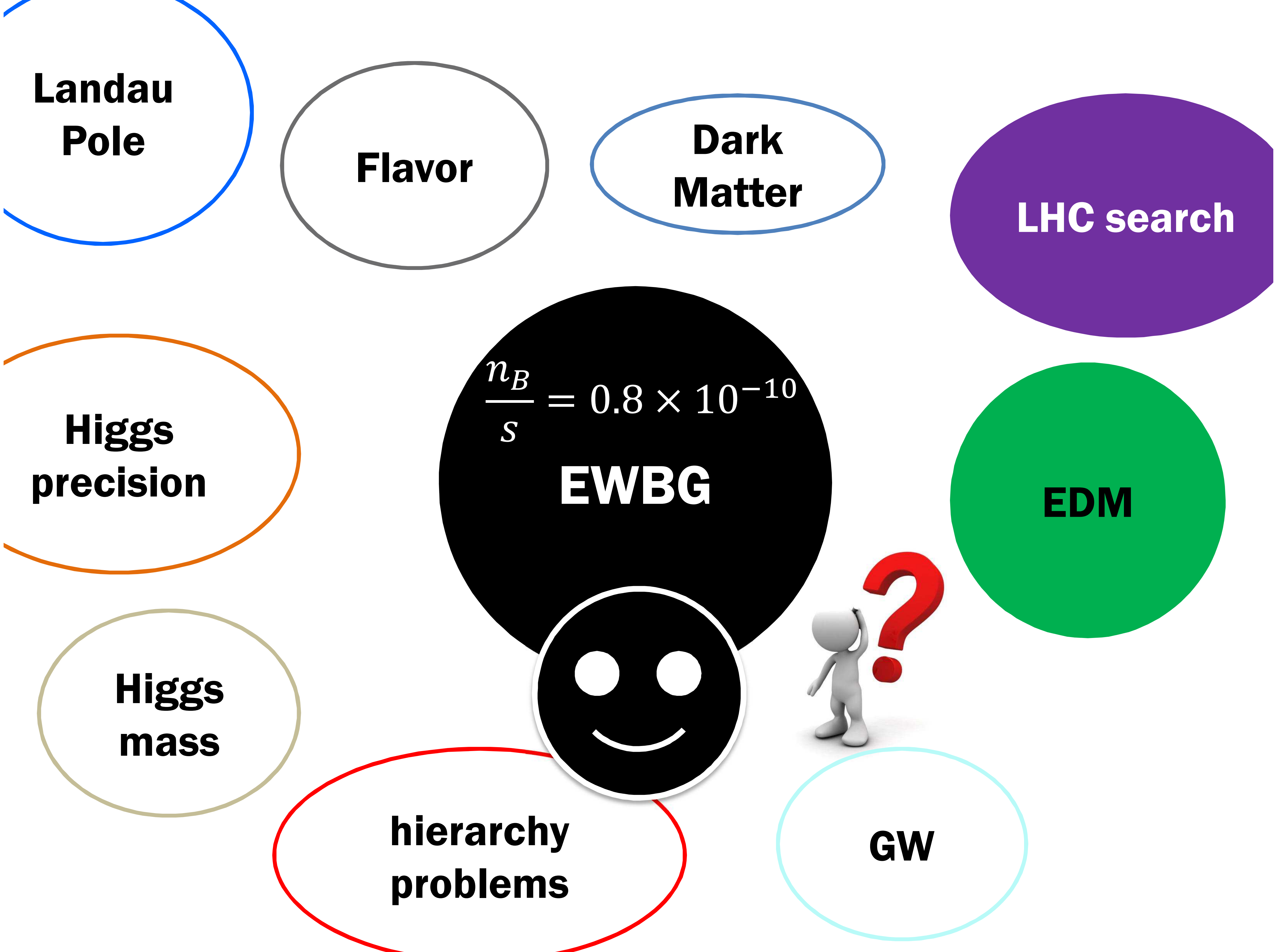
기초과학연구원
Institute for Basic Science

Electroweak baryogenesis and beyond the SM (3)

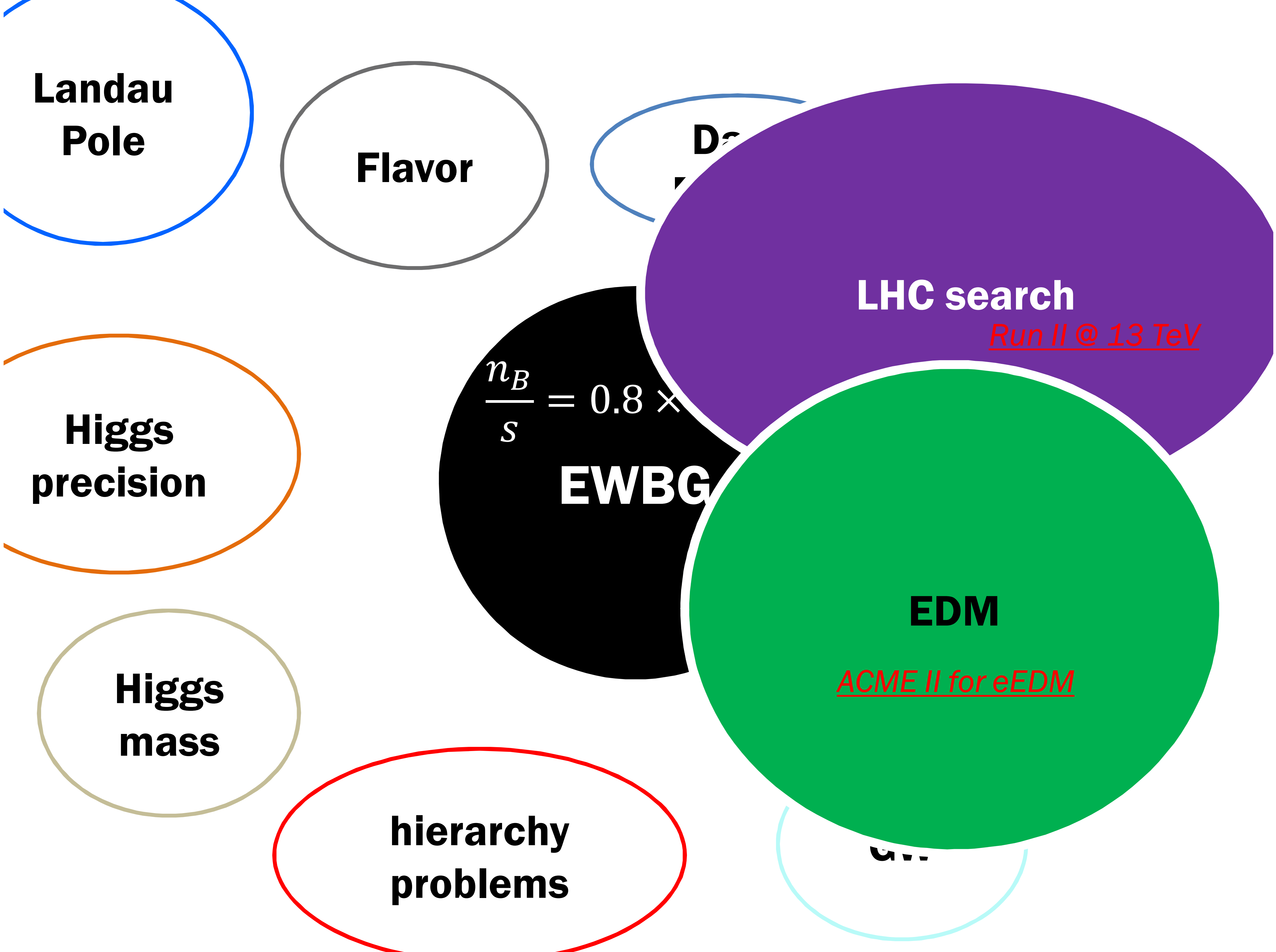
Chang Sub Shin (IBS-CTPU)

at Summer Institute 2019 (Sandpine)

Aug 18 – Aug 23, 2019



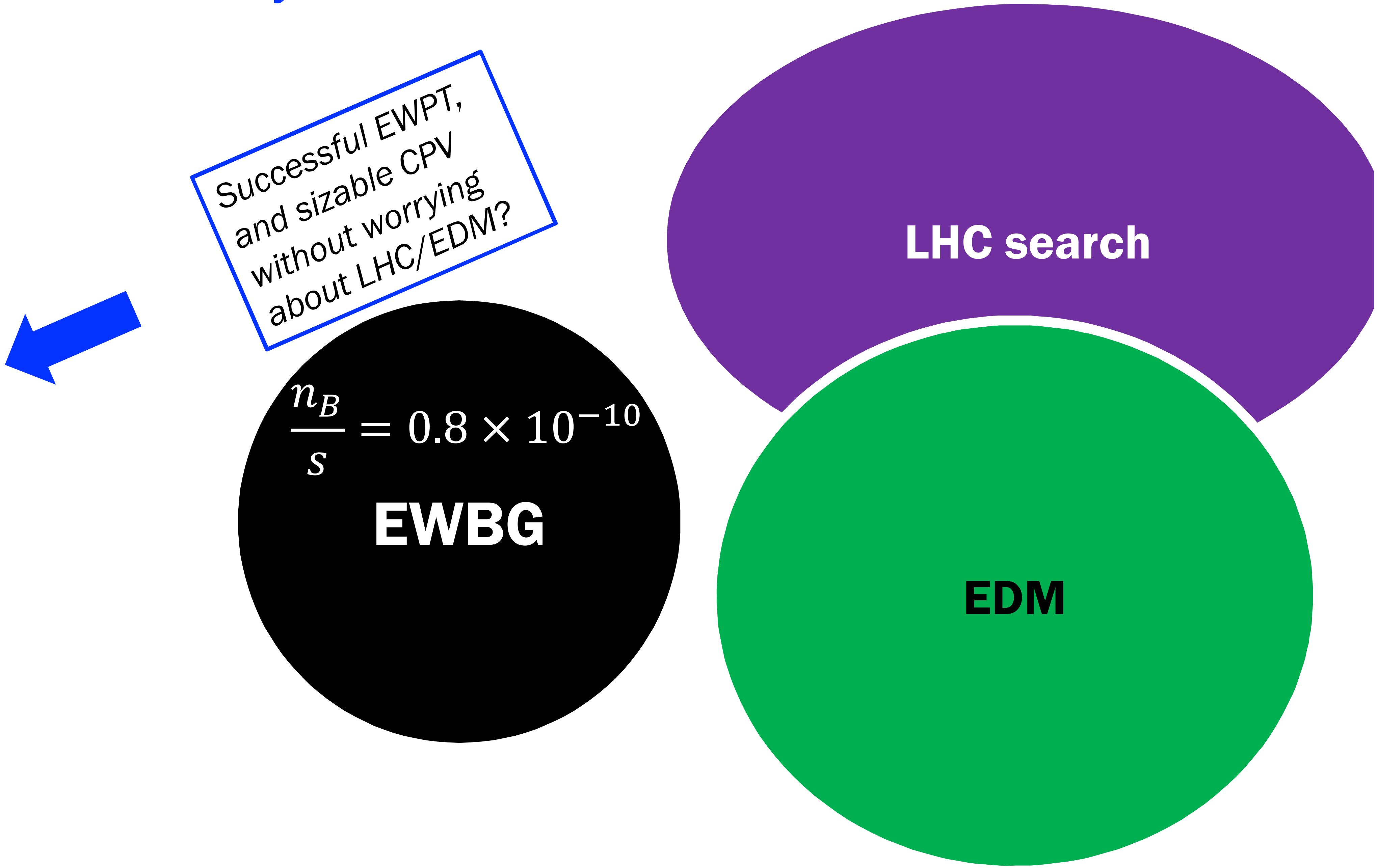
Landau Pole
Flavor
Dark Matter
LHC search
$\frac{n_B}{s} = 0.8 \times 10^{-10}$
EWBG
Higgs precision
EDM
Higgs mass
hierarchy problems
GW


Landau Pole
Flavor
LHC search
Run II @ 13 TeV
Higgs precision
$\frac{n_B}{s} = 0.8 \times$
EWBG
EDM
ACME II for eEDM
Higgs mass
hierarchy problems

Modified from fig of H. Murayama's slides

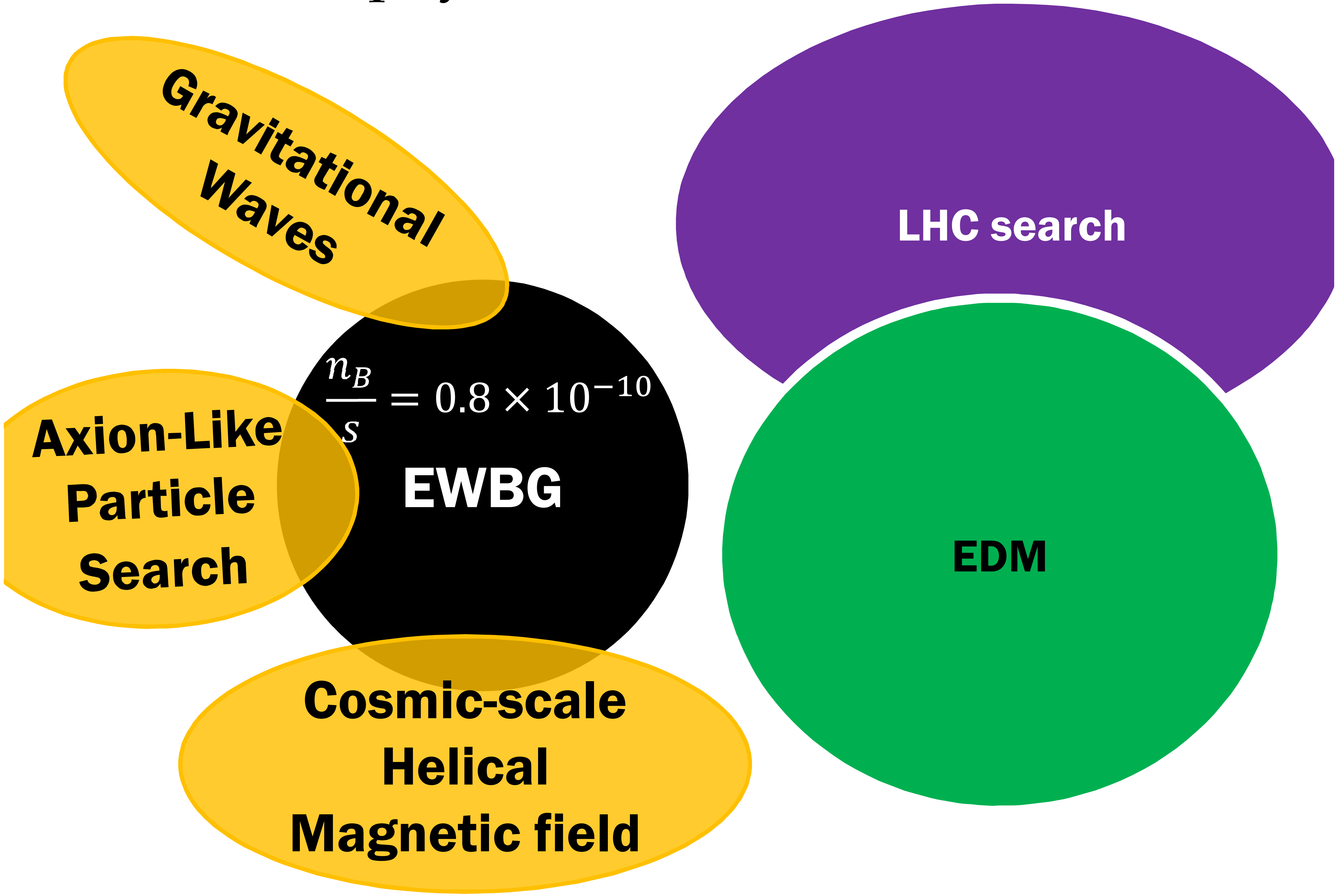

new or orthogonal
direction

1. Naturally safe from EDM and LHC constraints



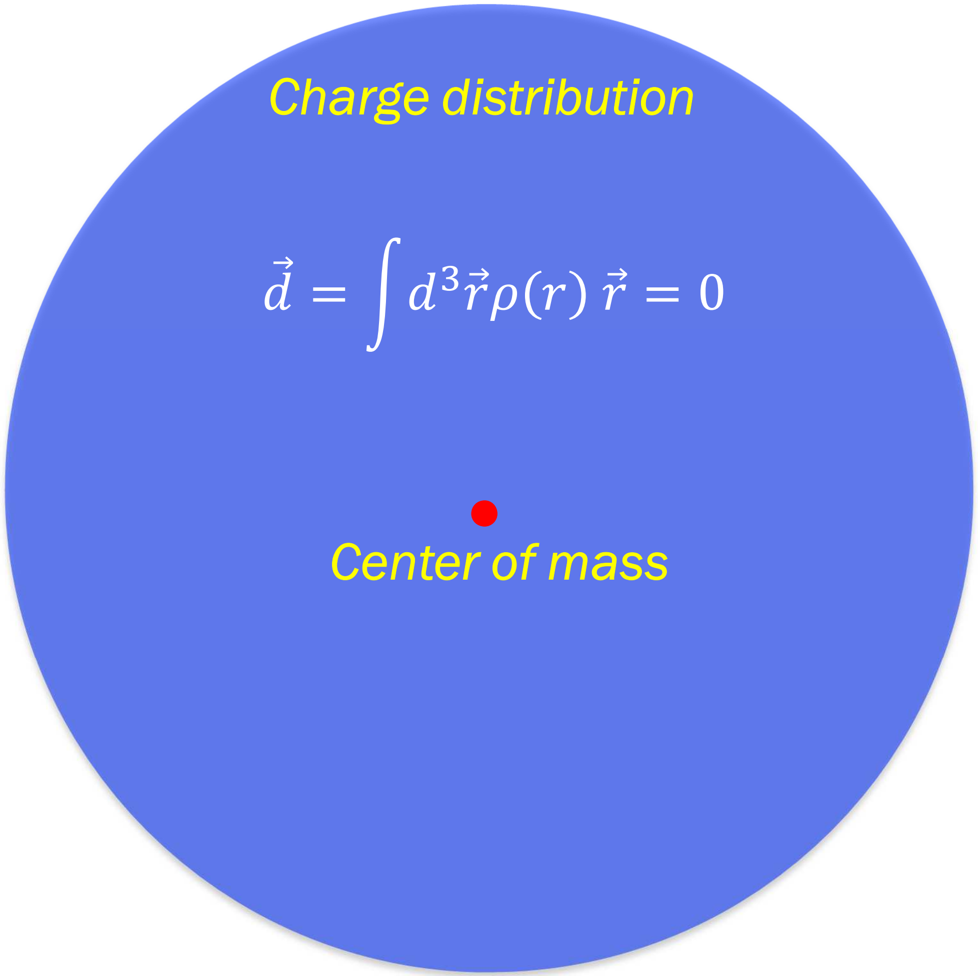
2. New experimental searches for the evidence of EWBG?

Astrophysical evidence for EWBG



Electric Dipole Moment (EDM)

Measure of the overall electric charge polarity



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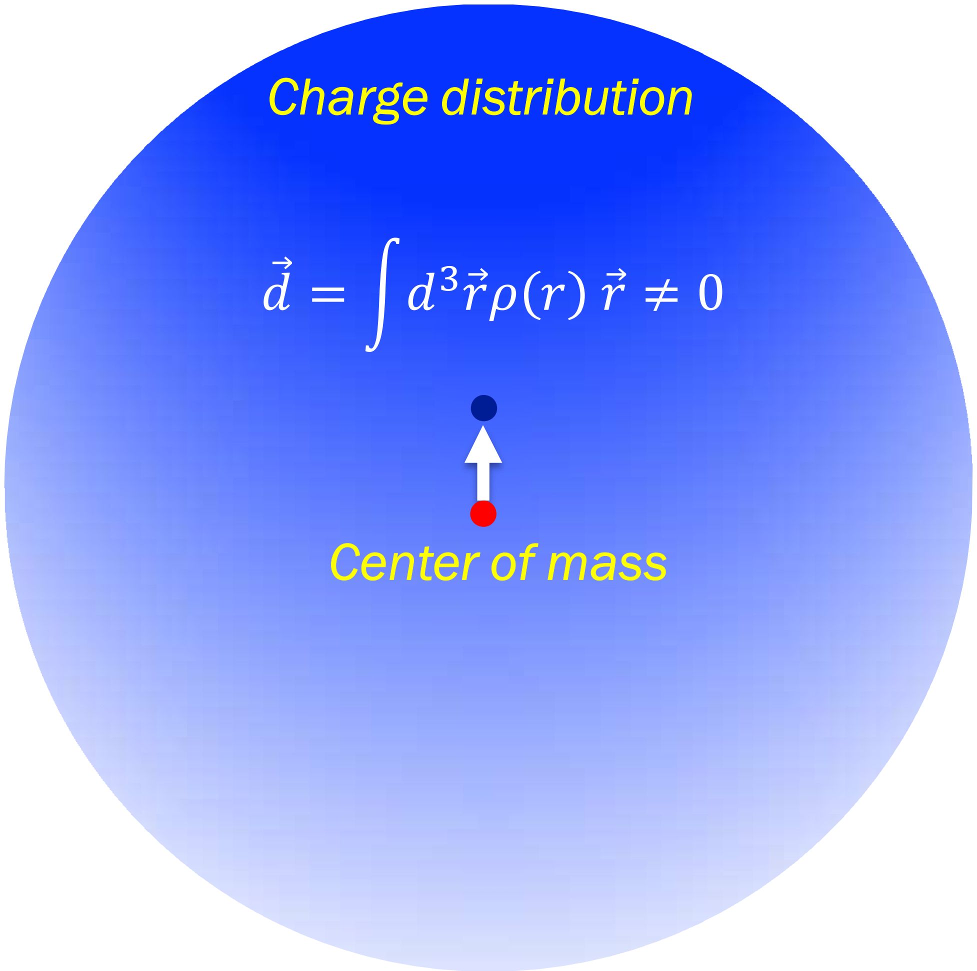

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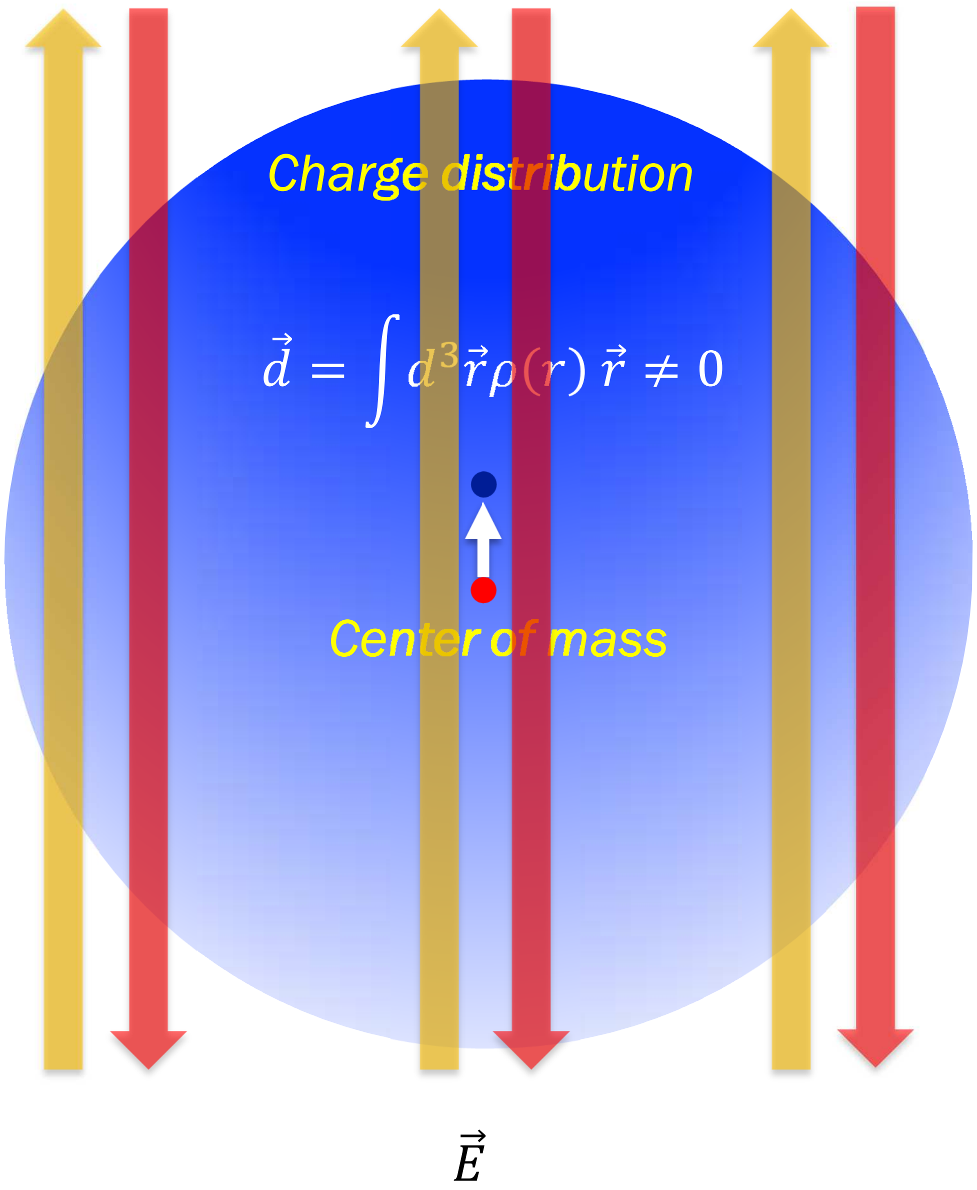
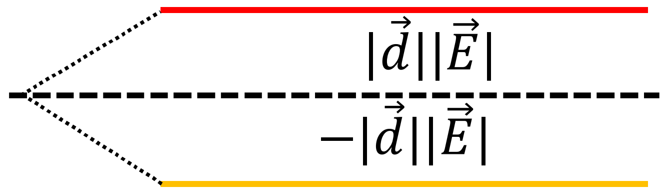


for the external E field,

$$\Delta U = -\vec{d}\cdot\vec{E}$$



For the elementary fermion, nonzero c_2: EDM

$$\Delta\mathcal{L}_{eff} = (c_1\bar{\psi}\sigma^{\mu\nu}\psi + c_2 i\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi)F_{\mu\nu}$$

$$\Delta\mathcal{L}_{eff} = \bar{\psi}\sigma^{\mu\nu}\psi(c_1F_{\mu\nu} - c_2\tilde{F}_{\mu\nu})$$

$$-\Delta U_{nr} = c_1\, q\vec{\boldsymbol{S}}\cdot\vec{\boldsymbol{B}} + c_2\, q\vec{\boldsymbol{S}}\cdot\vec{\boldsymbol{E}}$$

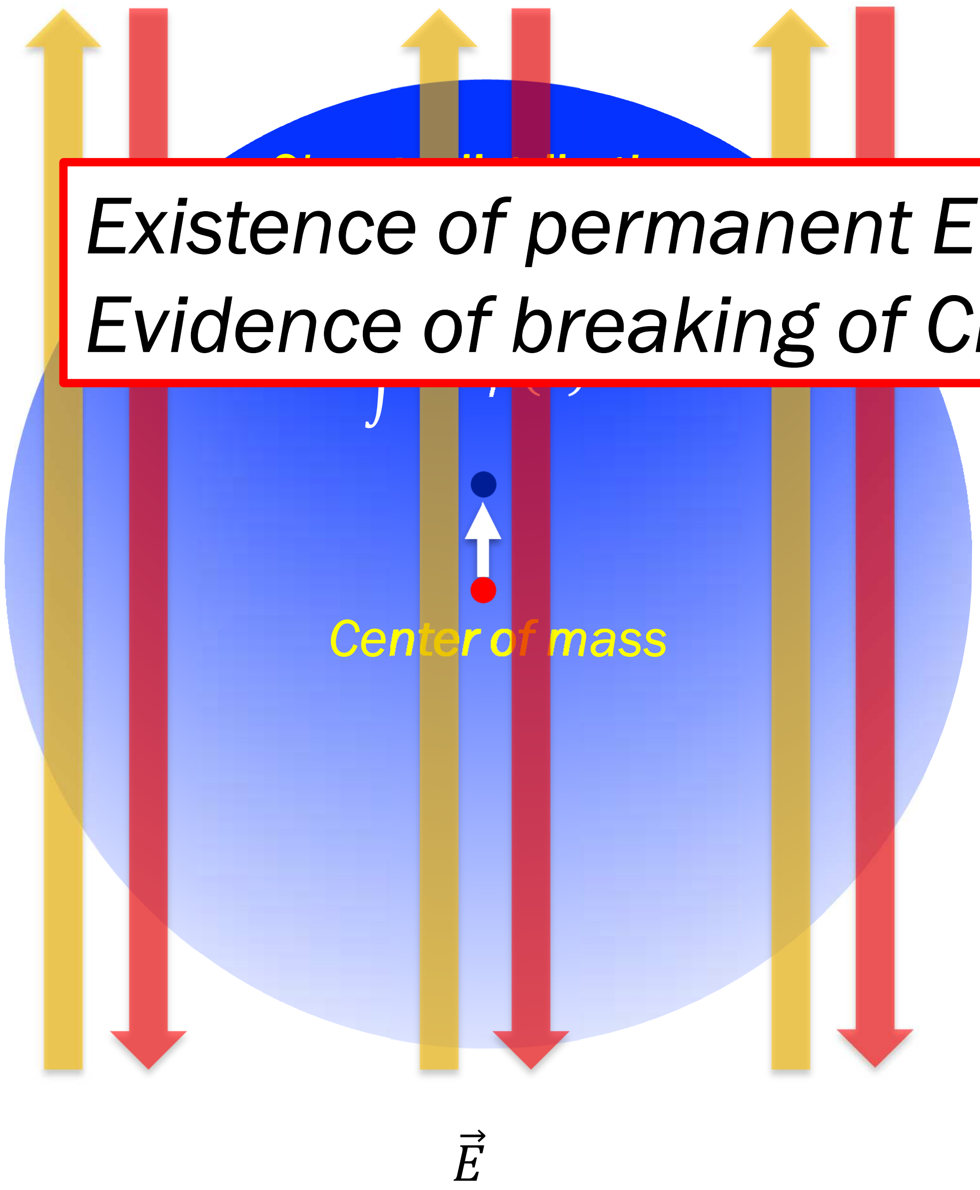
Under C,P,T transformation

$q = 1$ (particle)
$\;\;= -1$ (antiparticle)

	C	P	T
$q\vec{\boldsymbol{S}}$:	$-$	$+$	$-$
$\vec{\boldsymbol{B}}$:	$-$	$+$	$-$
$\vec{\boldsymbol{E}}$:	$-$	$-$	$+$

Electric Dipole Moment (EDM)

Measure of the overall electric charge polarity



$f$or the external E field,
$\Delta U = -\vec{d} \cdot \vec{E}$

Existence of permanent EDM:
Evidence of breaking of CP symmetry

For the elementary fermion, nonzero c_2: EDM

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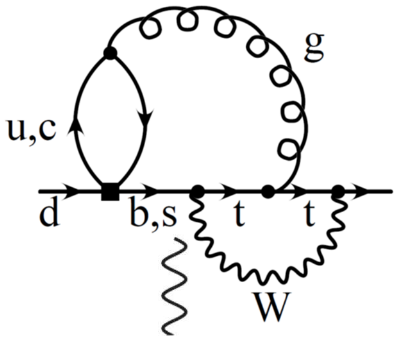
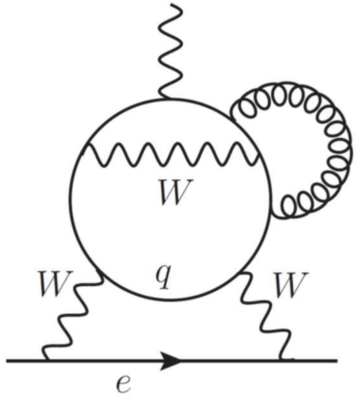
EDM and baryon asymmetry

SM contribution to the EDM





$$d_d \sim \left(\frac{em_d}{m_W^2}\right)\left(\frac{\alpha_s}{4\pi}\right)\left(\frac{\alpha_W}{4\pi}\right)^2\left(\frac{m_c^2}{m_W^2}\mathrm{Im}\left(V_{td}V_{tb}^*V_{cb}V_{cd}^*\right)\right)$$

$$\sim 10^{-34} e\ \mathrm{cm}$$

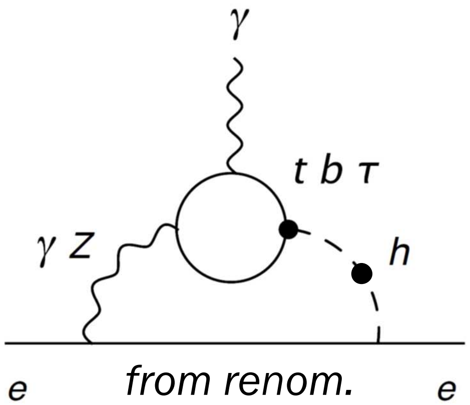
Khriplovich 1986, Czarnecki, Krause 1997

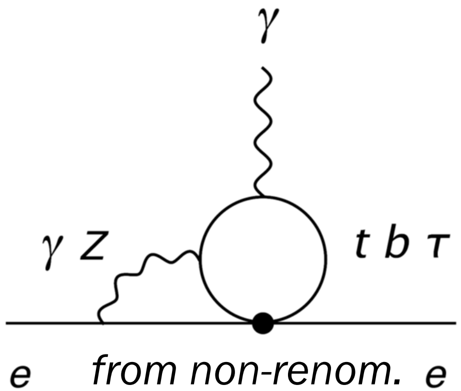
$$d_e \sim \left(\frac{em_e}{m_W^2}\right)\left(\frac{\alpha_s}{4\pi}\right)\left(\frac{\alpha_W}{4\pi}\right)^3\left(\frac{m_s^2 m_c^2}{m_W^4}\mathrm{Im}\left(V_{td}V_{tb}^*V_{cb}V_{cd}^*\right)\right)$$

$$\sim 10^{-38} e\ \mathrm{cm}$$

Khriplovich, Pospelov 1991

New physics contribution relevant for EWBG.





$$d_e \sim \left(\frac{em_e}{m_W^2}\right)\left(\frac{\alpha_{eff}}{4\pi}\right)^2\left(\frac{v^2}{\Lambda_{CP}^2}\delta_{CP}\right)$$

$$\sim 10^{-29} e\ \mathrm{cm}\left(\frac{v^2}{(0.1\ \Lambda_{CP})^2}\delta_{CP}\right)$$

Estimating baryon asymmetry (if the CPV effect during BG is the same as that of zero temp.)

$$\frac{n_B}{s} \sim \frac{\Gamma_{sph}(T_{EW})}{g_* T_{EW}^4}\left(\kappa_{ws}\Delta\theta_{W,\psi}\right)_{PT} \sim \kappa_{ws}\frac{\Gamma_{sph}(T_{EW})}{g_* T_{EW}^4}\left(\frac{v(T_{EW})^2}{\Lambda_{CP}^2}\delta_{CP}\right) < 10^{-10}\left(\frac{v^2}{(0.1\ \Lambda_{CP})^2}\delta_{CP}\right)$$

EDM and baryon asymmetry

It is the right time to think the implication of eEDM for electroweak baryogenesis

ACME II $|d_e| < 1.1 \times 10^{-29} e\ \mathrm{cm}$ at 90% confidence level

thorium monoxide: electrons inside the molecule feel exceptionally strong electric fields:

$\mathcal{E}_{eff} \simeq 78\ \mathrm{GeV/cm}$

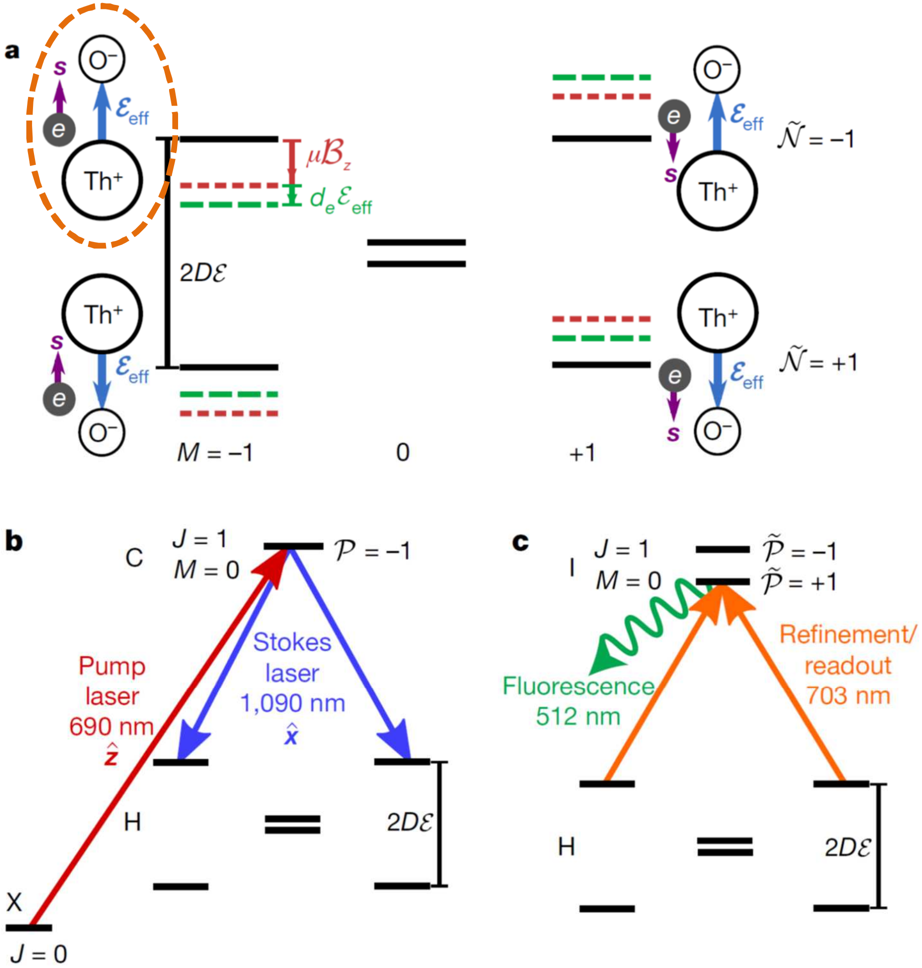
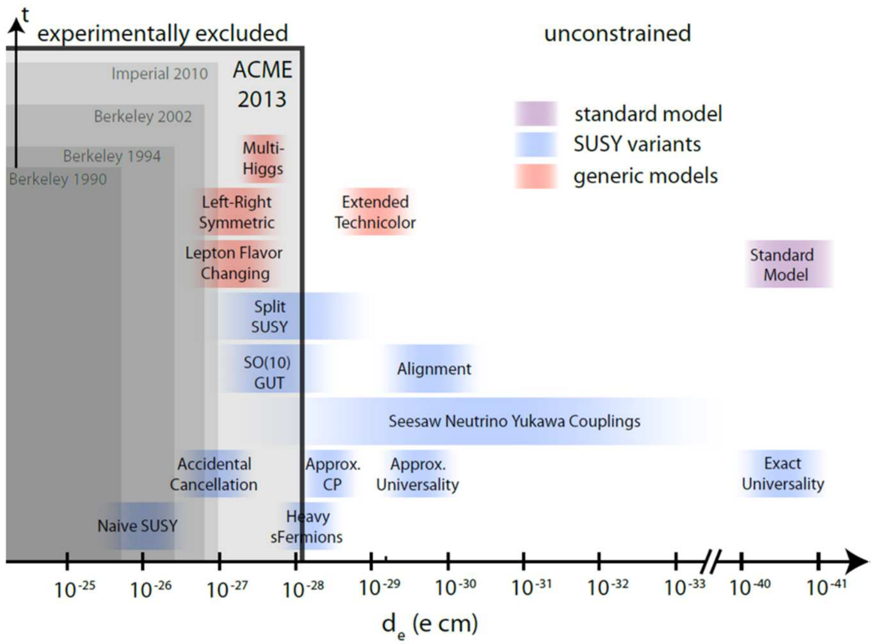
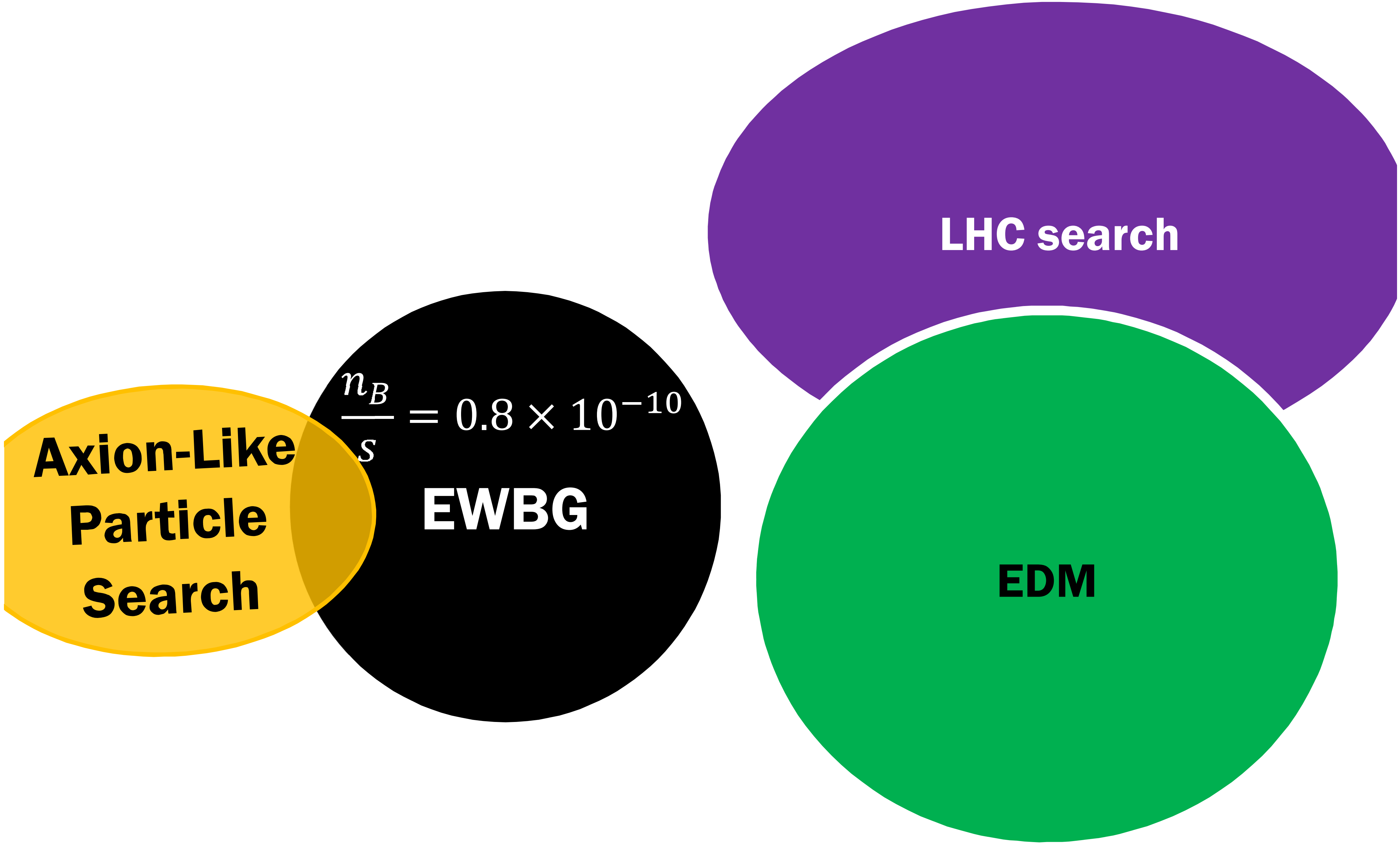


Fig. 1 | Energy levels of thorium monoxide and laser transitions.



EDM of some new physics models

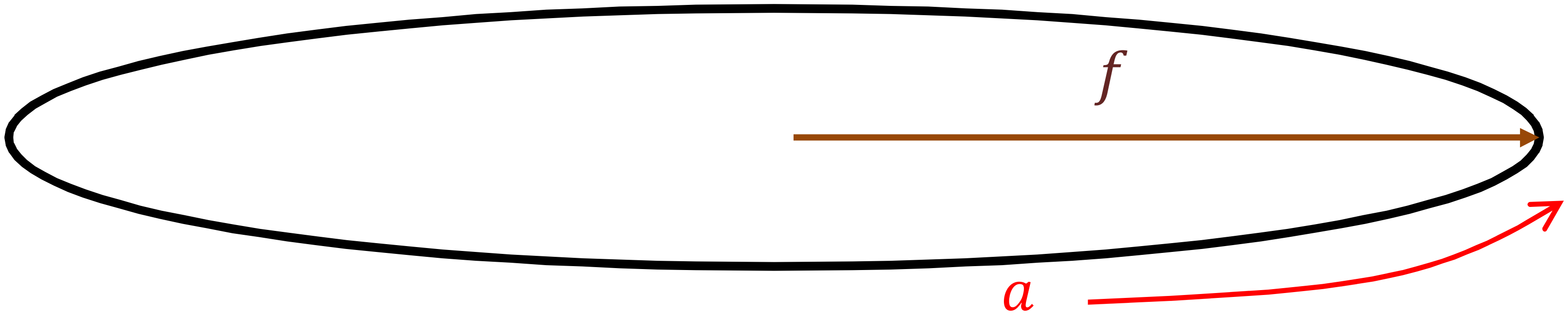
Axionic extension of the SM



ALP intro (1)

ALP, $a(x)$*, is the scalar field in effective theories well below the scale* f *:*

1) *The SM singlet, and compact with a period:* $2\pi f$



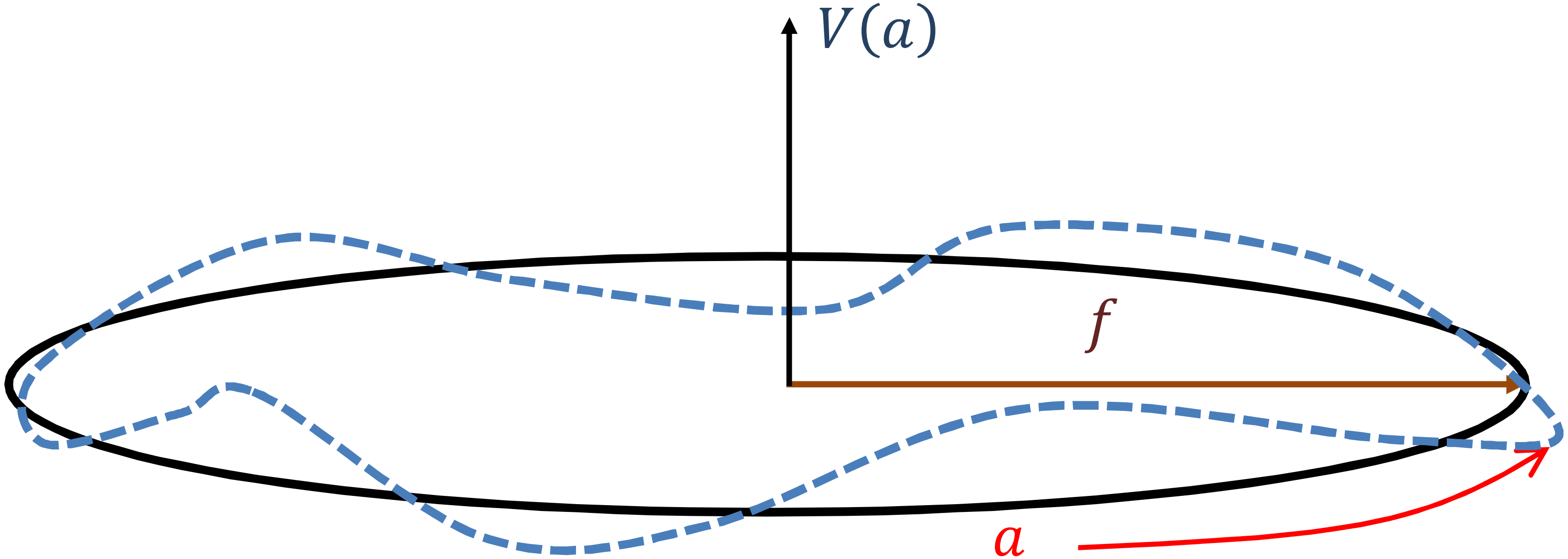
$$S[a] = S[a + 2\pi\mathbb{N}f]$$

ALP intro (2)

ALP, $a(x)$*, is the scalar field in effective theories well below the scale* f *:*

2) Approximate continuous shifty symmetry $U(1)_{PQ}$

($a \to a + 2\pi f \beta$, *where* $\beta \in \mathbb{R}$)



The potentials and interactions to explicitly break shift symmetry are generated at a scale (μ*) much lower than* f ($\mu \ll f$). *All interactions between ALP and matters can be given by the combination of*

$$\frac{a}{f}$$

ALP intro (3)

E.g.) considering the hidden non-abelian gauge group G_X, the axion-gauge field interactions can be generated if $U(1)_{PQ}$ is anomalous under the $SU(2)_L$, and G_X.

$$\Delta\mathcal{L}_1 = \frac{1}{16\pi^2}\frac{a}{f}\left(g^2\mathrm{Tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] + g_X^2\mathrm{Tr}\left[X_{\mu\nu}\tilde{X}^{\mu\nu}\right]\right)$$

For the particle contents of hidden sector, $N+\bar{N}$, $L+\bar{L}$, with following charges

Particle contents	$N+\bar{N}$	$L+\bar{L}$
G_X	$(F,\bar{F})$	$(F,\bar{F})$
$SU(2)_L\times U(1)_Y$	$\mathbf{1}_0,\mathbf{1}_0$	$\mathbf{2}_{-1},\bar{\mathbf{2}}_1$

Then the allowed Lagrangian density is

$$\Delta\mathcal{L}_2 = m_L L\bar{L} - m_N N\bar{N} + \lambda_L \bar{N}LH + \lambda_{\bar{L}} N\bar{L}H^+ + h.c.$$

G_X can be confined at Λ_X, with the following hierarchy $m_N \ll \Lambda_X \ll m_L$. Integrating out $L+\bar{L}$ gives

$$\Delta\mathcal{L}_{2eff} = -\left(m_N N\bar{N} + h.c.\right) - \left(\frac{\lambda_L\lambda_{\bar{L}}}{m_L}N\bar{N} + h.c.\right)|H|^2$$

Confinement gives chiral symmetry breaking $\langle N\bar{N}\rangle = \Lambda_X^3 e^{i\eta_N}$. Due to the chiral anomaly, η_N becomes heavy and get a mass of $O(\Lambda_X)$. Integrating out η_N gives $\eta_N \to a/f$. Finally,

$$\Delta\mathcal{L}_{eff} = \frac{g^2}{16\pi^2}\frac{a}{f}\mathrm{Tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - |m_N\Lambda_X^3|\cos\frac{a}{f} - \left|\frac{\lambda_L\lambda_{\bar{L}}\Lambda_X^3}{m_L}\right|\cos\left(\frac{a}{f}+\alpha\right)|H|^2 \quad \left(\alpha = \arg\frac{\lambda_L\lambda_{\bar{L}}}{m_L m_N}\right)$$

Axionic extension of the Higgs potential

A scalar potential is constructed by the Higgs and the angular field, $\theta(x) \equiv a(x)/f$

$$V(H, a) = \mu_1^2 |H|^2 + \lambda |H|^4 + \mu_2^2 \cos(\theta + \alpha)\,|H|^2 - \Lambda^4 \cos\theta\,.$$

Considering an expansion in terms of a/f,

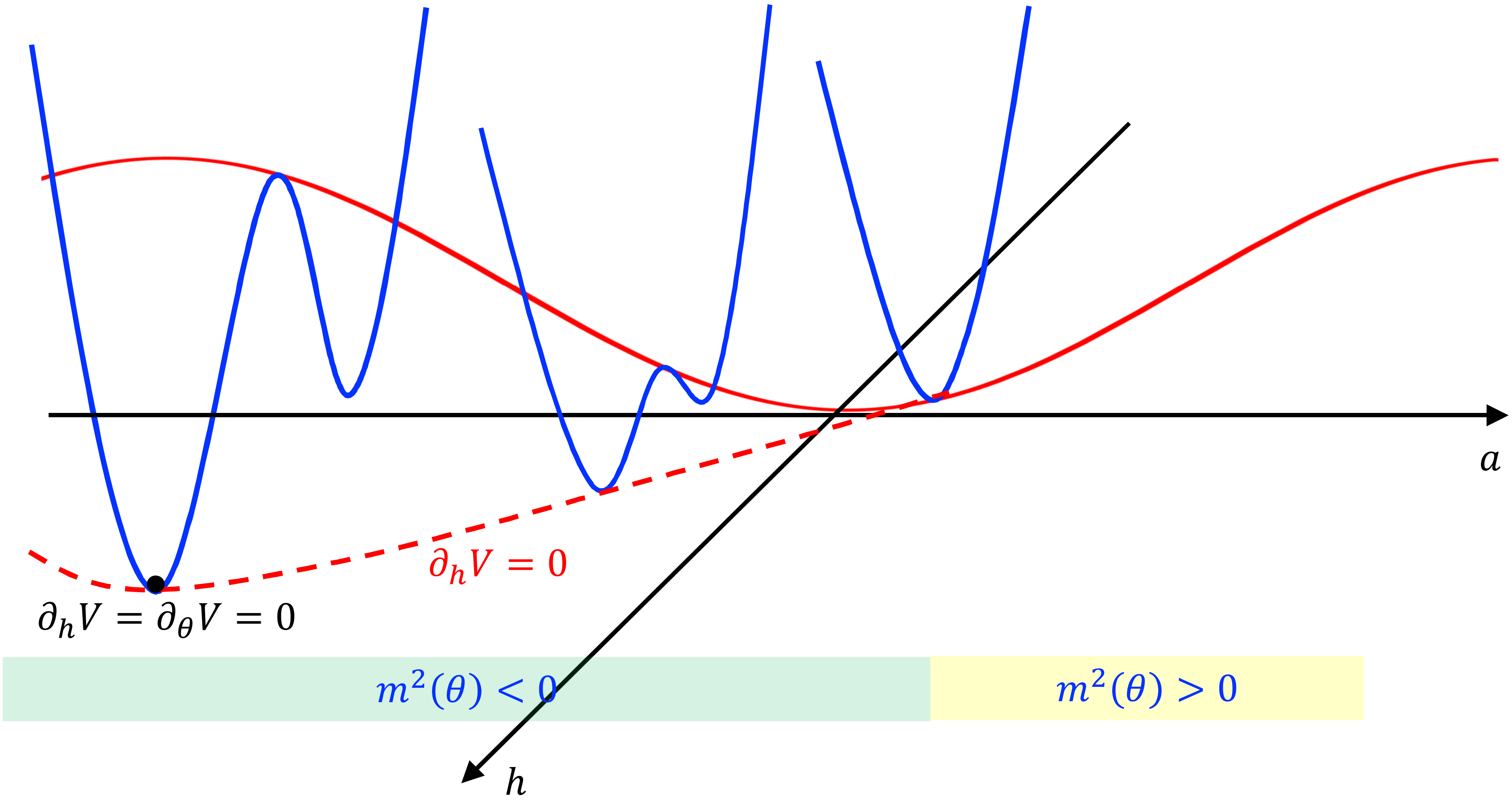
$$V(h, a) = \frac{1}{2}\left(\mu^2 + c_1 \frac{\mu^2}{f} a + c_2 \frac{\mu^2}{f^2} a^2 + c_3 \frac{\mu^2}{f^3} a^3 + \cdots\right) h^2 + \frac{\lambda}{4} h^4 + \frac{\Lambda^4}{2f^2} a^2 - \frac{\Lambda^4}{24 f^4} a^4 + \frac{\Lambda^4}{720 f^6} a^6 + \cdots.$$

The couplings between ALP and the Higgs are suppressed for $m_W \ll f$.

Tadpole, cubics and higher dimensional operators can be systematically introduced without worrying about stability of the scalar potential even if we consider $\Delta a = O(f)$ *during phase transition.*

Schematic description of the potential

The scalar potential can be written as $V(h,\theta) = \tilde{V}(\theta) + \frac{1}{2}m^2(\theta)h^2 + \frac{\lambda}{4}h^4.$

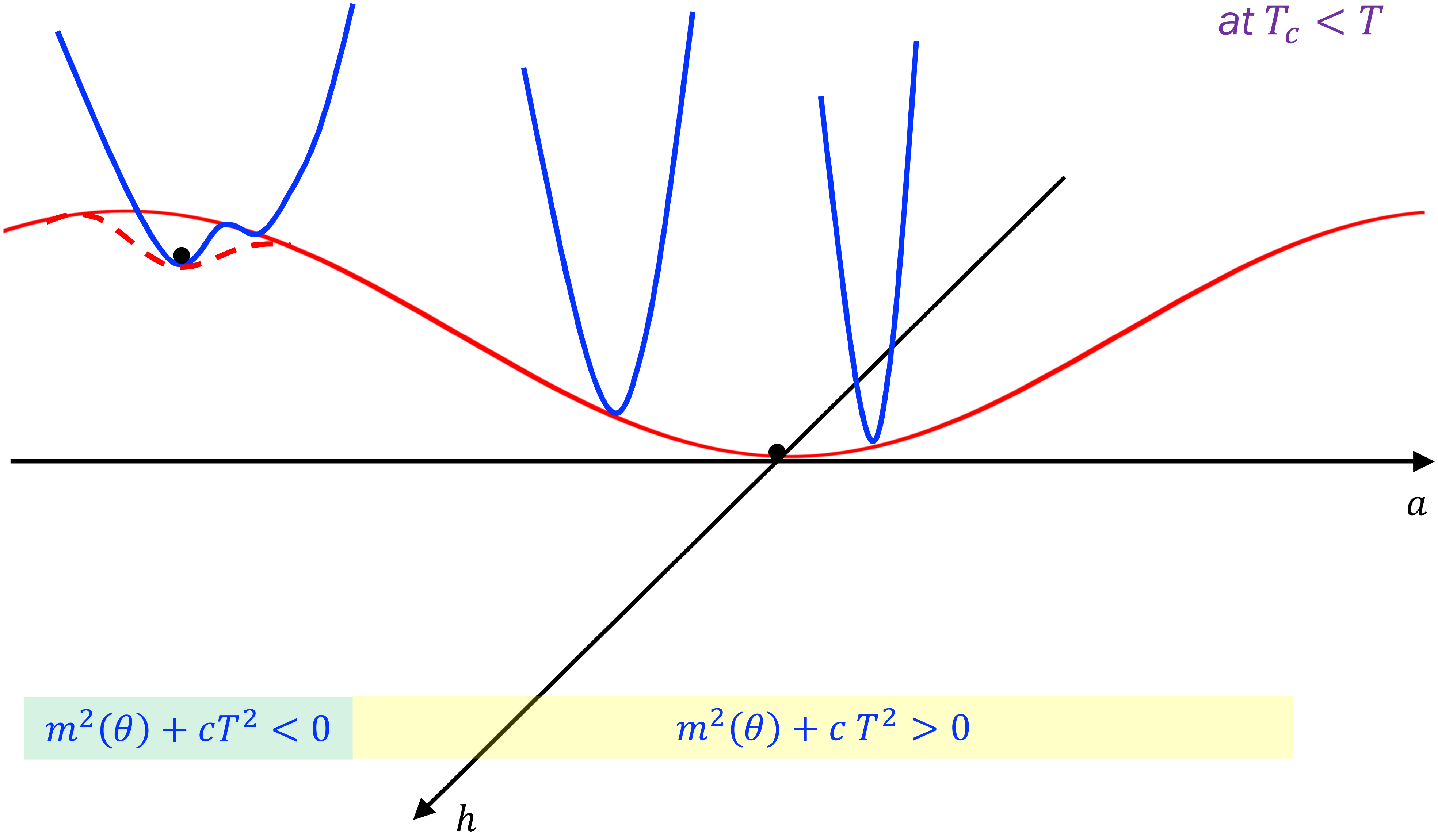


The potential is bounded from below due to the periodicity of the axion dependence

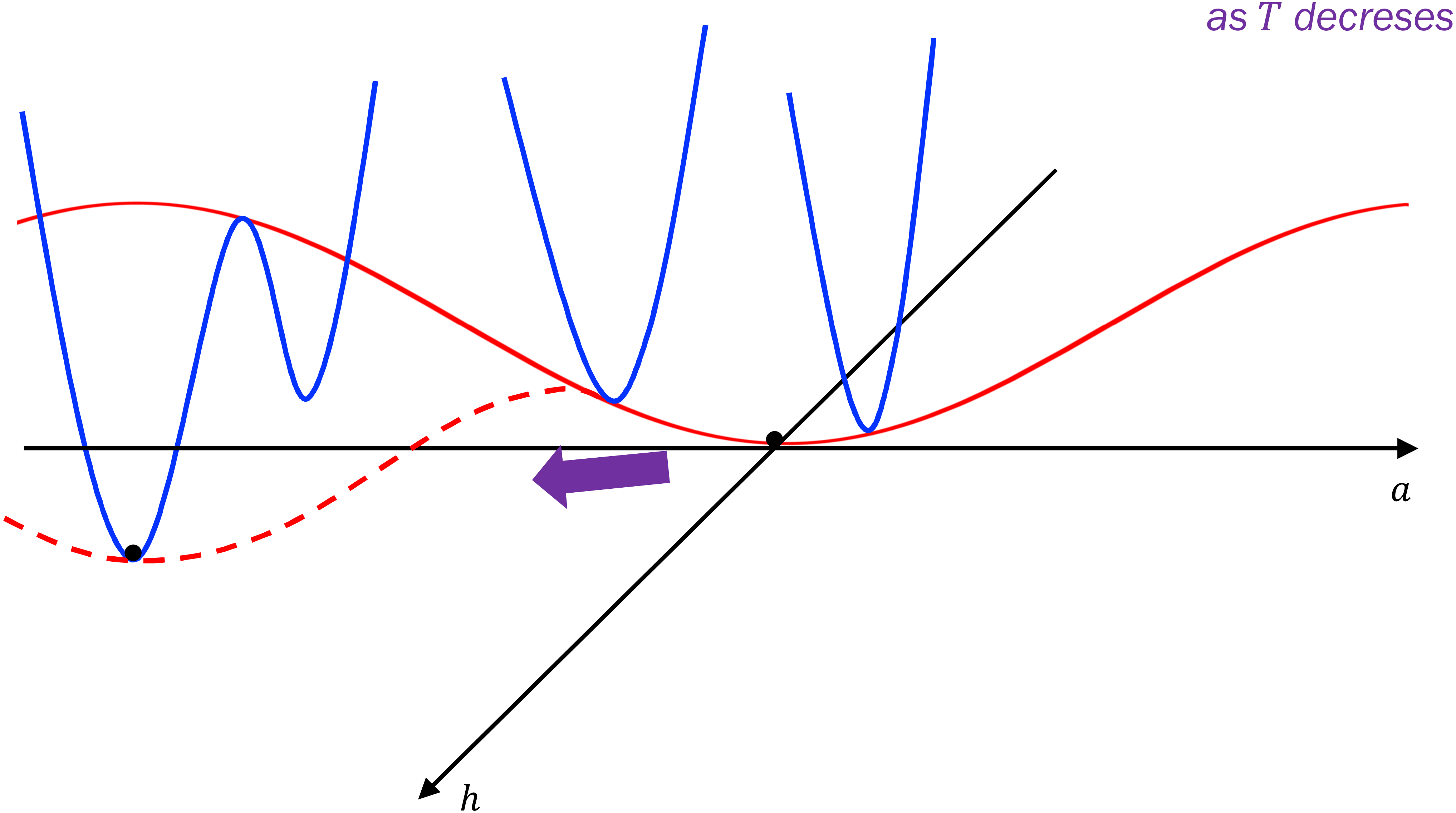
Schematic description of EWPT

The scalar potential can be written as $V_T(h,\theta) = \tilde{V}(\theta) + \frac{1}{2}(m^2(\theta) + cT^2)h^2 + \frac{\lambda}{4}h^4$

at $T_c < T$

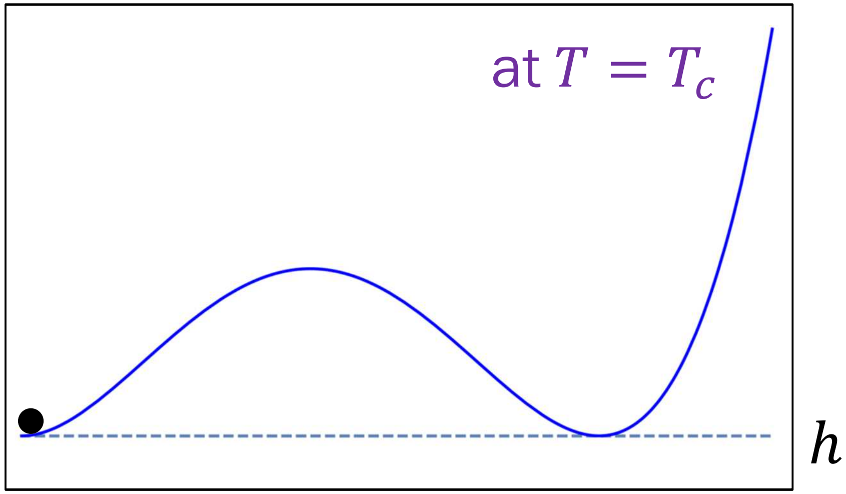


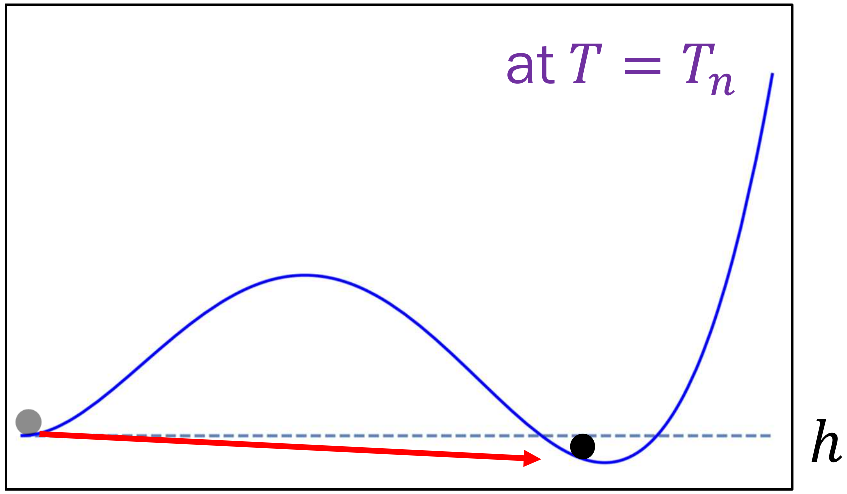
Schematic description of EWPT



Nucleation/thermal tunneling

For usual EWBGs ($\Delta h \sim m_W$), *the phase transition happens just after* T_c, *i.e.* $T_n \simeq T_c$.



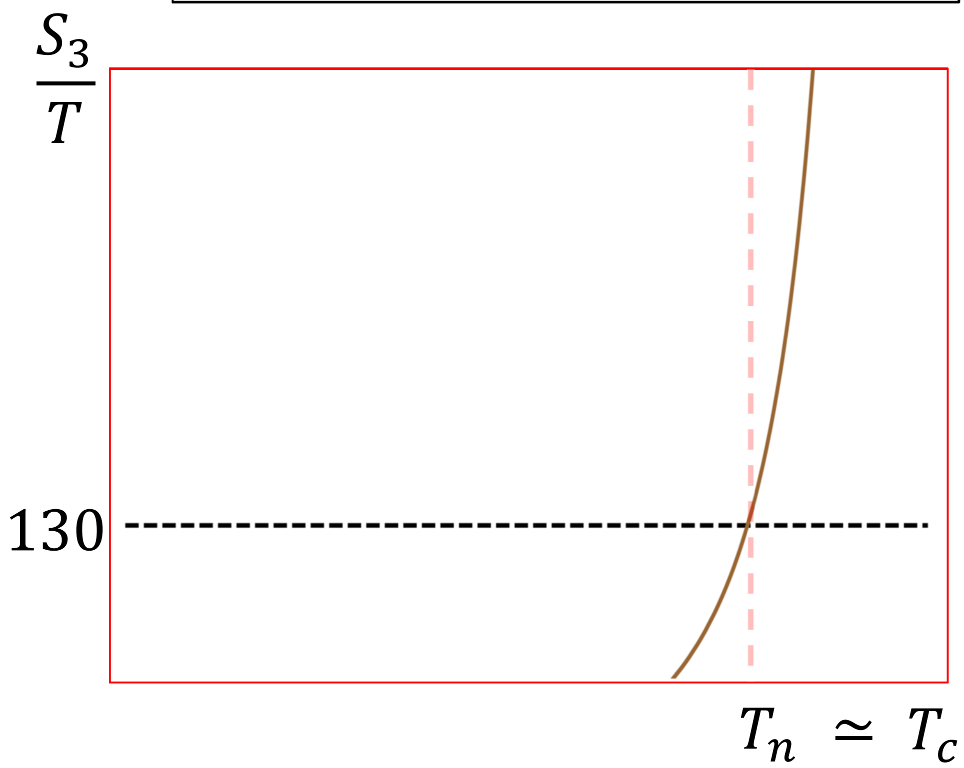


Bubble nucleation rate with the Euclidean action S_3 for an O(3)-symmetric critical bubble

$$\Gamma_{\rm nuc}(T_n)/H^3 = c\, T^4/H^3\, e^{-\frac{S_3}{T}} \simeq H(T_n)$$

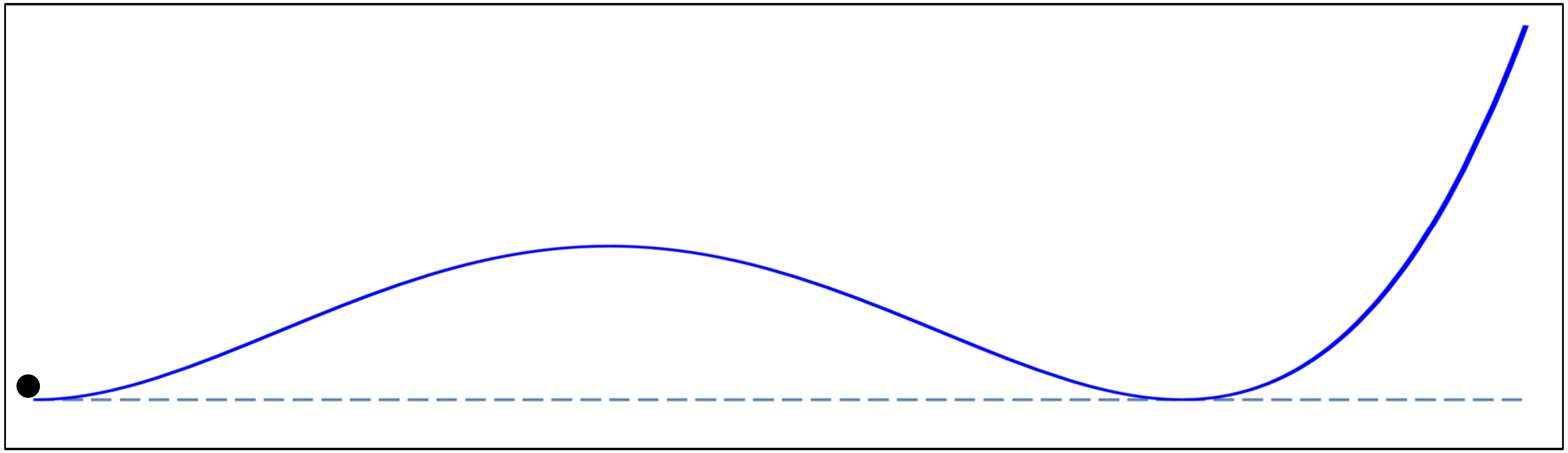
Typically in those cases,

$$1 - \frac{T_n}{T_c} \leq O(0.01 - 0.1)$$



Nucleation/thermal tunneling

As $f \gg m_W$, S_3 *increases as* $S_3 \propto f^3$ *, so phase transition is delayed.*



$a = f\theta$

$\Delta a \sim f$

$$S_3 = \int d^3\vec{x} \left(\frac{1}{2}(\vec{\nabla} h)^2 + \frac{1}{2}\left(\vec{\nabla} a\right)^2 + V_T(h,a) \right)$$

$$= 4\pi f^3 \int du\, u^2 \left(\frac{h'^2}{2f^2} + \frac{1}{2}\theta'^2 + V_T(h,\theta) \right)$$ *where* $u = r/f$ *with e.o.m.*

$$\frac{d^2\theta}{du^2} + \frac{2}{u}\frac{d\theta}{dt} = \frac{\partial V_T}{\partial \theta}, \qquad \frac{1}{f}\left(\frac{d^2 h}{du^2} + \frac{2}{u}\frac{dh}{dt} \right) = \frac{\partial V_T}{\partial h}$$

For a large f, the Higgs trajectory is nearly following $\partial_h V \approx 0$ *and its effect on* S_3 *negligible.*

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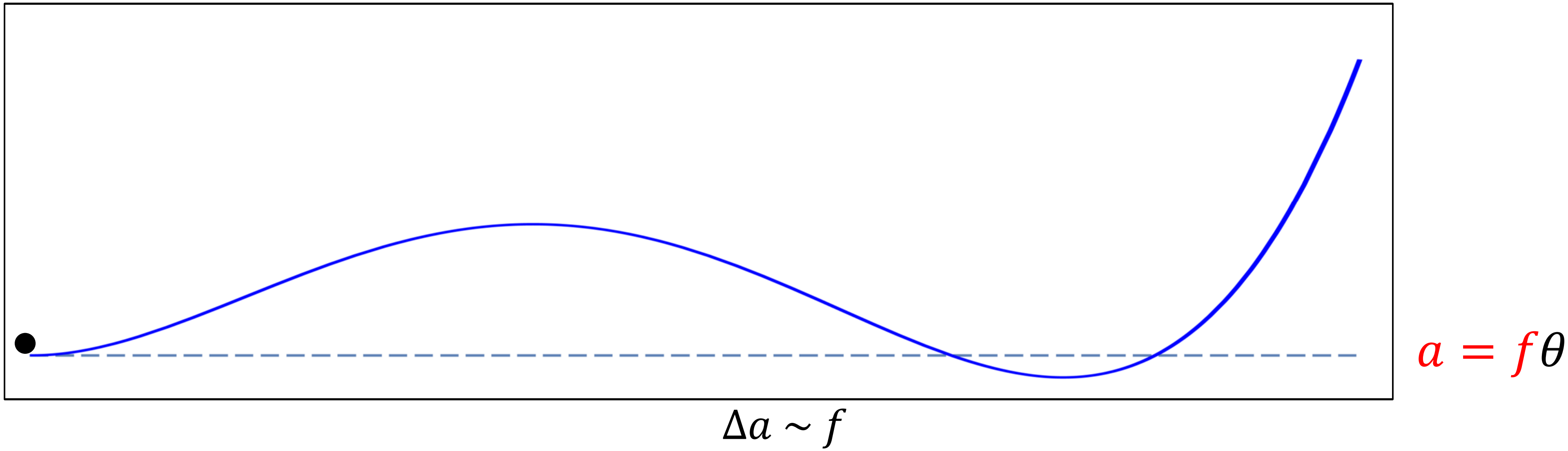

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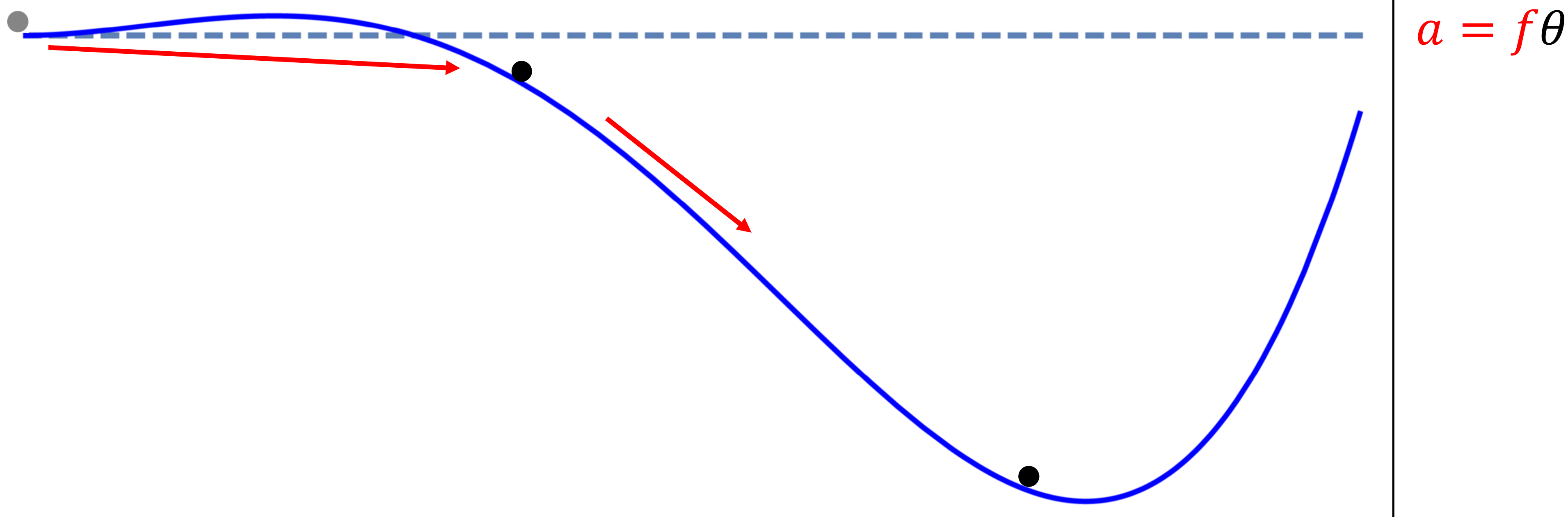
$$\frac{d^2\theta}{du^2} + \frac{2}{u}\frac{d\theta}{dt} = \frac{\partial V_T}{\partial\theta}, \qquad \frac{1}{f}\left(\frac{d^2h}{du^2} + \frac{2}{u}\frac{dh}{dt}\right) = \frac{\partial V_T}{\partial h}$$

For a large f, the Higgs trajectory is nearly following $\partial_h V \approx 0$ *and its effect on* S_3 *negligible.*

Nucleation/thermal tunneling

As increasing $f \gg m_W$, S_3 increases as f^3, so phase transition is delayed,

until the barrier is quite lowered (bubble wall is disappear at T_2.
T_n is lower than T_c —could be stronger first order phase transition

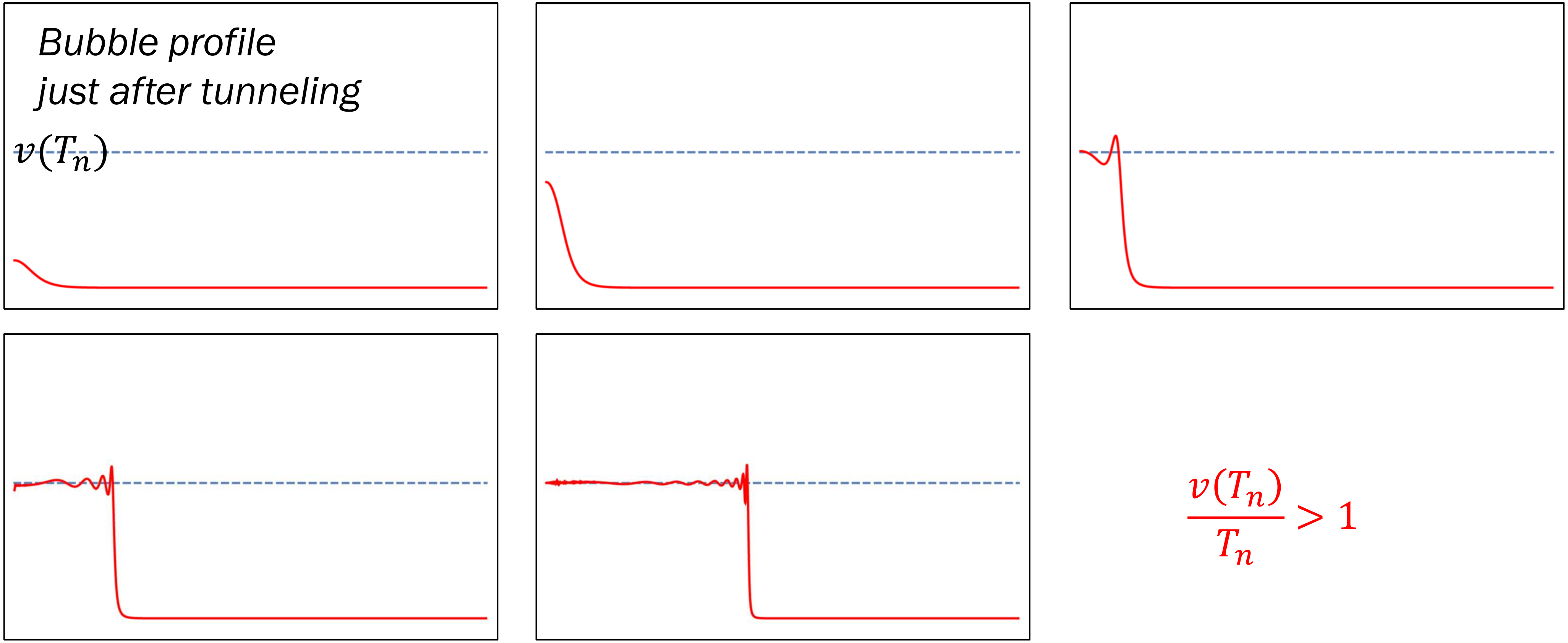


Still, very different from the second order phase transition

Conditions for baryogenesis

As the bubble expands, the scalar fields (a, h) will settle down at the potential minimum values : $(a(T), v(T))$ within time scales

$$\Delta t \sim \frac{1}{m_a} \sim \frac{f}{m_W^2} \ll \frac{1}{H(T)}$$



$$\frac{v(T_n)}{T_n} > 1$$

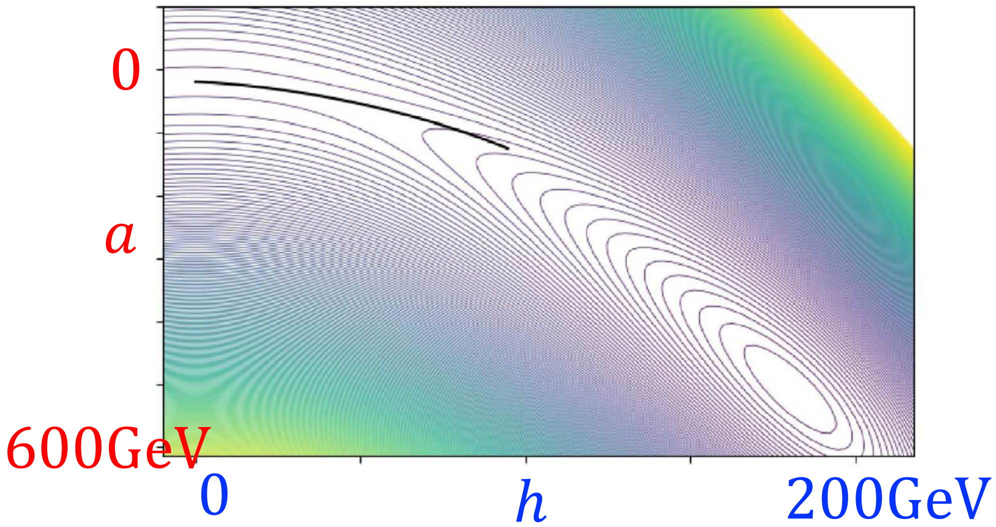
<u>*Still, very different from second order phase transition*</u>

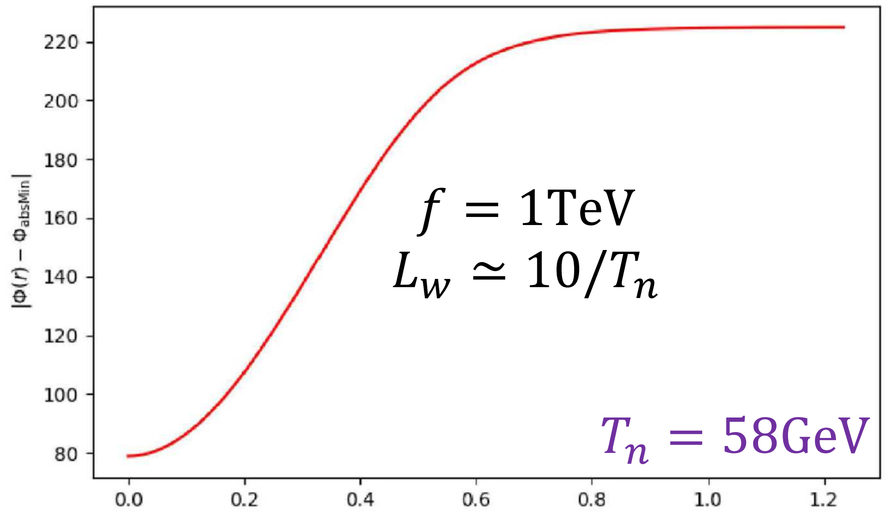
Bubble wall width

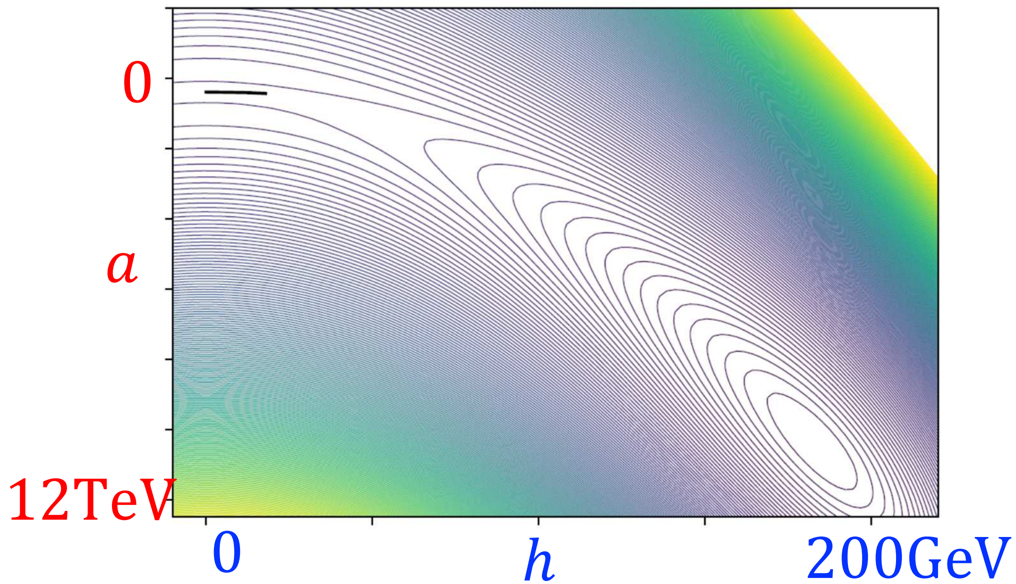
For large $f \gg m_W$,

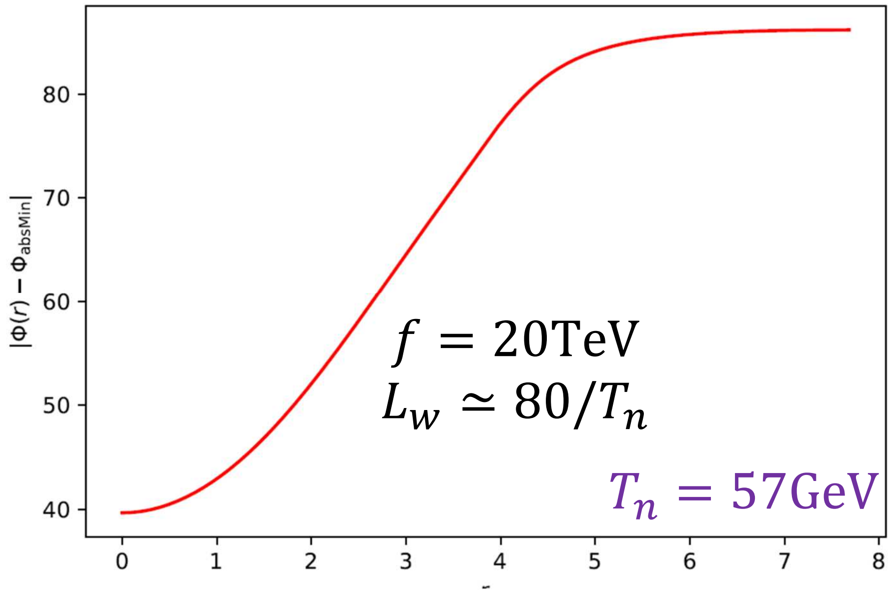
$$L_W \sim \frac{1}{m_a} \sim \frac{1}{T_n}\left(\frac{f}{m_W}\right)$$

$f \lesssim O(10-100)$ TeV : *non-local gen.*
$f \gtrsim O(10-100)$ TeV : *local gen.*



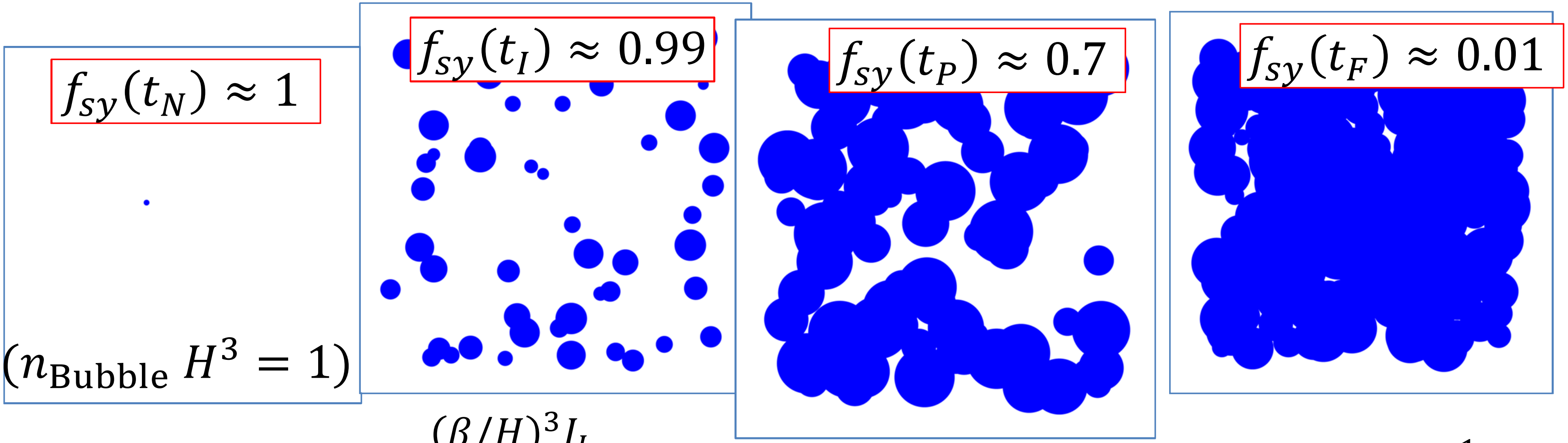






Time scales for bubble expansion

After a first bubble is formed, bubbles are continuously produced and expand. They percolate and fill the Universe. Using the fraction of symmetric phase, $f_{sy}(t)$



$$t_I - t_N \simeq \beta^{-1} \ln \frac{(\beta/H)^3 I_I}{8\pi v_w^3} \qquad t_F - t_I \simeq 6\beta^{-1}$$

[Megevand, Ramirez 16]

for a Euclidean action expanded as $S_3/T = S_3(t_N)/T - \beta(t - t_N) + O\big((t-t_N)^2\big)$ *where* $\beta/H = d(S_3/T)/d\ln T \simeq 130/(1 - T_2/T_n)$.

$$\beta \ll m_a \to \frac{10^{-3}\mathrm{eV}}{1 - T_2/T_n} \simeq 10^{-3}\mathrm{eV}\left(\frac{f}{m_W}\right)^{\gamma} \ll m_a \sim \frac{m_W^2}{f}$$

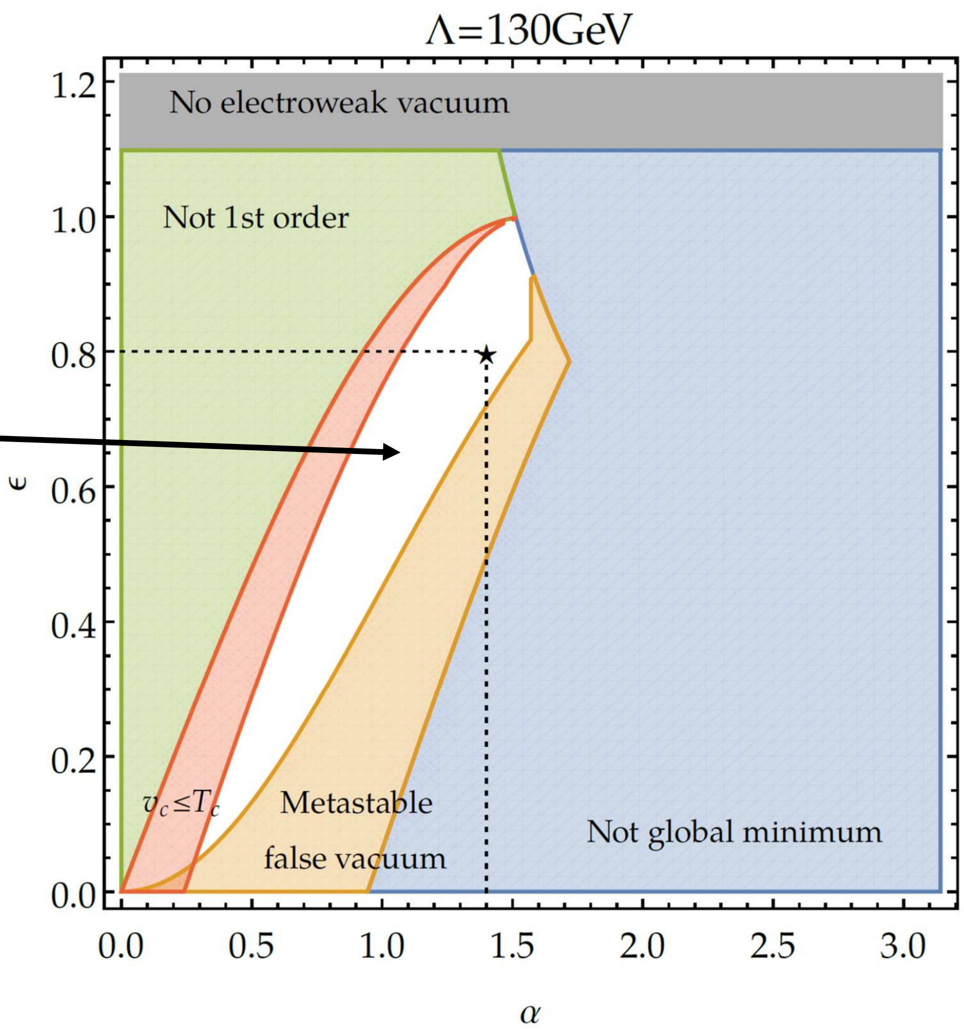
Sphaleron decoupling condition

After fixing parameters by the Higgs mas and the Higgs VEV from (*with* $\mu_1^2 > 0, \mu_2^2 < 0$)

$$V(h,a) = \frac{\mu_1^2}{2}\, h^2 + \frac{\lambda}{4} h^4 + \frac{\mu_2^2}{2} \cos(\theta + \alpha)\; h^2 - \Lambda^4 \cos\theta$$

the free parameters are $\Lambda, \alpha, \epsilon = \sqrt{2\lambda}\Lambda^2/(-\mu_2^2)$

$$\frac{v(T_n)}{T_n} > 1$$



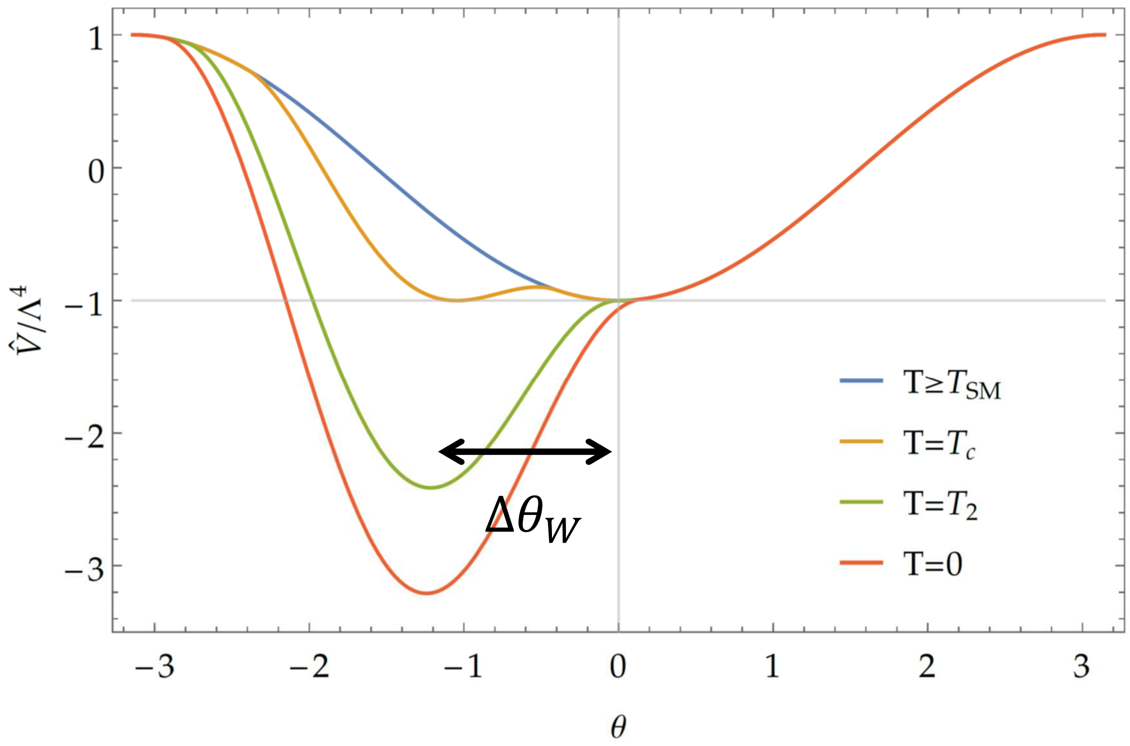
CP violation

CPV is provided by the field dependent electroweak theta-term: $\theta_W = a/f$.

$$\mathcal{L}_{CPV} \ni \frac{g_2^2}{16\pi^2}\frac{a}{f}\mathrm{Tr}\left[W_{\mu\nu}\,\widetilde{W}^{\mu\nu}\right]$$

During phase transition

$$(\Delta h)_{PT} \sim O(m_W),\ (\Delta\theta_W)_{PT} = \Delta a/f \sim O(1)$$



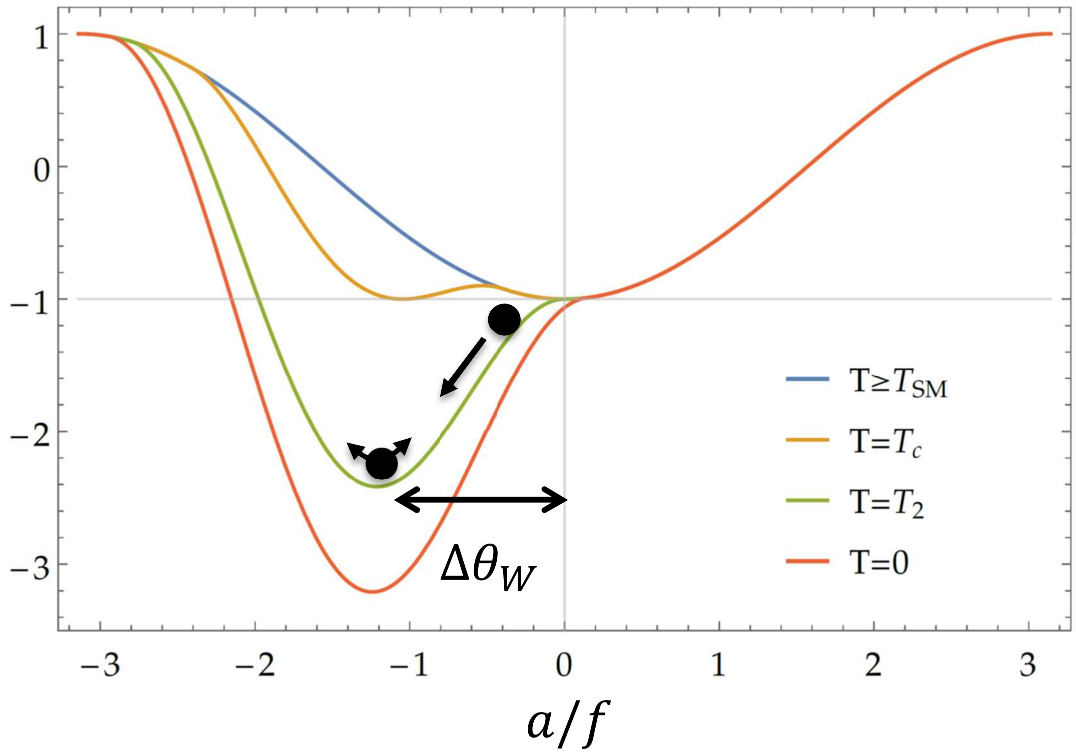
For the EDM contribution, it is always suppressed as $(v/f)^2 \ll 1$.

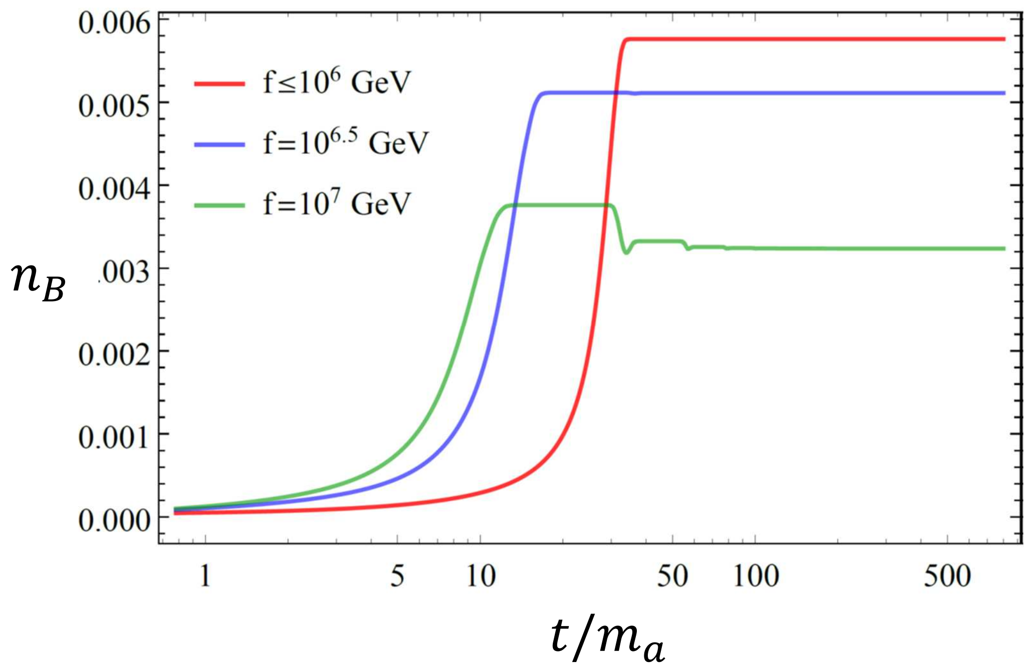
However, $\Delta\theta_W \sim O(1) \gg (v/f)^2$ ———— *Enhancing CPV effects*

1811.03294 For $f > O(10-100)$ TeV $\frac{g_2^2\,\theta_W}{16\pi^2}\mathrm{Tr}[W_{\mu\nu}\tilde{W}^{\mu\nu}]$

Baryon asymmetry is nearly independent of f for $f < O(10^7\ \mathrm{GeV})$ due to efficient dampings

$$\frac{dn_B}{dt} \simeq \frac{3}{2}\frac{\Gamma_{sph}(t)}{T}\left(\frac{d\theta_W}{dt} - \frac{13}{2}\frac{n_B}{T^2}\right) - \text{(wash out due to residual oscillation)}$$





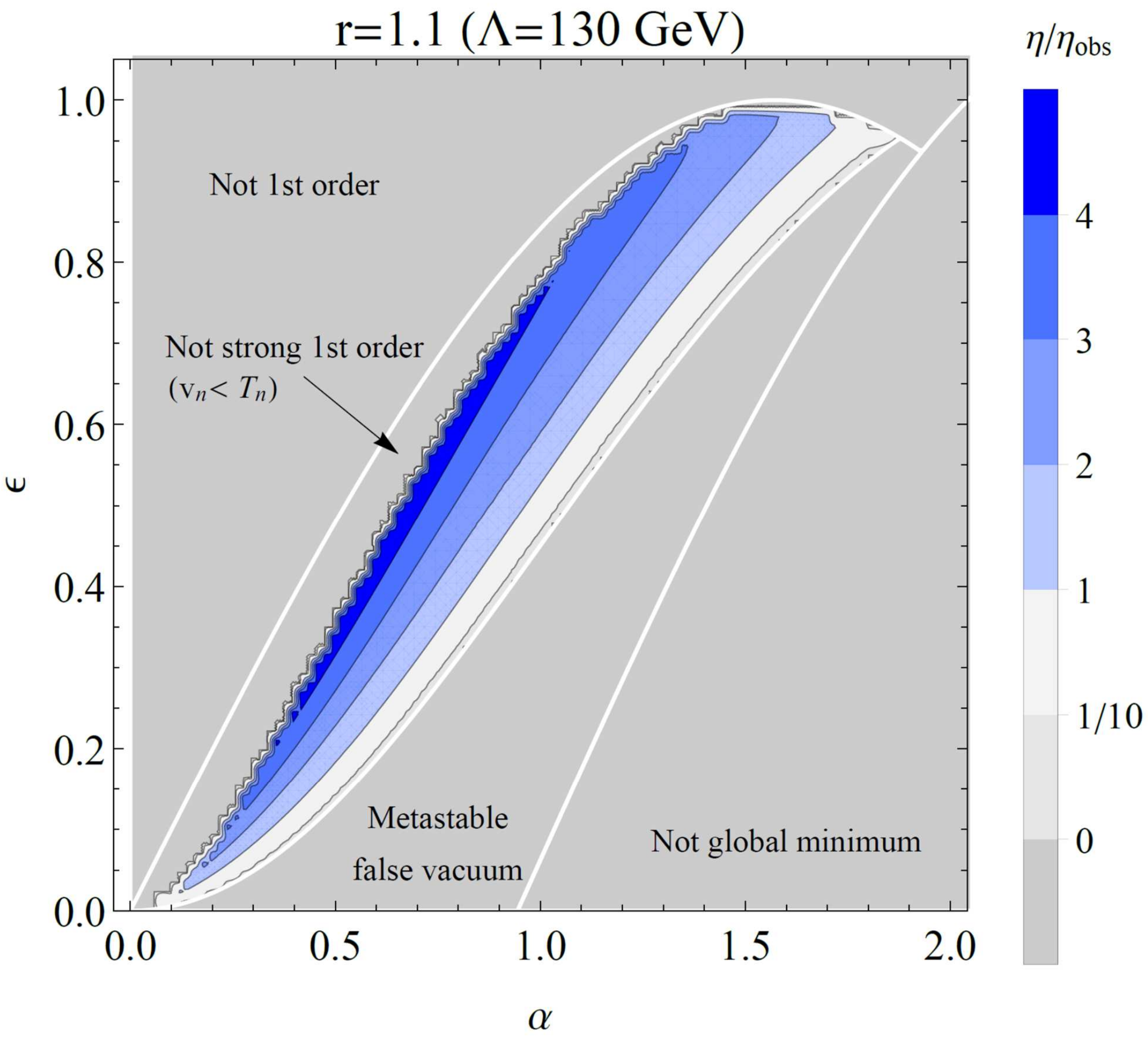
$$\frac{n_B}{s} \simeq \frac{27\alpha_W^5}{g_*}\Delta\theta_W\, e^{-K_{\mathrm{washout}}}$$

$$\frac{n_B^{eq}}{s} \sim \frac{\dot{\theta}_W}{g_* T_n} \sim \frac{m_a}{g_* T_n} \sim 10^{-10}\left(\frac{10^{10}GeV}{f}\right)$$

$\Delta\theta \sim O(1)$ is possible because of fast rolling after creation of bubbles ($m_a \gg H$)

For $f > O(10 - 100)$ TeV

Baryon asymmetry is nearly independent of f *for* $f < O(10^7\ \mathrm{GeV})$

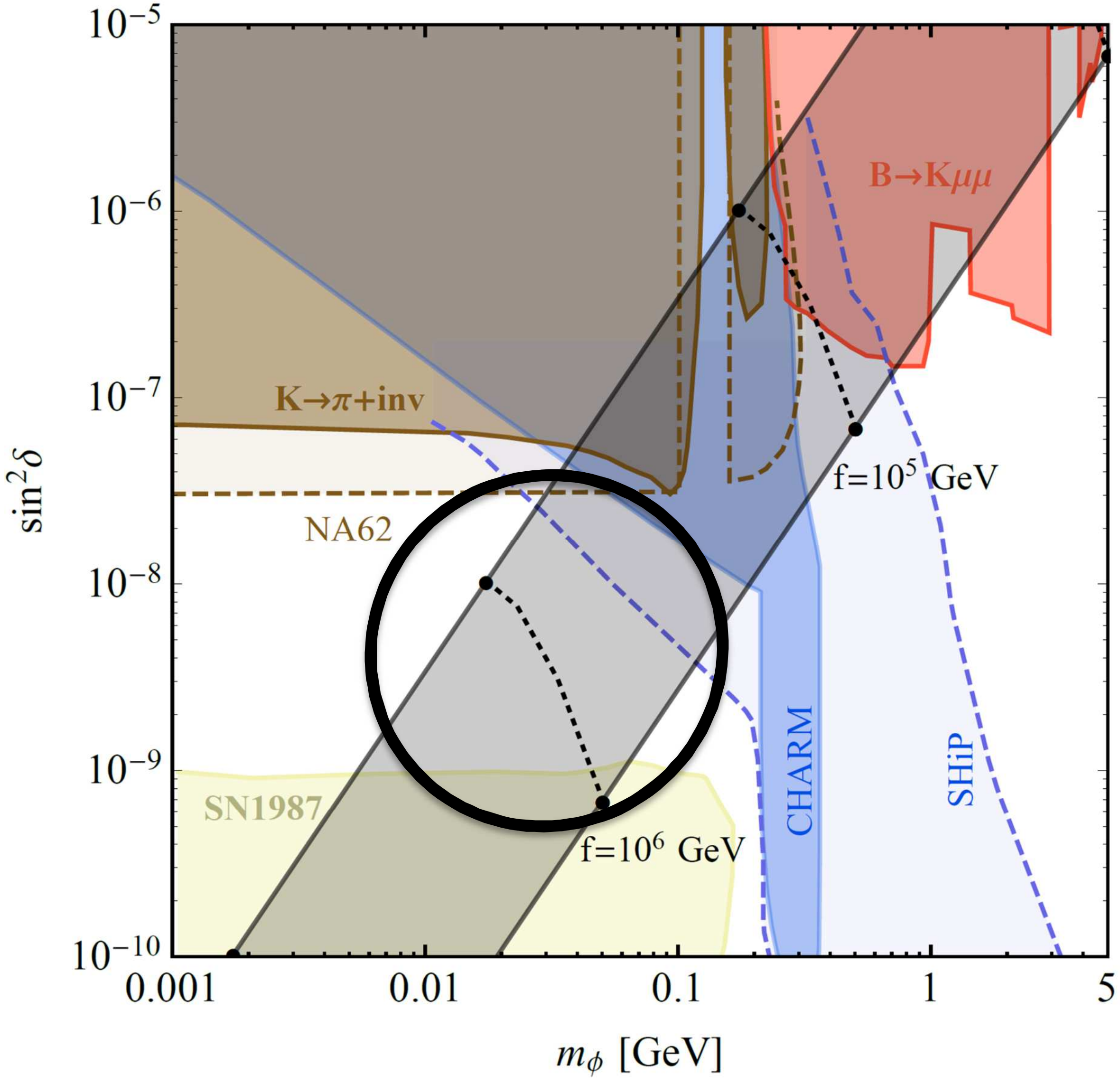


Totally safe from EDM and LHC constraints!

ALP searches

There is the interesting allowed window for $f \sim 10^6 - 10^7$ GeV *(*$m_a \sim 5 - 100$ MeV*)*

δ *= axion-Higgs mixing* $\propto 1/f$



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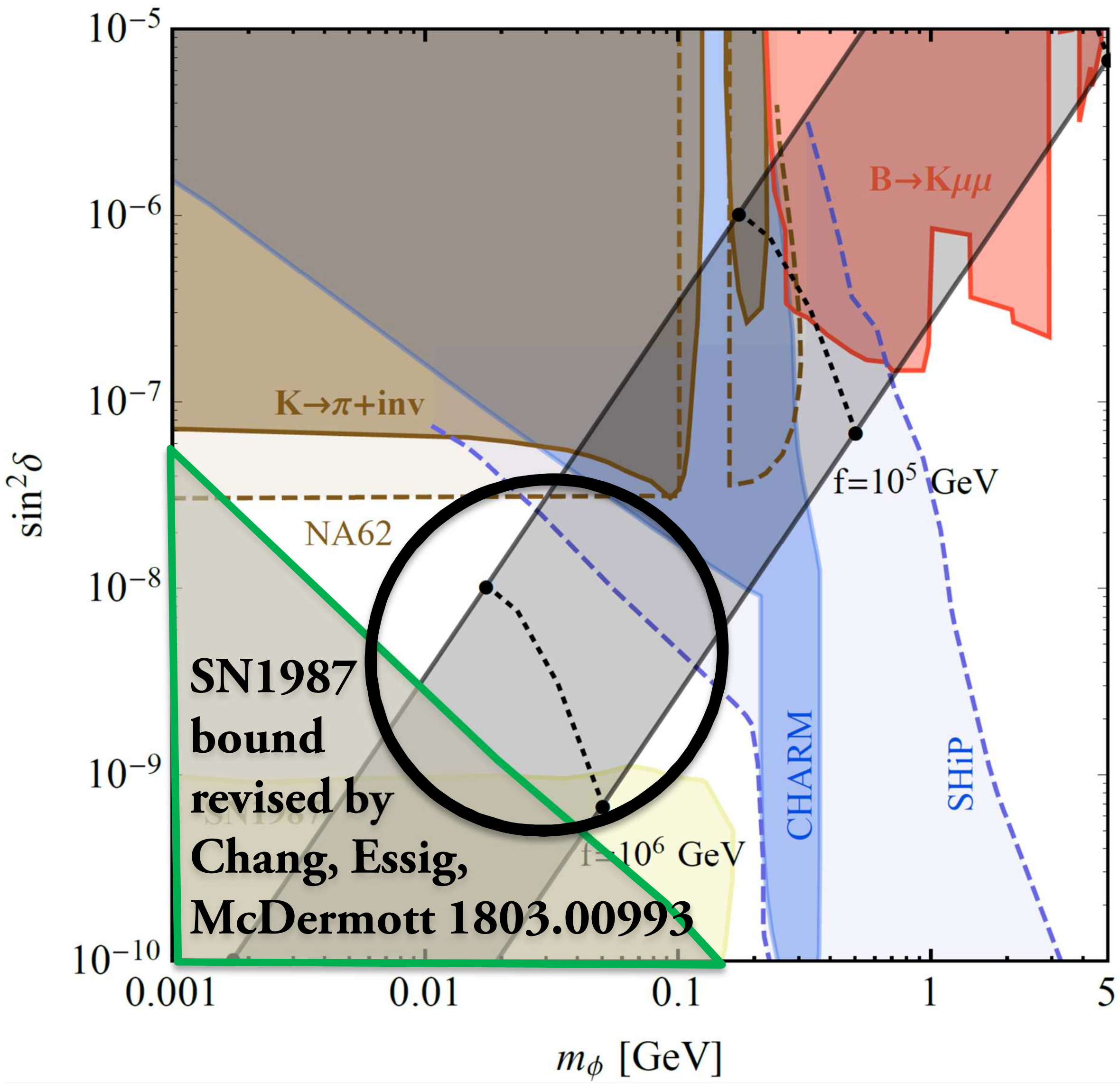

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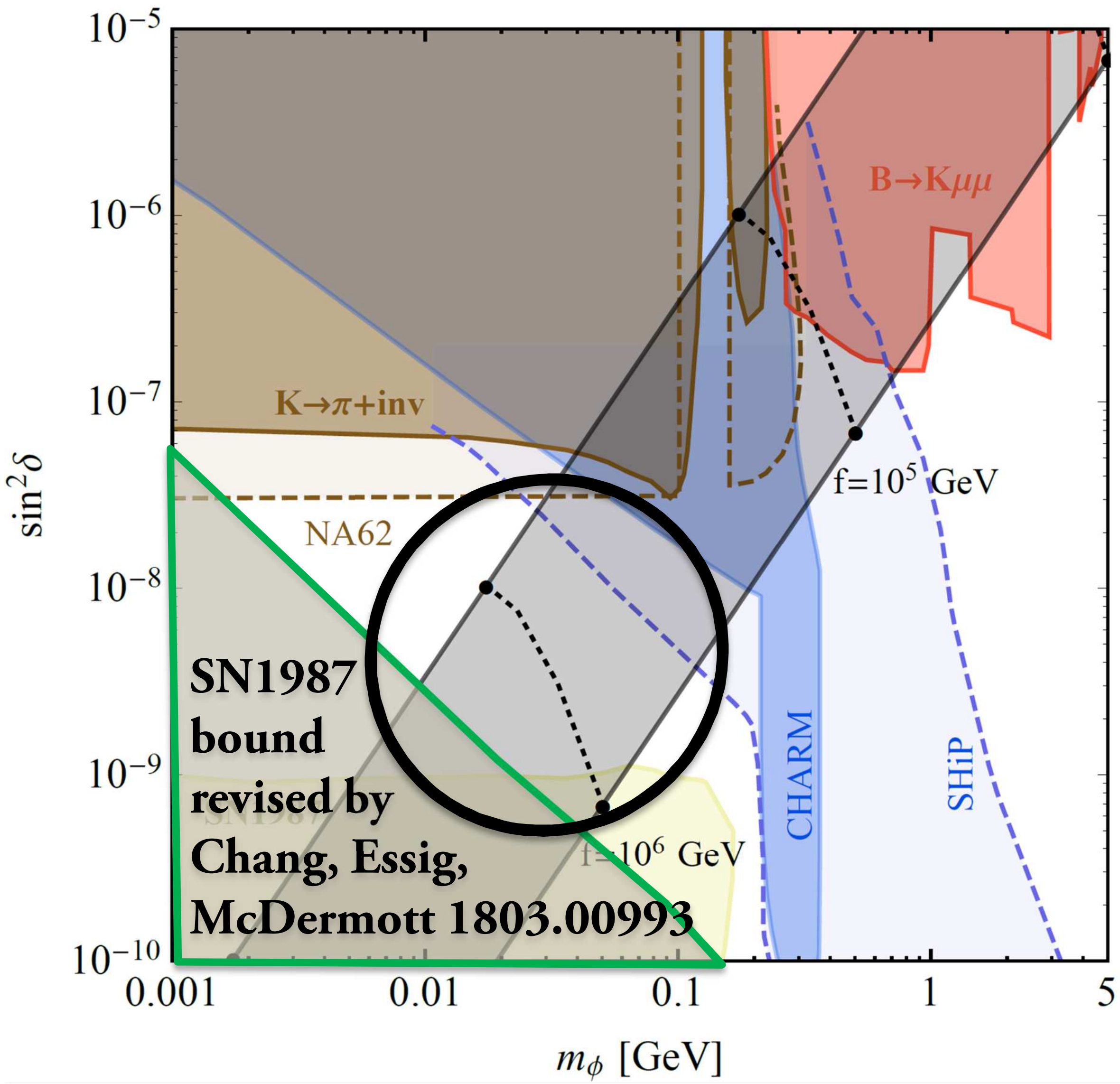
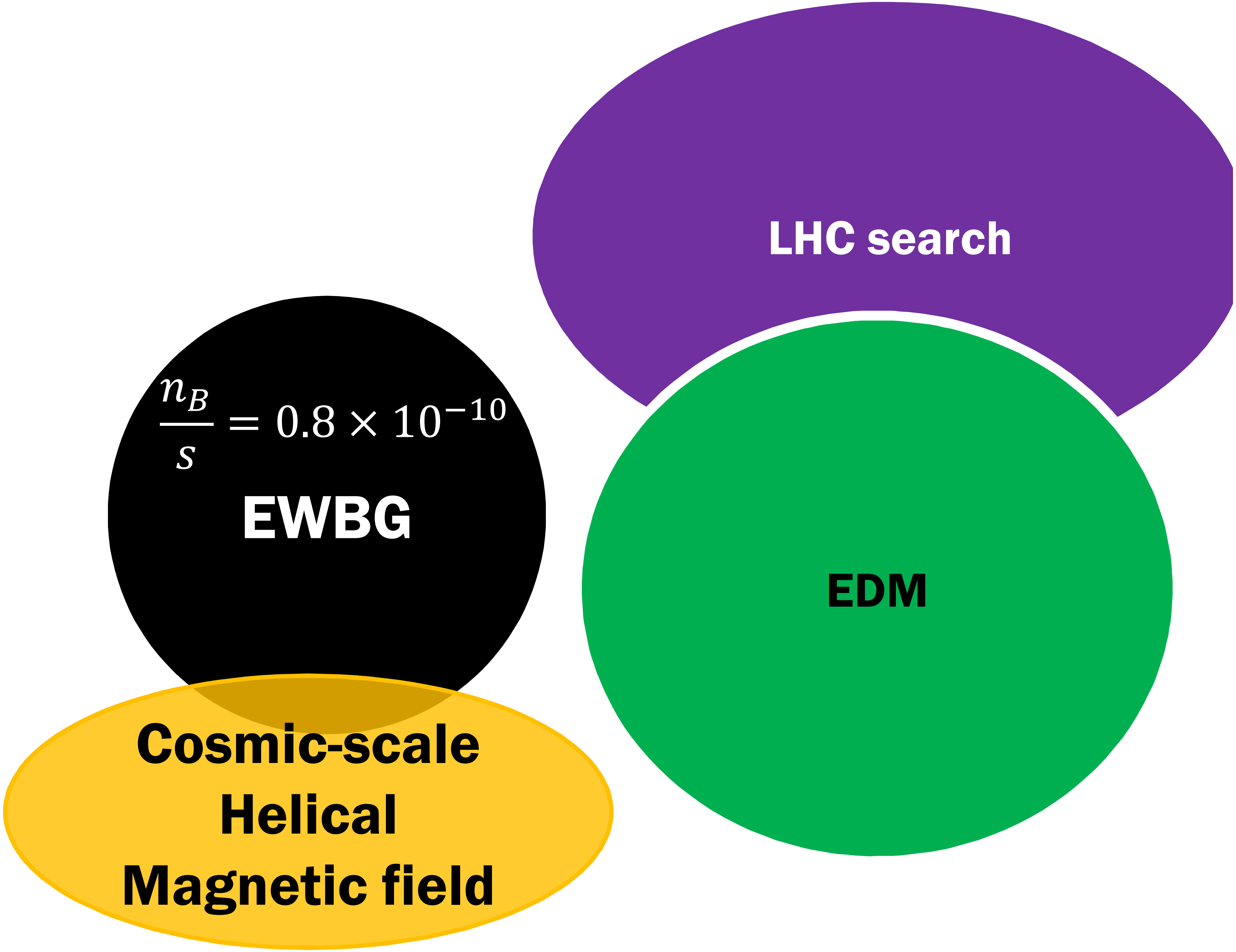
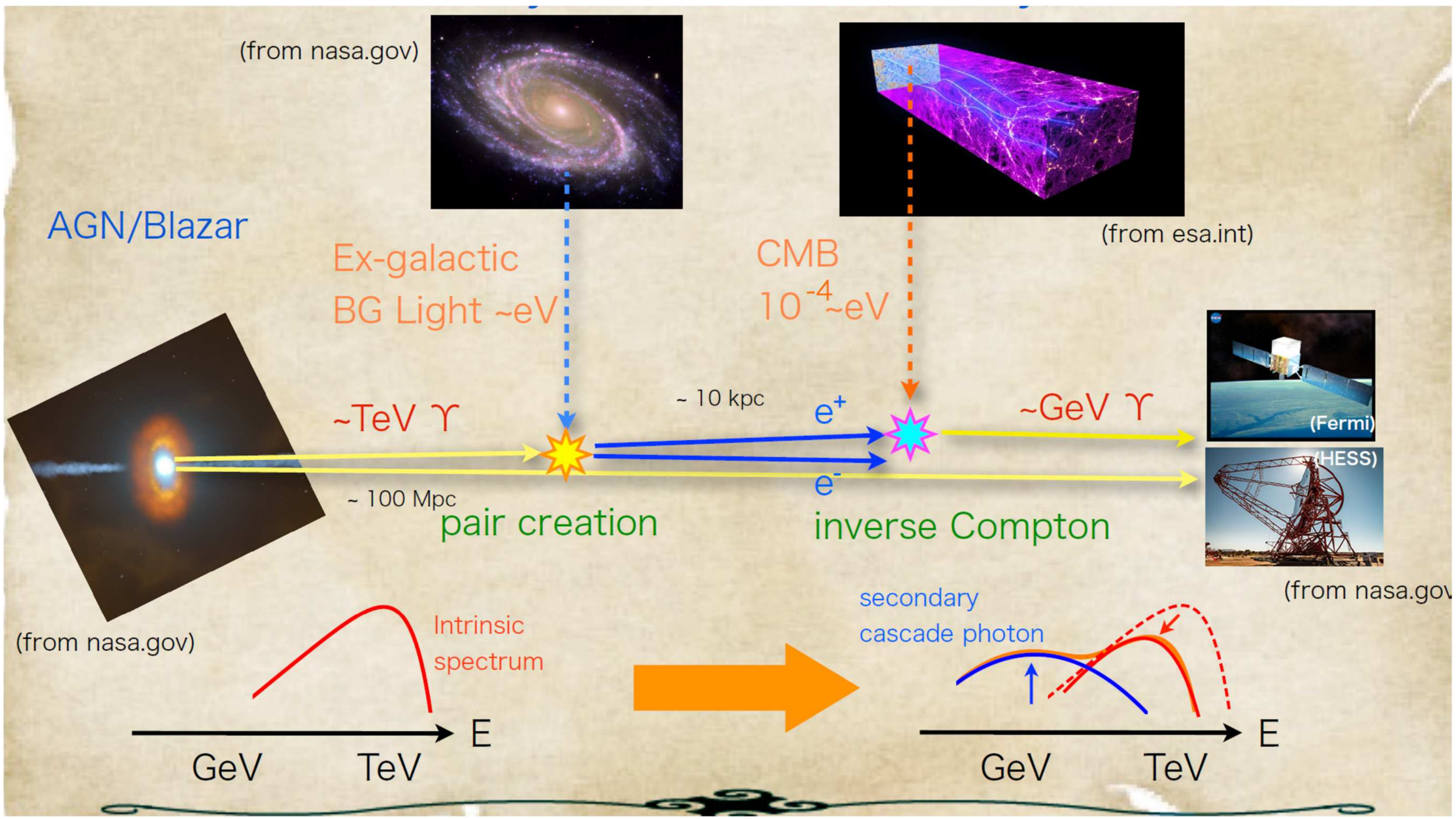


Brief sketch of the ideas



Cosmic magnetic fields

There are some indirect evidence/constraints on the cosmic scale magnetic fields (coherence length: sub pc ~ kpc)



From Kohei Kamada's slide

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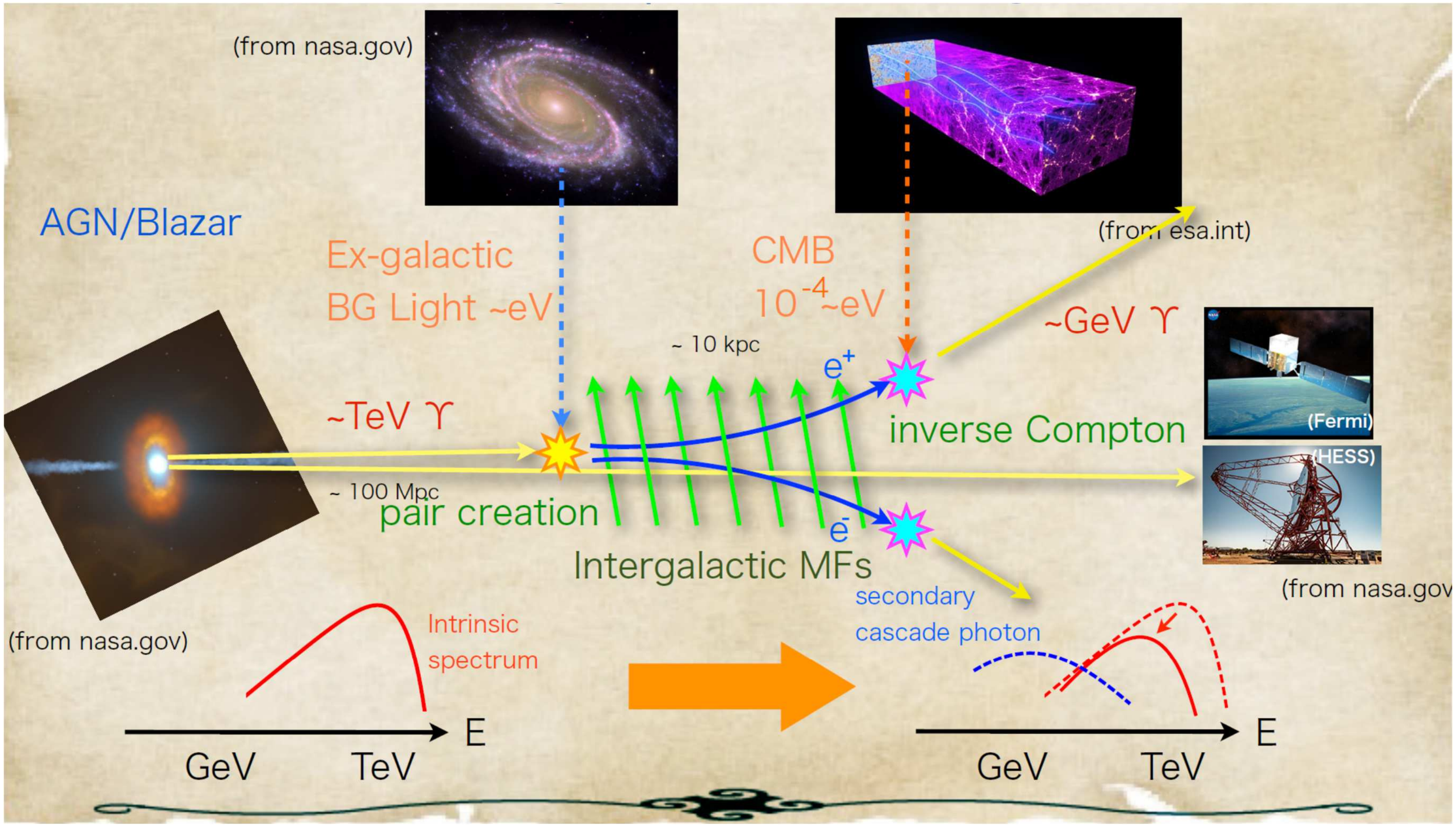
Intergalactic magnetic fields can change the spectrum of gamma-ray we observe



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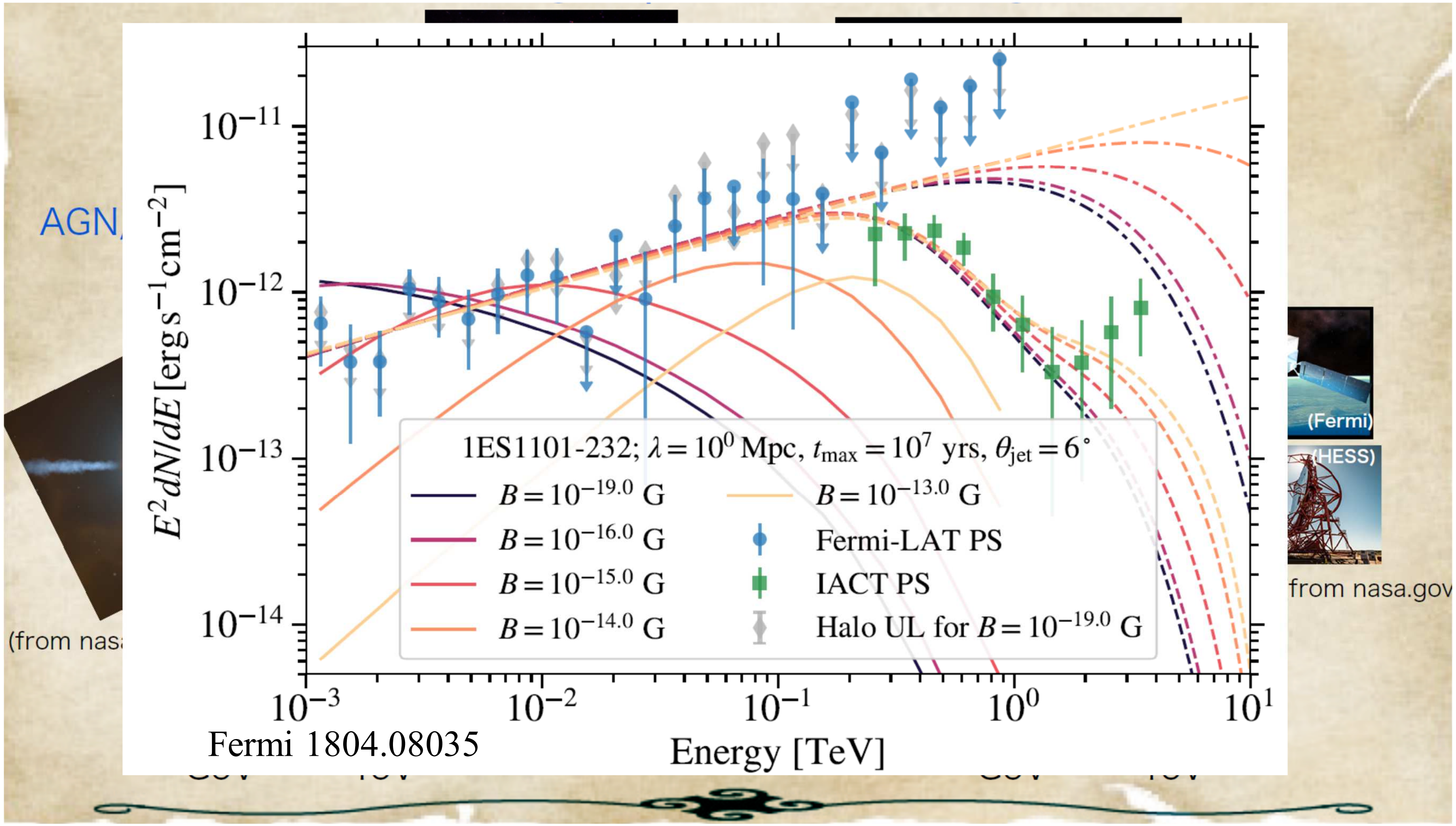

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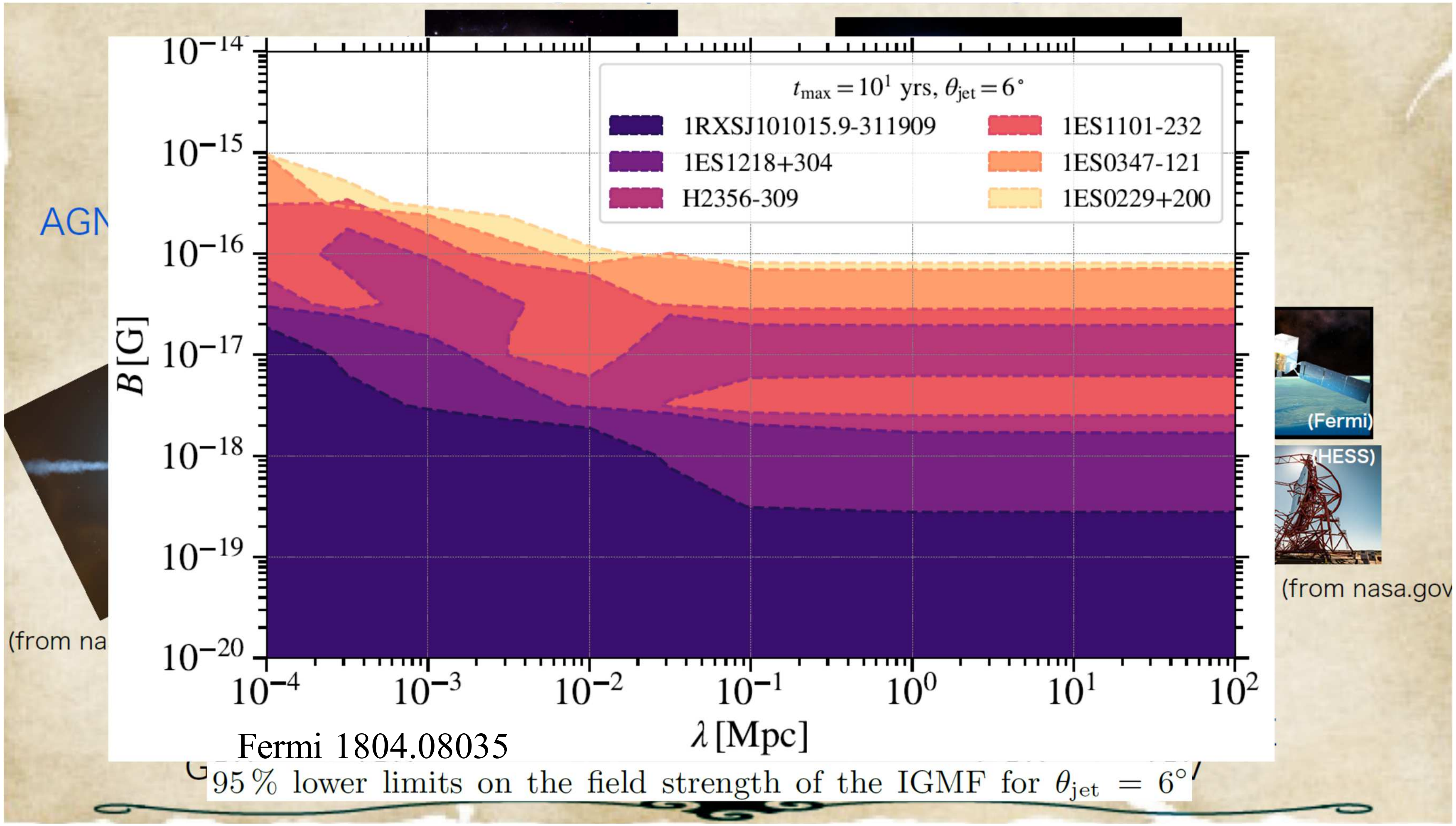


95 % lower limits on the field strength of the IGMF for $\theta_{jet} = 6^\circ$

Baryon asymmetry from helical magnetic fields

If the magnetic fields are generated before the electroweak phase transition, it will be that of the hypercharge magnetic field. Then it can be related with baryon asymmetry through

$$(\partial_\mu J_B^\mu) = (\partial_\mu J_L^\mu) = \frac{n_f}{32\pi^2}\left(2g^2 \mathrm{Tr}[W_{\mu\nu}\widetilde{W}^{\mu\nu}] - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

Taking a gauge $B_0 = 0$, $B_i = \vec{Y}$, $\frac{1}{2}\epsilon^{ijk}B_{ik} = \vec{B}_Y$, $B_{i0} = \vec{E}_Y$, *then* $B_{\mu\nu}\tilde{B}^{\mu\nu} = -4\,\vec{E}_Y \cdot \vec{B}_Y$.

At the early Universe, the helical gauge fields can be generated through the scalar field dynamics such as Affleck-Dine mechanism K.Kamada, CSS 1905.06966

$$\varkappa_Y = \int d^3\vec{x}\,\vec{Y}\cdot\vec{B}_Y = V\int \frac{d^3\vec{k}}{(2\pi)^3}\left(|Y_k^R|^2 - |Y_k^L|^2\right),$$

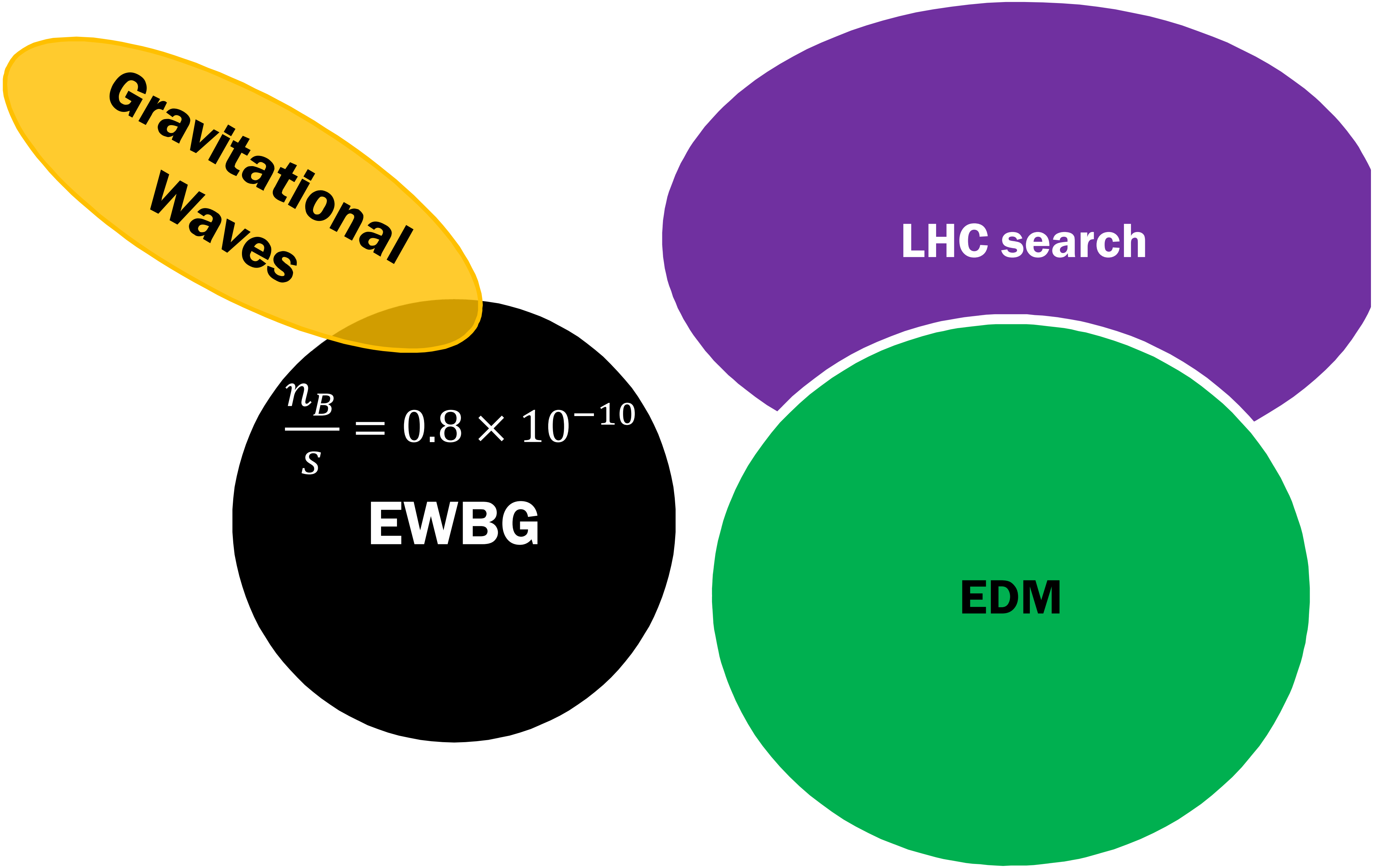
$$\frac{dn_B}{dt} = -\frac{n_f g'^2}{16\pi^2}\left(\frac{1}{V}\frac{d\varkappa_Y}{dt} = -2\int d^3\vec{x}\,\vec{E}_Y\cdot\vec{B}_Y\right)$$

The dramatic change of the helicity of the hypercharge magnetic field ($\varkappa_Y$) happens during EWPT, because of nonzero Weinberg angle (θ_w), which yields the baryon asymmetry without need of strong first order phase transition

$$\frac{n_B}{s} \simeq 10^{-10}\left(\sin 2\theta_w \frac{d\theta_w}{d\ln T}\right)_{T\simeq 135\mathrm{GeV}}\left(\frac{\lambda_{EW}}{10^6 GeV^{-1}}\right)\left(\frac{B_{EW}}{10^{-3} GeV^2}\right)^2$$

Kamada, Long 1606.08891

Brief sketch of the ideas



Gravitational waves from strong 1st order PT

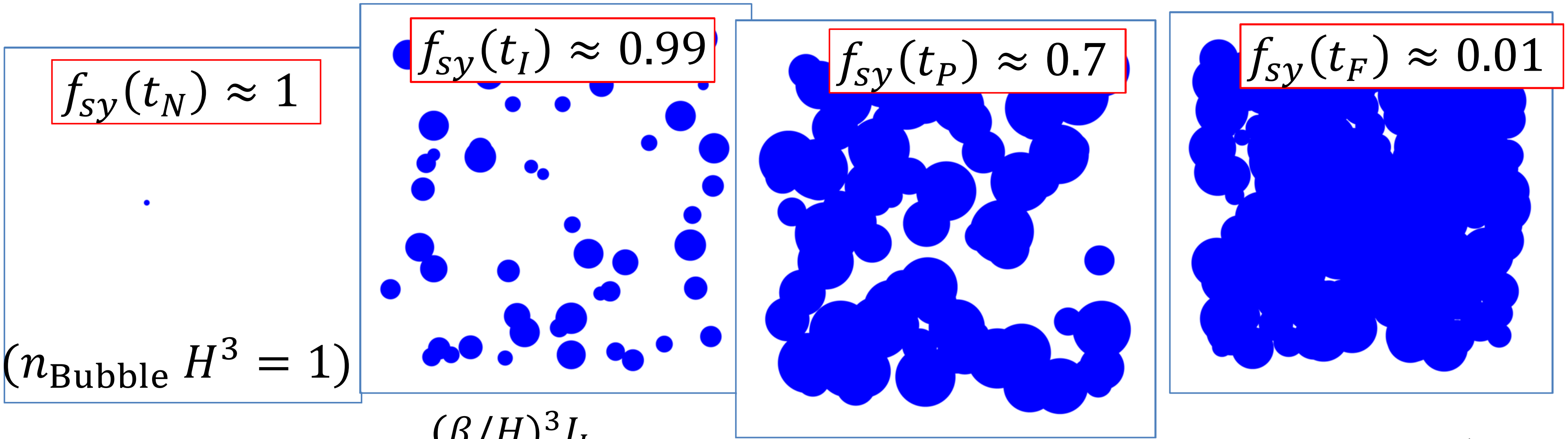
Production of bubbles and collision, and subsequent motion of plasma generate large anisotropy of the energy momentum tensor. Gravitational waves are generated with

$$(f_{gw})_{\text{peak}} \sim \left(\frac{\beta}{H}\right) H(T_*) \frac{T_0}{T_*} \sim \left(\frac{\beta}{H}\right) \frac{T_*}{M_{Pl}}$$

Late time transition gives a lower peak frequency.

The energy density of GW is determined by the energy fraction of the Universe for the bubble walls and shock waves when they collide.

-→ The super-cooled Universe gives lower frequency and larger GW energy.



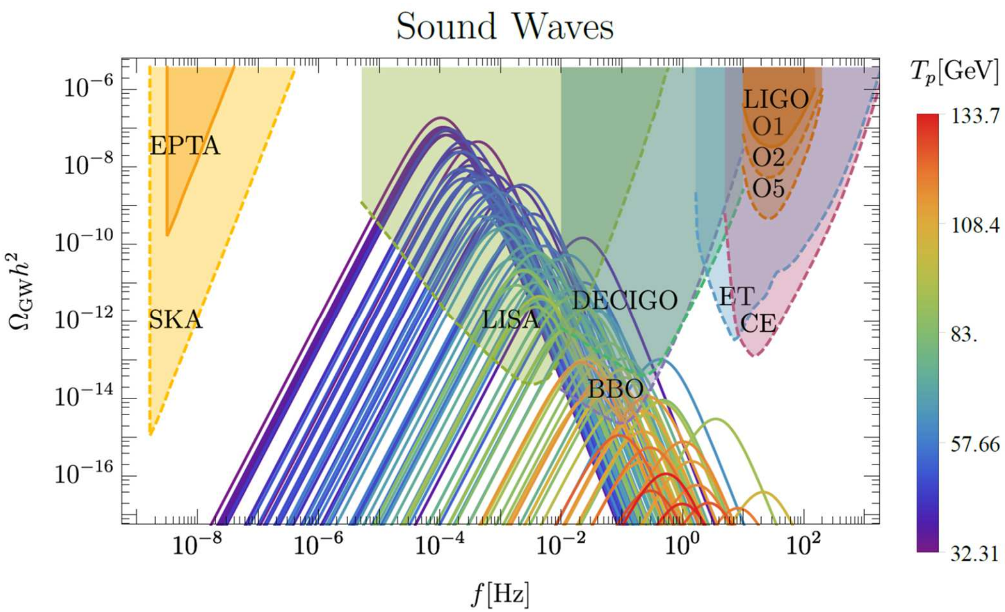
$$t_I - t_N \simeq \beta^{-1} \ln \frac{(\beta/H)^3 I_I}{8\pi v_w^3}$$

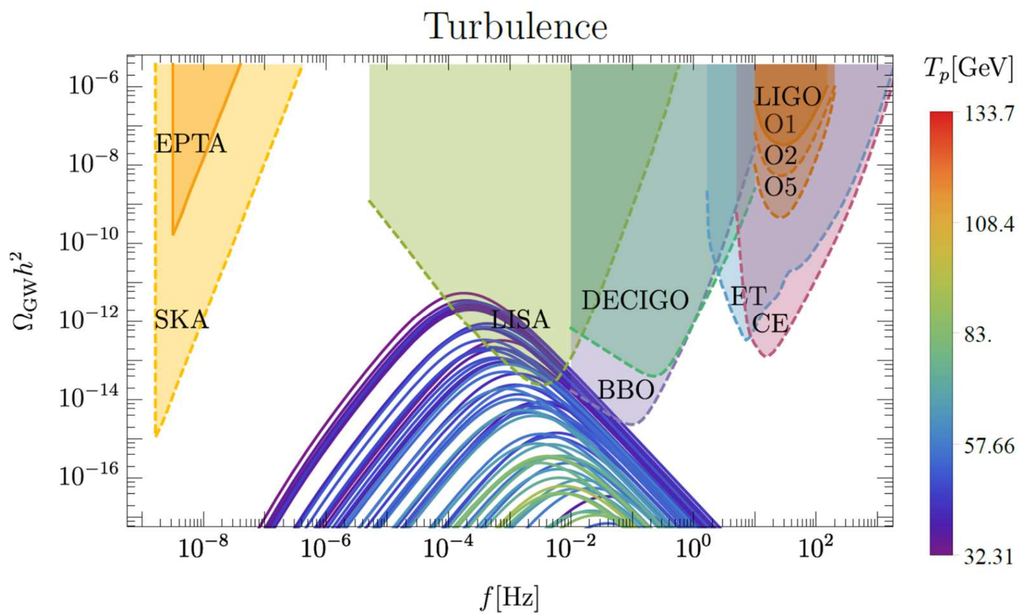
$$t_F - t_I \simeq 6\beta^{-1}$$

Gravitational waves from strong 1st order PT

Example in singlet extension

Beniwal, Lewicki, White, Williams 1810.02380





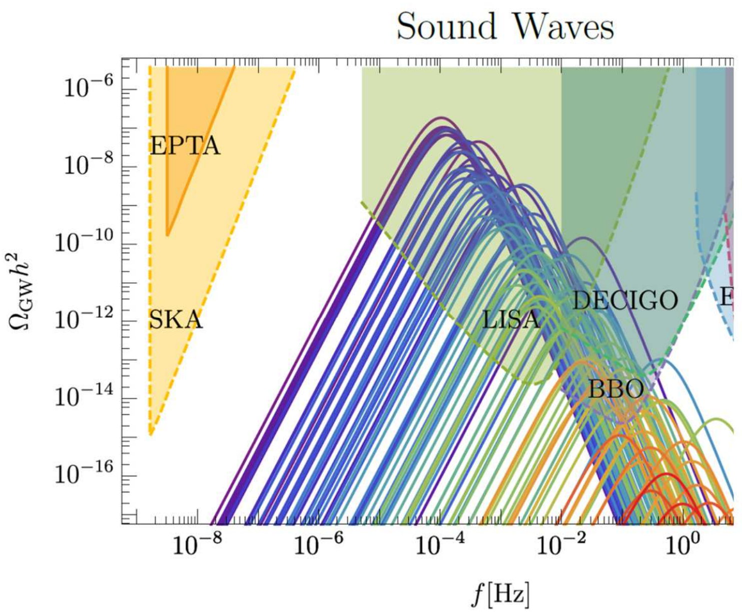
1st order phase transition in super-cooled Universe generically predicts $v_W \sim c$, which makes difficult to generate baryon asymmetry through CP-violating force from bubble walls.

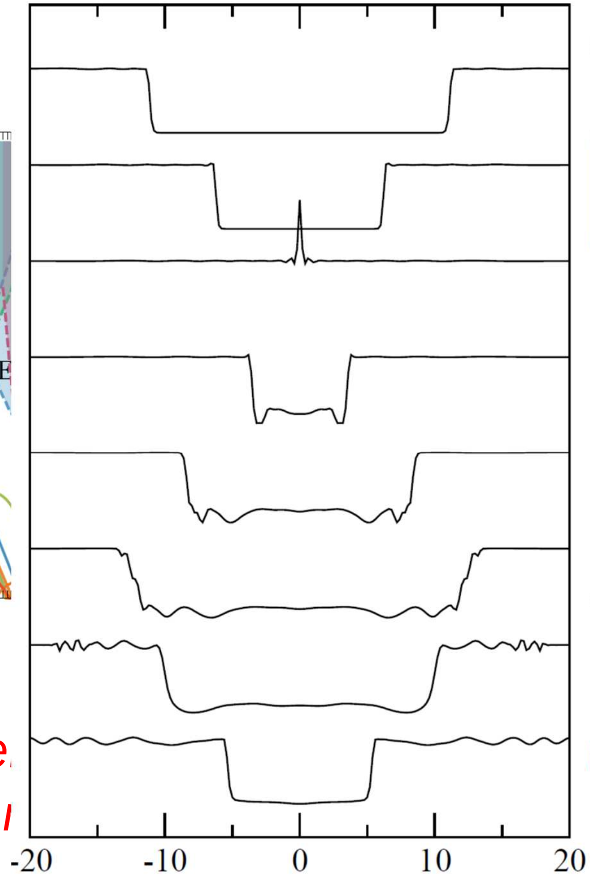
The Universe will be reheated through the collision of the bubble walls/plasma. Around the collision time, there can be local restoration of the electroweak symmetry. The stage of preheating: a kind of cold baryogenesis can happen.

Gravitational waves from strong 1st order PT

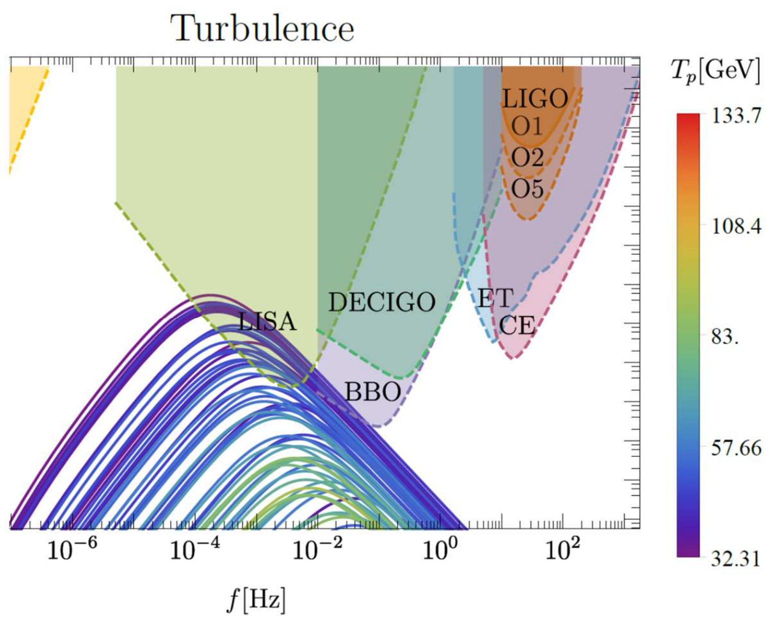
Example in singlet extension

ki, White, Williams 1810.02380





Konstandin Servant, 1104.4793



1st order phase transition in supe… …lly predicts $v_W \sim c$, which makes difficult to generate baryon asymm… …force from bubble walls.

The Universe will be reheated through the collision of the bubble walls/plasma. Around the collision time, there can be local restoration of the electroweak symmetry. The stage of preheating: a kind of cold baryogenesis can happen.

However, calculating the baryon asymmetry is quite difficult.

Summary

Electroweak baryogenesis is the natural idea to obtain the baryon asymmetry of the Universe. Especially its strong prediction at low energy experiments makes it very attractive.

So far, there is no clear evidence, and recent measurement of the electron EDM provides strong implication for the EWBG. We can think more interesting ideas to provide observable EDM in the future experiments or we can try the orthogonal direction more seriously, in which the new observables are presented.

The interesting connections with ALP searches, large scale helical magnetic fields, and the strong gravitational wave signals can be studied. New experiments and observations will eventually guide us to the correct direction for baryogenesis.