# Unparticle Physics

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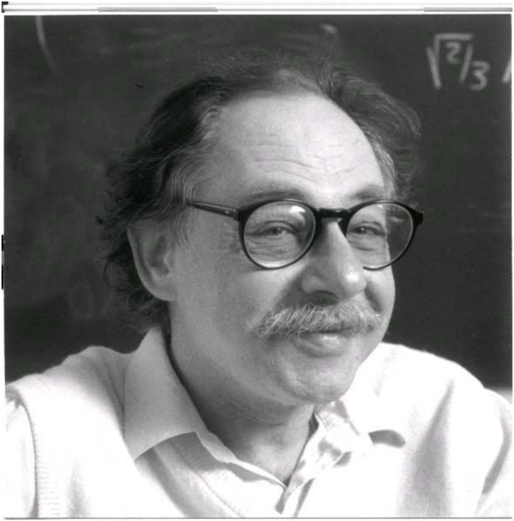

Unparticle stuff with scale dimension $d$ looks like a non-integral number $d$ of invisible massless particles.

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before I circulated the paper widely, I sent it to some of my smartest former students and grand-students, including Ann Nelson and Lisa Randall

The attached hallucination came to me a few days ago and I have been in a trance since then trying to work out the details. I thought it was time to try it out on some of my friends. Since this is very possibly embarrassingly nuts, I would appreciate it if you could keep it to yourselves for a day or so. Several possibilities occur to me.

1 - It is trivially wrong for some reason.

2 - Everyone knows it already and is not interested.

3 - Some other type of bound kills these theories so that the unparticles can never be seen.

I would be grateful for a little sanity check.

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We expect new particles! But could we see something else - not describable in the language of particles?

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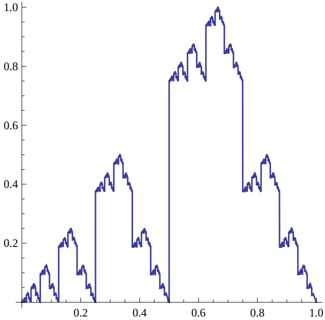
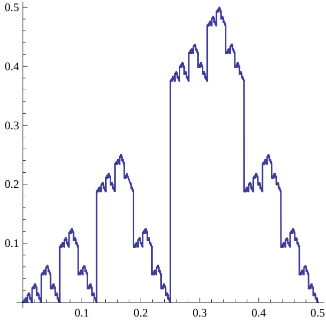
Start with a review of scale invariance - then show how it might yield an example of unparticle physics. Scale invariance is common in mathematics — start there.

# trivial discrete scaling

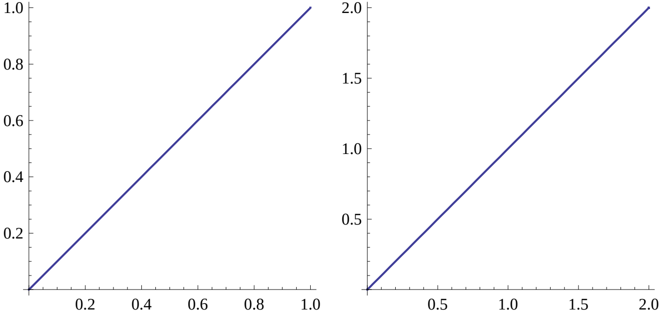
$$g(x) = \sum_{j=-\infty}^{\infty} 2^{-j}\, h(\mathrm{frac}(2^j x)) \qquad h(x) = \frac{3}{4}\Theta\Big(x-\frac{1}{2}\Big)\Theta\Big(\frac{3}{4}-x\Big)$$



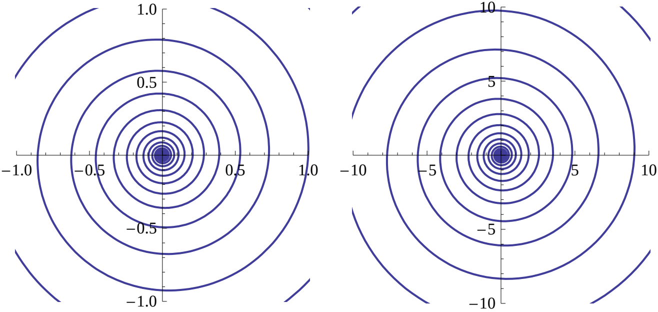
trivial
continuous
scaling

$$y = x$$



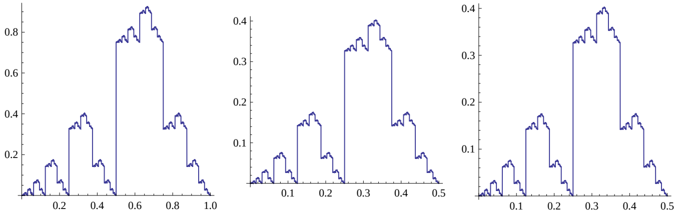
almost trivial continuous scaling

$$r = e^{\theta/20}$$



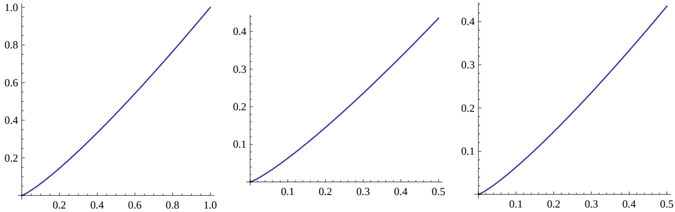
# non-trivial discrete scaling with $d = 1.2$

$$g(x) = \sum_{j=-\infty}^{\infty} 2^{-1.2j}\, h(\mathrm{frac}(2^j x)) \qquad h(x) = \frac{3}{4}\Theta\Big(x - \frac{1}{2}\Big)\Theta\Big(\frac{3}{4} - x\Big)$$



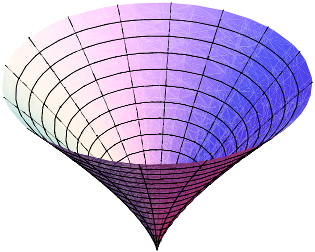
non-trivial
continuous
scaling with $d = 1.2$

$$y = x^{1.5}$$



pleasing
shapes

$$z = (x^2 + y^2)^\alpha$$



scale invariance is less common in physics

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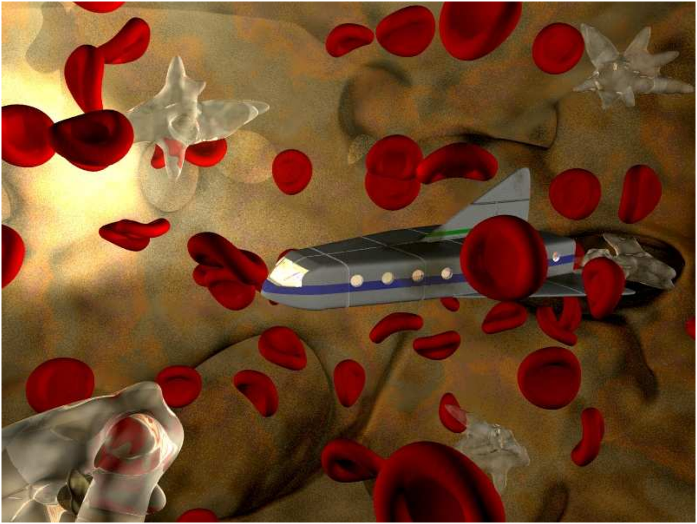

# $\hbar$ and $c$

all dimensional quantities are tied together

time and space and must scale together

if time and space are scaled up, energy and momentum must be scaled down

# $\hbar$ and $c$

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time and space and must scale together

if time and space are scaled up, energy and momentum must be scaled down

and there are massive particles

classically, particles = chunks of $p^\mu$

$$p^2 = p_\mu p^\mu = m^2 \qquad \vec{v} = \vec{p}/p^0 \qquad (c = 1)$$

in QM, $p^0, \vec{p} \rightarrow \omega, \vec{k}$ - dispersion relation

$$p_\mu p^\mu = m^2 \rightarrow \omega^2 = \vec{k}^{\,2} + m^2 \quad (\hbar = 1)$$

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$$p_\mu p^\mu = m^2 \to \omega^2 = \vec{k}^2 + m^2$$

either way - fixed non-zero $m$ breaks scale invariance - you can't scale energy and momentum or $x$ and $t$ without changing $m$

but theories of free massless relativistic particles have scale invariance theories of free massless relativistic particles have scale invariance - here I understand the physics! - if a state of free massless particles exists with $(E_j, \vec{p}_j)$ you can always make a "scaled" state with $(\lambda E_j, \lambda \vec{p}_j)$

$$P_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \rho_f$$

Fermi's Golden Rule - $\rho_f$ = density of final states - number of quantum states per unit volume - states in a cubical box with side $\ell$ with periodic boundary conditions - $\vec{p} = 2\pi\vec{n}/\ell$

$$d\rho(p) = \frac{\#\ \text{states}}{\ell^3} = \frac{d^3p}{(2\pi)^3}$$

"phase space" is a shorter phrase

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Fermi's Golden Rule - $\rho_f$ = density of final states - number of quantum states per unit volume - states in a cubical box with side $\ell$ with periodic boundary conditions - $\vec{p} = 2\pi\vec{n}/\ell$

$$d\rho(p) = \frac{d^3p}{2E(2\pi)^3} = \theta(p^0)\,\delta(p^2)\,\frac{d^4p}{(2\pi)^3}$$

"phase space" is a shorter phrase - conventional to make this relativistic massless particles phase space also scales

$$d\rho_1 = \frac{d^3p}{2E\,(2\pi)^3} = \Theta(p^0)\delta(p^2)\frac{d^4p}{(2\pi)^3}$$

$$E = p^0 = |\vec{p}|$$

$$p \to \lambda p \qquad \frac{d^3p}{2E\,(2\pi)^3} \to \lambda^2 \frac{d^3p}{2E\,(2\pi)^3}$$

this is trivial scaling - like $y = x$

massless particles phase space also scales

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this is trivial scaling - like $y = x$ - $d\rho_1$ is the phase space for one massless particle now suppose you have two massless particles in your final state that you don't see (neutrinos for example), so all you know is their total energy-momentum $P$

you can combine the phase spaces for the massless particles to get the phase space for the combination

$$\left( \overbrace{\int \delta^4 \left( P - \sum_{j=1}^{2} p_j \right)}^{\substack{P\text{=total}\\ \text{4−momentum}}} \overbrace{\prod_{j=1}^{2} \delta\left(p_j^2\right)\, \theta\left(p_j^0\right)\, \frac{d^4 p_j}{(2\pi)^3}}^{\substack{2\times\text{massless}\\ \text{phase space}}} \right) d^4 P$$

$$\equiv d\rho_2(P) = \frac{1}{8\pi}\, \theta\left(P^0\right)\, \theta\left(P^2\right)\, \frac{d^4 P}{(2\pi)^4}$$

assumes no other dependence on $p_1$ and $p_2$ -

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assumes no other dependence on $p_1$ and $p_2$ - no $\delta$-function - ${P^0}^2 - \vec{P}^2$ can by anything greater than zero - the two-neutrino system can have any mass - the SYSTEM is not a particle - not too surprising we know this system is a 2-particle state - don't we?

can't we see the particles individually?

not necessarily, if the 2 particles always appear in exactly the same combination in all the physics!

but we can see the 2-ness even if we can't see the particles - missing $E$ and $\vec{p}$

$$d\sigma \propto d\rho_2(P) = \begin{array}{c}\text{uniform}\\ \text{in } P^2\end{array}$$

any single event just tells you that the missing stuff is not a single particle with zero mass because $P^2 \neq 0$ - but the distribution of many events depends on the number of missing particles - phase space for more particles grows faster with $P^2$

$$d\rho_n(P) =$$

$$\left( \int \delta^4 \left( P - \sum_{j=1}^{n} p_j \right) \prod_{j=1}^{n} \delta\left(p_j^2\right) \theta\left(p_j^0\right) \frac{d^4 p_j}{(2\pi)^3} \right) d^4 P$$

$$= A_n \, \theta\left(P^0\right) \theta\left(P^2\right) \left(P^2\right)^{n-2} \frac{d^4 P}{(2\pi)^4} (2\pi)^4$$

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n+1/2)}{\Gamma(n-1)\,\Gamma(2n)}$$

1 - you get information about how many massless particles you are making by measuring the differential cross-section $d\sigma/d^4P$

2 - $d\rho_n(P)$ scales

$$d\rho_n(\lambda P) = \lambda^{2n}\, d\rho_n(P)$$

1 - you get information about how many massless particles you are making by measuring the differential cross-section $d\sigma/d^4P$

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3 - but this can be confused by factors of $P^2$ in $|M|^2$

what happens if we see a scale invariant $d\rho_d$, but $d$ is not integral? a fractional number of unseen particles? not sure what that would mean! but what would it be?

what happens if we see a scale invariant $d\rho_d$, but $d$ is not integral? a fractional number of unseen particles? not sure what that would mean! but what would it be? scale invariant unparticles with dimension $d$

could this stuff exist?

in fact non-trivial interacting scale invariant quantum field theories have been known for a long time - theorists know a lot about the correlation functions in Euclidean space in fact non-trivial interacting scale invariant field theories have been known for a long time - theorists know a lot about the correlation functions in Euclidean space

I realized that I understood the field theory better than I understood the physics

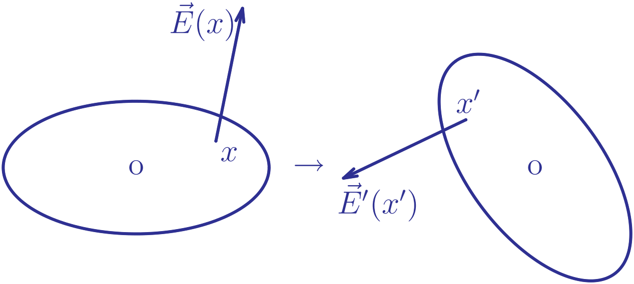
QFT - "obvious" quantum extension of classical field theory like E&M

the fields we are familiar with, like $\vec{E}(x)$ and $\vec{B}(x)$, are operators in the quantum mechanical Hilbert space of the world that create and destroy particles

symmetries of quantum field theory are my favorite things in physics scale transformation in a field theory

shrink coordinates by $\lambda \Rightarrow x \rightarrow \tilde{x} = x/\lambda$

- fields get rescaled for the same reason that vector fields rotate when the coordinates rotate



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$$O(x) \to \tilde{O}(\tilde{x}) = \lambda^d O(\lambda \tilde{x}) = \lambda^d O(x)$$

$d$ is scale "dimension" - for $\vec{E}(x)$ or $\vec{B}(x)$ describing free photons, this scale transformation is a symmetry for $d = 2$, the "engineering dimension" - not surprising since these fields create massless photons shrink coordinates by $\lambda \Rightarrow x \rightarrow \tilde{x} = x/\lambda$

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what does this have to do with unparticles?

$O(x)$ creates unparticle states with dimension $d$

shrink coordinates by $\lambda \Rightarrow x \rightarrow \tilde{x} = x/\lambda$

$$O(x) \rightarrow \tilde{O}(\tilde{x}) = \lambda^d O(\lambda \tilde{x}) = \lambda^d O(x)$$

$$\langle 0|\, O(x)\, O(0)\, |0\rangle = \Delta(x)$$

$$\langle 0|\, \tilde{O}(\tilde{x})\, \tilde{O}(0)\, |0\rangle = \Delta(\tilde{x})$$

$$\lambda^{2d}\, \langle 0|\, O(x)\, O(0)\, |0\rangle = \Delta(x/\lambda)$$

$$\Rightarrow \Delta(x) \propto x^{-2d}$$

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insert intermediate unparticle states

$$= \int e^{-ipx} \, |\langle \mathcal{U}, P|\, O(0)\, |0\rangle|^2 \, d\rho_{\mathcal{U}}(P)$$

where $|\mathcal{U}, P\,\rangle$ is an unparticle state and $d\rho_{\mathcal{U}}(P)$ is the density of unparticle states

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$$= \int e^{-ipx}\, |\langle \mathcal{U}, P|\, O(0)\, |0\rangle|^2\, d\rho_{\mathcal{U}}(P)$$

$$\langle \mathcal{U}, P|\, O(0)\, |0\rangle = 1 \quad \text{(wave function)}$$

$$\Rightarrow d\rho_{\mathcal{U}}(\lambda P) = \lambda^{2d}\, d\rho_{\mathcal{U}}(P)$$

$O(x)$ creates unparticle with dimension $d$

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More physical question might be easier - can it co-exist with the standard model?

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maybe if it couples to SM particles only at high energies - effective field theory

Example - Banks-Zaks - ordinary Yang-Mills gauge theories like QCD with massless quarks but with the number of colors and flavors chosen to make the running slow - asymptotically free at large energies - at low energies, the gauge coupling gets stuck at a nonzero value - a nontrivial IR fixed point

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Just an example! Not the most interesting case - but familiar and understandable.

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Just an example! Not the most interesting case - but familiar and understandable.

Take the physics seriously and see what happens!

at very high energies

| | | | | |
|---|---|---|---|---|
| standard model fields | $\leftrightarrow$ | fields of mass $M_{\mathcal{U}}$ | $\leftrightarrow$ | $\mathcal{BZ}$ fields (Banks-Zaks) |

below the scale $M_{\mathcal{U}}$

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|---|---|---|---|---|

below the scale $M_{\mathcal{U}}$

standard model fields

$$\frac{1}{M_{\mathcal{U}}^k} O_{sm} O_{\mathcal{BZ}}$$

$\mathcal{BZ}$ fields (Banks-Zaks)

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$\mathcal{BZ}$ fields (Banks-Zaks)

dimensional transmutation scale $\Lambda_{\mathcal{U}}$

$$O_{\mathcal{BZ}} \rightarrow \Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}-d} O$$

$$O(x) \rightarrow \tilde{O}(\tilde{x}) = \lambda^d O(x)$$

below the scale $\Lambda_{\mathcal{U}}$

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unparticle (physics)

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standard model fields $\quad \dfrac{\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}-d}}{M_{\mathcal{U}}^k} O_{sm} O \quad$ unparticle (physics)

dimensional transmutation scale $\Lambda_{\mathcal{U}}$

$$O(x) \to \tilde{O}(\tilde{x}) = \lambda^d O(x)$$

for $M_{\mathcal{U}}$ is large enough, the unparticle stuff just doesn't couple strongly enough to ordinary stuff to have been seen — but it could show up at larger energies

## What does unparticle stuff actually look like physically?

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This is too hard! By thinking about EFT, we have transformed the question into something that we can make some progress on.

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How does unparticle stuff begin to show up as the energy of our experiments is increased?

what does this do?

$$\epsilon \, O_{sm} \, O \quad \text{where} \quad \epsilon = \frac{\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}-d}}{M_{\mathcal{U}}^{k}}$$

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insertion in some standard model process

$$\epsilon^2 \, | \, \langle SM_{\text{out}} | \, O_{sm} \, | SM_{\text{in}} \rangle \; \langle \mathcal{U} | \, O \, | 0 \rangle \, |^2$$

what does this do?

$$\epsilon\, O_{sm}\, O \quad \text{where} \quad \epsilon = \frac{\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}-d}}{M_{\mathcal{U}}^{k}}$$

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$$\epsilon^2 \,|\, \langle SM_{\text{out}}|\, O_{sm}\, |SM_{\text{in}}\rangle \; \langle \mathcal{U}|\, O\, |0\rangle \,|^2$$

results in production of unparticle stuff $\rightarrow$ missing energy and momentum in $\mathcal{O}(\epsilon^2)$

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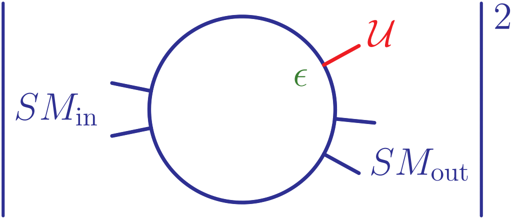
results in production of unparticle stuff $\rightarrow$ missing energy and momentum in $\mathcal{O}(\epsilon^2)$ — MISSING because (for one thing) seeing it again would require more $\epsilon$s




Feynman graph with one insertion — probability distribution is proportional to the phase space for scale invariant unparticle stuff which we already know goes like $d\rho_d(P)$ which looks like the production of $d$ massless particle.

# as promised the first amusing result

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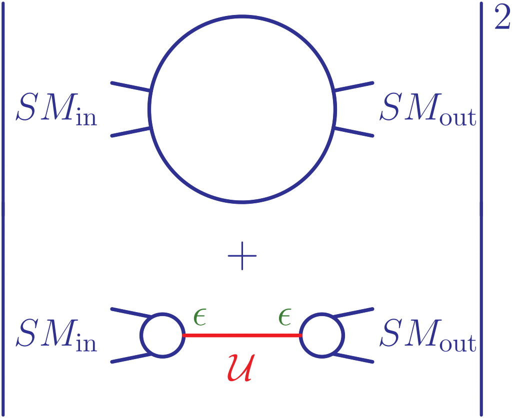
> Unparticle stuff with scale dimension $d$ looks like a non-integral number $d$ of invisible massless particles.

there is another effect that can appear in order $\epsilon^2$




virtual unparticles!

interference $\propto \epsilon^2 \times$ unparticle propagator

$$\int e^{iPx} \, \langle 0 | \, T(O(x) \, O(0)) \, | 0 \rangle \, d^4x$$

$$= i \frac{A_d}{2\pi} \int_0^\infty \left(M^2\right)^{d-2} \frac{1}{P^2 - M^2 + i\epsilon} \, dM^2$$

$$= i \frac{A_d}{2 \sin(d\pi)} \left(-P^2 - i\epsilon\right)^{d-2}$$

No pole - no ordinary propagation

Crazy phase - oddest for $d = (2j + 1)/2$

[1] P. J. Fox, A. Rajaraman, and Y. Shirman, "Bounds on unparticles from the higgs sector," *Phys. Rev.* **D76** (2007) 075004.

[2] M. Bander, J. L. Feng, A. Rajaraman, and Y. Shirman, "Unparticles: Scales and high energy probes," `arXiv:0706.2677 [hep-ph]`.

[3] A. Delgado, J. R. Espinosa, and M. Quiros, "Unparticles-higgs interplay," `arXiv:0707.4309 [hep-ph]`.

[4] G. Cacciapaglia, G. Marandella, and J. Terning, "Colored unparticles," `arXiv:0708.0005 [hep-ph]`.

$$\frac{1}{M_{\mathcal{U}}^{k}} O_{sm} O_{\mathcal{BZ}}$$ effective field theory

$$O_{\mathcal{BZ}} \to \Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}}-d} O$$ dimensional transmution

$$O(x) \to \tilde{O}(\tilde{x}) = \lambda^{d} O(x)$$ scale invariance

Does this make sense? Corrections?

other interactions

corrections to dimensional transmutation

breaking of scale invariance

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breaking of scale invariance

$$S = \int \mathcal{L}(x)\, d^4x \quad \text{where} \quad \mathcal{L}(x) =$$

$$\int_0^\infty \left(\frac{1}{2}\partial^\mu \phi_M\, \partial_\mu \phi_M - \frac{1}{2} M^2 \phi_M^2\right) dM^2$$

$$M \to \tilde{M} = \lambda M \qquad x \to \tilde{x} = x/\lambda$$

$$\phi_M(x) \to \tilde{\phi}_{\tilde{M}}(\tilde{x}) = \phi_M(\lambda \tilde{x}) = \phi_M(x)$$

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build unparticle field with $d$

$$O_{\mathcal{U}} = \int_0^\infty \sqrt{\frac{A_d}{2\pi}}\, M^{d-2}\, \phi_M \, dM^2$$

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connection with extra dimensions - $M$ like another momentum component - fractional power from warping - integral is a FT picking a position in the extra dimension

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not an explanation of anything but we can at least use the metaphor of a $\phi_M$ field for each $M$ to talk about corrections to unparticle physics at low energies.

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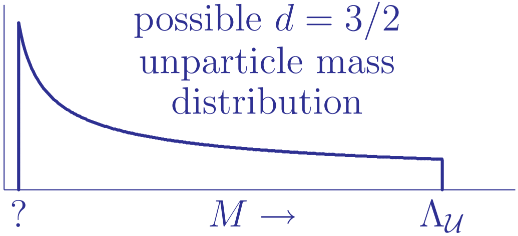
Are this these limits reasonable?




scale breaking from high-energy interactions - dependent on on detailed dynamics

transition to BZ theory - also shows up in couplings to higher dimension unparticle fields

## Why don't we see all these continuum states as different particles?