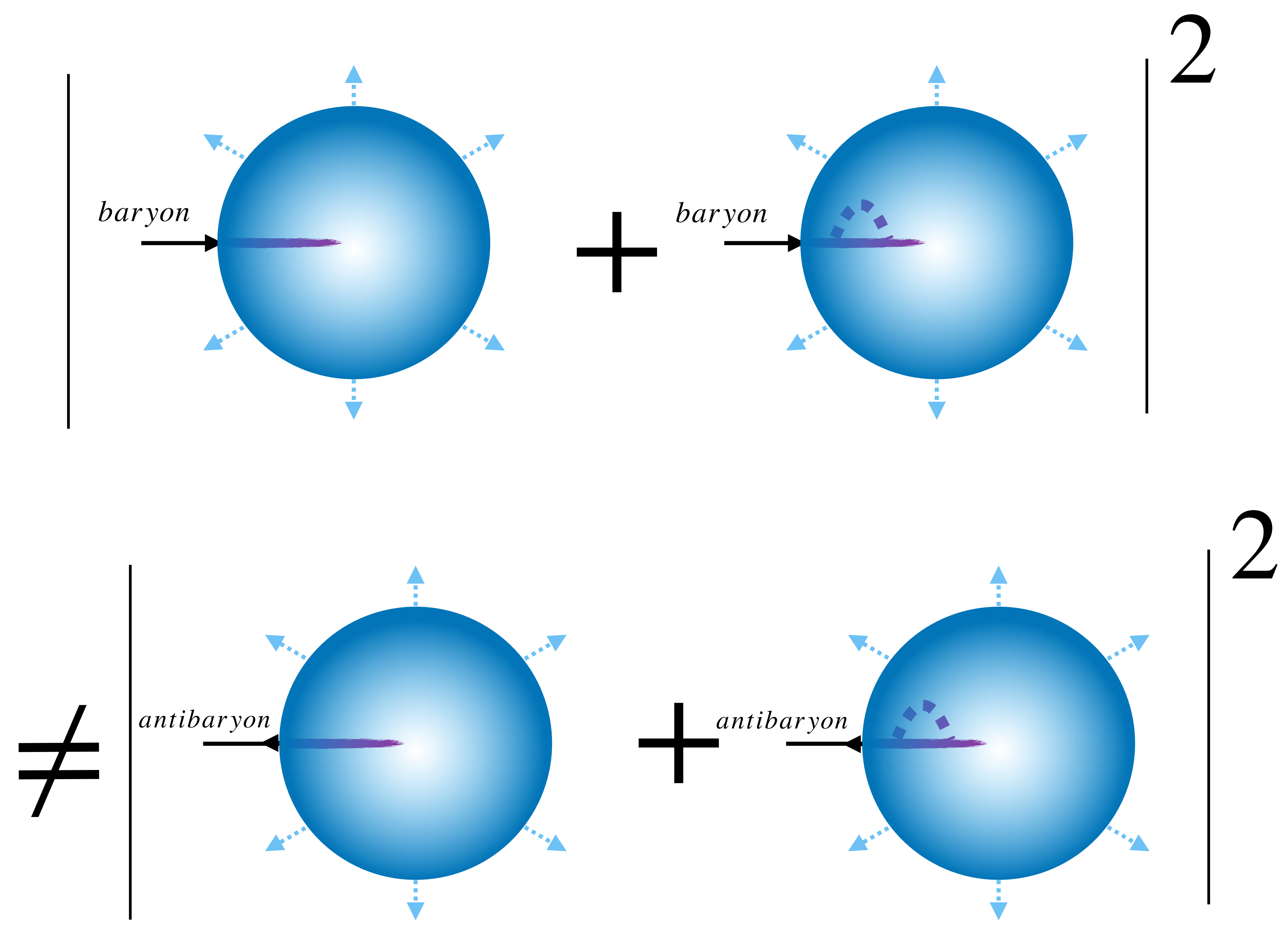
Cosmology of ultra-relativistic bubble wall expansion



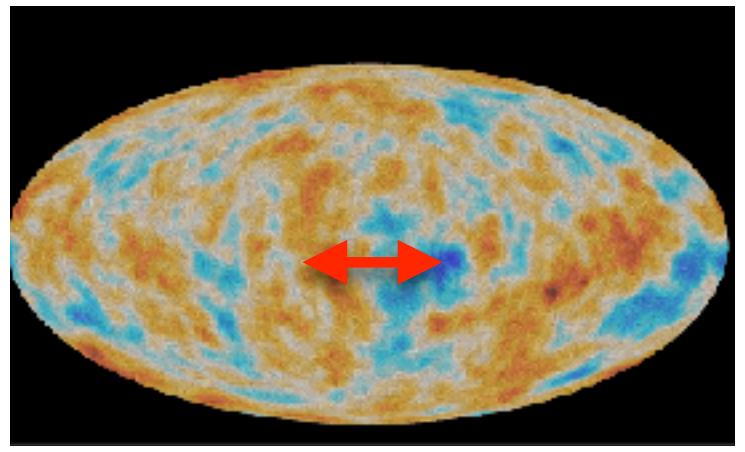
@Kagoshima Workshop on Particles, Fields, and Strings 2023, 2023/2/21

殷　文 (Tohoku Univ.)

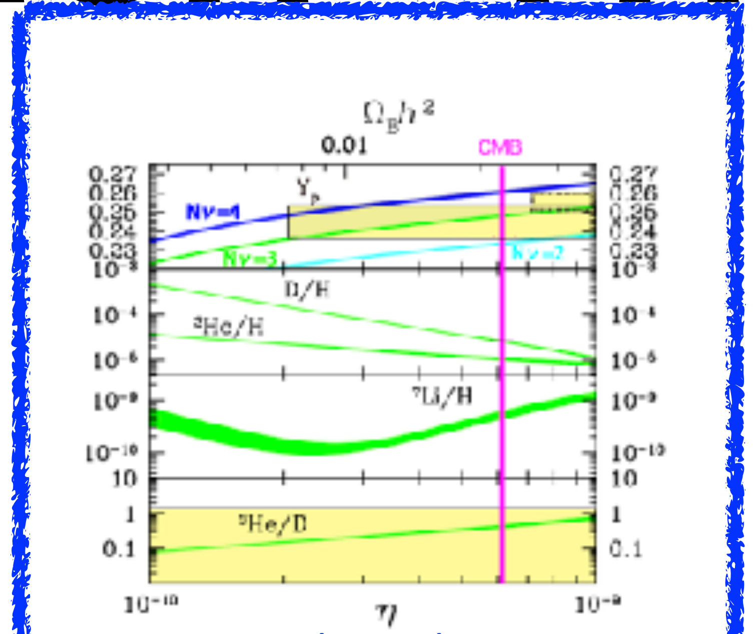
Based on 2101.05721, 2106.14913, 2207.02230 with A. Azatov, M. Vanvlasselaer, G. Barni, S. Chakraborty; 2206.06376 , with J. Jaeckel;

Contents

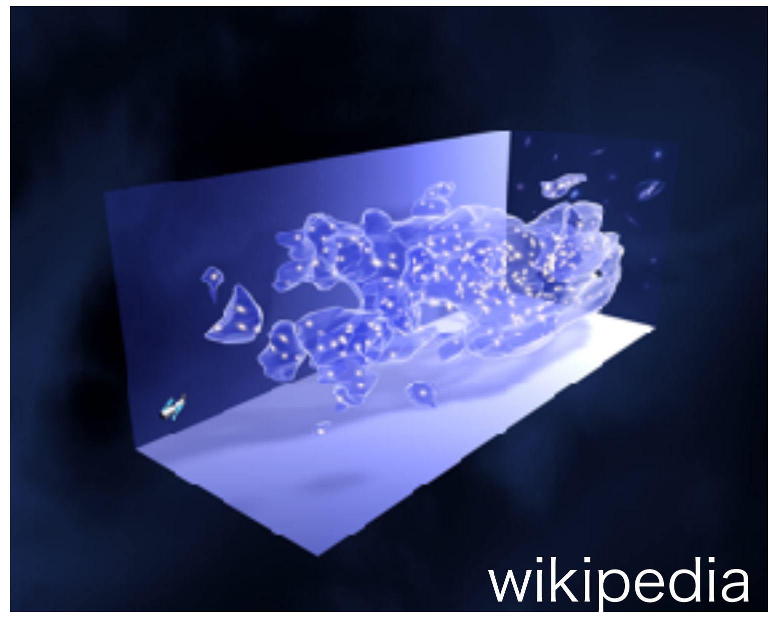
1: Introduction -Thermal History and BSM



https://www.esa.int/



Kawasaki et al, 1709.01211



Beyond SM phenomena:
Inflation,
baryon asymmetry,

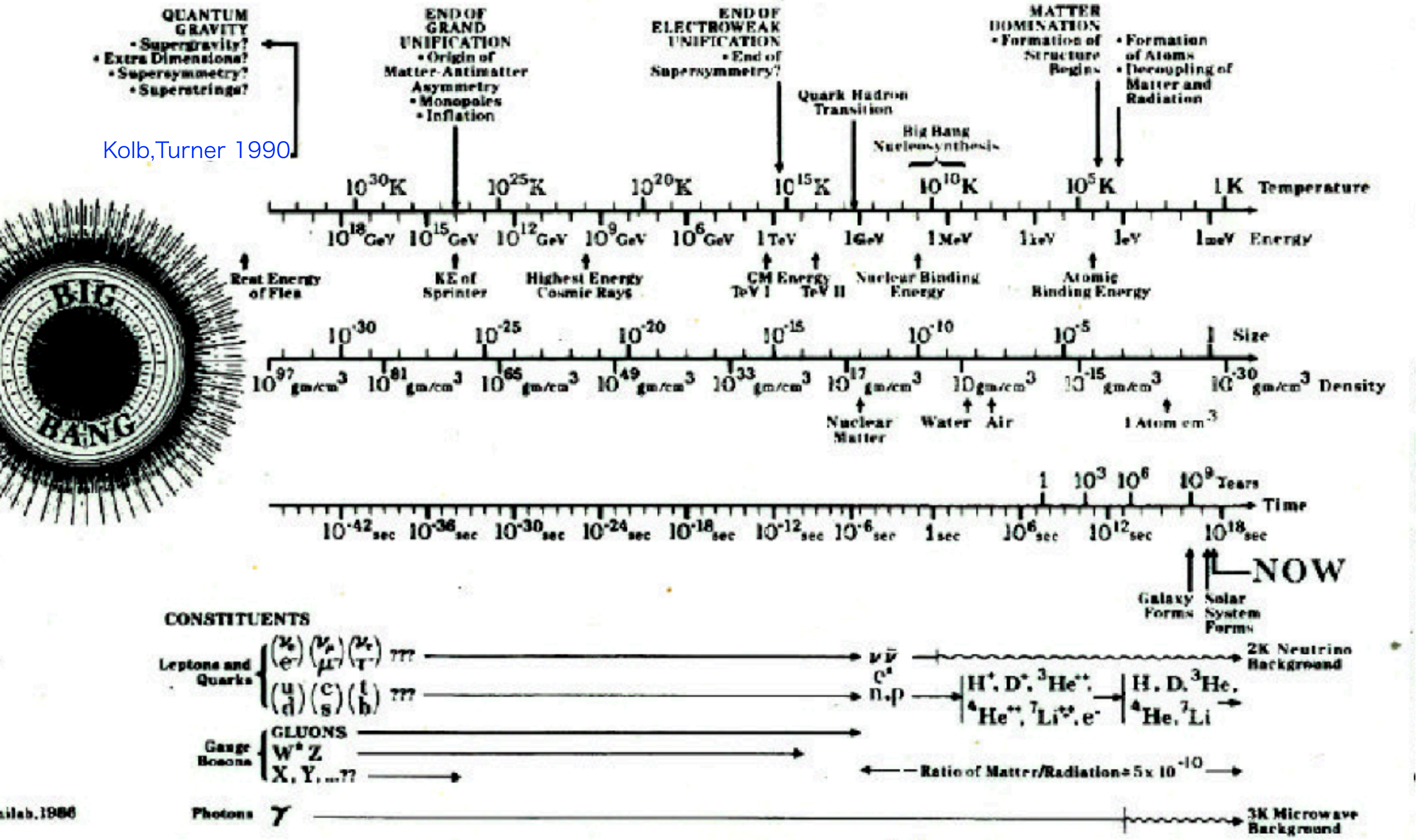
$$\frac{\Delta n_{\mathrm{Baryon}}}{s} \sim 10^{-10}$$

dark matter

現代宇宙論の示唆：
後ろの二つは初期条件じゃないだろう。

c.f. Realignment mechanism

Kolb,Turner 1990



1. バリオジェネシスの３条件

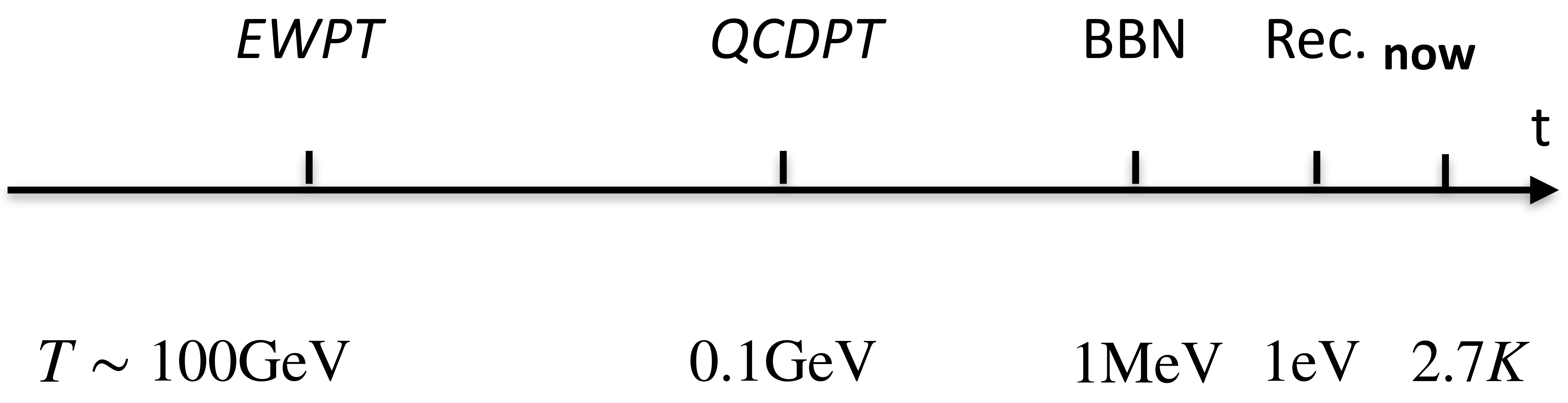
Sakharov, 1967

Baryon number violation
C and CP violation
Out of thermal equilibrium

バリオジェネシスの理想？

Kuzmin, et al, 1985; Shaposnikov, 1986; Huet, Sather, 9404302; Gavela et al, 9406289;

$\Gamma_{BV}^{sph} \sim \alpha_w^4 T$



Baryon number violation スファレロン

C and CP violation CKM phase in SM

Out of thermal equilibrium EWPT

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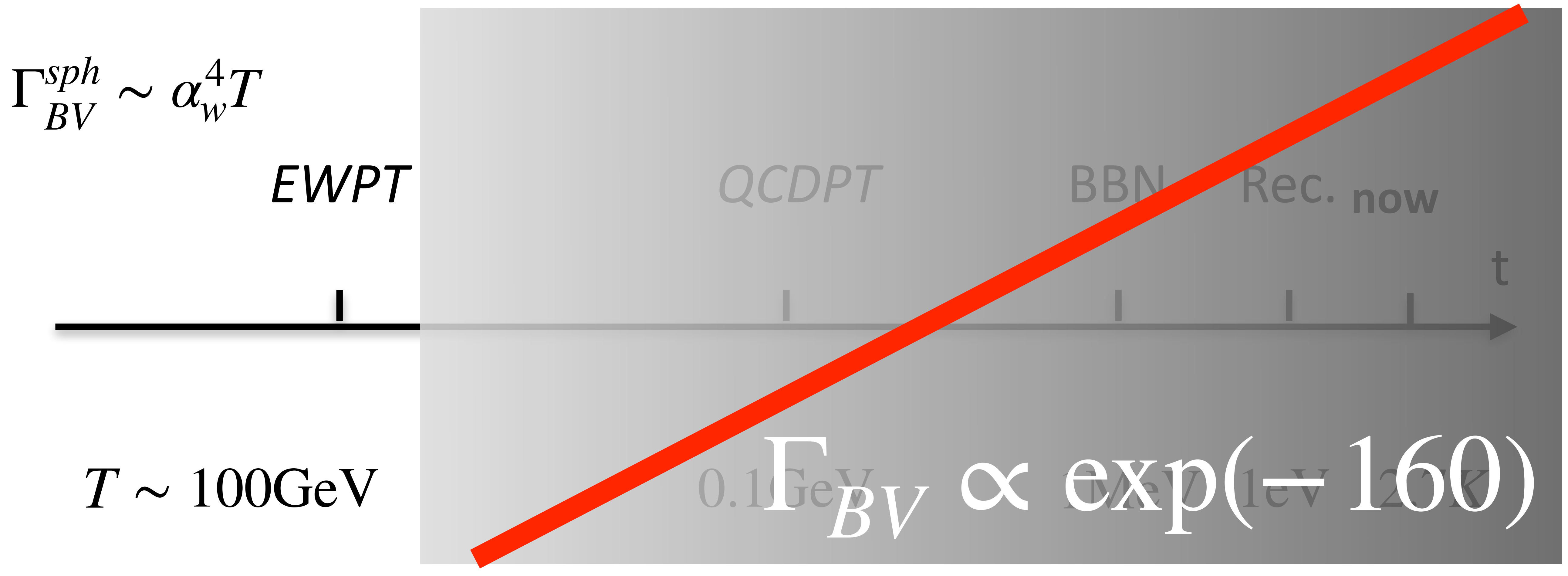

*Baryon number violation — スファレロン

*C and CP violation — CKM phase in SM

*Out of thermal equilibrium — EWPT

バリオジェネシスの理想？

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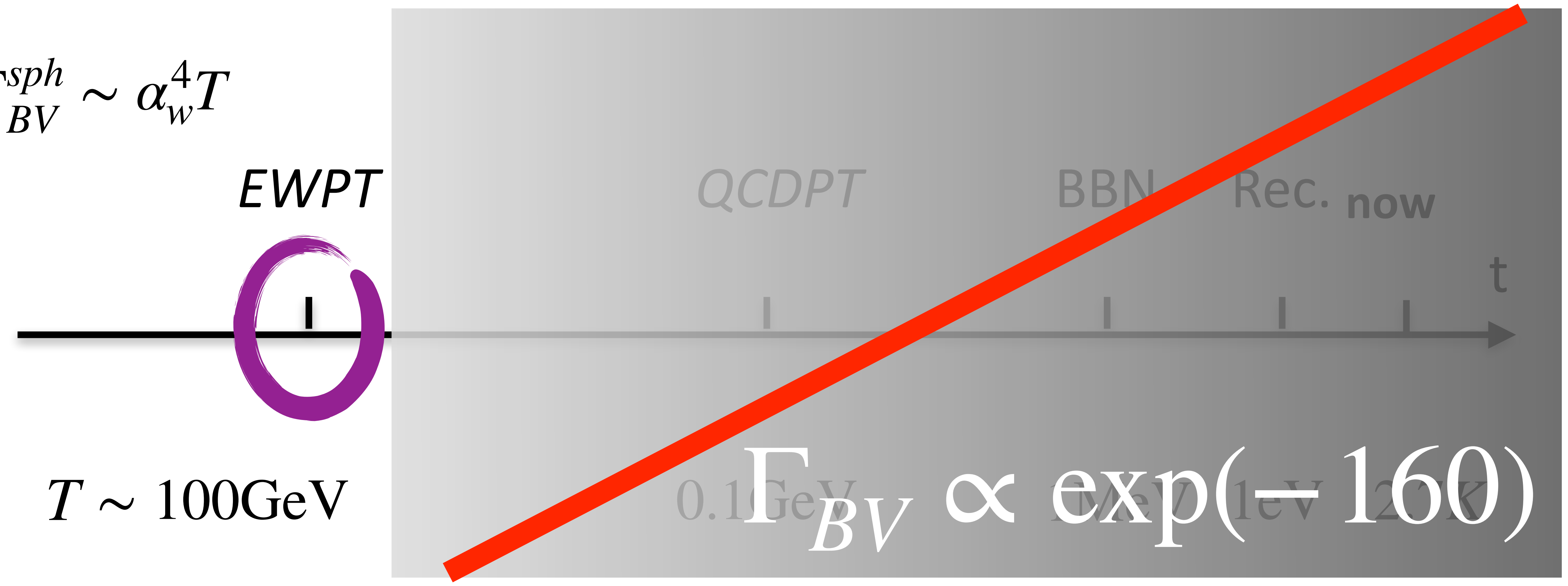
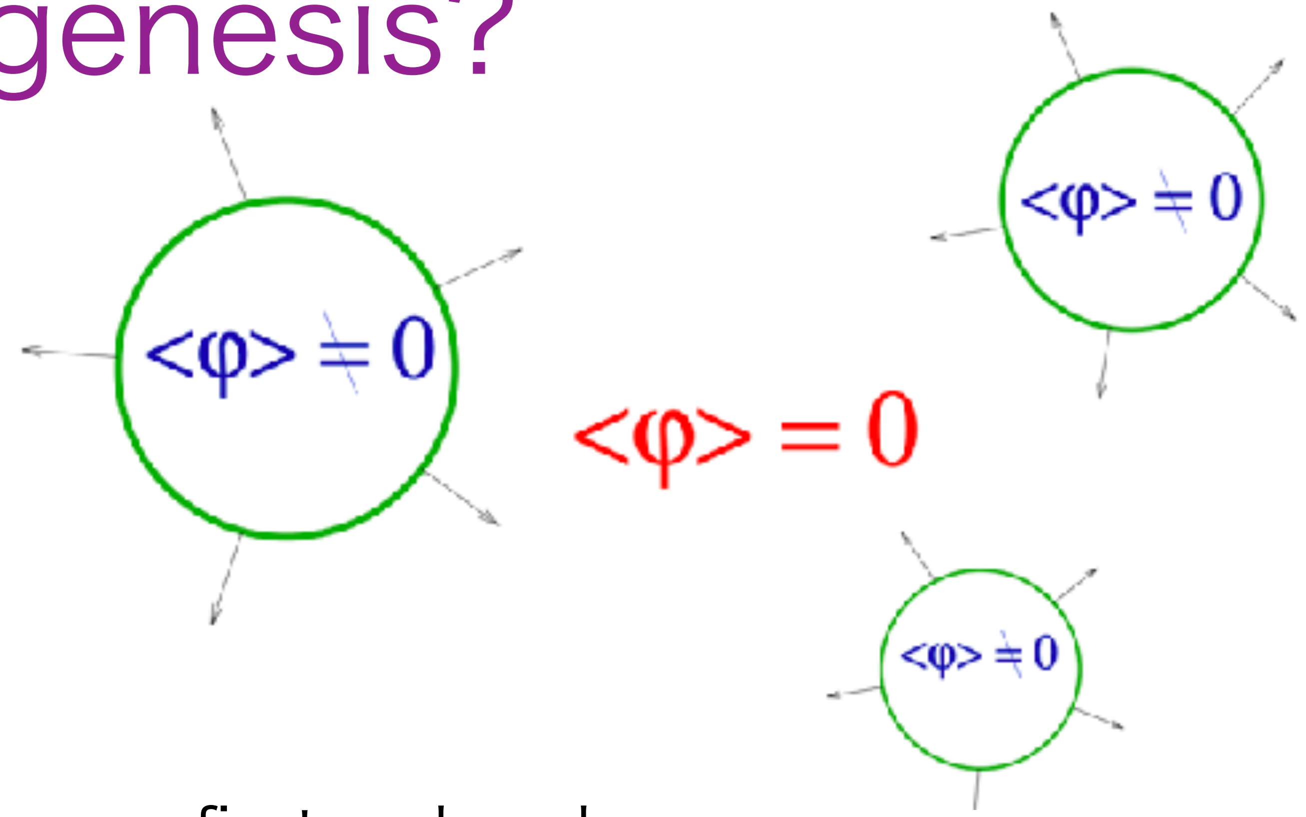


*Baryon number violation スファレロン

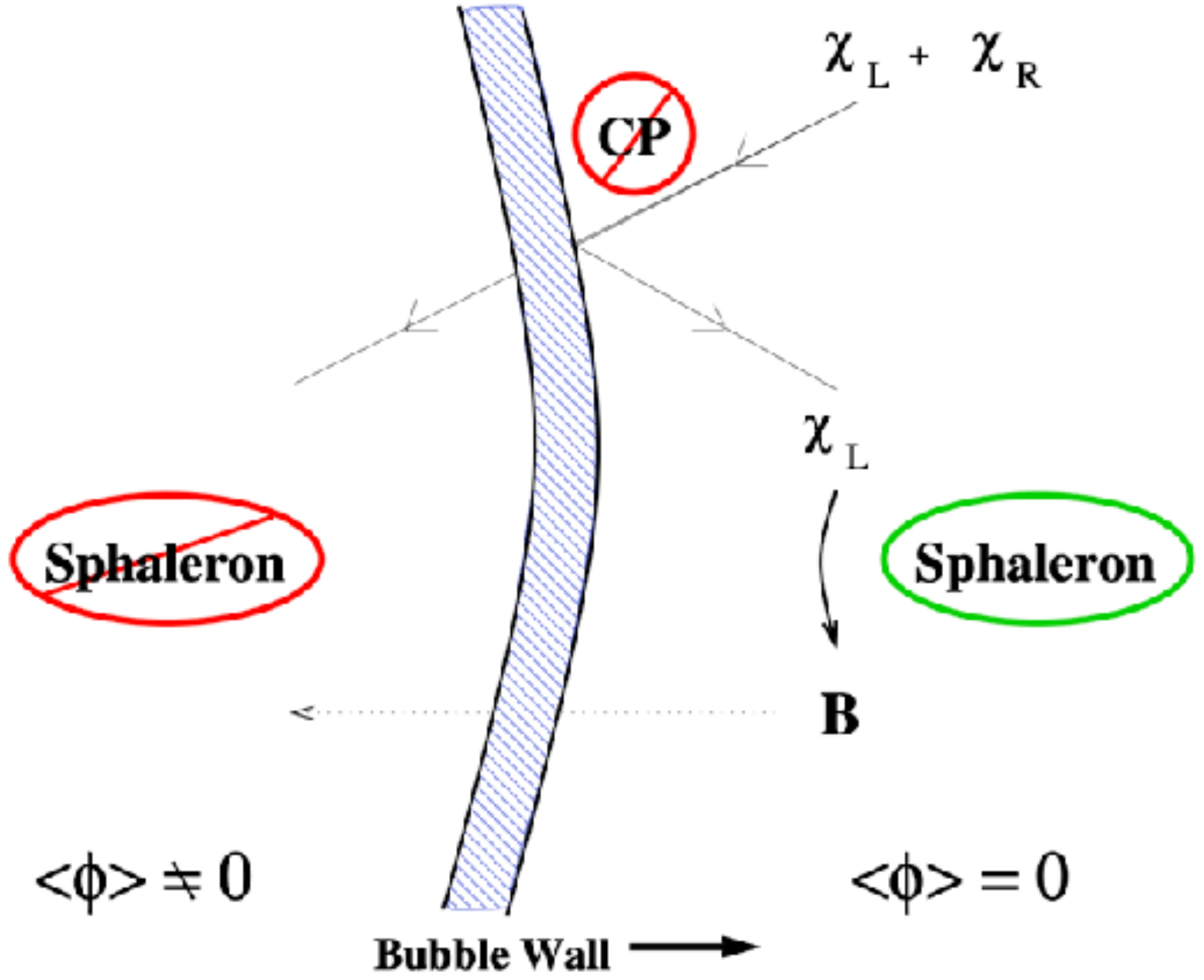
*C and CP violation CKM phase in SM

*Out of thermal equilibrium EWPT

Minimal electroweak baryogenesis?



If EWPT were first order phase

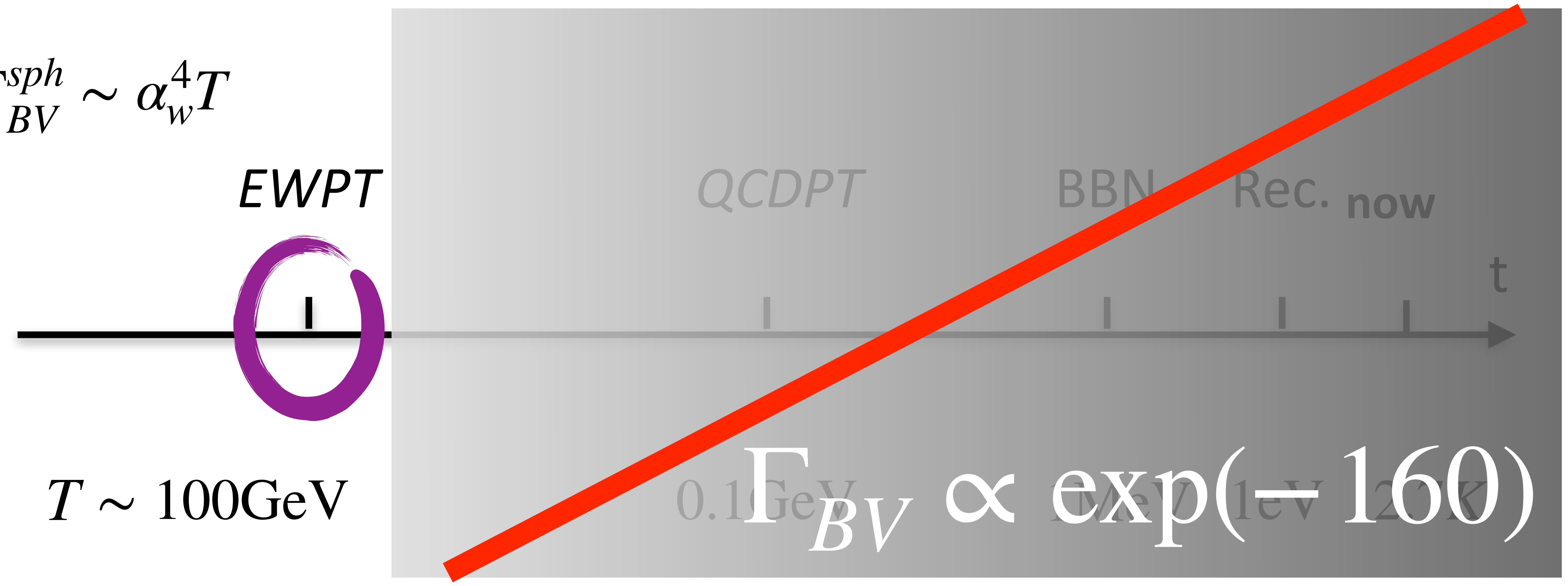


Morrissey, Ramsey-Musolf 1206.2942

現実

Kuzmin, et al, 1985; Shaposnikov, 1986; Huet, Sather, 9404302; Gavela et al, 9406289;

$\Gamma_{BV}^{sph} \sim \alpha_w^4 T$



*Baryon number violation スファレロン

✔ if $T \gtrsim 100\,GeV$

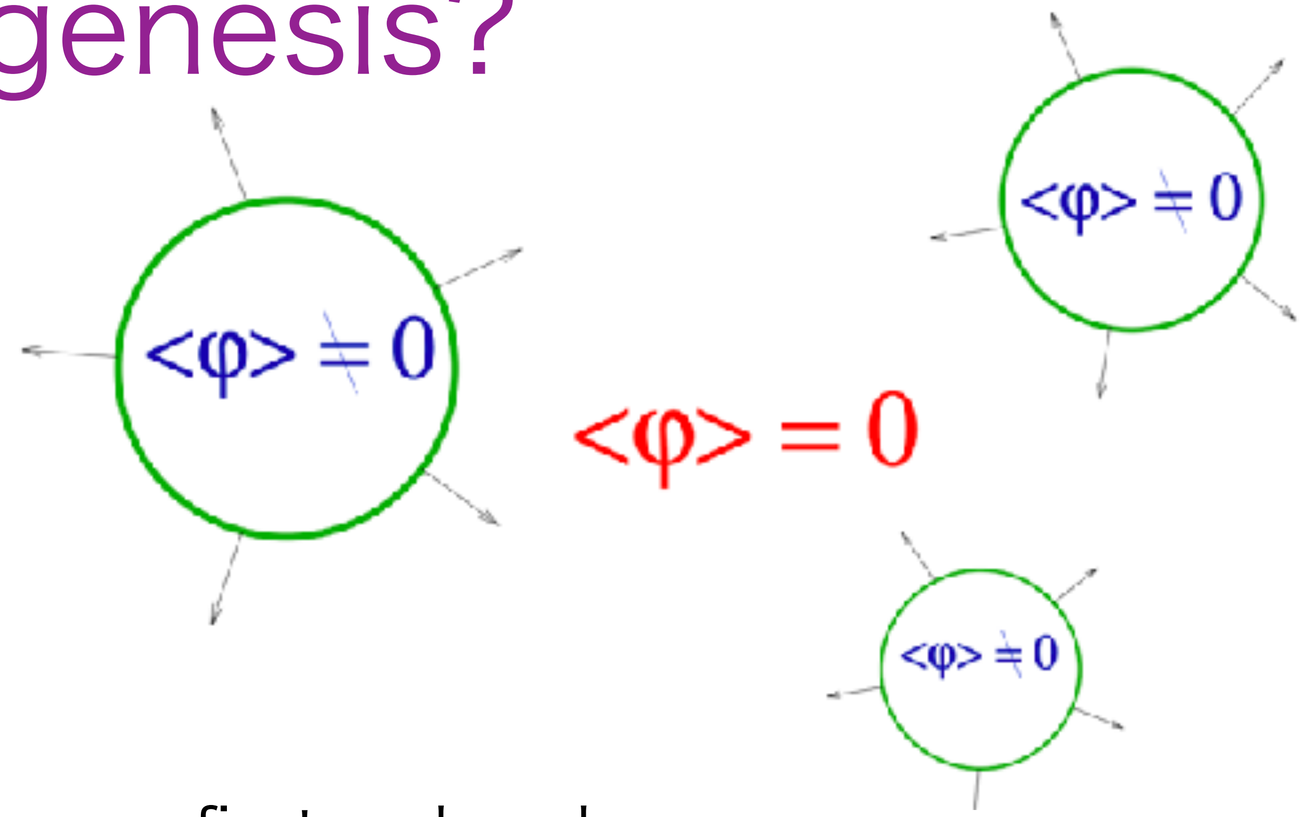
*C and CP violation CKM phase in SM

Jarlskog determinant $\propto 10^{-20}$ 😫

*Out of thermal equilibrium EWPT

Cross-over 😫

Minimal electroweak baryogenesis?



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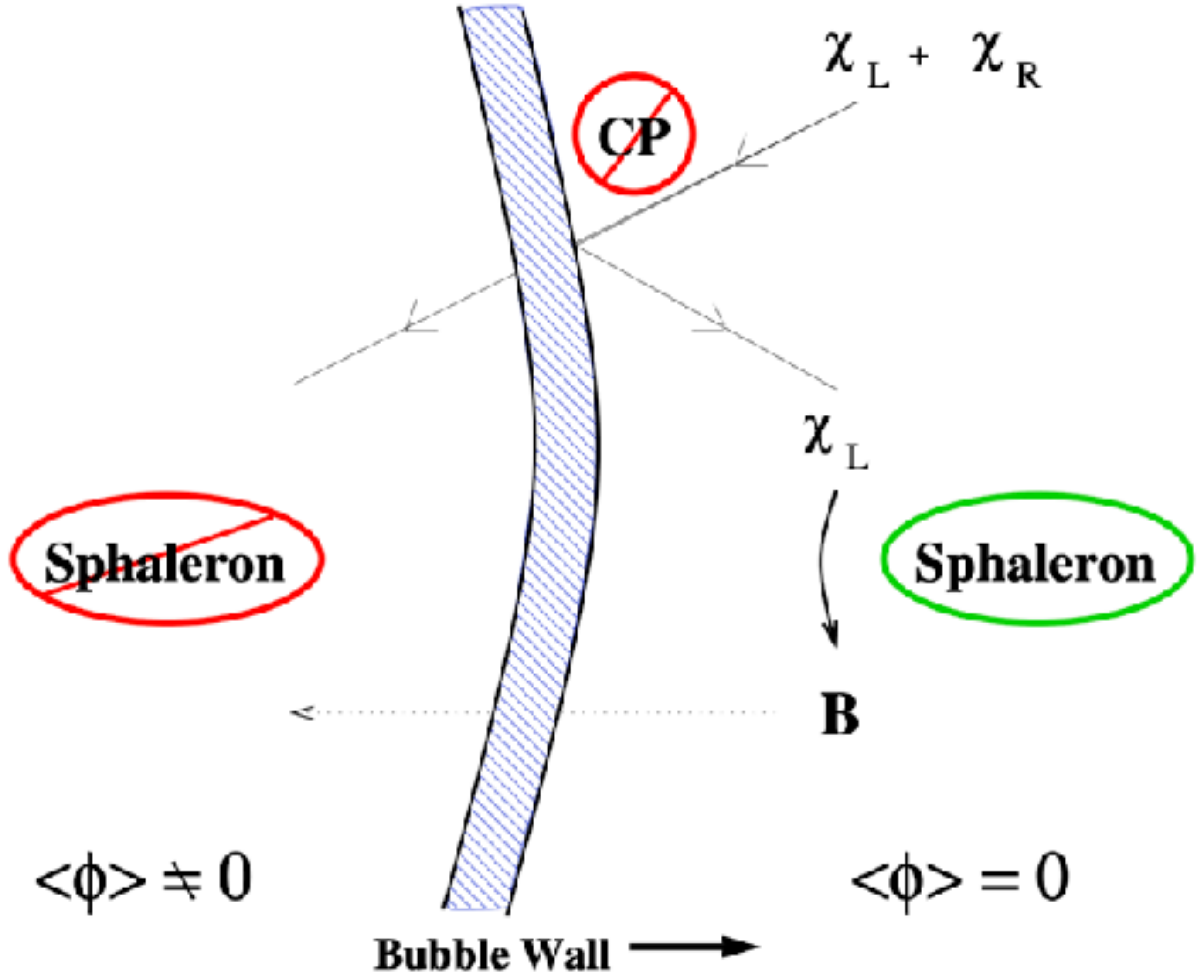
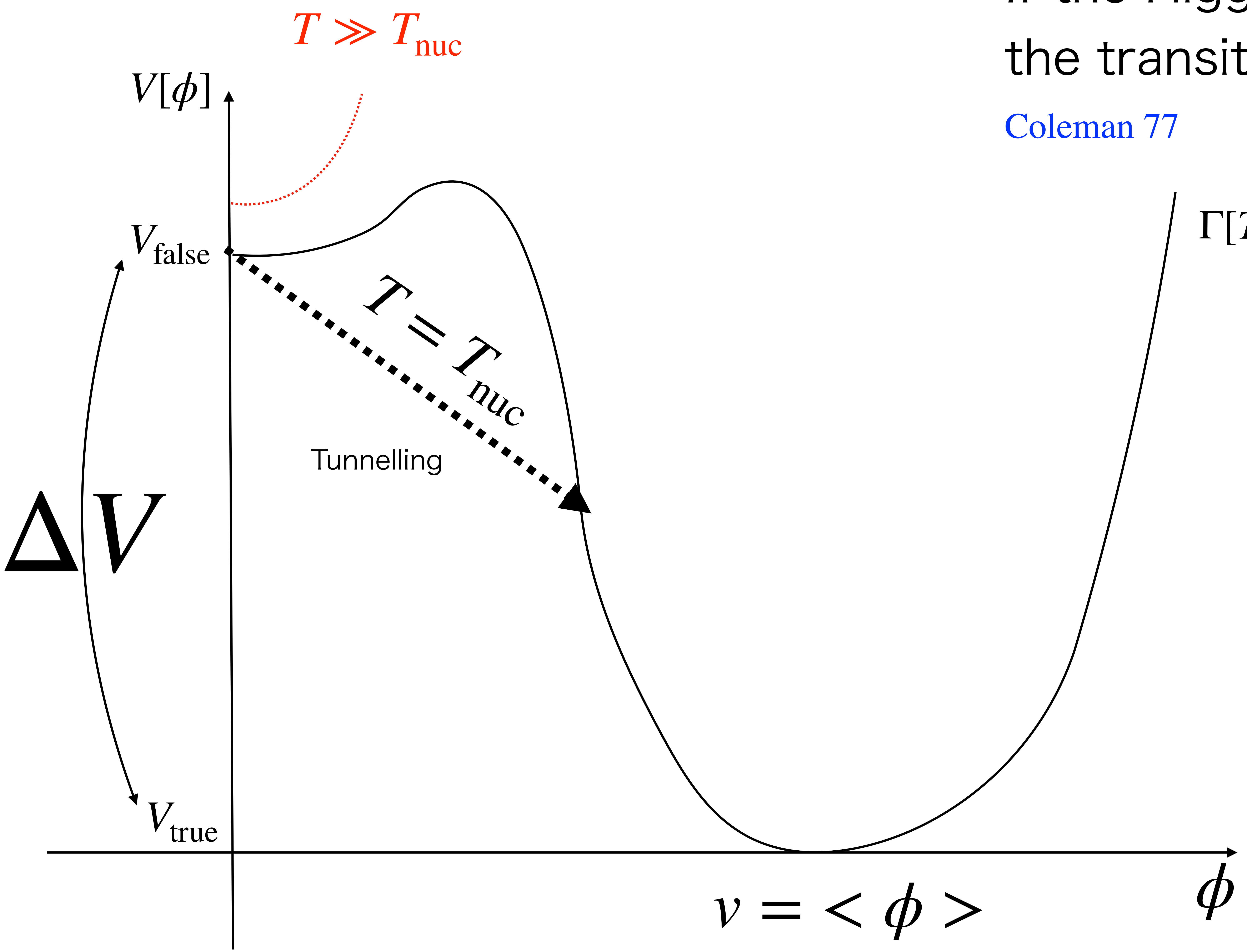


Morrissey, Ramsey-Musolf 1206.2942

**Introduction-*

Out of thermal equilibrium: First order EWPT (+some BSM)

強い一次相転移(FOPT)

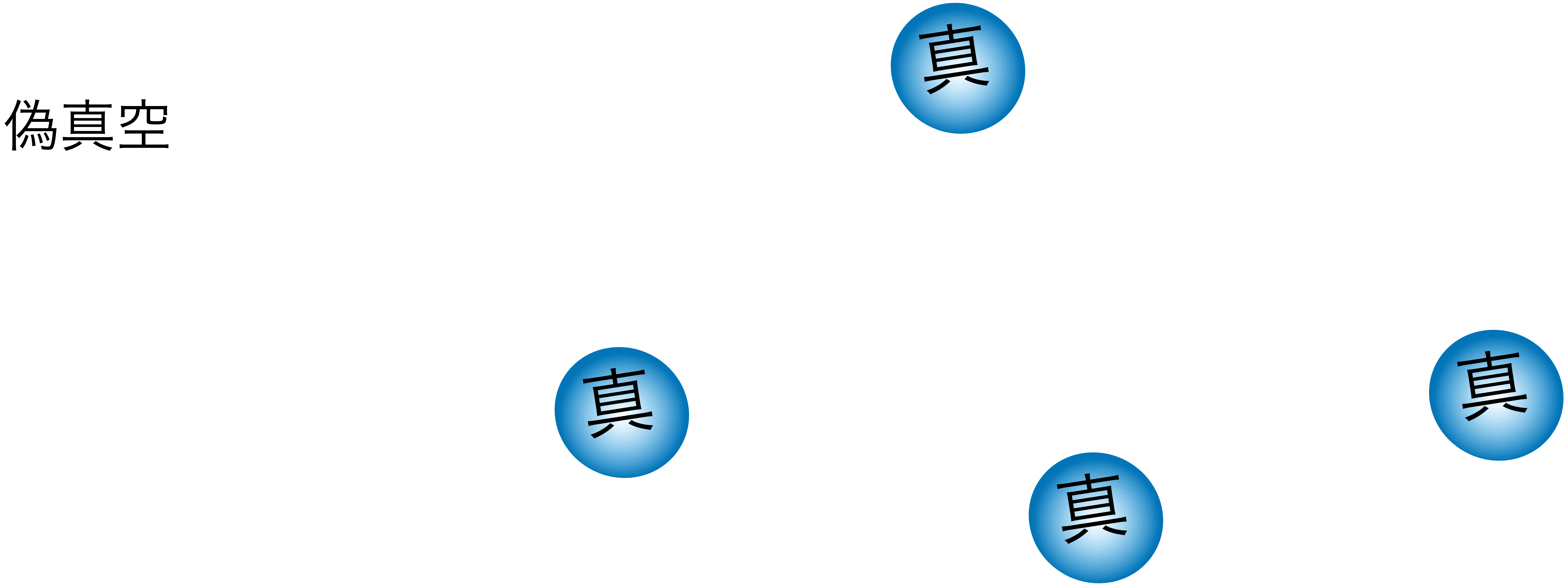


If the Higgs potential has a potential barrier, the transition occurs by quantum tunneling.

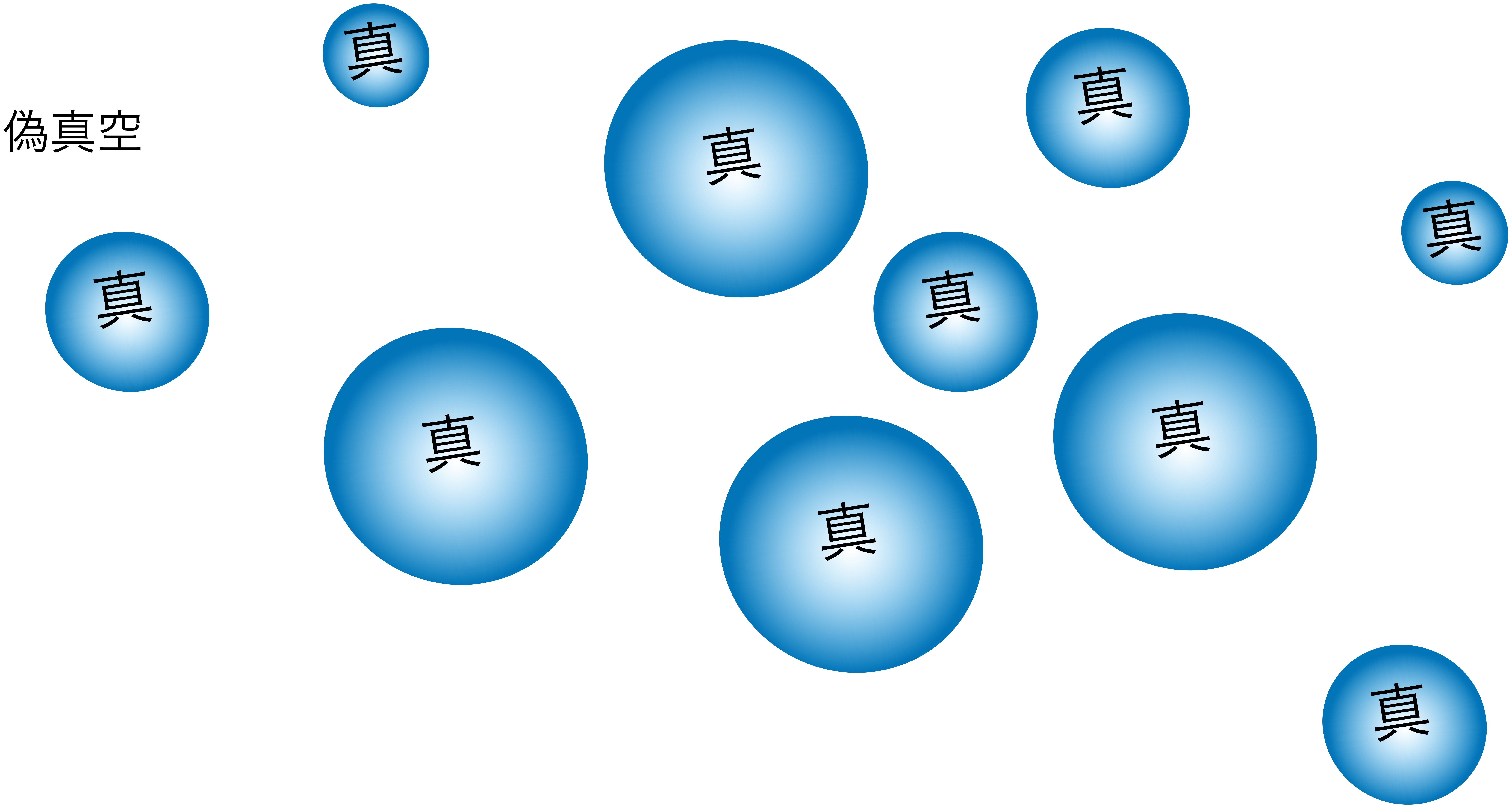
Coleman 77

$$\Gamma[T] \sim \max[T^4(\frac{S_3}{2\pi T})^{3/2} e^{-S_3/T}, R_0^{-4}(S_4/(2\pi))^2 e^{-S_4}]$$

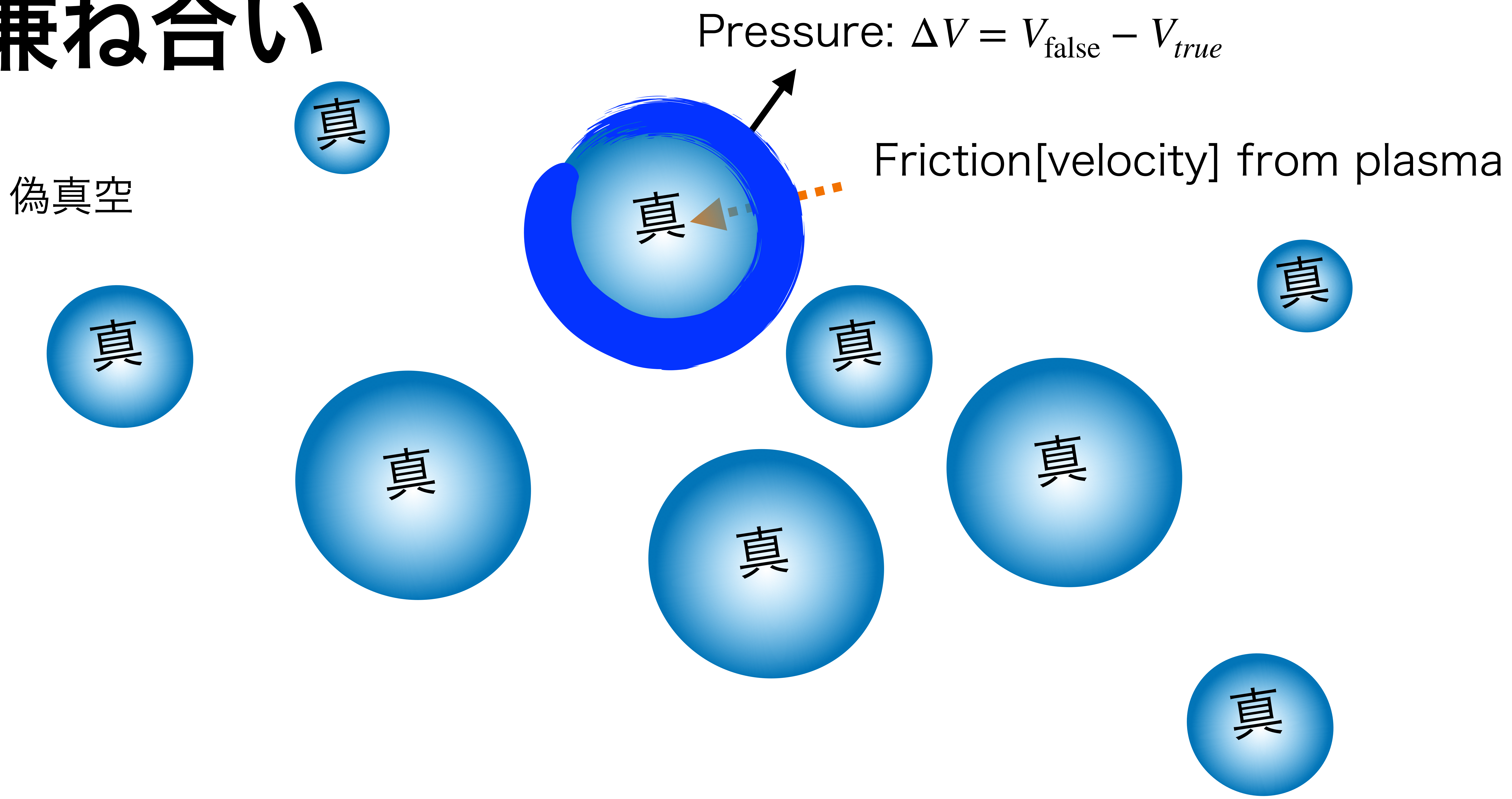
$$\Gamma[T] \sim H^4 \qquad @T \sim T_{\rm nuc}$$



$$\Gamma[T] \gtrsim H^4$$



泡壁の速度はPressureとFrictionの兼ね合い

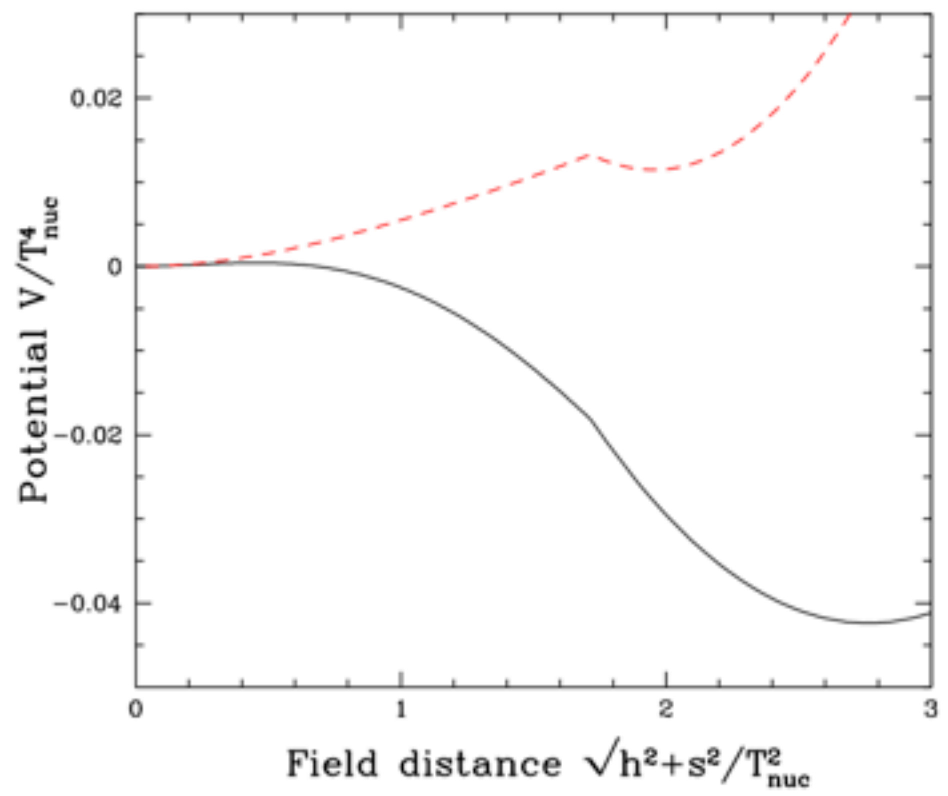


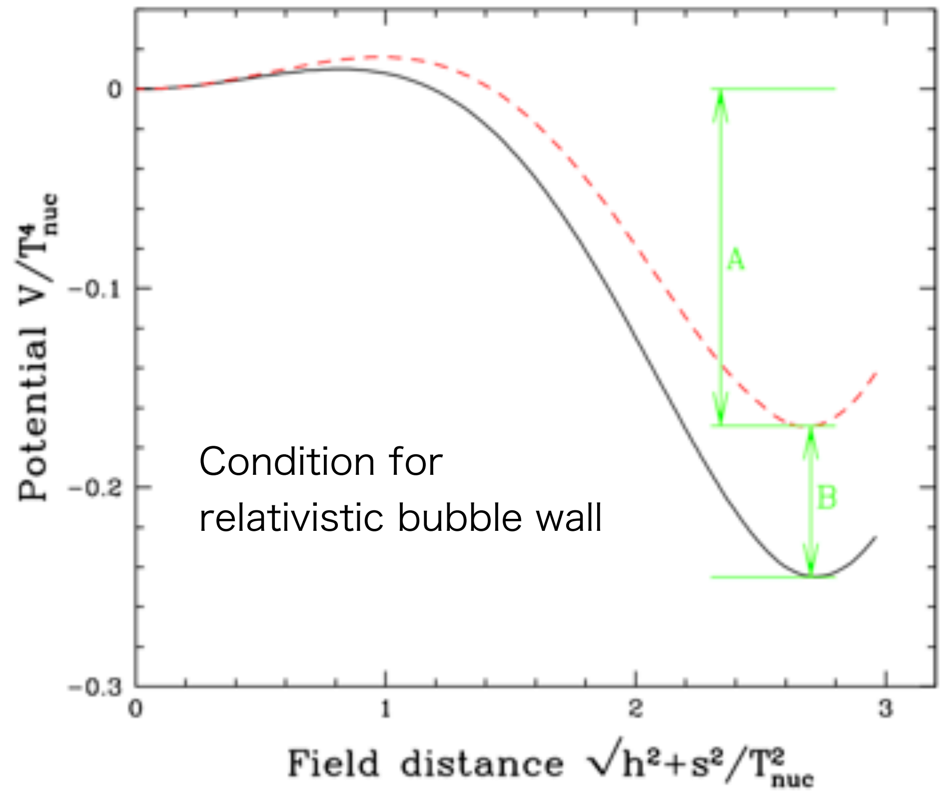
First order EWPT: Bubble wall velocity

Non-relativistic bubble walls | Relativistic bubble walls

(with certain BSM)

$V_{\rm eff}(\phi)$ at $T = T_{\rm nuc}$





Bodeker, Moore, 0903.4099

Friction due to SM plasma is too strong.

Bodeker and Moore, 1703.08215

$$SM\ friction \propto g_2^3 < \phi > \gamma T_{\rm nuc}^3$$

EWBG (SM+α)

Favored

Very difficult 😫

No reflection from wall

Gravitational waves

stronger gravitational waves

see also a discussion on photon emission H"och et al 2007.10343, and Azatov and Vanvlasselaer 2010.02590

$\sim 10^{-4}$

~ 0.2 speed of sound

~ 1 speed of light

$$\gamma_{\rm max} \sim 10^6 \left(\frac{30{\rm GeV}}{T_{\rm nuc}}\right)^3$$

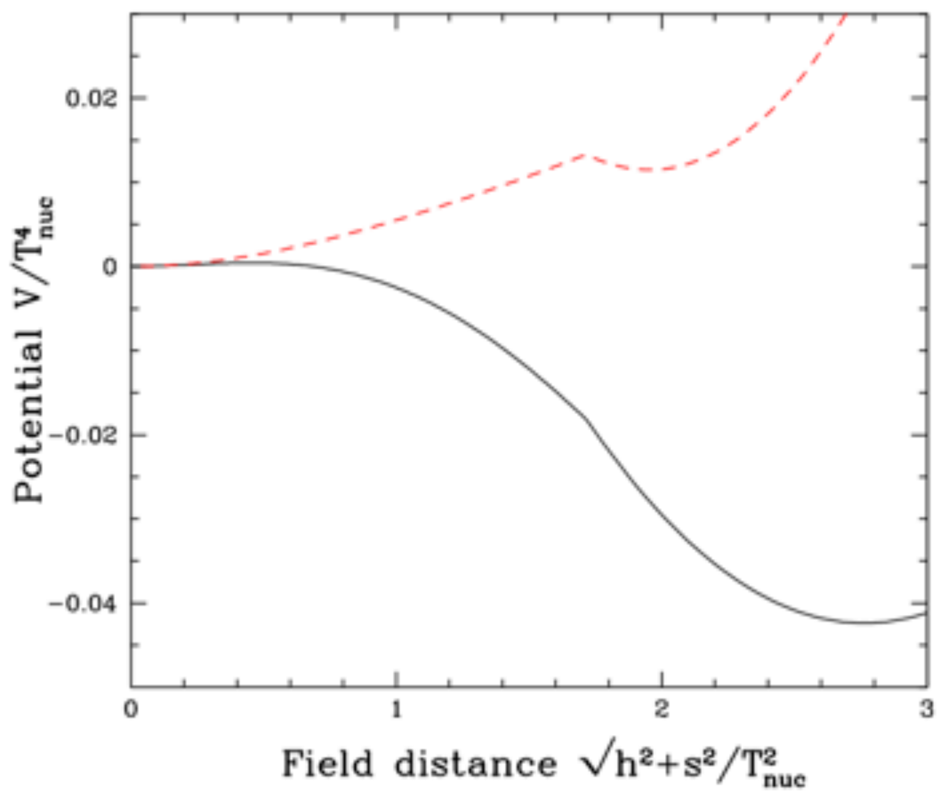
$\gamma - 1$

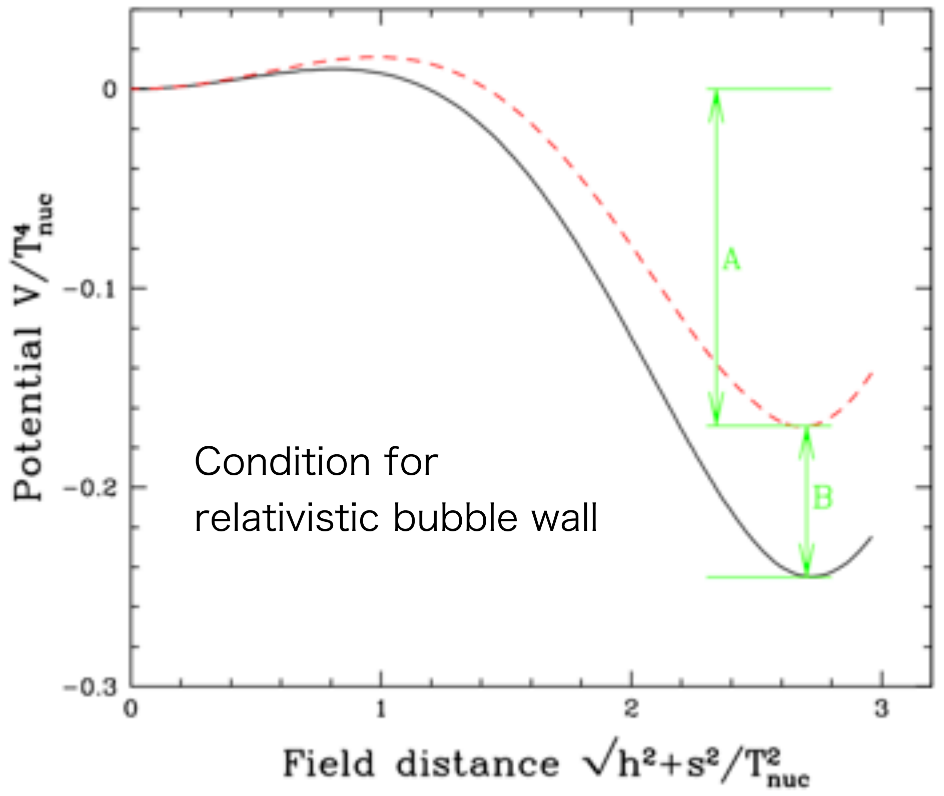
Conditions for relativistic wall are clear.

Non-relativistic bubble walls | Relativistic bubble walls

(with certain BSM)

$V_{\rm eff}(\phi)$ at $T = T_{\rm nuc}$





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(suppressed CPV ∵ Boost factor of wall)

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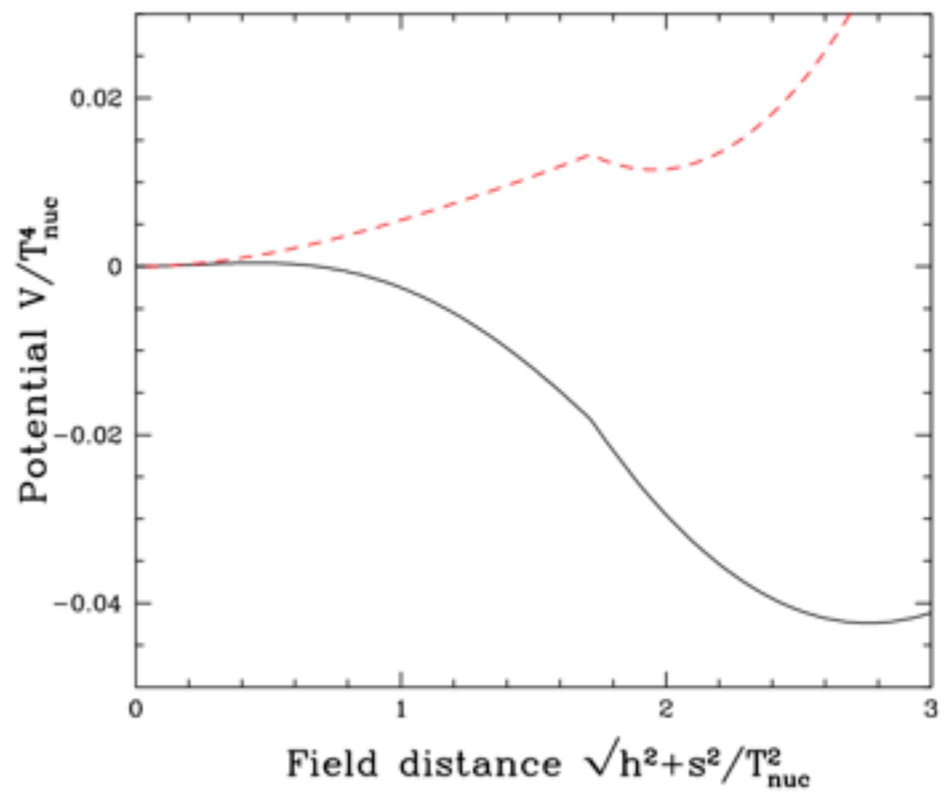
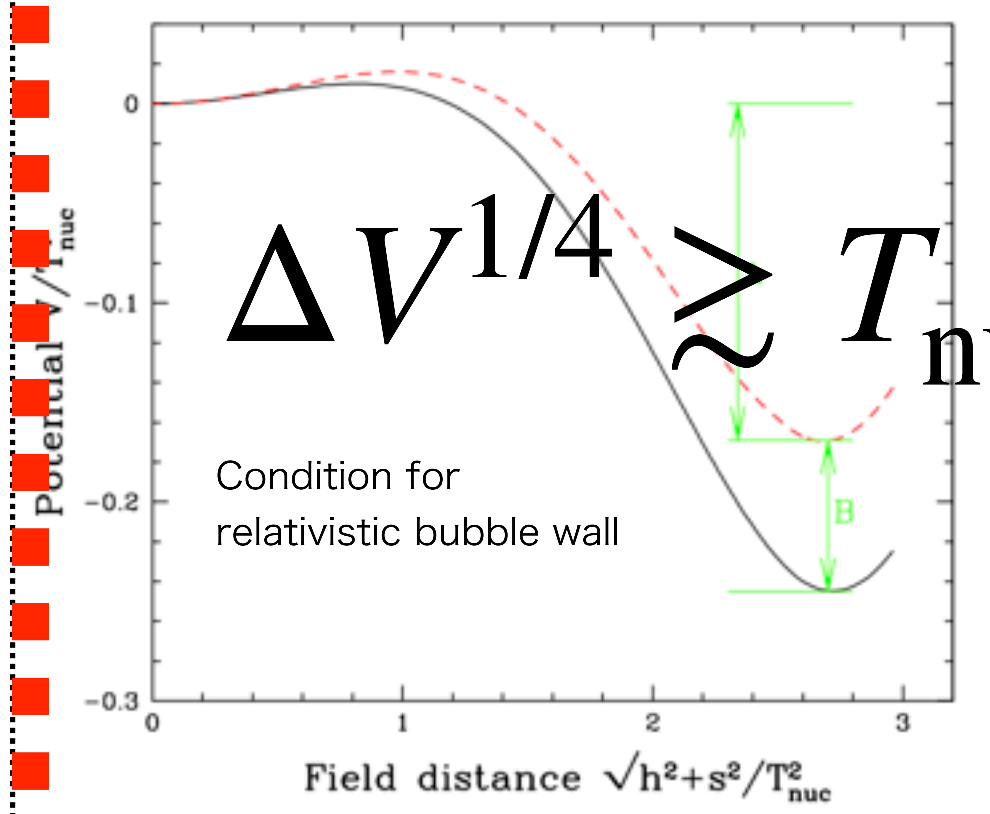
Non-relativistic bubble walls | Relativistic bubble walls | (with certain BSM)

$V_{\rm eff}(\phi)$ at $T = T_{\rm nuc}$





$\Delta V^{1/4} \gtrsim T_{\rm nuc}$

Condition for relativistic bubble wall

Bodeker, Moore, 0903.4099

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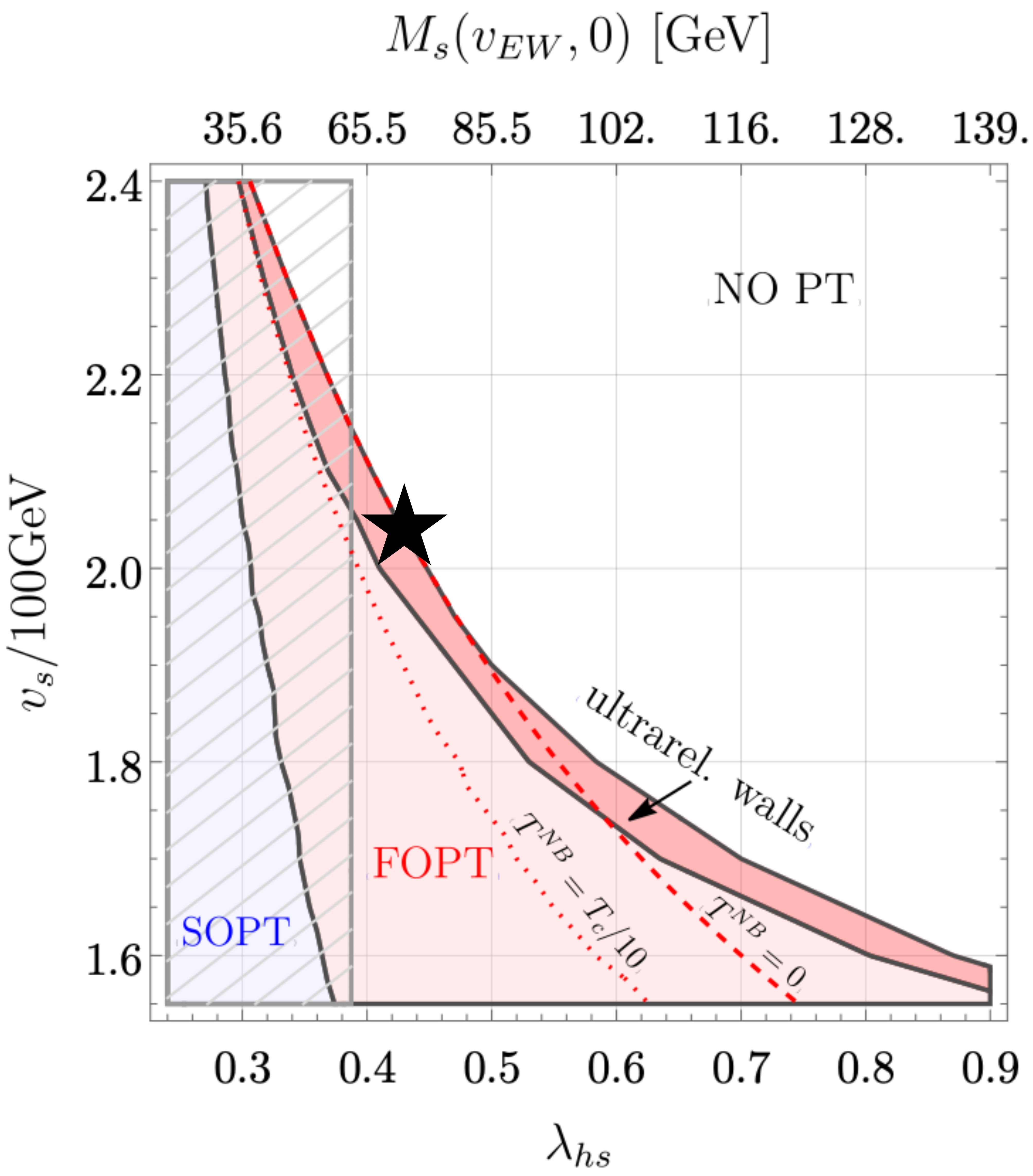
2. Out of thermal equilibrium by ultra-relativistic bubble-wall

Azatov, Barni, Chakraborty, Vanvlasselaer and WY 2101.05721, 2207.02230

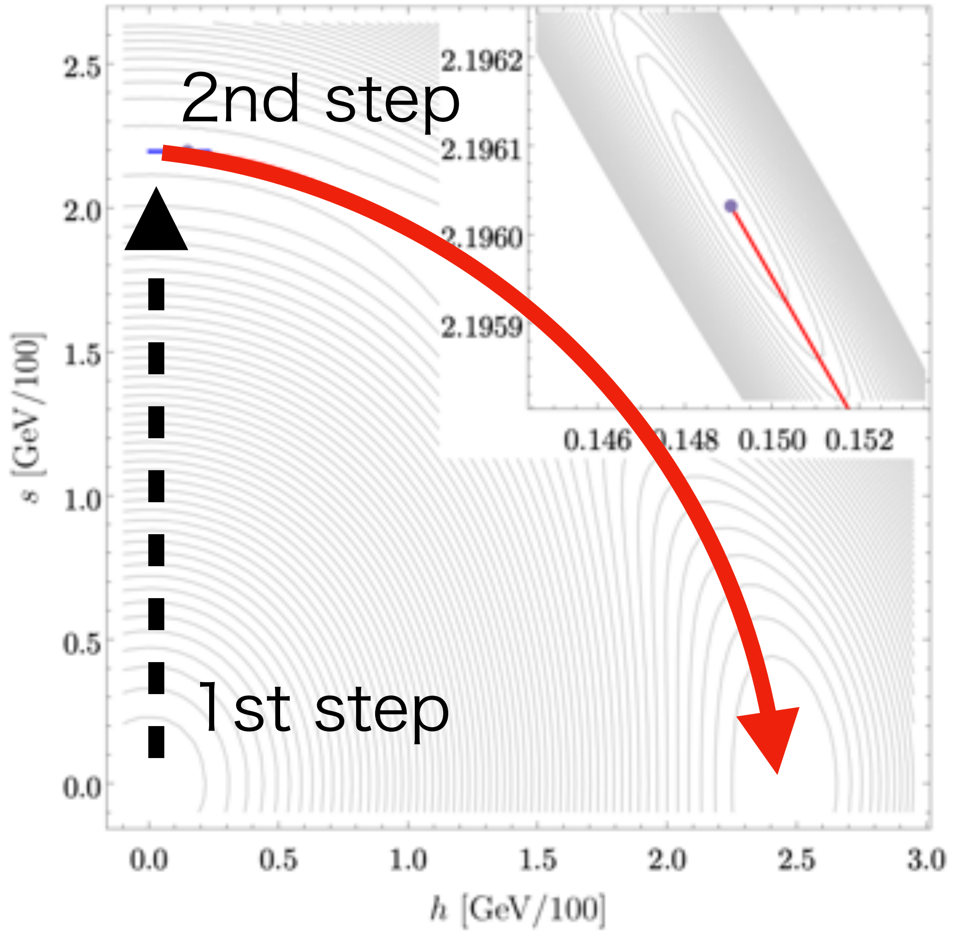
Ultra-relativistic bubbleはSM+Sで可

Azatov, Barni, Chakraborty, Vanvlasselaer and WY,2207.02230

$$V(\mathcal{H},s) = -\frac{m_h^2}{2}(\mathcal{H}^\dagger\mathcal{H}) + \lambda(\mathcal{H}^\dagger\mathcal{H})^2 - \frac{m_s^2}{4}s^2 + \frac{\lambda_{hs}}{2}s^2(\mathcal{H}^\dagger\mathcal{H}) + \frac{\lambda_s}{4}s^4\,,$$



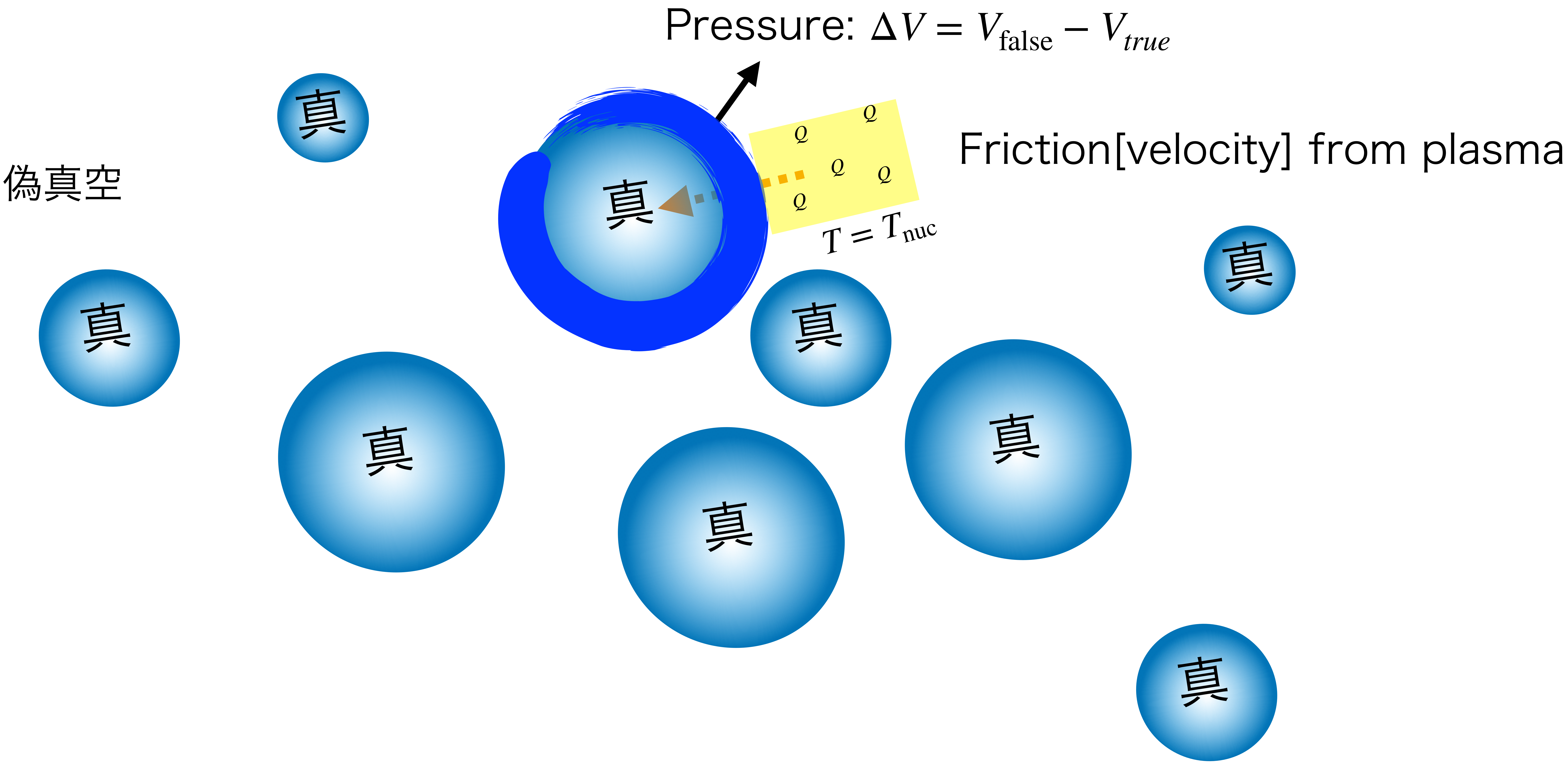
1. 1stepPTでは
   $\gamma \lesssim 10.$
2. 2stepPT works
3. A few tunings



★

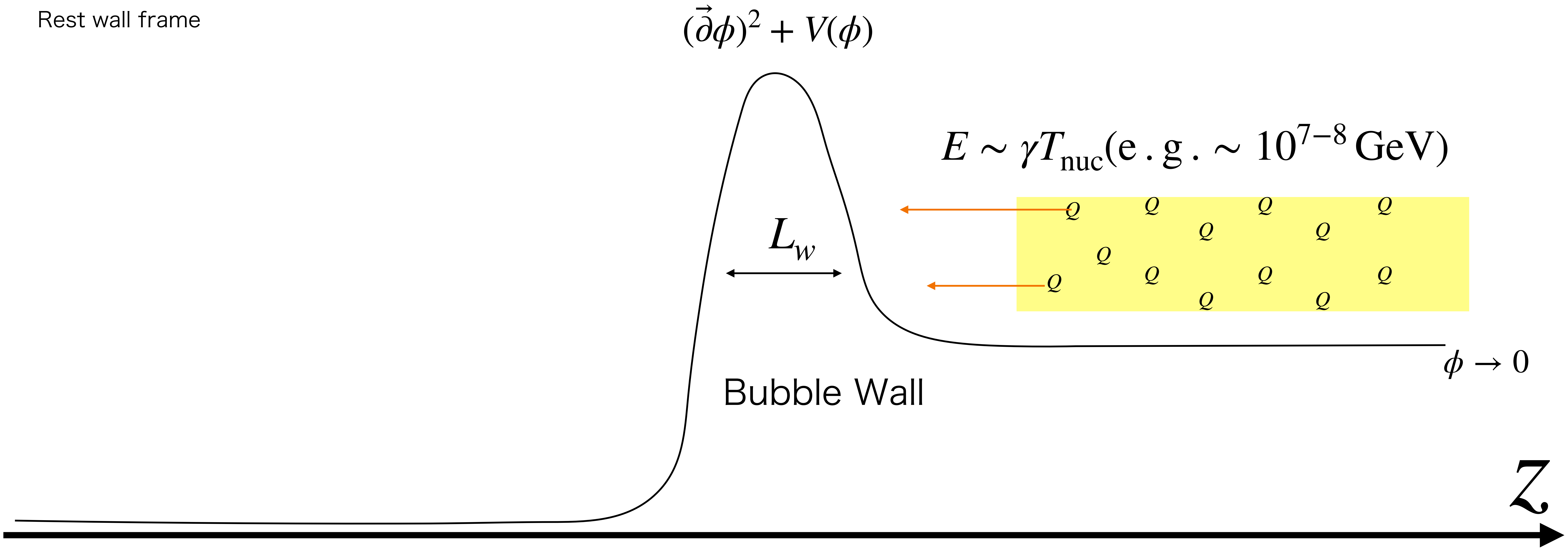
$m_s = 125$ GeV, $v_s = 205$ GeV							
λ_{hs}	$\frac{T_{reh}}{100\text{GeV}}$	$\frac{T_{nuc}}{100\text{GeV}}$	$\frac{T_{per}}{100\text{GeV}}$	γ_w	$\frac{\tilde{\beta}}{H} = \frac{(8\pi)^{1/3}}{R_* H}$	m_H^{False}/GeV	FM$_0$
0.397	0.577	0.564	0.544	4	371	19.1	No
0.405	0.530	0.512	0.488	8	268	19.1	No
0.4155	0.448	0.412	0.379	18	130	17.7	No
0.42	0.393	0.330	0.290	37	72	15.2	No
0.423	0.339	0.161	0.124	270	66	7.1	No
0.4234	0.335	0.107	0.095	805	109	3.9	No
0.424	0.335	0.051	0.051	$5.7\cdot10^3$	$3.3\cdot10^3$	0.7	No
0.4242	0.335	0.0337	0.0337	$1.8\cdot10^4$	$3.2\cdot10^4$	0.25	No
0.42424	0.335	0.028	0.0279	$3.0\cdot10^4$	$1.8\cdot10^3$	4.4	No
0.424266	0.335	0.018	0.017	$1.0\cdot10^5$	99	6.2	Yes
0.424267	0.335	0.016	0.014	$1.3\cdot10^5$	44	6.3	Yes

Bubble wallと重い粒子生成



相対論的壁での粒子生成@壁の静止系

$$\mathscr{L} = - M\bar{B}B - Y\phi\bar{B}P_L Q + h.c. + V(\phi) \qquad M \gtrsim Y < \phi >$$



相対論的壁での粒子生成@壁の静止系

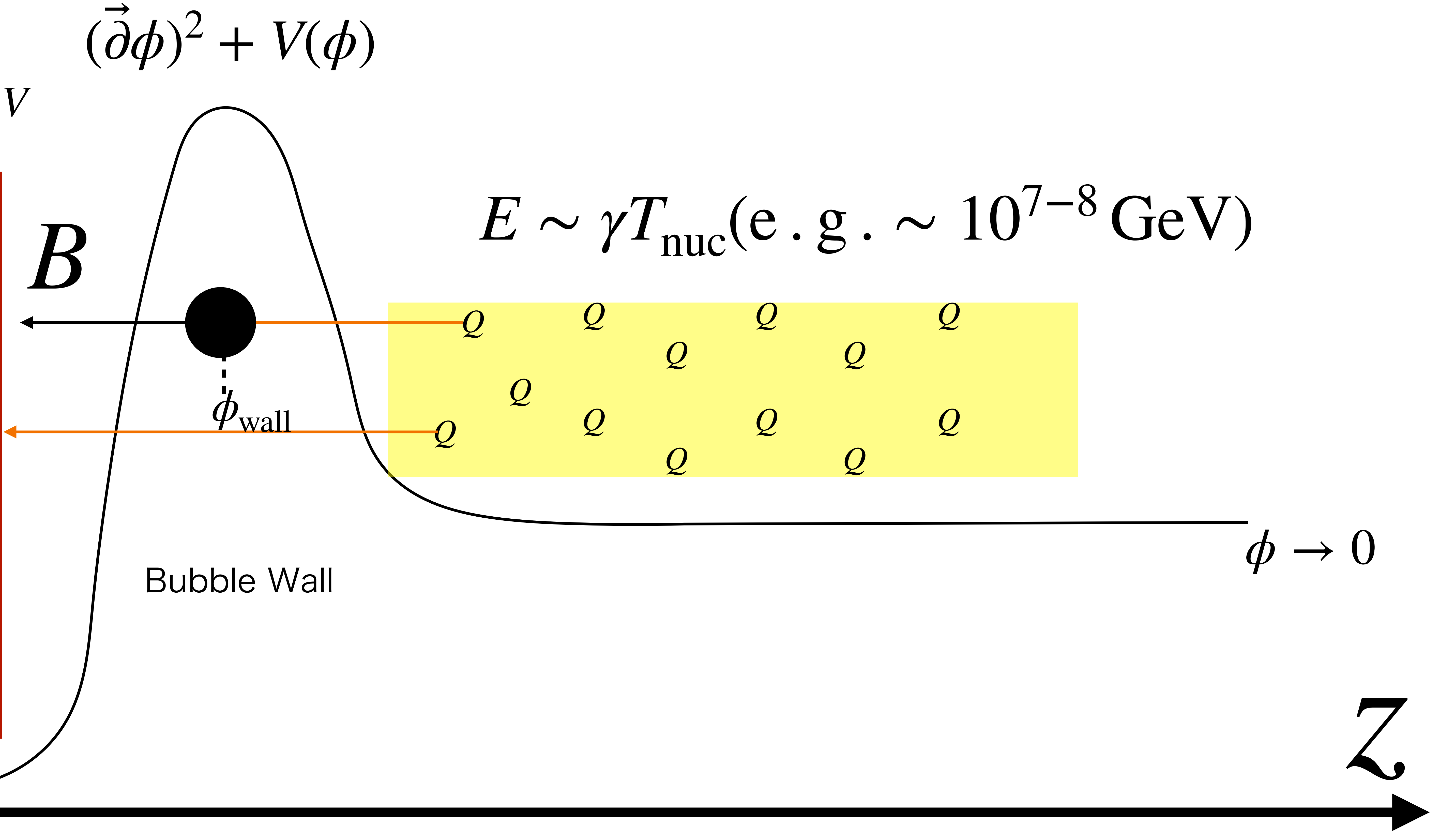
Azatov and Vanvlasselaer, 2010.02590

See QFT treatment in Azatov, Vanvlasselaer, WY, 2106.14913

$$\mathcal{L} = -M\bar{B}B - Y\phi\bar{B}P_L Q + h.c. + V(\phi)$$

Rest wall frame

$M \sim 10^4 GeV$



$$\langle B, p_f | Q, p_i \rangle_{\rm tree} =$$

$$\left[(2\pi)^3\delta^{(3)}(p_{\perp f} - p_{\perp i}) \int dz e^{-iz\Delta p_z}\phi_{wall}(z)\right] \times \bar{u}_B(p_f)u_Q(p_i)Y$$

$$\times (1 + O(\frac{Y<\phi>}{E})^2)$$

$$\mathcal{P}^{tree}(Q \to B) \approx \frac{Y^2 <\phi>^2}{M^2}\Theta(\gamma T_{\rm nuc} - M^2 L_w)$$

$$n_{B,\bar{B}} \sim \theta^2 T_{\rm nuc}^3 \quad (\theta \equiv Y<\phi>/M)$$

$\phi \to <\phi>$

相対論的壁での粒子生成@壁の静止系

Azatov and Vanvlasselaer, 2010.02590

See QFT treatment in Azatov, Vanvlasselaer, WY, 2106.14913

$$\mathscr{L} = -M\bar{B}B - Y\phi\bar{B}P_LQ + h.c. + V(\phi)$$

—壁系での知見—

1. エネルギーは保存する。

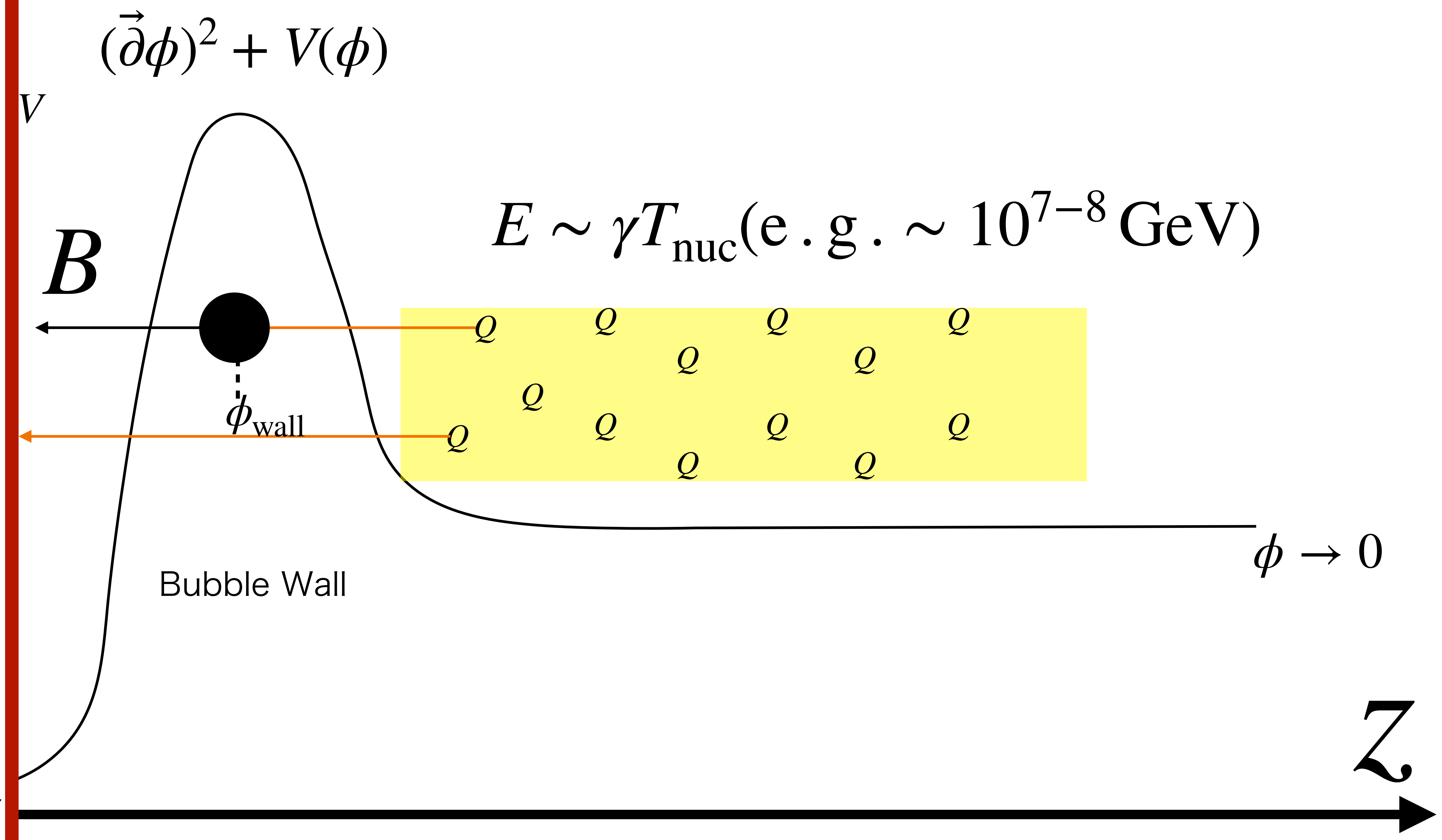
$$E_B = E$$

2. 運動量は保存**しない**!

$$p_{B,z} = E + \Delta p_z,$$

$$|\Delta p_z| \lesssim 1/L_w \sim m_h$$

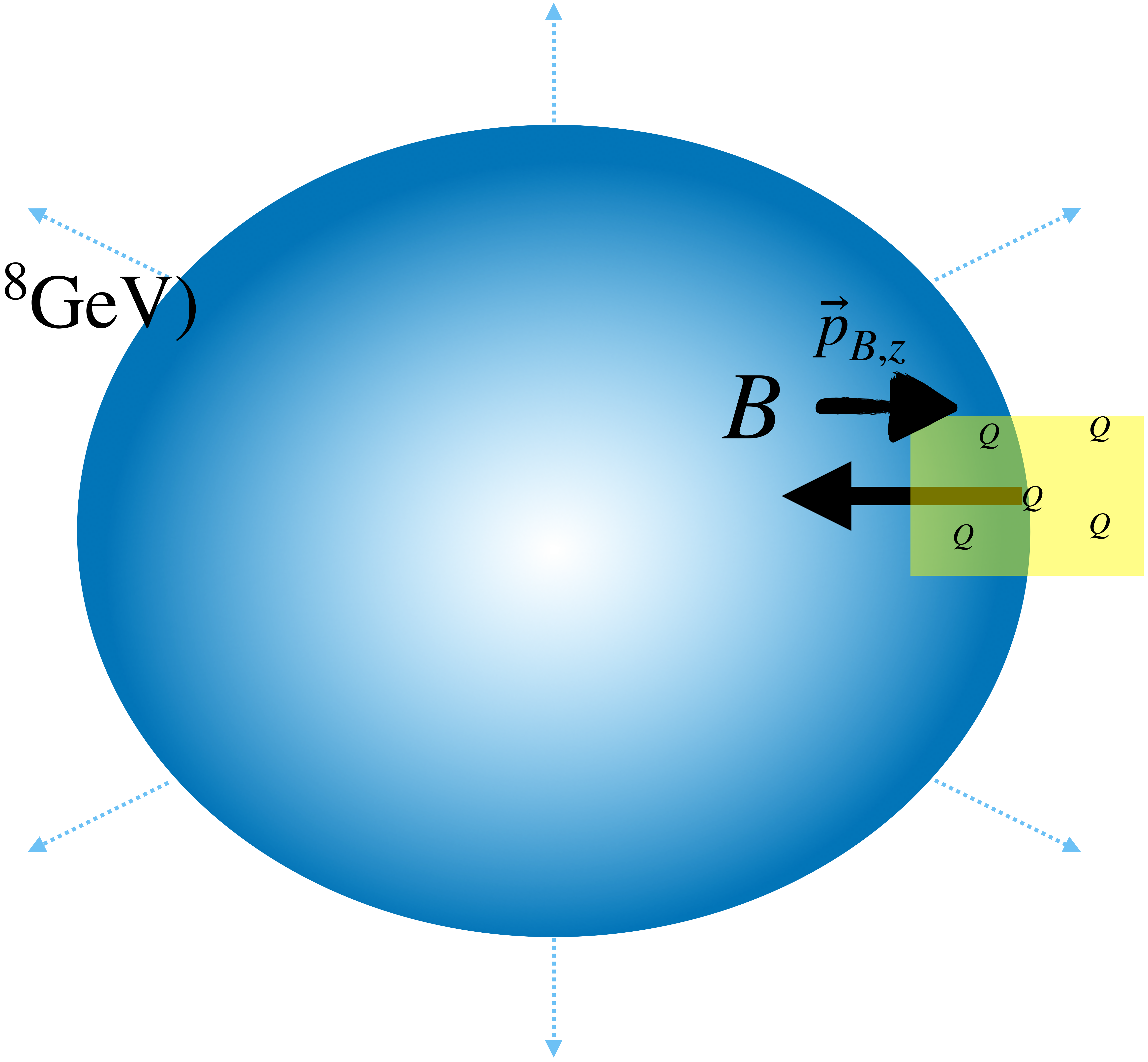
$$\Rightarrow \quad M_B^2 = E_B^2 - p_{B,z}^2 \lesssim E m_h$$



Bubble重心系に戻ってみる

$M_B^2 \lesssim T_{\rm nuc}\gamma m_h$ (e.g. $\sim (10^2 \rm TeV)^2$)

$E_B^{Cosmic\ frame} \sim \gamma \Delta p_z \sim \gamma m_h$(e.g. $\sim 10^8$GeV)



大雑把には、γにboost された

$E \sim \gamma m_h$のHiggsとQのBへの

Inverse decay $\phi_w Q \to B$

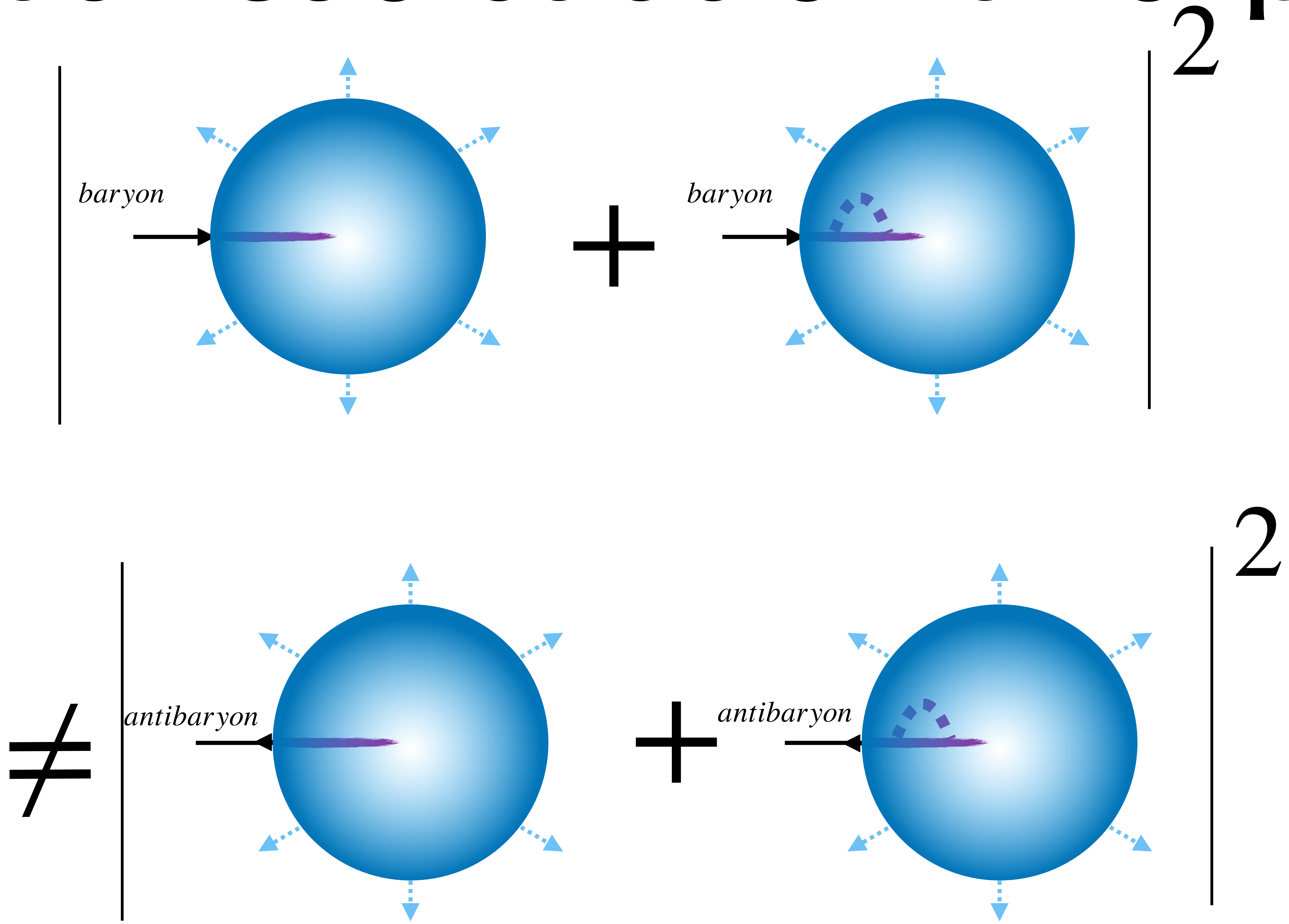
＊Backreactionはfriction

Short summary
-out-of-equilibrium-

・Plasmaはほとんど、壁を素通りするけど、**たまに、重い高エネルギーの粒子を生成**できる。

3. CP violation via ultra-relativistic bubble wall

CP violating particle production via relativistic bubble wall expansion



Azatov, Vanvlasselaer, WY, 2106.14913

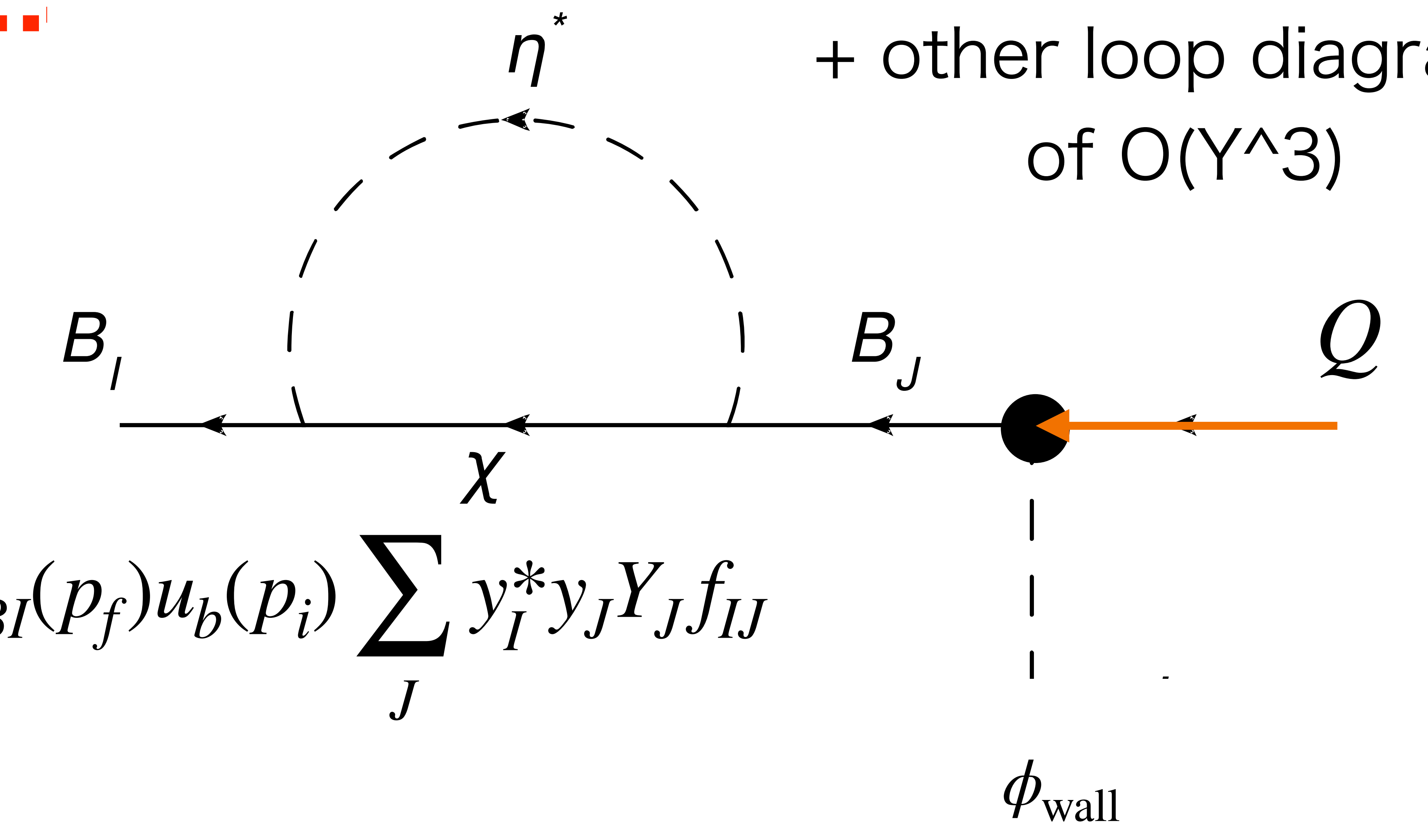
Particle production at 1loop level

Azatov, Vanvlasselaer, WY, 2106.14913

$$\mathscr{L} = -\sum_{I=1,2} M_I \bar{B}_I B_I + Y_I (\bar{B}_I \phi) P_L Q + y_I \eta^* \bar{B}_I P_R \chi + h.c. - V(\phi)$$

$Y \ll y$

+ other loop diagrams of O(Y^3)



From LSZ reduction, we obtain

$$\langle B_I, p_f | Q, p_i \rangle |_{1\mathrm{loop}} \supset \left[(2\pi)^3 \delta^{(3)}(p_f - p_i) \int dz e^{-iz\Delta p_z} \phi_{wall}(z) \right] \times \bar{u}_{BI}(p_f) u_b(p_i) \sum_J y_I^* y_J Y_J f_{IJ}$$

$$\mathrm{Im}[f_{IJ}] = \frac{1}{32\pi} \frac{M_I M_J}{M_I^2 - M_J^2} \frac{\sqrt{(M_I^2 - m_\eta^2 + m_\chi^2)^2 - 4 m_\chi^2 M_I^2}}{M_I^4} \left(M_I^2 + m_\chi^2 - m_\eta^2 \right)$$

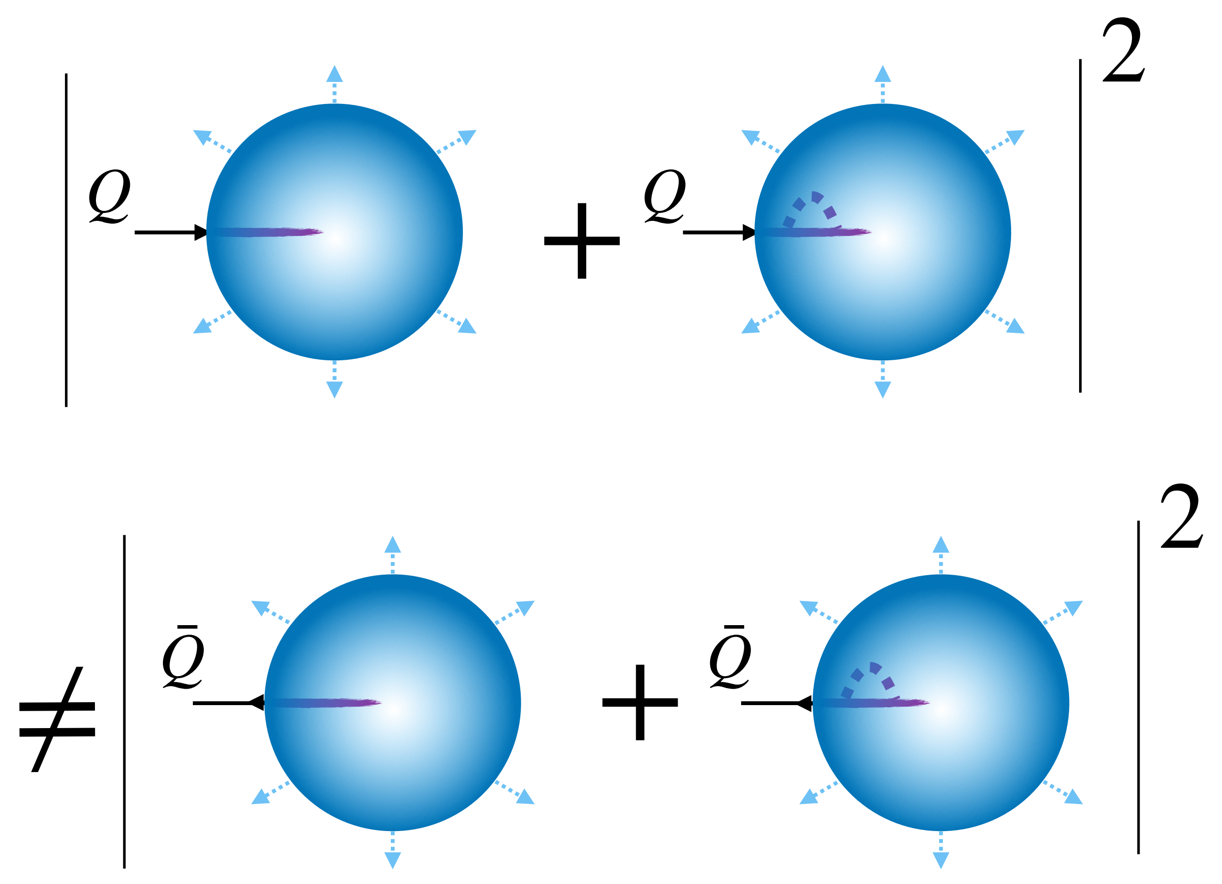
CP violation via relativistic wall expansion

Azatov, Vanvlasselaer, WY, 2106.14913

$$
\begin{cases}
\langle B_I | Q \rangle_{\text{tree}} \simeq \left[(2\pi)^3 \delta^{(3)}(p_f - p_i) \int dz e^{-iz\Delta p_z} \phi_{wall}(z)\right] \times \bar{u}_{BI}(p_f) u_Q(p_i) Y_I \\
\langle B_I | Q \rangle |_{\text{1loop}} \supset \left[(2\pi)^3 \delta^{(3)}(p_f - p_i) \int dz e^{-iz\Delta p_z} \phi_{wall}(z)\right] \times \bar{u}_{BI}(p_f) u_Q(p_i) \sum_J y_I^* y_J Y_J f_{IJ}
\end{cases}
$$

$$n_B - n_{\bar{B}} \sim \epsilon_{CPV} T_{\text{nuc}}^3 \theta^2$$

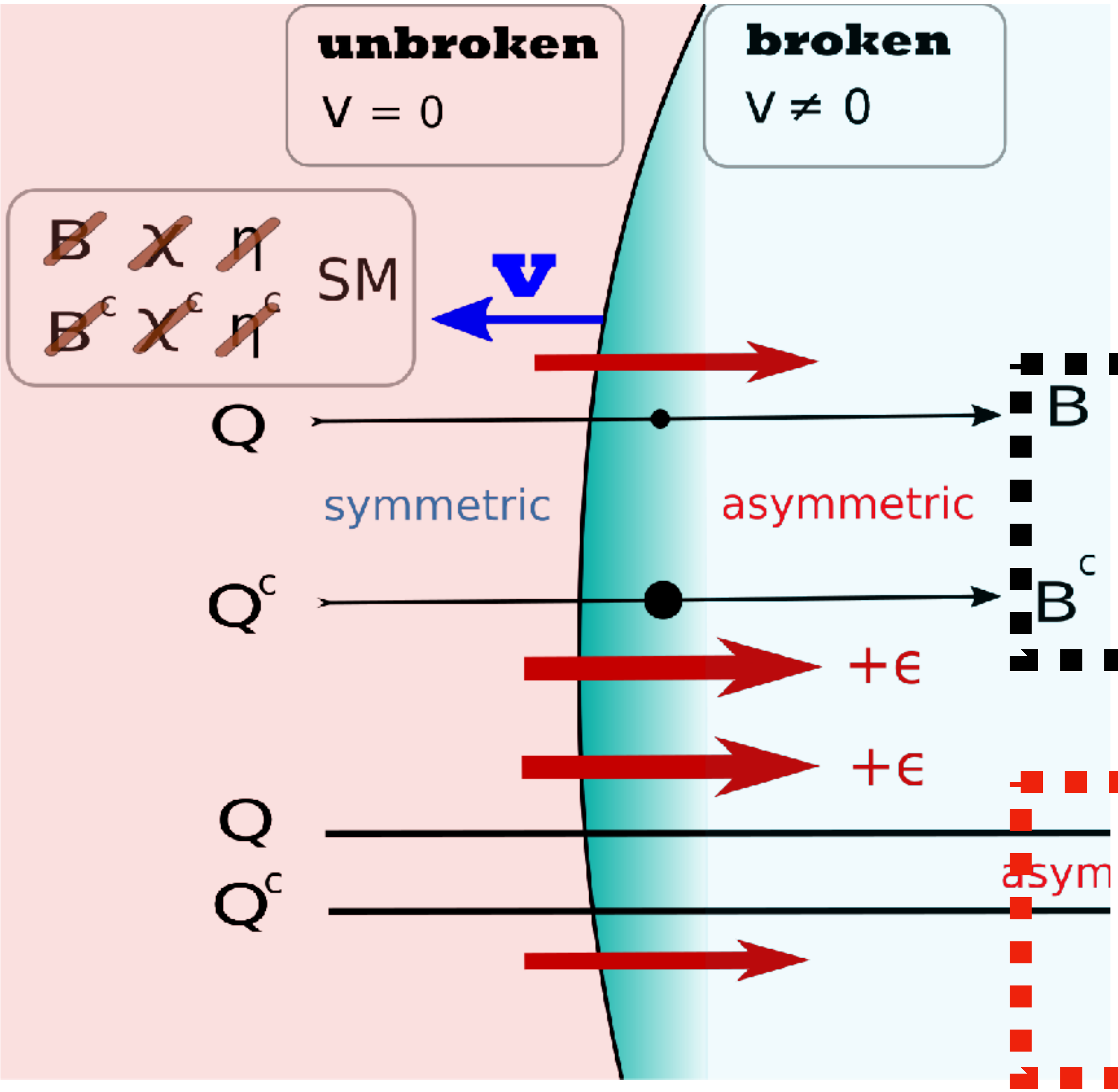
$$\epsilon_{\text{CPV}} = - \frac{4 \sum_{I>J} \text{Im}(Y_I Y_J^* y_J y_I^*) \text{Im} f_{IJ}}{\sum_I |Y_I|^2} + O(Y^2) \sim 0.1 O(y^2)$$



$$\text{Im}[f_{IJ}] = \frac{1}{32\pi} \frac{M_I M_J}{M_I^2 - M_J^2} \frac{\sqrt{(M_I^2 - m_\eta^2 + m_\chi^2)^2 - 4 m_\chi^2 M_I^2}}{M_I^4} \left(M_I^2 + m_\chi^2 - m_\eta^2\right)$$

A baryogenesis model

Azatov, Vanvlasselaer, WY, 2106.14913



$$\mathscr{L} = -\sum_{I=1,2} M_I \bar{B}_I B_I + Y_I(\bar{B}_I \phi) P_L Q + y_I \eta^* \bar{B}_I P_R \chi + h.c. - V(\phi)$$

$$y \gg Y$$

We have separated the baryon asymmetry in heavy (BSM) and light (SM) sectors within the bubble wall.

Heavy sector (BSM)

$$n_B - n_{\bar{B}} \sim \epsilon_{CPV} T_{\rm nuc}^3 \theta^2$$

$$n_d - n_{\bar{d}} \sim -\epsilon_{CPV} T_{\rm nuc}^3 \theta^2$$

$$Q = \{u, d\}$$

Light sector (SM)

Short summary-CPV

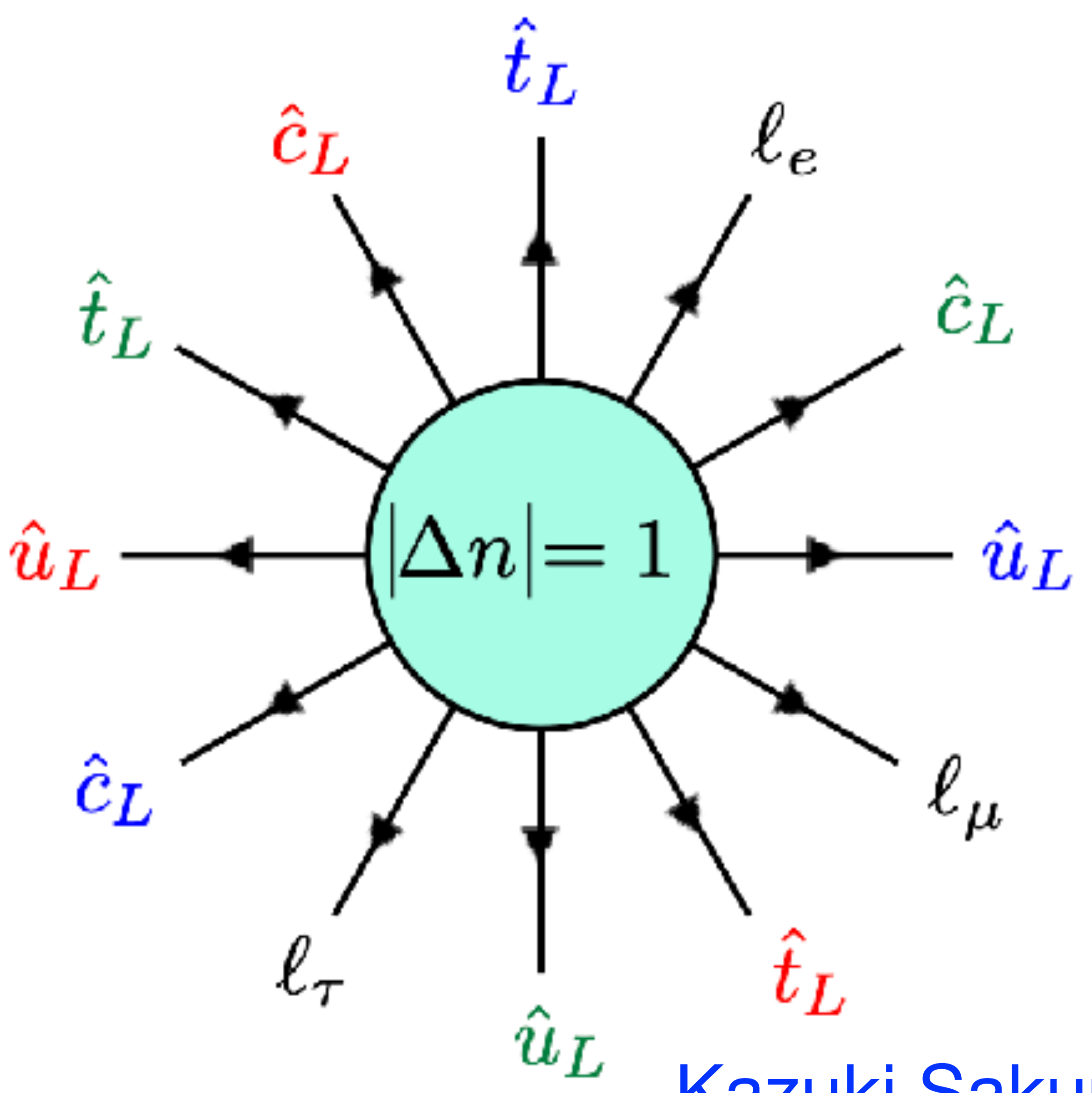
- Ultra-relativistic bubble wallの場合、重い粒子生成とともにCPVが起こりうる。

- 高エネルギーと低エネルギーでbaryon数を分ける。(c.f. 壁の外と内側で分けるEWBG)

- CPVには新物理が必要。

4. Baryon number violation via broken phase sphaleron

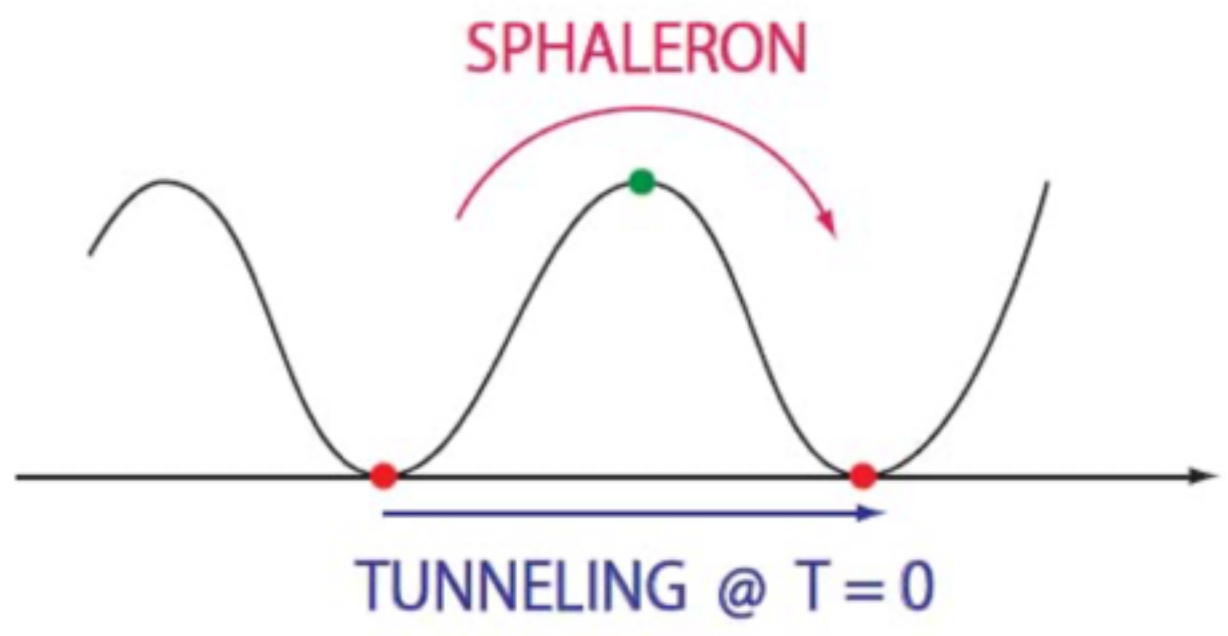
The only baryon number violating process in the SM is via anomaly. It is inefficient at low temperatures.



Kazuki Sakurai's slide

$$\Gamma_{instanton} \propto m_W \exp[-\frac{16\pi^2}{g_w^2}] \sim m_W \exp[-O(100)](T \ll 100GeV)$$

$$\Gamma_{Sphaleron} \sim \alpha_2^5 T (T \gg 100GeV)$$

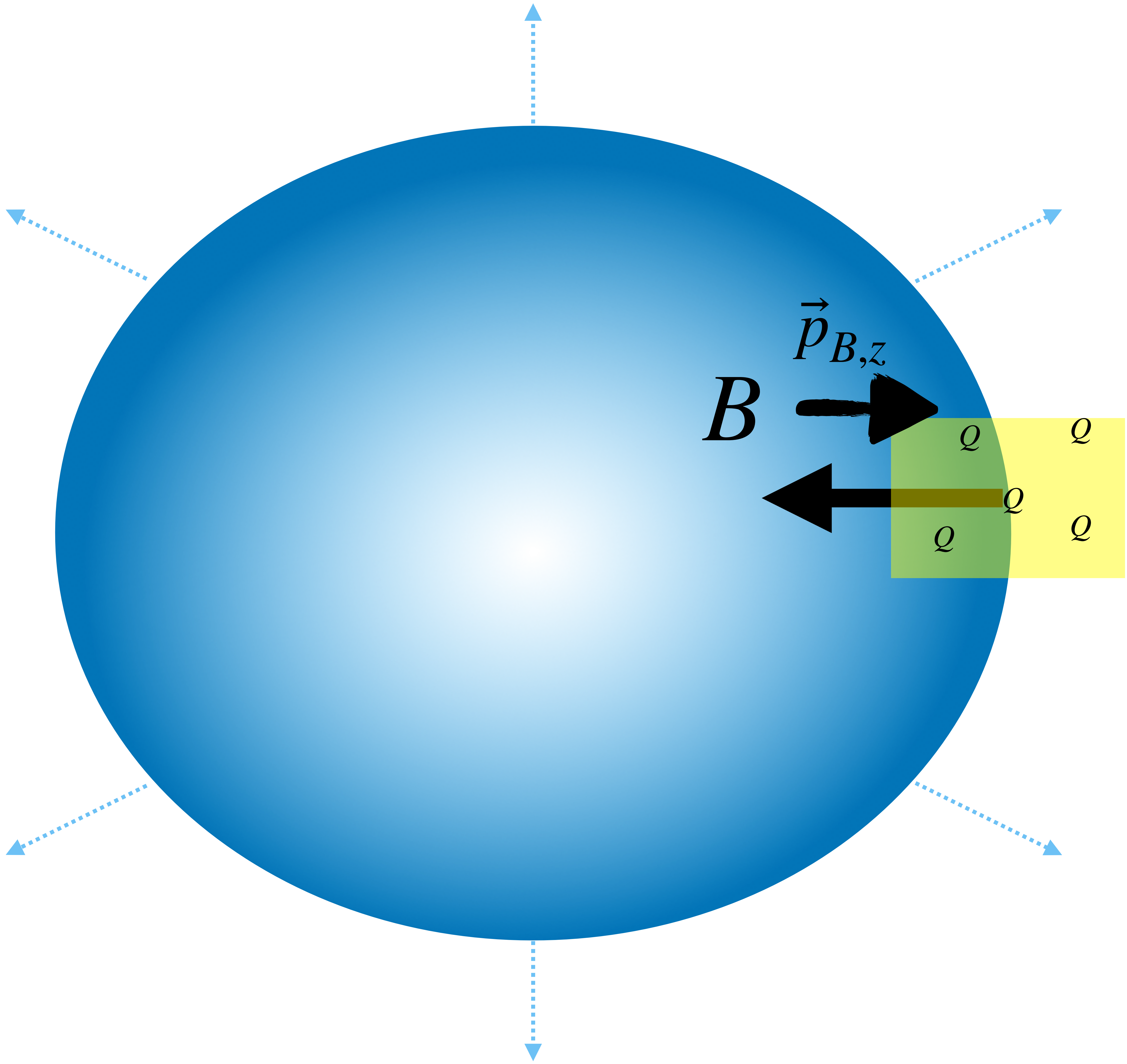


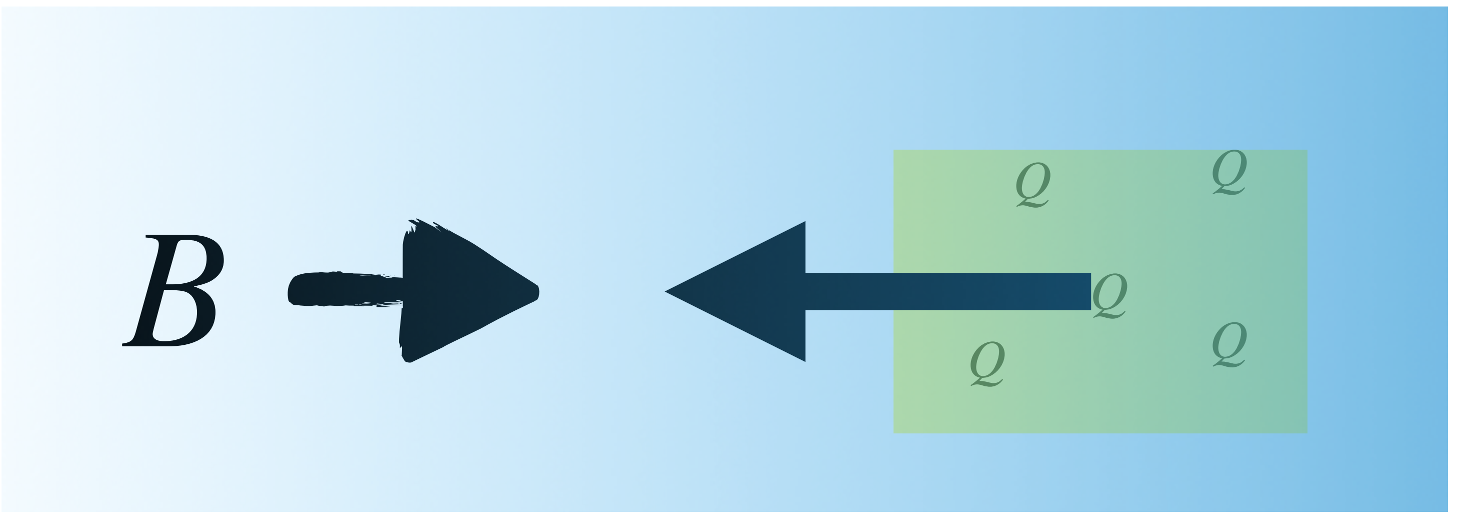
Yoshimura-san's slide, 09

People usually assume that the reheating temperature (the beginning of big-bang cosmology) is larger than 100GeV.

3. 非平衡のスファレロンによるバリオン数生成

Jaeckel, WY 2206.06376





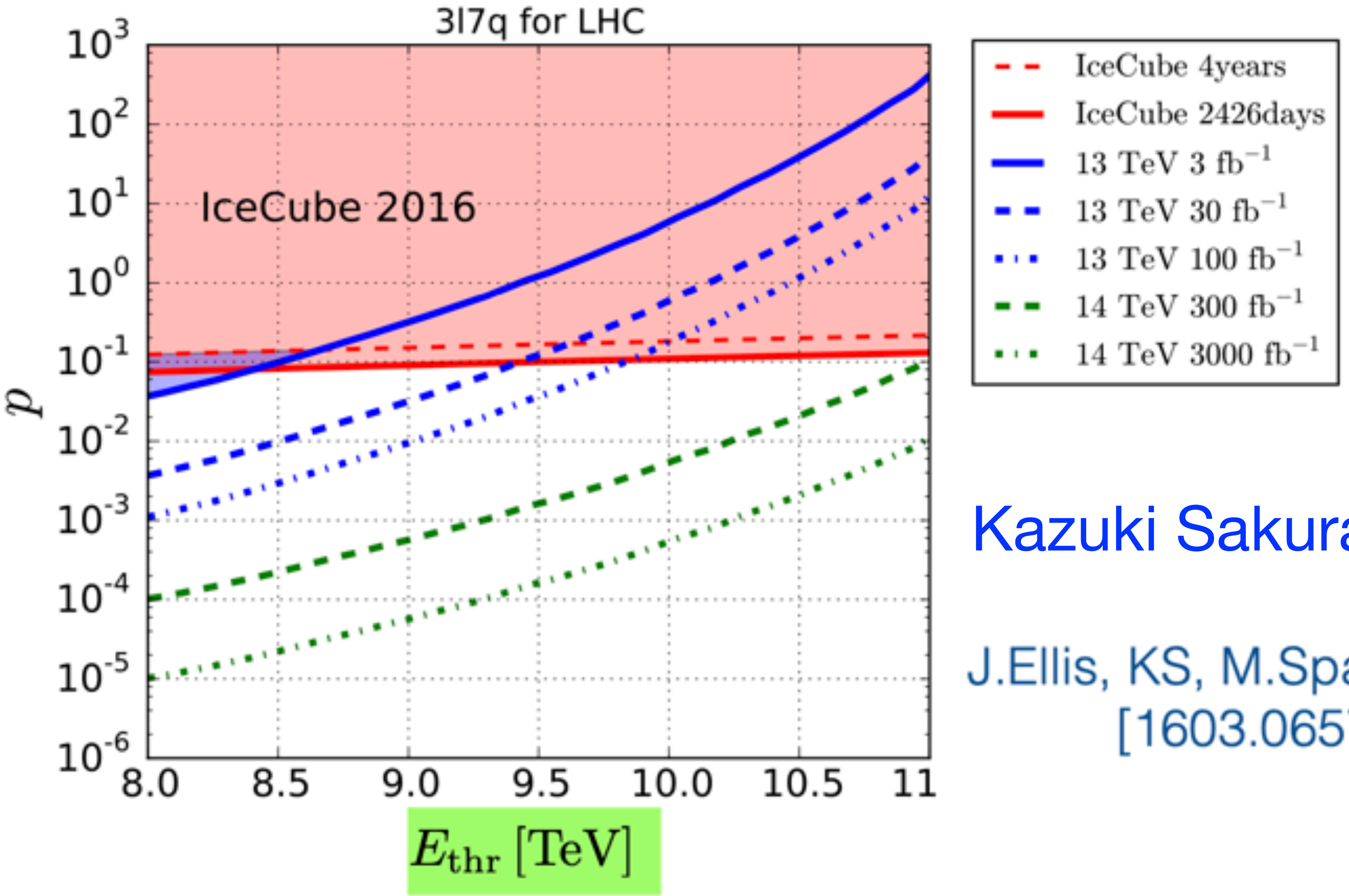
$$E_{\rm cm}^{(2)} \sim 10^4 GeV \sqrt{\frac{E_B}{10^7\, GeV} \frac{T_R}{10\, GeV}}$$

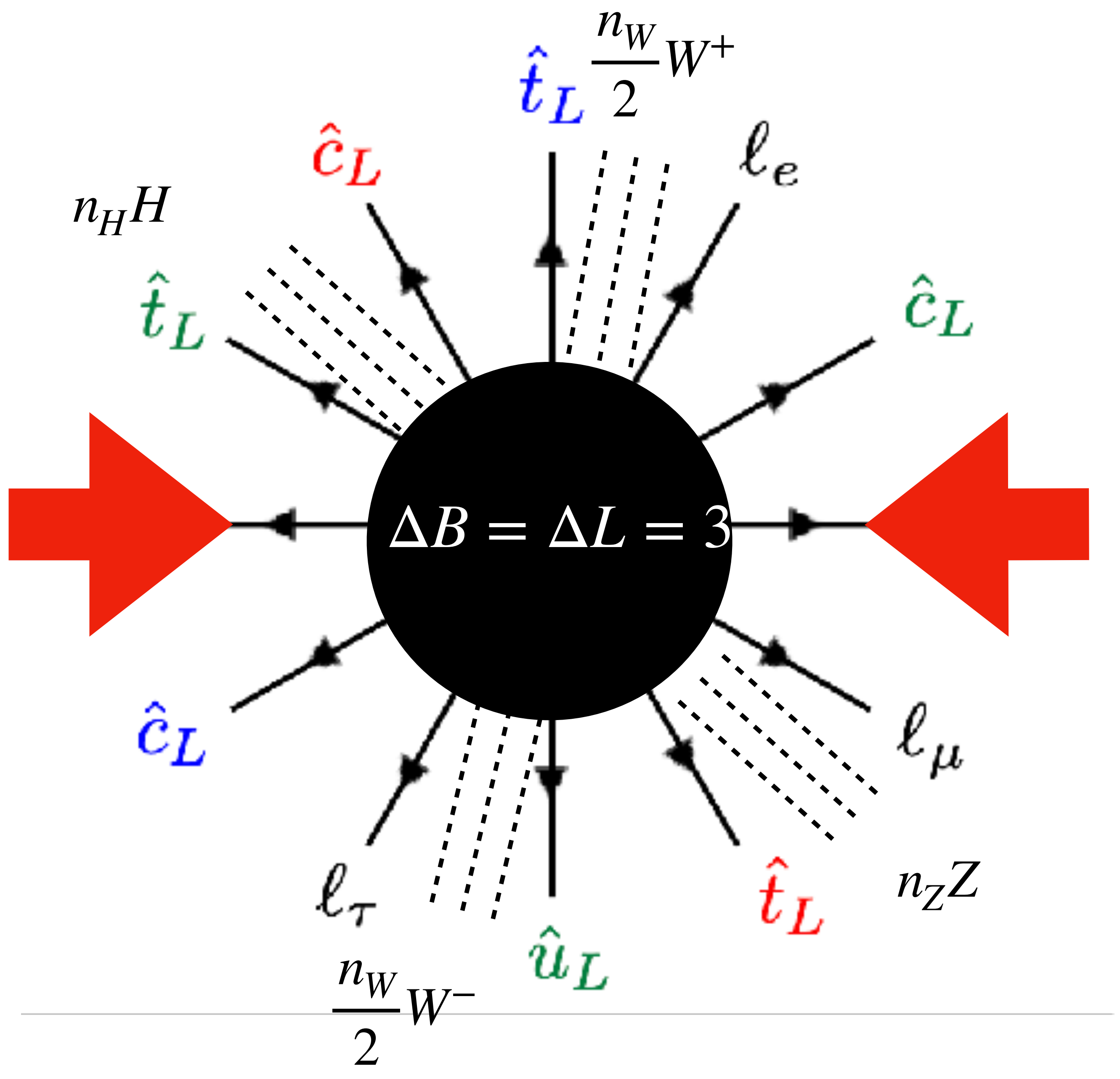
The sphaleron-induced high-energy collision in the broken phase has been studied in the context of cosmic-ray/collider experiments.

$e.g. \, QQ \to 7\bar{Q} + 3\bar{L} + n_Z Z + n_W W + n_H H$

Pioneered by Ringwald '90, Espinosa '90

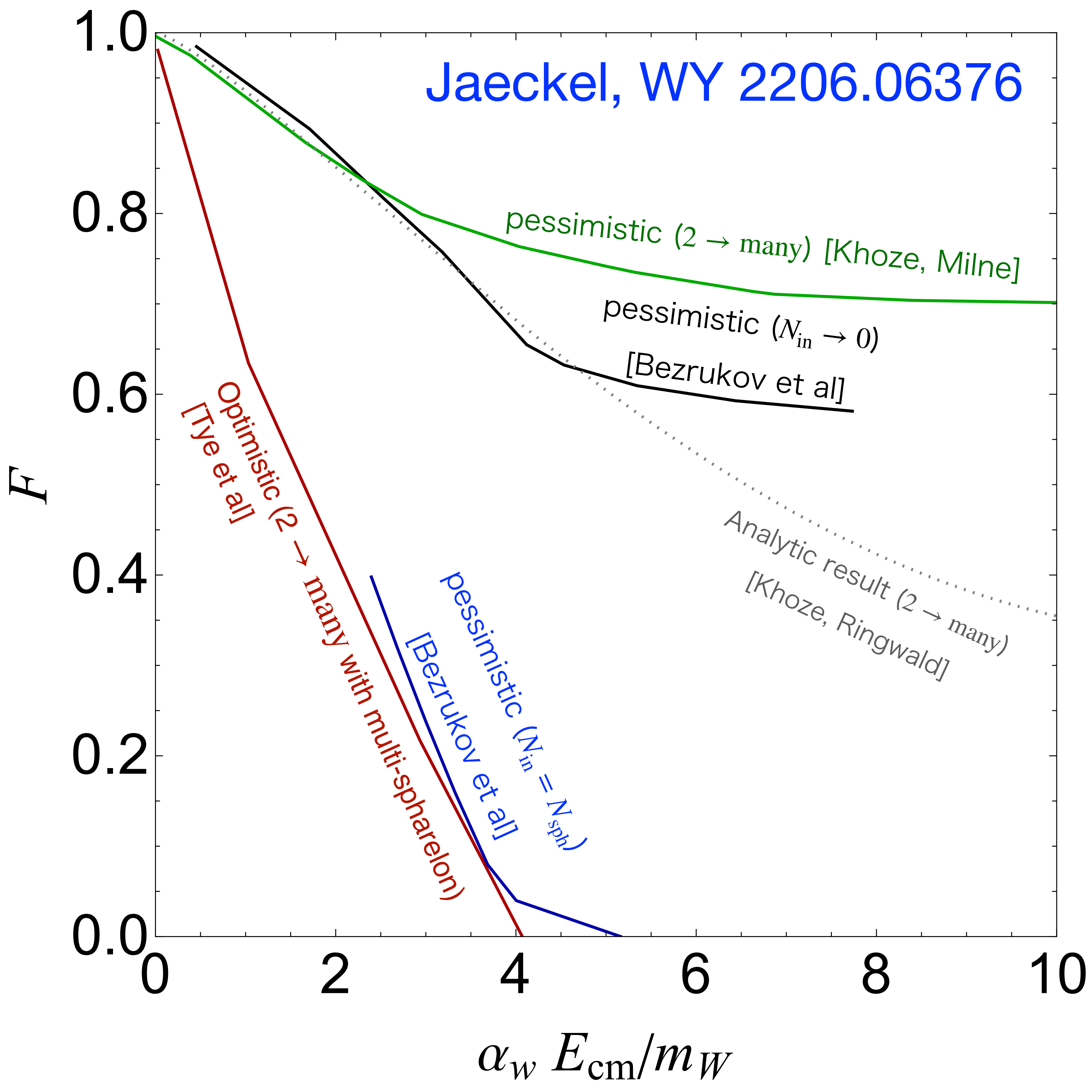
$$\sigma_{\rm sph} \approx \frac{1}{E_{\rm cm}^2} \exp\left(-\frac{4\pi}{\alpha_w} F(E_{\rm cm}) \right)$$





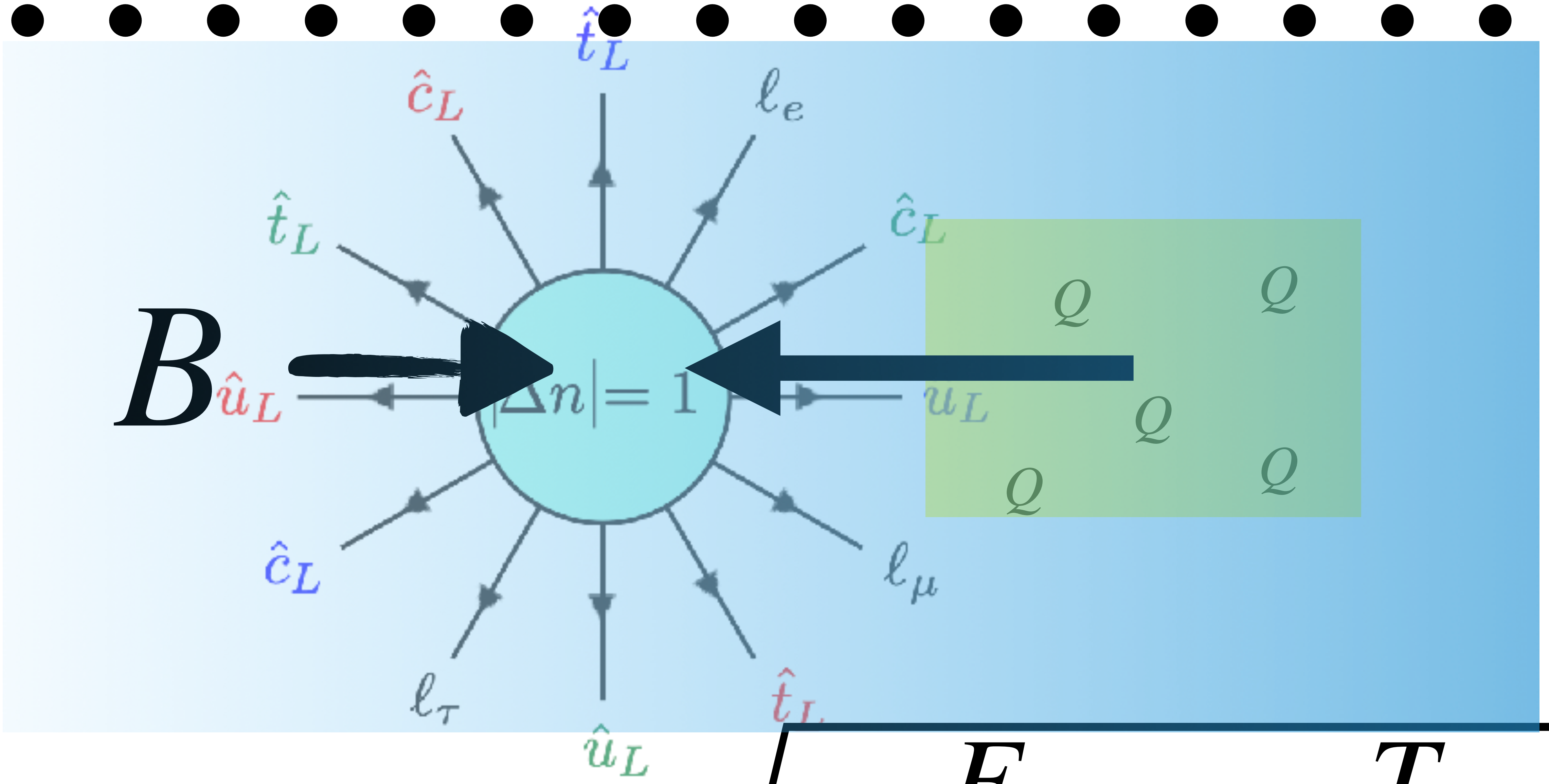
Kazuki Sakurai's slide

J.Ellis, KS, M.Spannowsky [1603.06573]

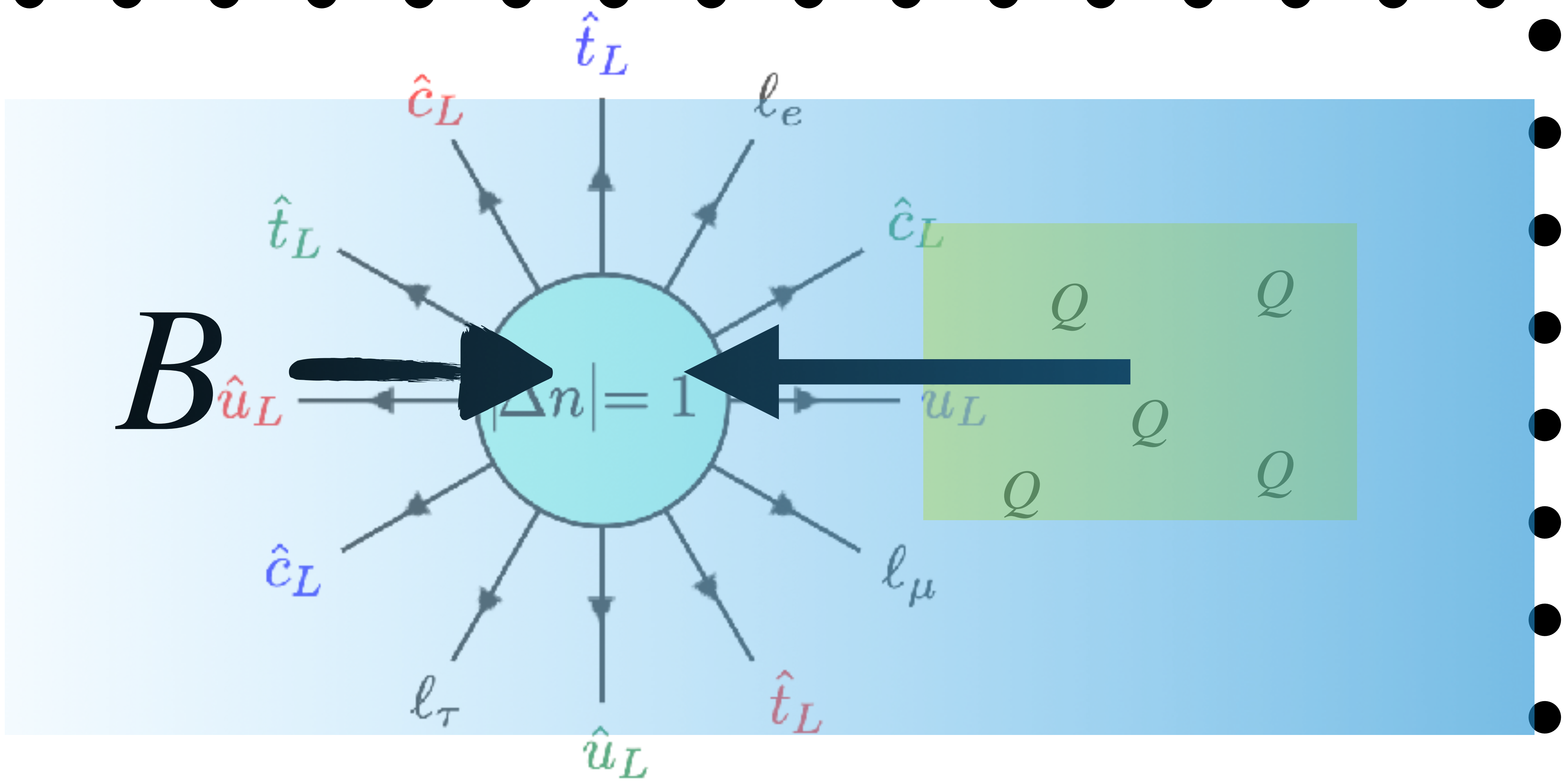


but still under debate

Relativistic bubble wall に付随する反応は重心エネルギーが高いので、スファレロンが増幅されている可能性がある。



$$E^{(2)}_{\rm cm} \sim 10^4 GeV \sqrt{\frac{E_B}{10^7\, GeV}\frac{T_R}{10\, GeV}}$$



$$E^{(2)}_{\rm cm} \sim 10^4 GeV \sqrt{\frac{E_B}{10^7\, GeV}\frac{T_R}{10\, GeV}}$$

$$\Delta n_B \sim \epsilon_{\rm CPV} T^3_{\rm nuc} \theta^2$$

$$\Gamma_{\rm sph} \sim \sigma_{\rm sph} T_R^3$$

$$\Delta n_{Baryon} \sim \Delta n_B \times \frac{\Gamma_{\rm sph}}{\Gamma_{\rm th}}$$

Boost BがThermalize/decay
するまでにsphaleronが起きる回数

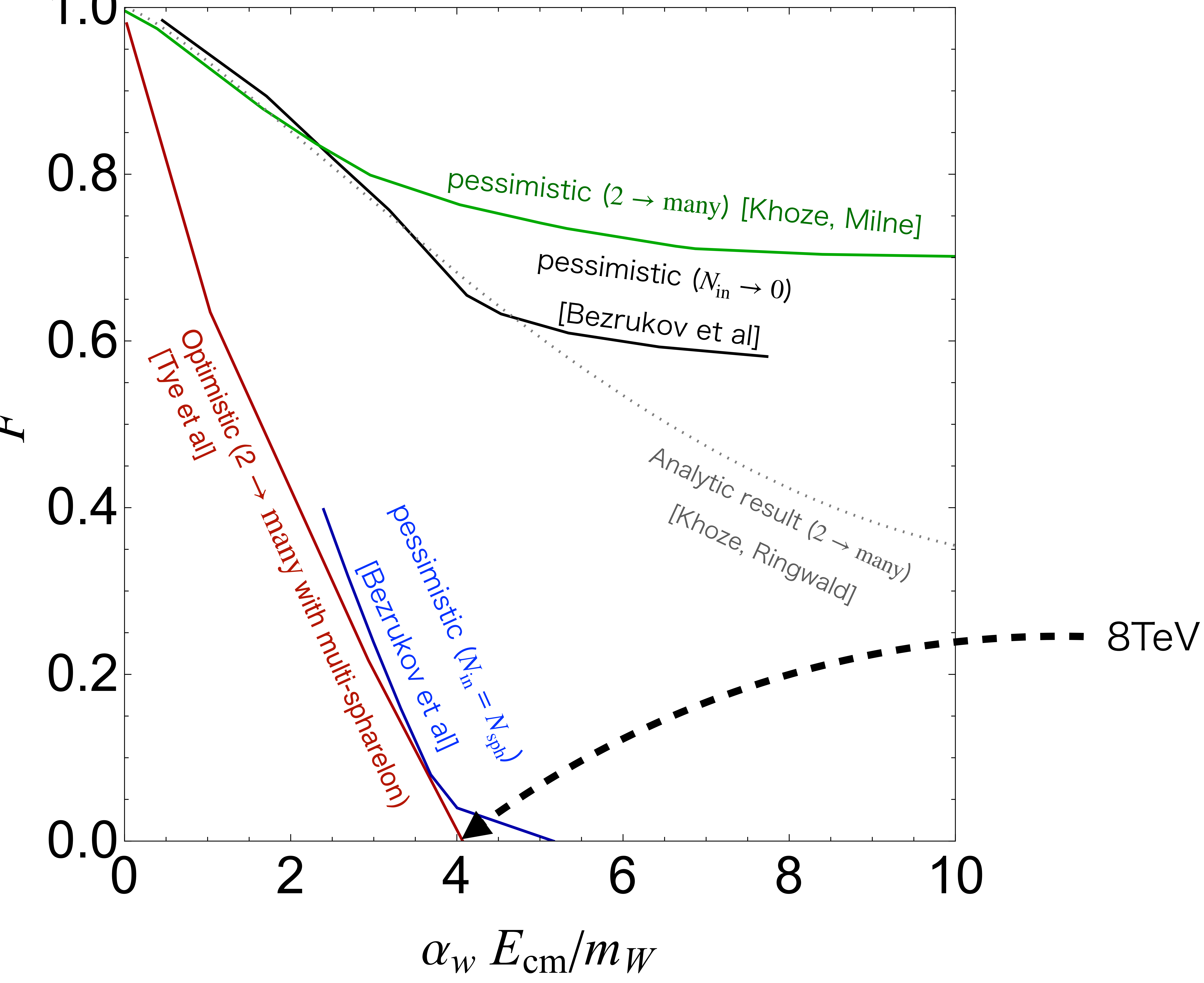
$$\Rightarrow \quad \theta^2 \frac{\Gamma_{\rm sph}}{\Gamma_{\rm th}} \epsilon_{\rm CPV} \sim 3 \times 10^{-7} \left(\frac{T_R/T_{\rm nuc}}{10}\right)^3$$

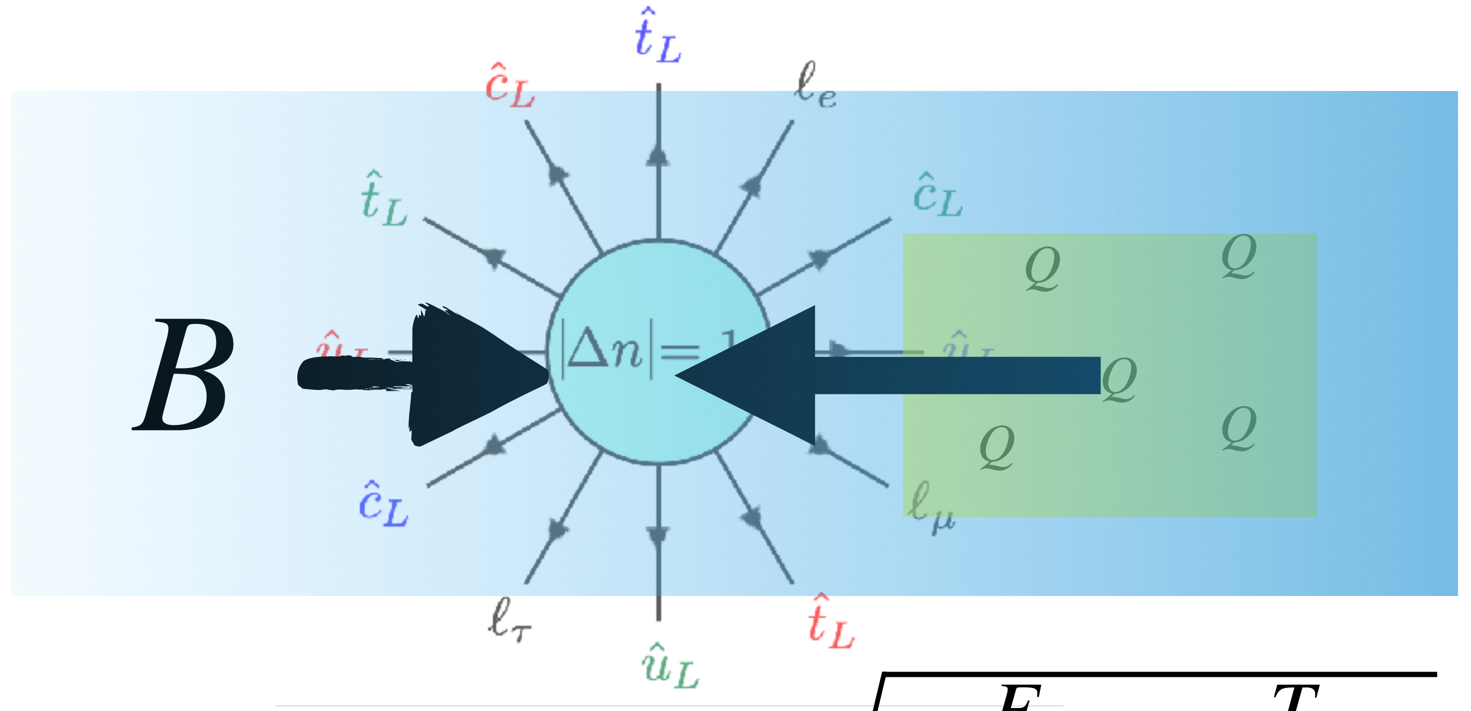
- B :SU(2) charged BSM particle

BSM soon decays into left handed SM particle

- $\frac{\Gamma_{\rm sph}}{\Gamma_{\rm th}} \lesssim 1$, since $\Gamma_{\rm sph}$ contributes to thermalization

Optimisticな場合にはバリオン数は充分





$$E_{\rm cm}^{(2)} \sim 10^4 GeV \sqrt{\frac{E_B}{10^7\, GeV}\frac{T_R}{10\, GeV}}$$

$$\theta^2 \frac{\Gamma_{\rm sph}}{\Gamma_{\rm th}} \epsilon_{\rm CPV} \sim 3 \times 10^{-7} \left(\frac{T_R/T_{\rm nuc}}{10}\right)^3$$

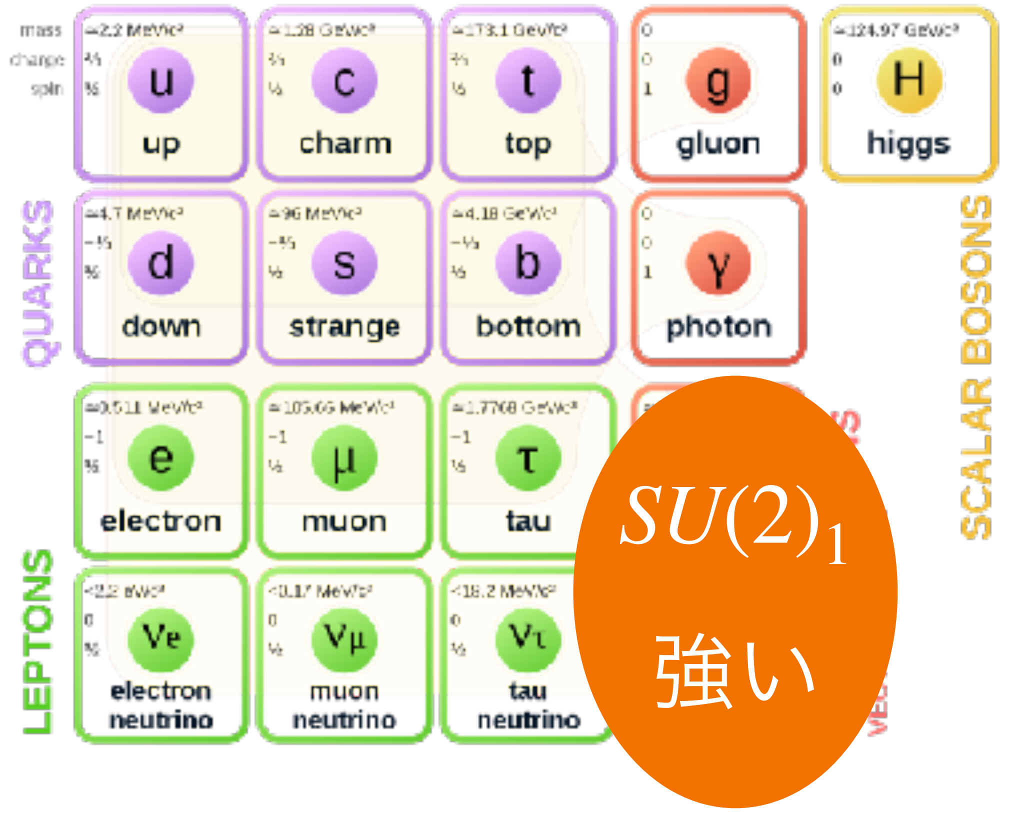
Pessimistic case: sphaleron を高いエネルギーで増幅する模型は簡単

No flavor, proton decay, neutron oscillation 問題

$SU(3)_c \times \color{red}{SU(2)_1} \times SU(2)_2 \times U(1)_Y$ $\qquad \mathscr{L} = -\frac{1}{4g_1^2} F_1 F_1 + \mathscr{L}_{H_b} + \mathscr{L}_{\rm SM}(A_2)\,,$

構成要素 $@\mu_{RG} \gg \text{BSM scale} \gtrsim \text{TeV}$

SM **但し$SU(2)_1$の強い**



Wikipedia

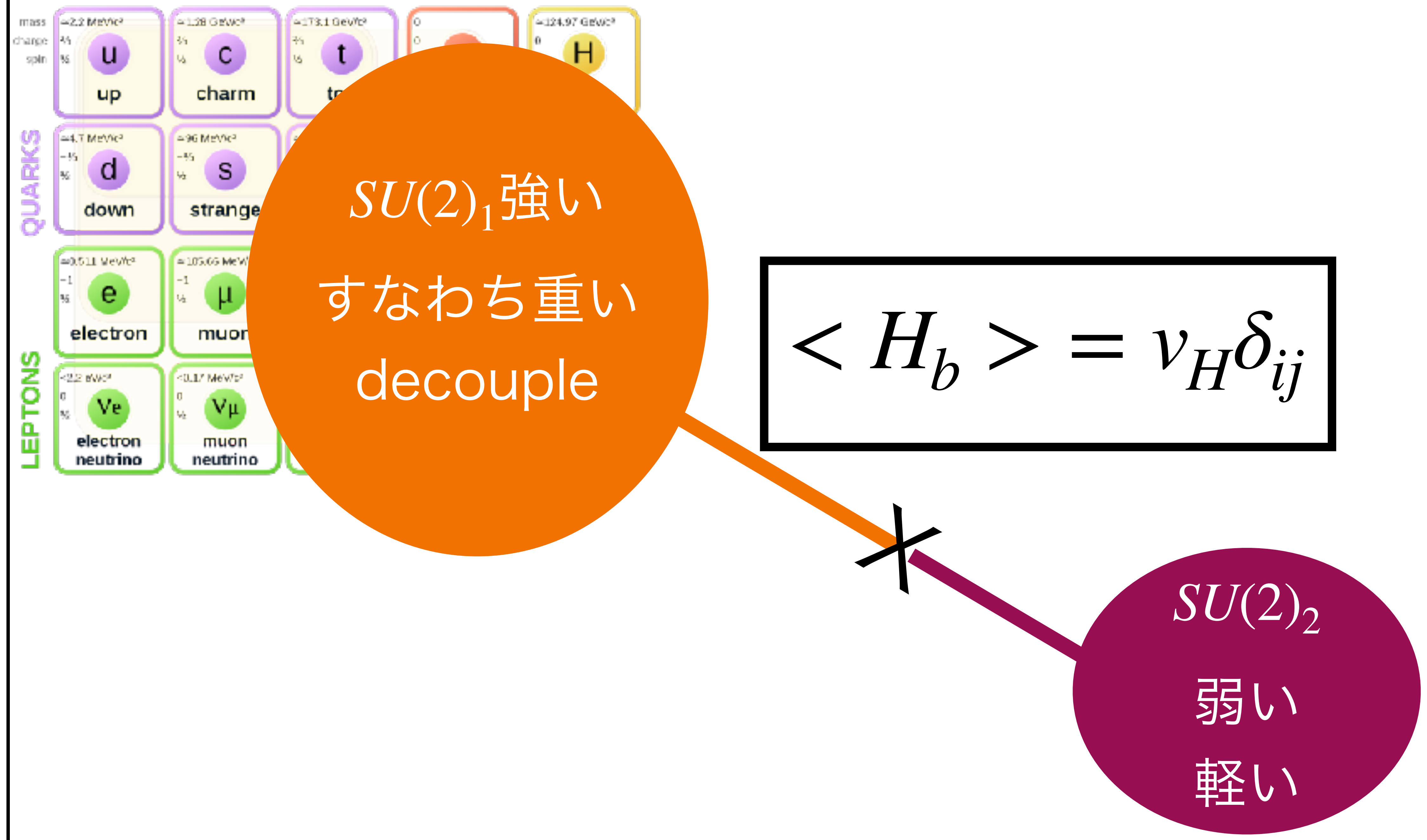
$+$ H_b $+$ $SU(2)_2$ 弱い

$2_1 \times 2_2$ Higgs

弱い pure SU(2)

SMフェルミオンに結合しているゲージ場の
スファレロンもインスタントンも増幅, e.g. $1/\alpha_1 \sim 1$

構成要素 $@\mu_{RG} \ll \text{BSM scale}$



$< H_b > = v_H \delta_{ij}$

ゲージ場混合により、弱い$SU(2)_2$
が低エネルギーで$SU(2)_L$になる->SM

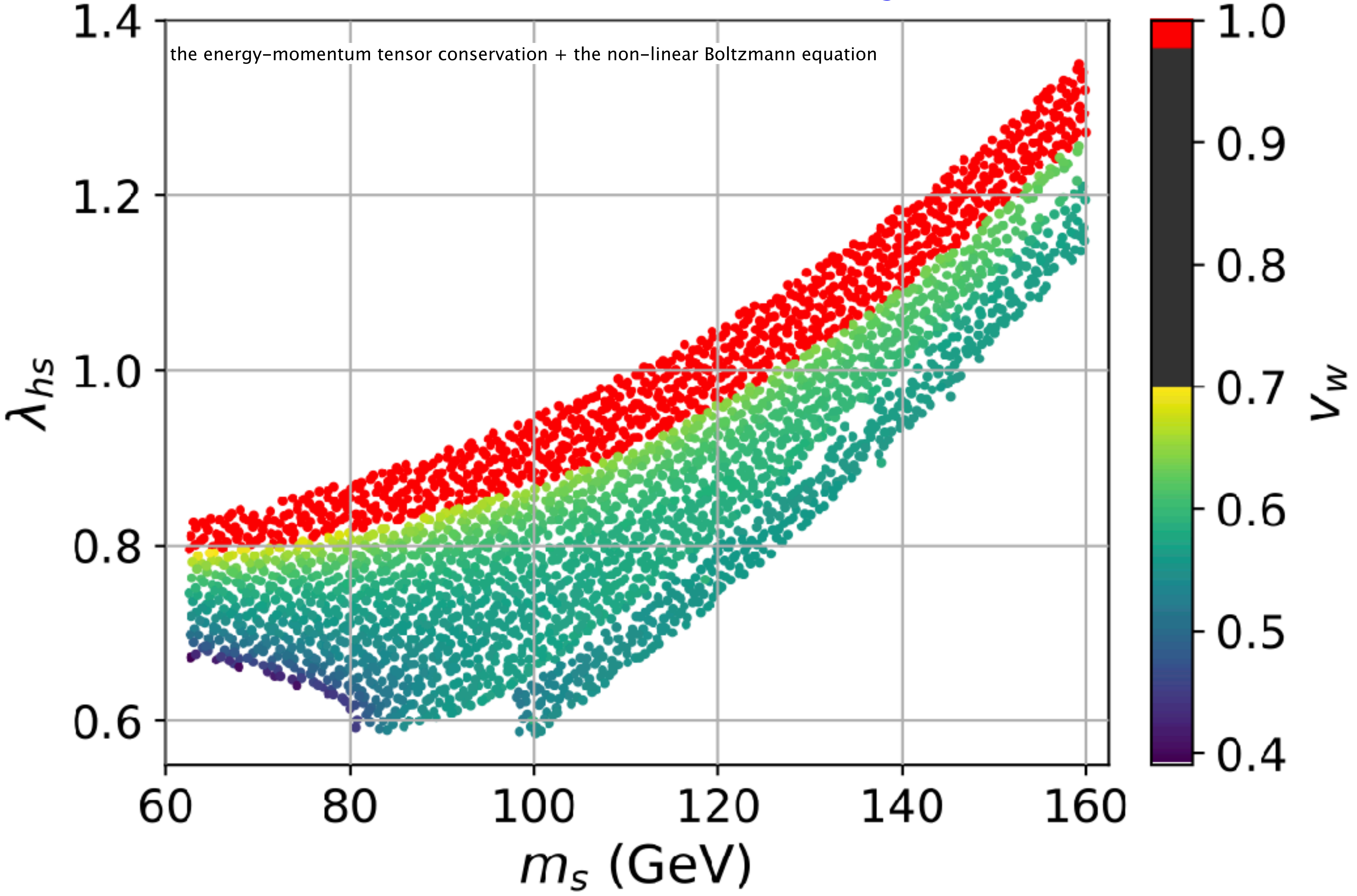
Conclusions,

電弱相転移でバリオン数が生成されるシナリオは重要。
電弱バリオン数生成以外のシナリオを作ってみた。

- 強い相転移のultra-relativistic bubbleとプラズマは高エネルギー素粒子反応を引き起こす。
- 重い、エネルギッシュな粒子が作れる。
- CPV起こる。
- 高エネルギー反応のスファレロンで、バリオン数破れる。

Bubble wall velocity, non-relativistic

Benoit Laurent, James M. Cline, 2204.13120+ Singlet extension



Ariel M´egevand, Alejandro D. S´anchez, arXiv:0908.3663

than detonations. Nevertheless, for models with extra bosons, which give a strongly first-order phase transition, the deflagration velocity is in general quite high, $0.1 \lesssim v_w \lesssim 0.6$. Therefore, such phase transitions may produce an important signal of gravitational waves. On the other hand, models with extra fermions which are strongly coupled to the Higgs boson may provide a strongly first-order phase transition and small velocities, $10^{-2} \lesssim v_w \lesssim 10^{-1}$, as required by electroweak baryogenesis.

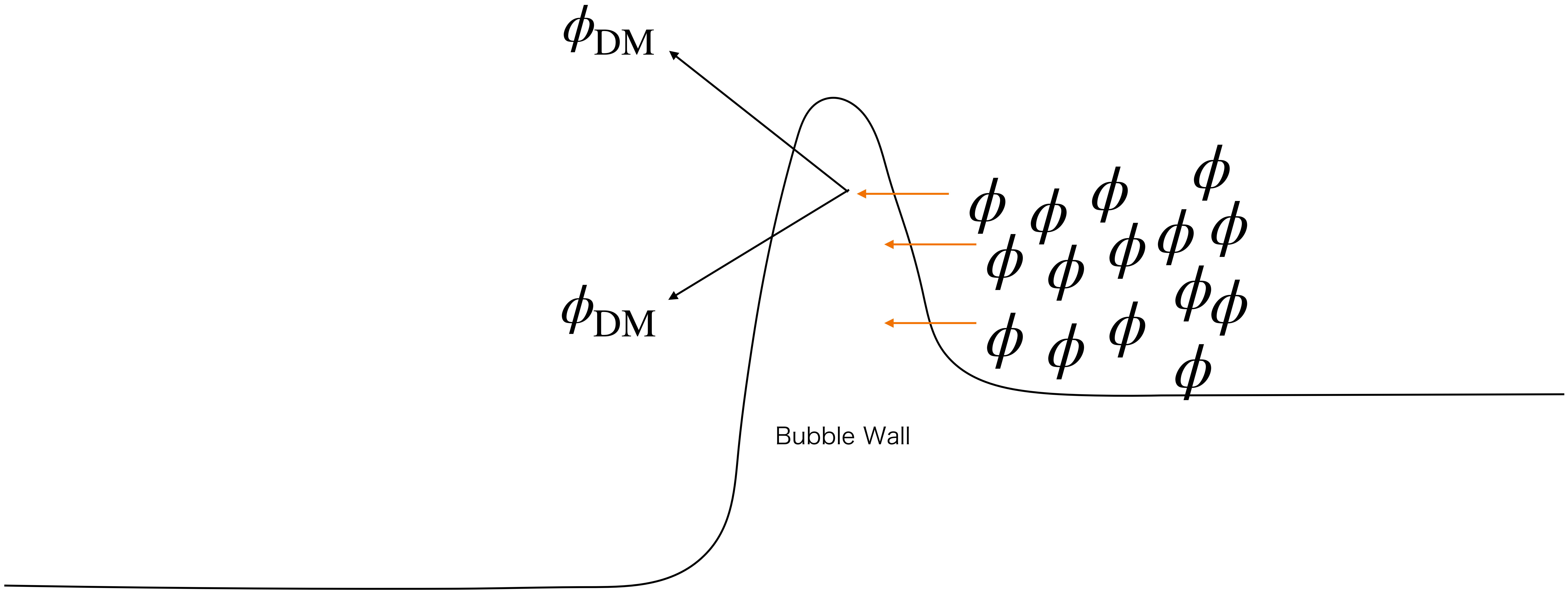
c.f. EWBG, $v_w \lesssim 0.1$

速度の計算が難しい?

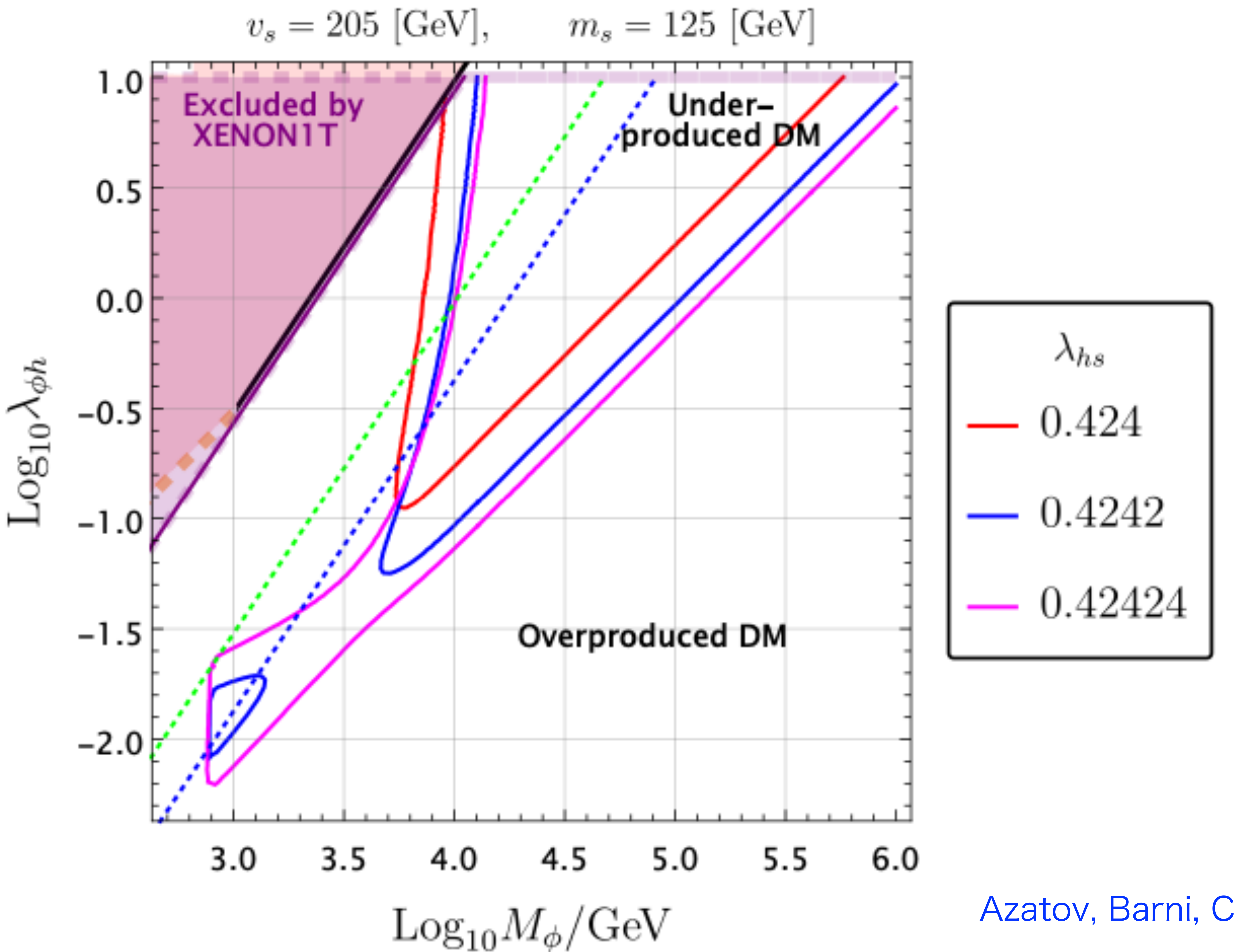
応用:$\phi_w\phi$-> XXも可能, Heavy Higgs portal DM

Azatov, Vanvlasselaer, WY 2101.05721

$$\delta\mathscr{L} = -\frac{1}{2}(\lambda_p|\phi|^2 + m_{\rm DM}^2)\phi_{\rm DM}^2$$



重めDMの予言が著しく変わる。



複数の効果:

- Bubble-expansion
- Super-cooling
- Freeze-out
- Freeze-in

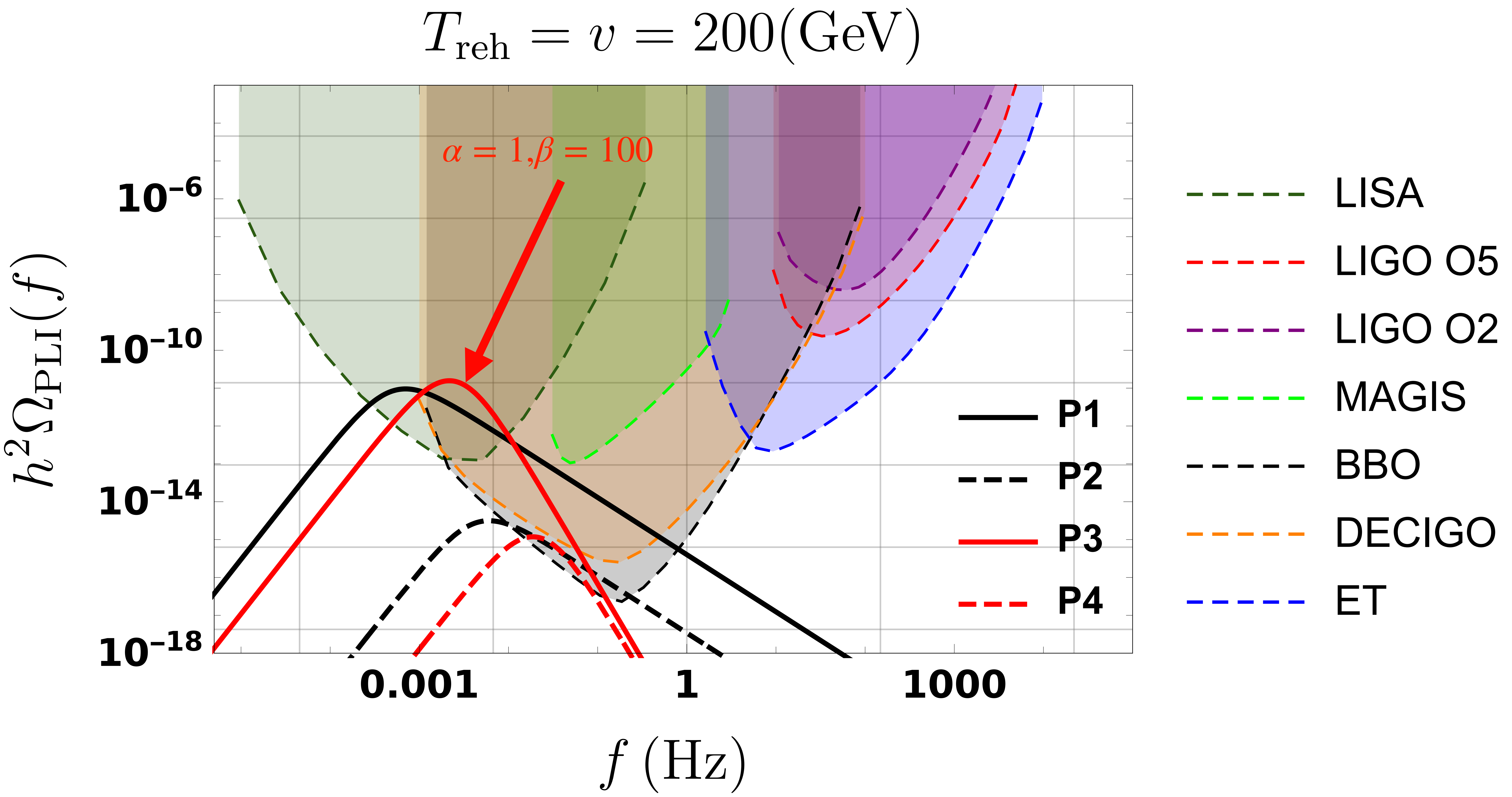
Higgs portal DMは将来的にXENONnT, Darwin CTAで探索可能。+重力波

Azatov, Vanvlasselaer, WY 2101.05721

Azatov, Barni, Chakraborty, Vanvlasselaer and WY,2207.02230

GW from FOPT with relativistic bubble wall

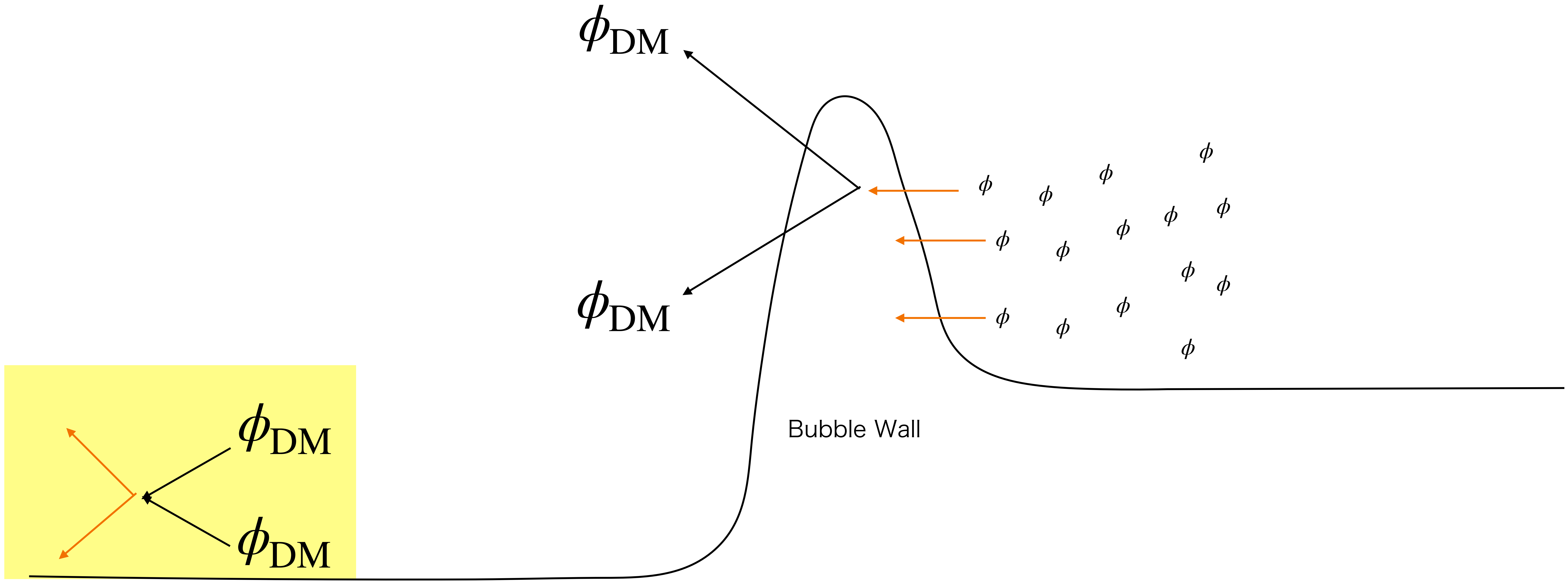
A.~Azatov, M.~Vanvlasselaer and WY, 2101.05721

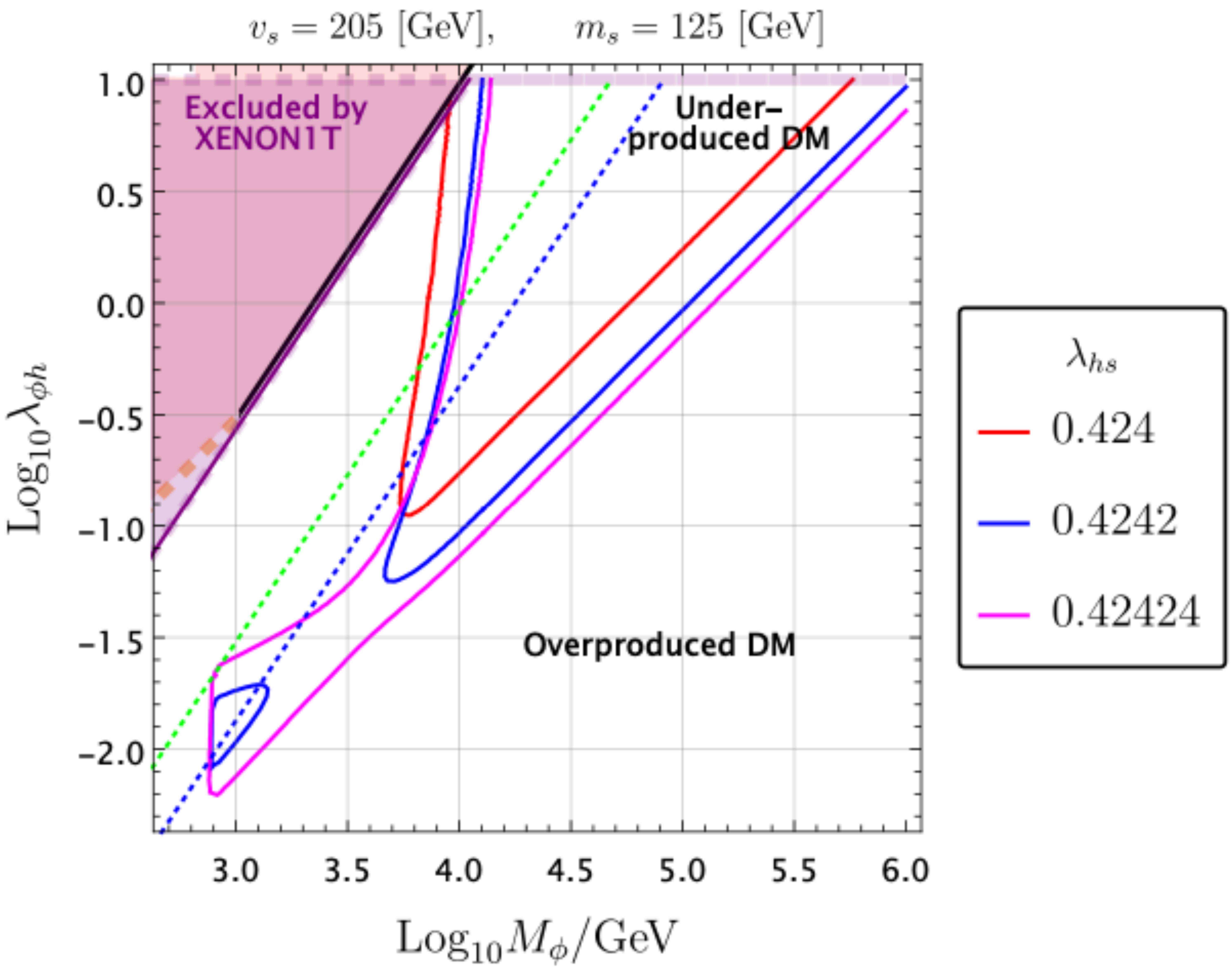


Heavy Higgs portal DM is compatible

Azatov, Vanvlasselaer, WY 2101.05721

$$\delta \mathscr{L} = -\frac{1}{2}(\lambda_p |\phi|^2 + m_{\rm DM}^2)\phi_{\rm DM}^2$$



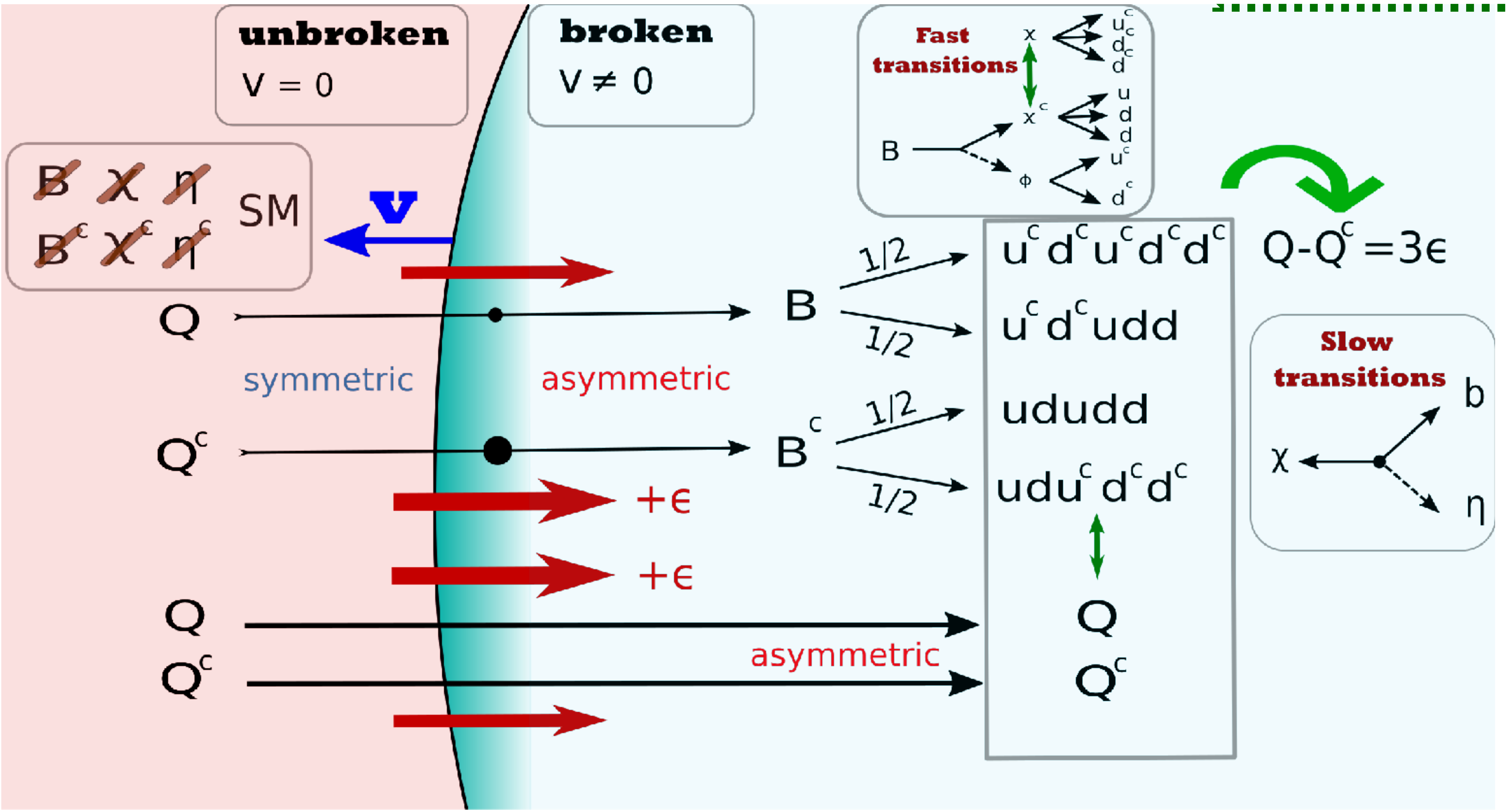


$v_s = 205$ [GeV], $m_s = 125$ [GeV]
Excluded by XENON1T
Under-produced DM
Overproduced DM
$\mathrm{Log}_{10}\lambda_{\phi h}$
$\mathrm{Log}_{10}M_\phi/\mathrm{GeV}$
λ_{hs}
0.424
0.4242
0.42424

A baryogenesis model

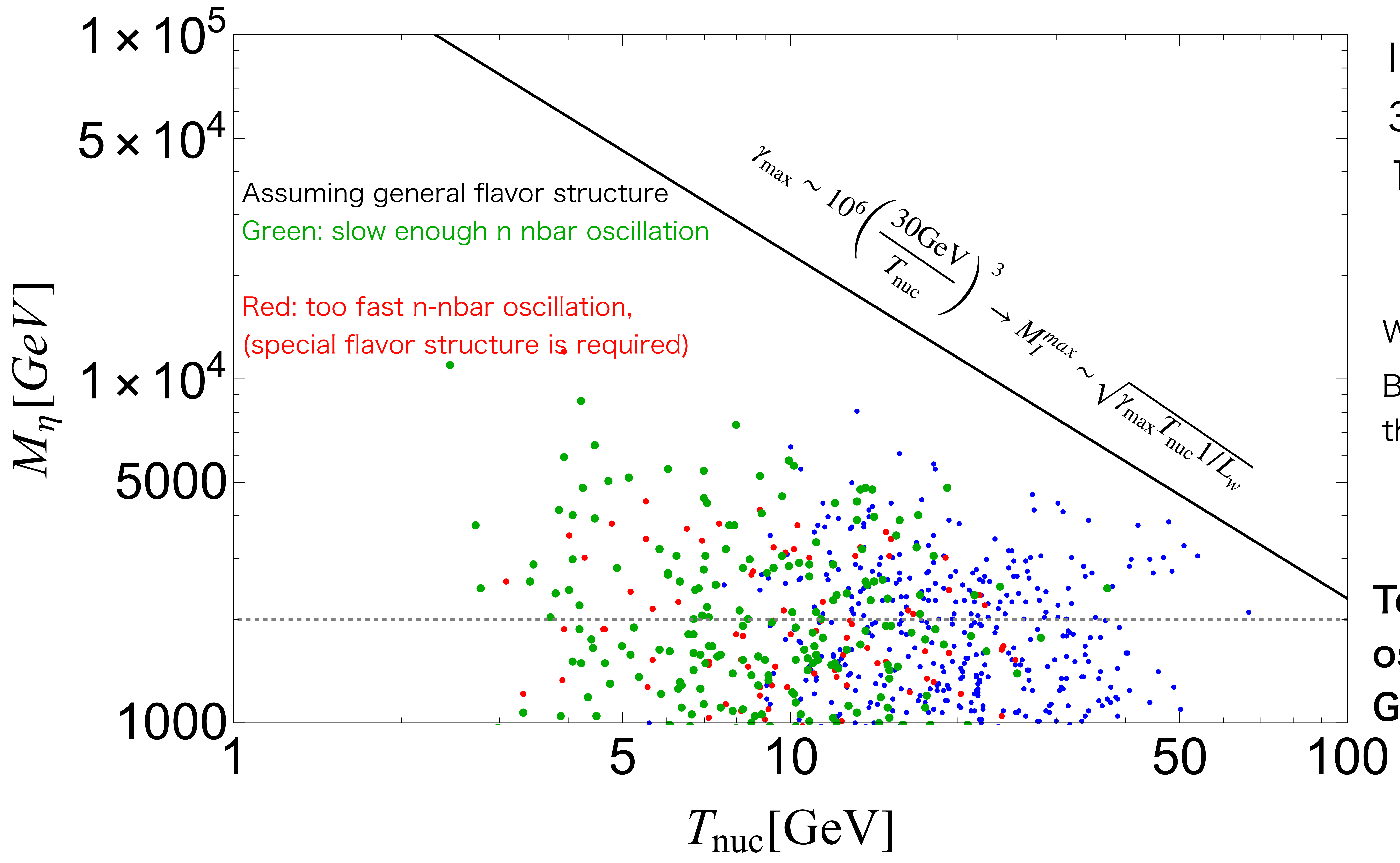
$$\mathscr{L} = -\sum_{I=1,2} M_I \bar{B}_I B_I + Y_I(\bar{B}_I \phi) P_L Q + y_I \eta^* \bar{B}_I P_R \chi + h.c. - V(\phi)$$

$$+\kappa \eta^c du + \frac{1}{2} m_\chi \bar{\chi}^c \chi - m_\eta^2 |\eta|^2 + h.c.$$



Parameter region assuming $M_I > m_\chi > m_\eta$

Azatov, Vanvlasselaer, WY, 2106.14913



Irrelevant constraints:

3 loop EDM,

1 loop FCNC.

Washout by $\chi \leftrightarrow \eta d$, which is Boltzmann suppressed thanks to the heavy scales, is taken into account.

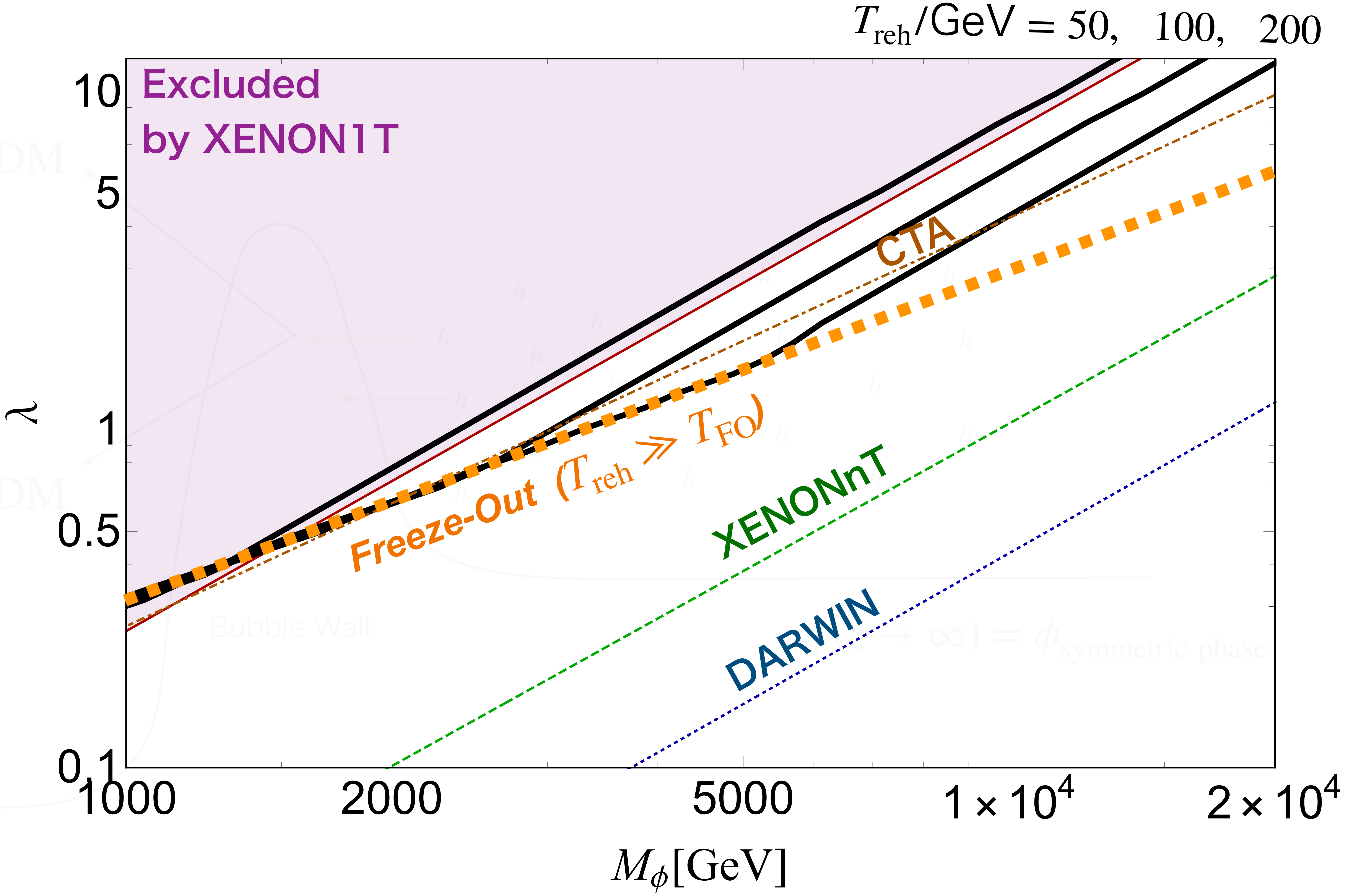
Tested in neutron-antineutron oscillation and colliders.

GW is a robust prediction!

Heavy Higgs portal DM is compatible

Azatov, Vanvlasselaer, WY 2101.05721

$$\delta\mathscr{L} = -\frac{1}{2}(\lambda_p|\phi|^2 + m_{\rm DM}^2)\phi_{\rm DM}^2$$



Comparison with the other calculations

- Our results reproduce the results of original Bodeker-Moore paper 1703.08215 i.e. LO pressure $\mathcal{P}^{LO} \propto T^2 \Delta M^2$, $\mathcal{P}^{NLO} \propto \gamma T^3 \Delta M$
- Calculations of 2005.10875 and 2010.08013 find the pressure scaling $\mathcal{P} \propto \gamma^2$, but these calculations assume local thermal equillibrium , not applicable for ultra-relativistc bubbles.
- 2005.10875 for ultra-relativistic bubbles "ballistic limit" reproduces LO result of Bodeker-Moore

The calculation of 2007.10343 (Hoeche et al) found $\mathcal{P}^{NLO} \propto \gamma^2 T^4$ in disagreement with our result as well as original BM paper

Taken from Azatov's slide

Comments/questions on 2007.10343

$$\boxed{\mathcal{P}^{NLO} \simeq \#\alpha_W \gamma^2 T^4 + \#\alpha_{QCD} \gamma^2 T^4 \quad ?}$$

- Pressure is independent of order parameter, in the limit of zero symmetry breaking when there is no electroweak symmetry breaking

$$v_{EW} \to 0, \quad \mathcal{P} \neq 0?$$

  Physics intuition tells us that $\mathcal{P} \to 0$ in this limit.

- Calculation ignores the bubble wall width effects, however this is motivated only if the momentum transfer is less than $\boxed{\Delta p_z < L^{-1}}$, but the pressure in (2007.10343) is dominated by the momentum transfers of order $\frac{\alpha C_F}{8\pi}\gamma T$, which can be much larger than $L^{-1} \sim v_{EW}$.

Taken from Azatov's slide