Completing the picture of black hole formation from first-order phase transitions

Piotr Toczek,

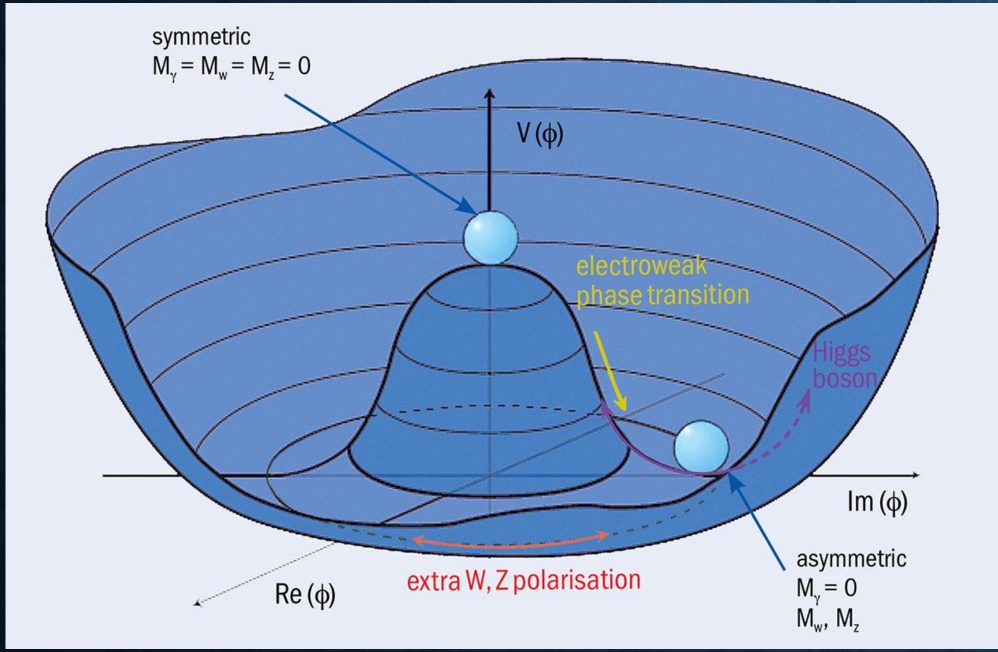
Faculty of Physics, University of Warsaw

in collaboration with
Yann Gouttenoire, Marek Lewicki
and Ville Vaskonen

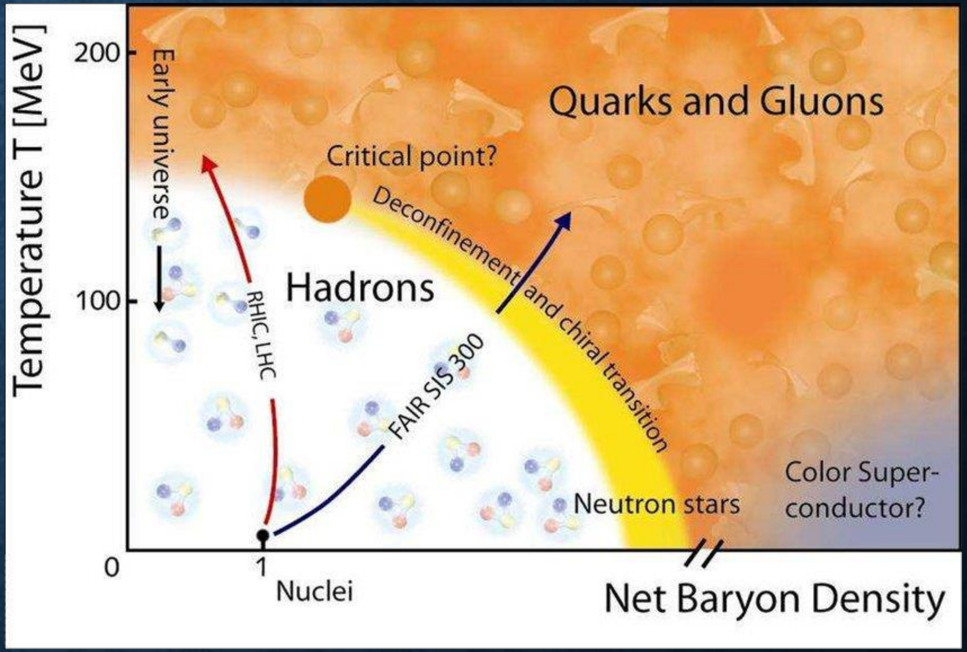
NATIONAL SCIENCE CENTRE POLAND

FNP Fundacja na rzecz Nauki Polskiej

PHASE TRANSITIONS IN THE EARLY UNIVERSE

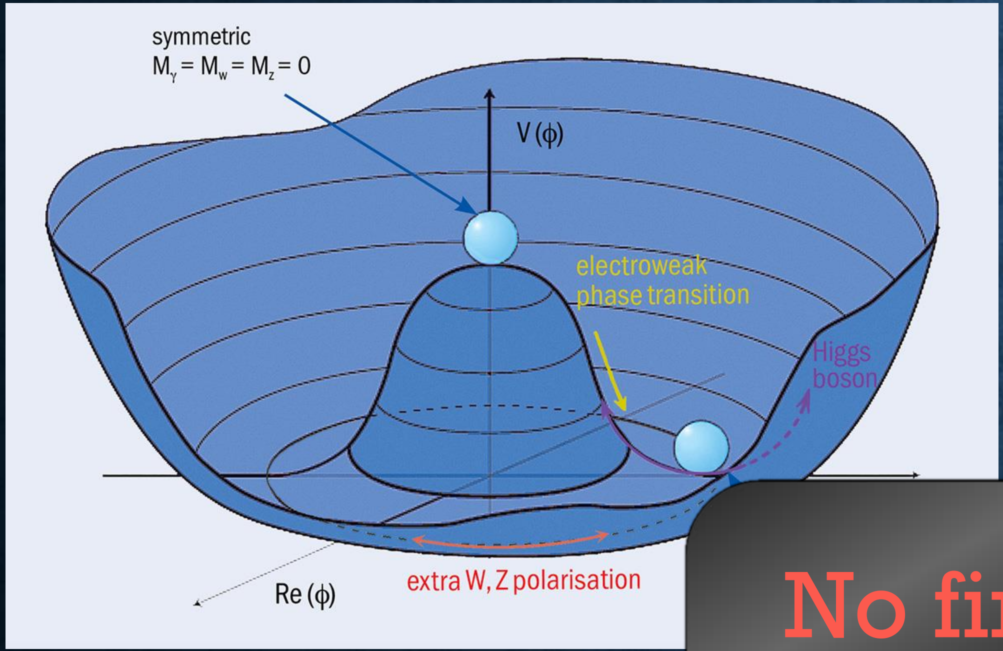


J. Ellis, M. Neubauer, *cerncourier.com*

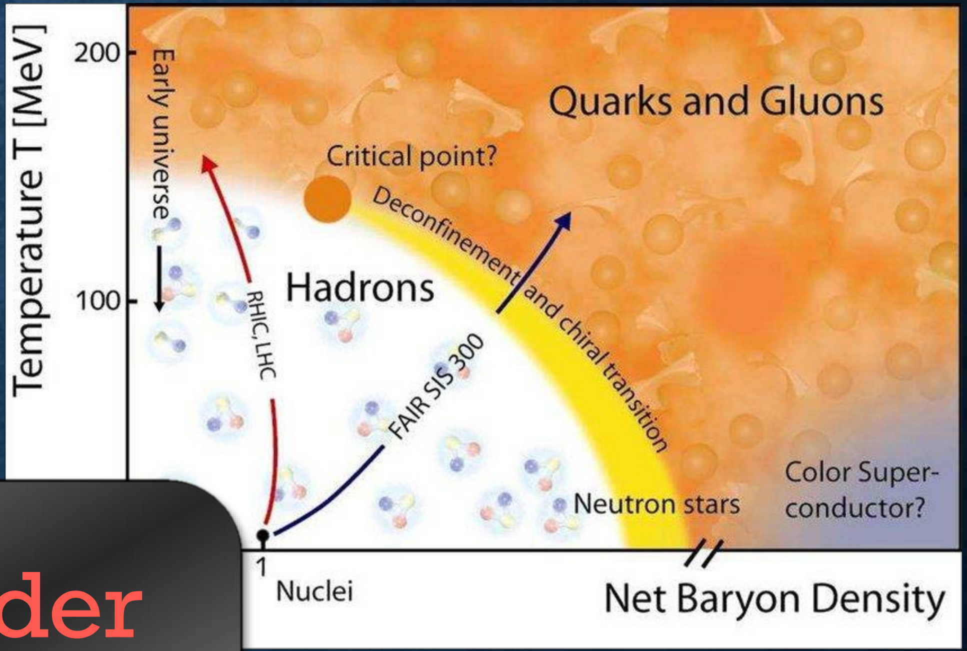


G. Aarts, *J.Phys.Conf.Ser.* 706 (2016) 2, 022004

PHASE TRANSITIONS IN THE EARLY UNIVERSE



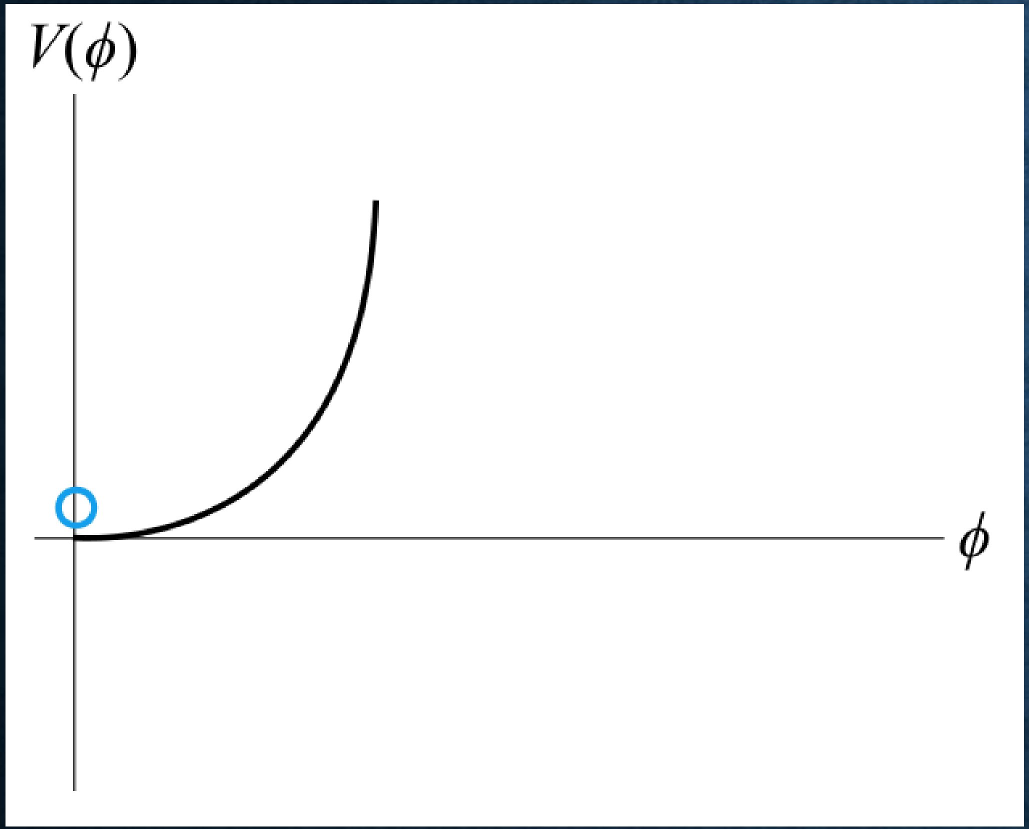
J. Ellis, M. Neubauer, *cerncourier.com*



G. Aarts, *J.Phys.Conf.Ser.* 706 (2016) 2, 022004

No first-order phase transition in the SM!

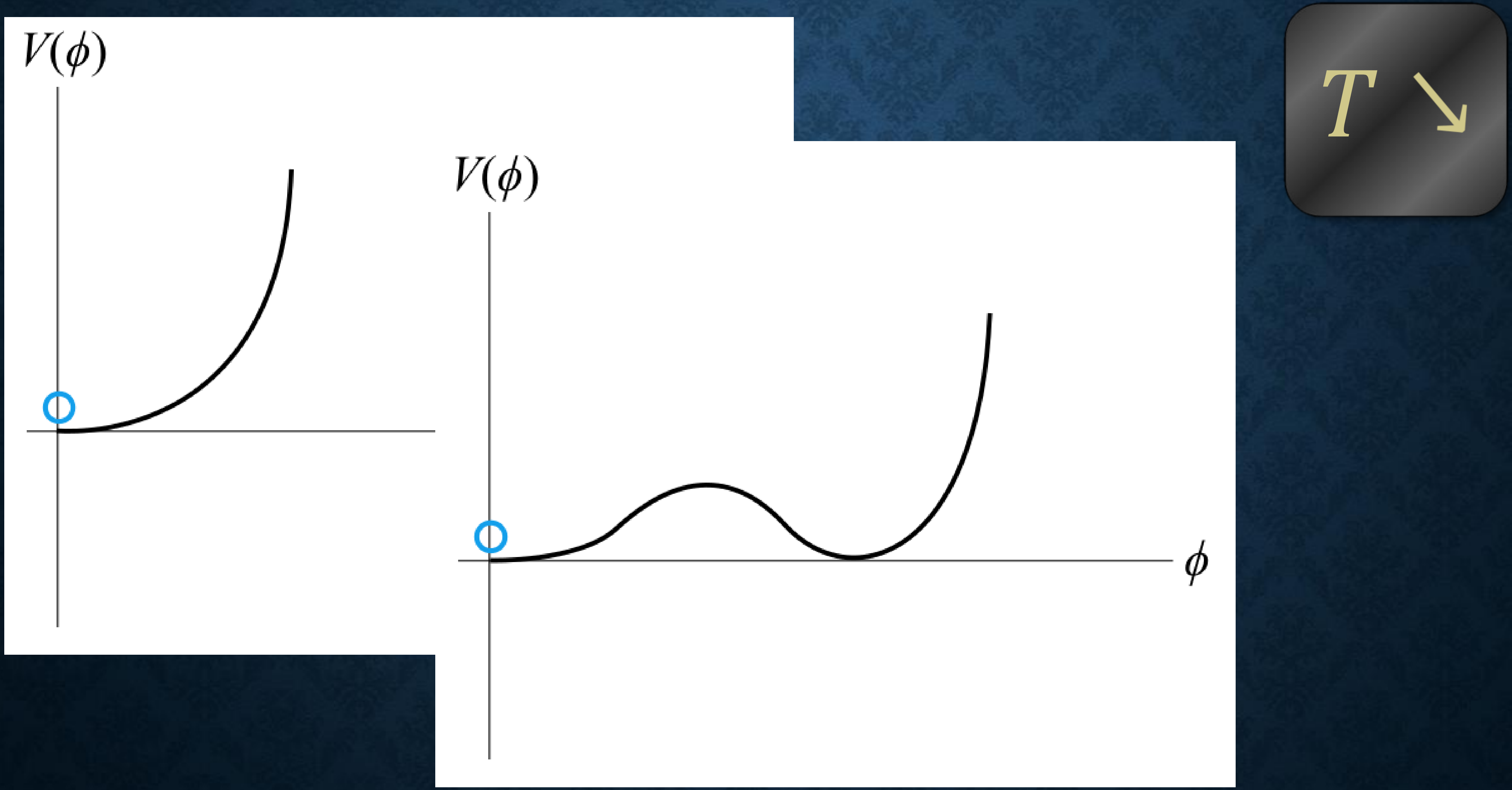
FIRST-ORDER PHASE TRANSITION



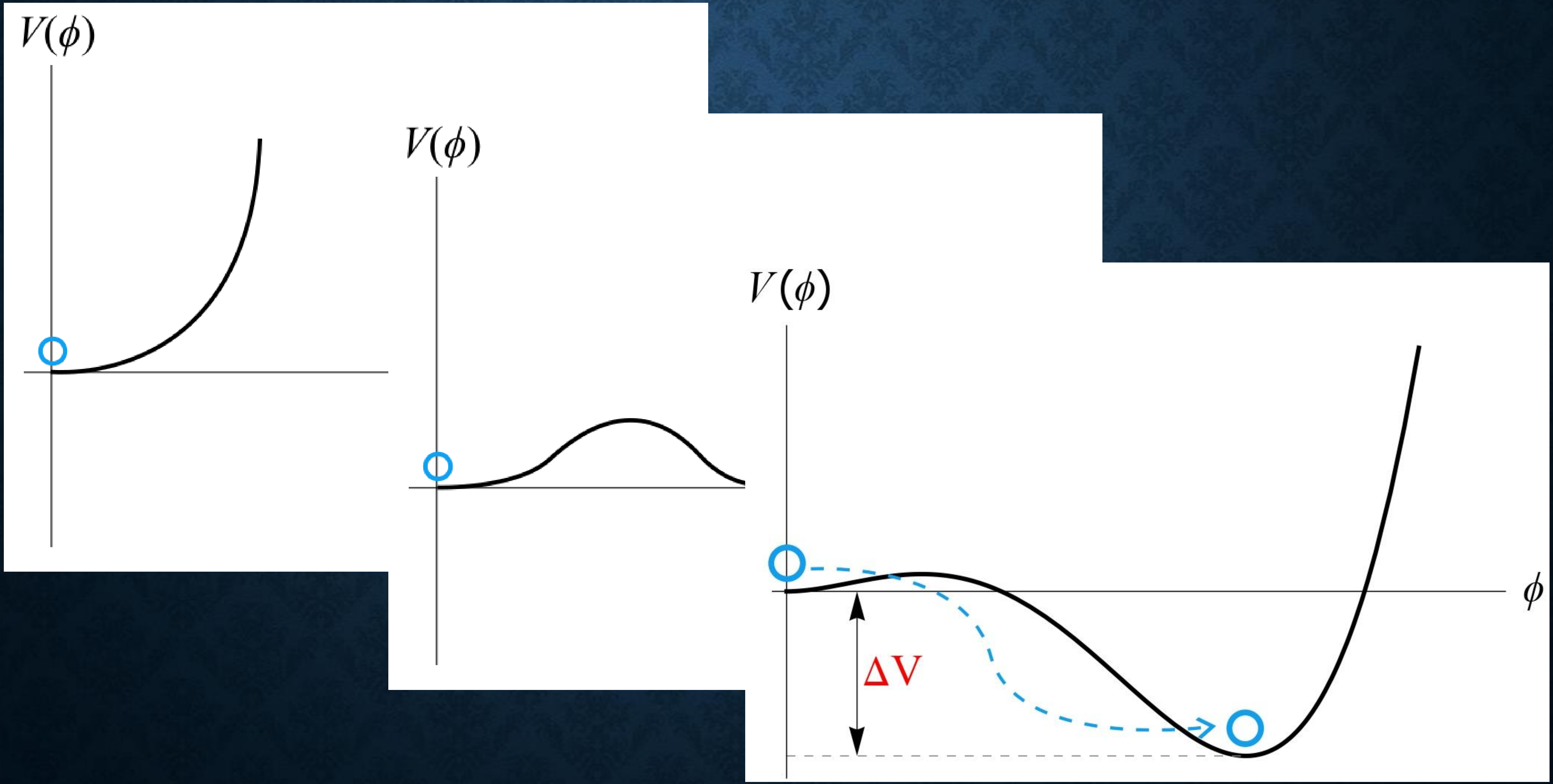
Thermal corrections

$\propto \phi^2 T^2$

FIRST-ORDER PHASE TRANSITION



FIRST-ORDER PHASE TRANSITION



FIRST-ORDER PHASE TRANSITION

nucleation of true vacuum bubbles

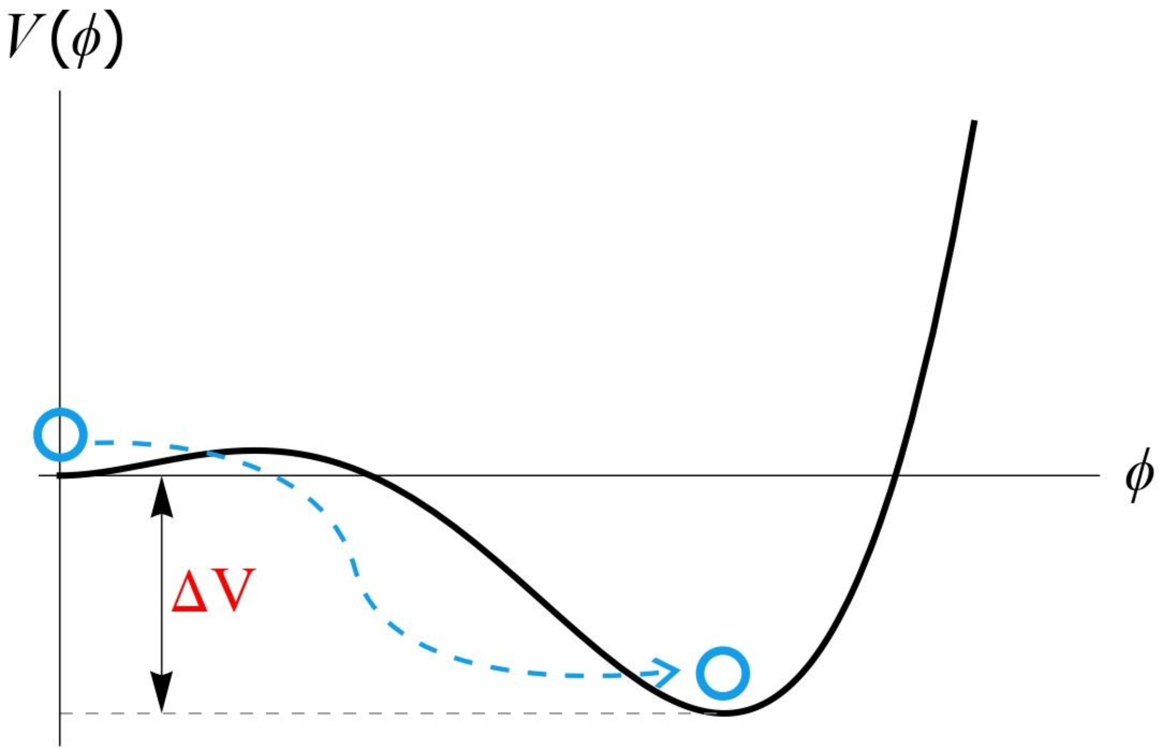
$$\Gamma(t) = Ae^{S(t)}$$

Transition strength

$$\alpha \approx \frac{\Delta V}{\rho_R}$$

bubble wall velocity

$$v_w$$



SUPERCOOLED PHASE TRANSITION

nucleation of true vacuum bubbles

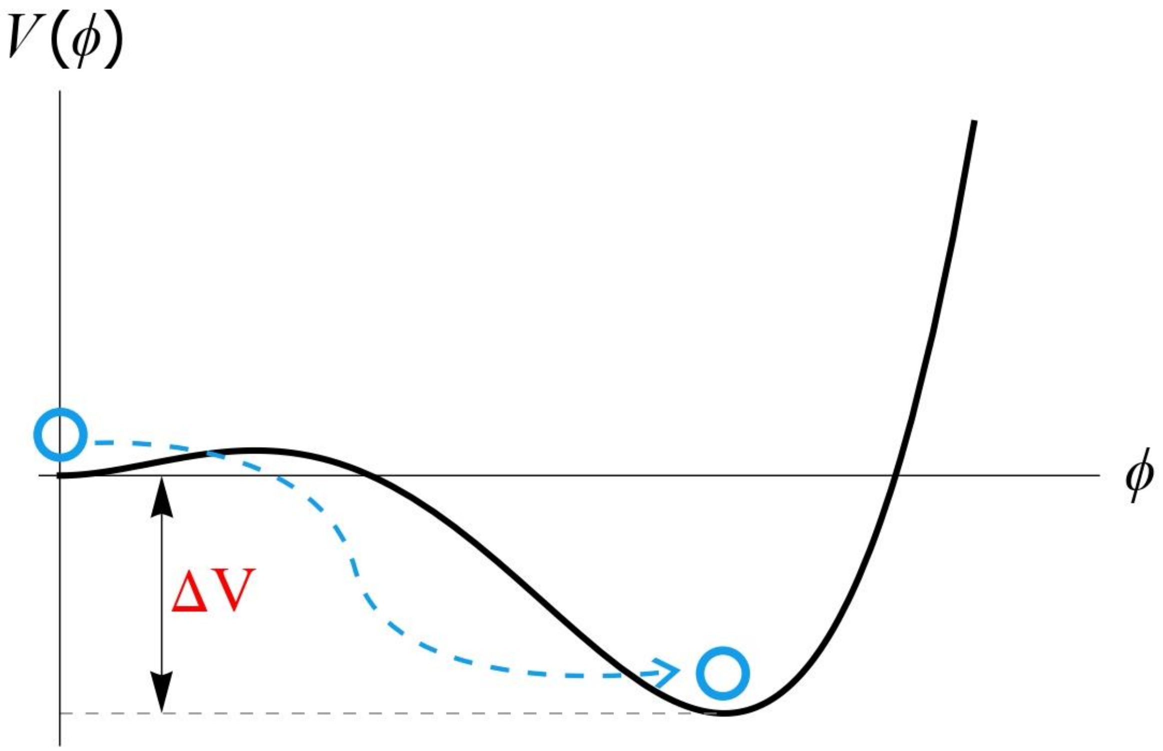
$$\Gamma(t) \approx H_I^4 e^{\beta t}$$

Transition strength

$$\alpha \approx \frac{\Delta V}{\rho_R} \gg 1$$

bubble wall velocity

$$v_w \approx 1$$



SUPERCOOLED PHASE TRANSITION

nucleation of true vacuum bubbles

$$\Gamma(t) \approx H_I^4 e^{\beta t}$$

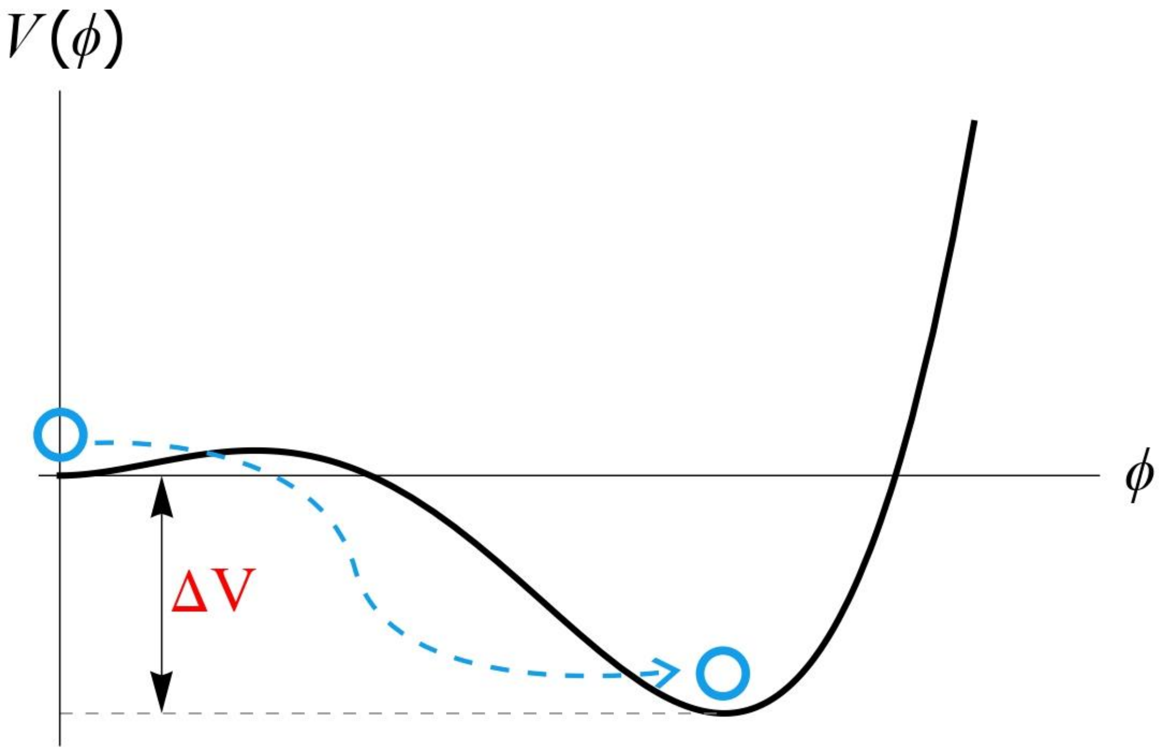
Transition strength

$$\alpha \approx \frac{\Delta V}{\rho_R} \gg 1$$

LATENT HEAT

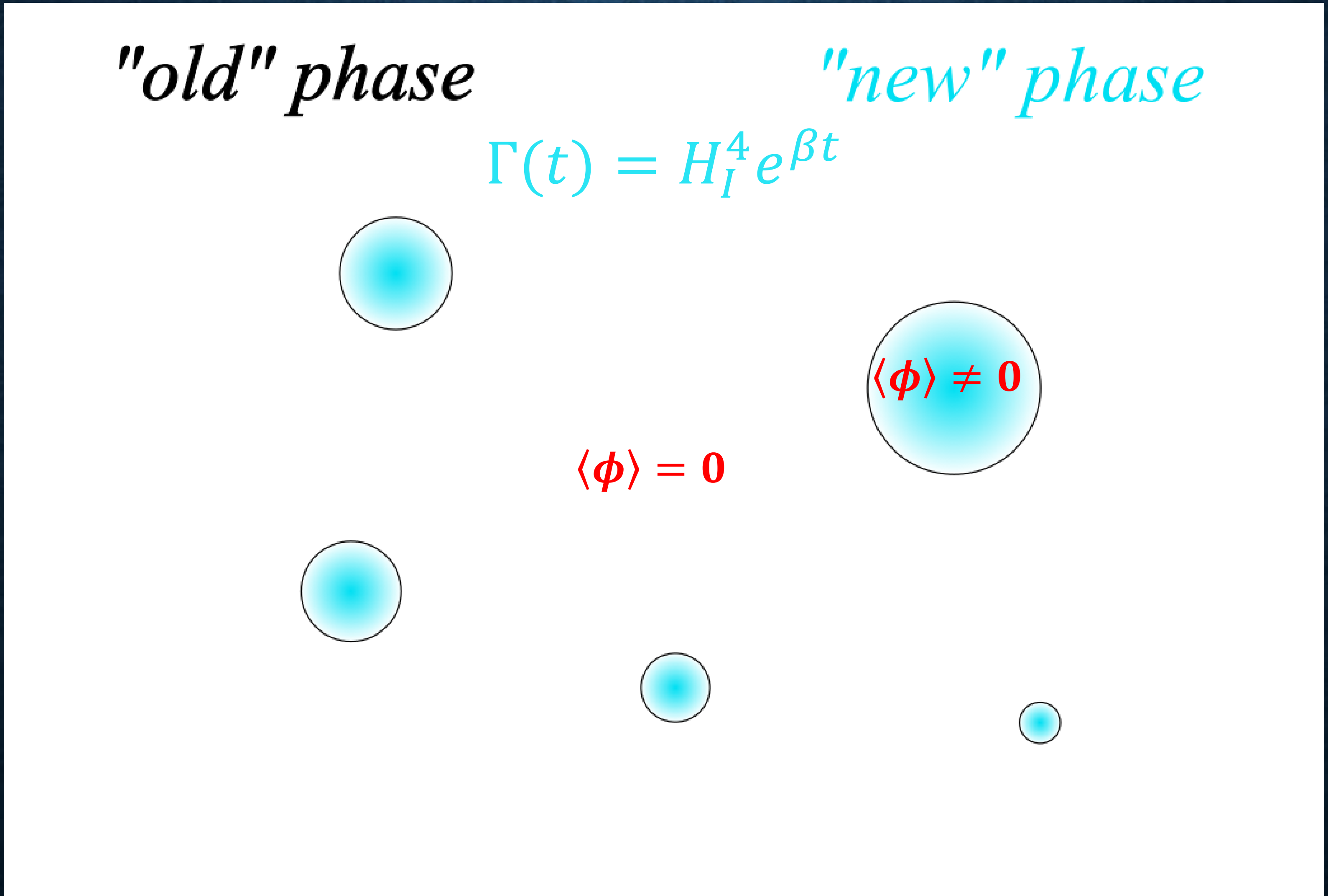
bu [illegible] velocity

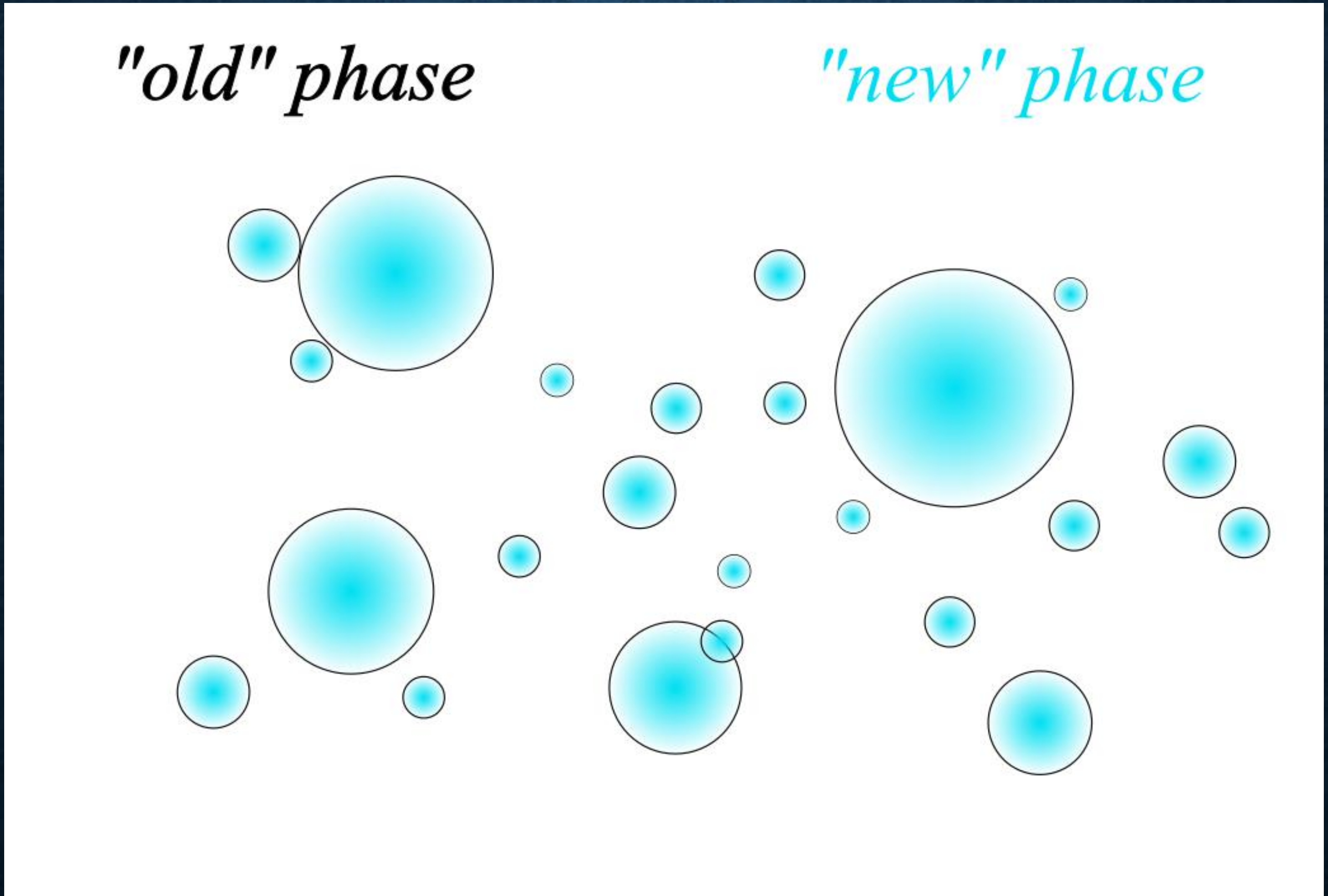
$$v_w \approx 1$$

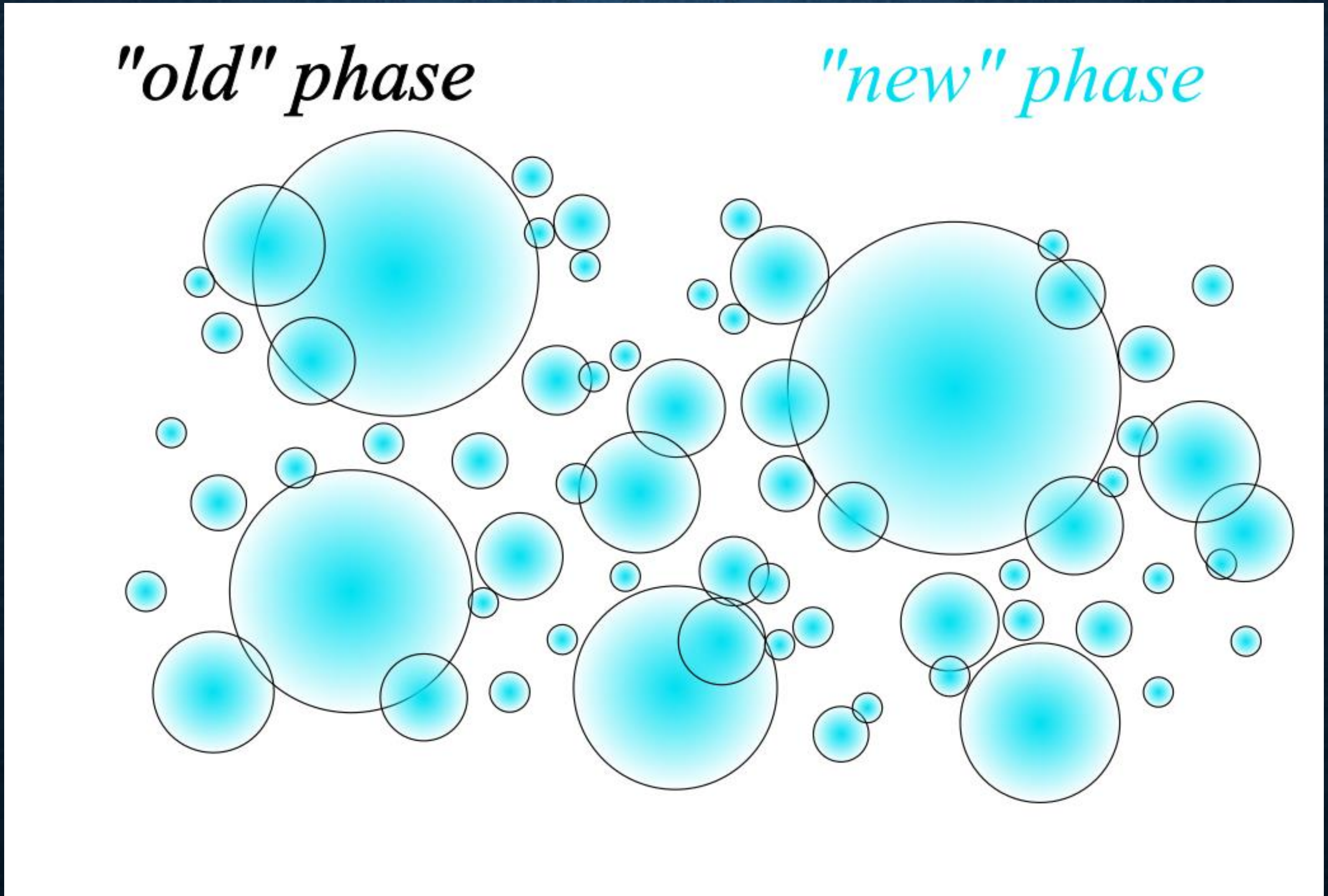


"old" phase

$$\langle \boldsymbol{\phi} \rangle = \mathbf{0}$$


"old" phase
"new" phase
$\Gamma(t) = H_I^4 e^{\beta t}$
$\langle \phi \rangle \neq 0$
$\langle \phi \rangle = 0$


"old" phase
"new" phase


"old" phase
"new" phase

PHASE TRANSITION DYNAMICS

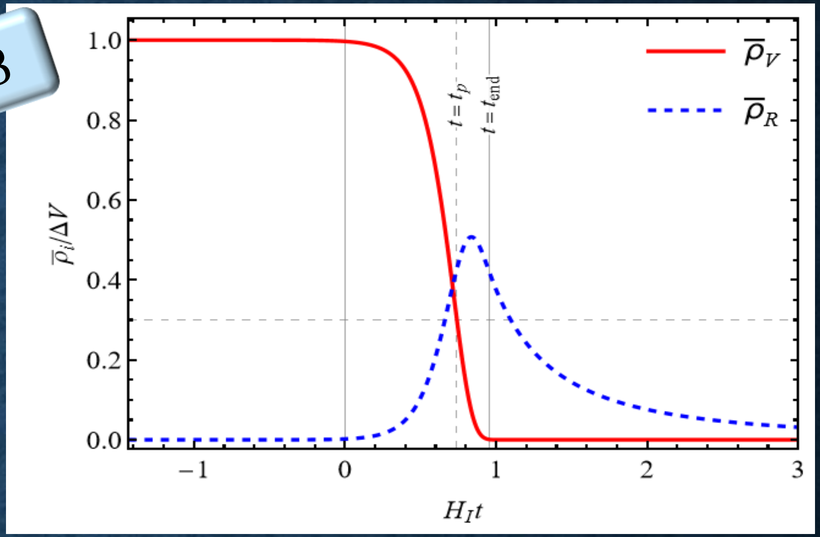
$\beta / H_I = 8$

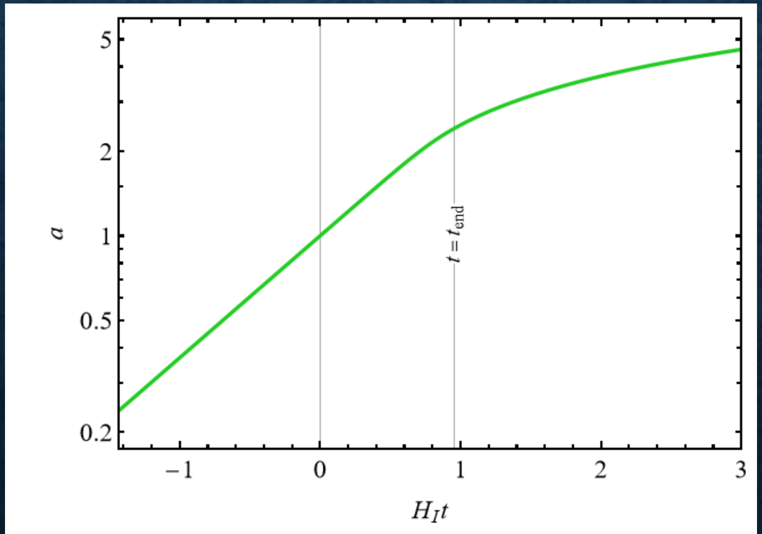
$$H^2 = \frac{1}{3M_P^2}(\overline{\rho_V} + \overline{\rho_R}),$$

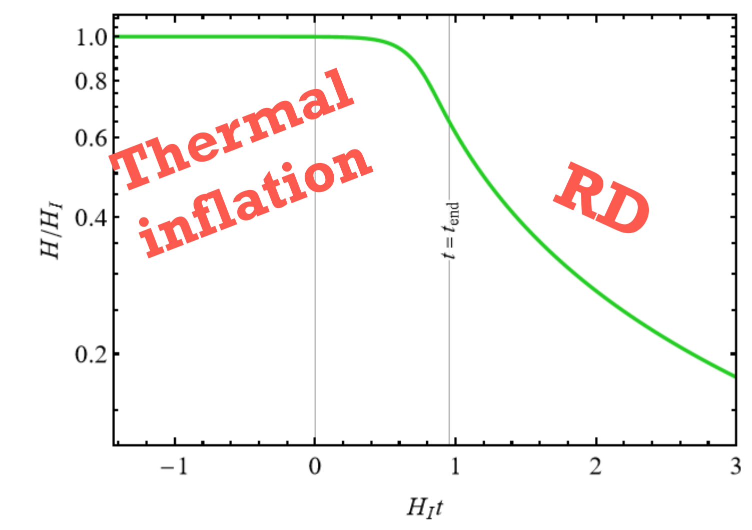
$$\frac{\mathrm{d}}{\mathrm{d}t}(\overline{\rho_R}) + 4H(\overline{\rho_R}) = -\frac{\mathrm{d}\overline{\rho_V}}{\mathrm{d}t}$$

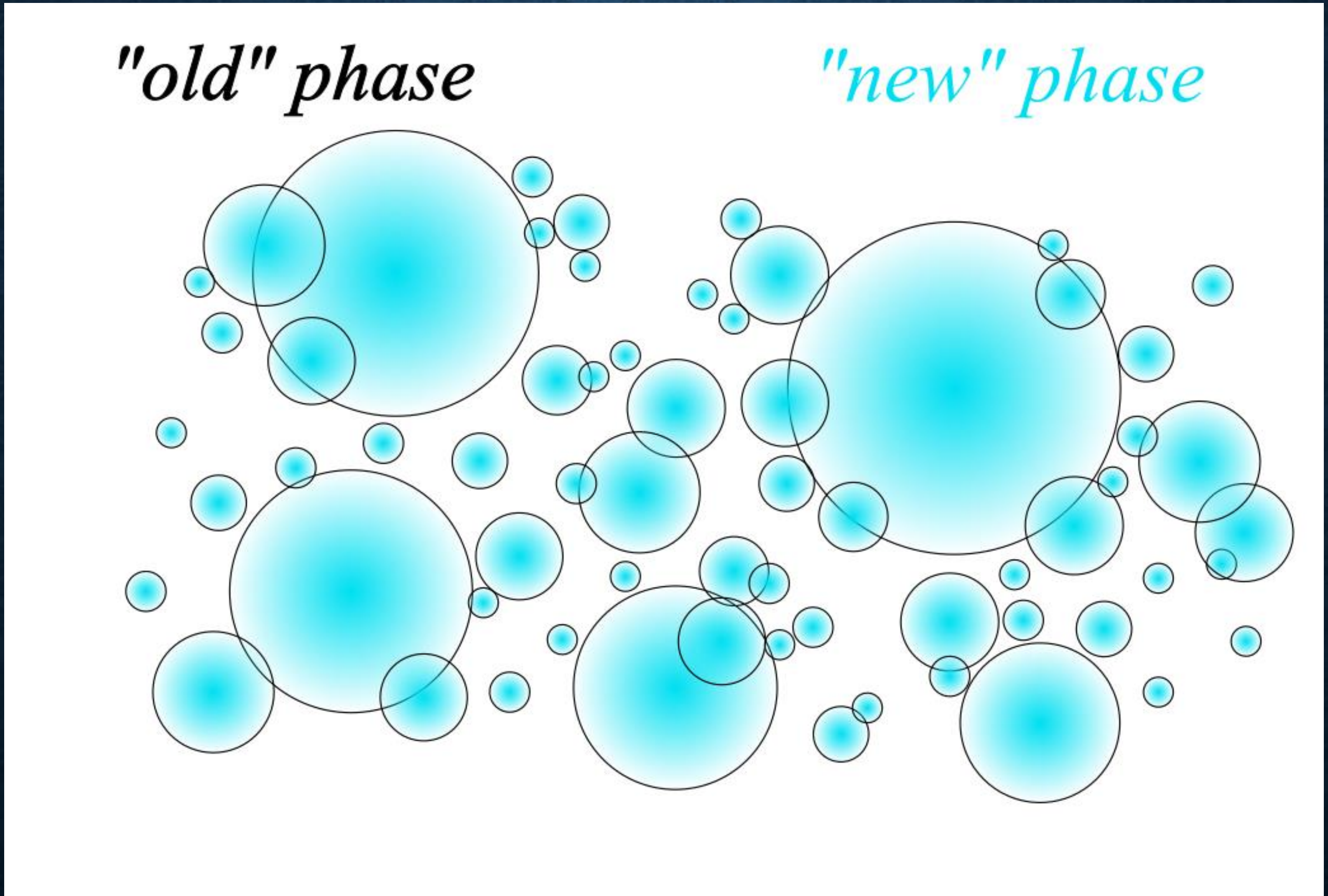
$$P(t) = \exp\left[-\frac{4}{3}\pi \int_{-\infty}^{t} \mathrm{d}t_n \Gamma(t_n) a(t_n)^3 R(t, t_n)^3\right],$$

$$\overline{\rho_V} = P(t)\,\Delta V$$








"old" phase
"new" phase

BLACK HOLE FORMATION

Statistical nature of bubble nucleation

↓

inhomogeneitites

Slow, supercooled transition

BLACK HOLE FORMATION

Statistical nature of bubble nucleation

$\downarrow$

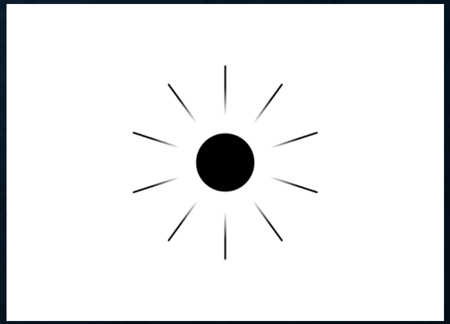
inhomogeneitites

Slow, supercooled transition

Large fluctuations of energy density

$$\delta = \frac{\langle\rho\rangle_V - \bar{\rho}}{\bar{\rho}} = \frac{\langle\delta\rho\rangle_V}{\bar{\rho}}$$

$$\delta > \delta_c$$



COSMIC EVOLUTION & PERTURBATIONS

$$G_{\mu\nu} = 8\pi \mathrm{G}\, T_{\mu\nu}$$

COARSE-GRAINING

$$\langle G_{\mu\nu} \rangle_V = 8\pi \mathrm{G} \langle T_{\mu\nu} \rangle_V$$

$$\langle f \rangle_V = \frac{1}{V_L} \int_{\mathcal{D}_L} \mathrm{d}^3 x \, f(\vec{x}) \xrightarrow[L \to \infty]{} \bar{f}$$

COSMIC EVOLUTION & PERTURBATIONS

$$\langle G_{\mu\nu} \rangle_V = 8\pi \mathrm{G} \langle T_{\mu\nu} \rangle_V$$

In the Newtonian gauge

$$\mathrm{d}s^2 = a^2\left[-(1 + 2\Phi)\mathrm{d}\eta^2 + (1 - 2\Psi)\mathrm{d}x_i\mathrm{d}x^i\right]$$

COSMIC EVOLUTION & PERTURBATIONS

$$\langle G_{\mu\nu} \rangle_V = 8\pi G \langle T_{\mu\nu} \rangle_V$$

In the Newtonian gauge

$$\mathrm{d}s^2 = a^2\left[-(1+2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)\mathrm{d}x_i\mathrm{d}x^i\right]$$

$$T^{\mu}{}_{\nu} = \begin{pmatrix} -\bar{\rho} - \delta\rho & (\bar{\rho}+\bar{p})v_j \\ (\bar{\rho}+\bar{p})v^i & (\bar{p}+\delta p)\delta^i{}_j + \Pi^i{}_j \end{pmatrix}$$

COSMIC EVOLUTION & PERTURBATIONS

$$\langle G_{\mu\nu} \rangle_V = 8\pi G \langle T_{\mu\nu} \rangle_V$$

In the Newtonian gauge

$$\mathrm{d}s^2 = a^2\left[-(1+2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)\mathrm{d}x_i \mathrm{d}x^i\right]$$

$$T^{\mu}{}_{\nu} = \begin{pmatrix} -\bar{\rho} - \delta\rho & (\bar{\rho}+\bar{p})v_j \\ (\bar{\rho}+\bar{p})v^i & (\bar{p}+\delta p)\delta^i{}_j + \Pi^i{}_j \end{pmatrix}$$

Obtained from the system of bubbles

COSMIC EVOLUTION & PERTURBATIONS

Gauge dependence

Perturbations change under the change of coordinate frame

$$\mathrm{d}s^2 = a^2\left[-(1+2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)\mathrm{d}x_i\mathrm{d}x^i\right]$$

$$T^{\mu}{}_{\nu} = \begin{pmatrix} -\bar{\rho} - \delta\rho & (\bar{\rho}+\bar{p})v_j \\ (\bar{\rho}+\bar{p})v^i & (\bar{p}+\delta p)\delta^i{}_j + \Pi^i{}_j \end{pmatrix}$$

COSMIC EVOLUTION & PERTURBATIONS

Gauge dependence

Perturbations change under the change of coordinate frame

$$\mathrm{d}s^2 = a^2\left[-(1+2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)\mathrm{d}x_i\mathrm{d}x^i\right]$$

$$T^{\mu}{}_{\nu} = \begin{pmatrix} -\bar{\rho} - \delta\rho & (\bar{\rho}+\bar{p})v_j \\ (\bar{\rho}+\bar{p})v^i & (\bar{p}+\delta p)\delta^i{}_j + \Pi^i{}_j \end{pmatrix}$$

Physical variables must be gauge-invariant

COSMIC EVOLUTION & PERTURBATIONS

$$\langle G_{\mu\nu}\rangle_V = 8\pi \mathrm{G}\langle T_{\mu\nu}\rangle_V$$

In the Newtonian gauge

$$\mathrm{d}s^2 = a^2\left[-(1+2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)\mathrm{d}x_i\mathrm{d}x^i\right]$$

$$T^{\mu}{}_{\nu} = \begin{pmatrix} -\bar{\rho} - \delta\rho & (\bar{\rho}+\bar{p})v_j \\ (\bar{\rho}+\bar{p})v^i & (\bar{p}+\delta p)\delta^i{}_j + \Pi^i{}_j \end{pmatrix}$$

Physical variables must be gauge-invariant

BLACK HOLE FORMATION

$$\delta^{(C)} = \frac{\delta\rho_{com}}{\bar{\rho}}$$

$$\delta\rho_{com} \equiv \delta\rho^{(X)} - 3H(\bar{\rho} + \bar{p})a(v^{(X)} + B^{(X)})$$

comoving energy
density perturbation

BLACK HOLE FORMATION

$$\partial_t \langle \delta\rho_{com} \rangle_V + 3H \langle \delta\rho_{com} \rangle_V = -(\bar{\rho} + \bar{p}) \frac{3}{aL} \langle \partial_r v \rangle_S + 2H \frac{3}{L} \langle \partial_r \Pi \rangle_S$$

$$\delta^{(C)} = \frac{\langle \delta\rho_{com} \rangle_V}{\bar{\rho}}$$

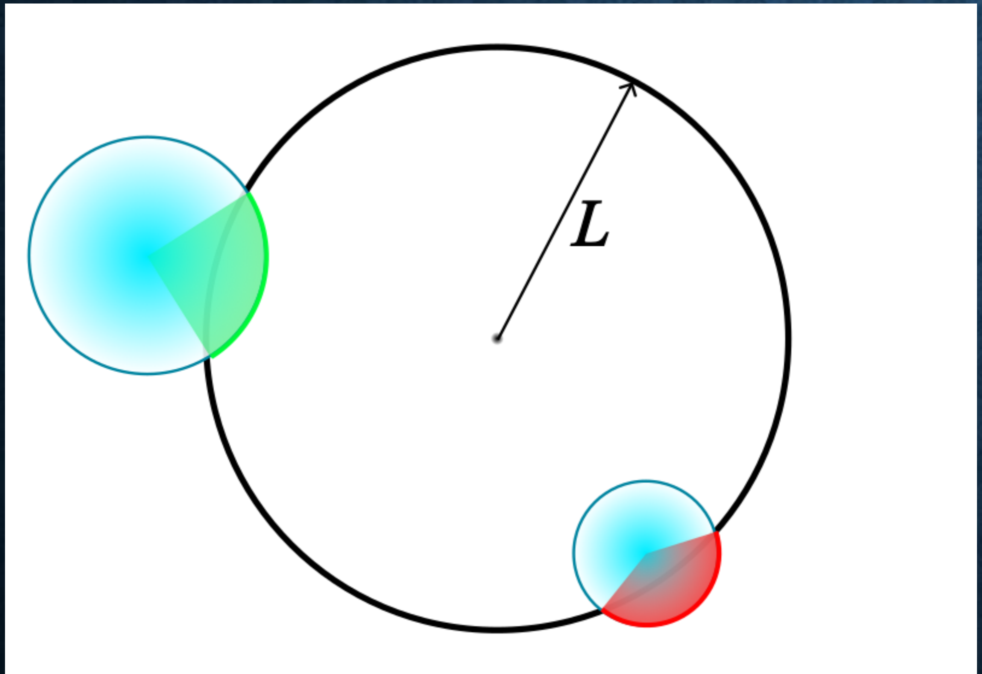
BLACK HOLE FORMATION

$$\partial_t \langle \delta\rho_{com} \rangle_V + 3H \langle \delta\rho_{com} \rangle_V = -(\bar{\rho} + \bar{p}) \frac{3}{aL} \langle \partial_r v \rangle_S + 2H \frac{3}{L} \langle \partial_r \Pi \rangle_S$$

Energy flow (boundary term $\mathcal{B}$)

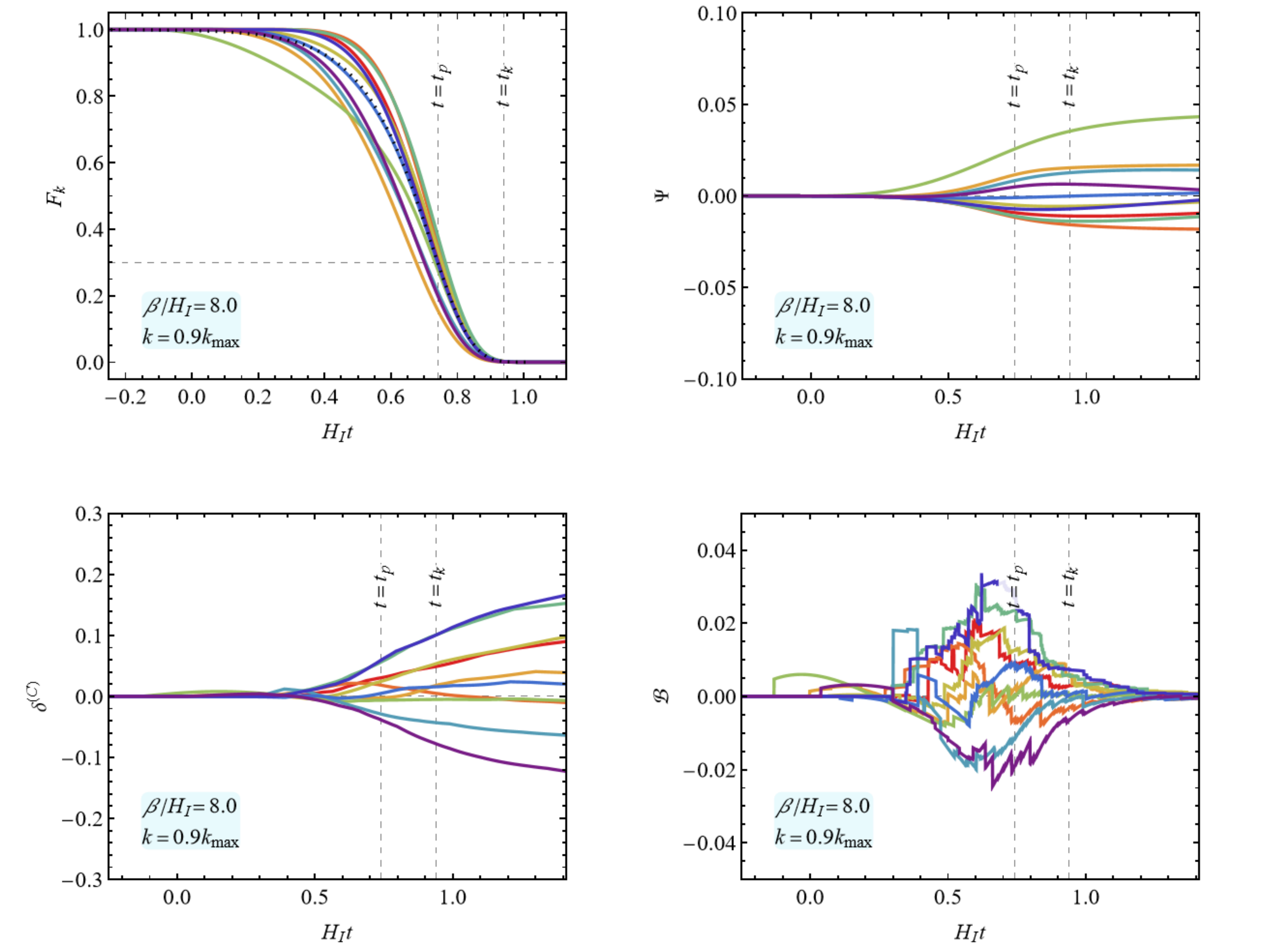
BLACK HOLE FORMATION

$$\partial_t \langle \delta\rho_{com} \rangle_V + 3H \langle \delta\rho_{com} \rangle_V = -(\bar{\rho} + \bar{p}) \frac{3}{aL} \langle \partial_r v \rangle_S + 2H \frac{3}{L} \langle \partial_r \Pi \rangle_S$$

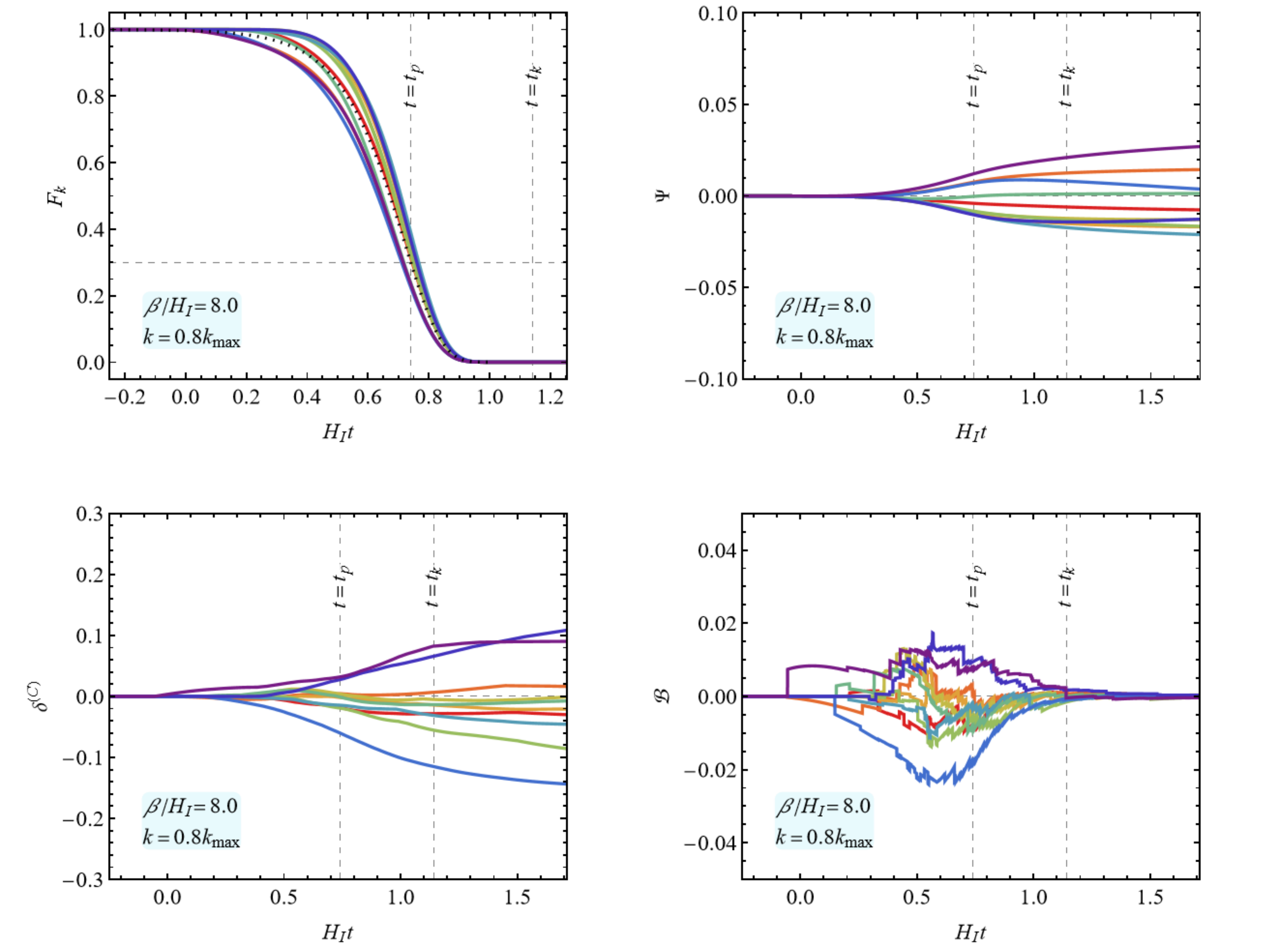


Energy flow (boundary term $\mathcal{B}$)

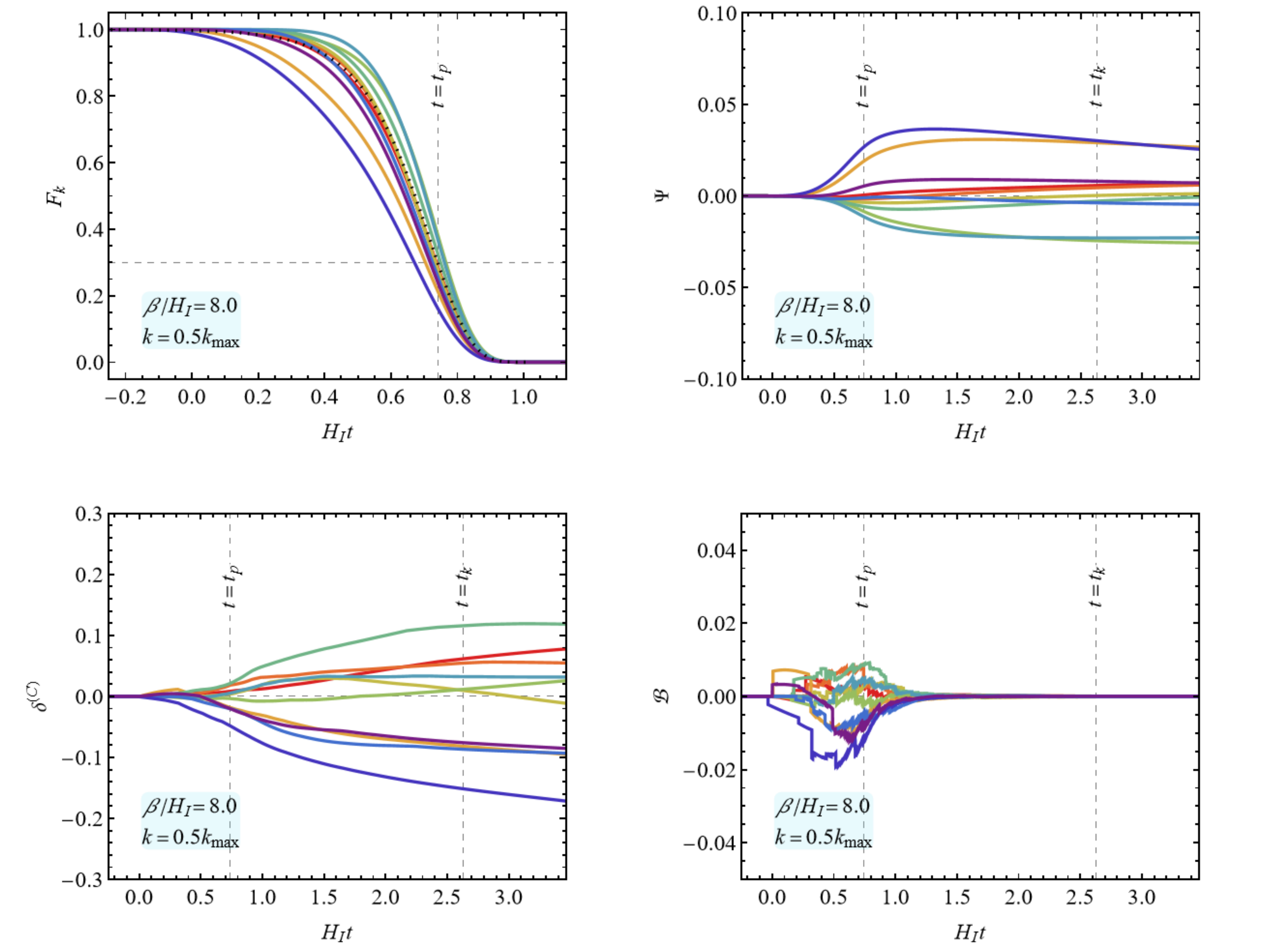
PRELIMINARY RESULTS



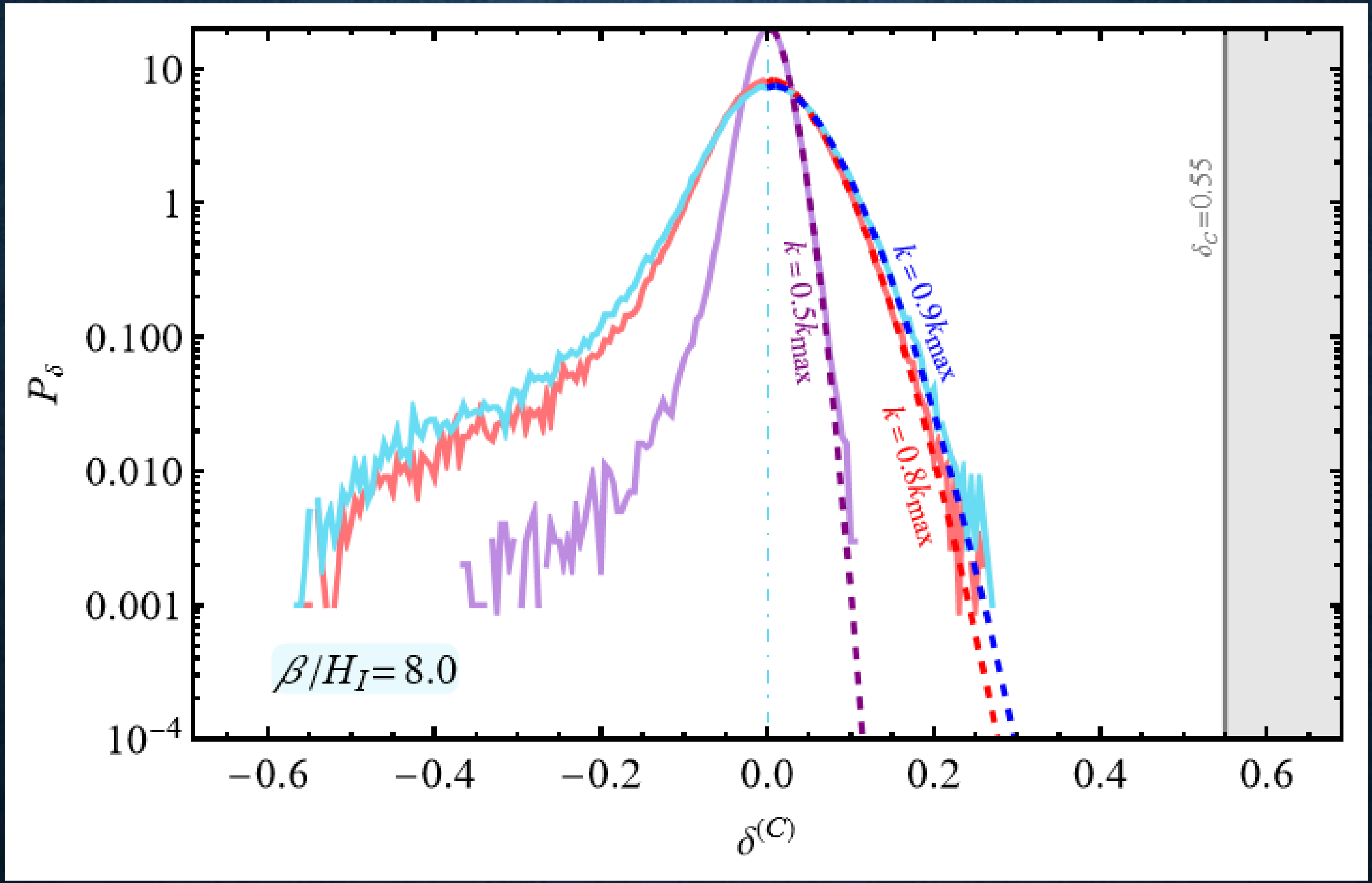
PRELIMINARY RESULTS



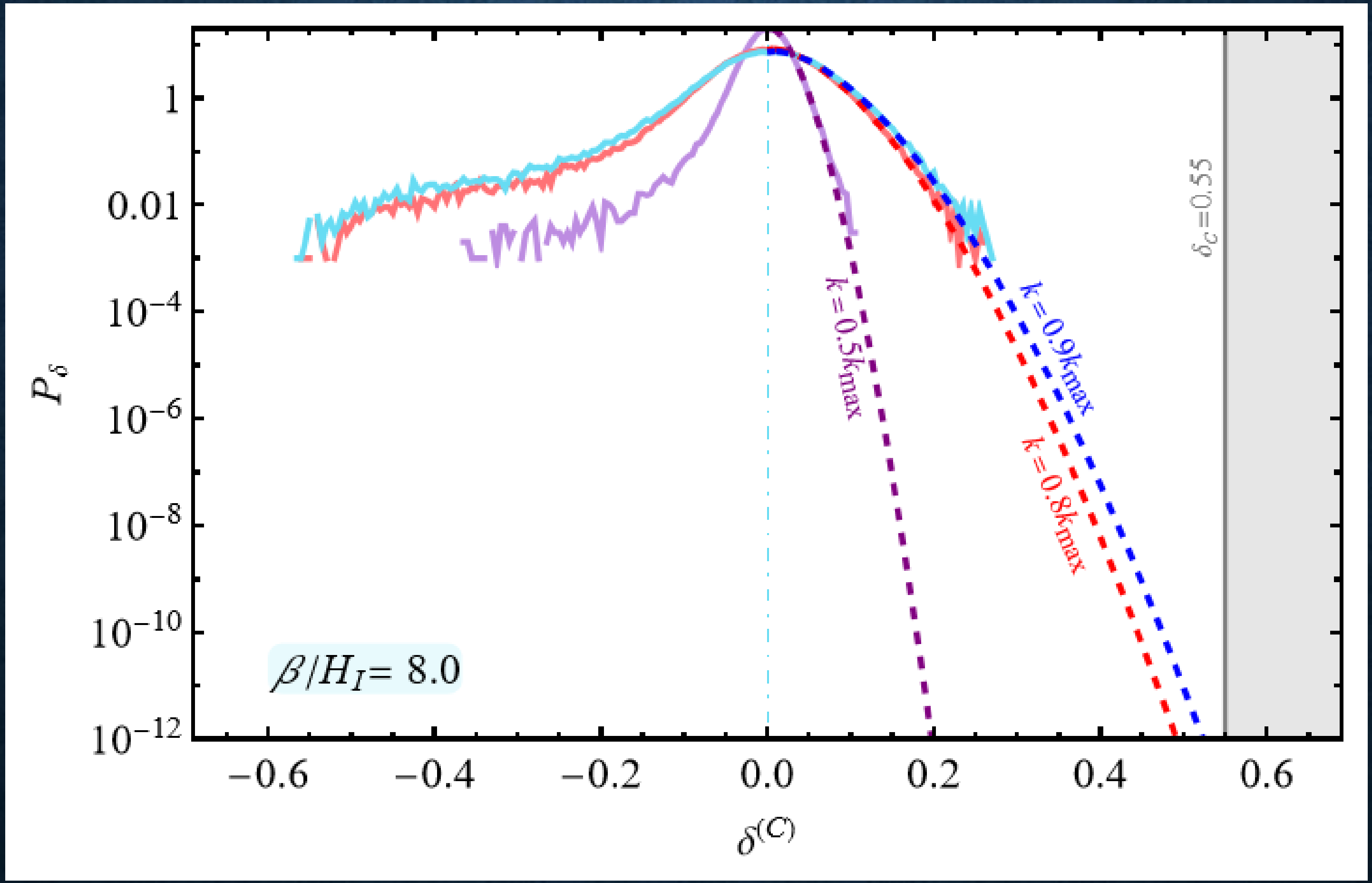
PRELIMINARY RESULTS



PRELIMINARY RESULTS



PRELIMINARY RESULTS



PBH MASSES

Critical scaling law

$$M(\delta) = \kappa M_k(\delta - \delta_c)^{\gamma}$$

$$\kappa = 4.2, \gamma = 0.38, \delta_c = 0.55$$

$$M_k = \frac{M_I H_I}{H(t_k)}$$

PBH MASSES

Critical scaling law

$$M(\delta) = \kappa M_k (\delta - \delta_c)^\gamma$$

$$\kappa = 4.2, \gamma = 0.38, \delta_c = 0.55$$

$$M_k = \frac{M_I H_I}{H(t_k)}$$

$$M_I \approx 0.05 M_\odot \left[\frac{100}{g_*}\right]^{1/2} \left[\frac{T_{\mathrm{reh}}}{\mathrm{GeV}}\right]^{-2}$$

PBH MASSES

Critical scaling law

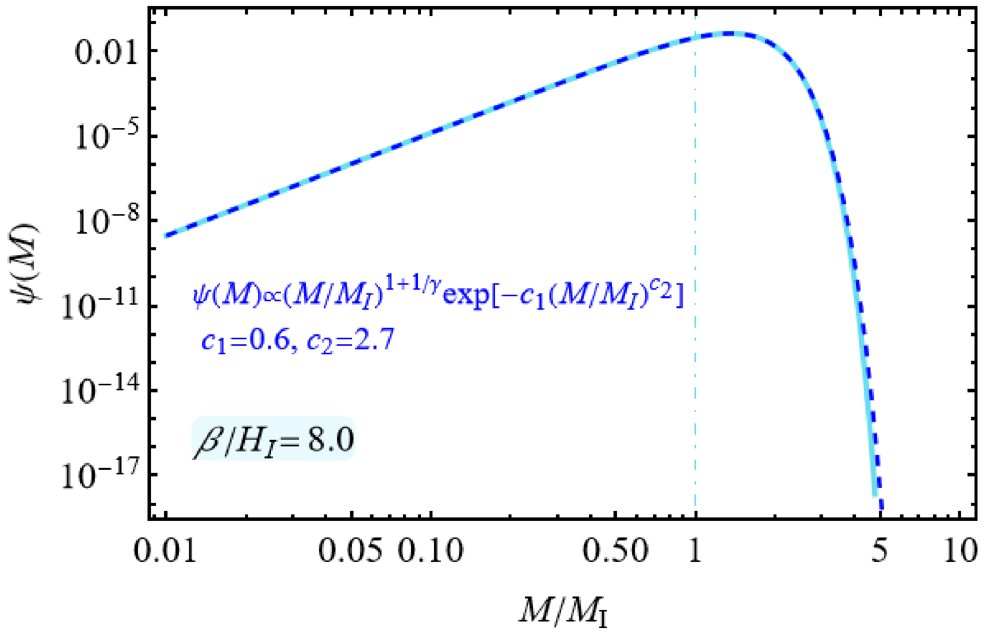
$$M(\delta) = \kappa M_k(\delta - \delta_c)^\gamma$$

$$\kappa = 4.2, \gamma = 0.38, \delta_c = 0.55$$

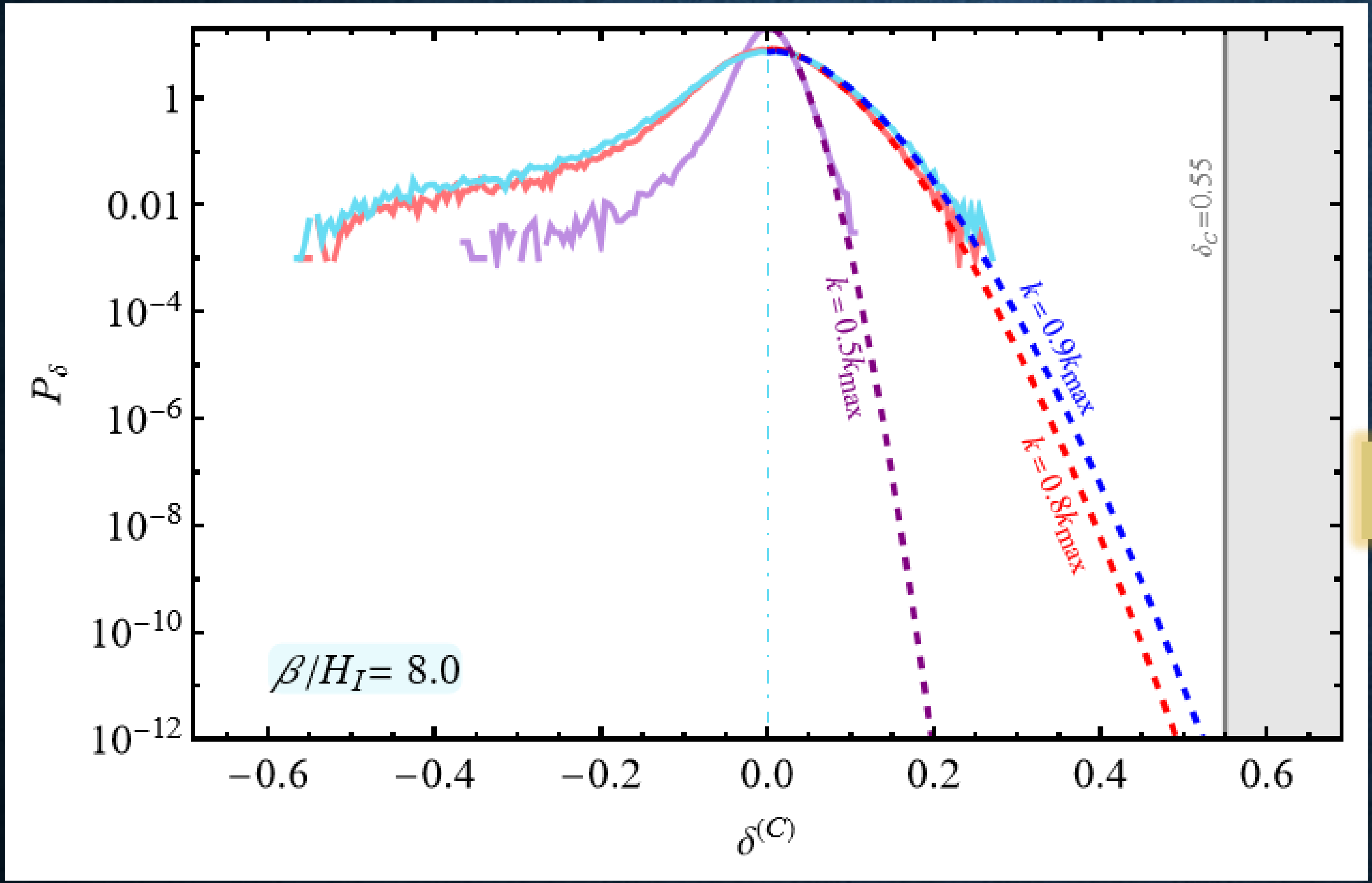
$$M_k = \frac{M_I H_I}{H(t_k)}$$

$$M_I \approx 0.05 M_\odot \left[\frac{100}{g_*}\right]^{1/2} \left[\frac{T_{\rm reh}}{\rm GeV}\right]^{-2}$$

$$\psi(M) = \frac{\mathrm{d}\,\Omega_{\rm PBH}}{\mathrm{d}\ln M}$$

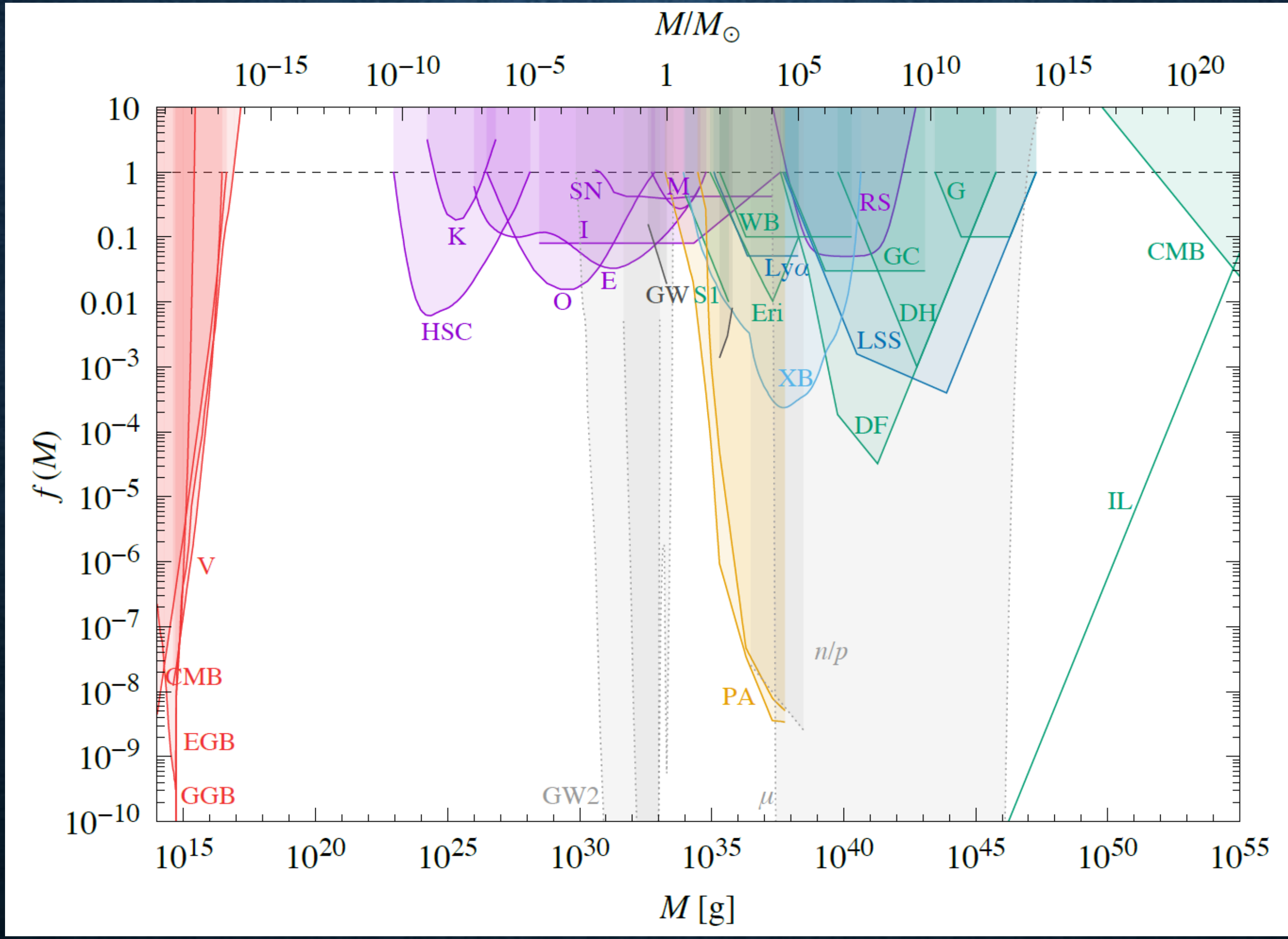


PRELIMINARY RESULTS



$f_{\mathrm{PBH}} \approx 0.3$
for
$T_{\mathrm{reh}} = 10^6\mathrm{GeV}$

Thank you!



B. Carr, K. Kohri, Y. Sendouda, J. Yokoyama, *Rept. Prog. Phys.* **84** (2021) 11, 116902