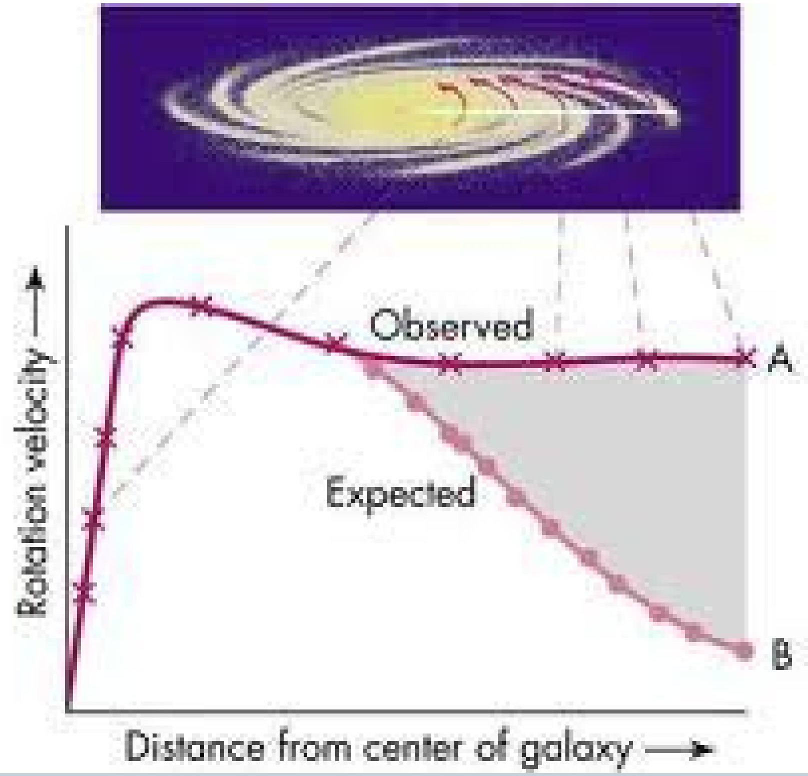
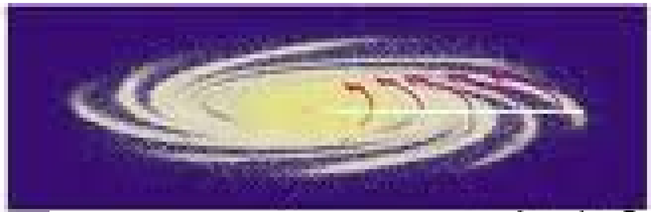
Gauge field as a dark matter candidate

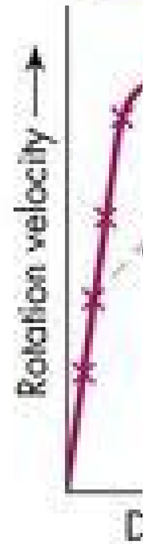
YASAMAN FARZAN
IPM, TEHRAN

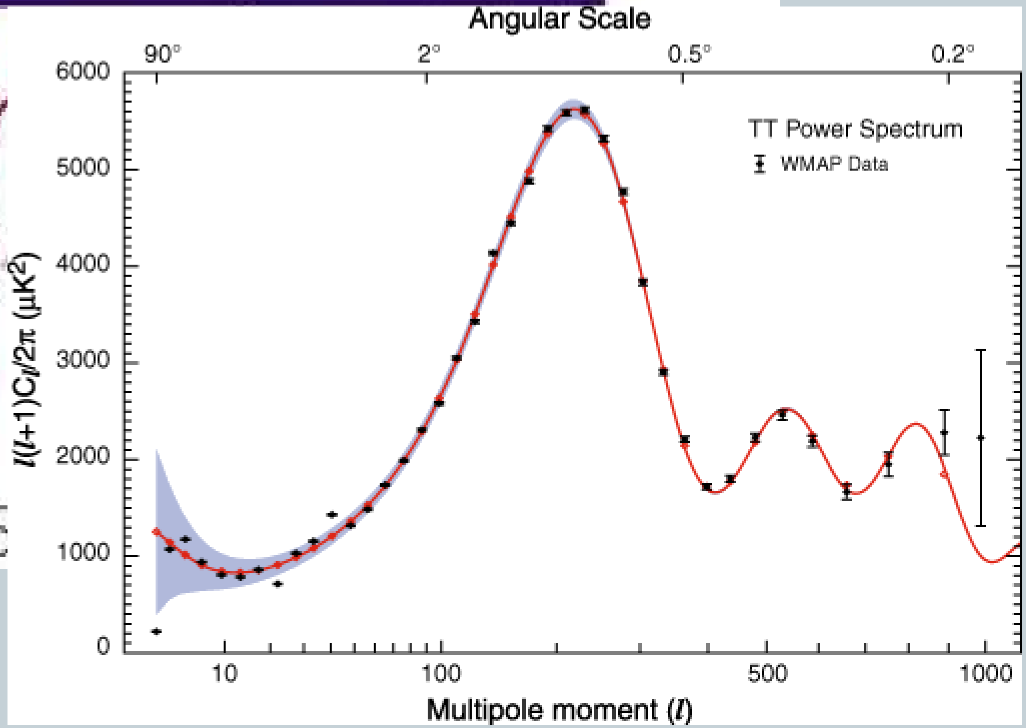
Outline

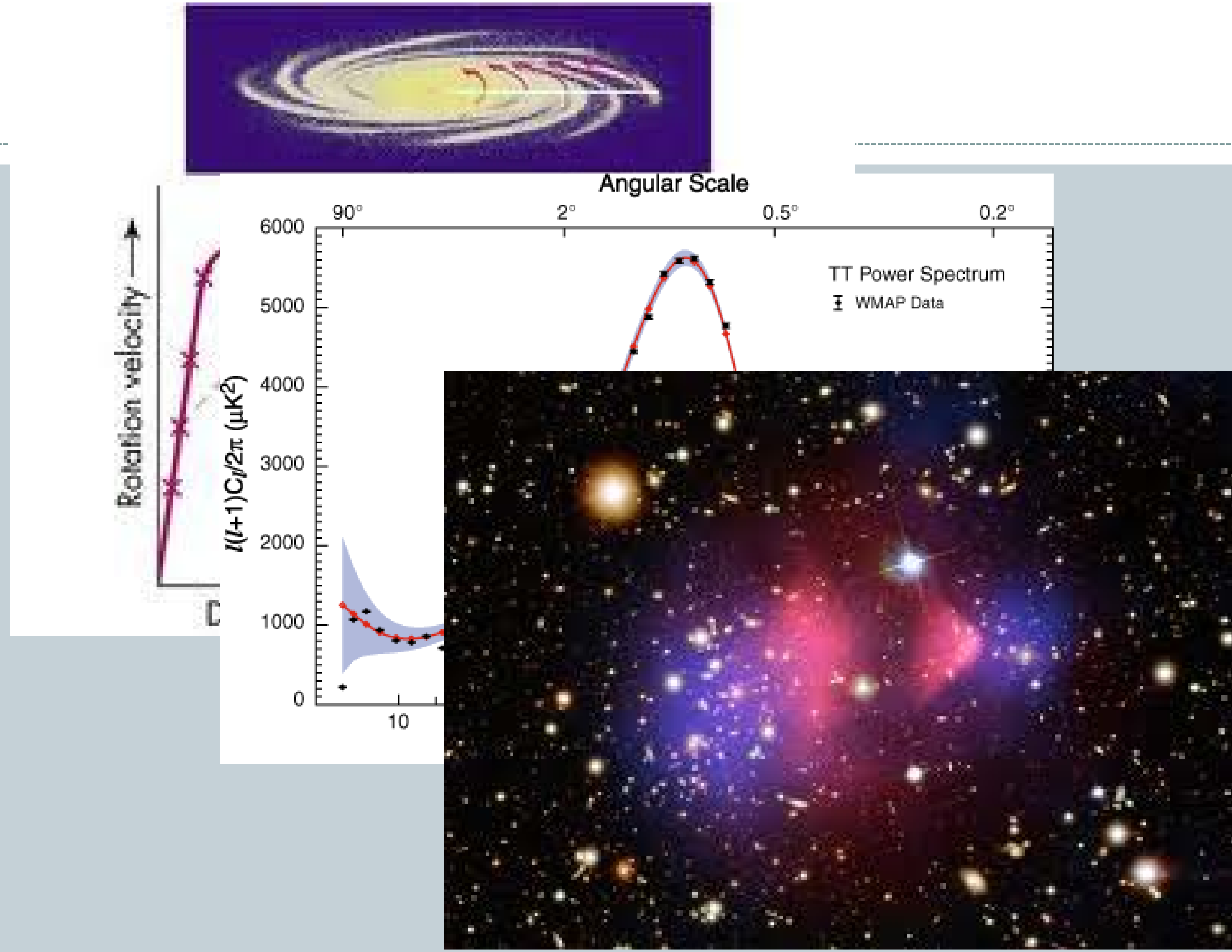
- Brief introduction to Vector like DM
- Our model
- Different phases
- Potential signals of model in colliders and direct DM searches
- Conclusions

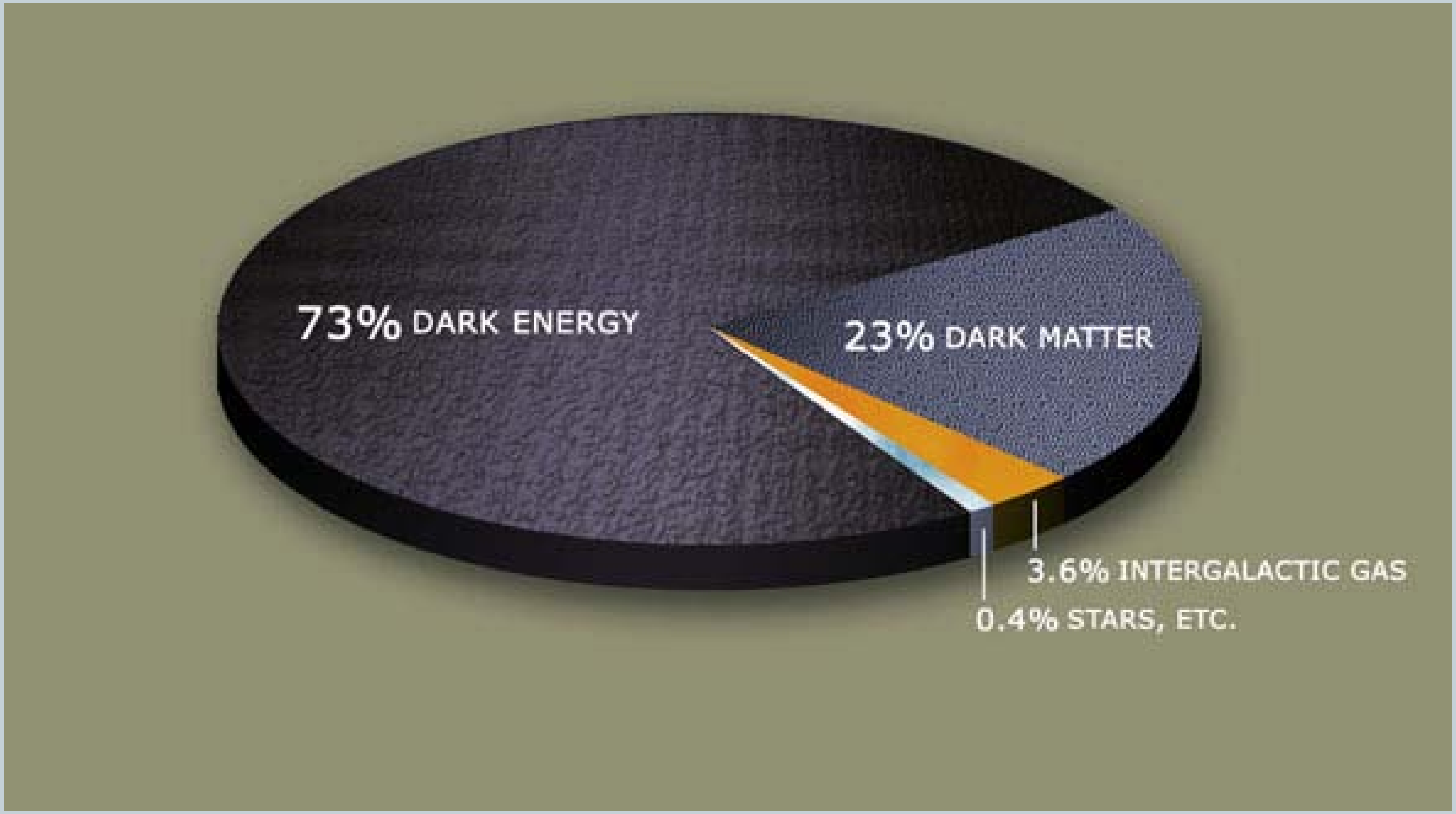

Observed
A
Expected
B
Rotation velocity
Distance from center of galaxy




Rotation velocity

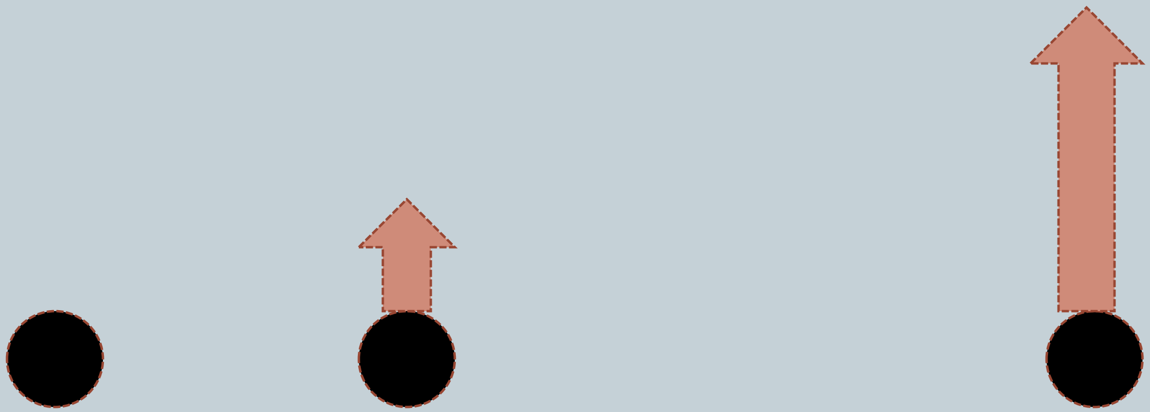

Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
TT Power Spectrum
WMAP Data
$l(l+1)C_l/2\pi\ (\mu K^2)$
10
100
500
1000
Multipole moment (l)


Rotation velocity
Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
10
$l(l+1)C_l/2\pi$ (μK^2)
TT Power Spectrum
WMAP Data


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

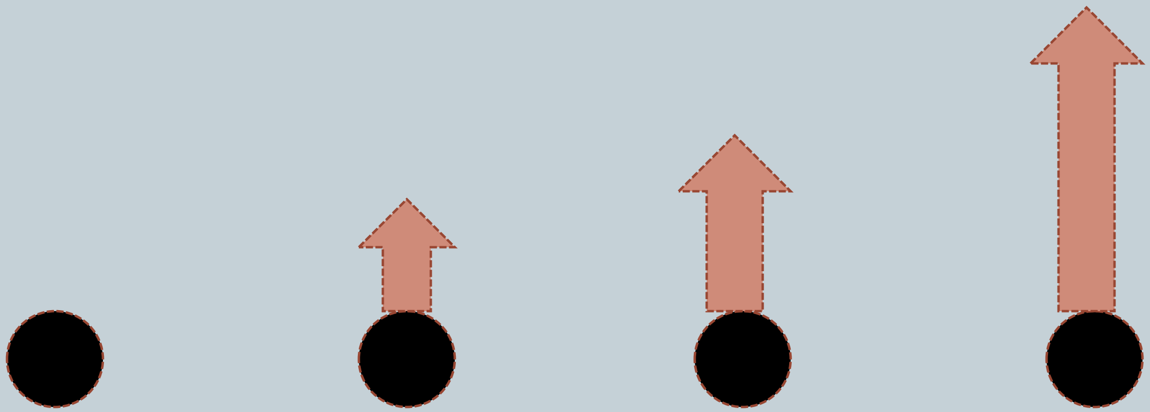
SPIN of dark matter?

- Spin 0, 1 /2, 3/2 are all extensively studied.



SPIN of dark matter?

- Spin 0, 1 /2, 3/2 are all extensively studied.



Spin 1 (vector boson)

Non-Abelian Gauge Group

Thomas Hambye and Tytgat, PLB683; T. Hambye, JHEP 0901;Bhattacharya, Diaz-Cruz, Ma and Wegman, Phys Rev D85

New: SU(2)

Abelian Vector boson

- Extra Large Dimension

Servant and Tait, Nucl Phys B650

- The little Higgs model

Birkedal et al, Phys Rev D 74

- Linear Sigma model

Abe et al, Phys Lett B

Vector Higgs-portal dark matter and invisible Higgs

Lebedev, Lee, Mambrini, Phys Let B 707

A model for Abelian gauge boson as Dark Matter

YF. And Rezaei Akbarieh

Gauge group: $SU(3) \times SU(2) \times U(1)_Y \times U(1)_X$

Gauge Vector: V_μ

- Scalar(s) to break the new gauge symmetry: Φ

Dark matter

Z_2 symmetry

$$V_\mu \to -V_\mu$$

$$\mathrm{SM} \to \mathrm{SM}$$

No kinetic mixing

Two versions of the model

- Minimal model

Vector Higgs-portal dark matter and invisible Higgs

Lebedev, Lee, Mambrini, Phys Let B 707 (integrating out the scalars)

Briefly mentioned in

T. Hambye, JHEP 0901

- Extended model

Minimal version of the Model

- Scalar sector: $\Phi = (\phi_r + i\phi_i)/\sqrt{2}$
- Lagrangian: $\mathcal{L} = D_\mu \Phi D^\mu \Phi - V(\Phi, H),$
- Covariant derivative: $D_\mu = \partial_\mu - i g_V V_\mu$

$$V = -\mu_\phi^2 |\Phi|^2 - \mu^2 |H|^2 + \lambda_\phi |\Phi|^4 + \lambda |H|^4 + \lambda_{H\phi} |\Phi|^2 |H|^2$$

Minimal version of the Model

- Scalar sector: $\Phi = (\phi_r + i\phi_i)/\sqrt{2}$
- Lagrangian: $\mathcal{L} = D_\mu \Phi D^\mu \Phi - V(\Phi, H),$
- Covariant derivative: $D_\mu = \partial_\mu - i g_V V_\mu$

$$V = -\mu_\phi^2 |\Phi|^2 - \mu^2 |H|^2 + \lambda_\phi |\Phi|^4 + \lambda |H|^4 + \lambda_{H\phi} |\Phi|^2 |H|^2$$

- Invariant under $V_\mu \to -V_\mu \ , \quad \phi_i \to -\phi_i$

Minimal version of the Model

- Scalar sector: $\Phi = (\phi_r + i\phi_i)/\sqrt{2}$
- Lagrangian: $\mathcal{L} = D_\mu \Phi D^\mu \Phi - V(\Phi, H),$
- Covariant derivative: $D_\mu = \partial_\mu - i g_V V_\mu$

$$V = -\mu_\phi^2 |\Phi|^2 - \mu^2 |H|^2 + \lambda_\phi |\Phi|^4 + \lambda |H|^4 + \lambda_{H\phi} |\Phi|^2 |H|^2$$

- Invariant under $V_\mu \to -V_\mu \ , \quad \phi_r \to -\phi_r ,$

Spontaneous symmetry breaking

- Unitary gauge

$$\Phi = \frac{\phi_r + v'}{\sqrt{2}} \text{ and } H = \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$$

$$V_\mu \to -V_\mu \ , \quad \phi_i \to -\phi_i$$

Goldstone boson absorbed as longitudinal component

Protecting the stability of the vector boson.

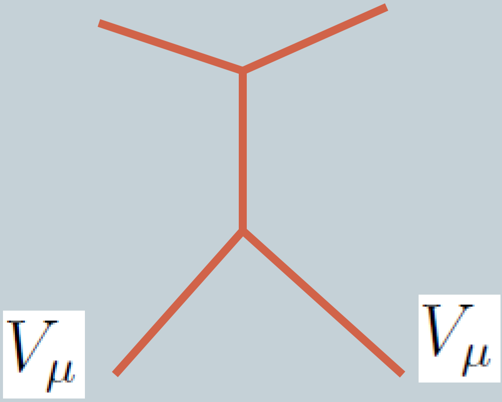
$$\frac{1}{2}[\phi_r \;\; h]\begin{bmatrix} 2\lambda_\phi v'^2 & \lambda_{H\phi} v v' \\ \lambda_{H\phi} v v' & 2\lambda v^2 \end{bmatrix}\begin{bmatrix} \phi_r \\ h \end{bmatrix}.$$

$$V_\mu \to -V_\mu\,, \quad \phi_r \to -\phi_r\,,$$

The new scalar can decay

Two regimes

- Scalar is heavier than the vector. (Higgs portal)

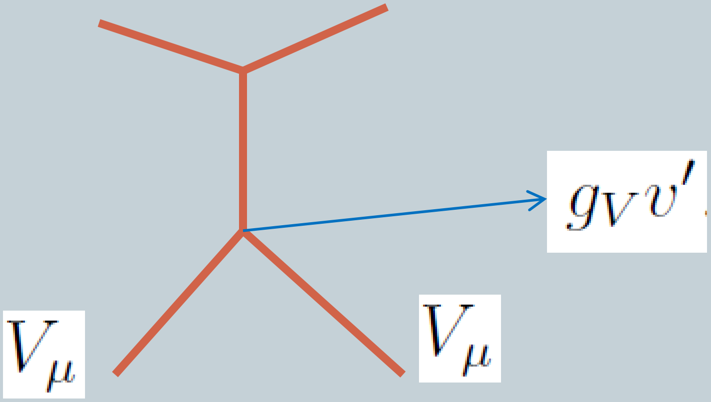


- Scalar is lighter than the vector

The annihilation diagram

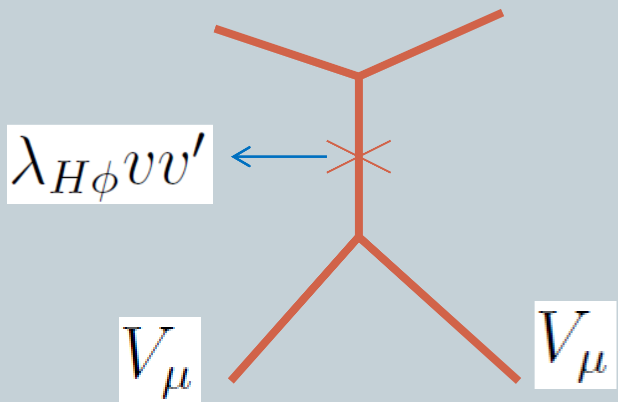
S-channel scalar exchange

Higgs portal



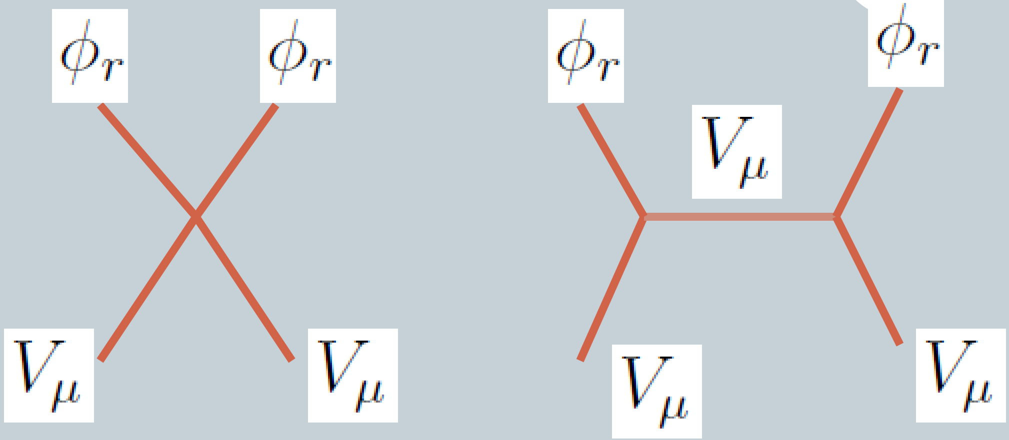
The annihilation diagram

$$\langle\sigma(V+V\to \mathrm{final})v_{rel}\rangle = \frac{64}{3}g_V^4\left[\frac{\lambda_{H\phi}vv'}{(m_h^2-4m_V^2)(m_{\phi_r}^2-4m_V^2)}\right]^2 F$$



$$F \equiv \lim_{m_{h^*}\to 2m_V}\left(\frac{\Gamma(h^*\to final)}{m_{h^*}}\right).$$

Second regime



$m_{\phi_r} < m_{DM}$.

$$\langle \sigma (V + V \to \phi_r + \phi_r) v \rangle = \frac{g_V^4}{8\pi m_V^2} g(m_{\phi_r}^2 / m_V^2)$$

$$g(x) = \sqrt{1-x} \left((1 + \frac{4}{x-2})^2 + \frac{16}{3} \frac{(1-x)^2}{(x-2)^2} + \frac{8}{3} (\frac{1-x}{x-2})(1 + \frac{4}{x-2}) \right)$$

Antimatter bound

- The produced scalar decays to the SM particles.

- With the same branching ratios as SM Higgs with the same mass

$$2m_b < m_{\phi_r} < 2m_W$$

- If it decays b-bbar, ...

- The scalar decays with branching ratios of the Higgs.
- To avoid the Antimatter bound (PAMELA):
- 1) $2m_W < m_{\phi_r} < m_V;$
- 2) $m_{\phi_r} < 2m_p$

Examples

$$2m_W < m_{\phi_r} < m_V;$$

Point I : $m_V = 250$ GeV, $m_{\phi_r} = 200$ GeV, $v' = 1023$ GeV, $\lambda_\phi = 0.13$, $g_V = 0.24$

$$m_{\phi_r} < 2m_p$$

Point II : $m_V = 8$ GeV, $m_{\phi_r} = 1.5$ GeV, $v' = 187$ GeV, $\lambda_\phi = 0.005$ $g_V = 0.042$

Point III : $m_V = 10$ GeV, $m_{\phi_r} = 1.5$ GeV, $v' = 210$ GeV, $\lambda_\phi = 0.005$ $g_V = 0.047$

Extended Model

- Vector boson: V_μ
- A pair of scalars: $\Phi = \begin{pmatrix} \phi_1 & \phi_2 \end{pmatrix}$

U(1) transformation

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \to U \cdot \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

Where

$$U = \begin{pmatrix} \cos\alpha & i\sin\alpha \\ i\sin\alpha & \cos\alpha \end{pmatrix}$$

Equivalently

$$\frac{(\phi_1 + \phi_2)}{\sqrt{2}} \to e^{i\alpha} \frac{(\phi_1 + \phi_2)}{\sqrt{2}}$$

$$\frac{(\phi_1 - \phi_2)}{\sqrt{2}} \to e^{-i\alpha} \frac{(\phi_1 - \phi_2)}{\sqrt{2}}.$$

A Z2 symmetry

$$Z_2^{(A)} : \phi_1 \to \phi_1 \ , \quad \phi_2 \to -\phi_2 \text{ and } \ V_\mu \to -V_\mu$$

$$\Phi^\dagger \Phi = \phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2$$

$$\Phi^T \sigma_3 \Phi = \phi_1^2 - \phi_2^2$$

Z2 even

$$\Phi^\dagger \sigma_1 \Phi = \phi_2^\dagger \phi_1 + \phi_1^\dagger \phi_2 \ .$$

→ Z2 odd

$$\Phi^T \sigma_2 \Phi = 0.$$

$$V(\Phi, H) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$+\lambda_{H\phi} H^\dagger H \Phi^\dagger \Phi + \xi' (\Phi^\dagger \sigma_1 \Phi)^2$$

$$+[\xi(\Phi^\dagger\Phi)(\Phi^T\sigma_3\Phi) - \mu'^2 \Phi^T \sigma_3 \Phi + \lambda' (\Phi^T \sigma_3 \Phi)^2 + \lambda'_{H\phi} H^\dagger H (\Phi^T \sigma_3 \Phi) + \mathrm{h}.c]$$

$$\mathcal{L} = \mathcal{L}^{SM} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H) - \frac{1}{4} V_{\mu\nu} V^{\mu\nu}$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \qquad D_\mu = \partial_\mu - i g_V \sigma_1 V_\mu .$$

$Z_2^{(A)}$ symmetry

~~$\Phi^\dagger \sigma_1 \Phi$~~

Imposing $Z_2^{(A)}$ → Accidental $Z_2^{(B)}$

$$Z_2^{(B)} : \phi_1 \to -\phi_1 \ , \quad \phi_2 \to \phi_2 \text{ and } V_\mu \to -V_\mu$$

Symmetry of the model

$$\boxed{U(1)_X \times Z_2 \times Z_2}$$

Stability of Potential

$$V(\Phi, H) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$+\lambda_{H\phi} H^\dagger H \Phi^\dagger \Phi + \xi' (\Phi^\dagger \sigma_1 \Phi)^2$$

$$+[\xi(\Phi^\dagger \Phi)(\Phi^T \sigma_3 \Phi) - \mu'^2 \Phi^T \sigma_3 \Phi + \lambda' (\Phi^T \sigma_3 \Phi)^2 + \lambda'_{H\phi} H^\dagger H (\Phi^T \sigma_3 \Phi) + \mathrm{h.}c]$$

Some conservative assumption

$$\lambda, \lambda_H, \lambda_{H\phi}, \xi' > 0 \quad \lambda + 2\lambda' > 2|\xi|, \text{ and } \lambda_{H\phi} > 2|\lambda'_{H\phi}|$$

Spontaneous symmetry breaking

$$\Phi^T = \left(\frac{v_r + \phi_r + iv_i + i\phi_i}{\sqrt{2}} \;\; \frac{v' + \phi'_r + i\phi'_i}{\sqrt{2}}\right)$$

The mass of the gauge boson

$$g_V\sqrt{v_r^2 + v_i^2 + v'^2}.$$

Remnant symmetry

$$U(1)_X \times Z_2 \times Z_2$$

$v' = 0$ and $v_r^2 + v_i^2 \neq 0.$

$$Z_2^{(A)} : \phi_1 \to \phi_1 \,, \quad \phi_2 \to -\phi_2 \text{ and } V_\mu \to -V_\mu \,.$$

Goldstone boson

$$G \equiv \frac{-v_i \phi'_r + v_r \phi'_i}{\sqrt{v_i^2 + v_r^2}}$$

The mode perpendicular to the Goldstone boson

$$\phi' \equiv \frac{v_r \phi'_r + v_i \phi'_i}{\sqrt{v_i^2 + v_r^2}}.$$

Gauge Interactions of ϕ'

$$\phi_2 = \phi' e^{i\beta}$$

$$\tan\beta \equiv \frac{v_i}{v_r}$$

$$\frac{g_V^2}{2} V_\mu V^\mu [(\phi_i^2 + \phi_r^2 + \phi'^2) + 2(\phi_i v_i + \phi_r v_r)] +$$
$$g_V V^\mu [-\sin\beta(\phi_r \partial_\mu \phi' - \phi' \partial_\mu \phi_r) + \cos\beta(\phi_i \partial_\mu \phi' - \phi' \partial_\mu \phi_i)]$$

Unitary gauge

$$\partial_\mu V^\mu = 0$$

$$V^0 = 0$$

No Goldstone boson

Dark matter candidate

- The new vector boson is a DARK MATTER candidate if

$$g_V^2(v_r^2 + v_i^2) < m_{\phi'}^2.$$

Different phases

$$\Phi^T = \left(\frac{v_r + \phi_r + iv_i + i\phi_i}{\sqrt{2}} \quad \frac{v' + \phi'_r + i\phi'_i}{\sqrt{2}}\right)$$

- Phase I $\quad v' = 0,\ v_i, v_r \neq 0;$
- Phase II $\quad v' = v_r = 0 \text{ and } v_i \neq 0;$
- Phase III $\quad v' = v_i = 0 \text{ and } v_r \neq 0;$

Equivalence of phases II and III

$$(\mu^2, \lambda_H, \lambda, \xi', \lambda', \lambda_{H\phi}, \mu'^2, \lambda'_{H\phi}, \xi) \rightarrow (\mu^2, \lambda_H, \lambda, \xi', \lambda', \lambda_{H\phi}, -\mu'^2, -\lambda'_{H\phi}, -\xi)$$

AND

$$\phi'_i \leftrightarrow \phi'_r$$

Phase I

$$\begin{pmatrix} \phi_r \\ \phi_i \\ h \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{pmatrix}$$

$v' = 0,\ v_i, v_r \neq 0;$ ⇒ Spontaneous CP-violation

Small mixing ⇒ $a_{31}, a_{32}, a_{13}, a_{23} \ll 1.$

$m_{\delta_3} \simeq m_h$

Phase I

$$\begin{pmatrix} \phi_r \\ \phi_i \\ h \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{pmatrix}$$

$v' = 0,\ v_i, v_r \neq 0;$ → Spontaneous CP-violation

Similar to the minimal model

Phase II

$v' = v_r = 0$ and $v_i \neq 0$;

$a_{12} = a_{13} = a_{21} = a_{31} = 0.$

In this case only ϕ_i mixes with h.

CP will be preserved.

Another Z2

- A new Z2 symmetry $\phi_r \longrightarrow -\phi_r.$

Another component of Dark Matter:

Interesting scenario

$$\sigma(V + V \to \text{anything}) = 1\ pb$$

$$\sigma(\delta_1 + \delta_1 \to h^* \to \text{final}) \gg 1\ pb.$$

Vector heavier than the stable scalar.

$$V + V \to \delta_1 \delta_1$$

Dominant DM : Vector boson
Sub-dominant DM: Scalar

Anti-matter constraint is relaxed.

Interesting scenario

$$\sigma(V + V \to \text{anything}) = 1\ pb$$

$$\sigma(\delta_1 + \delta_1 \to h^* \to \text{final}) \gg 1\ pb.$$

ξ	λ'	ξ'	λ	μ (GeV)	μ' (GeV)	g_V^2	$\lambda_{H\phi}$	$\lambda'_{H\phi}$
0.5	0.11	0.4	0.93	405	140	0.017	0.1	0.1

v_i	v_r	m_{δ_1}	m_{δ_2}	$m_{\phi'}$	m_V
795	0	100	500	1000	120

Interesting scenario

$$\sigma(V + V \to \text{anything}) = 1\ pb$$

$$\sigma(\delta_1 + \delta_1 \to h^* \to \text{final}) \gg 1\ pb.$$

Lower bound on coupling to Higgs

Interesting scenario

$$\sigma(V + V \to \text{anything}) = 1\ pb$$

$$\sigma(\delta_1 + \delta_1 \to h^* \to \text{final}) \gg 1\ pb.$$

→ $\lambda_{H\phi} + 2\lambda'_{H\phi} \sim 0.1$

ξ	λ'	ξ'	λ	μ (GeV)	μ' (GeV)	g_V^2	$\lambda_{H\phi}$	$\lambda'_{H\phi}$
0.5	0.11	0.4	0.93	405	140	0.017	0.1	0.1

v_i	v_r	m_{δ_1}	m_{δ_2}	$m_{\phi'}$	m_V
795	0	100	500	1000	120

Detection

- Direct detection and production at collider

  ↓

  $\lambda_{H\phi}$

- Phase II of extended model: annihilation of lighter DM component → Lower bound on $\lambda_{H\phi}$

-

Detection

- Direct detection and production at collider

$$\lambda_{H\phi}$$

- Phase II of extended model: annihilation of lighter DM component → $\lambda_{H\phi} + 2\lambda'_{H\phi} \sim 0.1$

- No such bound on minimal model or phase I of extended

Lower bound from thermalisation

$$Max[\lambda_{H\phi}, \lambda'_{H\phi}] \gtrsim 10^{-8} \left(\frac{m_\delta}{100 \text{ GeV}} \right)^{1/2}$$

Potential signal at the LHC

- If the new scalars have masses below 125/2 GeV

Invisible Higgs decay

New SM Higgs-like scalars with production suppressed by $|\lambda_{H\phi}|^2$

Potential signal at the LHC

- If the new scalars have masses below 126/2 GeV

Invisible Higgs decay

~~Phase II with $m_{\phi_r} < 63$ GeV~~

New SM Higgs-like scalars with production suppressed by $|\lambda_{H\phi}|^2$

$$m_{\phi_r} > 2m_W$$

Direct detection

- Minimal version:

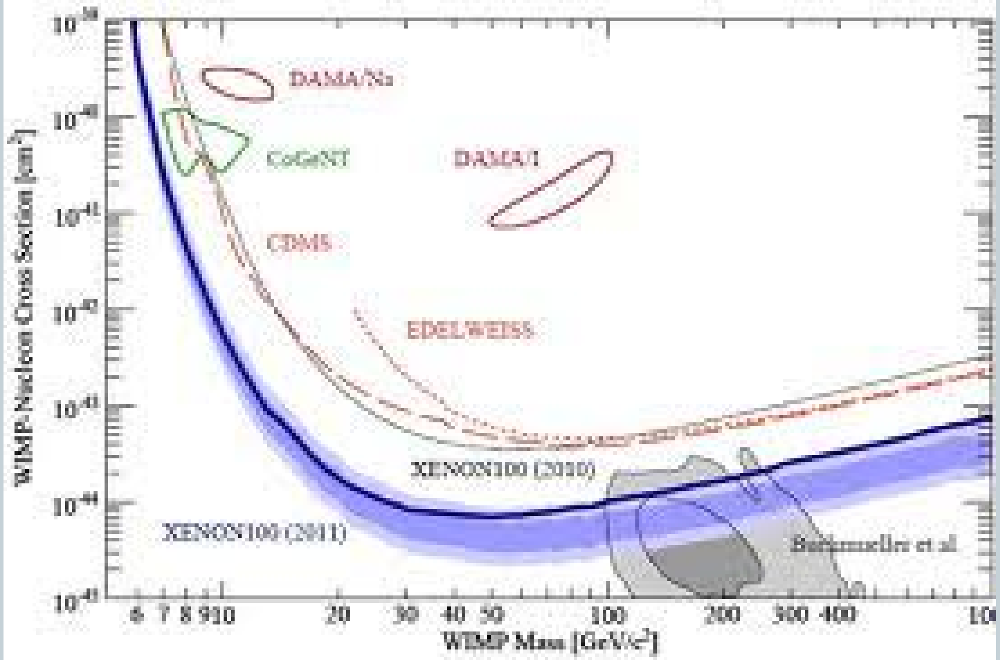
$$\sigma_N \equiv \sigma_{SI}(V + \mathrm{N} \to V + \mathrm{N}) = \frac{g_V^4 M_r^2 m_N^2}{\pi m_V^2 v_H^2}[\frac{\lambda_{H\phi} v v'^2}{m_h^2 m_{\phi_r}^2}]^2 f^2$$

- Extended model

$$\sigma_N \equiv \sigma_{SI}(V + \mathrm{N} \to V + \mathrm{N}) = \frac{g_V^4 M_r^2 m_N^2}{\pi m_V^2 v_H^2}[(\sum_{j=1}^{3} \frac{a_{3j}(a_{1j} v_r + a_{2j} v_i)}{m_{\delta_j}^2})]^2 f^2$$

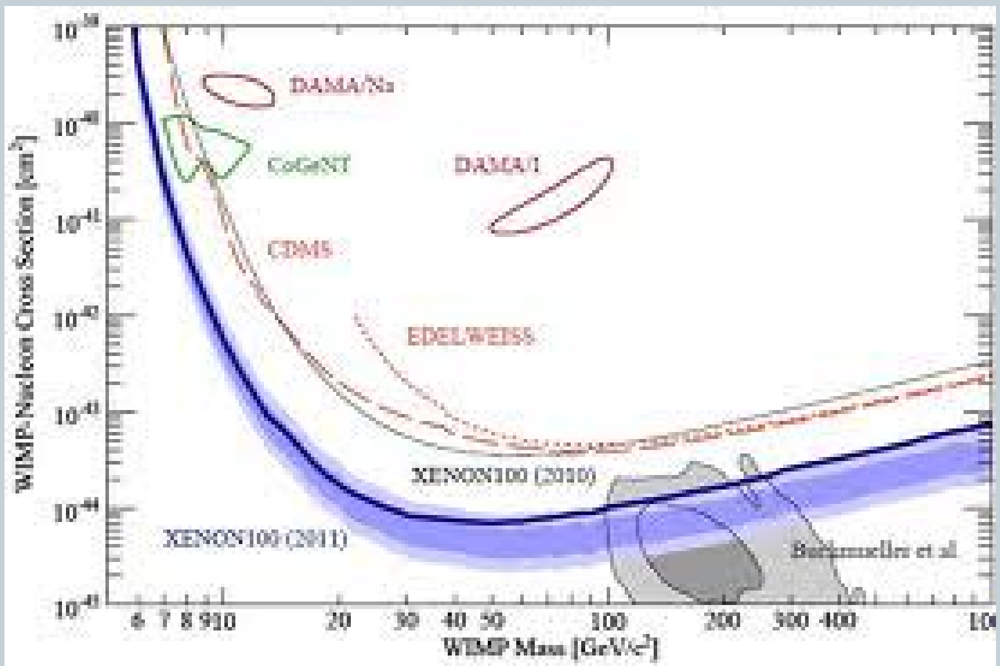
$$m_V \sim \text{few } 100 \text{ GeV}$$

$$10^{-46} \lambda_{H\phi}^2 (f/0.3)^2 \text{ cm}^2$$



- **Phase I with** $m_{\delta_1} < m_V$ **and** $m_{\delta_1} < 2m_p$

$$10^{-42}\lambda_{H\phi}^2 (f/0.3)^2 \text{ cm}^2$$

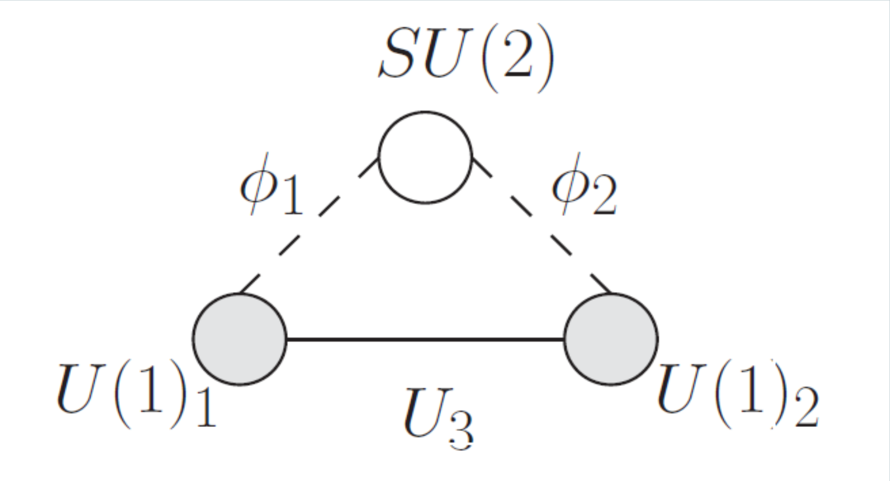


Summary

- Model based on $U(1)_X \times Z_2 \times Z_2$
- Vector gauge boson as DM
- Minimal and extended version
- Extended version: spontaneous CP violation/multiple DM candidate
- SM-like Higgs with suppressed production rate

Backup slides

Vector WIMP miracle



One single U(1) coupling

ABE et al

Condition for Local minimum

Extermum:

$$\frac{\partial V}{\partial v_X^2} = 0 \quad \text{or} \quad v_X = 0$$

Minimum:

$$\text{Eigenvalues}\left[\frac{\partial^2 V}{\partial v_X^2 \partial v_Y^2}\right] > 0$$

Conditions for Phase I

$$v' = 0,\; v_i, v_r \neq 0$$

$$v_r^2 = \frac{\mu^2(4\lambda' - \xi) + 2\mu'^2(\lambda - 2\lambda' - 2\xi)}{2(4\lambda\lambda' - 8\lambda'^2 - \xi^2)},$$

$$v_i^2 = \frac{\mu^2(4\lambda' + \xi) + 2\mu'^2(-\lambda + 2\lambda' - \xi)}{2(4\lambda\lambda' - 8\lambda'^2 - \xi^2)},$$

$$m_{\phi'}^2 = \frac{4(2\lambda' + \xi')(2\lambda'\mu^2 - \xi\mu'^2)}{4\lambda\lambda' - 8\lambda'^2 - \xi^2}.$$

$v_i^2, v_r^2, m_{\phi'}^2 > 0.$

$m_{\delta_1}^2, m_{\delta_2}^2, m_{\delta_3}^2 > 0$

Conditions for Phase II

$$\mu^2 - 2\mu'^2 > 0 \ , \ \ \mu^2(\xi + \xi' - 2\lambda') + 2\mu'^2(\xi + \xi' - \lambda) > 0$$

$$\mu^2(\xi - 4\lambda') + 2\mu'^2(\xi + 2\lambda' - \lambda) > 0 \ .$$

- Local Minimum

- Or

- Total Minimum

Our method

Given set of couplings and mass parameters

↓

$$\frac{\partial V}{\partial v_X^2} = 0 \quad \text{or} \quad v_X = 0$$

↓

$$V(\Phi, H)$$

↓

Global minimum