A note on Infraparticles and Unparticles

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Abstract

The observed astrophysical phenomenon of dark matter has generated new interest in the problem of whether the principles underlying QFT are consistent with invisibility/inertness of energy-momentum carrying "stuff" as e.g. "unparticles". We show that the 2-dim. model which has been used to illustrate the meaning of unparticles belong without exception to the class of former infraparticles. In $d=1+3$ infraparticle are identical to electrically charged particles which despite their nonlocality are our best particle physics "candles". The "invisibility" in this case refers to the infinite infrared photon cloud with energies below the resolution of the measuring apparatus which can be made arbitrarily small by increasing the photon registering sensitivity but not eliminated. This is not quite the kind of invisibility which the unparticle community attributes to their invisible "stuff" and whose existence would probably contradict the asymptotic completeness property. The main aim of the present work is to show that knowledge about this part of QFT is still in its infancy and express the hope that the work on unparticles may rekindle a new interest in conceptually subtle old unsolved important problems instead of inventing new once which after some time increase the list of unsolved old ones.

1 Previous incursions beyond the standard particle setting

The quest for understanding the particle content of QFT beyond the standard mass gap hypothesis (one-particle states separated by a finite distance from the continuum) has been an important topic for a long time. The study of these problems began after it became clear that interactions, which become sufficiently strong in the infrared regime, can and will change the conceptual basis of standard scattering theory. The oldest model to address this issue is the famous Bloch-Nordsieck model which, via the Yennie-Frautschi-Suura infrared treatment of scattering theory of charged particles, led in the early 60s to the first ideas
about infraparticles [2] i.e. charged particles permanently surrounded by an infinite cloud of soft photons below the visibility limit. The most recent attempt in this direction is Georgi’s proposal of “unparticles” [1] which are thought to lead to an “invisibility” of a certain kind of outgoing matter component, which shows its presence through the appearance of energy-momentum-carrying but otherwise undetectable “fractional particle stuff”.

Unlike the infraparticle concept this so formulated “unparticle”-problem is not imposed by any observational fact; it is at this stage a mere mind game, although dark matter is sometimes mentioned as a potential observational application. Clearly what is called ”stuff” by those authors is outside the standard particle world and its conjectured appearance together with scattering of ordinary particles is part of the larger ”asymptotic completeness” problem i.e. of the question whether it is possible that the particles which emerge asymptotically in a scattering process do not form a complete set of states but leave some stuff which dissipated into the vacuum in such a way that it cannot be accounted for in particle registering devices. So any set of physical assumption which leads to asymptotic completeness has a bearing on this problem; we will return to this point at the end of the paper.

It is our intention to test the consistency of this idea within the setting of local quantum fields and in particular to compare this unparticle proposal with the problem to detect infinite soft photon clouds around infraparticles. The study of infraparticles is a well researched subject which started in the 60s with the investigation of certain two-dimensional models [2] and reached a certain amount of conceptual maturity in the 80s, when it was shown that 4-dimensional (electrically) charged particles are infraparticles [5][13][14].

Some of these old results will be reviewed; this is warranted because the new development has apparently been taking place without much awareness about the old achievements. This is of particular relevance since the task to explore the field-particle relation beyond the boundaries of standard particle physics (existence of discrete masses separated by gaps from the continuum) was already the aim of the infraparticle investigations. By comparing the presently still only half-baked unparticle idea with the more mature infraparticle physics one hopes to learn if and in what sense the former represents a conceptually viable new trans-particle idea.

The unravelling of the relation between quantum fields and particles has been one of the most difficult tasks ever since field quantizations was discovered in the late 20s. The subtlety of this problem became first highlighted in the work of Furry and Oppenheimer [6] when these authors found that in interacting QFTs every field, including the ”fundamental” Lagrangian fields, never creates a pure one-particle state (and not even a one-particle state with a limited finite number of particle/antiparticle pairs), but its local creation is always in company with

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1The terminology is taken from the papers and probably refers to their presumed invisibility. The name ”stuff” is also used on several occasions in those papers.

2The presence of photon ”clouds” i.e. an infinite number of soft photons requires their exact masslessness.
an infinite particle/antiparticle polarization "cloud" whose extension and shape depends on the kind of local interaction. This observation followed in the heels of Heisenberg's discovery of a more mild form of vacuum polarization associated the composites (Wick-products) of free fields while trying to define the "partial" charge localized in a compact spatial region which is associated with the spatial integral over bilinear current of a free complex scalar quantum field.

In a modern setting the F-O observation amounts to the nontriviality of the (connected) formfactors of any local operator $A$ in an interacting QFT, which by the crossing property are all related to a an analytic master function, usually identified with the vacuum polarization formfactor of $A$

$$\langle p_1, ... p_n | A | 0 \rangle \neq 0 \quad (1)$$

These formfactors, as a result of their crossing analyticity, fulfill a kind of "Murphy's law", stating that all channels, whose coupling is not forbidden by charge superselection rules, and their associated symmetries, are indeed coupled. This is very different from QM (even in its relativistic form, as the theory of direct particle interactions (DPI) where one can couple/decouple channels at will by manipulating the interaction potentials. Whereas this "no decoupling of channels" situation in QFT does not have the status of a theorem which can be found in the literature but is certainly consistent with the the nonexistence of any counterexample, there is the weaker statement, the Åks theorem showing that in $d \geq 1 + 2$ a QFT must have on-shell particle creation if it has has any nontrivial elastic scattering at all. A breakdown of this kind of "benevolent Murphy's law" in the mass gap setting is only possible in a setting which avoids the crossing property. This in turn can only happens in theories in which at least some generating massive fields are semiinfinite stringlike localized. The problem with this putative partial "on-shell blackening" is that no interacting demonstration model has yet been found.

The problems related to these first (Furry-Oppenheimer) observations were finally solved in the late 50s with a reasonably good first understanding of the field-particle relation. Contrary to the Fock space formulation of QM, interacting QFT connects fields with particles only through the asymptotic large time limits of scattering theory. The derivation of incoming/outgoing free fields (which lead to a Wigner-Fock space particle structure of standard QFT) from the short range nature of the connected part of correlation functions (a consequence of the mass-gap energy momentum spectrum and causal locality) has been one of the high points in the conceptual understanding of QFT, with profound experimental consequences.

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$^3$In finite order of perturbation theory there is a finite admixture which increases with the order and becomes a "cloud" in the limit.

$^4$In standard QFT (pointlike interpolating fields, mass shells with spectral gaps) the vacuum polarisation formfactor is related by crossing to the formfactors with different distributions of in and out particles in ket and bra states.

$^5$Buchholz and Fredenhagen proved that semiinfinite string-localization is the most general possibility allowed by the mass gap hypothesis in conjunction with the assumption of the existence of a point-like generated neutral observable subalgebra.
The first necessity to go beyond this standard setting arose from the observation that electrically charged particles do not fit into this framework since the S-matrix, as represented by the on-shell restriction of time ordered correlations, has infrared divergencies which cannot be removed by renormalizing the parameters of QED. This divergencies are not a mere consequence of the violation of the gap hypothesis. As the Yukawa coupling between nucleons and massless pions which is infrared finite and fits perfectly into the standard particle/field framework shows, the infrared divergencies, which lead to a breakdown of the standard particle setting for electrically charged particles, are the result of an increase of interaction strength in the infrared of the coupling of photons to charged fields. It does not happen in the mention Yukawa coupling since no matter how large the coupling parameter is, scalar or pseudoscalar couplings cannot reach the necessary infrared strength. The Bloch-Nordsieck method and its refinement in the work of Frautschi-Venne-Suura [4] shows that the infrared stable quantities, which replace the standard scattering amplitudes, are the inclusive cross sections in which the photons below a certain resolution (which varies with the sensitivity of the measuring hardware) escape undetected.

This led to a profound revision of the particle-field relation. The simplest way in which this new particle aspect revealed itself was through a change in the two-point functions: instead of the mass-shell delta function in the Kallen-Lehmann two-point function of a physical (gauge invariant) electrically charged field does has a "infraparticle" singularity which starts at $p^2 = m^2$ in an inverse power-like fashion and extends into the multiparticle continuum. Unitarity (Hilbert space positivity) limits this interaction-dependent power to be milder than the mass shell singulariy. This in turn leads to a vanishing large time asymptotic LSZ limits, thus underlining the breakdown of standard scattering theory.

There has been steady progress in a nonperturbative structural understanding; the strongest result, a milestone in the conceptual conquest of infrared aspects of QFT, has been obtained by Buchholz. He showed that an appropriate formulation of the quantum Gauss law [14] is incompatible with the standard particle structure. The infraparticle structure, including the spontaneous breakdown of Lorentz invariance in electrically charged states, is a consequence of this observation.

The derivation of inclusive scattering formulas, which bypases amplitudes and produces directly inclusive probabilities, remained however a still incompletely achieved goal. Although one believes to have all the relevant concepts in place [18], these attempts did not really lead to useful nonperturbative formulas for inclusive scattering probabilities which can match the formal elegance of the standard LSZ formulas.

A related problem, raised by the unparticle community is the question of the possible particle manifestation of conformal QFT. Here the LSZ limits of

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6If the authors of the statement "Observed, known particle physics is based on theories which have a mass gap and/or are free in the infrared" [3] really mean what they write, they would have missed out on QED.

7It is not uncommon that an object which diverges in perturbation theory vanishes on structural grounds.
any field with noncanonical (anomalous) dimension again vanish, as in the case of infraparticles. But in addition one finds a stronger theorem stating that any conformal field with a canonical (free field) short distance behavior is necessarily itself a free field \[11\]. Every field has a scaling limit, but not all such limiting theories are conformal. On the other hand each conformal theory is believed to arise through a scaling limit of a standard theory. This raises questions about the possible particle physics aspects which can be extracted from a conformal theory.

Although according to the best of my knowledge there are no theorems, one believes that only highly inclusive cross sections can counteract the vanishing of the LSZ limits. Some people have pointed out that this may not be enough; in order to arrive at finite cross sections one should generalize the inclusiveness aspect as an averaging procedure over incoming configurations\[8\]. With other words, one expects such possibly "doubly inclusive cross sections" in a standard massive theory to remain finite in a scaling limit in which the inclusiveness (resolution energy) parameters remain fixed. There seem to exist no proofs for these claims of relating inclusive cross sections with conformal QFT. Whereas the answer concerning the simple inclusive cross sections seems to be negative (infrared divergent), the feasibility of the double K-L-N appears still open.

Even though the informed reader will recognize an identity of motivation since both the infraparticle setting and the unparticle idea aim at conquering the ground beyond the standard particle theory, there is one difference with respect to the issue of "invisibility". The infrared "stuff" which constantly oozes out from an infraparticle (the infinitely many soft photons below an energy resolution hover with nearly infinite extension around an electrically charge particle) is not invisible per se. The hard photons with energies above the resolution coming out of a scattering process involving charged infraparticles are very visible and the "invisibility" in the infrared is determined by outside resolution parameters on the registration side, although there is always an infinite cloud remaining which escapes detection. On the other hand, since the protagonists of unparticles do not seem to think in terms of resolving the hard component of their stuff, the only remaining possibility is that their unparticle stuff is intrinsically invisible, independent of the infrared strength of the interaction. But if this is the case, what role remains for the infrared properties of interactions as the cause of "invisibility".

The next section contains some details on infraparticles which up to the present constitute the only known mechanism to transcend the limitation of standard particle physics. At the end of that section the reader is expected to understand why a critique of unparticles requires a good understanding of infraparticles.

\[8\] Such doubly inclusive cross sections play a role in the Kinoshita-Lee-Nauenberg theorem \[19\].
2 A brief anthology of infraparticles

A conceptual understanding of infraparticles and their scattering in the realistic 3+1 dimensional case of charged particles in QED is much more difficult than the standard scattering theory of massive particles in the presence of a mass gap. Already in second order perturbation theory infrared divergencies arise in the scattering amplitudes. These divergencies cannot be absorbed into a renormalization of physical parameters. Although the suggestion that this indicates a conceptual change in the notion of particles is quite old, its concretization in the setting of QED turned out to be a long lasting scientific endeavor.

The infraparticle idea was first exemplified and tested in the "theoretical laboratory" of 2-dimensional models [2]. Those models which were known in the 60s had no genuine interactions in the sense of scattering, but they certainly contained interesting messages about a modified particle structure which could account for the infrared divergencies observed in collisions in which electrically charged particles participate [4].

These models strongly suggested that it was the modification of the particle structure whose nonobservance led to the divergencies. But the change from particles to infraparticles also required to abandon the standard setting of scattering amplitudes and pass to inclusive scattering probabilities. It was found that the logarithmic infrared divergences in on-shell perturbative amplitudes of charged particles, calculated according to the standard rules, are compensated with divergencies in multi photon creation contributions to inclusive cross sections; the remaining finite terms summed up to an interaction dependent power law for small values in the inclusive resolution parameter.

This model observation suggested that the radical change of the particle concept amounts in momentum space to an amalgamation of the particle mass-shell with the continuum which, unlike the ubiquitous vacuum polarization contributions in any interacting QFT, cannot be gotten rid of by the large time asymptotics of scattering theory. But if the standard scattering theory breaks down, then the Hilbert space of the model does not have the form of a multiparticle Fock space. Indeed the "exponential massless Boson fields" which appear at first in [2] (and later in all the other 2-dim. infraparticle models), do carry a superslected charge and therefore cannot live in the bosonic Fock space defined by the creation/annihilation operators of the well-defined current (derivative of the Boson field). Rather they generate a bigger algebra living in a bigger Hilbert space of which the chargeless algebra generated by the currents is a subalgebra and the original Fock space is a subspace of a space of charged states without a Fock space structure.

This change should reveal itself in the Källén-Lehmann representation as a modification of the mass-shell contribution and indeed this was precisely what one observed in the very first calculation [2] where instead of the mass-shell

\footnote{9}{Besides the mentioned model [2] list of those models consisted of the (massless) Thirring model, the Schwinger model and variations and combinations thereof.}

\footnote{10}{"Inclusive" meant that infrared photons below a certain sensitivity $\Delta$ of the registering apparatus were summed over.}
delta function one found a milder singularity in form of a cut starting at \( p^2 \geq m^2, \ p^0 \geq m \). In the setting of operators the basic field of this model (the derivative coupling of a massless scalar to a massive spinor) was described by a product of a free massive Dirac field with an exponential of a zero mass scalar Bose field i.e.

\[
\psi(x) = \psi_0(x) : e^{ig\varphi(x)} : \quad (2)
\]

There is a subtle point concerning the precise meaning of this exponential since as mentioned before the massless scalar boson \( \varphi \) itself is not to be considered as a bona fide pointlike object\(^1\) and the exponential is amalgamated with the free Dirac field in such a way that the Hilbert space of the model does not contain a \( \psi_0(x) \) Fock subspace.

There are different ways to make this point explicit. The simplest is to start from an exponential of a massive two-dimensional free field, which lives in the Fockspace of the free field\(^2\) and hence obeys the unrestricted Wick contraction rules, and to perform a zero mass limit within the vacuum expectation values. In the massless limit the exponential operators in the correlation function must be multiplied with a certain anomalous power in the mass which is chosen such that no correlation diverges, but not all vanish. The power needed is this is the same as given by a formal scaling argument.

Another method is to work in the Hilbert space of currents and define the desired exponentials as a limit of a bilocal line integral of the current with one end going to infinity; doing this inside the correlation functions leads again to the previous result.

The massive free field in 2 spacetime dimensions has no other physical representations than the usual charge-less vacuum representation. Its massless limit is however very special in that it leads to the only free field with continuously many charged representation formally generated by the exponential function, a fact which was noticed already by Jordan\(^3\). However his attempt to sell this observation under the heading "neutrino theory of light" (believing erroneously that this can be generalized to higher dimensions) was not very successful; it led to a very funny mocking song composed by his colleagues [?].

A field which is a local function of free fields (and hence is local relative to free fields) has no interaction (no scattering), even though its correlation function (even its two-point function) look like anything but free. This also holds true

\(^1\)This "field operator" is really an operator-valued distribution whose testfunctions space is restricted to those Schwartz test functions whose total integral vanishes. Its Hilbert space is generated by polynomials in the well-defined associated current (its derivative, the field is a line integral in terms of this current).

\(^2\)This property is lost in the zero mass limit when the free field diverges in the infrared (but its derivatives stay finite) and the Wick rules for exponentials suffer restrictions from the charge conservation.

\(^3\)Unfortunately Jordan used his correct observation of what we nowadays would call Bosonization/Fermionization to base his pet idea of "the neutrino theory of light" on [17]. The relation of the gauge invariant content of the Schwinger model in terms of a exponential massive free Boson which has no charge sectors to its short distance limit with infinitely many charge sectors is an impressive allegory for the transition from confinement to short distance charge liberation.
for fields which result from a charge generating scaling limit procedure from free fields, as the above exponential.

What can and does happen through the use of such charge-carrying exponentials however, is that the Hilbert space obtained from the reconstruction using the limiting correlation functions is different from the Wigner-Fock space of the original particles. It is easy to see that the presence of the charge-carrying exponential modifies the mass-shell delta function into a fractional power (not a fractional number of particles as the unparticle partisans claim) in terms of the Källén-Lehmann spectral variable $\kappa^2$, in short its defines an "infraparticle". The field (2) originates from a Lagrangian which describes a conventional derivative coupling of a two-dimensional massless scalar with a massive spinor. All other soluble models (including those which have recently been used to explain the notion of unparticles [33] see later) of the 60s and 70s, with the exception of the unmodified Schwinger model [35], have these charge-carrying zero mass exponential factors. The local observables of these models always contain the current operator $\partial \phi$, whereas the exponentials are charge creators in the mentioned sense i.e. objects which intertwine the different superselection sectors of the respective models.

The testfunction-smeared infraparticle operator applied the vacuum yields a state which captures much more of the localized testfunction than just the mass shell restriction of its Fourier transform which the free field was able to extract. As a result the separation into a "particle" like contribution and the remaining "stuff" is not as well-defined as in standard particle theories. Note also that if one attributes to the word "stuff" the meaning of an uncountable substrate, it is not the emitted higher frequency photons (which enter the registering device), but rather the invisible uncountable long range part which deserved the predicate "stuff" and is at least partially (below the resolution on the observer side which can never be completely eliminated) "invisible".

It is not uncommon that what is infrared-divergent in perturbations theory may sum up to be zero nonperturbatively. Indeed the LSZ limits of infraparticle fields as (2) are zero since Hilbert space positivity forces the mass-shell singularities to be milder than a delta function. This means that standard scattering theory is not applicable to infraparticles, but the objects beyond the standard setting are not necessarily "invisible". A calculationally efficient formalism to compute inclusive cross section for infraparticles exists only in a rudimentary fashion [18]; the most efficient method is still the Yennie-Frautschi-Suura infrared regularization-based compensation method which in turn is a generalization of the Bloch-Nordsieck formalism.

The conjecture, based on the change of the mass-shell structure of the Kallen-
Lehmann two-point function in those models, that the cause for the breakdown of the standard scattering theory was a rather radical change of notion of particles, was a bit audacious in the 60s. Merely viewing this change in the analytic setting of poles and singular cuts as a singular cut replacing the delta function in the K-L spectral function, would not reveal the full dynamical structure of infraparticles. What was needed was an understanding in terms of spacetime localization properties.

Partial results about the realistic case were found in [5], and a more complete conceptual picture emerged in [13][14] (see also [18][23]) where a theorem was proven according to which the infraparticle structure together with the spontaneous breakdown of the L-symmetry in charged sectors (related to the infinite cardinality of the infrared photon clouds) is a consequence of the appropriately formulated quantum version of the Gauss law. This limits the infraparticle nature to abelian gauge theories, but represents nevertheless (in my opinion) a high point for what can be achieved by rigorous structural arguments.

There remains a practical question namely how does a physical charge-carrying operator look like? From Buchholz’s theorem we can conclude that it must be extended up to infinity. The formal candidate which has the sharpest localization which is consistent with the Gauss law is of the Dirac-Jordan-Mandelstam form

\[ \Psi(x,e) = \int_0^\infty i e \Lambda \lambda \chi(x + \lambda e) d\lambda \]

where \( e \) is a spacelike unit vector which characterizes the localization along the line \( x + R_+ e \) and the electric charge is denoted by \( e \). This expression fulfills all the formal requirements. It is gauge invariant and extends to infinity in accordance with Gauss law. It is a string-localized field which transforms covariantly (second line) but the L-invariance is spontaneously broken i.e. the implementing global unitaries of the algebraic automorphism do not exist [14]. It is an interesting and poorly understood question whether such formulas are a necessary structural consequence of the nature of the local observables. Combining an old idea of reconstructing charged fields from neutral currents by using a lightlike limit procedure which Langerholm and myself designed in the 60s [15] Jacobs [?] introduced the concept of gauge bridges and showed that at least in the abelian case and in the quasiclassical approximation of QED the above formula is canonically distinguished in the sense that it can be obtained in a natural way from local observables only. Unfortunately it is not clear whether this holds also for the quasiclassical approximation of the QCD model.

Another unexpected but related feature was that the different spacelike directions, which after smearing with directional functions \( g(e) \) with small support become narrow spacelike cones, are defining superselection rules in addition to those of the electric charge (or the electric charge is the directional-independent part of a finer superselection structure). The physical mechanism behind is that these cones contain an infinite accumulation of soft photons which makes it impossible to pass from one cone direction to another by a local or at least
quasilocal change \[23\].

It takes tremendous computational stamina to proof that this formal expression (3) admits a renormalized version in every order of perturbation theory, but exactly this was accomplished by Steinmann\[16\] \[26\]. There are of course other noncovariant ways of organizing the localization in accordance with Gauss law as e.g. a Coulomb-like distribution which is rotationally invariant around x in a fixed reference frame, but the semiinfinite string localization which represents a singular limit of a spacelike cone is the best analogy to the point as the sharpest limit of a causally closed (i.e. double-cone shaped) compact region and in the sense of maintaining Poincaré covariance. Note that the line integral in the exponential corresponds to the zero mass scalar field in the 2-dim. setting in that its perturbative modifications in the exponential interaction strength also lead to momentum space logarithmic corrections (a power law modification after summation). This is in accord with the two-dim. exponential massless Boson calculation in \[2\] and \[33\], with the only difference that in the above case the gauge invariance prevents to attribute a separate Hilbert space meaning to the two factors in (3).

The spacetime analysis of infraparticle is not only more intricate than the study of the infraparticle structure of the two-point function near \(p^2 = m^2\), it is also much more revealing. For example it would be virtually impossible to conclude from the changed mass shell singularity structure of the two point function alone that the sharpest localization of infraparticles is semiinfinite spacelike and that Gauss’s Law is the cause of all these modifications.

Behind the esthetic flaw of having to do things "by hand" instead of getting them from the perturbative formalism as all the other expectations of pointlike fields, there exists a problem which becomes much more pressing in QCD, where no consistent formula "by hand" for nonlocal gauge invariant operators which corresponds to (3) has been found. This is of course related to the problem of gluon- and quark- confinement and possibly of dark matter (in the sense of matter which is largely inert with respect to standard matter but nevertheless appears to coexist in the same theory).

Such an "invisible" counterpart of the charged QED matter, if it exists, cannot be understood as part of the existing gauge theoretical formalism aiming at local observables which are identified as the gauge invariant part within an unphysical setting. Possibly nonlocal gauge invariants in QCD are a fortiori not part of the formalism but left to ingenious guesswork. Whereas in the above abelian case of physical charged fields this was still possible on a formal level \(3\) as well as under the more stringent conditions of renormalized perturbation , nothing is known about nonlocal operators in a physical Hilbert space in QCD-like models except those vague ideas associated for the last 4 decades with confinement of quarks and gluons\[17\] which draw their main support come

\[16\]The computational effort necessary to assure the perturbative existence of these DJM formulas goes beyond what any standard renormalization formalism as \[24\] or any of the more recent refinements can achieve. Steinmann had to develop a technique especially for this problem.

\[17\]The putative link between asymptotic freedom and infrared slavery has the flaw that it...
from placing quantum mechanical quarks into a vault created by the walls of a potential or from lattice gauge theory which is not even able to predict the simpler infraparticle properties of QCD. QFT does not dispose over such resources, contrary to the quantum mechanical vault mechanism its very restrictive causal locality principle only leave the infinite spacetime extension as the resource of "invisibility" of certain matter components. This resource was already used in a weak form by the undetected infrared photon component, but as mentioned, it is not a consequence of the presence of zero mass particles alone, one also needs an interaction which is sufficiently strong in the infrared; the $N/\pi$ interaction with massless $\pi$ does not have the strength to create infrared clouds.

The problem starts when a zero mass gluon acts on itself. In a metaphoric picture interacting should inherit the partial invisibility of infrared photons, but on the other hand they are also required to behave like charged infraparticles whose "least nonlocal" localization is a semiinfinite string as $\text{(3)}$ i.e. they have to be the source and that what it produces at the same time. How can these two tendencies be reconciled in a non-metaphoric way? It seems to me that the first step in this direction should be to look for a reformulation which loosens the shackles of gauge theory to local observables and get local and nonlocal observables (="nonlocal gauge invariants") under the same roof. But this can only be done mitigation on the gauge side i.e. by staying in a physical Hilbert space throughout the calculation.

Indeed some recent ideas about how to overcome this conceptual handicap go precisely into this deirction. In order to have also physical (alias gauge invariant) nonlocal operators within a unified formalism, one must leave the boundaries of gauge theory, because the latter by its very nature of being a quantized form of classical gauge theories is limited to local observables generated by pointlike fields.

There is a formulation for which free vectorpotentials are string-localized $A_{\mu}(x,e)$ where $e$ is a spacelike direction. This potential is covariant and fulfills the prerequisites of renormalization since its short distance dimension is $\text{add}=1$. It is transversal and fulfills the axial gauge condition $\epsilon^\mu A_\mu(x,e) = 0$ in addition to transversality $\partial_\mu A^\mu(x,e)$ \text{[12]}. One may call it the "axial gauge", but one should be aware that strictly speaking it is not a gauge but a covariant string-localized field in the physical Hilbert space which naturally fluctuates in both variables $x$ and $e$. With other words the direction $e$, unlike a gauge parameter, participates also in the L-transformations and is indistinguishable. From a point in 3-dim. de Sitter spacetime (space of spacelike directions) and finally should also be accountable for string localizations of charged fields $\text{(3)}$.

Different from the pointlike setting of free potentials in the BRST (or any other gauge fixing formalism), these covariant stringlike potentials share together with their field strength the same physical Hilbert space and, at least in the QED case, this continues in the presence of interactions. The difference in the covariant transformation law requires to keep the $e'$s (which participates in the Lorentz transformation) at generic values, unlike a fixed gauge parameter.

does not account for all degrees of freedom which were initially there.
in the pointlike BRST approach. Since these stringlike potentials do not admit a Lagrangian description, one has to take recourse to the setting of "causal perturbation theory". But this only exists for pointlike fields; the occurrence of stringlike localization leads to a significant change in the perturbative iterative Epstein-Glaser formalism which makes the perturbation theory different from those of pointlike gauge fields in that counterterms may now also be string-localized. Ignoring this aspect and treating it as a gauge problem in the axial gauge one inevitably runs into the unmanageable infrared divergencies well-known to anybody who tried to lay his hand on this problem.

In the string-localized setting the origin of all these problems becomes obvious since the infrared problems are equivalent to short distance problems in a 3-dimensional de Sitter space, but unfortunately the problem does not factorize in Minkowski and de Sitter, so that it necessitates a nontrivial generalization of the Epstein-Glaser iteration step. This is presently being investigated\[27\], but with only two people working on this problem, (one being well beyond retirement age and the other overburdened with teaching duties) this will take some time\[27\]. One obvious observation should be mentioned, for correlations of alias gauge invariant fields the new setting leads to $\epsilon$-independence on the level of the same formal arguments as in the BRST gauge formulation.

The renormalization theory involving string-localized fields is much more demanding since the time-ordering does not only effect the starting points of the semiinfinite strings, but also involves the string line as a whole (which leads to the mentioned significant change in the Epstein-Glaser iteration). It is very important to do the computation for generic values of the $\epsilon_i$ i.e. to treat them like independent points in de Sitter space and integrate, as one always does, over the inner $x_i$.

The question is then whether one should average over the internal $\epsilon_i$ (integration) i.e. as if the theory would be a QFT on de Sitter space, or whether one should smear all of them with the same testfunction $g(\epsilon)$ supported around one point in de Sitter space which the above formula \[3\] would suggest. As long as one keeps the $g$ fixed on keeps the terrible infrared problems of the axial gauge at bay. Most of our numerical understanding about QCD comes from lattice analogs. But the use of lattice theory is not such a good idea for problems of a more structural kind. Lattic theory has not even been able to shed a light on the infraparticle problem, how can it reasonably be expected to solve such structural conundrums as invisibility in the sense of gluons, quarks or dark matter?

The advantage of the formulation in terms of string-localized potentials (instead of the standard formulation) is that the physical origin of the infrared problems of QCD is clearer. But the problem is anything but simple, and remembering how long it took to get renormalization theory for pointlike fields into a manageable shape, it would be unrealistic to expect that its string analog can be worked out much faster than it took to elaborate renormalized perturbation theory for pointlike fields.

One would like to expect from the string reformulation of nonabelian Yang Mills theories some clarification of the following problems. The local degrees of
freedom, which can be described by pointlike physical fields, do not account for all degree of freedom of the system. Whereas the fate of the remaining one’s in QED is well understood, in the QCD case this is terra incognita and expected to account for the “invisible” degrees of freedom which are carried by gluons and quark fields. Hence one would like to think that the issue of invisible, inert or dark matter is connected to a very strong indecomposable nonlocality beyond the well-known infraparticle properties [28][29] of undetected infrared photon clouds. The aim would be to show that certain infrared degrees of freedom cannot be registered at all in counters which are at most quasilocal in their extension [23].

Even at standing accused of being repetitious let me state again that in contrast to QM which can, by using appropriate potentials, keep matter “out of sight” by placing it into a confining vault potential (“confinement”), the only resource of QFT for creating its structural richness is causal locality; there are no confining vaults in the arsenal of causal localization. There is of course no guaranty that properties as invisibility/darkness can be explained within QFT, but there can be no doubt that the only available resource is delocalization.

The analysis of irreducible representations has shown that there are two kinds of localization, pointlike or indecomposable stringlike. In its purest and strongest form the latter shows up in the stringlike fields associated with the Wigner infinite spin representations [12]. For arguments in favor of their inertness relative to ordinary matter see [28][29]. The nonexistence of local operators which carry certain charge superselection rules as in (3) is only possible as a result of interactions.

A new string-localized formalism may also shed a new light on the Schwinger Higgs formalism of charge screening and its nonabelian counterpart. Algebraically there is no difference between scalar QED (or its nonabelian counterpart) and the Higgs model, since the presence of a degree 4 term in a would be charged complex scalar field (needed for entering the “Mexican-hat” parameter region) is in any case required by renormalization theory. In the presence of spin 1 fields, a charged Boson may screen itself in the presence of vectorpotentials and become a real field. The other degree of freedom in the complex field together (in agreement with a structural screening theorem by Swieca [32]) with the two photon degrees of freedom combine to form a massive vectormeson.

At the end one has a fully pointlike local theory fitting into the standard framework of QFT and instead of the complex massive field obeying a charge selection rule the physical outcome consists in a real massive field without any rule which limits its copious production. Does this have an intrinsic meaning, can one experimentally tell that a model is the screened version of an originally charged one? Hard to say. In any case this fully local theory is very different from the nonlocal electrically charged model, not to speak about the even more nonlocal invisible hypothetical gluon degrees of freedom in YM models.

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18Schwinger was thinking of a screened “phase” in spinor QED, where a perturbative implementation of screening is not possible. To make his point more convincing, he invented the Schwinger model.
The only conceptual resource which one has at one’s disposal for the construction of interacting fields is Poincaré covariance and locality. In perturbation theory one also needs a minimal principle on the scaling degree, usually referred to as the renormalization principle. Although constructions based on operator algebraic methods had some recent success, the main source of qualitative and quantitative understanding is still the local Poincaré-invariant coupling between free fields of arbitrary spin and mass. Since all massive one-particle representations are pointlike generated, there is good reason to believe (apart from the remark at the end of the previous to last section) that, unless there are also zero mass representations entering the coupling, the resulting theory will be generated by pointlike fields. Adding global symmetries to these fields does not change the localization properties

Only the participation of higher helicity ($\geq 1$) fields can do this. Power counting requirements in limiting the dimension of the interaction to $sdd \leq 4$ which excludes working with field strength and requires to use instead their covariant potentials which turn out to be semiinfinite string-localized. The problem is then to avoid that the whole theories is becomes string-localized; each QFT should at least have a subset of (generally composite) pointlike localized fields which generate the subalgebra of local observables. This would be the analog of the gauge invariant algebra in the approach built on local gauge invariance which the latter playing the role of separating a physical content from an unphysical embedding. The local gauge formulation not only misses out on ”nonlocal gauge invariants” as the analogs of the string-localized generators, but it also creates the wrong impression that there is a mysterious gauge symmetry in analogy to an inner compact group symmetry, whereas it is really the existence requirement of a nontrivial local observables which restricts the interactions beween stringlike potentials and their coupling to massive matter. Nothing is known about such nonlocal degrees of freedom and their expected lack of ”visibility” beyond that related to the photon inclusiveness in QED. It would be intereting if the present unparticle activities could be directed towards these gaping holes in our understanding.

An indication of non-intrinsicness comes from the computation where one starts from the sdd=2 massive vectormeson, uses BRST to lower the dimension to ssd=1 (which leads to renormalizability by power counting) and requires that the BRST cohomological formalism also works in higher orders. It turns out that this can only be achieved by introducing an additional physical degree of freedom whose simplest realization is a scalar massive particle (naturally with a vanishing one-point function which is the hallmark of the Higgs). But there is an unsatisfactory aspect in such a derivation since cohomological requirements in a an indefinite metric space are not representing physical principles.

The use of ”ghostly crutches” could be avoided by using a string description of a massive vectormeson field which does the same job as BRST (namely reducing the sdd to 1) without introducing indefinite metric and remaining in the physical Wigner-Fock space. In that case the only remaining principle for the presence of an additional scalar particle is that without its presence there would be a problem with locality i.e. the use of a string-localized vectormeson
has made the interaction renormalizable in the sense of power counting and in
order not to remain stuck with only semiinfinite strings we would need a locality
restoring scalar particle. If the strings can be resoled in terms of pointlike fields
without the presence of an additional scalar then we would have learned that
there are fully local vectormeson theories without scalar companions. No matter
what LHC will tell us, both outcomes would have fundamental consequences for
the development of QFT. Arguments in favor of higher spin particles which only
can interact among each other in the presence of lower spin particles would be
much deeper than those based on higher symmetries as e.g. supersymmetry.
Only in this way can one get away from the Mexican hat cooking recipe for the
Schwinger-Higgs screening mechanism.

3 What are unparticles and are they related to infraparticles?

According to the existing literature unparticles [1][33][3] are hypothetical bursts
of scale invariant invisible "stuff" which is formed in high energy collisions of
ordinary particles and which dissipate without leaving direct traces ("invisibility")
through secondary interactions. Whereas the unobserved infrared photon
"stuff" below the resolution leads to inclusive cross sections and changes the
nature of the charged particles in a conceptually very radical way, the idea
around unparticles is different namely after pealing off some unobserved long
range "stuff" into the vacuum, the source particles remain the same ordinary
particles as before the interaction. Such a process appears somewhat strange.
since a short range source should not be able to give rise to "pealing off" long
range stuff unless this stuff consists of massless particles but not as members
of an infinite cloud. An example of such an reaction would be the before men-
tioned infrared-tame interaction of massive spinors with scalar massless (and
quite visible) mesons.

In order to avoid getting lost in vagueness, we first look at the concrete
and explicit 2-dim. illustration in [33] which consists of the modified Schwinger
model i.e. $QED_2$ with a massive vectormeson instead of photon. As men-
tioned in the previous section all soluble models of the 60s [20], apart from the
original Schwinger model itself, contain the subtle charge-carrying exponential
Boson factor and other standard free fields; this is also the case for the modified
Schwinger model. The authors chose for their illustration the chiral condensate
operator [21] which for the modified model has the form (here the details of how
this operator comes about from a Lagrangian are irrelevant)

$$\mathcal{O}(x) = e^{i\alpha A(x)} : e^{i\beta \varphi(x)} : \quad (4)$$

where $A(x)$ is the gauge invariant massive field the exponential of which already
appears in the gauge invariant solution of the Schwinger model. The second ex-
ponential is a charge carrying zero mass terms and $\alpha$ and $\beta$ are real parameter
related to the ratio of the mass coming from the Schwinger-Higgs mechanism.
and the Lagrangian vectormeson mass $m_0$. If it would not be for the second factor, the large distance limit would describe the Schwinger-Higgs chiral condensate with the massive one particle contribution being the next leading term in the expansion. The presence of the charge-carrying massless exponential undoes part of the screening and converts the leading term into a "infravacuum" whereas the next to leading term represents an infraparticle contribution in the previously explained sense.\footnote{A footnote in \cite{33} reveals that the authors are aware of this connection.} This charged "infravacuum\footnote{The quotation marks are there in order to distinguish this situation from a more radical notion of infravacuum \cite{22} which cannot be viewed as the application of a charge carrying zero mass field to the standard vacuum.} component of $\mathcal{O}\Omega$ is the only component which resembles separate scale-invariant "stuff" similar to what the authors envisage for unparticles; but try to have an interacting situation in which conformally invariant components coexist with massive ones in $d=1+3$ and watch yourself failing; to talk about a sector which is a little bit nonconformal is not much better than introducing the notion of a little bit pregnant in real life.

Two-dimensional models of the mentioned kind do not describe scattering.. Even though they are not free fields in the technical sense, they describe noninteracting charged "stuff". So in order to utilize the infrared contributions to the two-point function in Feynman diagrams, the authors couple $\mathcal{O}$ to the square of another field \cite{21}. They use the fact that the infra/unparticle structure in $d=1+1$ allows for interaction-free illustrations (which only look like containing interactions) whereas according to our discussion in the previous section it is not possible in $d=1+3$ to separate kinematical from dynamical aspects.

Whereas $d=1+1$ infraparticles were introduced in order to understand the scattering of charge particles, the unparticles in the sense of representing scale invariant "stuff" which, unlike the soft photons clouds which never liberate themselves from the charged particles, are apparently not hooked on massive matter. Accepting for the sake of the argument the properties their protagonists like to attribute to them it seems that they do not appear in the outgoing amplitudes and are not even accounted for in inclusive cross sections. It seems that the example of the extended Schwinger model (as all other examples with coupling to massless scalars) is not a good illustration for the creation of zero mass conformal stuff which, unlike that of infraparticles and its zero mass clouds, is supposed to separate itself from ordinary massive matter.

This model also points at two unsolved problems in QFT. The first one is: does it make sense to couple free fields with fields which are interacting from the start? Besides the question of practicality for a perturbative approach there looms an unsolved fundamental problem. One formulates interactions by coupling free fields not only for pragmatic computational reasons. One also believes that this insures the mentioned asymptotic completeness, which in the mass zero case amounts to a weaker form of completeness in terms of inclusive cross section. But it is doubtful that the coupling of anomalous dimensional conformal matter coupled to free fields stays in this setting.

The second difficulty which becomes particularly acute in $d=1+3$ is that
coupling of massive to massless matter never leads to scale-invariant "sectors"; the only theory which does this is the tensor product of a conformal theory with a massive one. As much as it is meaningless to use expressions as "a little bit pregnant" in daily life, one cannot fight structural properties of QFT by notions of effective field theories or what is more specific to the situation at hand by Bank-Saks arguments which claim that it is possible to overrule such structural facts and make sense out of violating conformal invariance in a region of a theory. Ideas of effective actions may have their place of validity, but one should not try to use them for overturning structural properties.

As the example of the photon shows, its interpolating Heisenberg field is not scale covariant, only the registered outgoing free photons are. What remains however intact is the gapless zero mass energy-momentum spectrum and its ensuing long range character. It is also interesting to point out that even on a formal level the coupling of anomalous dimensional fields with ordinary matter does not improve the long range aspect; to the contrary, as the scale dimension increased, the infrared coupling becomes weaker. The strongest infrared couplings are those which involve string-localized potential associated with \( (n = 0, s \geq 1) \) representations for which the aforementioned vectorpotential \( A_\mu(x,e) \) is the best studied case. The use of the string-localized description makes the long range which sets the infrared strength of the QED coupling manifest whereas (see previous section) in the gauge formulation this remains hidden and has to be brought out "by hand" through formulas as \( (3) \). Only they have a chance for accounting for the desired invisibility property.

Without wanting to lend support to the somewhat controversial physical interpretation of such couplings in the literature on unparticles, it may be interesting to mention that there are anomalous dimensional conformal fields which describe "stuff" in a more literal sense i.e. something which certainly cannot be interpreted as coming from a scaling limit from a standard theory and therefore cannot be associated with inclusive cross sections. These are the conformal *generalized free fields* as they e.g. arise from ordinary AdS free fields via the AdS-CFT correspondence. From a combinatorial point of view they behave as free fields\(^{21}\). Duetsch and Rehren \( [31] \) have investigated the suitability of the causality properties of such "stuff" for the formulation of a consistent perturbation theory and their results. The results are yet incomplete, but interesting and even somewhat encouraging. None of the unparticle lowest order calculations which only use unparticle two-point functions would change, if one uses these combinatorially much simpler fields.

Perhaps one should be careful with prematurely attaching physical attributes to unparticle calculations and rather study in more general terms what QFT has still in store once one goes beyond standard textbook particle physics. The most fruitful unexplored area seems to be the aforementioned interacting massless higher helicity objects coupled to themselves and to standard massive matter. It is the generalization of the mentioned string-localized electromagnetic vector

\(^{21}\)They are not the standard anomalous dimensional fields which are "interacting" in some sense which can be made precise.
potential with scale dimension sdd=1 which has a good chance to lead to the
kind of infrared singular interactions which one needs to get beyond the standard
matter and create "stuff" which consists of infinitely many objects in a finite
energy range. Zero mass is necessary but not sufficient; e.g. scalar zero mass
couplings do not have the sufficient infrared strength. It is not the size of
anomalous dimension but rather the algebraic form of the infrared coupling of
higher helicity free string-localized potentials which increases with spin that
increases this strength.

Among all at least partially studied models, the most promising are those
which involve couplings among several string-localized potentials $A^{(i)}_{\mu}(x,e)$. The
experience with nonabelian gauge theories suggest that in order to find pointlike
generated subalgebras the couplings must be related to each other in the way
they are in gauge theories; if not one will get stuck with a string-localized
theory which has no local subobservables at all. Assuming that the mentioned
string theoretic generalization of renormalized perturbation theory works, one
would have two kind of matter in such a setting: visible point-localized "glue-
ball" matter and string-localized and presumably invisible gluon matter. I am
convinced that without solving this problem one has no chance to understand
the issue of invisibility versus asymptotic incompleteness. The understanding
of the abelian counterpart QED where such string-localized fields represent the
charged operators and where a rest of undetected soft photon "stuff" always
remains outside observation is encouraging for a program of looking for stronger
forms of invisibility. The unparticle project certainly shares this aim even if
the proposals to implement it are quite different (apart from the shared low-
dimensional illustrations).

The unparticle project tries to achieve invisibility of interaction generated
"stuff" by using conformal matter with anomalous dimensions, in contrast the
project favoured in this article is based on a generalization of gauge theory.
Whereas the gauge formulation hides the nonlocality by introducing fake point-
like potentials together with BRST ghosts at the expense of the Hilbert space
positivity and as a result tends to overlook (even in the abelian case $SU(3)$) non-
local operators in the physical Hilbert space, the string like description catches
also those nonlocal field degrees of freedom which escape the pointlike descrip-
tion but nevertheless carry energy-momentum and hence react gravitationally.
This still speculative project which generalizes the infraparticle idea is expected
to explain the confinement of the gluon and quark degrees of freedom and to
attribute physical reality to genuinely invisible dark matter. In the conclud-
ing section I will address this speculative issue in a more general context than
un/infra particles.
4 Invisibility and lack of asymptotic completeness

Whereas in QM, which has no maximal velocity, fields are synonymous with particles and there is hardly any limit on the kind of interactions between them, QFT is more restrictive as a result that all of its properties at the end must be understood in terms of causal localization i.e. the localization in theories which have a maximal velocity [7]. The prize to pay for this is that its only measurable non-fleeting and genuinely intrinsic and stable objects, the particle states, are only appearing in the large time asymptotic limit of the fleeting field states respectively; an interacting theory with any interaction fulfilling the general principles will have no particles at any finite times! Since besides the stability (the existence of a lowest energy state) the realization of causal locality is the only handle at one’s disposal in order to control the asymptotic particle content, the study of admissible particle structure and their possible manifestations in the real world has remained the most subtle part of QFT.

Even the deeper understanding of the standard situation, in which one-particle states are separated from the continuum by a gap, has remained a 50 year challenge [32]. It started with the (at that time surprising) observation that the number of phase space degrees of freedom in a finite phase space cell (which as everybody learns is finite in QM), is infinite in QFT; an infinity which originates from the realization of the causal localization principle. The hope was that the precise quantitative understanding of this infinity could explain why the Hilbert space of QFT apparently can be fully described (even beyond perturbation theory) as a Wigner-Fock Hilbert space; a fact which ceases to be valid in QED.

For free fields this set is compact and (as was shown later) even nuclear [23] and there are good arguments that at least in physically reasonable theories (e.g. absence of Hagedorn temperature) it stays this way. Although many deep properties followed from this phase space structure, it is now agreed on that asymptotic particle completeness cannot be derived from phase space properties alone.

The infraparticle structure of electrically charged particles contained the important message that there are objects which cannot be generated by pointlike field and the formalism of gauge theories. Nonlocal objects in the physical Hilbert space as e.g. electrically charged particles are better constructed in a setting which permits stringlike localized potentials 22.

It is interesting to note that as long as the mass gap hypothesis holds, the formulation and derivation of scattering theory between pointlike and semi-infinite stringlike fields [23] is similar. The only significant difference is that the S-matrix and the formfactors of such models do not necessarily fulfill the

22From a point of view of positive energy irreducible representations of the Poincare group, the necessity to introduce stringlike generators only arises for the zero mass potentials of the pointlike helicity $\geq 1$ field strength and in a much stronger form for the so-called infinite spin representations (which possess no pointlike generators). There is no reason which forces one to go generators on higher dimensional submanifolds as branes.
important crossing property \cite{30}; with other words there is no analytic master function such that the different distributions of in and out particles are different boundary values of that master function. This has the interesting consequence that there may be a subterfuge to Aks theorem \cite{28,29}. In that case it would be possible that certain channels cannot be produced in scattering processes despite the fact that there is no charge superselection rule which prevents them. This kind of partial inertness may have some potential interest in connection with dark matter. Massive strings can only exist in interacting matter, free massive fields are always pointlike generated. Massive strings once applied to the vacuum create states which are always generated in terms of pointlike states (which themselves cannot be obtained by applying pointlike fields from the interacting field algebra).

From the existing formulation of the unparticle project it is not clear if and how they fit into the balance of asymptotic completeness. For standard mass gap situation of believes that the coupling between free fields is not only popular because it is simple and one cannot think of anything else which is in agreement with the locality principle, but it also preempts the property of asymptotic completeness by having from the very beginning those fields and their Fock space which are as close as possible to the incoming/outgoing fields. In the case of electrically charged fields though for infraparticles one losess the Fock space structure, but since the scattering probabilities still add up (the resolution can be made arbitrarily small). In the case of QCD and for unparticles this is not so clear, but for different reasons. The difficulty in the latter case is that one starts already with anomalous dimensional fields which are not only very far removed from a Fock space structure, but for which it is not even clear whether they permit a doubly inclusive cross section setting which appears to be the least one needs to fulfill asymptotic completeness in the sense of probabilities.

5 Concluding remarks, resumé

The unparticle idea presents an opportunity to recall previous successful and less successful works which explored the region beyond the standard (mass gap) particle setting. The theory of infraparticles which aimed at the incorporation of the observed infrared aspects of electrically charged particles is an example of a successful attempt. Apart from the issue of ”invisibility” which is the main motivation behind unparticles as a new kind of matter, the infraparticle models follow a similar construction recipe as those designed to illustrate unparticles, in fact its two-dimensional illustrations are identical.

On the other hand the popularity of unparticles may point our thinking again towards invisibility problems caused by noncompactly localized degrees of freedom within theories which we prematurely believed to have ”solved” (e.g. by analogies with lattice theories). Some nice catch words as (gluon-, quark-) confinement provided us with a quiet conscience. But lattice theory lacks those strong principles which relate indecomposable positive energy representation of the Poincaré group for certain zero mass representation to semiinfinite string
localization\textsuperscript{23}, although it is quite efficient at emulating standard QFT containing only compactly localized representations. Interaction-free illustrations exist in the form of string-localized infinite spin positive energy representations in Wigner’s list, but unfortunately they do not generate local subalgebras (they have no local conserved energy-stress tensor), at least not in this interaction-free form.

What one needs in order to have states ”out of sight” coexisting with states generated by local observables is a situation in which the interaction is so strong in the infrared, that besides ordinary matter (described by a local subalgebra) there are degrees of freedom (not ghosts!) which have a localization as bad as that of the mentioned infinite spin representations.

The existence of ordinary matter in QCD-like theories has become part of the accepted folklore (dimensional transmutation) and phenomenological schemes have been designed to link such mechanisms with Lagrangian QCD. But the other side of the coin, namely the fate of the nonlocal (gluonic) degrees of freedom which escape the gauge theoretic formalism (which by its very nature is only focussed to the local ones) have been left in a conceptual limbo.

Looking at the literature, it seems that most people believe that they do not exist, i.e. that all the degrees of freedom went via dimensional transmutation into the local observables which in turn form an asymptotically complete system. But in view of the electrically charged particles whose sharpest possible localization is semiinfinite string-like, this is not very credible.

In order to see what is going on, we have started to investigate quadrilinear interactions between stringlike free fields with special attention to those for which the string-like nature is not enforced by imposing renormalizability but is naturally emerging from the Wigner representation struture\textsuperscript{12}\textsuperscript{27}\textsuperscript{34}. Since such fields have \textit{sdd=1} independent of spin, there is no problem with the power counting prerequisite for renormalizability. The really hard problem, as mentioned before, is the perturbative Epstein-Glaser iteration for semiinfinite strings instead of pointlike particles\textsuperscript{27}.

There is no disagreement with the aims of unparticle physics since almost all the deep unsolved problems are in the infrared. Whatever the outcome will be, it is important to get particle physics away from those metaphoric inventions as e.g. supersymmetry and string theory back on track addressing the old unsolved problems with new ideas.

My attitude with respect to unparticles has been one of criticism (mainly connected to the knowledge which was lost during the last 3 decades) but at the same time encouragement because unparticles could serve as a catalyzer for a return to particle theory’s most rich research area, which, unfortunately left too many unsolved problems on the wayside\textsuperscript{23}. One central problem which was first

\textsuperscript{23}The problems of lattice approximatio of QFT is similar to the approximatability of operator algebras by matrix algebras. Although for hyperfinite von Neumann algebras this is possible, there is no way of keeping track of the richness of infinite class of hyperfinite algebras by looking at finite matrix algebras. Most of the interesing physical mechanism are only accounted for in the infinite limit.

\textsuperscript{24}Inasmuch I have lamented the loss of criticism in another context, I am of course also
formulated in the early 60s \cite{3} is: *when is a theory of quantized fields a theory of particles*, or more specifically, the problem of asymptotic completeness. The phase space structure of QFT (which is significantly different from that of QM) was identified as one local structural property which plays an important role in the understanding of the global particle structure. It was already clear at that time that there are field models which do not fulfill asymptotic completeness (generalized free fields, conformal models) and they should be excluded. But physically important structures as electrically charged particles and more general infraparticles are still inside an appropriately extended asymptotic completeness notion. Their history shows that structural problems of QFT cannot be solved by lowest order perturbation theory; the first order coupling between a conformal field theory and massive matter evaluated for the two point function, as used by unparticle followers, does not reveal anything.

It is far from being clear why, what was considered to be an important physical principle or at least a successful working hypothesis in those times, should be ignored now. After all there is presently not the slightest indication that nature does not like the old principles nor is there a theoretical guide outside of at least some form of asymptotic completeness in the sense of probability conservation when unparticle "stuff" fades away into the vacuum.

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