Gravitational waves as a probe of supersymmetric scale

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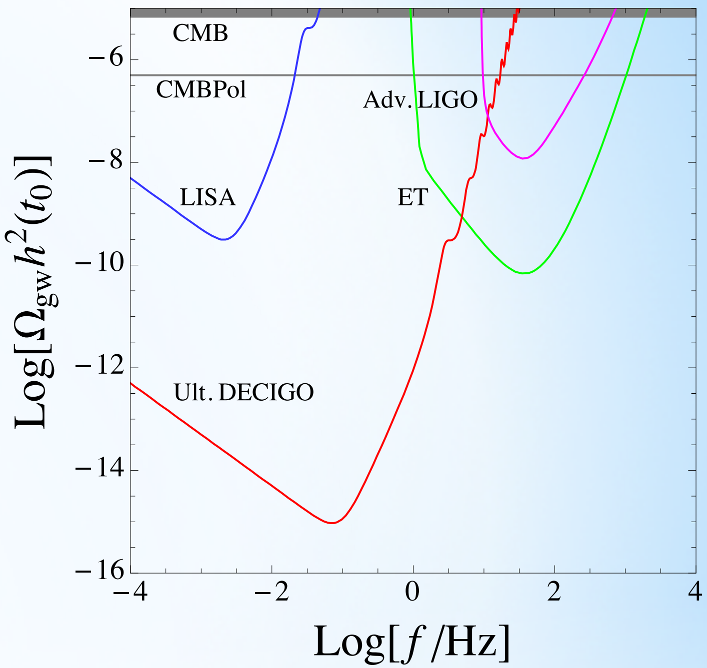
Introduction: Gravitational waves and new physics

Stochastic gravitational wave signals are predicted by physics beyond the Standard Model:

- topological defects (cosmic string, domain wall)
- first order phase transition
- preheating
- quantum fluctuations during inflation



Introduction: Gravitational waves and new physics

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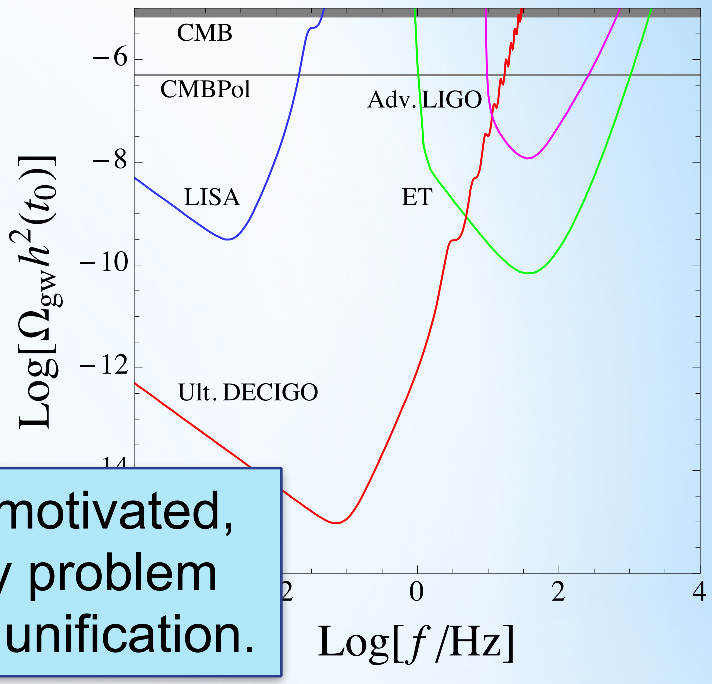


Supersymmetric theories are well-motivated, because it addresses the hierarchy problem and also achieves gauge coupling unification.

We have shown that
cosmic strings generally form after the end of inflation
in supersymmetric theories.

These cosmic strings emit observable gravitational wave signals and can be used as a probe of supersymmetric scale!

Flat directions in supersymmetric theories

Affleck, Dine, 85
Dine, Randall, Thomas, 96

Supersymmetric theories usually predict many complex scalar fields (called flat directions) whose potentials are absent except for soft terms.

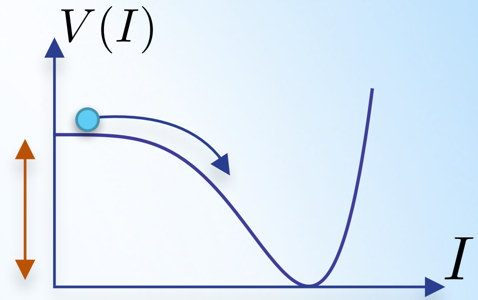
$$V(\phi) = m_\phi^2 |\phi|^2$$

The dynamics of such flat directions is nontrivial during and after inflation

flat directions in the MSSM	B-L
LH_u	-1
H_uH_d	0
udd	-1
LLe	-1
QdL	-1
$QQQL$	0
$QuQd$	0
$QuLe$	0
$uude$	0
$dddLL$	-3
$uuuee$	1
$QuQue$	1
$QQQQu$	1
$(QQQ)_4LLLe$	-1
$uudQdQd$	-1

Gherghetta, Kilda, Martin, 95

Inflation and Hubble-induced terms



Inflation is driven by a finite vacuum energy density, which affect the potentials of flat directions through supergravity effects:

$$\tilde{c}_H \frac{V(I)}{M_*^2} |\phi|^2 + \tilde{a}_H \frac{V(I)}{M_*^{2n-2}} |\phi|^{2n-2} \qquad (M_* \leq M_{\rm Pl})$$

$$V(\phi) = m_\phi^2 |\phi|^2 + c_H H^2 |\phi|^2 + a_H H^2 \frac{|\phi|^{2n-2}}{M_{\rm Pl}^{2n-4}} \qquad |c_H| \sim \left(\frac{M_{\rm Pl}}{M_*} \right)^2$$

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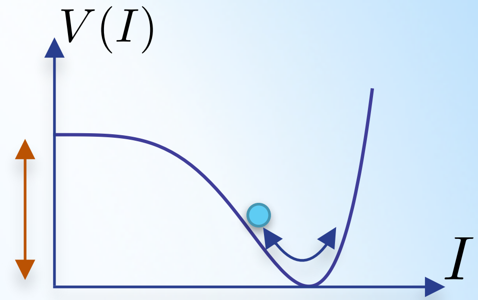
Inflation and Hubble-induced terms

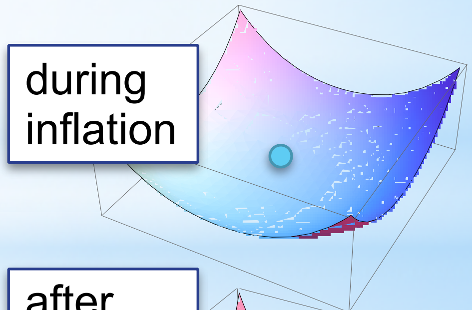


After inflation ends, the energy density of the Universe is dominated by that of inflaton oscillation, which again induces the following potentials:

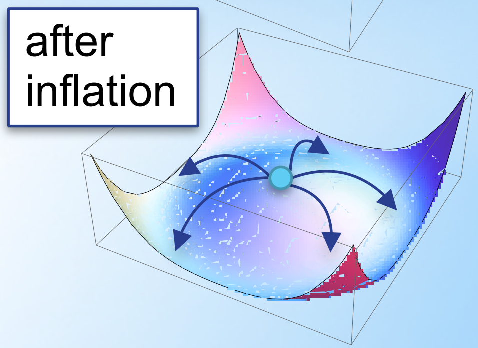
$$\tilde{c}'_H \frac{\dot{I}^2}{M_*^2} |\phi|^2 + \tilde{a}'_H \frac{\dot{I}^2}{M_*^{2n-2}} |\phi|^{2n-2} \qquad (M_* \leq M_{\rm Pl})$$

$$V(\phi) = m_\phi^2 |\phi|^2 + c_H H^2 |\phi|^2 + a_H H^2 \frac{|\phi|^{2n-2}}{M_{\rm Pl}^{2n-4}} \qquad |c_H| \sim \left(\frac{M_{\rm Pl}}{M_*}\right)^2$$

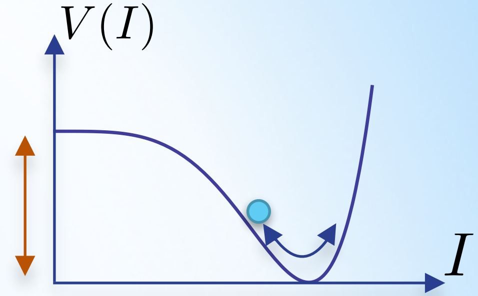
In general, c_H (during inflation) $\neq c_H$ (after inflation)



When $c_H > 0$ during inflation and $c_H < 0$ after inflation, global cosmic strings form after inflation



Inflation and Hubble-induced terms



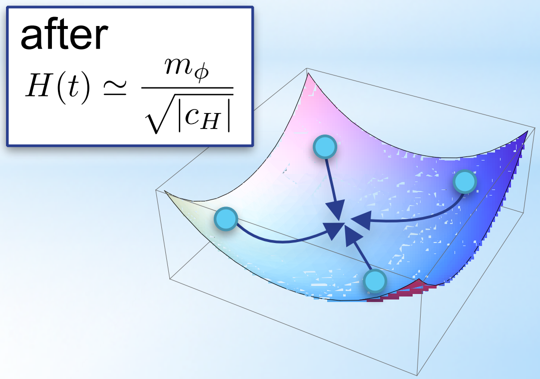
During inflaton oscillation era, the Hubble parameter decreases with time as

$$H^2(t) = \frac{\rho_I(t)}{3M_{\rm Pl}^2} \propto a^{-3}$$

Cosmic strings disappear at the time of $H(t) \simeq \frac{m_\phi}{\sqrt{|c_H|}}$

$$V(\phi) = m_\phi^2 |\phi|^2 + c_H H^2 |\phi|^2 + a_H H^2 \frac{|\phi|^{2n-2}}{M_{\rm Pl}^{2n-4}}$$

$$|c_H| \sim \left(\frac{M_{\rm Pl}}{M_*}\right)^2$$



Properties of cosmic strings

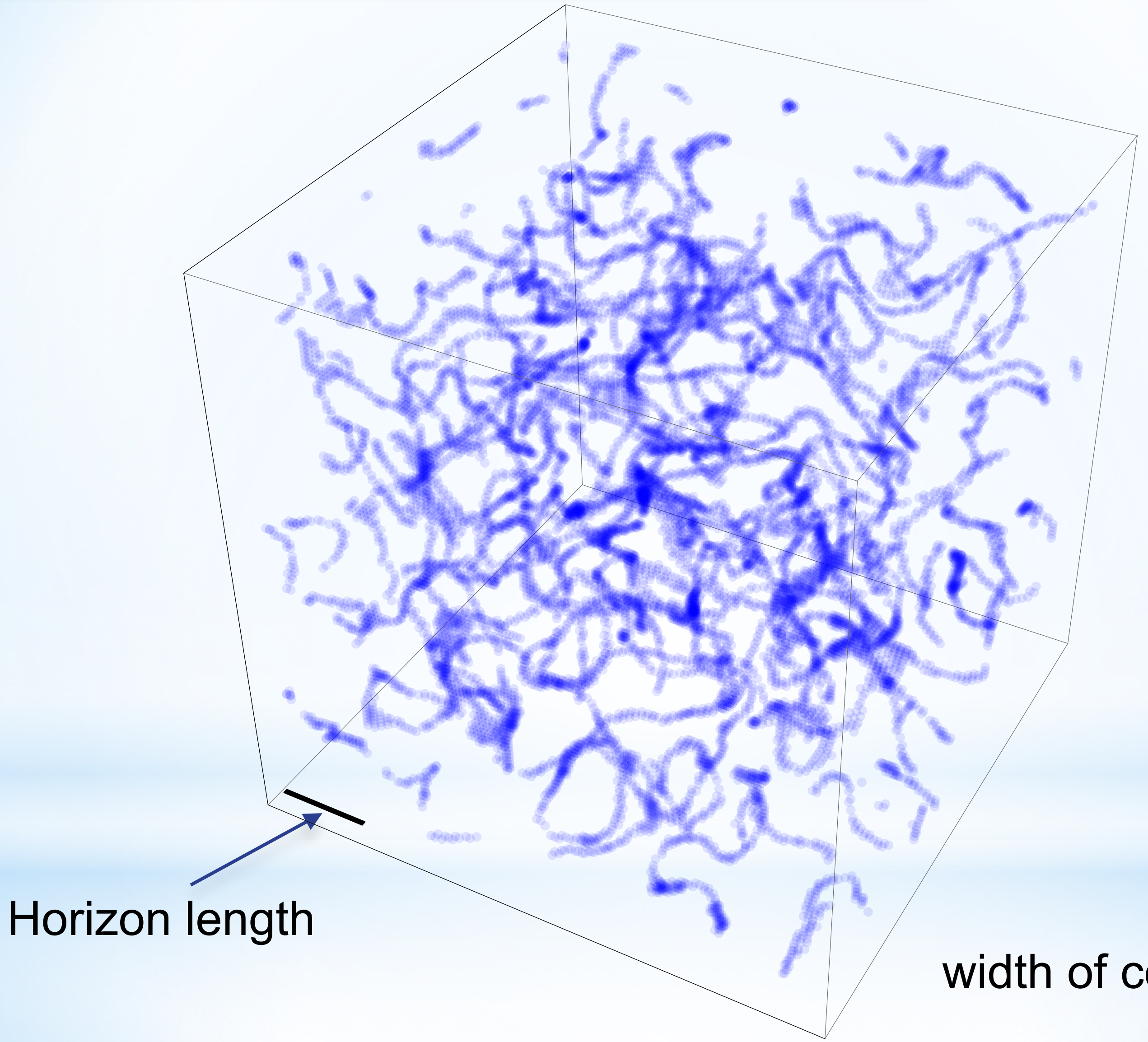
Kamada and M.Y., 14

$$V(\phi) = m_\phi^2 |\phi|^2 + c_H H^2 |\phi|^2 + a_H H^2 \frac{|\phi|^{2n-2}}{M_{\rm Pl}^{2n-4}}$$

$$c_H > 0 \ \Rightarrow \ c_H < 0$$

- the number of cosmic strings in the Hubble volume $= \mathcal{O}(1)$ (scaling law)
- energy density per unit length $\mu \sim \langle \phi \rangle^2 \sim M_*^2$
- width of a typical cosmic string $\sim 1/\sqrt{V''} \propto H^{-1}$

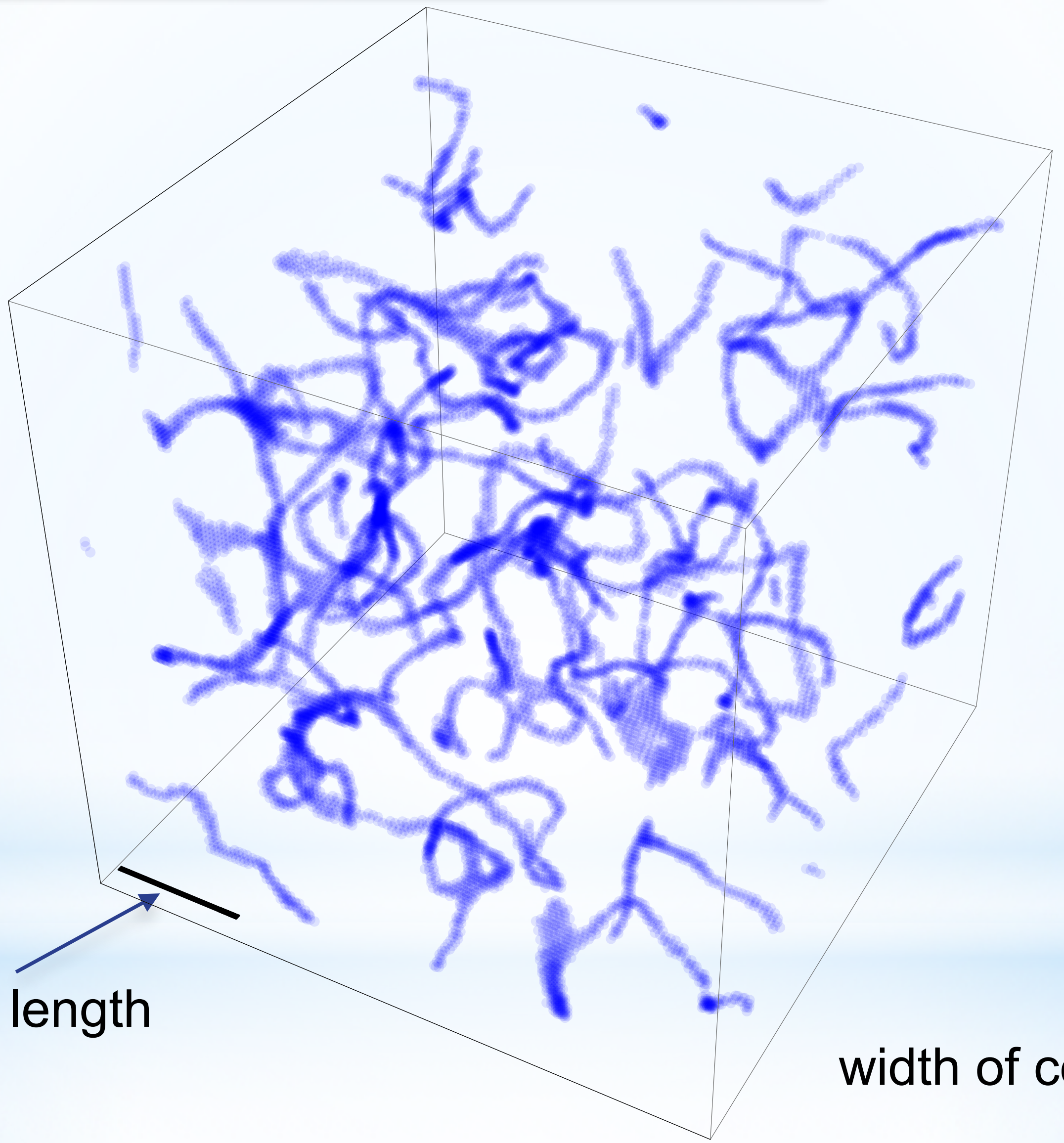
3+1 dim simulation of cosmic string formation



conformal time
$\tau = 32\ H_i^{-1}$

width of cosmic strings $\propto H^{-1}$

3+1 dim simulation of cosmic string formation

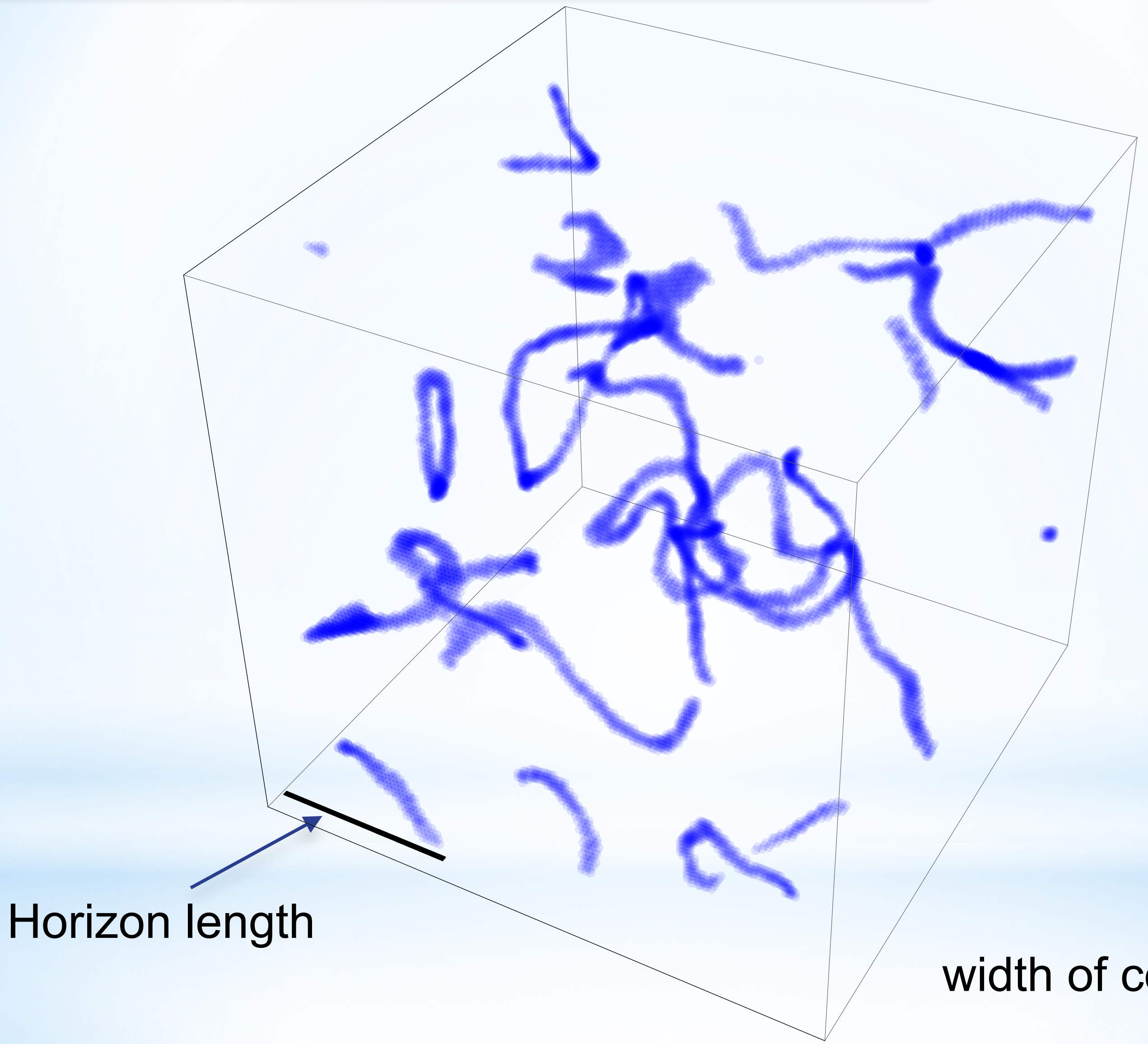


Horizon length

conformal time
$\tau = 44\ H_i^{-1}$

width of cosmic strings $\propto H^{-1}$

3+1 dim simulation of cosmic string formation



conformal time
$\tau = 64\ H_i^{-1}$

width of cosmic strings $\propto H^{-1}$

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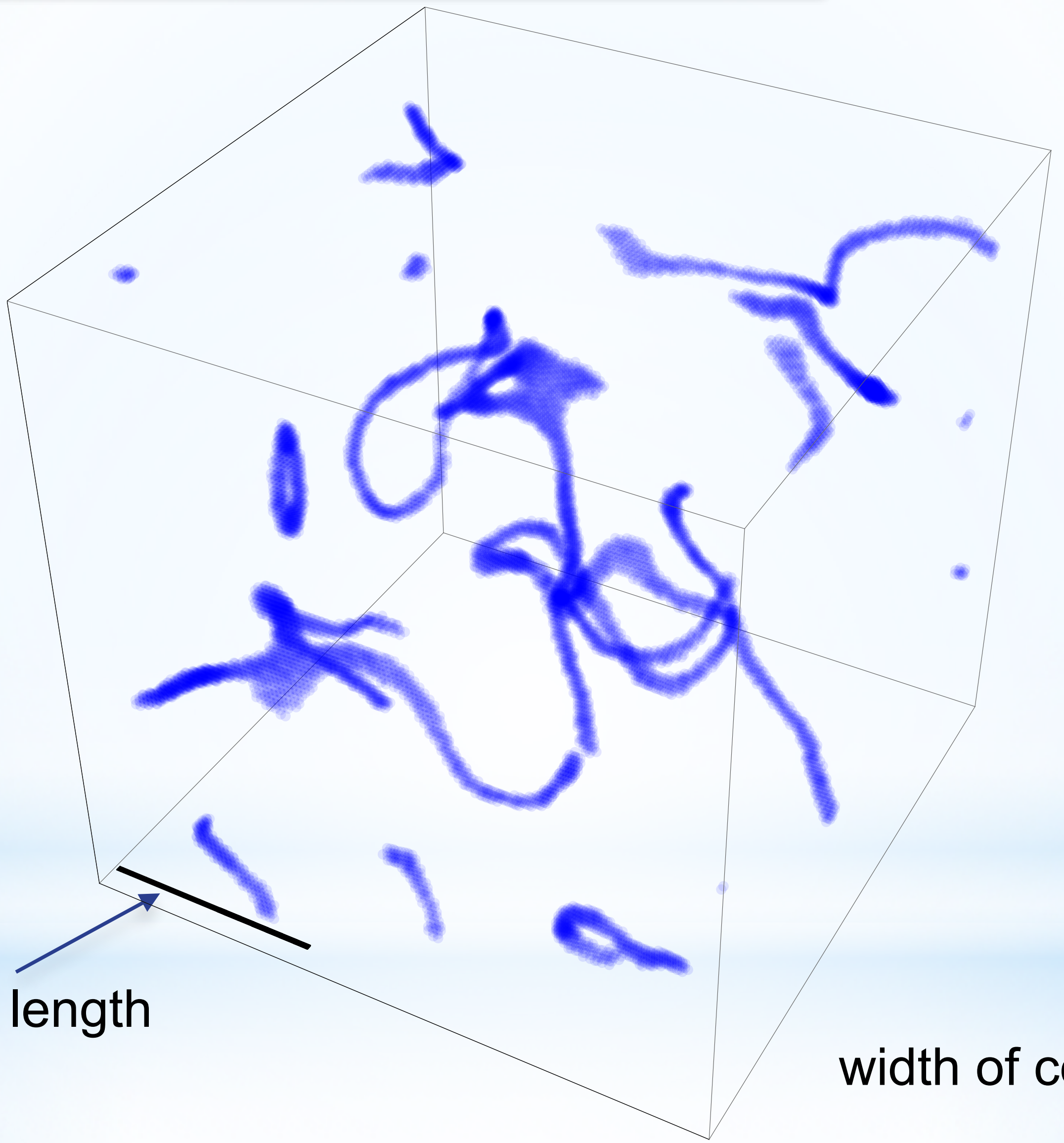
3+1 dim simulation of cosmic string formation



conformal time
$\tau = 70\ H_i^{-1}$

width of cosmic strings $\propto H^{-1}$

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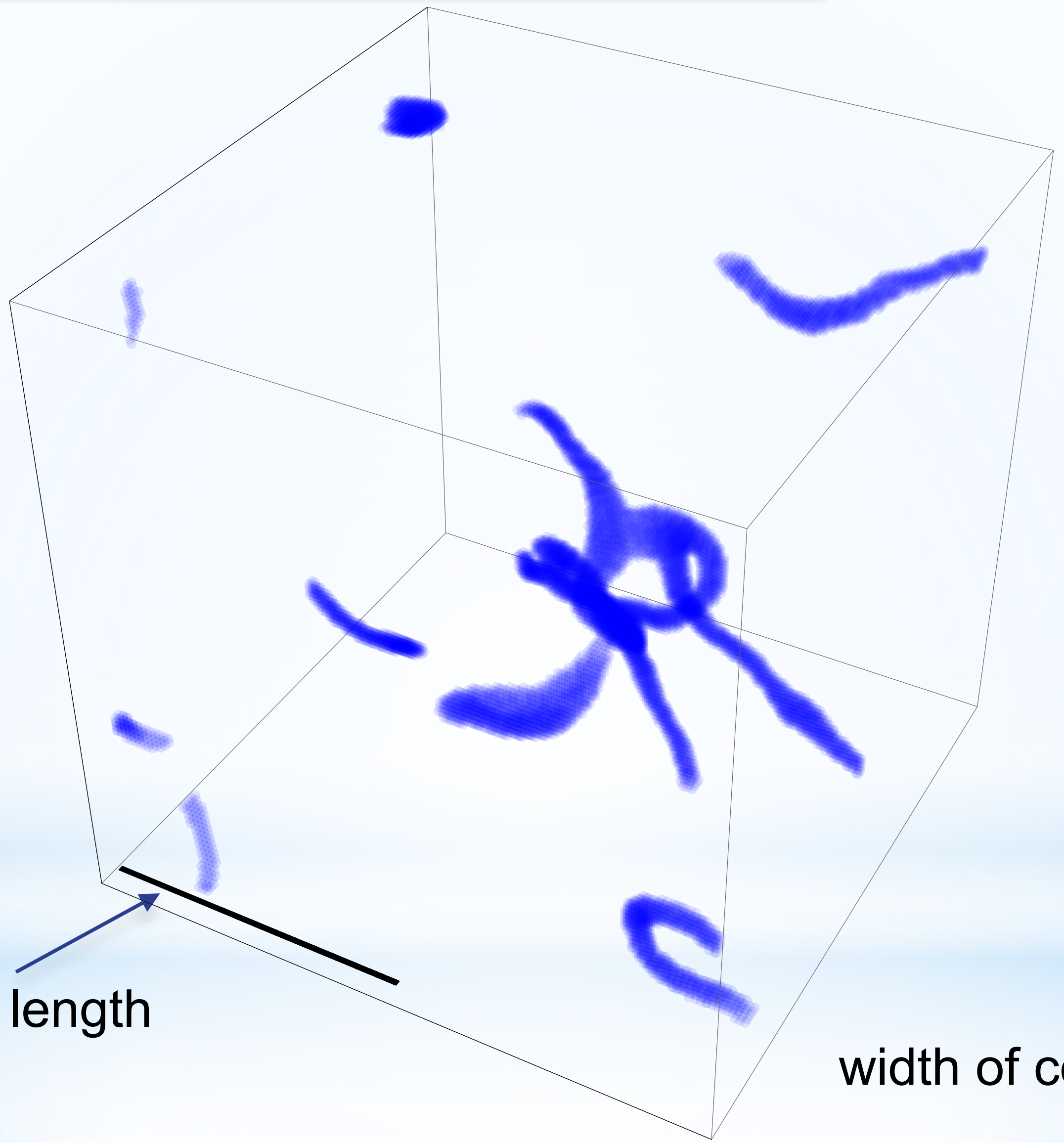
3+1 dim simulation of cosmic string formation



conformal time
$\tau = 100\ H_i^{-1}$

width of cosmic strings $\propto H^{-1}$

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GW spectrum

Kamada and M.Y., 14

- the number of cosmic strings in the Hubble volume $= \mathcal{O}(1)$ (scaling law)
- width of a typical cosmic string $\sim H^{-1}$

  $\rightarrow$ cosmic strings emit GWs
  with a peak wavenumber $k_{\rm peak} \simeq aH(t)$

- The energy density of GWs can be estimated by the quadrupole approximation.

  Quadrupole moment for an object with mass M: $Q \sim H^{-2} M \sim H^{-3} \mu$
  GW energy emitted by the object: $\Delta E_{\rm gw} \sim H^{-1} \times ({\rm Luminosity}) \sim H^{-1} M_{\rm Pl}^{-2} \dddot{Q}^2$

$$\Rightarrow \Delta \Omega_{\rm gw} \sim \frac{H^3 \Delta E_{\rm gw}}{H^2 M_{\rm Pl}^2} \sim \left(\frac{\langle \phi \rangle}{M_{\rm Pl}} \right)^4$$

$$\Omega_{\rm gw}(\tau) \equiv \frac{1}{\rho_{\rm tot}(\tau)} \frac{{\rm d}\rho_{\rm gw}(\tau)}{{\rm d}\log k}$$

GW spectrum

Kamada and M.Y., 14

- energy density of GWs can be calculated from the following formula:

$$h''_{ij} + 2\frac{a'}{a}h'_{ij} + k^2 h_{ij} = 16\pi G T^{TT}_{ij}$$

$$\rho_{\rm gw} = \frac{1}{32\pi G}\left\langle \dot{h}_{ij}(t,x)\dot{h}_{ij}(t,x)\right\rangle$$

$$\Omega_{\rm gw}(\tau) \equiv \frac{1}{\rho_{\rm tot}(\tau)}\frac{{\rm d}\rho_{\rm gw}(\tau)}{{\rm d}\log k}$$

- Because of the loss of causality at the large scale, wavenumber dependence at a scale larger than the Hubble scale is determined independently of the detail of T^{TT}_{ij}

Dufaux, et.al. 07
Kawasaki, Saikawa, 11

$\Omega_{\rm gw} \propto k$ for modes entering the horizon during MD
$\Omega_{\rm gw} \propto k^3$ for modes entering the horizon during RD

⇒ GW spectrum bends at $k \simeq aH(t_{\rm RH})$

GW spectrum

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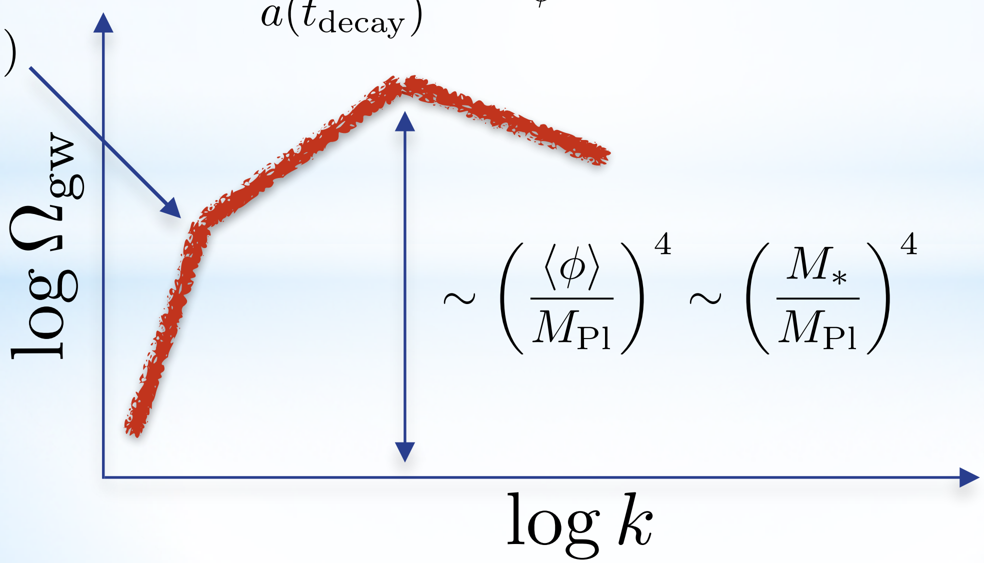
$$V(\phi) = m_\phi^2 |\phi|^2 + c_H H^2 |\phi|^2 + a_H H^2 \frac{|\phi|^{2n-2}}{M_{\rm Pl}^{2n-4}}$$

- cosmic strings disappear at the time of $H(t) \simeq \frac{m_\phi}{\sqrt{|c_H|}}$
  Thus, GW spectrum is "fixed" at this time

⇒ peak wavenumber is redshifted
$\Omega_{\rm gw} \propto a^{-1}$ during MD

$$\frac{k_{\rm peak}}{a(t_{\rm decay})} \simeq m_\phi$$

$$\frac{k_{\rm bend}}{a(t_{\rm RH})} \simeq H(t_{\rm RH})$$



GW spectrum

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present energy density:

$$\Omega_{\rm gw}h^2(t_0) \simeq \Omega_r h^2 \left(\frac{g_s(t_0)}{g_s(t_{\rm RH})}\right)^{4/3} \left(\frac{g_*(t_{\rm RH})}{g_*(t_0)}\right) \left(\frac{H_{\rm RH}}{H_{\rm decay}}\right)^{2/3} \Omega_{\rm gw}(t_{\rm decay})$$

$$\simeq 2\times 10^{-7} \left(\frac{m_\phi}{10^3 GeV}\right)^{-2/3} \left(\frac{T_{\rm RH}}{10^9 GeV}\right)^{4/3} \left(\frac{M_*}{M_{\rm Pl}}\right)^{10/3}$$

$$H_{\rm decay} \simeq \frac{m_\phi}{\sqrt{c_H}}$$

present peak frequency:

$$f_0 \simeq \left(\frac{g_s(t_0)}{g_s(t_{\rm RH})}\right)^{1/3} \left(\frac{T_0}{T_{\rm RH}}\right) \left(\frac{H_{\rm RH}}{H_{\rm decay}}\right)^{2/3} \frac{k_{\rm peak}}{2\pi a(t_{\rm decay})}$$

$$\simeq 7\times 10^2 \ {\rm Hz} \left(\frac{m_\phi}{10^3 \ {\rm GeV}}\right)^{1/3} \left(\frac{T_{\rm RH}}{10^9 \ {\rm GeV}}\right)^{1/3} \left(\frac{M_*}{M_{\rm Pl}}\right)^{1/3}$$

present bend frequency:

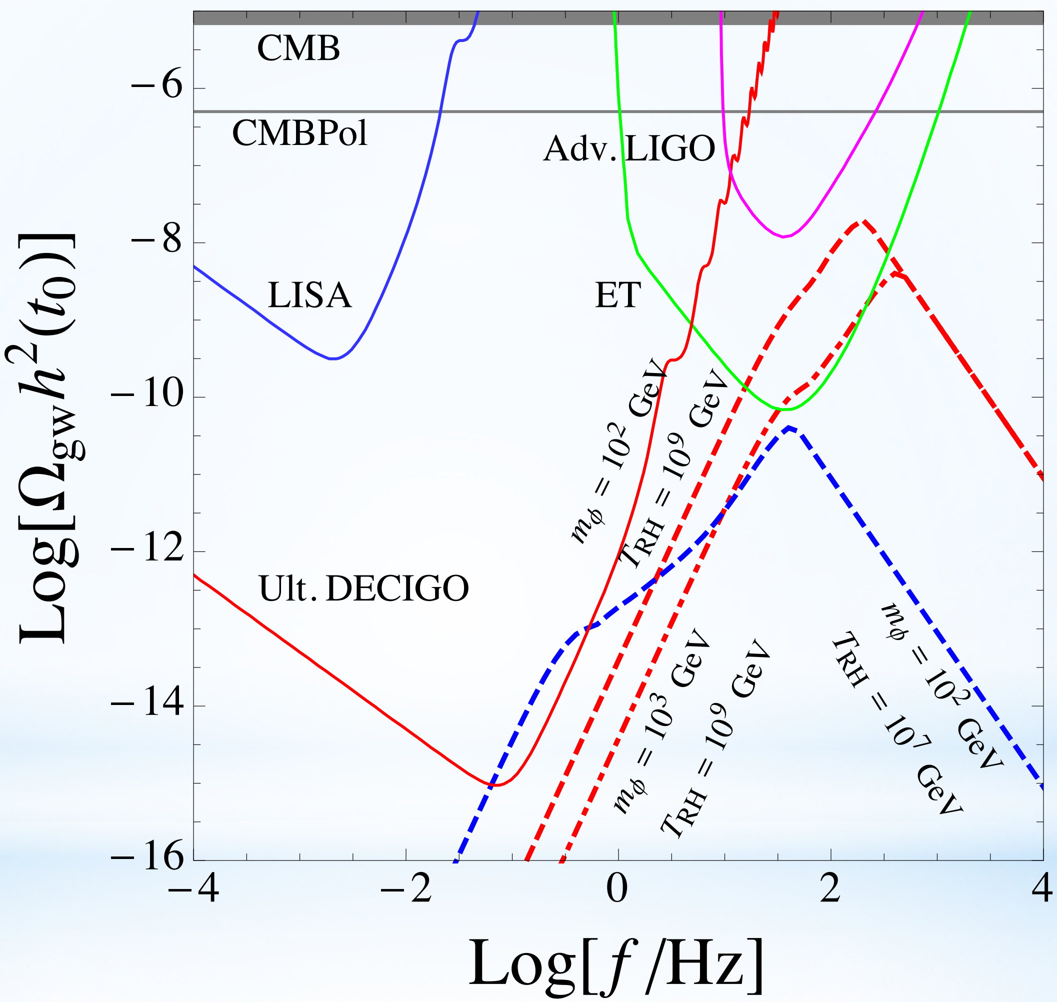
$$f_{\rm bend} = \left(\frac{g_s(t_0)}{g_s(t_{\rm RH})}\right)^{1/3} \left(\frac{T_0}{T_{\rm RH}}\right) \frac{k_{\rm bend}}{2\pi a(t_{\rm RH})}$$

$$\simeq 30 \ {\rm Hz} \left(\frac{T_{\rm RH}}{10^9 \ {\rm GeV}}\right)$$

We can probe $m_\phi, \ T_{\rm RH}, \ M_*$ through GW detection experiments!

GW spectrum

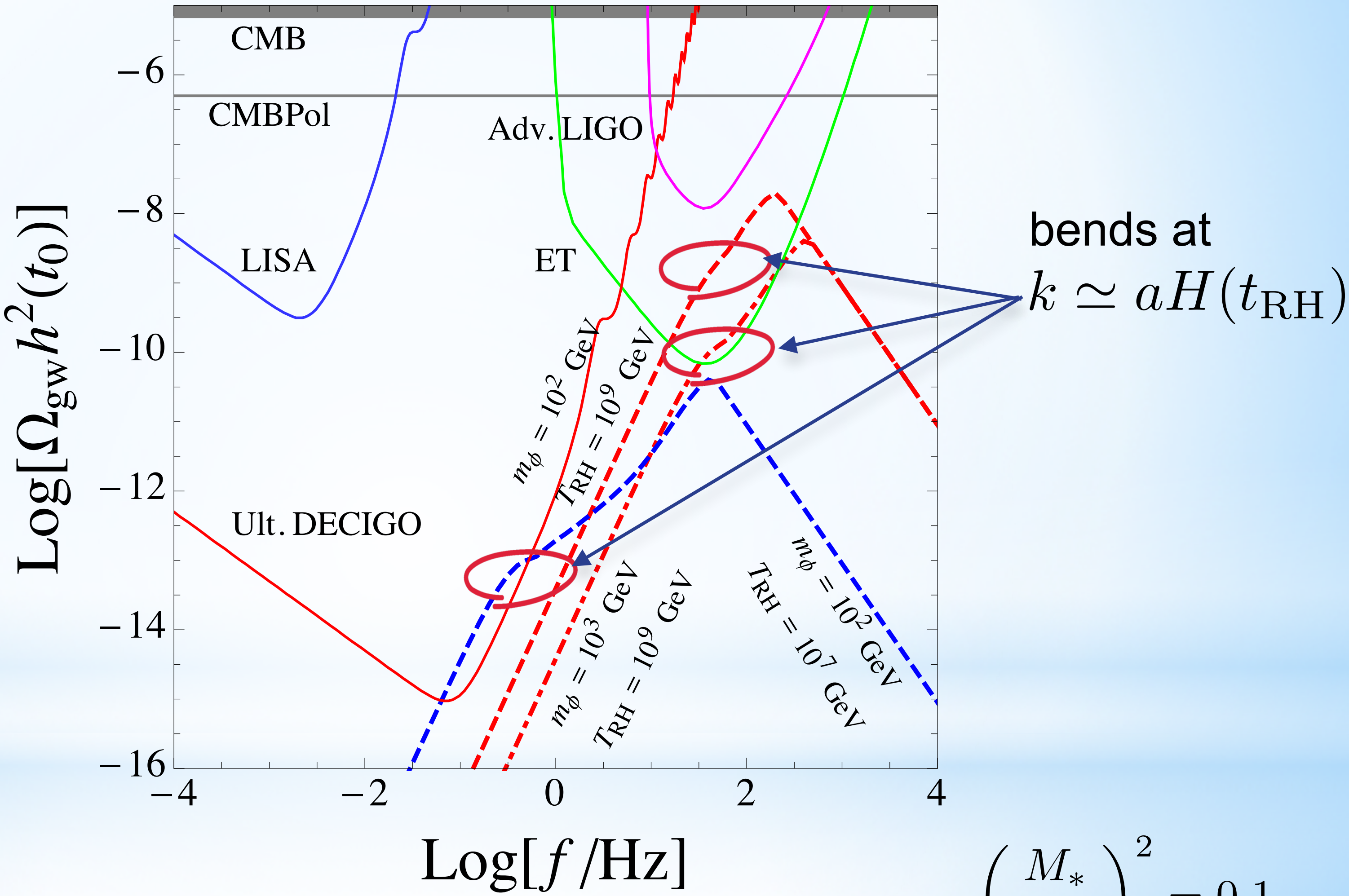
Kamada and M.Y., 14



$$\left(\frac{M_*}{M_{\rm Pl}}\right)^2 = 0.1$$

GW spectrum

Kamada and M.Y., 14



$$\left(\frac{M_*}{M_{\rm Pl}}\right)^2 = 0.1$$

Summary

Kamada and M.Y., 14

- We have investigated the dynamics of a flat direction, which usually exists in supersymmetric theories,
  and have shown that cosmic strings generally form after inflation.

- These cosmic strings disappear at the time of $H(t) \simeq \frac{m_\phi}{\sqrt{c_H}}$

- We can obtain
  the soft mass of the flat direction m_ϕ ,
  the reheating temperature of the Universe $T_{\rm RH}$,
  and the cut-off scale M_*
  through detection of GWs emitted from cosmic strings.