universitätbonn bctp Bethe Center for Theoretical Physics

Is Dark Matter
Elementary
or
Composite
or
Partially Composite?

Masaki Asano
(Bonn University)

Dark Matter

In this talk

- Elementary ⇦ Supersymmetry
- Composite ⇦ Composite Higgs
- Partially Composite

I discuss possibilities Beyond the vanilla WIMP DM from model building side.

Elementary DM

Elementary DM

Neutralino in SUSY: Thermal relic can be consistent with observations.

But,

- **Gravitino (and/or moduli) can spoil the BBN and/or usual WIMP scenario in SUSY.**
- **Thermal Neutralino WIMP scenario restricts the SUSY breaking and mediation scenario.**

For example, gauge mediation cannot be such a thermal neutralino WIMP scenario?

Elementary DM

Neutralino in SUSY: Thermal relic can be consistent with observations.

But,

- **Gravitino (and/or moduli) can spoil the BBN and/or usual WIMP scenario in SUSY.**
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We discuss

Gauge mediation with a 100 TeV Gravitino

- **Very heavy gravitino**
- **Neutralino LSP**

Elementary DM

Gauge mediation can suppress dangerous FCNCs.

Gravity mediation does not spoil this advantage, if

$$M_{mess} << M_{pl}$$

Small gravitino mass

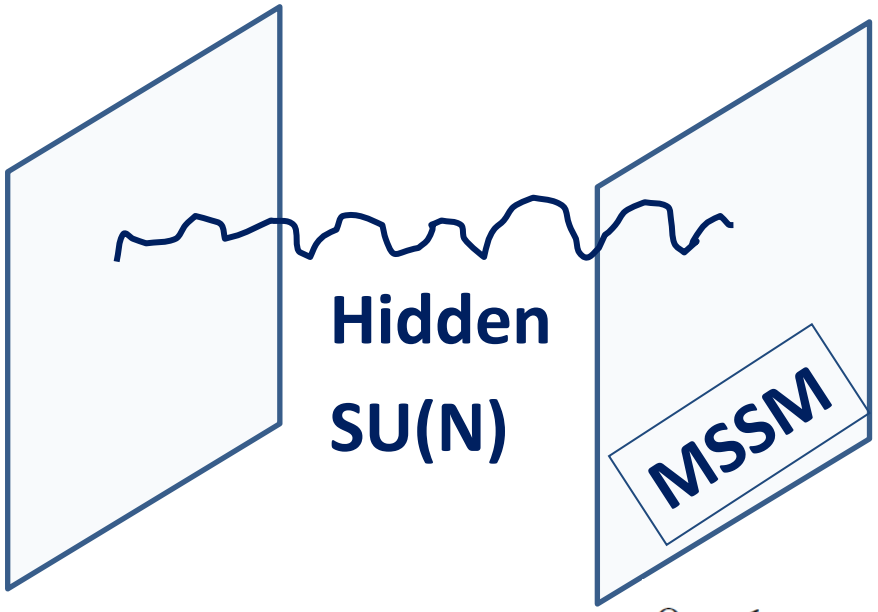
- **Only O(1) eV gravitino is allowed.**
- **Such a low-scale mediation is constrained from LHC results and vacuum instability.**

Gauge mediation with a 100 TeV Gravitino

MA, Nakai, Yokozaki '15

Elementary DM

Scherk-Schwarz SUSY breaking



$$0 \leq y \leq 2\pi R \text{ with identification } y \leftrightarrow -y$$

- **flat 5D space & y is compactified on an S^1/Z_2 orbifold.**

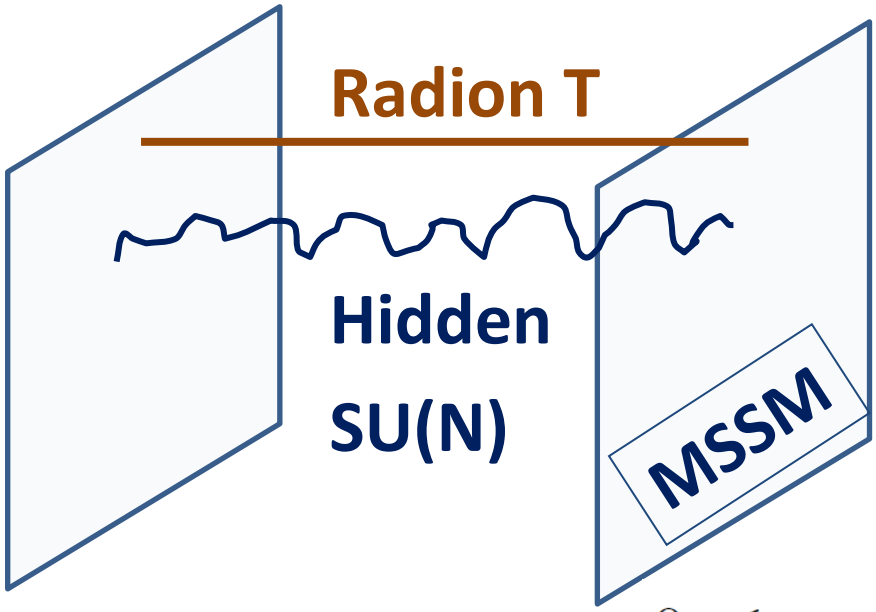
4D Planck: $M_4^2 = 2\pi R M_5^3 = L M_5^3$

5D Planck: $M_5 \approx 3.9 \times 10^{17}\text{GeV} \left(\frac{L^{-1}}{10^{16}\,\text{GeV}} \right)^{1/3}$

MA, Nakai, Yokozaki '15

Elementary DM

Scherk-Schwarz SUSY breaking ↔ radion Fterm breaking



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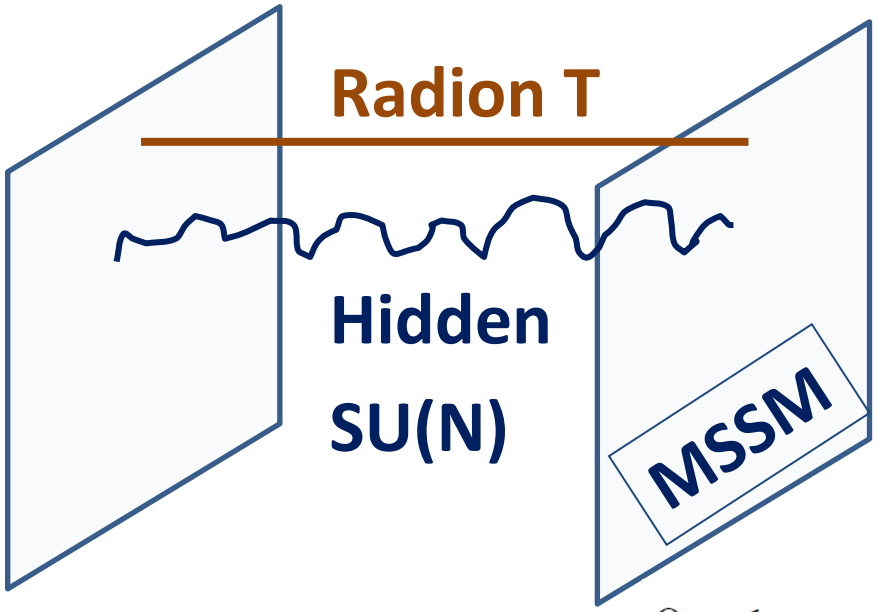

compensator

$$\mathcal{L}_4^{\rm eff} \supset -3M_5^3 \int d^4\theta\, \phi^\dagger \phi\, (T+T^\dagger) + \int d^2\theta\, \phi^3 \mathcal{C} + {\rm h.c.}$$

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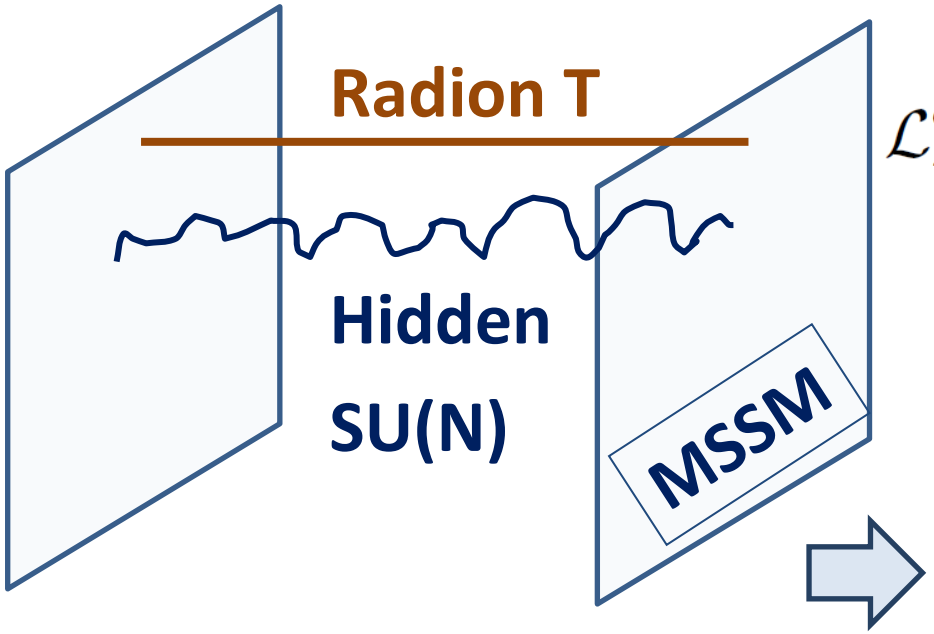

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Luty, Okada '02

$$F_T = \frac{\mathcal{C}^*}{M_5^3}\,, \quad F_\phi = 0\,,$$

MA, Nakai, Yokozaki '15

Elementary DM

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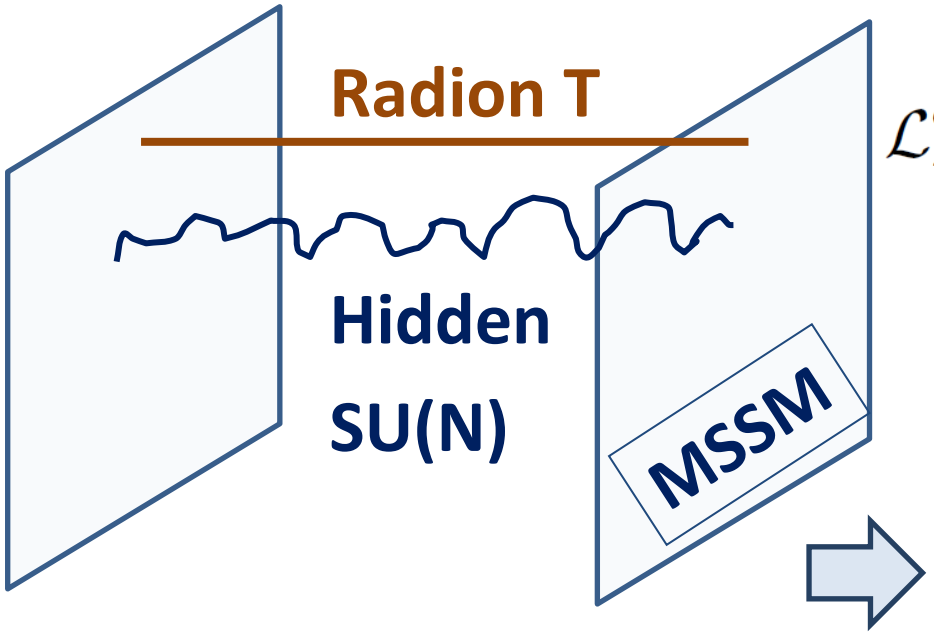

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$$F_T = \frac{\mathcal{C}^*}{M_5^3}\,, \quad F_\phi = 0\,,$$

Even if large gravitino mass $m_{3/2} = \dfrac{\mathcal{C}^*}{M_4^2} = \dfrac{F_T}{L}$

No large anomaly mediation.

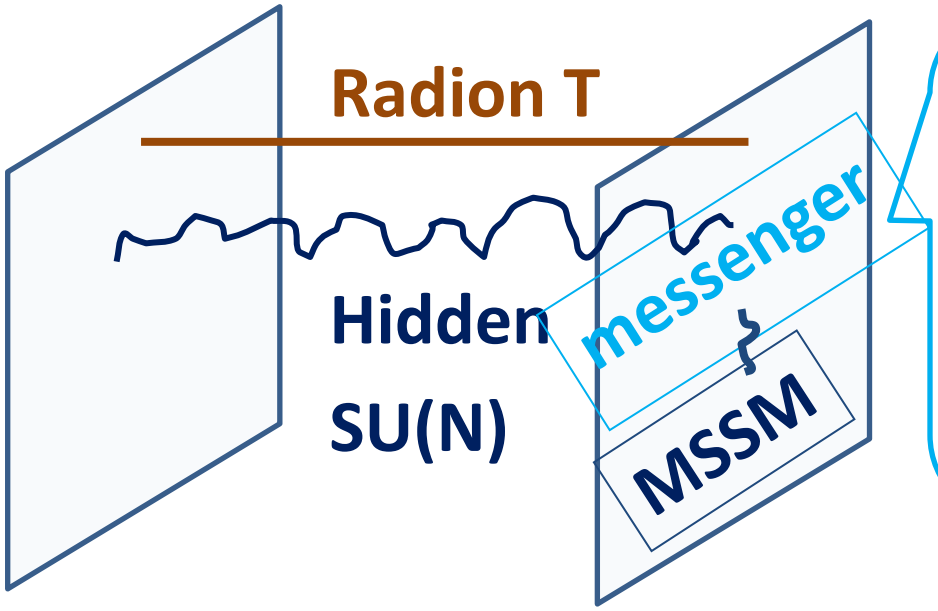
(Note that 5D gravitational multiplet in the bulk mediate ~~SUSY~~.)

MA, Nakai, Yokozaki '15

Elementary DM

Scherk-Schwarz SUSY breaking

Gauge mediation sector



$$W = \lambda_1 X Q \bar{Q} + \lambda_m X \Psi \bar{\Psi} + \frac{\kappa}{3} X^3$$

MA, Nakai, Yokozaki '15

Elementary DM

Scherk-Schwarz SUSY breaking

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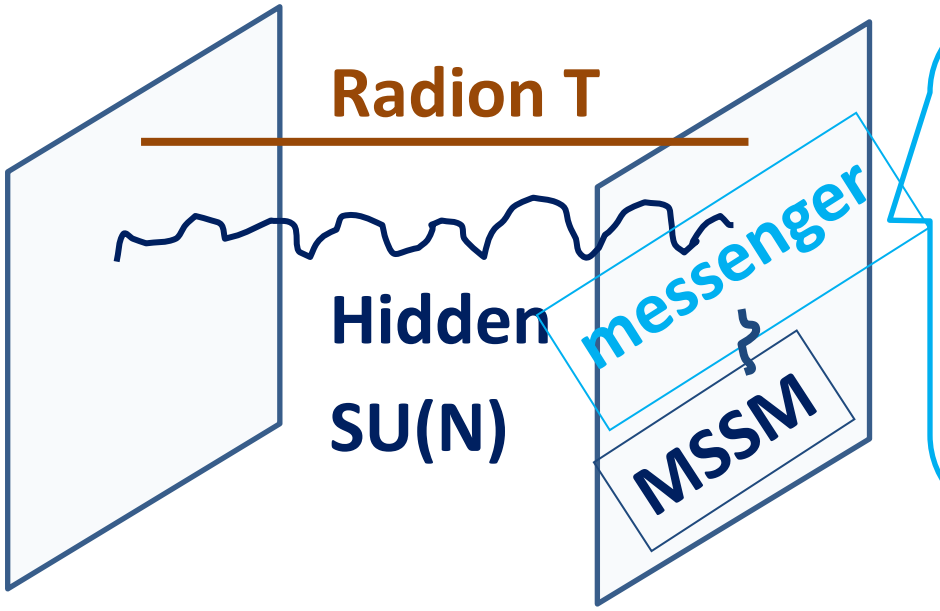

$$W = \lambda_1 X Q \bar{Q} + \lambda_m X \Psi \bar{\Psi} + \frac{\kappa}{3} X^3$$

Usual messenger

MA, Nakai, Yokozaki '15

Elementary DM

Scherk-Schwarz SUSY breaking

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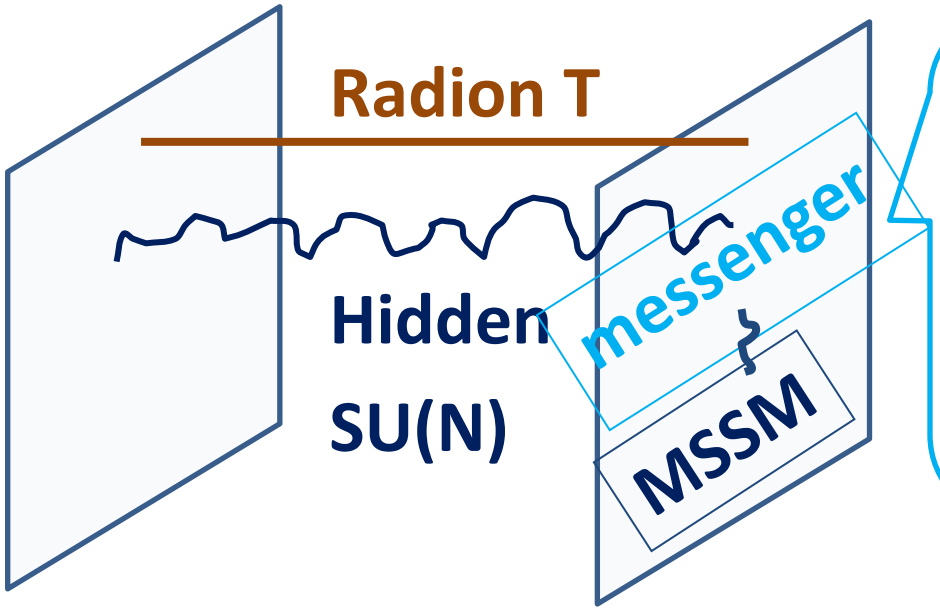

Hidden SU(N) charged

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Usual messenger

MA, Nakai, Yokozaki '15

Elementary DM

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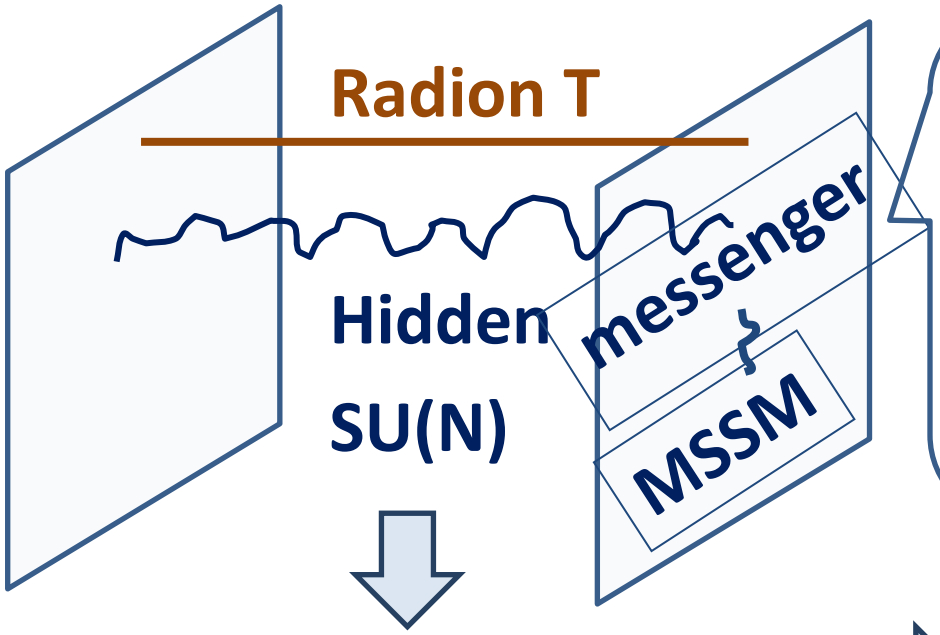

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Hidden gaugino mass ⇒ Scalar Q&Qbar mass

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Elementary DM

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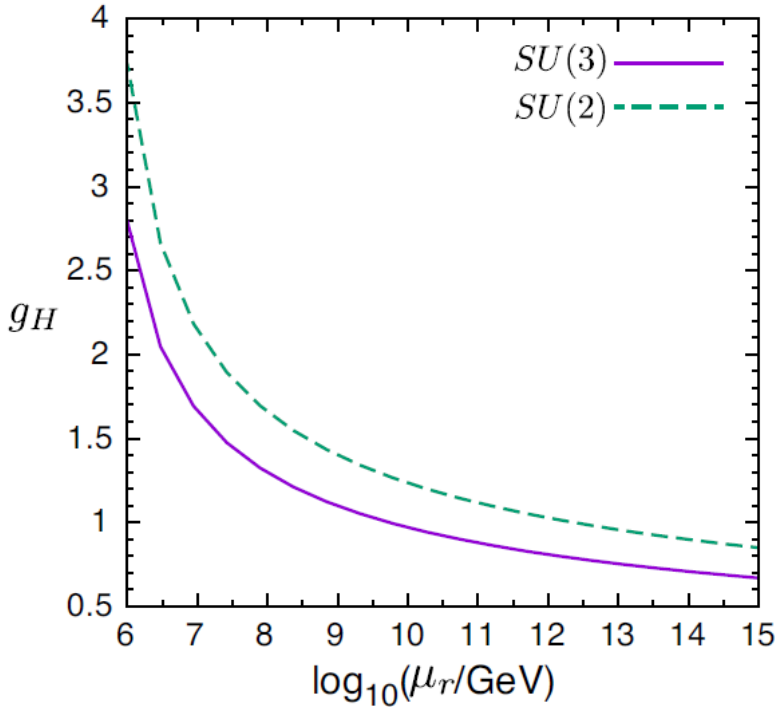

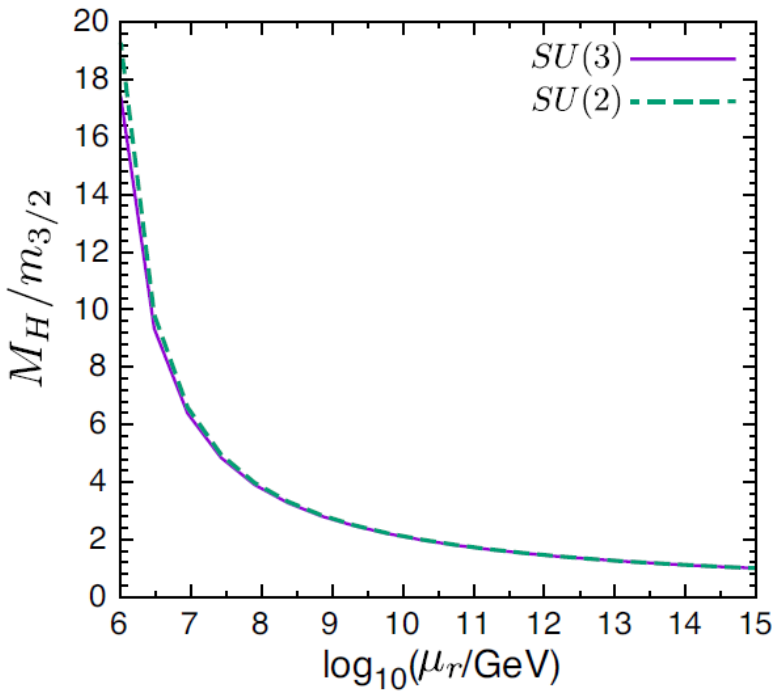

Hidden gaugino mass ⇒ **Scalar Q&Qbar mass**

~ 10 $m_{3/2}$ (@ low scale) **~ 10 $m_{3/2}$ (@ low scale)**

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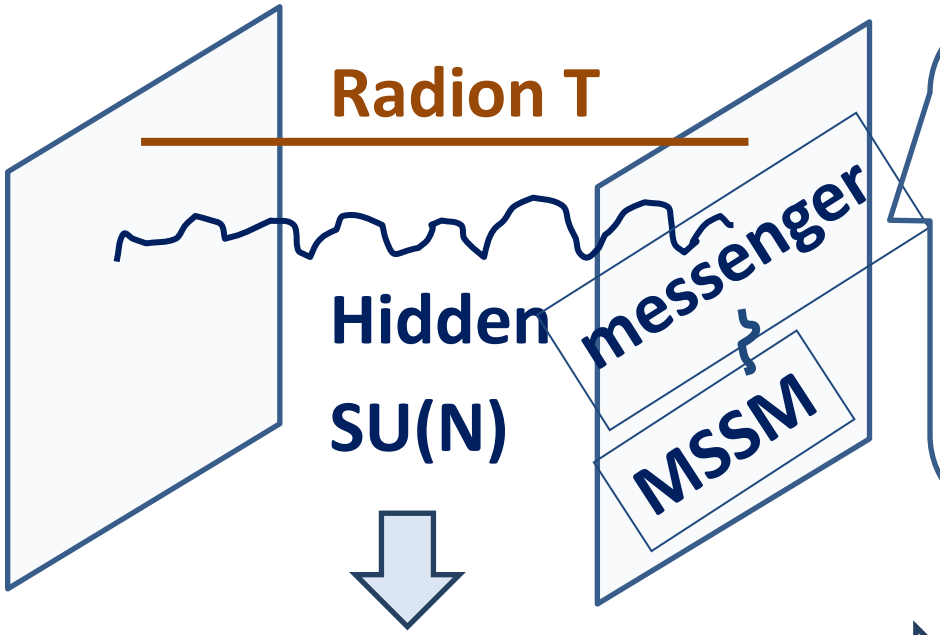
Elementary DM

Scherk-Schwarz SUSY breaking



Gauge mediation sector

Hidden SU(N) charged

$$W = \lambda_1 X Q \bar{Q} + \lambda_m X \Psi \bar{\Psi} + \frac{\kappa}{3} X^3$$

Hidden gaugino mass

$$V = -|m_X^2||X|^2 \quad + \ldots$$

Scalar Q&Qbar mass

X has negative soft mass

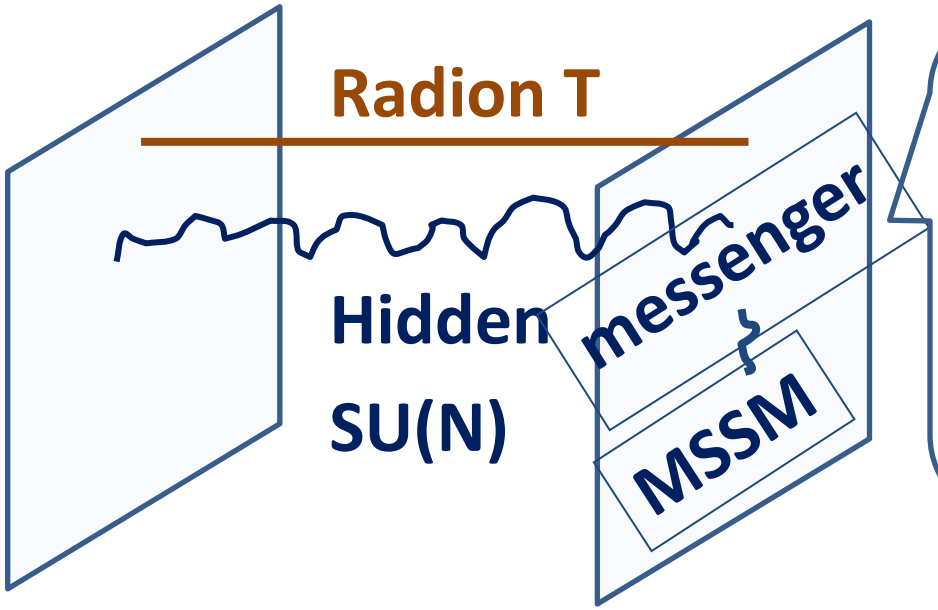
X gets non-zero VEV and F

MA, Nakai, Yokozaki '15

Elementary DM

Scherk-Schwarz SUSY breaking

Gauge mediation sector



Hidden SU(N) charged

$$W = \lambda_1 X Q \bar{Q} + \lambda_m X \Psi \bar{\Psi} + \frac{\kappa}{3} X^3$$

$\Psi\bar{\Psi}$: usual messenger

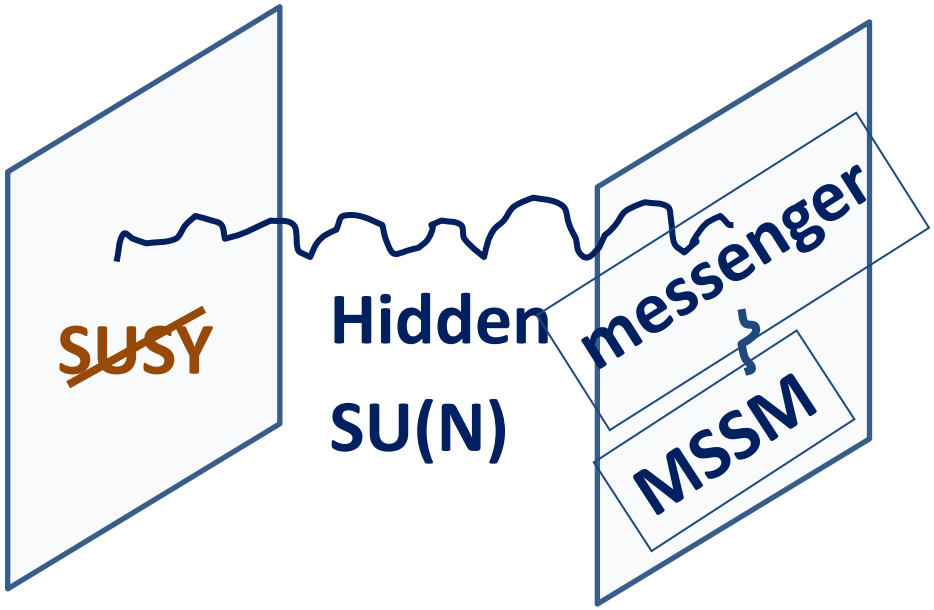
$$M_{\rm mess} = \lambda_m \langle X \rangle \qquad \Lambda_m = \left(\kappa \frac{\langle X^\dagger \rangle^2}{\langle X \rangle} + A_m \right)$$

can be ~ $m_{3/2}$

MA, Nakai, Yokozaki '15

Elementary DM

Localized SUSY breaking is also OK.



$$F_\phi = 0\,,$$

By assuming a shift symmetry of a ~~SUSY~~ field Z,

→ Z dependence in the superpotential vanishes

→ Compensator F term become zero

as in the Scherk-Schwarz case.

Elementary DM

Gauge mediation with a 100 TeV Gravitino

is possible!!

- **Very heavy gravitino**
- **Neutralino LSP**
- **Soft masses of MSSM are the same as usual gauge mediation**

But,

There are several possibilities of how to get the 125 GeV Higgs mass, neutralino LSP and correct thermal relic.

Viable neutralino DM scenario would require extensions from the simple messenger multiplet.

Dark Matter

In this talk

- Elementary ⇦ Supersymmetry
- Composite ⇦ Composite Higgs
- Partially Composite

Composite Higgs

- **Higgs boson is a pseudo-NG boson**

  arising from a Global symmetry breaking.

Minimal Composite Higgs Model (MCHM)

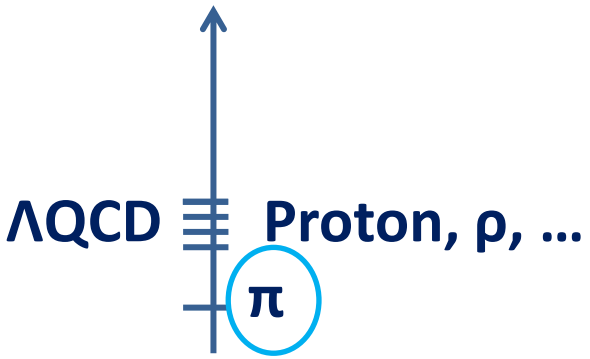
Agashe,Contino,Pomarol '04

SO(5)/SO(4) breaking

↓

4 NG bosons $\pi(x)$,

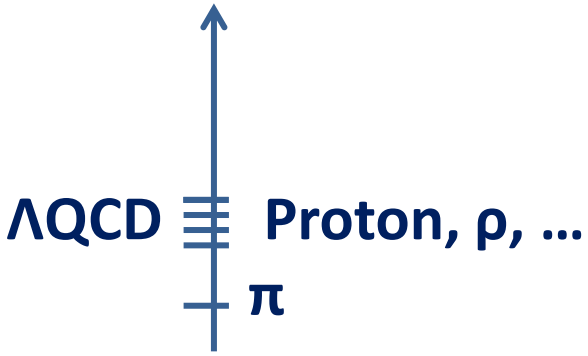
Higgs!!



Is there DM candidates?

Composite DM

Composite DM



For example, possibilities are

- Additional pseudo-NG boson

  e.g., singlet η from O(6)/O(5) with parity(η) in O(6)

  $m_{DM} \sim O(100)$ GeV

  Frigerio, Pomarol, Riva, Urbano '12;
  …

- Skyrmion

  topological stable configuration in π_3 (G/H) $\neq 0$ case

  $m_{DM} \sim O(1\text{-}10)$ TeV

  e.g., Murayama, Shu '09 (for little higgs);
  …

…

Dark Matter

In this talk

- Elementary ⇦ Supersymmetry
- Composite ⇦ **Composite Higgs**
- **Partially Composite**

DM plays an important role also for EWSB:

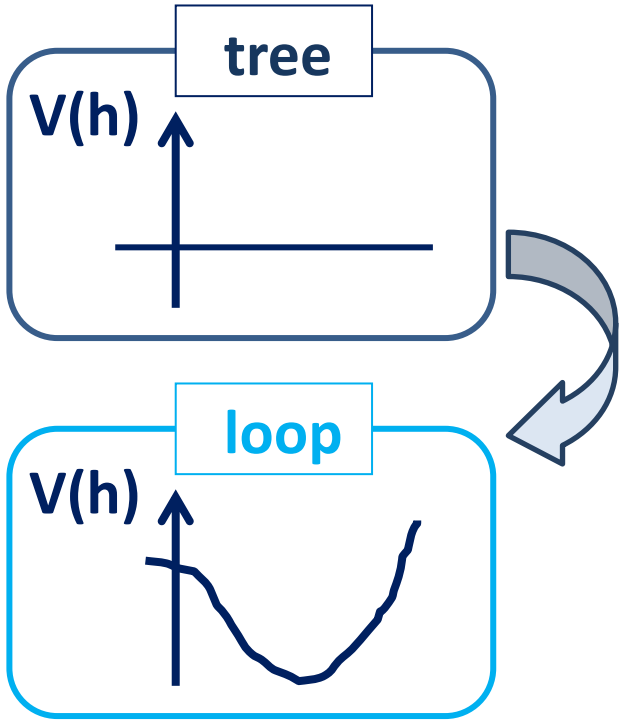
DM produces the Higgs potential like top!!

Partially Composite DM

At first, we discuss how to make the Higgs potential in the composite Higgs model →

Composite Higgs

- **Higgs boson is a pseudo-NG boson.**
  - Higgs potential is protected by the Global Symmetry.
  - EWSB scale is produced by the Explicit Breaking. (Yukawa & gauge couplings)

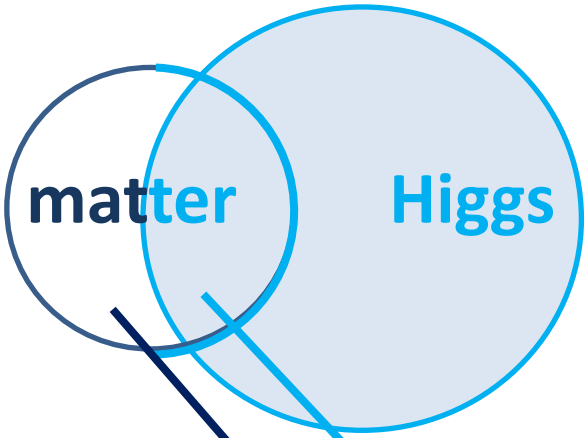


[Next] How implement the top quark? →

Composite Higgs

Top quark is implemented as

Partially composite fermions Kaplan '91



Elementary sector

Composite sector

Elementary -Composite mixing

$$\mathcal{L} \ni \lambda_L \psi_L O_R + (L \Leftrightarrow R)$$

Composite Higgs

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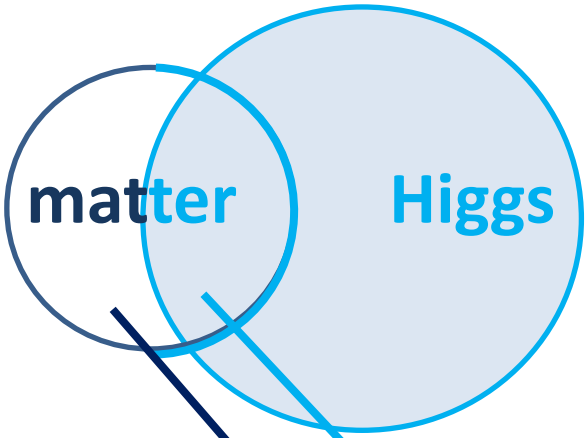


Elementary sector

Composite sector

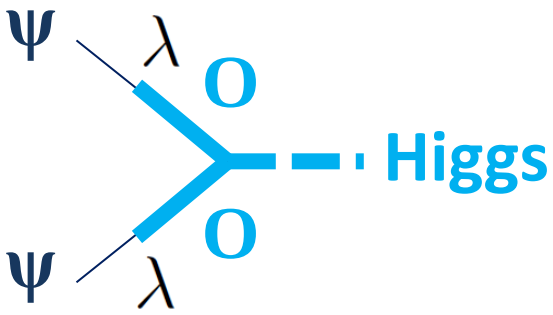
Elementary -Composite mixing

$$\mathcal{L} \ni \lambda_L \psi_L O_R + (L \Leftrightarrow R)$$

Explicit breaking couplings

→ produce Yukawa coupling & Higgs potential.

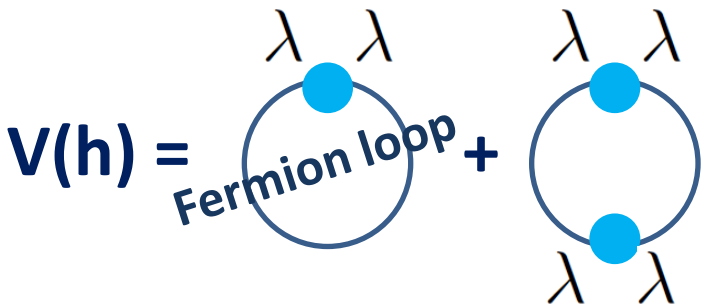
■ Yukawa coupling (very rough discussion)



$$y_t \sim \frac{\lambda^2}{4\pi} \sim 1$$

■ Higgs potential

For current study with $m_h \sim 125$GeV, e.g., Matsedonskyi, Panico, Wulzer '12; Marzocca, Serone, Shu '12 ;…



$$m_h^2 \sim \frac{\lambda^4}{(16\pi^2)^2}\frac{v^2}{f^4}m_T^4$$

Light top partner (~1 TeV) is favored.

$$\sim \frac{y_t^2}{16\pi^2}\frac{v^2}{f^4}m_T^4$$

[Next] How to get vev ~ 246 GeV? →

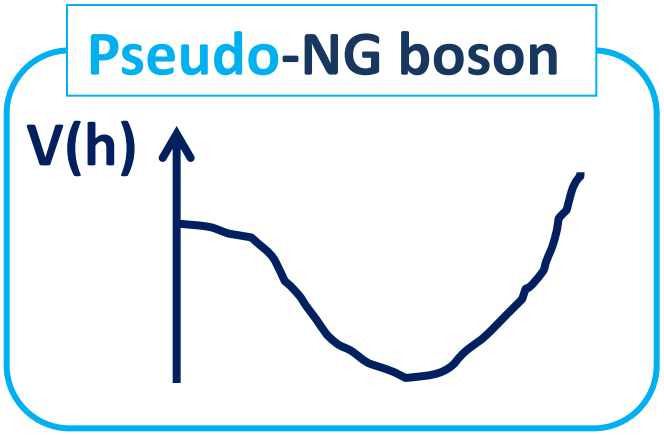
Minimal Composite Higgs Model

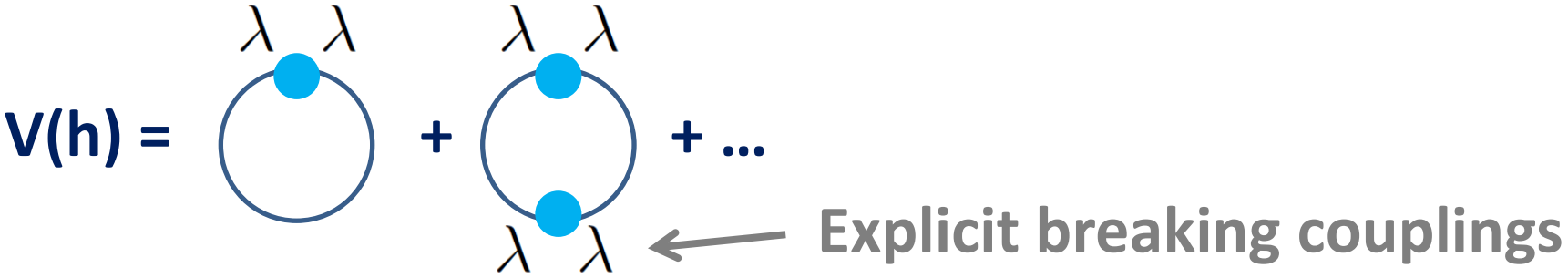
Agashe,Contino,Pomarol '04

Potential

$\mathbf{O_t}$: spinorial rep. 4 of SO(4)

$$V(h) \simeq \alpha_t \cos\frac{h}{f} - \beta_t \sin^2\frac{h}{f}$$





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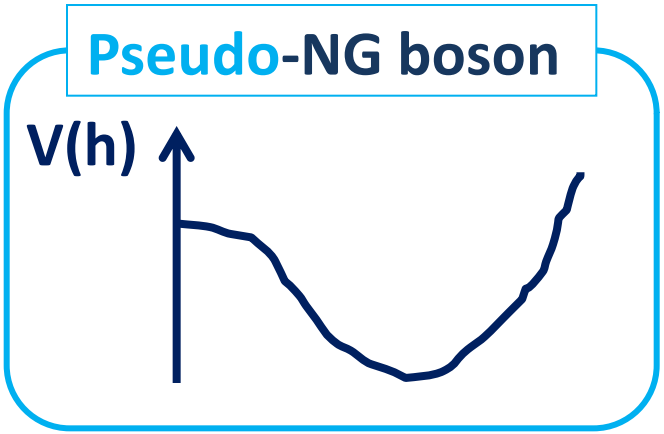
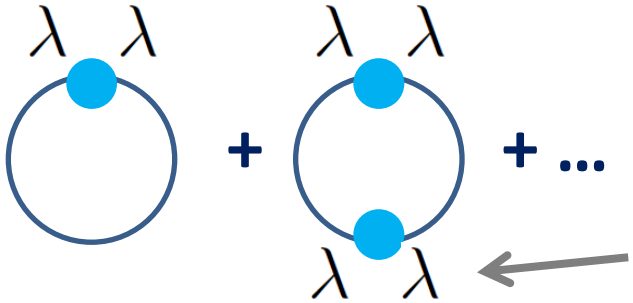


$$\alpha_t \sim \frac{\lambda^2}{(4\pi)^2}\left[\frac{m_{t'}^4}{(4\pi)^2}\right] \qquad \beta_t \sim \left(\frac{\lambda^2}{(4\pi)^2}\right)^2\left[\frac{m_{t'}^4}{(4\pi)^2}\right]$$

V(h) = 

Explicit breaking couplings

Minimal Composite Higgs Model

Agashe,Contino,Pomarol '04

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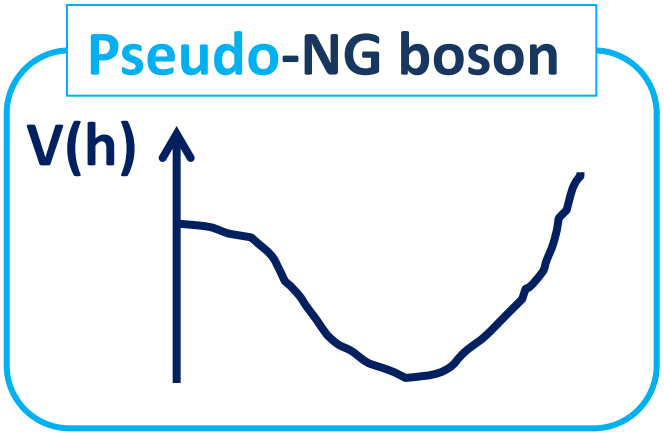
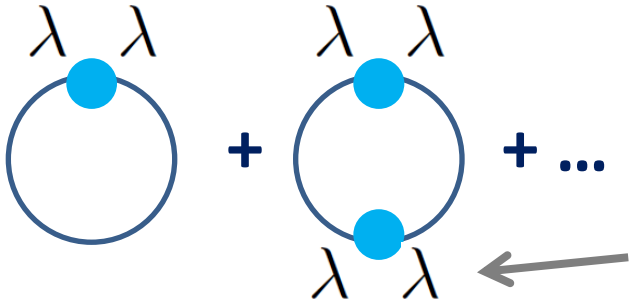


NDA $\quad \alpha_t \gg \beta_t$

V(h) =  + + ...

Explicit breaking couplings

Minimal Composite Higgs Model

Agashe,Contino,Pomarol '04

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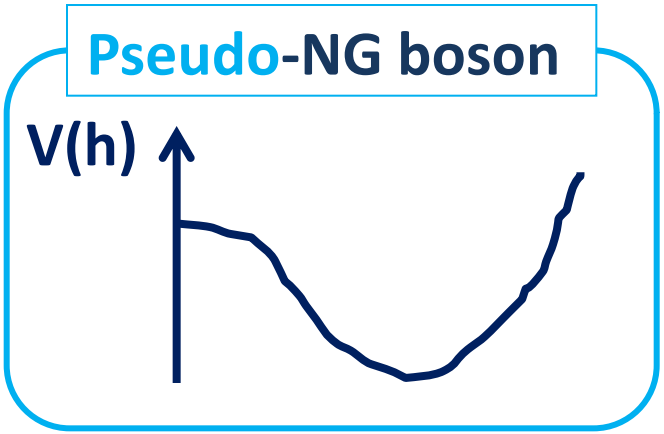
O_t: spinorial rep. 4 of SO(4)

$$V(h) \simeq \alpha_t \cos\frac{h}{f} - \beta_t \sin^2\frac{h}{f}$$

$$\frac{\partial V}{\partial h} = 0$$

$$v/f = \sqrt{1 - \frac{\alpha_t^2}{4\beta_t^2}} \equiv \epsilon$$



NDA $\quad \alpha_t \gg \beta_t$

Small ϵ (i.e. v << f)

is favored by experiments.

Minimal Composite Higgs Model

Agashe,Contino,Pomarol '04

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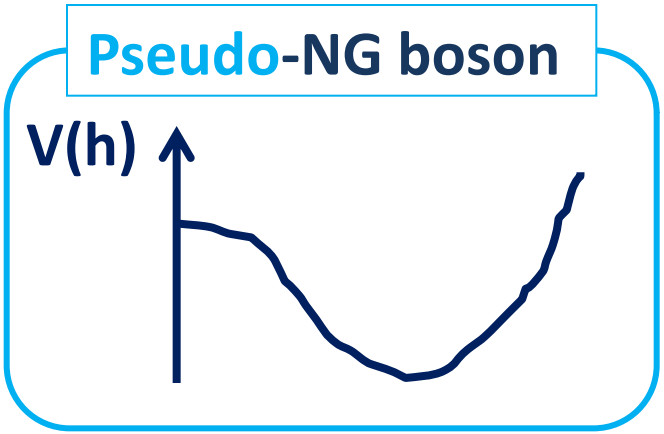

$\epsilon \equiv v/f$ < 1 $\qquad \alpha_t \simeq 2\beta_t$ NDA $\qquad \alpha_t \gg \beta_t$

$$v/f = \sqrt{1 - \frac{\alpha_t^2}{4\beta_t^2}} \equiv \epsilon$$

Small ϵ (i.e. v << f)
is favored by experiments.

$\frac{\alpha_t^2}{4\beta_t^2}$ ~ 1

Minimal Composite Higgs Model

Agashe,Contino,Pomarol '04

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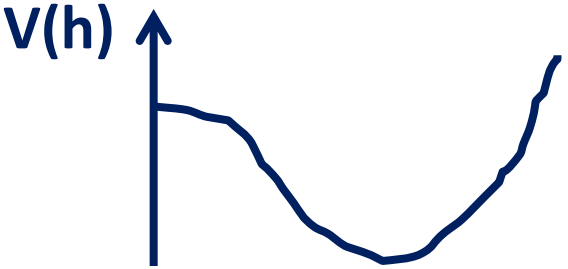
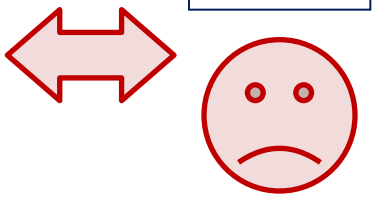
Pseudo-NG boson



$\epsilon \equiv v/f$ < 1

$\alpha_t \simeq 2\beta_t$ NDA $\alpha_t \gg \beta_t$



To solve the tension,

People consider, for example, another representations,

4 -> 5 or 10 or 14...

Panico, Redi Tesi, Wulzer '12

The situation can change by considering Dark matter!

- We know “WIMP Miracle”
  - Observed DM relic can be explained by a DM has weak scale mass & weak coupling

Possibility:

DM also couple to Higgs weakly.

The situation can change by considering Dark matter!

- We know “WIMP Miracle”
  - Observed DM relic can be explained by a DM has weak scale mass & weak coupling

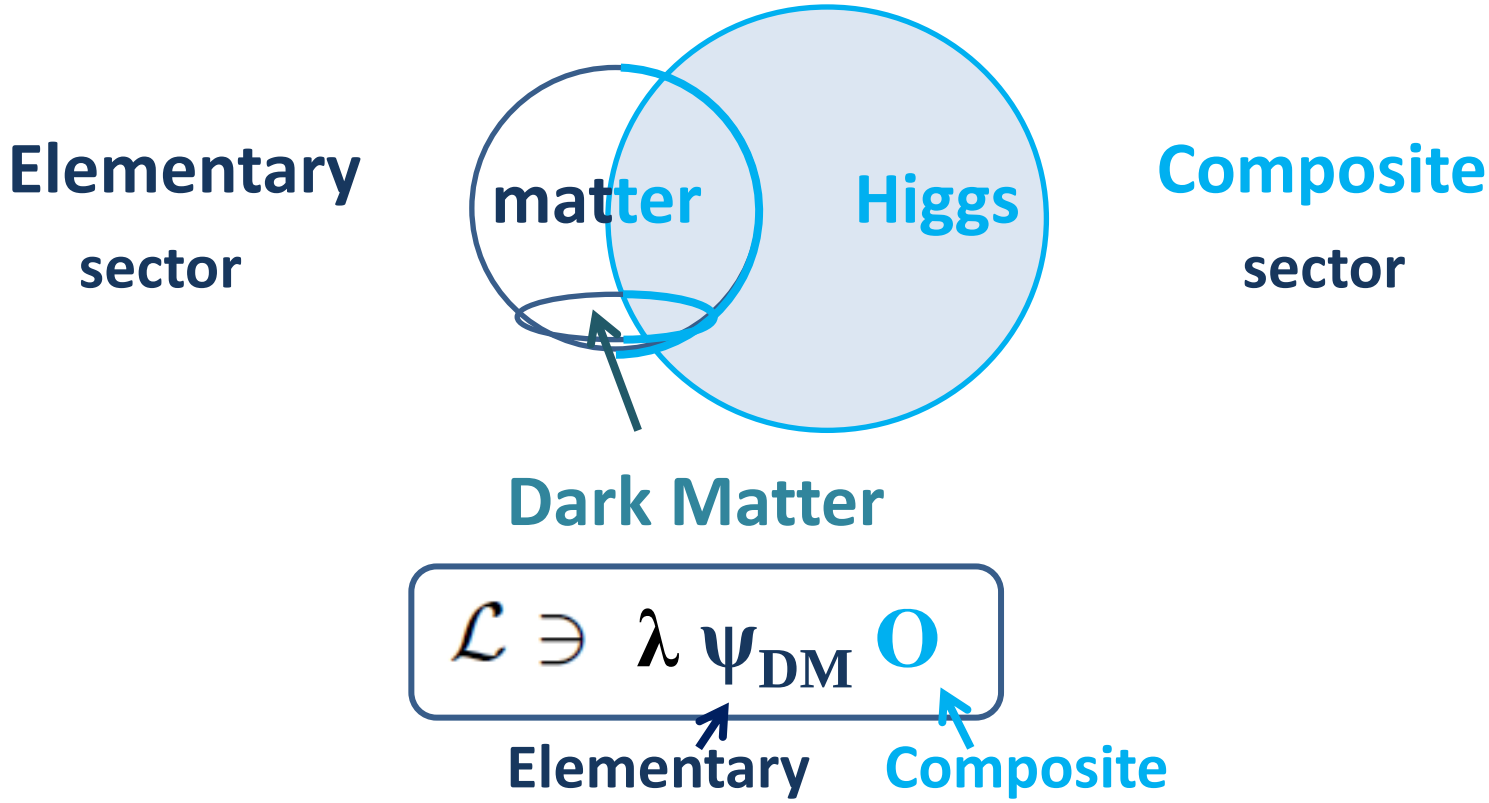
Possibility:

DM also couple to Higgs (i.e. strong sector) weakly.

Partially Composite DM !!

MA, Kitano '14

Partially Composite DM



DM is also a partially composite fermion & the explicit breaking also contributes to Higgs potential!

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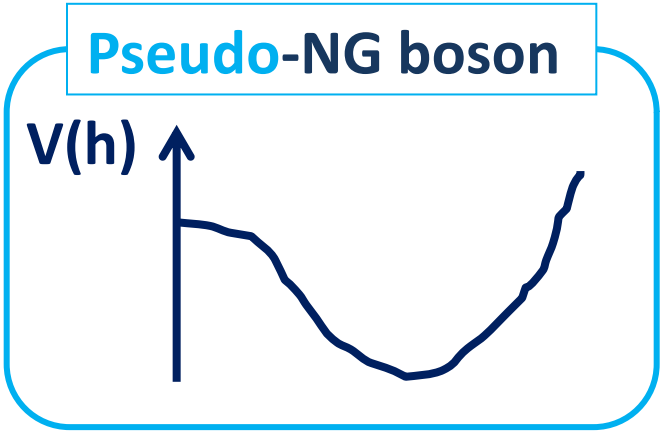
Partially Composite DM

Ot: spinorial rep. 4 of SO(4)

$$V(h) \simeq \alpha_t \cos\frac{h}{f} - \beta_t \sin^2\frac{h}{f}$$

$$v/f = \sqrt{1 - \frac{\alpha_t^2}{4\beta_t^2}} \equiv \epsilon$$



$\epsilon \equiv v/f$ **< 1** $\quad \alpha_t \simeq 2\beta_t \Longleftrightarrow$ **NDA** $\quad \alpha_t \gg \beta_t$

Partially Composite DM

If O_{DM} is in SO(5) vector representation, 5,

the leading Dark sector contribution is $\propto \sin^2(h/f)$.

Ot: spinorial rep. 4 of SO(4)

$$V(h) = \alpha_t \cos\frac{h}{f} - (\beta + \beta_t)\sin^2\frac{h}{f}$$

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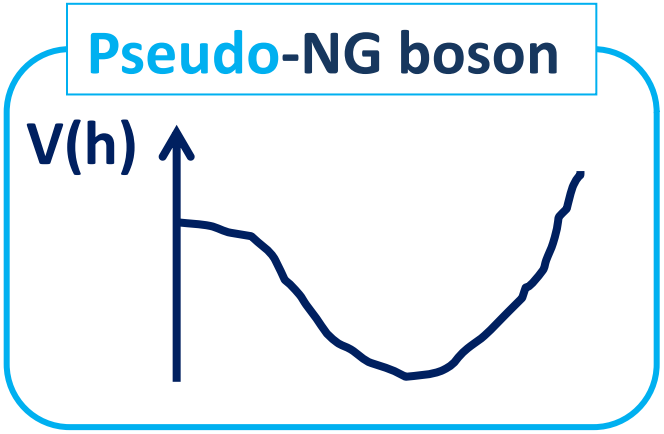

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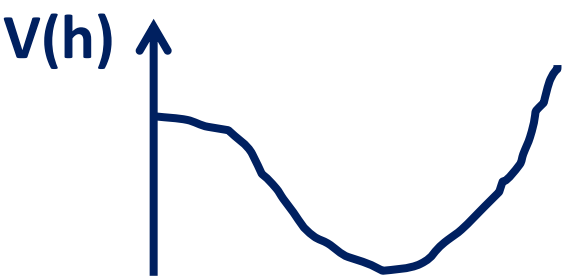
Pseudo-NG boson



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NDA $\alpha_t \gg \beta_t$

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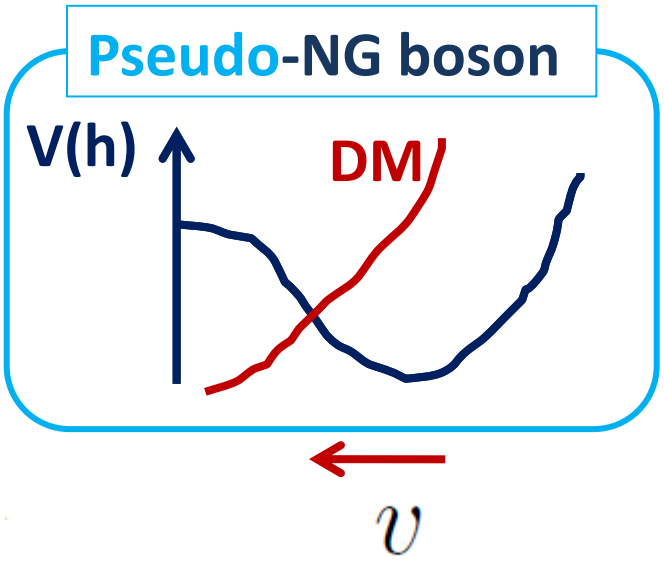

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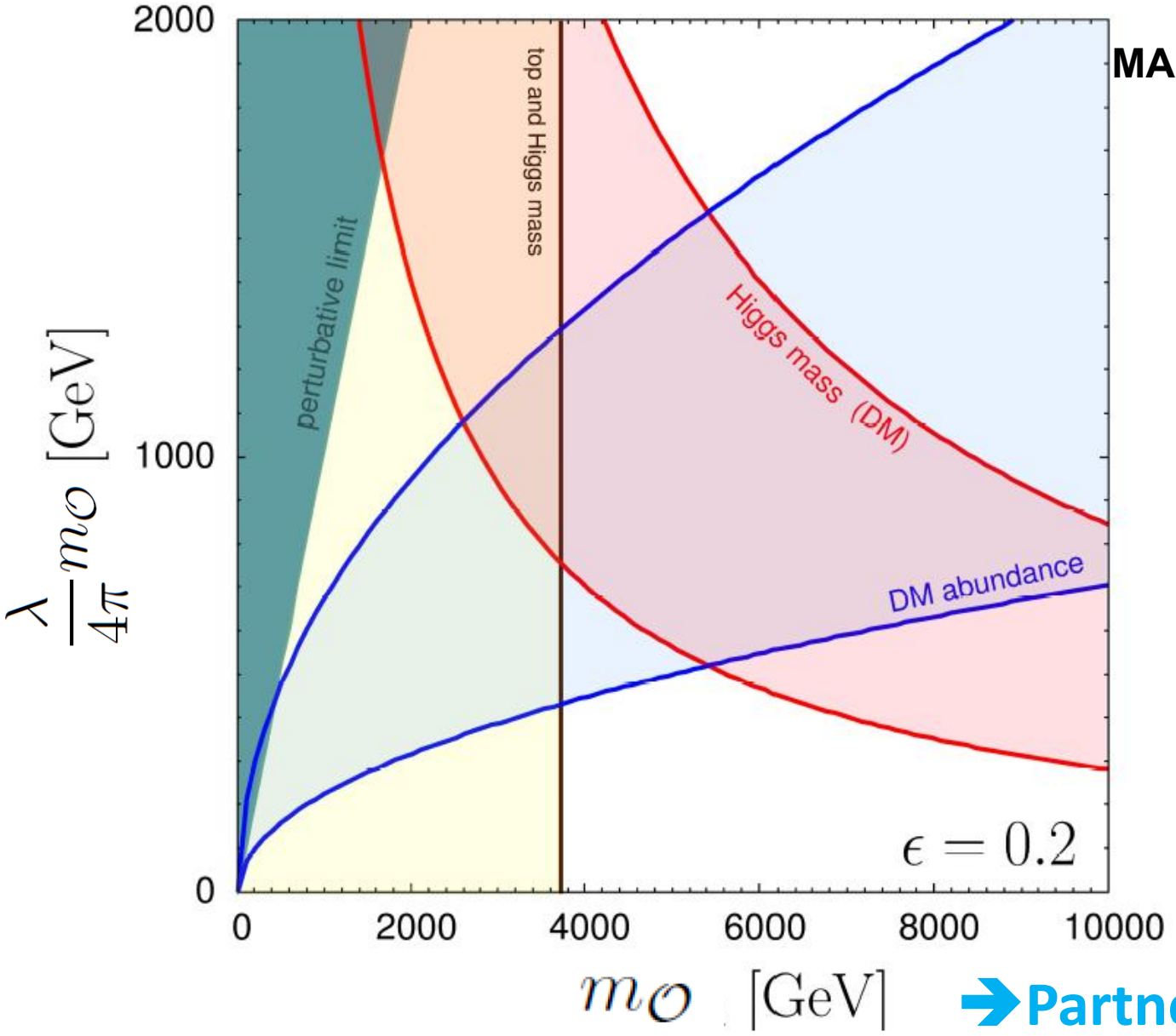
➔Explicit breaking



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➔Partner mass

It's also consistent with DM relic!

Partially Composite DM

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Dark matter phenomenology

Partially Composite DM

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After integrating out Composite O,

we obtain the low-energy effective theory as

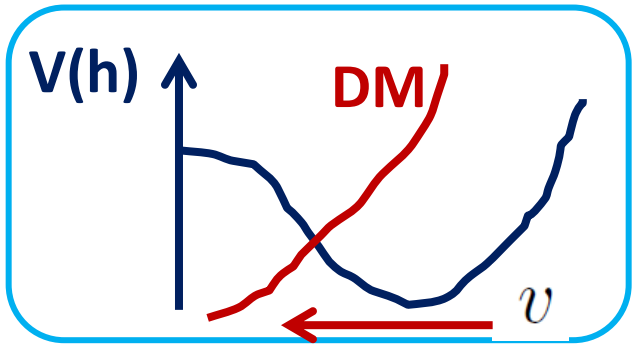
$$\mathcal{L}_{\rm eff} = -\frac{m_{\rm DM}}{2}\bar{\psi}_S\psi_S + \frac{\kappa}{2}\bar{\psi}_S\psi_S \sin^2\frac{h}{f} + \frac{i\kappa_5}{2}\bar{\psi}_S\gamma_5\psi_S \sin^2\frac{h}{f}$$

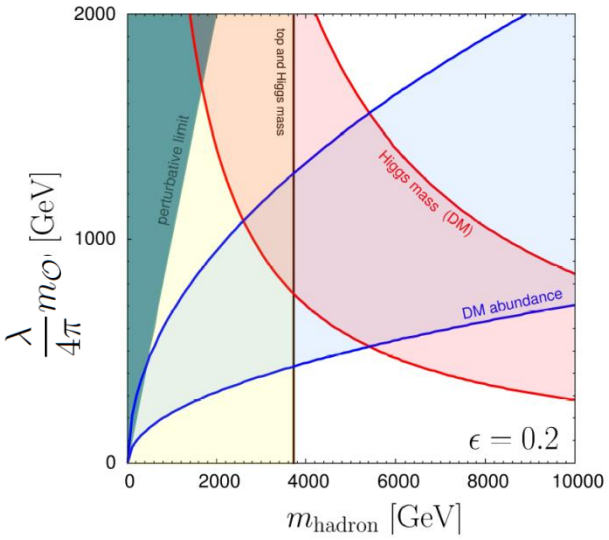
⇨ **This is similar to "Higgs portal DM model".**

$$m_{\rm DM} \sim \kappa \sim \kappa_5 = c\left(\frac{\lambda}{4\pi}\right)^2 m_{\mathcal{O}}$$

Partially Composite DM

- DM also contribute making Higgs potential.
- Parameter space consists with both Higgs & DM observables.
- It would be measure by DM DD in near future.





Summary

Summary

Is Dark Matter

Elementary

or

Composite

or

Partially Composite?

I have no idea.

Summary

Is Dark Matter

In this talk

Elementary ⇦ **Supersymmetry**

or

Composite ⇦ **Composite Higgs**

or

Partially Composite?

All possibilities can be in motivated models which is a candidate of the origin of the EWSB.

It will be studied through not only DM measurements but also EWSB physics model search.

Partially Composite DM

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- **Annihilation cross section**

$$\langle \sigma_{\rm ann.} v \rangle \propto (\kappa^2 \ {\rm v}^2 \ \ {\rm term}) + \kappa_5^2$$

- **Direct detection cross section**

$$\sigma_{\rm SI} \propto \kappa^2 + (\kappa_5^2 \ {\rm v}^2 \ \ {\rm term})$$

$$\mathcal{L}_{\rm eff} = -\frac{m_{\rm DM}}{2}\bar{\psi}_S\psi_S + \frac{\kappa}{2}\bar{\psi}_S\psi_S \sin^2\frac{h}{f} + \frac{i\kappa_5}{2}\bar{\psi}_S\gamma_5\psi_S \sin^2\frac{h}{f}$$

Partially Composite DM

MA, Kitano '14

- **Annihilation cross section**

$$\langle \sigma_{\mathrm{ann.}} v \rangle \propto (\kappa^2 \, \mathrm{v}^2 \quad \mathrm{term}) + \kappa_5^2$$

- **Direct detection cross section**

$$\sigma_{\mathrm{SI}} \propto \kappa^2 + (\kappa_5^2 \, \mathrm{v}^2 \quad \mathrm{term})$$

If ~~CP~~ in strong sector, $\kappa \sim \kappa_5$, large κ is not required to explain observed DM relic, then, constraints from direct detection can be mild.

Partially Composite DM

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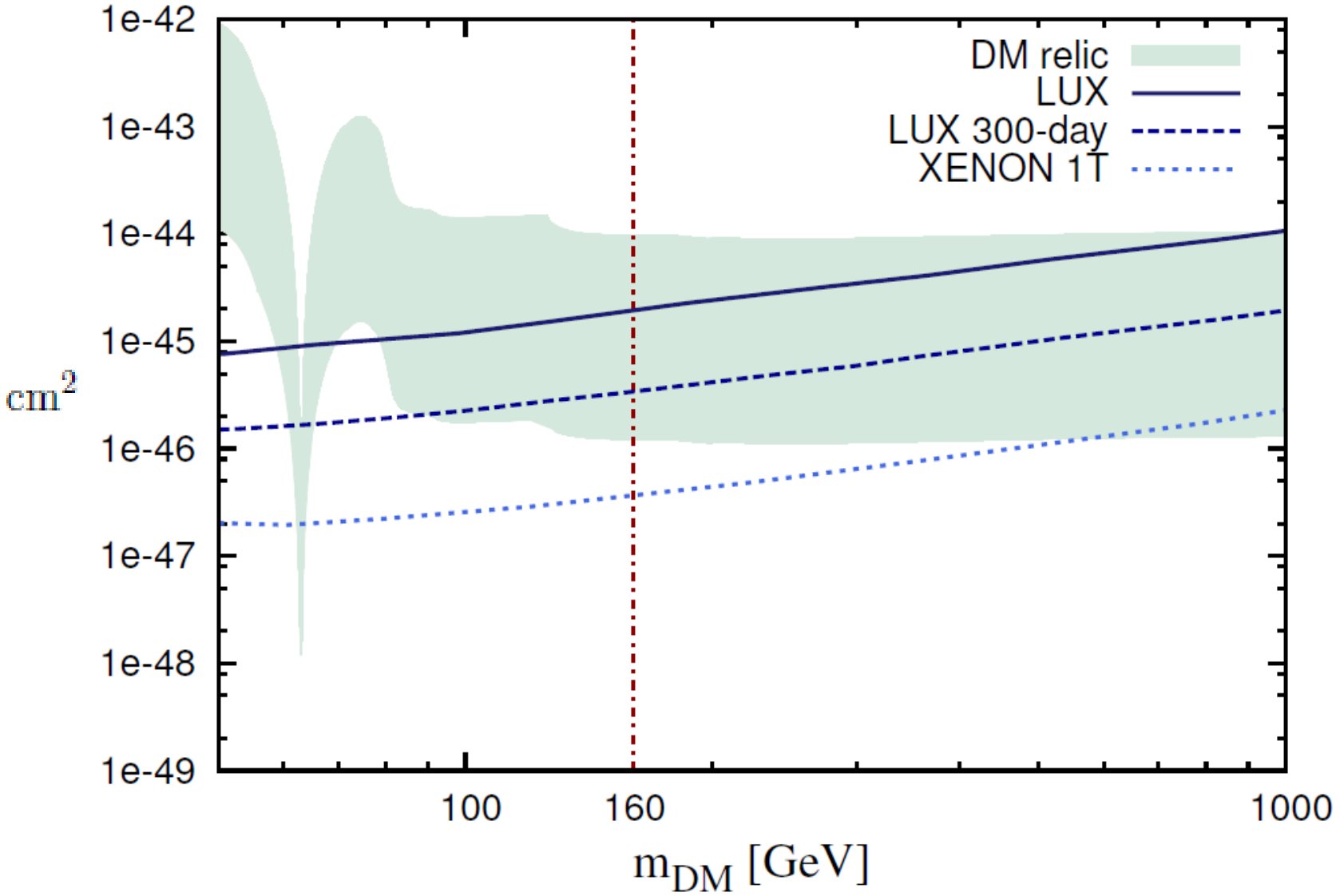


$$1/3 < \kappa/\kappa_5 < 3$$

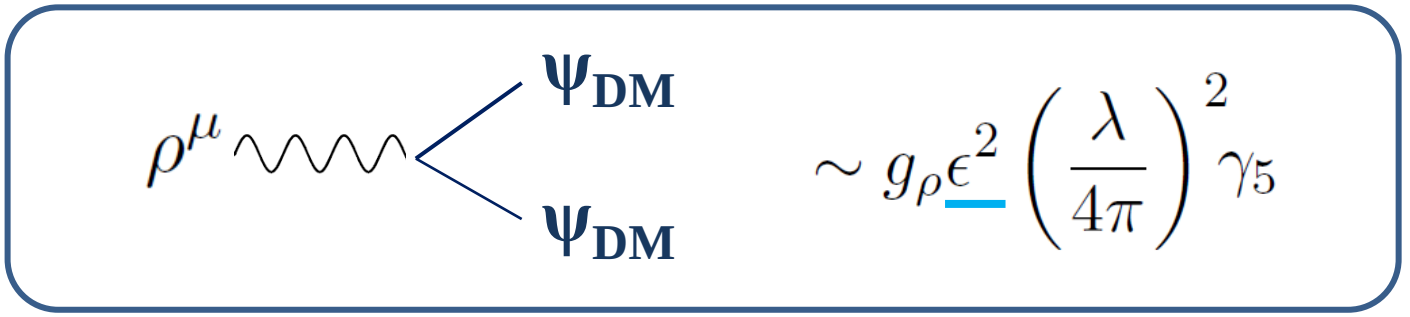
In progress

Partially Composite DM

$$5_0 = (2,2)_0 + (1,1)_0$$

$$\mathcal{O} = \begin{pmatrix} \mathcal{O}_4 \\ \mathcal{O}_1 \end{pmatrix}$$

Spin-1 resonance ρ^μ



Due to the ε^2 supression, this Br is small.

If it is kinematically allowed,