Remo Ruffini

Dr. Remo Ruffini recieved his PhD degree in 1966, and then he was post-doctoral fellow at the Mainz Academy of Sciences, working with Pascual Jordan, in Germany. Then, he was post-doctoral fellow with John Archibald Wheeler and Member of the Institute for Advanced Study in Princeton and later became instructor and assistant professor at Princeton University. In the years 1975–78, he cooperated with NASA being member of the task force on the scientific use of space stations. In 1976 he became Professor of Theoretical Physics at the University of Catania and in 1978 he was appointed Professor at the University "Sapienza". His research interest focuses on astrophysics.

Ruffini is Director of ICRANet, the International Centre for Relativistic Astrophysics Network. Moreover, he is President of the International Centre for Relativistic Astrophysics (ICRA); he initiated the International Relativistic Astrophysics Ph.D. (IRAP-PhD), a common graduate school program of several universities and research institutes for the education of theoretical astrophysicists. In the years 1989–1993, he was President of the Scientific Committee of the Italian Space Agency. He won the Cressy Morrison Award of the New York Academy of Sciences in 1972, Alfred P. Sloan Fellow in 1974 and Space Scientist of the Year in 1992.

Events in Relativistic Astrophysics

A Contribution to Prof. Shing-Tung Yau's 70^{th} *Birthday*

1. Early Moments

In the seventies I did overlap with Prof. Shing-Tung Yau both in Princeton, at the Institute for Advanced Study (IAS) and at Stanford University but at that time we did not interact, I became very interested in Yau's work later in 1979, as I will describe below.

Those were the times, in 1967 I had just arrived in the United States of America after graduating from the University of Rome, and had a postdoctoral period with Pascual Jordan at the University of Hamburg. I was invited to Princeton by John Archibald Wheeler as a postdoctoral fellow and I soon after transferred first to the IAS and later again to Princeton University first as an instructor then as an assistant Professor. The ambience at Princeton was very exciting: some of the historical people who had collaborated with Einstein were still very active, including Valentine Bargmann, Eugene Wigner and Kurt Godel. The action in general relativity was clustered around three people: John Wheeler, Tullio Regge (who had completed with Jonny his classical paper on the perturbation of the Schwarzschild metric using the tensorial harmonic techniques [21]), and finally Martin Kruskal, who had just completed his "Kruskal Diagram" [13]: with the advice and pictorial help of Johnny. Essential part of the group were the graduate students, Hans Ohanian with whom I shared many conceptual discussions which materialized years later in our books "Gravitation and Spacetime" [17] and a newer version [18]. This book has been translated to Italian and Chinese. Frank Zerilli was there approaching a great work both in mathematical physics and in General Relativity developing in the Regge-Wheeler formalism, for addressing the gravitational waves emission from a particle plunging in radially into a Schwarzschild black hole. This work of Frank opened the way to an enormous number of contributions (see e.g. in [37, 6]).

My complete attention in Princeton was initially dedicated to complete a work on self gravitation particles in general relativity: both the case of Fermions and Bosons were considered [28]. That work was initially started in Rome for my thesis, and was then developed first in Hamburg in the Jordan group and then in a very long activity protracting for almost two years discussing the most effective presentation with Johnny. The effort was well justified, recently in this

Figure 1. Some members of the group of John Wheeler in 1971. Johnny is seated on the right. Tullio Regge is standing, reading a biography of Hilbert. I am sitting on the table, while Karol Kuchar and Terry Sinowski have theirs backs to the camera. Terry has become since a celebrated neurologist.

month when the paper has reached 500 citations, it is a "renowned paper" the inspire classification.

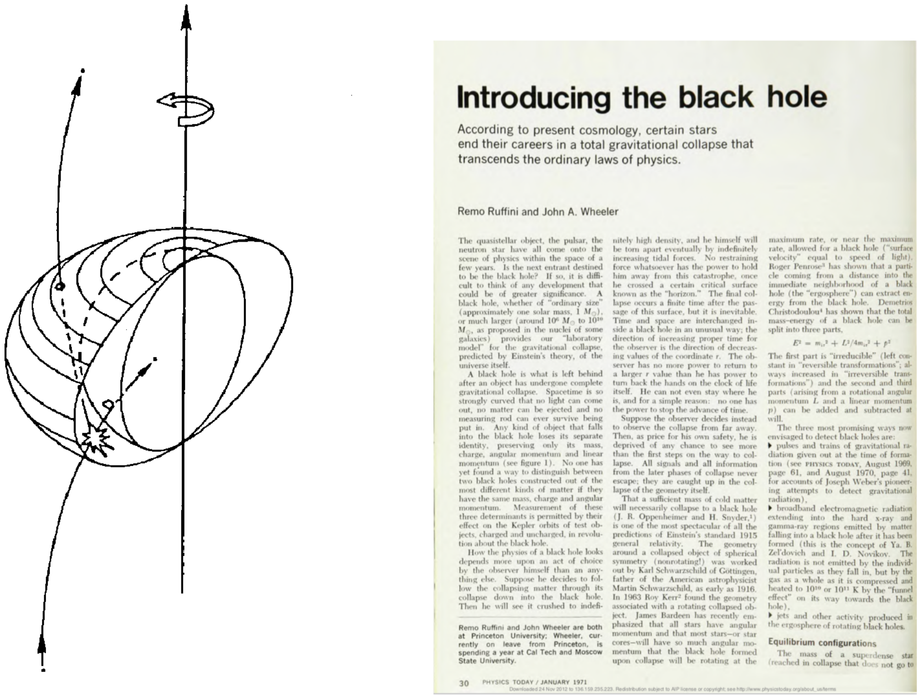
Our main effort with Wheeler (Figure 1) was to identify in astrophysics a role for the mathematical solution developed in the earliest sixties by Roy Kerr [12]. We first identified the "ergosphere" (Figure 2, left) outside the horizon of the Kerr metric, then we identified the last stable orbits both co-rotating and counter-rotating around the horizon, for which we received a "medal" by Yevgeny Lifschitz who had granted Johnny and I the honor of having a problem in the Landau-Lifschitz named after us. Finally, inspired by the birth of X-ray astrophysics, we moved forward and wrote the celebrated article "Introducing the Black Hole" [32] (Figure 2, right). The name "black hole" was first introduced by Johnny and I in a NASA institute meeting in New York. This paper was then followed by the book "Black holes, gravitational waves and cosmology" written by Martin Rees, Remo Ruffini and John Archibal Wheeler [20].

These were just the preamble of a great experience which was then followed by the birth of X-ray astrophysics by the UHURU satellite lead by Riccardo Giacconi and the identification of the first black hole. For this I was awarded in 1973 the Creassy Morrison Award of the New York Academy of Science, and in 2002 Riccardo Giacconi was awarded the Nobel prize.

In parallel, the coming to Princeton of a group of highly motivated students made all possible difference. First the arrival of a sixteen-year old undergraduate student from Greece carried by Johnny from Paris: Demetrios Christodoulou. In one year, Demetrios entered the graduate school, in one additional year passed the general examination and he was then ready to start his thesis work. The thesis was followed jointly by Johnny and me. Johnny proposed to Demetrios the problem of a scalar waves imploding to a black hole. It took Demetrios almost thirty years to complete this work, which is a clear manifestation of his remarkable mathematical abilities. I proposed Demetrios to work jointly on the effective potential techniques I had previous developed with Johnny.

The success was immediate, and led to the mass energy formula of the black hole. We obtained the celebrated formula in a series of articles [4, 5] neck to neck with a complementary interpretation by Steven Hawking [9, 10] (see Figure 3). Demetrios successfully passed his thesis on the sole summary of these works successfully, discussed in front of Eugene Wigner. That moment, the Christodoulou-Ruffini-Hawking mass formula since profoundly influenced the field of relativistic astrophysics by leading monotonically in the last forty years to the complete understanding of the gamma-ray bursts. It was indeed a great satisfaction for me to celebrate with Steven on June 20, 2017 the almost fiftieth anniversary of the discovery of this formula in presence of Roy Kerr (Figure 3), who was just awarded the Crafford Prize. The celebration took place in Steven's beautiful house near a bridge on the river Cam in England.

Still in Princeton a number of outstanding graduate students were working in our group. Most no-



Introducing the black hole

According to present cosmology, certain stars end their careers in a total gravitational collapse that transcends the ordinary laws of physics.

Remo Ruffini and John A. Wheeler

The quasistellar object, the pulsar, the neutron star have all come onto the scene of physics within the space of a few years. Is the next entrant destined to be the black hole? If so, it is difficult to think of any development that could be of greater significance. A black hole, whether of "ordinary size" (approximately one solar mass, 1 $M_\odot$), or much larger (around $10^6\ M_\odot$ to $10^{10}\ M_\odot$, as proposed in the nuclei of some galaxies) provides our "laboratory model" for the gravitational collapse, predicted by Einstein's theory, of the universe itself.

A black hole is what is left behind after an object has undergone complete gravitational collapse. Spacetime is so strongly curved that no light can come out, no matter can be ejected and no measuring rod can ever survive being put in. Any kind of object that falls into the black hole loses its separate identity, preserving only its mass, charge, angular momentum and linear momentum (see figure 1). No one has yet found a way to distinguish between two black holes constructed out of the most different kinds of matter if they have the same mass, charge and angular momentum. Measurement of these three determinants is permitted by their effect on the Kepler orbits of test objects, charged and uncharged, in revolution about the black hole.

How the physics of a black hole looks depends more upon an act of choice by the observer himself than an anything else. Suppose he decides to follow the collapsing matter through its collapse down into the black hole. Then he will see it crushed to indefinitely high density, and he himself will be torn apart eventually by indefinitely increasing tidal forces. No restraining force whatsoever has the power to hold him away from this catastrophe, once he crossed a certain critical surface known as the "horizon." The final collapse occurs a finite time after the passage of this surface, but it is inevitable. Time and space are interchanged inside a black hole in an unusual way; the direction of increasing proper time for the observer is the direction of decreasing values of the coordinate r. The observer has no more power to return to a larger r value than he has power to turn back the hands on the clock of life itself. He can not even stay where he is, and for a simple reason: no one has the power to stop the advance of time.

Suppose the observer decides instead to observe the collapse from far away. Then, as price for his own safety, he is deprived of any chance to see more than the first steps on the way to collapse. All signals and all information from the later phases of collapse never escape; they are caught up in the collapse of the geometry itself.

That a sufficient mass of cold matter will necessarily collapse to a black hole (J. R. Oppenheimer and H. Snyder,[1]) is one of the most spectacular of all the predictions of Einstein's standard 1915 general relativity. The geometry around a collapsed object of spherical symmetry (nonrotating!) was worked out by Karl Schwarzschild of Göttingen, father of the American astrophysicist Martin Schwarzschild, as early as 1916. In 1963 Roy Kerr[2] found the geometry associated with a rotating collapsed object. James Bardeen has recently emphasized that all stars have angular momentum and that most stars—or star cores—will have so much angular momentum that the black hole formed upon collapse will be rotating at the maximum rate, or near the maximum rate, allowed for a black hole ("surface velocity" equal to speed of light). Roger Penrose[3] has shown that a particle coming from a distance into the immediate neighborhood of a black hole (the "ergosphere") can extract energy from the black hole. Demetrios Christodoulou[4] has shown that the total mass–energy of a black hole can be split into three parts,

$$E^2 = m_{ir}^2 + L^2/4m_{ir}^2 + p^2$$

The first part is "irreducible" (left constant in "reversible transformations"; always increased in "irreversible transformations") and the second and third parts (arising from a rotational angular momentum L and a linear momentum p) can be added and subtracted at will.

The three most promising ways now envisaged to detect black holes are:

- pulses and trains of gravitational radiation given out at the time of formation (see PHYSICS TODAY, August 1969, page 61, and August 1970, page 41, for accounts of Joseph Weber's pioneering attempts to detect gravitational radiation),
- broadband electromagnetic radiation extending into the hard x-ray and gamma-ray regions emitted by matter falling into a black hole after it has been formed (this is the concept of Ya. B. Zel'dovich and I. D. Novikov. The radiation is not emitted by the individual particles as they fall in, but by the gas as a whole as it is compressed and heated to 10^{10} or 10^{11} K by the "funnel effect" on its way towards the black hole),
- jets and other activity produced in the ergosphere of rotating black holes.

Equilibrium configurations

The mass of a superdense star (reached in collapse that does not go to

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Remo Ruffini and John Wheeler are both at Princeton University; Wheeler, currently on leave from Princeton, is spending a year at Cal Tech and Moscow State University.

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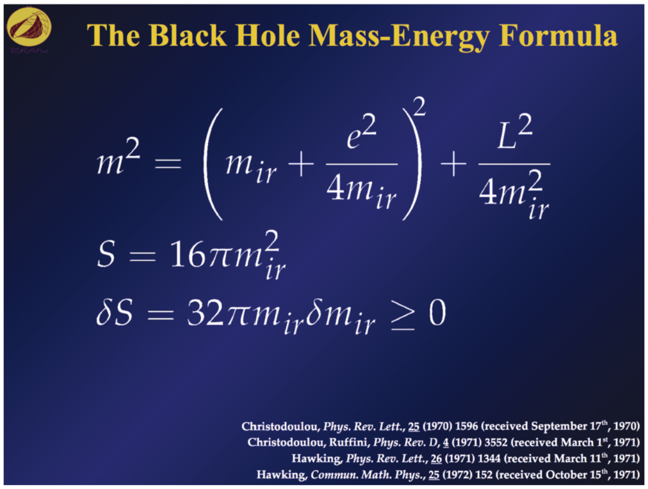
Figure 2. ***Left***: *Ergosphere of a rotating black hole. The ergosphere is a region located outside a rotating black hole's outer event horizon. It is named by Remo Ruffini and John Archibald Wheeler. The name derived from the Greek word ergon, which means "work".* ***Right***: *Introducing black hole. The first article formally introducing the name of "Black hole".*



The Black Hole Mass-Energy Formula

$$m^2 = \left(m_{ir} + \frac{e^2}{4m_{ir}}\right)^2 + \frac{L^2}{4m_{ir}^2}$$

$$S = 16\pi m_{ir}^2$$

$$\delta S = 32\pi m_{ir}\delta m_{ir} \geq 0$$

Christodoulou, *Phys. Rev. Lett.*, 25 (1970) 1596 (received September 17th, 1970)
Christodoulou, Ruffini, *Phys. Rev. D*, 4 (1971) 3552 (received March 1st, 1971)
Hawking, *Phys. Rev. Lett.*, 26 (1971) 1344 (received March 11th, 1971)
Hawking, *Commun. Math. Phys.*, 25 (1972) 152 (received October 15th, 1971)

Figure 3. The Christodoulou-Ruffini-Hawking black hole mass formula [4, 5, 9, 10], m is the total mass seen from infinity, m_{ir} is the irreducible mass, e is the charge, L is the angular momentum, S is the surface area, all in geometric units. δS is the increase of mass, ≥ 0 for irreversible and reversible.

tably Jacob Bekenstein, who carried on the physics of reversible transformation of the Kerr Black hole we had introduced with Demetrios, developing there the thermodynamical analogies. Jacob later recalled in a book my concern about these extrapolations. Clifford Rhodes, an ROTC soldier, who derived with me the absolute upper limit to the neutron star mass in 3.2 solar masses [22]. Finally Robert Wald who at the time generalized some of the work we did on the electrodynamics of Black holes with Demetrios. Actually Bob worked very actively with Jayme Tiomno who was visiting the IAS from Brazil. On his thesis, I was asked by Johnny a written declaration, in which I expressed a positive consensus. I am still today very happy with that decision. Bob thesis contained among others the "Wald Solution" [35], which today, after almost fifty years, is proving fundamental for the understanding of the "inner engine" of Gamma-ray bursts [30].

2. My First Visit to China

This pioneering period was followed by my first visit to China in 1975 (Figure 5), and the publication a few years later of my first books with Fang Lizhi (方励之, Figure 6, left).

3. Schoen and Yau's Proof of Positive Energy

My first contact with the work of Yau was triggered by an article of Bob Geroch [8]. Bob was Wheeler's student who has not participated, as well

Figure 4. Prof. Remo Ruffini and Prof. Roy Kerr with his wife at Prof. Stephen Hawking's home in Cambridge for dinner on June 20th, 2017.

Figure 5. Visiting China, Peking University, Beijing, 1975.

as Wheeler's other former students as Dieter Brill, Charles Misner, Kip Thorne to our black hole era in Wheeler's group.

Geroch states: "There is an old conjecture in general relativity to the effect that, for any object constructed of matter with non-negative local mass-density, the total mass-energy, measured in terms of the asymptotic gravitational field, must also be non-negative. The conjecture, a bit more precisely, asserts that the total energy must be non-negative

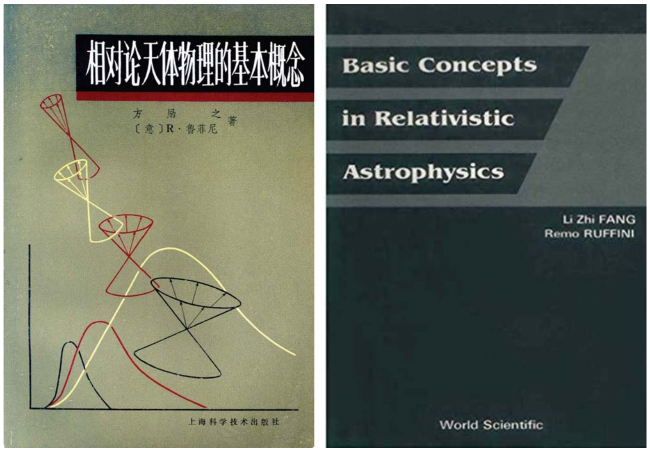


Figure 6. Fang Lizhi's book, Chinese version (left) and English version (right). This book is based on the lectures given by Fang Lizhi and Remo Ruffini in China.

for any space-time which is asymptotically flat (in order that "total energy" makes sense), which is not too badly singular (in order to rule out such space-times as the $m < 0$ Schwarzschild), and whose stress-energy satisfies the local energy condition. This conjecture, despite the fact that it seems obvious physically that it should be true, remains open. Most attempts to resolve this conjecture have been along the following lines. One introduces a suitable three-dimensional surface in the space-time, and then, from the fields and their equations in the space-time, induces on this surface certain fields satisfying certain differential equations. One next characterizes the total energy in terms of the asymptotic behavior of these fields, and finally tries to relate this total energy to the local properties of the fields via their differential equations. In fact, there are two versions of this conjecture, depending on whether one chooses one's surface to be asymptotically a "null cone", or asymptotically a "spacelike three-plane". For the former, one imposes asymptotic flatness at null infinity, and the total energy becomes the Bondi energy. Essentially all that is known in this case is that a number of promising-looking potential counterexamples fail. For the latter, one imposes asymptotic flatness at spatial infinity, 51,and the total energy becomes the Arnowitt-Deser-Misner energy. In this case, the conjecture is known to hold under a variety of simplifying assumptions, e.g., that the space-time is spherically symmetric, that the surface is area-extremal (Figure 7 and [33])."

My strong interest in Yau's work was, and still is, justified in trying to understand better the implications of our Christodoulou-Ruffini-Hawking mass formula by using the Yau geometrical interpretation. Our mass formula is derived in an asymptotically flat space based on the Kerr-Newman solution. Globally it is axially, not spherically symmetric. The total mass at infinity is positive. The contribution to the total mass by rotation and charge occur outside the black hole horizon: they are clearly identifiable by the ergostorus-dyadotorus, outside the horizon. The mass energy contribution of rotation and charge are extractable, all these processes are well understood. Still unknown is the physical nature of the irreducible mass (m_{ir}) I originally introduced. We have proved that the irreducible mass (m_{ir}) is independent of the charge and rotation, and is only a function of the rest mass, its gravitational binding energy and the kinetic energy of implosion at the horizon. This quest has been left open for next MG XVI in 2020 on the fiftieth anniversary of the mass formula.

4. Yau's Marcel Grossmann Award

Since then we had many interactions in international meetings including the Marcel Grossmann meetings. These strong interactions finally manifested with the attribution to Yau the Marcel Grossmann award:

> *"for the proof of the positivity of total mass in the theory of general relativity and perfecting as well the concept of quasi-local mass, for his proof of the Calabi conjecture, for his continuous inspiring role in the study of black holes physics"*

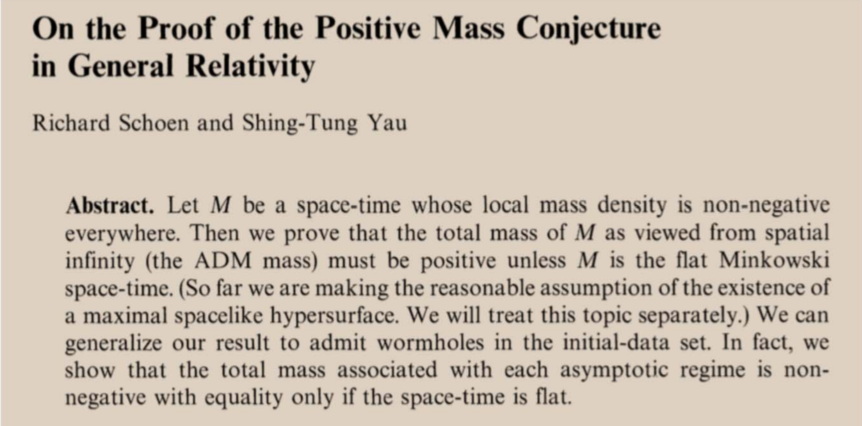
The award named "Trascinamento di Eventi Spazio Temporali" (TEST), consists in a silver sculpture, by an Italian artist Attilio Pierelli, following precisely the trajectories of five particles co-rotating around a Kerr black hole computed by Johnston and Ruffini (Figure 8 and 9).

$$\begin{aligned}
\dot{r} &= \rho^{-2}\{[E(r^2+a^2)-a\Phi]^2-\Delta(\mu^2 r^2+K)\}^{1/2}\\
\dot{\theta} &= \rho^{-2}\{K-(\Phi-aE)^2-\cos^2\theta[a^2(\mu^2-E^2)+\Phi^2\sin^{-2}\theta]\}^{1/2}\\
\dot{t} &= -a\rho^{-2}(aE\sin^2\theta-\Phi)+\rho^{-2}(r^2+a^2)\Delta^{-1}P\\
\dot{\phi} &= -\rho^{-2}(aE-\Phi\sin^{-2}\theta)+a\rho^{-2}\Delta^{-1}P\\
E &= .968, \quad \Phi = 2, \quad Q = 10, \quad a = e = 1/\sqrt{2}
\end{aligned}$$

Here you can see a series of figures for the ceremony (Figures 10 and 11).

5. Yau's Poems

During the 15th Marcel Grossmann meeting (MG15) in 2018, Yau sent a booklet of his poems on the history of China, covering many anecdotes of emperors and the development of science, literature and art. Yau wrote that the fundamental science had a boost during the Wei, Jin, Southern and Northern dynasties (220-589 AD), the society was pursuing beauty and nature, this period was thought as a Renaissance in China.



On the Proof of the Positive Mass Conjecture in General Relativity

Richard Schoen and Shing-Tung Yau

Abstract. Let M be a space-time whose local mass density is non-negative everywhere. Then we prove that the total mass of M as viewed from spatial infinity (the ADM mass) must be positive unless M is the flat Minkowski space-time. (So far we are making the reasonable assumption of the existence of a maximal spacelike hypersurface. We will treat this topic separately.) We can generalize our result to admit wormholes in the initial-data set. In fact, we show that the total mass associated with each asymptotic regime is non-negative with equality only if the space-time is flat.

Figure 7. The original proof of the positive energy theorem provided by Richard Schoen and Shing-Tung Yau using the variational methods in 1979 [33]. The positive energy theorem states that the mass of an asymptotically flat spacetime is non-negative.

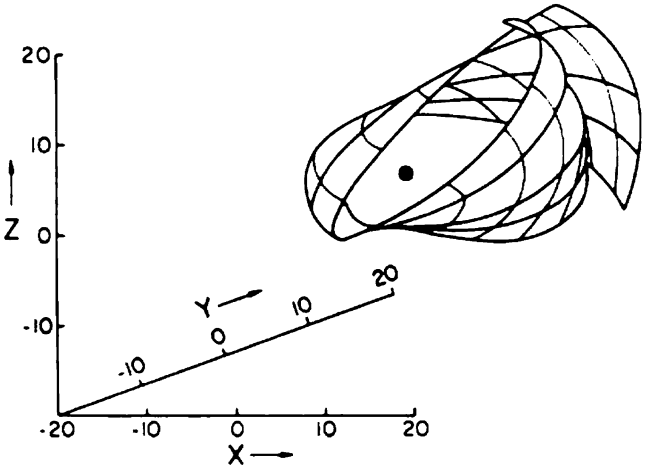


Figure 8. Equations for a family of geodesics in a Kerr black hole and their graphical representation (M. Johnston and R. Ruffini, 1974).

We recalled with Yau how the first European Renaissance from the 12th to 14th century was followed by Marco Polo's memorable trips to China, followed by the publication of his book "Il Milione" which led and, still does today, so many people dream about the "celestial empire (天朝)". We clearly recalled with him the European Renaissance of the 14th–17th centuries, stemming from the Italian city of Florence, which enlightened the modern natural sciences. Its tide was spread by Matteo Ricci (Figure 13) and his Jesuit missionaries (Figure 12) to the very far eastern country, China. There the towering Chinese personality was a student of Matteo Ricci (利玛窦, Li Madou), the Mandarin Xu Guangqi (徐光启): he had translated Euclid's book into Chinese, opening China to the western culture of mathematics. He was also nominated as the Grand Secretariat and with the help of Matteo Ricci, he succeeded in the formulation of a new Chinese calendar.

We had recalled with Fang Lizhi a TV program about the history of that first optical instrument developed in 1608 by a Dutch optician to better scrutinise the ships in the Amsterdam harbour, and how the optical design of the instrument was soon improved by Galileo Galilei, which was totally revolutionary. That initial earthbound instrument was turned into an authentic telescope to study our solar system and our galaxy. Galileo introduced the fundamental conceptual revolution, requesting the invariance of all physical laws for uniform translation in space and time. But in all this story we also insisted in recalling how the crucial moment came when Matteo Ricci and de Ursis could predict an eclipse of the moon with much greater accuracy than the Chinese astronomer. They earned the respect and admiration of the Emperor and Empress (Figure 14), and many emperors to follow. In 1615, during the Ming dynasty, the Jesuit missionary Manuel Dias the Younger (阳玛诺, Yang Manuo) introduced the telescope to China with his book "Tian Wen Lue (Handbook of Astronomy)", written in Chinese. In 1626, the first telescope was brought to China by a German Jesuit, Johann Adam Schall von Bell (汤若望, Tang Ruowang) (Figure 12). He translated the book "Yuan Jing Shuo (The Far-Seeing Optic Glass)" with Li Zubai, and played an important role in promoting celestial observations, especially for the royal court. We recalled that during the last years of the Ming Dynasty Xu Guangqi established a government department to revise the calendar. Both Tang Ruowang and Matteo Ricci were proficient in astronomical calendars, thus they helped with the revision (Figure 13).

Figure 9. TEST, the Marcel Grossmann Award sculpture by A. Pierelli, photo by S. Takahashi. The TEST sculpture provides an innovative example of interaction between science and art, not abstractly interpreted as a result of a subsequent critical analysis but indeed an active and creative collaboration between an astrophysicist and a sculptor.

Figure 10. Prof. Shing-Tung Yau receving the Marcel Grossmann Award, 2018. ***Upper****: From left to right: Prof. Leo Hollberg, Prof. Rashid Sunyaev, Prof. Shing-Tung Yau, Prof. Remo Ruffini, Rector Eugenio Gaudio, Prof. Roy Kerr, Prof. Lyman Page, Prof. Jean-Loup Puget and Prof. Elia Battistelli.* ***Lower left****: Prof. Remo Ruffini reading Shing-Tung Yau MG15 Award motivation.* ***Lower right****: Prof. Roy Patrick Kerr giving the MG15 Award to Prof. Shing-Tung Yau.*

Figure 11. The Others Marcel Grossmann Award EES. ***Upper left:*** *The MG15 award to the Plank Scientific Collaboration (ESA) presented to Jean-Loup Puget, the Principal Investigator of the High Frequency Instrument (HFI) "for obtaining important constraints on the models of inflationary stage of the Universe and level of primordial non-Gaussianity; measuring with unprecedented sensitivity gravitational lensing of Cosmic Microwave Background fluctuations by large-scale structure of the Universe and corresponding B-polarization of CMB, the imprint on the CMB of hot gas in galaxy clusters; getting unique information about the time of reionization of our Universe and distribution and properties of the dust and magnetic fields in our Galaxy".* ***Upper right:*** *The MG15 award to the Hansen Experimental Physics Laboratory at Stanford University presented to Leo Hollberg, HEPL Assistant Director "to HEPL for having developed interdepartmental activities at Stanford University at the frontier of fundamental physics, astrophysics and technology".* ***Lower left:*** *The MG15 award presented to Lyman Page "for his collaboration with David Wilkinson in realizing the NASA Explorer WMAP mission and who now leads the Atacama Cosmology Telescope as its project scientist".* ***Lower right:*** *The MG15 award presented to Rashid Alievich Sunyaev "for the development of theoretical tools in the scrutinising, through the CMB, of the first observable electromagnetic appearance of our Universe".*

Figure 12. Jesuit missionaries. From left to right: Matteo Ricci (Li Madou) from Italy, Johann Adam Schall von Bell (Tang Ruowang) from Germany and Ferdinand Verbiest (Nan Huairen) from Netherlands. These three priests are buried in the same place inside the College of Political Science, Beijing.

Figure 13. ***Left***: *Xu Guangqi (April 24, 1562 – November 8, 1633), student of Matteo Ricci.* ***Right***: *Matteo Ricci (October 6, 1552 – May 11, 1610) and Xu Guangqi.*

Figure 14. ***Left***: *The emperor of Wanli (September 4, 1563 – August 18, 1620), the 14th emperor of the Ming dynasty of China.* ***Right***: *The empress Xiaoduanxian (1565 – April, 1620).*

6. Galileo–Xu Guangqi Meetings

After these historical recollections, it seemed appropriate to establish a joint meeting between Western countries and China in the name of Galileo and Xu Guangqi. The first Galileo–Xu Guangqi meeting was held in Shanghai in 2009, under the leadership of my former student Jing Yipeng (Figure 15). It was then followed by a second meeting in Nice, France, (2010) a third one in Beijing, (2011) a fourth one in Beijing in 2015, and a fifth one, with a great success, in Chengdu (Figure 16) in 2017.

7. Prediction of Supernova

Following MG15, held from the July 1 to 7, 2018, a very special GRB exploded and was designated as GRB 180728A on July 28, 2018 (Figure 18, left). It was soon identified as a BdHN II. We accepted the challenge to make a successful prediction of an astrophysical event: not a prediction of a scary astronomical event as a lunar eclipse would be in the time of Galileo and Xu Guangqi, but predicting the time of appearance of a very luminous and serene supernova giving origin to a GRB. We decided, than, to celebrate this observation first with the scientists at the Yau Mathematical Science Center in Beijing, and the following days at the T. D. Lee Center in Shanghai.

During MG15, our group already presented many new results on GRBs, including:

1. The evidence that nine different families of GRBs existed in the cosmos, all originating in binary systems composed of different combinations of neutron stars (NS), of black holes (BH), of FeCo core undergoing supernova explosion, of white dwarfs (see Table 1)
2. Particular attention was dedicated to the analysis of binary driven hypernovae (BdHN), originating from a compact binary system composed of a FeCo core undergoing supernova explosion in presence of a companion NS. If the binary period is shorter than 4 minutes, then the hypercritical accretion process of the supernova ejecta onto the NS will give origin to a BH with energies emitted up to 10^{54} erg. We had defined these systems as BdHN of type I. If the binary period is longer than 4 minutes, the hypercritical accretion process is not sufficient to form a BH and a more massive NS is formed and a X-ray flash occurs, later defined as a BdHN of type II, with the emission of a GRB up to 10^{52} erg (Figure 17 shows the simulation of two types of BdHNe).
3. All the above results based on many decades of our work have given us the certitude that already from the first 100 seconds of observation of any GRBs, with a known redshift we could identify the nature of the GRB sub-family, and in the case of BdHN I and BdHN II, it is able to predict the time of appearance of the SN.

7.1 Prediction of Supernova in GRB 130427A

This kind of prediction had been successfully tested in the case of GRB 130427A, a BdHN I, creating a BH. Our prediction on the Gamma-ray Coordinates Network (GCN) and the confirmation by the Nordic optical telescope are quoted:

> **GCN 14526** ***GRB 130427A: Prediction of supernova appearance***
> *R. Ruffini, C. L. Bianco, M. Enderli, M. Muccino, A. V. Penacchioni, G. B. Pisani, J. A. Rueda, N. Sahakyan, Y. Wang, L. Izzo report:*
> *The late x-ray observations of GRB 130427A by Swift-XRT clearly evidence a pattern typical of a family of GRBs associated to supernova (SN) following the Induce Gravitational*

Figure 15. The first Galileo–Xu Guangqi meeting was held in Shanghai from Oct. 26 to 30, 2009, to celebrate the 400th anniversary of Galileo Galilei's telescope, which was developed in order to study the structure of our universe. ***Left****: The poster of the meeting.* ***Right****: Group photo.*

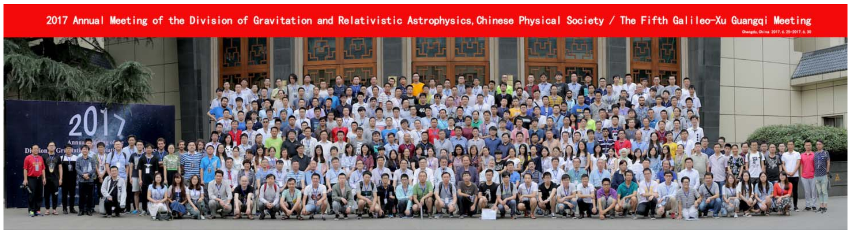


Figure 16. On June 25–30, 2017, the annual meeting of the Division of Gravitation and Relativistic Astrophysics of the Chinese Physical Society, jointed with the fifth Galileo–Xu Guangqi meeting, was held in the School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, China.

Class	Type	Previous Alias	Number	*In-state*	*Out-state*	$E_{\rm p,i}$ (MeV)	$E_{\rm iso}$ (erg)	$E_{\rm iso,Gev}$ (erg)
Binary Driven Hypernova (BdHN)	I	BdHN	329	$\mathrm{CO_{core}}$-NS	νNS-BH	~ 0.2–2	$\sim 10^{52}$–10^{54}	$\gtrsim 10^{52}$
	II	XRF	(30)	$\mathrm{CO_{core}}$-NS	νNS-NS	~ 0.01–0.2	$\sim 10^{50}$–10^{52}	–
	IIII	HN	(19)	$\mathrm{CO_{core}}$-NS	νNS-NS	~ 0.01	$\sim 10^{48}$–10^{50}	–
	IV	BH-SN	5	$\mathrm{CO_{core}}$-BH	νNS-BH	$\gtrsim 2$	$> 10^{54}$	$\gtrsim 10^{53}$
Binary Merger (BM)	I	S-GRF	18	NS-NS	MNS	~ 0.2–2	$\sim 10^{49}$–10^{52}	–
	II	S-GRB	6	NS-NS	BH	~ 2–8	$\sim 10^{52}$–10^{53}	$\gtrsim 10^{52}$
	IIII	GRF	(1)	NS-WD	MNS	~ 0.2–2	$\sim 10^{49}$–10^{52}	–
	IV	FB-KN⋆	(1)	WD-WD	NS/MWD	< 0.2	$< 10^{51}$	–
	V	U-GRB	(0)	NS-BH	BH	$\gtrsim 2$	$> 10^{52}$	–

Table 1. Summary of the GRB subclasses. In addition to the subclass name, we report the number of GRBs identified in each subclass updated by the end of 2016. We recall as well the "in-state" representing the progenitors and the "out-state" as well as the $E_{\rm p,i}$ and $E_{\rm iso}$ for each subclass. We finally indicate the GeV emission in the last column which for the long GRBs is only for the BdHN Type I and Type IV, and in the case of short bursts is only for BM Type II and in all of them the GeV emission has energy more than 10^{52} erg. The number of each class with known redshift is given in "number" column, the value in a bracket indicates the lower limit.

⋆ FB-KN stands for fallback-powered kilonova. It has been shown that the WD-WD merger produces an infrared-optical transient from the merger ejecta, a kilonova, peaking at ~ 5 days post-merger and powered by accretion of fallback matter onto the merged remnant [25, 26]. A kilonova is also an infrared-optical counterpart of NS-NS merger but in that case the transient is powered by the energy release by the decay of r-process heavy nuclei processed in the merger ejecta (e.g. [15, 16, 34, 2]).

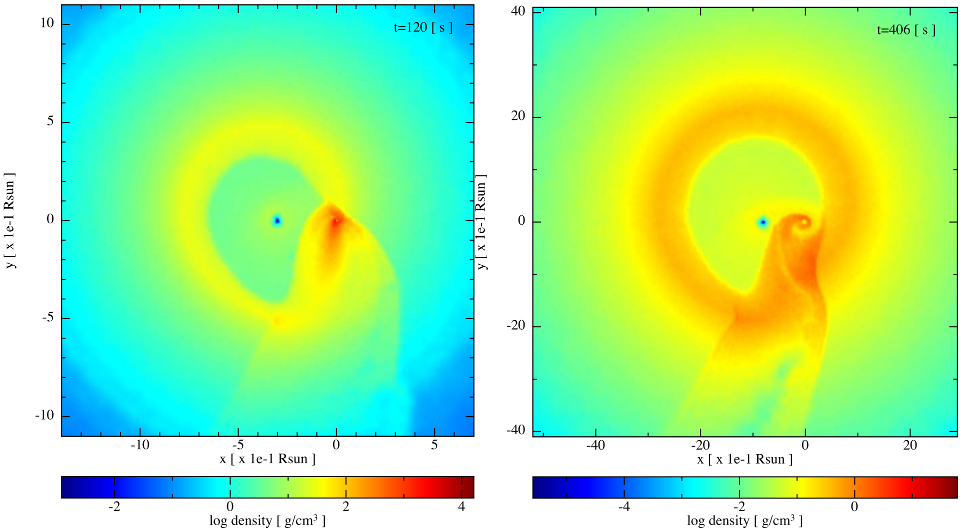


Figure 17. Two selected SPH simulations from [1] of the exploding CO_{core} as SN in presence of a companion NS: Model '25m1p08e' with $P_{\text{orb}} = 4.8$ min (left panel) and Model '25m3p1e' with $P_{\text{orb}} = 11.8$ min (right panel). The CO_{core} is taken from the $25\ M_\odot$ ZAMS progenitor, so it has a mass $M_{\text{CO}} = 6.85\ M_\odot$. The mass of the NS companion is $M_{\text{NS}} = 2\ M_\odot$. The plots show the density profile on the equatorial orbital plane; the coordinate system has been rotated and translated in such a way that the NS companion is at the origin and the νNS is along the -x axis. The system in the left panel leads to a BdHN I and the snapshot is at the time of the gravitational collapse of the NS companion to a BH, $t = 120$s from the SN shock breakout ($t = 0$ of our simulation). The system forms a new binary system composed by the νNS (at the center of the deep-blue region) and the BH formed by the collapsing NS companion (at the center of the red vortices). The system in the right panel leads to an BdHN II since the NS in this case does not reach the critical mass. This snapshot corresponds to $t = 406$s post SN shock breakout. In this simulation, the new system composed by the νNS and the NS companion becomes unbound after the explosion.

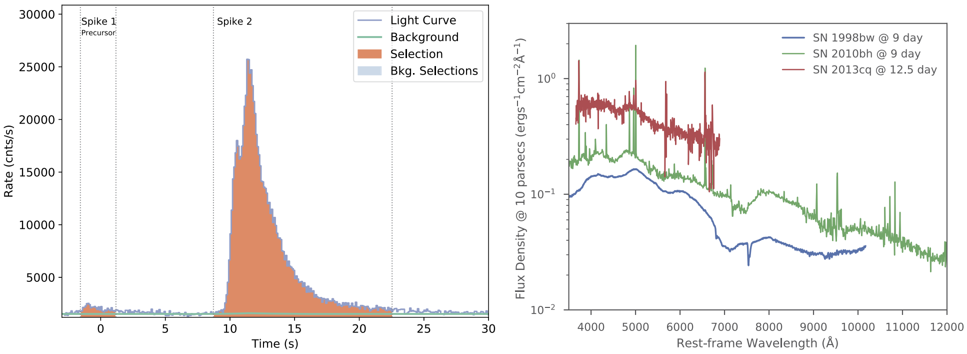


Figure 18. ***Left****: Count rate light-curve of the prompt emission: Data are retrieved from the NaI7 detector on-board Fermi-GBM. The prompt emission of GRB 180728A contains two spikes. The first spike, the precursor, ranges from -1.57s to 1.18s. The second spike, which contains the majority of energy, rises at 8.72s, peaks at 11.50s, and fades at 22.54s.* ***Right****: Optical spectra comparison of three SNe: 1998bw, 2010bh, 2013cq, flux density is normalized at 10 parsec, data are retrieved from the Wiserep website (https://wiserep.weizmann.ac.il).*

Collapse (IGC) paradigm [24, 19]. We assume that the luminosity of the possible SN associated to GRB 130427A would be the one of 1998bw, as found in the IGC sample described in [19]. Assuming the intergalactic absorption in the I-band (which corresponds to the R-band rest-frame) and the intrinsic one, assuming a Milky Way type for the host galaxy, we obtain a magnitude expected for the peak of the SN of $I = 22-23$ occurring 13–15 days after the GRB trigger, namely between the 10th and the 12th of May 2013. Further optical and radio observations are encouraged.

GCN 14597 ***GRB 130427A: Excess optical emission consistent with an emerging supernova***

D. Xu (DARK/NBI), A. de Ugarte Postigo (IAA-CSIC, DARK/NBI), T. Kruehler, D. Malesani (DARK/NBI), G. Leloudas (OKC, Stockholm and DARK/NBI), J. P. U. Fynbo, J. Hjorth, (DARK/NBI), S. Schulze (PUC and MCSS), P. Jakobsson, Z. Cano (U. Iceland), J. Gorosabel (IAA-CSIC/UPV-EHU), report:

We have been monitoring the optical counterpart of GRB 130427A ... mainly using the 2.5 Nordic Optical Telescope

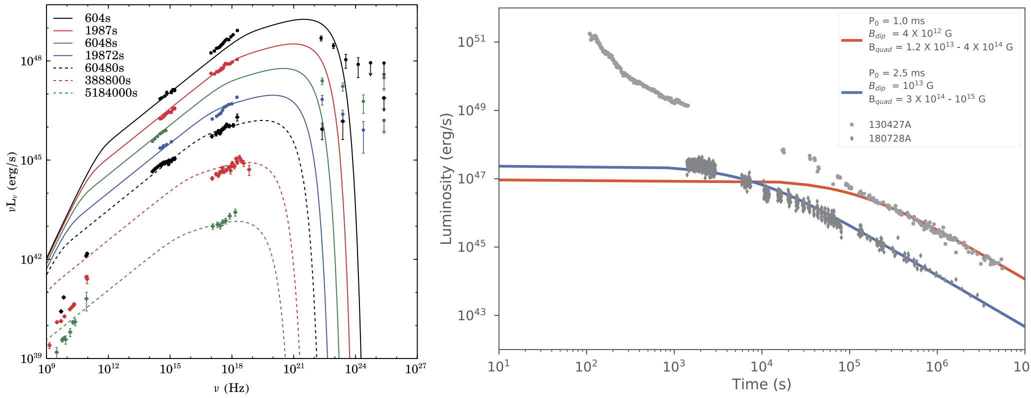


Figure 19. ***Left****: The spectra of GRB 130427A at different time, and the corresponding fittings by a synchrotron model without self-absorption. The optical and X-ray are well fitted. The observed radio data is below the fitting line because of the strong self-absorption. The UHE photons have different origins than the low energy photons [29, 30]. We expect similar synchrotron features in GRB 180728A.* ***Right****: Afterglow powered by the νNS pulsar: the grey and dark points correspond to the bolometric afterglow light-curves of GRB 1340427A and 180728A, respectively. The red and blue lines are the fitting of the energy injection from the rotational energy of the pulsar, the fitted parameters are shown in the legend.*

> *(NOT) equipped with the ALFOSC camera ... The flattening in the decay, the change of the spectral shape, and the overall flux level are all consistent with the emergence of a SN, though detailed spectroscopy and long-term monitoring will be required to fully assess the nature of the flux excess...*

7.2 Prediction of Supernova in GRB 180728A

On 31 July 2018, after the detection of the redshift of GRB 180728A, we predicted that a SN would appear at 14.7 ± 2.9 days [27]. On 18 August 2018, Luca Izzo, a former student who had obtained his PhD with us at ICRA and ICRANet using the VLT/X-shooter telescope created at ESA by Riccardo Giacconi reported the discovery of the SN appearance [11].

> ***GCN 23066 – GRB 180728A: A long GRB of the X-ray flash (XRF) subclass, expecting supernova appearance*** *R. Ruffini, Y. Aimuratov, C. L. Bianco, Y. C. Chen, D. M. Fuksman, M. Karlica, R. Moradi, D. Primorac, J. A. Rueda, N. Sahakyan, Y. Wang, on behalf of the ICRANet team, report:*
> *GRB 180728A has $T_{90} = 6.4s$ [23], peak energy $142(-15, +20)$keV, and isotropic energy $E_{\rm iso} = (2.33 \pm 0.10) \times 10^{51}$ erg [7]. It presents the typical characteristic of a subclass of long GRBs called X-ray flashes[1] (XRFs, see [31]), originating from a tight binary of a $CO_{\rm core}$ undergoing a supernova explosion in presence of a companion neutron star (NS) that hypercritically accretes part of the supernova matter. The outcome is a new binary composed by a more massive NS (MNS) and a newly born NS (νNS). Using the averaged observed value of the optical peak time of supernova [3], and considering the redshift $z = 0.117$ [23], a bright optical signal will peak at 14.7 ± 2.9 days after the trigger (August 12, 2018, uncertainty from August 9th to August 15th) at the location of $RA = 253.56472$ and $DEC = -54.04451$, with an uncertainty 0.43 arcsec [14]. The follow-up observations, especially the optical bands for the SN, as well as attention to binary NS pulsar behaviours in the X-ray afterglow emission, are recommended.*

> ***GCN 23142 – GRB 180728A: discovery of the associated supernova***
> *L. Izzo (HETH/IAA-CSIC), A. Rossi (INAF/OAS), D. B. Malesani (DAWN/NBI and DARK/NBI), K. E. Heintz (Univ. Iceland and DAWN/NBI), J. Selsing (DAWN/NBI), P. Schady (Univ. Bath), R. L. C. Starling (Univ. Leicester), J. Sollerman (OKC Stockholm), G. Leloudas (DTU space), Z. Cano (BCA), J. P. U. Fynbo (DAWN/NBI), M. Della Valle (INAF-Naples), E. Pian (INAF/OAS), D. A. Kann (HETH/IAA-CSIC), D. A. Perley (LJMU), E. Palazzi (INAF/OAS), S. Klose (TLS Tautenburg), J. Hjorth (DARK/NBI), S. Covino (INAF-OAB), V. Da Elia (SSDC), N. R. Tanvir (Univ. Leicester), A. J. Levan (Univ. Warwick), D. Hartmann (Clemson U.), C. Kouveliotou (GWU) report: ... Up to now, we have observed at three epochs, specifically at 6.27, 9.32 and 12.28 days after the GRB trigger. The optical counterpart is visible in all epochs using the X-shooter acquisition camera in the g, r and z filters. We report a rebrightening of 0.5 ± 0.1 mag in the r band between 6.27 and 12.28 days. This is consistent with what is observed in many other lo 170827w-redshift GRBs, which in those cases is indicative of an emerging type Ic SN ...*

7.3 Understandings from GRB 180728A

The main conclusions we have reached are:

1. A most fundamental role is played by the supernova ejecta and by the newly born neutron star, the νNS, created in the process of gravitational collapse of the FeCo Core. In their interaction with the binary neutron star companion. The hypercritical accretion of the supernova ejecta on the companion neutron star determine its further evolution, either to a more massive neutron star, originating a BdHN I, or to a black hole, originating a BdHN II, the simulation is presented in Figure 17
2. The difference of energy (Figure 17) between the two cases is enormous up to 10^{52} erg for the

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[1] The previous name of BdHN I

Figure 20. ***Upper****: August 13, 2018. Discussion with Prof. Shing-Tung Yau on the GRB 180728A in the Yau Mathematical Sciences Center, Tsinghua University. From left to right: Dr. Yu Wang, Prof. Remo Ruffini, and Prof. Shing-Tung Yau.* ***Lower****: August 14, 2018. In the office of Prof. T. D. Lee at Shanghai Jiaotong University. Prof. Hongjian He holds the Marcel Grossmann TEST sculpture awarded to Prof. T. D. Lee.*

BdHN I, and up to 10^{54} erg for BdHN II. In both cases, reach a luminosity, during 100 seconds, comparable to the integrated luminosities of all the stars of the universe. What we have observed is that in both cases the afterglow originating from the synchrotron radiation powered by the νNS originated by the SN explosion (Figure 19, left). The initial spin is faster in the BdHN I and slower in the BdHN II, happened to be related to the initial binary period of the progenitors system, the spin of GRB 130427A is 1 ms and of GRB 180728A is 2.5 ms (Figure 19, right).

3. The supernova acts almost as a catalyst: it participate to the hypercritical accretion process only with fraction of $2-3$ solar masses of its total mass ejecta of approximately $7-10$ solar masses. The crucial factor which determines such enormous energetic difference is the binary period of the progenitors or, equivalently, the distance between the FeCo core undergoing supernova and the companion neutron star: this determines the different accretion rate on the companion neutron star and consequently the formation or not formation of a black hole. The final appearance of the supernova is similar (Figure 18, right), originating from the nickel decay, is practically not affected by these enormous energies in photons, but paradoxically, not sufficiently hard as to affect the deep nuclear process achieved in the nuclear formation occurring during the gravitational collapse from the FeCo Core to the birth of the νNS .

These results were presented in Beijing from August 8 to August 13, 2018. And in Shanghai on August 14, 2018 (Figure 20). The related paper has been submitted to the Astrophysical Journal [36].

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