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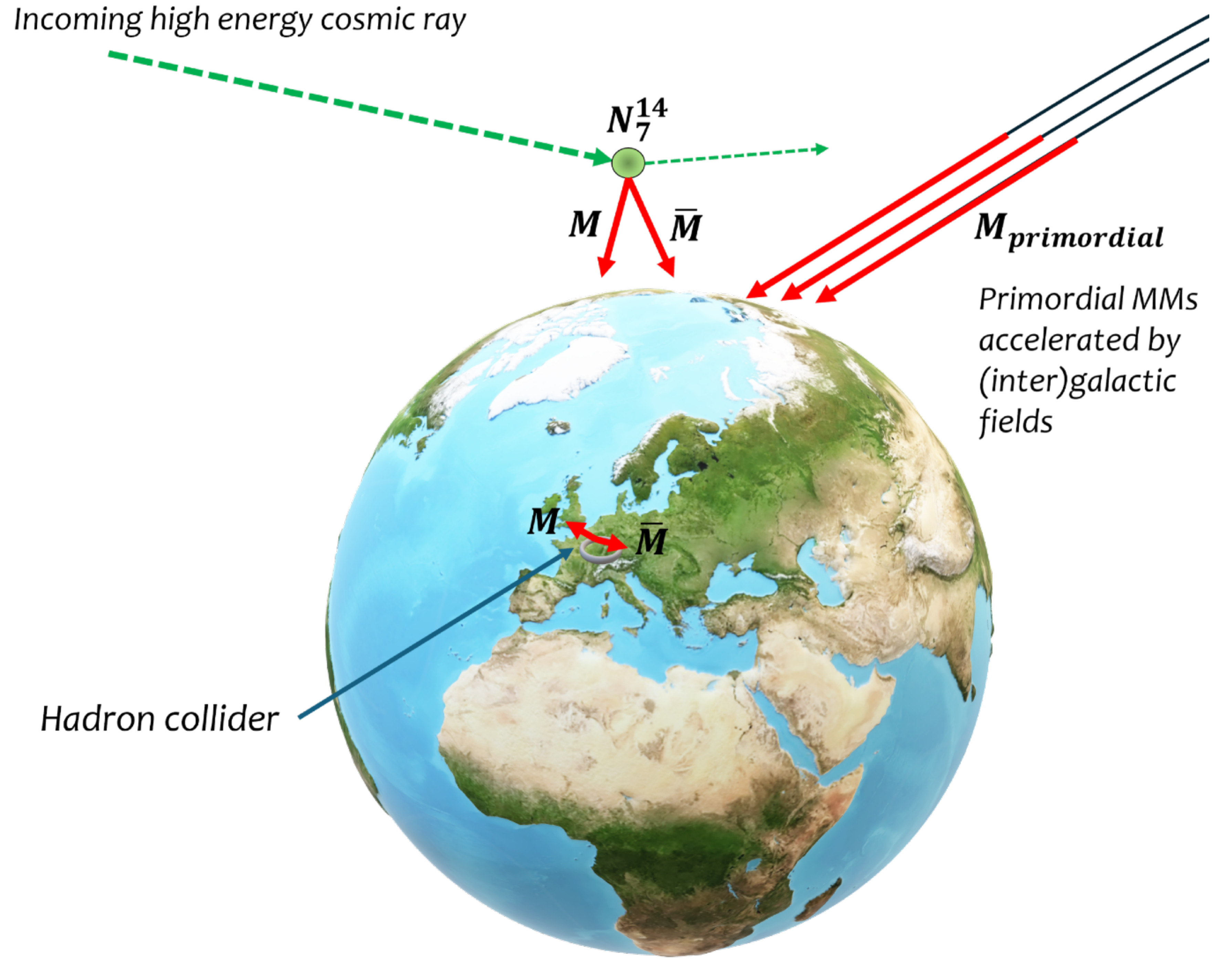


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# Cosmological Implications of GUT Monopoles for Gravitational Waves

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# Homotopy group ⇔ topological defects

- Kibble mechanism, 1976
  —— originally proposed for defects generated in a continuous phase transition.

- Topological defects depend on the homotopy groups (同伦群) of the manifold of degenerate vacua.

For symm breaking $G \to H$, degenerate vacua form a manifold $\mathscr{M} = G/H$, a homotopy group $\pi_k(\mathscr{M})$ is defined by the set of mapping $S^k \to \mathscr{M}$

- If $\pi_k(G/H) \neq 1$, $(2-k)$-dim topological defects defects form

  - $k = 2 \Rightarrow$ monopoles (单极子), 0-dim point in the core
  - $k = 1 \Rightarrow$ cosmic strings (宇宙弦), 1-dim string in the core
  - $k = 0 \Rightarrow$ domain walls (畴壁), 2-dim surface in the core

# ’t Hooft-Polyakov monopole

’t Hooft, NPB, 74; Polyakov, JEPT Lett., 74

- A gauge $SU(2)$ symmetry with an adjoint scalar

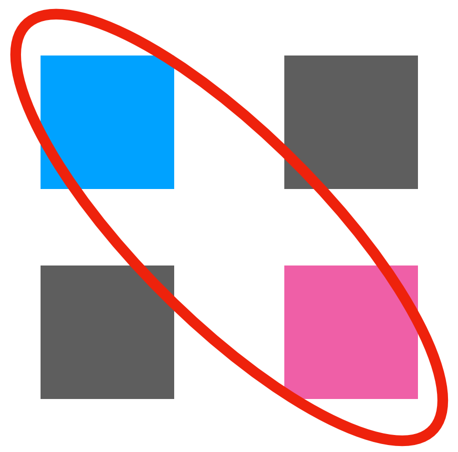
$$\Phi = \frac{1}{2}\tau^a\Phi^a = \frac{1}{2}\begin{bmatrix} \Phi^3 & \Phi^1 - i\Phi^2 \\ \Phi^1 - i\Phi^2 & -\Phi^3 \end{bmatrix}$$

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + \mathrm{Tr}\, D_\mu\Phi D^\mu\Phi - V(\Phi)$$

- After $\Phi$ gains the VEV, $SU(2)$ is spontaneously broken to $U(1)$

$$\langle\Phi\rangle = U(\Omega)\frac{1}{2}\begin{bmatrix} v & 0 \\ 0 & -v \end{bmatrix} U^{-1}(\Omega)$$

$SU(2)$



$U(1)$

- The $\Phi$ VEV does not have to be a constant in the gauge space

$$\begin{aligned} A_i^a &= \epsilon_{iam}\hat{r}^m\left[\frac{1-u(r)}{er}\right] \\ \Phi^a &= \hat{r}^a h(r) \end{aligned}$$

$$\begin{aligned} 0 &= h'' + \frac{2}{r}h' - \frac{2u^2h}{r^2} + \lambda(v^2 - h^2)h \\ 0 &= u'' - \frac{u(u^2-1)}{r^2} - e^2uh^2 \end{aligned}$$

$\pi_2(SU(2)/U(1)) = Z$

in hedgehog gauge

- This field configuration leads to an energy condensation, referring to the monopole mass

$$M_{\rm mono} = \frac{4\pi v}{e} f(\lambda/e^2)$$

In the BPS limit, $\lambda/e^2 \to 0$, $f(\lambda/e^2) \to 1$

Most energy is restricted in the narrow radius $R \sim 1/v$

# Monopoles in GUT framework

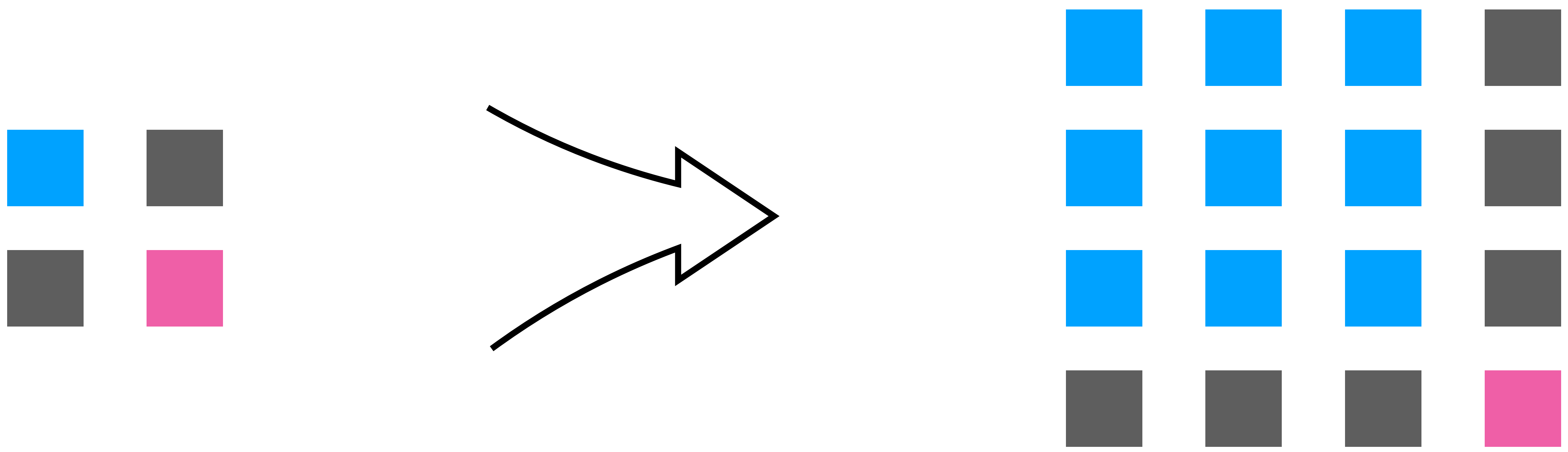
Preskill, Ann. Rev. Nucl. Part. Sci., 1984

Pati-Salam monopoles

- Gauge symmetry $G_{422} = SU(4)_c \times SU(2)_L \times SU(2)_R$
- $SU(4)_c$ is spontaneously broken to $SU(3)_c \times U(1)_{B-L}$

$$\pi_2\left(\frac{SU(4)}{SU(3) \times U(1)}\right) = \pi_2(CP^3) = Z$$

- The breaking of $SU(2) \to U(1)$ can be embedded into $SU(4) \to SU(3) \times (1)$
- Monopole arises from the breaking of Pati-Salam symmetry.
  Its property is determined by the embedding of $SU(2)$ into the gauge space of $SU(4)$

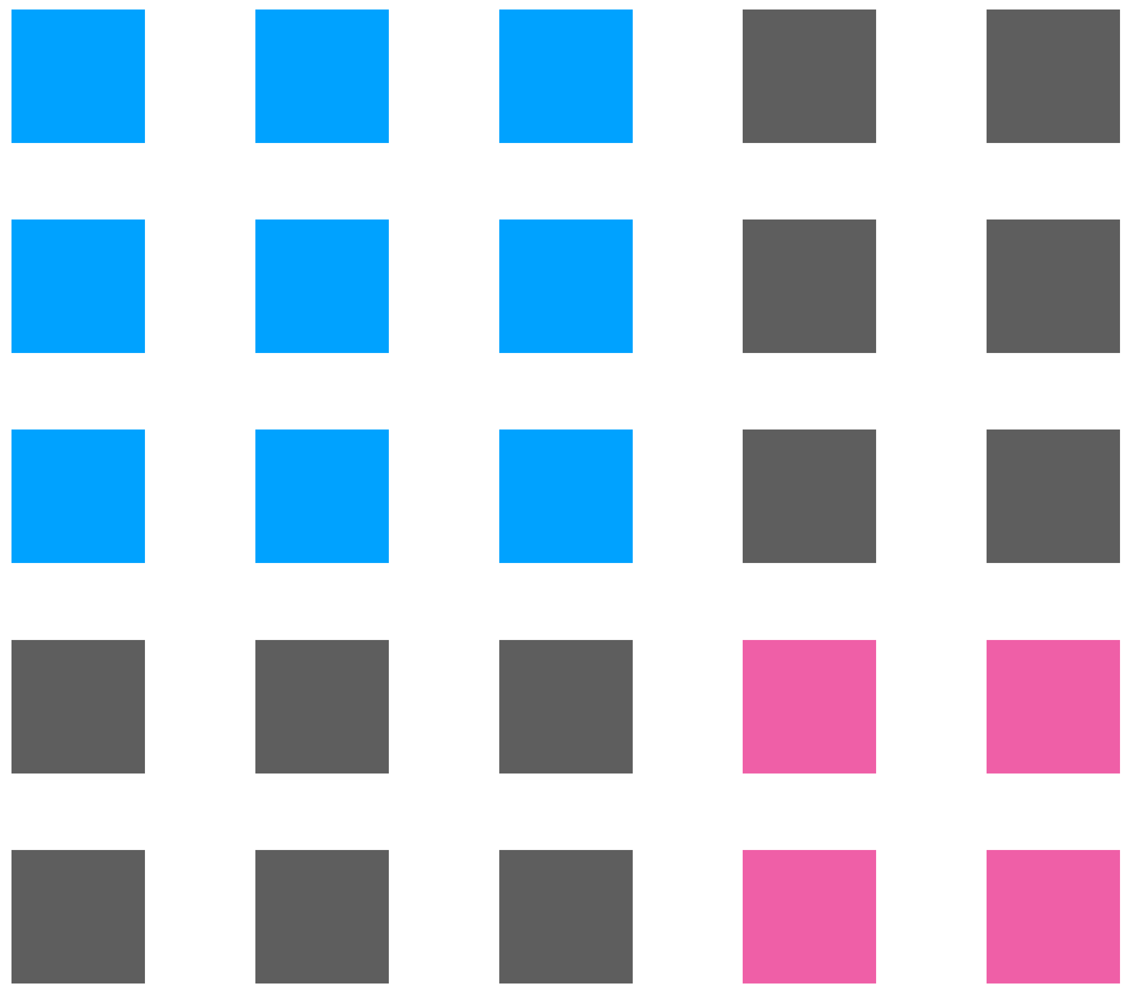


# Monopoles in GUT framework

Preskill, Ann. Rev. Nucl. Part. Sci., 1984

## SU(5) monopoles

- Gauge symmetry $SU(5)$, broken to SM gauge symmetry directly via an adjoint 24-plet Higgs



$$SU(5) \to S(U(3) \times U(2)) \simeq \frac{SU(3)_c \times SU(2)_L \times U(1)_Y}{Z_3 \times Z_2}$$

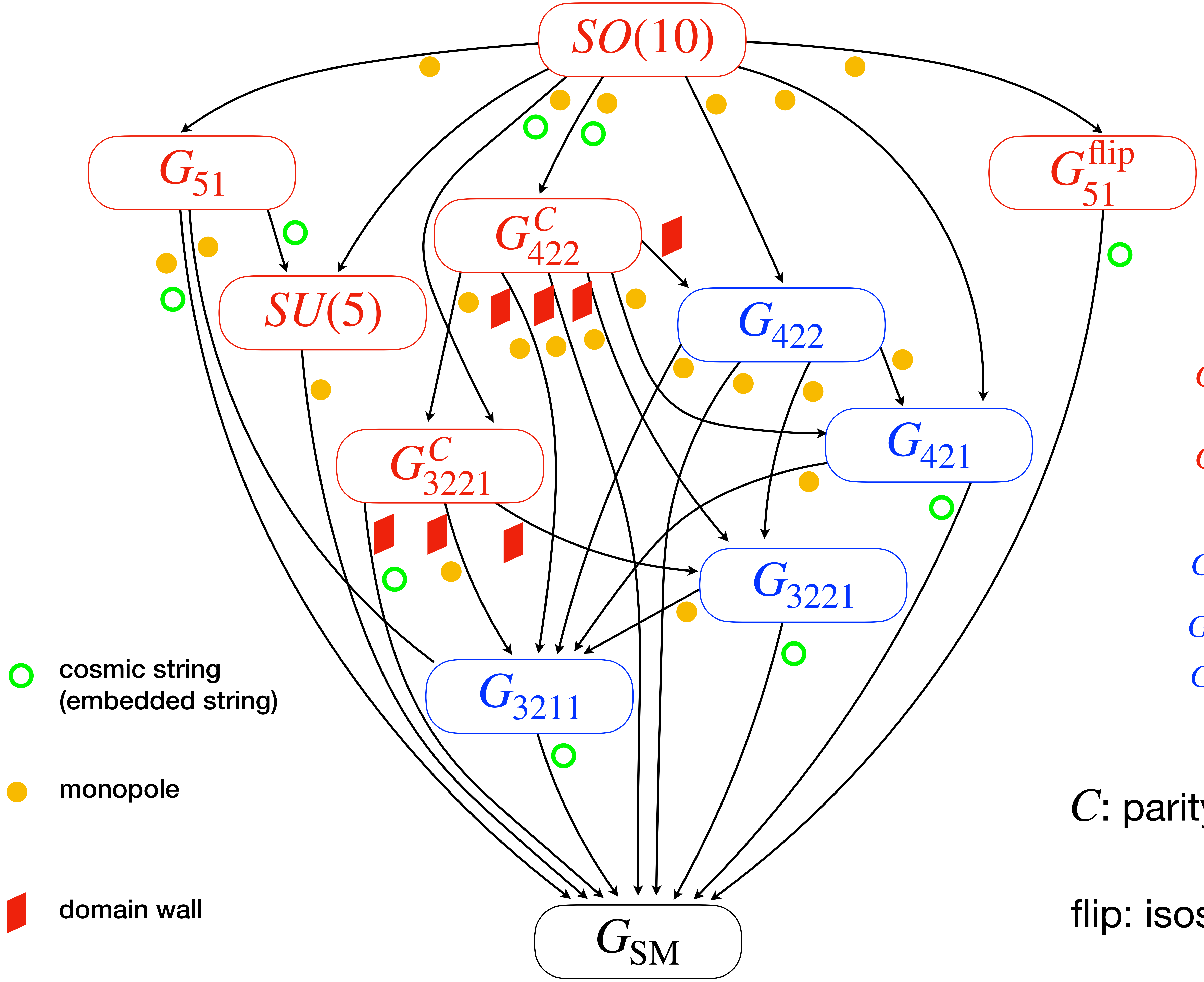
$$\pi_2 = Z$$

## SO(10) monopoles: two scales

$$SO(10) \to SU(4)_c \times SU(2)_R \times SU(2)_L$$

$$SU(4)_c \to SU(3)_c \times U(1)_{B-L}$$

# Monopoles is a general prediction of GUTs




$G_{422} = SU(4)_c \times SU(2)_L \times SU(2)_R$

$G_{51} = SU(5) \times U(1)$

$G_{421} = SU(4)_c \times SU(2)_L \times U(1)_R$

$G_{3221} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$G_{3211} = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

$C$: parity $\psi_L \leftrightarrow \psi_R^C$

flip: isospin flipping $u \leftrightarrow d, \nu \leftrightarrow e$

# GUT monopole problem

't Hooft, NPB, 1974; Zeldovich & Khlopov, PLB, 1978; Preskill, 1979

- Monopoles as topological defects are produced during cosmological phase transition, referring to spontaneous symmetry breaking of certain non-Abelian gauge symmetry.

- Typical distance between monopoles is around the Hubble length scale at phase transition, $L_{\rm m} \sim H_\star^{-1}$. Thus, the initial number density $n_\star \sim H_\star^3$.

- Monopoles, once they are produced, evolve as matter during Hubble expansion. The number density today is given by

$$\dot{n} = -3Hn - Dn^2 \quad \xrightarrow{H \gg Dn} \quad n_{\rm mono}(t_0) = \left(\frac{a(t_\star)}{a(t_0)}\right)^3 n_\star$$

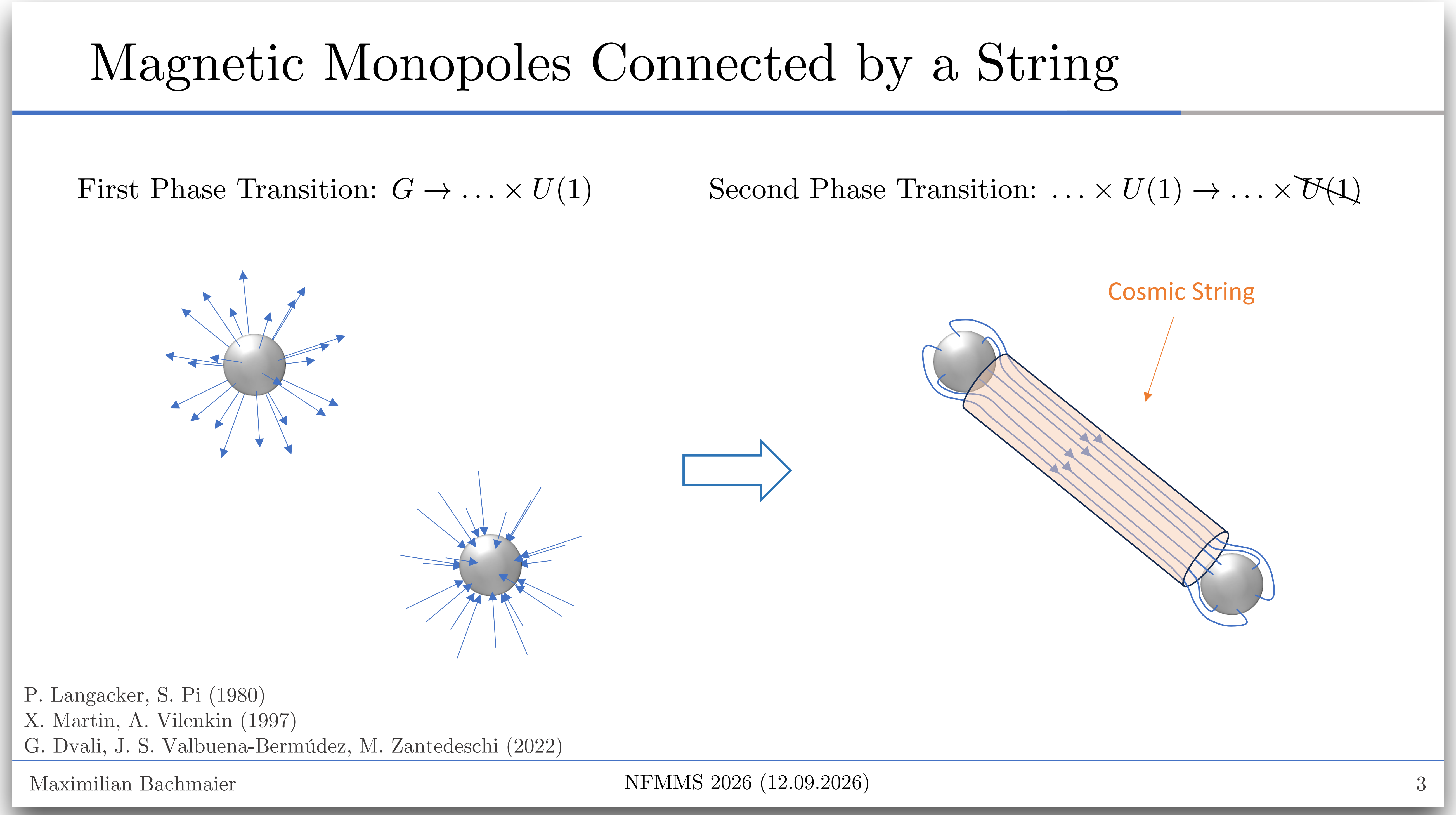
- GUT monopole problem: GUT monopoles $M_{\rm mono} \sim M_{\rm GUT}/\alpha_{\rm GUT} \gtrsim 10^{16}$ GeV, $H_\star \sim 0.1\, M_{\rm GUT}^2/M_{\rm pl}$. Their energy density fraction $\Omega_{\rm mono} = M_{\rm mono} n(t_0)/\rho_c$ is given by

$$\Omega_{\rm mono} = \frac{8\pi G M_{\rm mono} H_\star^3}{3H_0^2(1+z_{\rm Rh})^3} \sim 10^{14}\left(\frac{T_{\rm Rh}}{10^{15}\ {\rm GeV}}\right)^4 \qquad \gg 1$$

- Inflation is the standard way to solve the GUT monopole problem

# Solving monopole problem via slingshot effect?

$\Rightarrow$ Maximilian Bachmaier's talk




$$G_{3221} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$\pi_2 = Z$ $\downarrow$ monopole

$$G_{3211} = SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$

$\pi_1 = Z$ $\downarrow$ string

$$G_{\mathrm{SM}} = SU(3)_c \times SU(2)_L \times 1 \times U(1)_{B-L}$$

$\pi_2 = \pi_1 = 0$

The slingshot effect does not apply to PS or SU(5) monopoles.

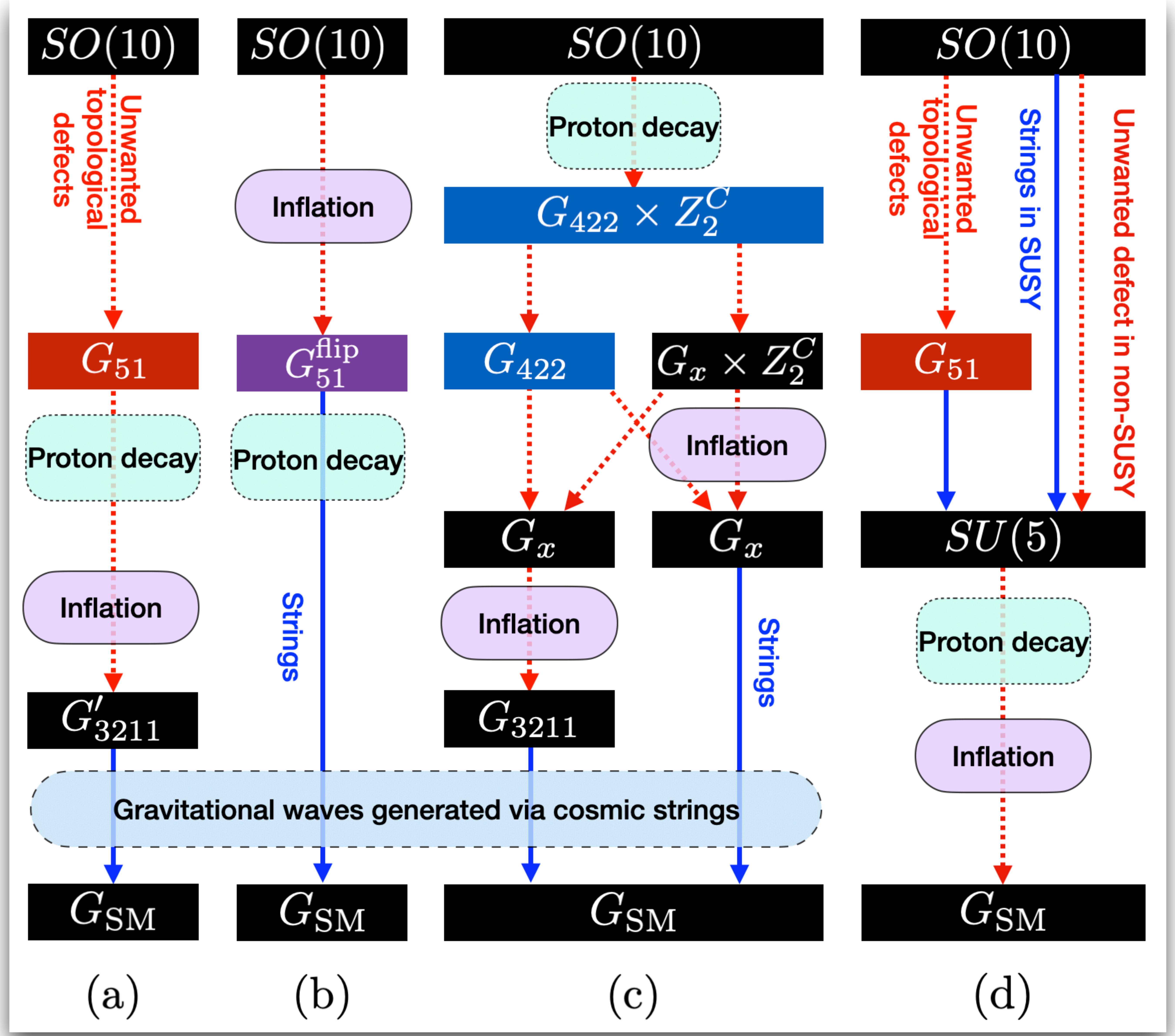
$\pi_2(G_{422}/G_{\mathrm{SM}}) = Z$ $\qquad$ $\pi_1(G_{422}/G_{\mathrm{SM}}) = 0$

# Monopoles are point-like objects, how do they affect GWs?

- GWs via cosmic strings:
  It may influence cosmic string evolution, and thus change the spectrum of GWs via cosmic strings

- GWs via GUT phase transition:
  Solving the monopole problem does not require the inflation fully after GUT phase transition. If phase transition happens during inflation, inflated GW spectrum is predicted.

# GWs via cosmic strings are widely predicted in GUTs




Unwanted topological defects: monopoles and domain walls

In any breaking chains, inflation has to been introduced to inflate unwanted defects

$$G_{422} = SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$G_{51} = SU(5) \times U(1)_X$$

$$G_{51}^{\rm flip} = SU(5)_{\rm flip} \times U(1)_{\rm flip}$$

$$Z_2^C: \quad \psi_L \leftrightarrow \psi_R^c$$

$$G_x = G_{421} \text{ or } G_{3221}$$

$$G_{3221} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$G_{421} = SU(4)_C \times SU(2)_L \times U(1)_Y$$

$$G_{3211} = SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$

$$G'_{3211} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$$

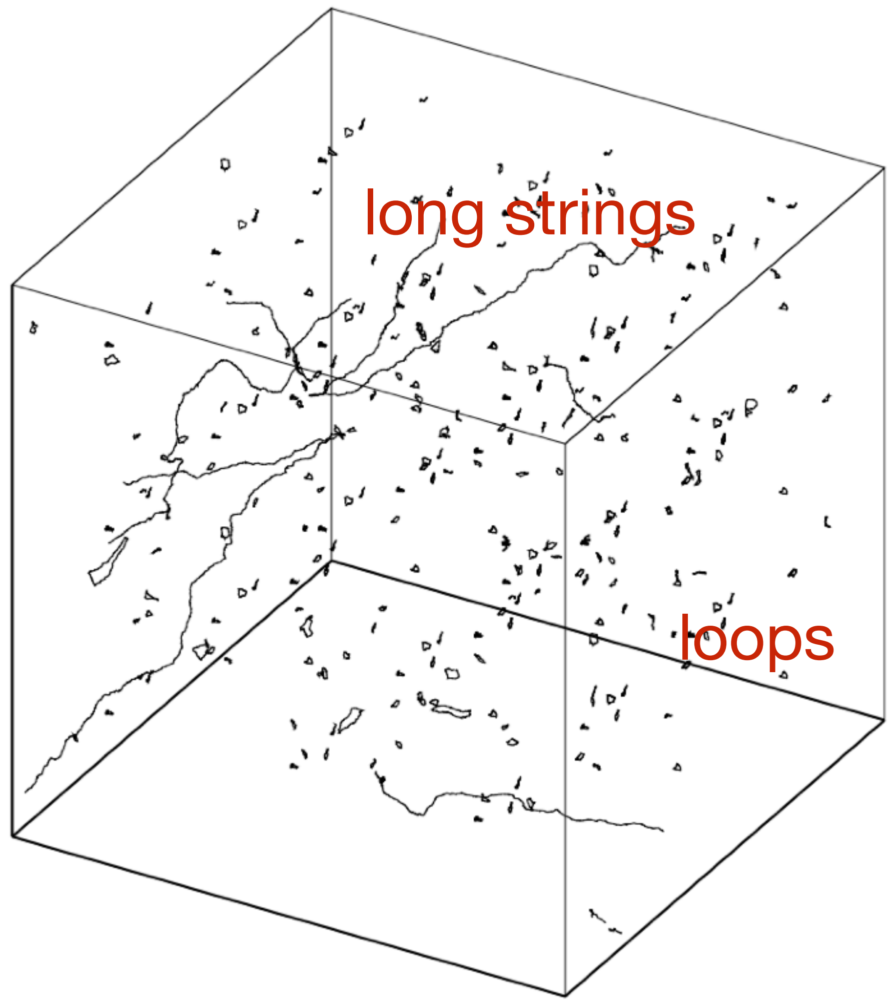
$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

King, Pascoli, Turner, YLZ, 2005.13549

# Mechanism of GWs via cosmic strings in GUTs

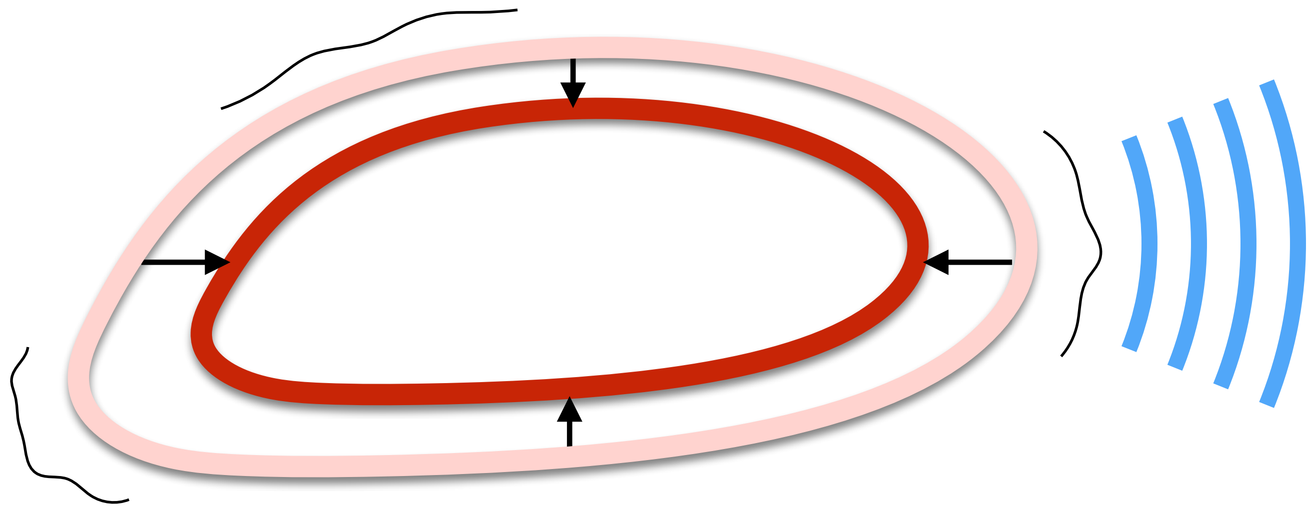
## GW via cosmic strings

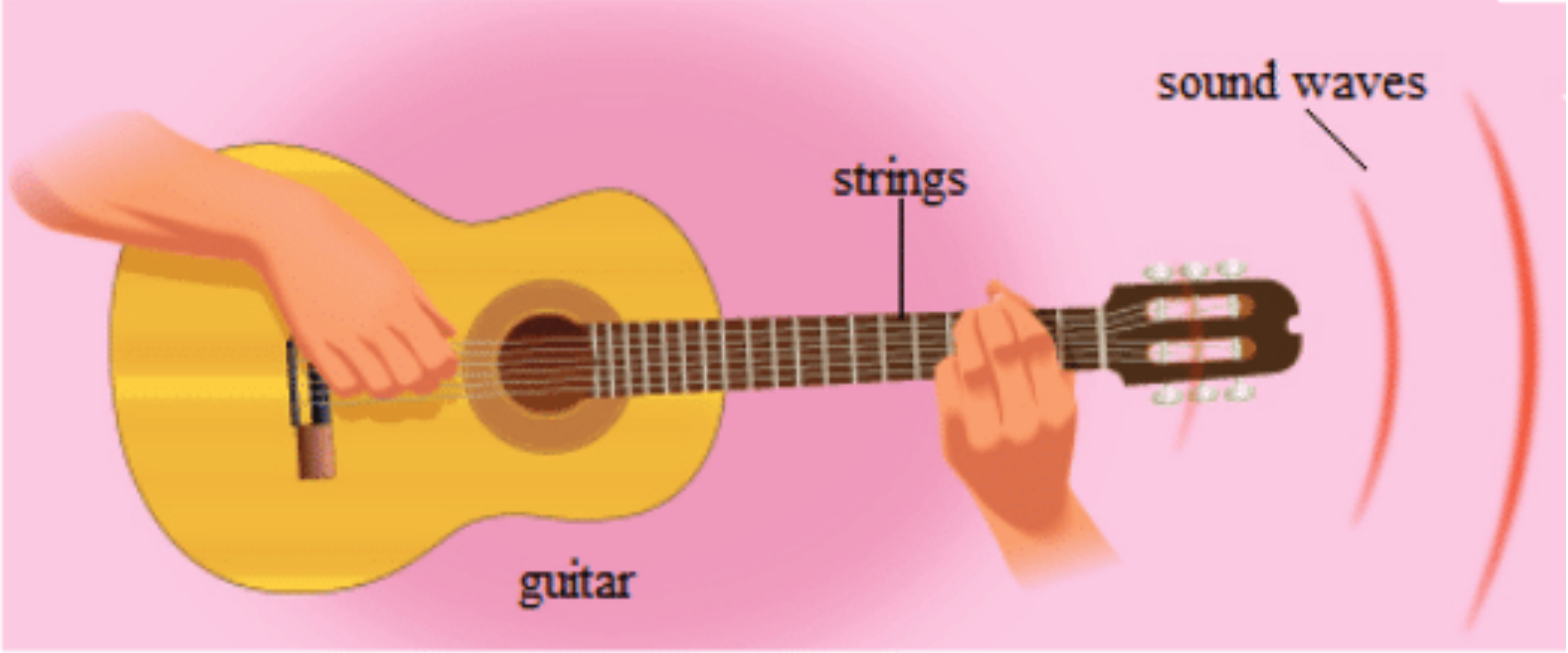
$$\pi_1(U(1)) = Z$$




Vanchurin, Olum, Vilenkin, 0511159

- Most GUTs include $U(1)_{B-L}$, denotes the scale as $M_{B-L}$
- Spontaneous breaking of $U(1)_{B-L}$ generates cosmic strings.
- Strings intersect and intercommute to form loops and cusps
- Loops oscillates via gravitational radiation

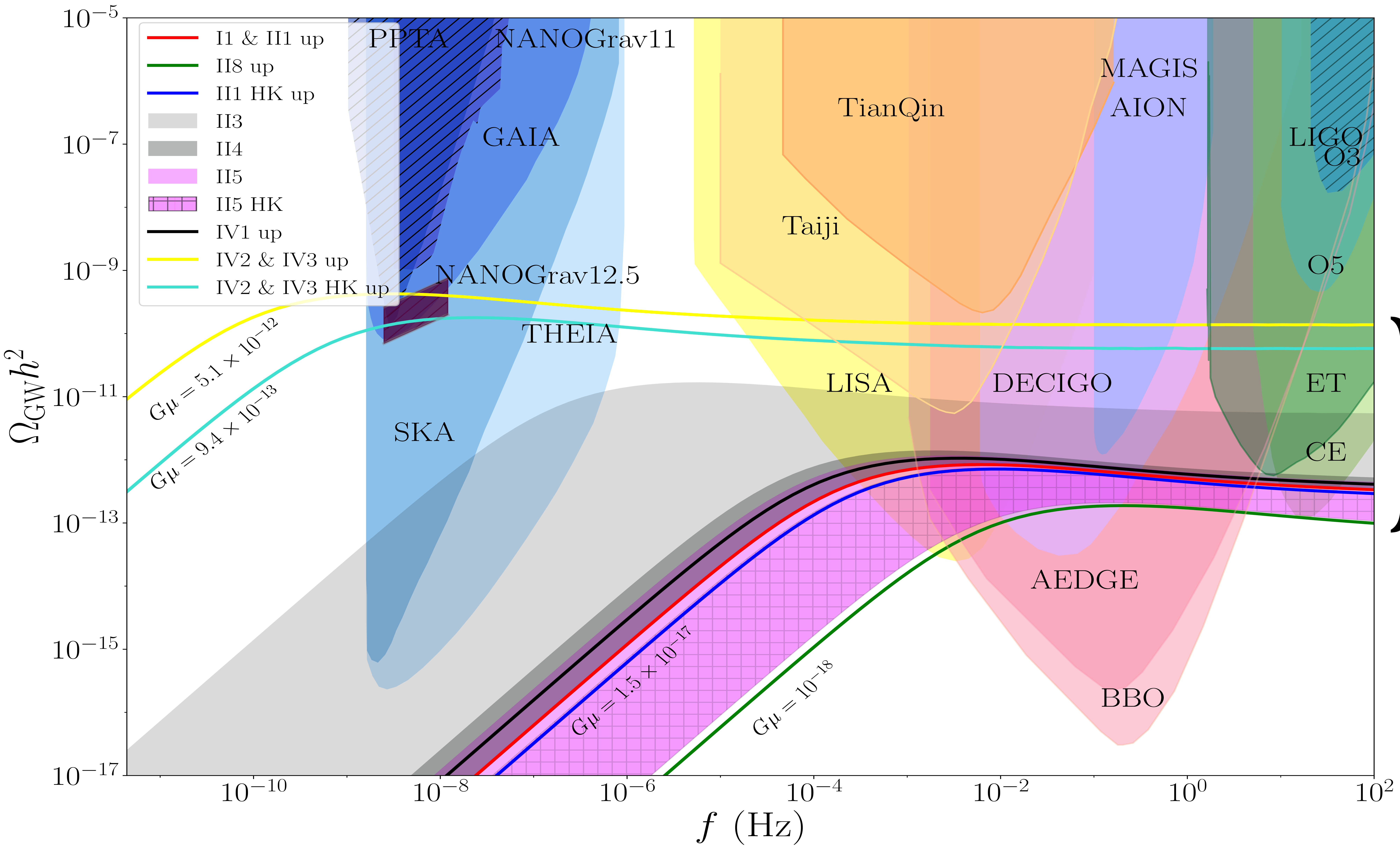





Another mechanism: GW via GUT phase transition?

——require technique developments to measure high-frequency GW, see e.g., 2011.12414, 2310.06607

# Predictions of GWs via cosmic strings in non-SUSY GUTs

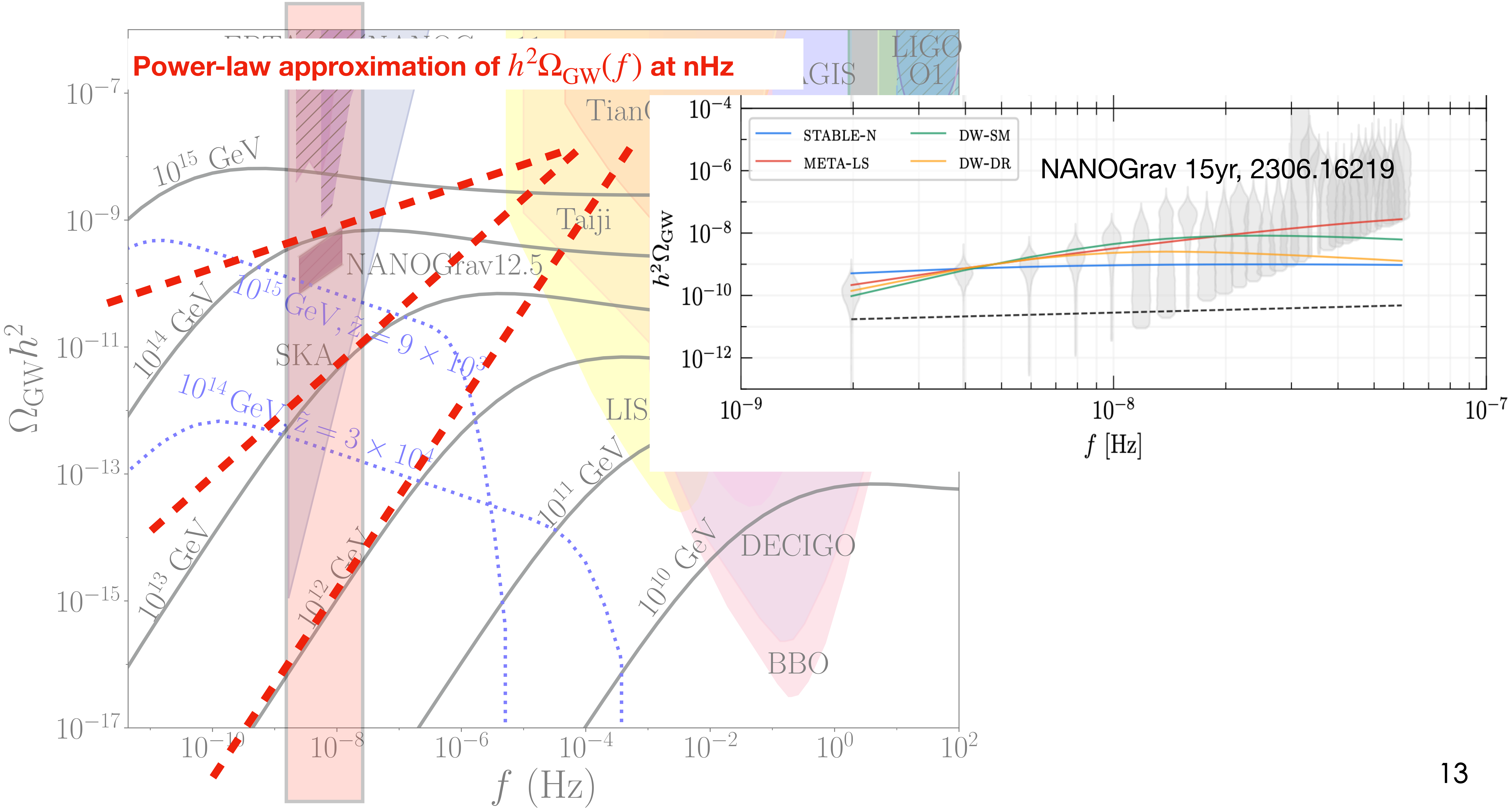



$\Omega_{\rm GW} h^2 \propto M_{B-L}$

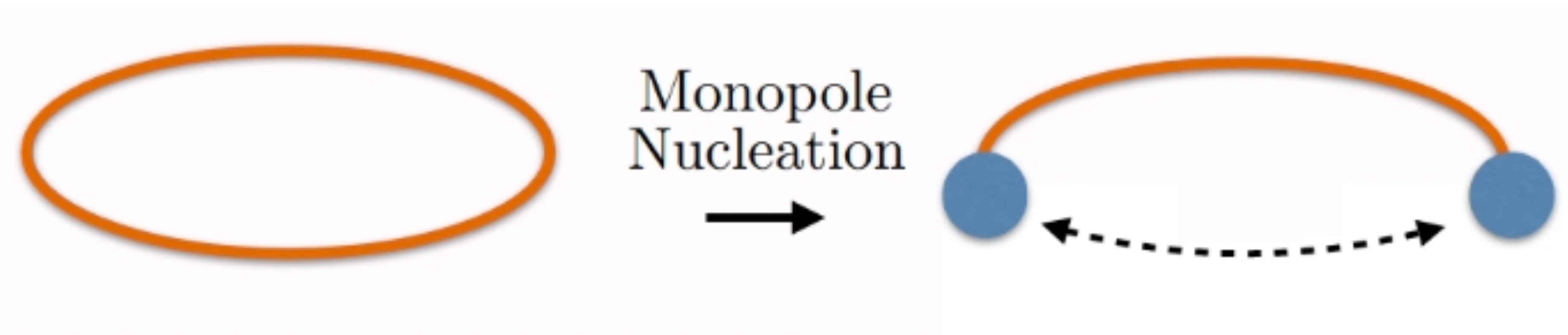
Different colours for different breaking chains

King, Pascoli, Turner, **YLZ**, 2106.15634

# Tensions between NANOGrav and GWs via cosmic strings



# Metastable strings: decaying via monopole-antimonopol pairs

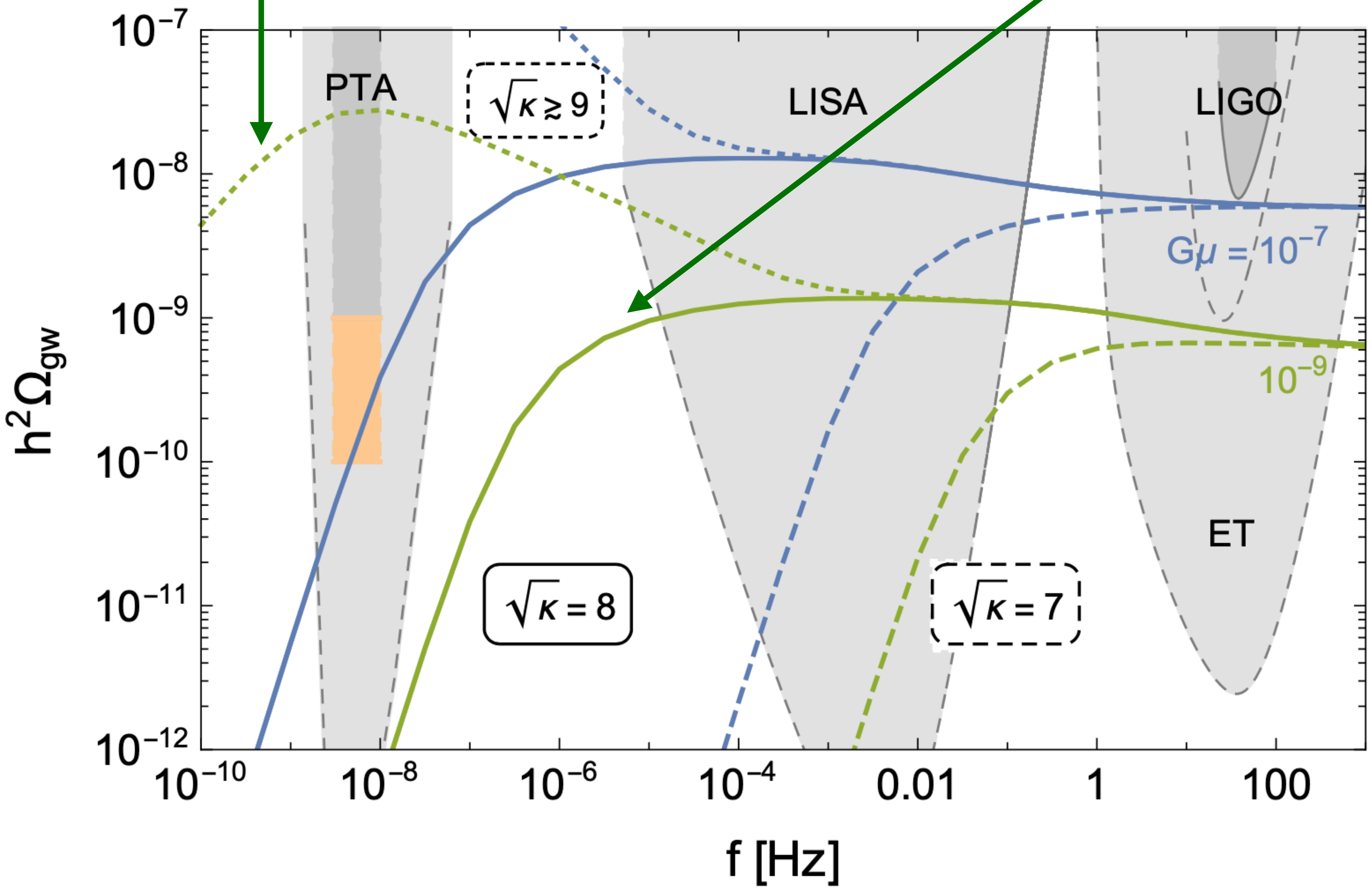



Vilenkin, NPB(1982); Preskill, Vilenkin, 9209210; Leblond, Shlaer, Siemens, 0903.4686; Monin, Voloshin, 0808.1693; Buchmuller, Domcke, Schmitz, 2107.04578

$n(l,t)$ of loops from NG strings

$n(l,t)\, e^{-\Gamma_d\, l\, t}$ of metastable loops

$$\Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa}$$




$$\sqrt{\kappa} = \frac{m_{\mathrm{monopole}}}{\sqrt{\mu_{\mathrm{string}}}} \sim \alpha_{\mathrm{GUT}}^{-1/2} \frac{M_{\mathrm{GUT}}}{M_{B-L}}$$

$$\sqrt{\kappa} \simeq (8{,}9) \Rightarrow M_{\mathrm{GUT}} \sim M_{B-L}$$

Buchmuller, Domcke, Schmitz, 2307.04691

A GUT inflation separates the GUT breaking and B-L breaking in the time scale is required.

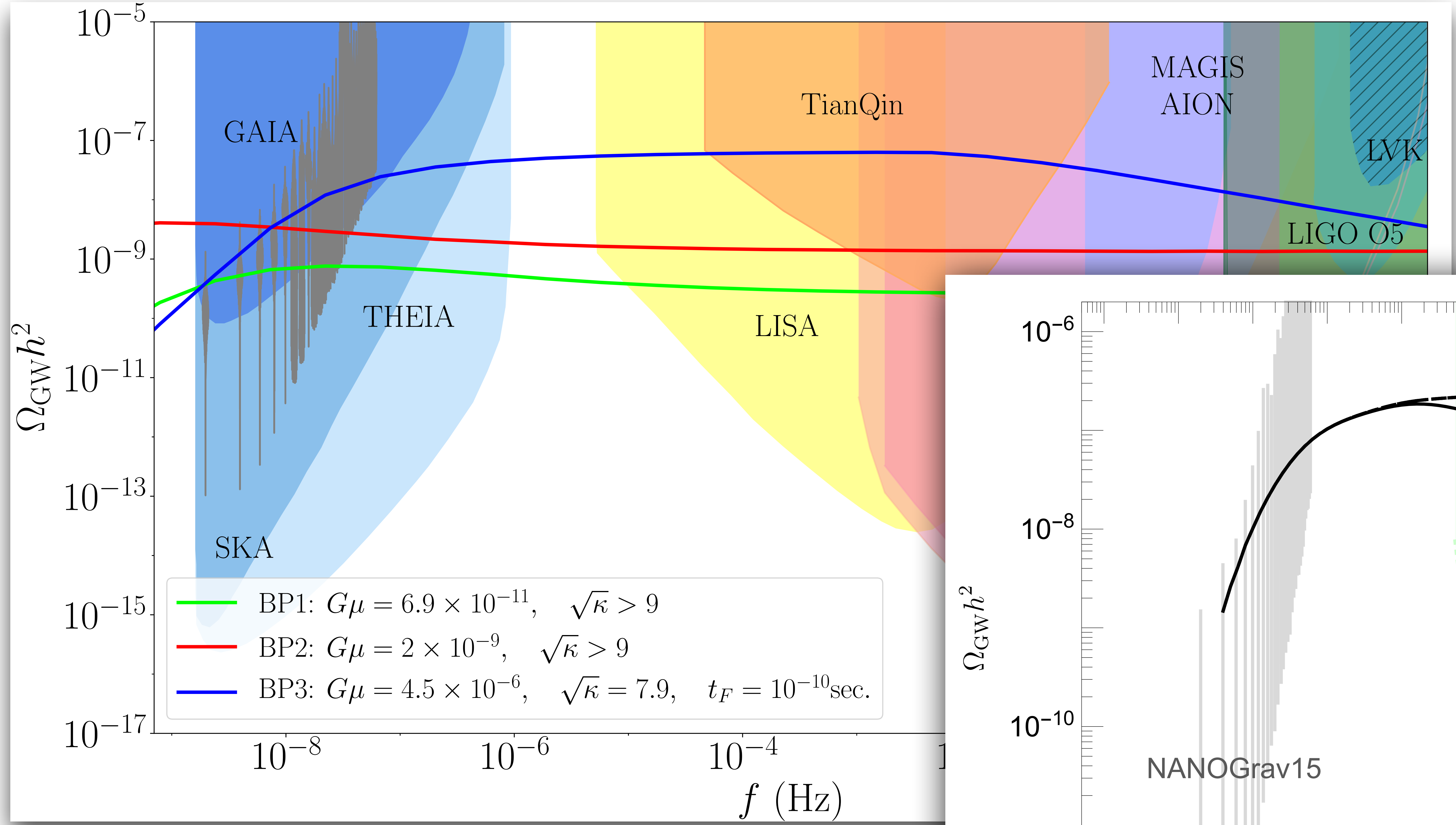
Antusch, Hinze, Saad, Steiner, 2307.04595

See also Lazarides, Maji, Moursy, Shafi, 2308.07094

# Realisation in GUT models

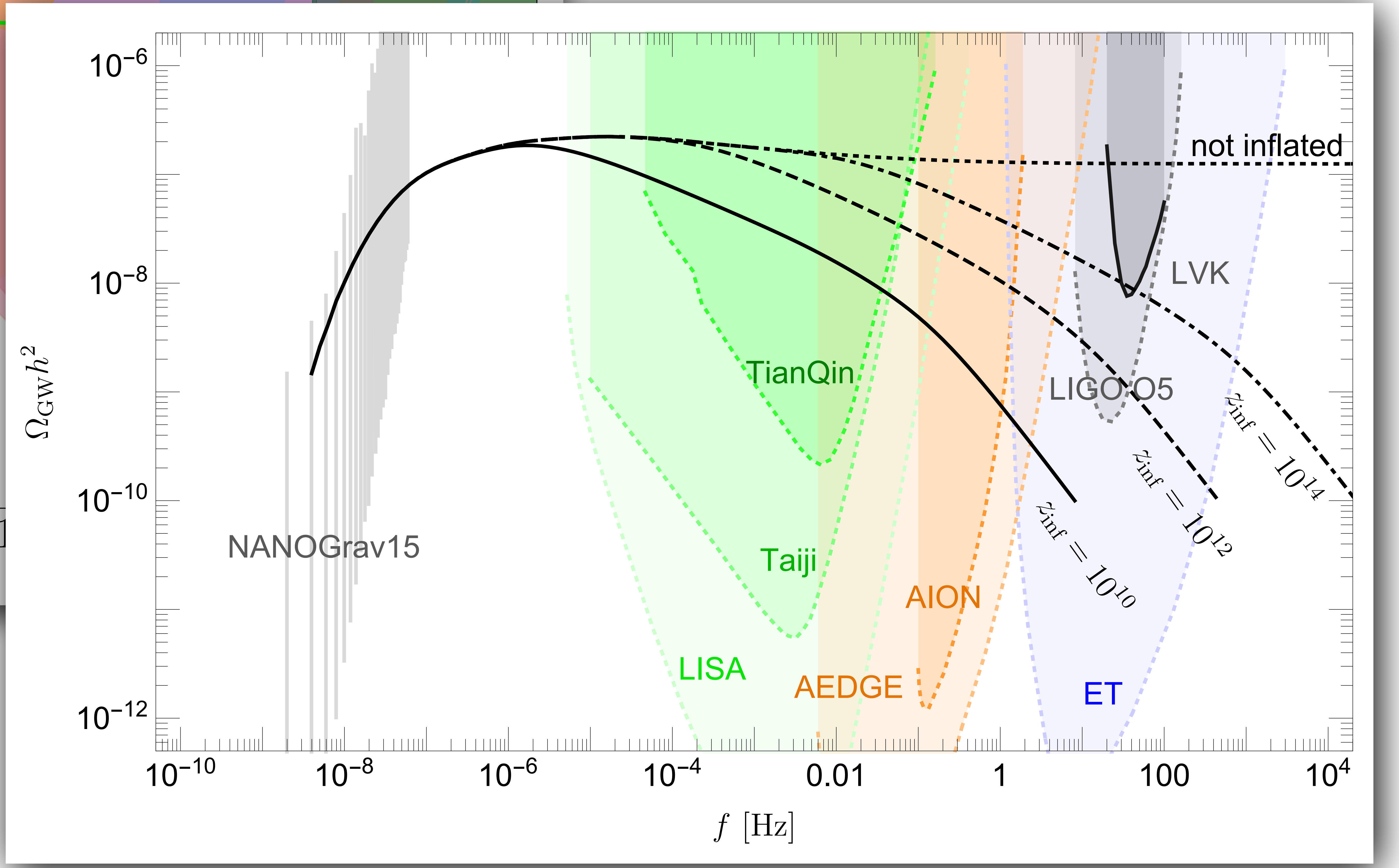
## GWs in SUSY SO(10) GUTs

Fu, King, Marsili, Pascoli, Turner, **YLZ**, 2308.05799



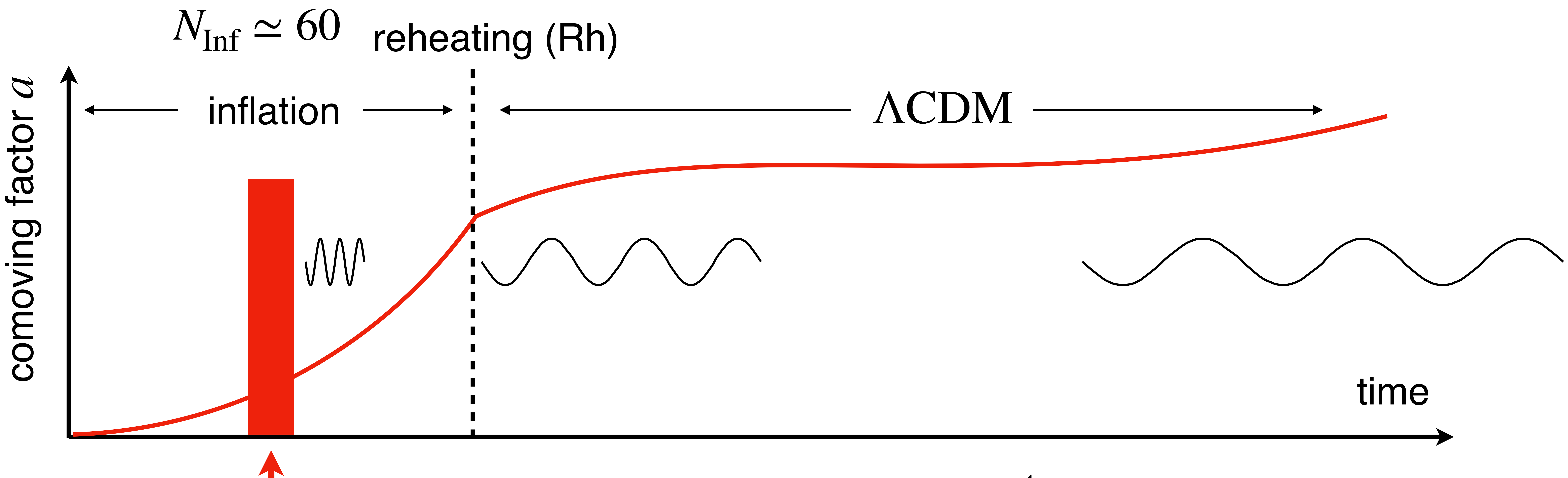

## GWs in flipped SU(5)

King, Leontaris, **YLZ**, 2311.11857



# GUT breaking during inflation

- Locating the GUT PT during inflation can also solve the monopole problem. And if the PT is first order …




$N_{\rm Inf} > N_\star > 0$ GUT PT at $N_\star$

$$\Omega_{\rm mono} \sim 10^{-5} \left(\frac{T_{\rm Rh}}{10^{15}\ {\rm GeV}}\right)^4 e^{-3(N_\star - 15)}$$

$\Lambda_{\rm GUT} = T_{\rm Rh}$ assumed

- Explicit model constructions, underway …

SU(5) inflation, Vilenki, Shafi, PRL, 1984

Smooth hybrid inflation, Lazarides, Panagiotakopoulos, hep-ph/9506325

Shifted hybrid inflation in PS model, Jeannerot, Khalil, Lazarides, Shafi, hep-ph/0002151, …

# GWs from phase transition during inflation: formalism

- The mechanism was originally proposed in [An, Lyu, Wang, Zhou, 2009.12381, 2201.05171 ]

- We repeat and generalise the formalism to PT happens at any e-folds to the end of inflation (=reheating), and interpret the formalism in a more transparent way (in my opinion)

- Conformal frame $ds^2 = a^2(\tau)\left[\mathrm{d}\tau^2 - \mathrm{d}\mathbf{x}^2\right],\ \mathrm{d}t = a\mathrm{d}\tau$

- GWs as perturbation of the metric $ds^2 = a^2(\tau)\left[\mathrm{d}\tau^2 - (\delta_{ij} + h_{ij}(\tau, \mathbf{x}))\mathrm{d}x^i\mathrm{d}x^j\right]$

- EOM of GWs $h''_{ij}(\tau, \mathbf{x}) + 2a(\tau)H\, h'_{ij}(\tau, \mathbf{x}) - \nabla^2 h_{ij}(\tau, \mathbf{x}) = 16\pi G_\mathrm{N} a^2(\tau)\sigma_{ij}(\tau, \mathbf{x})$

- Fourier Trans. $\tilde{h}''_{ij}(\tau, \mathbf{k}) + 2a(\tau)H\, \tilde{h}'_{ij}(\tau, \mathbf{k}) + k^2\tilde{h}_{ij}(\tau, \mathbf{k}) = 16\pi G_\mathrm{N} a^2(\tau)\tilde{\sigma}_{ij}(\tau, \mathbf{k})$

- GW metric proportional from $\tau'$ to $\tau$ ($\tau' < \tau$) is given by

$$h_1^{\mathrm{Inf}}(\tau, \mathbf{k}) = \cos k\tau + k\tau \sin k\tau$$

$$h_2^{\mathrm{Inf}}(\tau, \mathbf{k}) = \sin k\tau - k\tau \cos k\tau$$

$$\tilde{h}_{ij}(\tau, \mathbf{k}) = 16\pi G_\mathrm{N} \int \mathrm{d}\tau'\, \theta(\tau - \tau')\, a^2(\tau')\, \tilde{\sigma}_{ij}(\tau', \mathbf{k}) \times \mathcal{G}(\tau, \tau'; \mathbf{k})$$

Green function: $$\mathcal{G}(\tau, \tau'; \mathbf{k}) = \left[\frac{\partial h_1}{\partial \tau} - \frac{h_1}{h_2}\frac{\partial h_2}{\partial \tau}\right]^{-1}_{\tau=\tau'} h_1(\tau, \mathbf{k}) + \left[\frac{\partial h_2}{\partial \tau} - \frac{h_2}{h_1}\frac{\partial h_1}{\partial \tau}\right]^{-1}_{\tau=\tau'} h_2(\tau, \mathbf{k})$$

# GWs from phase transition during inflation: formalism

- GW propagation in Inflation (Inf) era

$$\tilde{h}_{\mu\nu}(\tau^{\mathrm{Inf}}, \mathbf{k}) = C^{\mathrm{Inf}}_{\mu\nu,1}\, h^{\mathrm{Inf}}_1(\tau^{\mathrm{Inf}}, \mathbf{k}) + C^{\mathrm{Inf}}_{\mu\nu,2}\, h^{\mathrm{Inf}}_2(\tau^{\mathrm{Inf}}, \mathbf{k})$$

$$h^{\mathrm{Inf}}_1(\tau, \mathbf{k}) = \cos k\tau + k\tau \sin k\tau$$

$$h^{\mathrm{Inf}}_2(\tau, \mathbf{k}) = \sin k\tau - k\tau \cos k\tau$$

- GW propagation in Radiation Domination (RD) era

$$\tilde{h}_{\mu\nu}(\tau^{\mathrm{RD}}, \mathbf{k}) = C^{\mathrm{RD}}_{\mu\nu,1}\, h^{\mathrm{RD}}_1(\tau^{\mathrm{RD}}, \mathbf{k}) + C^{\mathrm{RD}}_{\mu\nu,2}\, h^{\mathrm{RD}}_2(\tau^{\mathrm{RD}}, \mathbf{k})$$

$$h^{\mathrm{RD}}_1(\tau, \mathbf{k}) = \frac{\cos k\tau}{k\tau} \qquad h^{\mathrm{RD}}_2(\tau, \mathbf{k}) = \frac{\sin k\tau}{k\tau}$$

- Matching between the end of Inflation and the beginning of RD (ignoring the influence of reheating)

$$\tilde{h}^{\mathrm{Inf}}_{ij}(\tau^{\mathrm{Inf}}, \mathbf{k})\Big|_{\mathrm{Rh}} = \tilde{h}^{\mathrm{RD}}_{ij}(\tau^{\mathrm{RD}}, \mathbf{k})\Big|_{\mathrm{Rh}} \qquad \partial_t \tilde{h}^{\mathrm{Inf}}_{ij}(\tau^{\mathrm{Inf}}, \mathbf{k})\Big|_{\mathrm{Rh}} = \partial_t \tilde{h}^{\mathrm{RD}}_{ij}(\tau^{\mathrm{RD}}, \mathbf{k})\Big|_{\mathrm{Rh}}$$

- GW energy density

$$\rho_{\mathrm{GW}} = \frac{1}{32\pi G_{\mathrm{N}} a^2(t)} \int_{T_\tau} \frac{\mathrm{d}\tau}{T_\tau} \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3 V} \left| h'_{ij}(\tau, \mathbf{k}) \right|^2$$

And the ratio to the critical energy density

$$h^2\Omega_{\mathrm{GW}}(f) = \frac{h^2}{\rho_{\mathrm{c}}} \frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}\log k}\bigg|_{t = t_0,\, k = 2\pi a_0 f}$$

- PS. Matching from RD to Matter Domination (MD) and further to Vacuum Domination (VD) eras are also considered. These periods induce no new effect, thus ignored in the discussion.

# GW spectrum: inflated vs uninflated

Inflated GW Uninflated GW

$$h^2\Omega_{\rm GW}(f) = h^2\widetilde{\Omega}_{\rm GW}(fe^{N_\star}) \times S(f)$$

redshift deformation

$$h^2\widetilde{\Omega}_{\rm GW}(\tilde{f}) \equiv \frac{h^2}{\rho_c}\frac{\mathrm{d}\rho_{\rm GW}^{\rm flat}}{\mathrm{d}\log k} \times \frac{a_{\rm Rh}^4}{a_0^4}$$

Instant-source approximation $S(f) = S_0(f) + S_1(f)$

$$S_0(f) = \left\{\frac{\cos[y(1-\epsilon)]}{y^2} - \frac{\sin[y(1-\epsilon)]}{y^3}\right\}^2 \qquad y = \frac{2\pi a_0 f}{a_\star H_\star}$$

Derived in [An et al, 2009.12381]

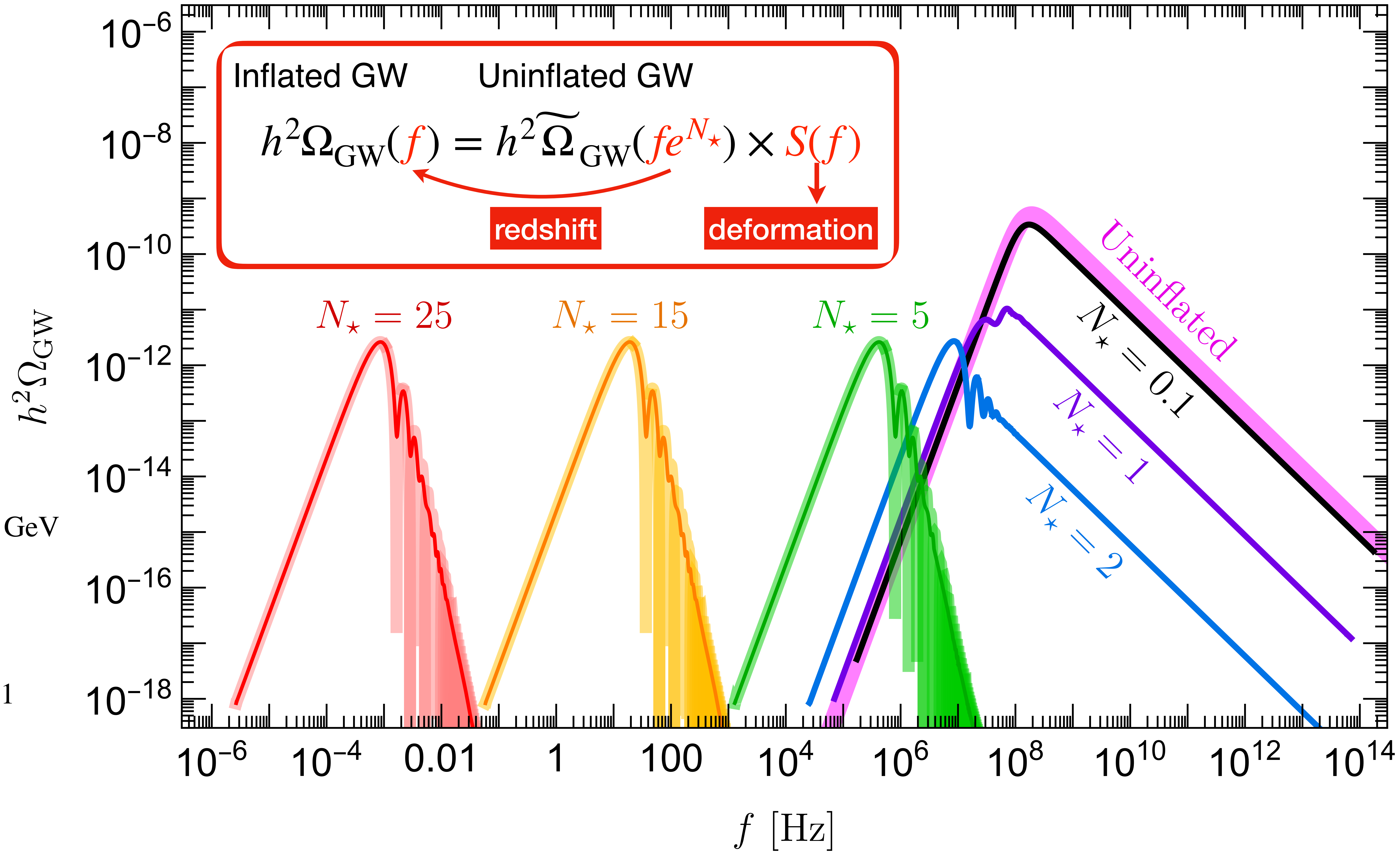
$$S_1(f) = y\epsilon \times \left\{\left[\frac{1}{y^2} + 2\epsilon - 1\right]\frac{\sin[2y(1-\epsilon)]}{y^4} - \left[\frac{2-\epsilon}{y^2} + \epsilon\right]\frac{\cos[2y(1-\epsilon)]}{y^3} + \frac{\epsilon^3}{y}\left(\frac{1}{y^2} + 1\right)\right\}$$

Our correction

Transitory-source approximation

$$S(f) \to \bar{S}(f) = \frac{1}{\Delta_y}\int_{\bar{y}-\Delta_y/2}^{\bar{y}+\Delta_y/2} \mathrm{d}y\, S(f)\Big|_{\bar{y}=\frac{2\pi a_0 f}{a_\star H_\star}} \qquad \Delta_y = \frac{a_\star \Delta_\tau}{1/H_\star}\bar{y}$$

# GW spectrum: inflated vs uninflated




$T_{\rm Rh} = 10^{15}$ GeV

$\dfrac{\beta}{H_\star} = 5$

$\dfrac{\rho_{\rm PT}}{\rho_{\rm tot}} = 0.1$

# Three bands of frequencies

| | **Infrared (IR)** | **Ultraviolet (UV)** | **Far Ultraviolet (FUV)** |
|---|---|---|---|
| **Wave length** | $\lambda_\star = \frac{2\pi a_\star}{k} \gg H_\star^{-1}$ | $\lambda_\star \ll H_\star^{-1} \ll \lambda_\star \frac{a_{\rm Rh}}{a_\star}$ | $H_\star^{-1} \gg \lambda_\star \frac{a_{\rm Rh}}{a_\star}$ |

A quantity with subscript ★ means its value during phase transition, which happens during the inflation

The Hubble rate is the same as that during inflation $H_\star = H_{\rm Inf}$

The coming factor is much smaller than that at reheating $a_\star = a_{\rm Rh}\, e^{-N_\star}$

| | | | |
|---|---|---|---|
| **Co-moving momentum** | $k \ll a_\star H_\star$ | $a_\star H_\star \ll k \ll a_{\rm Rh} H_\star$ | $k \gg a_{\rm Rh} H_\star$ |
| **Frequency today** | $f \ll \frac{a_\star H_\star}{2\pi a_0}$ | $\frac{a_\star H_\star}{2\pi a_0} \ll f \ll \frac{a_{\rm Rh} H_\star}{2\pi a_0}$ | $f \gg \frac{a_{\rm Rh} H_\star}{2\pi a_0}$ |

**GW propagation to the radiation domination (RD)**

$$h_{\rm RD}^{\rm IR} \simeq \frac{1}{k}\frac{a_{\rm Rh}^2}{a(t)} \times \frac{1}{3}\sin\left(k\tau - \frac{k}{a_{\rm Rh} H_\star}\right)$$

$$h_{\rm RD}^{\rm UV} \simeq \frac{-1}{k}\frac{a_{\rm Rh}^2}{a(\tau)}\frac{\cos[y(1-\epsilon)]}{y^2}\sin(k\tau - y\epsilon)$$

$$h_{\rm RD}^{\rm FUV} \simeq \frac{1}{k}\frac{a_\star^2}{a(t)}\sin[k\tau + y(1-2\epsilon)]$$

**Deformation function**

$$\boxed{S(f)^{\rm IR} \simeq \frac{1}{9}}$$

$$S(f)^{\rm UV} \simeq \frac{\cos[2y(1-\epsilon)]+1}{2y^4}$$

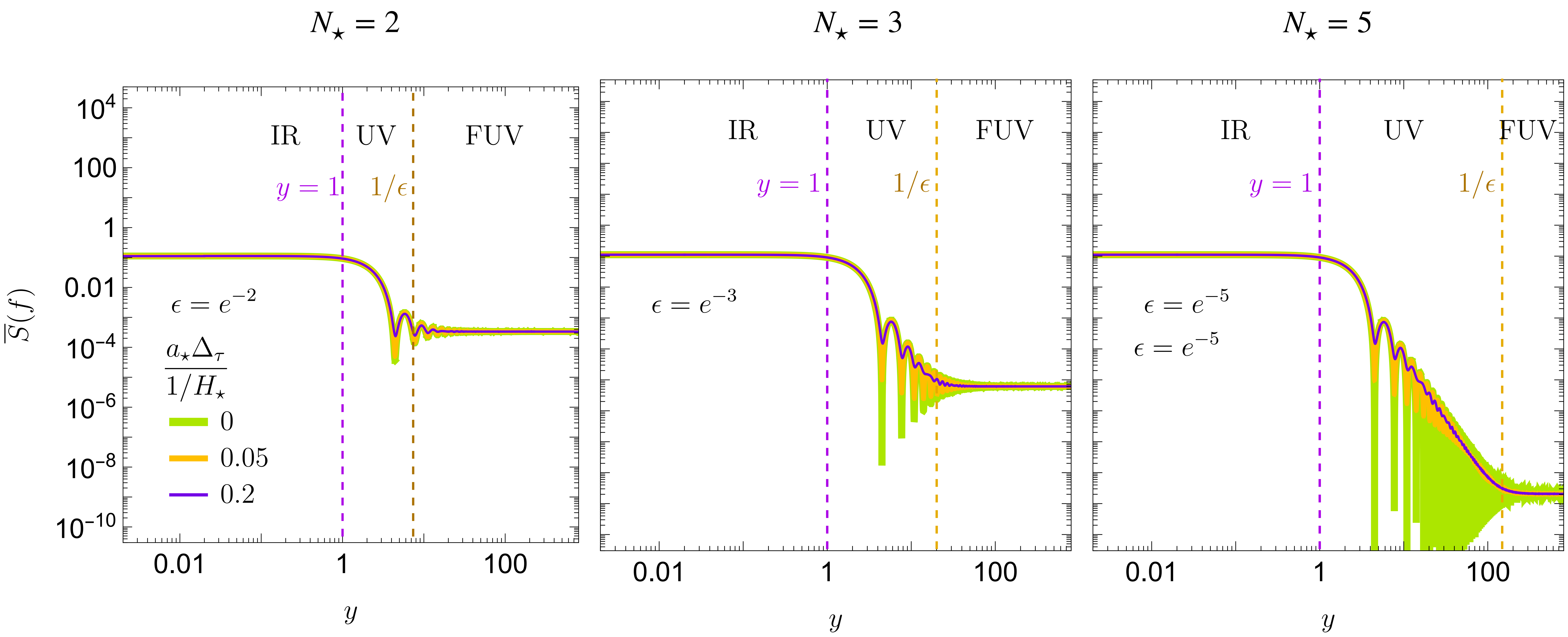
$$S(f)^{\rm FUV} \simeq \frac{a_\star^4}{a_{\rm Rh}^4}$$

Frozen

Oscillation and partial dilution

Dilution as radiation

# Deformation function in three regimes



# Source of GWs during phase transition

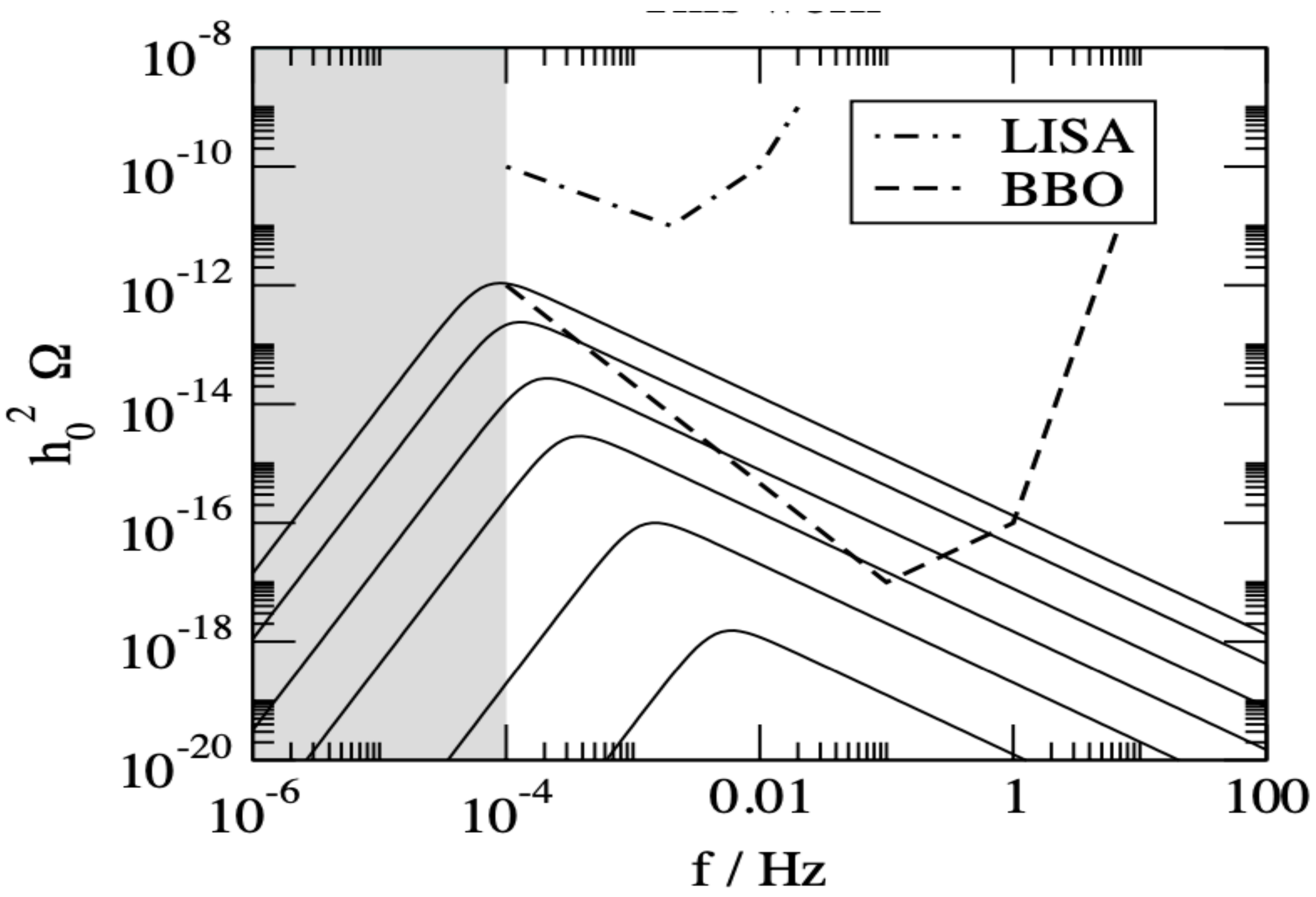
- GWs via bubble collisions in FOPT

$$h^2\widetilde{\Omega}_{\rm GW}(\tilde{f}) = 1.27\times 10^{-6}\times\left(\frac{H_\star}{\beta}\right)^2\left(\frac{\rho_{\rm PT}}{\rho_{\rm tot}}\right)^2\left(\frac{100}{g_\star}\right)^{1/3}\times\frac{(a+b)(\tilde{f}/\tilde{f}^{\rm peak})^a}{a(\tilde{f}/\tilde{f}^{\rm peak})^{a+b}+b}$$

$$\tilde{f}^{\rm peak} = 37.8\ \text{MHz}\times\left(\frac{\beta}{H_\star}\right)\left(\frac{T_\star}{10^{15}\ \text{GeV}}\right)\left(\frac{g_\star}{100}\right)^{1/6}$$

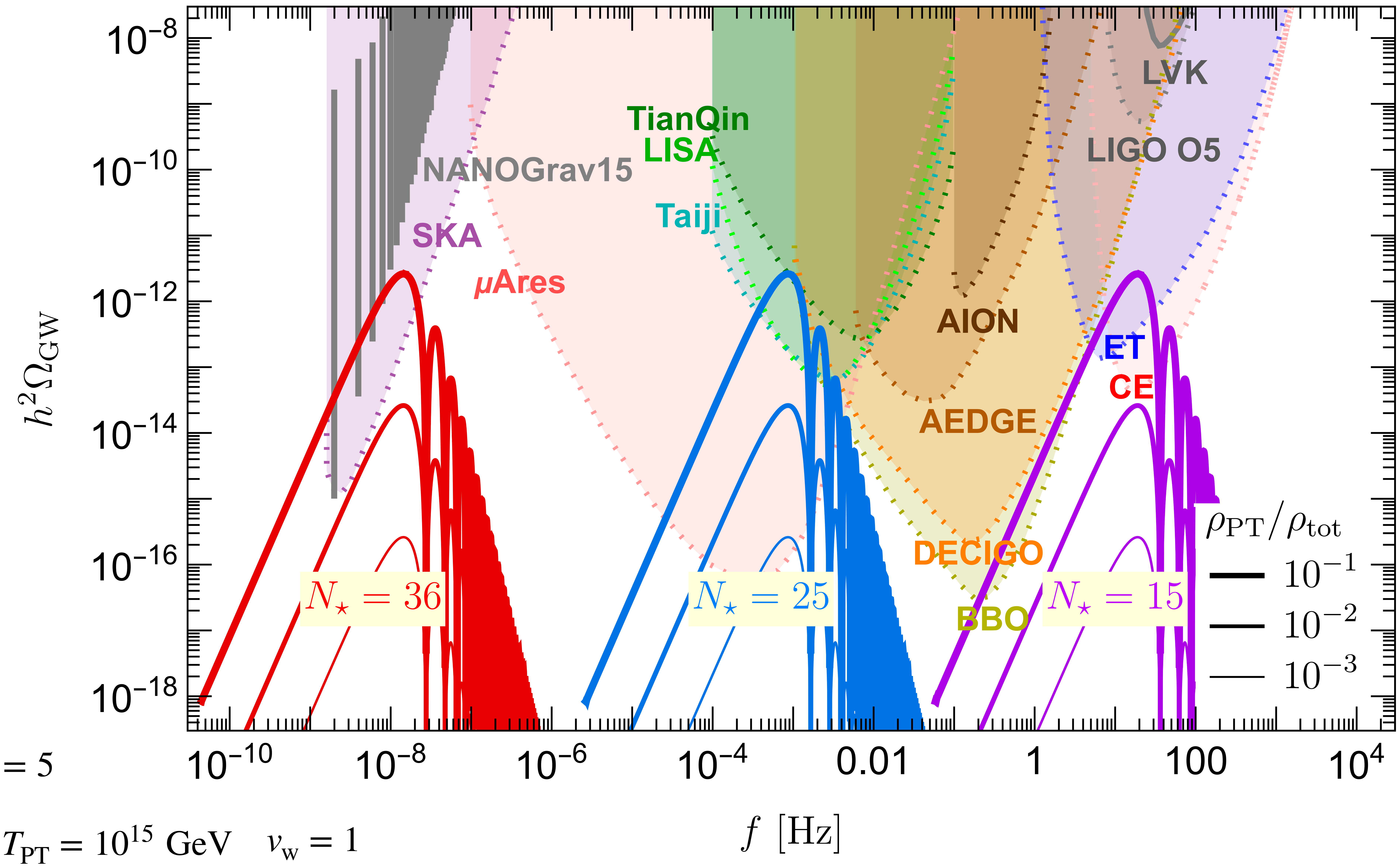
$$a = 2.8,\ b = 1$$

Kosowsky, Turner, Watkins, PRD, 92;
Huber, Konstandin, 0806.1828



# Inflated GWs via GUT phase transition

Instant source approximation

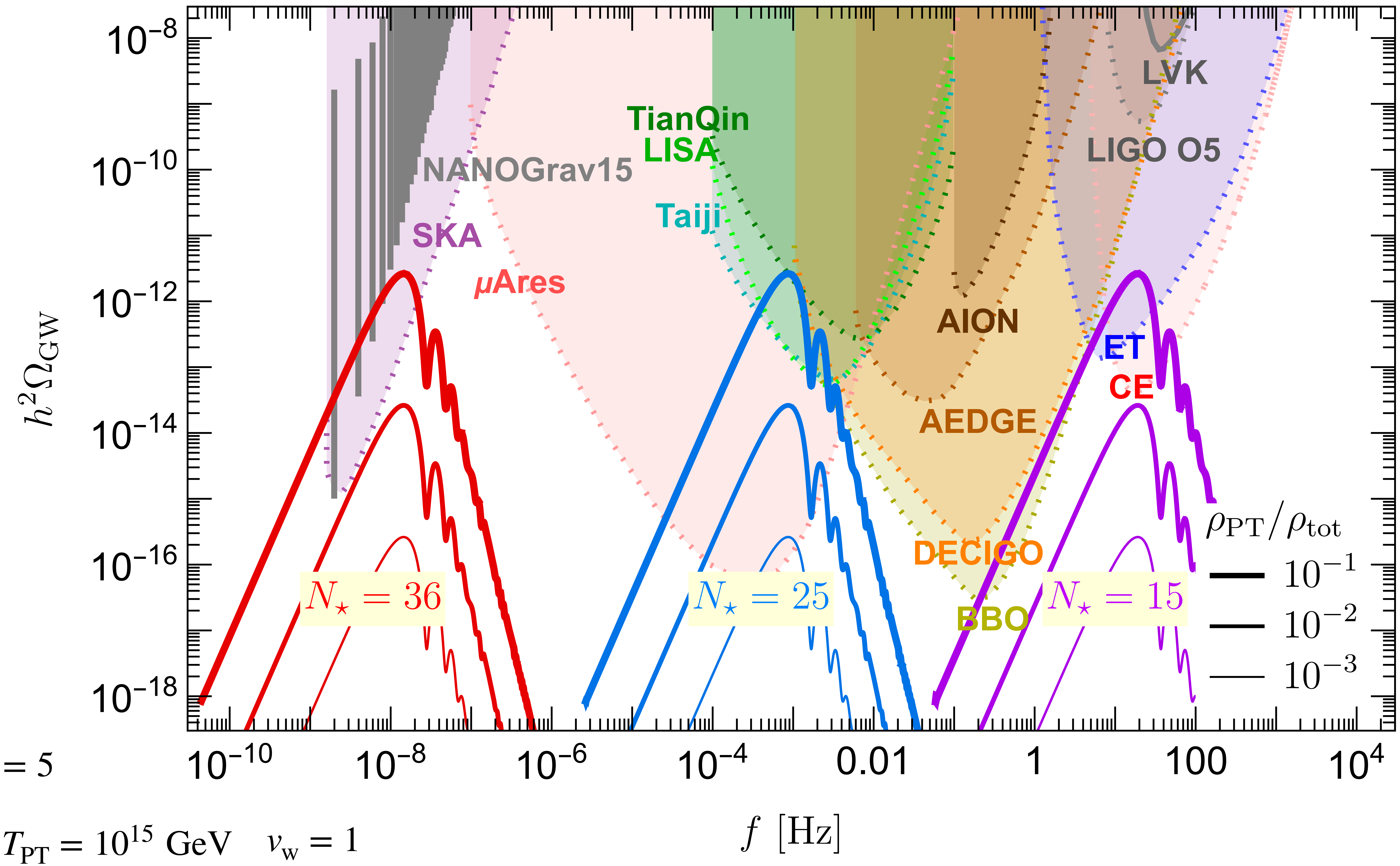



$\beta/H_\star = 5$

$T_\star = T_{\rm PT} = 10^{15}$ GeV $\quad v_{\rm w} = 1$

# Inflated GWs via GUT phase transition

transitory source approximation

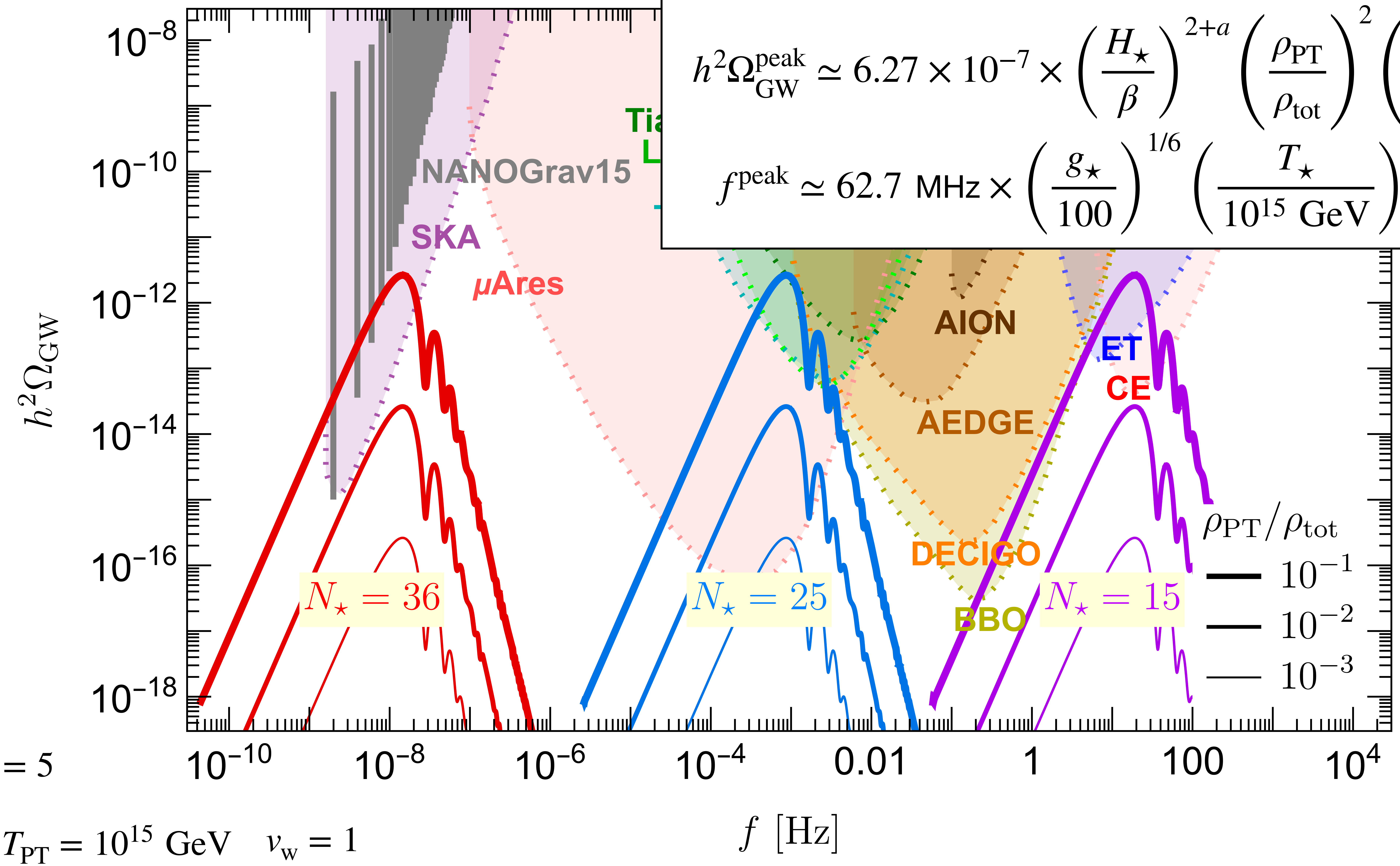



$\beta/H_\star = 5$

$T_\star = T_{\rm PT} = 10^{15}$ GeV $\quad v_{\rm w} = 1$

# Inflated GWs via GUT phase transition

transitory source approximation



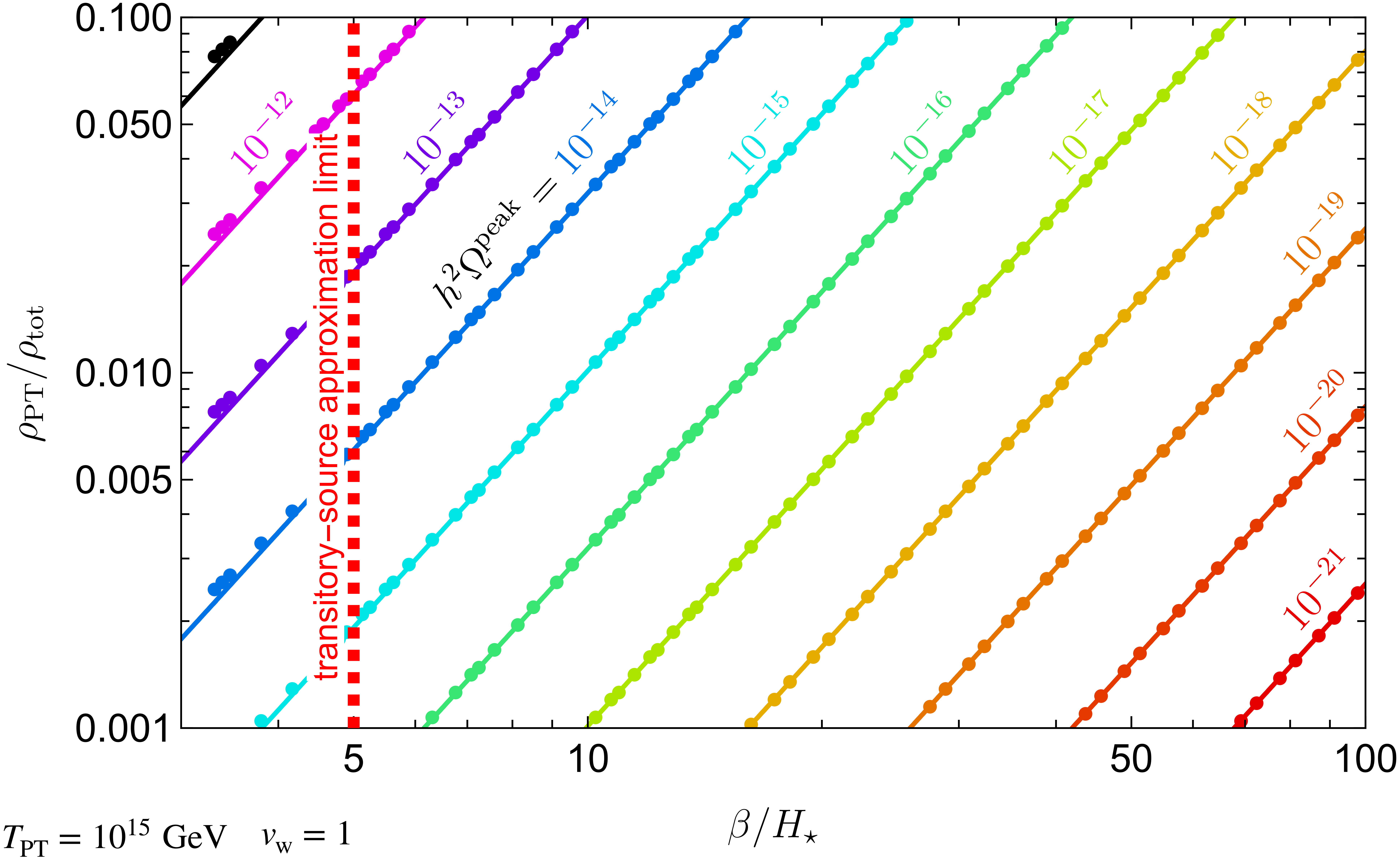

$$h^2\Omega_{\rm GW}^{\rm peak} \simeq 6.27\times 10^{-7}\times\left(\frac{H_\star}{\beta}\right)^{2+a}\left(\frac{\rho_{\rm PT}}{\rho_{\rm tot}}\right)^2\left(\frac{100}{g_\star}\right)^{1/3}$$

$$f^{\rm peak} \simeq 62.7\ \text{MHz}\times\left(\frac{g_\star}{100}\right)^{1/6}\left(\frac{T_\star}{10^{15}\ \text{GeV}}\right)\times e^{-N_\star}$$

$\beta/H_\star = 5$

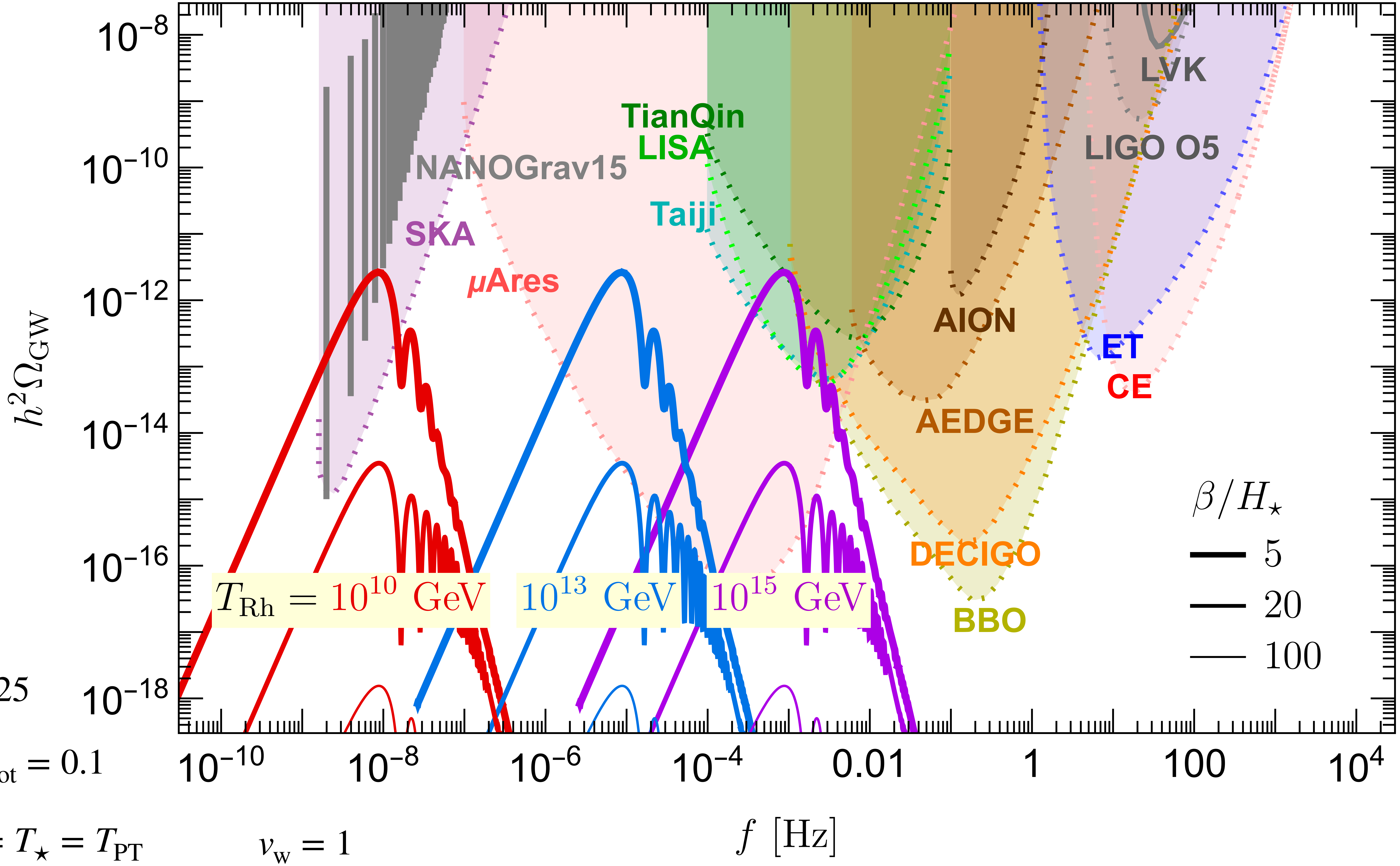
$T_\star = T_{\rm PT} = 10^{15}$ GeV $\quad v_{\rm w} = 1$

# Testable region respect to the peak of GW spectrum




$T_\star = T_{\rm PT} = 10^{15}$ GeV $\quad v_{\rm w} = 1$

# Application to other phase transition (e.g. Pati-Salam)

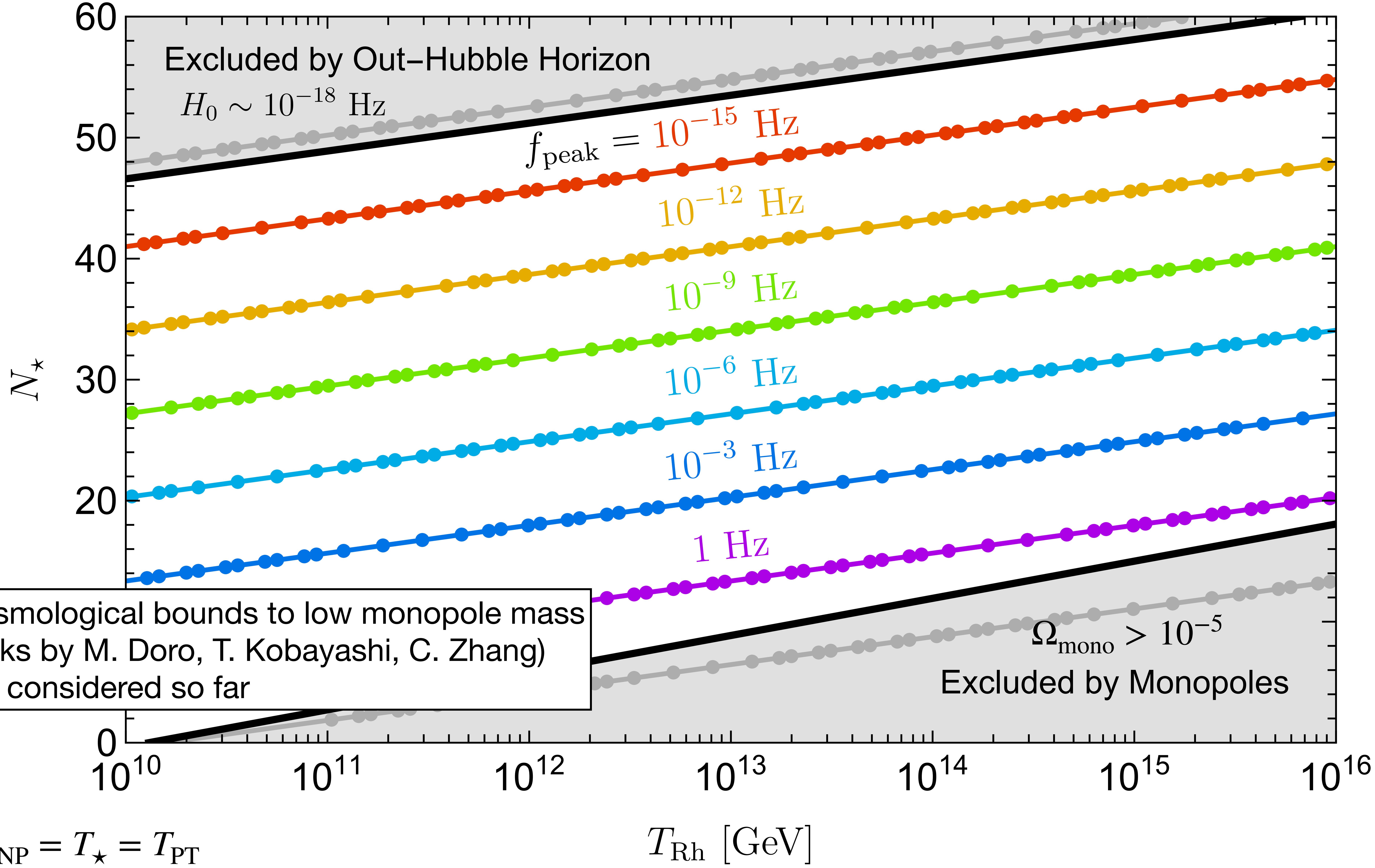



$N_\star = 25$

$\rho_{\rm PT}/\rho_{\rm tot} = 0.1$

$\Lambda_{\rm NP} = T_\star = T_{\rm PT}$ $\quad v_{\rm w} = 1$

# Application to other phase transition (e.g. Pati-Salam)




Cosmological bounds to low monopole mass
(Talks by M. Doro, T. Kobayashi, C. Zhang)
not considered so far

$\Lambda_{\rm NP} = T_\star = T_{\rm PT}$

# Conclusion

- Monopoles are general predictions in GUTs. Inflation is required to solve the GUT monopole problem.
- As point-like objects, monopoles do not radiate GWs directly, but can influence GWs generated from phase transition or other topological defects.
- Monopoles play a role in GWs via cosmic strings.
  - String can be metastable via the decay to monopole-antimonopole pairs.
  - The process solves the tensions between NANOGrav and GWs via cosmic strings.
  - Requirement: scales for monopoles and strings are nearby, naturally released in SUSY GUTs and flipped SU(5).
- A scenario of GUT phase transition with testable GWs and without monopole problem
  - It happens during inflation and the phase transition is strong first order
  - We generalise the formalism to phase transition at any e-folds before before the end of inflation
  - We specify three frequency bands: IR, UV and FUV.
  - Testable regimes: e-folds 15 → 36, 100 Hz → nHz; $\rho_{\rm PT}/\rho_{\rm tot} > 10^{-3}$, $5 < \beta/H_\star < 100$

Thanks and questions …