Neutron Stars, Black Holes, and Gamma-Ray Bursts:

three events with Eugene Wigner in Princeton

Remo Ruffini

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ICRANet – Piazzale della Repubblica 10, Pescara
ICRANet – Nice, Université de Nice Sophia-Antipolis

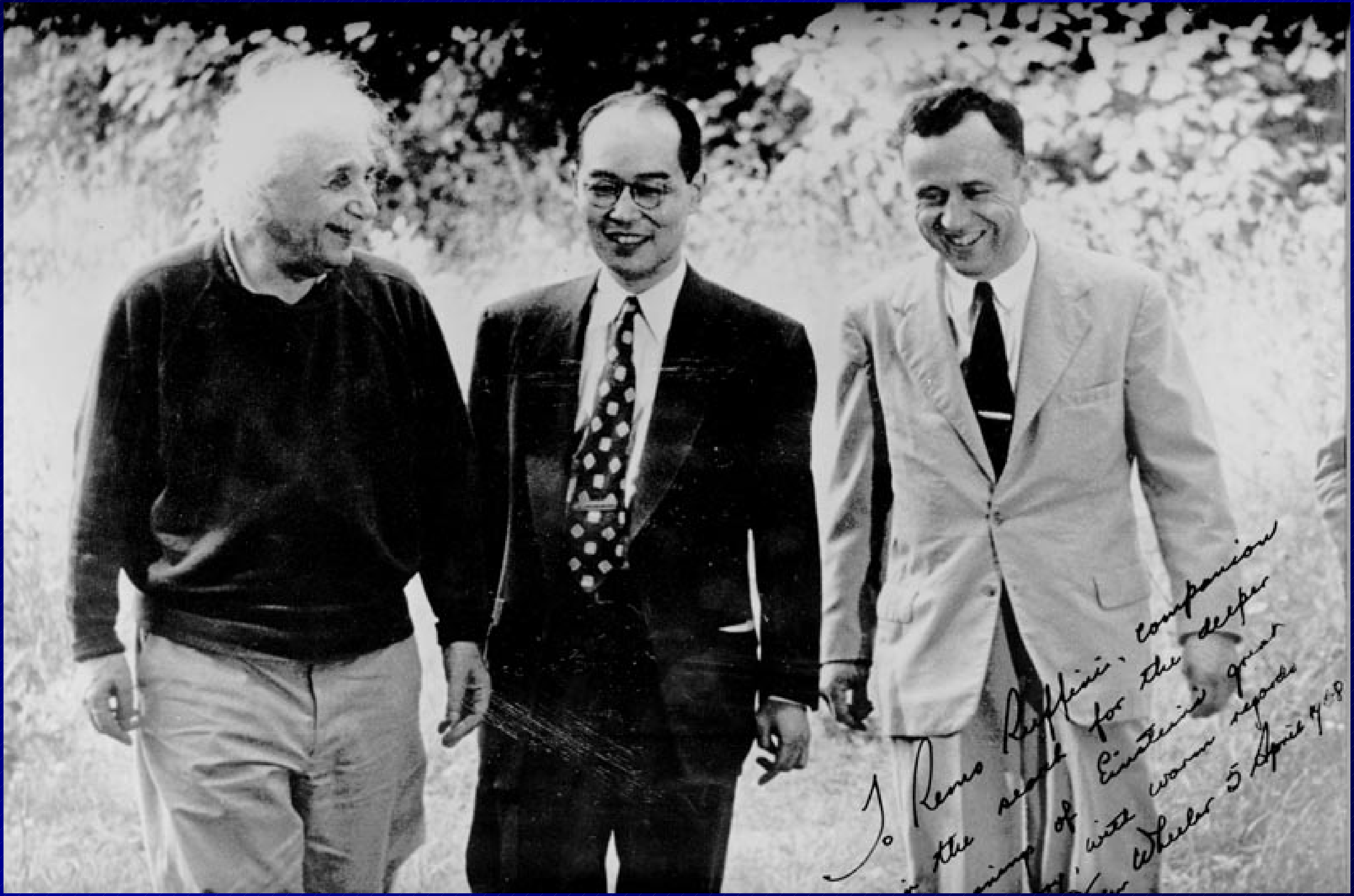
Wigner 111 Meeting – November 11th, 2013
Hungarian Academy of Sciences

1967: Hamburg and Paris

Paul Dirac

Pascual Jordan

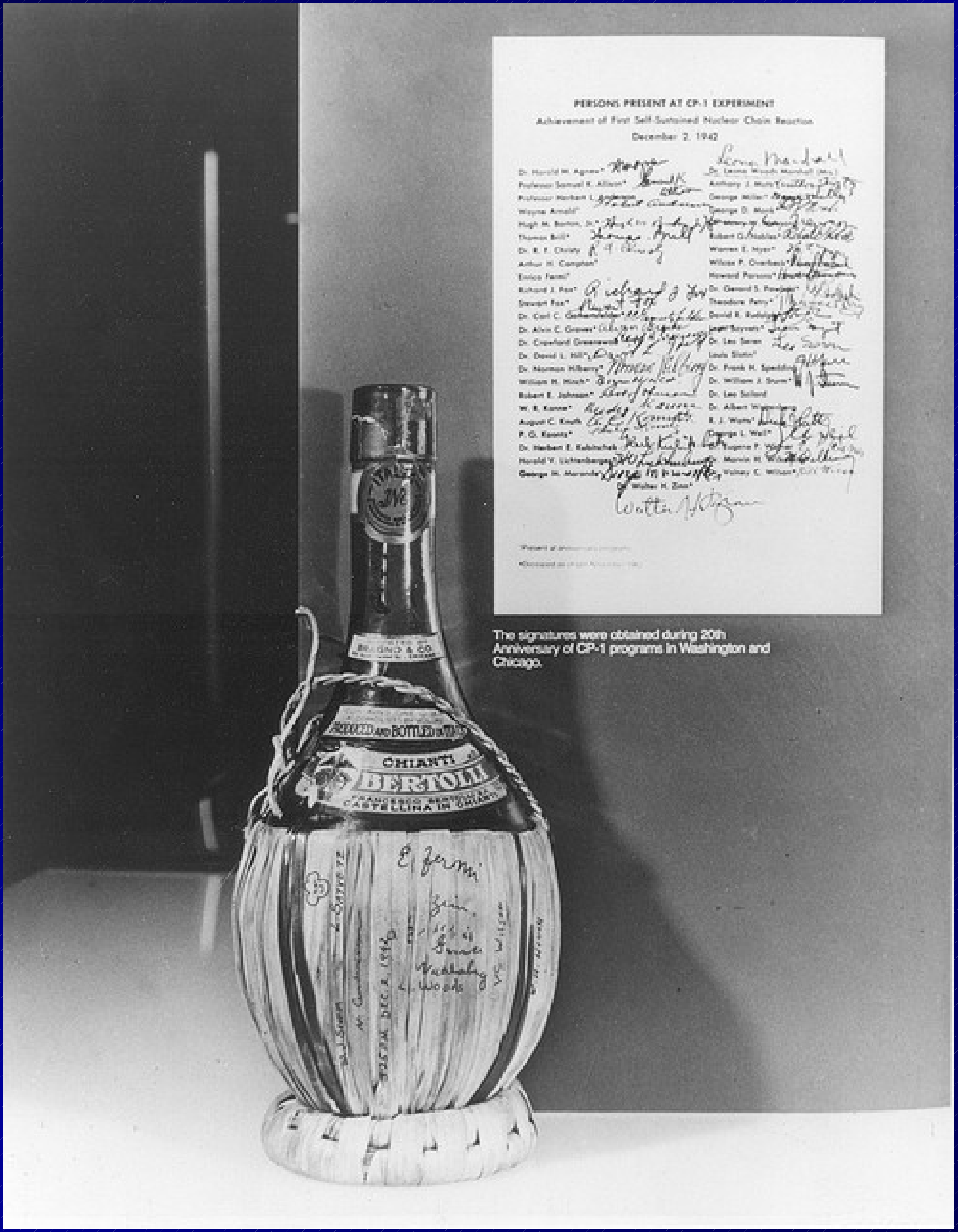
Einstein, Yukawa and Wheeler: the birth of Relativistic Astrophysics



To Remo Ruffini, companion
i the search for the deeper
ning of Einstein's great
y, with warm regards
Wheeler 5 April 1968

Einstein 70th birthday


THE PHYSICAL THEORY of NEUTRON CHAIN REACTORS



PERSONS PRESENT AT CP-1 EXPERIMENT

Achievement of First Self-Sustained Nuclear Chain Reaction

December 2, 1942

Dr. Harold M. Agnew*
Professor Samuel K. Allison*
Professor Herbert L. Anderson
Wayne Arnold*
Hugh M. Barton, Jr.*
Thomas Brill*
Dr. R. F. Christy
Arthur H. Compton*
Enrico Fermi*
Richard J. Fox*
Stewart Fox*
Dr. Carl C. Gamertsfelder*
Dr. Alvin C. Graves*
Dr. Crawford Greenewalt
Dr. David L. Hill*
Dr. Norman Hilberry*
William H. Hinch*
Robert E. Johnson*
W. R. Kanne*
August C. Knuth
P. G. Koontz*
Dr. Herbert E. Kubitschek
Harold V. Lichtenberger
George M. Maronde
Dr. Leona Woods Marshall (Mrs.)
Anthony J. Muth*
George Miller*
George D. Monk*
[illegible]
Robert G. Nobles*
Warren E. Nyer*
Wilcox P. Overbeck*
Howard Parsons*
Dr. Gerard S. Pawlicki*
Theodore Petry*
David R. Rudolph*
Leon Sayvetz*
Dr. Leo Seren
Louis Slotin*
Dr. Frank H. Spedding
Dr. William J. Sturm*
Dr. Leo Szilard
Dr. Albert Wattenberg
R. J. Watts*
George L. Weil*
Eugene P. Wigner
Marvin H. Wilkening
Volney C. Wilson*
Walter H. Zinn*

Leona Marshall

Richard J. Fox

Leo Seren

Walter H. Zinn

The signatures were obtained during 20th Anniversary of CP-1 programs in Washington and Chicago.


CHIANTI
BERTOLLI
FRANCESCO BERTOLLI USA
CASTELLINA CHIANTI
E Fermi
George Weil

Pulsars and Neutron stars rotational energy

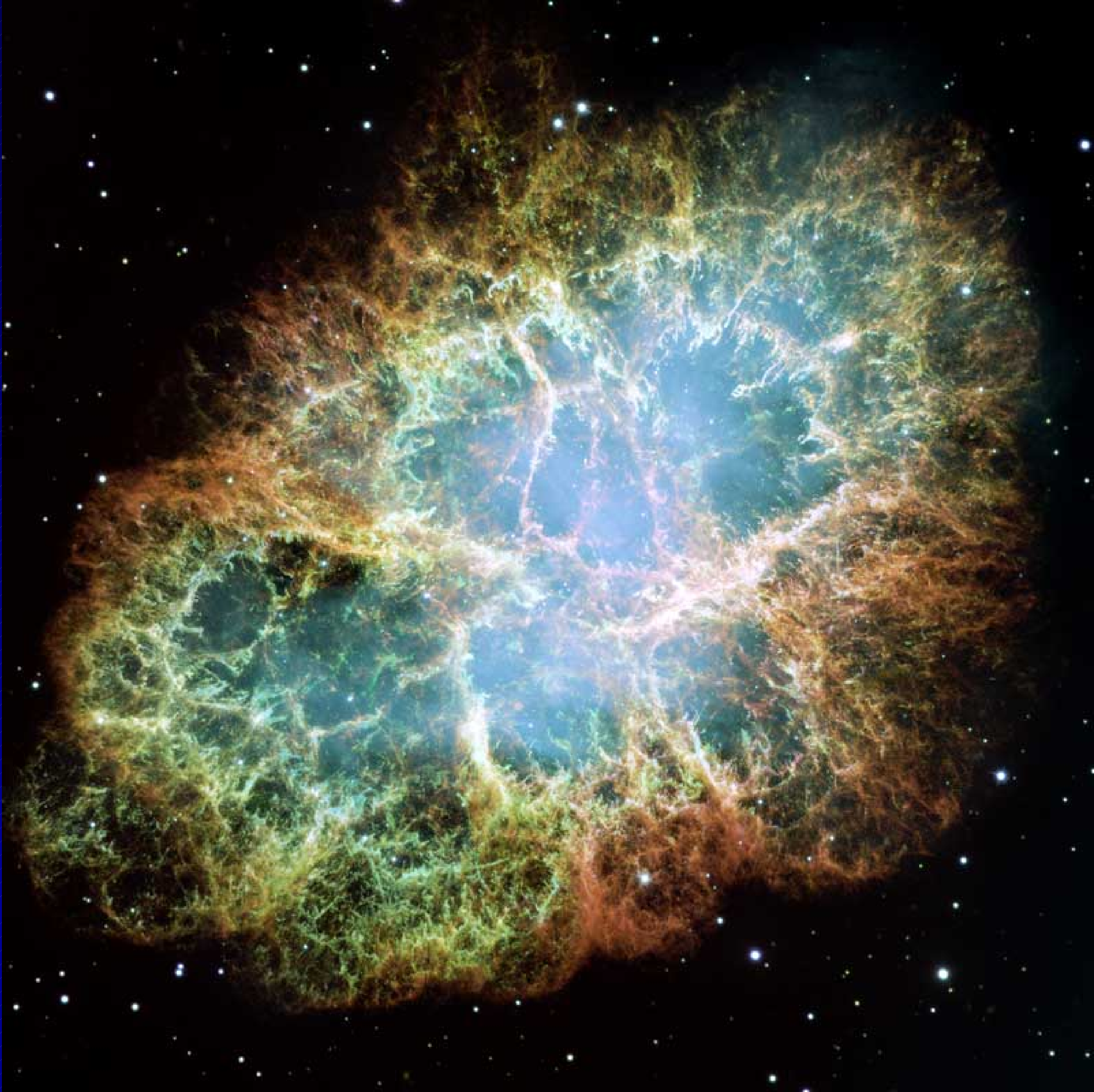
$$\left(\frac{dE}{dt}\right)_{obs} \simeq 4\pi^2 \frac{I_{NS}}{P^3}\frac{dP}{dt}$$

Chinese, Japanese, Korean astronomers (1054 A.D.)

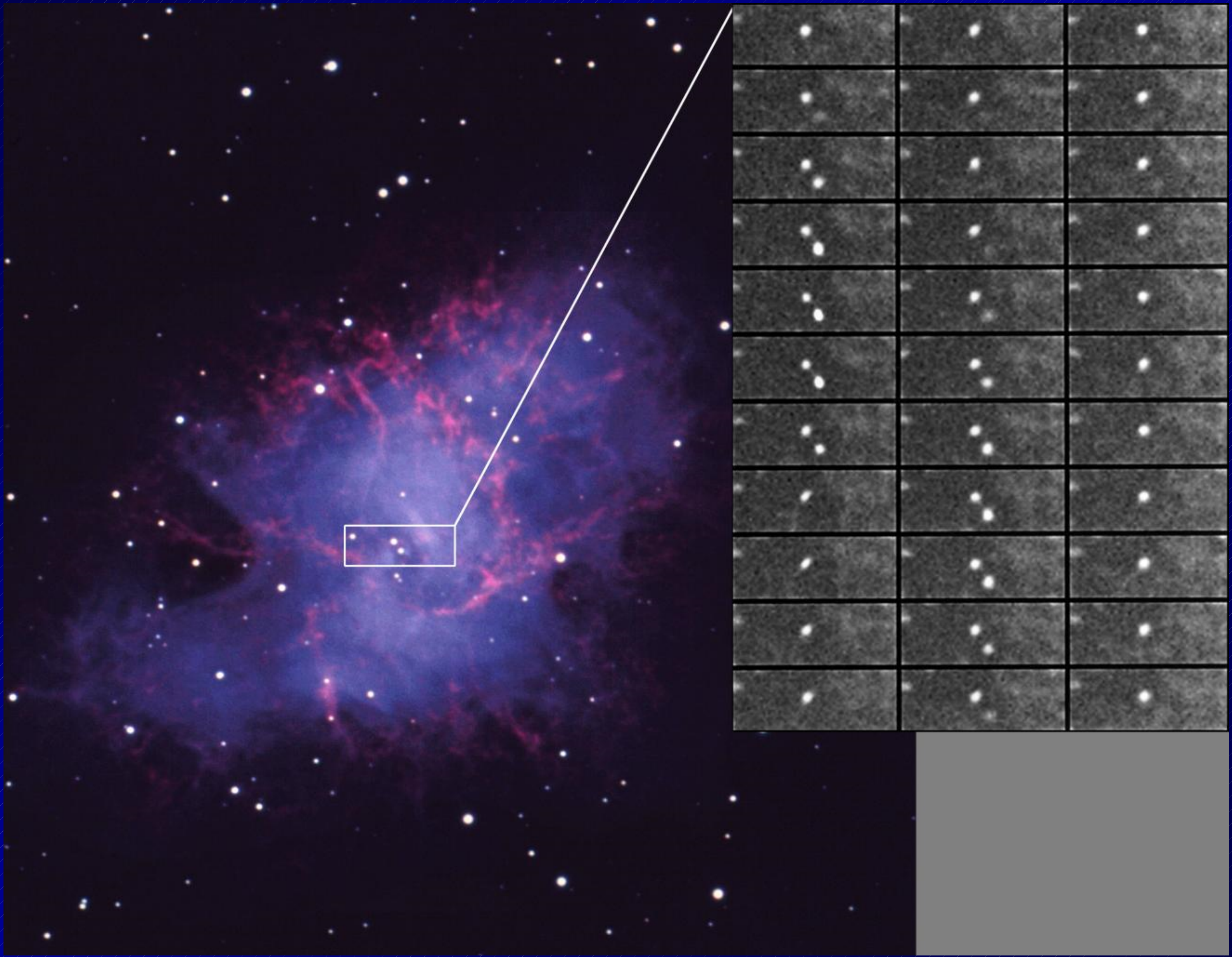
R. Oppenheimer & R. Volkoff (1939)

J. Bell & T. Hewish (1967)

A. Finzi & R. Wolf (1968)



The Crab Nebula Pulsar



Princeton, 1967

“You like very much George Gamow: he used a special set of units:
$G = \hbar = c = \pi = 1$”

(E. Wigner to R. Ruffini)

Princeton, 1971

Joseph Henry Laboratories, Princeton University

The Breit-Wigner formula applied to gravitational waves detectors

The cross-section for radiative capture of a neutron is described by the Breit-Wigner formula[125]

$$\sigma(\omega) = \pi\bar{\lambda}^2 \frac{(2J+1)}{(2s+1)(2I+1)} \frac{A_{\mathrm{neut}} A_{\mathrm{rad}}}{(\omega-\omega_0)^2 + (\frac{1}{2}A_{\mathrm{neut}} + \frac{1}{2}A_{\mathrm{rad}})^2}$$

consider the bar of Weber[112] with a mass of 1.4×10^6 g, composed of aluminium ($v = 6.42 \times 10^5$ cm/sec, $\beta = 2.14 \times 10^{-5}$) and operating in its lowest mode, $n = 1$:

$$\int_{\mathrm{res,\ random}} \sigma(\nu)\, d\nu = 0.679 \times (2.22 \times 10^{-18}\,\mathrm{cm^2\,Hz/g}) \times (1.4 \times 10^6\,\mathrm{g}) \times (2.14 \times 10^{-5})^2$$

$$= 1.0 \times 10^{-21}\,\mathrm{cm^2\,Hz}$$

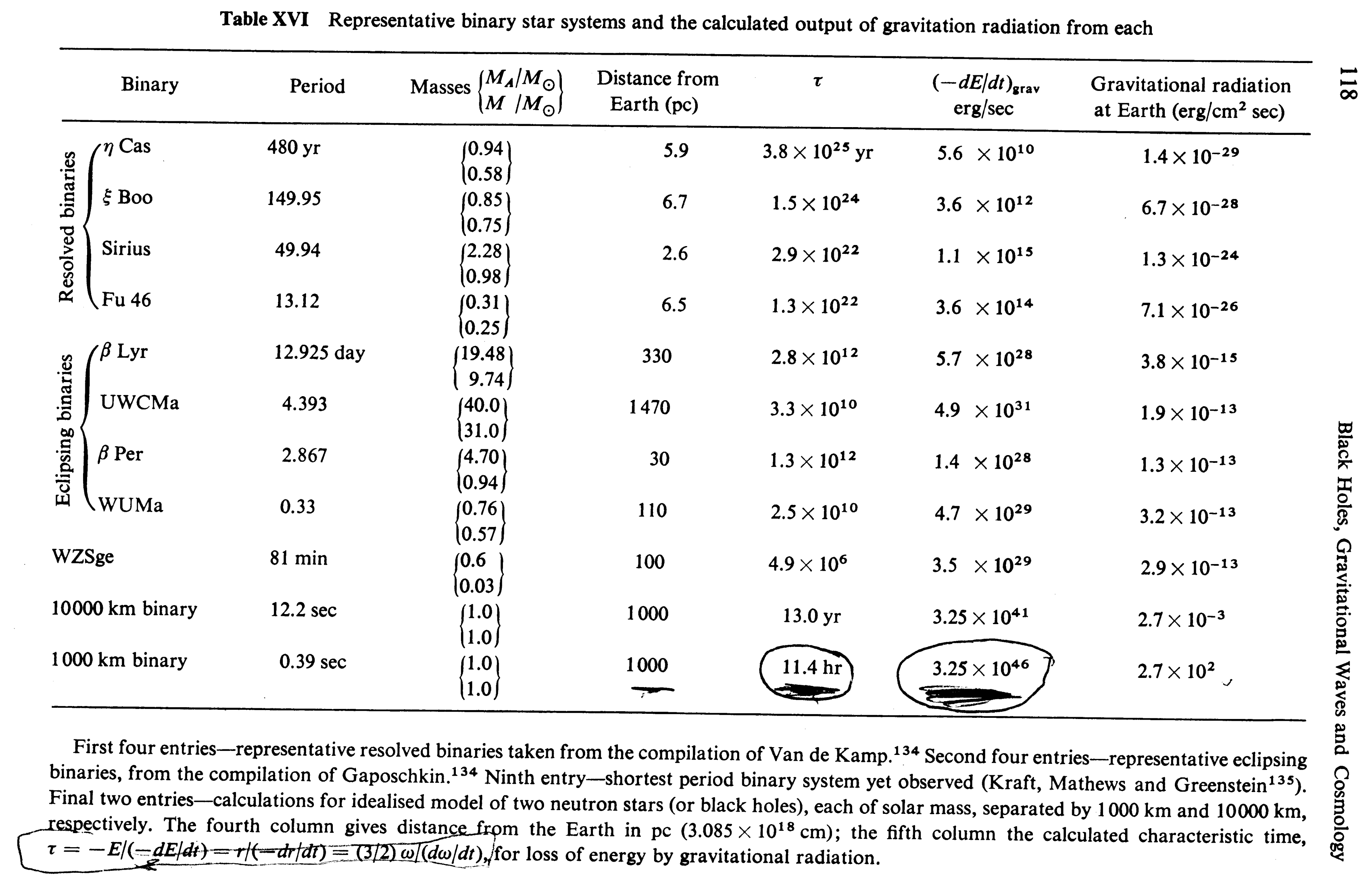


Table XVI Representative binary star systems and the calculated output of gravitation radiation from each

	Binary	Period	Masses $\begin{Bmatrix} M_A/M_\odot \\ M\ /M_\odot \end{Bmatrix}$	Distance from Earth (pc)	τ	$(-dE/dt)_{\text{grav}}$ erg/sec	Gravitational radiation at Earth (erg/cm² sec)
Resolved binaries	η Cas	480 yr	$\begin{Bmatrix} 0.94 \\ 0.58 \end{Bmatrix}$	5.9	3.8×10^{25} yr	5.6×10^{10}	1.4×10^{-29}
	ξ Boo	149.95	$\begin{Bmatrix} 0.85 \\ 0.75 \end{Bmatrix}$	6.7	1.5×10^{24}	3.6×10^{12}	6.7×10^{-28}
	Sirius	49.94	$\begin{Bmatrix} 2.28 \\ 0.98 \end{Bmatrix}$	2.6	2.9×10^{22}	1.1×10^{15}	1.3×10^{-24}
	Fu 46	13.12	$\begin{Bmatrix} 0.31 \\ 0.25 \end{Bmatrix}$	6.5	1.3×10^{22}	3.6×10^{14}	7.1×10^{-26}
Eclipsing binaries	β Lyr	12.925 day	$\begin{Bmatrix} 19.48 \\ 9.74 \end{Bmatrix}$	330	2.8×10^{12}	5.7×10^{28}	3.8×10^{-15}
	UWCMa	4.393	$\begin{Bmatrix} 40.0 \\ 31.0 \end{Bmatrix}$	1470	3.3×10^{10}	4.9×10^{31}	1.9×10^{-13}
	β Per	2.867	$\begin{Bmatrix} 4.70 \\ 0.94 \end{Bmatrix}$	30	1.3×10^{12}	1.4×10^{28}	1.3×10^{-13}
	WUMa	0.33	$\begin{Bmatrix} 0.76 \\ 0.57 \end{Bmatrix}$	110	2.5×10^{10}	4.7×10^{29}	3.2×10^{-13}
	WZSge	81 min	$\begin{Bmatrix} 0.6 \\ 0.03 \end{Bmatrix}$	100	4.9×10^{6}	3.5×10^{29}	2.9×10^{-13}
	10000 km binary	12.2 sec	$\begin{Bmatrix} 1.0 \\ 1.0 \end{Bmatrix}$	1000	13.0 yr	3.25×10^{41}	2.7×10^{-3}
	1000 km binary	0.39 sec	$\begin{Bmatrix} 1.0 \\ 1.0 \end{Bmatrix}$	1000	11.4 hr	3.25×10^{46}	2.7×10^{2} ✓

First four entries—representative resolved binaries taken from the compilation of Van de Kamp.[134] Second four entries—representative eclipsing binaries, from the compilation of Gaposchkin.[134] Ninth entry—shortest period binary system yet observed (Kraft, Mathews and Greenstein[135]). Final two entries—calculations for idealised model of two neutron stars (or black holes), each of solar mass, separated by 1000 km and 10000 km, respectively. The fourth column gives distance from the Earth in pc (3.085×10^{18} cm); the fifth column the calculated characteristic time, $\tau = -E/(-dE/dt) = r/(-dr/dt) = (3/2)\,\omega/(d\omega/dt)$, for loss of energy by gravitational radiation.

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

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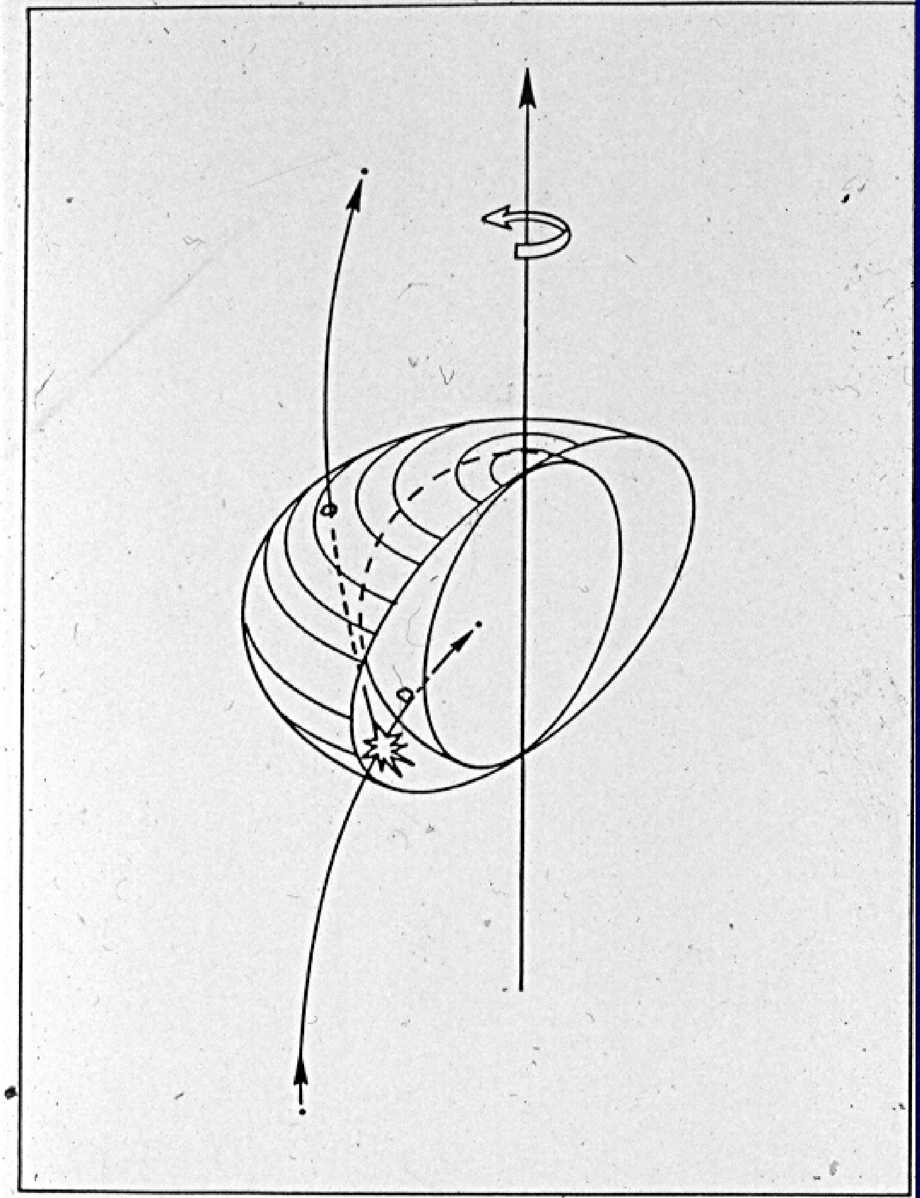
Remo Ruffini and John Wheeler are both at Princeton University; Wheeler, currently on leave from Princeton, is spending a year at Cal Tech and Moscow State University.

The Ergosphere



Ergosphere of a rotating black hole. The region between the surface of infinite redshift (outer) and the event horizon (inner), here shown in a cutaway view, is called the "ergosphere." When a particle disintegrates in this region and one of the fragments falls into the black hole, the other fragment can escape to infinity with more rest plus kinetic energy than the original particle. Figure 5

Ruffini, Wheeler, *Phys.Today*, January 1971

Reversible and Irreversible Transformations in Black-Hole Physics*

Demetrios Christodoulou
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

(Received 17 September 1970)

The concepts of irreducible mass and of reversible and irreversible transformations in black holes are introduced, leading to the formula $E^2 = m_{\rm ir}^2 + (L^2/4m_{\rm ir}^2) + p^2$ for a black hole of linear momentum p and angular momentum L.

VOLUME 25, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1970

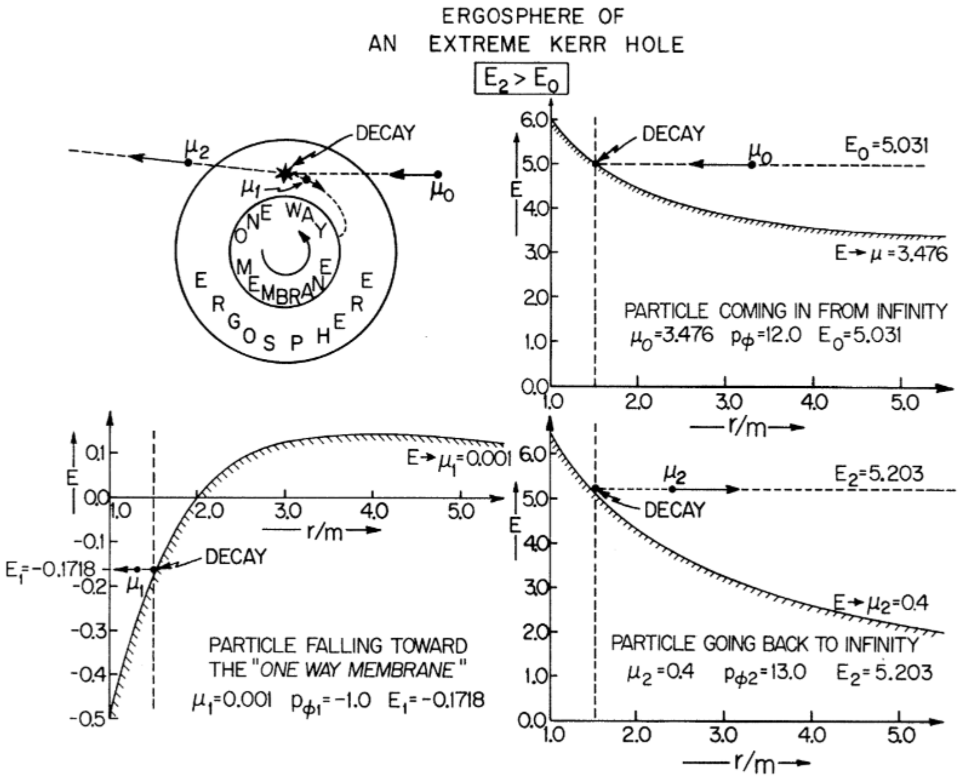


FIG. 2. (Reproduced from Ruffini and Wheeler, Ref. 4, with their kind permission.) Decay of a particle of rest-plus-kinetic energy E_0 into a particle which is captured into the black hole with positive energy as judged locally, but negative energy E_1 as judged from infinity, together with a particle of rest-plus-kinetic energy $E_2 > E_0$ which escapes to infinity. The cross-hatched curves give the effective potential (gravitational plus centrifugal) defined by the solution $\boldsymbol{E}$ of Eq. (2) for constant values of p_φ and μ.

Demetrios Christodoulou's Ph.D. Thesis defence Committee

Demetrios Christodoulou's Ph.D. Thesis defence Committee

Wigner questioning

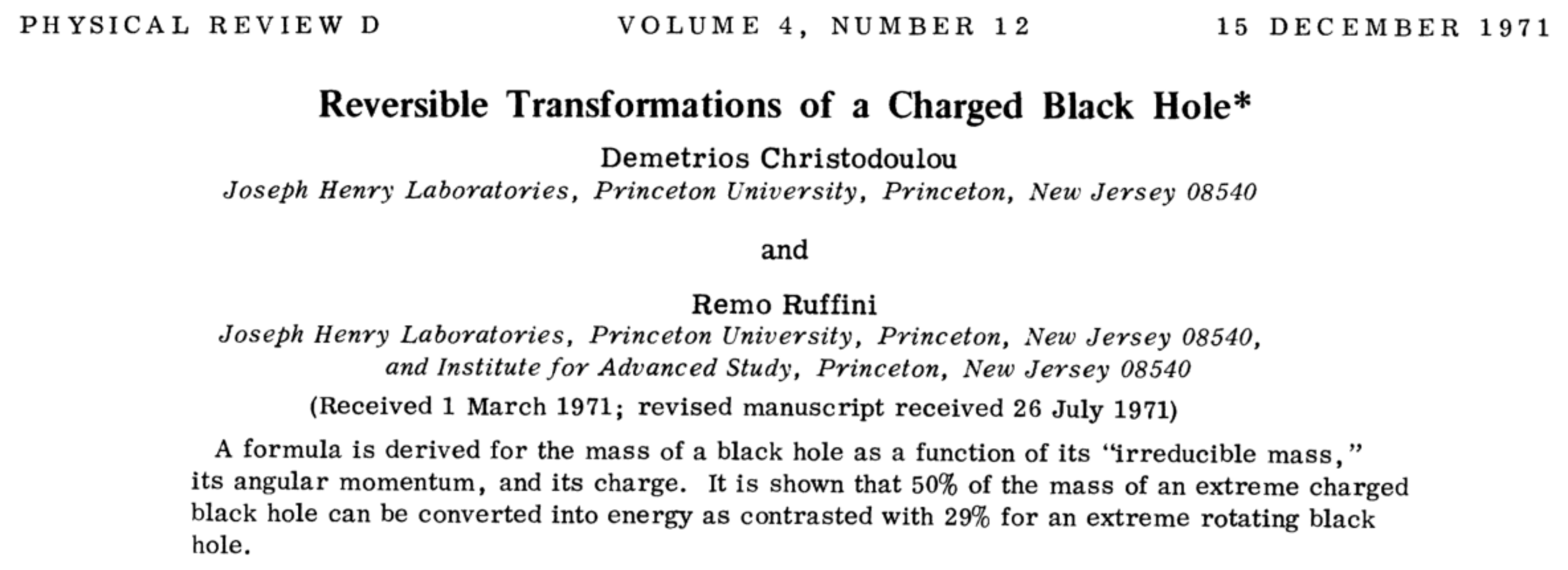
Wigner attacks

Princeton, Physics graduate students, 1968

1. Jerol M. Lind
2. Danny L. Hawley
3. Alan M. Nathan
4. William C. Mead
5. Glennys R. Farrar
6. Richard Chang
7. Niall O Murchadha
8. Robert T. Baumel
9. Edward J. Groth
10. George C-N Hsieh
11. James R. Milch
12. Jesse I. Treu
13. David M. Fram
14. Robert M. Wald
15. Charles S. Borso
16. Mark R. Nelson
17. Charles P. Benedict
18. Vincent P. Ruddy
19. William E. Caswell
20. William R. Shanahan
21. Robert C. Webb
22. Peter C. Colter
23. Paul T. Debevec
24. Demetrios Christodoulou
25. Frank A. Chambers
26. Edward A. Williams
27. Thomas C. Rich
28. Richard T. Williams
29. James R. Campbell
30. J. David Cohen
31. Matthew D. Miller

Not present: Terrence J. Sejnowski

DEPARTMENT OF PHYSICS - GRADUATE STUDENTS, ENTERING CLASS 1968



PHYSICAL REVIEW D VOLUME 4, NUMBER 12 15 DECEMBER 1971

Reversible Transformations of a Charged Black Hole*

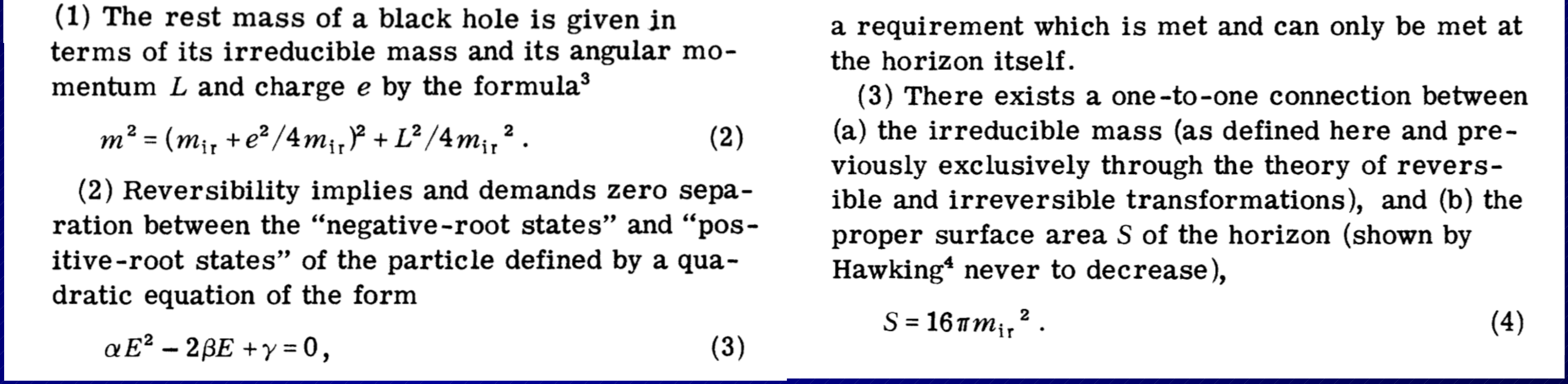
Demetrios Christodoulou
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

and

Remo Ruffini
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540,
and Institute for Advanced Study, Princeton, New Jersey 08540

(Received 1 March 1971; revised manuscript received 26 July 1971)

A formula is derived for the mass of a black hole as a function of its "irreducible mass," its angular momentum, and its charge. It is shown that 50% of the mass of an extreme charged black hole can be converted into energy as contrasted with 29% for an extreme rotating black hole.



(1) The rest mass of a black hole is given in terms of its irreducible mass and its angular momentum L and charge e by the formula[3]

$$m^2 = (m_{\text{ir}} + e^2/4m_{\text{ir}})^2 + L^2/4m_{\text{ir}}^2 . \qquad (2)$$

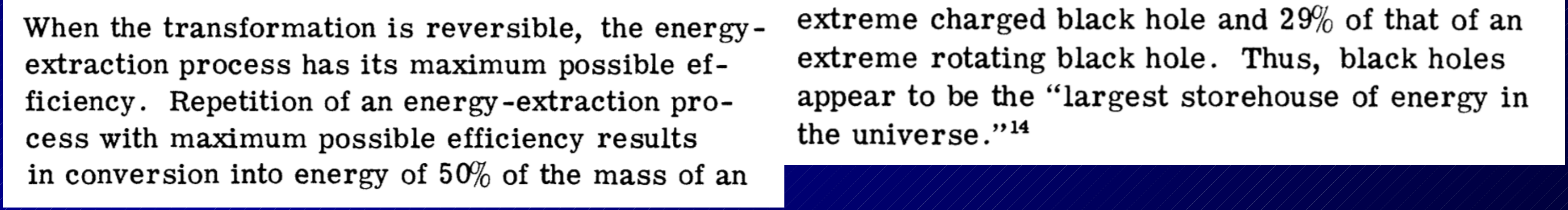
(2) Reversibility implies and demands zero separation between the "negative-root states" and "positive-root states" of the particle defined by a quadratic equation of the form

$$\alpha E^2 - 2\beta E + \gamma = 0, \qquad (3)$$

a requirement which is met and can only be met at the horizon itself.

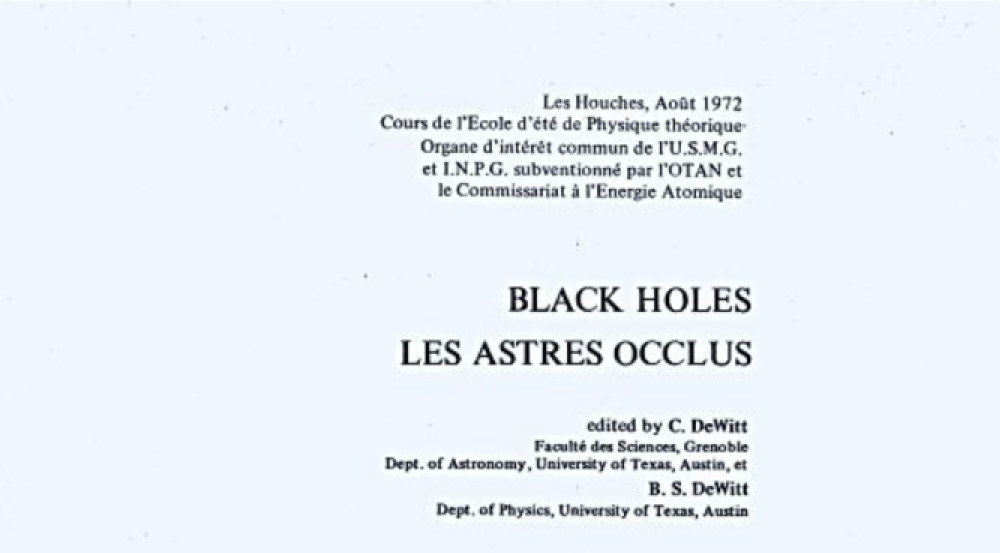
(3) There exists a one-to-one connection between (a) the irreducible mass (as defined here and previously exclusively through the theory of reversible and irreversible transformations), and (b) the proper surface area S of the horizon (shown by Hawking[4] never to decrease),

$$S = 16\pi m_{\text{ir}}^2 . \qquad (4)$$



When the transformation is reversible, the energy-extraction process has its maximum possible efficiency. Repetition of an energy-extraction process with maximum possible efficiency results in conversion into energy of 50% of the mass of an extreme charged black hole and 29% of that of an extreme rotating black hole. Thus, black holes appear to be the "largest storehouse of energy in the universe."[14]

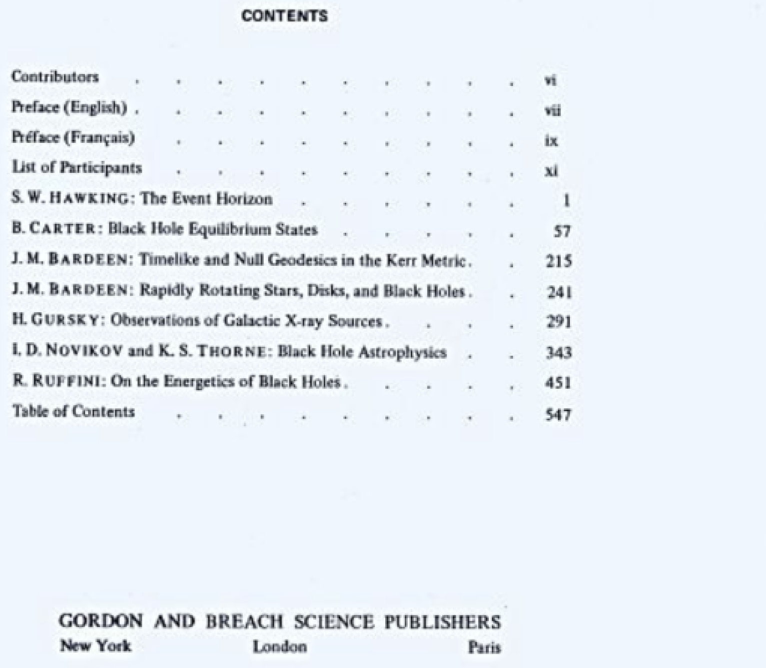
Les Houches, Mont Blanc, 1972



Les Houches, Août 1972
Cours de l'Ecole d'été de Physique théorique
Organe d'intérêt commun de l'U.S.M.G.
et I.N.P.G. subventionné par l'OTAN et
le Commissariat à l'Energie Atomique

BLACK HOLES
LES ASTRES OCCLUS

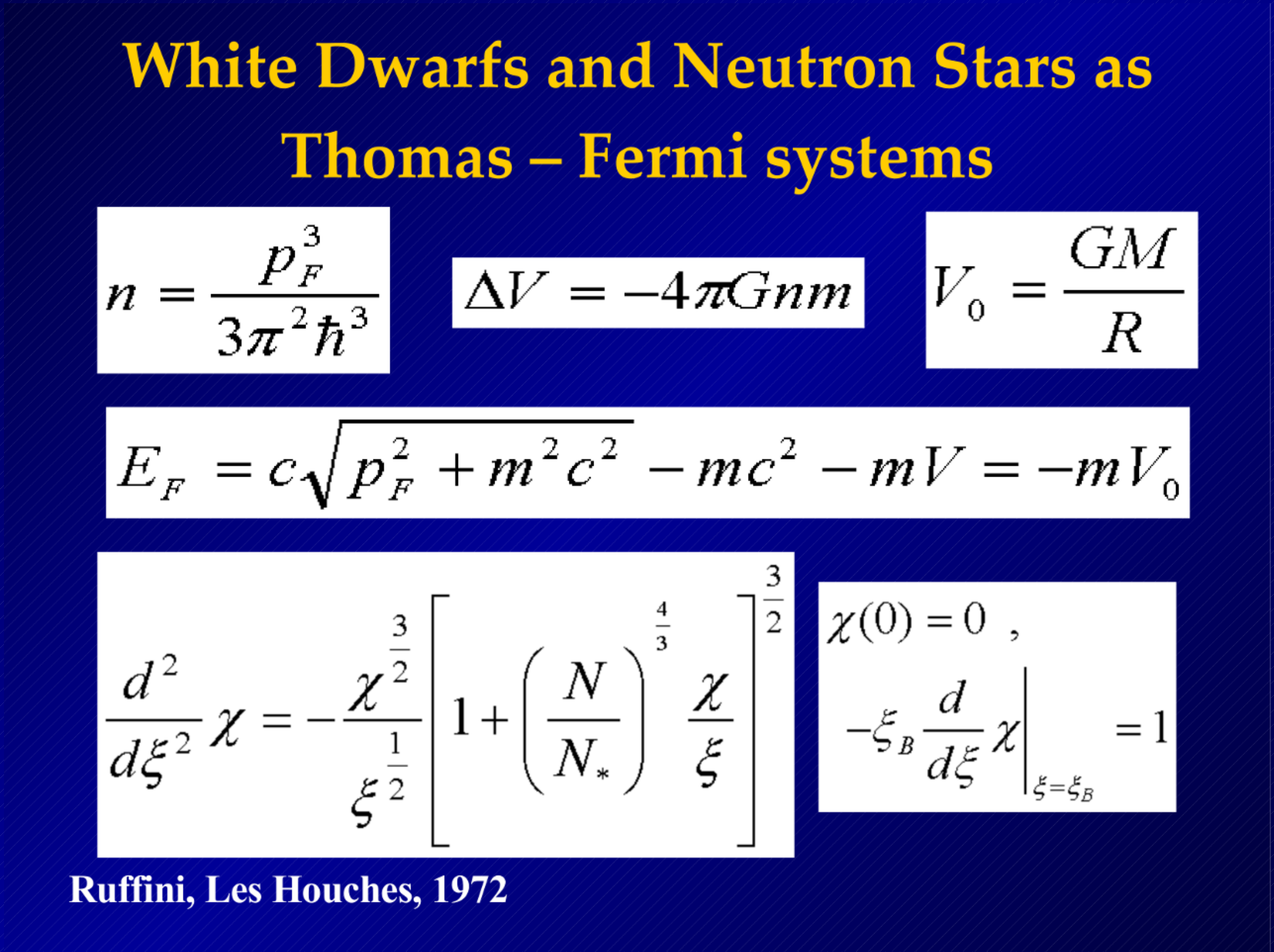
edited by **C. DeWitt**
Faculté des Sciences, Grenoble
Dept. of Astronomy, University of Texas, Austin, et
B. S. DeWitt
Dept. of Physics, University of Texas, Austin



CONTENTS

GORDON AND BREACH SCIENCE PUBLISHERS
New York London Paris

“The Thomas-Fermi model works much better than it should” (E. Wigner to R. Ruffini, 1972)



White Dwarfs and Neutron Stars as Thomas – Fermi systems

$$n = \frac{p_F^3}{3\pi^2\hbar^3}$$

$$\Delta V = -4\pi G n m$$

$$V_0 = \frac{GM}{R}$$

$$E_F = c\sqrt{p_F^2 + m^2c^2} - mc^2 - mV = -mV_0$$

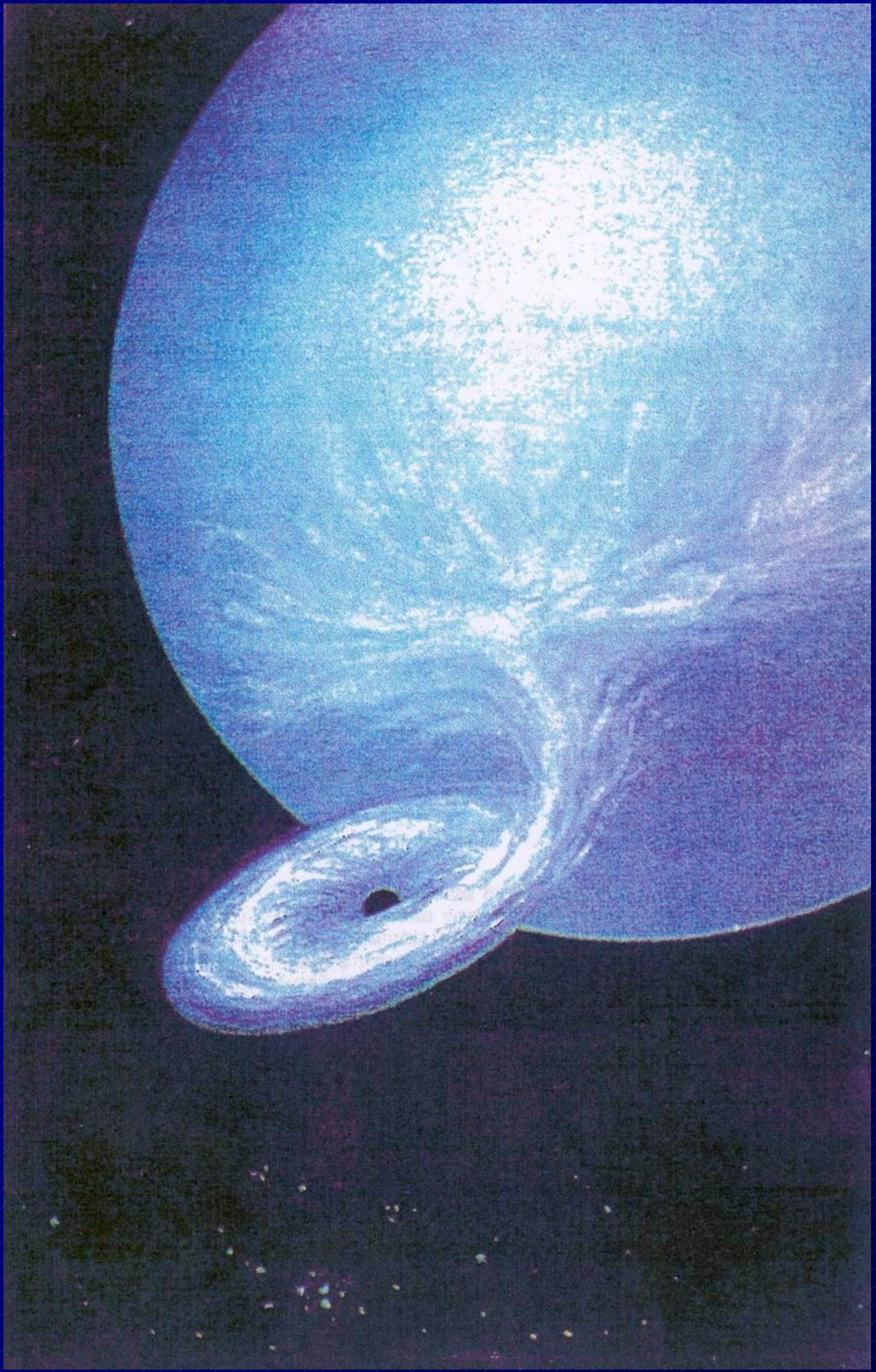
$$\frac{d^2}{d\xi^2}\chi = -\frac{\chi^{\frac{3}{2}}}{\xi^{\frac{1}{2}}}\left[1 + \left(\frac{N}{N_*}\right)^{\frac{4}{3}}\frac{\chi}{\xi}\right]^{\frac{3}{2}}$$

$$\chi(0) = 0\ ,$$

$$-\xi_B \frac{d}{d\xi}\chi\Big|_{\xi=\xi_B} = 1$$

Ruffini, Les Houches, 1972

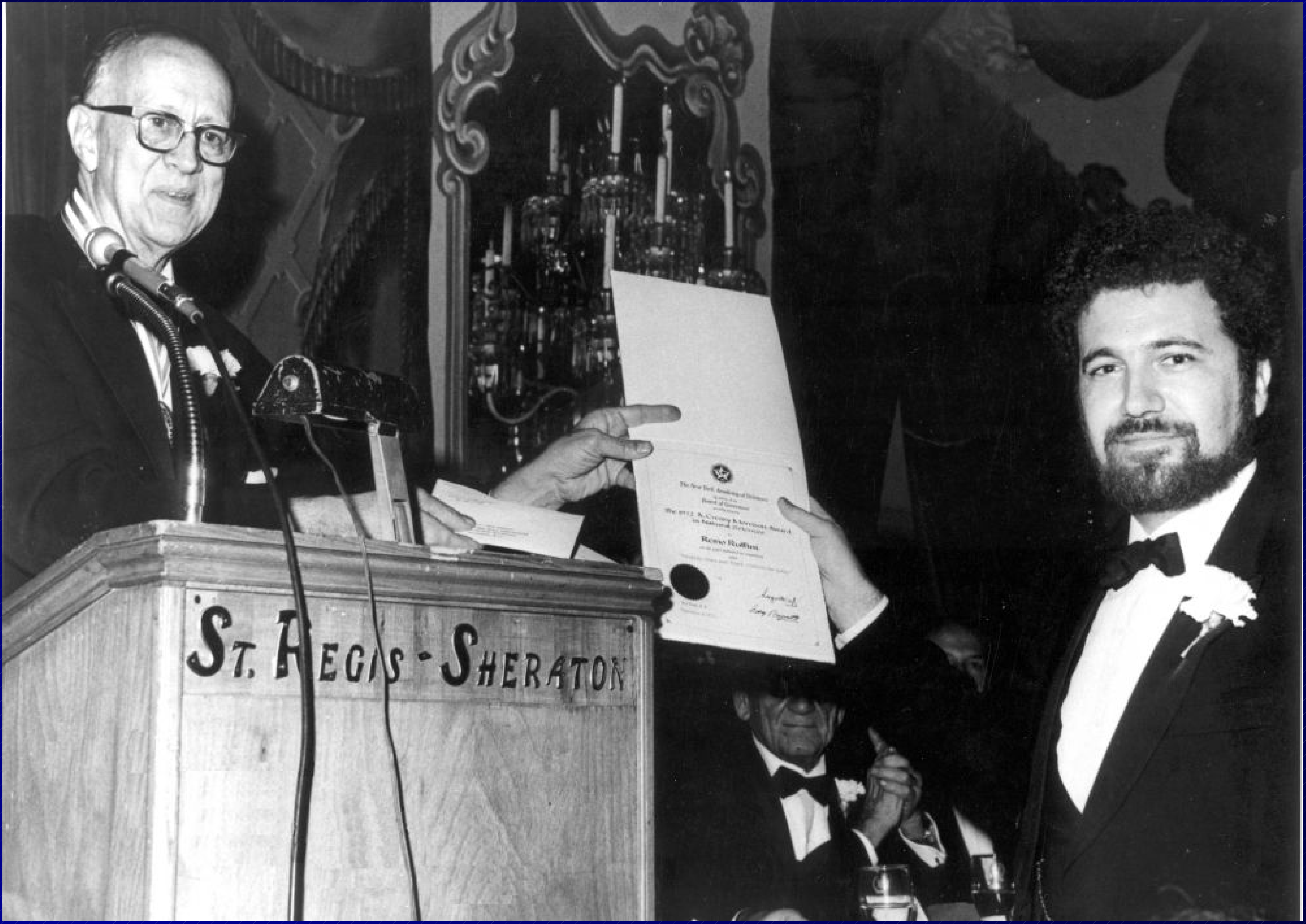
Accretion Energy. The identification of the first black hole: Cygnus X-1



- $\Phi = 10^{37}$ erg/s $= 10^4 L_\odot$
  $= 0.01(dm/dt)_{\mathrm{acc}}c^2$
- Absence of pulsation due to the uniqueness of Kerr-Newman metric
- $M > 3.2\ M_\odot$

Leach & Ruffini, 1973

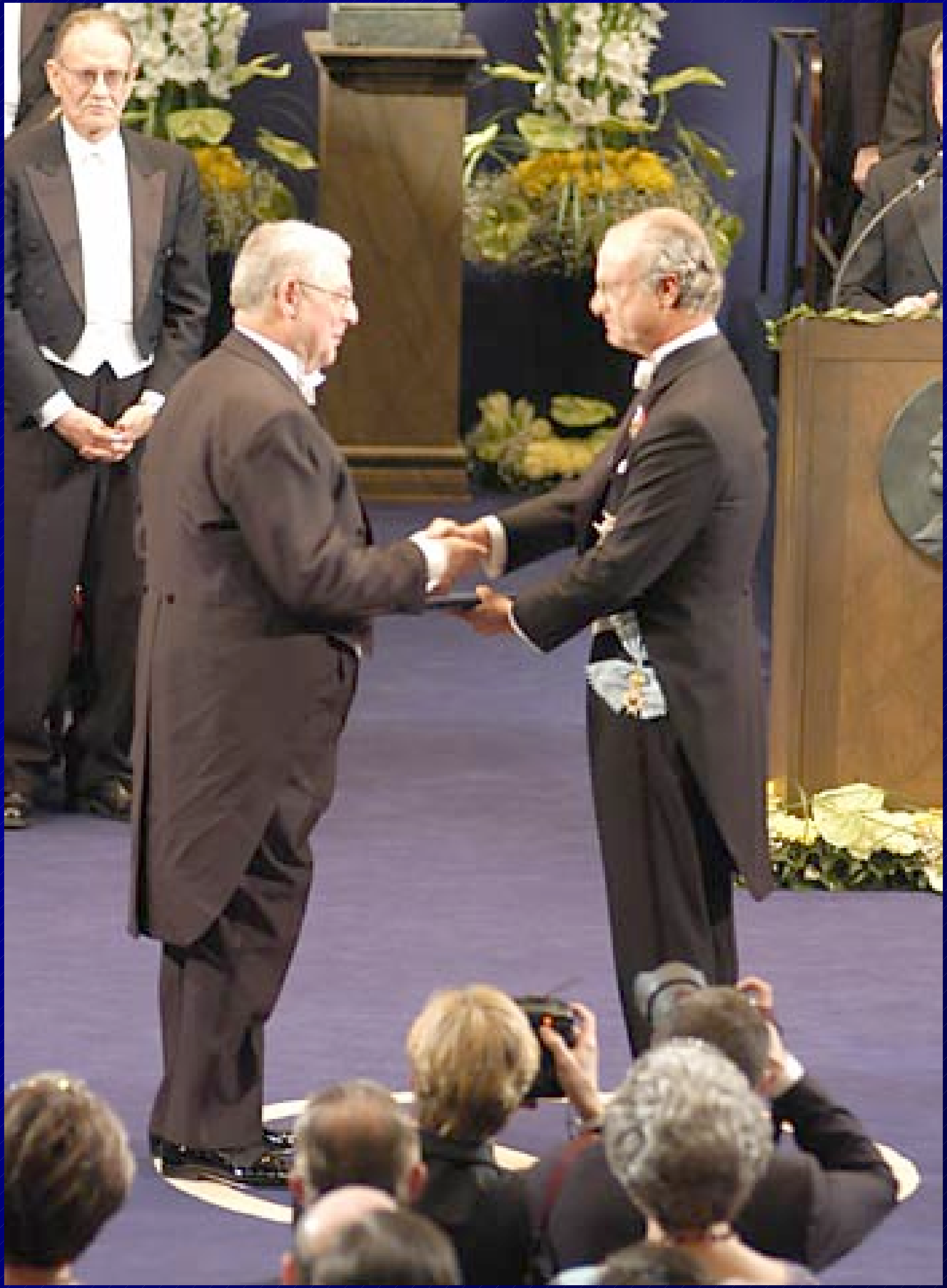
Cressy – Morrison award (NY, 1973)



Hulse and Taylor, 1993

Hulse & Taylor, *ApJ*, 195, L51-L53 (1975).

Giacconi, Sweden (2002)



“Alive Black Holes”

The Mass-Energy Formula

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

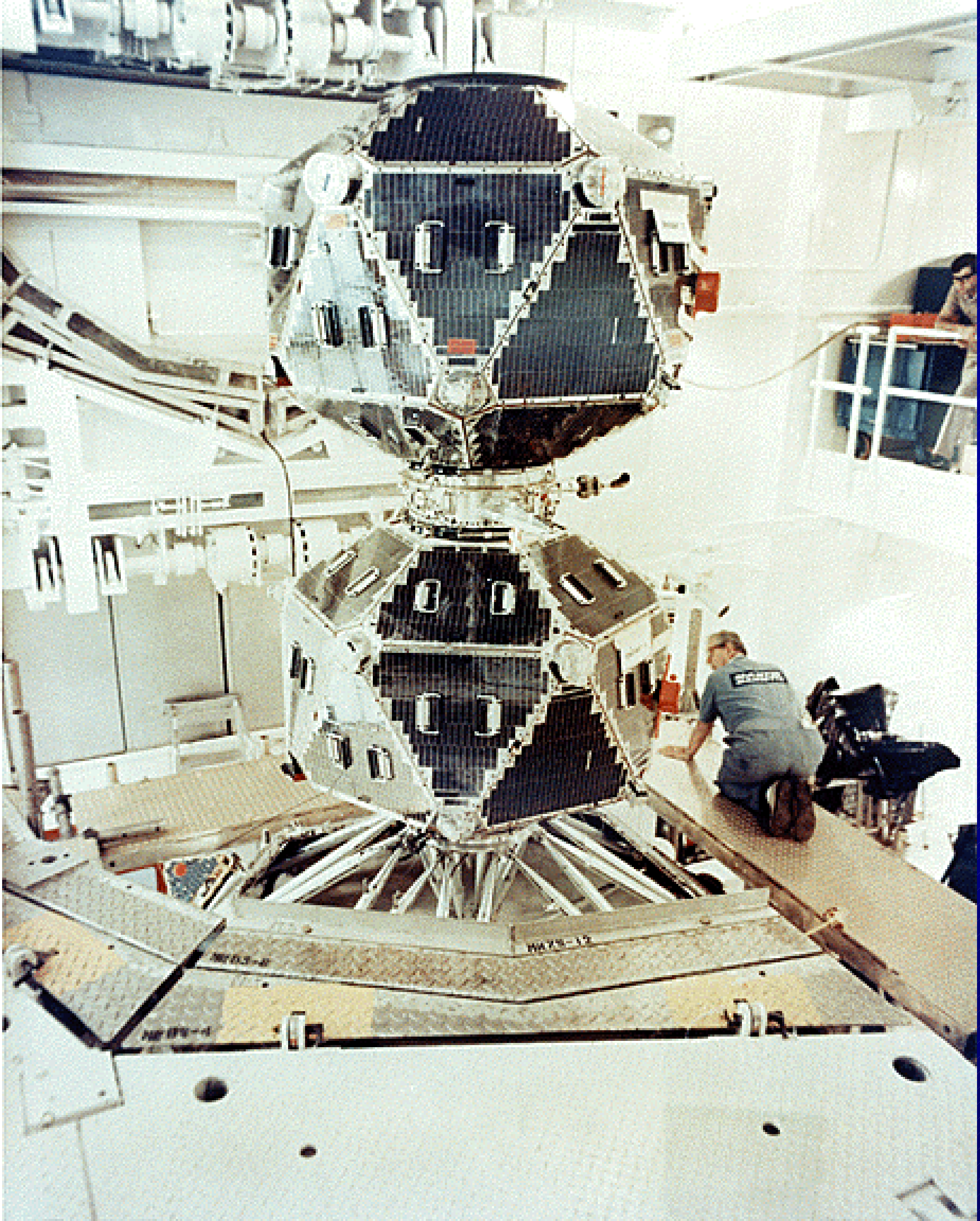
$$S = 16\pi m_{ir}^2\,,$$

$$\frac{L^2}{4m_{ir}^4} + \frac{e^4}{16m_{ir}^4} \leq 1\,,$$

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

Up to 50% of the energy extractable

Christodoulou, Ruffini, 1971



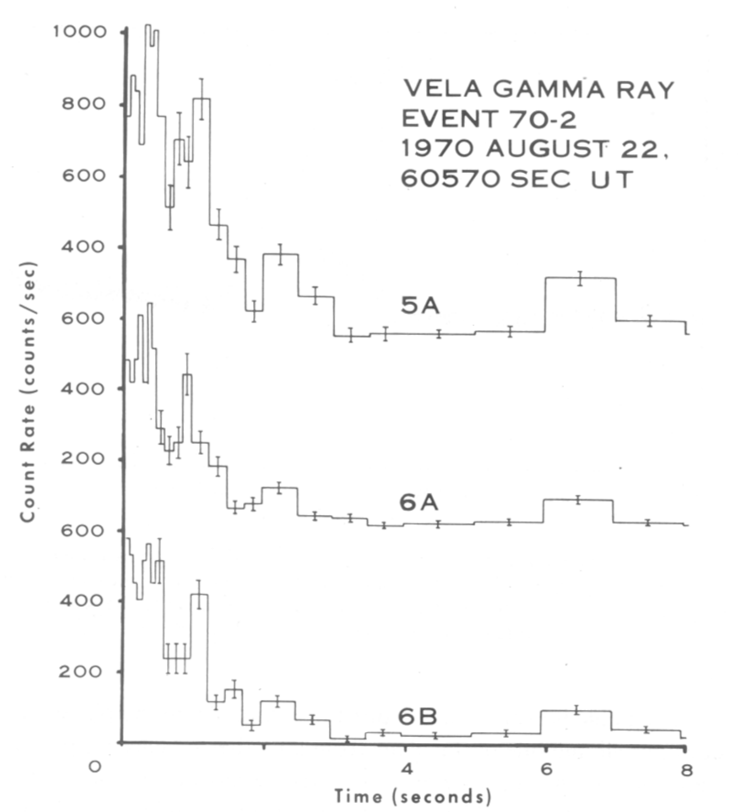
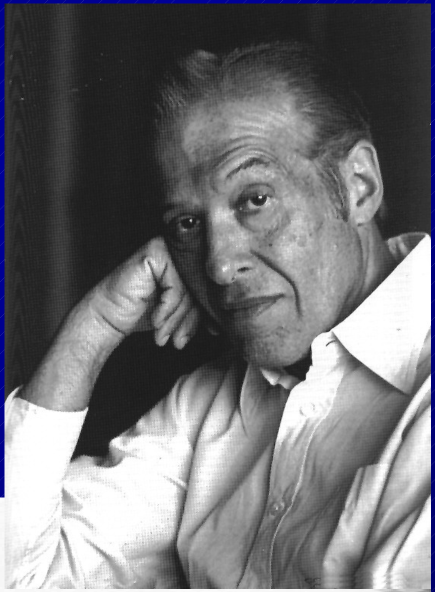
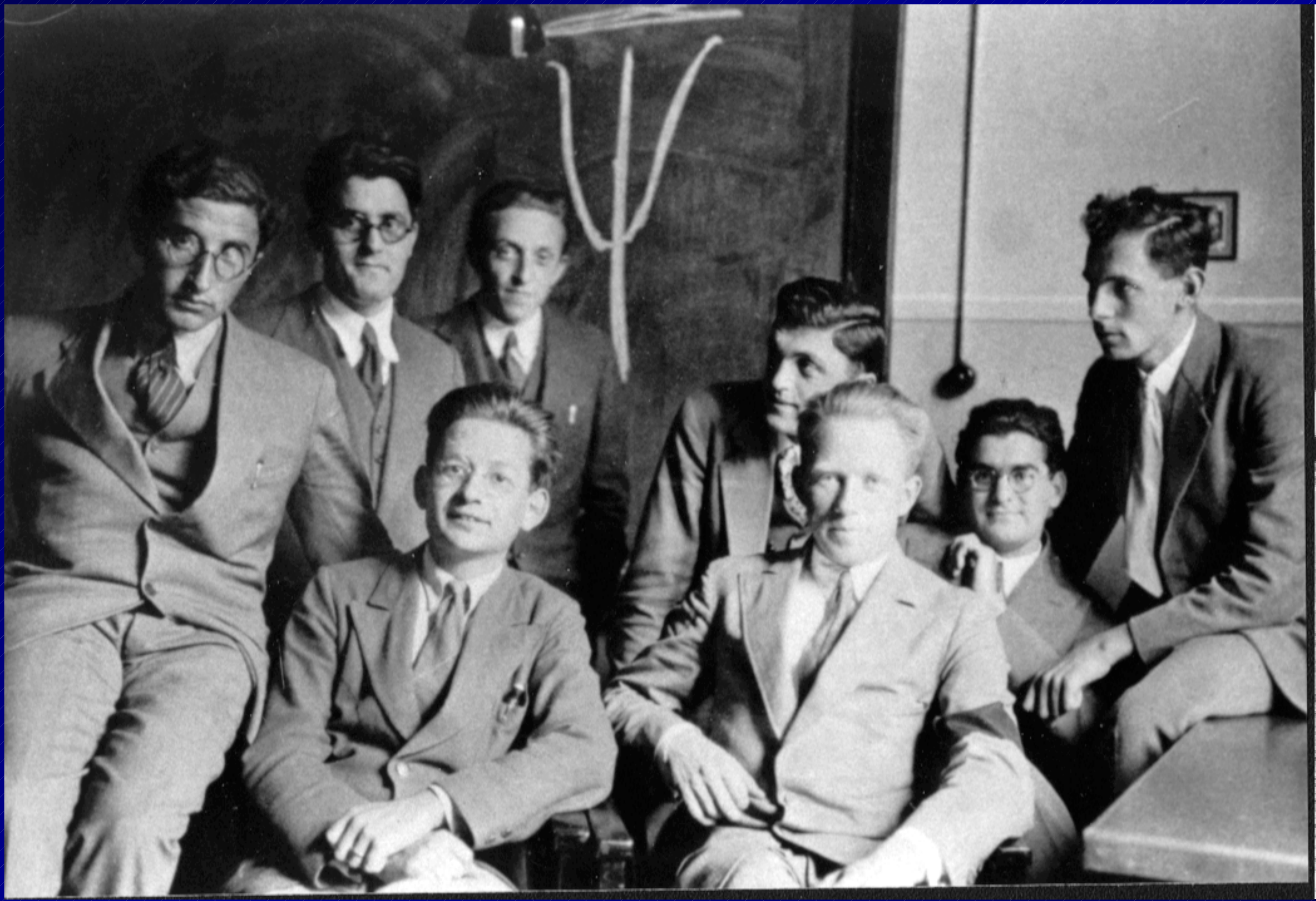
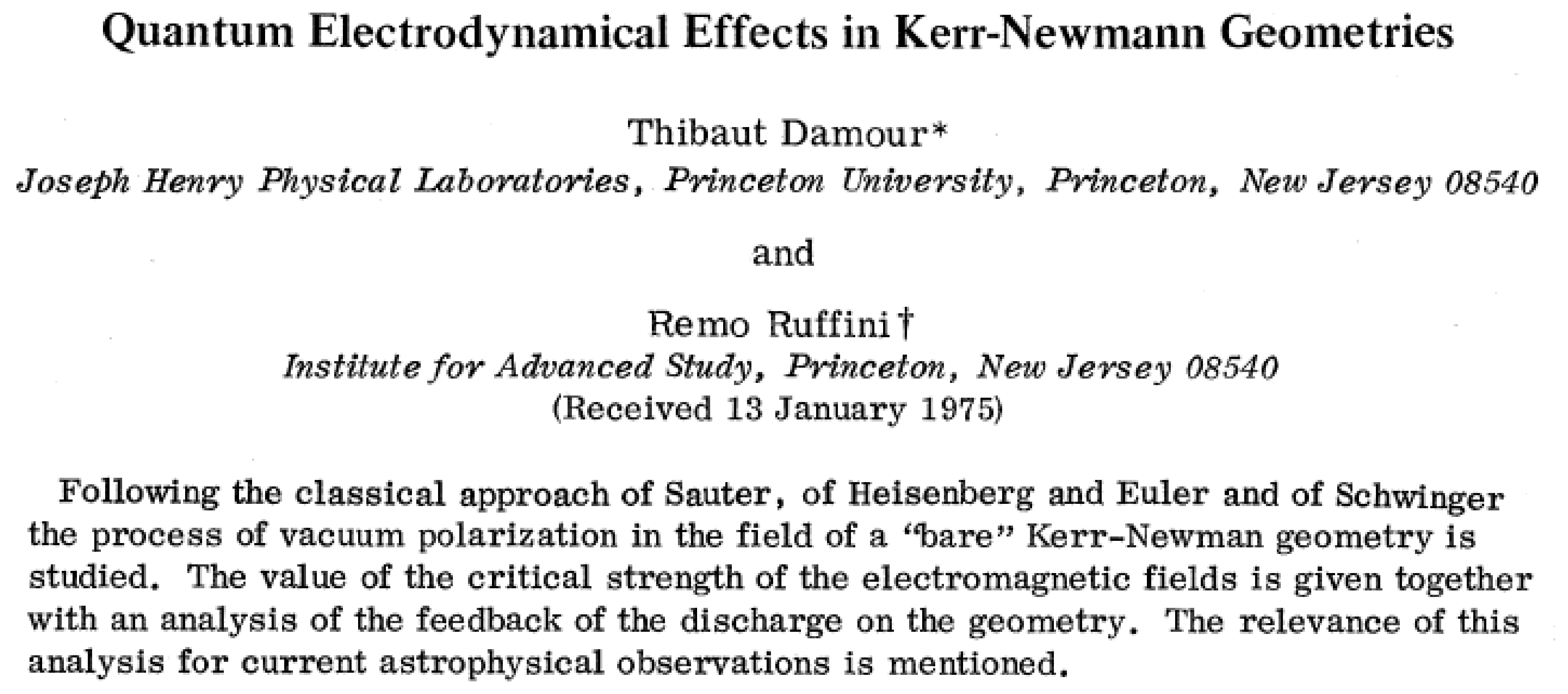


Fig. 5. Event 70-2, on 1970 August 22, beginning 60571 s UT.

Electron-Positron creation out of the vacuum







Quantum Electrodynamical Effects in Kerr-Newmann Geometries

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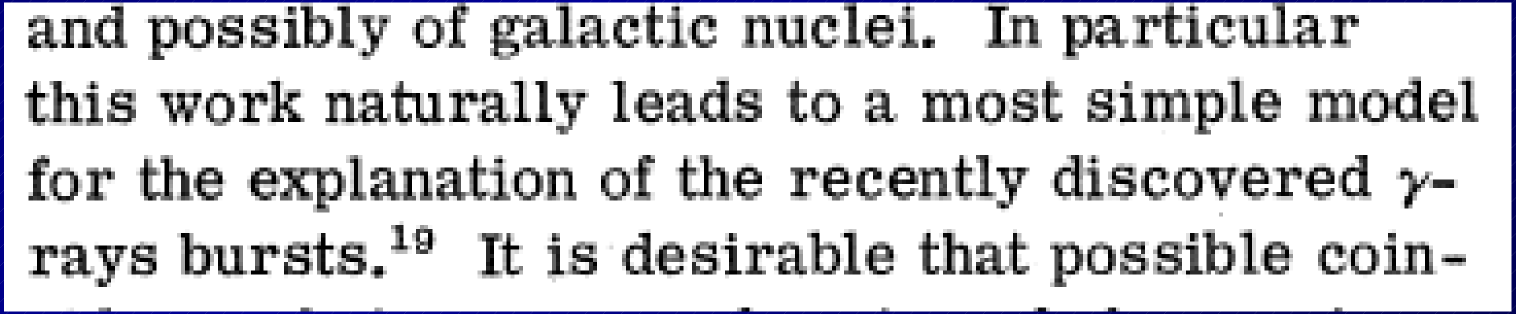
and

Remo Ruffini†
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 13 January 1975)

Following the classical approach of Sauter, of Heisenberg and Euler and of Schwinger the process of vacuum polarization in the field of a "bare" Kerr-Newman geometry is studied. The value of the critical strength of the electromagnetic fields is given together with an analysis of the feedback of the discharge on the geometry. The relevance of this analysis for current astrophysical observations is mentioned.



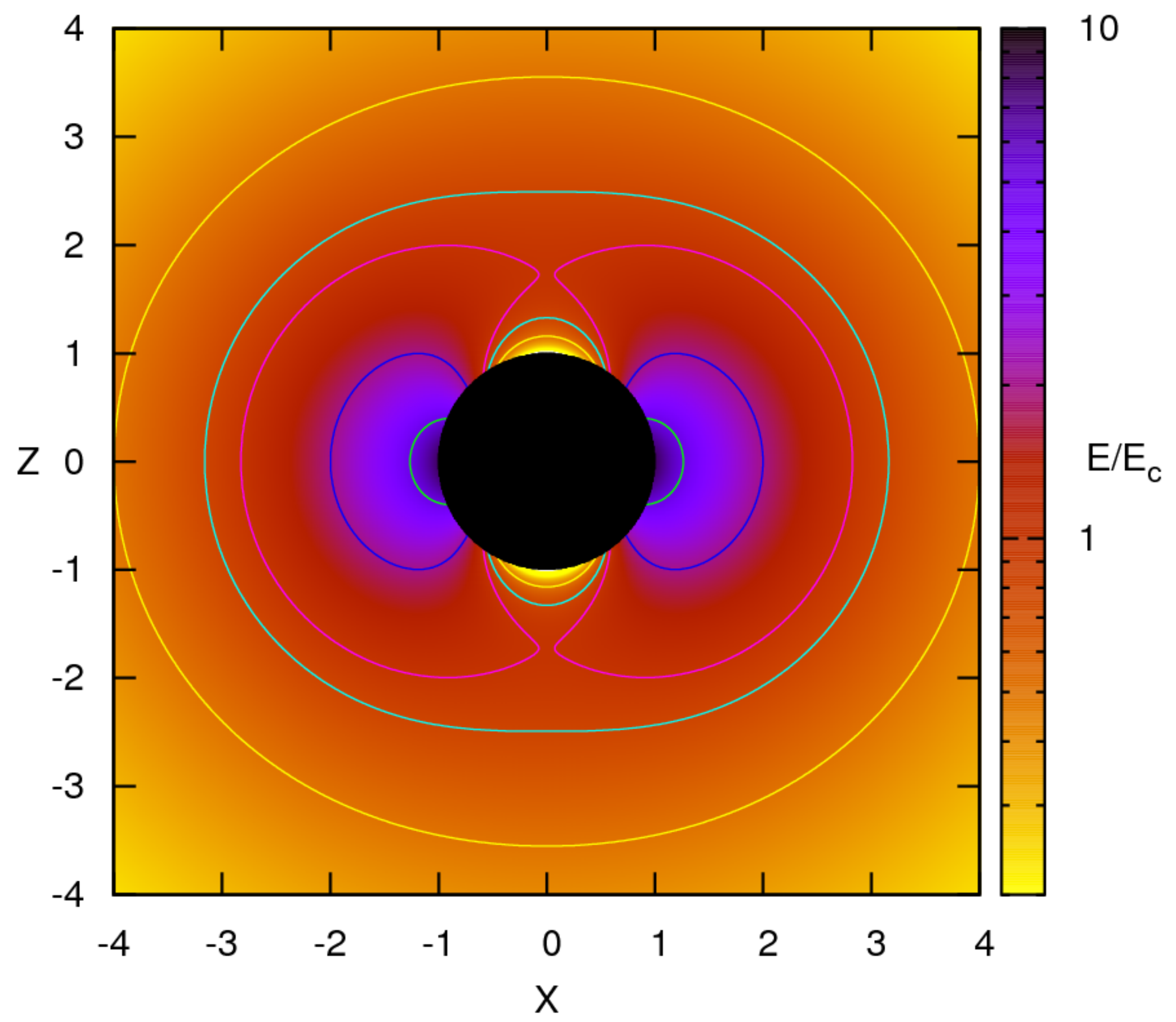
and possibly of galactic nuclei. In particular this work naturally leads to a most simple model for the explanation of the recently discovered γ-rays bursts.[19] It is desirable that possible coin-

Expected energy: $\sim 10^{54}\,(M_{BH}/M_{Sun})$ erg

Vallée des Merveilles, 1975

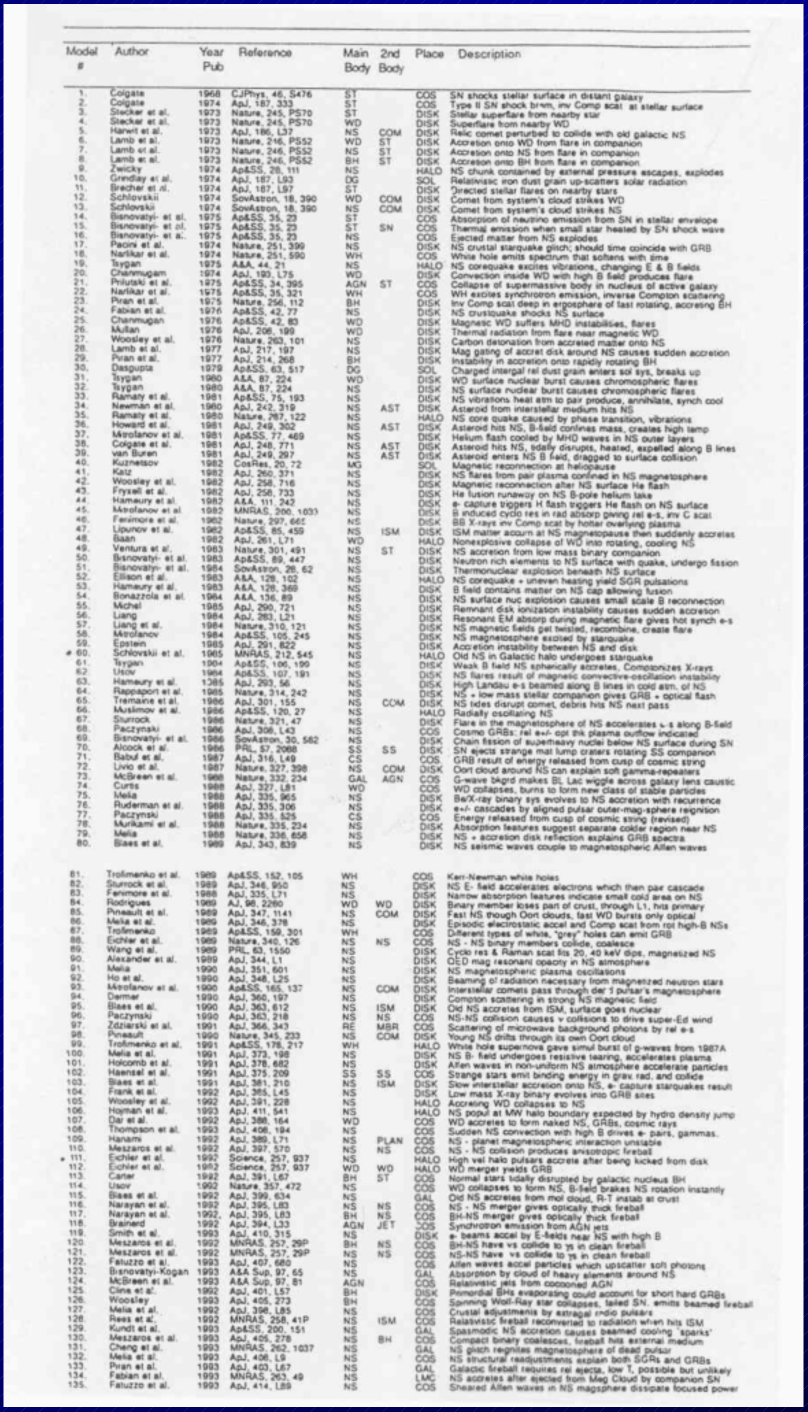
Wilson – Everitt – Ruffini – Damour

Mass, charge and angular momentum: the Kerr-Newman Black Hole



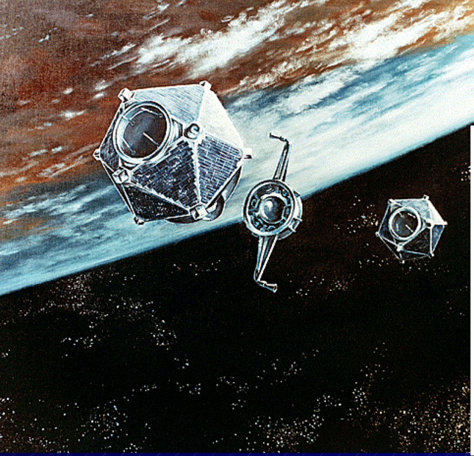
Cherubini, Geralico, Rueda, Ruffini, *PRD* 79, 124002 (2009).
Ruffini, Vereshchagin, Xue, *Phys.Rep.* 487, 1 (2010).

Theoretical attempts to explain GRBs before BeppoSAX



Model #	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap&SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flares on nearby stars
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap&SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap&SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap&SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugan	1976	Ap&SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag gating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap&SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap&SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap&SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al.	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap&SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap&SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot synch e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap&SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
* 60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap&SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap&SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm. of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap&SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e+/- opt thk plasma outflow indicated
69.	Bisnovatyi- et al.	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
72.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
73.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic
74.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
75.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion with recurrence
76.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+/- cascades by aligned pulsar outer-mag-sphere reignition
77.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
78.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
79.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
80.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
81.	Trofimenko et al.	1989	Ap&SS, 152, 105	WH		COS	Kerr-Newman white holes
82.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E- field accelerates electrons which then pair cascade
83.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
84.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
85.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS though Oort clouds, fast WD bursts only optical
86.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NSs
87.	Trofimenko	1989	Ap&SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRB
88.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
89.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
90.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
91.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
92.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
93.	Mitrofanov et al.	1990	Ap&SS, 165, 137	NS	COM	DISK	Interstellar comets pass through der 1 pulsar's magnetosphere
94.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
95.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
96.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes ν collisions to drive super-Ed wind
97.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
98.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
99.	Trofimenko et al.	1991	Ap&SS, 178, 217	WH		HALO	White hole supernova gave simul burst of g-waves from 1987A
100.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B- field undergoes resistive tearing, accelerates plasma
101.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
102.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav. rad. and collide
103.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
104.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolves into GRB sites
105.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapses to NS
106.	Hoyman et al.	1993	ApJ, 411, 541	NS		HALO	NS popul at MW halo boundary expected by hydro density jump
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRBs, cosmic rays
108.	Thompson et al.	1993	ApJ, 408, 194	NS		COS	Sudden NS convection with high B drives e- pairs, gammas.
109.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
110.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
* 111.	Eichler et al.	1992	Science, 257, 937	NS		HALO	High vel halo pulsars accrete after being kicked from disk
112.	Eichler et al.	1992	Science, 257, 937	WD	WD	HALO	WD merger yields GRB
113.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
114.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
115.	Blaes et al.	1992	ApJ, 399, 634	NS		GAL	Old NS accretes from mol cloud, R-T instab at crust
116.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
117.	Narayan et al.	1992,	ApJ, 395, L83	BH	NS	COS	BH-NS merger gives optically thick fireball
118.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
119.	Smith et al.	1993	ApJ, 410, 315	NS		DISK	e- beams accel by E-fields near NS with high B
120.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have νs collide to γs in clean fireball
121.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have νs collide to γs in clean fireball
122.	Fatuzzo et al.	1993	ApJ, 407, 680	NS		COS	Alfen waves accel particles which upscatter soft photons
123.	Bisnovatyi-Kogan	1993	A&A Sup, 97, 65	NS		GAL	Absorption by cloud of heavy elements around NS
124.	McBreen et al.	1993	A&A Sup, 97, 81	AGN		COS	Relativistic jets from cocooned AGN
125.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
126.	Woosley	1993	ApJ, 405, 273	BH		COS	Spinning Wolf-Rayet star collapses, failed SN, emits beamed fireball
127.	Melia et al.	1992	ApJ, 398, L85	NS		COS	Crustal adjustments by extragal radio pulsars
128.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM
129.	Kundt et al.	1993	Ap&SS, 200, 151	NS		GAL	Spasmodic NS accretion causes beamed cooling 'sparks'
130.	Meszaros et al.	1993	ApJ, 405, 278	NS	BH	COS	Compact binary coalesces, fireball hits external medium
131.	Cheng et al.	1993	MNRAS, 262, 1037	NS		GAL	NS glitch reignites magnetosphere of dead pulsar
132.	Melia et al.	1993	ApJ, 408, L9	NS		COS	NS structural readjustments explain both SGRs and GRBs
133.	Piran et al.	1993	ApJ, 403, L67	NS		GAL	Galactic fireball requires rel ejecta, low T, possible but unlikely
134.	Fabian et al.	1993	MNRAS, 263, 49	NS		LMC	NS accretes after ejected from Mag Cloud by companion SN
135.	Fatuzzo et al.	1993	ApJ, 414, L89	NS		COS	Sheared Alfen waves in NS magsphere dissipate focused power

$E=10^{54}$ erg



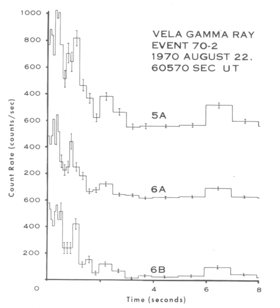
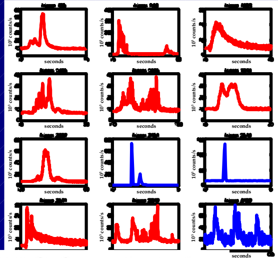
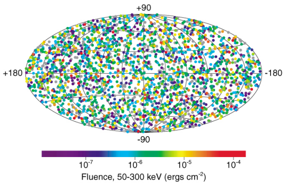
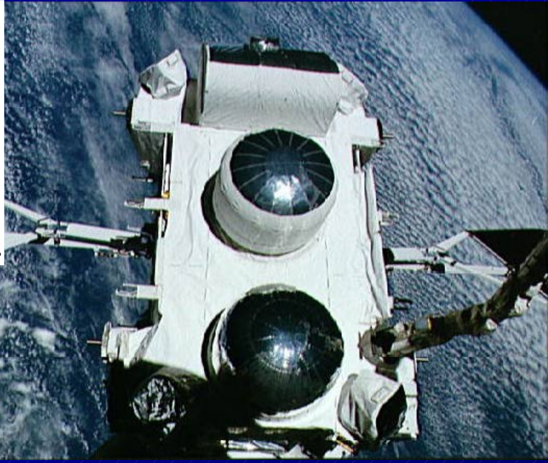


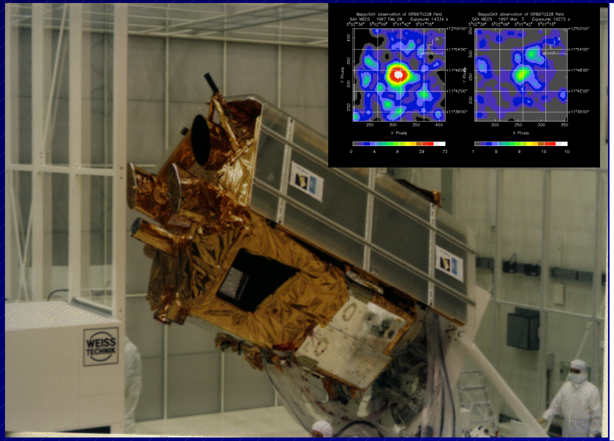
Fig. 5. Event 70-2, on 1970 August 22, beginning 60571 s UT.

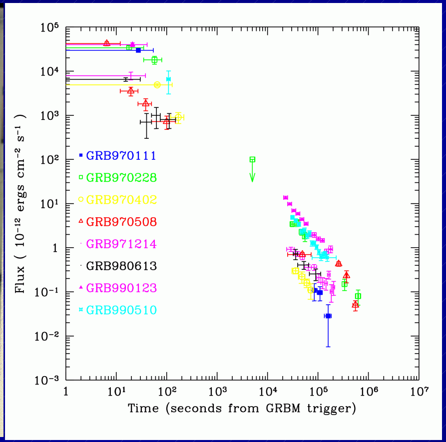


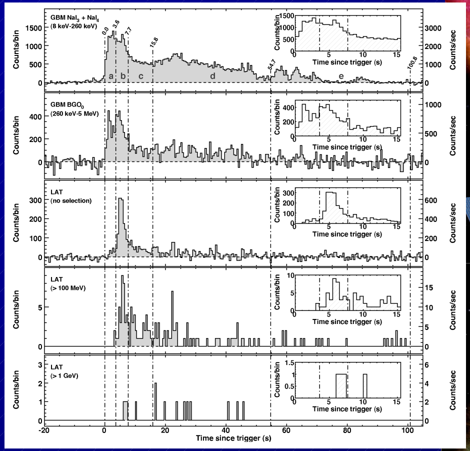
2704 BATSE Gamma-Ray Bursts

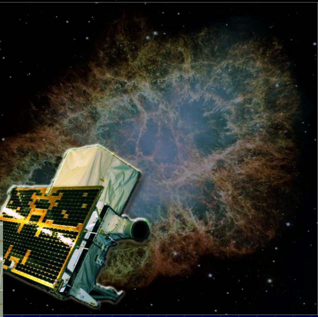


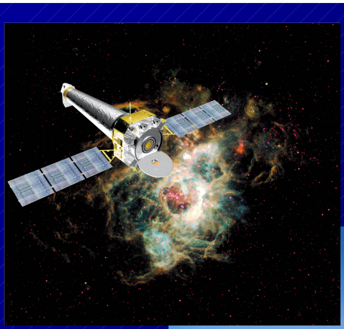


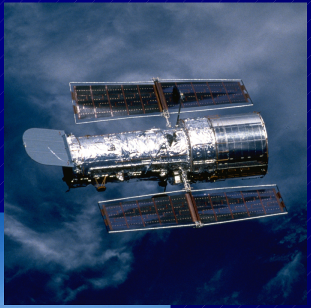


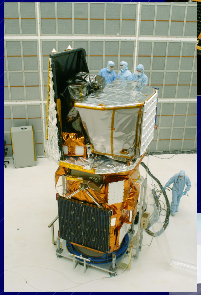






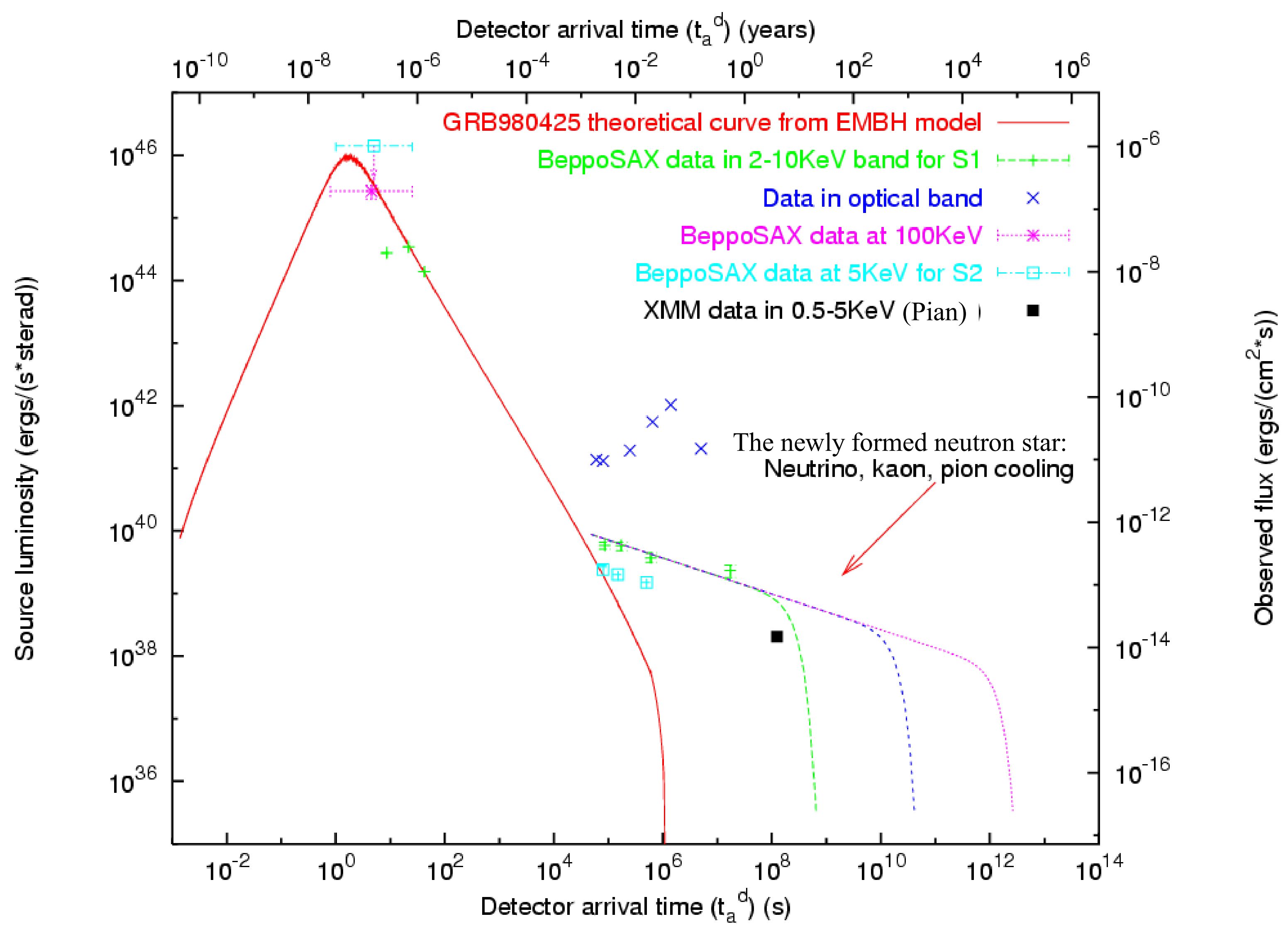






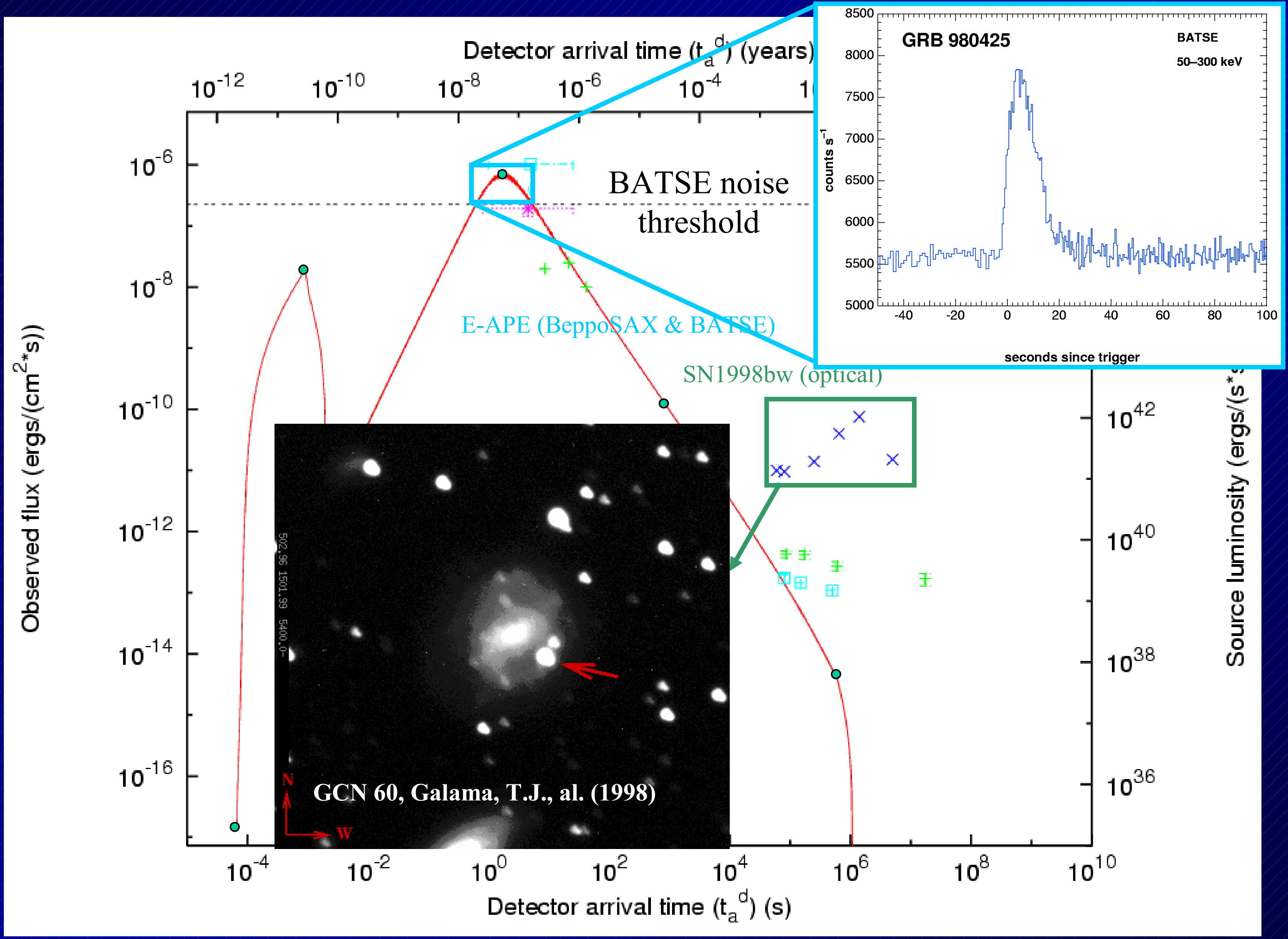
GRB 980425 - SN1998bw:

A newly formed neutron star



Ruffini, Bernardini, Bianco, Chardonnet, Fraschetti, Xue, *Adv. Sp. Res.*, 34, 2715 (2004)

GRB 980425 - SN1998bw



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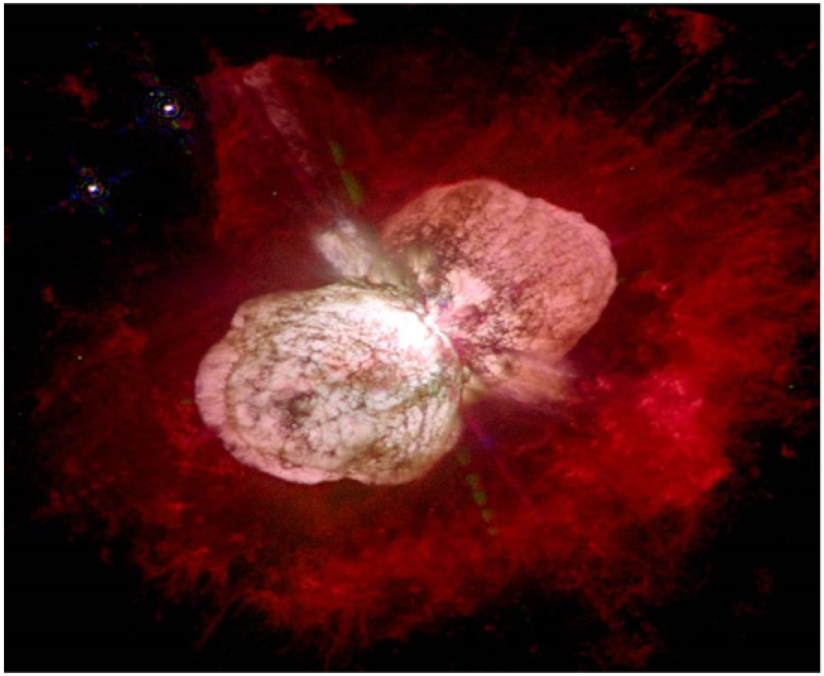
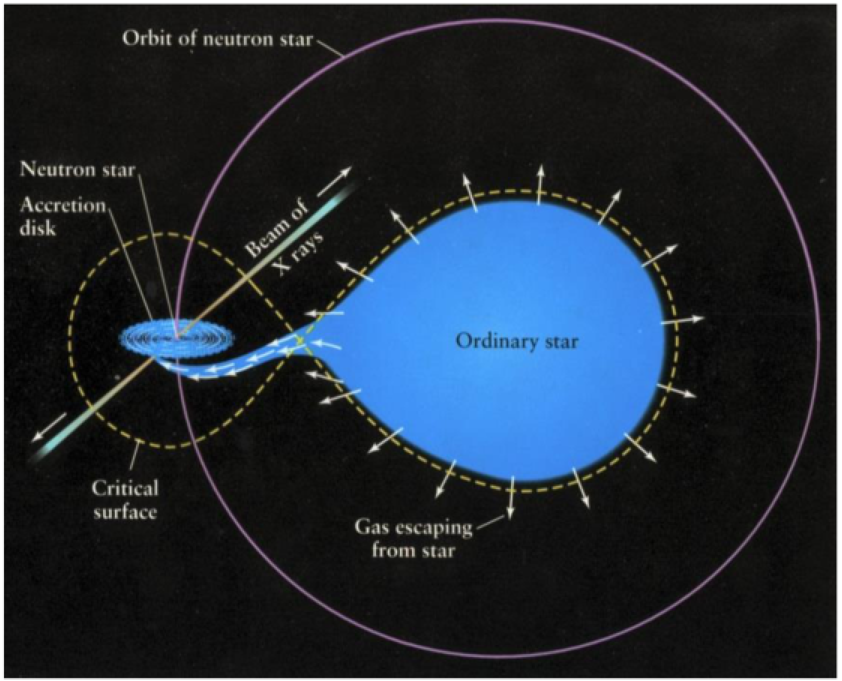
From the progenitor to the IGC sequence



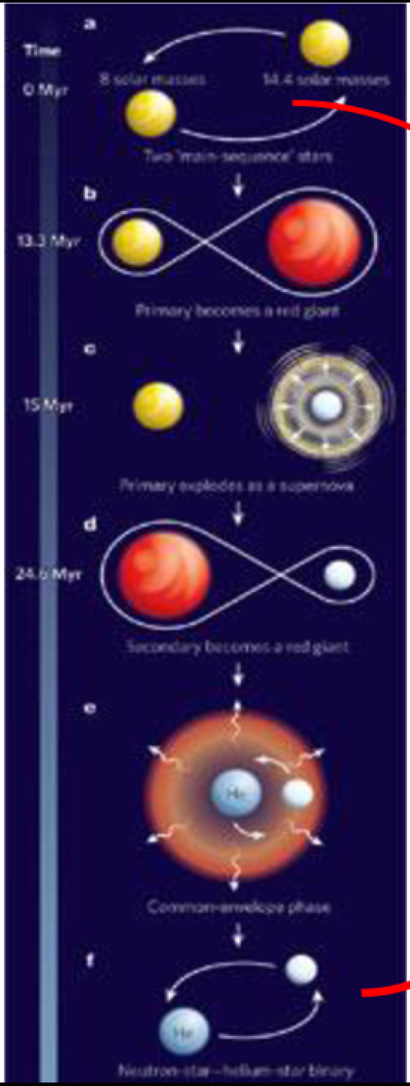
Massive Binary
(Eta Carinae, Porb=5.5 yr)



Massive Star-Neutron Star X Ray Binary
(Centaurus X-3, Porb=2.1 days)

The IGC Binary Progenitor

Binary sequence

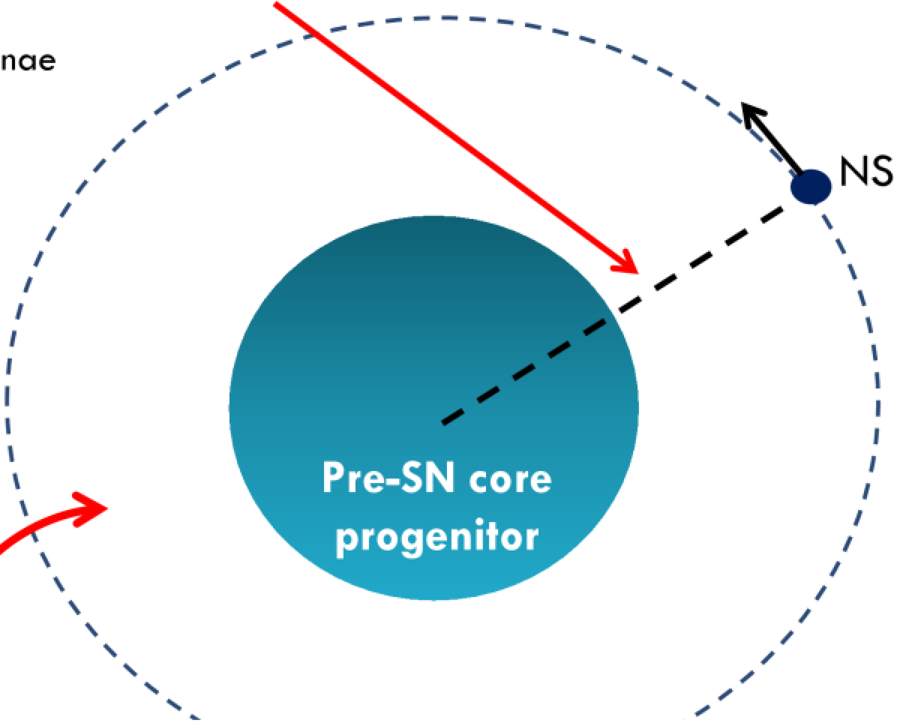


Nomoto & Hashimoto (1988)
Nomoto et al. (1994)
Iwamoto et al. (1994)
and others…

Eta Carinae

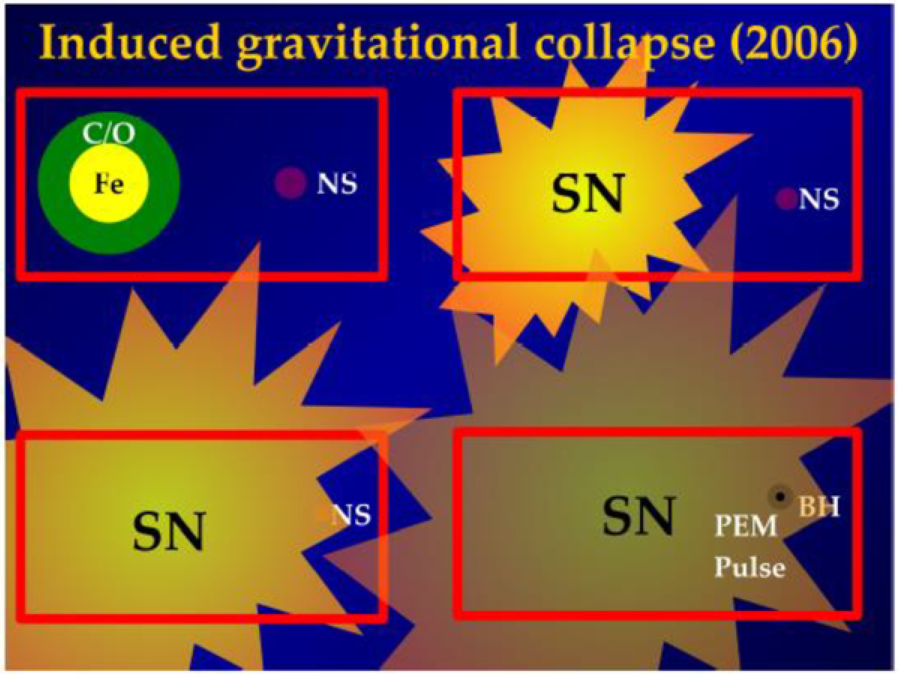
Cen X-3

$$v_{\rm orb} = \sqrt{\frac{G(M_{\rm SN-prog} + M_{\rm NS})}{a}} = 1.15 \times 10^8 \left(\frac{M_{\rm SN-prog} + M_{\rm NS}}{M_\odot}\right)^{1/2} \ {\rm cm\,s^{-1}}$$

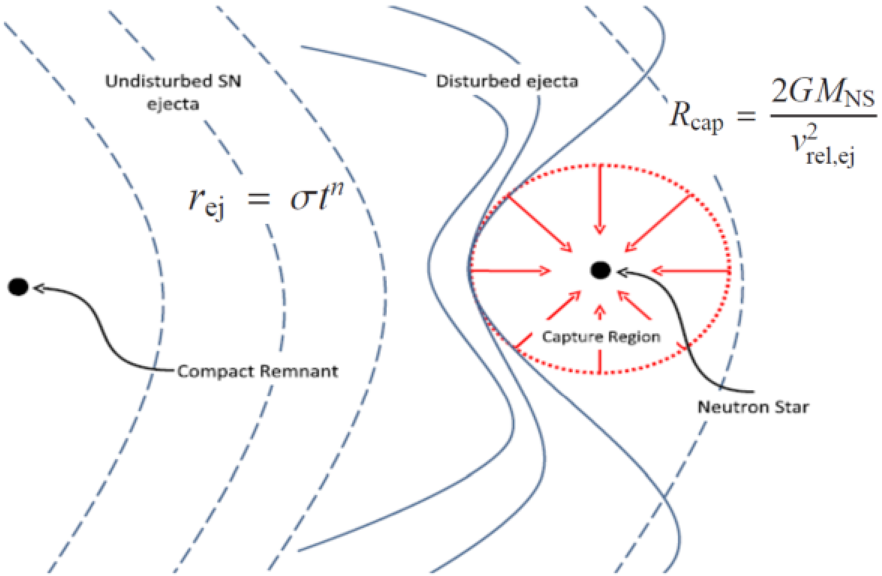


$$P = \sqrt{\frac{4\pi^2 a^3}{G(M_{\rm SN-prog} + M_{\rm NS})}} = 545 \left(\frac{M_{\rm SN-prog} + M_{\rm NS}}{M_\odot}\right)^{-1/2} \ {\rm s}$$

Ruffini et al. at MG11, Berlin (2006)



Rueda & Ruffini, ApJ Lett. 758, L7 (2012)
Izzo, Rueda, Ruffini, A&A Lett. 548, L5 (2012)



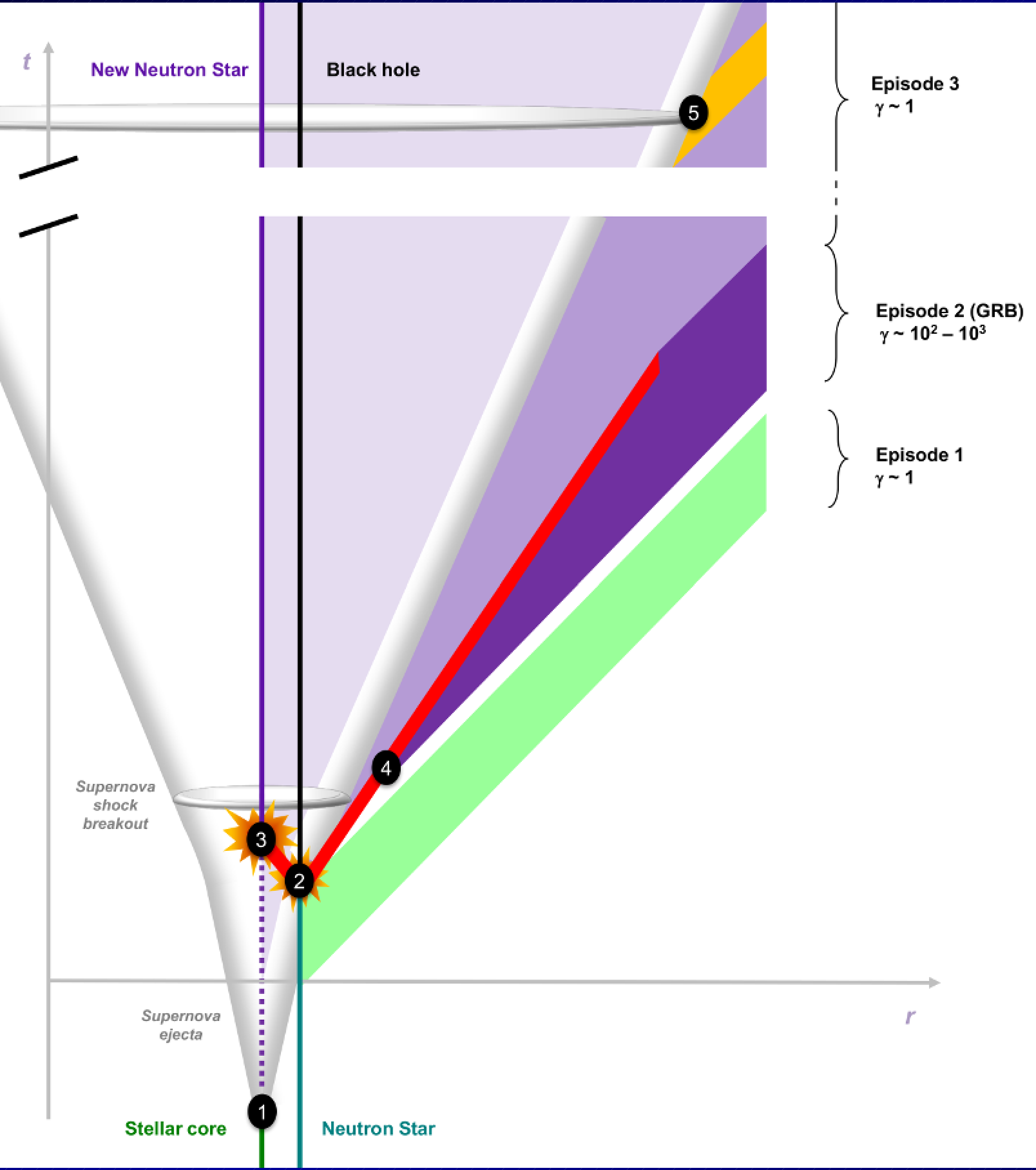
Accreted Mass onto the NS

$$v_{\rm rel,ej} = \sqrt{v^2_{\rm orb} + v^2_{\rm ej}}, \quad v_{\rm orb} = \sqrt{\frac{G(M_{\rm SN-prog} + M_{\rm NS})}{a}}$$

$$\Delta M(t) = \int \dot{M} dt = \pi (2GM_{\rm NS})^2 \frac{3M_{\rm ej}}{4\pi n^3 \sigma^6} \mathcal{F} + \text{constant}$$

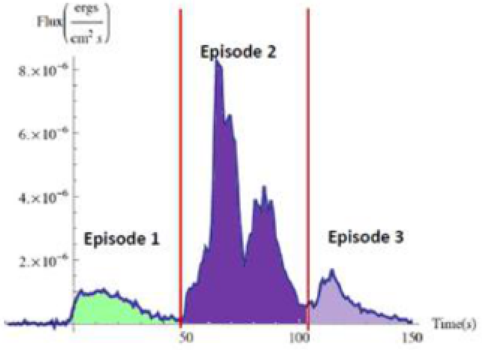
$$\mathcal{F} = \frac{t^{-3(n+1)} \left(-4n(2n-1) t^{4n} \sqrt{kt^{2-2n} + 1}\, {}_2F_1\left(\frac{1}{2}, \frac{1}{n-1}; \frac{n}{n-1}; -kt^{2-2n}\right) - k^2 \left(n^2 - 1\right) t^4 + 2k(n-1)(2n-1) t^{2n+2} + 4n(2n-1) t^{4n} \right)}{k^3 (n-1)(n+1)(3n-1) \sqrt{k + t^{2n-2}}}$$

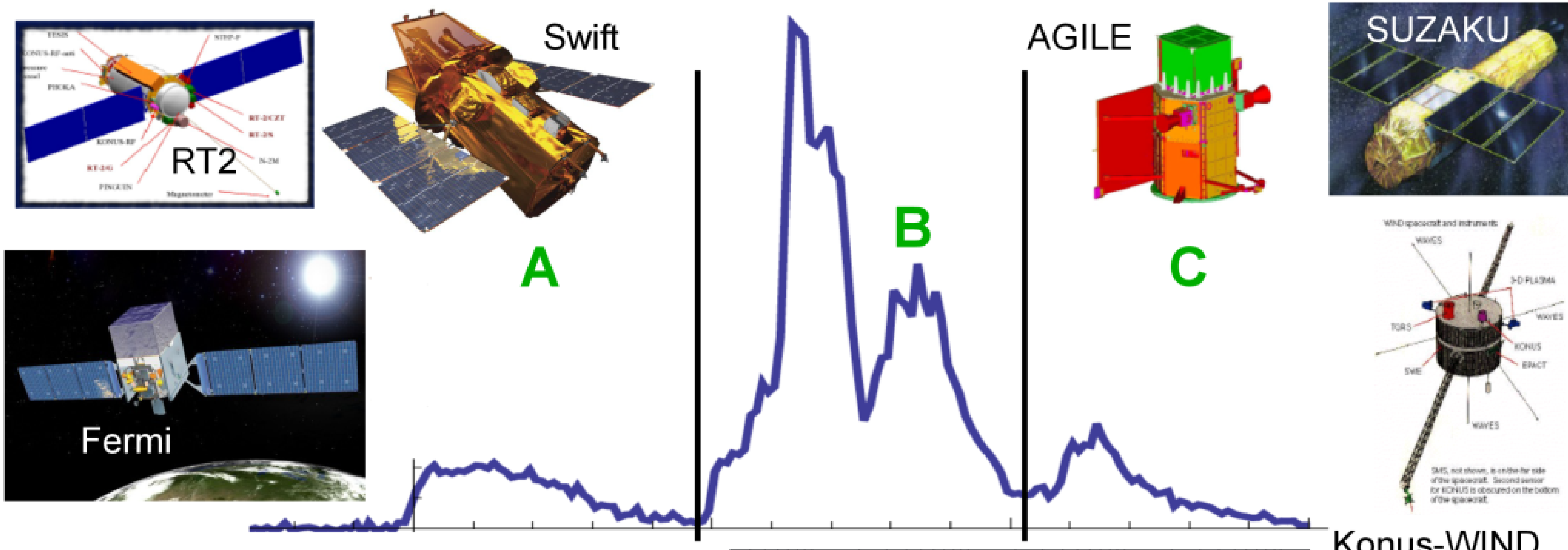
The
Induced Gravitational Collapse paradigm
in a nutshell



Start with an evolved stellar core and a companion neutron star.

- ❶ **The stellar core goes supernova and leaves a neutron star remnant.**
- ❷ **Accretion of the supernova ejecta on the companion neutron star induces black hole formation and emission of the fireshell.**
- ❸ **The optically thick fireshell interacts with the supernova and the neutron star remnant.**
- ❹ **The ultrarelativistically expanding fireshell reaches transparency and becomes optically thin.**
- ❺ **After t ~10 (1+z) days in observer frame, the supernova peaks in the optical due to 56Ni decay .**

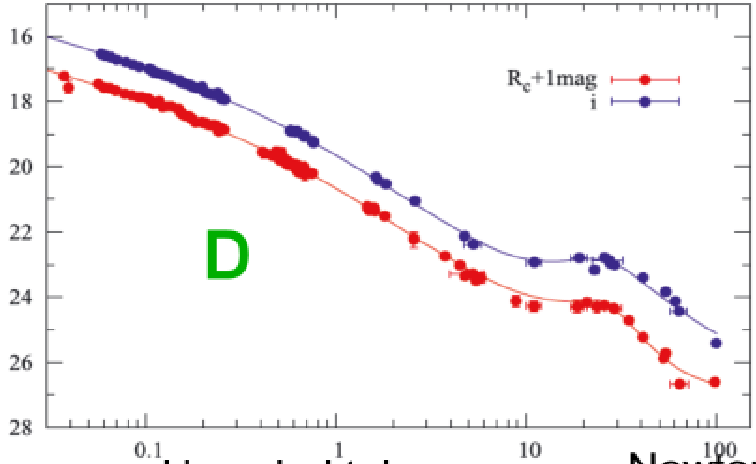




GRB 090618

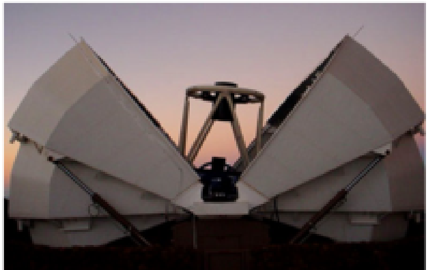
Eiso=2.8x10^{53} erg

Z=0.54



Ruffini et al. *PoS(Texas2010)*, 101 (2011)
Izzo et al., *A&A*, 543, A10 (2012)

Faulkes North

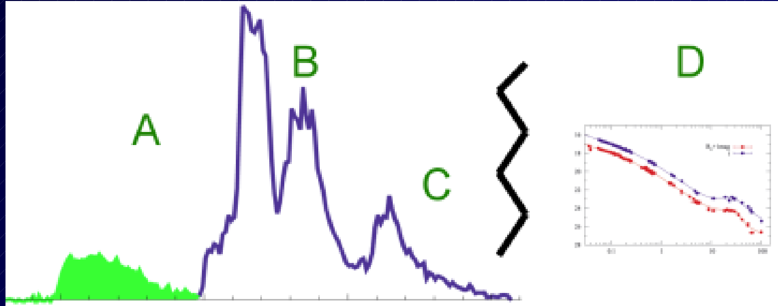


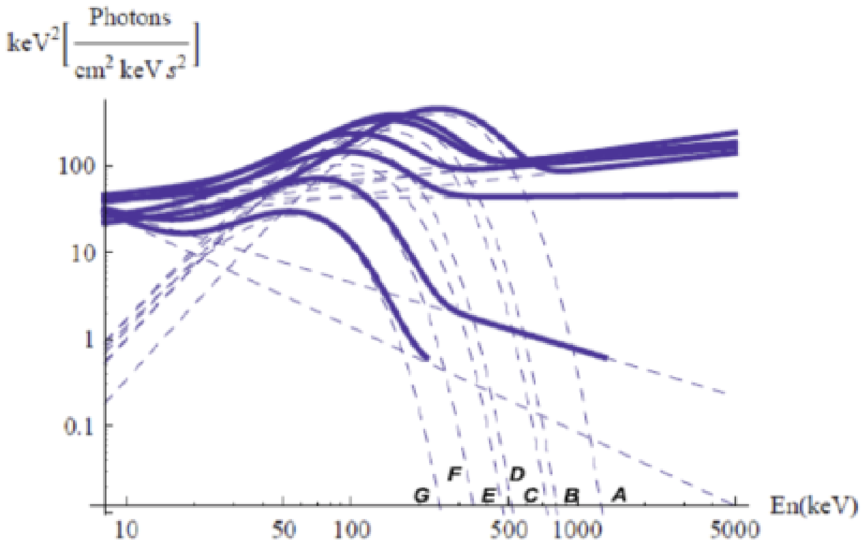
Gemini North

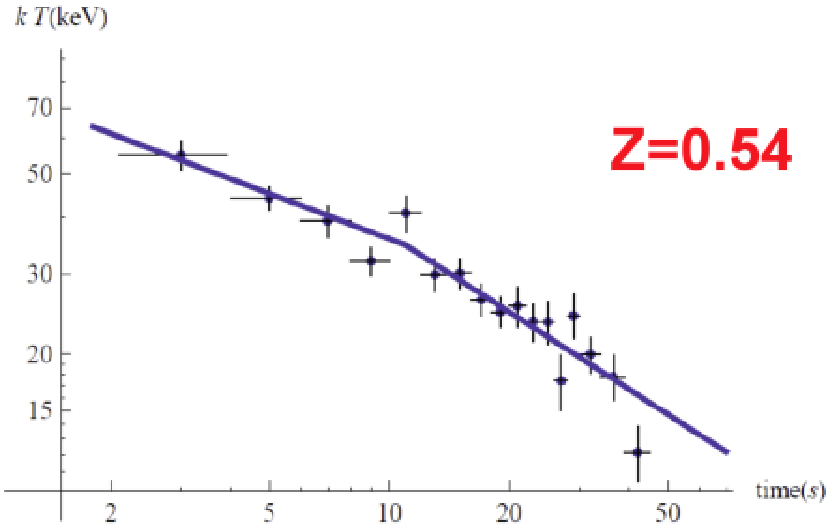
Herschel telescope

Newton telescope

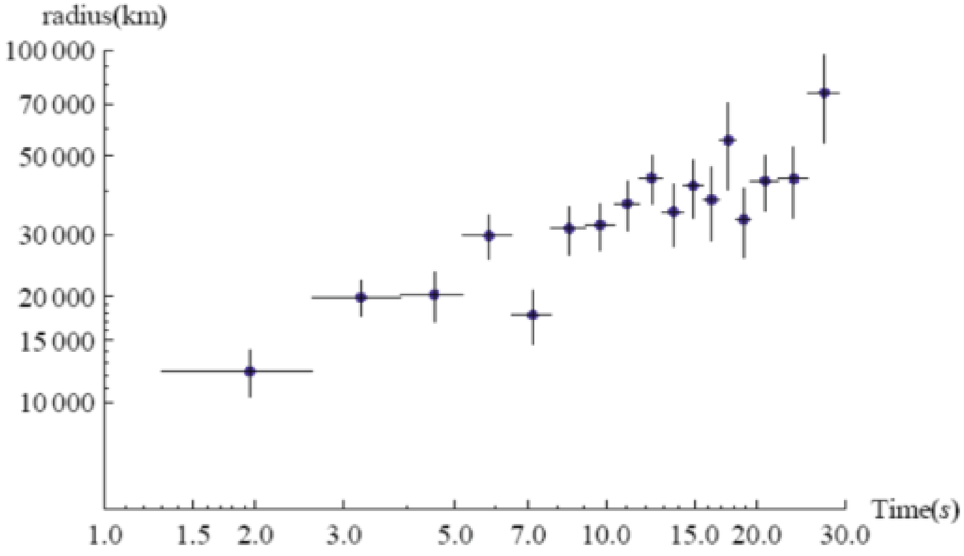
The first emission episode
Eiso = 3.4×10^{52} ergs

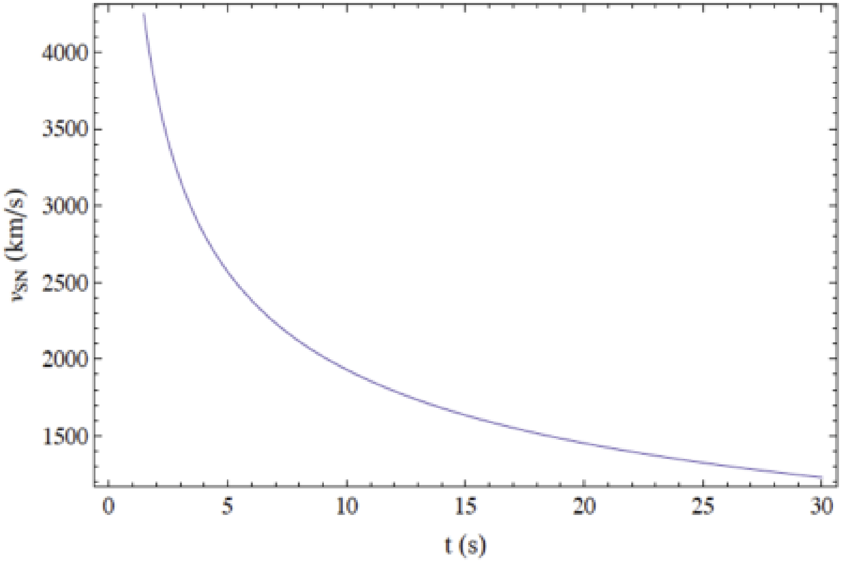


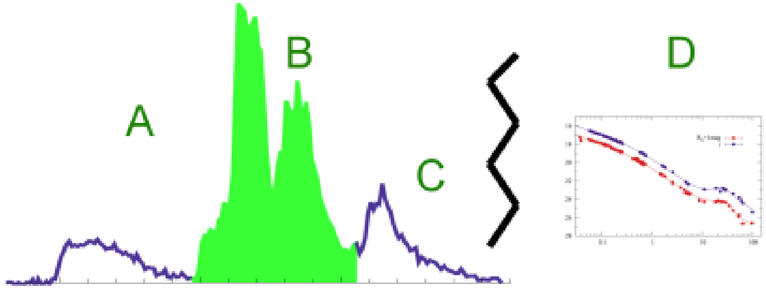




Z=0.54

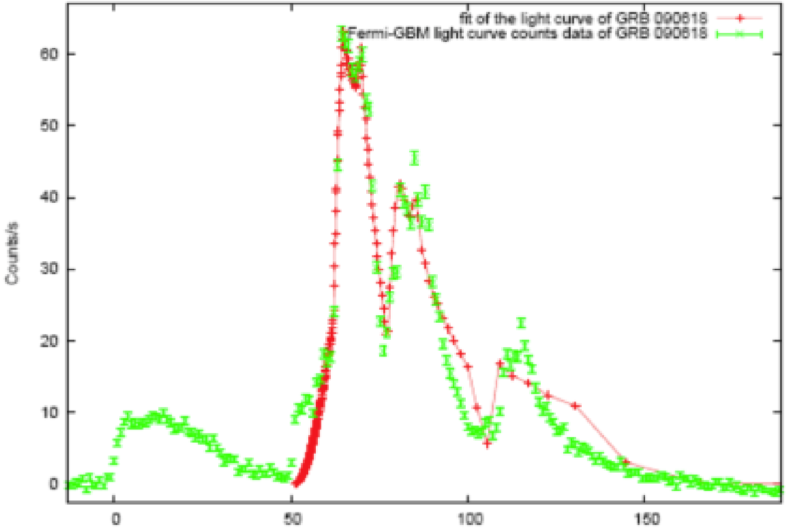


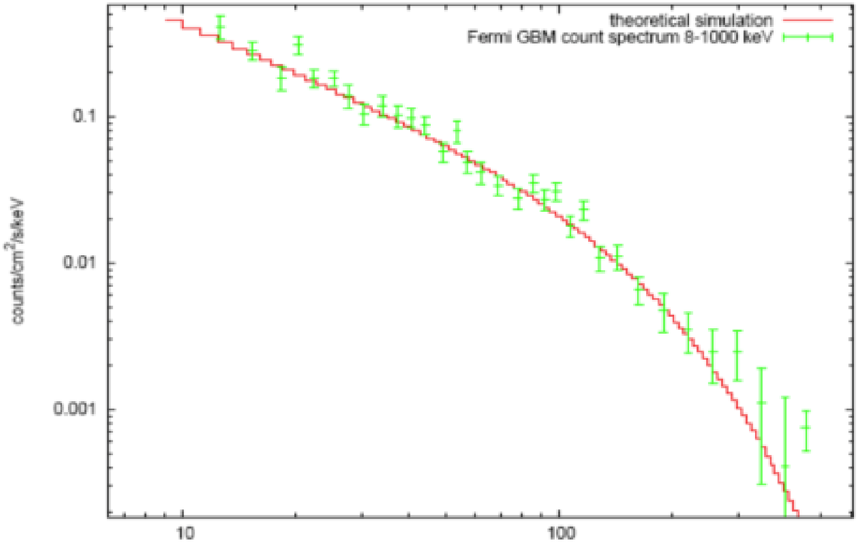


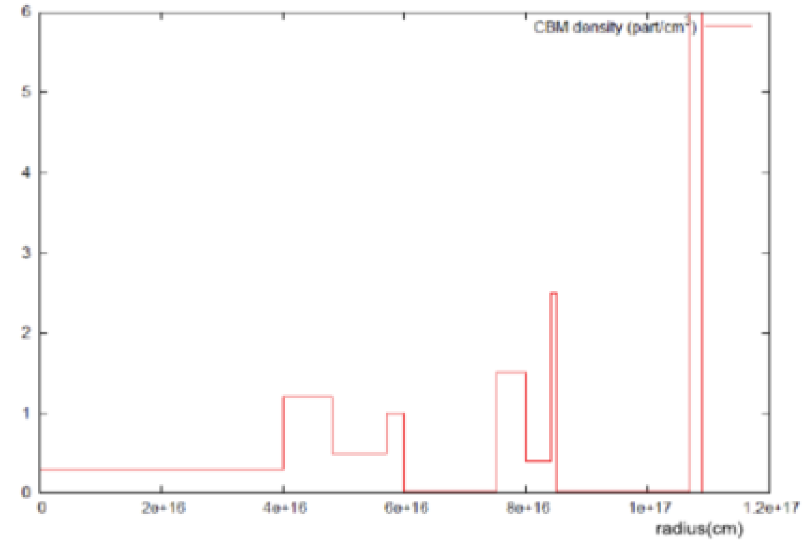


The second emission episode : the GRB

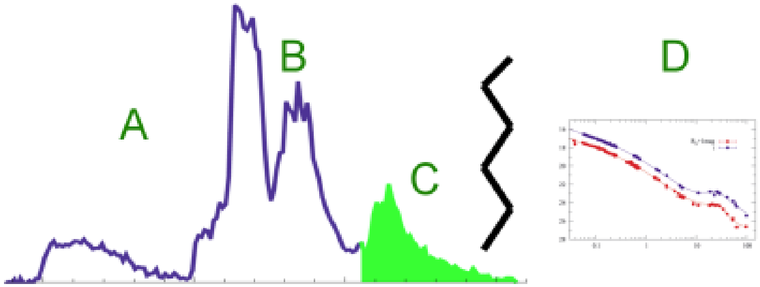
Eiso = 2.49 x 10^{53} ergs



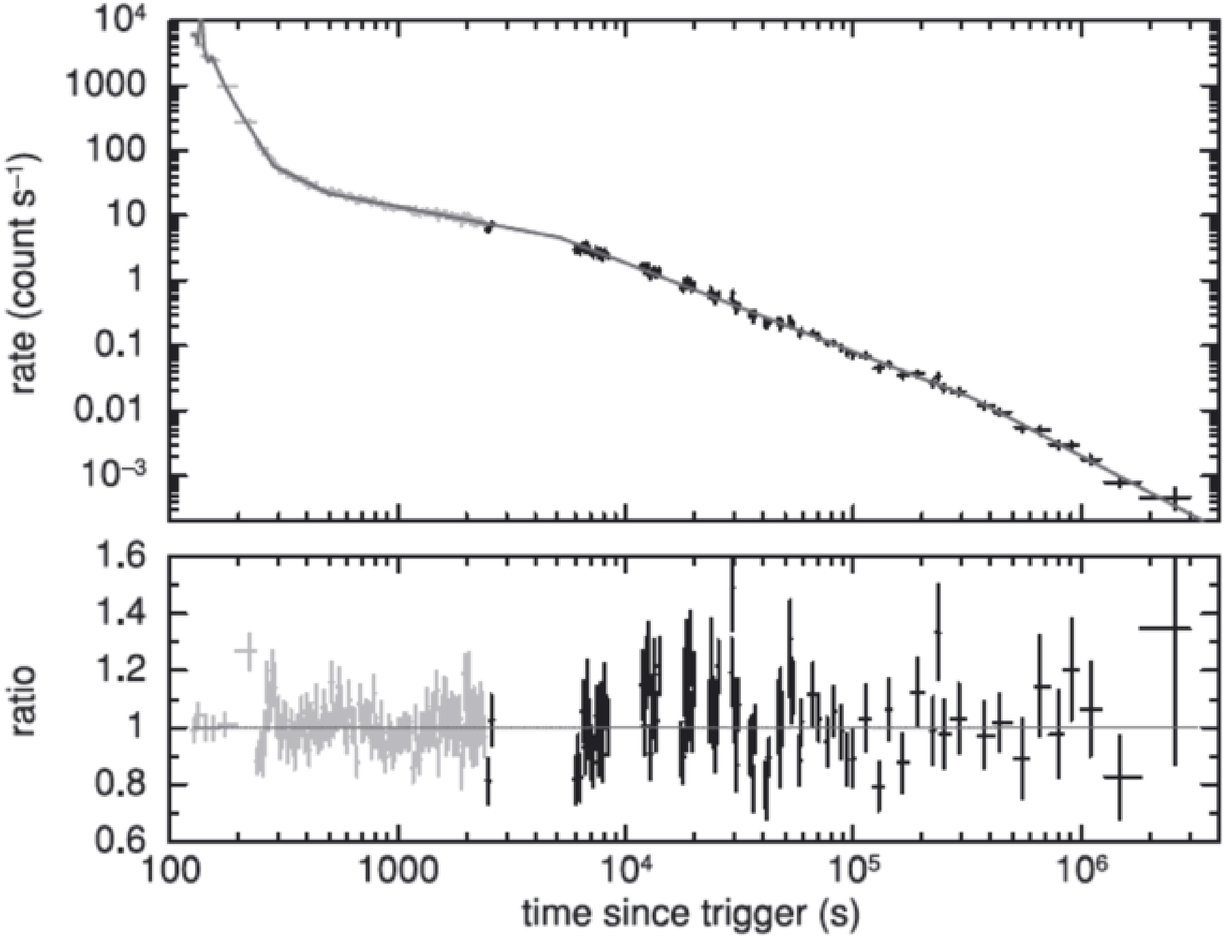




Parameter	Value
$E_{tot}^{e^+e^-}$	$2.49 \pm 0.02 \times 10^{53}$ ergs
B	$1.98 \pm 0.15 \times 10^{-3}$
Γ_0	495 ± 40
kT_{th}	29.22 ± 2.21 keV
$E_{P-GRB,th}$	$4.33 \pm 0.28 \times 10^{51}$ ergs
$< n >$	$0.6\ part/cm^3$
$< \delta n/n >$	$2\ part/cm^3$

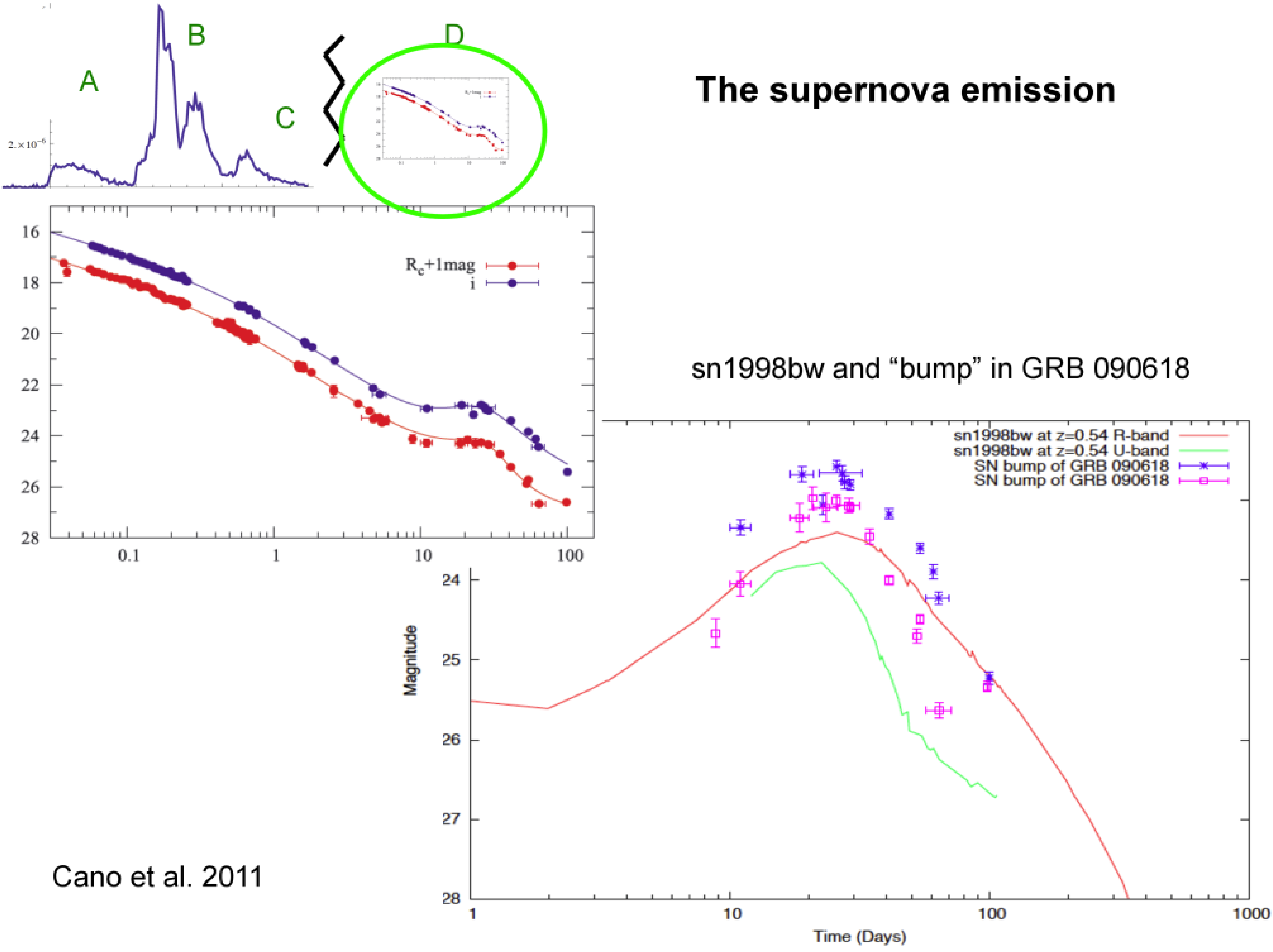


The X-ray afterglow



Page et al. 2011

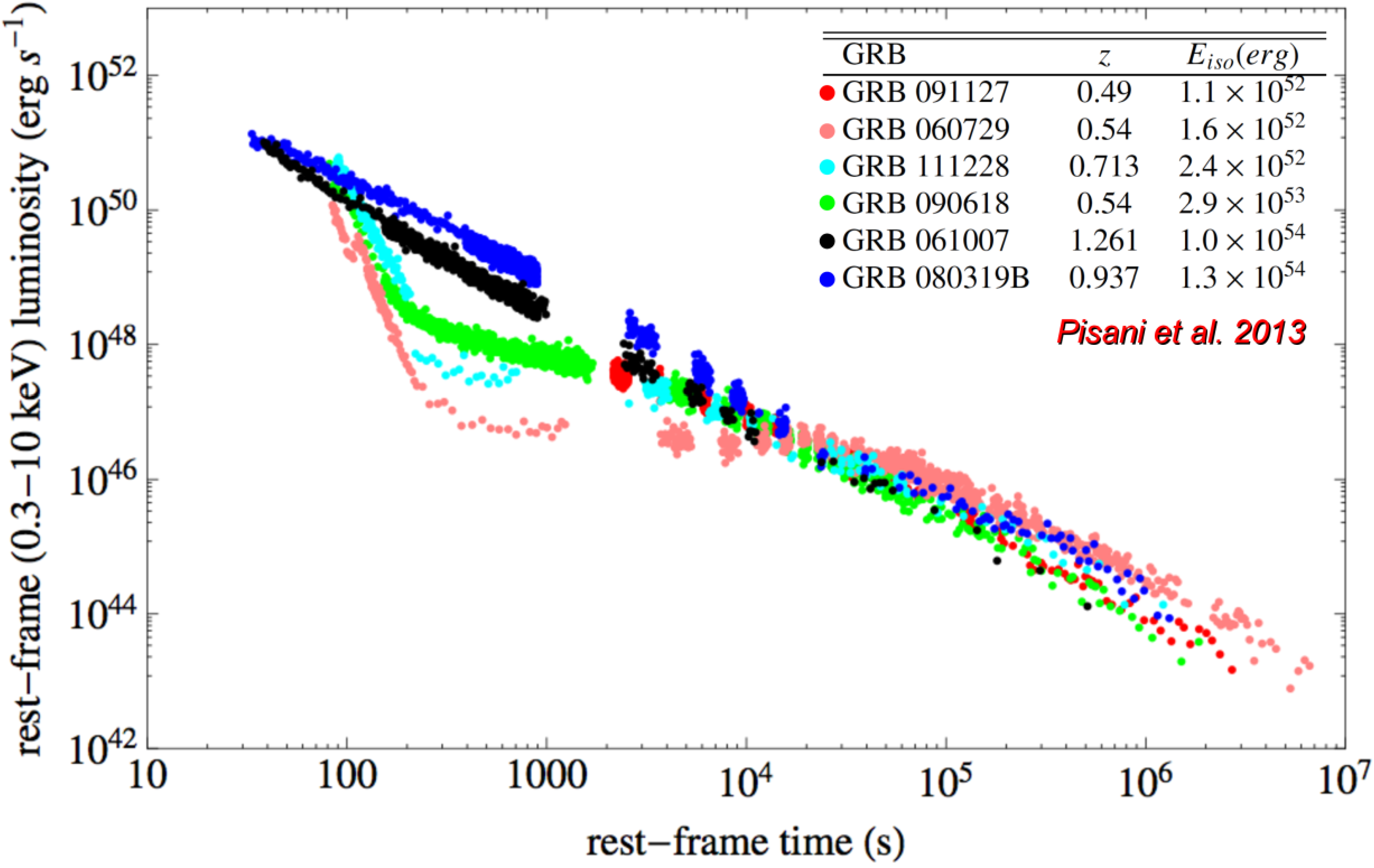
The supernova emission



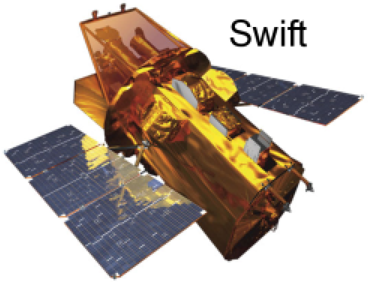
sn1998bw and “bump” in GRB 090618

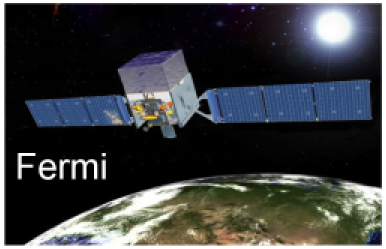
Cano et al. 2011

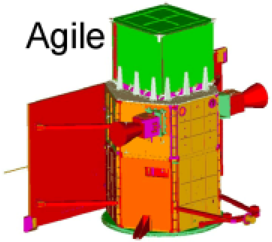
The universal behavior of late time X-ray emission in IGC GRB-SN events

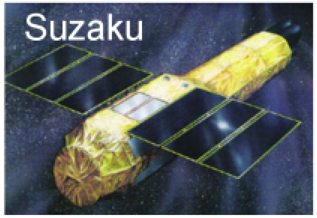


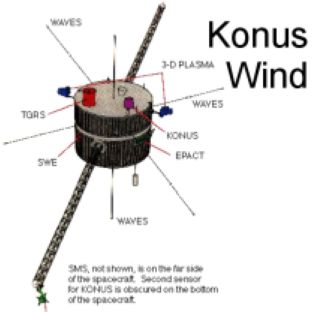
Pisani et al. 2013

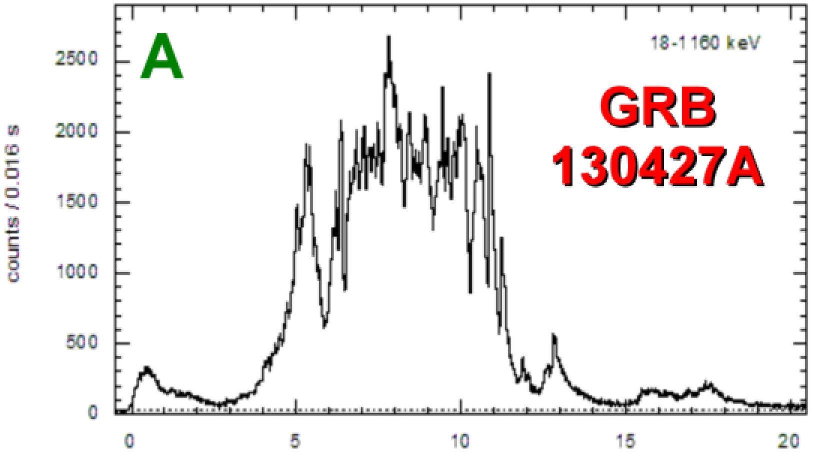


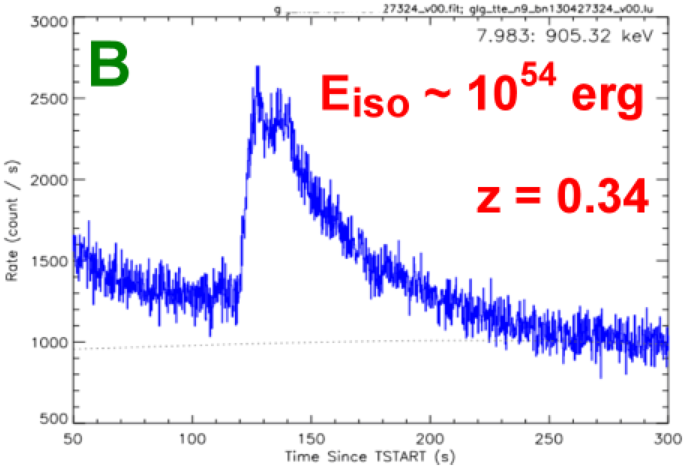


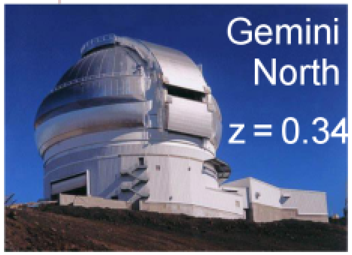


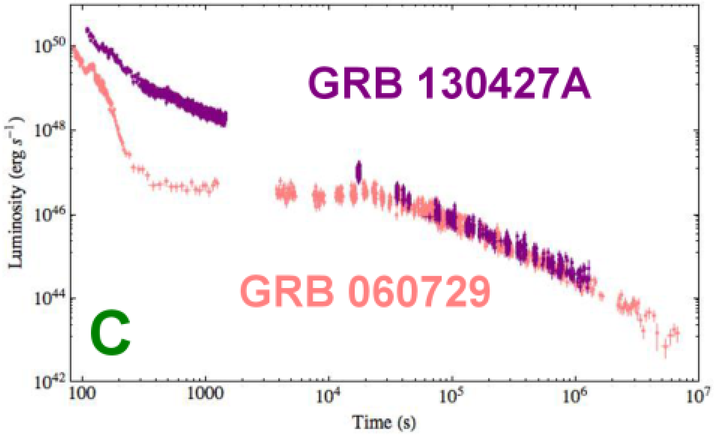


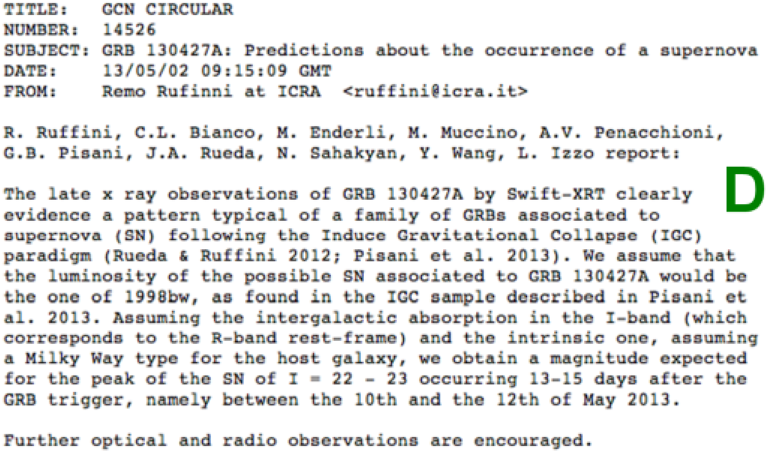












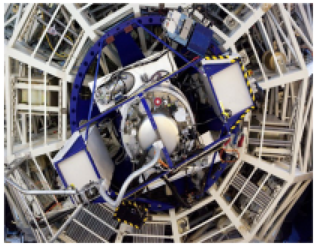
```
TITLE:   GCN CIRCULAR
NUMBER:  14526
SUBJECT: GRB 130427A: Predictions about the occurrence of a supernova
DATE:    13/05/02 09:15:09 GMT
FROM:    Remo Ruffini at ICRA  <ruffini@icra.it>
```

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:

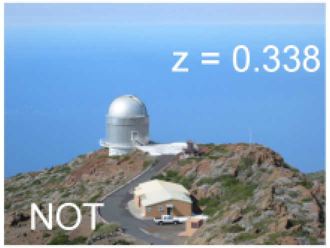
The late x ray observations of GRB 130427A by Swift-XRT clearly evidence a pattern typical of a family of GRBs associated to supernova (SN) following the Induce Gravitational Collapse (IGC) paradigm (Rueda & Ruffini 2012; Pisani et al. 2013). We assume that the luminosity of the possible SN associated to GRB 130427A would be the one of 1998bw, as found in the IGC sample described in Pisani et al. 2013. 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.

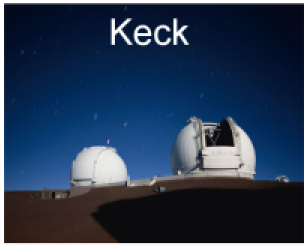
Further optical and radio observations are encouraged.

VLT/X-shooter

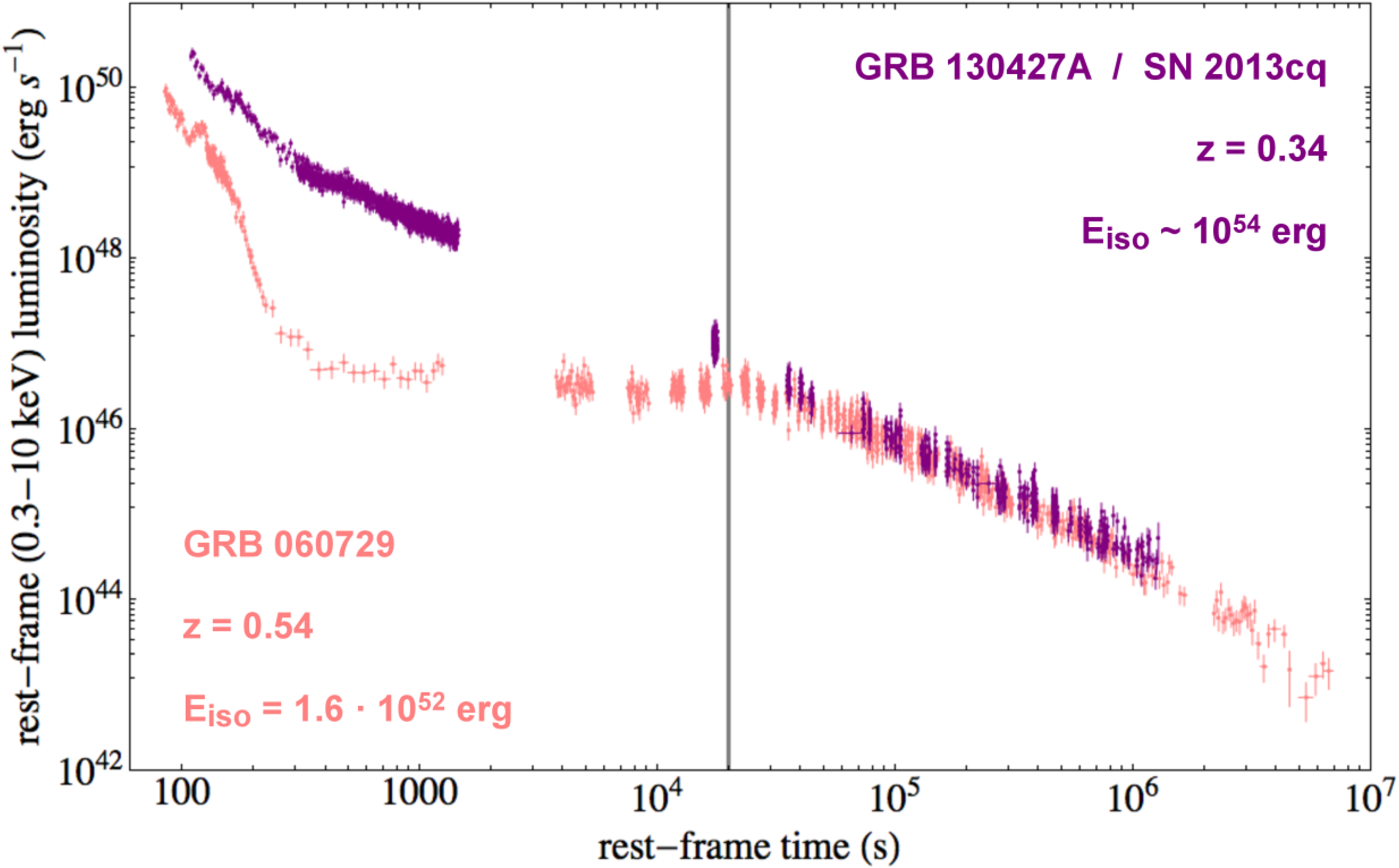


z = 0.3399



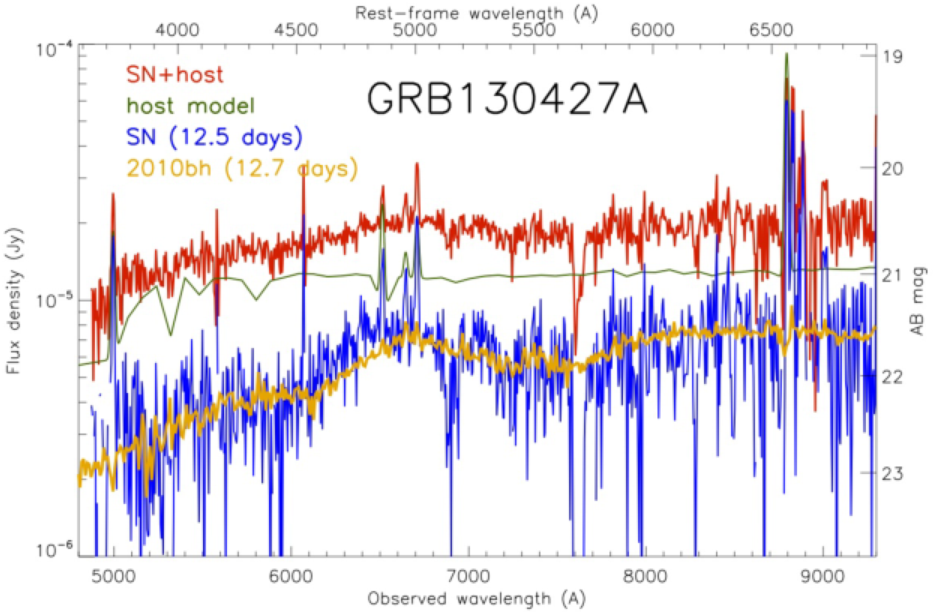


GRB 130427A: late X-ray luminosity overlap with GRB 060729

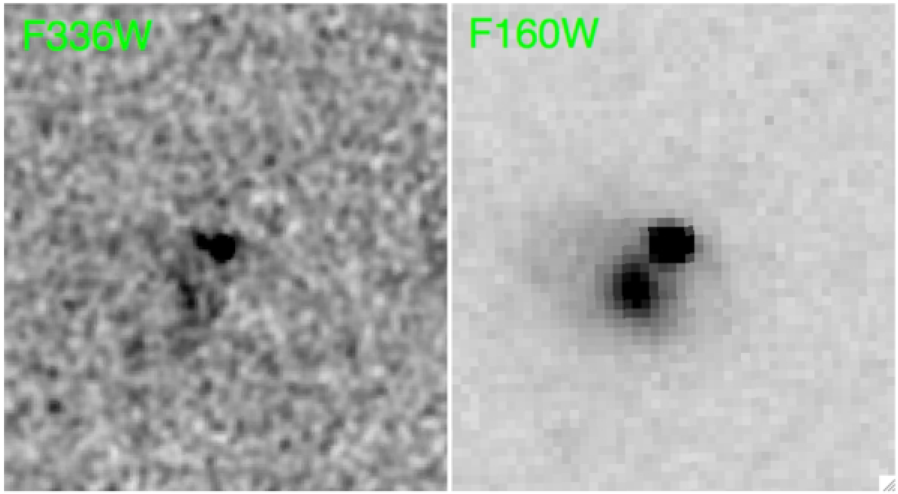


Ruffini et al. (in preparation)

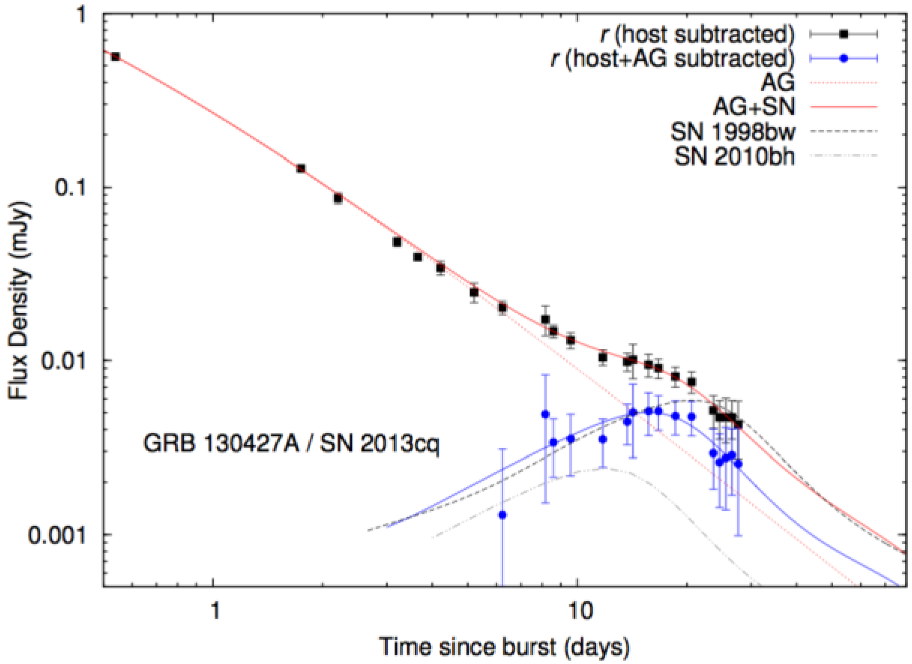
GRB 130427A / SN 2013cq



de Ugarte Postigo et al. 2013
(Gran Telescopio Canarias)



Levan et al. 2013 (Hubble Space Telescope)

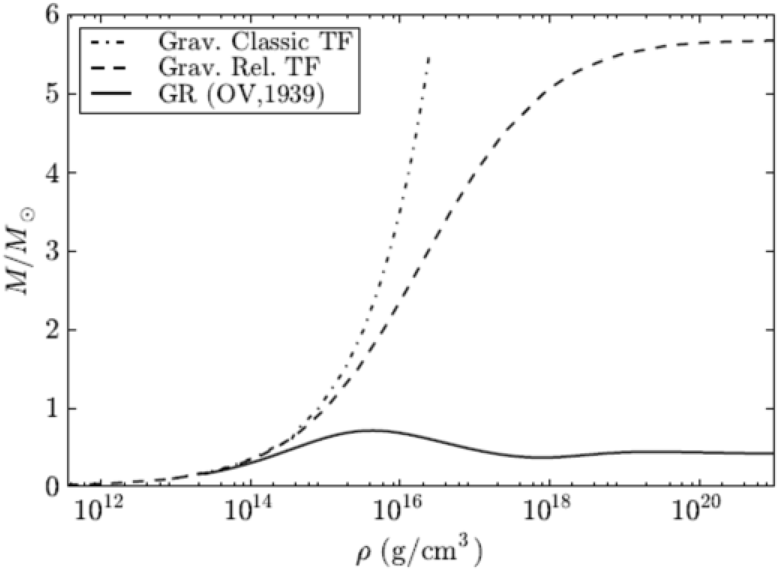


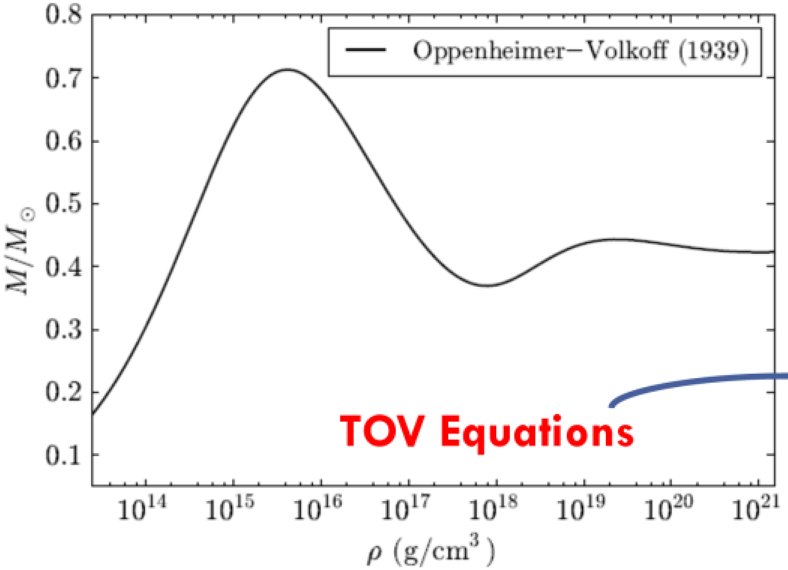
Xu et al. 2013

“The Thomas-Fermi model works much better than it should” (E. Wigner to R. Ruffini, 1972)

The Oppenheimer-Volkoff Neutron Star

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)\,, \qquad \frac{dP(r)}{dr} = -\frac{G[\rho(r) + P(r)/c^2][4\pi r^3 P(r)/c^2 + M(r)]}{r^2[1 - 2GM(r)/(c^2 r)]}$$





TOV Equations

“The Thomas-Fermi model works much better than it should” (E. Wigner to R. Ruffini, 1972)

Generalizing to the Strongly Interacting Case

(Rueda, Ruffini, Xue, Nucl. Phys. A 872, 286, 2011)

Einstein-Maxwell-Thomas-Fermi with sigma-omega-rho Model

$$
\begin{aligned}
&\mathrm{e}^{-\lambda(r)}\left(\frac{1}{r^2}+\frac{1}{r}\frac{d\nu}{dr}\right)-\frac{1}{r^2}=-8\pi G T_1^1,\\
&\frac{d^2V}{dr^2}+\frac{dV}{dr}\left[\frac{2}{r}-\frac{1}{2}\left(\frac{d\nu}{dr}+\frac{d\lambda}{dr}\right)\right]=-e\,\mathrm{e}^{\nu/2}\mathrm{e}^{\lambda}(n_p-n_e),\\
&\frac{d^2\sigma}{dr^2}+\frac{d\sigma}{dr}\left[\frac{2}{r}+\frac{1}{2}\left(\frac{d\nu}{dr}-\frac{d\lambda}{dr}\right)\right]=\mathrm{e}^{\lambda}\left[\partial_\sigma U(\sigma)+g_s n_s\right],\\
&\frac{d^2\omega}{dr^2}+\frac{d\omega}{dr}\left[\frac{2}{r}-\frac{1}{2}\left(\frac{d\nu}{dr}+\frac{d\lambda}{dr}\right)\right]=-\mathrm{e}^{\lambda}\left[g_\omega J_0^\omega-m_\omega^2\omega\right],\\
&\frac{d^2\rho}{dr^2}+\frac{d\rho}{dr}\left[\frac{2}{r}-\frac{1}{2}\left(\frac{d\nu}{dr}+\frac{d\lambda}{dr}\right)\right]=-\mathrm{e}^{\lambda}\left[g_\rho J_0^\rho-m_\rho^2\rho\right],\\
&E_e=\mathrm{e}^{\nu/2}\mu_e-eV=\text{constant},\\
&E_p=\mathrm{e}^{\nu/2}\mu_p+\mathcal{V}_p=\text{constant},\\
&E_n=\mathrm{e}^{\nu/2}\mu_n+\mathcal{V}_n=\text{constant},
\end{aligned}
$$

Energy-Momentum Tensor

$$
\begin{aligned}
T_\gamma^{\mu\nu}&=F^\mu{}_\alpha F^{\alpha\nu}+\frac{1}{4}g^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta},\\
T_\sigma^{\mu\nu}&=\nabla^\mu\sigma\nabla^\nu\sigma-g^{\mu\nu}\left[\frac{1}{2}\nabla_\sigma\sigma\nabla^\sigma\sigma-U(\sigma)\right],\\
T_\omega^{\mu\nu}&=\Omega^\mu{}_\alpha\Omega^{\alpha\nu}+\frac{1}{4}g^{\mu\nu}\Omega_{\alpha\beta}\Omega^{\alpha\beta}+m_\omega^2\left(\omega^\mu\omega^\nu-\frac{1}{2}g^{\mu\nu}\omega_\alpha\omega^\alpha\right),\\
T_\rho^{\mu\nu}&=\mathcal{R}^\mu{}_\alpha\mathcal{R}^{\alpha\nu}+\frac{1}{4}g^{\mu\nu}\mathcal{R}_{\alpha\beta}\mathcal{R}^{\alpha\beta}+m_\rho^2\left(\mathcal{R}^\mu\mathcal{R}^\nu-\frac{1}{2}g^{\mu\nu}\mathcal{R}_\alpha\omega^\alpha\right)
\end{aligned}
$$

Nucleon Potentials $\begin{cases}\mathcal{V}_p=g_\omega\omega+g_\rho\rho+eV,\\ \mathcal{V}_n=g_\omega\omega-g_\rho\rho.\end{cases}$

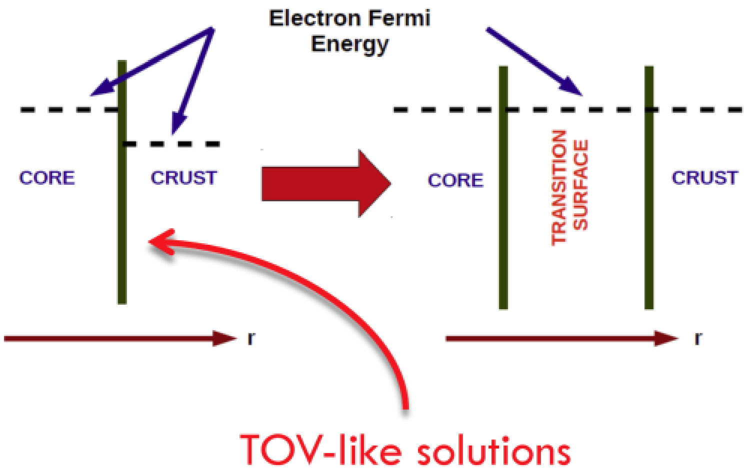
Constancy of Klein Potentials (Generalized, Non-local Particle Chemical Potentials)

“The Thomas-Fermi model works much better than it should” (E. Wigner to R. Ruffini, 1972)

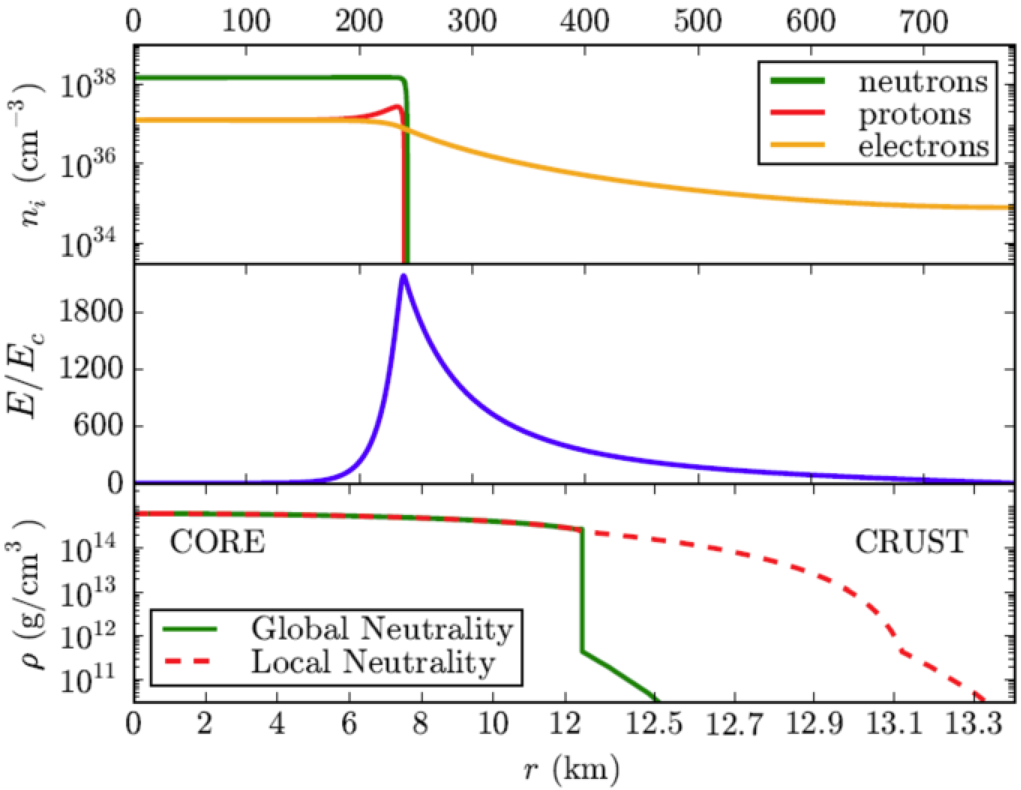
Neutron Star Equilibrium Configurations

(Belvedere, Pugliese, *Rueda, Ruffini, Xue, Nucl. Phys. A 883, 1, 2012)*

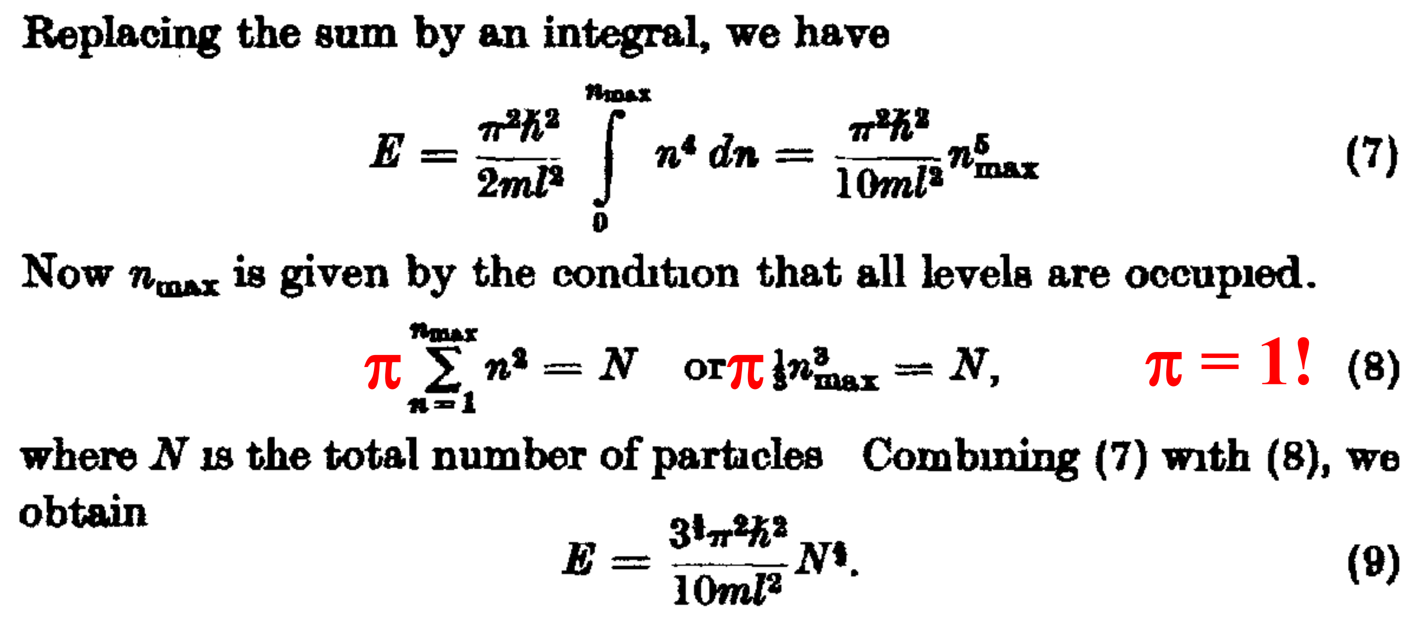
Boundary Conditions



See Belvedere´s talk for details



$M_{crit} = (5\pi)^{0.5} 15 m_p{}^3/(16m^2) \sim 6.89\ M_\odot$



Replacing the sum by an integral, we have

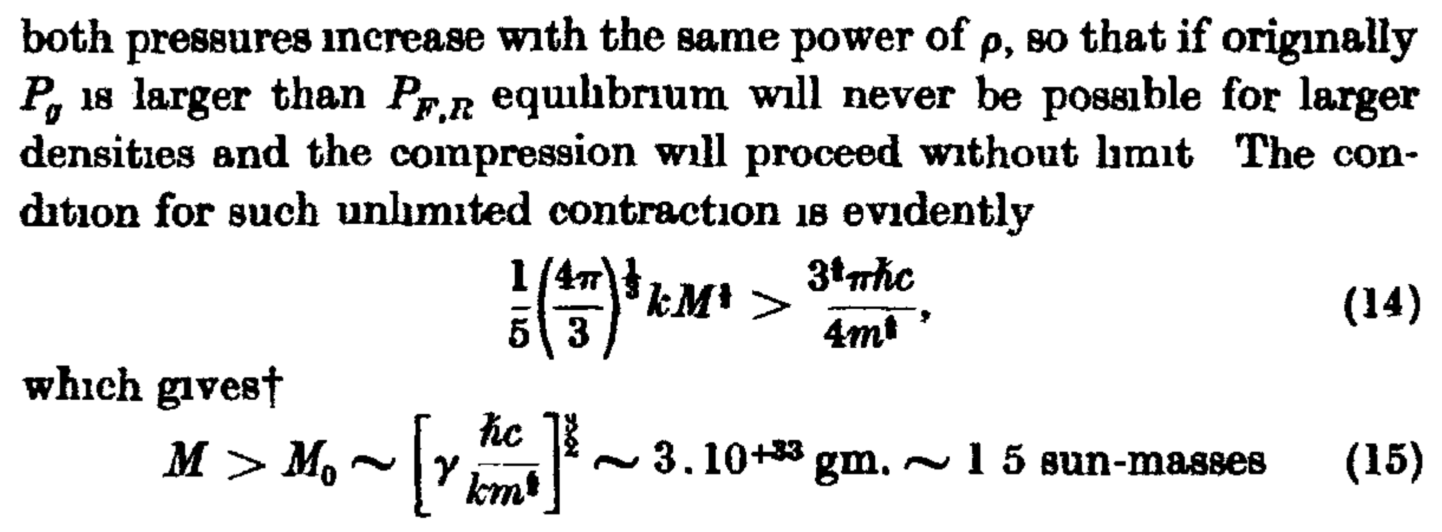
$$E = \frac{\pi^2\hbar^2}{2ml^2}\int_0^{n_{\max}} n^4\,dn = \frac{\pi^2\hbar^2}{10ml^2}n_{\max}^5 \qquad (7)$$

Now $n_{\max}$ is given by the condition that all levels are occupied.

$$\pi\sum_{n=1}^{n_{\max}} n^2 = N \quad \text{or}\,\pi\,\tfrac{1}{3}n_{\max}^3 = N, \qquad \pi = 1! \qquad (8)$$

where N is the total number of particles. Combining (7) with (8), we obtain

$$E = \frac{3^{\frac53}\pi^2\hbar^2}{10ml^2}N^{\frac53}. \qquad (9)$$



both pressures increase with the same power of ρ, so that if originally P_g is larger than $P_{F,R}$ equilibrium will never be possible for larger densities and the compression will proceed without limit. The condition for such unlimited contraction is evidently

$$\frac{1}{5}\left(\frac{4\pi}{3}\right)^{\frac13} kM^{\frac43} > \frac{3^{\frac13}\pi\hbar c}{4m^{\frac43}}, \qquad (14)$$

which gives†

$$M > M_0 \sim \left[\gamma\frac{\hbar c}{km^{\frac43}}\right]^{\frac32} \sim 3.10^{+33}\ \text{gm.} \sim 1.5\ \text{sun-masses} \qquad (15)$$

ICRANet Members

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