IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Probing Variant Axion Models at LHC

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@CERN

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Chen, Frampton, FT, Yanagida, arXiv:1005.1185,
to appear in JHEP.

Strong CP problem:

$$\mathcal{L}_\theta \ = \ \theta \frac{g_s^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

Experimental bound (from neutron EDM) reads

$$|\theta| < 10^{-(9-10)} \equiv \theta^{(\exp)}$$

Why is θ so small??

The Peccei-Quinn mechanism: Peccei and Quinn, `77

We introduce a global chiral $U(1)_{PQ}$ symmetry, which has a QCD anomaly.

$$\mathcal{L} = \bar{q}_L q_R \Phi + \text{h.c.}$$

PQ trans.: $q \longrightarrow e^{i\alpha\gamma_5} q$, $\Phi \longrightarrow e^{-2i\alpha} \Phi$ results in $\Delta\mathcal{L} = 2\alpha \frac{g_s^2}{32\pi^2} G^{\mu\nu}\tilde{G}_{\mu\nu}$

If $U(1)_{PQ}$ is spontaneously broken by $\langle\Phi\rangle = f_a \neq 0$, there appears the associated NG boson, a, the axion.

$$\mathcal{L} = \left(\frac{a}{f_a} + \theta\right) \frac{g_s^2}{32\pi^2} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Astrophysical/cosmological constraints

invisible axion $f_a \gg v_{\rm EW}$ → Axion may play an important role in cosmology.

- Star cooling/supernovae: $f_a \gtrsim 10^9\ \mathrm{GeV}$
- Dark matter abundance: $f_a \lesssim 10^{12}\ \mathrm{GeV}$

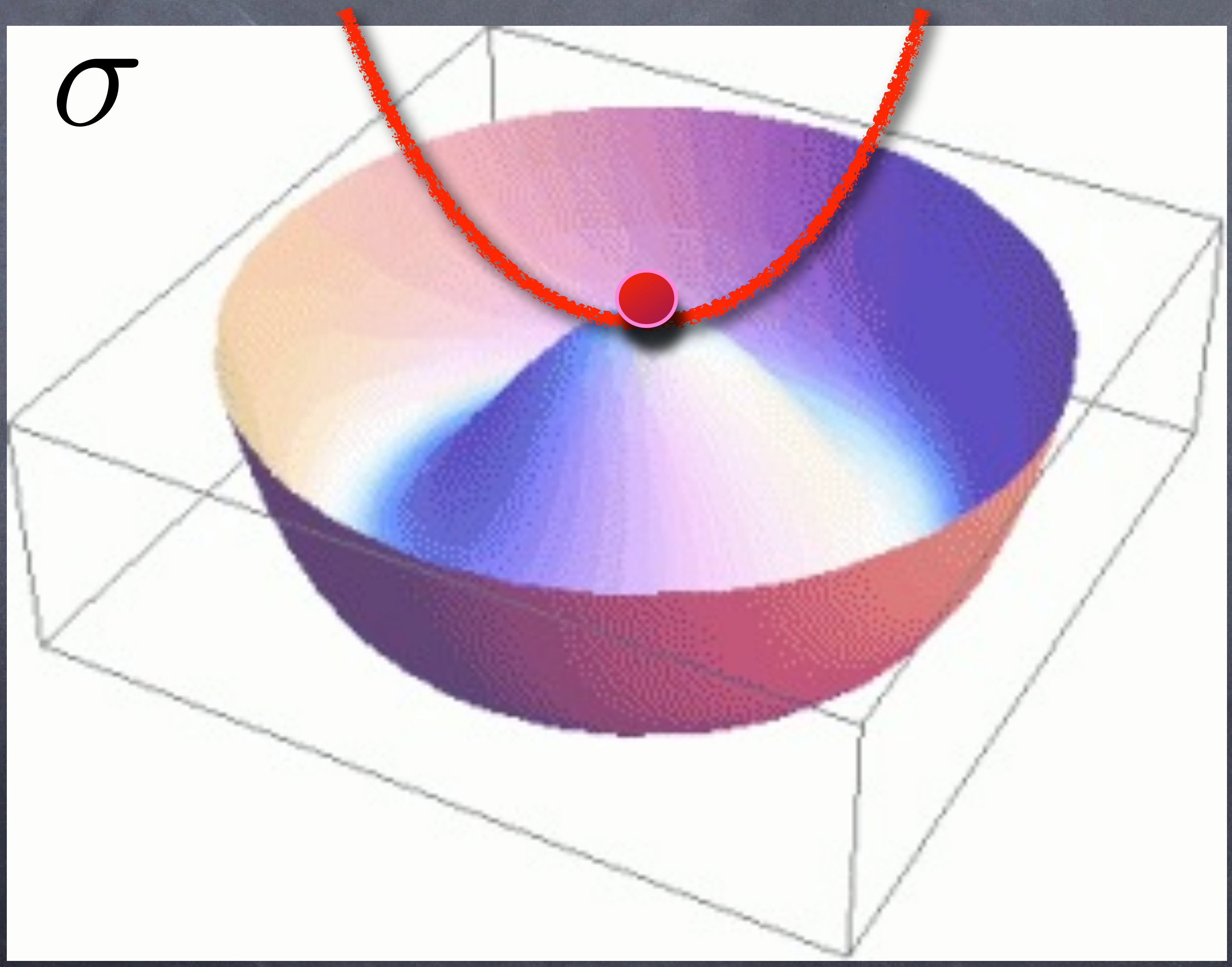
Moreover,

- if $U(1)_{PQ}$ is spontaneously broken during inflation:
  DM isocurvature fluc. w/ non-Gaussianity

- if $U(1)_{PQ}$ is restored during/after inflation:
  axionic strings/walls.

This talk

If the $U(1)_{PQ}$ symmetry is restored during/ after inflation, the axionic strings and domain walls may be produced.



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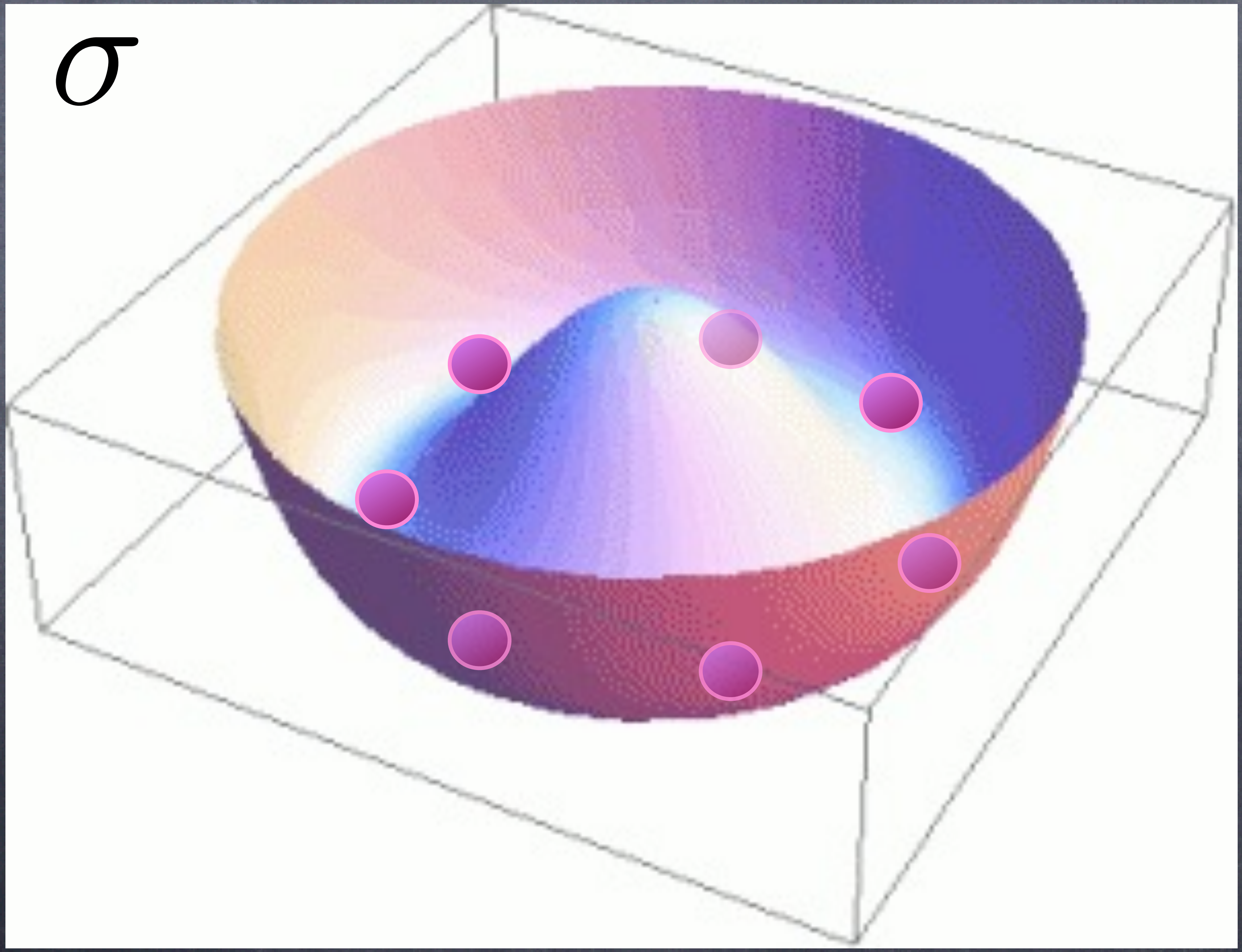
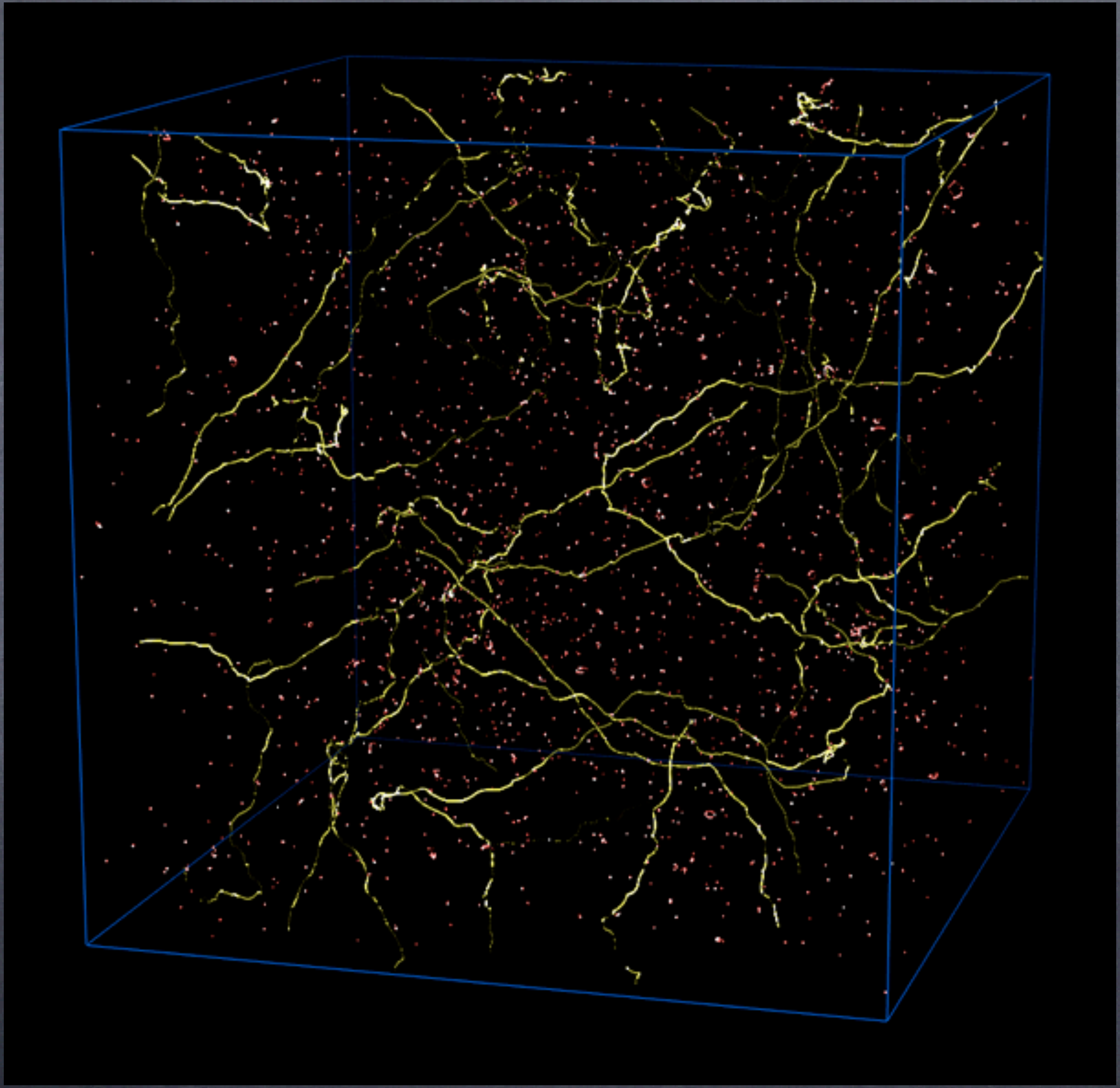


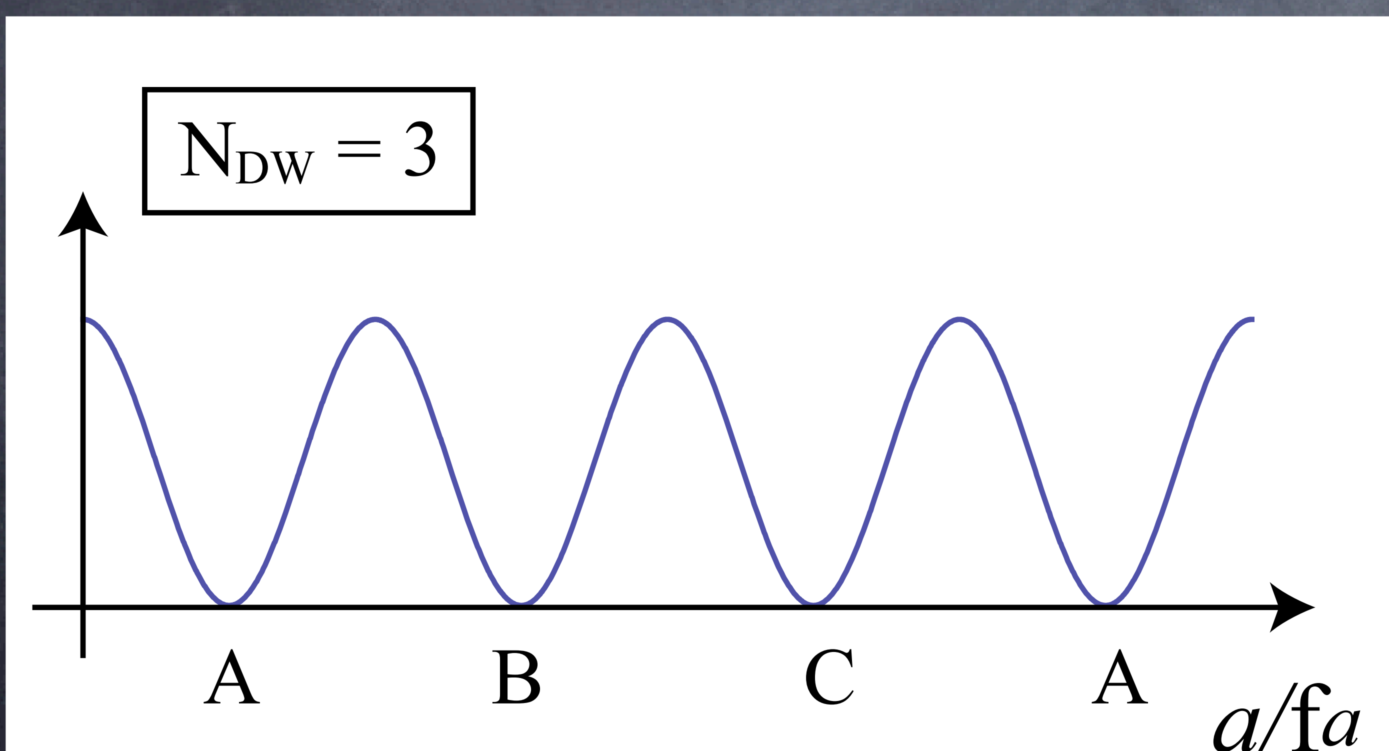
Cosmic strings are formed at $T \approx f_a$

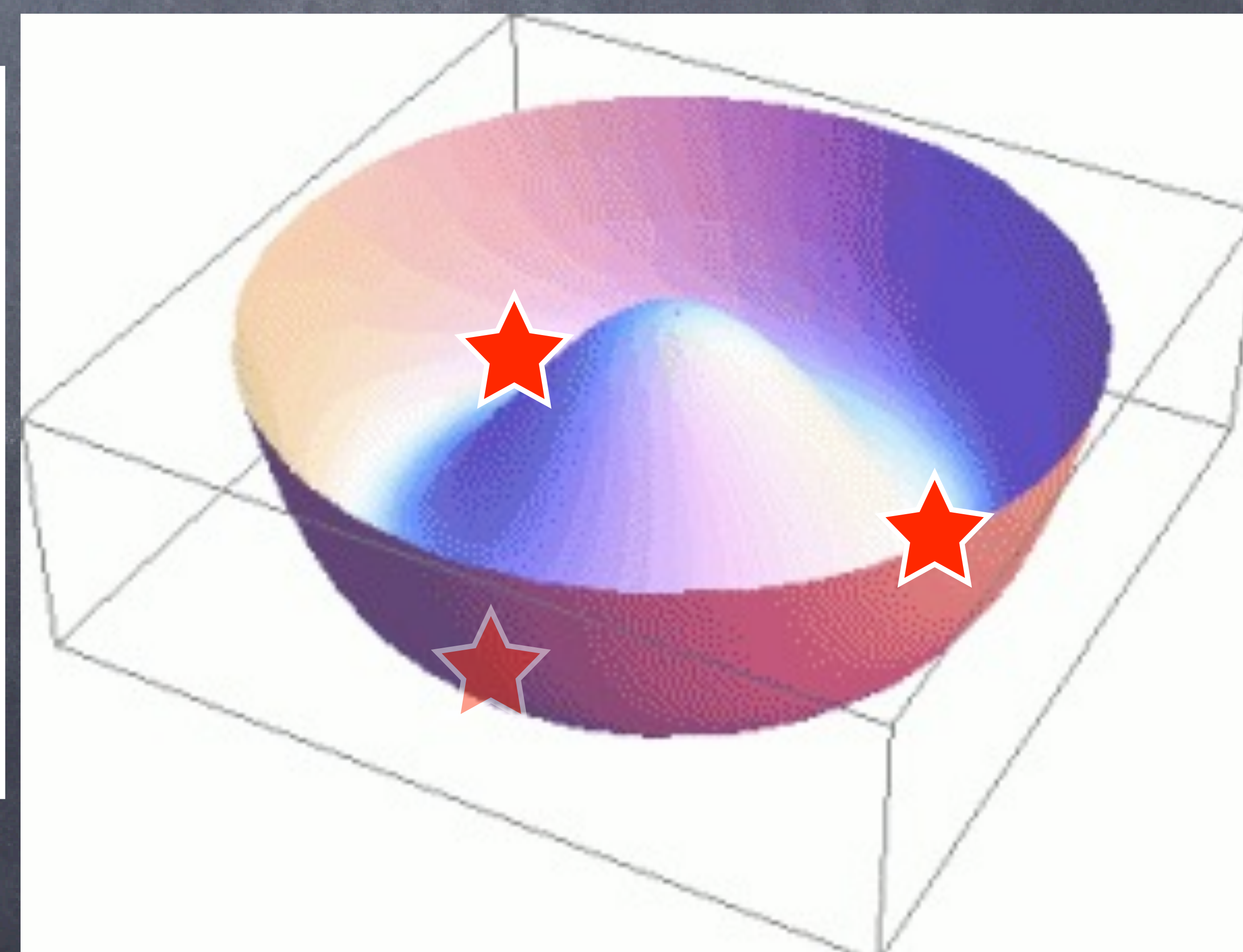


Allen, Shellard

Moreover, domain walls may be formed, if there are multiple degenerate vacua.

Sikvie,`82





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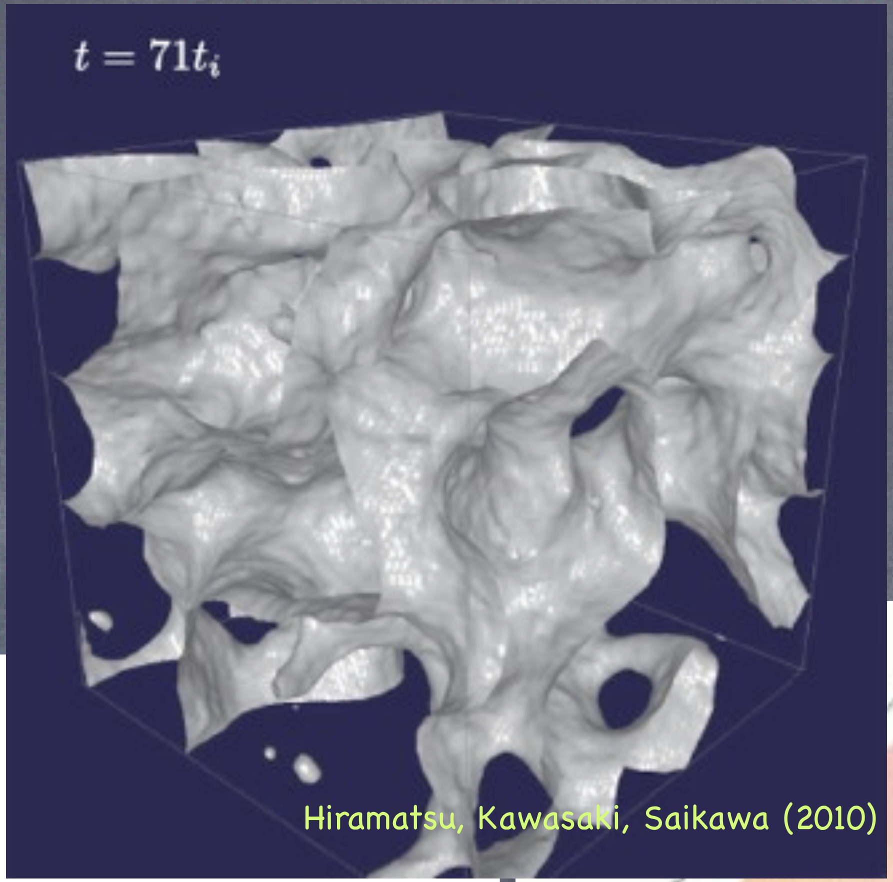

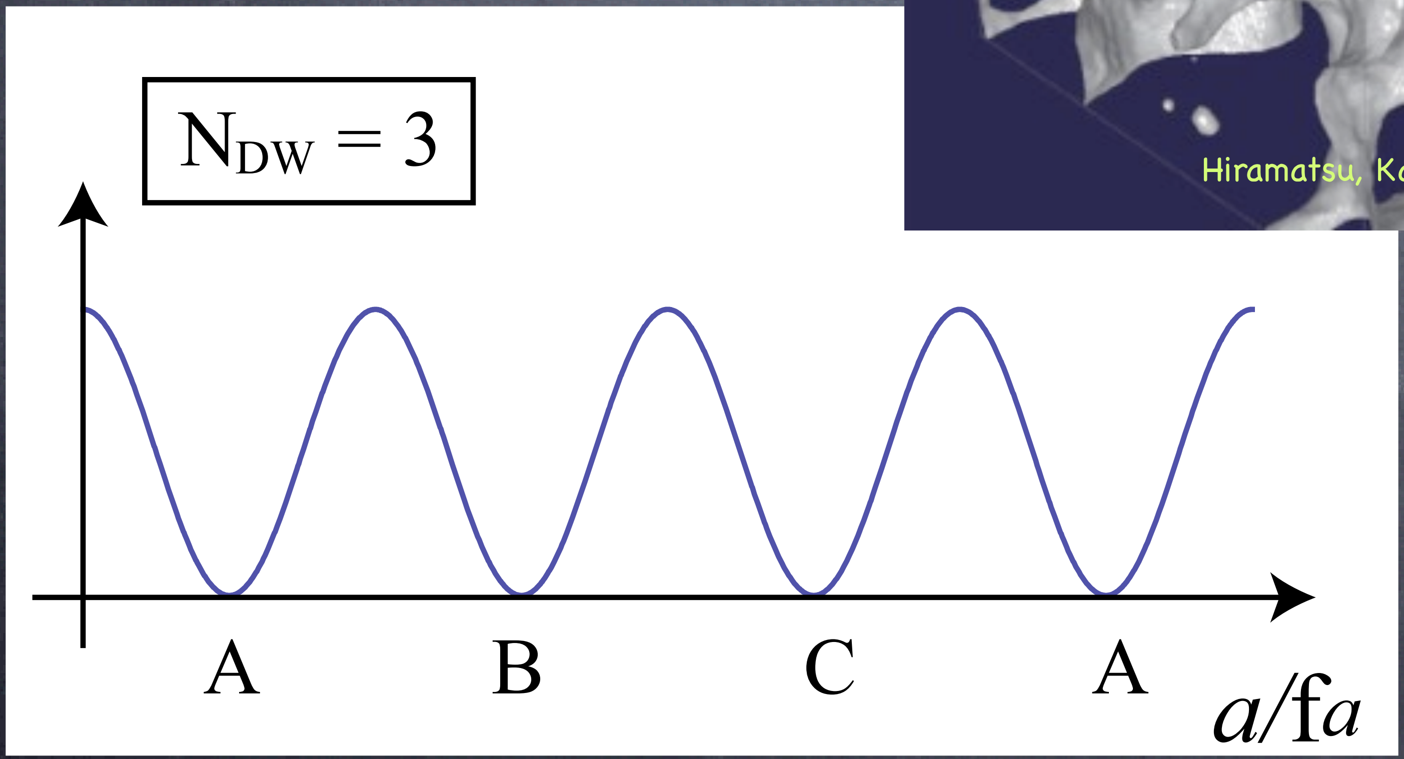

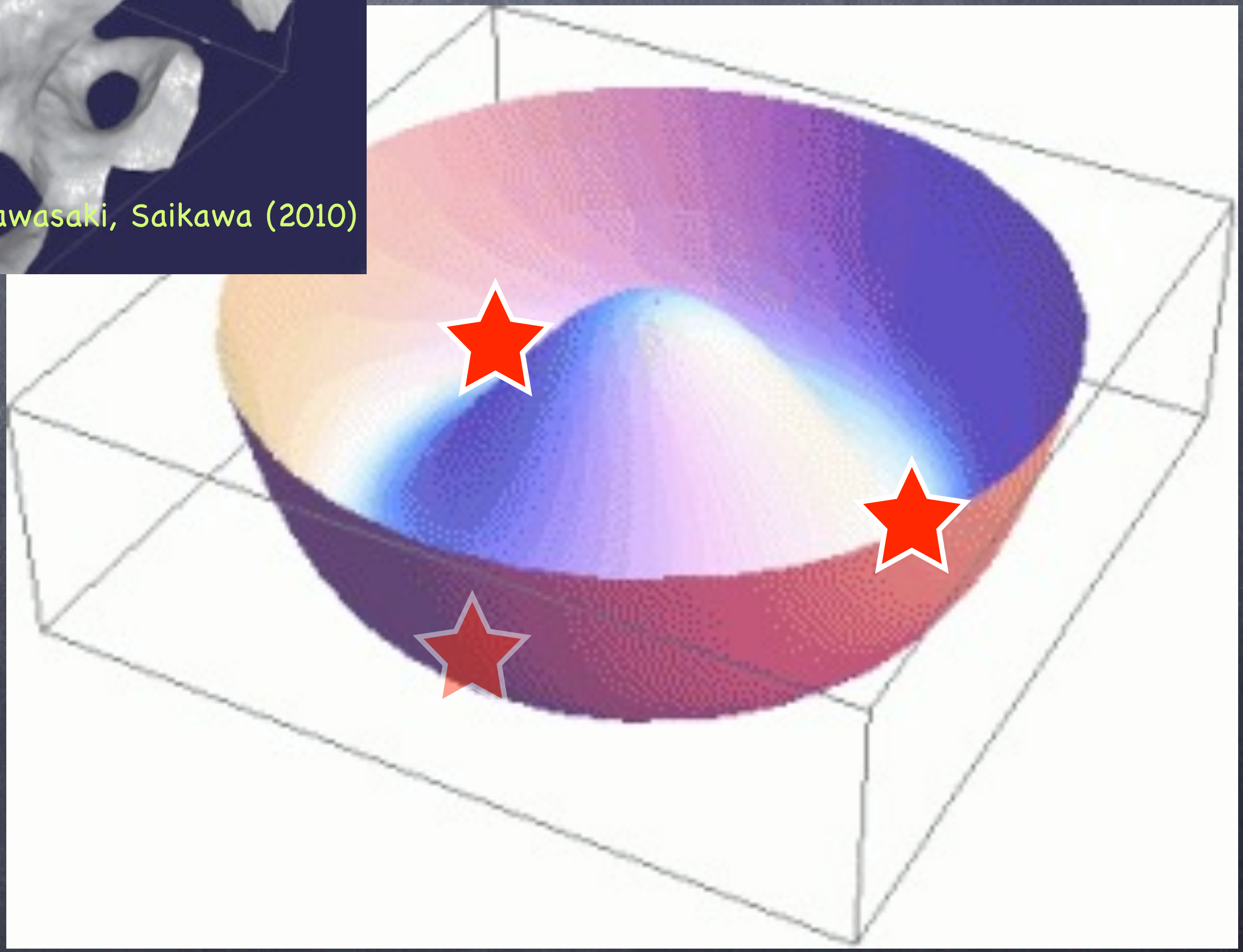

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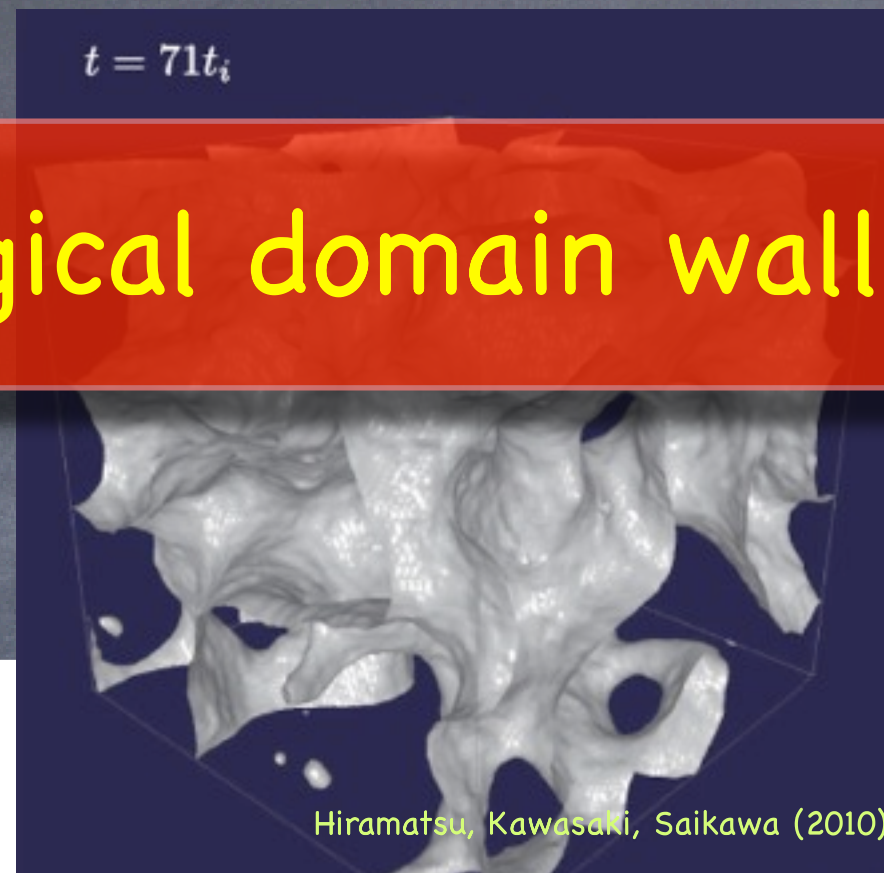
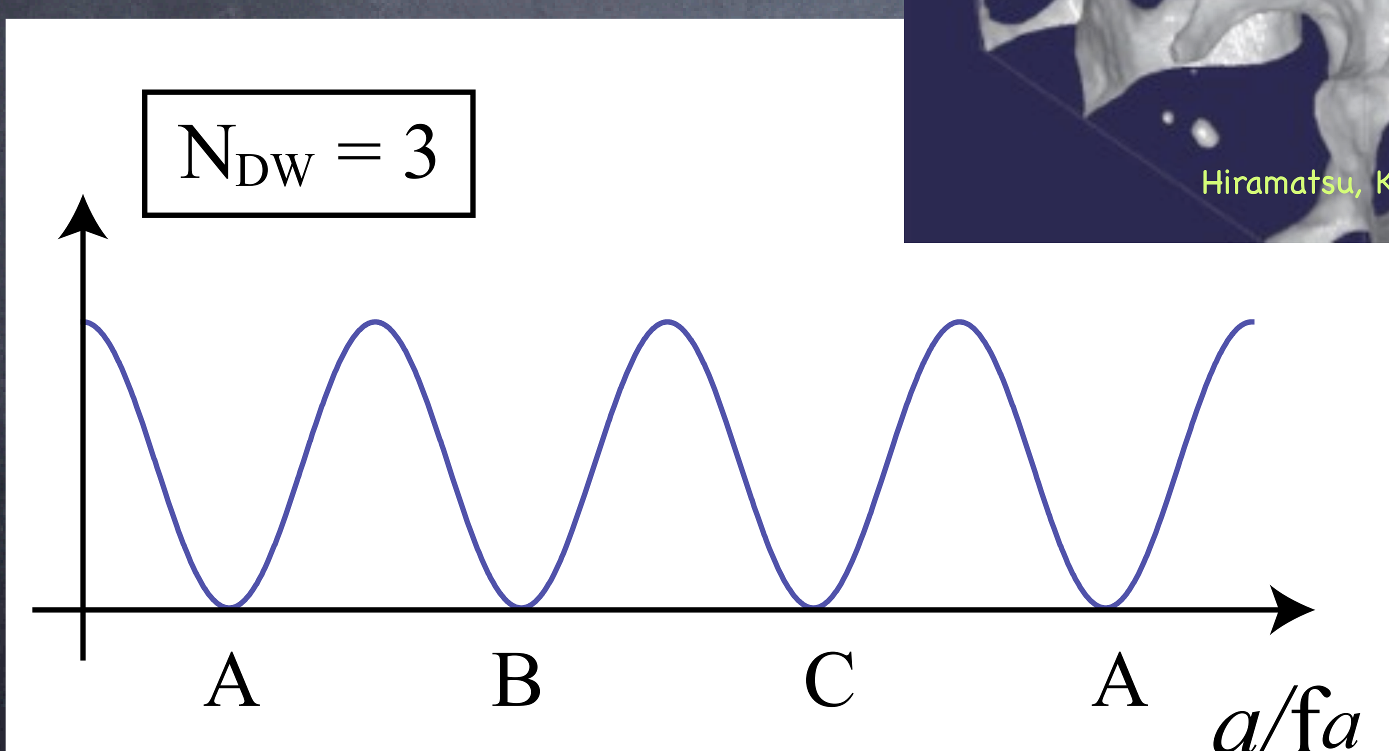
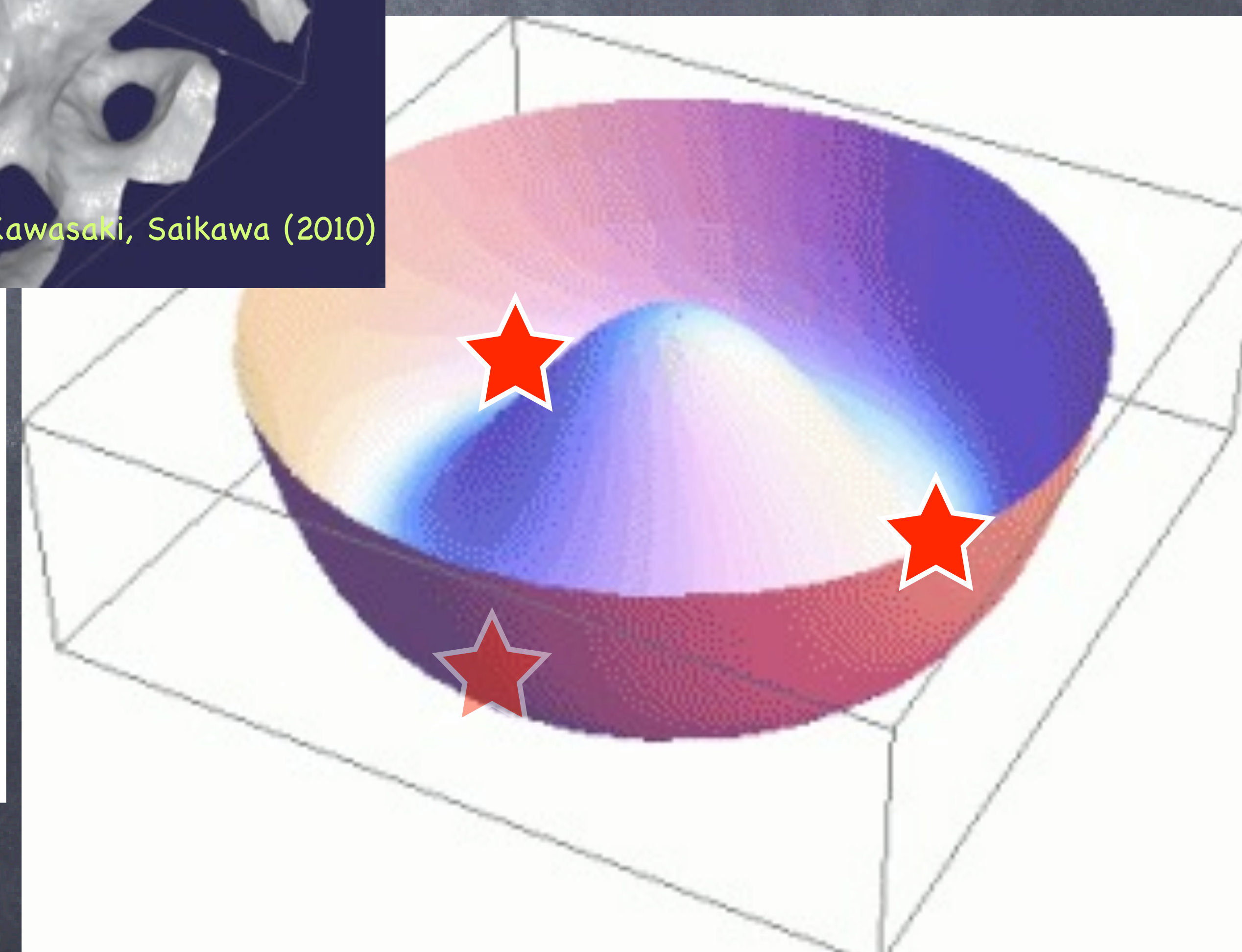


Cosmological domain wall problem!





Solutions to the domain wall problem

1. Add explicit breaking of $U(1)_{PQ}$
2. Low inflation/reheating
3. $N_{DW} = 1$

- Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) axion model has $N_{DW} = 3$.

  (This is because there are three generations of quarks which carry PQ charges)

- Kim-Shifman-Vainshtein-Zakharov axion model has $N_{DW} = 1$, if there is only one heavy quark with a PQ charge.

- Variant axion models have $N_{DW} = 1$.

Variant Axion Models

[Peccei, Wu, Yanagida `86 Krauss, Wilczek `86]

Two Higgs doublets: $\Phi_1, \ \Phi_2$ (+ PQ singlet: σ)

In DFSZ model, Φ_1 is coupled to the down-type quarks and Φ_2 is to the up-type quarks. ⇒ $N_{\rm DW} = 3$

If we couple Φ_2 to only the t (or u or c) quark, we can avoid the domain wall problem!

$$N_{\rm DW} = 1$$

PQ charge assignment [Model T]

	Φ_1	Φ_2	σ	t_R	others
PQ charge	0	-1	1	-1	0

$$
\begin{aligned}
V(\Phi_1, \Phi_2, \sigma) \;=\; & \lambda_1 \left(|\Phi_1|^2 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(|\Phi_2|^2 - \frac{v_2^2}{2} \right)^2 + \lambda \left(|\sigma|^2 - \frac{v^2}{2} \right)^2 \\
& + a\,|\Phi_1|^2|\sigma|^2 + b\,|\Phi_2|^2|\sigma|^2 + \left(m\,\Phi_1^\dagger \Phi_2 \sigma + \text{h.c.} \right) \\
& + d\,|\Phi_1^\dagger \Phi_2|^2 + e\,|\Phi_1|^2\,|\Phi_2|^2 .
\end{aligned}
$$

Yukawa interactions

$$
\begin{aligned}
-\mathcal{L}_{\text{Yukawa}} \;=\; & y_{ij}^{(d)} \bar{Q}_{Li} \Phi_1 d_{Rj} + y_i^{(t)} \bar{Q}_{Li} \tilde{\Phi}_2 t_R \\
& + y_i^{(u)} \bar{Q}_{Li} \tilde{\Phi}_1 u_R + y_i^{(c)} \bar{Q}_{Li} \tilde{\Phi}_1 c_R
\end{aligned}
$$

Light and heavy Higgs, h and H:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + ig_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ig_2) \end{pmatrix}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}$$

1. Where is the light higgs?

$\sin\alpha$ In extreme cases, h_1 or h_2

2. The couplings to gauge bosons?

$\tan\beta$ $\tan\beta \gtrsim 1$ or $\tan\beta \lesssim 1$

Couplings to gauge bosons:

$$HVV \;:\; \cos(\beta-\alpha)\; g_{\rm SM}^{hVV},$$

$$hVV \;:\; \sin(\beta-\alpha)\; g_{\rm SM}^{hVV},$$

≈ 1

$\alpha \sim 0 \quad \beta \sim \frac{\pi}{2}$

V = W or Z

→ SM like

Couplings to fermions: (Model T)

$$hcc \;:\; -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{hcc},$$

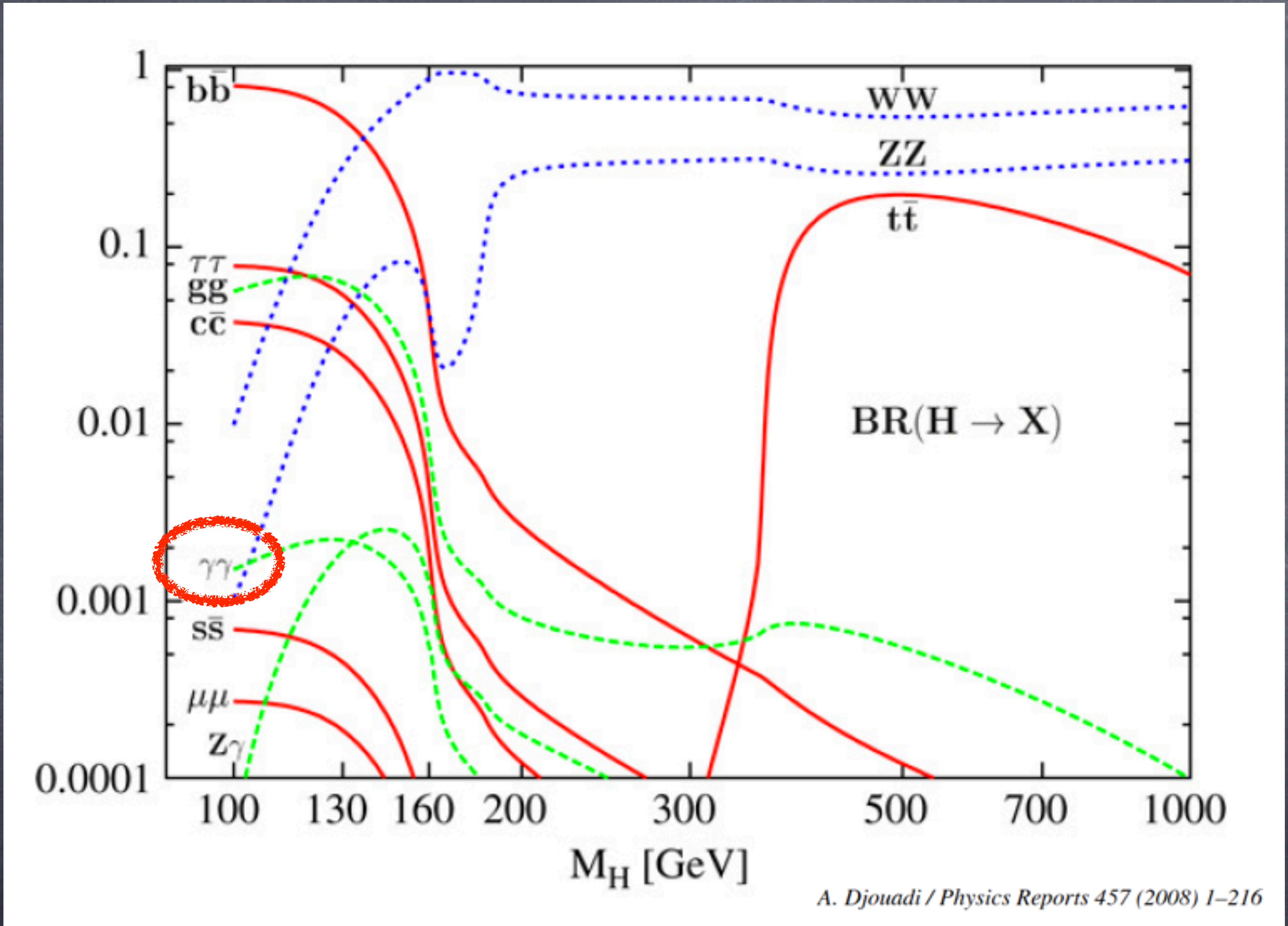
$$hbb \;:\; -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{hbb},$$

$$htt \;:\; \frac{\cos\alpha}{\sin\beta} g_{\rm SM}^{htt}.$$

Suppressed, if $|\sin\alpha| \ll \cot\beta$ (hcc, hbb)

→ SM like (htt)

The SM Higgs boson decay branching ratios

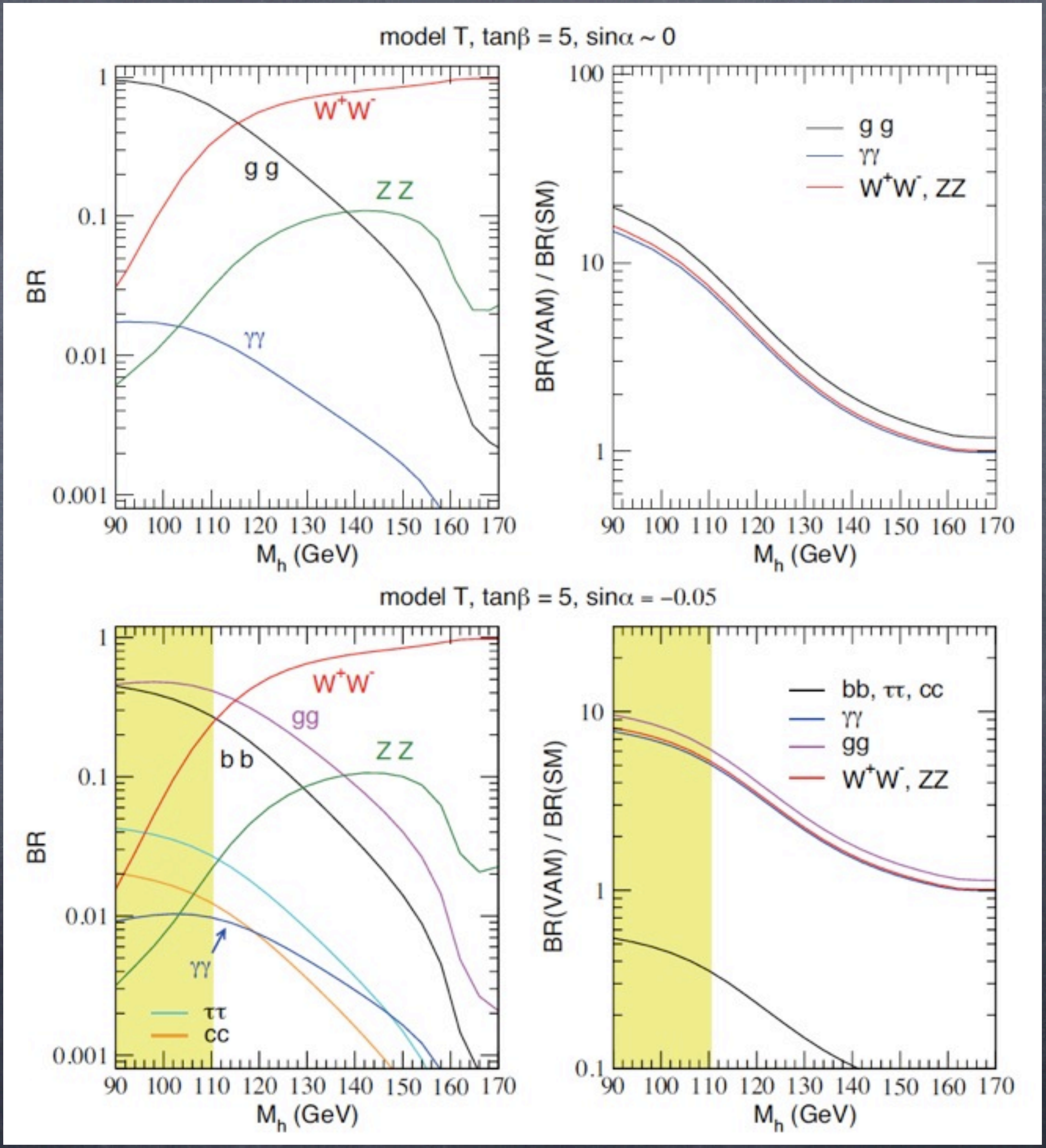


If h→bb (and h→gg) is suppressed, h→2γ can be enhanced.

Model T

$\sin \alpha = 0$

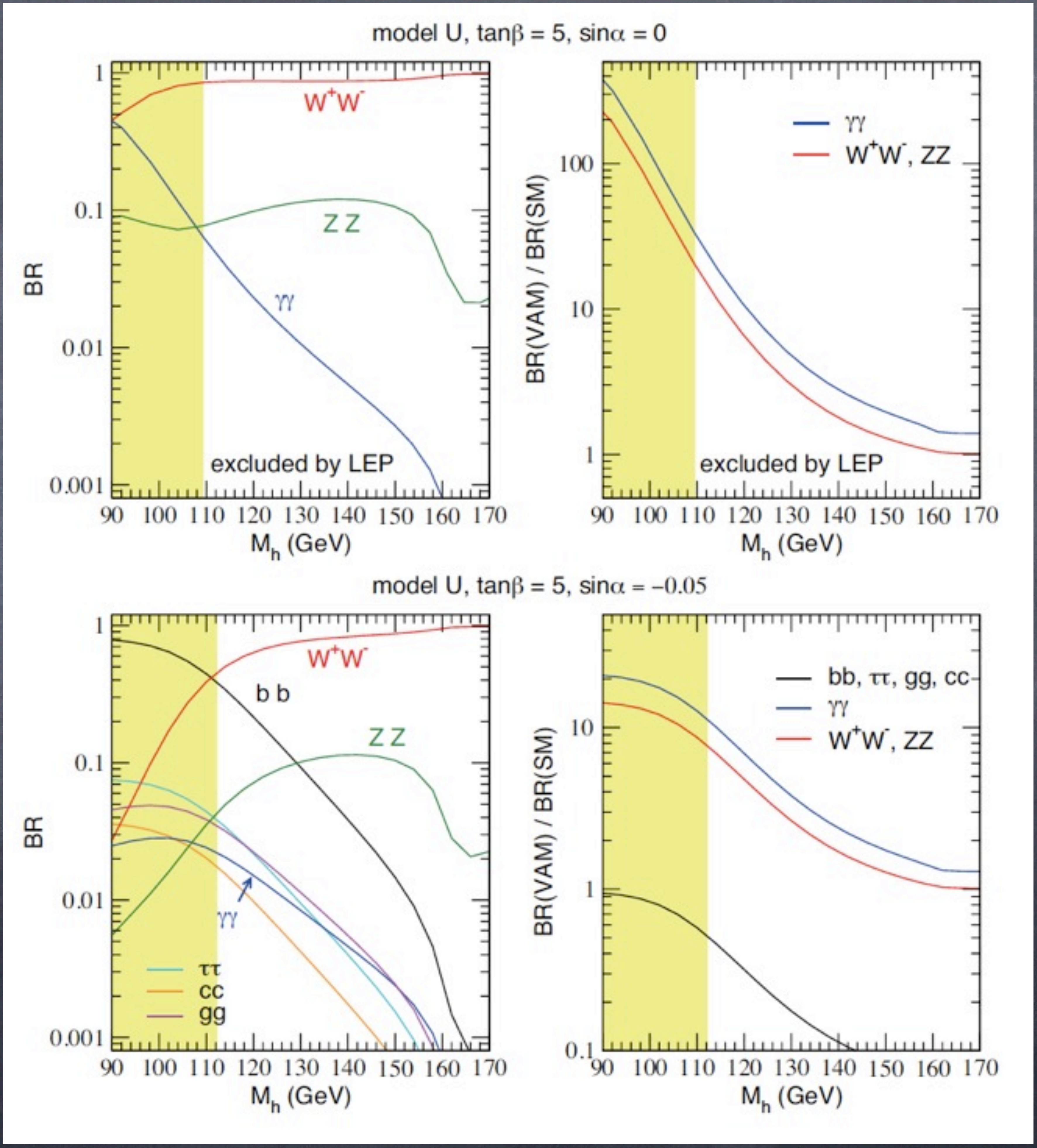
$\sin \alpha = -0.05$



Model U

$$\sin\alpha = 0$$

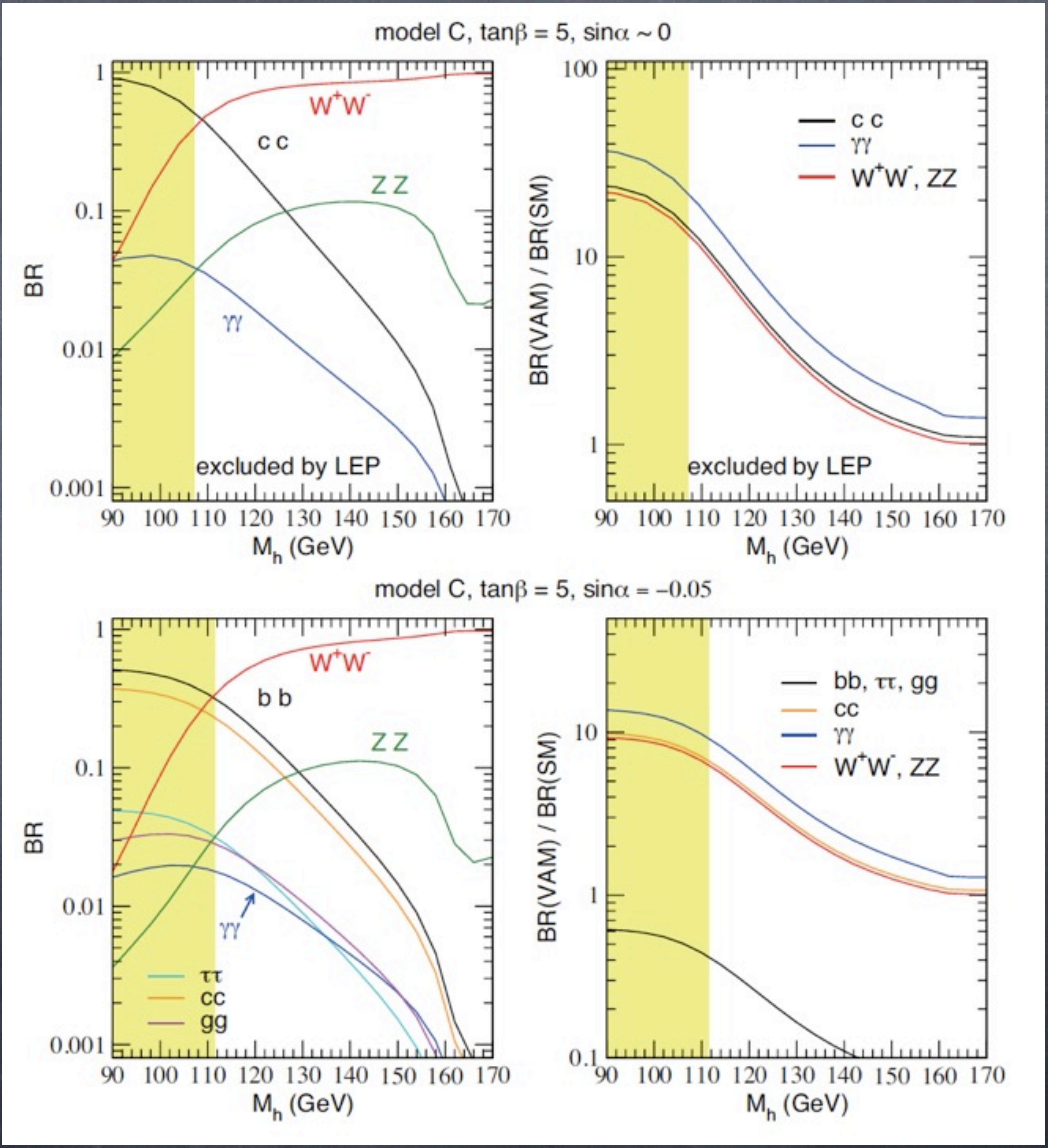
$$\sin\alpha = -0.05$$



Model C

$$\sin\alpha = 0$$

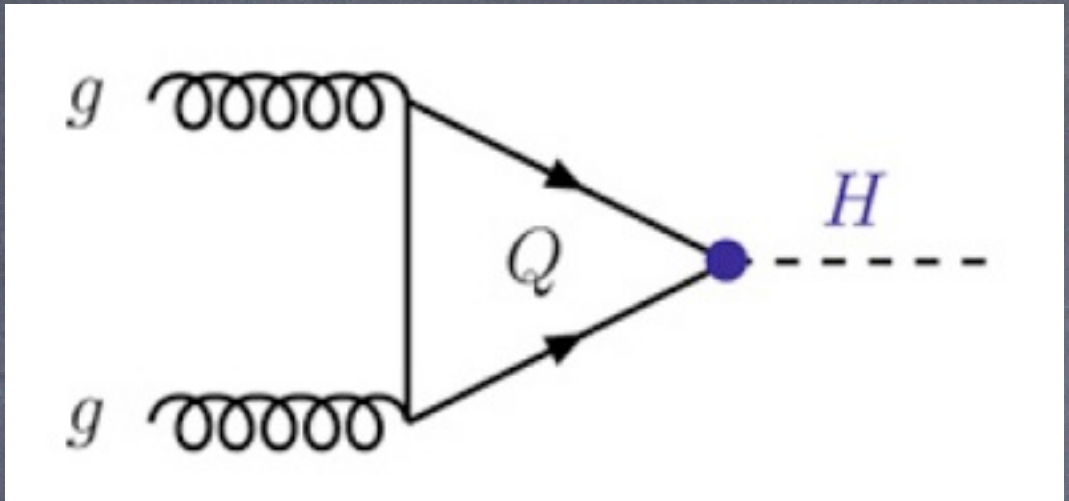
$$\sin\alpha = -0.05$$



Production processes

Model T:

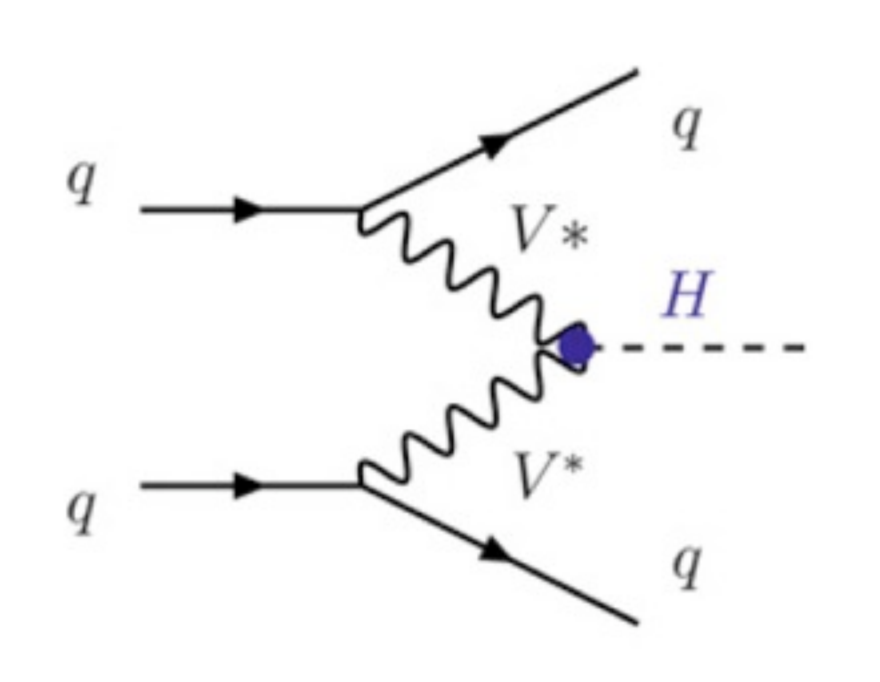
gluon-gluon fusion (GGF)



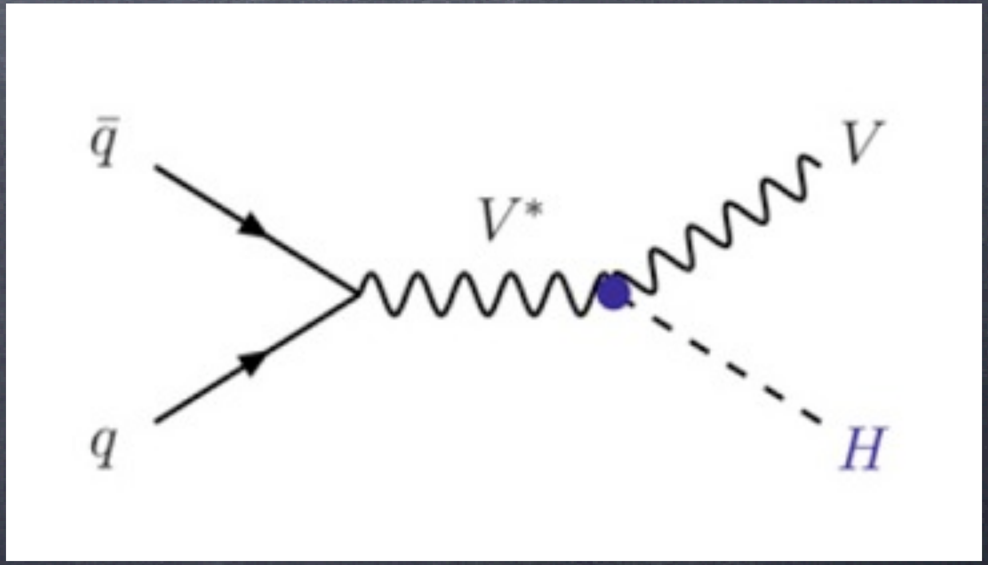
+ the sub-dominant processes below.

Models U and C:

Vector boson fusion (VBF)



Associated production (VH)



Prospect for discovery of the light Higgs through the two-photon decay

SM Higgs search at LHC:

- Will be discovered through $h \to \gamma\gamma$ at ATLAS/CMS with $30fb^{-1}$ and 14TeV c.m. energy for M_h < 130GeV in the inclusive search.

- Estimated significance for $h \to \gamma\gamma$ in VBF and VH is 2.2 sigma with $30fb^{-1}$ at CMS.

In the case of VAM:

- Model T

✓Enhanced by 4(3) at M_h = 120GeV for $\sin\alpha = 0(-0.05)$

✓Will be discovered with $3fb^{-1}$($4fb^{-1}$).

✓Production c.s. will be reduced by a factor of (3-4) with 7TeV compared to 14TeV. The significance will be about 2 sigma with 1 fb^{-1}.

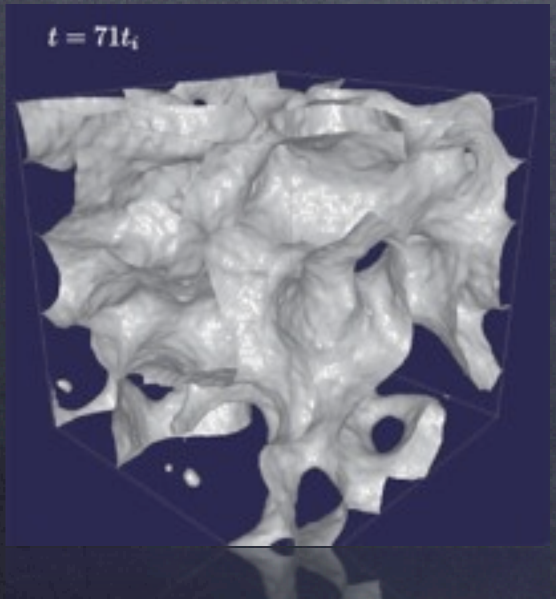
- Models U and C

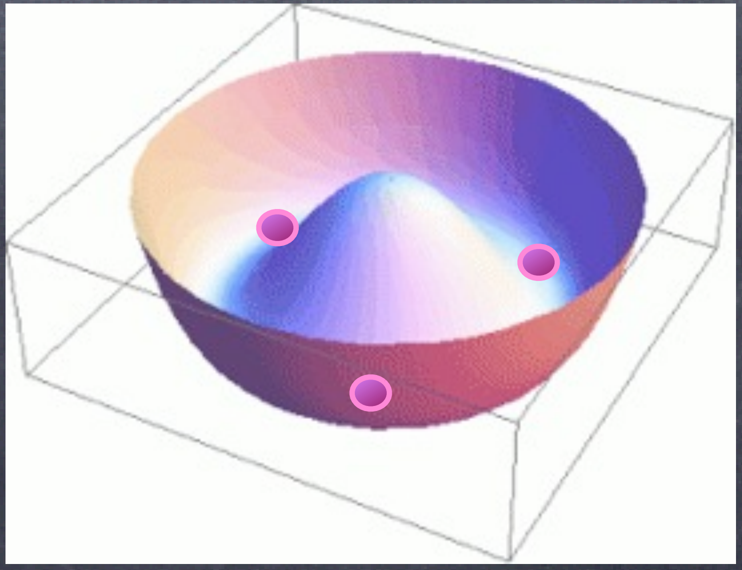
✓e.g., $\mathrm{BR}(h \to \gamma\gamma)$ is enhanced by 8(5) in the model C with M_h = 120GeV, for $\sin\alpha = 0(-0.05)$.

✓Will be discovered only with $3fb^{-1}$ ($10fb^{-1}$).

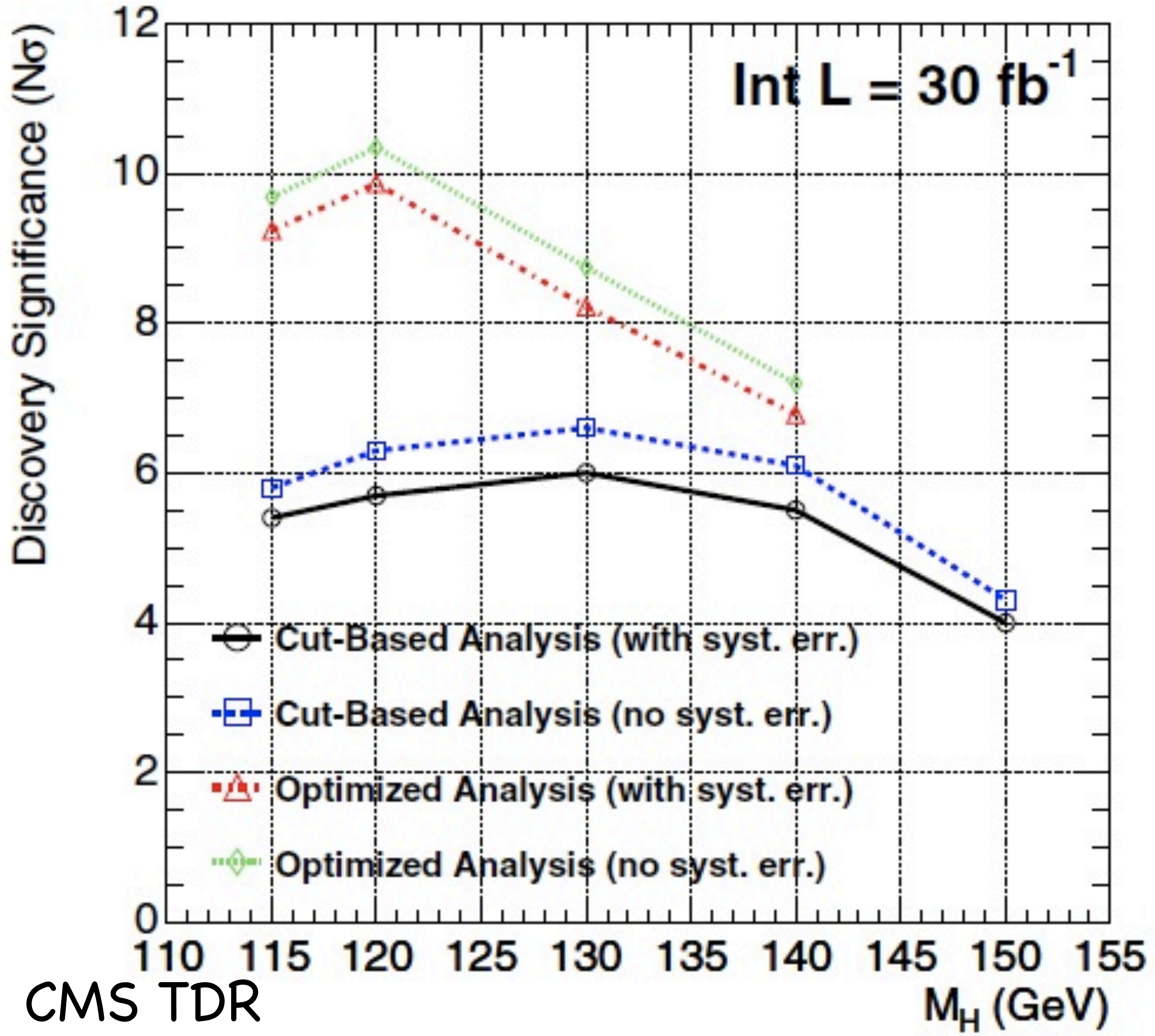
Conclusions

- The PQ mechanism predicts the presence of a light particle, axion.
- If the PQ symmetry is restored during/after inflation, domain walls may be produced. One way-out is the variant axion model.
- The special Yukawa structure of the VAM may lead to the enhancement of $h \to 2\gamma$.






Back-up slides


Int L = 30 fb-1
Discovery Significance (Nσ)
12
10
8
6
4
2
0
110 115 120 125 130 135 140 145 150 155
MH (GeV)
Cut-Based Analysis (with syst. err.)
Cut-Based Analysis (no syst. err.)
Optimized Analysis (with syst. err.)
Optimized Analysis (no syst. err.)

CMS TDR