



Unparticle Dark Matter

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in collaboration with

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e-Print: [arXiv:0711.1506](https://arxiv.org/abs/0711.1506) [hep-ph].

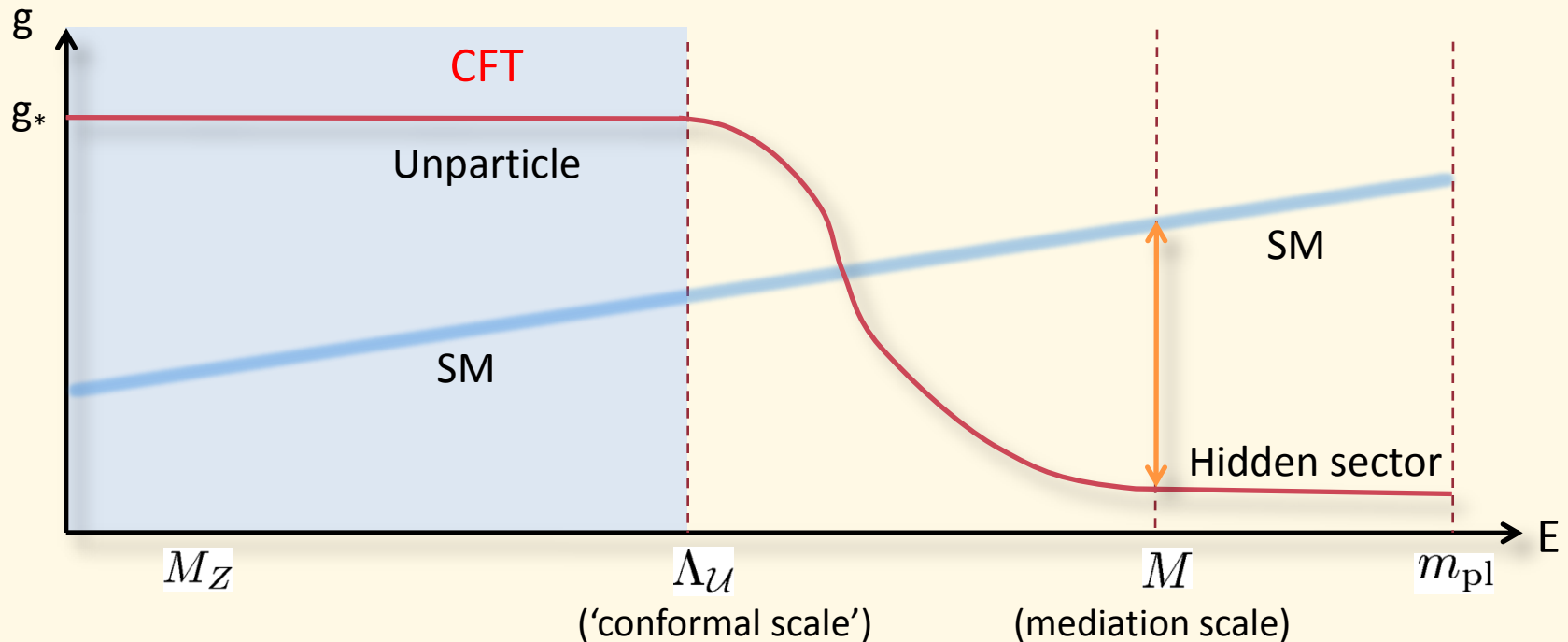


Introduction

- **Beyond the SM** (for model buildings in this LHC era): **Are there totally unexpected phenomena which has not yet discovered so far?** What would be expected to happen at LHC that might be originated from some unknown models, not only SUSY or extra dimensional models, etc.? This is basically the motivation to consider about unparticle physics as a model of unexpected phenomena.
- **Unparticle**: A hypothetical *conformal hidden sector* which couples to the Standard Model particles only through the higher dimensional operators. [H. Georgi, PRL 98, 221601 (2007)]
- **One concrete example**: Banks-Zaks theory has a perturbative infrared (IR) fixed point [Banks and Zaks, NPB 196, 189 (1982)]. There might exist several other candidates in a gauge theory as in the SUSY QCD.
- **Question**: Can such a hidden conformal invariant theory (CFT) have any effects on the low energy phenomena (SM sector) at the LHC?

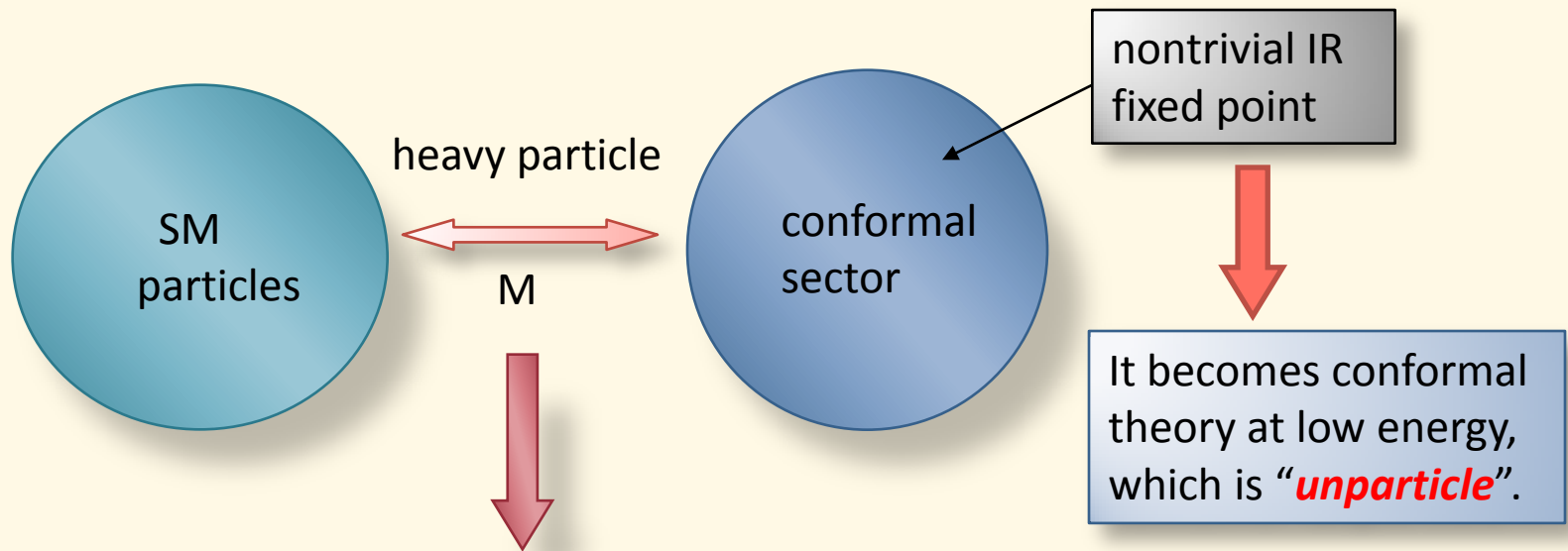
A global viewpoint of unparticle

- Unparticle (**conformal theory**) is assumed to be realized at low energy from a theory which has an IR fixed point as in the Banks-Zaks theory.
- Interactions between the SM and the conformal sector is introduced at a high energy scale, M , via the exchange of some massive fields.



Interaction for BZ fields with SM particles

Effective field theory (EFT) description of interactions between the SM and the conformal sector.

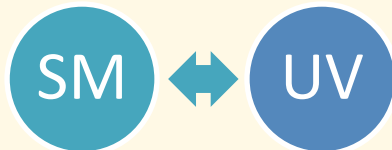


Integrating out the heavy particle, below the scale M_U ,

$$\sum \frac{1}{M} \mathcal{O}_{\text{SM}} \mathcal{O}_{\text{UV}}$$

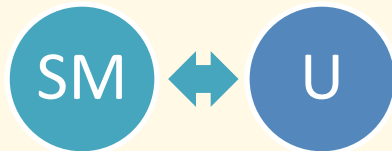
Effective field theory

- The interactions between the SM sector and the BZ fields are introduced just in an effective field theory way.



$$\mathcal{L}_{\text{eff}} = \frac{1}{M^{d_{\text{UV}}+n-4}} \mathcal{O}_{\text{SM}} \mathcal{O}_{\text{UV}}$$

- After the *dimensional transmutation* at a scale $\Lambda_{\mathcal{U}}$, where the hidden sector goes into the conformal window, the hidden sector have to be matched onto the *unparticle* at the scale.



$$\mathcal{L}_{\text{eff}} = c_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{\text{UV}}-d_{\mathcal{U}}}}{M^{d_{\text{UV}}+n-4}} \mathcal{O}_{\text{SM}} \mathcal{O}_{\mathcal{U}} \equiv \frac{1}{\Lambda^{d_{\mathcal{U}}+n-4}} \mathcal{O}_{\text{SM}} \mathcal{O}_{\mathcal{U}}$$

- The essential point to make lowered a cutoff scale is to have large enough anomalous dimensions for the hidden sector, and it causes a difference in each operator's dimension at UV scale and IR scale.

Basic function for the unparticle

- 2-point function of the unparticle operator:

$$\langle 0 | \mathcal{O}_U(x) \mathcal{O}_U(0) | 0 \rangle = \int \frac{d^4 p}{(2\pi)^4} e^{-ipx} |\langle 0 | \mathcal{O}_U(0) | p \rangle|^2 \rho(p^2)$$

- Imposing the spectral function to be scale invariant, it leads to the unusual behavior of the spectral function:

$$|\langle 0 | \mathcal{O}_U(0) | p \rangle|^2 \rho(p^2) = A_{d_U} \theta(p^0) \theta(p^2) \frac{1}{(p^2)^{2-d_U}}$$

- The most characteristic point of the unparticle is this *unusual scaling law of the spectral function*.
- This spectral function corresponds to introduce the following kinetic term for the unparticle in the action.

$$S = \frac{2 \sin(\pi d_U)}{A_{d_U}} \int d^4 x \mathcal{U}^\dagger \square^{2-d_U} \mathcal{U}$$

Unparticle interactions with \mathbf{Z}_2 parity

T.K. and N. Okada, arXiv:0711.1506 [hep-ph]

- We assign a \mathbf{Z}_2 parity for which **the unparticle has an odd parity**, while **the Standard Model particles have even parity**.
- The lowest operators in the SM is the Higgs mass term. So, it is natural to consider first the interaction between the unparticle and the Higgs doublet which is written by

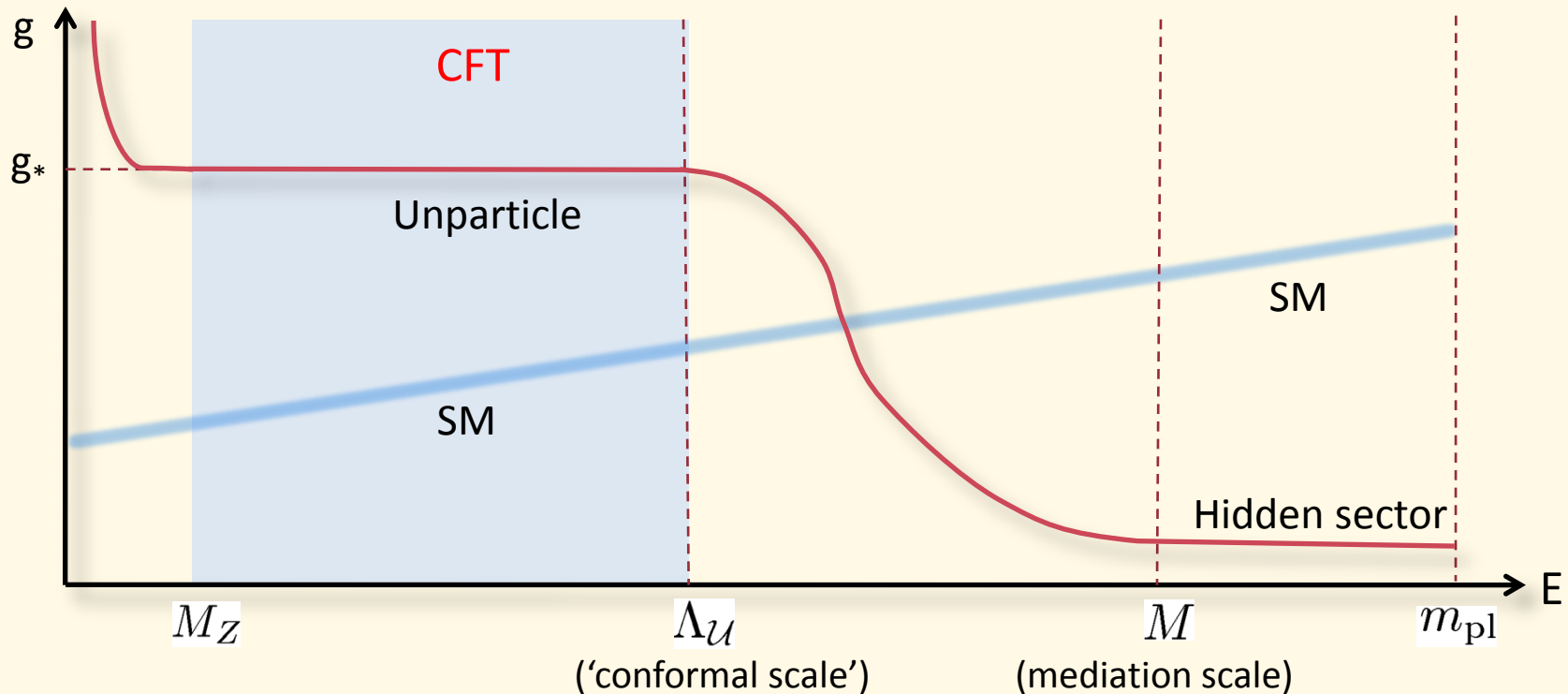
$$\mathcal{L}_{\text{eff}} = \frac{\lambda}{\Lambda^{2d_{\mathcal{U}}-2}} \mathcal{U}^2 H^\dagger H \rightarrow \mathcal{L}_{\text{mass}} = \frac{\lambda v^2}{\Lambda^{2d_{\mathcal{U}}-2}} \mathcal{U}^2 \quad (\text{after EW breaking})$$

- This means that if the interaction between the Higgs doublet and the unparticle is introduced, it generically provides a **'mass' term for the unparticle** after the electroweak symmetry breaking, inducing the **conformal symmetry breaking**.
- The corresponding action is, again, given by

$$S = \frac{2 \sin(\pi d_{\mathcal{U}})}{A_{d_{\mathcal{U}}}} \int d^4x \mathcal{U}^\dagger (\square - m_{\mathcal{U}}^2)^{2-d_{\mathcal{U}}} \mathcal{U}$$

Conformal symmetry is broken below M_Z

- After developing the VEV of the Higgs doublet, conformal symmetry is broken at the weak scale, and the coupling constant in the hidden sector re-start its running.



- Then, unparticle may become much stronger below the weak scale so that it realizes a confinement in the hidden sector.

Comparison with massless particles

- Remember the spectral function of the unparticle:

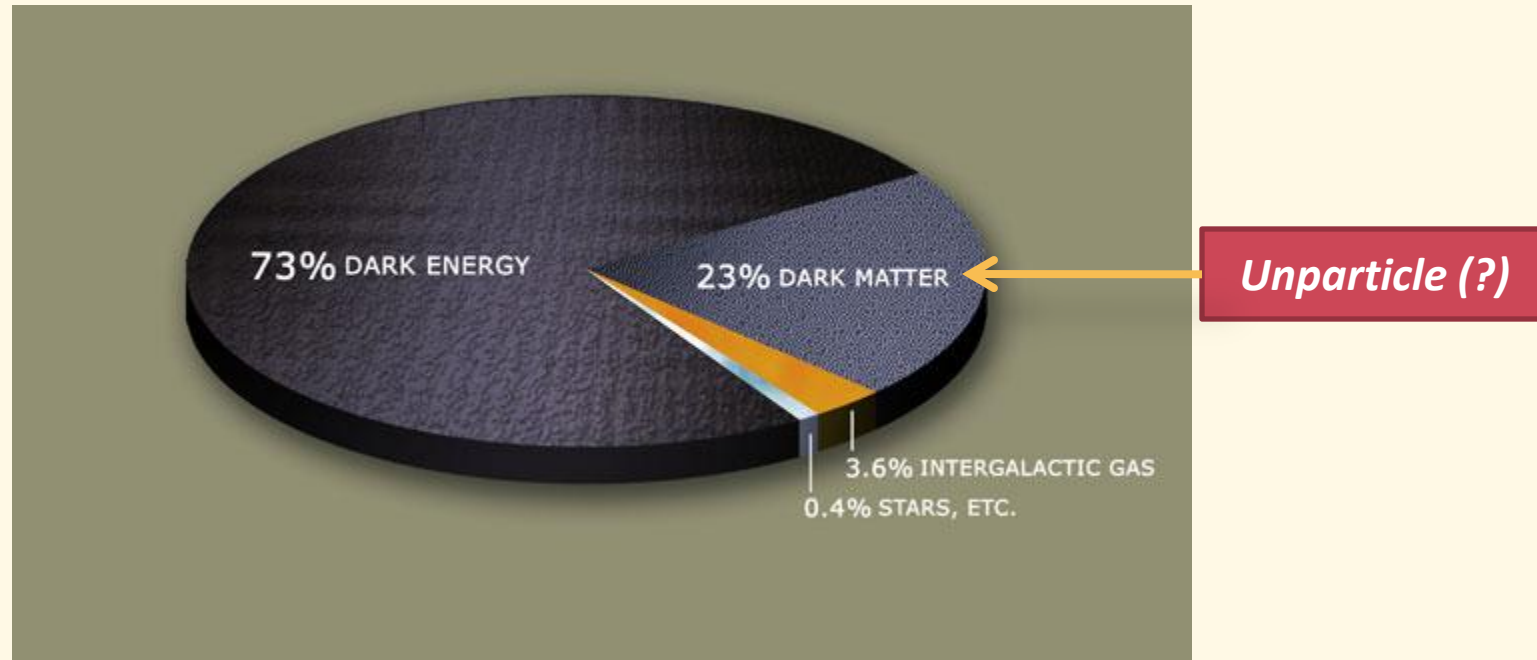
$$|\langle 0 | \mathcal{O}_U(0) | p \rangle|^2 \rho(p^2) = A_{d_U} \theta(p^0) \theta(p^2) (p^2)^{d_U - 2}$$

- It is impressive to compare this result of the unparticle with that of the n collections of the massless particles:

$$\Phi_n(0) = \frac{1}{(2\pi)^{3n}} \frac{(\pi/2)^{n-1}}{(n-1)!(n-2)!} (p^2)^{n-2} = \frac{1}{\pi^{3/2} (2\pi)^{2n}} \frac{\Gamma(n+1/2)}{\Gamma(2n)\Gamma(n-1)} (p^2)^{n-2}$$

- Thus, we could say that:
 - “unparticle of scale dimension d_U behaves like a collection of d_U massless invisible particles” H. Georgi, PRL 98, 221601 (2007)
- A special case: $d_U=1 \Rightarrow$ unparticle = one massless particle, which couples weakly to the SM particles.

Energy budget of Universe



1. SM can only explain 4% of total energy budget of universe.
2. At least, the DM should be explained in the context of the particle physics, which cannot be done within the frame of the SM.
3. We explore the possibility for the ***Unparticle as the Dark Matter scenario!***

Unparticle interaction with Z_2 parity

T.K. and N. Okada, [arXiv:0711.1506](https://arxiv.org/abs/0711.1506) [hep-ph]

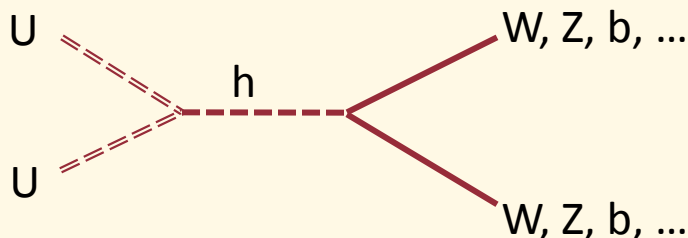
- The interaction between the unparticle and the Higgs boson is introduced in the following form:

$$\mathcal{L}_{\text{eff}} = \frac{\lambda}{\Lambda^{2d_U-2}} \mathcal{U}^2 H^\dagger H$$

- After developing the VEV for the Higgs boson, the unparticle gains a mass, and after that, it can decay into the Higgs boson.

$$\mathcal{L}_{\text{int}} = \frac{m_U^{4-2d_U}}{v^2} \left(v h + \frac{h^2}{2} \right) \mathcal{U}^2$$

- Then the annihilation cross section can easily be calculated by considering the following diagrams.



Relic abundance of the unparticle

T.K. and N. Okada, arXiv:0711.1506 [hep-ph]

- The relic abundance of the dark matter is obtained by solving the Boltzmann equation, and the solution is approximately given as

$$\Omega_{\mathcal{U}} h^2 = \frac{1.07 \times 10^9 x_f \text{GeV}^{-1}}{\sqrt{g_*} m_{\text{PL}} \langle \sigma v \rangle} ; \quad x_f \cong 23$$

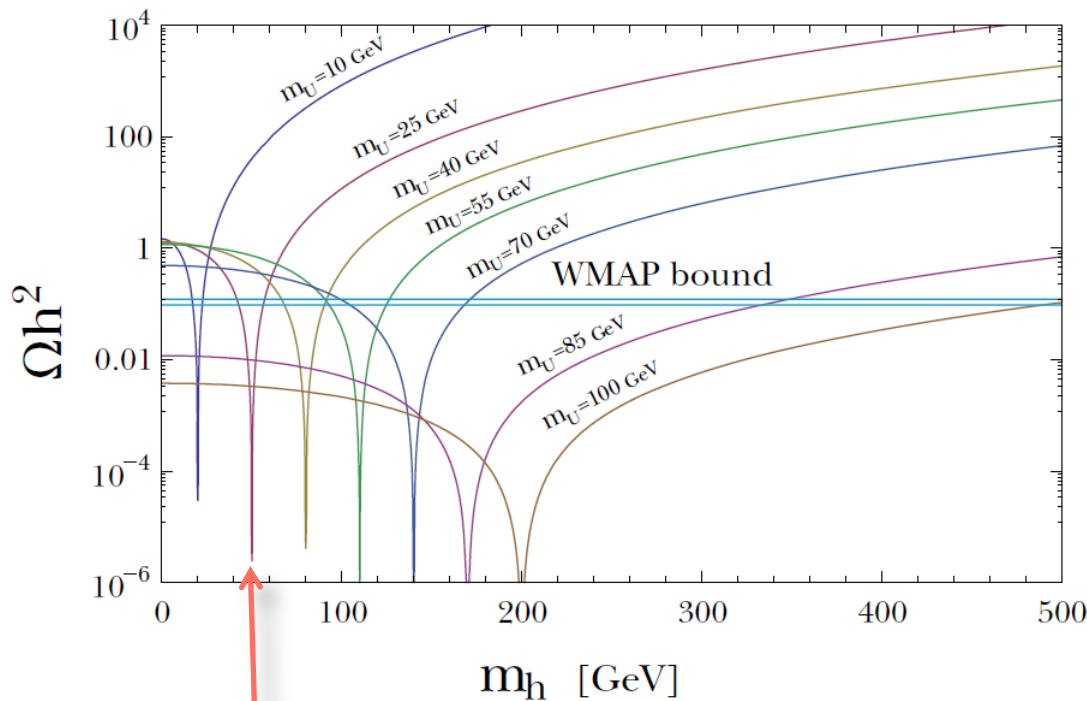
- The thermally averaged cross section $\langle \sigma v \rangle$ can easily be evaluated in this model. The annihilation cross section for the unparticle, $UU \rightarrow h \rightarrow IJ$ ($IJ=WW, ZZ, ff, \dots$), is given by

$$\sigma v|_{IJ} = 4 \frac{m_{\mathcal{U}}^3}{v^2} \frac{\Gamma(h \rightarrow IJ)|_{m_h=2m_{\mathcal{U}}}}{(4m_{\mathcal{U}}^2 - m_h^2)^2 + m_h^2 \Gamma_h^2}$$

- The annihilation cross section for the unparticle is enhanced a lot at the point where the unparticle picks up the pole of the Higgs mass ($m_h = 2m_{\mathcal{U}}$). Therefore, **the allowed region is expected to appear on both sides of the Higgs pole.**

Relic abundance of the unparticle

T.K. and N. Okada, arXiv:0711.1506 [hep-ph]



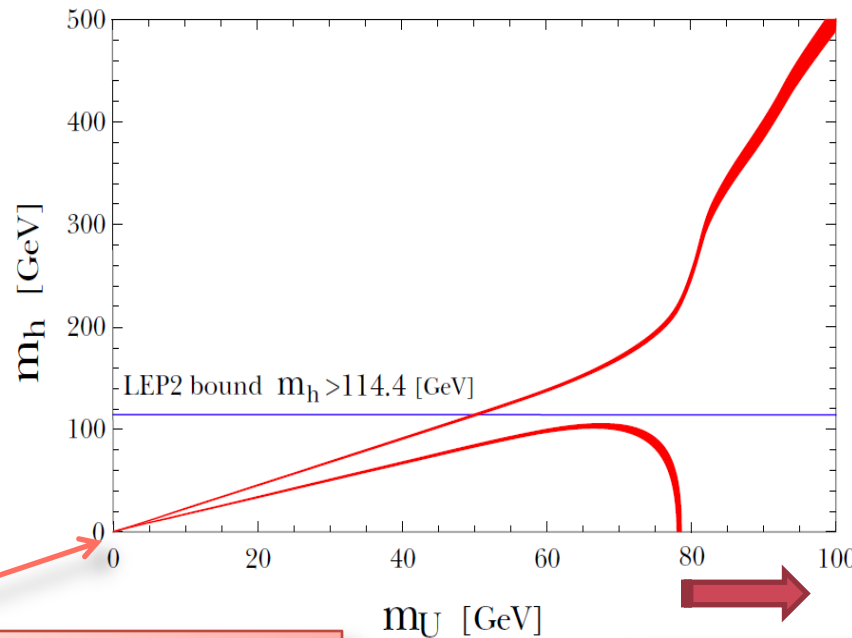
The relic abundance of the unparticle dark matter as a function of the Higgs boson mass for fixed unparticle masses, $m_U = 10, 25, 40, 55, 70, 85, 100$ GeV.

Higgs pole (on the line the annihilation cross section becomes too large)

The result shows that there exists enough parameter spaces, which are consistent with the WMAP measurements in the unparticle as the CDM scenario!

Relic abundance of the unparticle

T.K. and N. Okada, arXiv:0711.1506 [hep-ph]



The shaded region is the region which is consistent with the WMAP data for the unparticle as the CDM scenario!

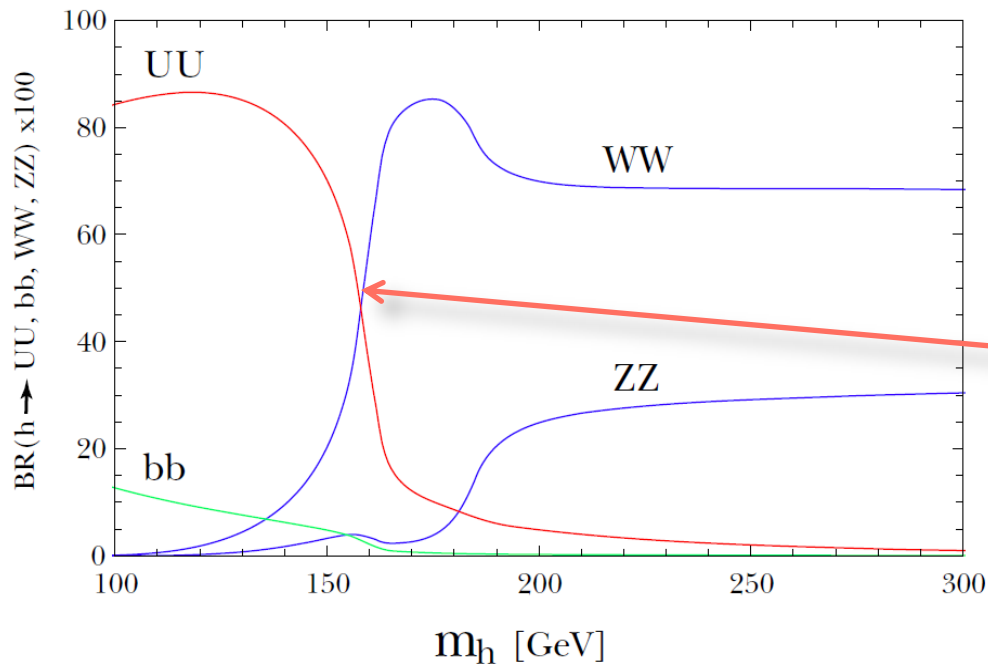
Higgs pole (on the line the annihilation cross section becomes too large)

W threshold (above which the annihilation cross section becomes too large)

Light Higgs boson mass $m_h < 250$ GeV is favored from the electroweak precision measurements, so that the unparticle mass is constrained to be in the range, $50 \text{ GeV} < m_U < 80 \text{ GeV}$ for the unparticle as the CDM scenario!

Invisible Higgs boson decay

T.K. and N. Okada, arXiv:0711.1506 [hep-ph]



The left Fig. shows the branching ratios of the Higgs boson decays as a function of the Higgs mass along with the WMAP allowed region.

For $m_h = 160$ GeV, the branching ratio of invisible Higgs boson is **50%**! This is extraordinary thing and should be checked at future collider experiments.

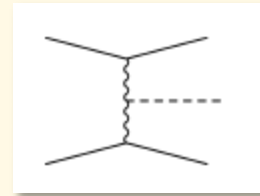
For $m_h < 160$ GeV, Higgs boson dominantly decays into the unparticle dark matters. Even for $m_h = 200$ GeV, the branching ratio of invisible Higgs boson decay is sizable, $BR(h \rightarrow UU) \sim 8.5\%$.

An invisible Higgs at the LHC

Search modes:

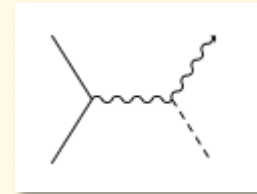
- WW fusion $\longrightarrow H_{\text{inv}}$ [Eboli & Zeppenfeld (2000)]

Signal is jjp_T ; jets are hard and forward



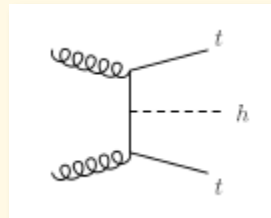
- $Z + H_{\text{inv}}$ [Frederiksen, Johnson, Kane & Reid (1994); Choudhury & Roy (1994)]

Signal is $l^+l^-p_T$, with $m(l^+l^-) = m_Z$ ($l = e, \mu$)



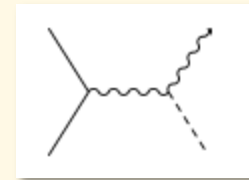
- $t\bar{t} + H_{\text{inv}}$ [Gunion (1994)]

Signal is $bjj + bl + p_T$



- $W + H_{\text{inv}}$ [Choudhury & Roy (1994)]

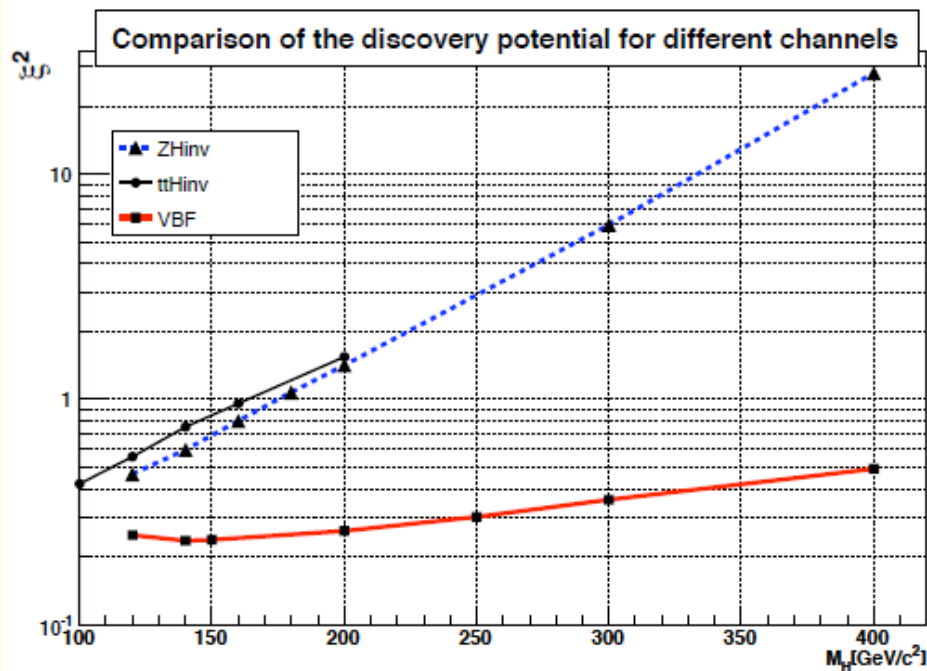
Signal is lp_T ; totally swamped by background



Discovery potential for invisible Higgs in different channels

95% CL exclusion limits with 30 fb^{-1} at LHC

ξ^2 is a scaling factor: $\sigma \times \text{BR}(H \rightarrow \text{invis}) \equiv \xi^2 \sigma_{\text{SM}}$



ZH_{inv} – uses
 $Z \rightarrow l^+l^-$

VBF looks very good,
but not clear how
well events can be
triggered.

$t\bar{t}H_{\text{inv}}$ – may be room
for improvement?
ATLAS study in
progress.

[Plot from [ATL-PHYS-PUB-2006-009](#)]

Summary

- **Unparticle** is a hidden **conformal sector** which couples to the SM particles only through the higher dimensional operators.
- **Spectral function of the unparticle has very unusual behavior!** Because of the conformal invariance in the unparticle sector, unparticle propagator and the phase space are completely different from the usual scalar case, especially, its momentum dependence goes: $1/(p^2)^{2-d}$ (d: dimension of the unparticle operator).
- **We have considered the Unparticle Dark Matter scenario!** The mixing between the unparticle and Higgs boson make the Higgs phenomenology much more interesting, and predictive.
- **Unparticle can become a viable candidate of the dark matter!** We have evaluated the relic abundance of the unparticle dark matter and the resultant abundance can match with the WMAP result.
- **Invisible decay of Higgs boson could be enhanced a lot!** That is, including the interaction between the Higgs and the unparticle could cause a sizable enhancement of an *invisible decay* of the Higgs boson.