Electroweak-Skyrmion as Topological Dark Matter

Masafumi Kurachi
KEK

Seminar at Kyoto, November 9, 2016

Reference:
Ryuichiro Kitano, Masafumi Kurachi,
JHEP07 (2016) 037 (arXiv:1605.07355)

Introduction

Great success of the LHC experiment

- Discovery of the Higgs

Sensitivity to New Physics is already a few TeV

- No evidence of New Physics so far

A new era for particle physics phenomenology

Introduction

Question:

What is a (practical) guideline for choosing a research subject

(one of) Answer(s):

Focus on **something** which is:

- simply assumed in the SM, but actually **not** established experimentally yet
- and, at the same time, significant experimental progress is expected near future

Introduction

Question:

What is a (practical) guideline for choosing a research subject

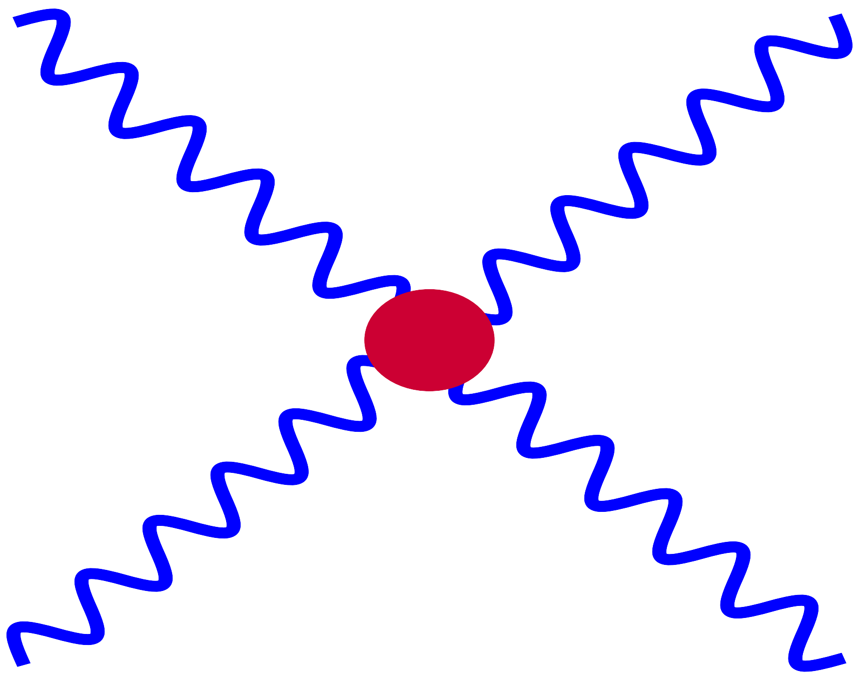
(one of) Like what??

Focus on **something** which is:

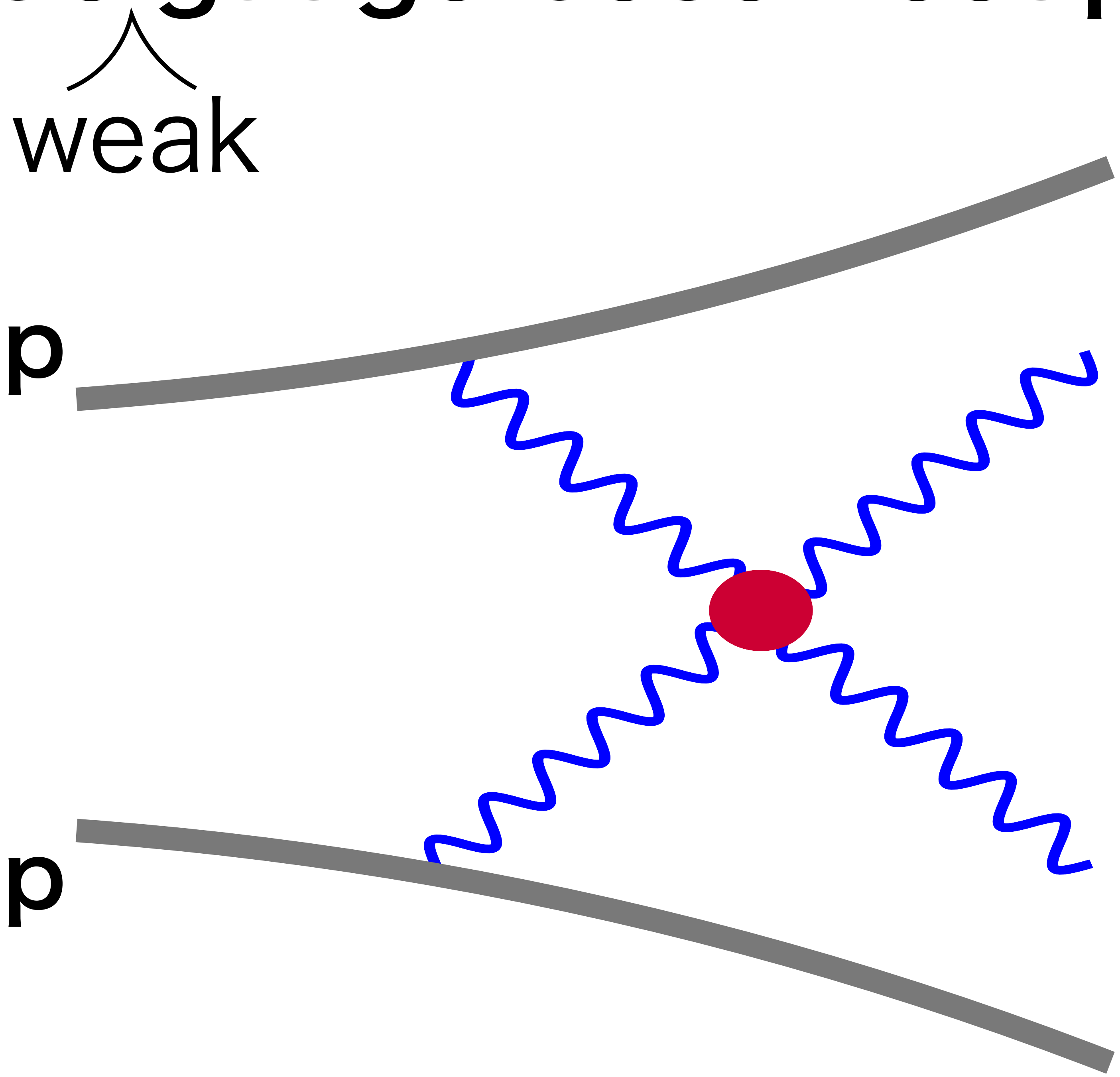
- simply assumed in the SM, but actually **not** established experimentally yet
- and, at the same time, significant experimental progress is expected near future

Quartic gauge boson coupling (QGC)

weak



Quartic gauge boson coupling (QGC)



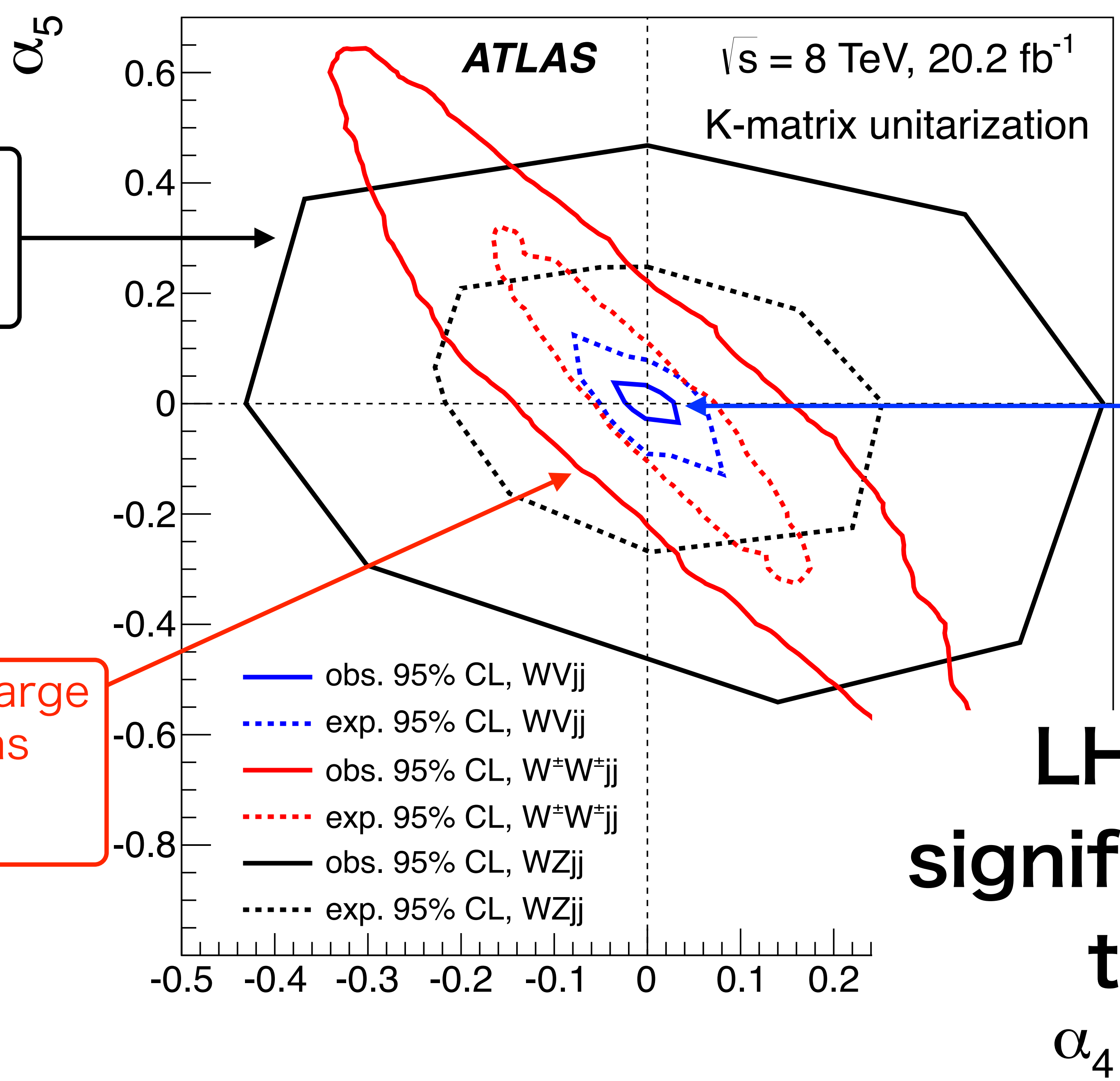
LHC has just begun to measure it!

Constraints on anomalous QGC parameters (α_4, α_5)

($\alpha_4 = \alpha_5 = 0$ corresponds to the SM)

explained later (roughly speaking, these represent deviation from the SM QGC)

$W^\pm Z \to \ell' \nu \ell \ell$
(arXiv:1603.02151)



WV ($V = W$ or Z)
$W \to \ell\nu$
$V \to jj$ or J
(arXiv:1609.05122)

$W^\pm W^\pm \to$ same-charge leptons
(arXiv:1405.6241)

LHC RUN2 will significantly improve this further

figure taken from arXiv:1609.05122 (ATLAS)

α_4, α_5 **is** something which is:

- simply assumed (to be 0) in the SM,
  but actually **not** established experimentally yet
- and, at the same time, significant experimental progress is expected near future
- and the existence of non-zero α_4, α_5 has interesting (qualitative) impacts
  - high-energy growth of WW scattering amplitude
  - **non-trivial topological object in the Higgs sector**

EW Chiral Lagrangian parameters: α_4, α_5

Higgs sector of the SM

Higgs doublet: $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ (conjugate: $\tilde{\phi} = i\sigma_2 \phi^*$)

2x2 matrix notation: $\Phi = \begin{pmatrix} \tilde{\phi} & \phi \end{pmatrix}$

$$\mathcal{L}_{\text{Higgs}} = \frac{1}{2}\text{Tr}\left[D_\mu \Phi^\dagger D_\mu \Phi\right] + \frac{\lambda}{4}\left(\text{Tr}\left[\Phi^\dagger \Phi\right] - v_{\text{EW}}^2\right)^2$$

Invariant under global $SU(2)_L \times SU(2)_R$ **trans.** $\Phi \;\longrightarrow\; L\Phi R^\dagger$

↓ SSB $\langle \Phi \rangle = \frac{v_{\text{EW}}}{\sqrt{2}} \mathbf{1}_{2\text{x}2}$

$SU(2)_V$

(custodial sym.)

EW Chiral Lagrangian parameters: α_4, α_5

$\Phi(x)$ can be rewritten as: $\Phi(x) = \frac{v_{\rm EW} + h(x)}{\sqrt{2}} U(x)$

NG field : $U(x) = e^{i\,\pi^i(x)\,\sigma^i / v_{\rm EW}}$

Scalar (Higgs) : $h(x)$

Equivalence theorem: $E \gg m_W$

$$\mathcal{A}\,(W_{\rm L}W_{\rm L} \to W_{\rm L}W_{\rm L}) \quad \simeq \quad \mathcal{A}\,(\pi\pi \to \pi\pi)$$

Effective Lagrangian of $U(x)$ is appropriate for the study of weak gauge boson scattering processes

EW Chiral Lagrangian parameters: α_4, α_5

$\Phi(x)$ can be rewritten as: $\Phi(x) = \dfrac{v_{\rm EW} + h(x)}{\sqrt{2}}\, U(x)$

NG field : $U(x) = e^{i\,\pi^i(x)\,\sigma^i / v_{\rm EW}}$

Scalar (Higgs) : $h(x)$

EW Chiral Lagrangian: low-energy effective theory of $U(x)$

$$\mathcal{L}_{\rm EWCL} = \mathcal{L}_{\mathcal{O}(p^2)} + \mathcal{L}_{\mathcal{O}(p^4)} + \cdots$$

kinetic term ⟶ $\mathcal{L}_{\mathcal{O}(p^2)} = \dfrac{v_{\rm EW}^2}{4} {\rm Tr}\left[D_\mu U^\dagger D^\mu U\right]$

anomalous QGC ⟶ $\mathcal{L}_{\mathcal{O}(p^4)} = \alpha_4\, {\rm Tr}\left[D_\mu U^\dagger D_\nu U\right] {\rm Tr}\left[D^\mu U^\dagger D^\nu U\right]$

$$+ \alpha_5\, {\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] {\rm Tr}\left[D_\nu U^\dagger D^\nu U\right] + \cdots$$

EW Chiral Lagrangian parameters: α_4, α_5

typical example of physics beyond the SM:

new heavy vector resonance

$$\alpha_4 = -\alpha_5 \quad \left(\sim \frac{M_W^2}{M_{W'}^2}\right)$$

$$\mathcal{L}_{\mathcal{O}(p^4)} = -\frac{1}{2}\alpha_5 \mathrm{Tr}\left[D_\mu U U^\dagger, D_\nu U U^\dagger\right]^2$$

We take this term as a **minimal addition to the SM**, and study physical consequences

Lagrangian

$$\mathcal{L} = \frac{v_{\rm EW}^2}{4}\left(1+\frac{h(x)}{v_{\rm EW}}\right)^2 {\rm Tr}\left[\partial_\mu U(x)\,\partial^\mu U(x)^\dagger\right] + \frac{1}{2}\partial_\mu h(x)\partial^\mu h(x) - V(h(x))$$

$$+\frac{1}{32e^2}{\rm Tr}\left[\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\right]^2$$

Standard Model + $O(p^4)$ term

NG field : $U(x) = e^{i\,\pi^i(x)\,\sigma^i/v_{\rm EW}}$

Scalar (Higgs) : $h(x)$

$$V(h(x)) = \lambda v_{\rm EW}^2\,h(x)^2 + \lambda v_{\rm EW}\,h(x)^3 + \frac{\lambda}{4}\,h(x)^4$$

Lagrangian

$$\mathcal{L} = \frac{v_{\rm EW}^2}{4}\left(1+\frac{h(x)}{v_{\rm EW}}\right)^2 {\rm Tr}\left[\partial_\mu U(x)\,\partial^\mu U(x)^\dagger\right] + \frac{1}{2}\partial_\mu h(x)\partial^\mu h(x) - V(h(x))$$
$$+\frac{1}{32e^2}{\rm Tr}\left[\,\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\,\right]^2$$

Standard Model **+** $O(p^4)$ **term**

If you ignore the scalar,

and replace $v_{\rm EW} \Rightarrow f_\pi$

it is equivalent to the **Skyrme model**

Skyrme Model

T.H.R. Skyrme “A Nonlinear field theory,”
Proc. Roy. Soc. Lond. A 260, 127 (1961)

Nucleon ⇔ soliton solution in the chiral Lagrangian

(non-trivial configuration of the pion field)

$$\mathcal{L} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\left[\partial_\mu U(x)\,\partial^\mu U(x)^\dagger\right] + \frac{1}{32e^2}\,\mathrm{Tr}\left[\,\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\,\right]^2$$

$$U(x) = e^{i\,\pi^i(x)\,\sigma^i/f_\pi}$$

Skyrme term

Procedure

- assume the form of static configuration
- derive the expression of the energy
- minimize the energy (solve Euler-Lagrange eq.)

Skyrme Model

T.H.R. Skyrme "A Nonlinear field theory,"
Proc. Roy. Soc. Lond. A 260, 127 (1961)

Nucleon ⇔ soliton solution in the chiral Lagrangian
(non-trivial configuration of the pion field)

$$\mathcal{L} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\left[\partial_\mu U(x)\,\partial^\mu U(x)^\dagger\right] + \frac{1}{32e^2}\,\mathrm{Tr}\left[\,\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\,\right]^2$$

$$U(x) = e^{i\,\pi^i(x)\,\sigma^i/f_\pi}$$

Skyrme term

- assume the form of static configuration

"hedgehog" solution

unknown function

$$U(x) = e^{iF(r)\sigma^i\hat{x}_i}$$

$$\left(\, r \equiv \sqrt{x_i x_i}, \quad \hat{x}_i \equiv x_i/r \,\right)$$

Skyrme Model

T.H.R. Skyrme "A Nonlinear field theory,"
Proc. Roy. Soc. Lond. A 260, 127 (1961)

Nucleon ⇔ soliton solution in the chiral Lagrangian
(non-trivial configuration of the pion field)

$$\mathcal{L} = \frac{f_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu U(x)\,\partial^\mu U(x)^\dagger\right] + \frac{1}{32e^2} \mathrm{Tr}\left[\,\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\,\right]^2$$

$$U(x) = e^{i\,\pi^i(x)\,\sigma^i/f_\pi}$$

Skyrme term

- derive the expression of the energy

$$E\left[\tilde{F}(\tilde{r})\right] = 2\pi\left(\frac{f_\pi}{e}\right)\int_0^\infty d\tilde{r}\left[\left(\tilde{r}^2 + 2\sin^2\tilde{F}(\tilde{r})\right)\tilde{F}'(\tilde{r})^2 + \left(2\tilde{r}^2 + \sin^2\tilde{F}(\tilde{r})\right)\frac{\sin^2\tilde{F}(\tilde{r})}{\tilde{r}^2}\right]$$

$$\tilde{r} = \frac{r}{R}, \quad \text{where} \quad R \equiv \frac{1}{e\,f_\pi} \qquad \left(\, F(r) = F(\tilde{r}R) \equiv \tilde{F}(\tilde{r}) \,\right)$$

Skyrme Model

T.H.R. Skyrme "A Nonlinear field theory,"
Proc. Roy. Soc. Lond. A 260, 127 (1961)

Nucleon ⇔ soliton solution in the chiral Lagrangian

(non-trivial configuration of the pion field)

$$\mathcal{L} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\left[\partial_\mu U(x)\,\partial^\mu U(x)^\dagger\right] + \frac{1}{32e^2}\,\mathrm{Tr}\left[\,\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\,\right]^2$$

$$U(x) = e^{i\,\pi^i(x)\,\sigma^i/f_\pi}$$

Skyrme term

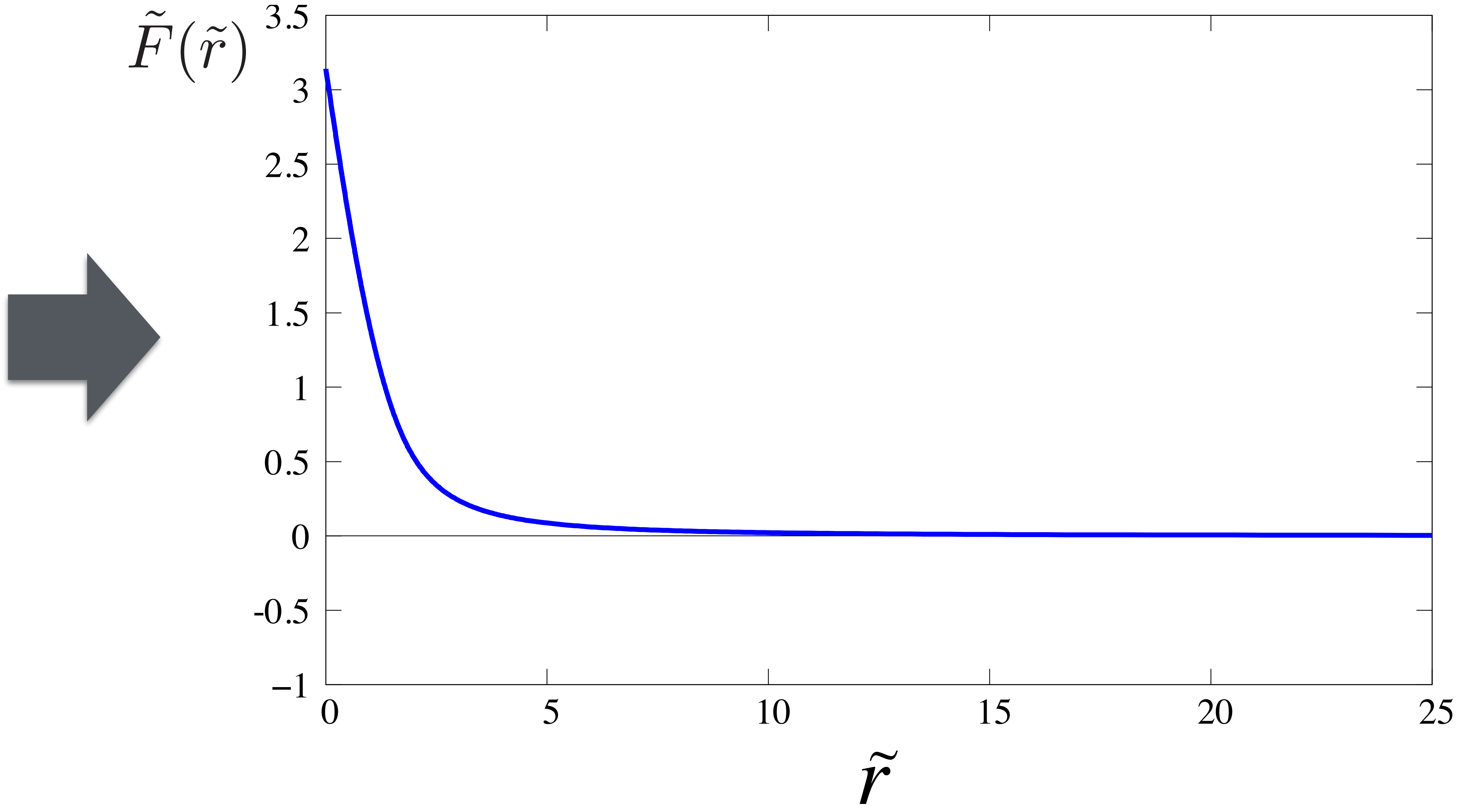
- minimize the energy (solve Euler-Lagrange eq.)

$$\left(\tilde{r}^2 + 2\sin^2\tilde{F}(\tilde{r})\right)\tilde{F}''(\tilde{r}) + 2\,\tilde{r}\,\tilde{F}'(\tilde{r}) + \sin 2\tilde{F}(\tilde{r})\left(\tilde{F}'(\tilde{r})^2 - 1 - \frac{\sin^2\tilde{F}(\tilde{r})}{\tilde{r}^2}\right) = 0$$

(equation does not explicitly depend on Lagrangian parameters)

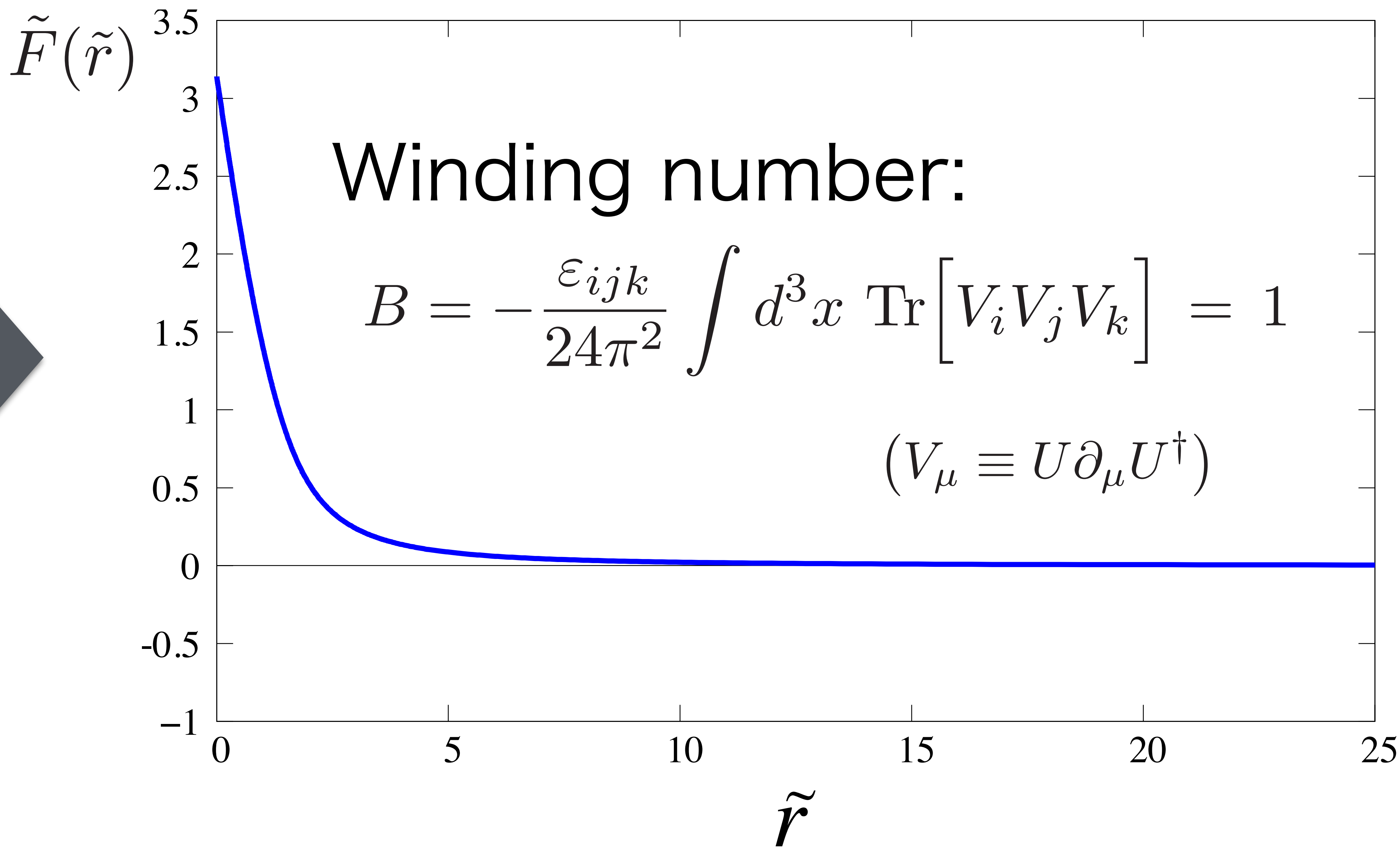
Skyrme Model

$$\left(\tilde{r}^2 + 2\sin^2\tilde{F}(\tilde{r})\right)\tilde{F}''(\tilde{r}) + 2\,\tilde{r}\,\tilde{F}'(\tilde{r}) + \sin 2\tilde{F}(\tilde{r})\left(\tilde{F}'(\tilde{r})^2 - 1 - \frac{\sin^2\tilde{F}(\tilde{r})}{\tilde{r}^2}\right) = 0$$



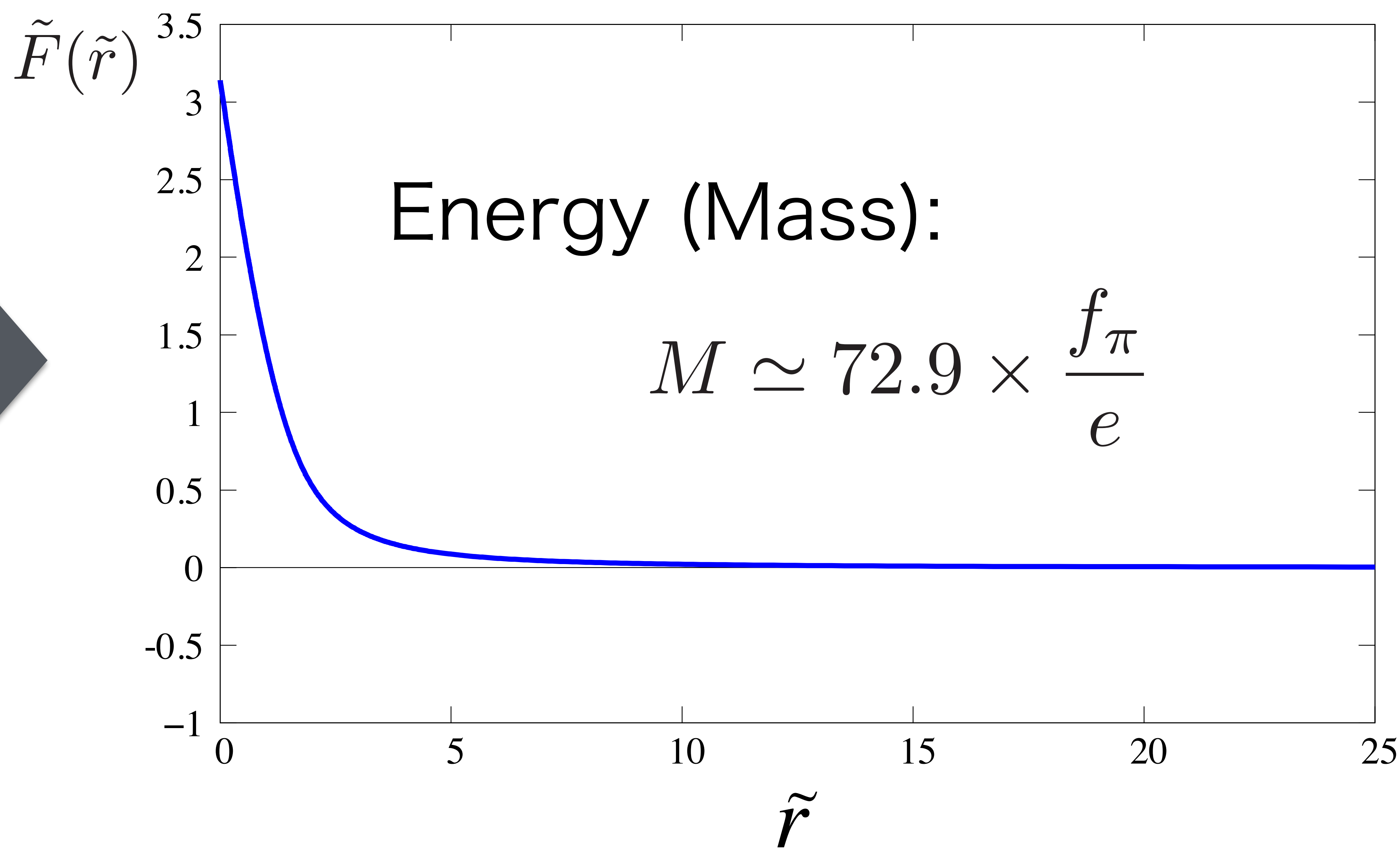
Skyrme Model

$$\left(\tilde{r}^2 + 2\sin^2\tilde{F}(\tilde{r})\right)\tilde{F}''(\tilde{r}) + 2\,\tilde{r}\,\tilde{F}'(\tilde{r}) + \sin 2\tilde{F}(\tilde{r})\left(\tilde{F}'(\tilde{r})^2 - 1 - \frac{\sin^2\tilde{F}(\tilde{r})}{\tilde{r}^2}\right) = 0$$



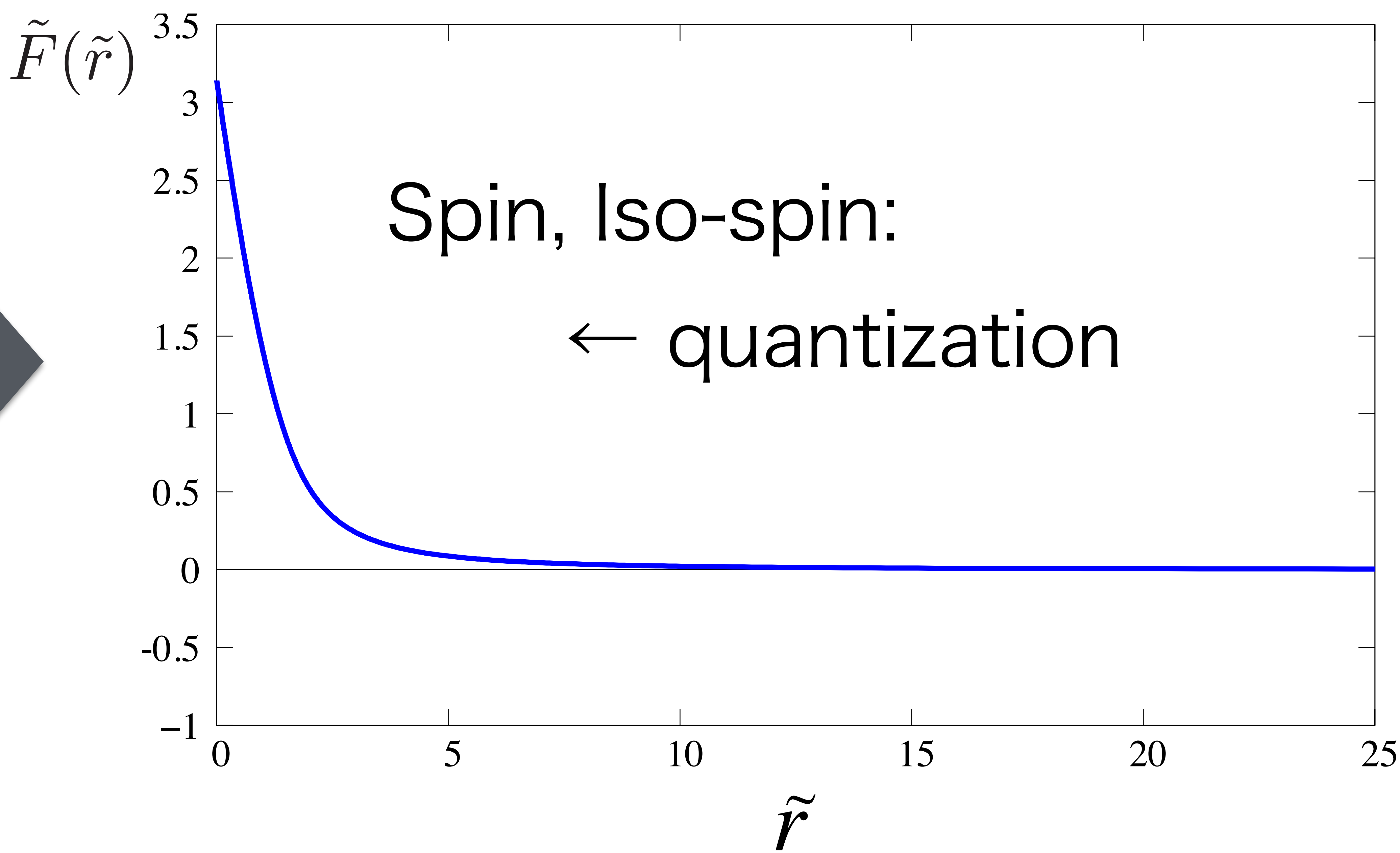
Skyrme Model

$$\left(\tilde{r}^2 + 2\sin^2\tilde{F}(\tilde{r})\right)\tilde{F}''(\tilde{r}) + 2\,\tilde{r}\,\tilde{F}'(\tilde{r}) + \sin 2\tilde{F}(\tilde{r})\left(\tilde{F}'(\tilde{r})^2 - 1 - \frac{\sin^2\tilde{F}(\tilde{r})}{\tilde{r}^2}\right) = 0$$



Skyrme Model

$$\left(\tilde{r}^2 + 2\sin^2 \tilde{F}(\tilde{r})\right) \tilde{F}''(\tilde{r}) + 2\,\tilde{r}\,\tilde{F}'(\tilde{r}) + \sin 2\tilde{F}(\tilde{r}) \left(\tilde{F}'(\tilde{r})^2 - 1 - \frac{\sin^2 \tilde{F}(\tilde{r})}{\tilde{r}^2} \right) = 0$$



We repeat the same procedure in the Higgs sector (+ Skyrme term)

$$\mathcal{L} = \frac{v_{\rm EW}^2}{4}\left(1+\frac{h(x)}{v_{\rm EW}}\right)^2 \mathrm{Tr}\left[\partial_\mu U(x)\,\partial^\mu U(x)^\dagger\right] \;+\; \frac{1}{2}\partial_\mu h(x)\partial^\mu h(x) - V(h(x))$$

$$+\frac{1}{32e^2}\,\mathrm{Tr}\left[\,\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\,\right]^2$$

Differences compared to the Skyrme model:

- scale $f_\pi \;\Rightarrow\; v_{\rm EW}$
- existence of the scalar

Assume:

$$U(x) = e^{iF(r)\sigma^i \hat{x}_i}$$ (hedgehog)

$$h_0(x)/v_{\mathrm{EW}} = \phi(r)$$ (spherially symmetric)

Energy:

$$E\left[\tilde{F}(\tilde{r}), \tilde{\phi}(\tilde{r})\right] = 2\pi \left(\frac{v_{\mathrm{EW}}}{e}\right) \int_0^\infty d\tilde{r}\tilde{r}^2 \Bigg[\left(1+\tilde{\phi}(\tilde{r})\right)^2 \left(\tilde{F}'(\tilde{r})^2 + 2\frac{\sin^2 \tilde{F}(\tilde{r})}{\tilde{r}^2}\right) + \frac{\sin^2 \tilde{F}(\tilde{r})}{\tilde{r}^2}\left(\frac{\sin^2 \tilde{F}(\tilde{r})}{\tilde{r}^2} + 2\tilde{F}'(\tilde{r})^2\right) + \tilde{\phi}'(\tilde{r})^2 + \boxed{\frac{m_h^2}{e^2\, v_{\mathrm{EW}}^2}}\left(\tilde{\phi}(\tilde{r})^2 + \tilde{\phi}(\tilde{r})^3 + \frac{1}{4}\tilde{\phi}(\tilde{r})^4\right)\Bigg]$$

$$\tilde{r} = \frac{r}{R}, \quad \text{where} \quad R \equiv \frac{1}{e\, v_{\mathrm{EW}}}$$

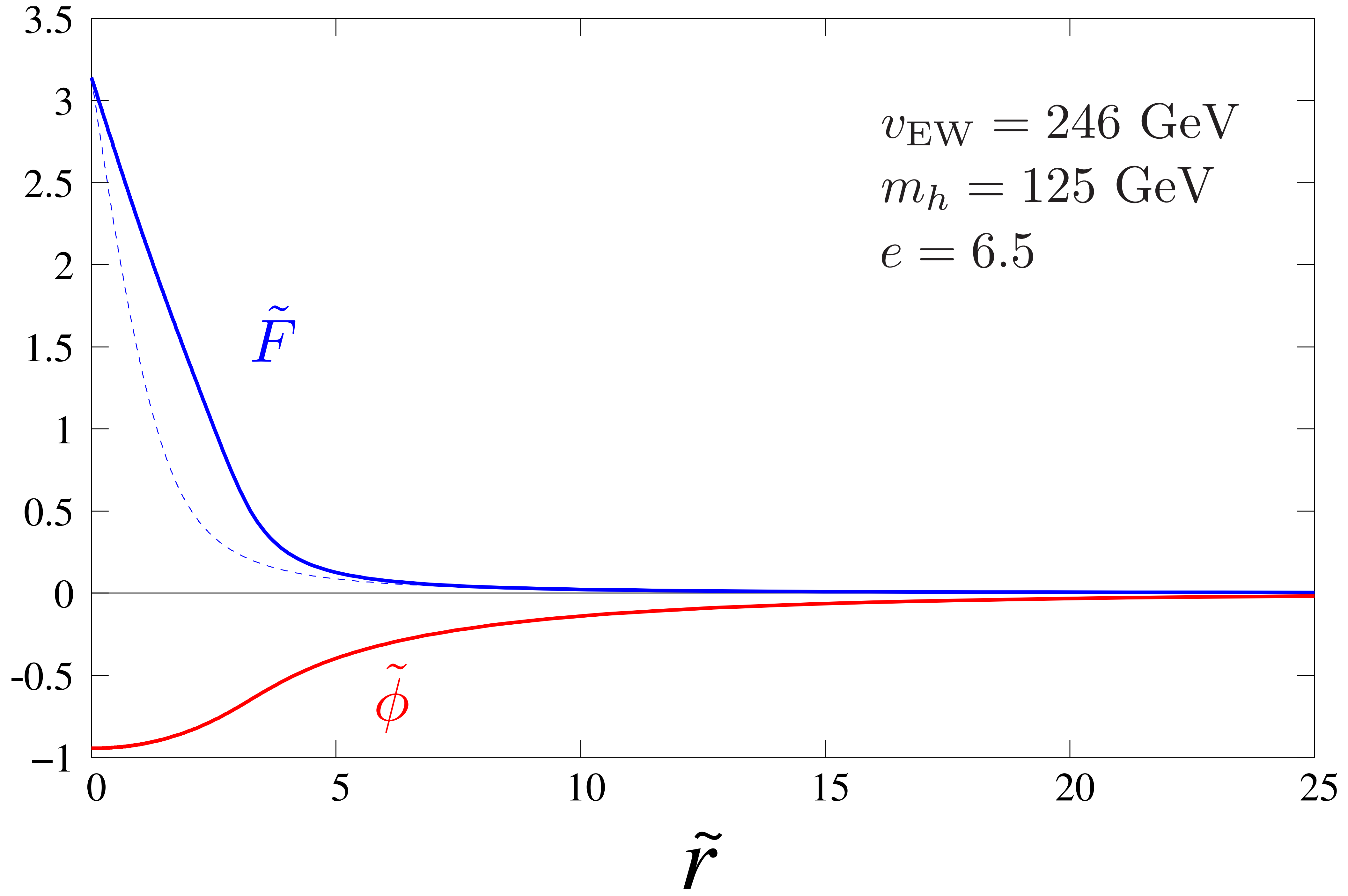
$$\phi(r) = \phi(\tilde{r}R) \equiv \tilde{\phi}(\tilde{r})$$

Coupled equations for $\tilde{F}$ and $\tilde{\phi}$

$$\left(1+\tilde{\phi}(\tilde{r})\right)^2\left(-\sin 2\tilde{F}(\tilde{r})+2\tilde{r}\tilde{F}'(\tilde{r})+\tilde{r}^2\tilde{F}''(\tilde{r})\right)+2\left(1+\tilde{\phi}(\tilde{r})\right)\tilde{\phi}'(\tilde{r})\,\tilde{r}^2\tilde{F}'(\tilde{r})$$
$$-\frac{\sin^2\tilde{F}(\tilde{r})\sin 2\tilde{F}(\tilde{r})}{\tilde{r}^2}+\sin 2\tilde{F}(\tilde{r})\,\tilde{F}'(\tilde{r})^2+2\sin^2\tilde{F}(\tilde{r})\,\tilde{F}''(\tilde{r})=0$$

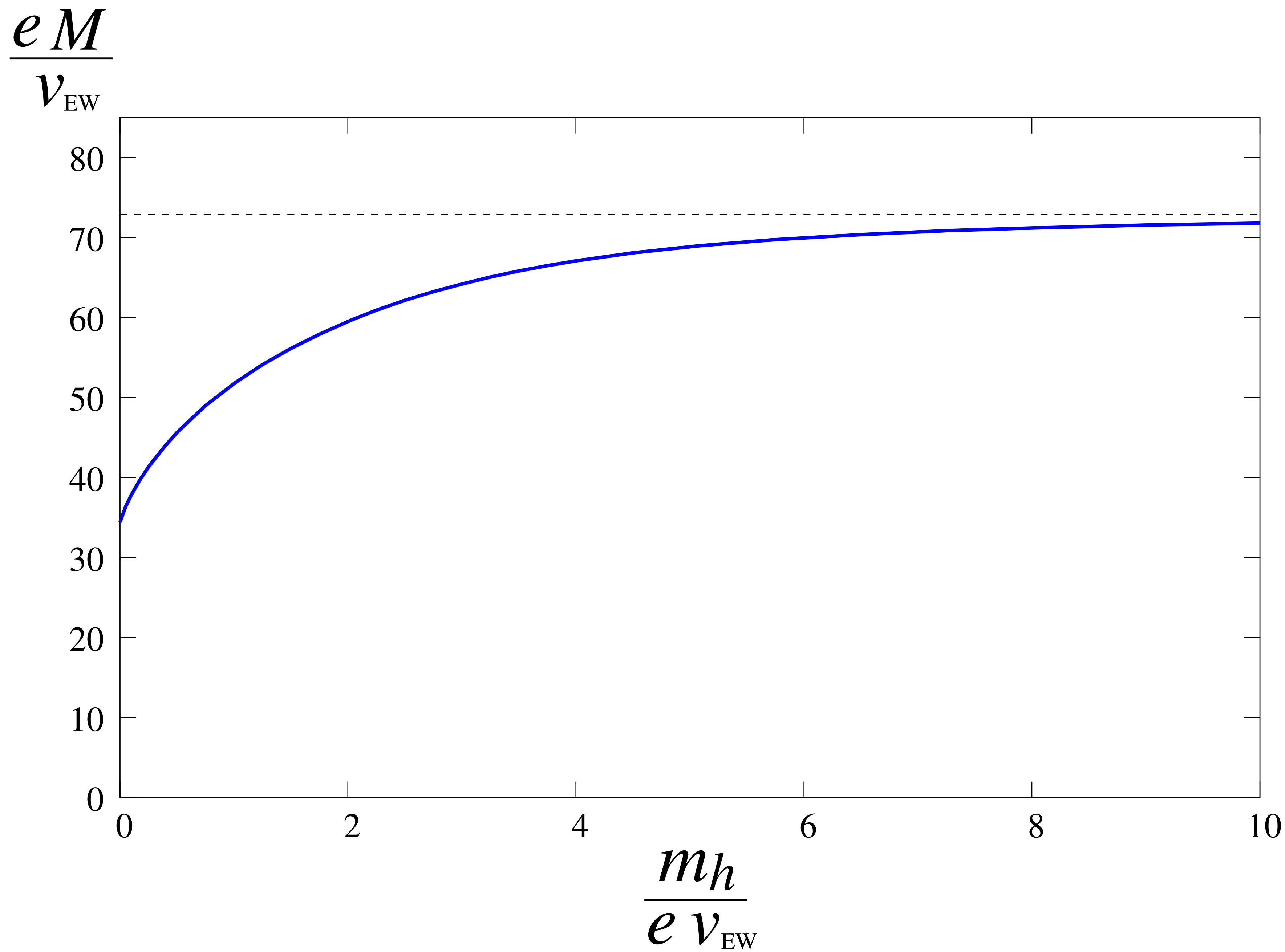
$$\left(1+\tilde{\phi}(\tilde{r})\right)\left(\tilde{r}^2\tilde{F}'(\tilde{r})+2\sin^2\tilde{F}(\tilde{r})\right)-2\tilde{r}\tilde{\phi}'(\tilde{r})-\tilde{r}^2\tilde{\phi}''(\tilde{r})$$
$$+\frac{1}{2}\boxed{\frac{m_h^2}{e^2\,v_{\mathrm{EW}}^2}}\,\tilde{r}^2\left(2\,\tilde{\phi}(\tilde{r})+3\,\tilde{\phi}(\tilde{r})^2+\tilde{\phi}(\tilde{r})^4\right)\;=\;0$$

Solution:



3.5
3
2.5
2
1.5
1
0.5
0
-0.5
−1
0
5
10
15
20
25
$v_{\rm EW} = 246$ GeV
$m_h = 125$ GeV
$e = 6.5$
$\tilde{F}$
$\tilde{\phi}$
$\tilde{r}$

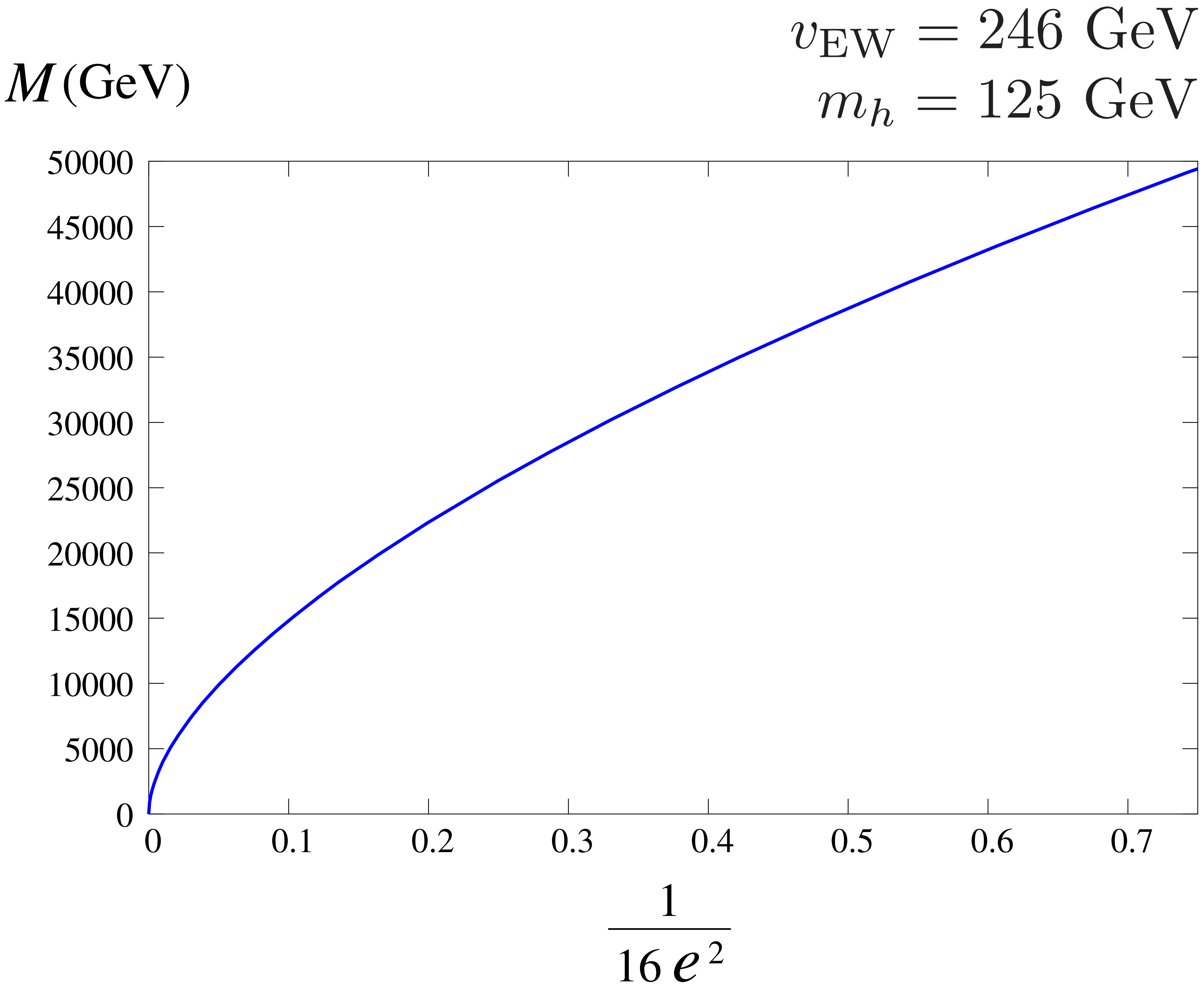
Mass (in the unit of $\frac{v_{\mathrm{EW}}}{e}$)



$m_h \to$ large $\quad \frac{M}{v_{\mathrm{EW}}/e}$ approaches to the value in the Skyrme model

$m_h \to$ small $\quad \frac{M}{v_{\mathrm{EW}}/e}$ is reduced

Mass

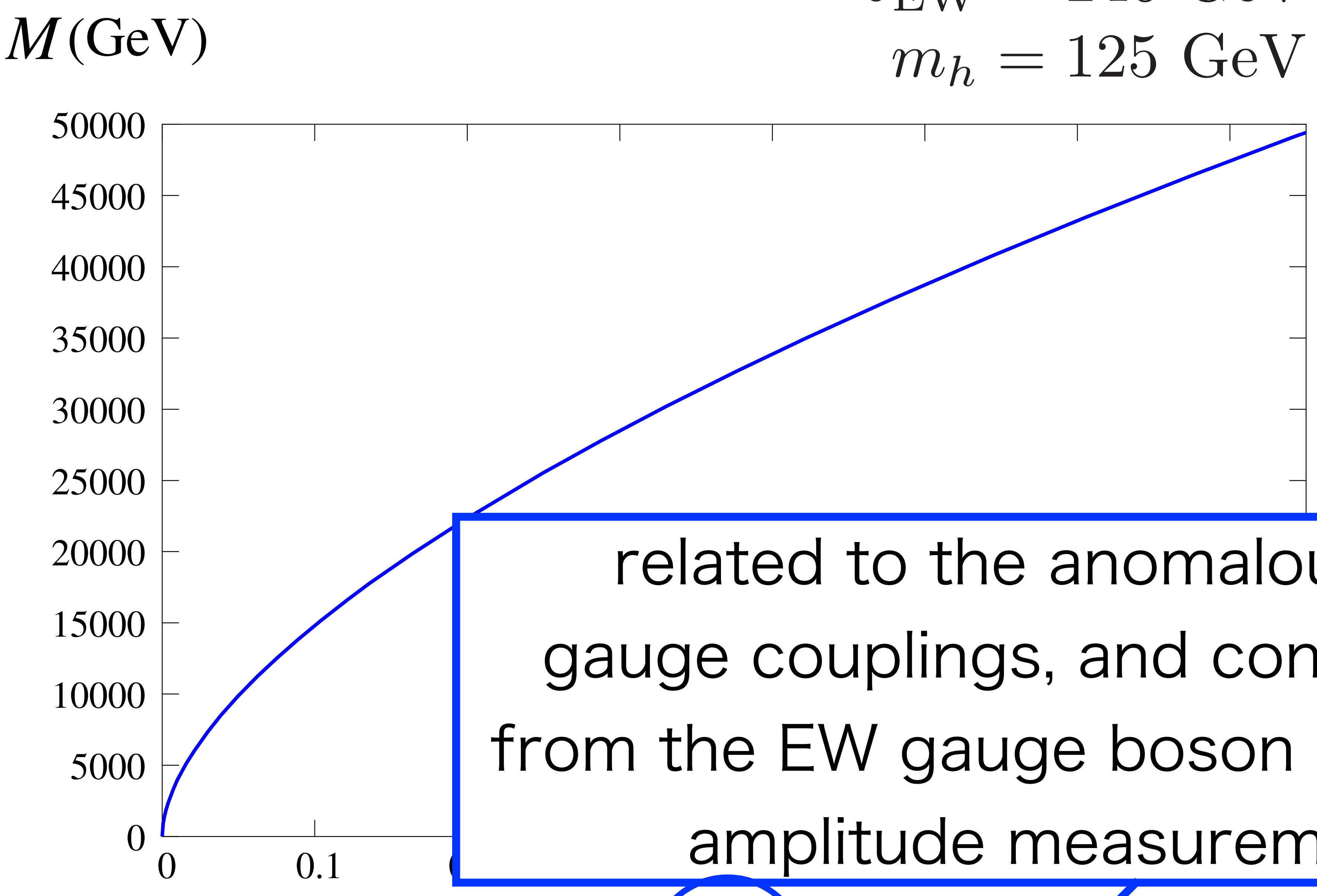


$v_{EW} = 246$ GeV
$m_h = 125$ GeV
M (GeV)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$\frac{1}{16 e^2}$

Mass

experimental constraint

$v_{\rm EW} = 246\ \text{GeV}$
$m_h = 125\ \text{GeV}$

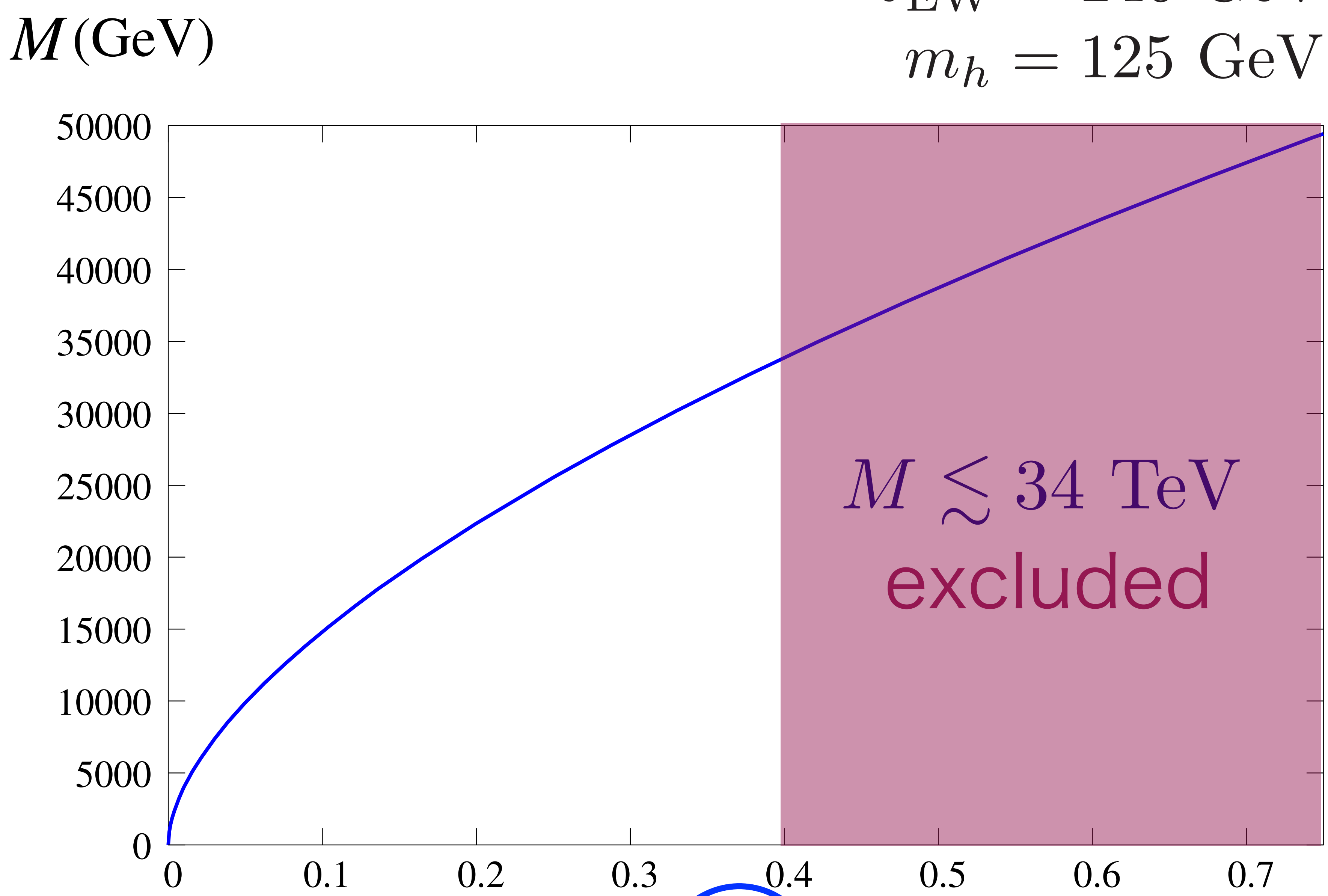


related to the anomalous EW gauge couplings, and constrained from the EW gauge boson scattering amplitude measurement

$$\frac{1}{16e^2} = -\alpha_5$$

Mass experimental constraint

$$v_{\rm EW} = 246\ {\rm GeV}$$
$$m_h = 125\ {\rm GeV}$$

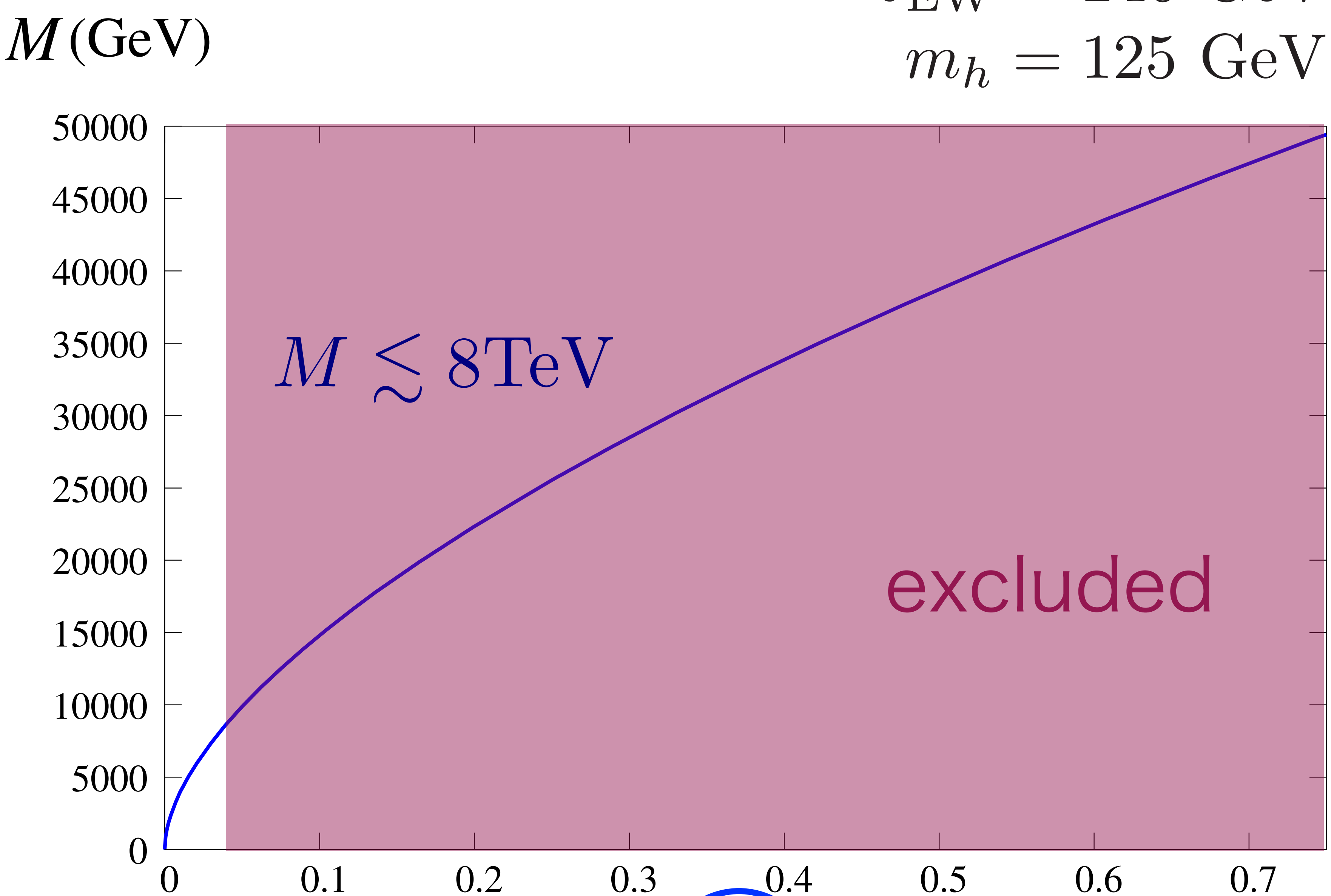


$$\frac{1}{16e^2} = -\alpha_5 \lesssim 0.4$$

G. Aad et al. [ATLAS Collaboration], PRL 113, 141803 (2014)
(arXiv:1405.6241)

Mass   experimental constraint

$$v_{\rm EW} = 246\ \text{GeV}$$
$$m_h = 125\ \text{GeV}$$



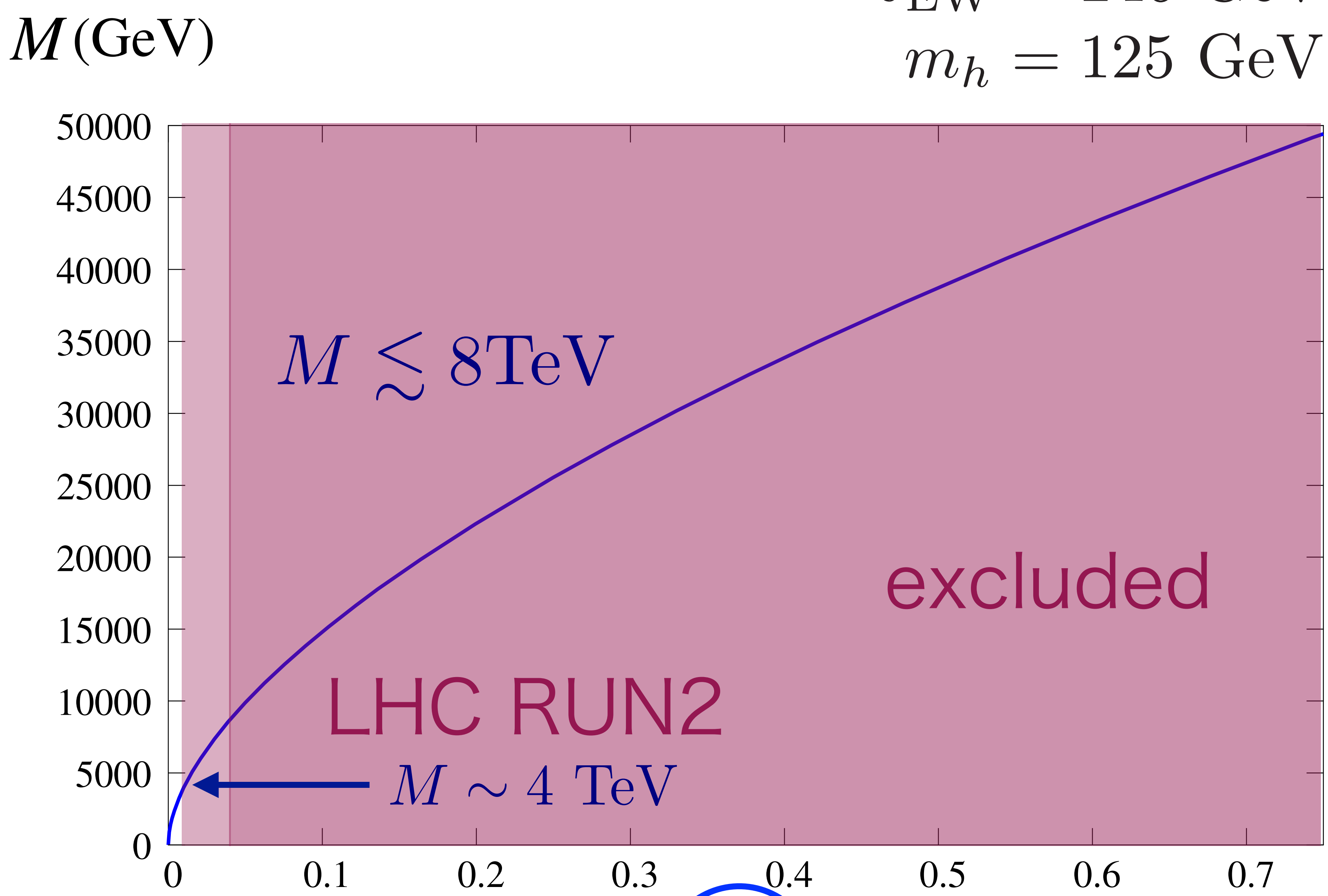
$$\frac{1}{16e^2} = -\alpha_5 \lesssim 0.04$$

arXiv:1609.05122 (ATLAS)

Mass

experimental constraint

$v_{\rm EW} = 246$ GeV
$m_h = 125$ GeV



$$\frac{1}{16e^2} = -\alpha_5 \lesssim 0.04$$

arXiv:1609.05122 (ATLAS)

Cosmology: EW-Skyrmion as Dark Matter

Thermal production?

$$\Omega_S h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{sec}}{\langle \sigma_A v_{\mathrm{rel}} \rangle} \approx 0.1$$

$$\sim \pi R^2 = \pi/(e\, v_{\mathrm{EW}})^2$$

$$e \sim 150 \quad (\Leftrightarrow M \sim 60 \text{ GeV})$$

(strongly) disfavored by the direct detection experiment

We simply assume the right amount of the asymmetry was produced in the history of the Universe

Cosmology: EW-Skyrmion as Dark Matter

Constraint from the direct detection experiment (LUX)

simple assumption for a rough estimate: $\mathcal{L}_{\rm eff} = -2\kappa |S|^2 |H^2|$

$$\sigma_{\rm SI} \approx \frac{\kappa^2 m_N^4 f^2}{\pi M^2 m_h^4}$$

$$\simeq \left(\frac{\kappa}{1.0}\right)^2 \left(\frac{1\,\text{TeV}}{M}\right)^2 \left(\frac{f}{0.3}\right)^2 \times 3.6 \times 10^{-44}\ \text{cm}^2$$

LUX updated

2.5TeV

$f = 0.3$

$\kappa = 1.0\ \ (0.5,\ \pi)$

→

$M \gtrsim 1.5\ \text{TeV}$

$(M \gtrsim 1.0,\ 3.5\ \text{TeV})$

as of May 2016

Summary

- Topological dark matter exists in the SM with a minimal addition of the higher-dimensional operator
- Its mass is constrained from both sides by

DM direct detection & WW scattering

$$1.5\ \mathrm{TeV} \lesssim M \lesssim 34\ \mathrm{TeV}$$ ← May, 2016

↓ ↓

$2.5\,\mathrm{TeV}$ $8\,\mathrm{TeV}$ ← today

↓ ↓

Xenon1T $\sim 5\ \mathrm{TeV}$ $\sim 4\ \mathrm{TeV}$ ← near future

LZ $\sim 10\ \mathrm{TeV}$ LHC RUN2

Summary

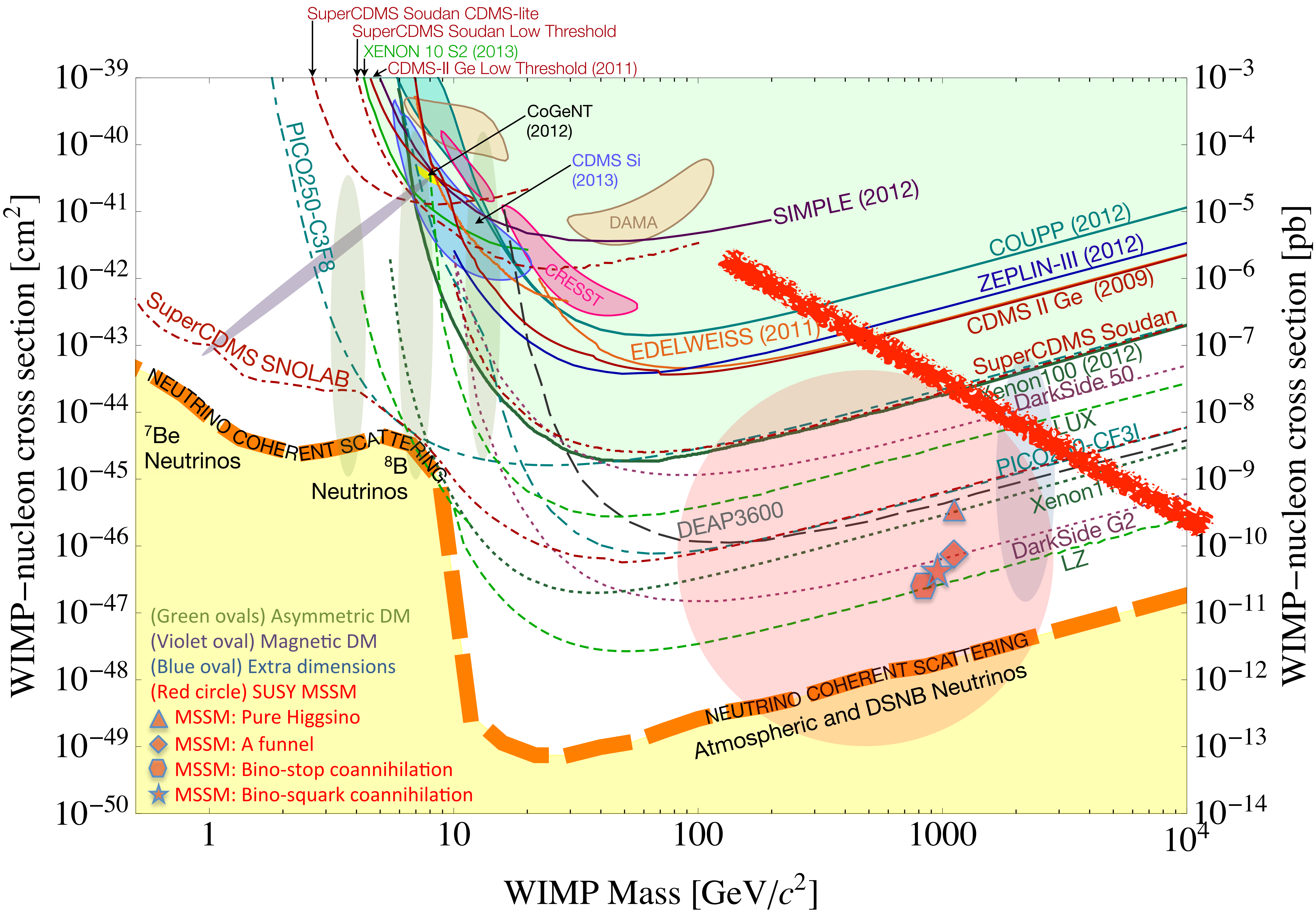
- Topological dark matter exists in the SM with a minimal addition of the higher-dimensional operator
- Its mass is constrained from both sides by

Wide mass range will be probed from **both** sides!
If the DM is directly detected, and we find
anomalous gauge couplings at the same time,
it could be the **EW-Skyrmion**!!!

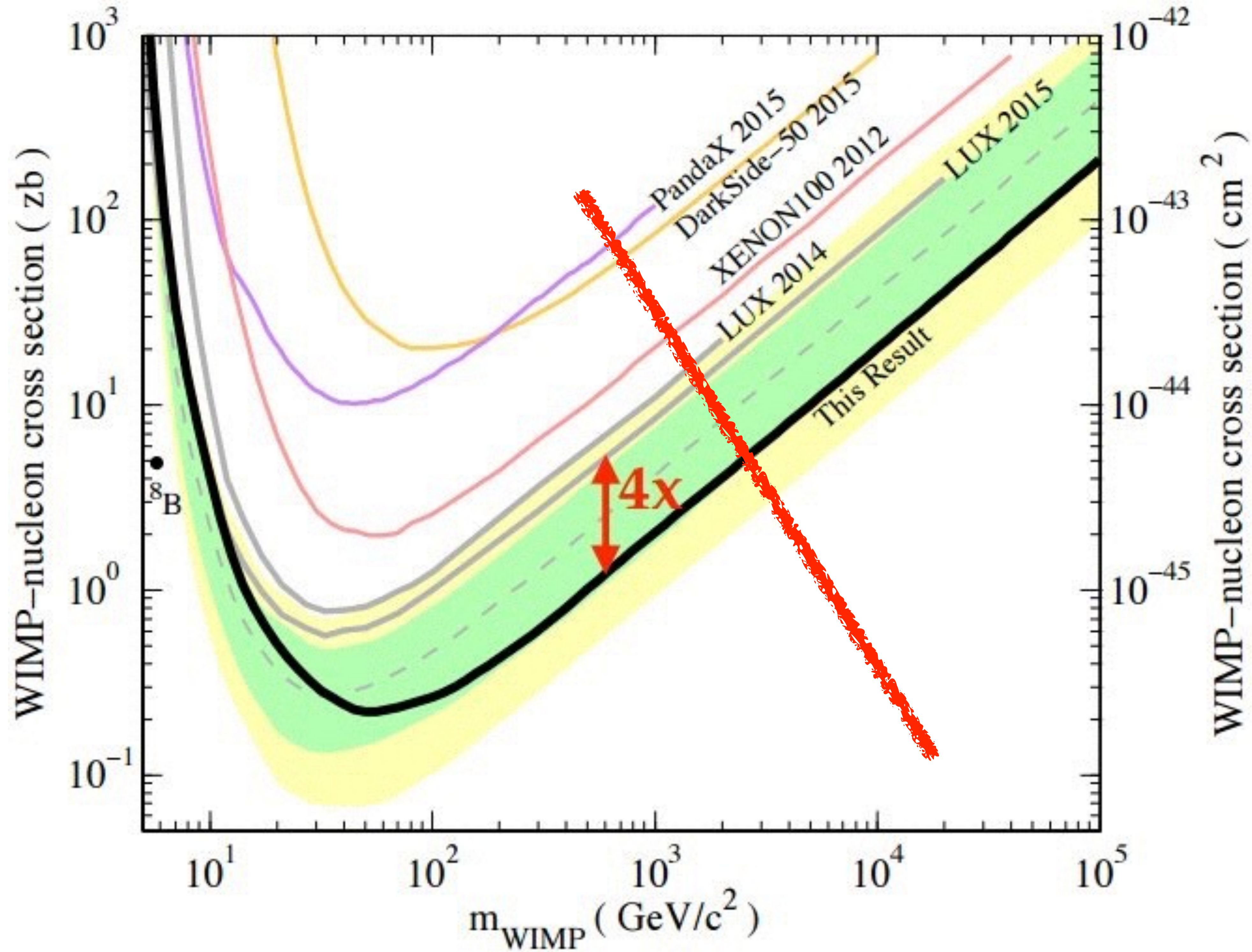
Xenon1T $\sim 5\ \mathrm{TeV}$
LZ $\sim 10\ \mathrm{TeV}$

$\sim 4\ \mathrm{TeV}$
LHC RUN2 ← near future

Backup



SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]


PandaX 2015
DarkSide-50 2015
XENON100 2012
LUX 2014
LUX 2015
This Result
4x
8B
WIMP–nucleon cross section (zb)
WIMP–nucleon cross section (cm 2)
m WIMP (GeV/c2)
10^3
10^2
10^1
10^0
10^-1
10^-42
10^-43
10^-44
10^-45
10^1
10^2
10^3
10^4
10^5