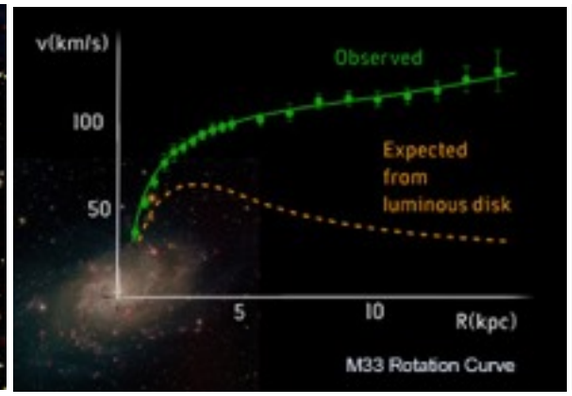
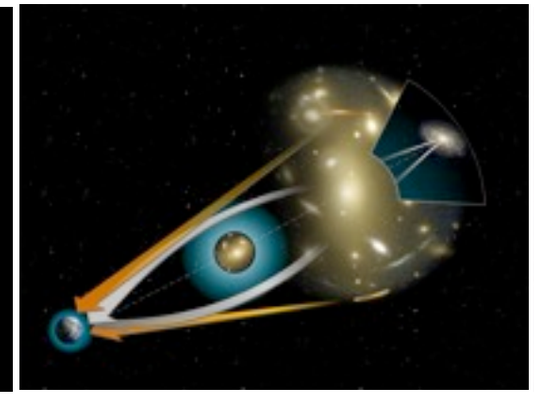
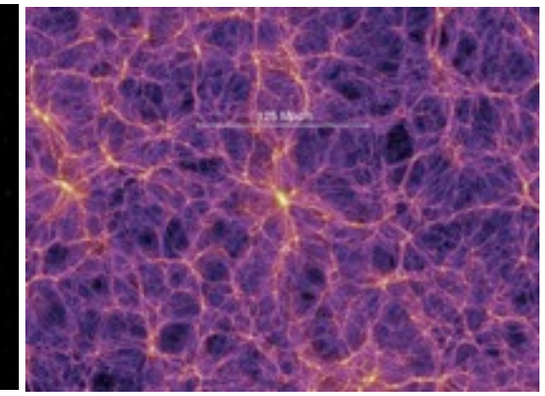
Exploring Dark Matter and Baryon Asymmetry: Higgs is the Key

Yue Zhang
California Institute of Technology

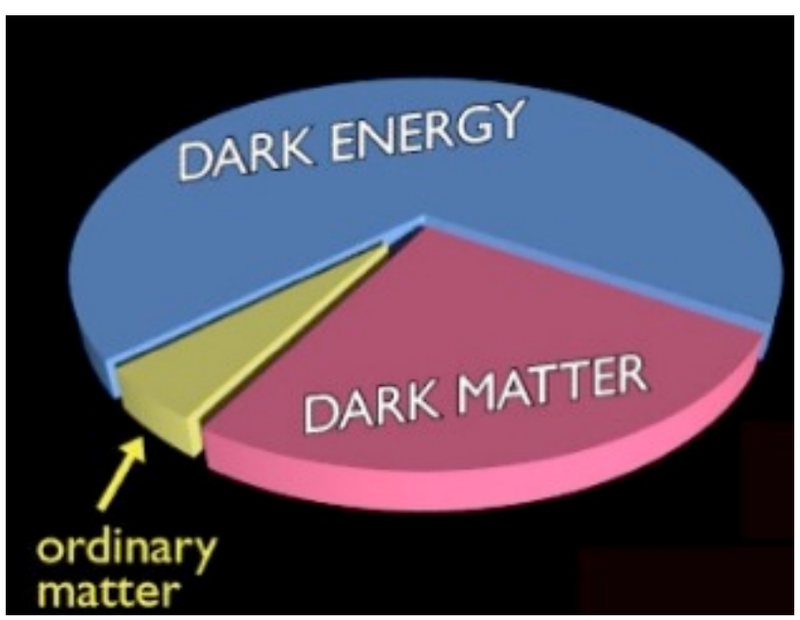
Fermilab Theory Seminar, 9 October 2014

Dark Matter



- Many evidences for its existence.
- DM contributes 23% of the total energy budget.



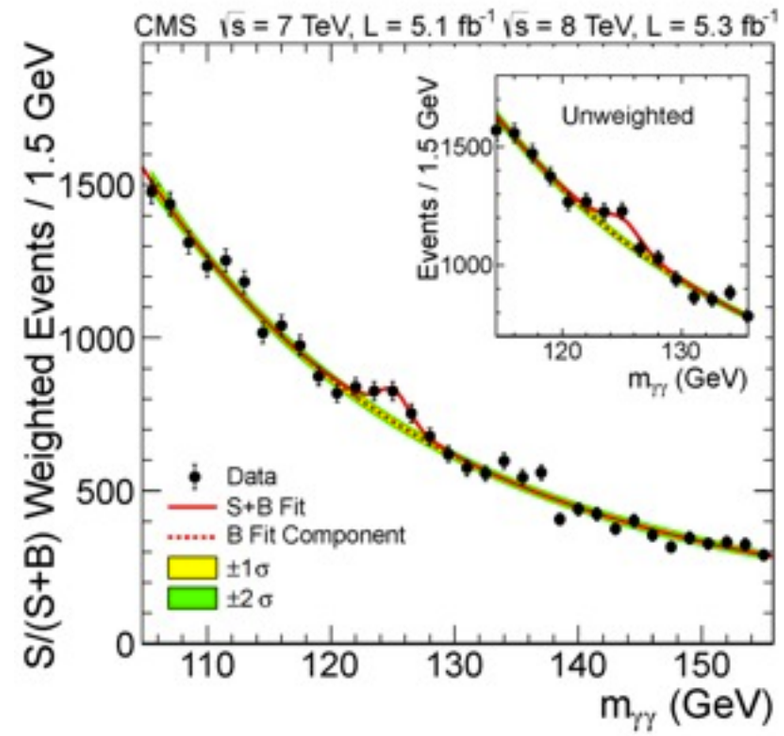
- Cosmologically long lived.
- Non-relativistic.
- (less than) weakly interacting.

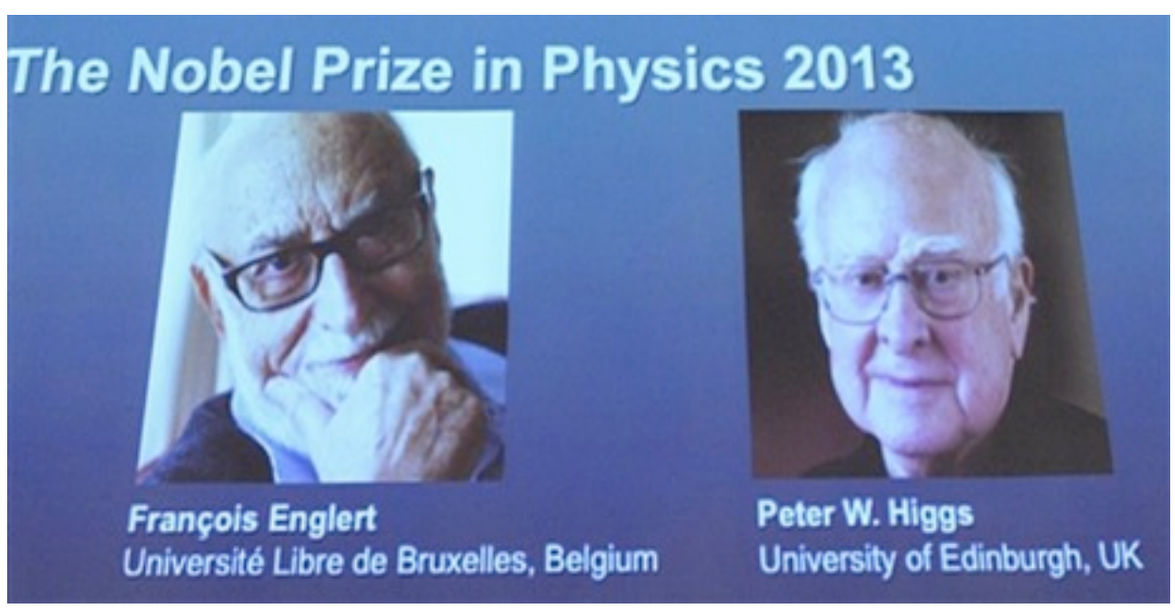
Particle physics Standard Model contains no DM candidate.

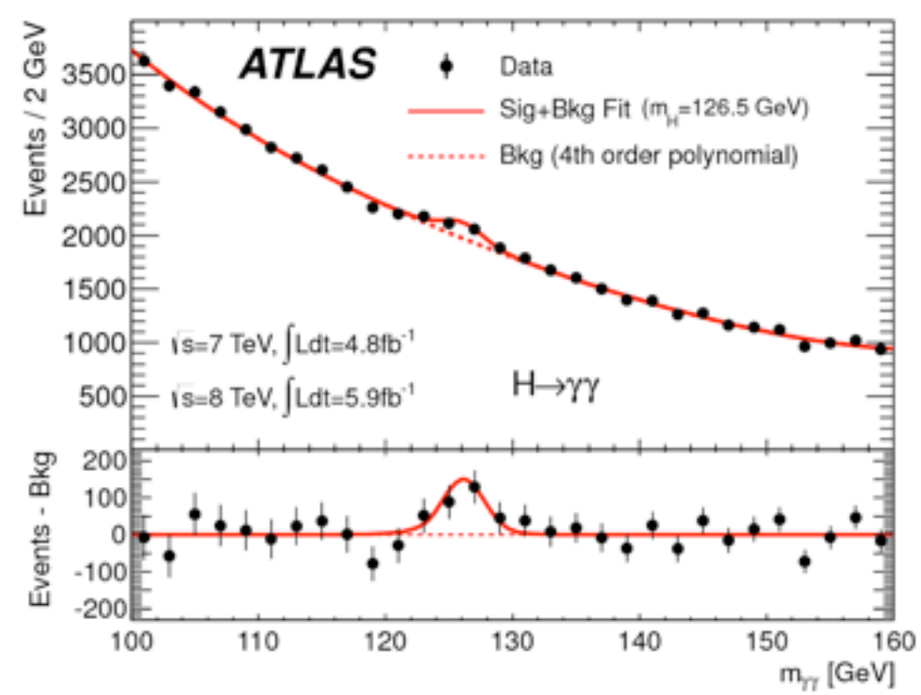
Discover of a boson

- LHC found a spin-0 particle with mass 125-126 GeV.
- Look like SM Higgs boson.

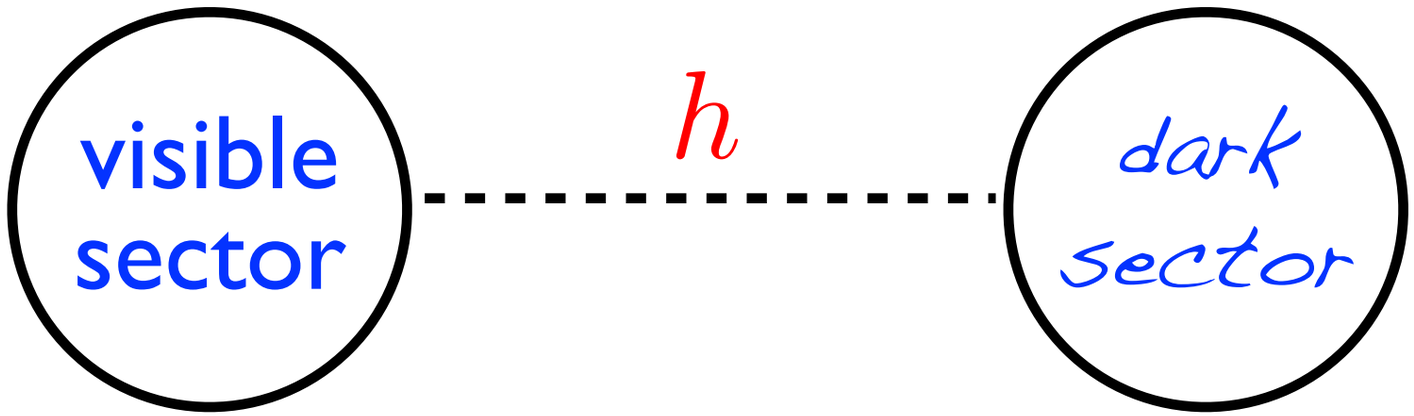
Milestone in particle physics







Higgs portal to DM



The Higgs boson

in addition to giving particle masses

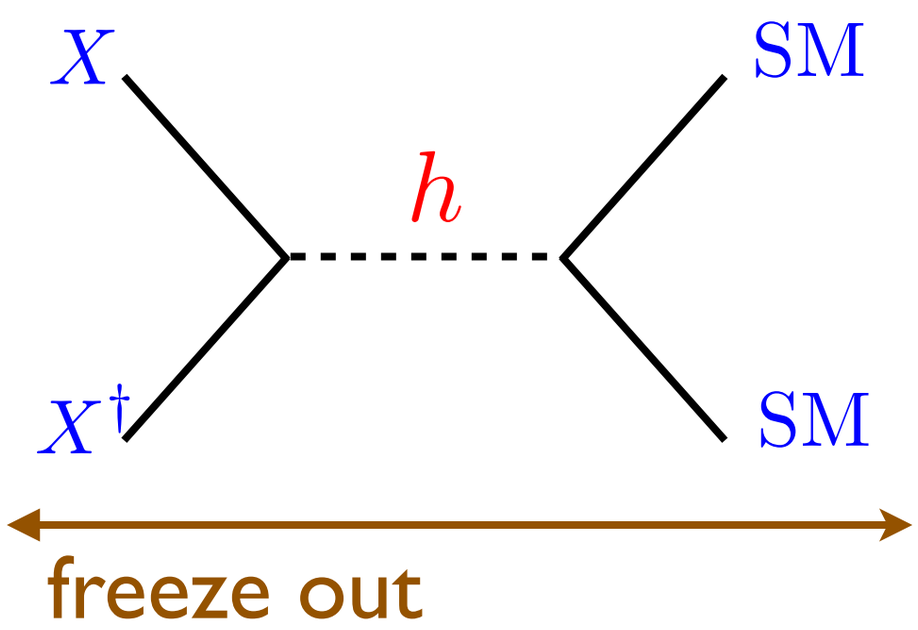
- can mediate interactions between the two sectors.
- Testable - we now probing the electroweak scale.

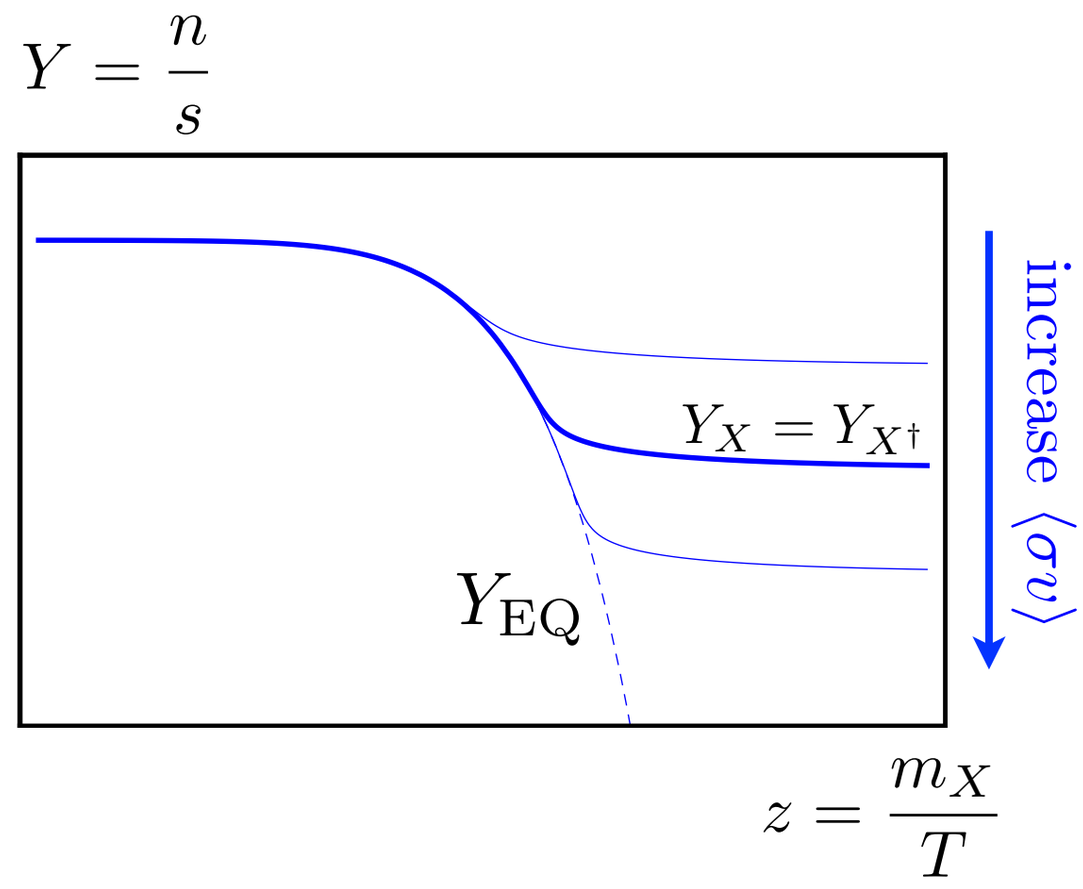
The simplest model

Add a complex scalar singlet X, odd under Z_2 or U(1).

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda |X|^2 |H|^2 + m_X^2 |X|^2$$

The WIMP miracle: initial condition $n_X = n_{X^\dagger}$





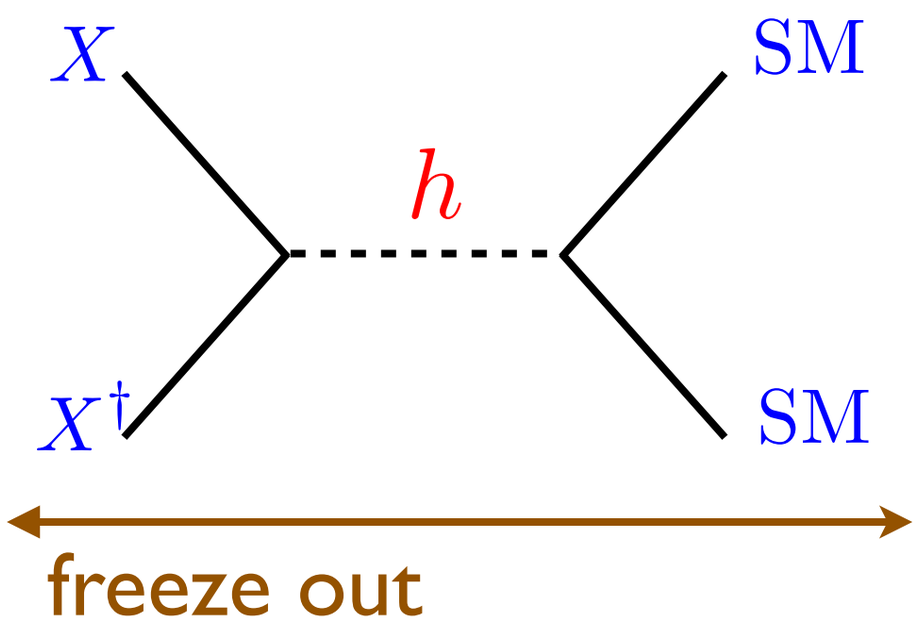
$$\Omega_X \simeq 0.23 \left(\frac{1\,\text{pb}}{\langle \sigma v \rangle} \right)$$

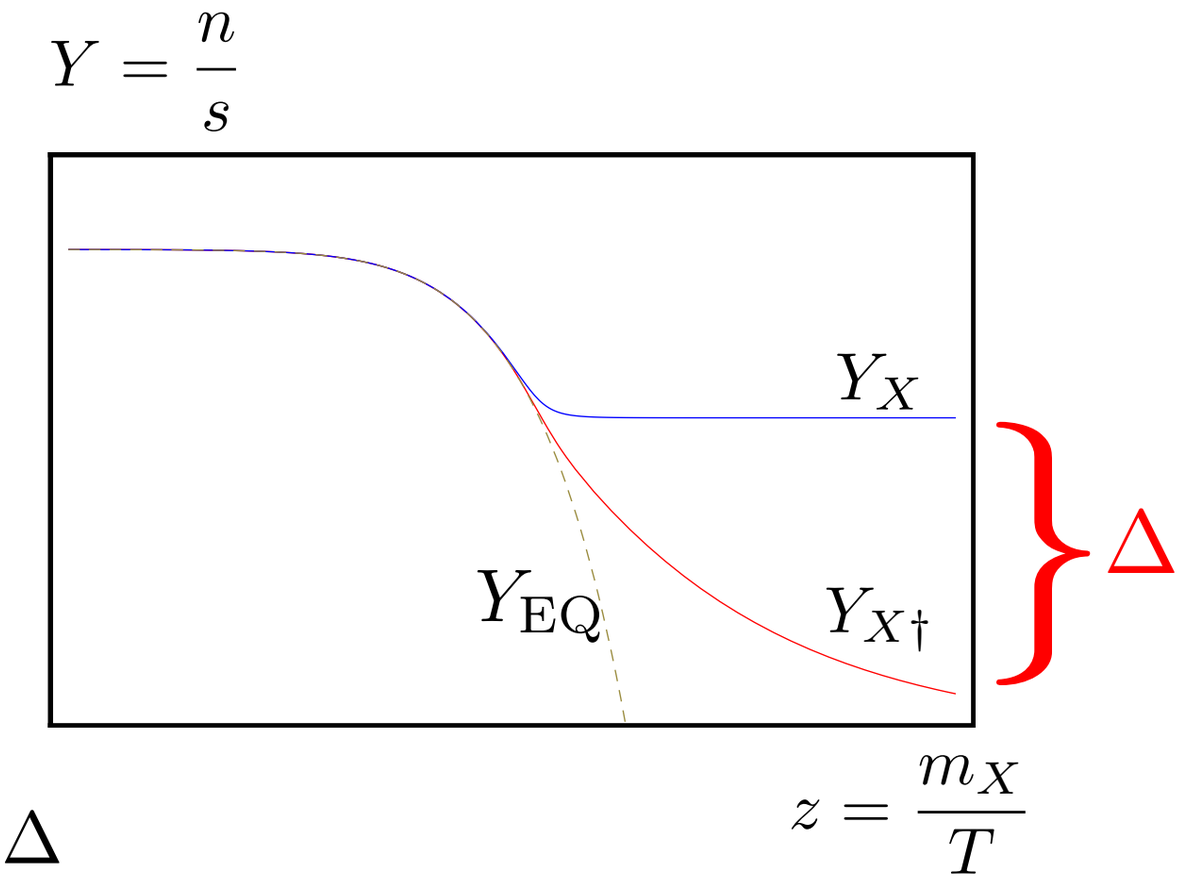
The simplest model

Add a complex scalar singlet X, odd under Z_2 or U(1).

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda |X|^2 |H|^2 + m_X^2 |X|^2$$

Asymmetric dark matter: $n_X = n_{X^\dagger} + \Delta$





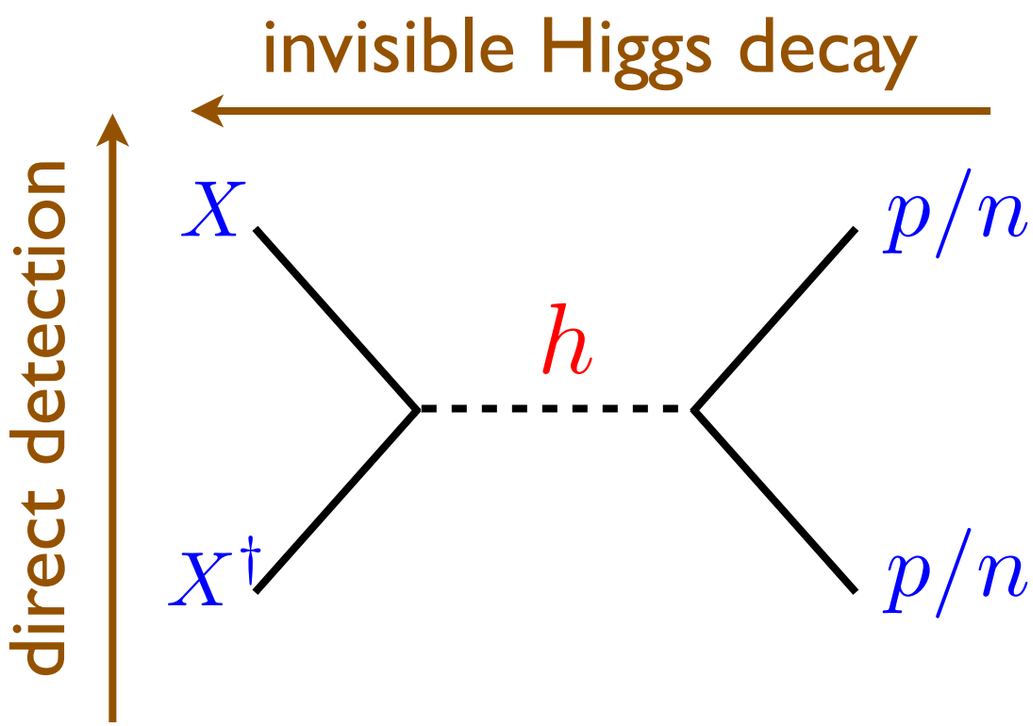
For $\langle \sigma v \rangle \gg 1\,\mathrm{pb}$

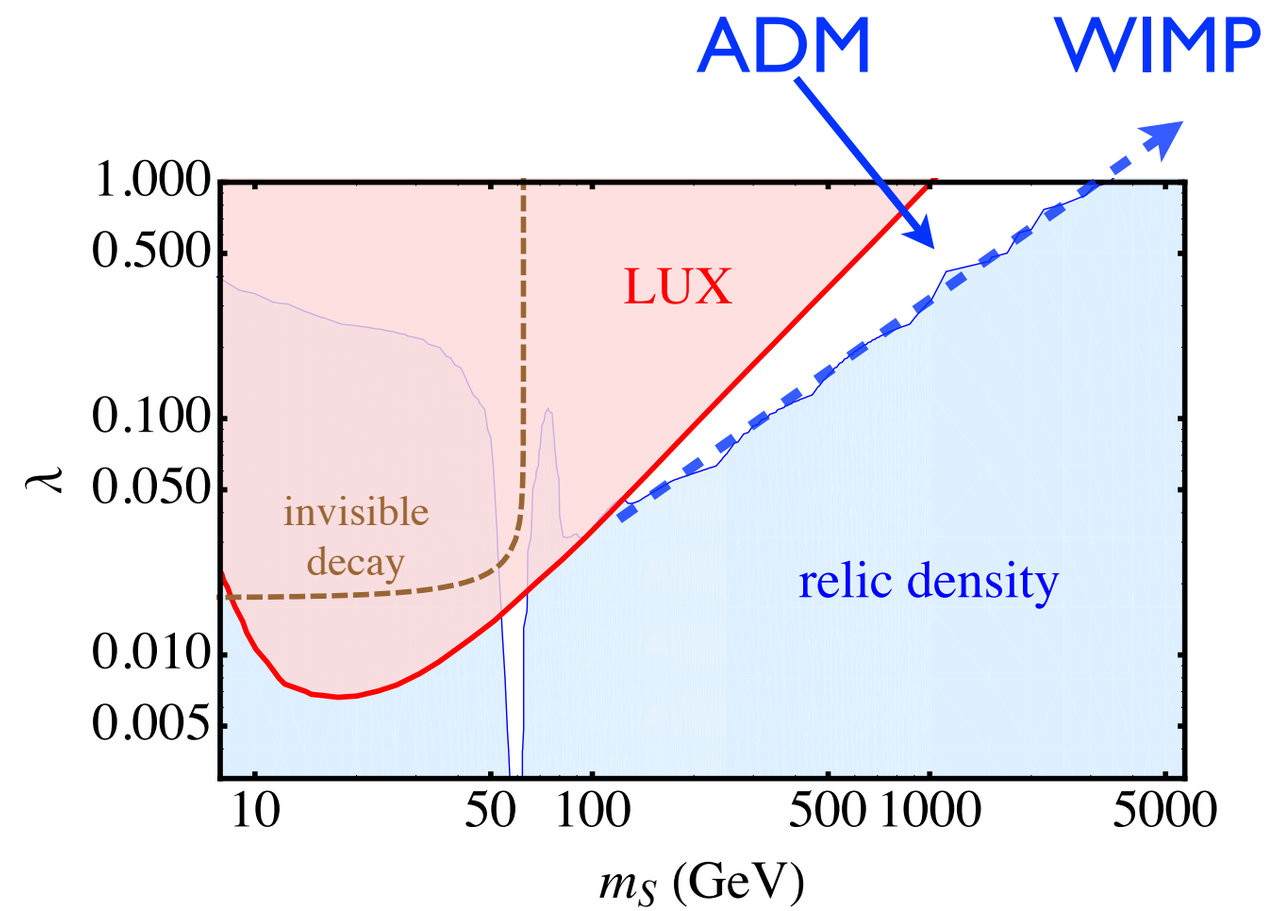
Ω_X determined by Δ

The simplest model

Add a complex scalar singlet X, odd under Z_2 or U(1).

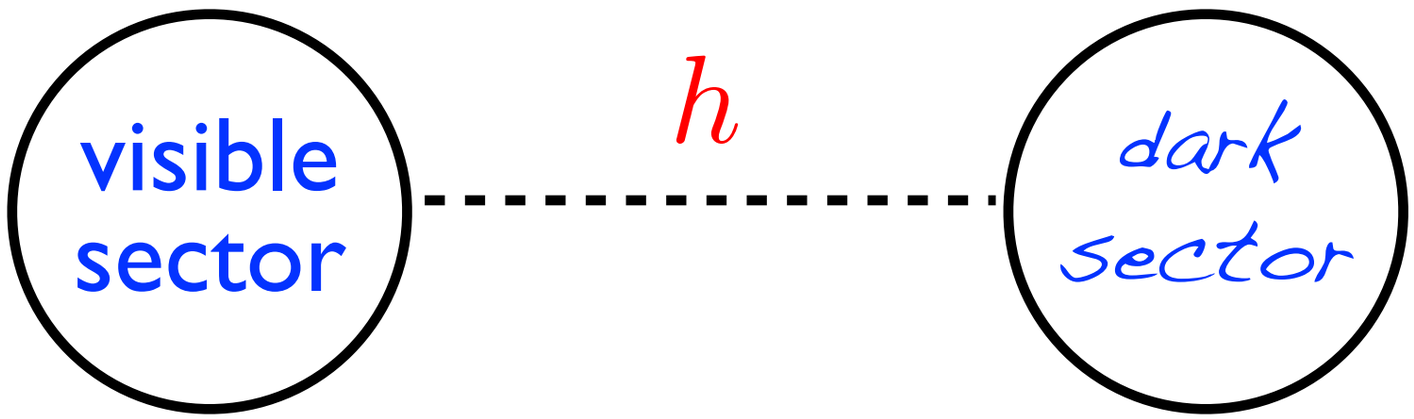
$$\mathcal{L} = \mathcal{L}_{SM} + \lambda |X|^2 |H|^2 + m_X^2 |X|^2$$





Higgs boson also mediates dark matter direct detection

Going beyond



The dark sector may be more complicated - be open minded

I will discuss two possibilities:

- Higgs portal to Fermionic DM leads to an additional scalar in dark sector, DM bound states may exist.
- Higgs evolution in early universe generates asymmetries in both DM and baryons $\Rightarrow$ CP violating Higgs physics.

Fermionic dark matter

Non-renormalizable theory

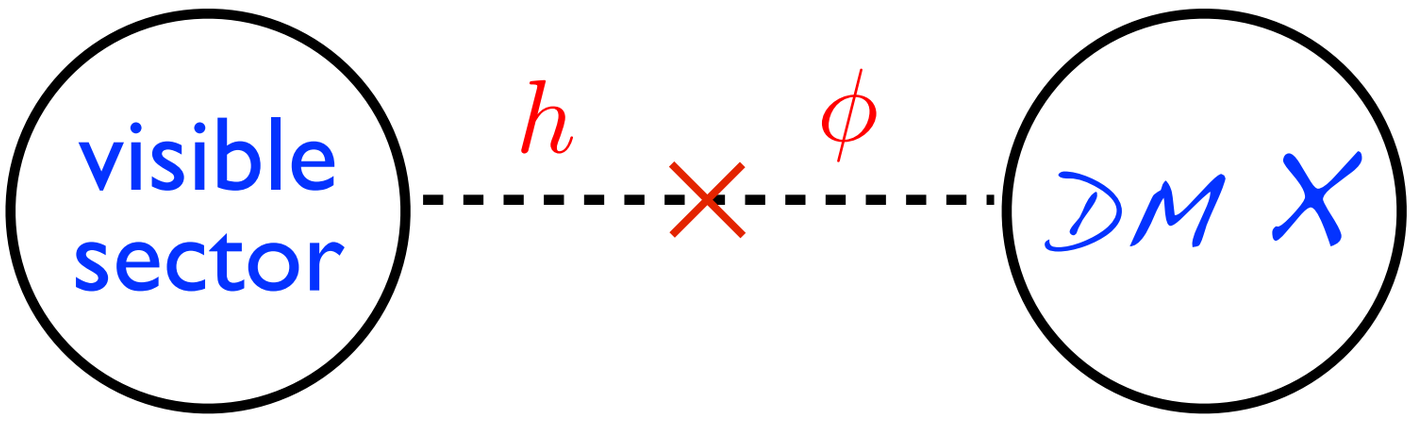
$$\mathcal{L} = \bar{\chi} i \partial\!\!\!/ \chi + m_\chi \bar{\chi}\chi + \frac{1}{\Lambda}\bar{\chi}\chi H^\dagger H$$

If $\Lambda \gg m_\chi, m_h$, repeat the same analysis and results

I focus on the opposite case, UV complete theory

$$\mathcal{L} = \bar{\chi} i \partial\!\!\!/ \chi + m_\chi \bar{\chi}\chi + g_\chi \bar{\chi}\chi\phi + (\lambda_{\phi h}\phi^2 + \mu_{\phi h}\phi)(H^\dagger H - v^2/2) + V(\phi)$$

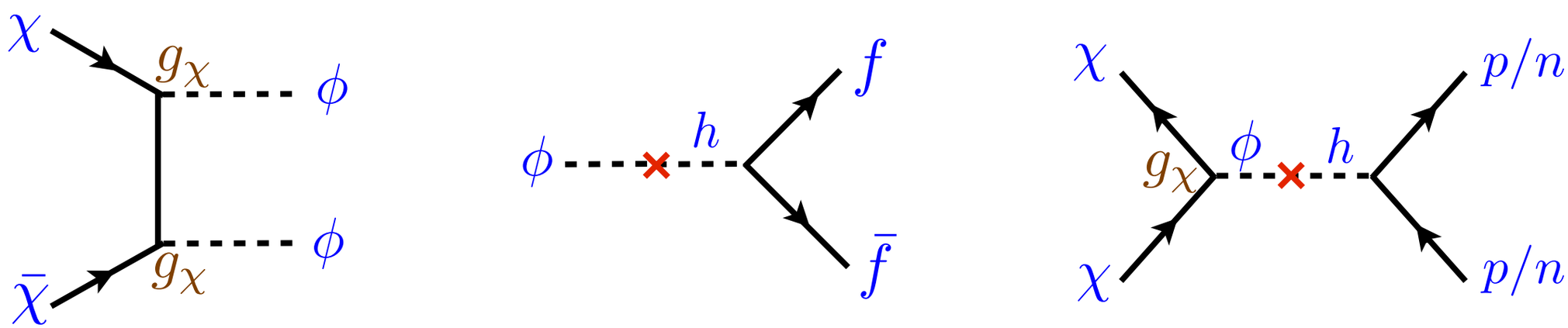
ϕ SM singlet



Annihilation and Scattering

If mediator ϕ is lighter than the DM

Slightly different pheno



large enough g_χ decay before BBN ⇨ lower bound on direct detection

Requires ϕ mass to be above the $\mu^+\mu^-$ threshold

M.B.Wise, **Y.Z.**, arXiv:1407.4121, PRD

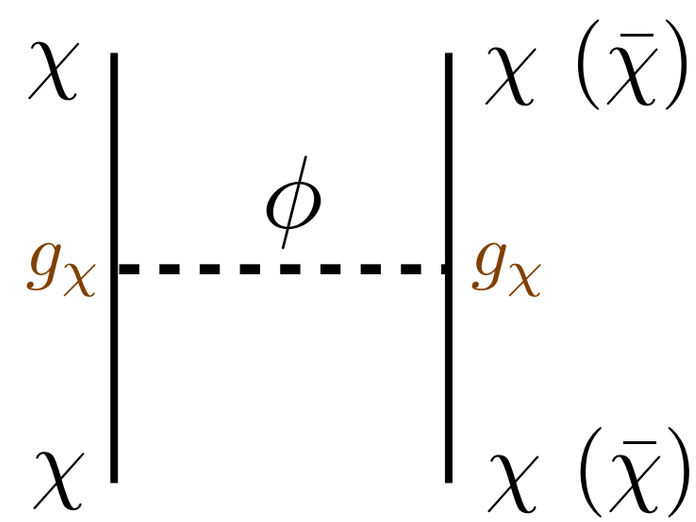
DM bound states

Additional role of the mediator ϕ , self interaction between DM particles

has astrophysical interests, might solve problems of CDM: core/cusp, too big to fail..

I will consider a more particle physics/field theory possibility: DM could form bound states.

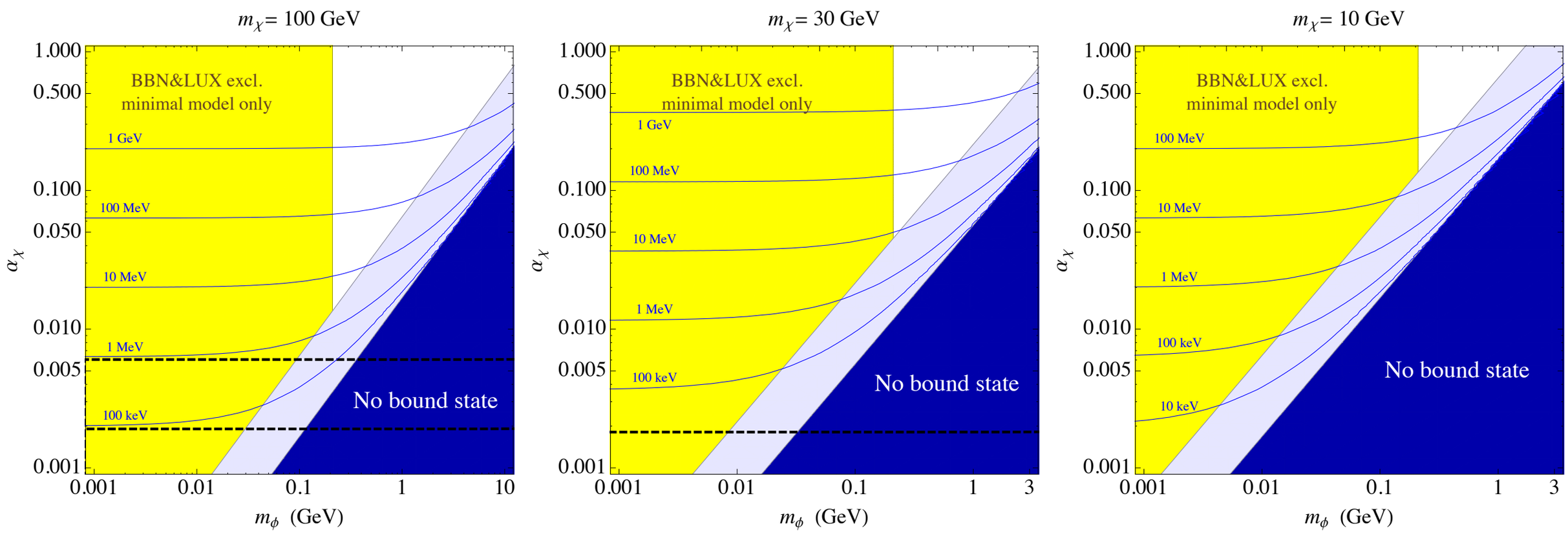
ϕ exchange is always attractive



bound state condition:

$$\frac{1}{\alpha_\chi m_\chi} \lesssim \frac{1}{m_\phi}$$

Stable bound states



Bound state can exist in quite large parameter space

$(\chi\bar{\chi})$ unstable.

$(\chi\chi)$ stable, mostly form if only χ particle is around.

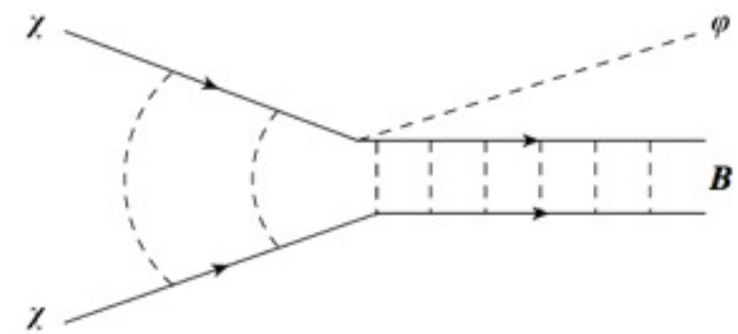
Quantitative question: how many bound states exist today?

Wise, **Y.Z.**, arXiv:1407.4121, PRD

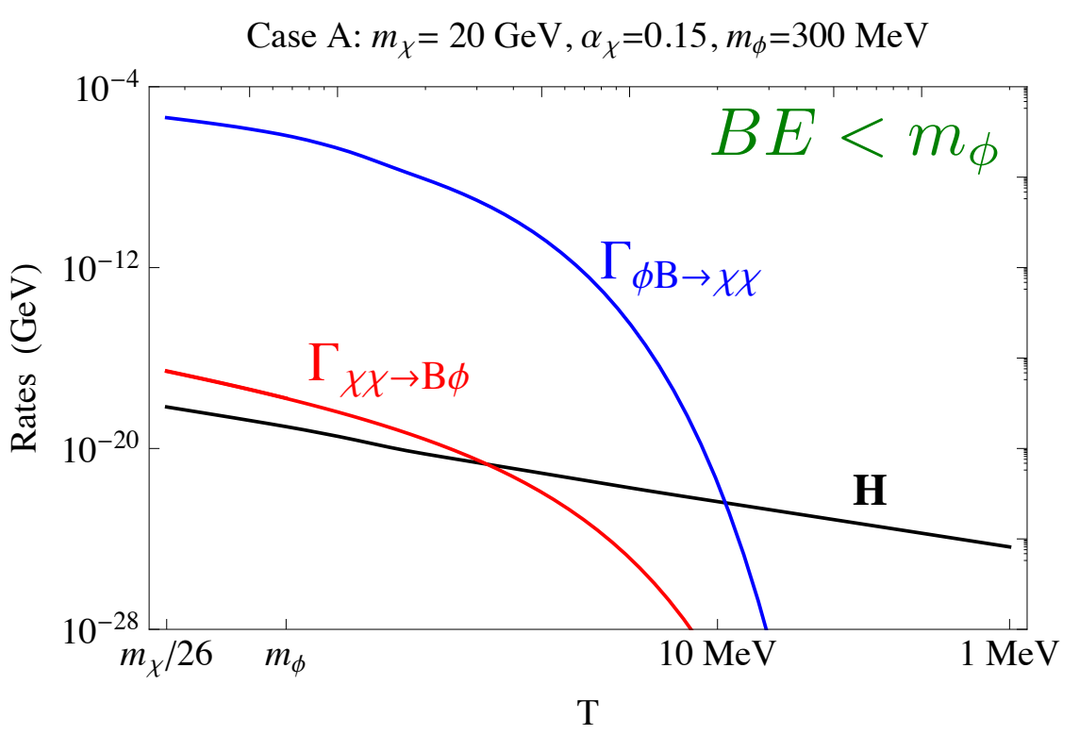
Production in early universe

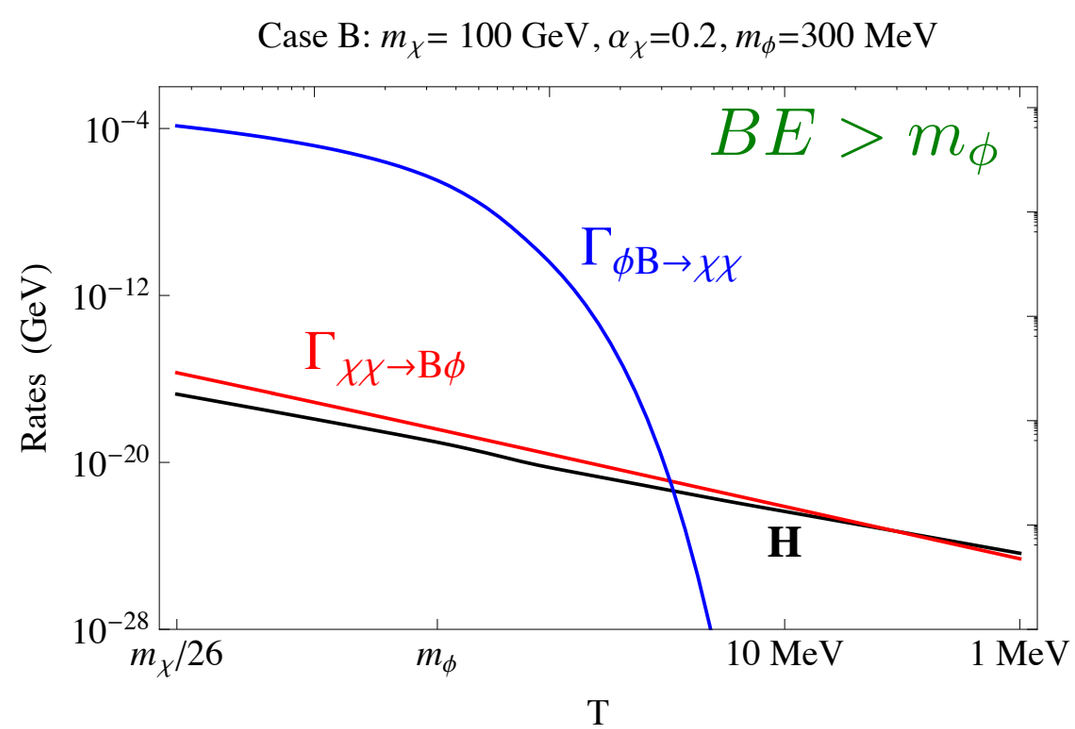
Bound state formation can happen

- shortly after freeze out if an asymmetry in ϕ number is left over.



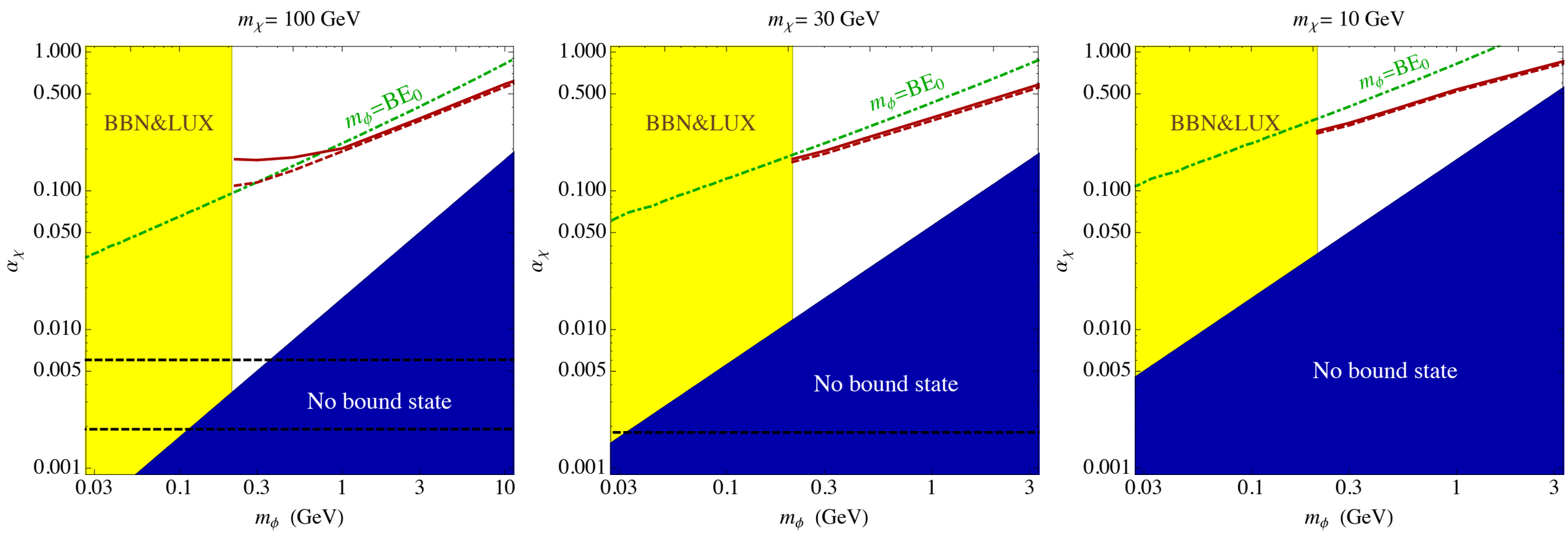
$$\int d^3x \psi_B^* \left(1 + \frac{\nabla^2}{m_\chi}\right) \psi_c(x) e^{i\mathbf{k}_\phi \mathbf{x}}$$





Wise, **Y.Z.**, arXiv:1407.4121, PRD

Production in early universe



Above red curve: bound state efficiently form in early universe

More bounds can form during non-linear structure growth.

Wise, **Y.Z.**, arXiv:1407.4121, PRD

Nuggets (N>>2)

Interaction through scalar exchange always attractive.

Consider bound states with N>>2, nuggets.

Degenerate Fermi gas picture

When $N < \alpha_\chi^{-3/2}$, scaling in non-relativistic regime

$$KE \sim \frac{N^{5/3}}{R^2 m_\chi}, \quad PE \sim -\frac{\alpha_\chi N^2}{R} \qquad \Rightarrow R \sim \frac{1}{\alpha_\chi m_\chi N^{1/3}}$$

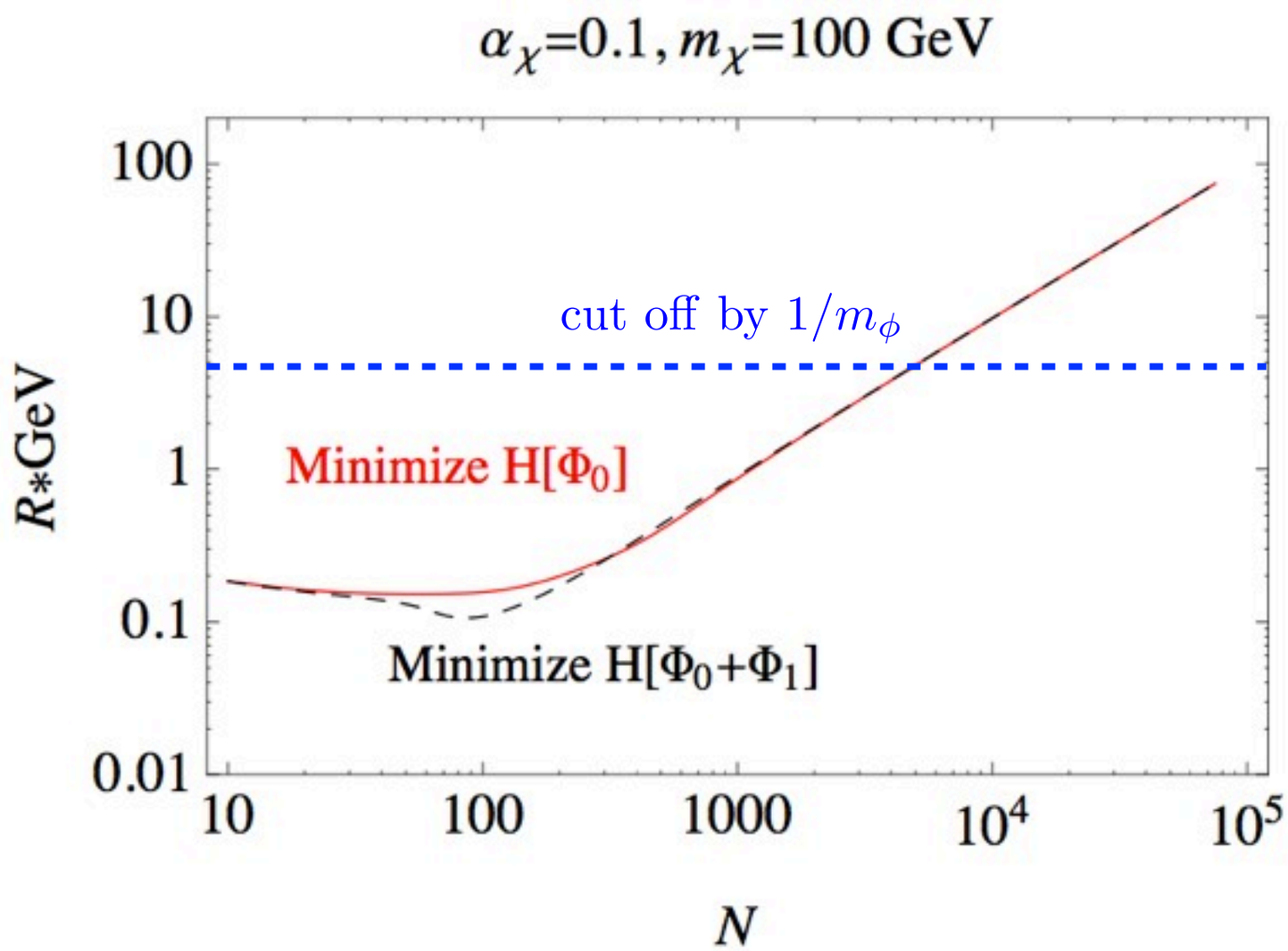
this regime similar to degenerate star

Yukawa force gets weaker when relativistic

$$\nabla^2 \phi(x) = g_\chi \sum_i \delta^3(x - x_i) \frac{m_\chi + g_\chi \phi(x_i)}{\sqrt{p_i^2 + (m_\chi + g_\chi \phi(x_i))^2}} \qquad \Rightarrow R \sim \frac{N}{\alpha m_\chi}$$

Wise, **Y.Z.**, to appear

Nuggets (N>>2)



very heavy bound states allowed

General behavior of bound states from Yukawa theory -- may have applications other than dark matter .

Wise, **Y.Z.**, to appear

Applications to DM

Example of supermassive DM can have a thermal history.

Direct detection: $n_\chi \sim \frac{1}{N_\chi}$

$\sigma v \sim N_\chi^2$ when $qR \ll 1$

only excite near Fermi surface

if $qR \gg 1$

Accretion inside the neutron star, Yukawa interaction.

To solve structure problem with self-interaction?

the story may change in case of bound states

dissipation may cause new problems.

Wise, **Y.Z.**, to appear

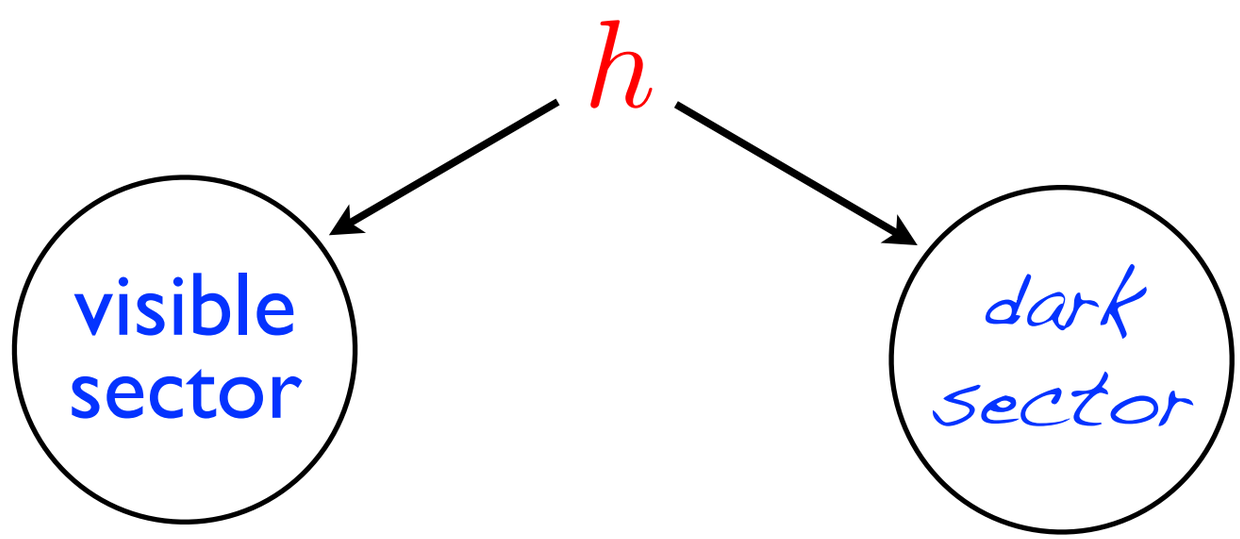
Summary

UV complete Higgs portal to Fermionic DM with ϕ

Attractive interaction $\Leftrightarrow$ Stable bound states

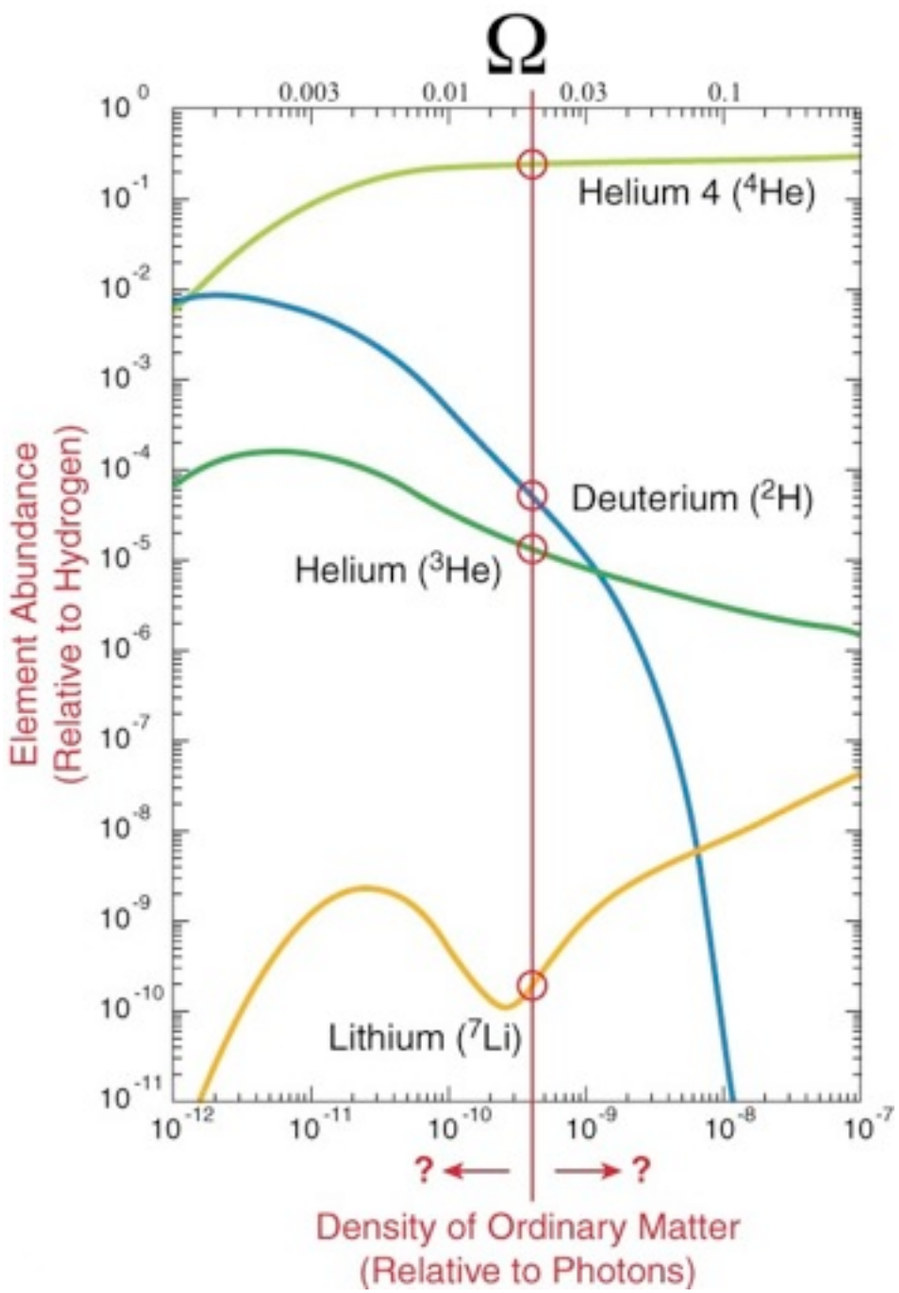
$$n_{\rm DM} = n_\chi \quad n_{\bar{\chi}} \simeq 0$$

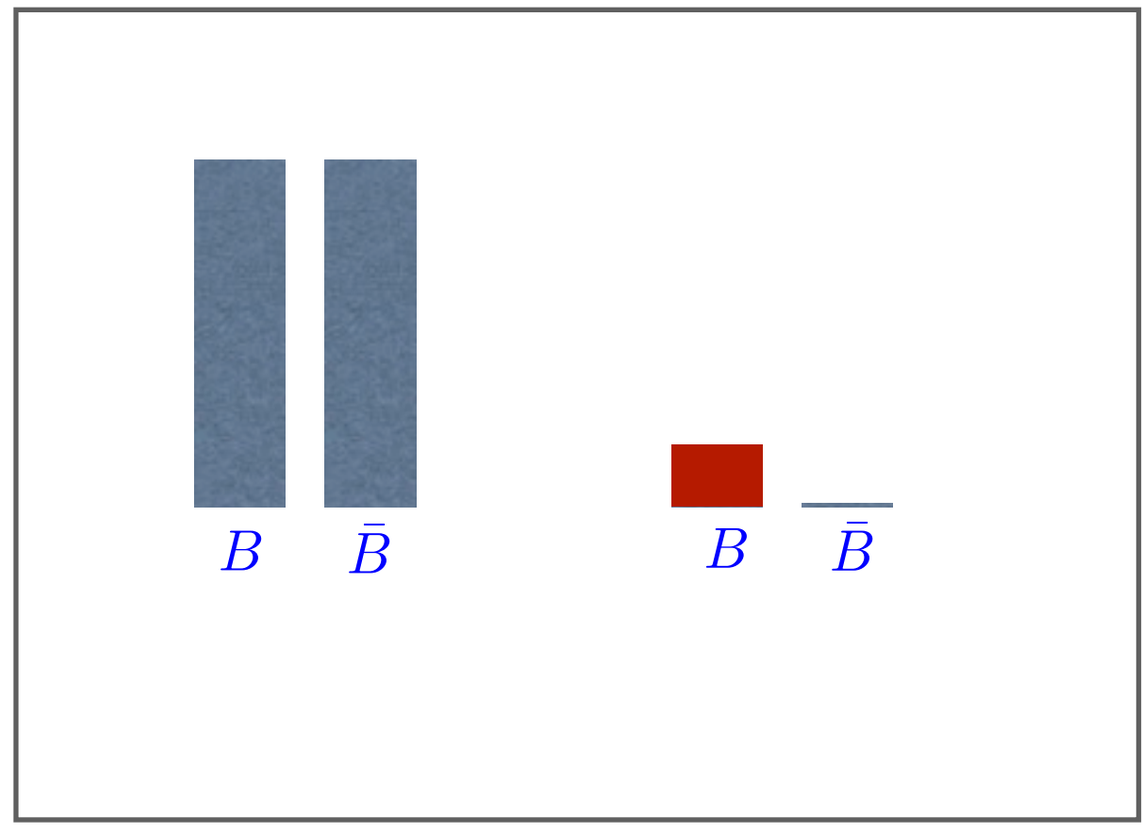
Higgs could be the Key to generate initial asymmetries in both dark matter and baryons



Cogenesis

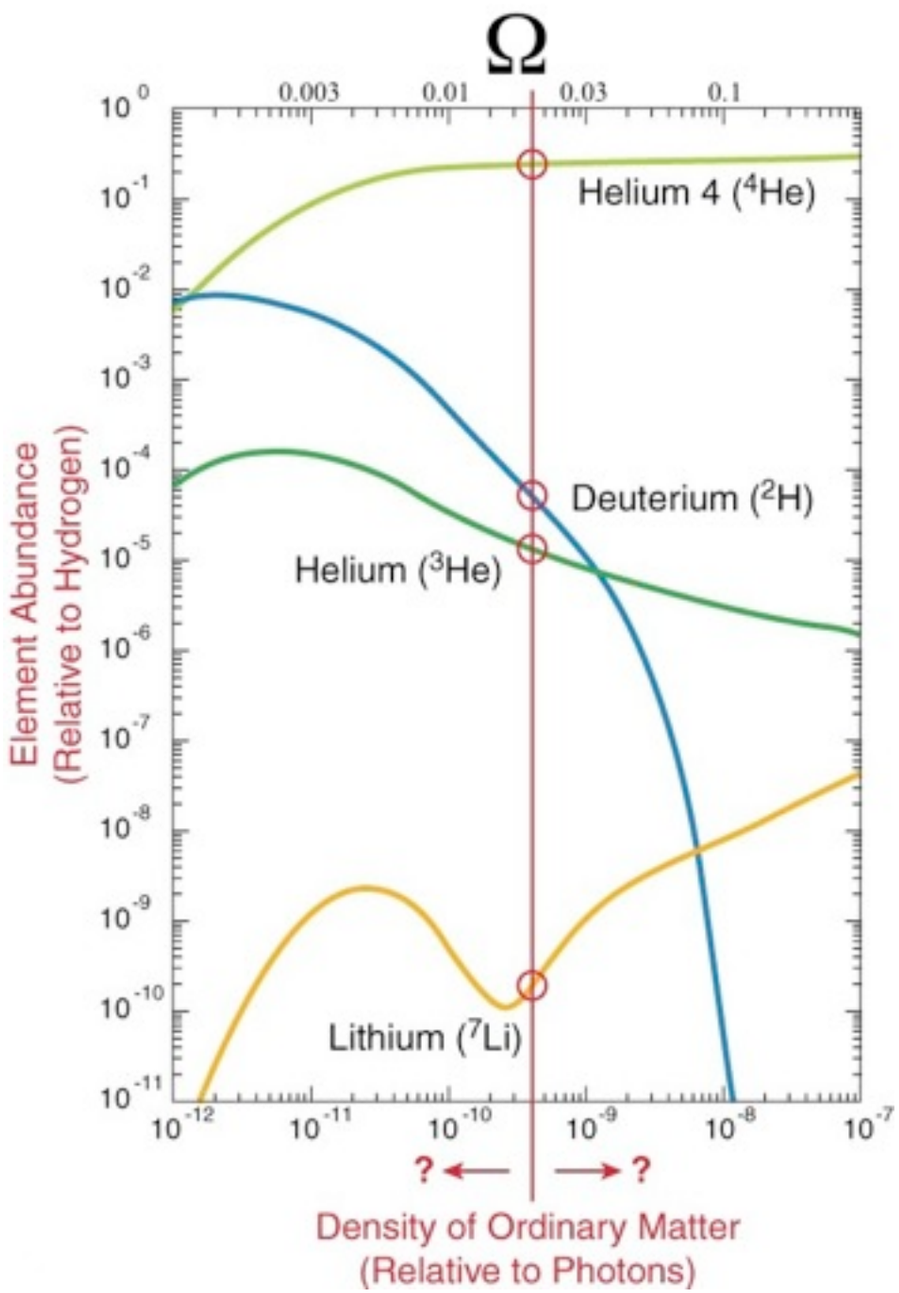
Baryon asymmetric universe

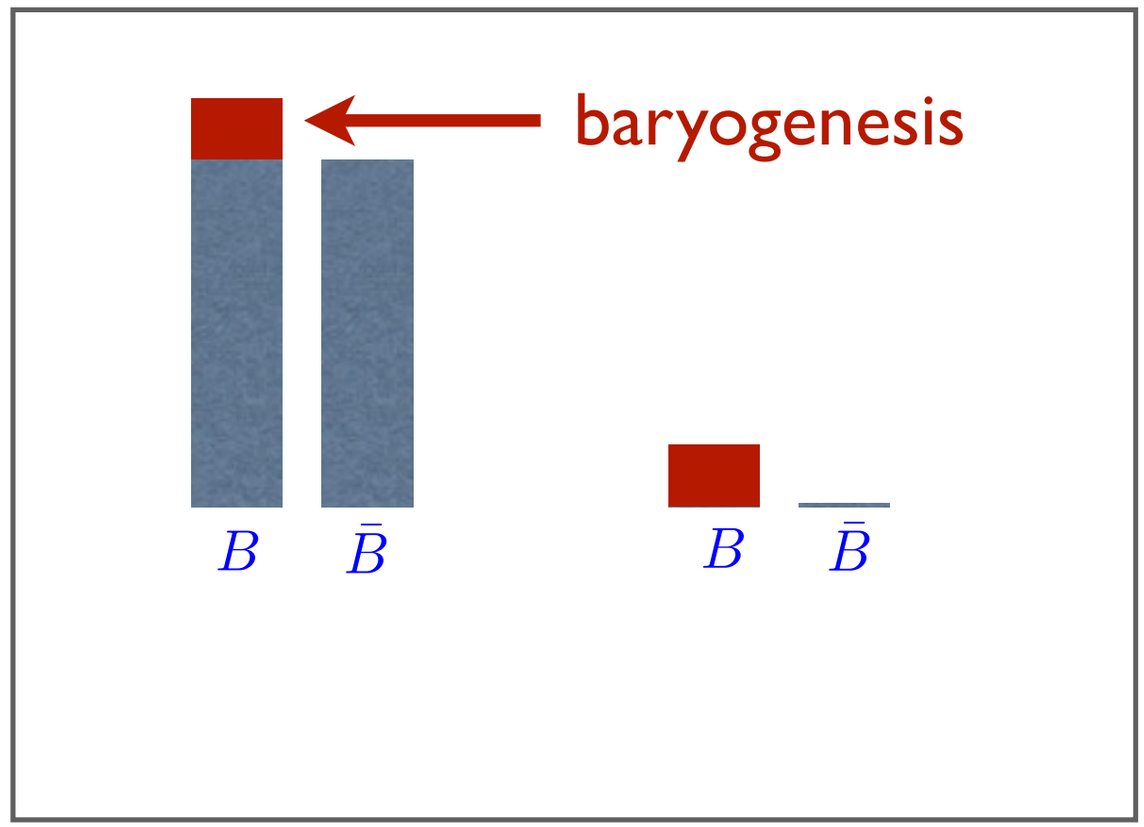




WMAP-9 $\frac{n_b}{n_\gamma} \simeq 6 \times 10^{-10}, \quad n_{\bar{b}} \approx 0$

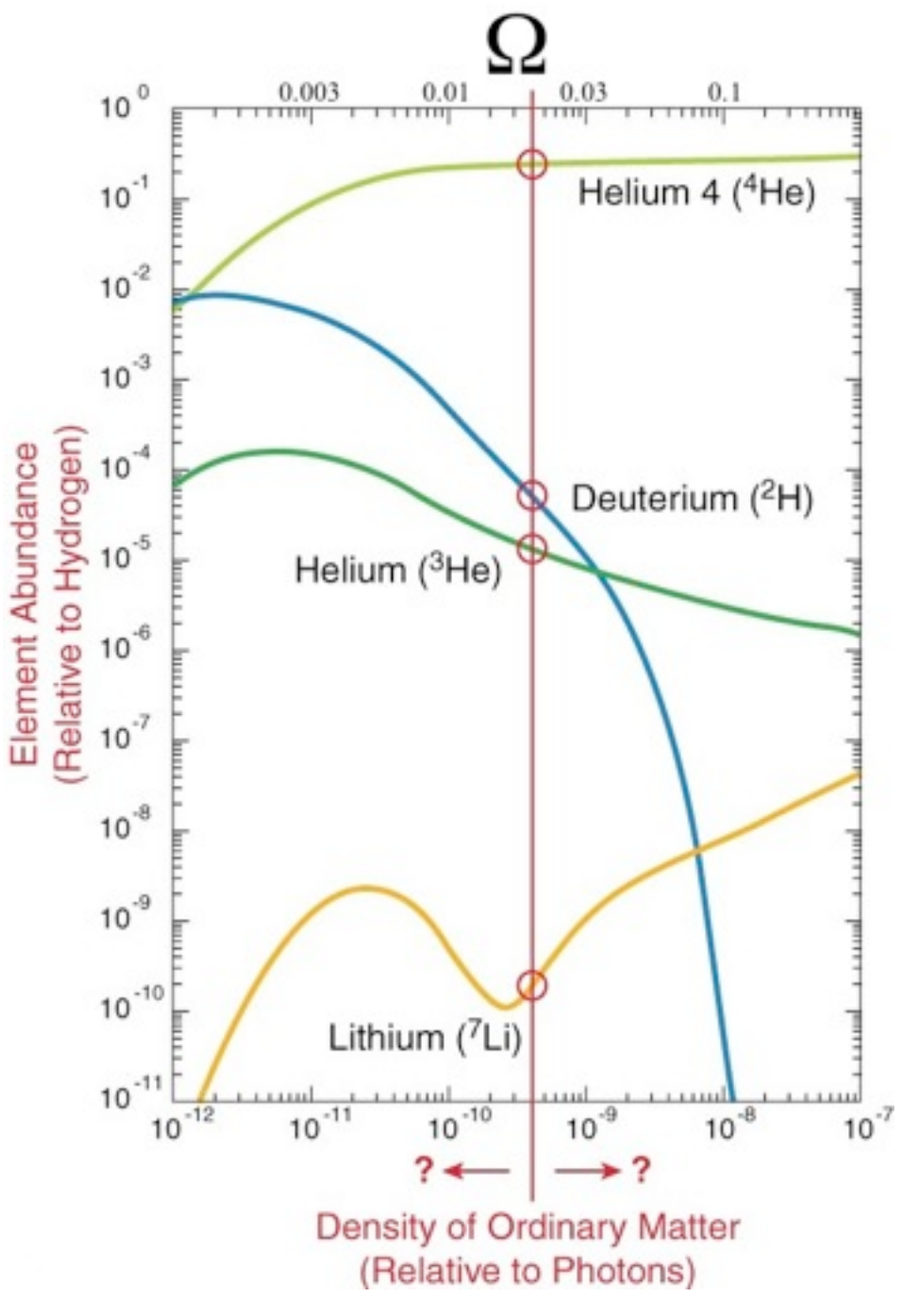
Baryon asymmetric universe

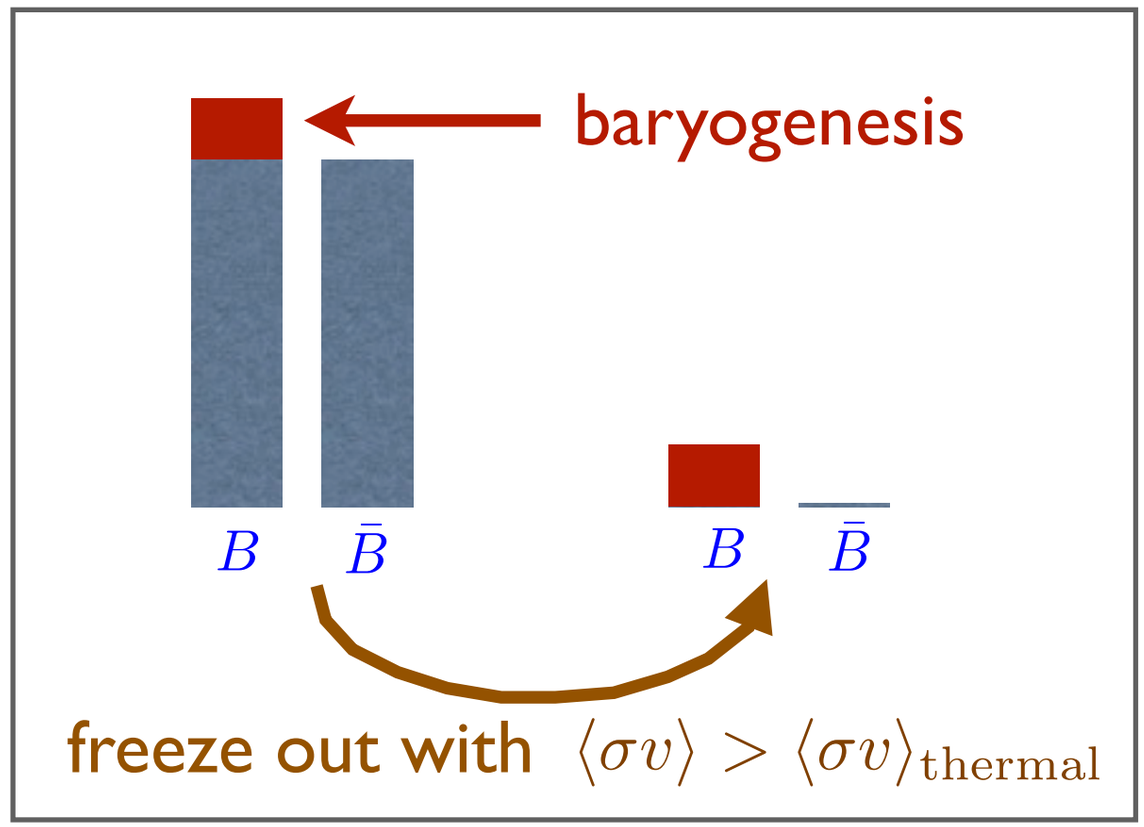




WMAP-9 $\frac{n_b}{n_\gamma} \simeq 6 \times 10^{-10}, \quad n_{\bar{b}} \approx 0$

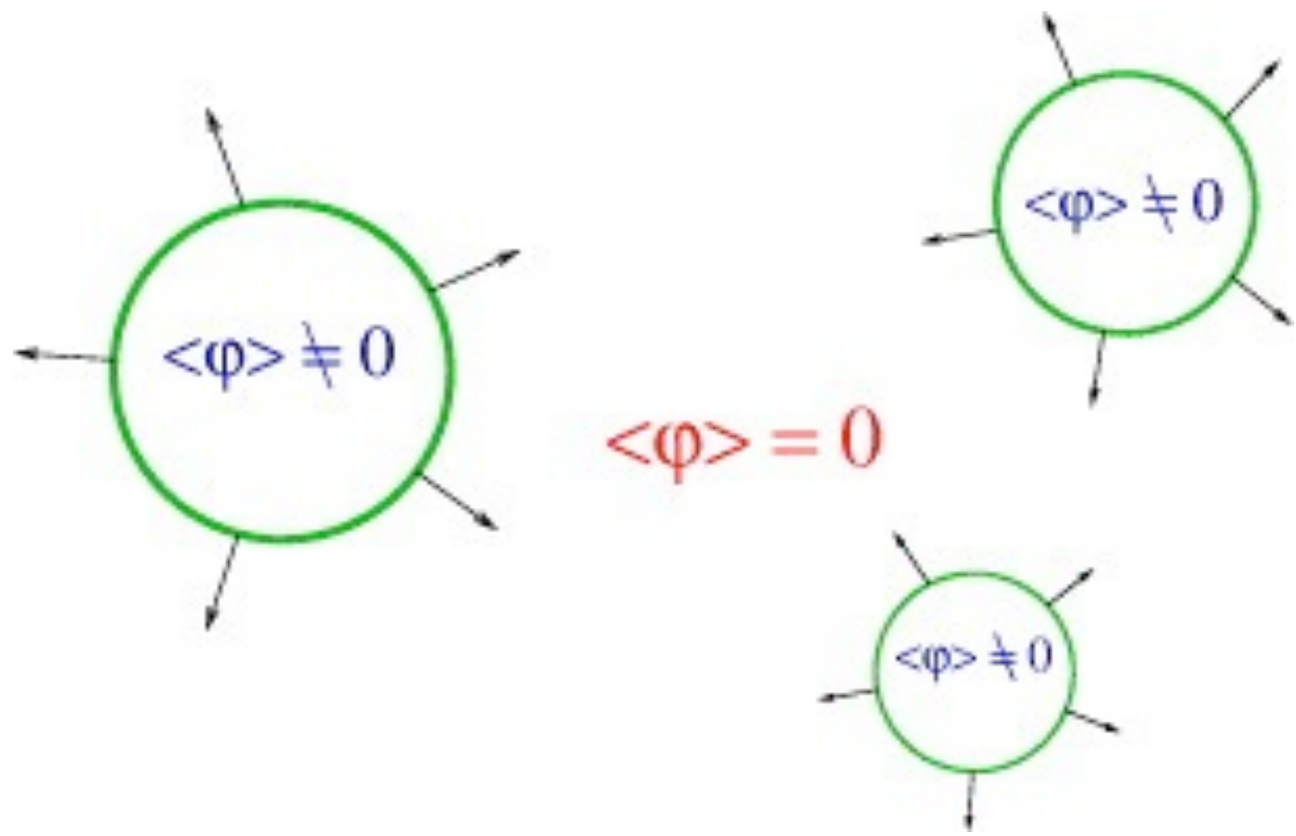
Baryon asymmetric universe





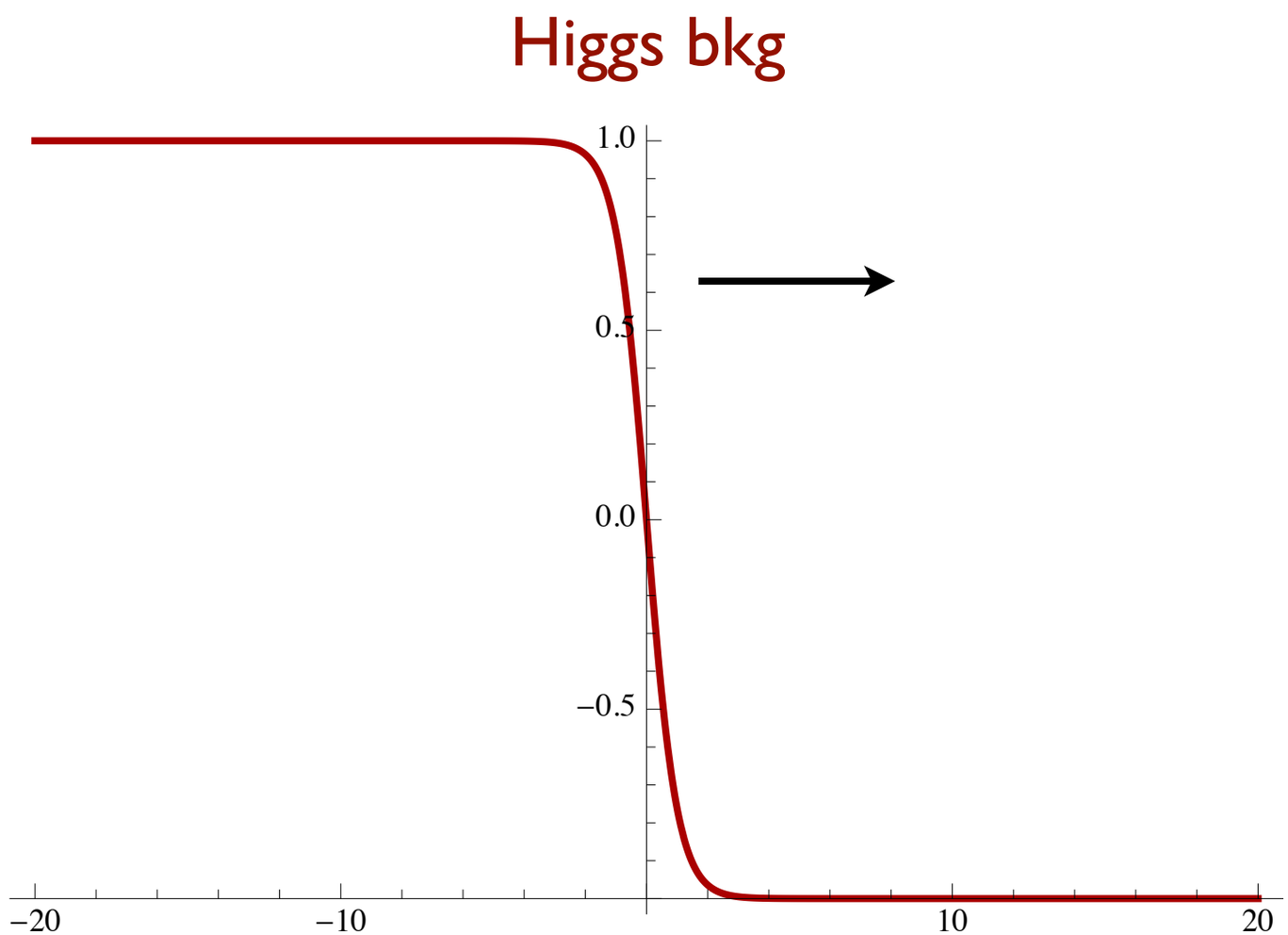
WMAP-9 $\dfrac{n_b}{n_\gamma} \simeq 6 \times 10^{-10}, \quad n_{\bar{b}} \approx 0$

Electroweak baryogenesis



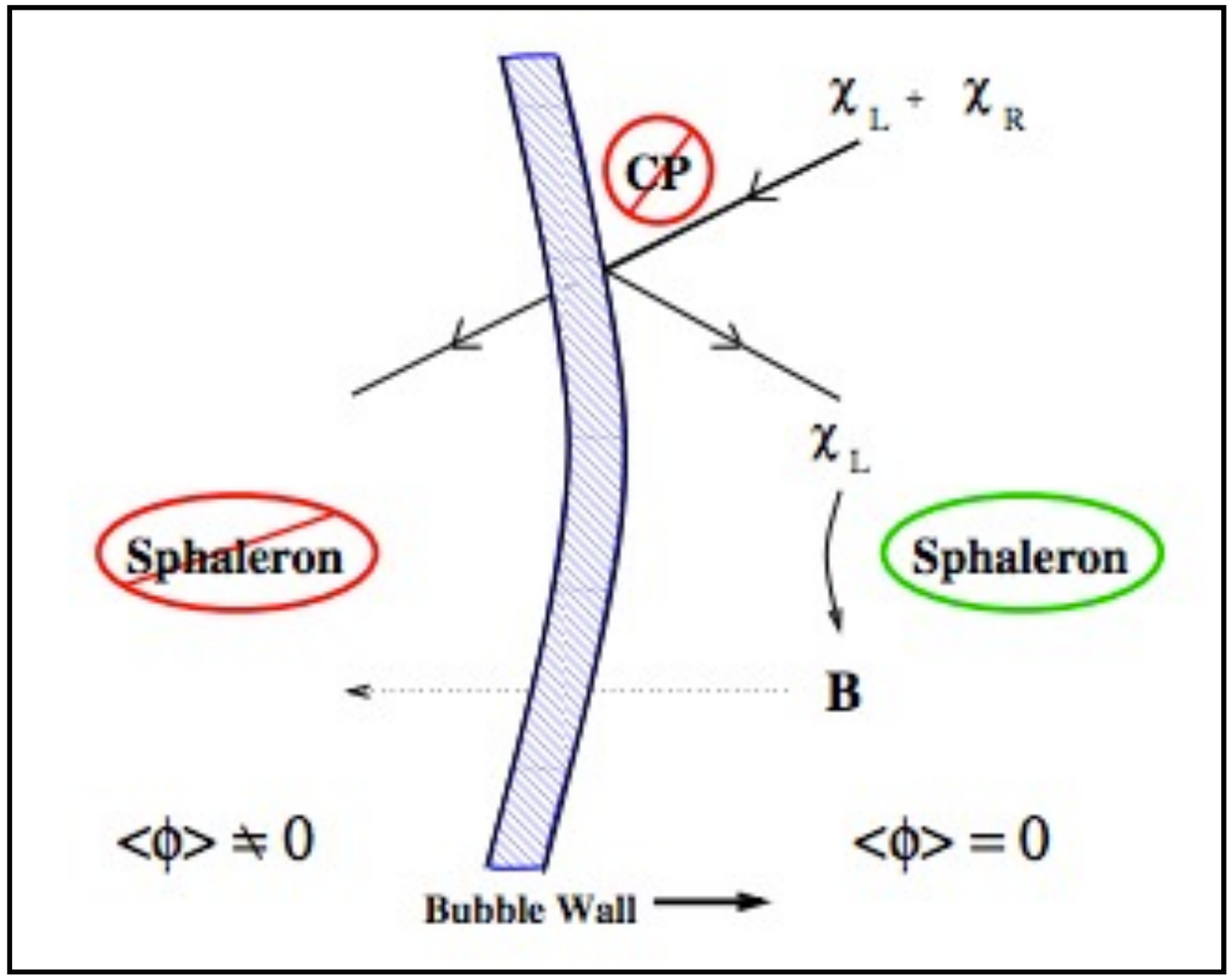
- B-L violation from EW sphaleron, controlled by Higgs VEV.
- Simplest scenario: time dependent ξ d.o.f. from a two Higgs doublet model.

Electroweak baryogenesis



- B-L violation from EW sphaleron, controlled by Higgs VEV.
- Simplest scenario: time dependent ξ d.o.f. from a two Higgs doublet model.

Electroweak baryogenesis



- B-L violation from EW sphaleron, controlled by Higgs VEV.
- Simplest scenario: time dependent ξ d.o.f. from a two Higgs doublet model.

Electroweak baryogenesis

Two Higgs doublet model $\mathcal{L}_Y = \bar{Q} Y_U (i\tau_2)\phi_2^* U + \bar{Q} Y_d \phi_1 D$

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v\cos\beta/\sqrt{2} \end{pmatrix}, \ \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi}/\sqrt{2} \end{pmatrix}$$

spacetime dependent during EWPT

Electroweak baryogenesis

Two Higgs doublet model $\mathcal{L}_Y = \bar{Q} Y_U (i\tau_2)\phi_2^* U + \bar{Q} Y_d \phi_1 D$

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v\cos\beta/\sqrt{2} \end{pmatrix}, \ \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi}/\sqrt{2} \end{pmatrix}$$

spacetime dependent during EWPT

on the bubble wall

$$\mathcal{L} \sim y_t \bar{t}_L v e^{i\xi} t_R + \text{h.c.}$$

$$\downarrow$$

$$y_t v \bar{t} t + (\partial_\mu \xi)\bar{t}\gamma_5\gamma^\mu t$$

$$\downarrow$$

$$n_{t_L} - n_{\bar{t}_R} \neq 0$$

source term in Boltzmann eqn's

Electroweak baryogenesis

Two Higgs doublet model $\mathcal{L}_Y = \bar{Q} Y_U (i\tau_2)\phi_2^* U + \bar{Q} Y_d \phi_1 D$

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v\cos\beta/\sqrt{2} \end{pmatrix}, \ \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi}/\sqrt{2} \end{pmatrix}$$

spacetime dependent during EWPT

on the bubble wall

$$\mathcal{L} \sim y_t \bar{t}_L v e^{i\xi} t_R + \text{h.c.}$$

$$y_t v \bar{t} t + (\partial_\mu \xi)\bar{t}\gamma_5\gamma^\mu t$$

$$n_{t_L} - n_{\bar{t}_R} \neq 0$$

Diffuse to front of bubble wall

B+L violation by EW sphaleron

$$\frac{n_{\rm B}}{s} \sim \alpha_w^4 \Delta\xi$$

source term in Boltzmann eqn's

Electroweak Cogenesis

- Observation: $\Omega_{\rm B} \sim \Omega_{\rm DM}$
- Conjecture: dark matter number also asymmetric.
- Same source of CPV (from CPV Higgs sector) also couples to a DM current

$$\mathcal{L} \sim (\partial_\mu \xi)(J^\mu_{\rm DM} + J^\mu_{\rm B-L})$$

- Theory must have two global symmetries

$$U(1)_{\rm B-L} \qquad U(1)_{\rm DM}$$

both broken at EW scale, restored afterwards.

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

The minimal model

Dark sector

Two SM singlets, oppositely charged under the $U(1)_{\rm DM}$

$$\mathcal{L} = \lambda \phi_1^\dagger \phi_2 S X + \text{h.c.} \sim \lambda\ v e^{i\xi}\ S\ X + \text{h.c.}$$

$$\downarrow$$

X dark matter

S partner/dark Higgs

$$n_X - n_{X^*} = n_{S^*} - n_S \neq 0$$

$$\frac{n_{\rm X}}{s} = -\frac{n_{\rm S}}{s} \sim |\lambda|^2 \Delta\xi$$

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

The minimal model

Dark sector

Two SM singlets, oppositely charged under the $U(1)_{\rm DM}$

$$\mathcal{L} = \lambda \phi_1^\dagger \phi_2 S X + \text{h.c.} \sim \lambda\ v e^{i\xi}\ S\ X + \text{h.c.}$$

X dark matter

S partner/dark Higgs

$$n_X - n_{X^*} = n_{S^*} - n_S \neq 0$$

$$\frac{n_X}{s} = -\frac{n_S}{s} \sim |\lambda|^2 \Delta\xi$$

Control the $U(1)_{\rm DM}$ breaking with the dark Higgs vev.

$$M_s^2 |S|^2 + \lambda_s |S|^4 \to \left(M_s^2 + \lambda_s |\langle S \rangle|^2\right) |S|^2 + \lambda_s \langle S^* \rangle^2 S^2$$

Majorana-like mass washes out asymmetry in S

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Order Parameters

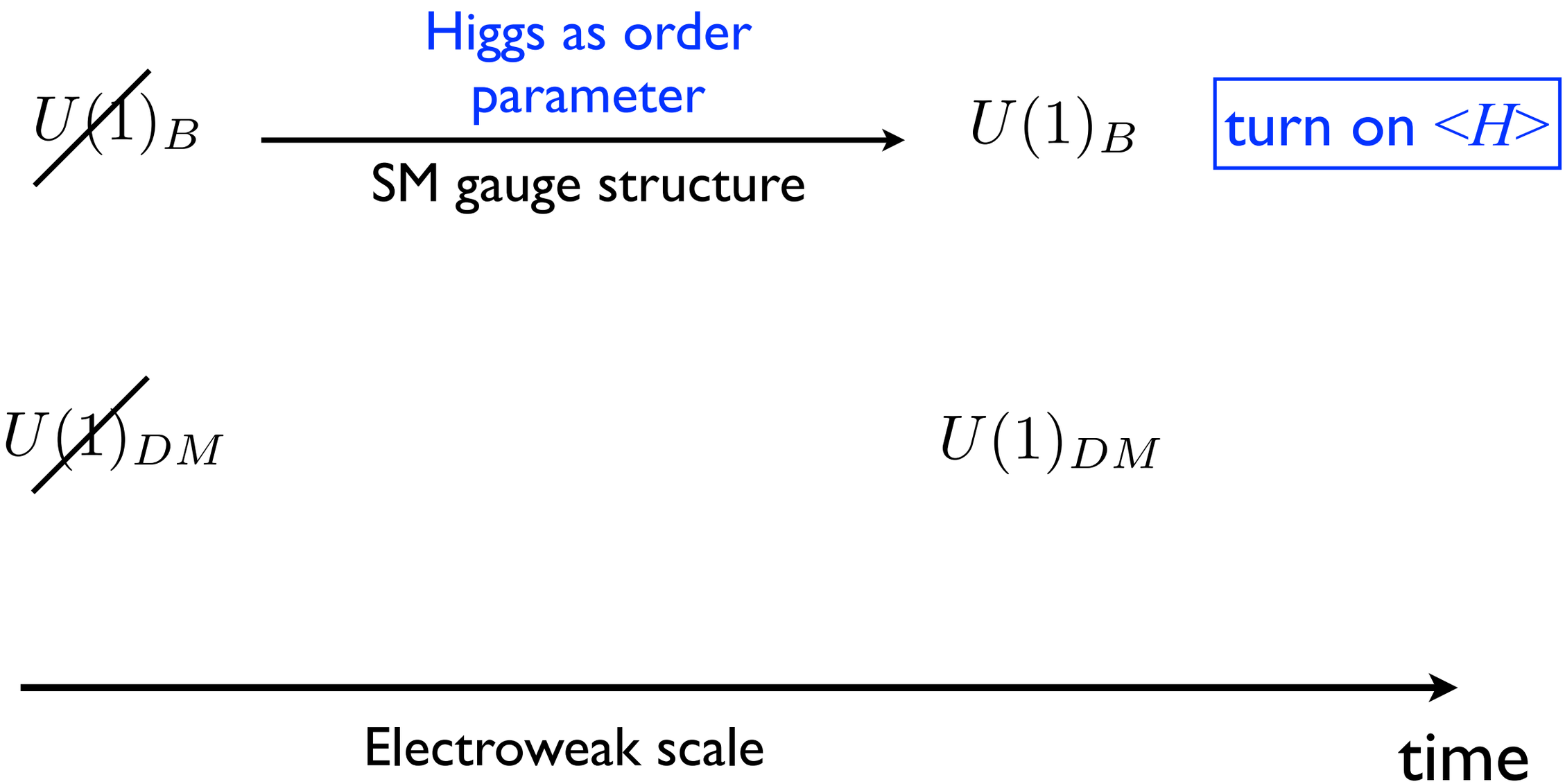
$\cancel{U(1)}_B$ $\qquad$ $U(1)_B$

$\cancel{U(1)}_{DM}$ $\qquad$ $U(1)_{DM}$

Electroweak scale $\longrightarrow$ time

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Order Parameters



Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Order Parameters

$\cancel{U(1)}_B$ —— Higgs as order parameter / SM gauge structure ——→ $U(1)_B$ $\boxed{\text{turn on } \langle H \rangle}$

$\cancel{U(1)}_{DM}$ —— New order parameter / Dark Higgs S ——→ $U(1)_{DM}$ $\boxed{\text{turn off } \langle S \rangle}$

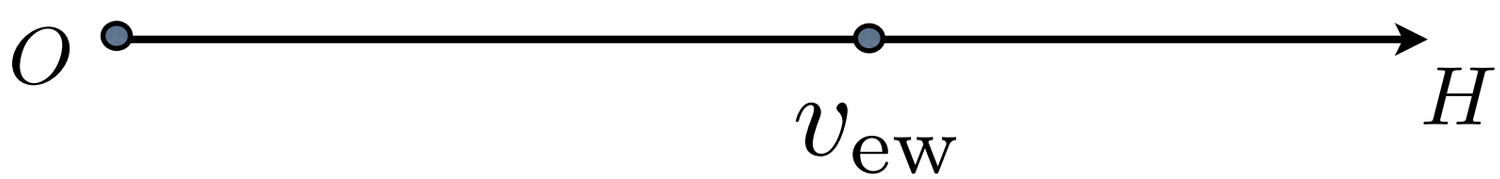
Electroweak scale ——→ time

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Restore two symmetries

In a single step

Electroweak phase transition

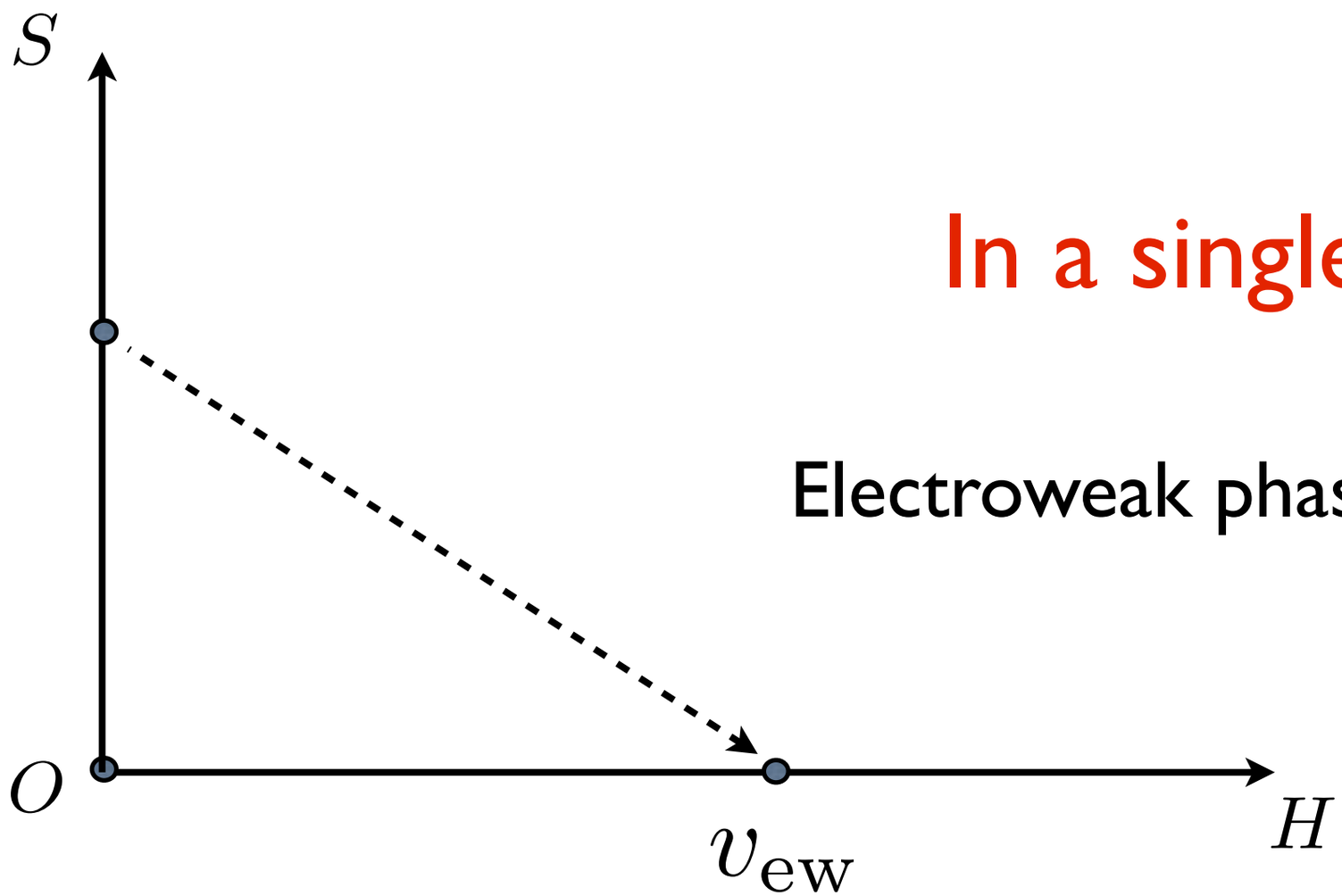


$$m_h^2(T) \sim -\mu_h^2 + 3\lambda h^2 + \frac{T^2}{12}(\lambda + g^2 + y_t^2 + \cdots)$$

$$m_s^2(T) \sim -\mu_s^2 + 3\lambda_s s^2 + \frac{T^2}{12}(\lambda_s + \cdots)$$

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Restore two symmetries



In a single step

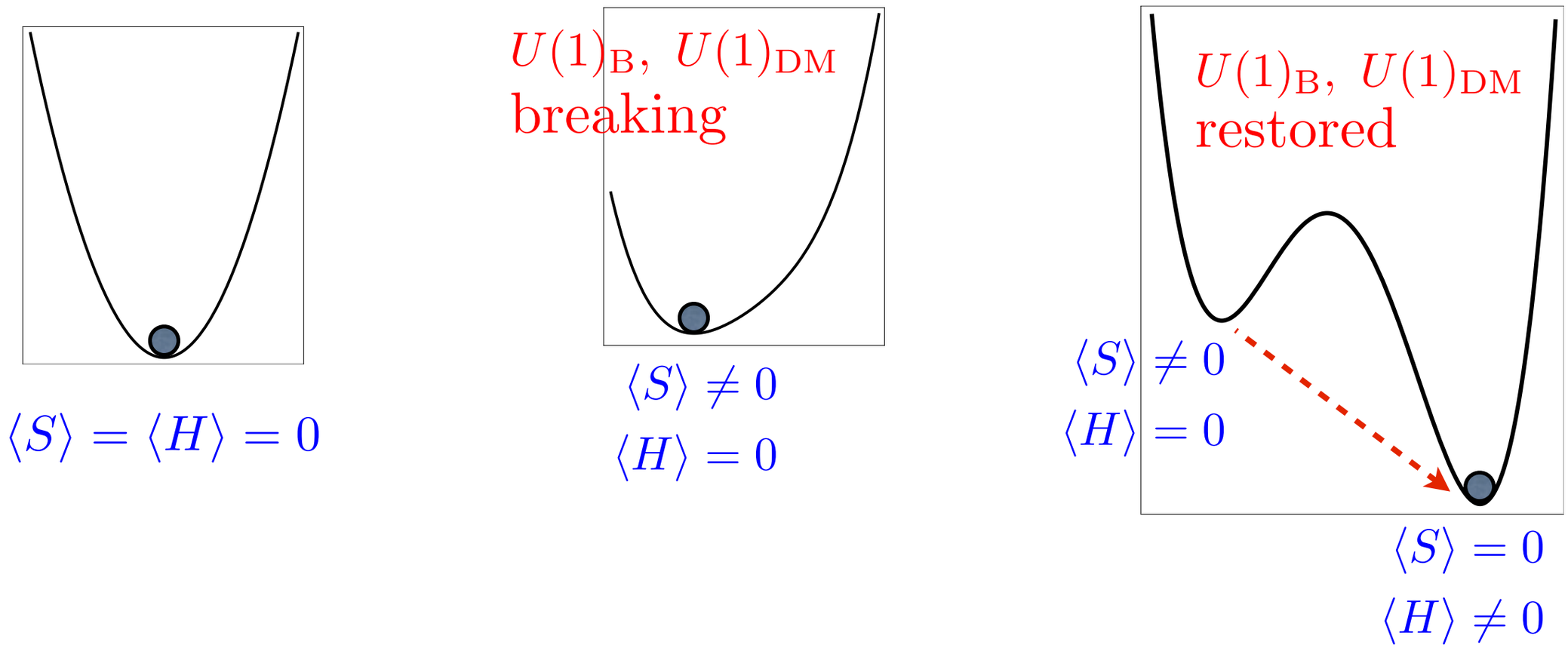
Electroweak phase transition

$$m_h^2(T) \sim -\mu_h^2 + 3\lambda h^2 + \frac{T^2}{12}(\lambda + g^2 + y_t^2 + \cdots)$$

$$m_s^2(T) \sim -\mu_s^2 + 3\lambda_s s^2 + \frac{T^2}{12}(\lambda_s + \cdots)$$

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

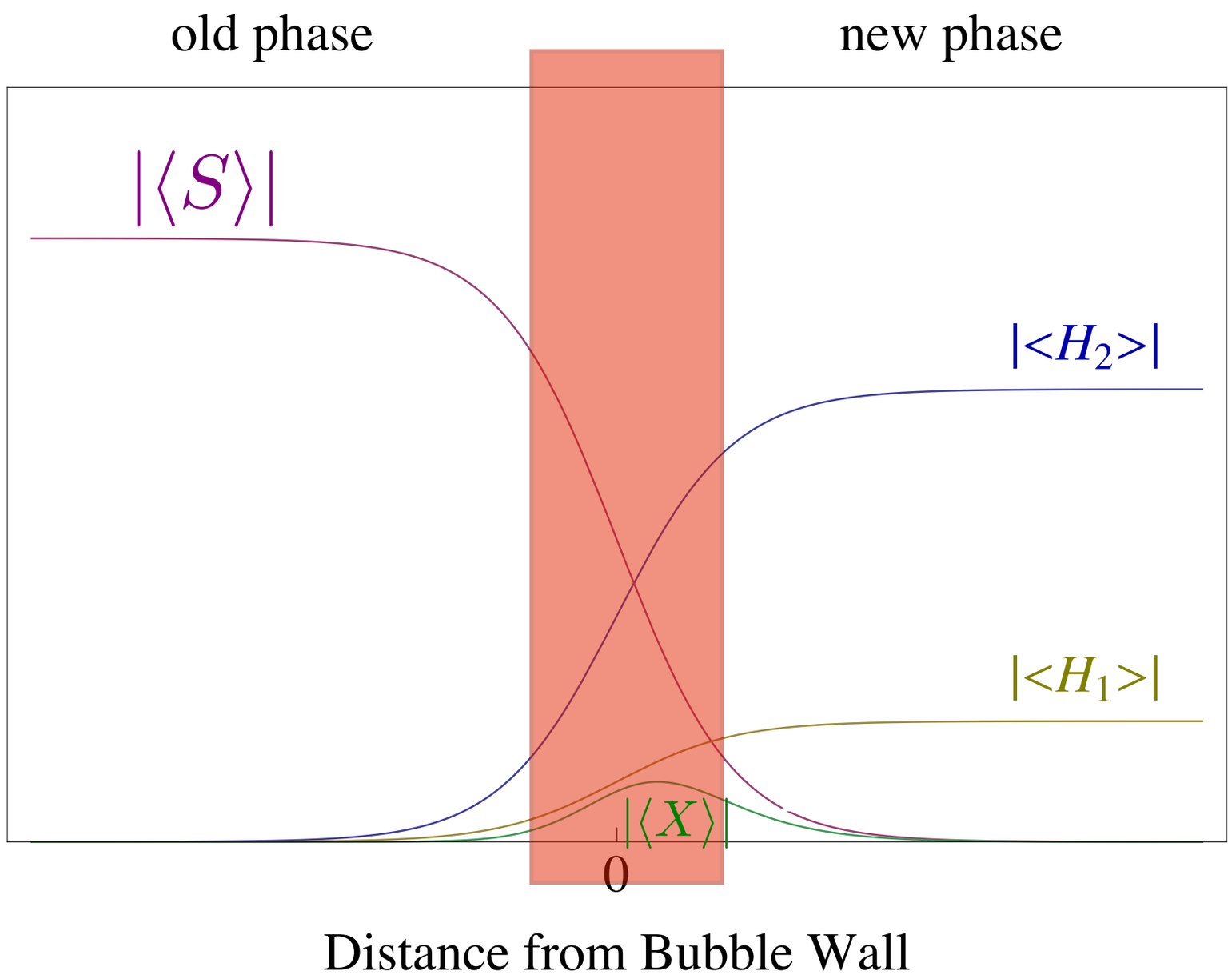
History of symmetries



- Dark matter sector helps triggering strong first order EW phase transition.
- No effect on Higgs coupling to fermions/gauge bosons.

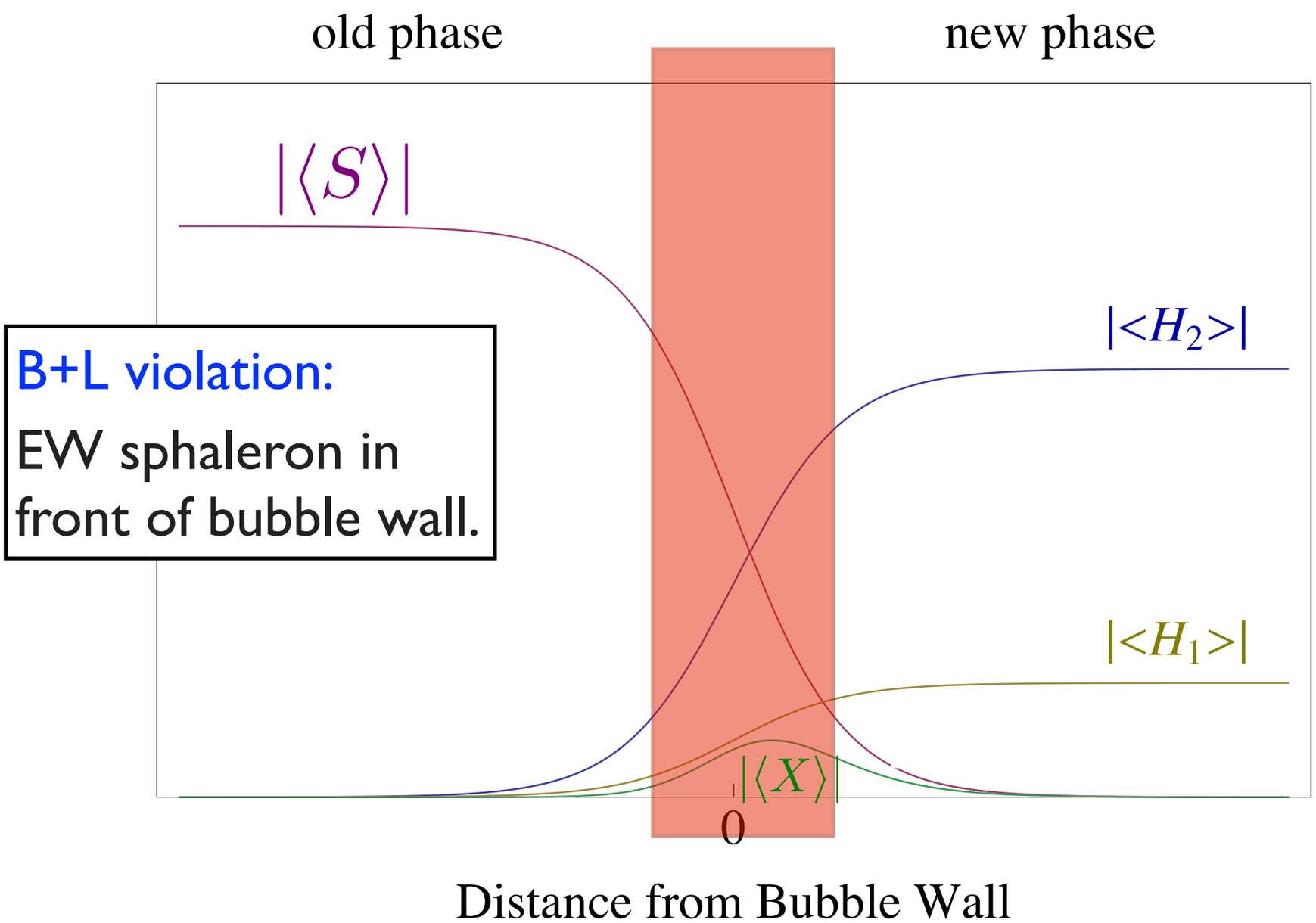
Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

The cogenesis picture



Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

The cogenesis picture

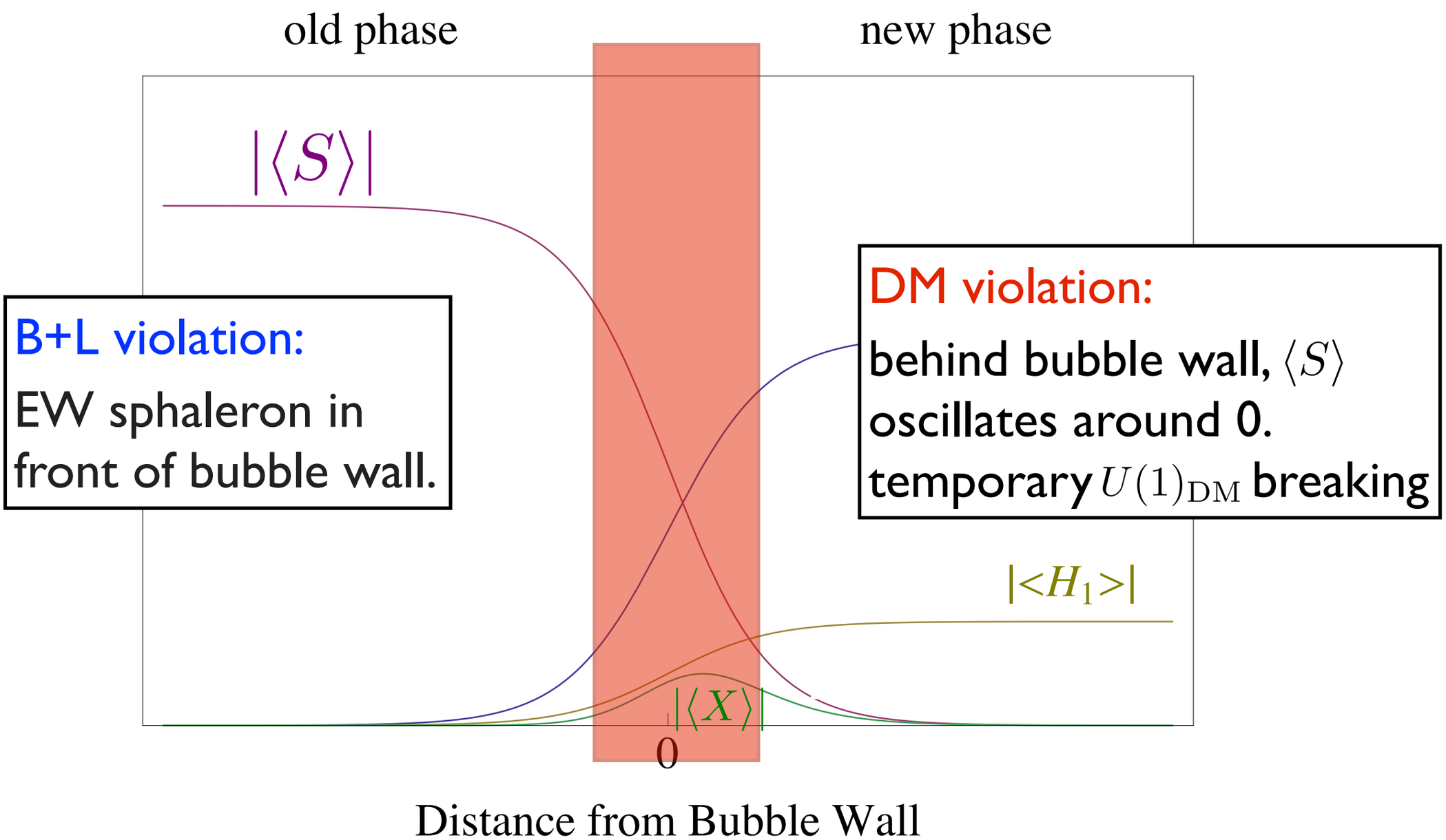


B+L violation:

EW sphaleron in front of bubble wall.

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

The cogenesis picture

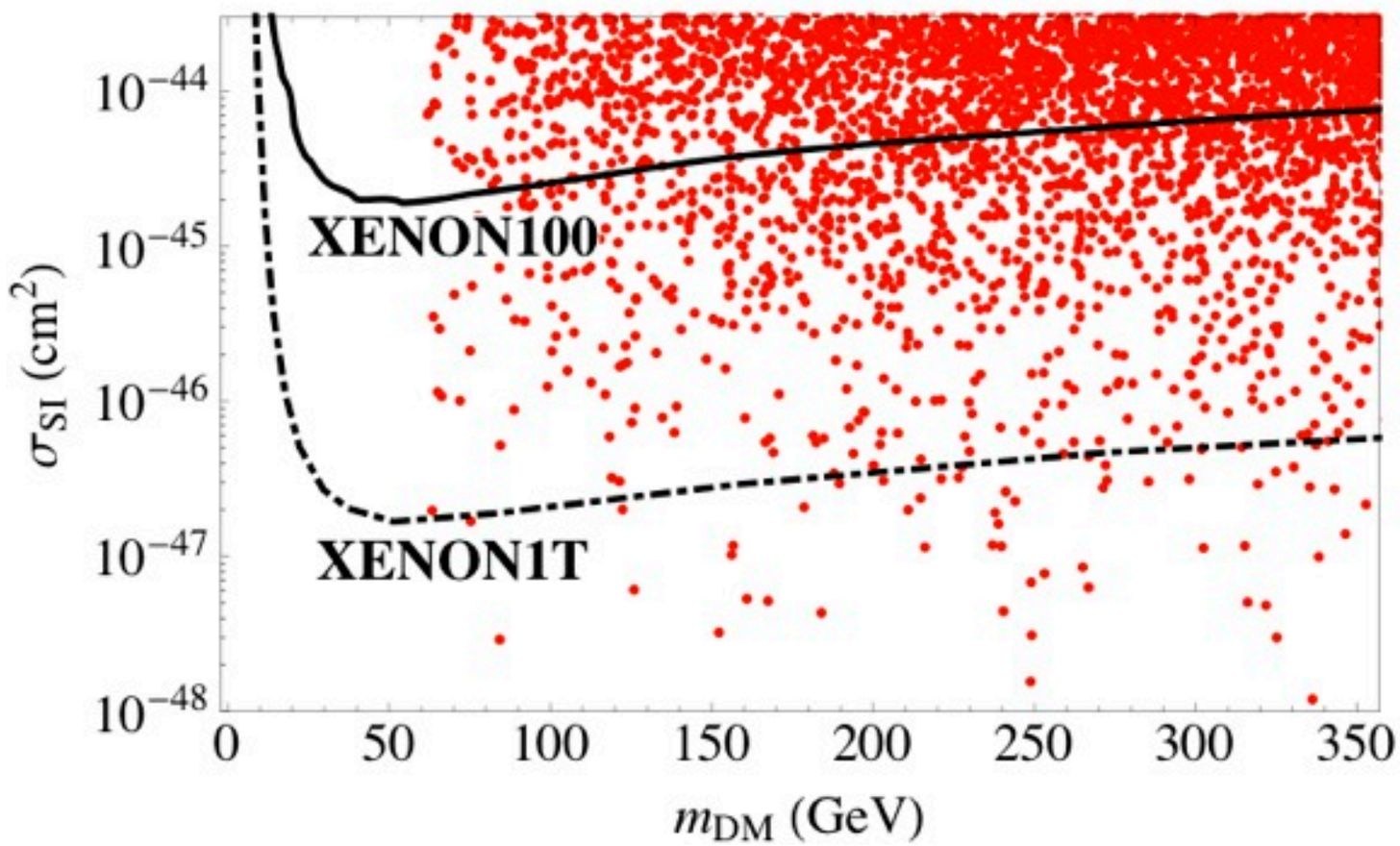


Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Final relic densities

Strong annihilation via two-Higgs portal

$$\lambda_{X1}|X|^2|\phi_1|^2 + \lambda_{X2}|X|^2|\phi_2|^2$$



$\Omega_B \sim \alpha_w^4 \Delta\xi, \quad \Omega_{DM} \sim |\lambda|^2 \Delta\xi$ $\quad \frac{\Omega_{DM}}{\Omega_B} \sim 5$ requires $\lambda \sim 10^{-3}$

Cheung, **Y.Z.**, arXiv:1306.4321, JHEP

Impact on Higgs physics

- The absolute value of asymmetries depends on $\Delta\xi$;
  Studies of 2HDM EW phase transitions showed $\Delta\xi \sim \xi$

Dorsch, Huber, No, 1305.6610; Fromme, Huber, Seniuch, hep-ph/0605242

Exciting connection early universe and Higgs physics today.

- Higgs boson as a mixture of CP even and odd components.

$$\mathcal{L} = \frac{m_f}{v}\bar{f}(v + c_f h + \tilde{c}_f i\gamma_5 h)f + \frac{M_W^2}{v}(v + 2ah)W_\mu W^\mu$$

- Effective interactions

calculable

$$\mathcal{L}_{\text{eff}} = c_g h G^{a\mu\nu}G^a_{\mu\nu} + \tilde{c}_g h G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$
$$+ c_\gamma h F^{a\mu\nu}F^a_{\mu\nu} + \tilde{c}_\gamma h F^{a\mu\nu}\tilde{F}^a_{\mu\nu}$$

Higgs sector in 2HDM-II

Higgs couplings in CPV 2HDM

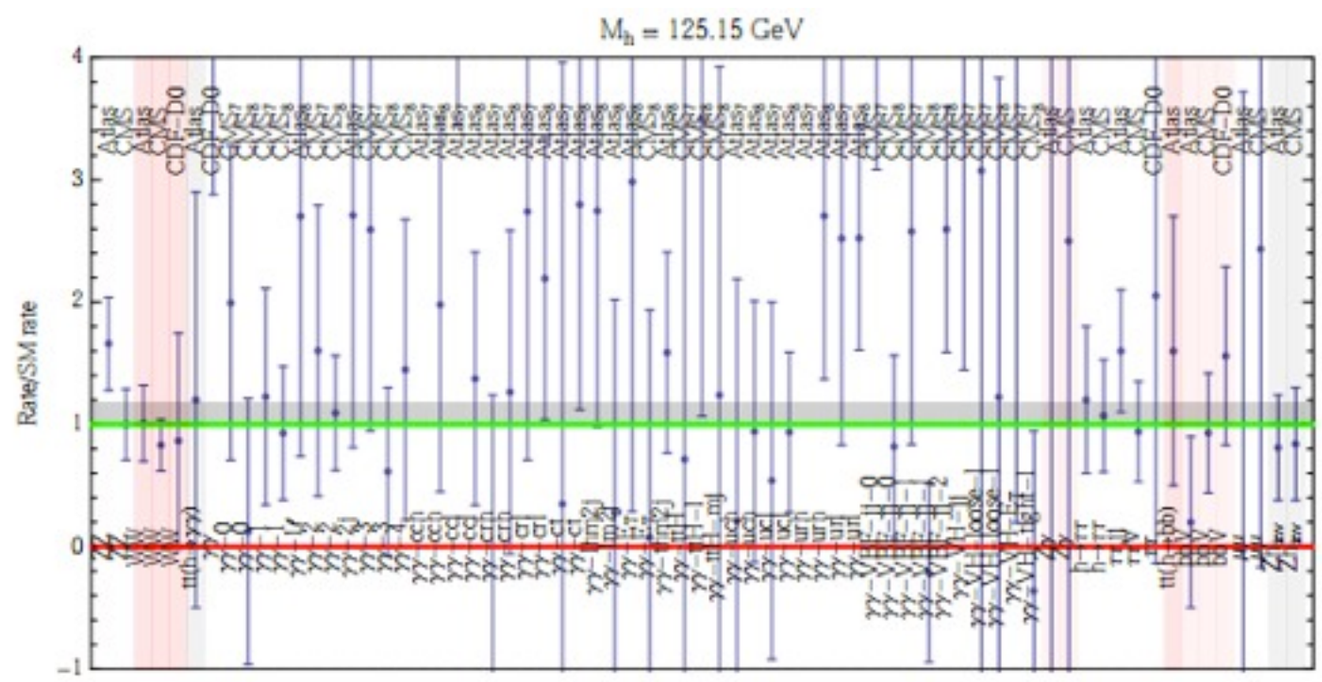
universal for all up/down type fermions

$$c_t = \frac{\cos\alpha\cos\alpha_b}{\sin\beta}, \quad c_b = -\frac{\sin\alpha\cos\alpha_b}{\cos\beta} \qquad a = \cos\alpha_b \sin(\beta-\alpha)$$

$$\tilde{c}_t = -\cot\beta\sin\alpha_b, \quad \tilde{c}_b = -\tan\beta\sin\alpha_b$$

CPV angles

$$\alpha_b,\ \alpha_c \sim \Delta\xi$$



SM limit

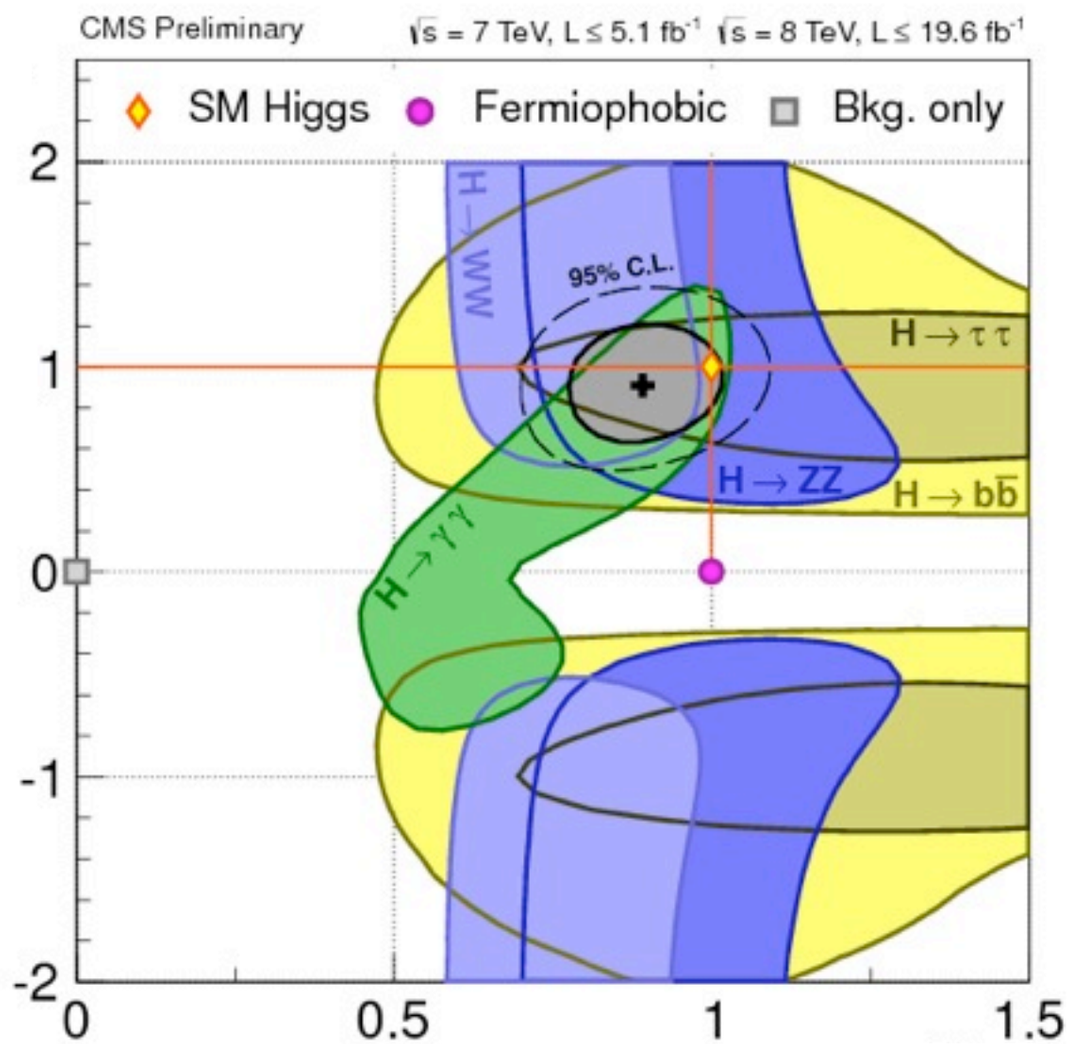
$$c_t = c_b = a = 1$$

$$\tilde{c}_t = \tilde{c}_b = 0$$

Recall $\mathcal{L} = \frac{m_f}{v}\bar{f}(v + c_f h + \tilde{c}_f i\gamma_5 h)f + \frac{M_W^2}{v}(v + 2ah)W_\mu W^\mu$

Higgs couplings

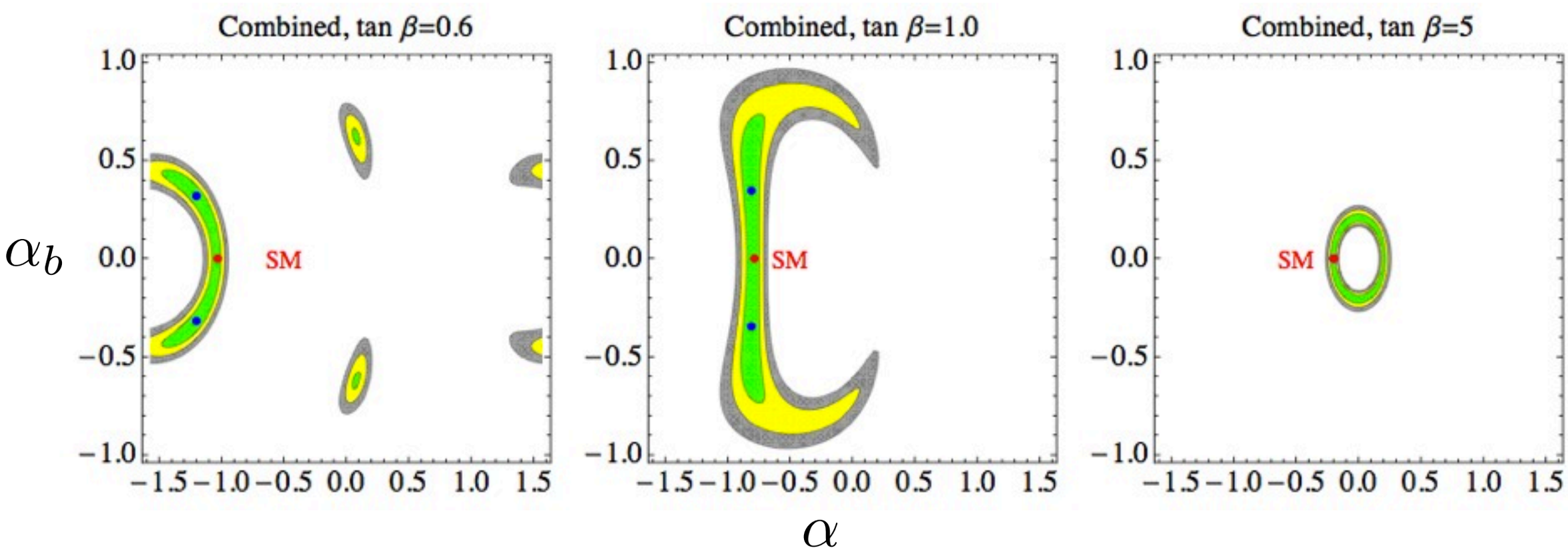
$c_t = c_b$



a

- Rescale existing couplings in SM. Overlooked the CP violating direction.
- I will show there is still sizable room for CPV.

Global Fit to Higgs data



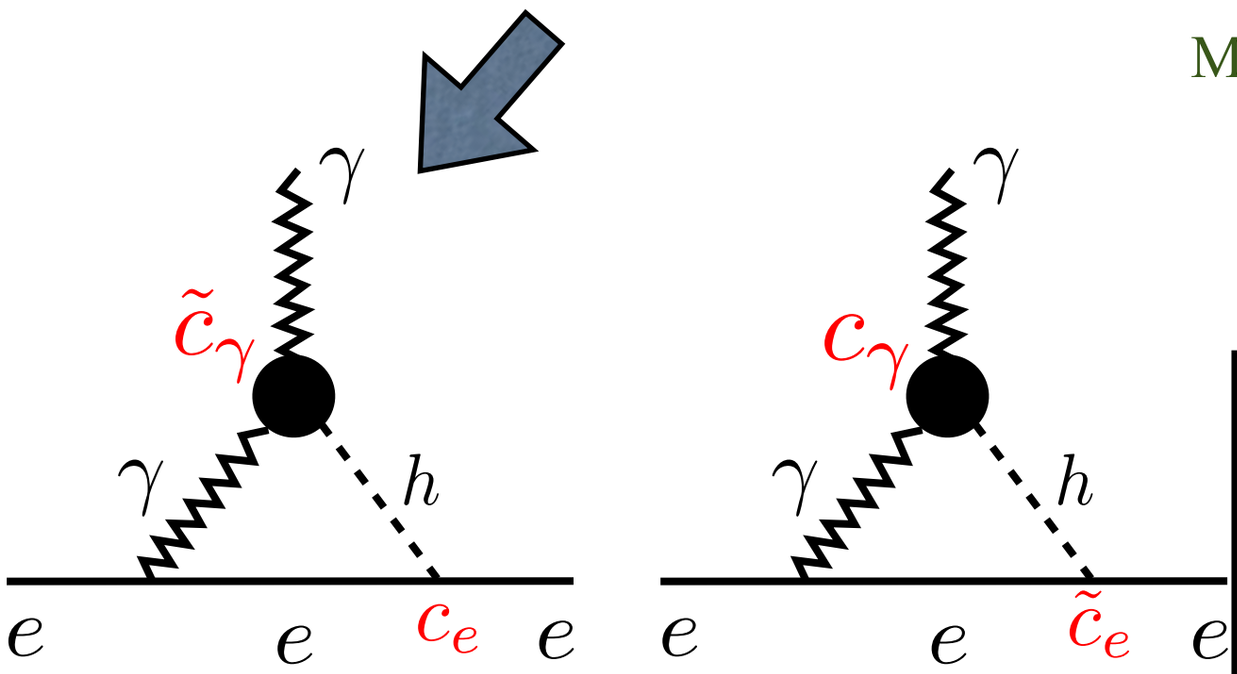
- Strong constraint on: $\alpha \approx \beta - \pi/2$ (alignment)
- Large room if turn on CPV in such limit and $\tan\beta \approx 1$

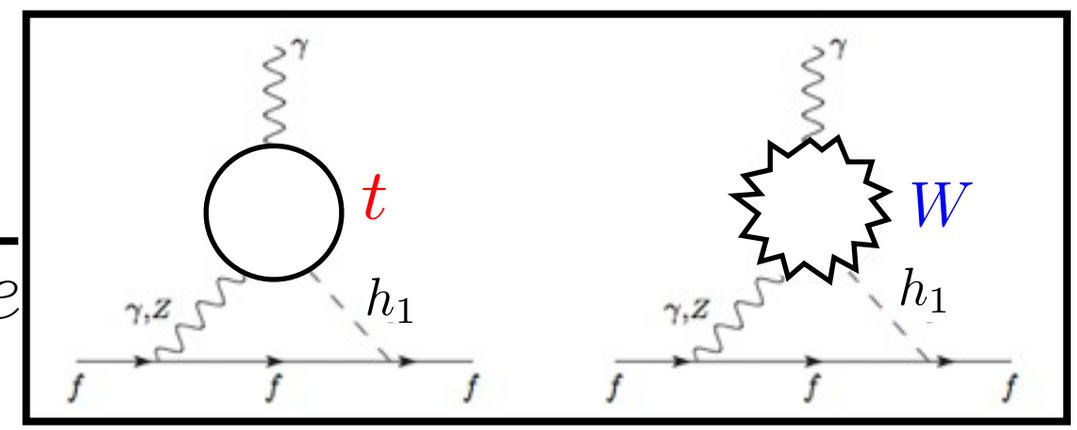
Jing Shu, **Y.Z.**, arXiv: 1304.0773, Phys. Rev. Lett.

Electric dipole moment

- Strong constraint on CPV Higgs-photon coupling.

McKeen, Pospelov, Ritz, arXiv: 1208.4597

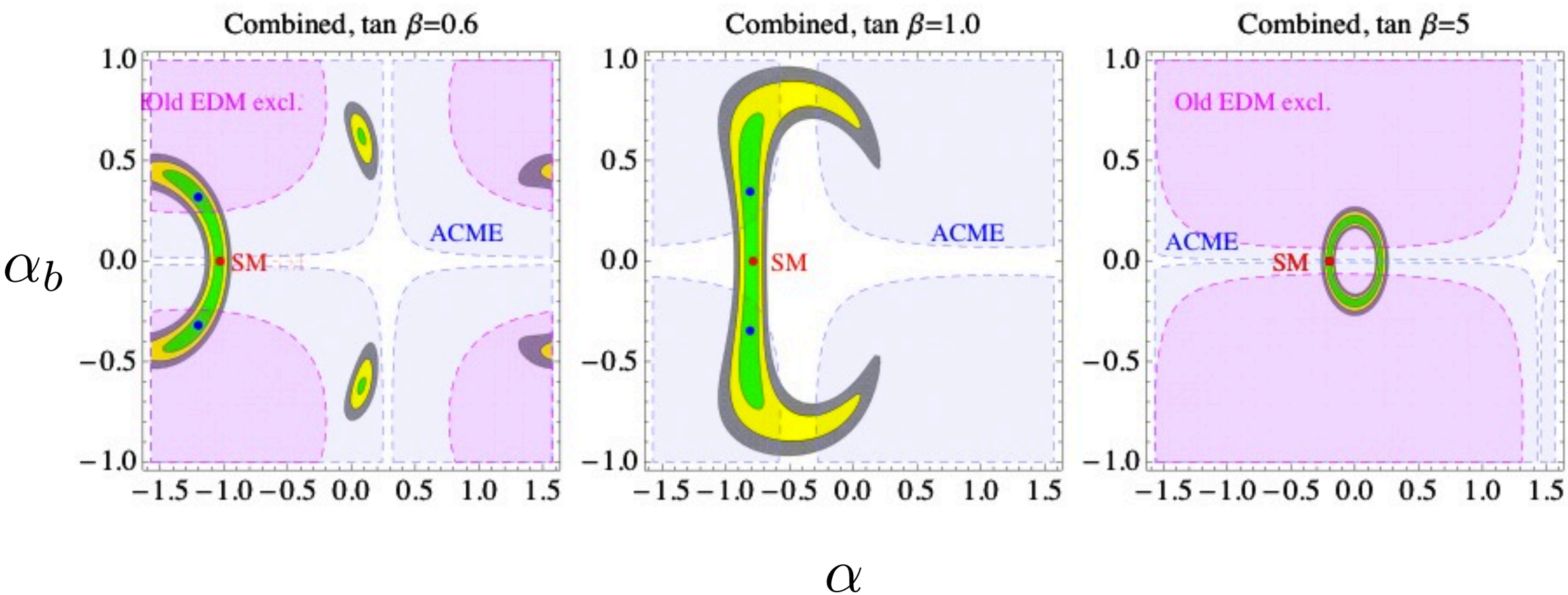




- I will show in 2HDM-II, cancelations can naturally happen to suppress the EDM.

Jing Shu, **Y.Z.**, arXiv: 1304.0773, Phys. Rev. Lett.

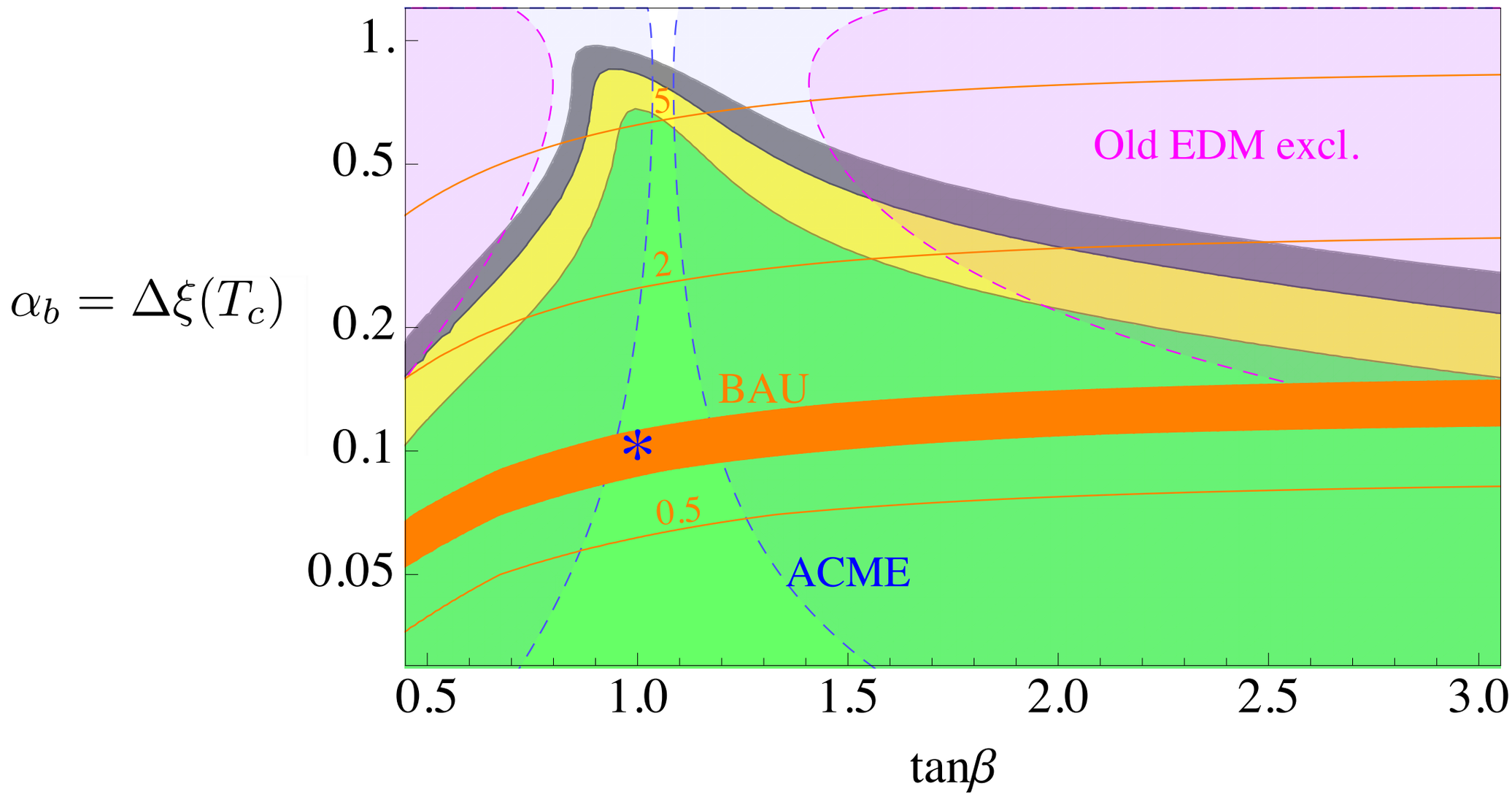
Higgs Fit + EDM constraints



- Higgs data and EDMs are complementary.
- Hold when nEDM bound and heavy Higgs are included.

S. Inoue, M. Ramsey-Musolf, **Y.Z.**, arXiv:1403.4257, PRD

Connections



If Higgs boson CP violating effect is found at LHC in future, we may be probing the theory for genesis.

Jing Shu, **Y.Z.**, arXiv: 1304.0773, Phys. Rev. Lett.

Future searches

Direct CPV: azimuthal phase shift:

- Higgs decays (also the heavy Higgs decays)

$$h \to ZZ^* \to 2\ell^+ 2\ell^-$$

Whitbeck, Moriond QCD 2013

$$h \to \tau^+\tau^- \to 2\pi 2\nu, 2\rho 2\nu$$

Harnik, Martin, Okui, Primolando, Yu, 1308.1094

$$h \to \gamma\gamma \quad \text{convert to } 4e$$

Bishara, Grossman, Harnik, Robinson, Shu, Zupan, 1312.2955

- Production with two forward jets

$$pp \to h + 2j$$

Klamke, Zeppenfeld, '07

- Virtual Higgs effects in $t\bar{t}$ channel

Schmidt, Peskin '92

- Look for CPV effects in heavier scalars from 2nd doublet.

Dawson, Shu, **Y.Z.**, in progress

Conclusion

- The Higgs boson could be the key to understanding the dark matter and baryon asymmetry.
- UV complete fermionic DM via the Higgs portal can accommodate bound states.
  - Exhibit new DM properties and pheno.
- Higgs field evolution in early universe provide new/ common origin for DM and baryon relic densities (asymmetric).
  - Closely connected to Higgs physics, EDM, collider.

Thank you!