Gravitational waves from self-ordering scalar fields

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in collaboration with
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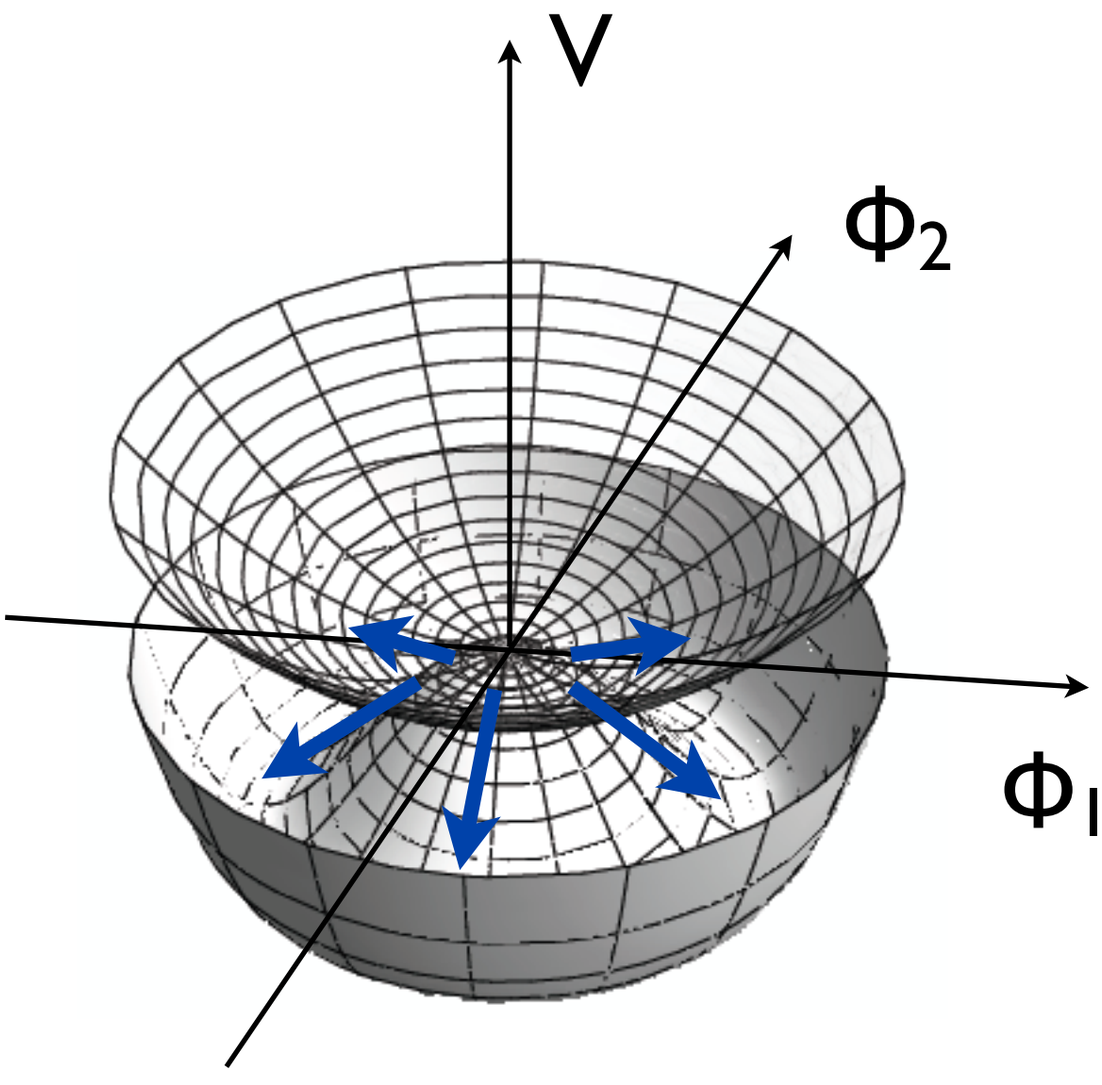
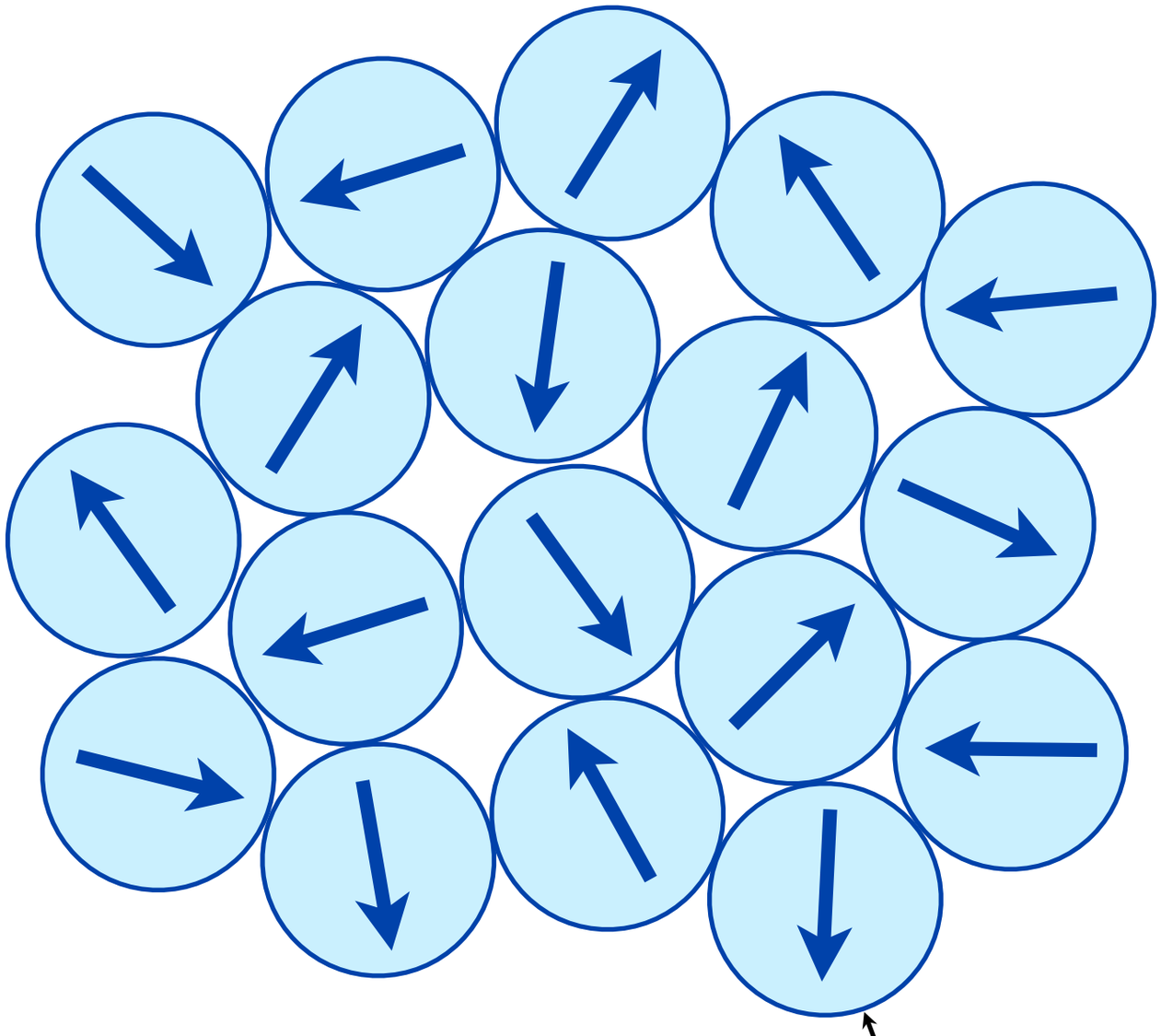
Self-ordering scalar field?

breaking global symmetry

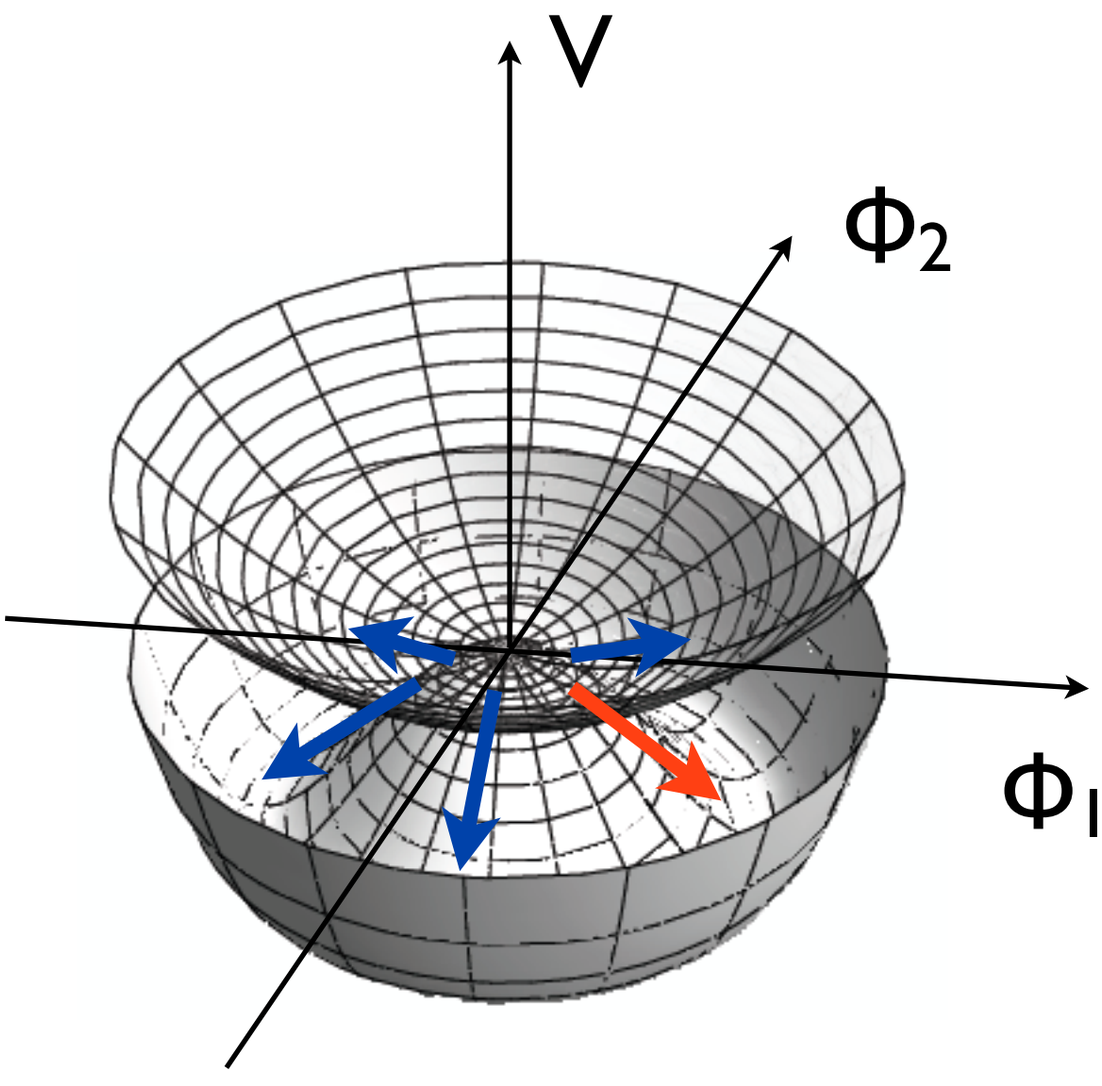


In the Universe...

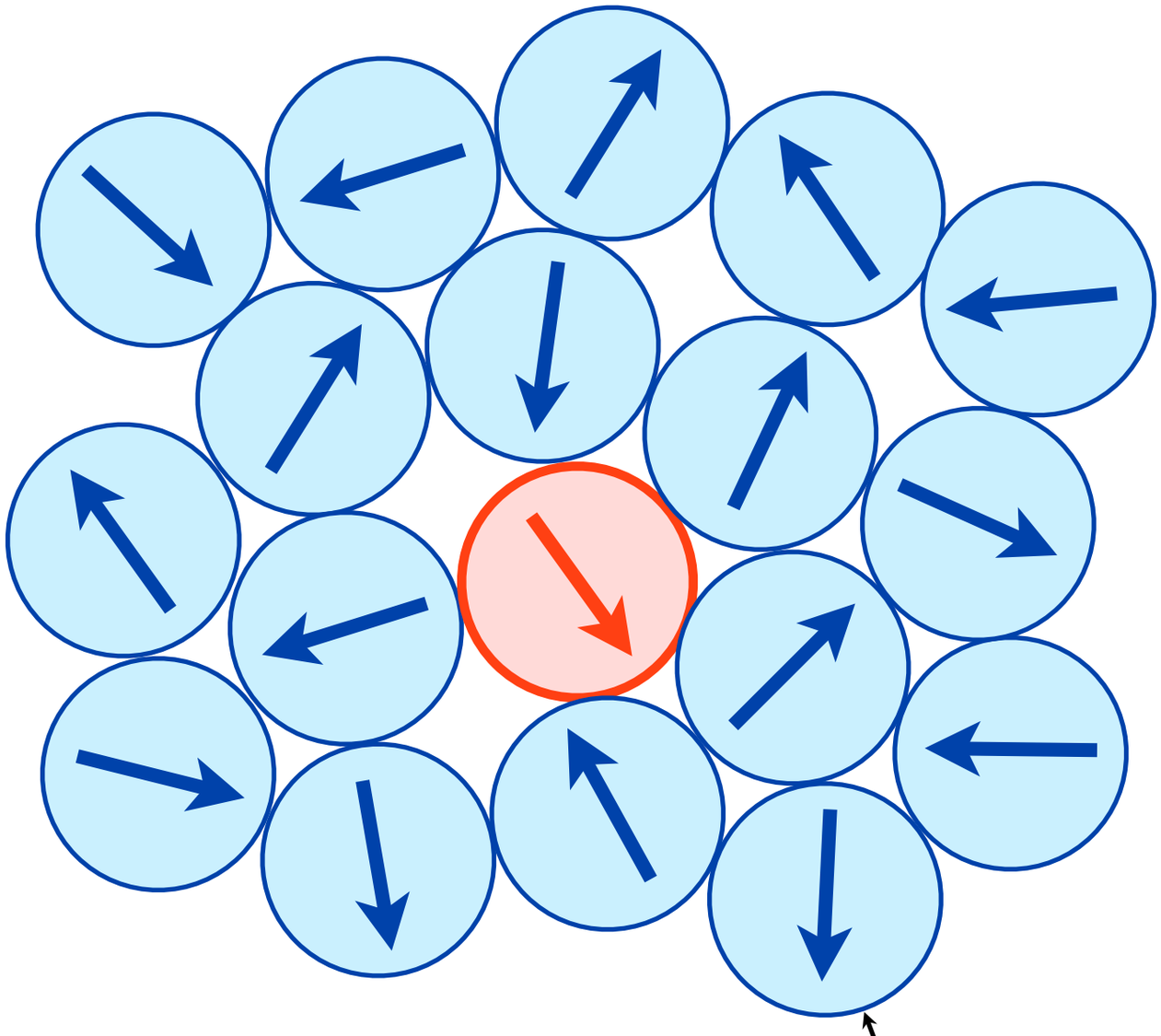


Self-ordering scalar field?

breaking global symmetry

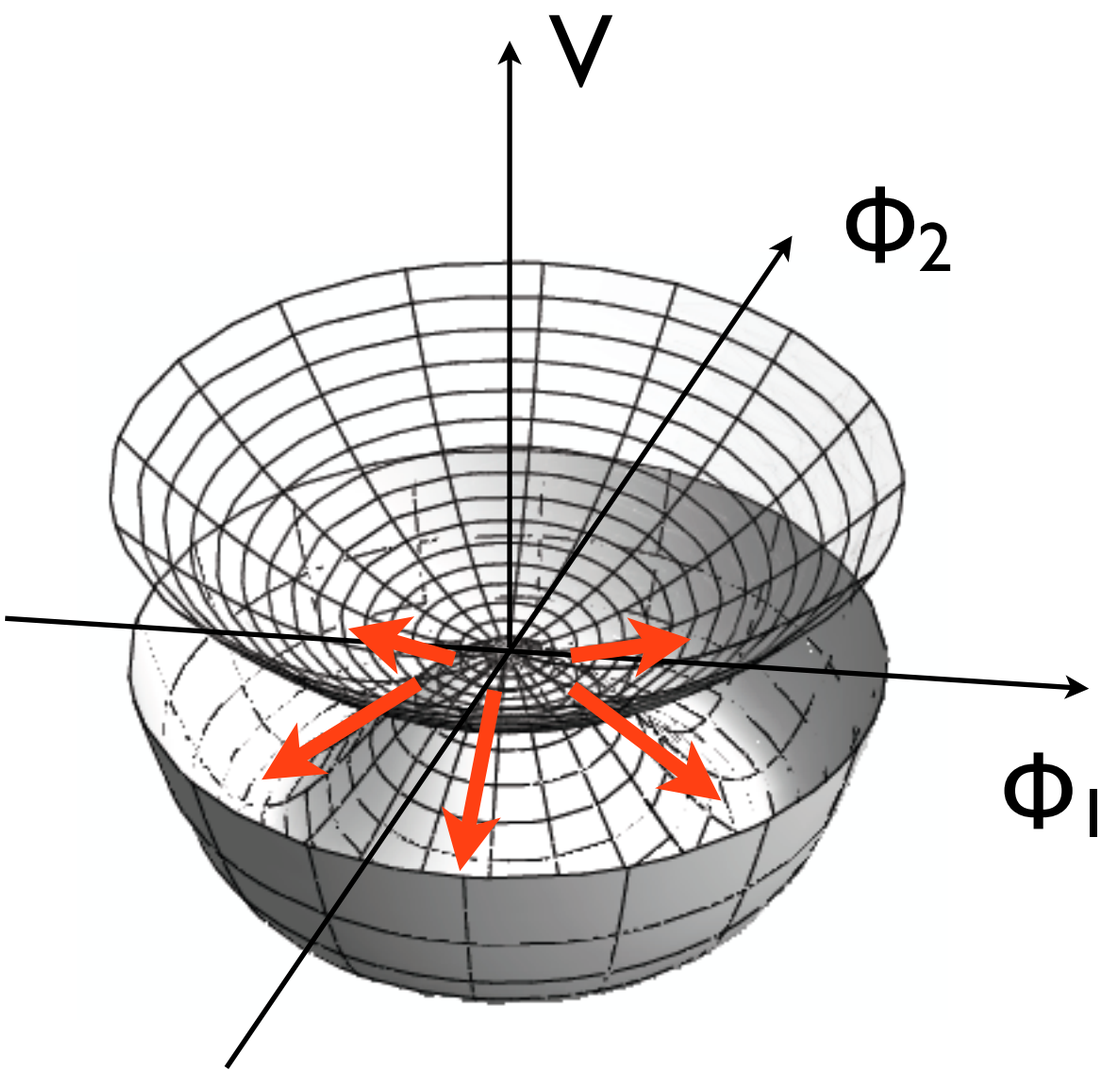


In the Universe...

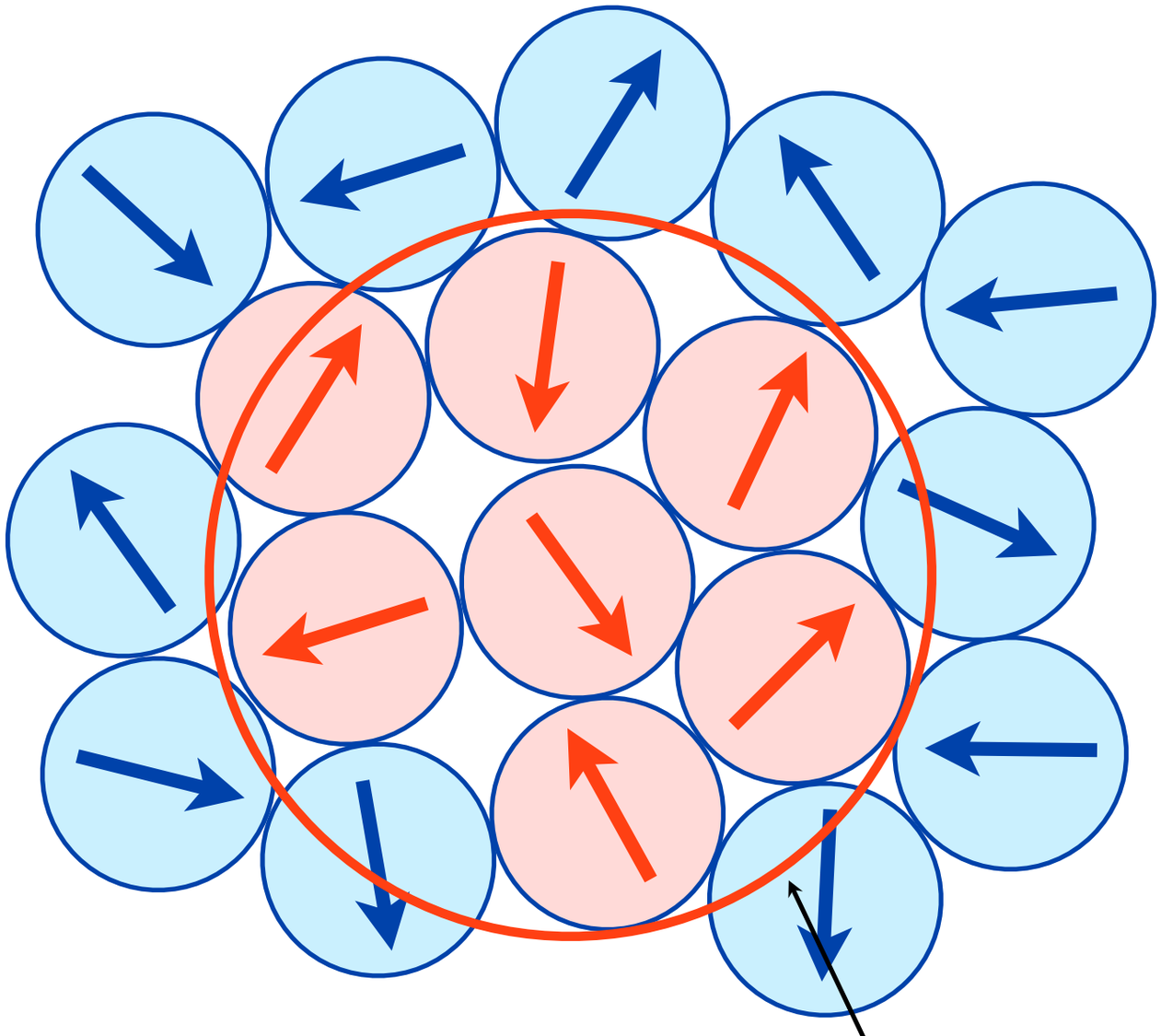


Self-ordering scalar field?

breaking global symmetry

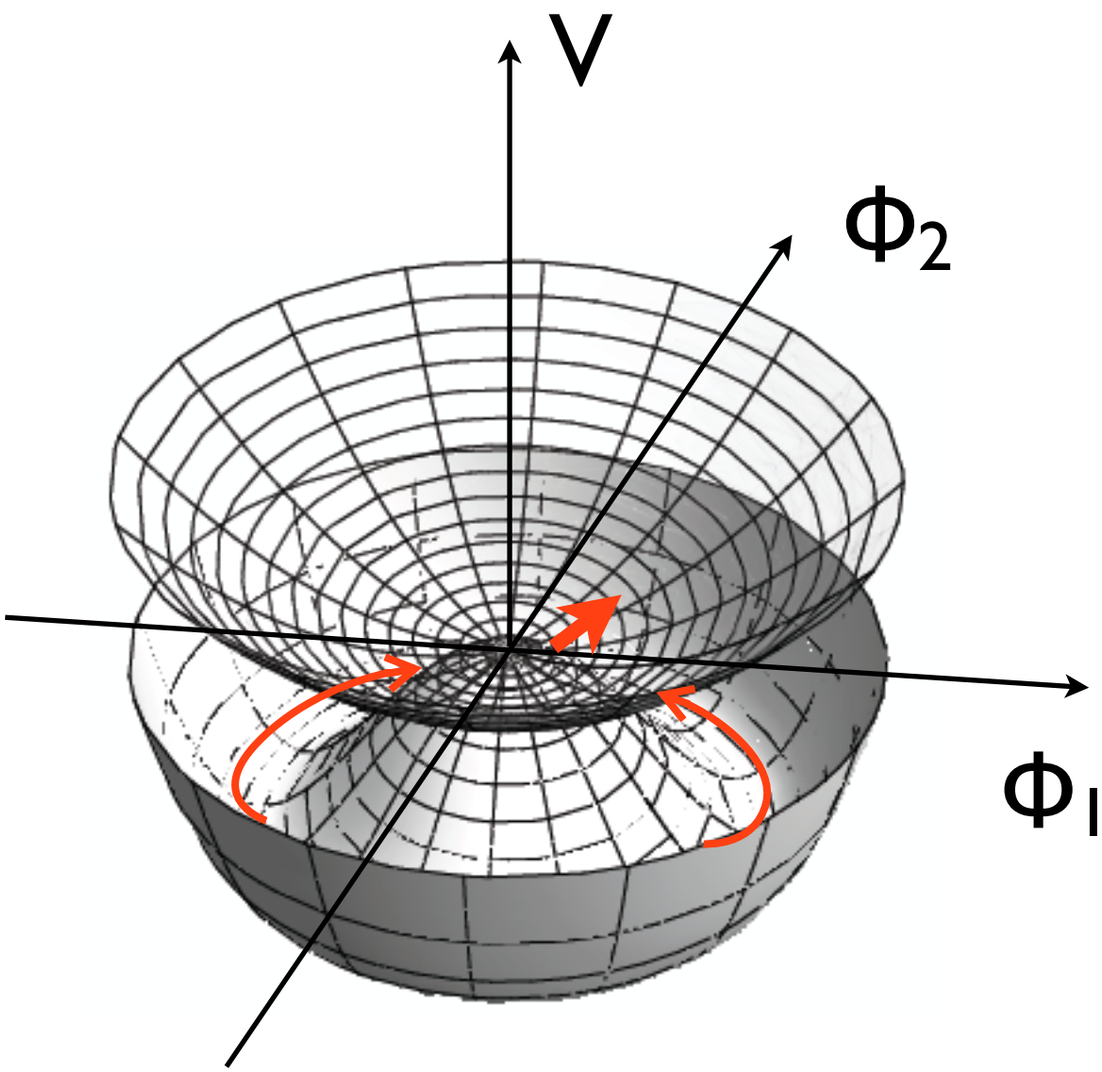


as the Hubble horizon grows...



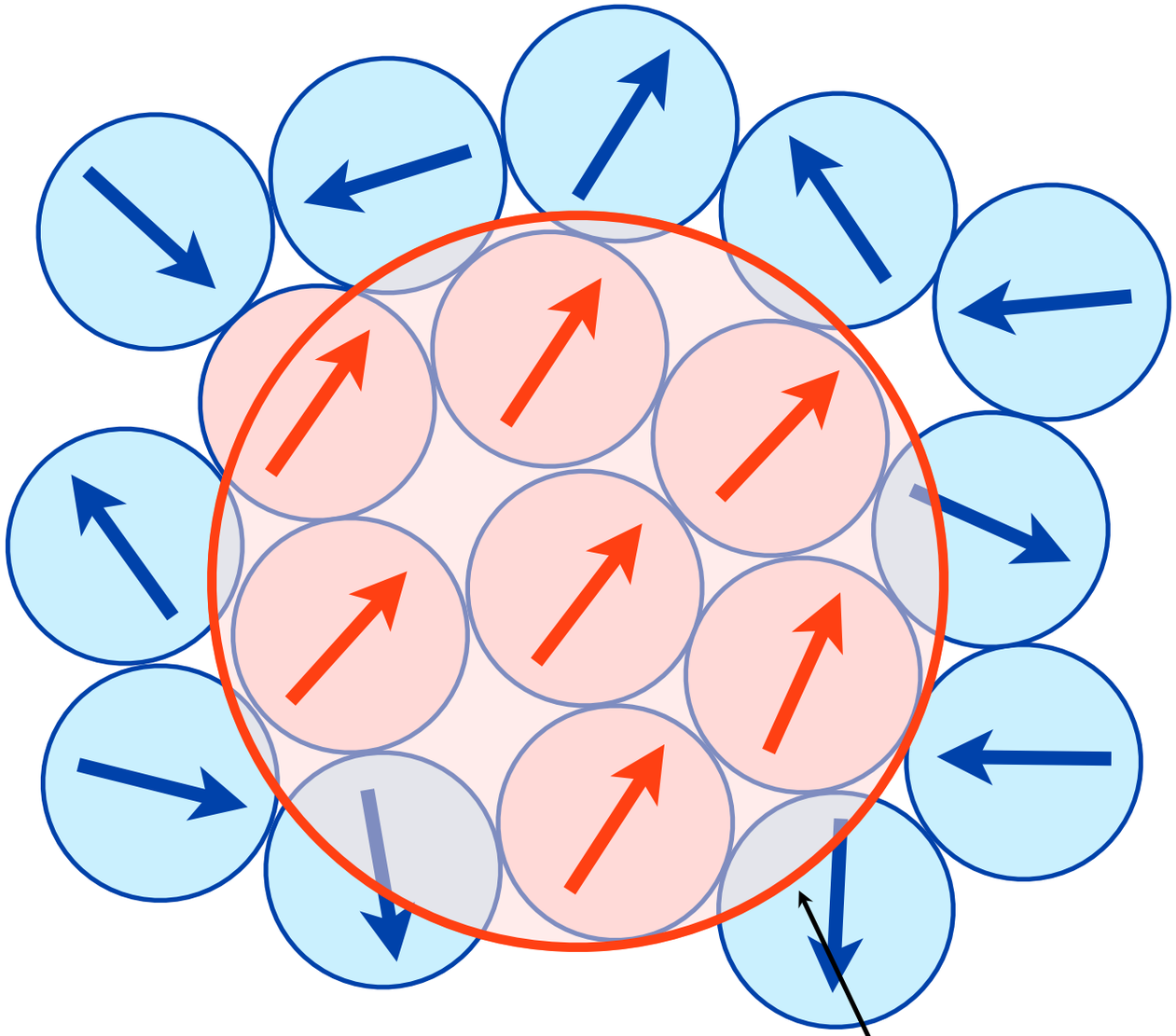
Self-ordering scalar field?

breaking global symmetry

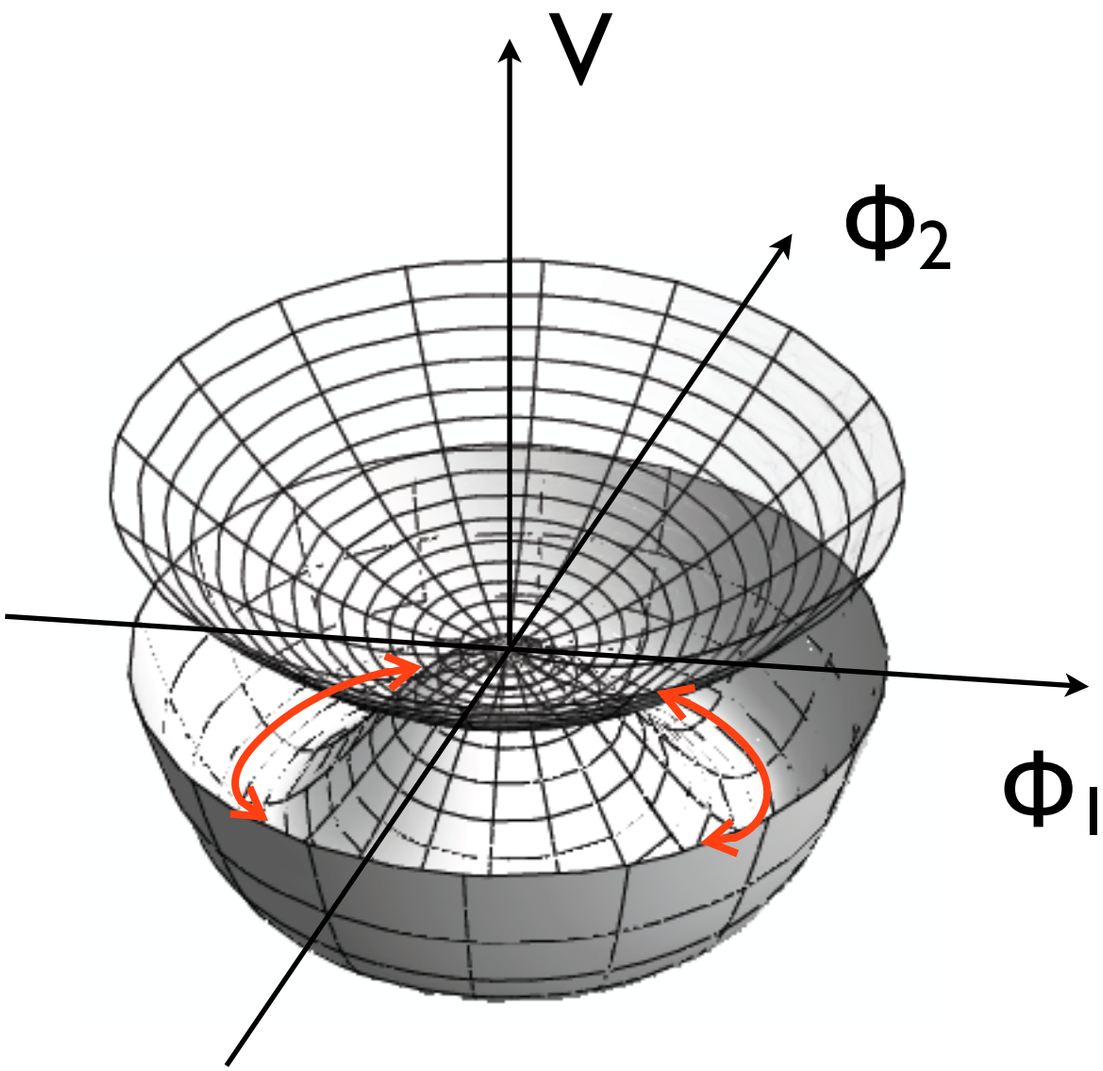


ordering

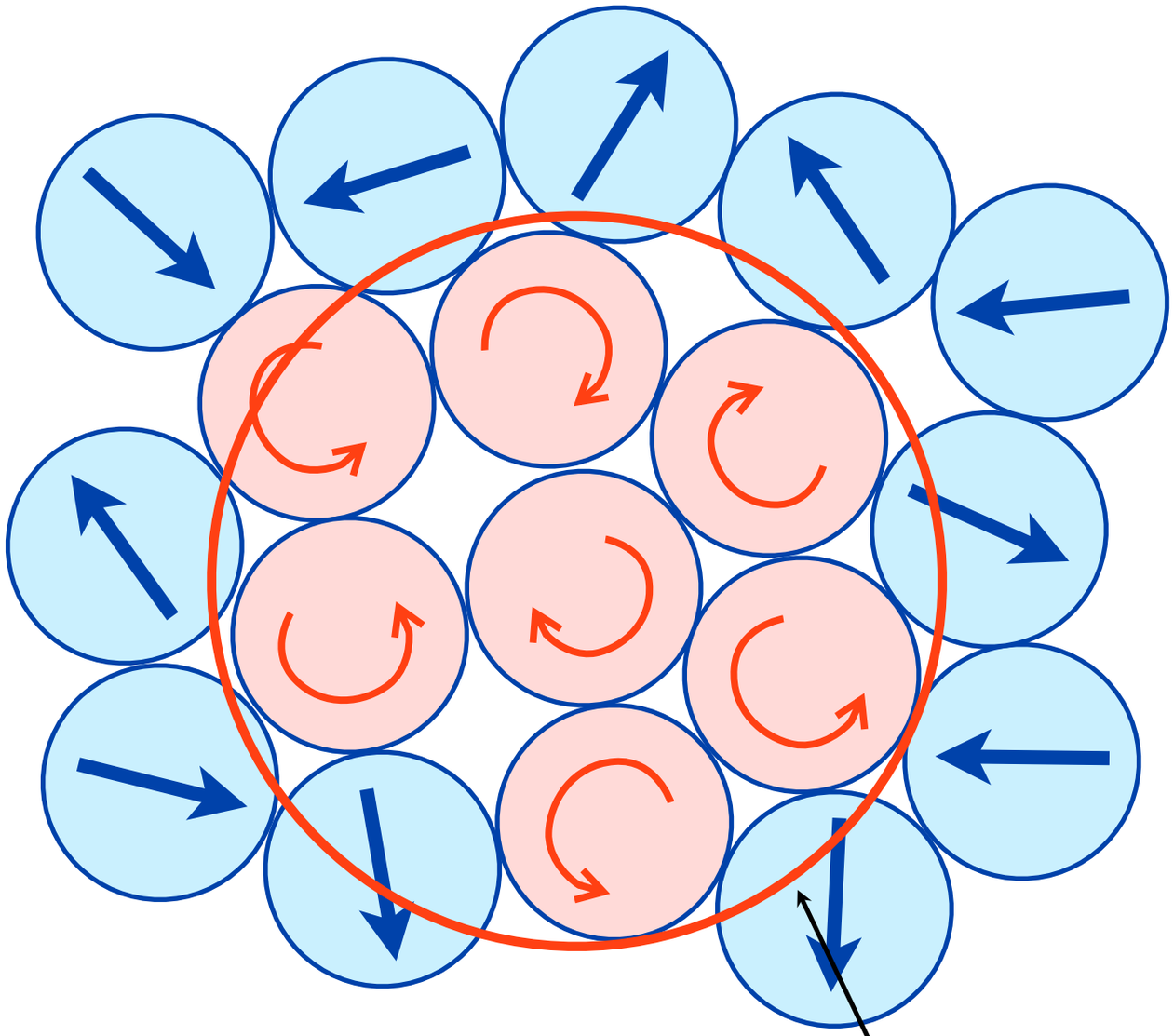
= realignment of the field



GWs from self-ordering scalar field



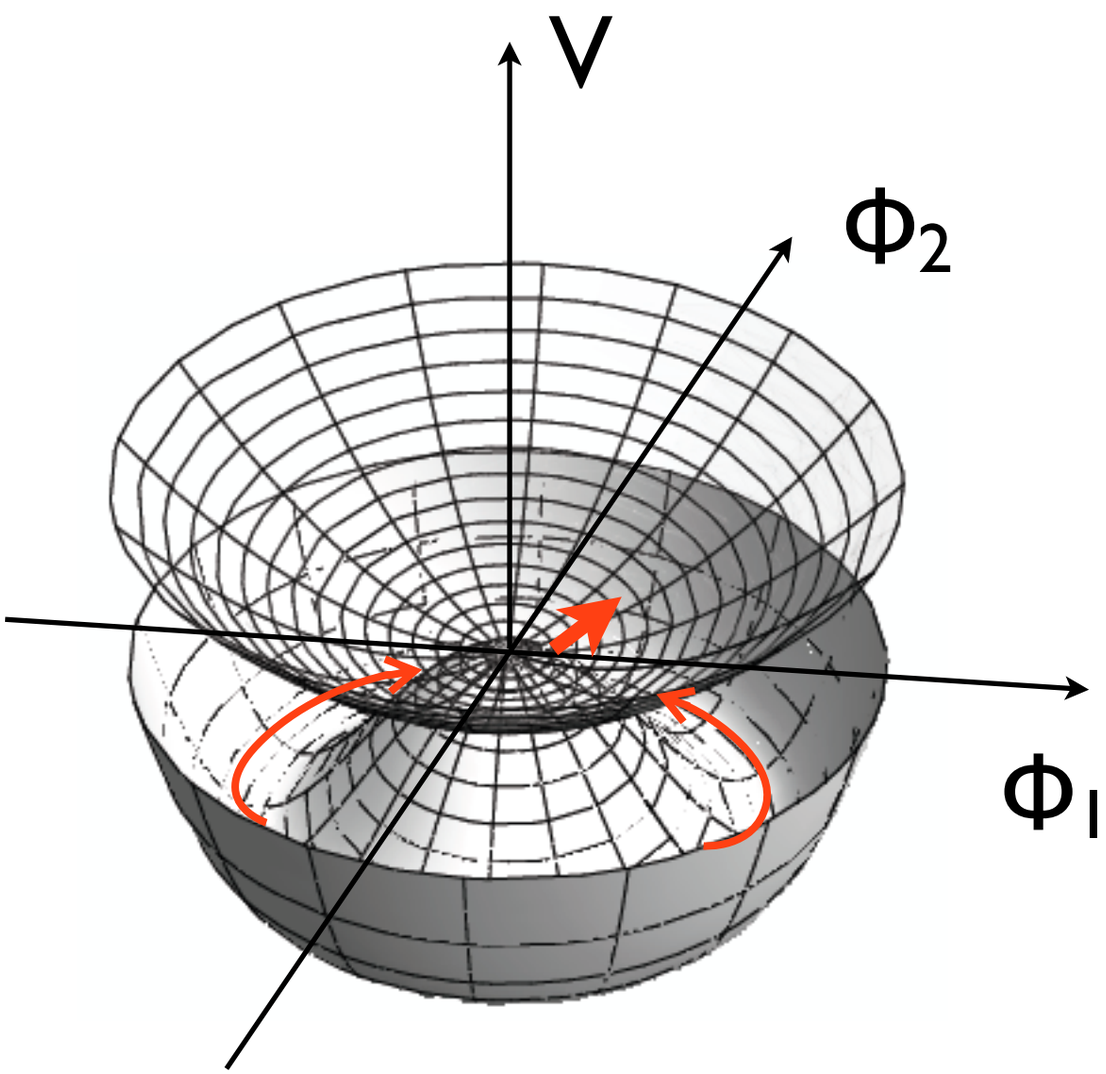
generation of gravitational waves

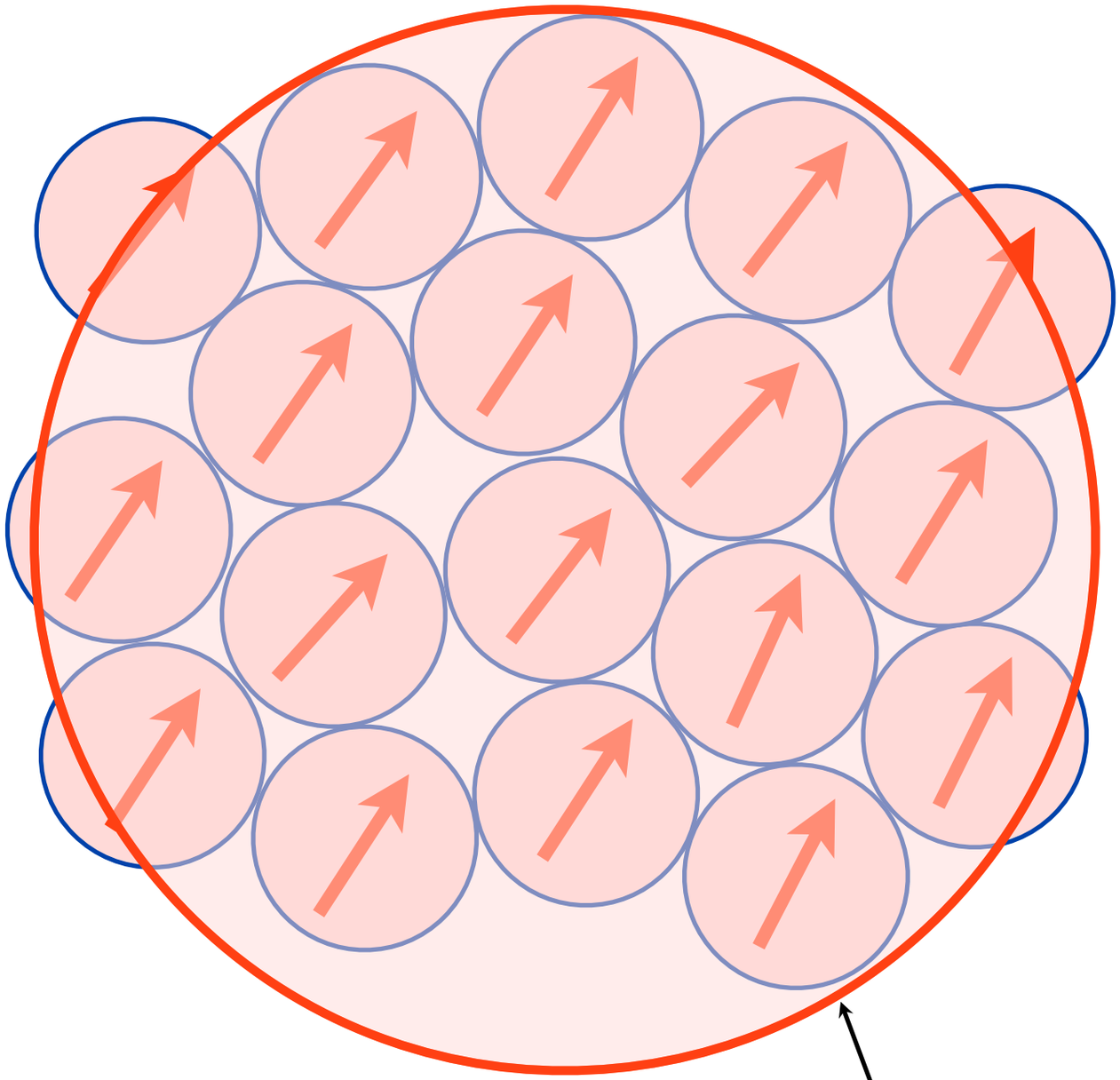


GWs from self-ordering scalar field

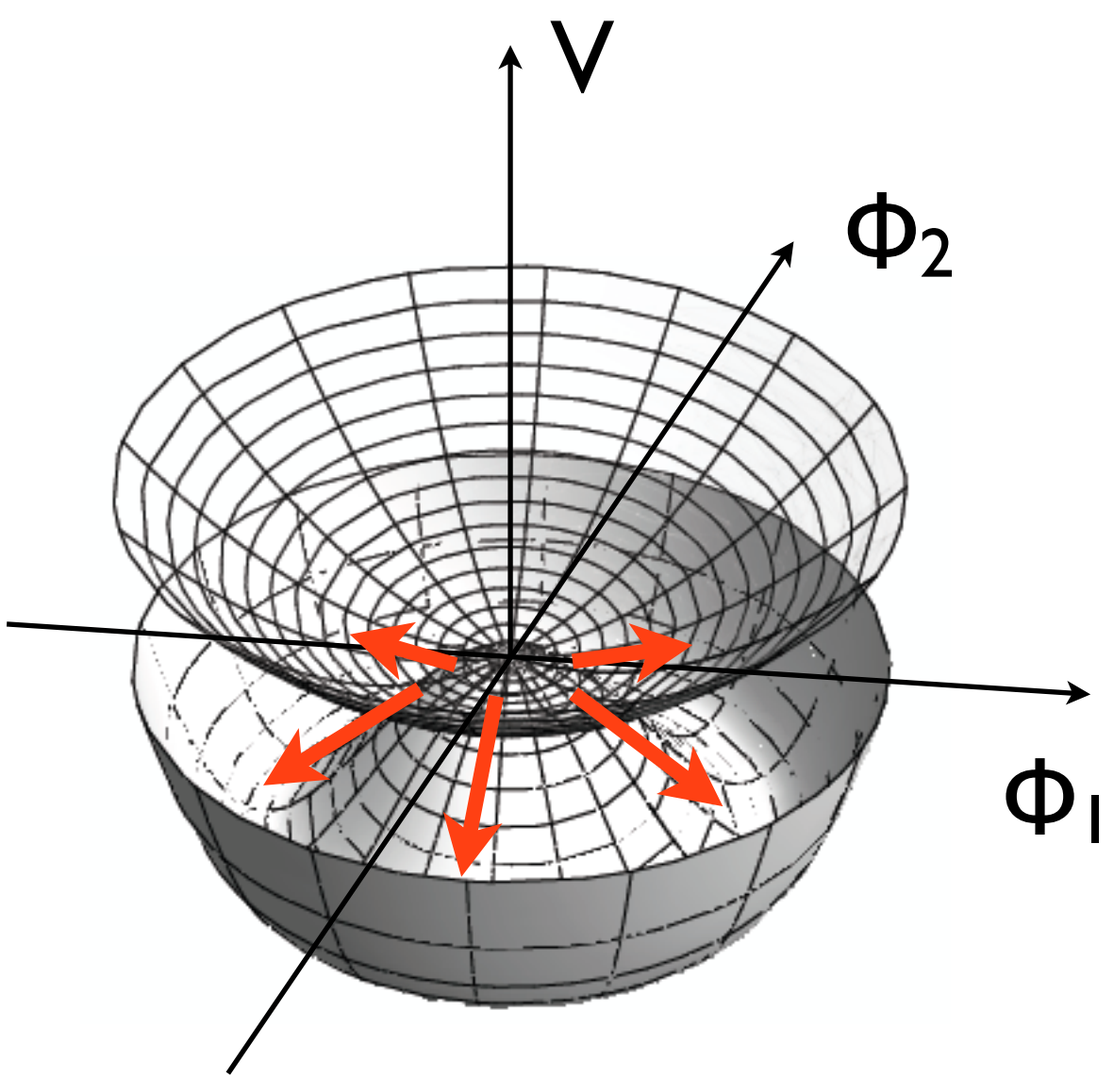
the realignment always happens at horizon scale

→ scale-invariant gravitational waves





Equation for scalar fields (i=1,2,...,N)



$$\phi_i'' + 2\mathcal{H}\phi_i' - \underline{\triangle\phi_i} = a^2 V'(\phi_i)$$

zero zero non-zero zero

(radial component)

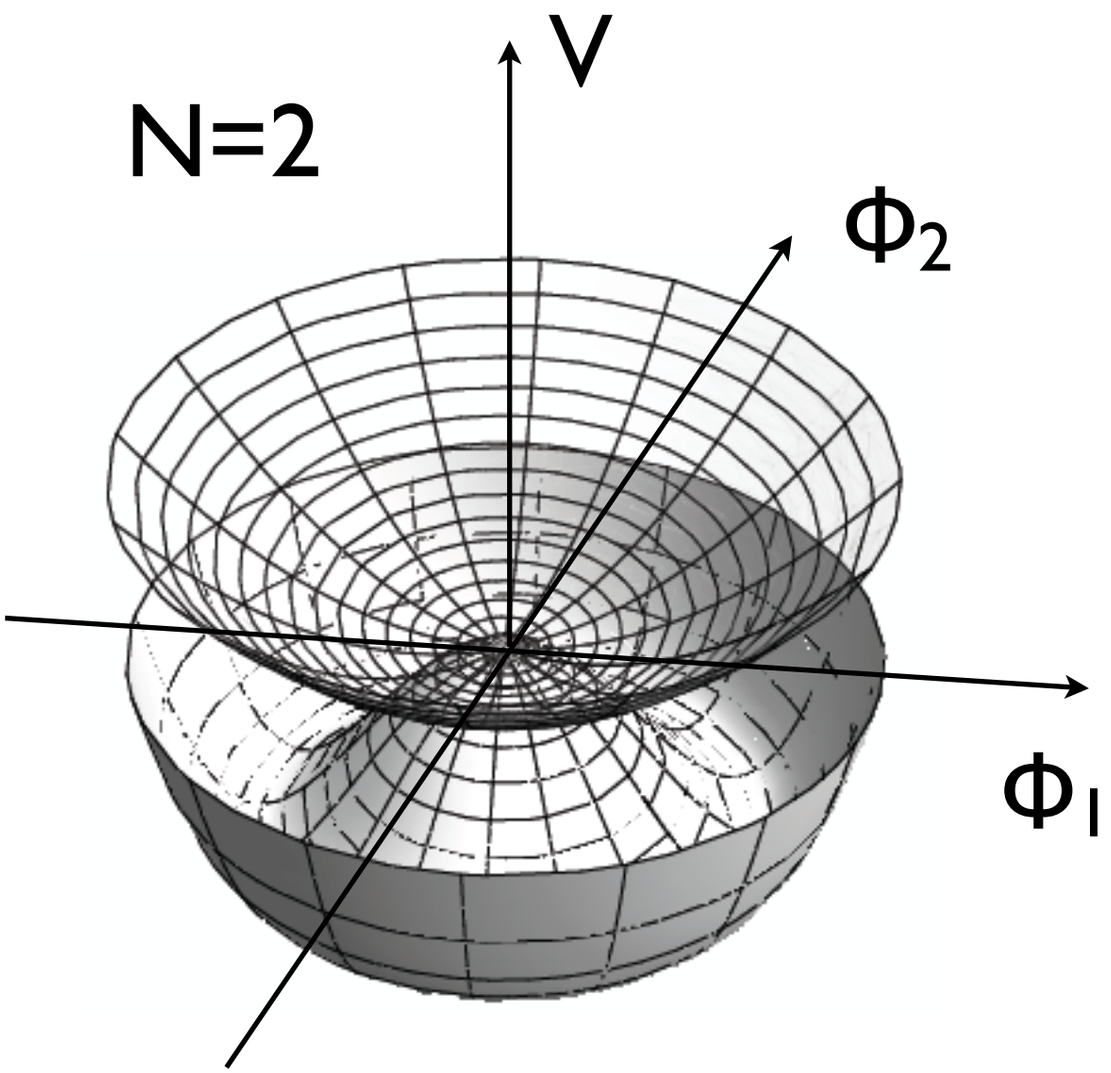
produce the motion
(Φ" and Φ')
in radial direction

Equation for gravitational waves

$$h_{ij}'' + 2\mathcal{H}h_{ij}' - \triangle h_{ij} = \frac{2}{m_{\rm pl}^2}\left(\sum_m \underline{\partial_k\phi_m\partial_\ell\phi_m}\right)^{\rm TT}$$

anisotropic stress

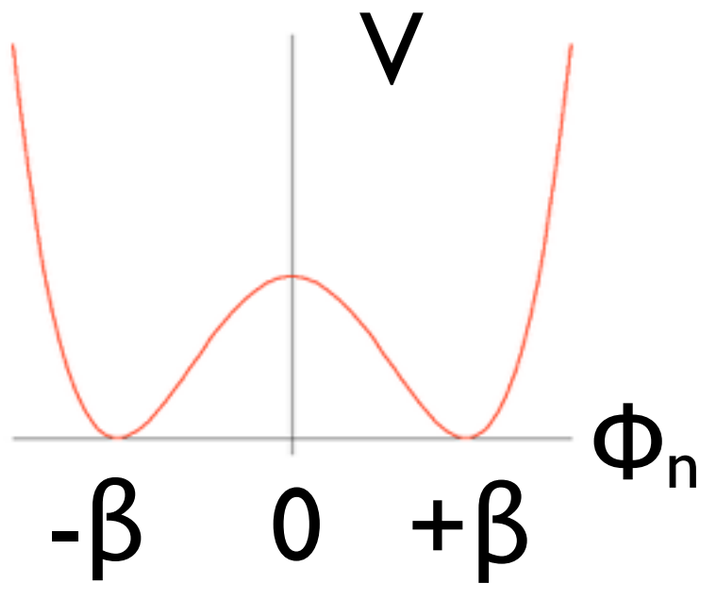
2 parameters



N: the number of field

- N=1 domain wall
- N=2 cosmic string
- N=3 monopole
- N=4 texture

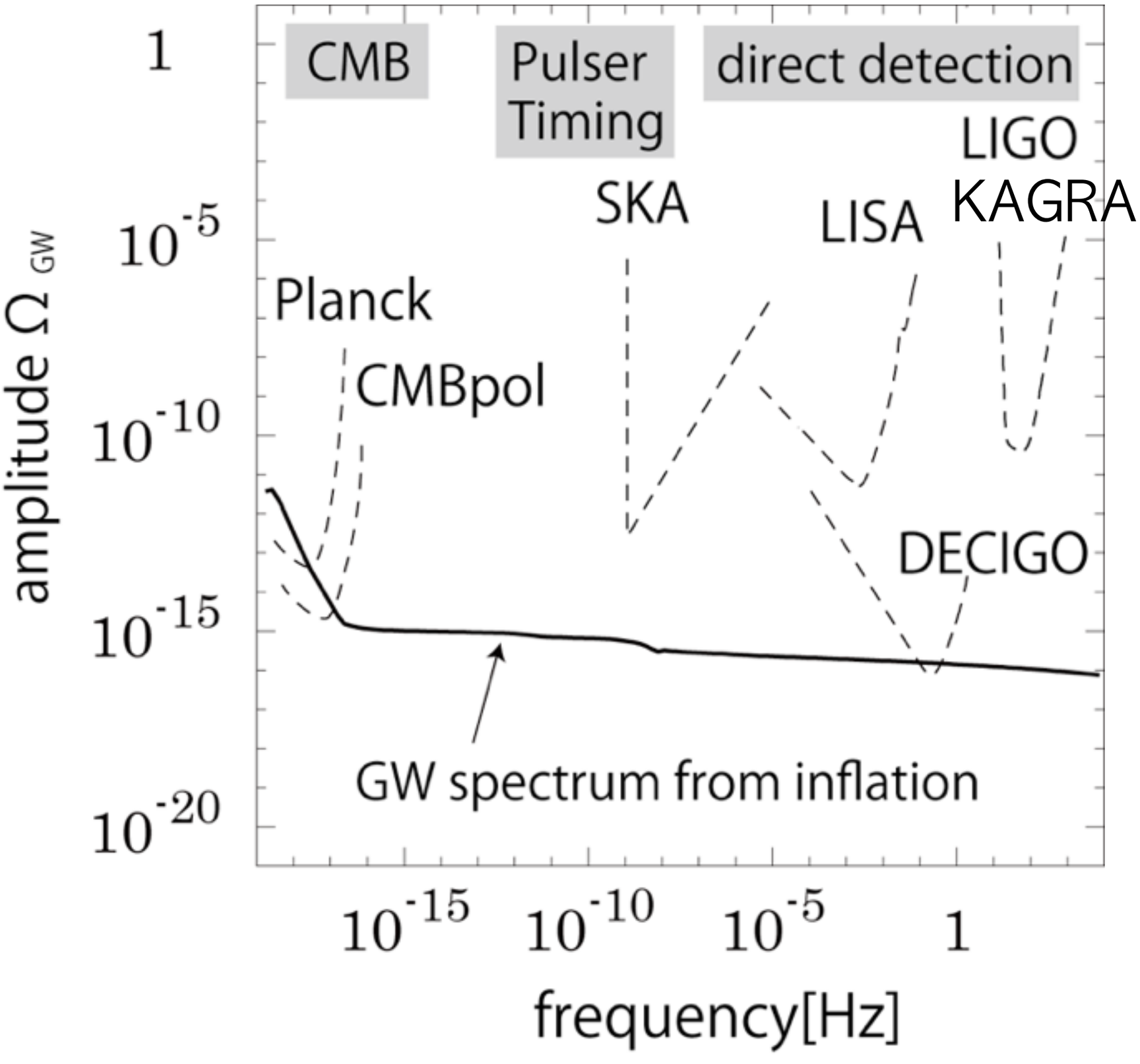
β: expectation value <Φ>



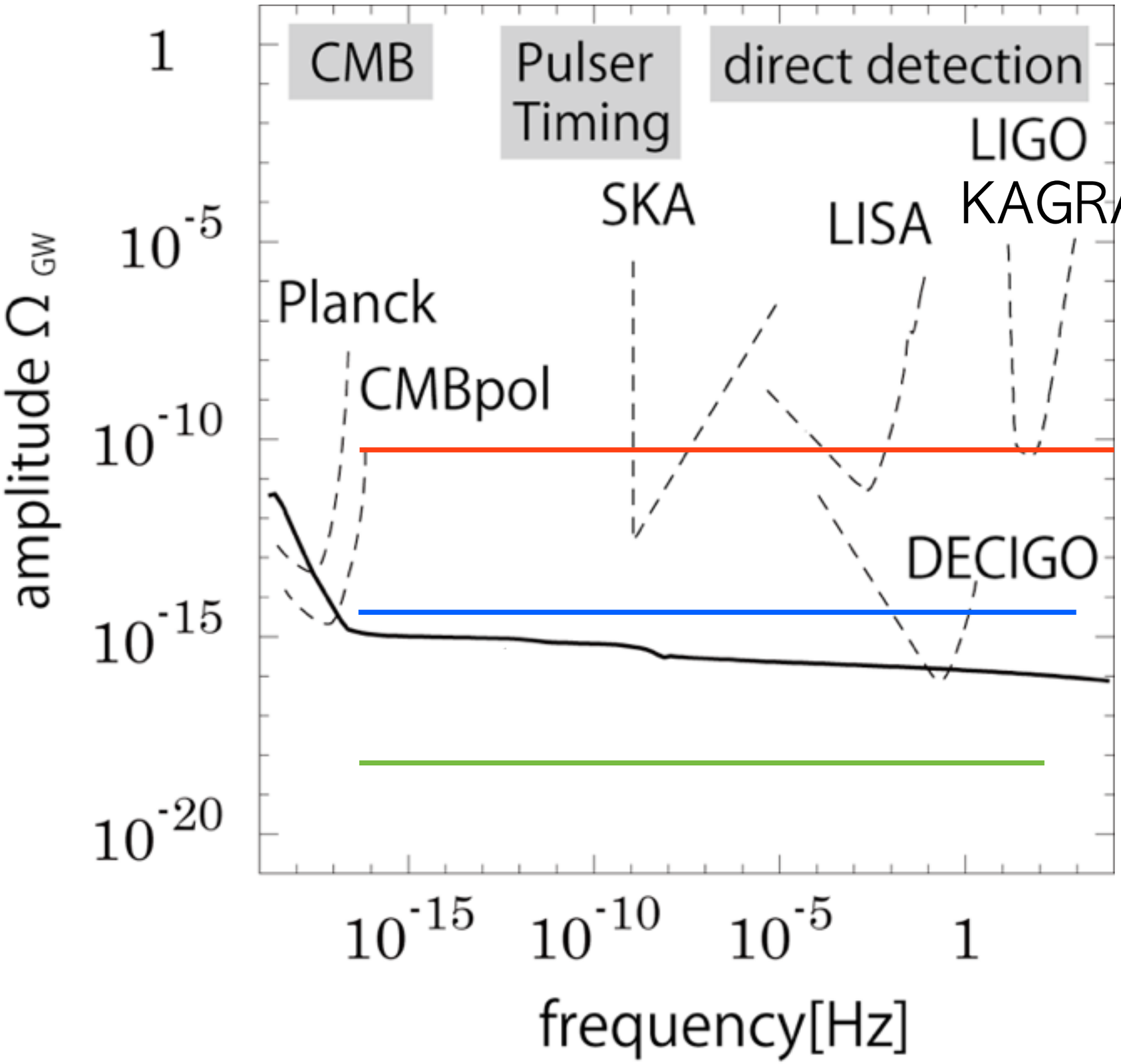
power of GWs $\propto$ β^4/N

L. Krauss, PLB 284 (1992) 229; K. Jones-Smith, PRL 100 (2008) 131302

Sensitivity curves of GW experiments



GWs from self-ordering fields



$\beta = 10^{-2} m_{pl}$

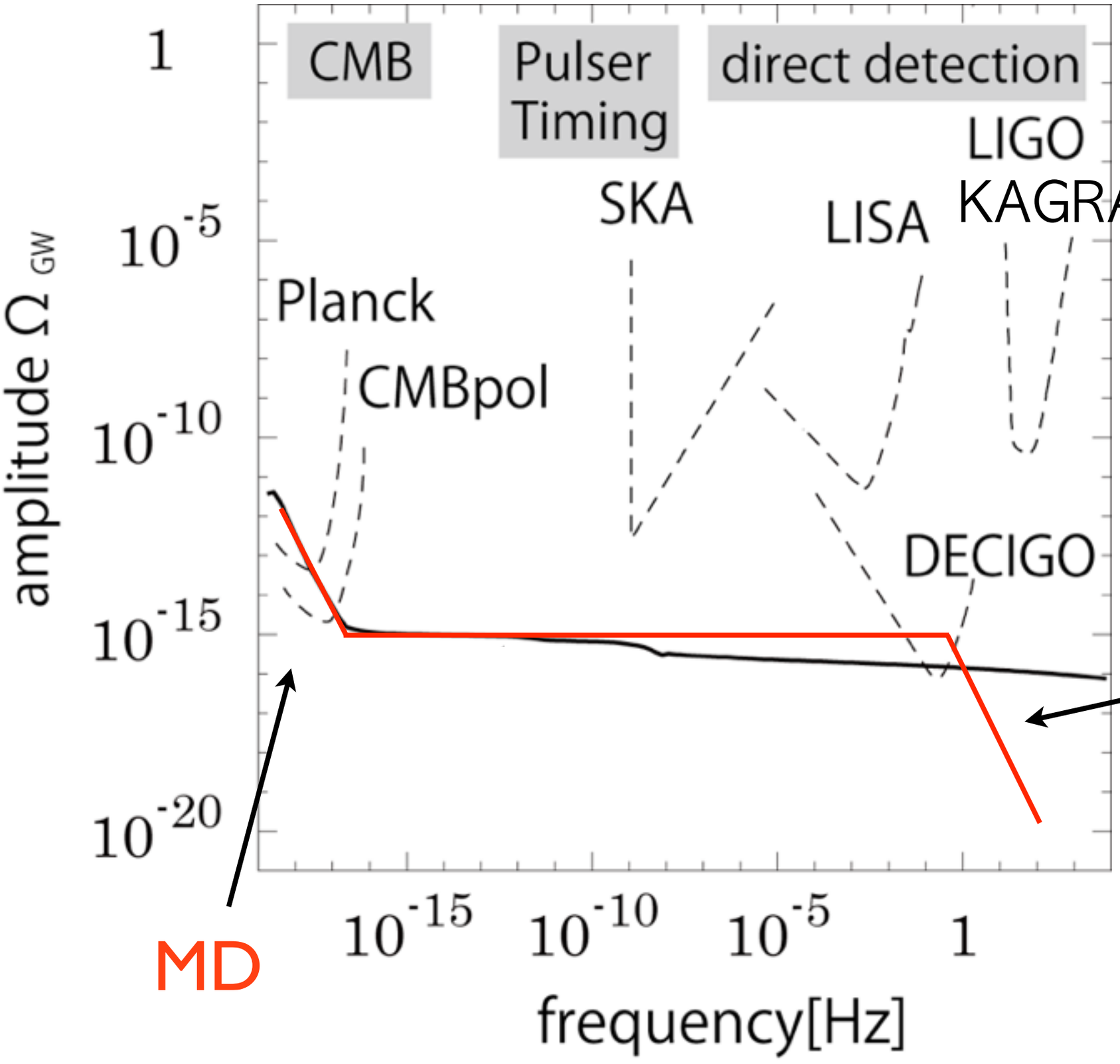
$\beta = 10^{-3} m_{pl}$ (GUT)

$\beta = 10^{-4} m_{pl}$

for N=4

E. Fenu et al, JCAP10 (2009) 005

flat spectrum = predicted assuming RD universe



could be different in the early Universe

e.g.

reheating

→ MD phase

affects the spectrum shape

My work

- run lattice simulations
- study the behavior of GWs for different Hubble expansion rate
- investigate how reheating affect the spectrum
- compare with gravitational wave spectrum from inflation

Equations to solve

Equation for scalar fields (i=1,2,...,N)

$$\phi_i'' + 2\mathcal{H}\phi_i' - \triangle\phi_i = a^2 V'(\phi_i)$$

Effect of the Hubble expansion rate

Equation for gravitational waves

$$h_{ij}'' + 2\mathcal{H}h_{ij}' - \triangle h_{ij} = \frac{2}{m_{\rm pl}^2}\left(\sum_m \partial_k\phi_m\partial_\ell\phi_m\right)^{\rm TT}$$

anisotropic stress

conformal Hubble: $\mathcal{H} = \frac{8\pi G}{3}a^2\rho$

result of numerical simulation (RD)

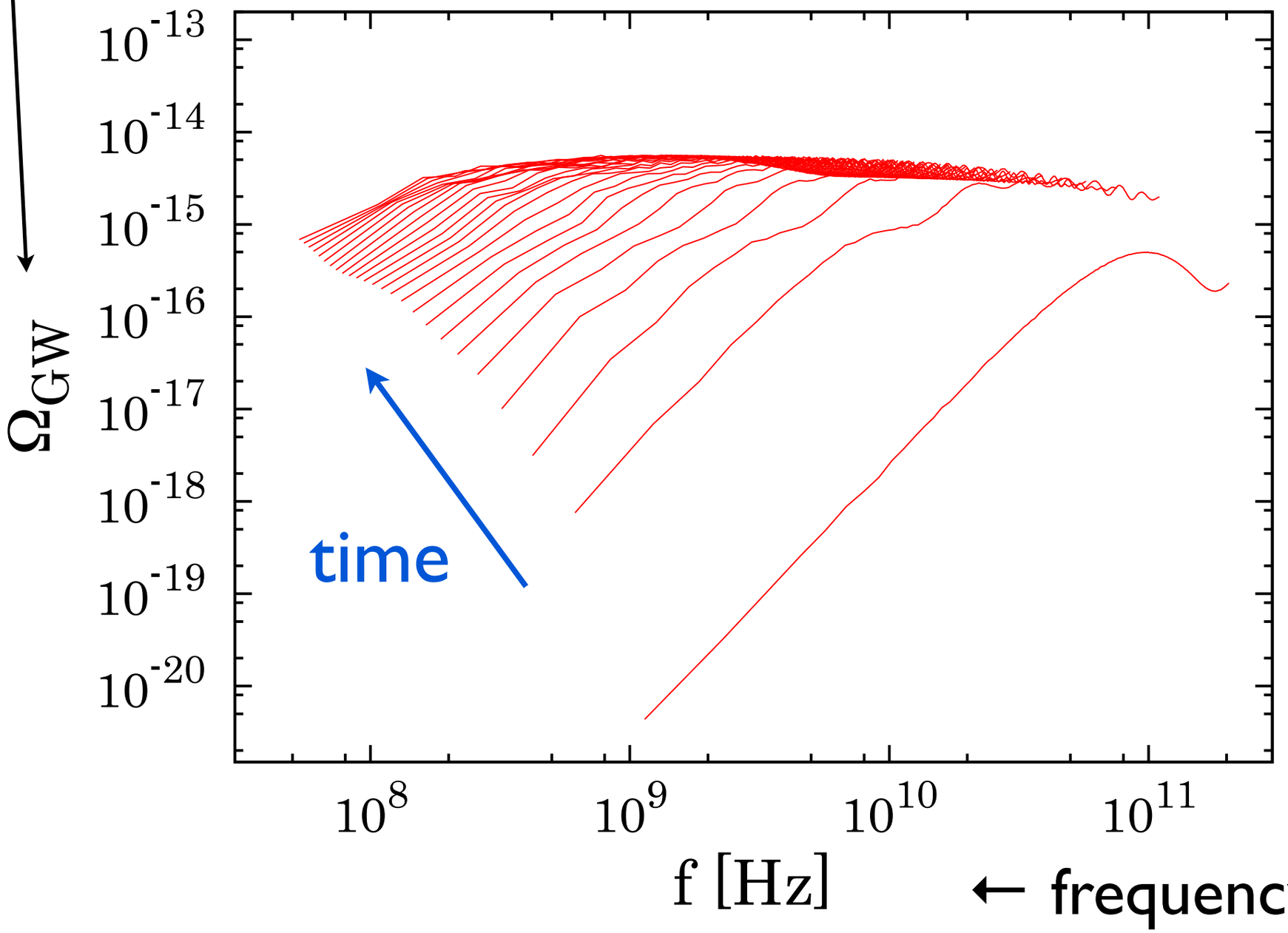
$(512)^3$ lattice simulation

Spectral amplitude of GWs (today)

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln k}$$

N=4

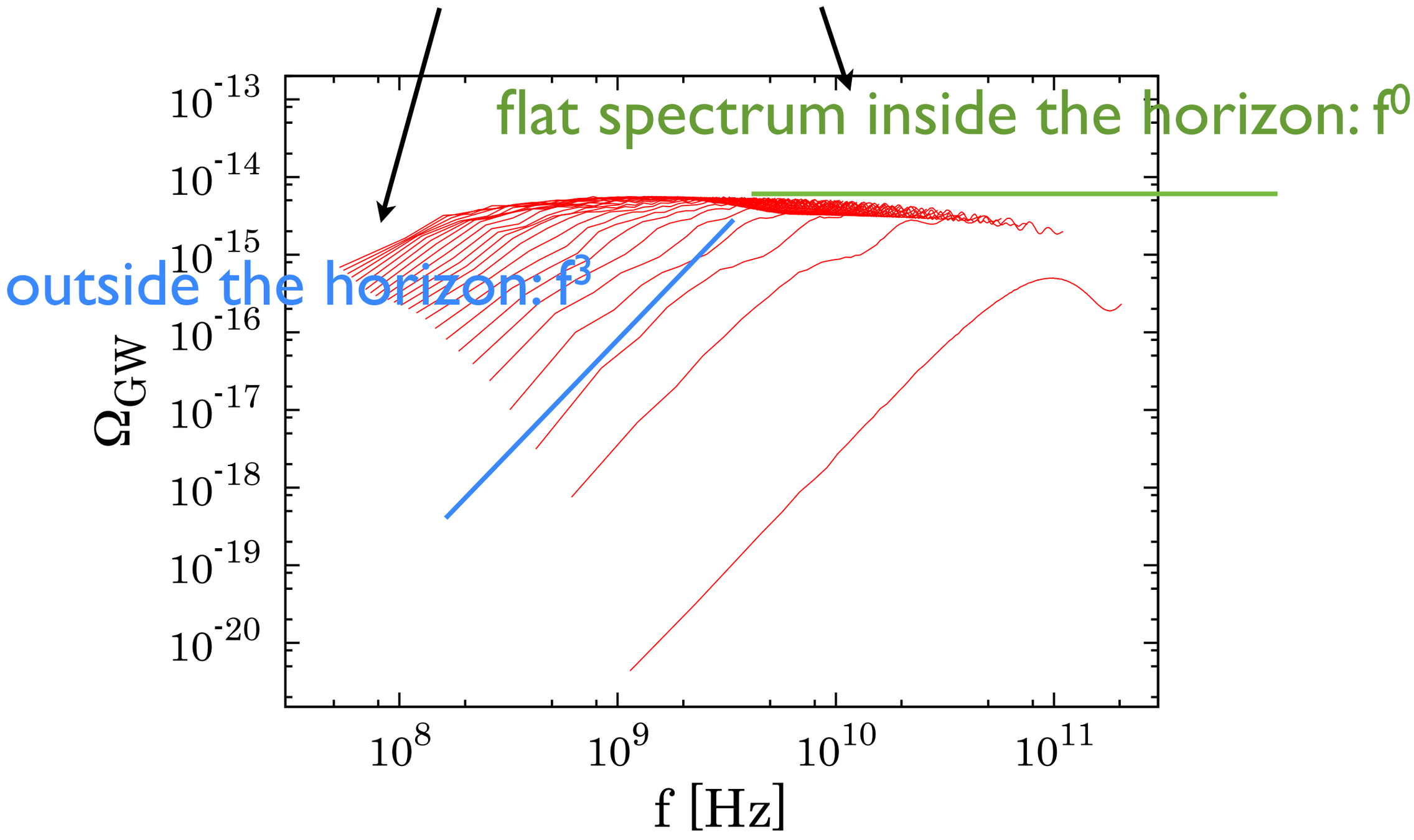
$\beta = 0.9\times10^{-3} m_{pl}$



result of numerical simulation (RD)

Good agreement with analytical stydies

L. Krauss, PLB 284 (1992) 229; K. Jones-Smith, PRL 100 (2008) 131302; E. Fenu et al, JCAP10 (2009) 005



result of numerical simulation

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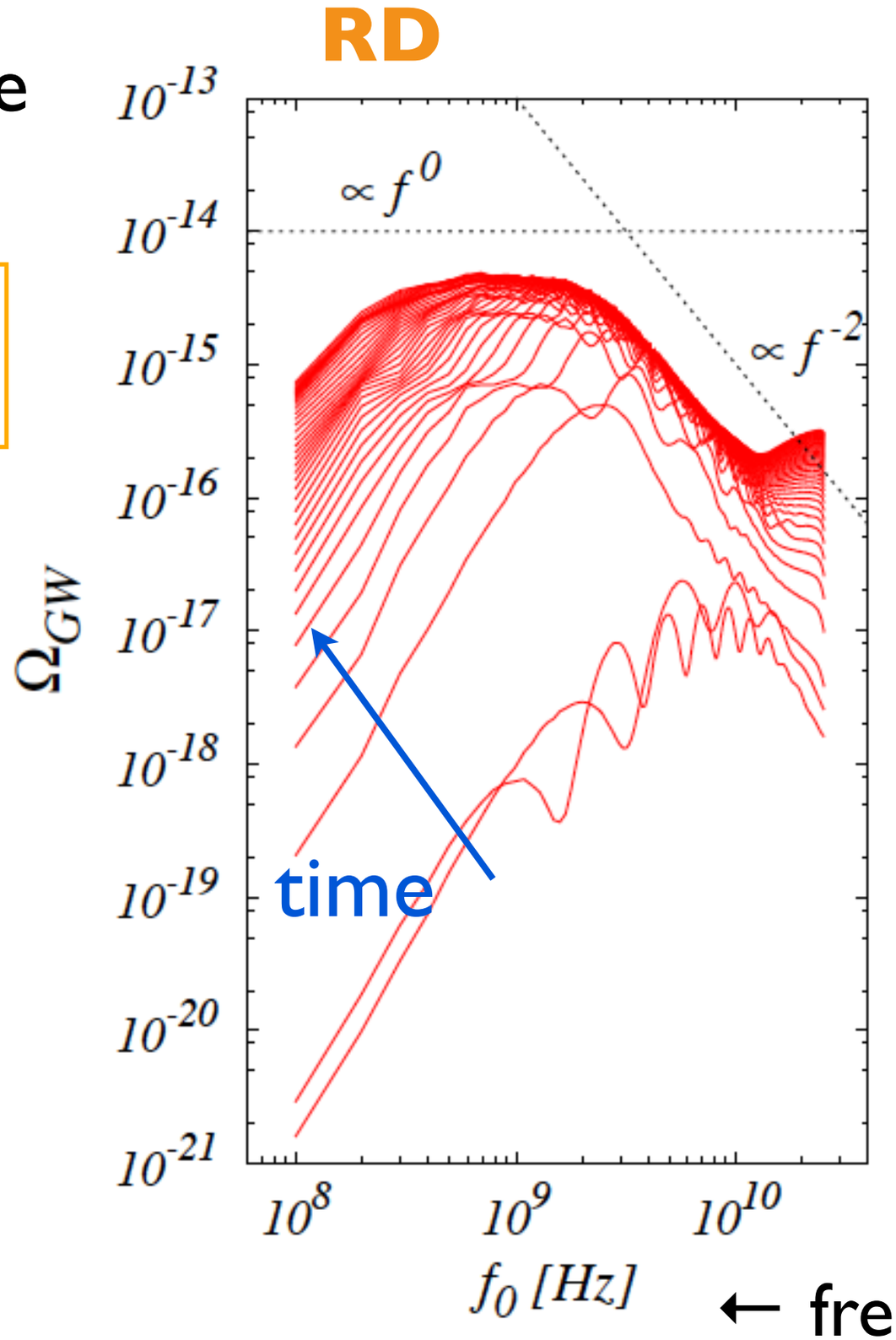


N=4

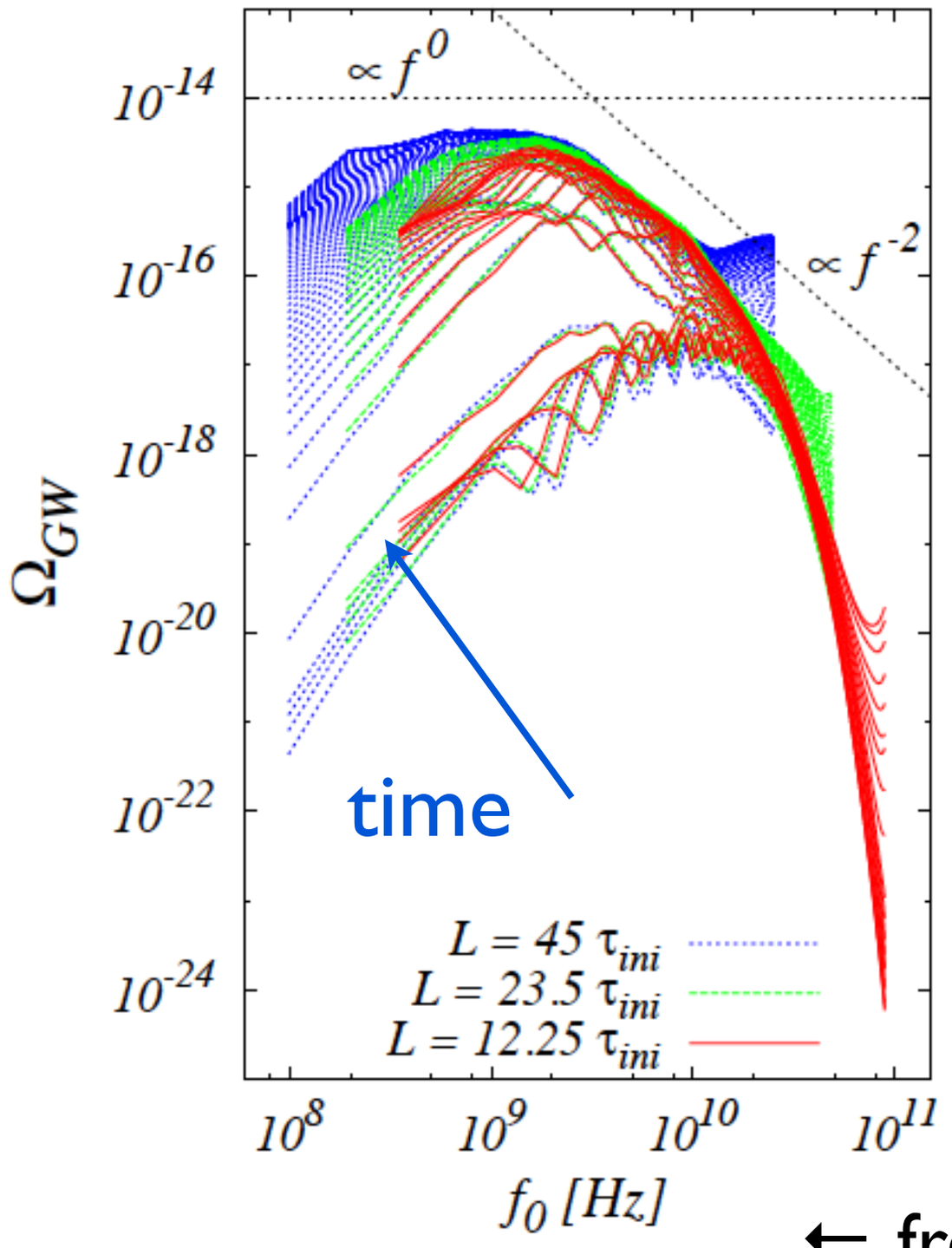
$\beta = 0.9\times10^{-3} m_{pl}$

← frequency (comoving)

result of numerical simulation

different box size

RD



N=4

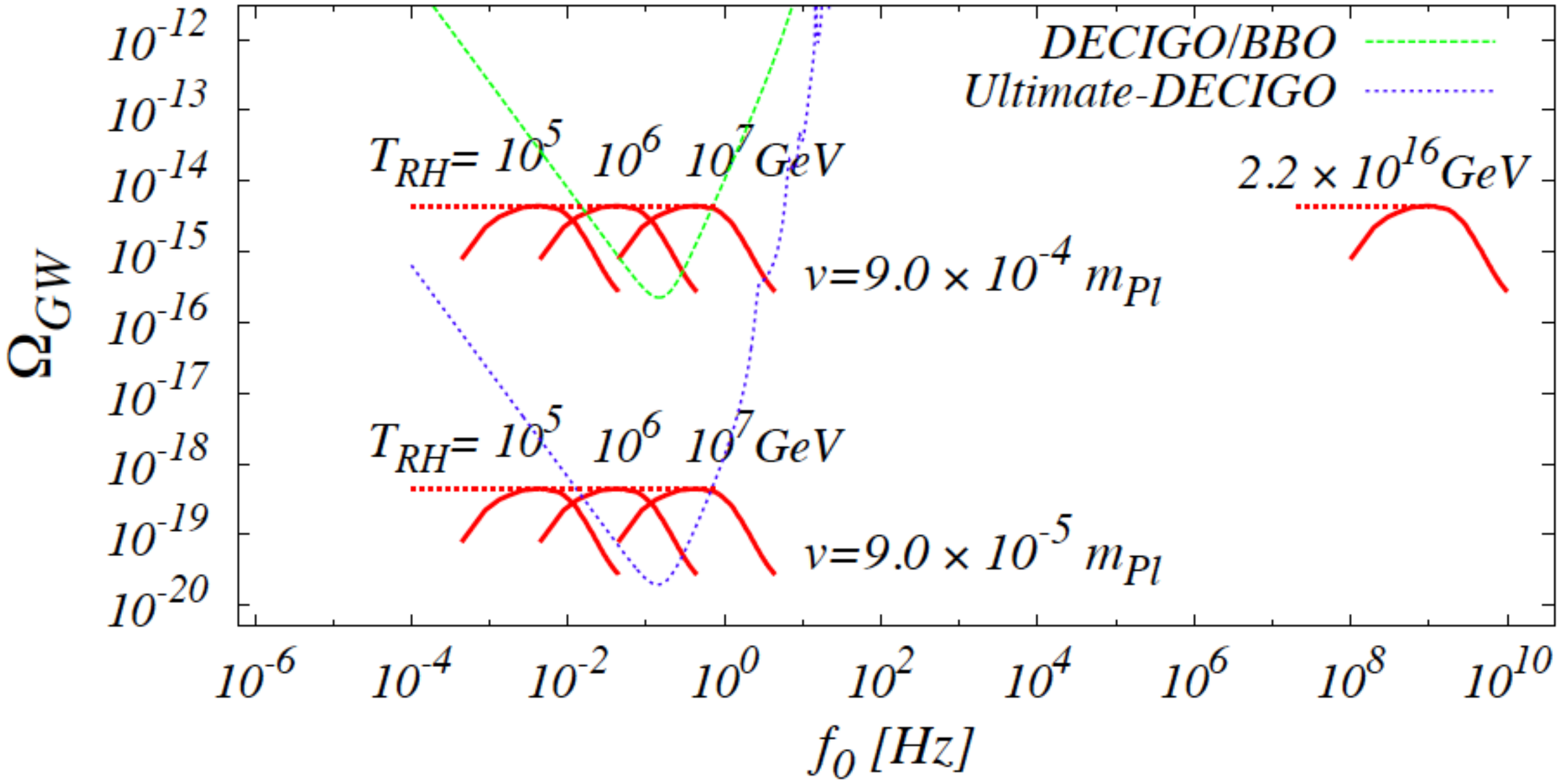
$\beta = 0.9\times10^{-3} m_{pl}$

MD

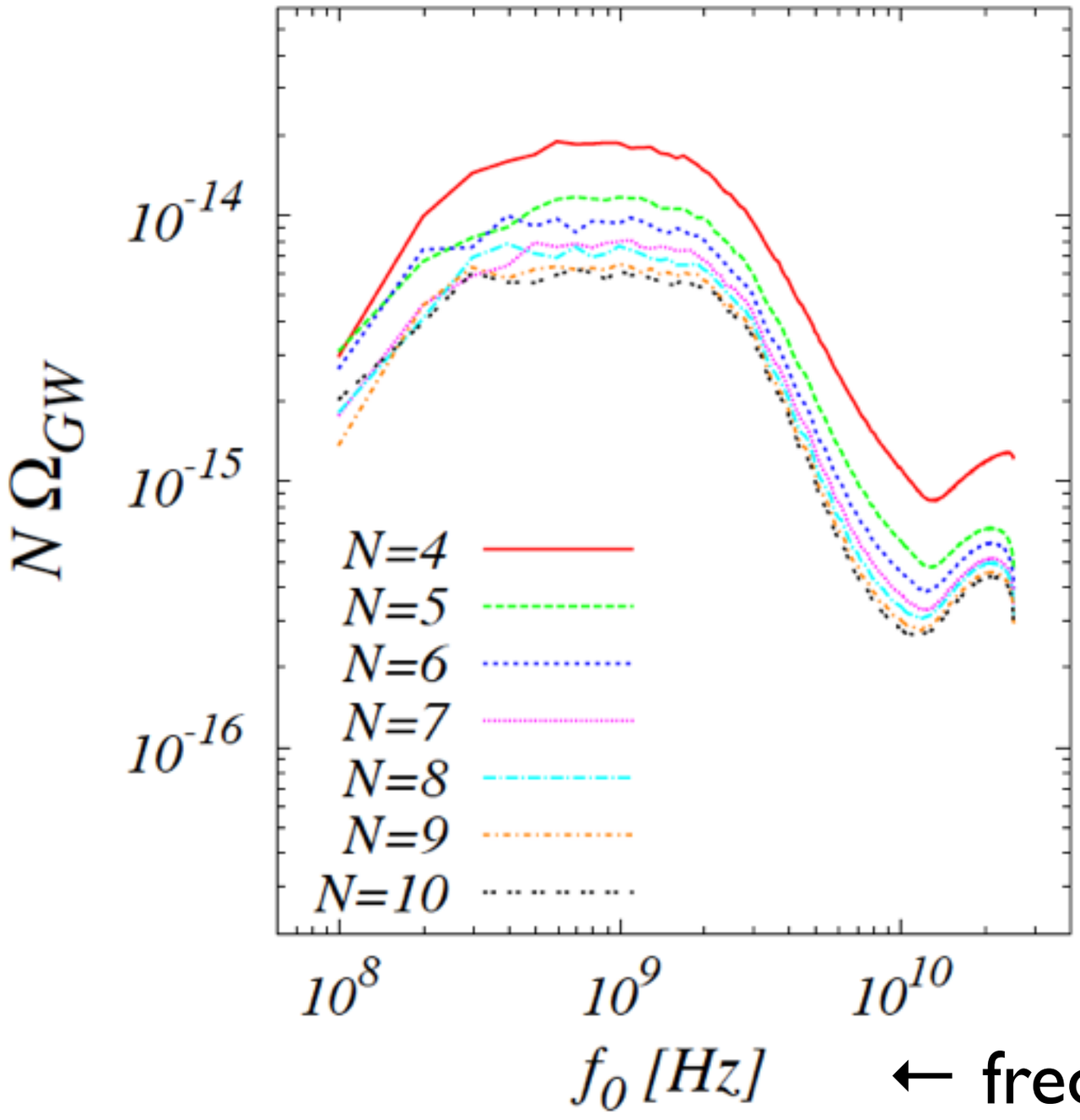
← frequency (comoving)

detectability in DECIGO

N=4



different N

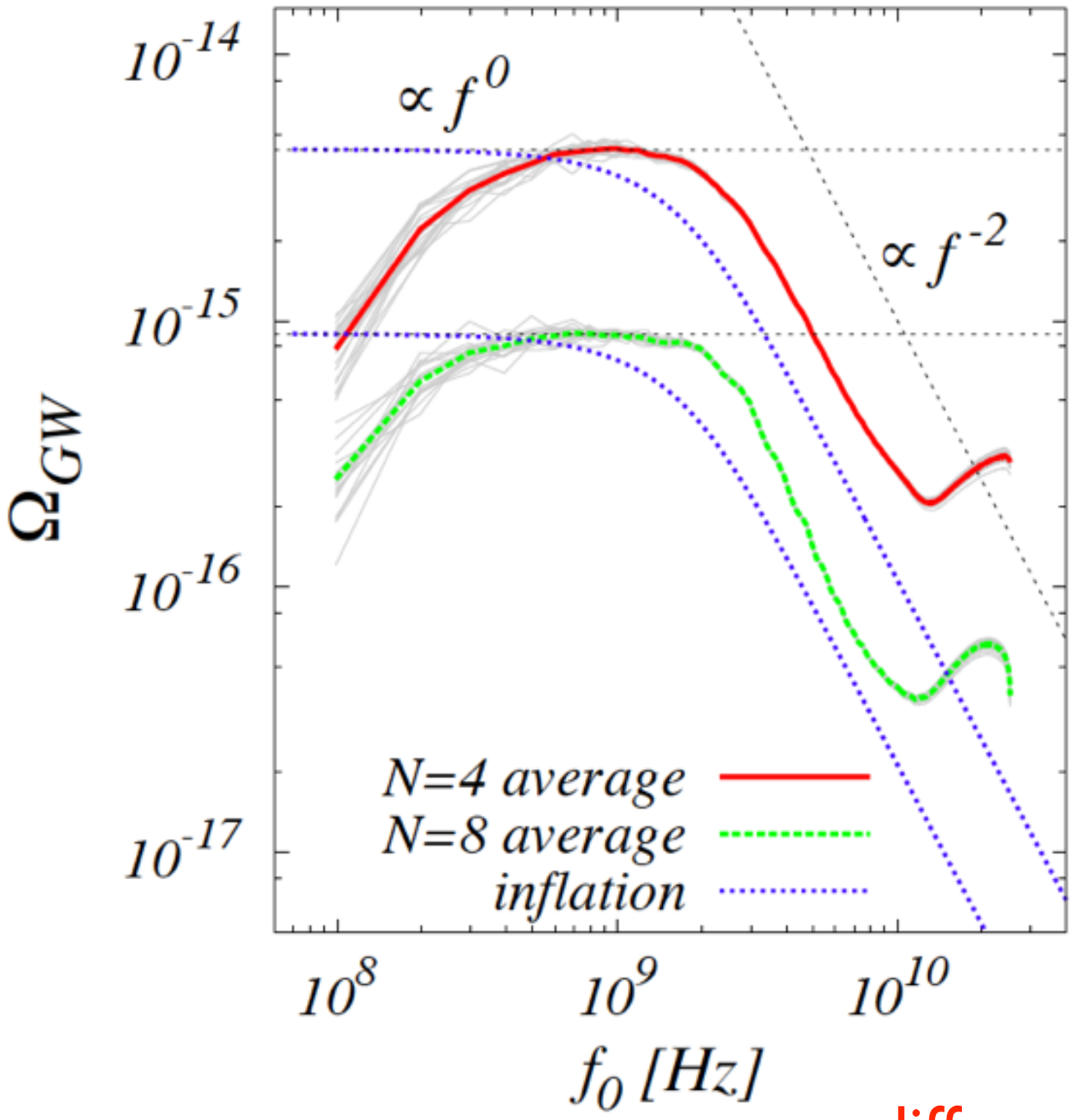


$\beta = 0.9\times10^{-3}m_{pl}$

← frequency (comoving)

power of GWs $\propto$ β^4/N

Comparison with inflationary GWs

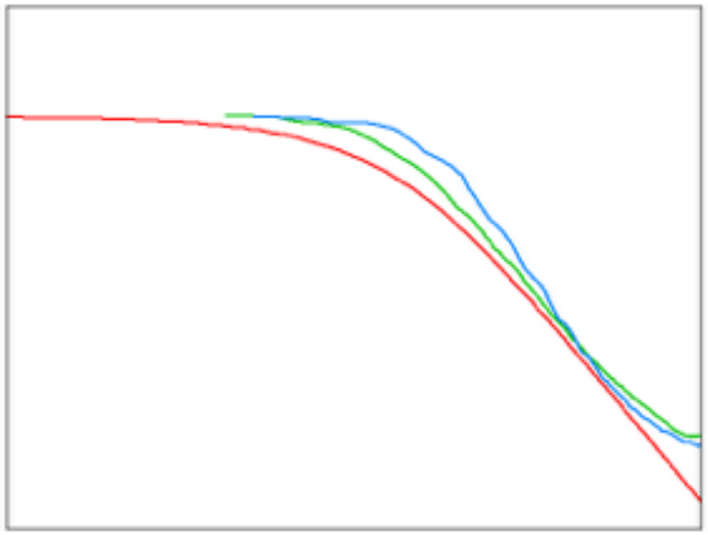


$\beta = 0.9\times10^{-3}m_{pl}$

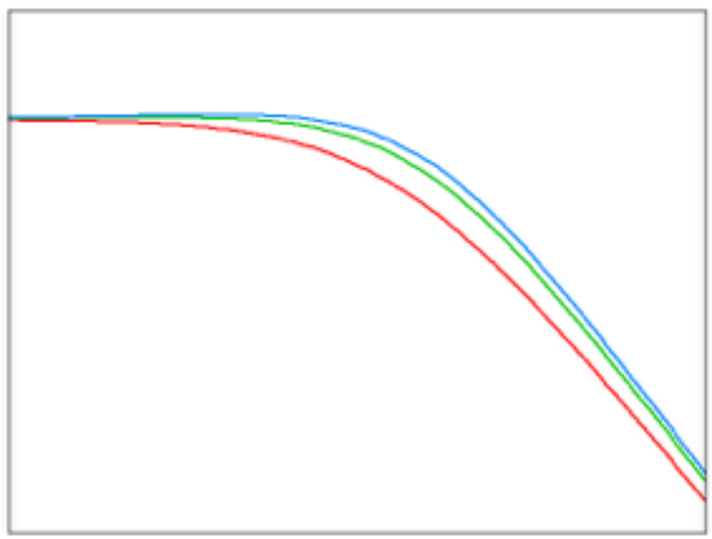
difference seen in large N case?

Can we distinguish the origin?

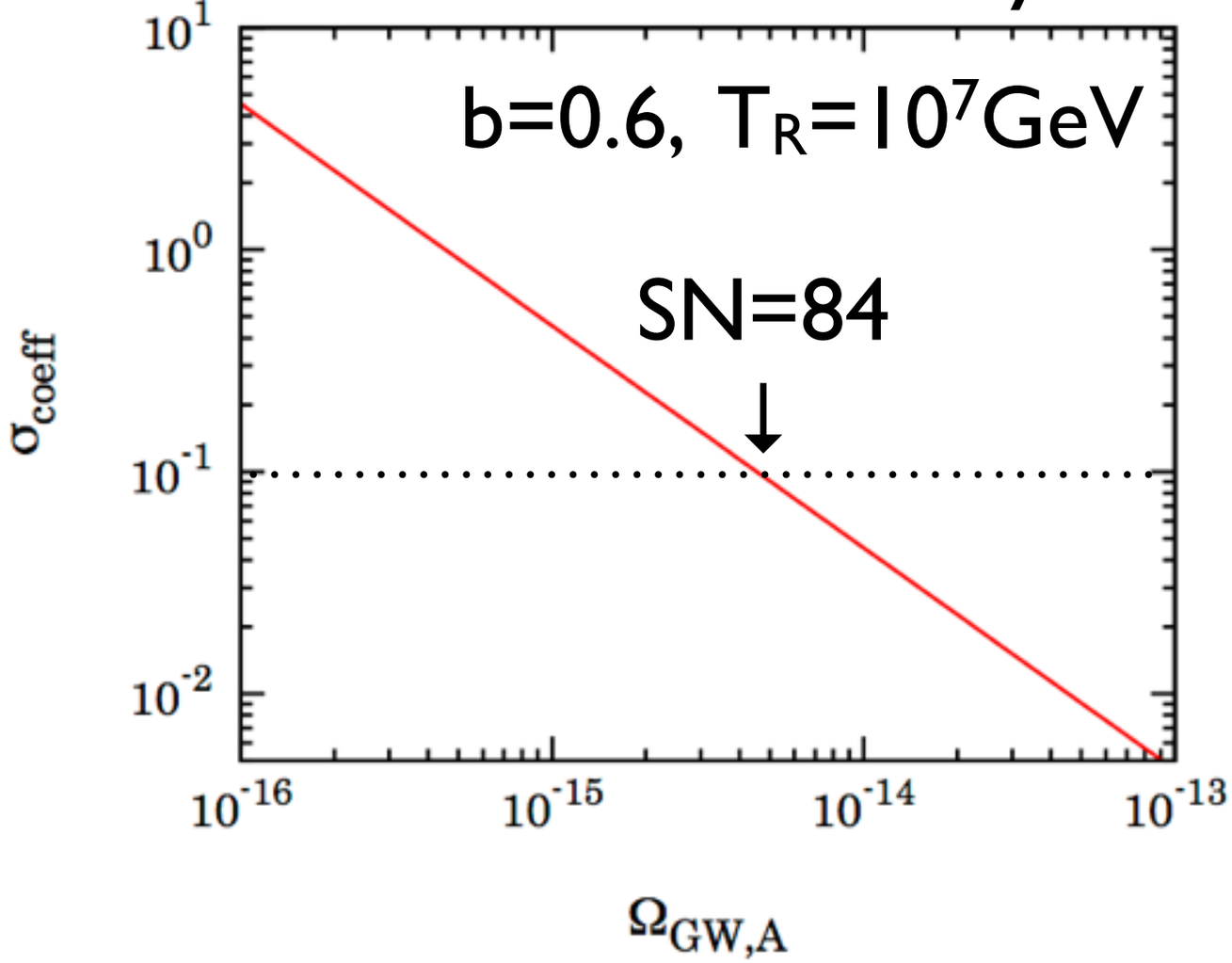
spectra by
numerical calculations



fit



DECIGO 3years



$\Omega_{GW}=\Omega_{GW,A}(1-bx_R^{1.5}+0.65x_R^2)^{-1}$ $x_R=f/f_R$

b=0.22 for inflation

b~0.5 for N=4

b~0.6 for N=8

Summary

- Self-ordering scalar fields generate scale-invariant gravitational waves
- Our numerical simulation shows good agreement with the analytic estimation.
- We found reheating signature is induced in the similar way to inflationary GWs, but it has a small differences.
- We investigated whether future GW experiments can distinguish the origin of GWs.

  → would be possible if $\Omega_{GW} > 10^{-14}$