can be heavy, the production rate is generically small

A mechanism to produce enough superheavy dark matter during inflation via symmetry restoration first order phase transition

Complementary gravitational wave signals

Large enhancement in the primordial power spectrum

Associated primordial blackhole mass fraction