Gravitational waves from cosmic domain walls

Ken'ichi Saikawa (Max-Planck-Institute for Physics)

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

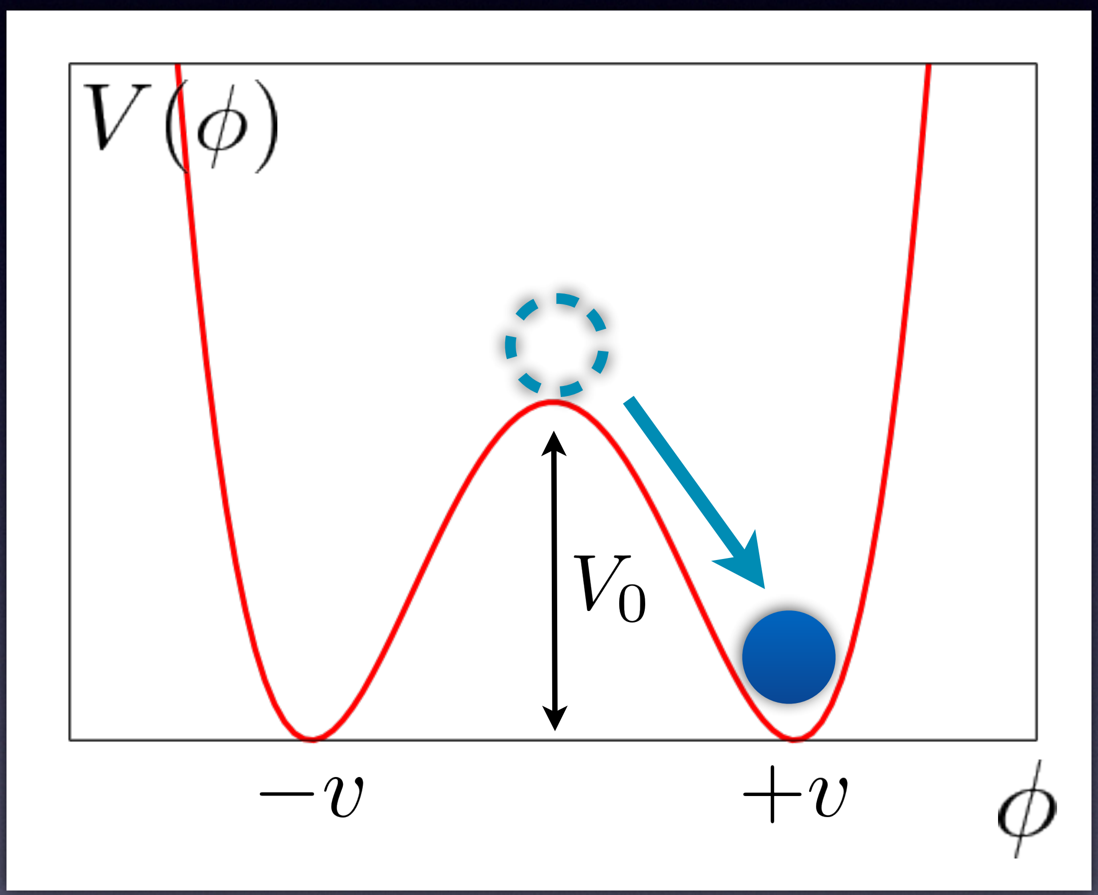
Based on
KS, Universe 3 (2017) 40 [arXiv:1703.02576]
also
T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, JCAP 10 (2013) 001 [arXiv:1207.3166]
T. Hiramatsu, M. Kawasaki, KS, JCAP 02 (2014) 031 [arXiv:1309.5001]
K. Kadota, M. Kawasaki, KS, JCAP 10 (2015) 041 [arXiv: 1503.06998]

30 November 2018, DISCRETE18/VCES, Vienna

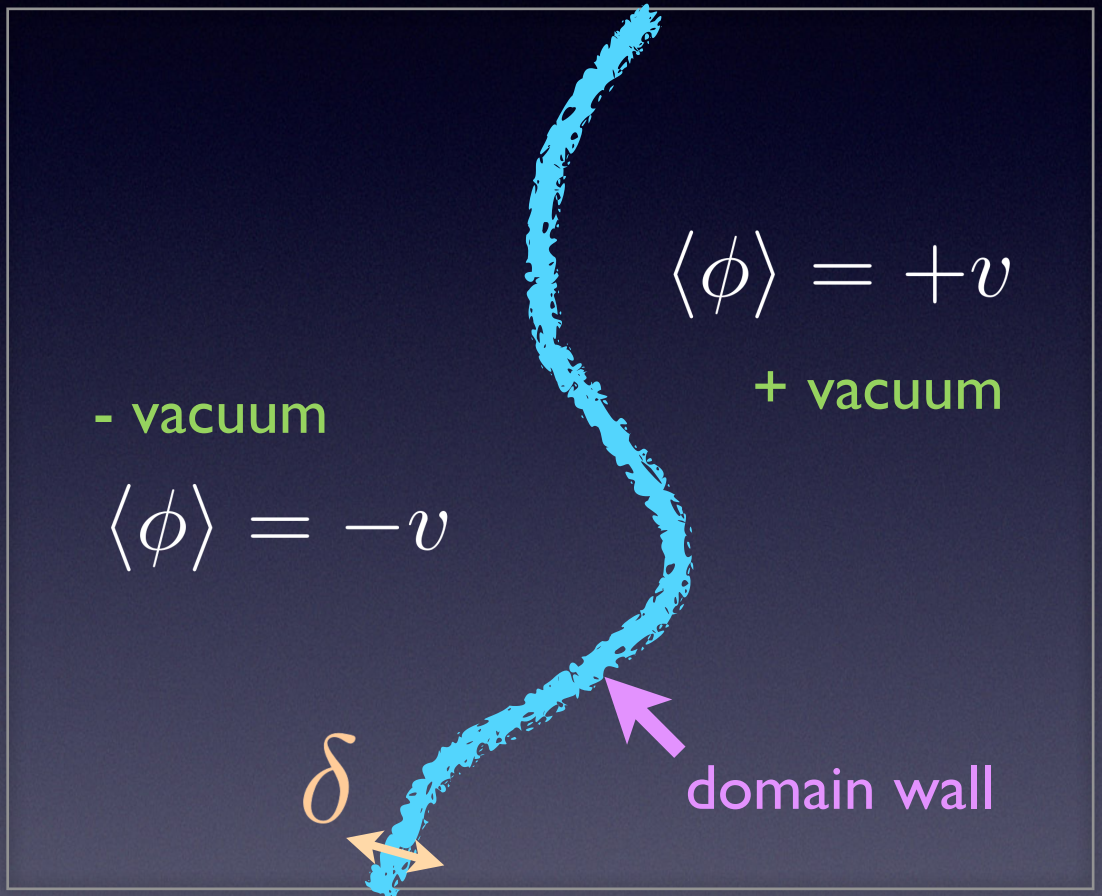
Domain wall

Example: $Z_2 \to 1$

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$$



field space



real space

Width of wall : $\delta \sim m_\phi^{-1} \sim (\sqrt{\lambda} v)^{-1}$

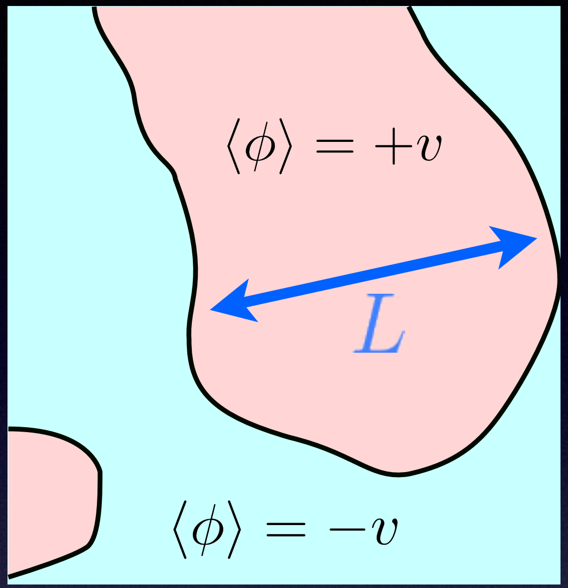
Surface energy density (tension) : $\sigma \sim \delta \cdot V_0 \sim \lambda^{1/2} v^3$

Cosmological evolution

- Scaling solution Press, Ryden and Spergel (1989)
  - One wall per one Hubble radius

$$L \sim H^{-1} \sim t$$

L : distance between two neighboring walls



  - Energy density

$$\rho_{\rm wall} \sim \sigma L^2 / L^3 \sim \sigma / t$$

decays slower than $\rho_{\rm matter} \propto a^{-3}$ and $\rho_{\rm radiation} \propto a^{-4}$

$a(t)$: scale factor of the universe

- Come to overclose the universe (domain wall problem)

Zel'dovich, Kobzarev and Okun (1975)

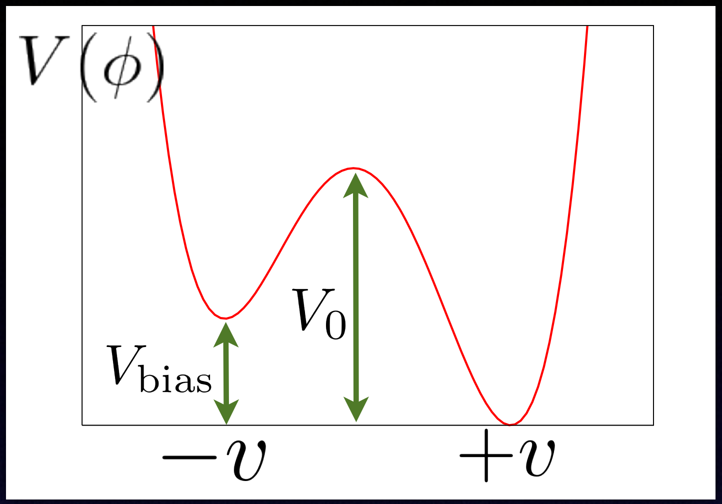
  - Possible scenarios to avoid the problem:
    Inflation after the spontaneous symmetry breaking or
    unstable domain walls

Collapse of domain walls

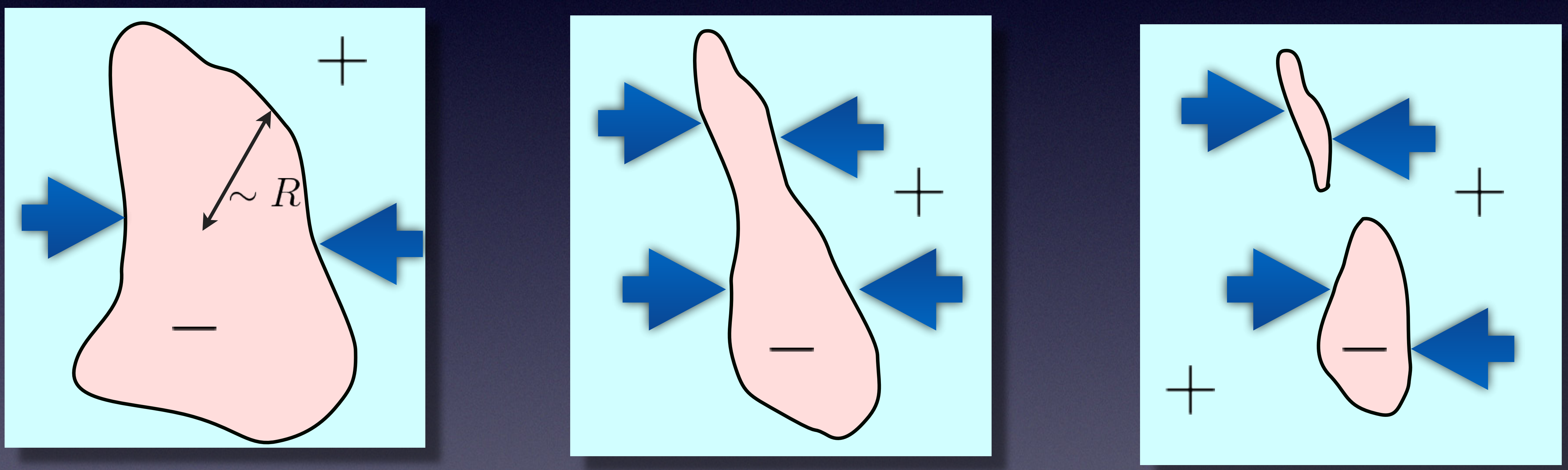
Approximate discrete symmetry (energy bias)

Vilenkin (1981); Gelmini, Gleiser and Kolb (1989); Larsson, Sarkar and White (1997)

$$V_{\rm bias} = V(-v) - V(+v) > 0 \qquad V_{\rm bias} \ll V_0$$



Acts as a volume pressure $p_V \sim V_{\rm bias}$



Annihilation occurs when p_V becomes comparable to the tension of the walls $p_T \sim \sigma/R$.

R : curvature radius

Time scale $t_{\rm ann} \sim \sigma/V_{\rm bias}$

corresponding to the temperature of the universe

$$T_{\rm ann} \sim 10\,{\rm MeV} \left(\frac{\sigma}{\rm TeV^3}\right)^{-1/2} \left(\frac{V_{\rm bias}}{\rm MeV^4}\right)^{1/2}$$

Gravitational waves from domain walls

Vilenkin (1981); Preskill, Trivedi, Wilczek and Wise (1991); Gleiser and Roberts (1998)

- Gravitational waves are expected to be produced from domain walls until they are annihilated at $T \simeq T_{\rm ann}$.
- Magnitude of gravitational waves
  - Quadrupole formula

$$P \sim G\dddot{Q}_{ij}\dddot{Q}_{ij} \sim M_{\rm wall}^2/t^2$$

: Power [energy / time]

$$Q_{ij} \sim M_{\rm wall}t^2$$

$$M_{\rm wall} \sim \sigma\mathcal{A}t^2$$

During the scaling regime

$$L \sim t$$

$$\rho_{\rm wall} \sim \sigma/t$$

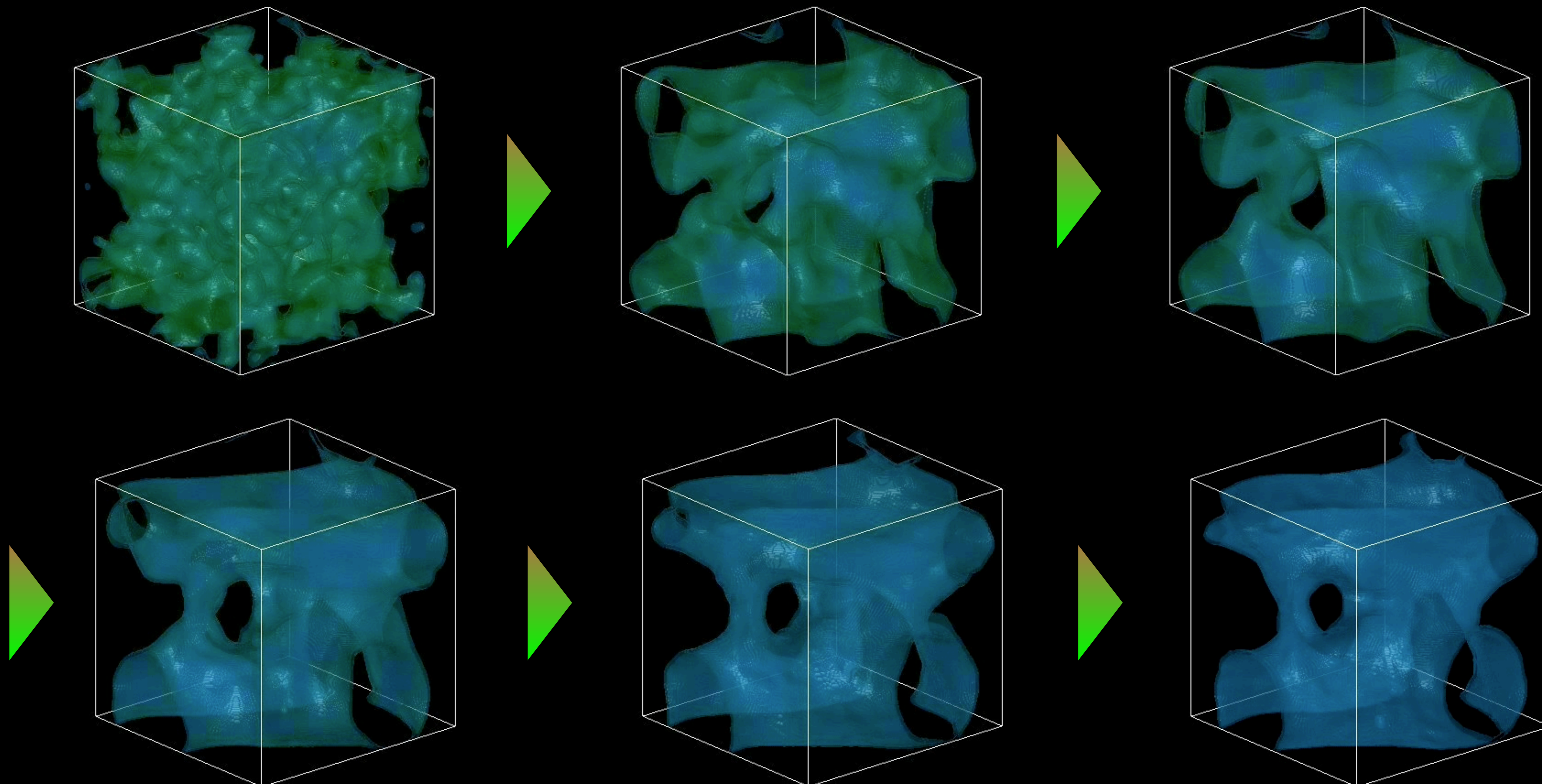
$$\mathcal{A} \equiv \frac{\rho_{\rm wall}}{\sigma}t \simeq \text{const. of } \mathcal{O}(1)$$

  - Energy density

$$\rho_{\rm gw} \sim \frac{Pt}{L^3} \sim G\mathcal{A}^2\sigma^2$$

Numerical study

Hiramatsu, Kawasaki and KS (2010)
Kawasaki and KS (2011)
Hiramatsu, Kawasaki and KS (2014)

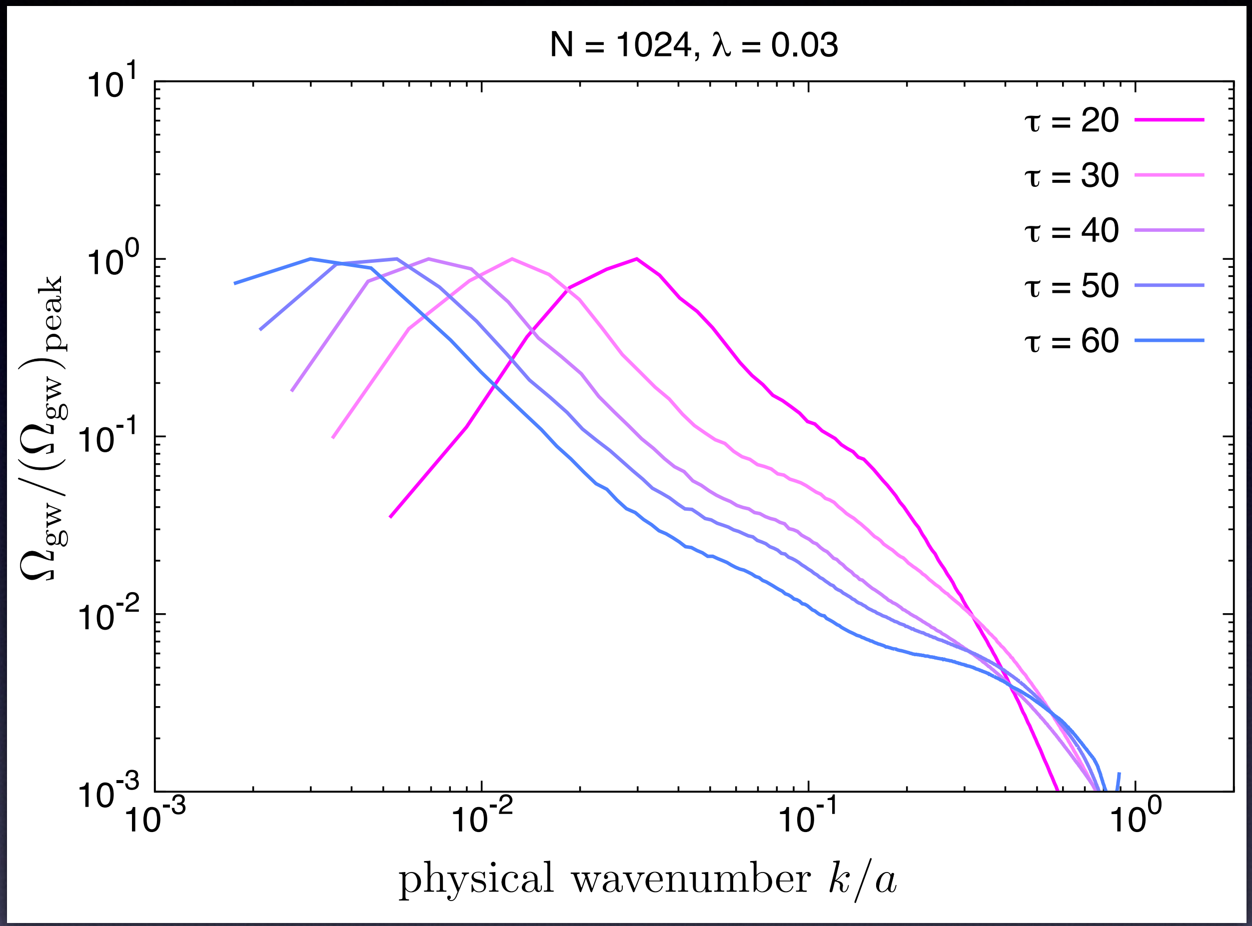


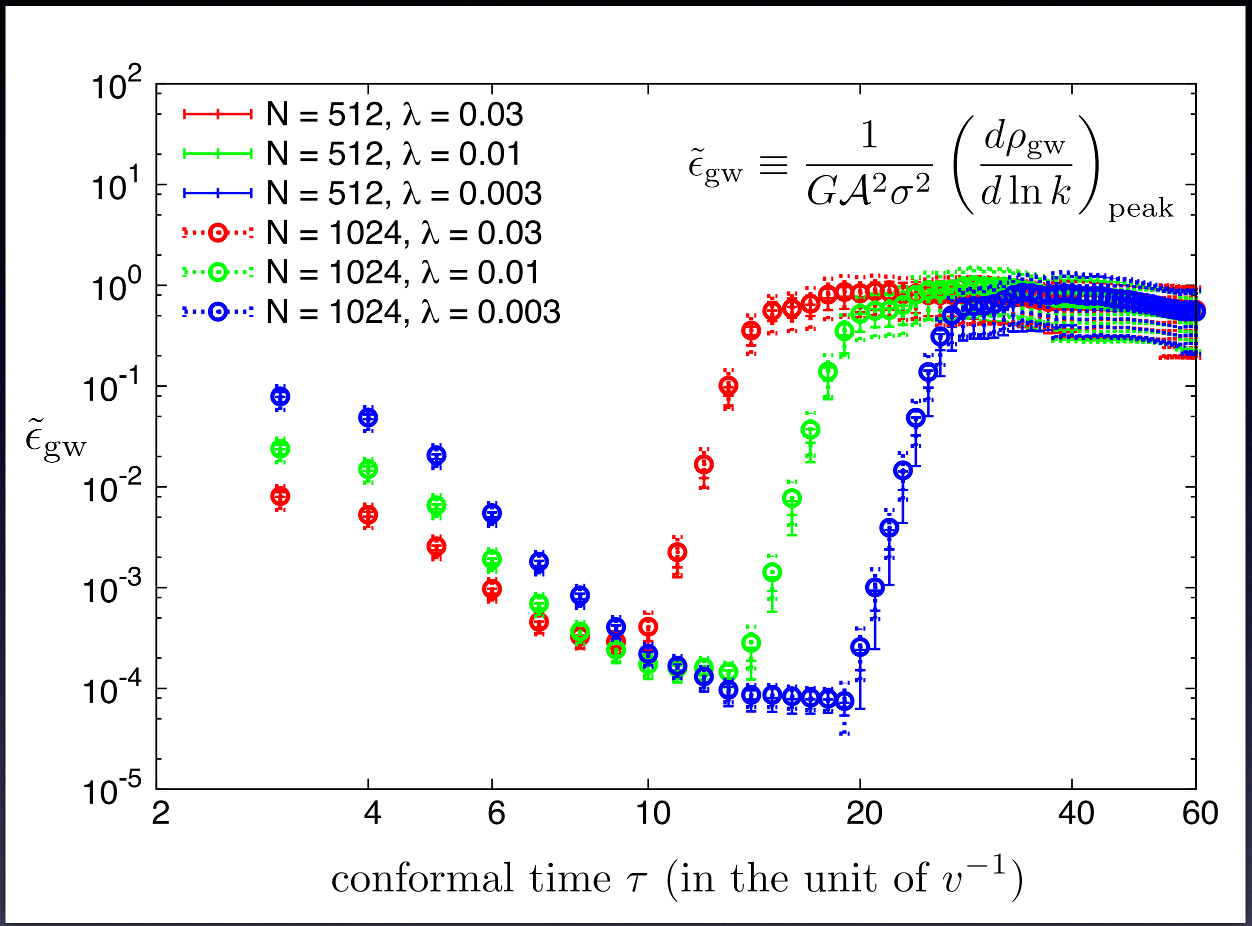
Solve the classical field equation on the lattice:

$$\ddot{\phi} + 3H\dot{\phi} - a(t)^{-2}\nabla^2\phi = -\frac{\partial V}{\partial \phi}, \qquad V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

Numerical study

Hiramatsu, Kawasaki and KS (2014)





- Spectrum of GWs has a peak at $k/a \sim H$ and declines as $\sim k^{-1}$ at higher k.
- Confirmed the behavior $\rho_{gw} \sim G\mathcal{A}^2\sigma^2 \sim \text{constant}$ during the scaling regime.

Peak amplitude and frequency at the present time

- Assume that the production of gravitational waves is terminated at $T = T_{\rm ann}$.
- Peak amplitude:

  Since $\rho_{\rm gw}(t_{\rm ann}) \sim G\mathcal{A}^2\sigma^2$,

$$\Omega_{\rm gw}h^2(t_0)_{\rm peak} \equiv \frac{1}{\rho_{\rm crit}(t_0)/h^2}\left(\frac{d\rho_{\rm gw}(t_0)}{d\ln k}\right)_{\rm peak}$$
$$\sim 3\times 10^{-18}\left(\frac{g_{*s}(T_{\rm ann})}{10}\right)^{-4/3}\left(\frac{\sigma}{1\,{\rm TeV}^3}\right)^2\left(\frac{T_{\rm ann}}{10\,{\rm MeV}}\right)^{-4}$$

- Peak frequency:

$$f_{\rm peak} \sim \left(\frac{a(t_{\rm ann})}{a(t_0)}\right)H(t_{\rm ann})$$
$$\sim 10^{-9}\,{\rm Hz}\left(\frac{g_{*\rho}(T_{\rm ann})}{10}\right)^{1/2}\left(\frac{g_{*s}(T_{\rm ann})}{10}\right)^{-1/3}\left(\frac{T_{\rm ann}}{10\,{\rm MeV}}\right)$$

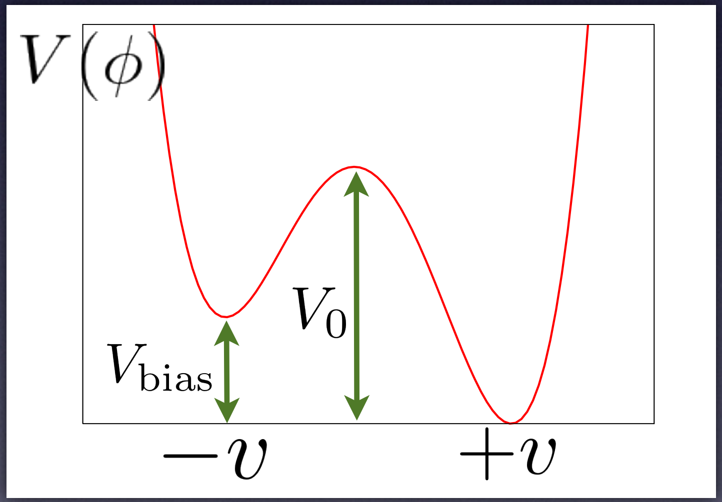
$g_{*\rho}(T),\ g_{*s}(T)$: effective d.o.f. for the energy density and entropy density

Model dependence

$$\Omega_{\rm gw}h^2_{\rm peak} \sim 3\times 10^{-18}\left(\frac{\sigma}{1\,{\rm TeV}^3}\right)^2\left(\frac{T_{\rm ann}}{10\,{\rm MeV}}\right)^{-4}, \quad f_{\rm peak}\sim 10^{-9}\,{\rm Hz}\left(\frac{T_{\rm ann}}{10\,{\rm MeV}}\right)$$

- The peak amplitude and frequency are determined by two parameters:
  - Tension (or surface mass density) of domain walls σ
  - Temperature at their annihilation $T_{\rm ann}$

$$T_{\rm ann}\sim 10{\rm MeV}\left(\frac{\sigma}{1\,{\rm TeV}^3}\right)^{-1/2}\left(\frac{V_{\rm bias}}{1\,{\rm MeV}^4}\right)^{1/2}$$



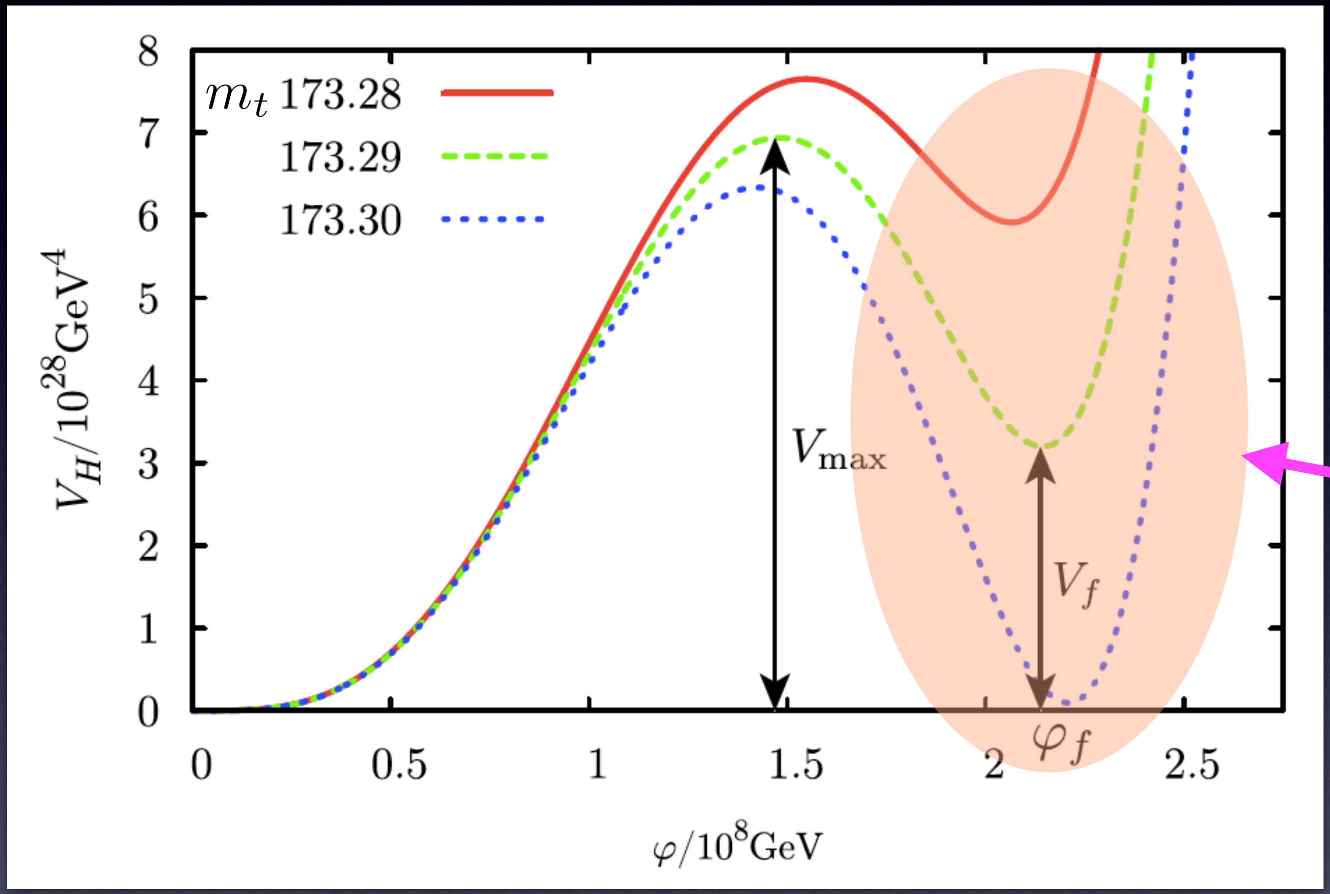
- The values of σ and $V_{\rm bias}$ (and hence $T_{\rm ann}$) depend on underlying particle physics models.

➡ Prediction for the gravitational wave signatures differs according to the details of the models.

Standard Model Higgs field

Kitajima and Takahashi (2015)

- Higgs potential at high energy scales: $V_H = \frac{1}{4}\lambda(\varphi)\varphi^4 + \frac{\varphi^6}{\Lambda^2}$



- Quantum fluctuations during inflation lead to the formation of Higgs domain walls.
- Up to parameter values, a significant amount of gravitational waves can be produced.

Axion models

- QCD axion models can lead to N > 1 degenerate minima in the low energy effective potential.
  (N: integer determined by QCD anomaly)

- Formation of domain walls at the epoch of QCD phase transition. Sikivie (1982)

$$\sigma \approx 8 m_a f_a^2$$
$$\approx 5 \times 10^9\,\mathrm{GeV}^3 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)$$

f_a : axion decay constant

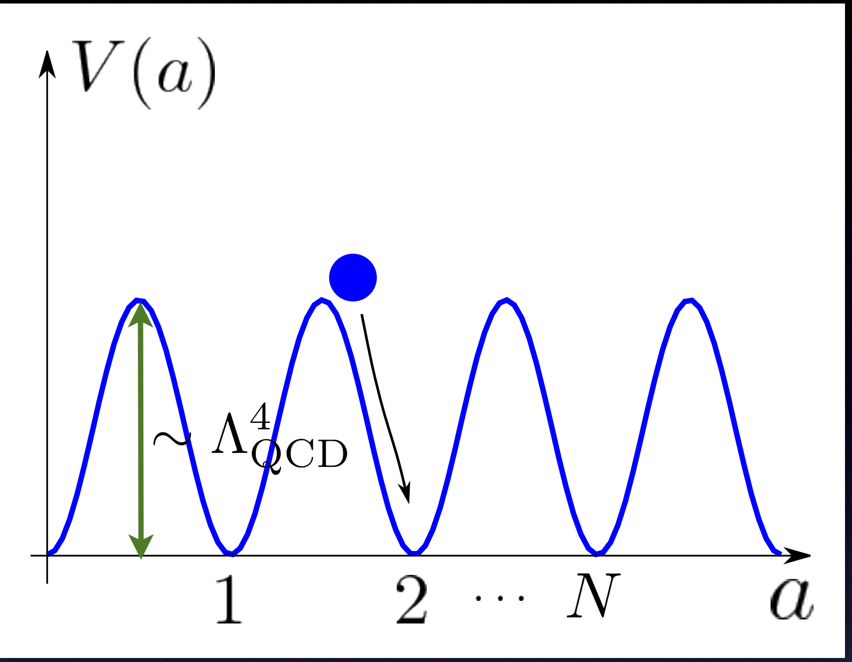
- Resulting GW spectrum has a peak at $\sim 10^{-11}\,\mathrm{Hz}$, but its amplitude is quite small.
  (otherwise cold axions are overproduced)

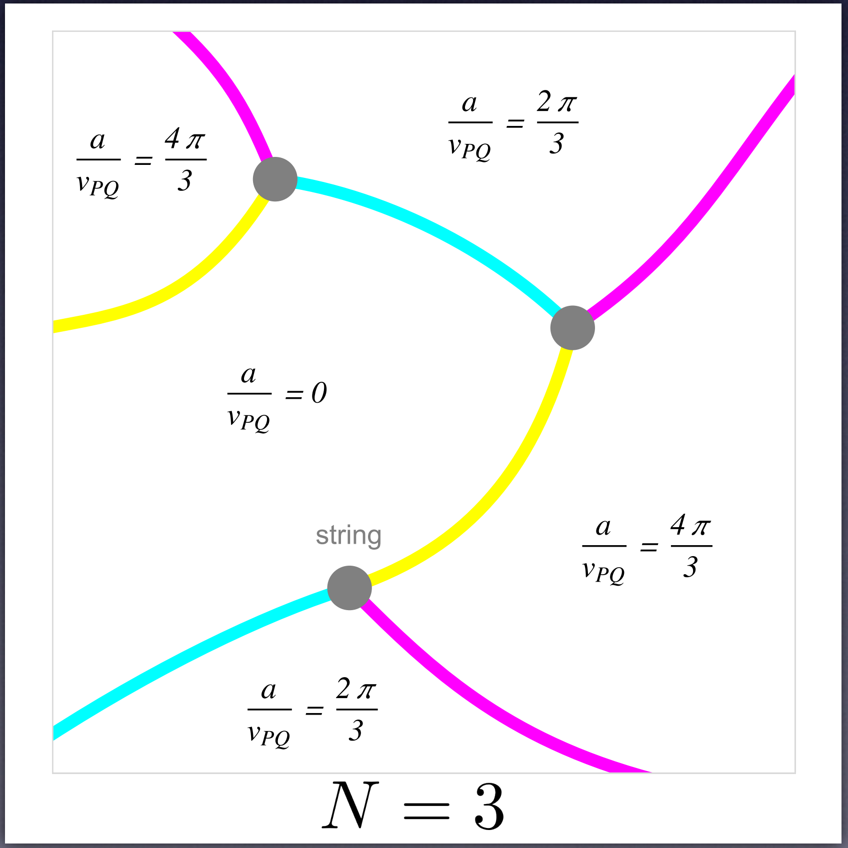
$$\Omega_{\rm gw} h^2_{\rm peak} \lesssim 10^{-20}$$

Hiramatsu, Kawasaki, KS and Sekiguchi (2013)

- A large GW amplitude is predicted in models with axion-like particles (ALPs) or aligned axion models.

Daido, Kitajima and Takahashi (2015)
Higaki, Jeong, Kitajima, Sekiguchi and Takahashi (2016)





Next-to-minimal supersymmetric Standard Model (NMSSM)

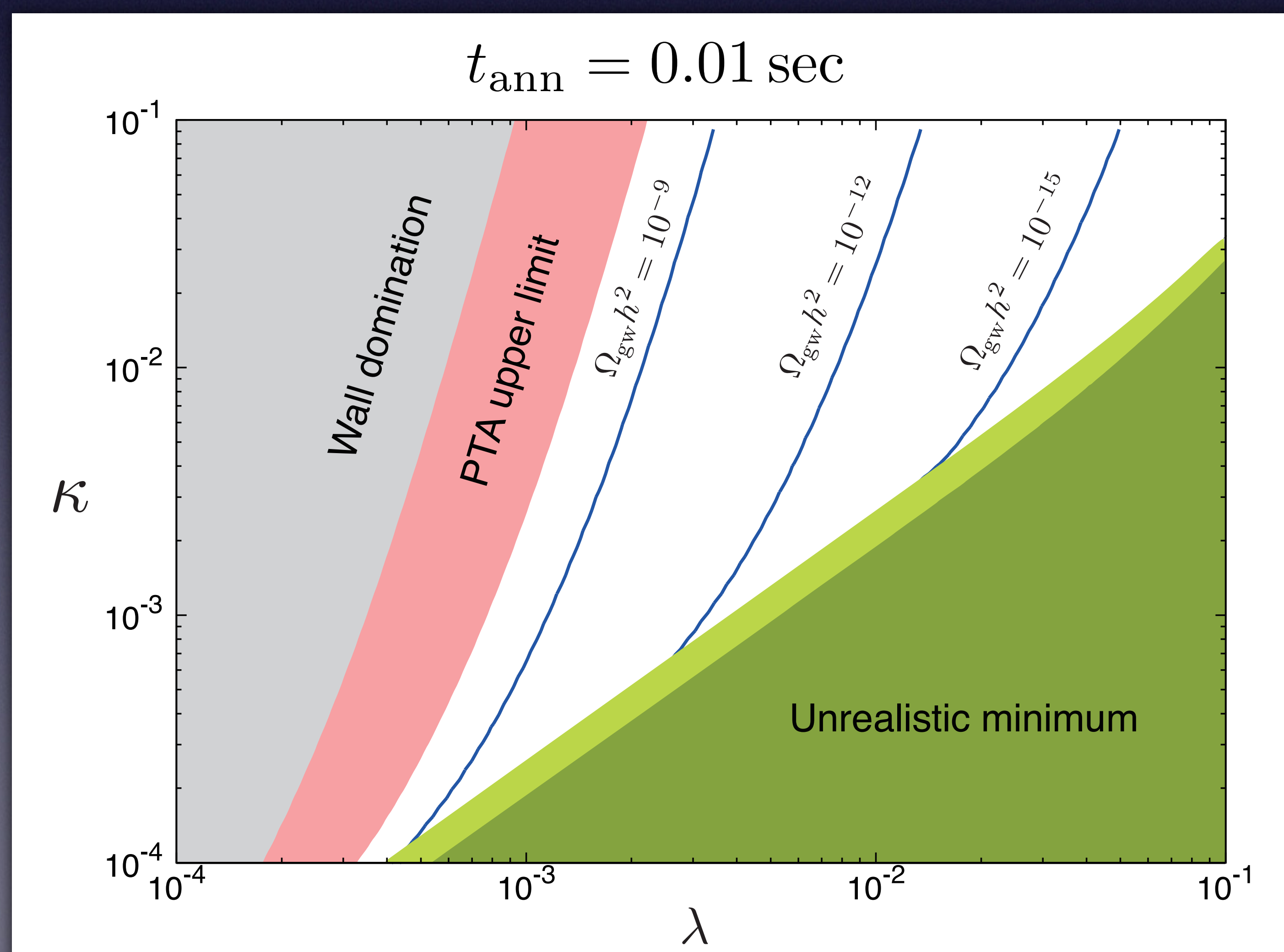
- Additional singlet supermultiplet with an approximate discrete Z_3 symmetry.

$$W_{\rm NMSSM} \supset \lambda S H_u H_d + \kappa S^3 \quad \Rightarrow \quad \mu_{\rm eff} = \lambda \langle S \rangle$$

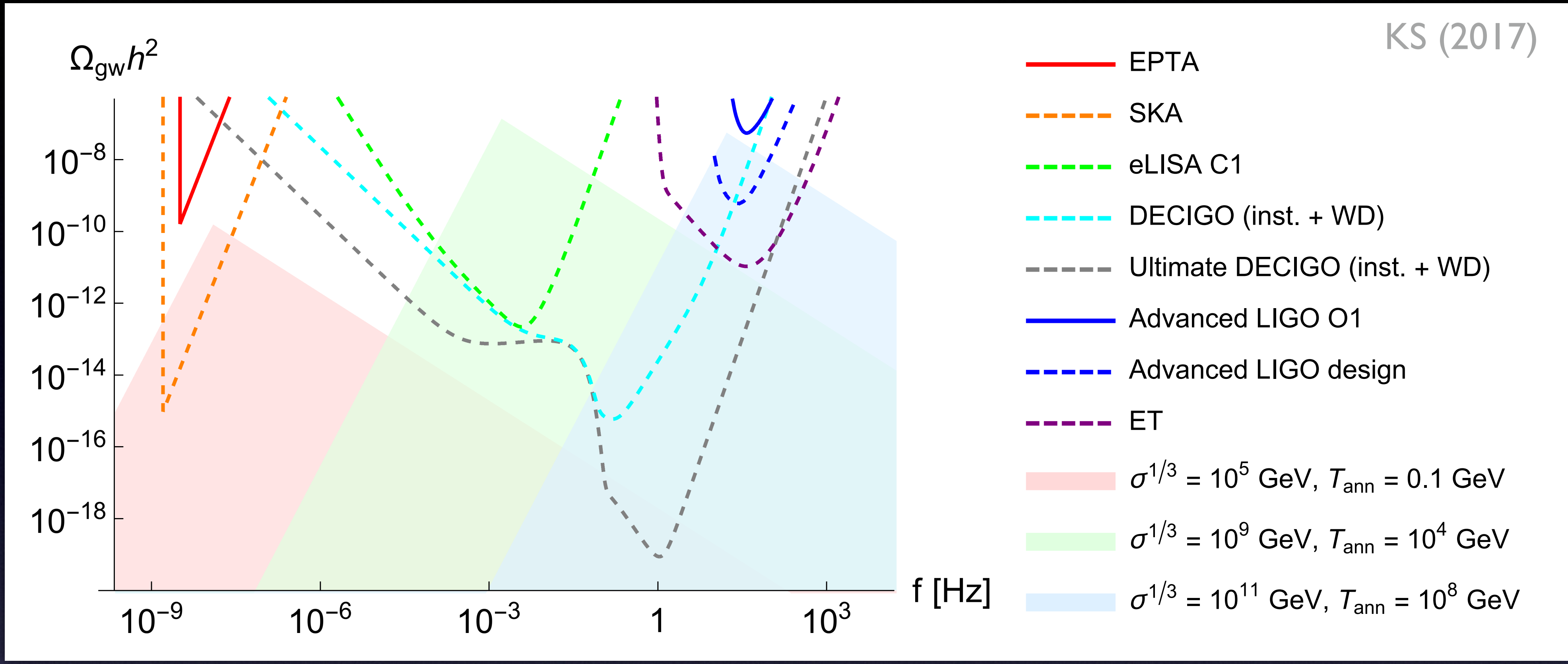
$$Z_3 \,:\, \Phi \to e^{2\pi i/3}\Phi$$

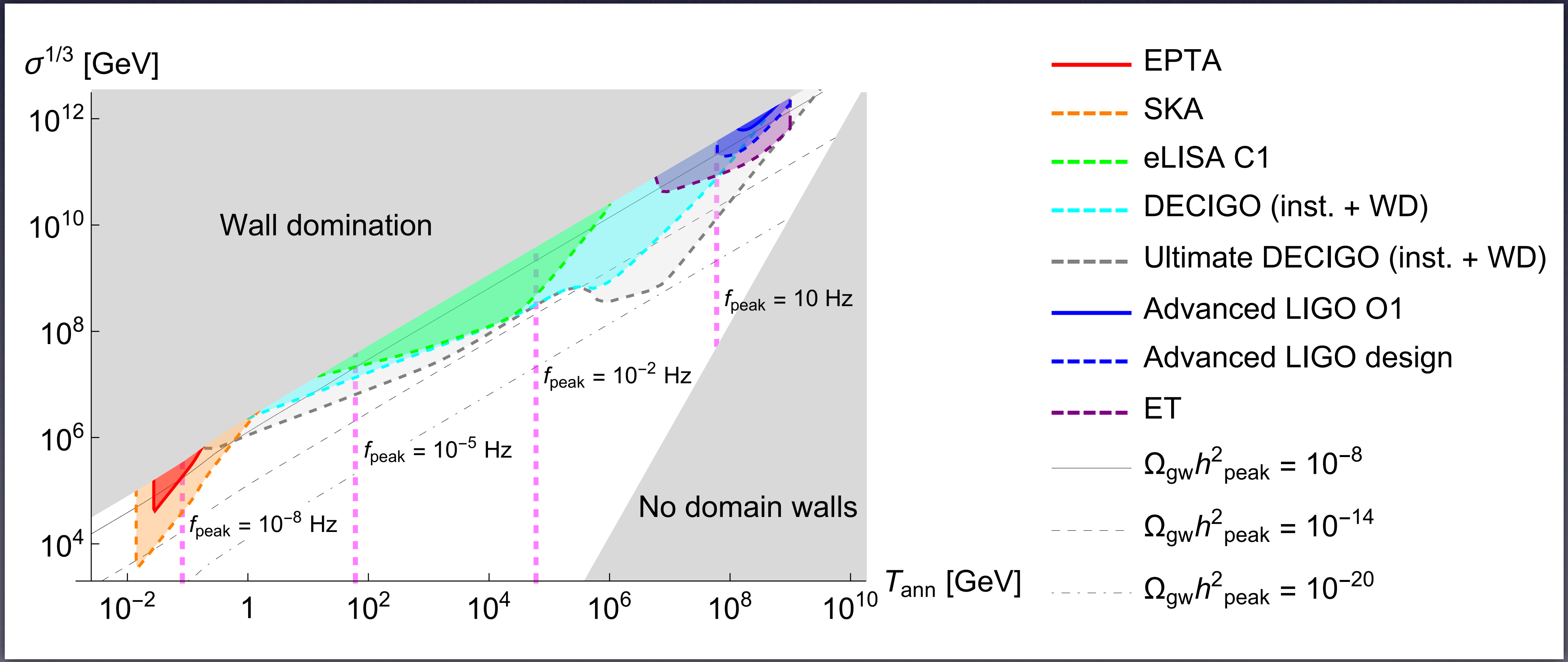
Φ : every chiral supermultiplets of the NMSSM

- If the annihilation of domain walls happens slightly before BBN, a significant amount of GWs can be produced. Kadota, Kawasaki and KS (2015)



Implications for present and future observations





Summary

- Formation of domain walls:
  Prediction of particle theory with spontaneously broken discrete symmetry.

- Domain walls must be unstable and annihilated in order to avoid cosmological problem.
  They can leave an imprint on gravitational waves.

- Various well-motivated particle physics models.

- Signatures can potentially be observed in forthcoming gravitational wave experiments.