40 years since GGRT: some personal considerations

Gabriele Veneziano
October 1972: GGRT

The Dual Resonance Model becomes String Theory!
(and is abandoned soon after...)
The Birth of String Theory

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Part I

Lessons from two success stories and from their puzzles/problems
The Standard Model of Nature  
(updated July 4th, 2012)

1. A Gauge Theory with a light $H$ for electro-weak and strong interactions.
2. General Relativity with a small $\Lambda$ for gravity.

...can be written in one page!
\[ L_{SMN} = L_{SMG} + L_{SMP}^{(\text{gen. cov.})} \]

\[ L_{SMG} = - \frac{1}{16\pi G_N} \sqrt{-g} \, R(g) \]
\[ + \frac{1}{8\pi G_N} \sqrt{-g} \, \Lambda \]

\[ L_{SMP} = - \frac{1}{4} \sum_a F_{\mu\nu}^a F_{\mu\nu}^a + \sum_{i=1}^{3} i\bar{\Psi}_i \gamma^\mu D_\mu \Psi_i + D_\mu \Phi^* D^\mu \Phi \]
\[ - \sum_{i,j=1}^{3} \lambda_{ij}^{(Y)} \Phi \Psi_{\alpha i} \Psi_{\beta j}^c \epsilon_{\alpha\beta} + c.c. \]
\[ + \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 \]
\[ - \frac{1}{2} \sum_{i,j=1}^{3} M_{ij} \nu_{\alpha i}^c \nu_{\beta j}^c \epsilon_{\alpha\beta} + c.c. \]
The SM of Elementary Particles

Very widely tested in accelerator experiments (... LEP, HERA, Tevatron, LHC)

Its quantum-relativistic nature manifests itself through real and virtual particle production. Taking this into account is essential for agreement between theory and experiment. Gave first definite indications in favor of a light H!
After LEP

| Measurement       | Fit                          |
|-------------------|-----------------------------|
| $\Delta \alpha_{\text{had}}^{(5)}(m_Z)$ | $0.02758 \pm 0.00035$ $0.02767$ |
| $m_Z$ [GeV]       | $91.1875 \pm 0.0021$ $91.1874$ |
| $\Gamma_Z$ [GeV]  | $2.4952 \pm 0.0023$ $2.4959$ |
| $\sigma_{\text{had}}^0$ [nb] | $41.540 \pm 0.037$ $41.478$ |
| $R_l$             | $20.767 \pm 0.025$ $20.743$ |
| $A_{\text{fb}}^{0,l}$ | $0.01714 \pm 0.00095$ $0.01643$ |
| $A_{(P_c)}$       | $0.1465 \pm 0.0032$ $0.1480$ |
| $R_b$             | $0.21629 \pm 0.00066$ $0.21581$ |
| $R_c$             | $0.1721 \pm 0.0030$ $0.1722$ |
| $A_{(\mu,b)}^{0,b}$ | $0.0992 \pm 0.0016$ $0.1037$ |
| $A_{(\mu,b,c)}^{0}$ | $0.0707 \pm 0.0035$ $0.0742$ |
| $A_{\chi b}$      | $0.923 \pm 0.020$ $0.935$ |
| $A_{c}$           | $0.670 \pm 0.027$ $0.668$ |
| $A_{(SLD)}$       | $0.1513 \pm 0.0021$ $0.1480$ |
| $\sin^2\theta_{\text{eff}}(Q_{fb})$ | $0.2324 \pm 0.0012$ $0.2314$ |
| $m_W$ [GeV]       | $80.404 \pm 0.030$ $80.376$ |
| $\Gamma_W$ [GeV]  | $2.115 \pm 0.058$ $2.092$ |
| $m_t$ [GeV]       | $172.5 \pm 2.3$ $172.9$ |

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**Theory uncertainty**

$\Delta \alpha_{\text{had}}^{(5)} =$

- $0.02758 \pm 0.00035$ (solid line)
- $0.02749 \pm 0.00012$ (dotted line)
- *incl. low $Q^2$ data* (dashed line)

Excluded

$m_H$ [GeV] vs. $\Delta \chi^2$
Freshly squeezed EWK plots

After 5 fb\(^{-1}\) (2011 LHC run @ 7 TeV)
After $\sim 6 \text{ fb}^{-1}$ more (2012 run @ 8 TeV)
Figure 4: Limits on the cross section of a Higgs boson decaying to two photons relative to the SM expectation for the combined 7 and 8 TeV datasets, obtained with the three analysis methods. The primary result is shown in (a).

(a) mass-fit MVA.
The SM of Gravity

Equivalence pr. tested with incredible precision
(universality of free-fall)

GR corrections better and better tested

New predictions:

1. Black holes (overwhelming evidence)
2. Gravitational waves (indirect evidence)

NB: All tests of Classical GR!!
Increasing precision of UFF tests
Sagittarius A* is it more than 10^6 solar masses?
Courtesy of Thibault Damour (review for particle data group)
...and of Cosmology

The "Concordance Model"
CMB vs. inflation

TT and TE correlations from WMAP (while waiting for PLANCK?)
Peak position favors spatially flat Universe
The SMEP and the SMG nicely combined in inflationary cosmology. NB: Semiclassical quantization of the geometry is part of the game explaining the large-scale structure of the Universe.
Figure 13. REFLEX II power spectrum (filled circles with error bars) for clusters with luminosities $L_X > L_{min}$. The REFLEX power spectrum is shown by the open triangles. The error bars for these two measurements are taken from equation (14). For comparison we also show the measured power spectrum from the 2dfGRS from Cole et al. (2005) (open circles). The solid and dashed line represent the $\Lambda$CDM power spectrum convolved with the REFLEX II and the 2dfGRS window function respectively, and adjusted to match the corresponding spectra. Error-bars exceeding the range of the plot are represented by arrows.

The shape of the cluster power spectrum is given by

$$P_{cl}(k, > L_{min}) = b_{eff}(> L_{min})^2 \left(1 + Q_k^2 \right)^{1/2} \left(1 + A_k + B_k^2 \right) P_{lin}^{mat}(k),$$

where $P_{lin}^{mat}(k)$ is the linear theory matter power spectrum. Although this model was originally developed and calibrated to describe the power spectrum of the 2dFRGS, its application has been extended to the analysis of other samples (e.g. Tegmark et al. 2006; Padmanabhan et al. 2007). In particular, Sánchez et al. (2008) showed that this model can give a good description of the clustering of the LRG sample from SDSS even though it was not specifically designed to do so. At the same time this model does not give a good description of the shape of $P(k)$ for the galaxy sample in SDSS. The results from the application of the $Q$-model to $N$-body simulations show that it can correctly describe the clustering of dark matter halos above a given mass threshold (Tegmark et al. 2006).

We follow Cole et al. (2005) and fix the value of $A = 1.4$ as obtained from the analysis of $N$-body simulations, while $Q$ and $B$ are left as free parameters whose values will depend on the limiting luminosity of the sample. We assumed all the cosmological parameters to be known and fitted for $Q$ and $B$, marginalizing analytically over the amplitude (as described in Lewis & Bridle 2002). From this analysis we obtain the values $Q = 24.9 \pm 1.1$ and $B = 12.0 \pm 2.1$, corresponding to the sub-sample defined by $L_{min}^2$. The best fit model obtained this way is shown by the solid line in Fig. 12. It can be clearly seen that the model of equation (28) gives an accurate description of the shape of the mean power spectrum from our ensemble of mock catalogues. This can be also seen in panel b) of the same figure, where we show the ratio between the difference of the mean mock power spectrum and the best fit-model to the variance from the ensemble. The parameters $B$ and $Q$ fitting the power spectrum of the sub-sample follow a degeneracy that can be described approximately by $B(Q) = 0.805 Q - 0.15$. This degeneracy is
Cosmic acceleration

Type Ia Supernovae

Perlmutter, Physics Today (2003)

Supernova Cosmology Project
High-Z Supernova Search
Calan/Tololo Supernova Survey

Accelerating Universe
Decelerating Universe

Relative brightness
Magnitude
Redshift

Mass density

Without vacuum energy
With vacuum energy
Is dark energy unavoidable?

- Our Universe is **not** homogeneous on “small” scales.
- In 1202.1247, 1207.1286 Ben-Dayan, Gasperini, Marozzi, Nugier & GV have re-examined \( d_L(z) \) relation using gauge-invariant light-cone averaging in presence of (stochastic) inhomogeneities.
- No IR or UV sensitivity encountered at 2nd order, unlike for other (more formal) averages.
- Effect much larger than naively expected \( (10^{-10}) \) but still too small to mimic a sizable \( \Omega_\Lambda(z) \).
- Could be relevant for its precise determination because of the predicted intrinsic scatter.
Gauge invariant light-cone averages

Adapted coordinates for light-cone averaging

(Gasperini, Marozzi, Nugier & GV, 1104.1167)

\[ ds^2 = \ U^2 dw^2 - 2 \ U dw d\tau + \gamma_{ab}(d\theta^a - U^a dw)(d\theta^b - U^b dw) \]

\( w = w_0 \) defines our past light cone

luminosity distance \( d_L \) simply related to \( \gamma = \det \gamma_{ab} \)

\[ (1 + z) = \frac{\gamma_o}{\gamma_s} \]
\[ \langle d_L^{-2} \rangle (z, w_0) = \frac{4\pi (1 + z)^{-4}}{\int d^2 \theta \sqrt{\gamma(w_0, \tau(z, \theta^a), \theta^b)}} \]
Putting all together

Cosmic Concordance

- No Big Bang
- Supernovae: expands forever
- Clusters: recollapses eventually
- CMB
- Vacuum energy density (cosmological constant)
- Mass density
- Open, Flat, Closed models
The cosmic fluid composition pie...
Strong evidence that our SMN cannot be the full story...
but what have we learned?
Nature likes $m=0, J=1, 2$ particles...
This is why it is well described by theories with either gauge or diff. invariance.

Many phenomenological puzzles for which we find hardly any clues from presently accessible length/energy scales.
1. Why $G = SU(3) \times SU(2) \times U(1)$?
2. Why do the fermions belong to such a bizarre, highly reducible representation of $G$?
3. Why 3 families? Who ordered them? (Cf. I. Rabi about $\mu$)
4. Why such an enormous hierarchy of fermion masses?
5. Can we understand the mixings in the quark and lepton (neutrino) sectors? Why are they so different?
6. What’s the true mechanism for the breaking of $G$?
7. If it’s the Higgs mechanism: what keeps the boson “light”?
8. If it is SUSY, why did we see no signs of it yet?
9. Why no strong CP violation? If PQSB where is the axion?
10. ...
Puzzles in Gravitation & Cosmology

1. Has there been a big bang, a beginning of time?
2. What provided the initial (non vanishing, yet small) entropy?
3. Was the big-bang fine-tuned (homogeneity/flatness problems)?
4. If inflation is the answer: Why was the inflaton initially displaced from its potential’s minimum?
5. Why was it already fairly homogeneous?
6. What’s Dark Matter?
7. What’s Dark Energy? Why is $\Omega_\Lambda \approx 1$ today?
8. What’s the origin of matter-antimatter asymmetry?
9. ...
Missing quantum corrections?

- Radiative corrections to marginal and irrelevant operators have been "seen" in precision experiments:
  - running of gauge couplings, anomalous dimensions
  - anomalies in global symmetries (U(1)-problem)
  - effective 4-Fermi interactions (neutral-K system)
- Some to relevant operators have not. Basically:
  - the Higgs mass (hierarchy problem)
  - the cosmological constant (120 orders off?)
- Latter(former) (in)sensitive to short-distance physics.
- Telling us, once more, that SM & GR are not the full story?
Theoretical/conceptual problems

In spite of the common denominator of gauge and gravity the SMN is “limping”.

The two legs it is resting on are uneven.

**GR** should be elevated to a full quantum theory

Two reasons to be unhappy about leaving gravity classical:

1. Ubiquitous *classical* singularities;
2. The *quantum* origin of LSS.
The SMN's puzzles & problems appear to be related to our ignorance about short-distance physics!

Insisting on better UV behavior has paid off (from Fermi to GWS)
Q: Is it supersymmetry?

Appealing for solving some puzzles (hierarchy, dark matter, grand unification, ...)

It will be explored at LHC up to some energy scale...wait and see...
Q: Is it **Quantum String Theory**?

- Provides a UV completion (with a scale!)
- Provides the massless particles the SMN needs... plus more (moduli = Achille’s heel?)
- Unifies (or even may reduce) gravity with (to) other forces (AdS/CFT).
- Sheds light on quantum Black-Holes (stat. mech. interpr. of $S_{\text{BH}}$, AdS/CFT)
Part II

Two gedanken experiments for exploring quantum string gravity
I. Transplanckian-energy string-string collisions in flat spacetime

(Amati, Ciafaloni, GV + ...: 1987-2010)

An executive summary
Example: a two-loop contribution

color code:
- red: in, out
- green: exchanged
- yellow: produced
\[ R(E) = (GE)^{1/(D-3)} \]

expected "phase diagram"
from classical collapse criteria

\[ l_P / l_s = g_s \ll 1 \]

\[ E = E_{th} \sim M_s / g_s^2 \gg M_P \]

Collapse

Critical line?

\[ l_P \]

\[ l_s \]

\[ E \]

\[ M_P \]
• An ideal theory lab. for studying several conceptual issues arising from interplay of QM and gravity within a fully consistent framework.

• In the weak-gravity regime \((b \gg R, l_s)\) we reproduce classical expectations (grav. deflection, tidal effects from emerging geometry) within a unitarity-preserving semiclassical description.

• When string-size effects dominate \((l_s \gg R)\) we found no evidence for BH formation (even for \(b < R\)) but rather a fast growth of multiplicity and softening of the final state resembling Hawking radiation.

• As one moves to \(R > l_s\) this should smoothly evolve into a BH-evaporation-like regime (not easy to study!).
In the strong gravity regime \((R \gg b, l_s)\) successes are still limited. Amusingly, a drastic approximation of the dynamics (ACV 2007) appears to reproduce at the semiquantitative level expectations based on classical collapse criteria.

A general pattern seems to emerge where, at the quantum level, the sharp classical transition between the dispersive and collapse phases is smoothed out by QM.

Many issues remain unsettled (in particular the saturation of unitarity) possibly due to our drastic approximations and/or to our lack of understanding of the BH singularity.
An easier problem?

High-energy string-brane collisions
(in flat spacetime)
High energy string-brane collisions

G. D’Apollonio, P. Di Vecchia, R. Russo & G.V. (1008.4773 and in progress)
W. Black and C. Monni, 1107.4321
M. Bianchi and P. Teresi, 1108.1071
Disc(tree)-level scattering

gravi-reggeon (closed string) exchanged in t-channel

heavy open string produced in s-channel
open strings produced in s-channel

Annulus (1-loop) level scattering
Tidal excitation of initial string

another representation of the annulus diagram
expected phase diagram from classical considerations

E = |M_p |

I_p

l_p / l_s = g_s \ll 1

I_s

Capture

Critical line?
The large-b regime

- At the disc and annulus level an effective classical brane geometry emerges through the deflection formulae satisfied at the saddle point of b-integral (after resummation).

- Unlike in ACV this can be done reliably to next-to-leading order in the deflection angle (extension to all orders?).

\[ ds^2 = \frac{1}{\sqrt{H(r)}} \left( \eta_{\alpha\beta} dx^\alpha dx^\beta \right) + \sqrt{H(r)}(\delta_{ij} dx^i dx^j) , \]

\[ e^\phi(x) = g \left[ H(r) \right]^{\frac{3-p}{4}} , \quad C_{01\ldots p}(x) = \frac{1}{H(r)} - 1 , \]

\[ H(r) = 1 + \left( \frac{R_p}{r} \right)^{7-p} , \quad R_p^{7-p} = \frac{gN(2\pi \sqrt{\alpha'})^{7-p}}{(7-p)\Omega_{8-p}} , \quad \Omega_n = \frac{2\pi^{n+1}}{\Gamma\left(\frac{n+1}{2}\right)} \]
• Tidal effects can also be computed. To leading order in $R_p/b$ and $l_s/b$ they come out in complete agreement with what one obtains by quantizing the string in the D-brane metric.

• Tidal excitation spectrum has been double checked even for external massive strings by W. Black & C. Monni. M. Bianchi & P. Teresi have computed some of these processes at the one-loop level.

• We (DDRV) are still finding some discrepancy between the scattering amplitude calculation in flat spacetime and string quantization in the D-brane metric at subleading order in $R_p/b$. 
• Extension to classical-capture regime should be possible and would allow to understand how quantum coherence is preserved through the production of a coherent multi-open-string state living on the branes.

• For p = 3 this gedanken experiment should shed new light on the AdS/CFT correspondence within an S-matrix framework (NB: we are in asymptotically-flat spacetime).
String-string vs string-brane scattering
@ b, R < l_s (prelim.)

In string-string scattering:

$$\langle n_{\text{closed}} \rangle \sim \frac{ER_S}{h} \left( \frac{R_S}{l_s} \right)^{D-4} \Rightarrow \langle E_{\text{closed}} \rangle \sim M_s \left( \frac{l_s}{R_S} \right)^{D-3} \sim \frac{M_s^2}{g_s^2 E}$$

Naively extrapolated to R > l_s gives only massless string modes (Hawking radiation?). Approx. cannot be trusted.

In string-brane scattering (work in progress):

$$\langle n_{\text{open}} \rangle \sim \frac{E l_s}{\hbar} \left( \frac{R_p}{l_s} \right)^{7-p} \Rightarrow \langle E_{\text{open}} \rangle \sim M_s \left( \frac{l_s}{R_p} \right)^{7-p} \sim M_s (g_s N)^{-1}$$

Calculation should be reliable even for R_p > l_s (large gN). This is where we hope to make contact with a CFT living on the branes.
Thank You!