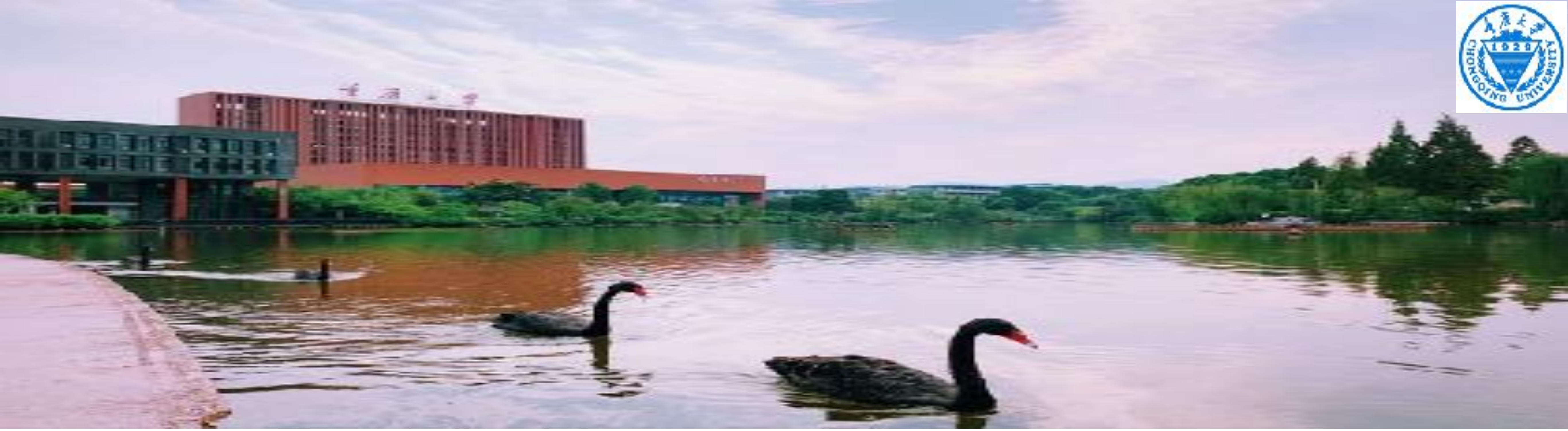

Probing BSM physics with Magnetic Fields and Gravitational waves observations

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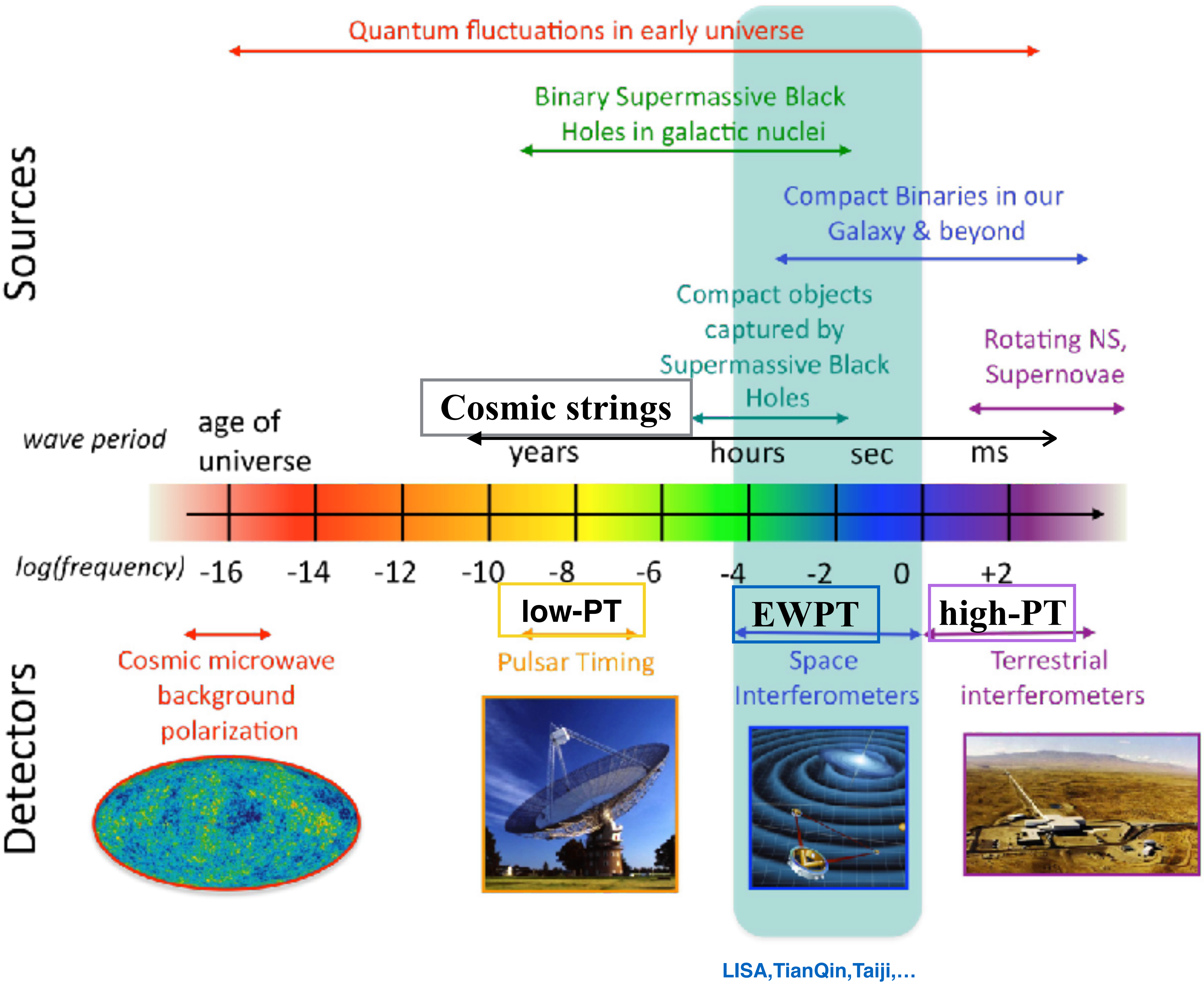
中国格点QCD第一届年会, 10/30-11/02, 2021

Contents

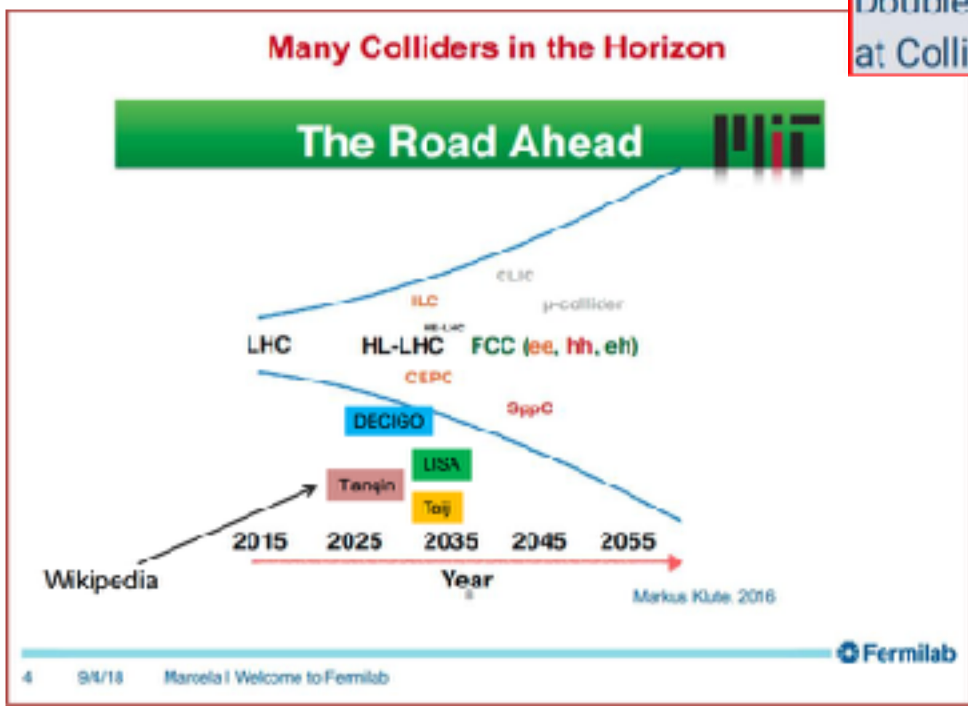
- GW from first-order phase transition
- B violation and sphaleron
- PMF from Bubble Collisions
- Future prospect

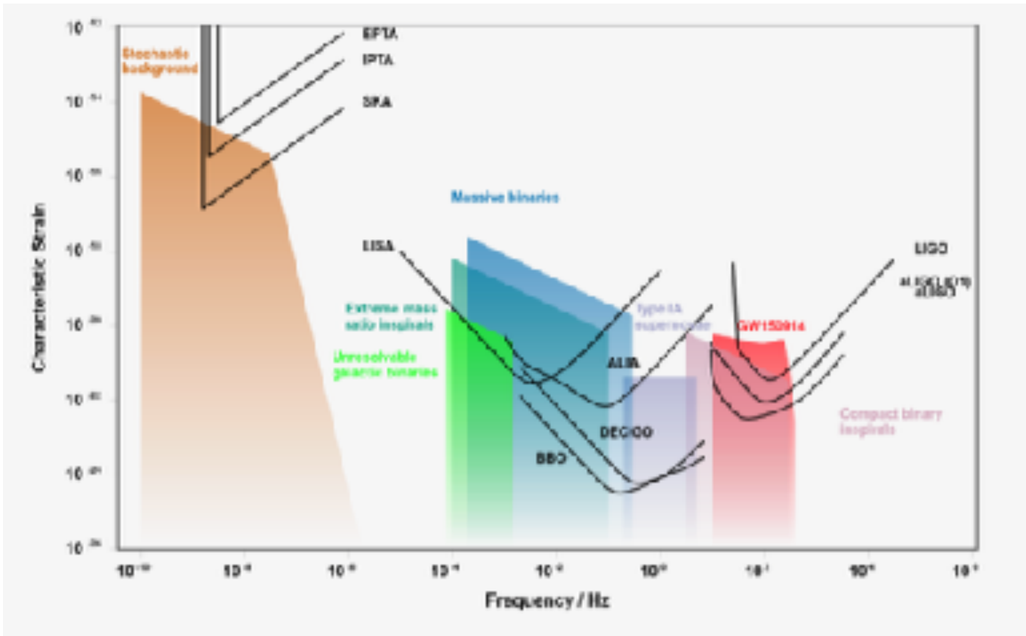
The Gravitational Wave Spectrum



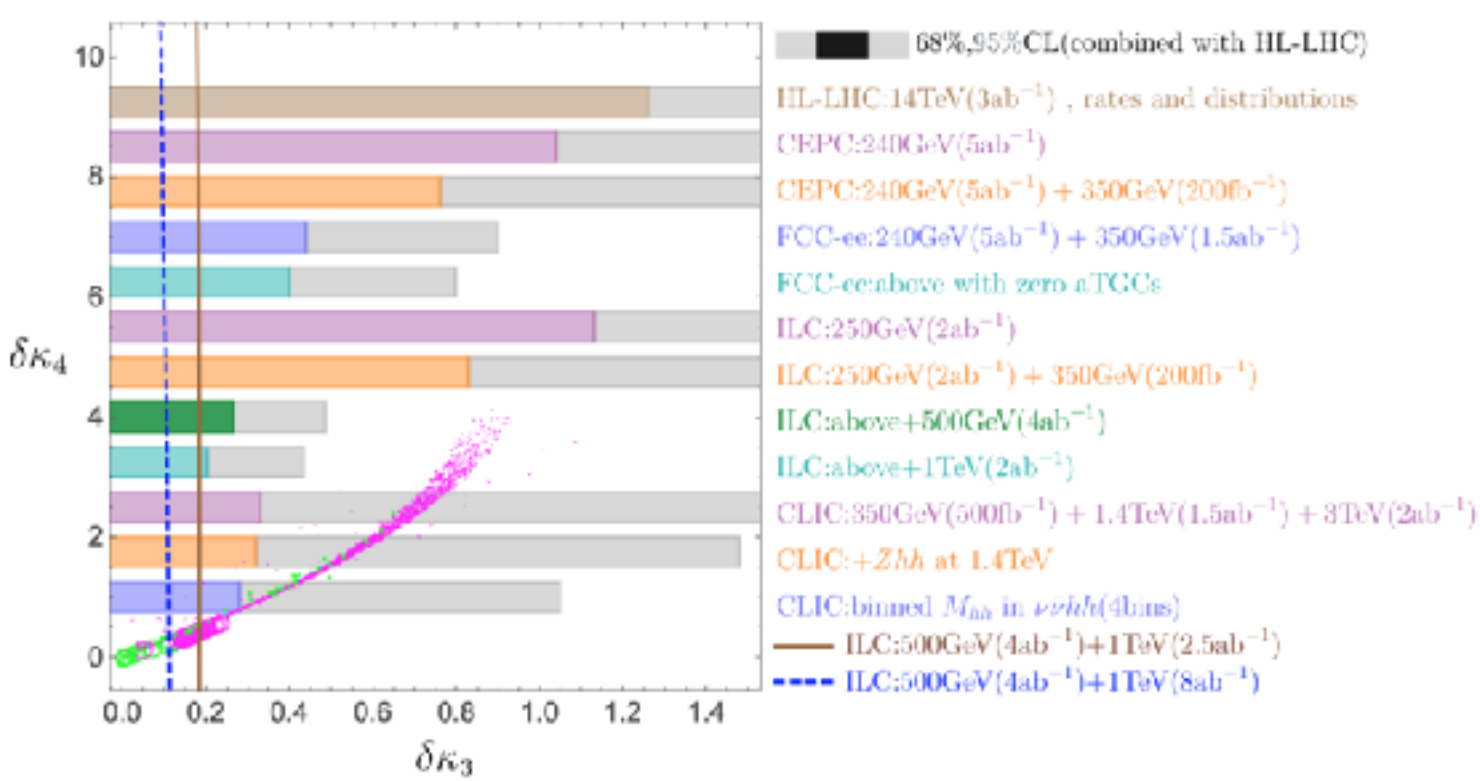
PTGW and collider search

Double Higgs Production at Colliders Workshop





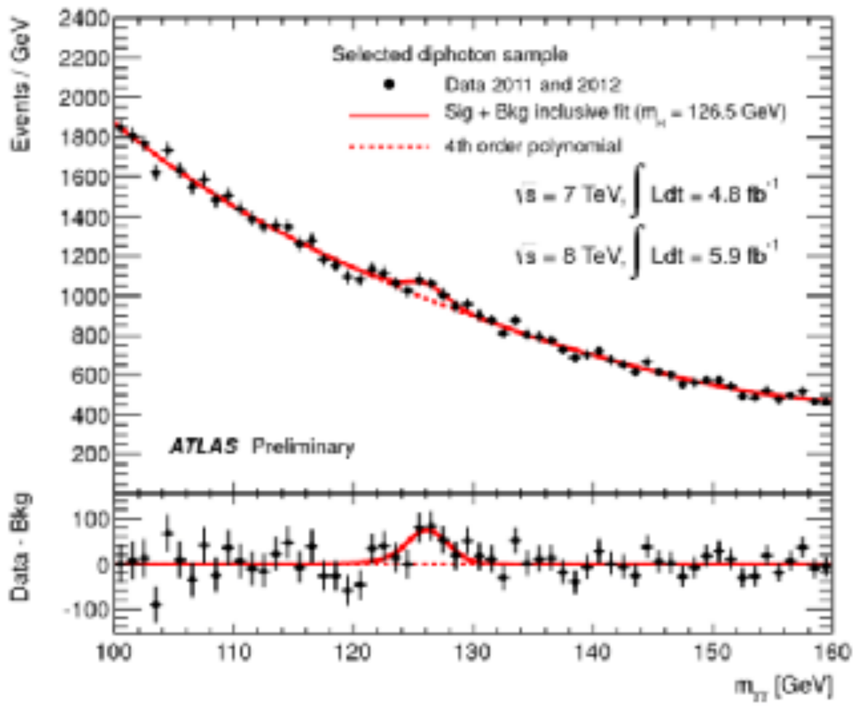
C J Moore et al. Class. Quantum Grav. 32 (2015) 015014.

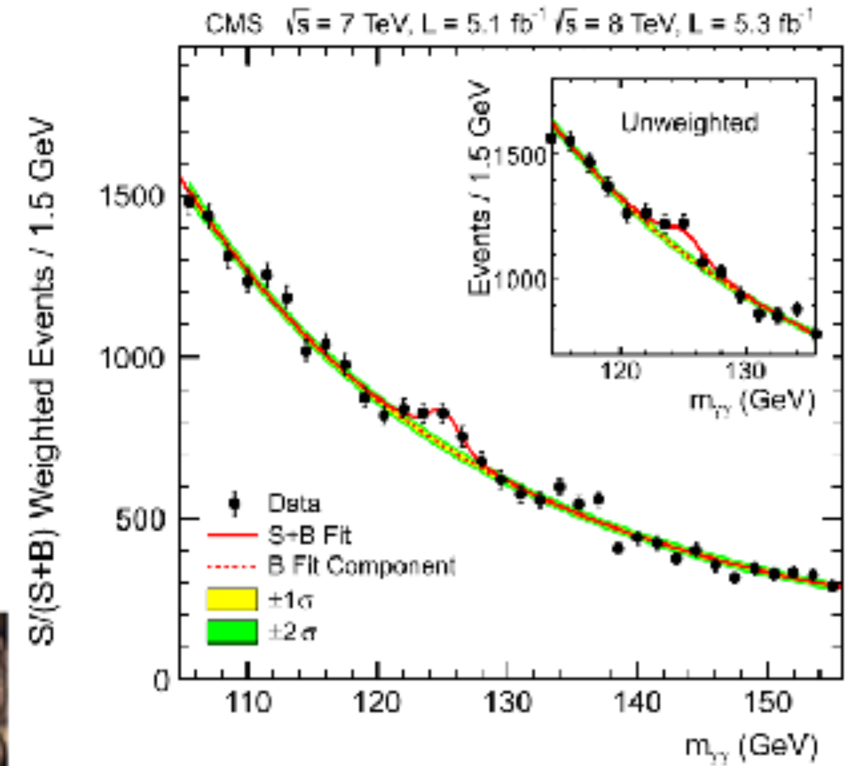


$$\Delta\mathscr{L} = -\frac{1}{2}\frac{m_h^2}{v}(1+\delta\kappa_3)h^3 - \frac{1}{8}\frac{m_h^2}{v^2}(1+\delta\kappa_4)h^4$$

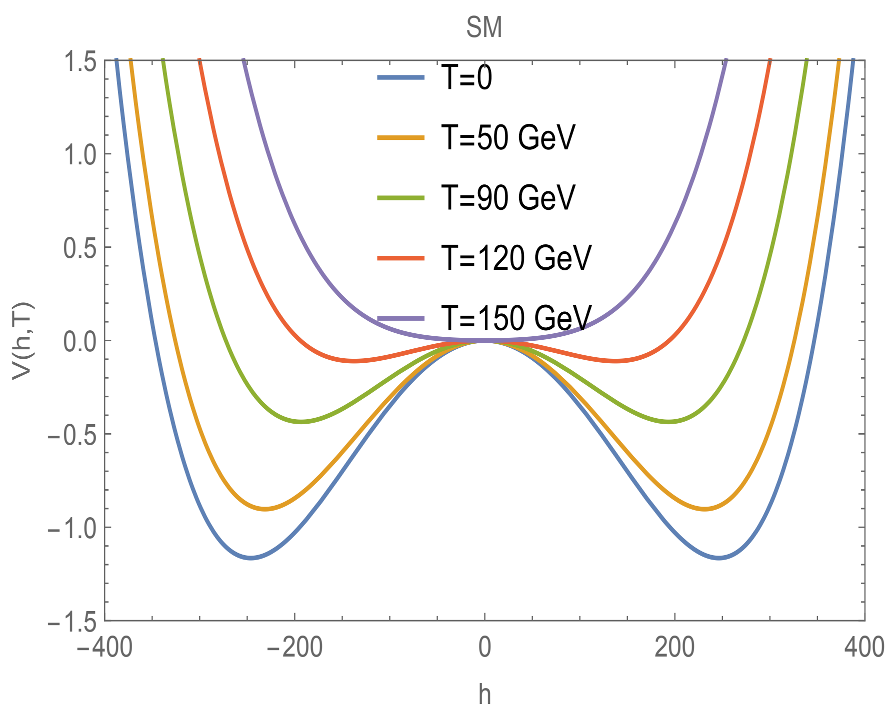
SNR > 10 for two-step and one-step SFOEWPT

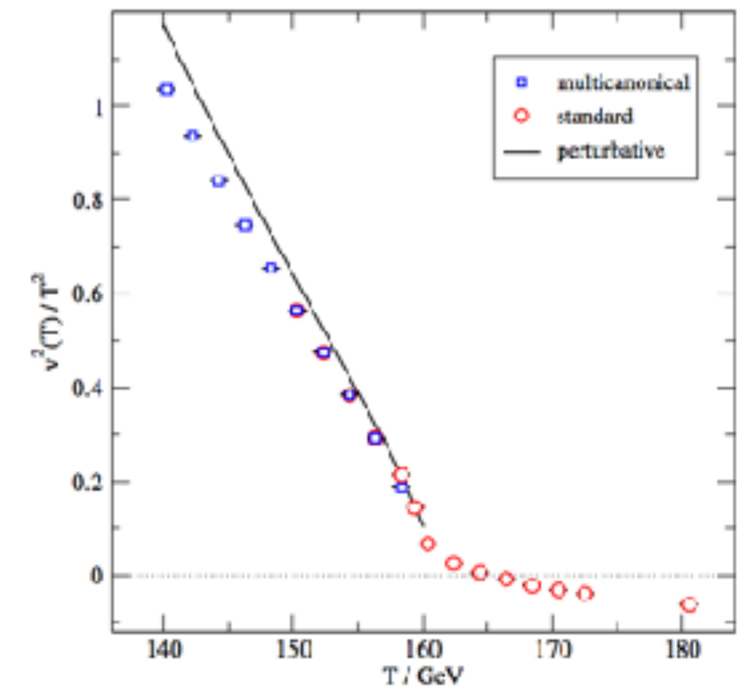
Implication of 125 GeV Higgs






Higgs announcement seminar on 4 July 2012

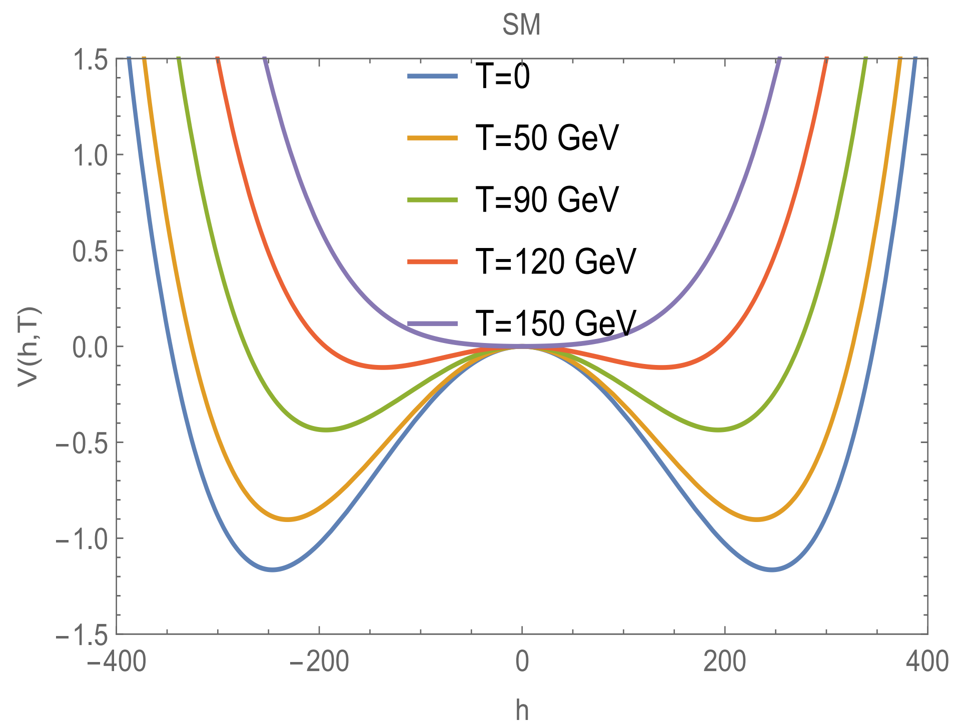


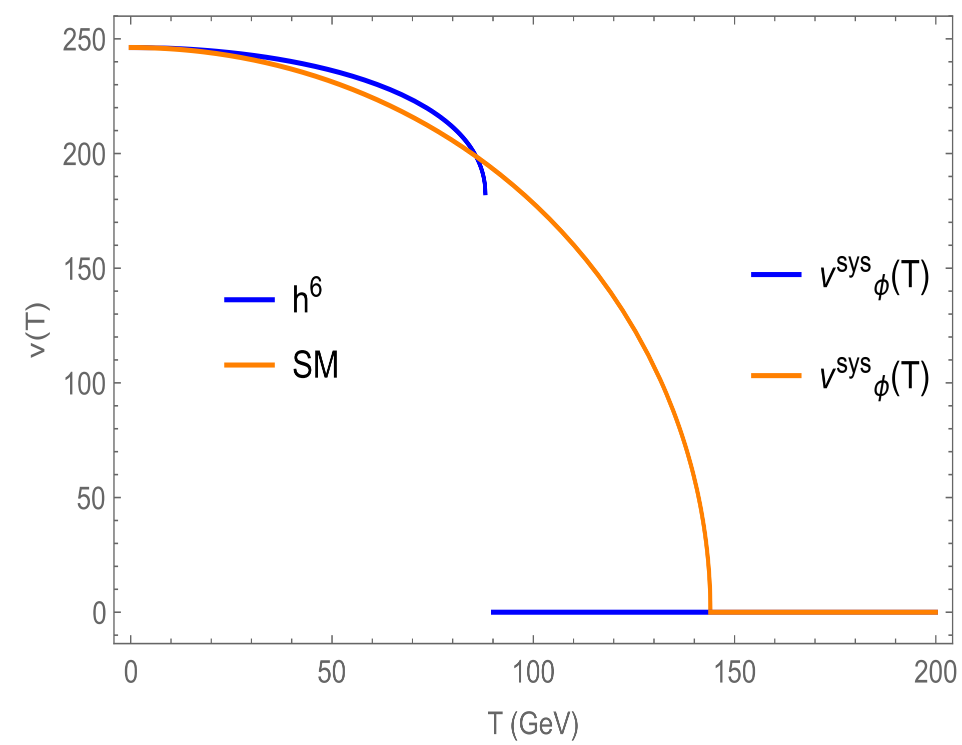


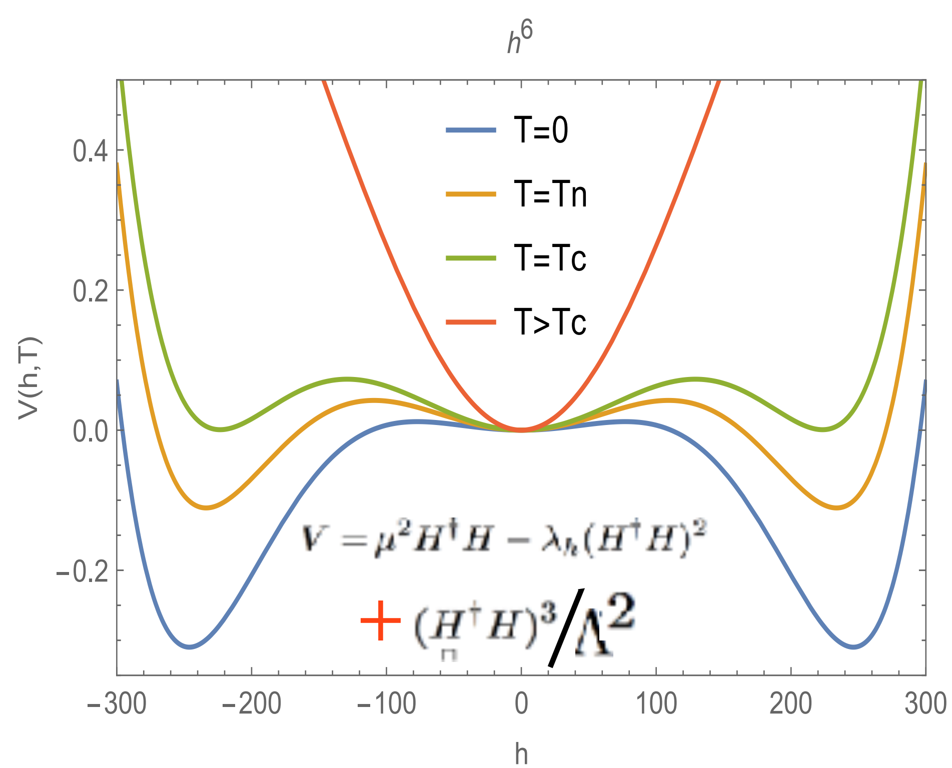
PRL 113, 141602 (2014)

Higgs Potential Shape??? EFT or ???

First or second order



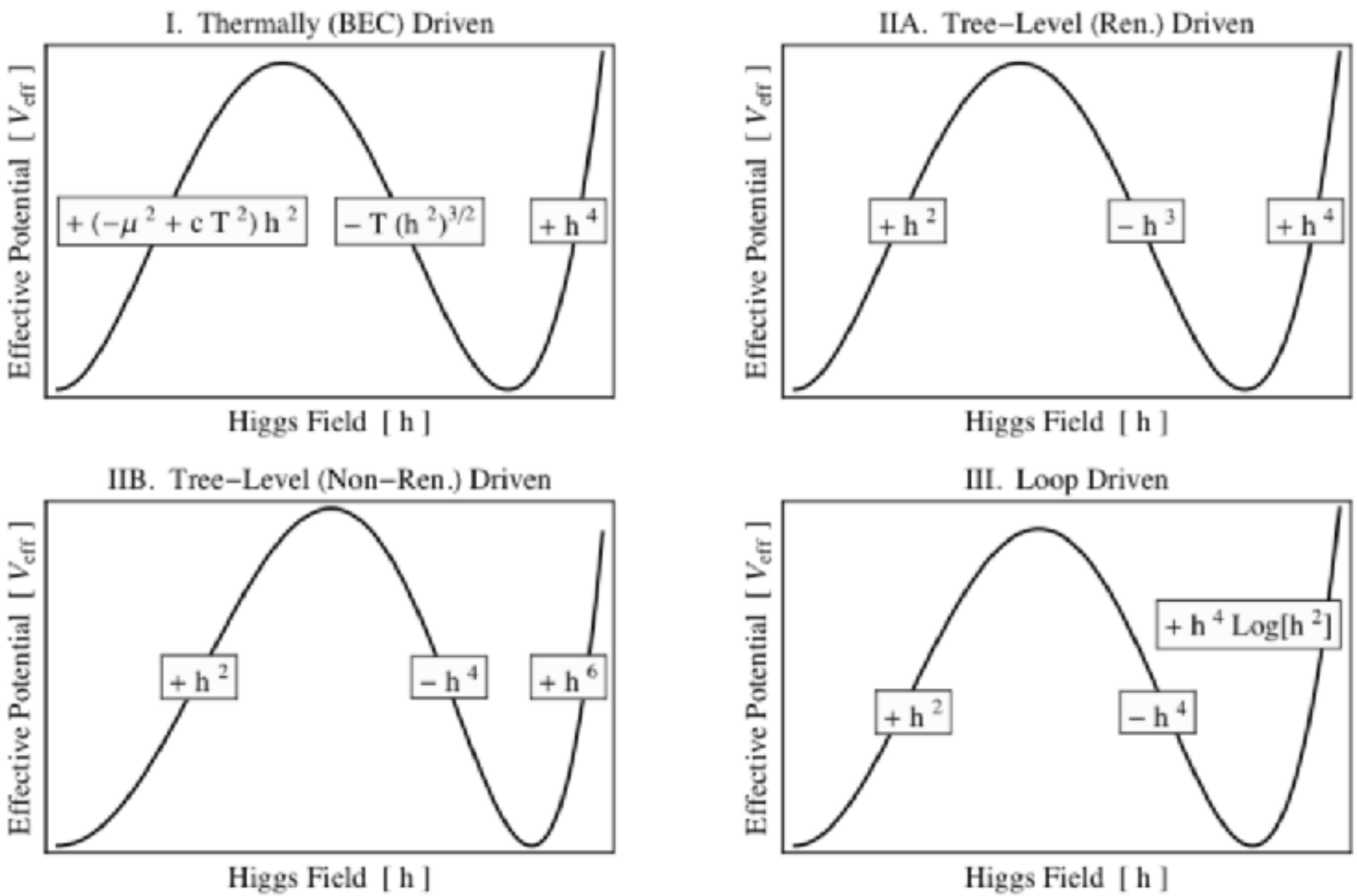




Grojean, Servant, Wells 05, P. Huang, Jokelar, Li, Wagner 15,Cao, F.P. Huang, Xie, & Zhang 17, Zhou, Bian, Guo 19

LHC say the quantum fluctuation (quadratic oscillation) around h=v with mh=126 GeV, not sensitive to the specifically potential shape

Model classes for catalyzing a strongly first order electroweak phase transition



PRD87, 023509 (2013)

BSM for EWPT

- **SM+Scalar Singlet**

Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel- Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, **Jiang, Bian, Huang, Shu 15,** Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17,**Cheng, Bian 17, Bian, Tang 18,Chen, Li, Wu, Bian,19**…

- **SM+Scalar Doublet**

Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, **Bernon, Bian, Jiang 17, Bian, Liu 18,…**

- **SM + Scalar Triplet**

Profumo, Ramsey-Musolf 12, Chiang 14, **Zhou, Cheng, Deng, Bian, Wu 18,Zhou, Bian, Guo,Wu 19,…**

- **NMSSM**

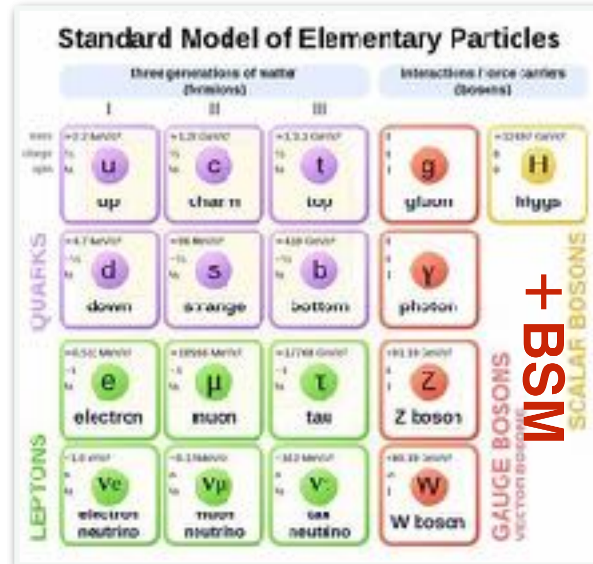
Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15, **Bi, Bian, Huang, Shu, Yin 15, Bian, Guo, Shu 17,…**

- **Composite Higgs**

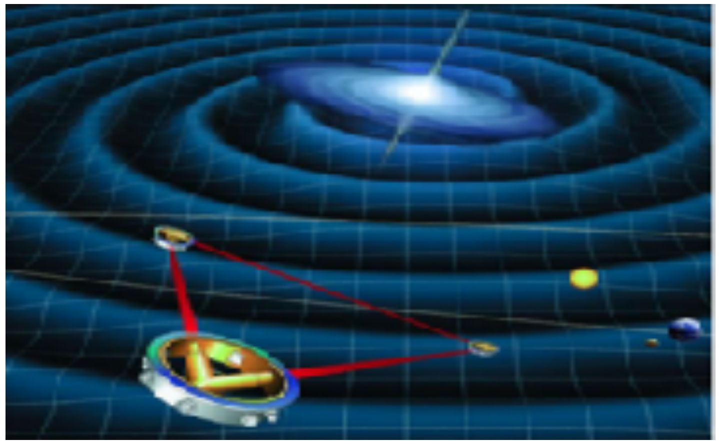
Espinosa, Gripaios, Konstandin, Riva 11, Bruggisser, Von Harling, Matsedonskyi, Servant 18, **Bian,Wu,Xie 19**, De Curtis, Delle Rose, Panico 19, **Bian,Wu,Xie 20**,…

- **EFT**

Grojean, Servant, Wells 05, Bodeker, Froome, Huber, Seniuch 05, Huang, Joglekar, Li, Wagner 15,Cai,Sasaki ,Wang17,**Zhou, Bian, Guo 19,** …



LISA,TianQin,Taiji,...



Particle physics model

↓

PT parameters

Effective action → β, H_*

Energy budget → α, $\kappa(\alpha, v_w)$

Bubble wall dynamics → v_w

→ **GW power spectrum**

Numerical simulations → $h^2\Omega_{GW}(f; H_*, \alpha, \beta, v_w)$

→ **LISA sensitivity**

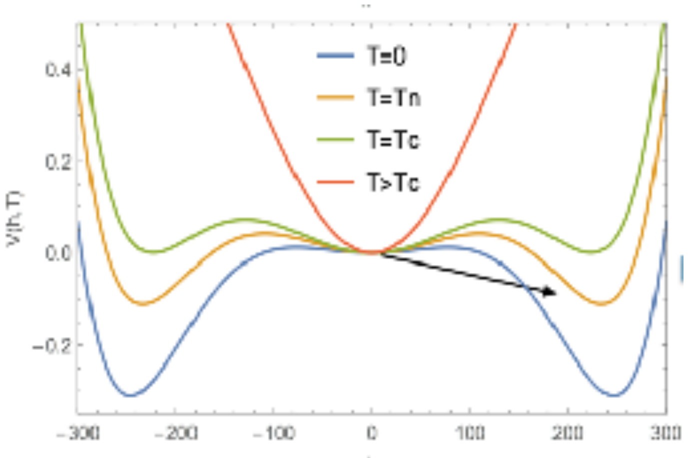
Configuration + noise level → $h^2\Omega_{sens}(f)$

↓

Signal-to-noise ratio

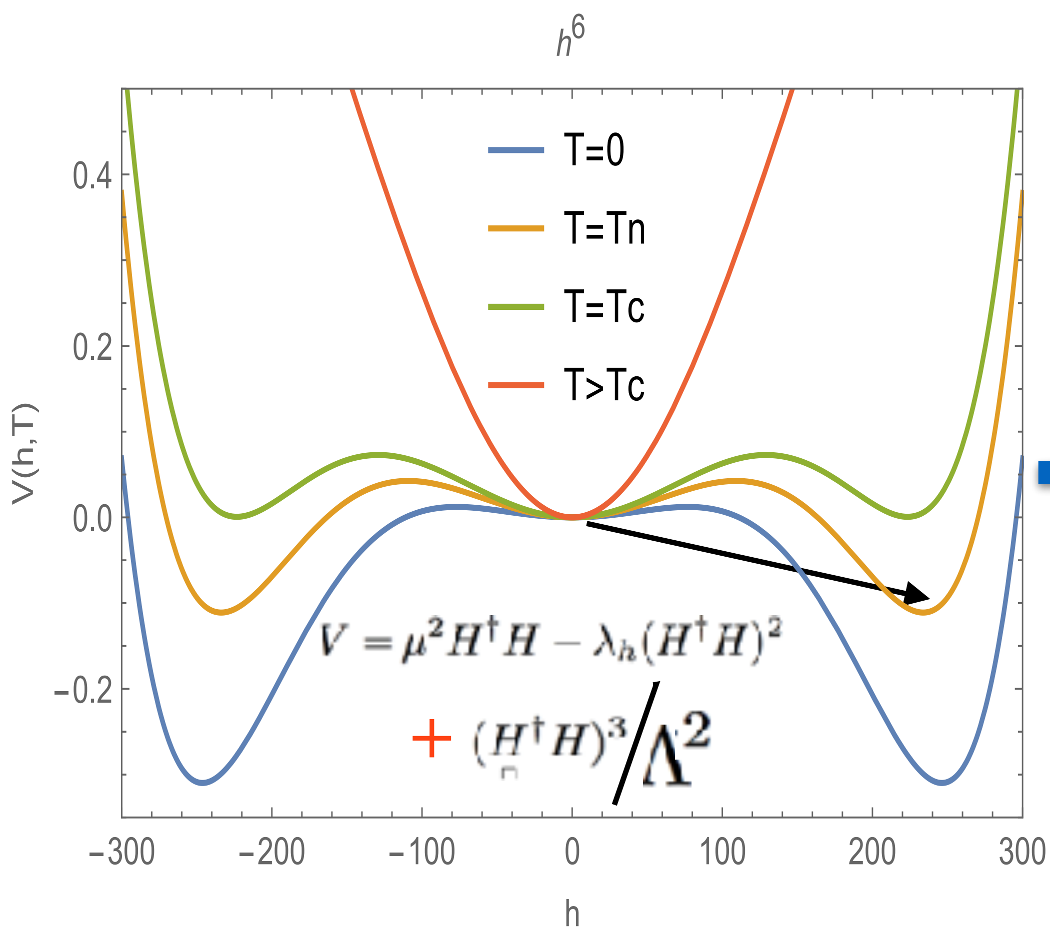
Lattice simulation

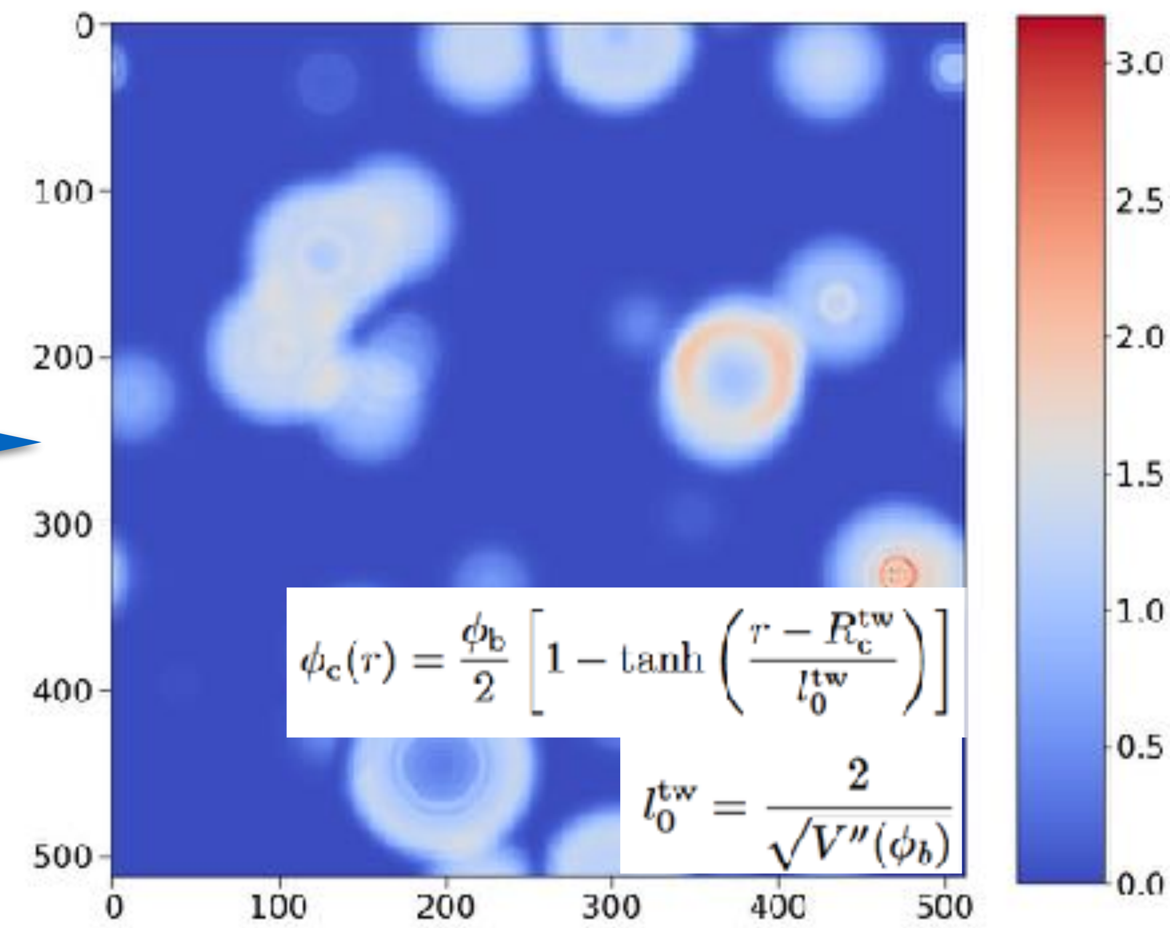
Thermal field theory



Chiara Caprini *et al* JCAP03(2020)024

Higgs Potential Shape and the Bubble picture





$$\alpha = \frac{\Delta\rho}{\rho_R} = \frac{1}{\rho_R}\left[-V(\vec{\phi}_b, T) + T\frac{\partial V(\vec{\phi}_b, T)}{\partial T}\right]\Bigg|_{T=T_n}$$

$$S(t_N) \sim 4\ln(m_P/T_N)$$

$$\frac{\beta}{H_*} \simeq \frac{2S(t_N)}{(1 - T_N/T_c)}$$

$$p(t_N) = H^4(t_N)$$

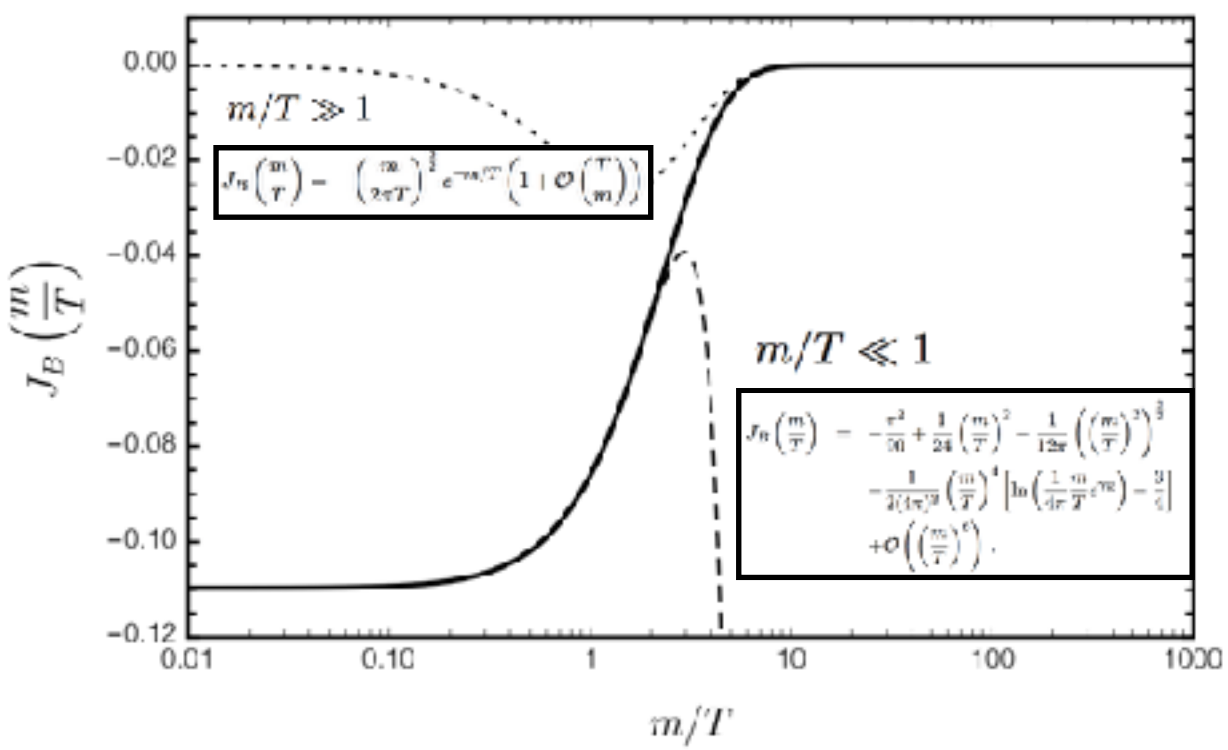
$$p(t) \simeq \Gamma_0 e^{-S(t_N)+\beta(t-t_N)} \qquad \Gamma 0 \sim \alpha^5_w T_N^4$$

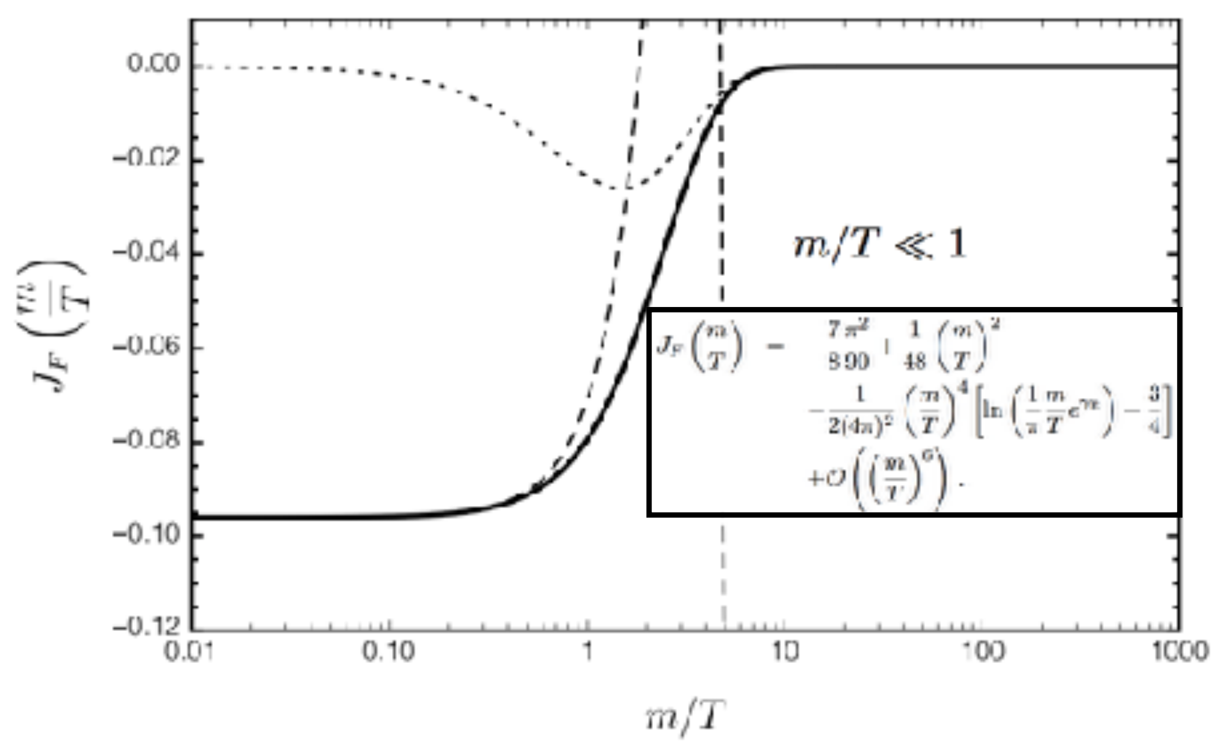
$$\beta = -\, d\ln p(t)/dt|_{t_f}$$

Thermal effective scalar potential for PT study

$$V_T(\phi, T) = V_0(\phi) + T^4 \left[\sum_B J_B\left(\frac{M_B}{T}\right) + \sum_F J_F\left(\frac{M_F}{T}\right) \right]$$

all fermions F and bosons B that are relativistic at temperature T





High-T expansion

$m/T \ll 1$

$$V_T(\phi) = V_0(\phi) + \frac{T^2}{24}\left(\sum_S M_S^2(\phi) + 3\sum_V M_V^2(\phi) + 2\sum_F M_F^2(\phi)\right) - \frac{T}{12\pi}\left(\sum_S \left(M_S^2(\phi)\right)^{\frac{3}{2}} + \sum_V \left(M_V^2(\phi)\right)^{\frac{3}{2}}\right) + \text{higher order terms}\,.$$

MS, MV , MF are the masses of the scalar fields S, vector fields V and fermonic fields F

GW parameters and FOPT

Bounce solution

$$S_3(T) = \int 4\pi r^2 dr \left[\frac{1}{2} \left(\frac{d\phi_b}{dr} \right)^2 + V(\phi_b, T) \right]$$

$$\lim_{r \to \infty} \phi_b = 0 \, , \qquad \frac{d\phi_b}{dr} \Big|_{r=0} = 0$$

Bubble nucleation

$$\Gamma \approx A(T) e^{-S_3/T} \sim 1$$

Latent heat

$$\alpha = \frac{1}{\rho_R} \left[-(V_{\rm EW} - V_f) + T \left(\frac{dV_{\rm EW}}{dT} - \frac{dV_f}{dT} \right) \right] \Bigg|_{T=T_*}$$

Phase transition inverse duration

$$\frac{\beta}{H_n} = T \frac{d(S_3(T)/T)}{dT} \Big|_{T=T_n}$$

GW spectrum from FOPT

- **Bubble collisions**

$$\Omega_{\rm col}h^2 = 1.67\times10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}\left(\frac{0.11v_b^3}{0.42+v_b^2}\right)\frac{3.8(f/f_{\rm env})^{2.8}}{1+2.8(f/f_{\rm env})^{3.8}}$$

peak frequency: $f_{\rm env} = 16.5\times10^{-6}\left(\frac{f_*}{H_*}\right)\left(\frac{T_*}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}{\rm Hz}$

- **Sound Wave**

$$\Omega h^2_{\rm sw}(f) = 2.65\times10^{-6}(H_*\tau_{sw})\left(\frac{\beta}{H}\right)^{-1}v_b\left(\frac{\kappa_\nu\alpha}{1+\alpha}\right)^2\left(\frac{g_*}{100}\right)^{-\frac{1}{3}}\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3\left(f/f_{\rm sw}\right)^2}\right)^{7/2}$$

phase transition duration: $\tau_{sw} = min\left[\frac{1}{H_*},\frac{R_*}{U_f}\right],\ H_*R_* = v_b(8\pi)^{1/3}(\beta/H)^{-1}$

Root-mean-square four-velocity of the plasma: $\bar{U}_f^2 \approx \frac{3}{4}\frac{\kappa_\nu\alpha}{1+\alpha}$

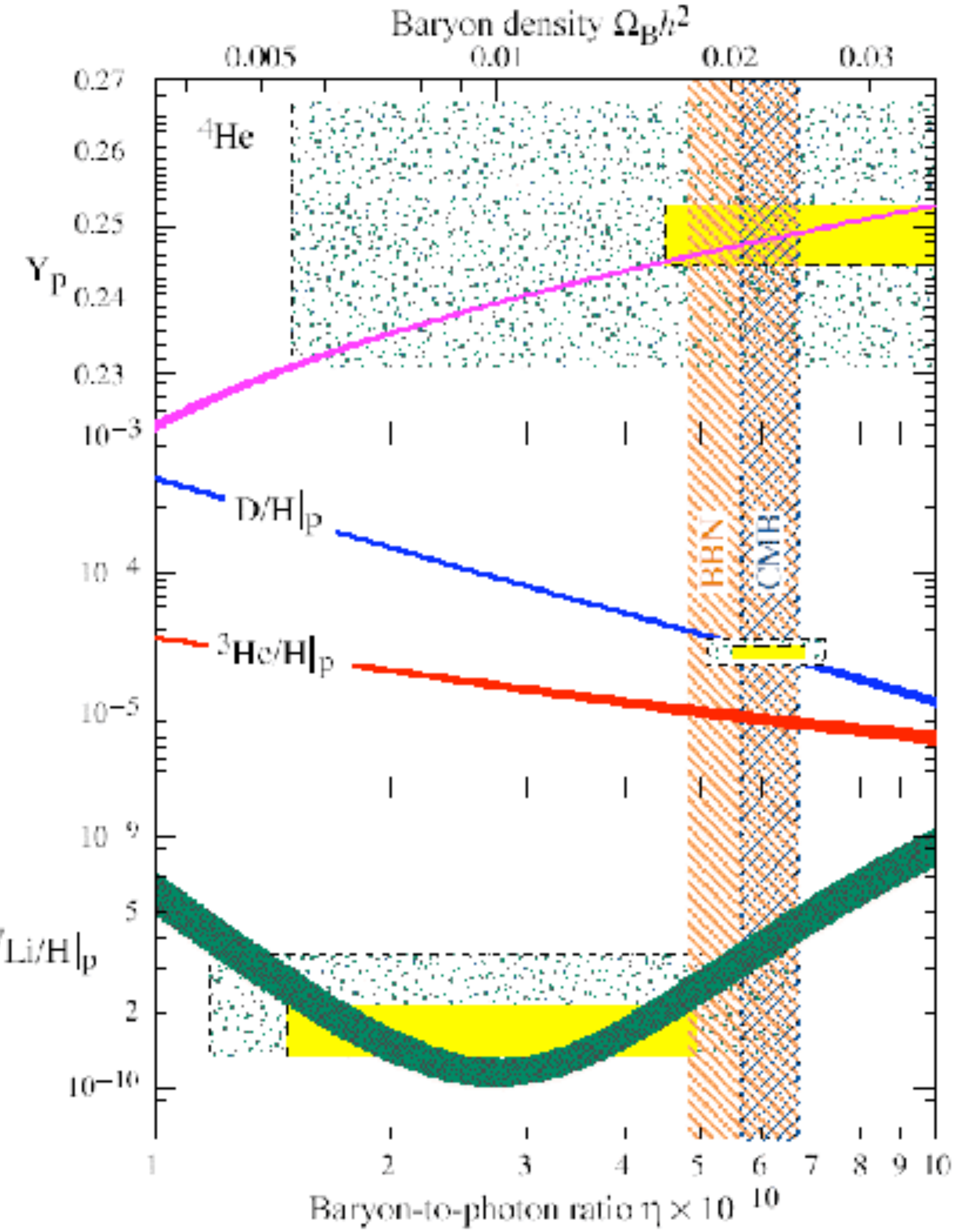
peak frequency: $f_{\rm sw} = 1.9\times10^{-5}\frac{\beta}{H}\frac{1}{v_b}\frac{T_*}{100}\left(\frac{g_*}{100}\right)^{\frac{1}{6}}{\rm Hz}$

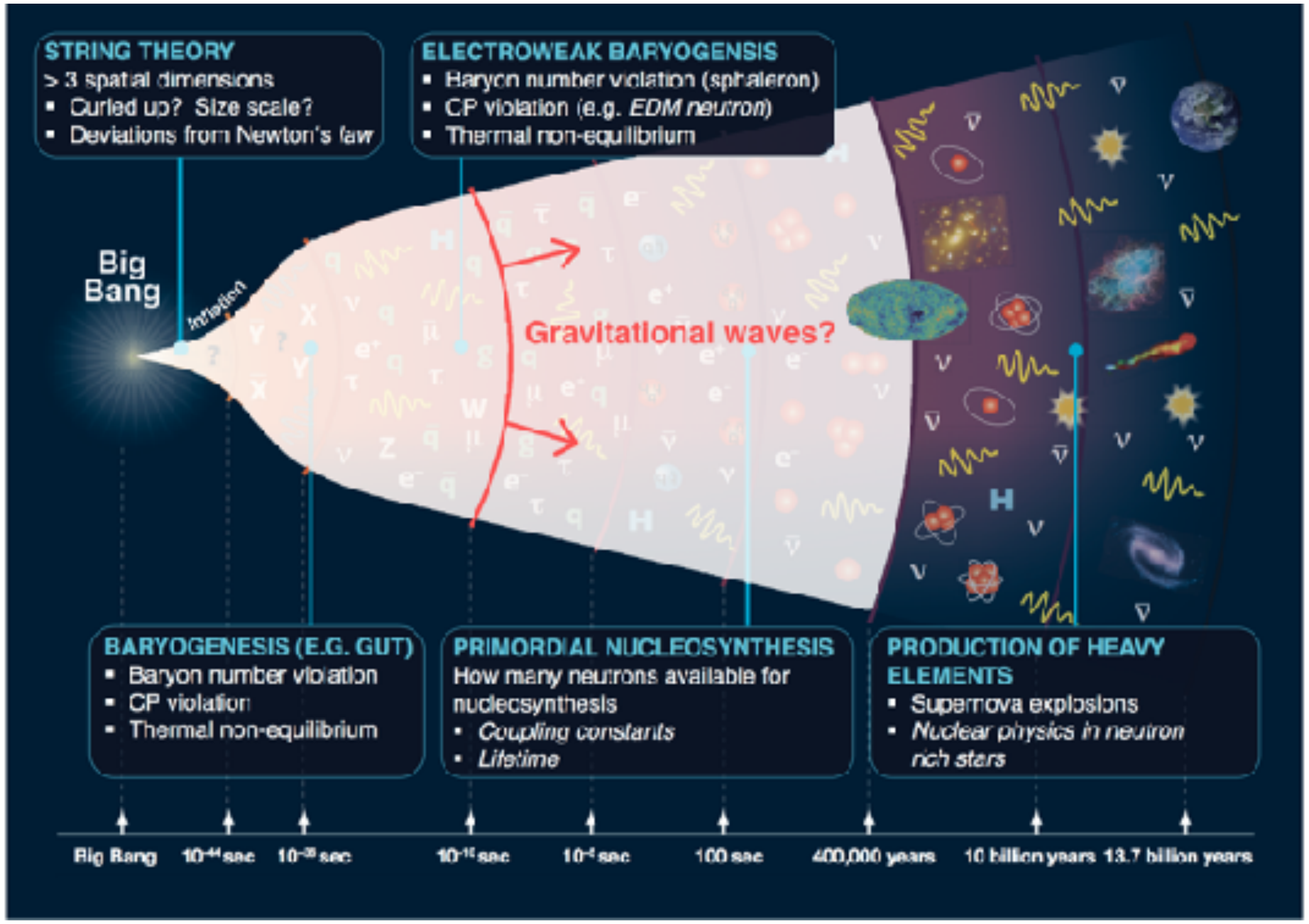
- **MHD turbulence**

$$\Omega h^2_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{\beta}{H}\right)^{-1}\left(\frac{\epsilon\kappa_\nu\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{g_*}{100}\right)^{-\frac{1}{3}}v_b\frac{(f/f_{\rm turb})^3(1+f/f_{\rm turb})^{-\frac{11}{3}}}{[1+8\pi f a_0/(a_*H_*)]}$$

peak frequency: $f_{\rm turb} = 2.7\times10^{-5}\frac{\beta}{H}\frac{1}{v_b}\frac{T_*}{100}\left(\frac{g_*}{100}\right)^{\frac{1}{6}}{\rm Hz}$

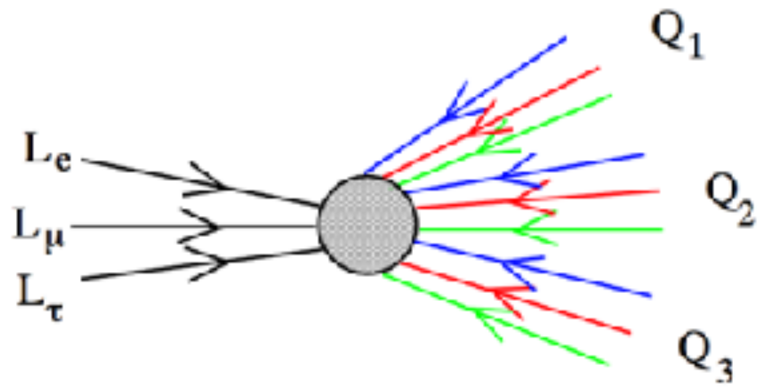
Baryon Asymmetry of the Universe

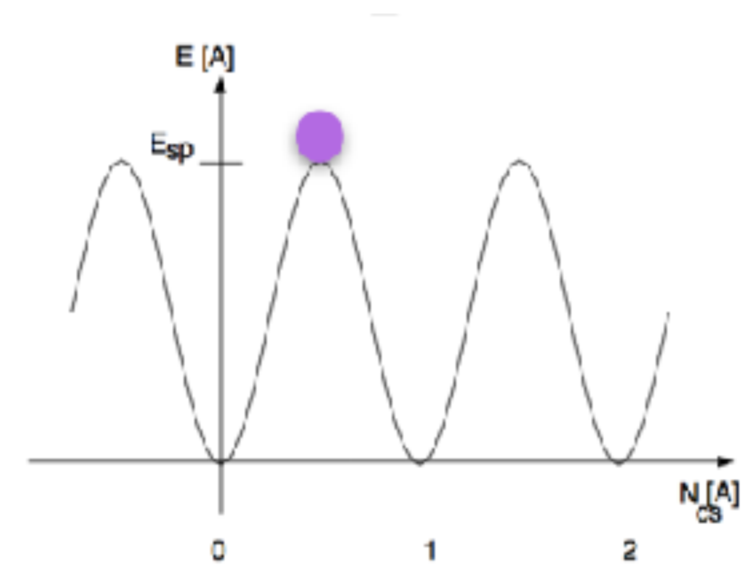




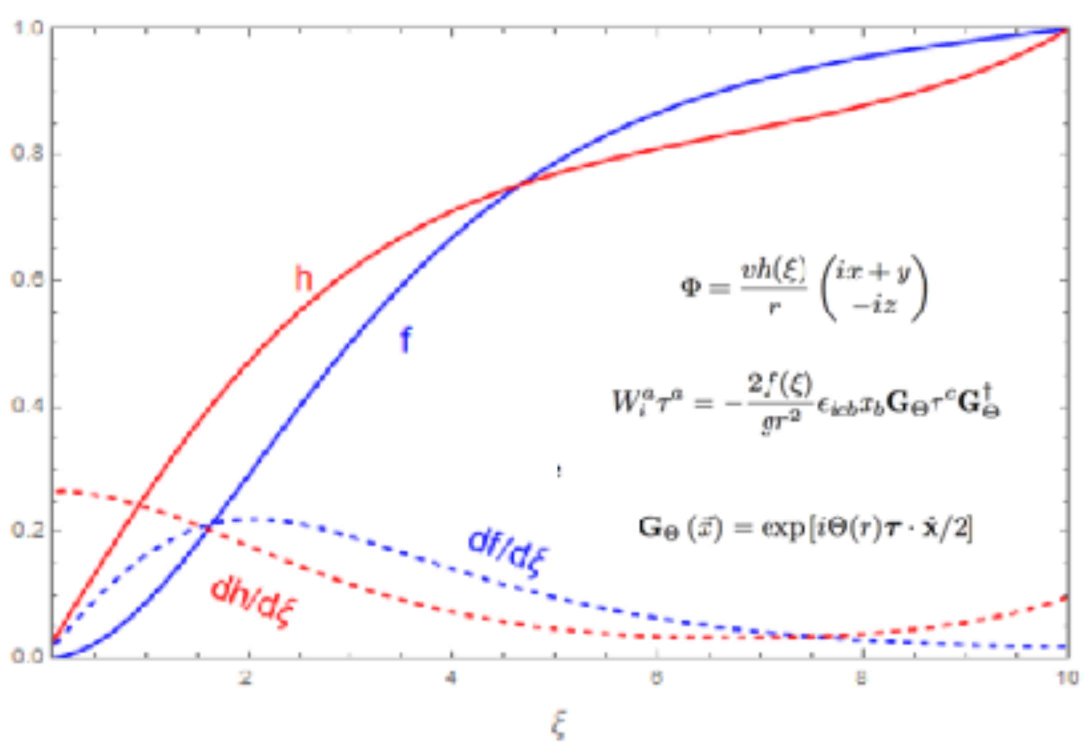
B violation and sphaleron

The Standard Model already contains a process that violates B-number. It is known as the electroweak sphaleron ("sphaleros" is Greek for "ready to fall").





Klinkhammer & Manton (1984); Kuzmin, Rubakov, & Shaposhnikov (1985); Harvey & Turner (1990) but also identified earlier by Dashen, Hasslacher, & Neveu (1974) and Boguta (1983)



$$\partial_\mu J^\mu_B = i\frac{N_F}{32\pi^2}\left(-g_2^2 F^{a\mu\nu}\tilde{F}^a_{\mu\nu} + g_1^2 f^{\mu\nu}\tilde{f}_{\mu\nu}\right),$$

$$\Delta B = N_F(\Delta N_{CS} - \Delta n_{CS}),$$

$$N_{CS} = -\frac{g_2^2}{16\pi^2}\int d^3x\, 2\epsilon^{ijk}\,\mathrm{Tr}\left[\partial_i A_j A_k + i\frac{2}{3}g_2 A_i A_j A_k\right],$$

$$n_{CS} = -\frac{g_1^2}{16\pi^2}\int d^3x\, \epsilon^{ijk}\,\partial_i B_j B_k,$$

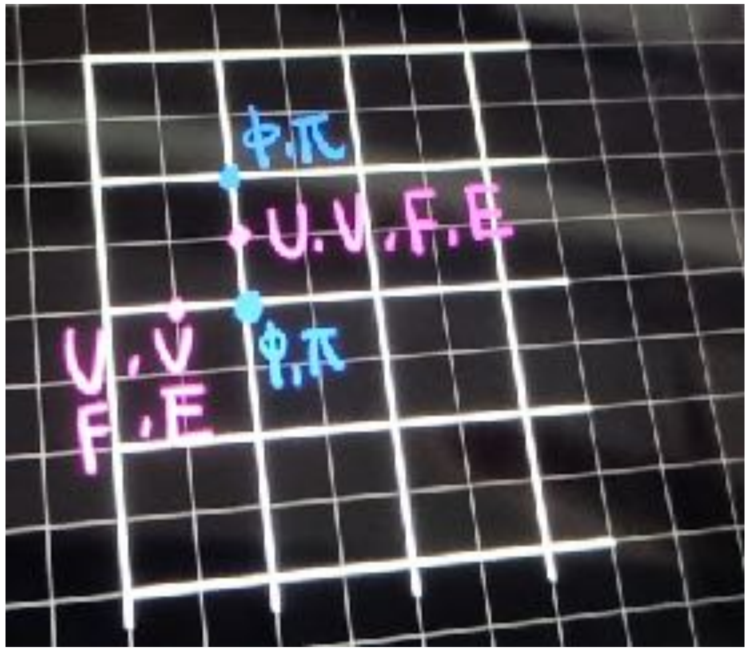
Lattice EW field foundation

Φ(t, x) : Higgs field doublet defined on sites;

Ui (t, x) and Vi (t, x) : SU(2) and U(1) link fields, defined on the link between the neighboring sites x and x + i , Φ(t, x), Ui (t, x) and Vi (t, x) are defined at time steps t + Δt, t + 2Δt, . . .;

Conjugate momentum fields: Π(t+Δt/2, x), F (t+Δt/2, x) and E(t+ Δt/2, x), are defined at time steps t + Δt/2, t + 3Δt/2.

$$U_i(t,x) = \exp\left(-\frac{i}{2} g \Delta x \sigma^a W_i^a\right)$$
$$U_0(t,x) = \exp\left(-\frac{i}{2} g \Delta t \sigma^a W_0^a\right)$$
$$V_i(t,x) = \exp\left(-\frac{i}{2} g \Delta x B_i\right)$$
$$V_0(t,x) = \exp\left(-\frac{i}{2} g \Delta t B_0\right).$$



$$D_i\Phi = \frac{1}{\Delta x}\left[U_i(t,x)V_i(t,x)\Phi(t,x+i) - \Phi(t,x)\right]$$
$$D_0\Phi = \frac{1}{\Delta t}\left[U_0(t,x)V_0(t,x)\Phi(t+\Delta t,x) - \Phi(t,x)\right].$$
$$\Phi(t+\Delta t,x) = \Phi(t,x) + \Delta t \Pi(t+\Delta t/2,x)$$
$$V_i(t+\Delta t,x) = \frac{1}{2} g' \Delta x \Delta t E_i(t+\Delta t/2,x) V_i(t,x)$$
$$U_i(t+\Delta t,x) = g \Delta x \Delta t F_i(t+\Delta t/2,x) U_i(t,x),$$

Temporal gauge
U0 (t, x) = I2, V0 (t, x) = 1

leapfrog

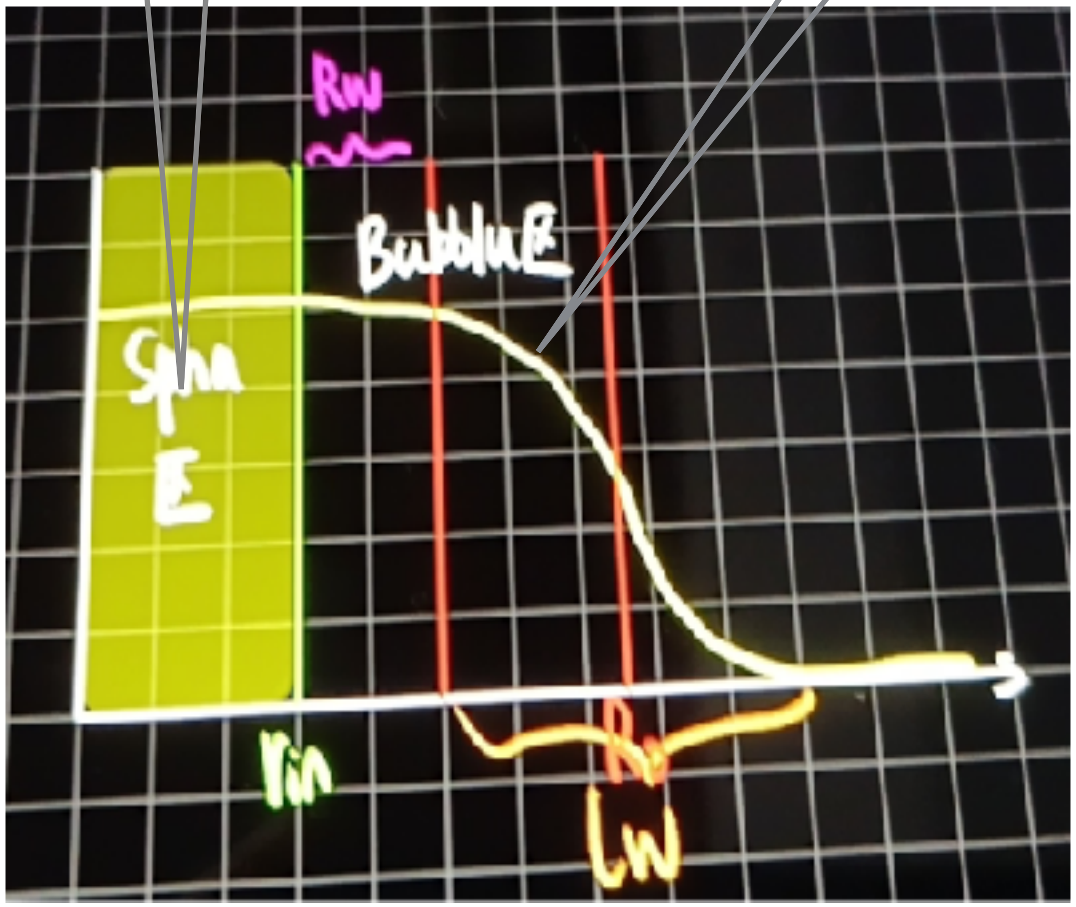
Bubble with sphaleron

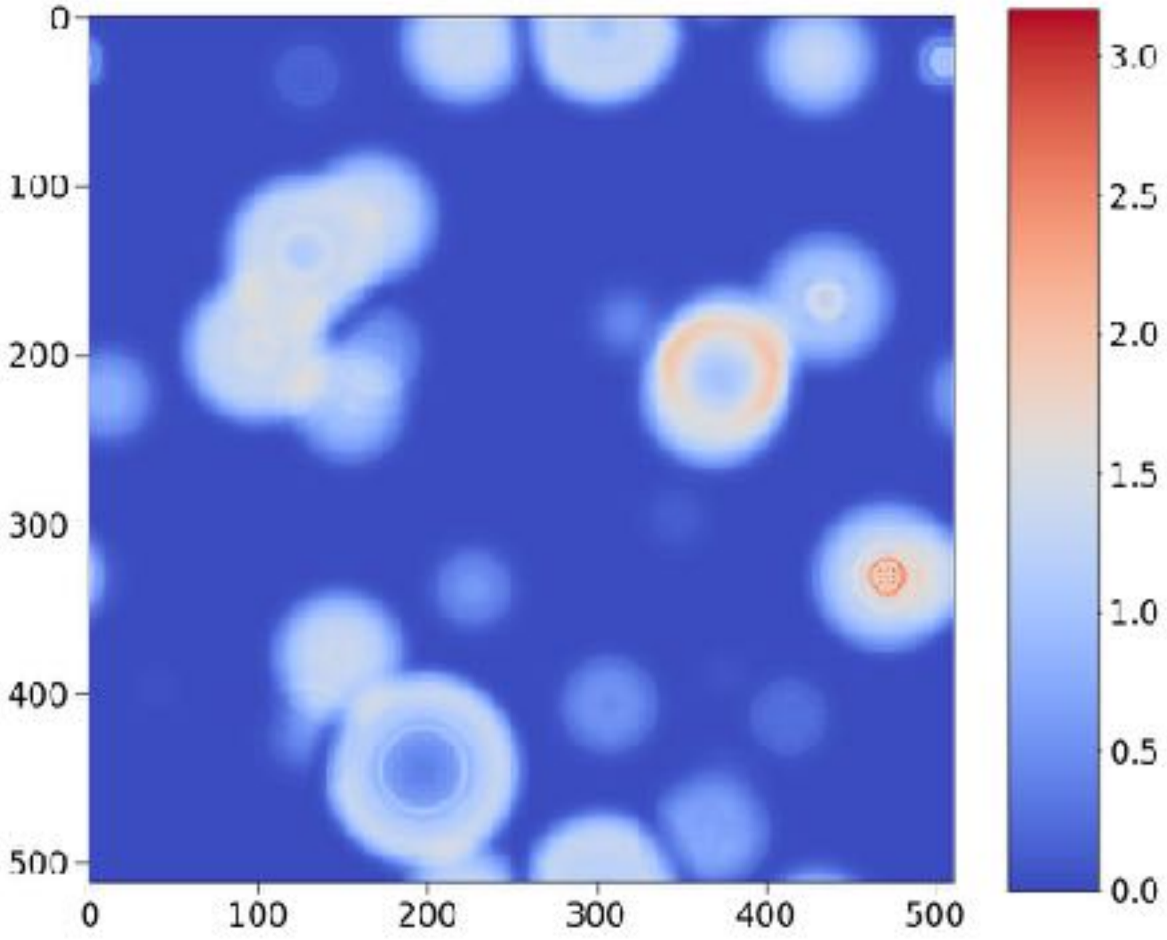
$$\Phi = \frac{v h(\xi)}{r}\begin{pmatrix} ix + y \\ -iz \end{pmatrix}$$

$$W_i^a \tau^a = -\frac{2f(\xi)}{g r^2}\epsilon_{icb} x_b \mathbf{G}_\Theta \tau^c \mathbf{G}_\Theta^\dagger$$

$$\mathbf{G}_\Theta(\vec{x}) = \exp\left[i\Theta(r)\boldsymbol{\tau}\cdot\hat{\mathbf{x}}/2\right]$$

$$\phi_c(r) = \frac{\phi_b}{2}\left[1 - \tanh\left(\frac{r - R_c^{\rm tw}}{l_0^{\rm tw}}\right)\right]$$





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EOM

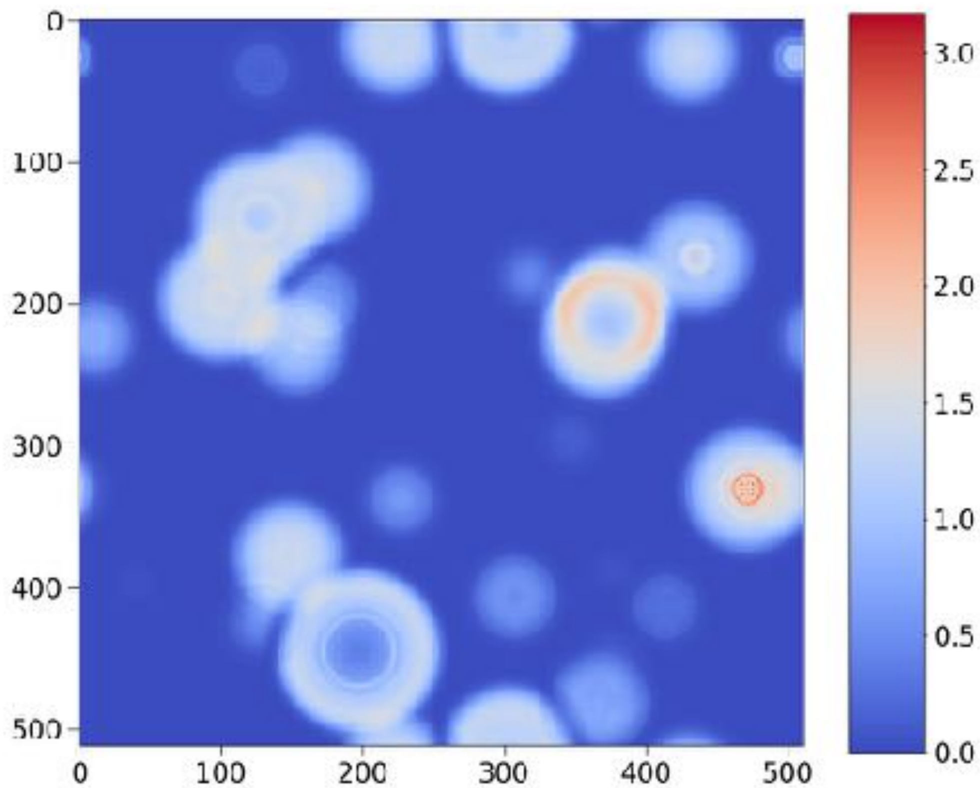
Field basis

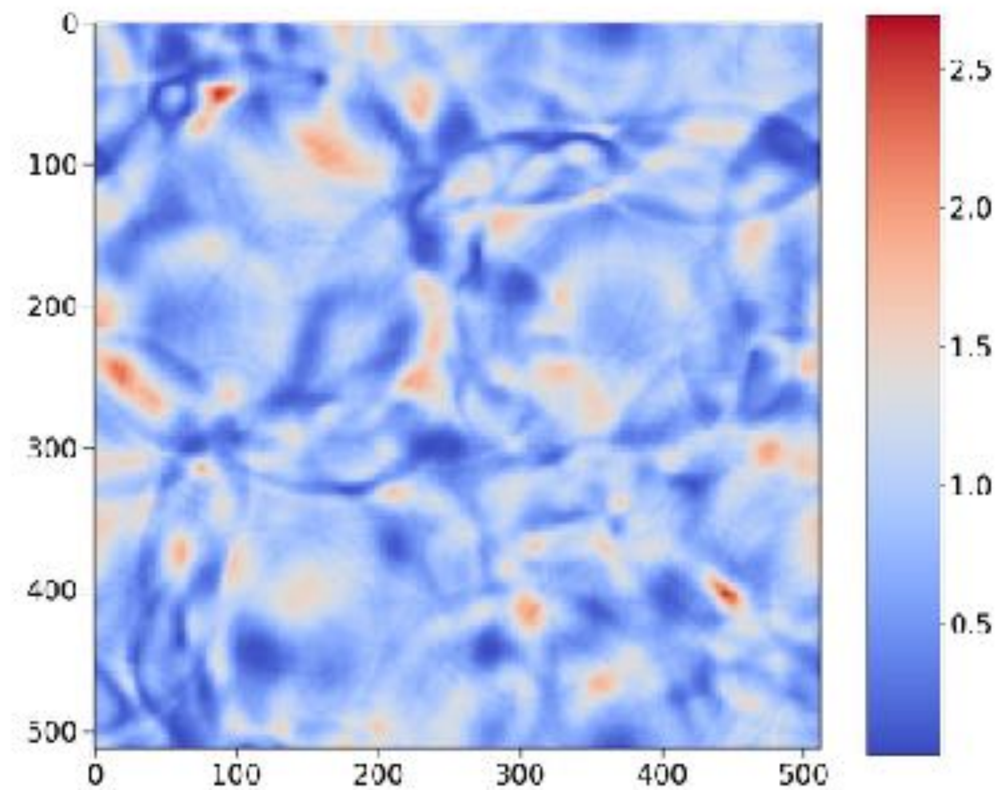
$$
\begin{aligned}
\partial_0^2\Phi &= D_i D_i \Phi - 2\lambda(|\Phi|^2 - \eta^2)\Phi - 3(\Phi^\dagger\Phi)^2\Phi/\Lambda^2, \\
\partial_0^2 B_i &= -\partial_j B_{ij} + g' \,\mathrm{Im}[\Phi^\dagger D_i \Phi], \\
\partial_0^2 W_i^a &= -\partial_k W_{ik}^a - g\,\epsilon^{abc} W_k^b W_{ik}^c + g\,\mathrm{Im}[\Phi^\dagger \sigma^a D_i \Phi].
\end{aligned}
$$

$$
\begin{aligned}
&\partial_0\partial_j B_j - g' \,\mathrm{Im}[\Phi^\dagger \partial_0 \Phi] = 0, \\
&\partial_0\partial_j W_j^a + g\,\epsilon^{abc} W_j^b \partial_0 W_j^c - g\,\mathrm{Im}[\Phi^\dagger \sigma^a \partial_0 \Phi] = 0.
\end{aligned}
$$

Lattice implementation

$$
\begin{aligned}
\Pi(t+\Delta t/2, x) =& \Pi(t-\Delta t/2, x) + \Delta t\Big\{ \frac{1}{\Delta x^2} \sum_i \big[U_i(t,x)V_i(t,x)\Phi(t,x+i) \\
& - 2\Phi(t,x) + U_i^\dagger(t,x-i)V_i^\dagger(t,x-i)\Phi(t,x-i)\big] - \frac{\partial U}{\partial \Phi^\dagger}\Big\} \\
\mathrm{Im}[E_k(t+\Delta t/2, x)] =& \mathrm{Im}[E_k(t-\Delta t/2, x)] + \Delta t\Big\{ \frac{g'}{\Delta x}\mathrm{Im}[\Phi^\dagger(t,x+k)U_k^\dagger(t,x)V_k^\dagger(t,x)\Phi(t,x)] \\
& - \frac{2}{g'\Delta x^3} \sum_i \mathrm{Im}[V_k(t,x)V_i(t,x+k)V_k^\dagger(t,x+i)V_i^\dagger(t,x) \\
& + V_i(t,x-i)V_k(t,x)V_i^\dagger(t,x+k-i)V_k^\dagger(t,x-i)]\Big\} \\
\mathrm{Tr}[i\sigma^m F_k(t+\Delta t/2, x)] =& \mathrm{Tr}[i\sigma^m F_k(t-\Delta t/2, x)] + \Delta t\Big\{ \frac{g}{\Delta x}\mathrm{Re}[\Phi^\dagger(t,x+k)U_k^\dagger(t,x)V_k^\dagger(t,x)i\sigma^m\Phi(t,x)] \\
& - \frac{1}{g\Delta x^3} \sum_i \mathrm{Tr}[i\sigma^m U_k(t,x)U_i(t,x+k)U_k^\dagger(t,x+i)U_i^\dagger(t,x) \\
& + i\sigma^m U_k(t,x)U_i^\dagger(t,x+k-i)U_k^\dagger(t,x-i)U_i(t,x-i)]\Big\},
\end{aligned}
$$





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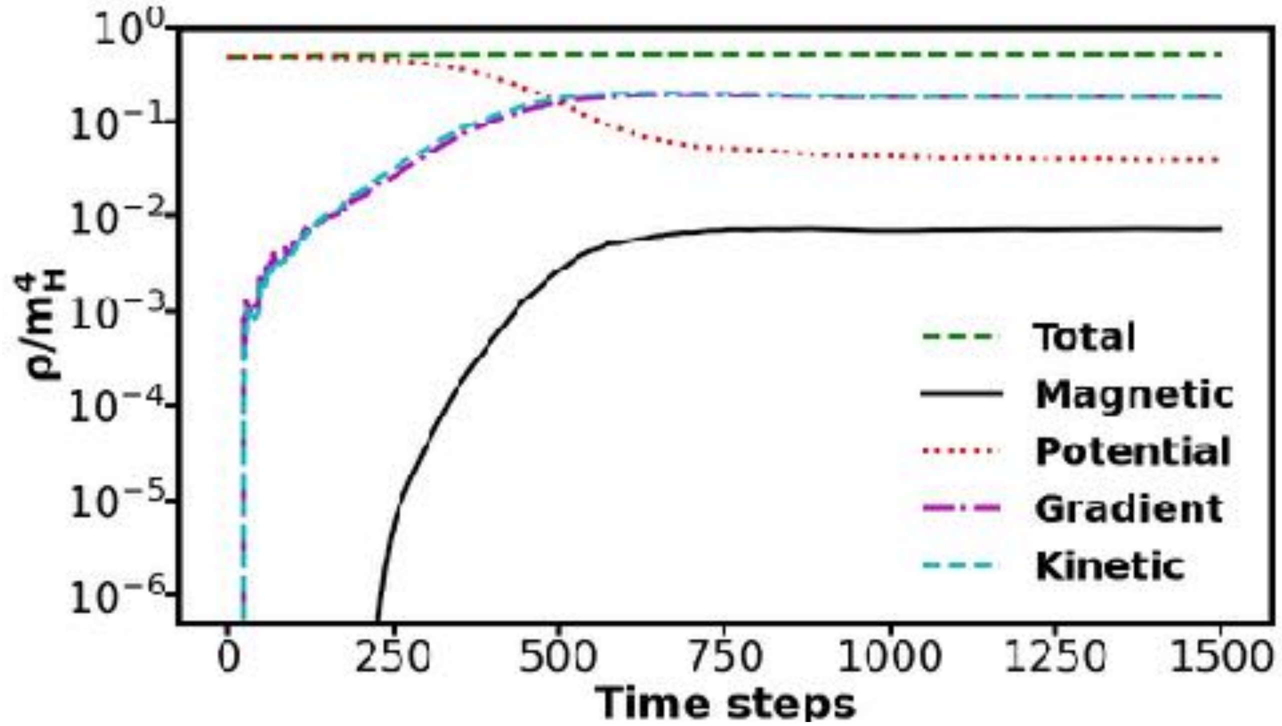
GW from Bubble collisions

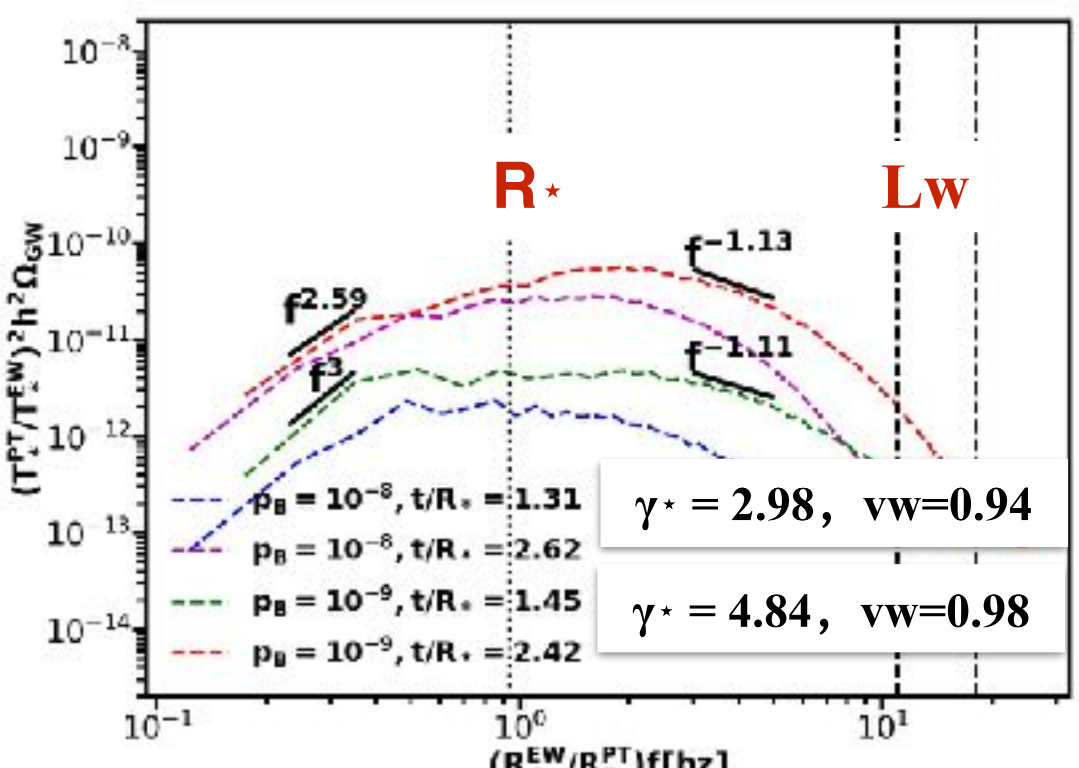
$$\ddot{h}_{ij} - \nabla^2 h_{ij} = 16\pi G T_{ij}^{\mathrm{TT}}$$

$$T_{\mu\nu} = \partial_\mu \Phi^\dagger \partial_\nu \Phi - g_{\mu\nu} \frac{1}{2} \mathrm{Re}[(\partial_i \Phi^\dagger \partial^i \Phi)^2]$$

$$\langle \dot{h}_{ij}^{TT}(\mathbf{k}, t) \dot{h}_{ij}^{TT}(\mathbf{k}', t) \rangle = P_{\dot{h}}(\mathbf{k}, t)(2\pi)^3 \delta(\mathbf{k} + \mathbf{k}')$$

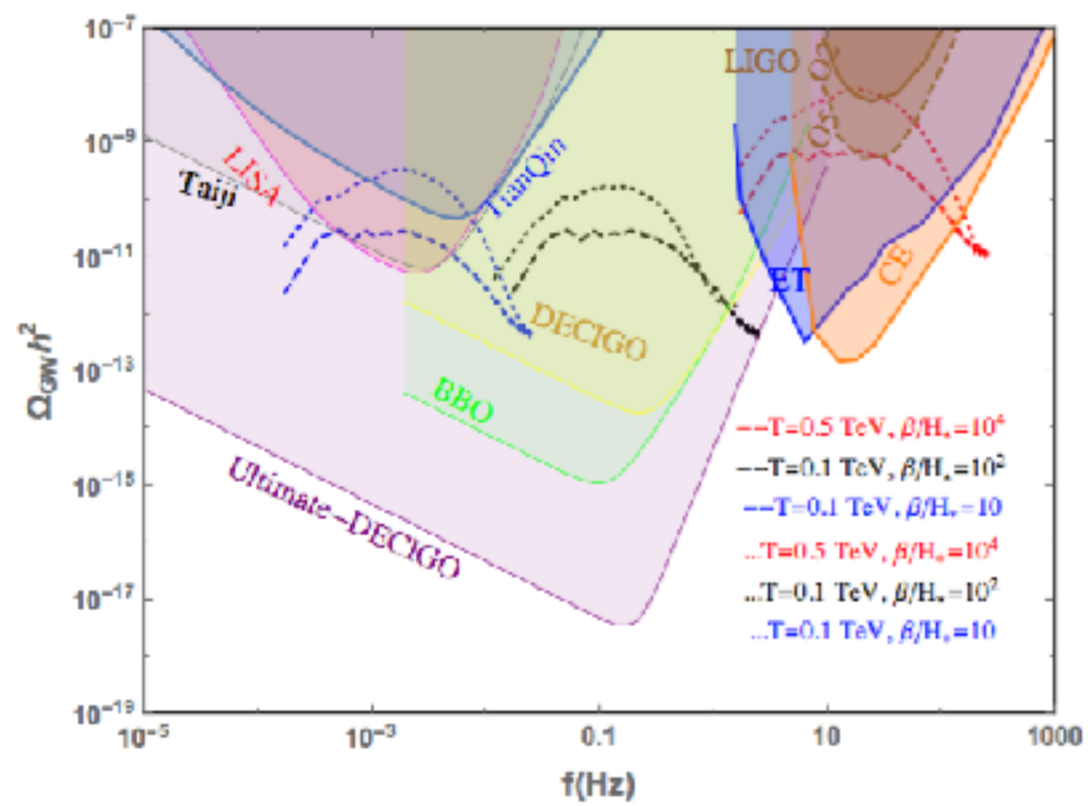
$$\frac{d\Omega_{\mathrm{gw}}}{d\ln(k)} = \frac{1}{32\pi G \rho_c} \frac{k^3}{2\pi^2} P_{\dot{h}}(\mathbf{k}, t)$$





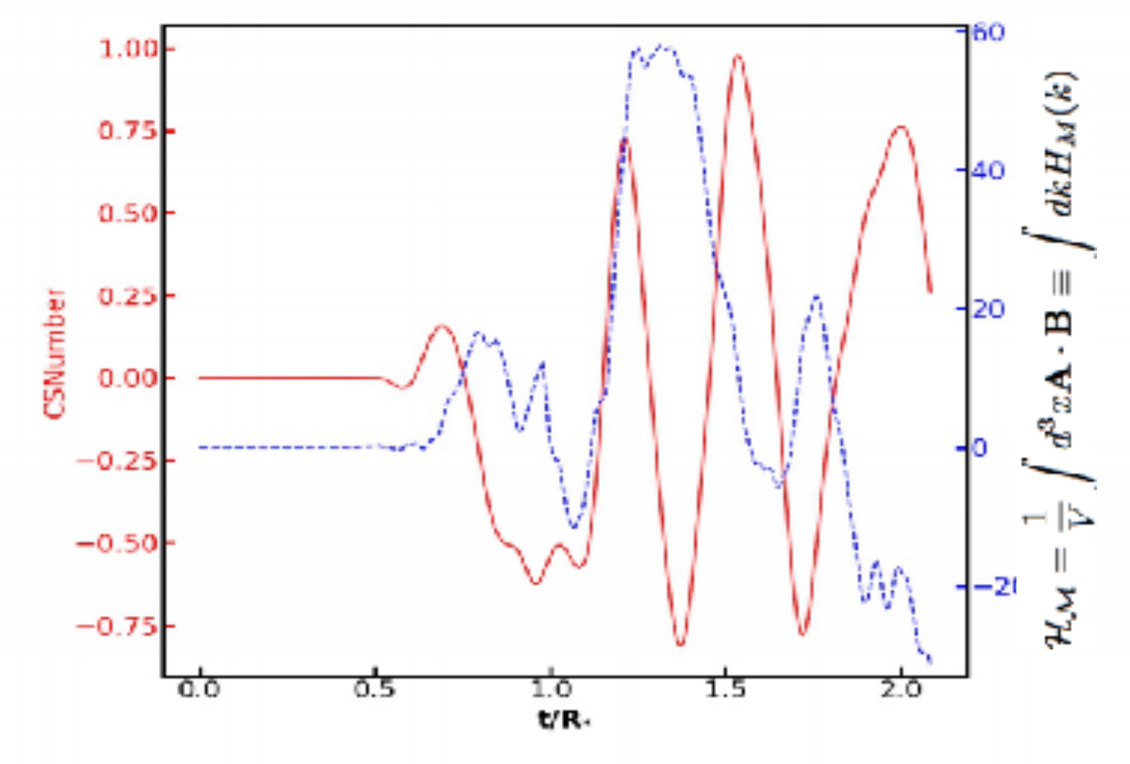
$\gamma_\star = R_\star/(2Rc)$

$R_* = \left(\frac{\mathcal{V}}{N_b}\right)^{1/3}$

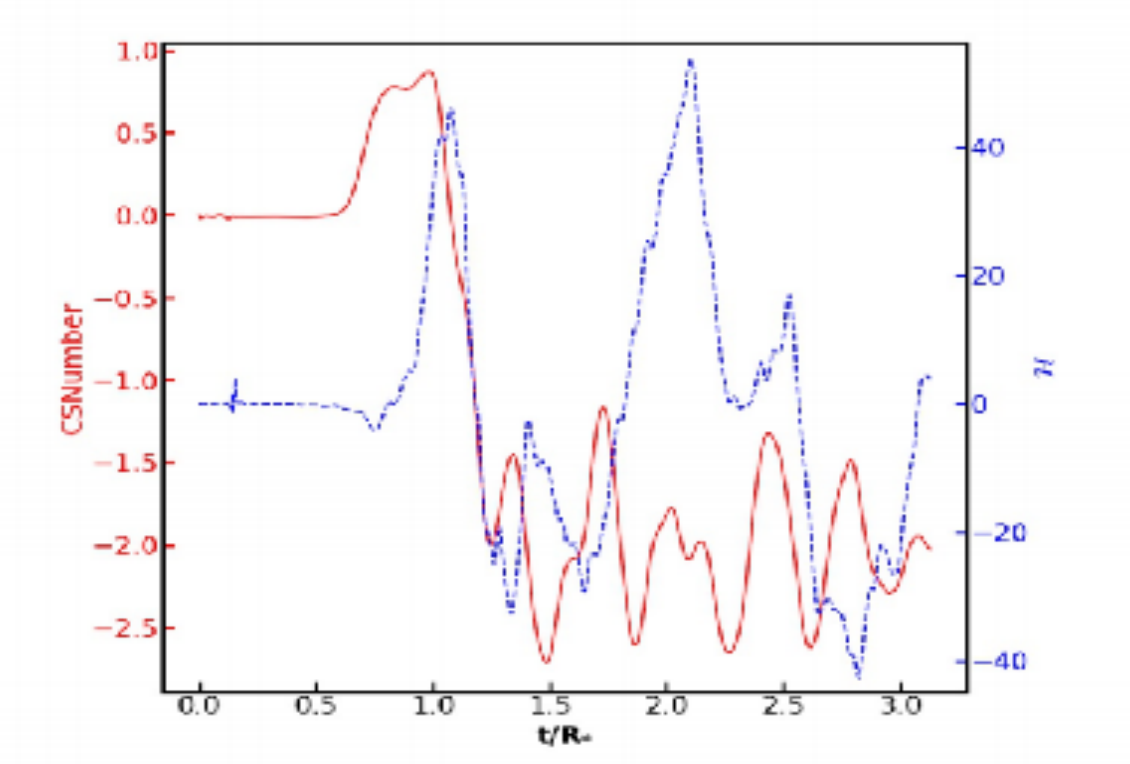


Di, Wang, Zhou, **Bian***, Cai*,Liu*, Phys.Rev.Lett. 126 (2021) 251102

CS number and the magnetic helicity



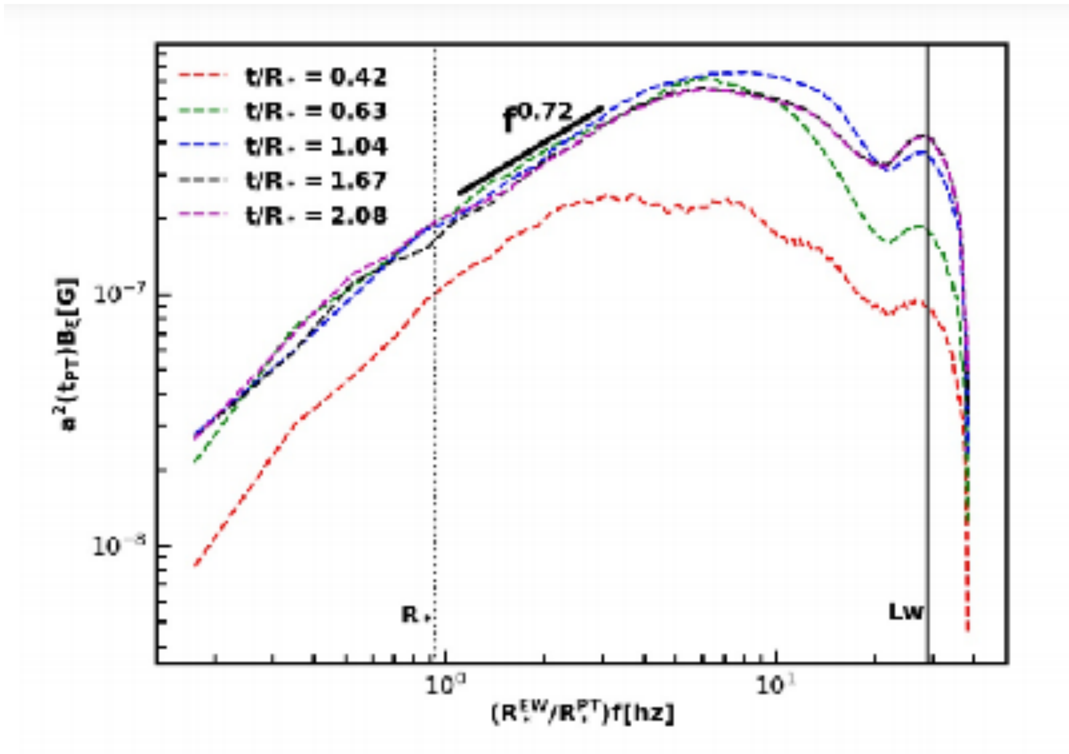
Without sphaleron, the CS number oscillates around zero throughout the PT process.

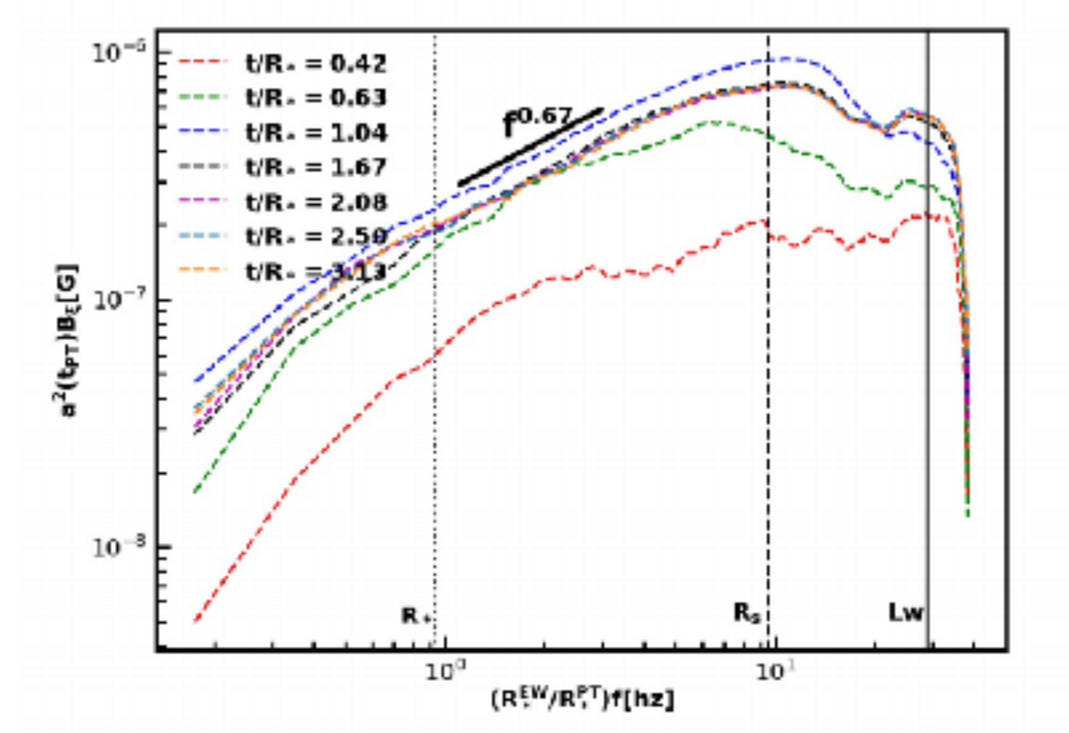


B + L anomaly: ΔNB = 3 ΔNCS~3 ;
Magnetic helicity and NCS: |H|~18ΔNCS~6ΔNB.

Di, Wang, **Bian***, Cai*, Liu*, 2107.08978

MF versus Sphaleron





Non-vanishing gradients of the Higgs fields can generate magnetic fields when bubbles collide

$$A_{\mu\nu} = \sin\theta_w n^a W^a_{\mu\nu} + \cos\theta_w B_{\mu\nu} - i\frac{2}{gv^2}\sin\theta_w\left[(D_\mu\Phi)^\dagger(D_\nu\Phi) - (D_\nu\Phi)^\dagger(D_\mu\Phi)\right].$$

$$\langle B_i^*(\boldsymbol{k},t)B_j(\boldsymbol{k}',t)\rangle = (2\pi)^3\delta^{(3)}(\boldsymbol{k}-\boldsymbol{k}')F_{ij}(\boldsymbol{k},t)$$

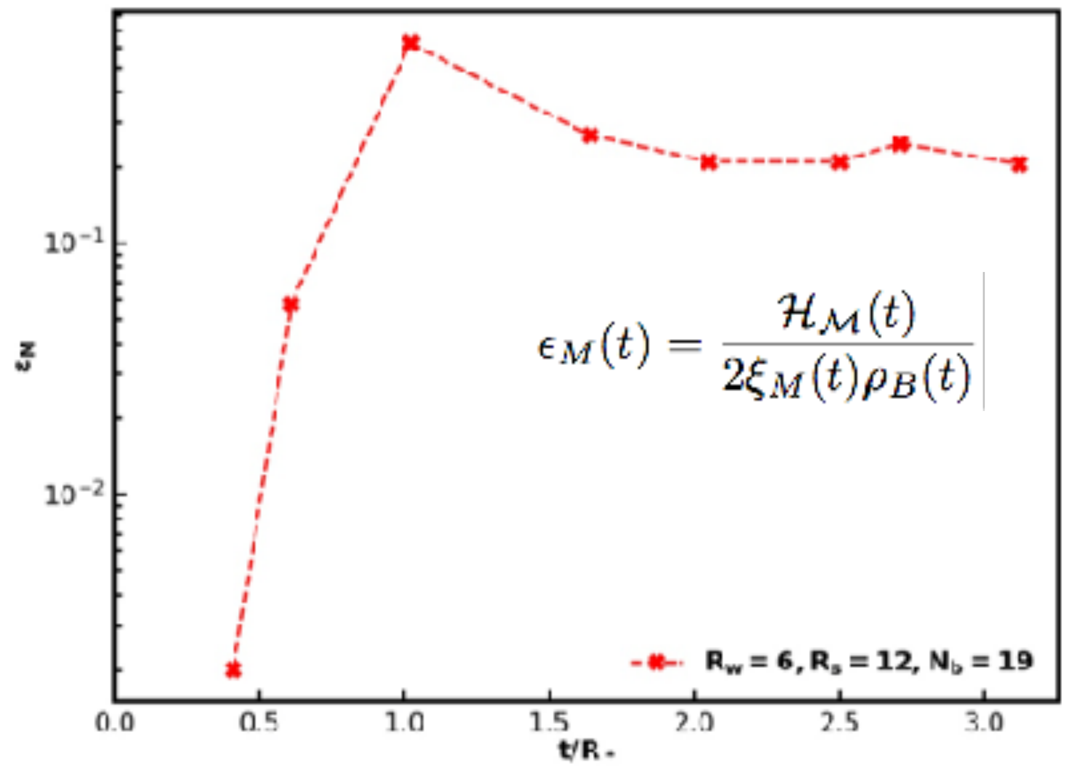
$$F_{ij}(\boldsymbol{k},t) = (\delta_{ij} - \hat{k}_i\hat{k}_j)E_M(k,t)/(4\pi k^2) + i\epsilon_{ijl}k_l H_M/(8\pi k^2)$$

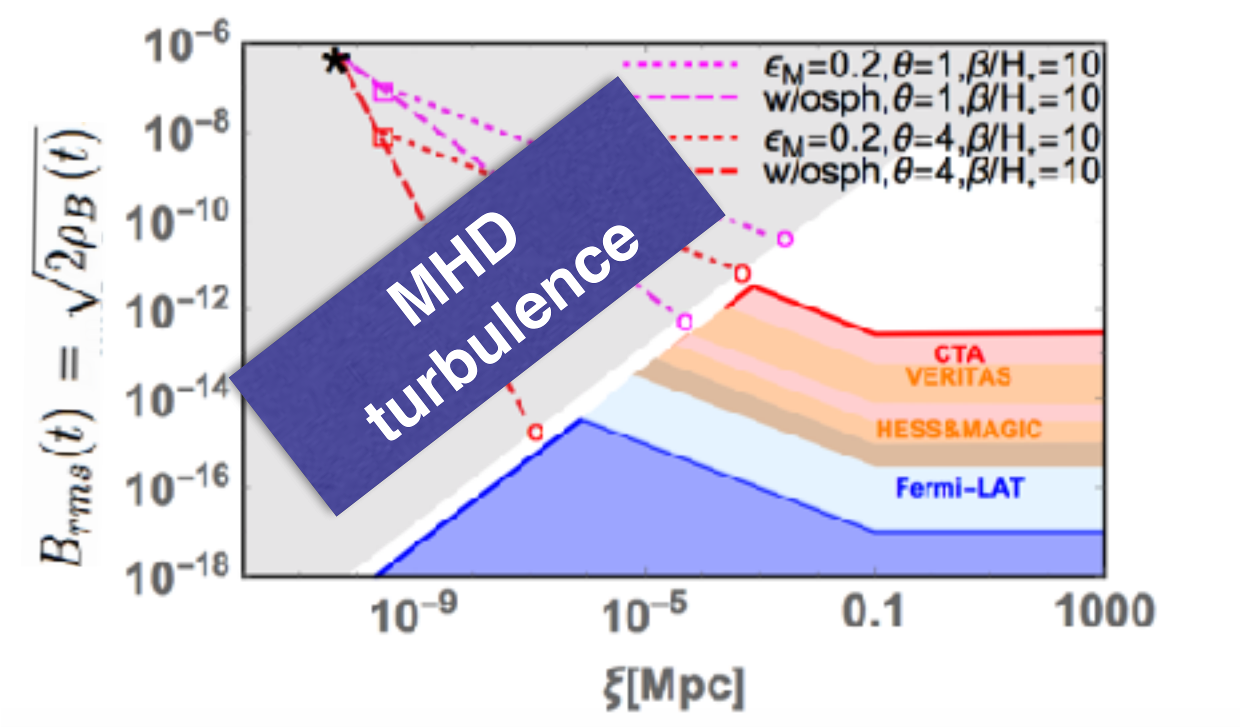
$$\rho_B(t) = \int_0^\infty E_M(k,t)\,dk$$

$$B_\xi = \sqrt{2d\rho_B/d\log(k)} \quad \xi_M(t) = \int dk k^{-1} E_M(k,t)/\rho_B(t)$$

Di, Wang, **Bian***, Cai*, Liu*, 2107.08978

MF versus Sphaleron





MF helicity evolution with PT proceeding

$$\Phi = \frac{vh(\xi)}{r}\begin{pmatrix} ix+y \\ -iz \end{pmatrix}$$

$$W_i^a\tau^a = -\frac{2f(\xi)}{gr^2}\epsilon_{icb}x_b\mathbf{G}_\Theta\tau^c\mathbf{G}_\Theta^\dagger$$

$$\mathbf{G}_\Theta(\vec{x}) = \exp\left[i\Theta(r)\boldsymbol{\tau}\cdot\hat{\mathbf{x}}/2\right]$$

Cosmic-ray and gamma ray observations can tell the helicity of the MF

Di, Wang, **Bian***, Cai*, Liu*, 2107.08978

Stochastic GW for PTA ???

$\langle \delta t(t_i, \vec{n_I}) \rangle = 0$

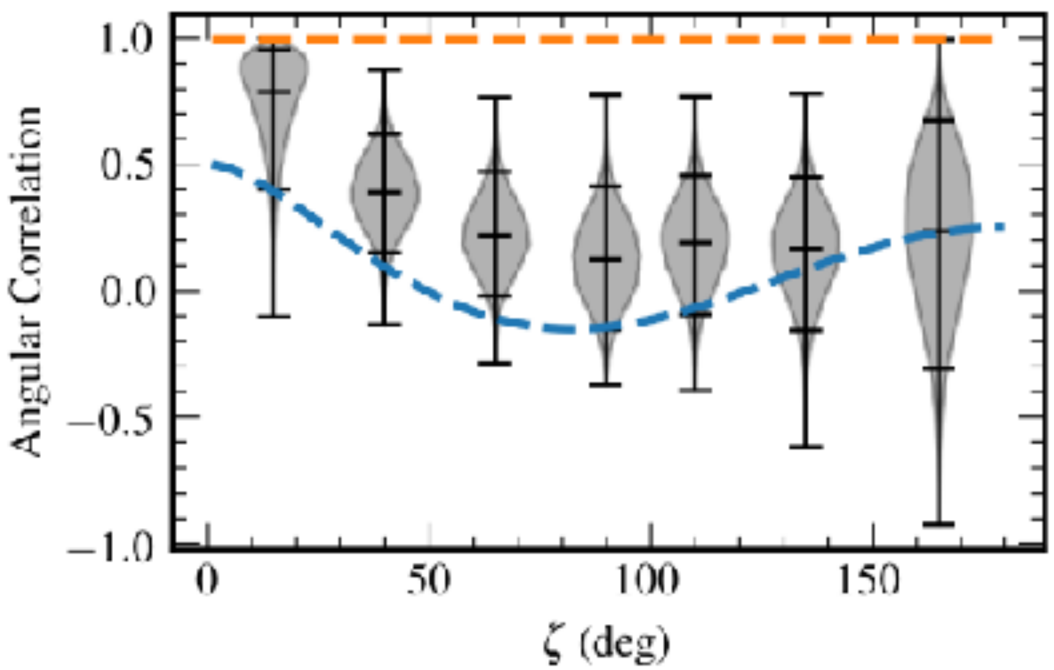
Isotropic, unpolarized

Residual= Data-Model

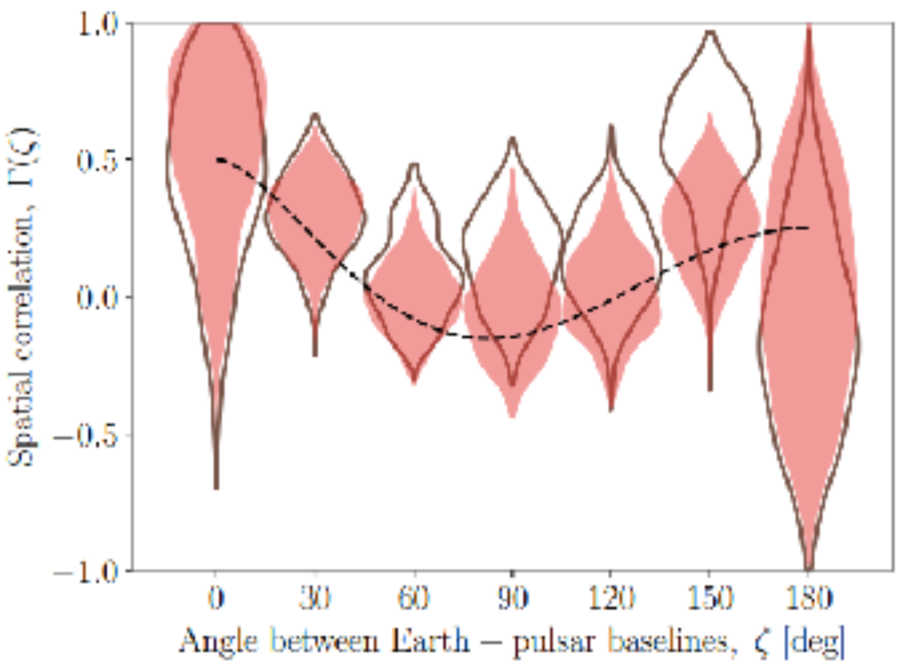
$$\langle \delta t(t_i, \vec{n_I}) \delta t(t_j, \vec{n_J}) \rangle = \int_0 df \, \boxed{\Gamma(\vec{n_i}, \vec{n_j})} \cos\left(2\pi f (t_i - t_j)\right) \boxed{\frac{1}{12\pi^2} \frac{1}{f^5} \frac{3H_{100}^2}{2\pi^2} \Omega_{gw}(f) h^2}$$

Hellings-Downs Curve

Auto-correlation : $\vec{n_I} = \vec{n_J}$
Cross-correlation : $\vec{n_I} \neq \vec{n_J}$



NANOGrav, 2009.04496

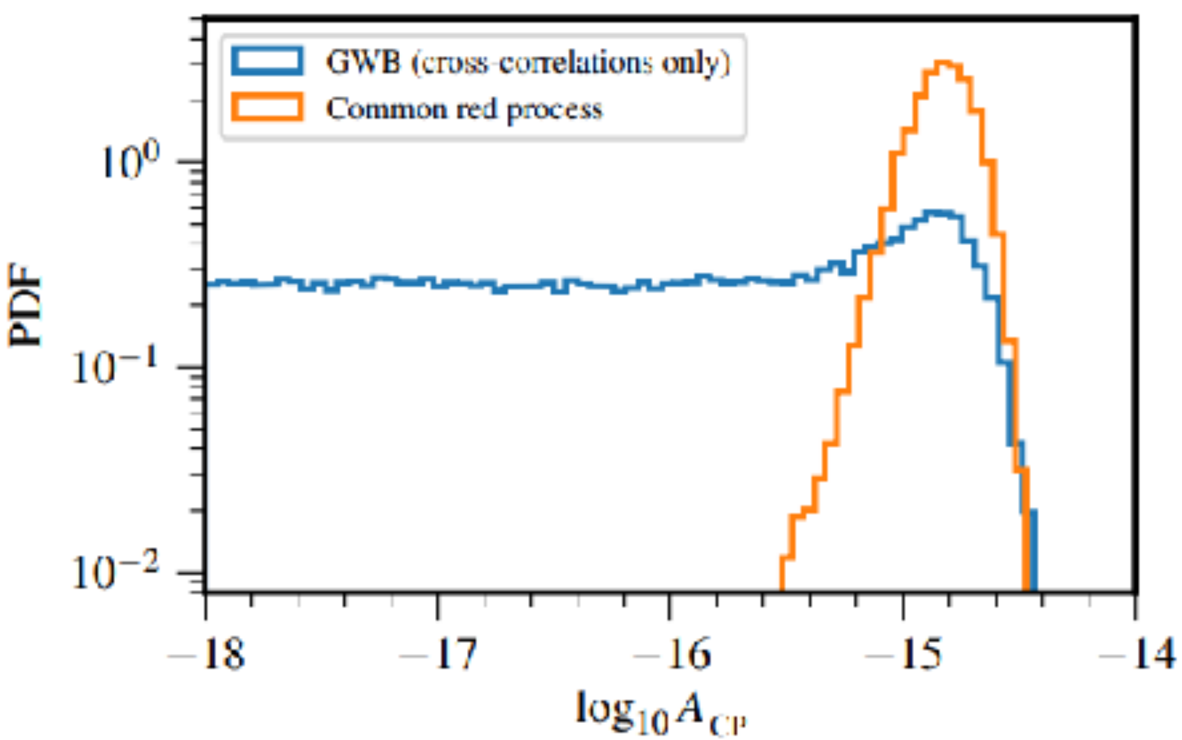


PPTA, 2107.12112

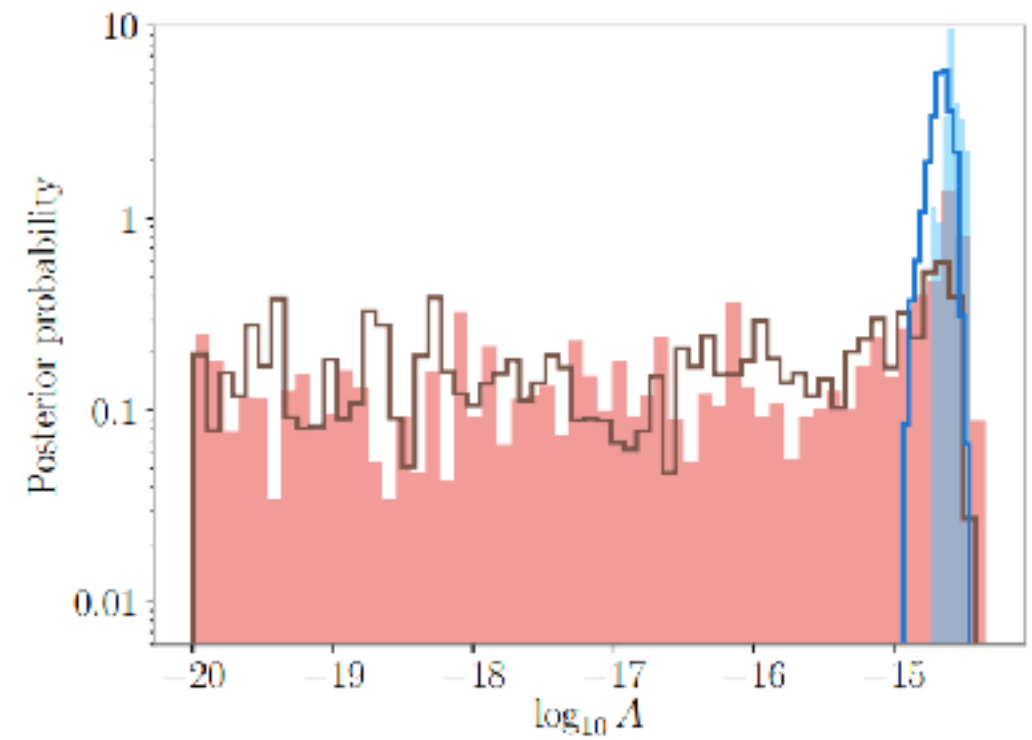
Stochastic GW for PTA ???

NANOGrav: **cross-correlation only** – No evidence

PPTA: auto-correlation + cross correlation – Better explanation than **common red noise**



NANOGrav, 2009.04496



PPTA, 2107.12112

No decisive conclusion is made by NANOGrav or PPTA

GW for NanoGrav ???

Table I: Bayes factors can be interpreted as follows: given candidate models M_i and M_j, a Bayes factor of 20 corresponds to a belief of 95% in the statement "M_i is true", this corresponds to strong evidence in favor of M_i [53].

B_{ij}	Evidence in favor of M_i against M_j
$1-3$	Weak
$3-20$	Positive
$20-150$	Strong
≥ 150	Very strong

$$B_{ij} = \begin{pmatrix} 1 & 0.09 & 0.37 & 0.28 & 0.83 & 0.16 & 0.12 & 0.17 \\ 10.8 & 1 & 3.96 & 3.01 & 8.93 & 1.75 & 1.32 & 1.84 \\ 2.73 & 0.25 & 1 & 0.76 & 2.26 & 0.44 & 0.33 & 0.47 \\ 3.6 & 0.33 & 1.32 & 1 & 2.97 & 0.58 & 0.44 & 0.61 \\ 1.21 & 0.11 & 0.44 & 0.34 & 1 & 0.2 & 0.15 & 0.21 \\ 6.18 & 0.57 & 2.26 & 1.72 & 5.11 & 1 & 0.76 & 1.05 \\ 8.17 & 0.76 & 2.99 & 2.27 & 6.75 & 1.32 & 1 & 1.39 \\ 5.86 & 0.54 & 2.15 & 1.63 & 4.85 & 0.95 & 0.72 & 1 \end{pmatrix}$$

A positive evidence in favor of the cosmic strings explanation against SMBHBs, scalar induced GWs, FOPT, and domain walls, and a weak evidence in favor of cosmic strings against cosmic strings+SMBHBs, cosmic strings+scalar induced GWs, and cosmic strings+domain walls.

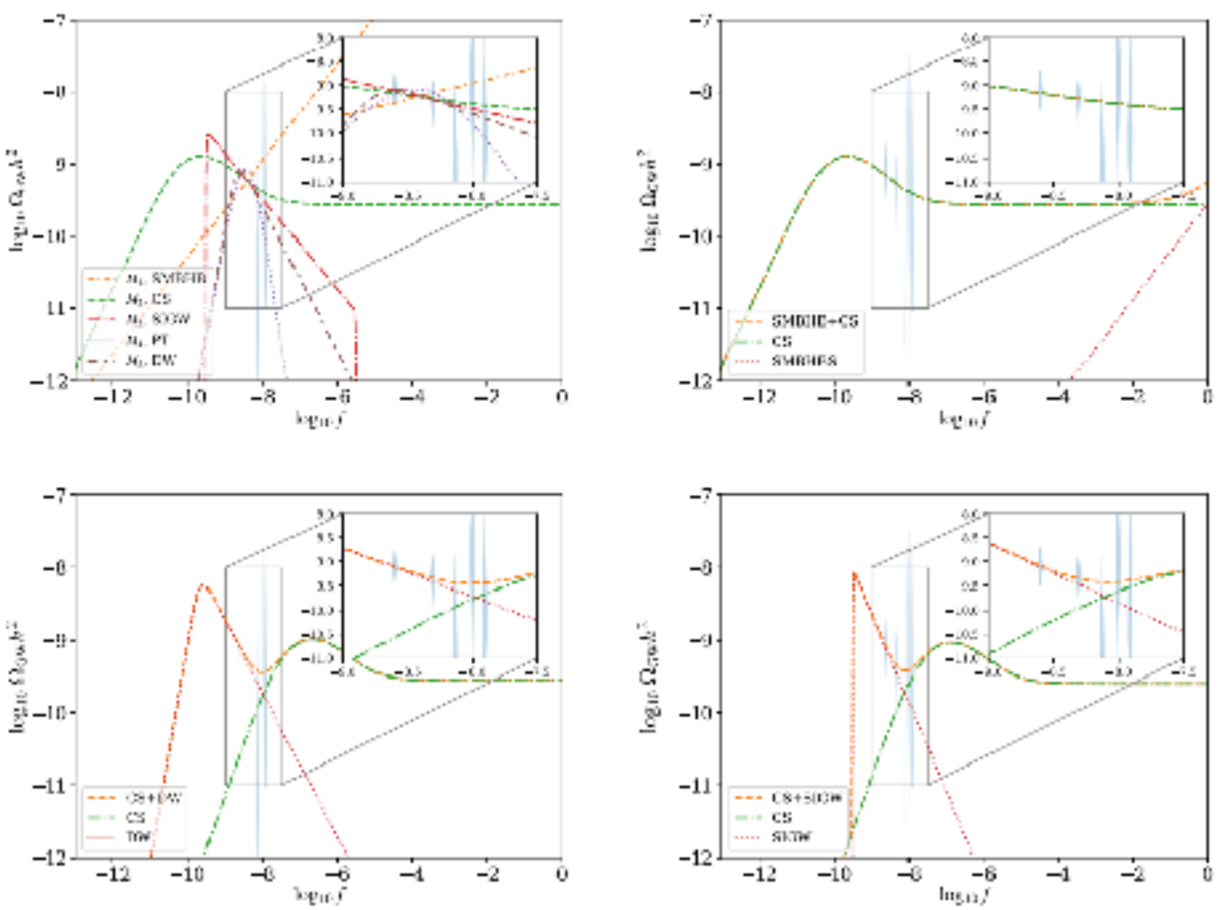


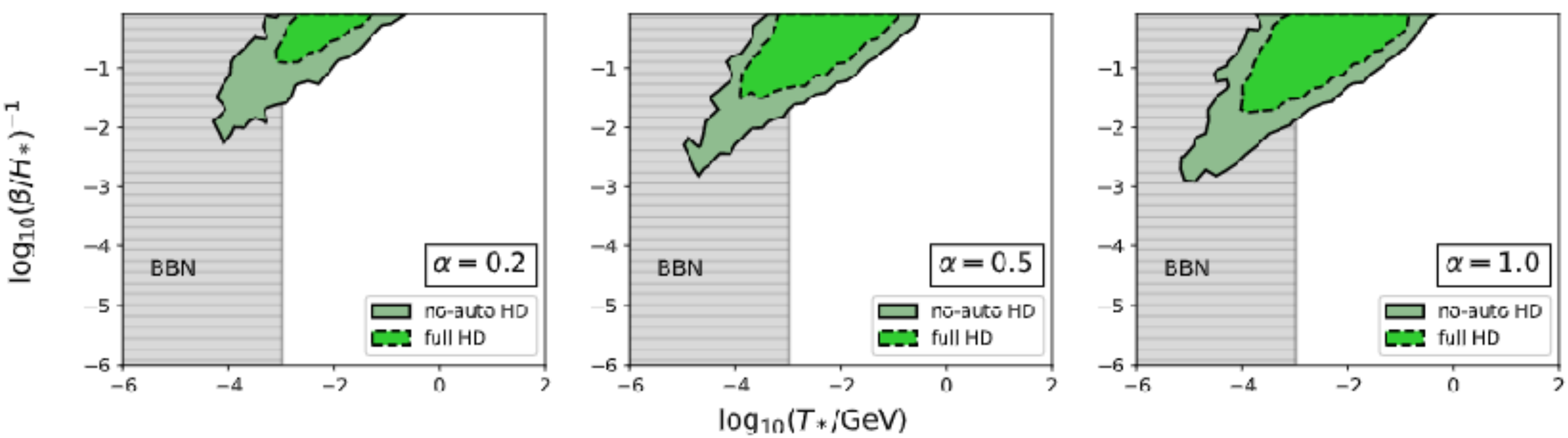
FIG. 5. GW energy spectrum for different models with best-fit value of parameters (which are shown in Supplemental Material [53]). The violin plots show the first five frequency bins of the NANOGrav 12.5-yr data set. The top-left panel shows individual GW source scenario, and the other three plots show the combined explanations with SMBHB + cosmic strings, cosmic strings + domain walls, and cosmic strings + scalar induced GWs.

Bian, Cai, Liu, Zhou, Phys.Rev.D 103 (2021) 8, L081301

PTGW for PPTA ???

TABLE I: Description of hypotheses tested in this work and the Bayes factors between them.

Hypothesis	Pulsar noise	Common red process	HD process FOPT spectrum	Bayes Factors	Parameter Estimation (median and 1-σ interval)	
					T_*/MeV, $\alpha\times10^3$, β/H_*	$A_{\rm comred}$, $\gamma_{\rm comred}$
H0:Pulsar Noise	yes	no	no			
H1:Common Red	yes	yes	no	$10^{3.5}$ (against H0)		$-14.45^{+0.62}_{-0.64}$,$3.31^{+1.36}_{-1.53}$
H2:FOPT	yes	no	yes (full HD)	$10^{1.8}$ (against H0)	$7.4^{+11.9}_{-4.7}$, 271^{+165}_{-92}, $9.9^{+11.4}_{-5.4}$	
H3:FOPT1	yes	yes	yes (full HD)	1.04 (against H1)	$9.6^{+232.2}_{-9.2}$, $3.8^{+27.9}_{-3.4}$, 854^{+9622}_{-782}	$-14.51^{+0.64}_{-0.68}$,$3.36^{+1.39}_{-1.54}$
H4:FOPT2	yes	yes	yes (no-auto HD)	0.96 (against H1)	$10.9^{+290.5}_{-10.6}$, $3.2^{+19.9}_{-2.8}$, 1053^{+11256}_{-962}	$-14.45^{+0.62}_{-0.64}$,$3.27^{+1.37}_{-1.54}$

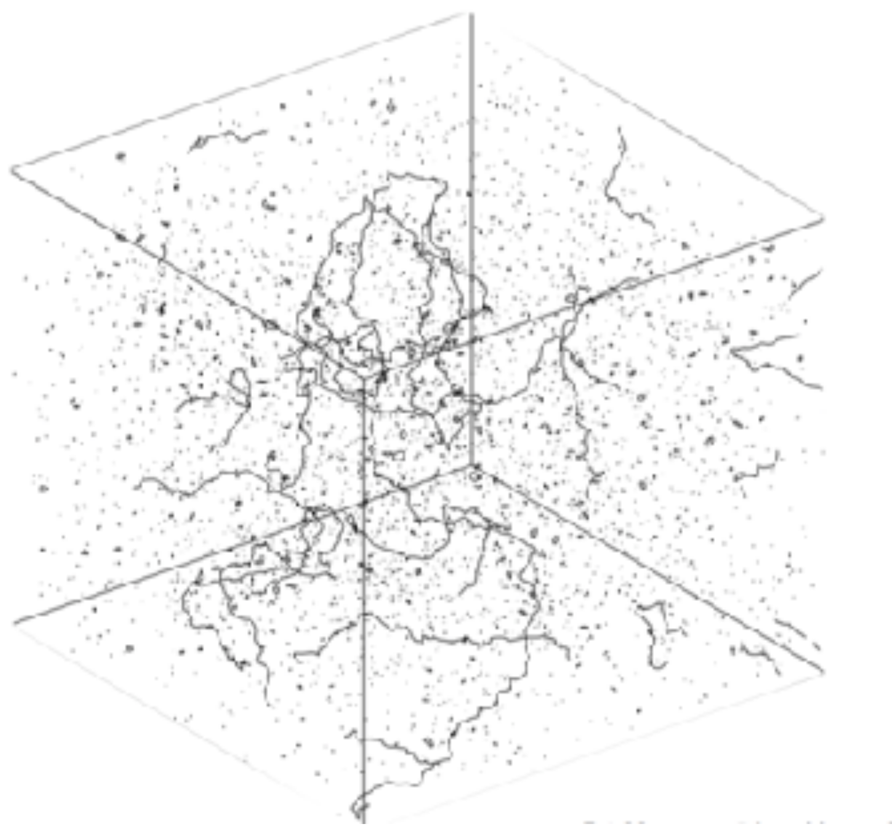


95% CL. Excl.

Xue, **Bian***, Shu*, Yuan*, Zhu*, Bhat, Dai et al. "Constraining cosmological phase transitions with the Parkes Pulsar Timing Array." *arXiv preprint arXiv:**2110.03096*** (2021), **PRL in press, Editor's suggestion.**

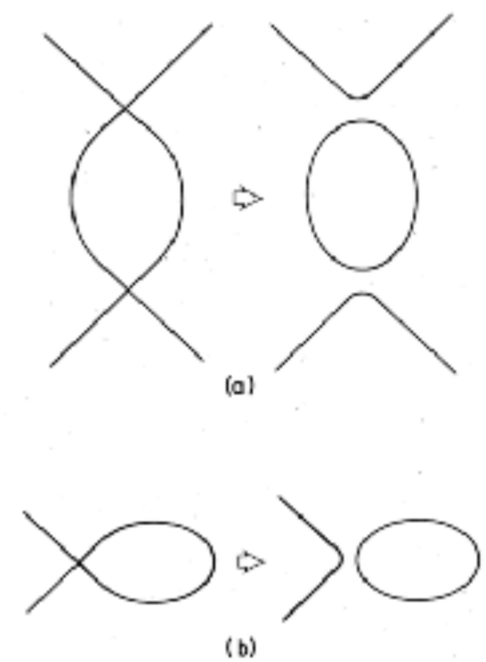
CS loops and GWs emission

CS: SSB of U(1) symmetry



Allen&Shellard PRL 64,119 (1990)

Loop formation



Closed-loop formation by intercommuting strings.

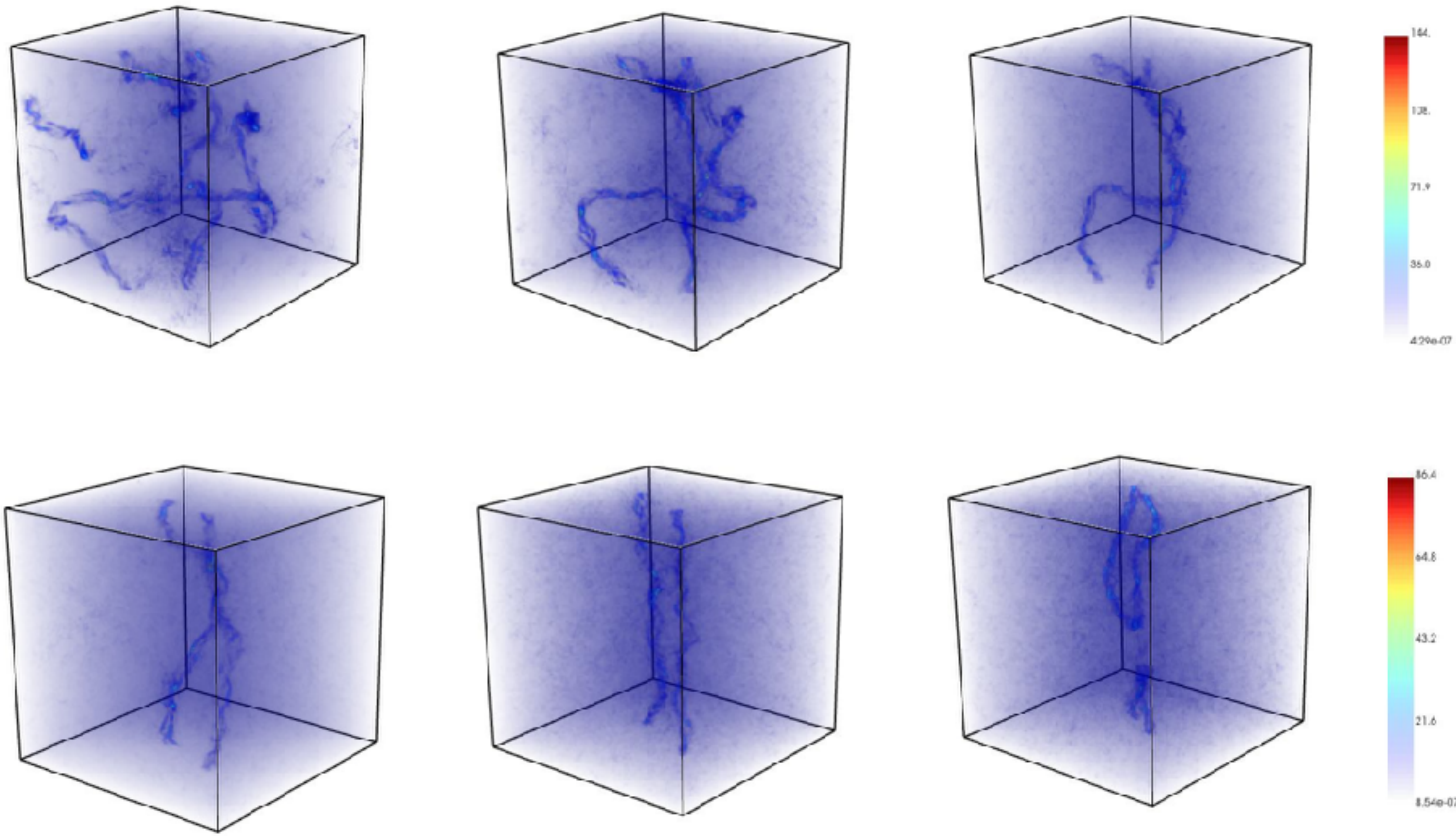
Cosmic string loop formation. A loop forms (a) when two strings interacts in 2 separate points or (b) when a string crosses itself.

Tanmay Vachaspati, Alexander Vilenkin Phys.Rev.D 30 (1984) 2036

GW emission

Cusps: a pointed and highly Lorentz-boosted region which appear few times per oscillation period

CS from first-order PT of abelian U(1)



Summary and future

Observation of the cosmic Magnetic field seeded by phase transition, with GW production may hint the B+L violation

Interaction between bubble wall and Plasma, and interaction among different bubbles are important

1）Magnetic field feedback to the phase transition
2）Baryogenesis and/or at fast-wall request by the GW

Higgs Potential shape

1) The future collider prospect, with dihiggs, Zh and/or Zhh production
2) Thin wall or thick wall tell by gravitational wave, wall profile and GW spectrum

Topological defects at the early Universe and gravitational waves relics

cosmic string, domain wall, …

Thanks
谢谢！