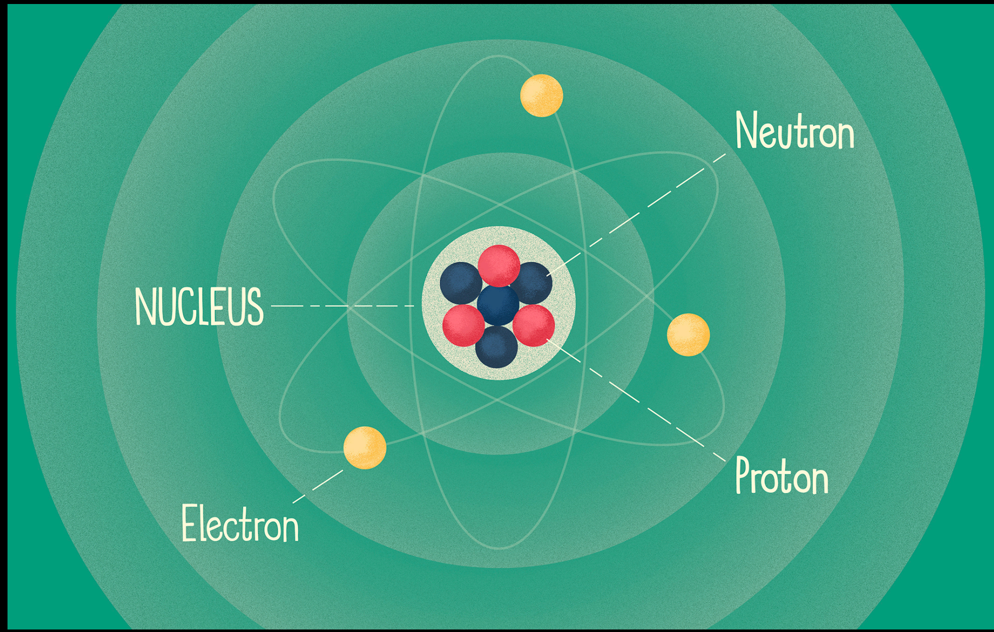
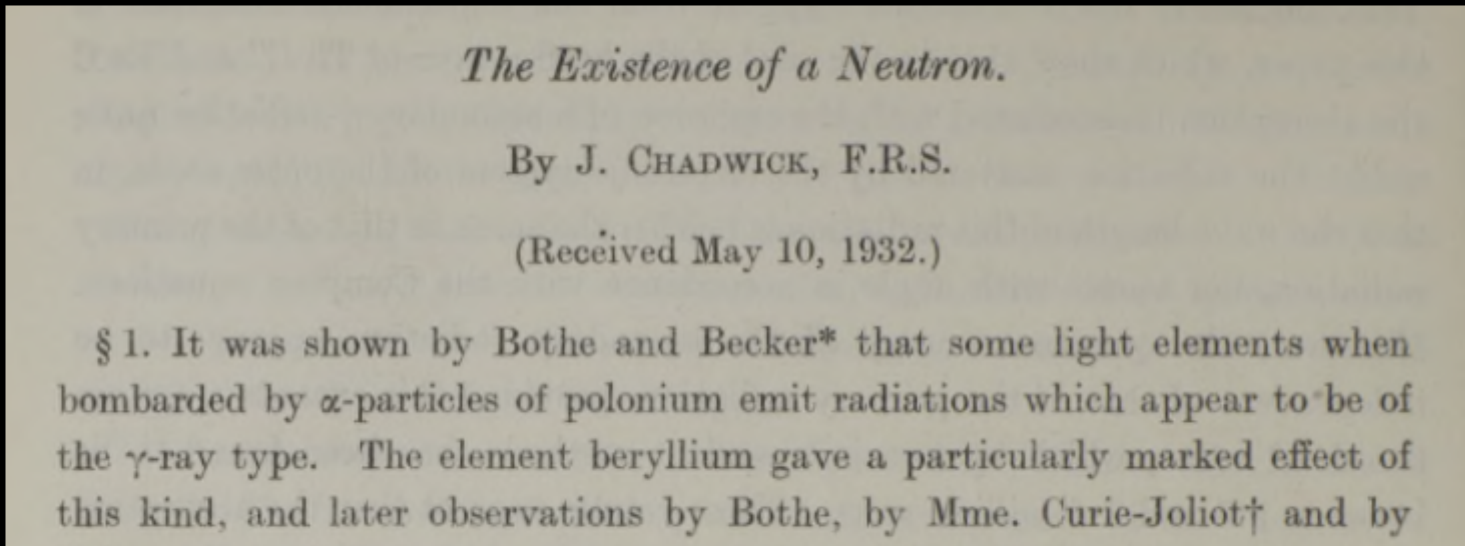
NEUTRON STAR OBSERVATIONS AND EXTREME MATTER PROPERTIES

LECTURE 1 - INTRODUCTION

PROF. ANNA WATTS (UNIVERSITY OF AMSTERDAM)


Image: Robert Gendler





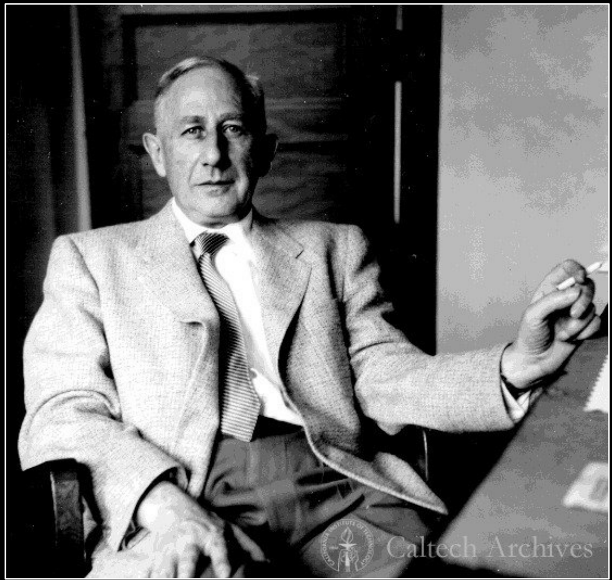
The Existence of a Neutron.

By J. Chadwick, F.R.S.

(Received May 10, 1932.)

§ 1. It was shown by Bothe and Becker* that some light elements when bombarded by α-particles of polonium emit radiations which appear to be of the γ-ray type. The element beryllium gave a particularly marked effect of this kind, and later observations by Bothe, by Mme. Curie-Joliot† and by

"I am afraid neutrons will not be of any use to anyone."
James Chadwick - their discoverer



COSMIC RAYS FROM SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

" "With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density."

NOTES

ON COLLAPSED NEUTRON STARS

ABSTRACT

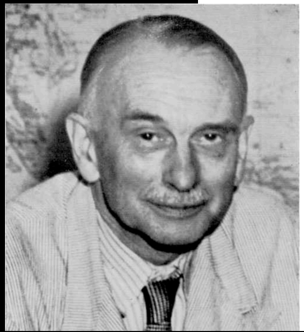
Some consequences are discussed of the hypothesis that certain stars and cores of stars are composed mainly of neutrons. On the assumption that supernovae represent rapid transitions of ordinary stars into neutron stars, the large red shifts observed in the spectra of the recent bright supernovae are interpreted as gravitational red shifts. The neutron-star hypothesis, in conjunction with the general theory of relativity, leads to a theory of critical stellar masses.

In view of the rapid advances made recently in the observation of supernovae, it seems appropriate to give here a brief summary of some conclusions of a series of theoretical investigations concerning the properties of highly collapsed neutron stars, which it is hoped may be ready for publication in the near future.

Zwicky, ApJ, November 1938

“With the designation “neutron star” we do not wish to imply, however, that such a star is to be regarded as a giant nucleus composed of separate neutrons of precisely the same character as free neutrons.”

"The fascinating problem now presents itself of investigating how certain well-known physical processes, such as nuclear reactions, will be modified when they take place inside of highly collapsed stars in which the very properties of time and space are drastically altered."



FEBRUARY 15, 1939 PHYSICAL REVIEW VOLU

Static Solutions of Einstein's Field Equations for Spheres of Fluid

RICHARD C. TOLMAN
Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena, California
(Received January 3, 1939)

A method is developed for treating Einstein's field equations, applied to static spheres of fluid, in such a manner as to provide explicit solutions in terms of known analytic functions. A number of new solutions are thus obtained, and the properties of three of the new solutions are examined in detail. It is hoped that the investigation may be of some help in connection with studies of stellar structure. (See the accompanying article by Professor Oppenheimer and Mr. Volkoff.)

[2] My own present interest in solutions of Einstein's field equations for static spheres of fluid is specially due to conversations with Professor Zwicky of this Institute, and with Professor Oppenheimer and Mr. Volkoff of the University of California, who have been more directly concerned with the possibility of applying such solutions to problems of stellar structure. Professor Zwicky in a recent note (Astrophys. J. **88**, 522 (1938); see also Phys. Rev. **54**, 242 (1938)) has suggested the use of Schwarzschild's interior solution for a sphere of fluid of constant density as providing a model for a "collapsed neutron star." He is making further calculations on the properties of such a model, and it is hoped that the considerations given in this article may be of assistance in throwing light on the questions that concern him. Professor Oppenheimer and Mr. Volkoff have undertaken the specific problem of obtaining numerical quadratures for Einstein's field equations applied to spheres of fluid obeying the equation of state for a degenerate Fermi gas, with special reference to the particular case of neutron gas. Their results appear elsewhere in this same issue. My own solutions of the field equations, as

$$\frac{dM(r)}{dr} = 4\pi r^2 \epsilon(r) \qquad + P = P(\epsilon)$$

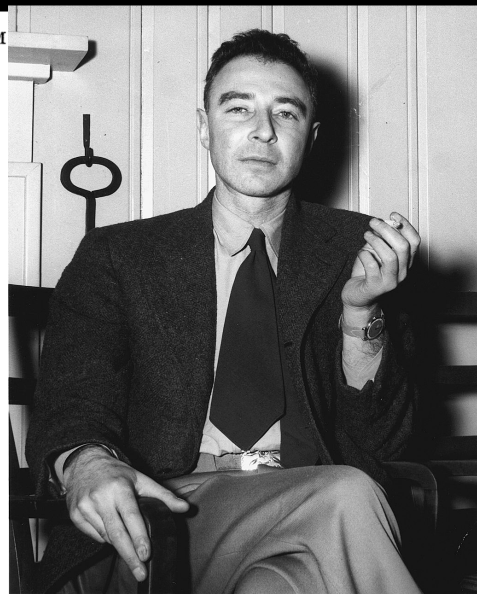
$$\frac{dP(r)}{dr} = \frac{-G\left(\epsilon(r) + P(r)/c^2\right)\left(M(r) + 4\pi r^3 P(r)/c^2\right)}{r(r - 2GM(r)/c^2)}$$

FEBRUARY 15, 1939 PHYSICAL REVIEW VOLUM

On Massive Neutron Cores

J. R. OPPENHEIMER AND G. M. VOLKOFF
Department of Physics, University of California, Berkeley, California
(Received January 3, 1939)

It has been suggested that, when the pressure within stellar matter becomes high enough, a new phase consisting of neutrons will be formed. In this paper we study the gravitational equilibrium of masses of neutrons, using the equation of state for a cold Fermi gas, and general relativity. For masses under $\frac{1}{3}\odot$ only one equilibrium solution exists, which is approximately described by the nonrelativistic Fermi equation of state and Newtonian gravitational theory. For masses $\frac{1}{3}\odot < m < \frac{3}{4}\odot$ two solutions exist, one stable and quasi-Newtonian, one more condensed, and unstable. For masses greater than $\frac{3}{4}\odot$ there are no static equilibrium solutions. These results are qualitatively confirmed by comparison with suitably chosen special cases of the analytic solutions recently discovered by Tolman. A discussion of the probable effect of deviations from the Fermi equation of state suggests that actual stellar matter after the exhaustion of thermonuclear sources of energy will, if massive enough, contract indefinitely, although more and more slowly, never reaching true equilibrium.



INSTITUT INTERNATIONAL DE PHYSIQUE SOLVAY

ONZIÈME CONSEIL DE PHYSIQUE

tenu à l'Université de Bruxelles
du 9 au 13 juin 1958

MATTER-ENERGY AT HIGH DENSITY; END POINT OF THERMONUCLEAR EVOLUTION

(K.H.; M.W.; J.A.W.)

In seeking the consequences of Einstein's theory for the structure and evolution of the universe we have been forced to consider what happens during contraction. Such implosion can be expected to

Among the problems some of the most challenging are : (1) to observational science, the approximate magnitude of the so-far unexplored sources of mass-energy (fig. 5); (2) to geometrodynamical analysis, what goes on in an unsymmetric implosion and reexpansion of the universe (a redo of fig. 7!) and (3) to elementary particle physics, the fate of a great number of nucleons under the action of their mutual gravitational attraction.

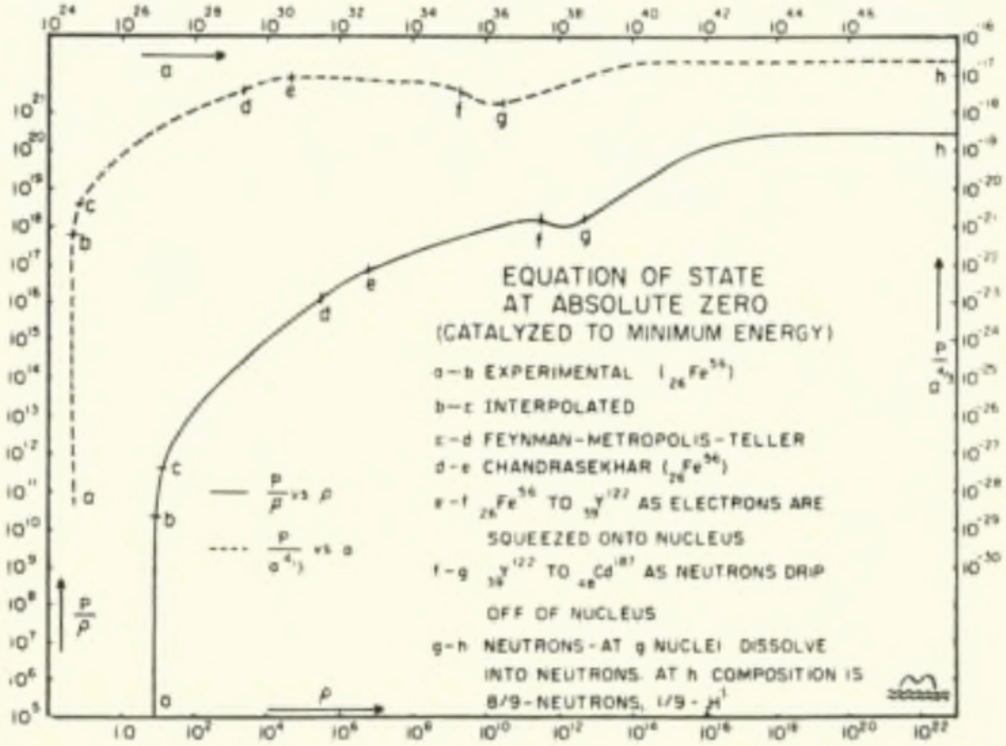


Fig. 11.

NEUTRON STAR MODELS

A. G. W. Cameron
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
Received June 17, 1959

ABSTRACT

Previous models of neutron stars were constructed with the assumption that the equation of state of a neutron gas is that of non-interacting Fermi gas. Such models have a maximum observable mass of about 0.7 solar mass. In fact, the potential energy of a neutron gas depends on the density; this introduces additional terms into the equation of state. A revised equation of state has been derived which makes use of a mean nuclear potential recently given by T. H. R. Skyrme. Twenty neutron star models have been constructed by integrating the general relativistic equations of hydrostatic equilibrium of the neutron gas. The results show that there is an upper limit to the observable mass of about 2 solar masses; the corresponding upper limit to the proper mass is about 3 solar masses. There is a lower limit to each of these masses of about 0.05 solar mass, below which the neutron star is unstable against transformation into an iron star. The radii of these neutron stars lie in the range 7–9 km. A qualitative discussion of the effects of transformation of neutrons into hyperons at very high densities is given.

THE DEGENERATE SUPERDENSE GAS OF ELEMENTARY PARTICLES

V. A. Ambartsumyan and G. S. Saakyan

Byurakan Astrophysical Observatory, Academy of Sciences, ArmSSR

(Translated from: Astronomicheskii Zhurnal, Vol. 37, No. 2, pp. 193-209, March-April, 1960)

(Original article submitted January 20, 1960)

The composition of a degenerate gas whose density is of the order of nuclear density or higher, is considered. The temperature is assumed so low that all types of fermions are degenerate. It is shown that, with increasing density, different hyperons should successively appear and increase in number. They should be stable because of the Pauli principle. The threshold densities of different hyperons are calculated. Paradoxically, the smallest threshold density does not correspond to the Λ-hyperon, having the smallest mass of rest, but to the Σ^- - hyperon.

In accordance with this, a sufficiently massive cosmic body in gravitational equilibrium should consist of a hyperon core, a neutron layer, and an outer envelope having the usual composition (electrons, protons, and composite nuclei).

ANNALS OF PHYSICS: **26**, 364–410 (1964)

Supernovae, Neutrinos, and Neutron Stars

H.-Y. Chiu*

Goddard Institute for Space Studies, New York 27, N. Y.
and
Department of Physics, Columbia University, New York 27, N. Y.

What is left as the core collapses is not immediately clear. In the past, it was usually assumed that ordinary white dwarfs (whose mean density is around 10^6 gm/cm^3) are remnants of supernova explosion. The large number of white dwarfs discovered (around 10% of the stars in the solar neighborhood are white dwarfs) however, cannot be explained by the relative scarcity of supernovae per galaxy (which occur at a rate of around 1/50–300 years) (*9*). The other alternative that neutron stars may be the remnants of supernovae has so far been accepted only with skepticism[3] (*10*, *11*). Moreover, there is *no astronomical evidence* yet that such stars even exist.

for neutron stars. Beyond this mass limit no static structure is possible. Neutron stars can only be detected by extraterrestrial x-ray telescopes. If detected, they pose interesting questions on our present theory of fundamental particles.

Published: 28 March 1964

Neutron Stars as X-ray Sources

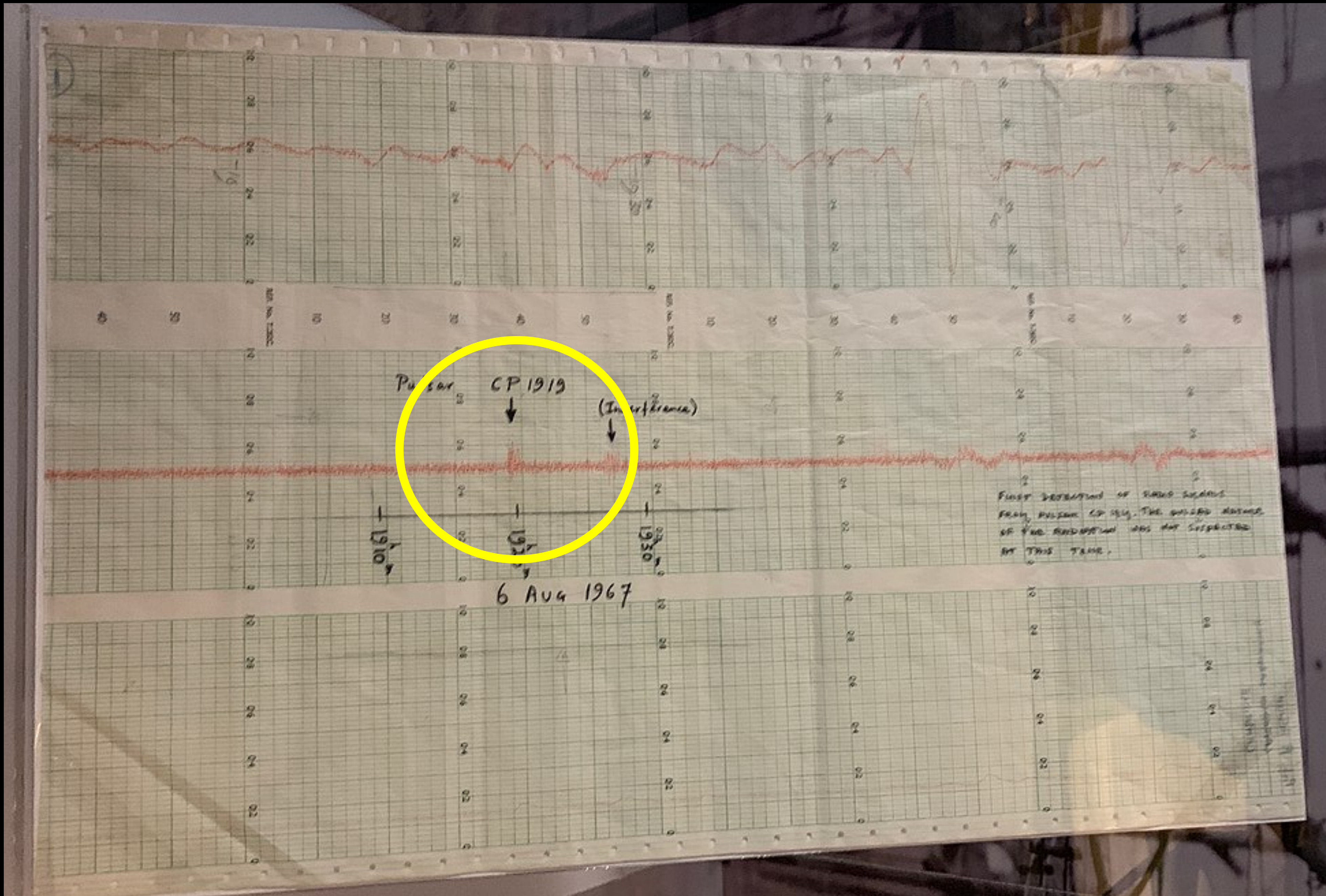
DONALD C. MORTON

Nature **201**, 1308–1309 (1964) | Cite this article

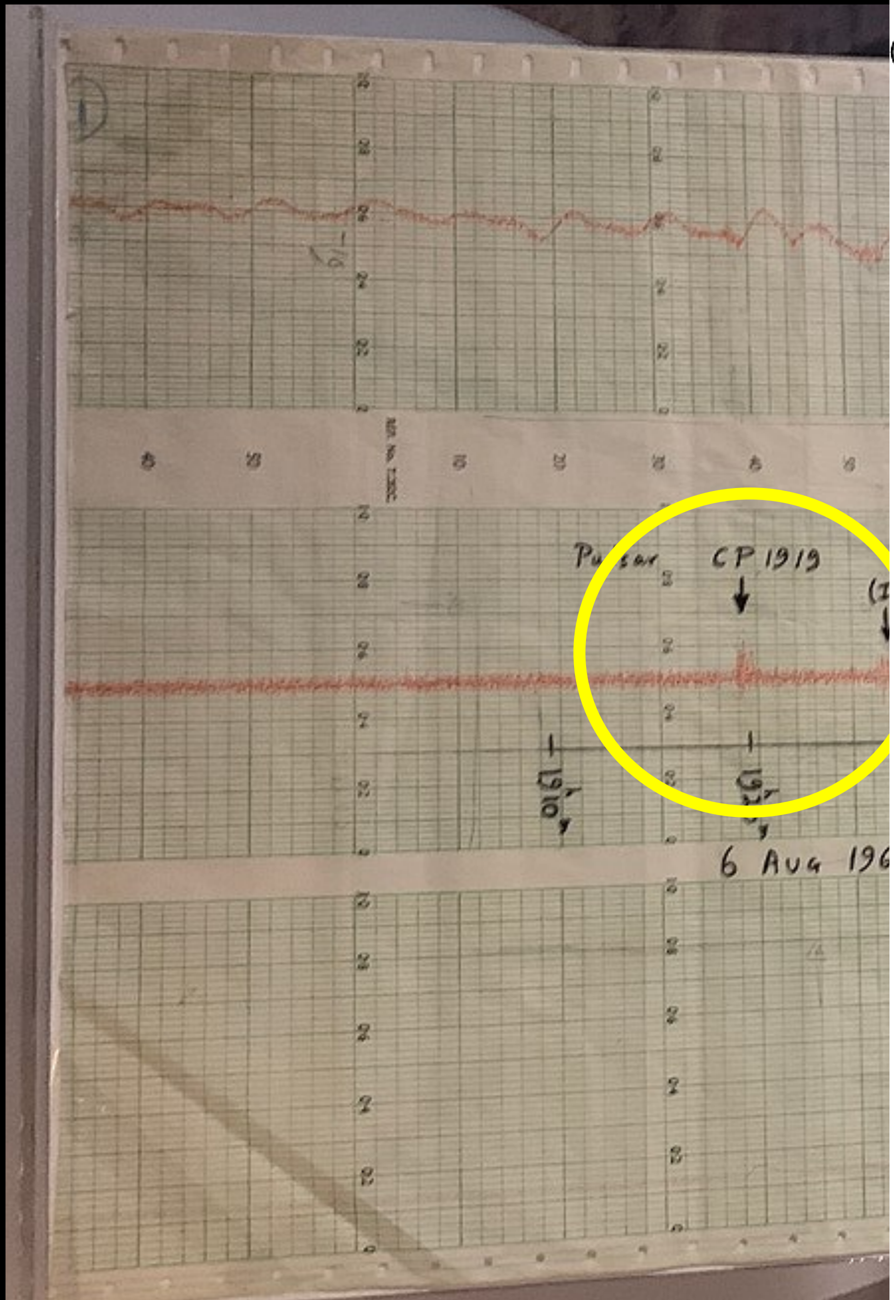
Abstract

DURING the rocket flight reported in the preceding communication, Bowyer *et al.* found two celestial X-ray sources with diameters less than 5°. One was located in the northern part of Scorpius in a region of faint stars but devoid of visible nebulosity and radio objects, while the other was coincident with the Crab Nebula, the well-known source of optical and radio synchrotron emission.

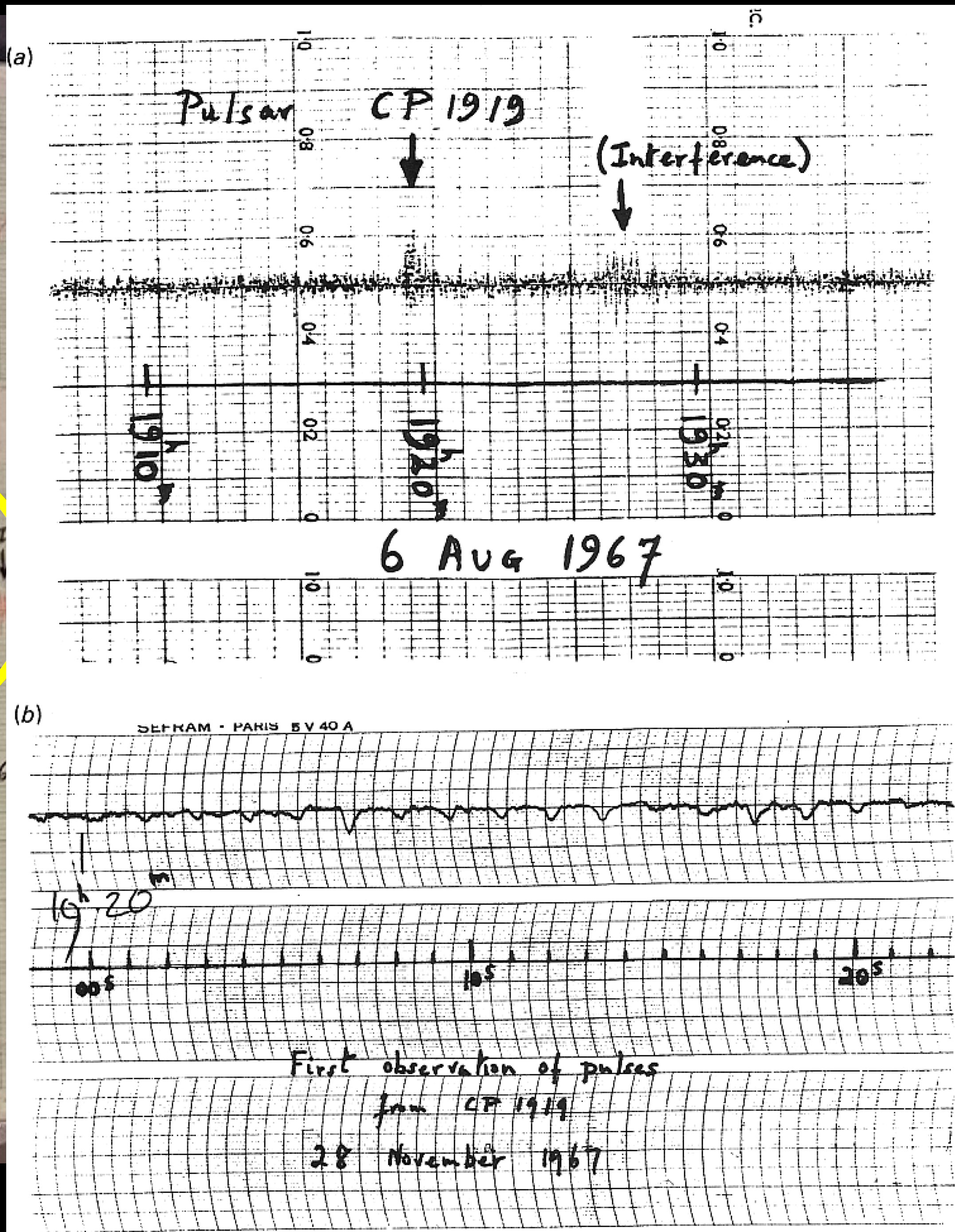
"...upon entering the faculty, each student was issued a set of tools: a pair of pliers, a pair of long-nose pliers, a wire cutter, and a screwdriver..." - Jocelyn Bell



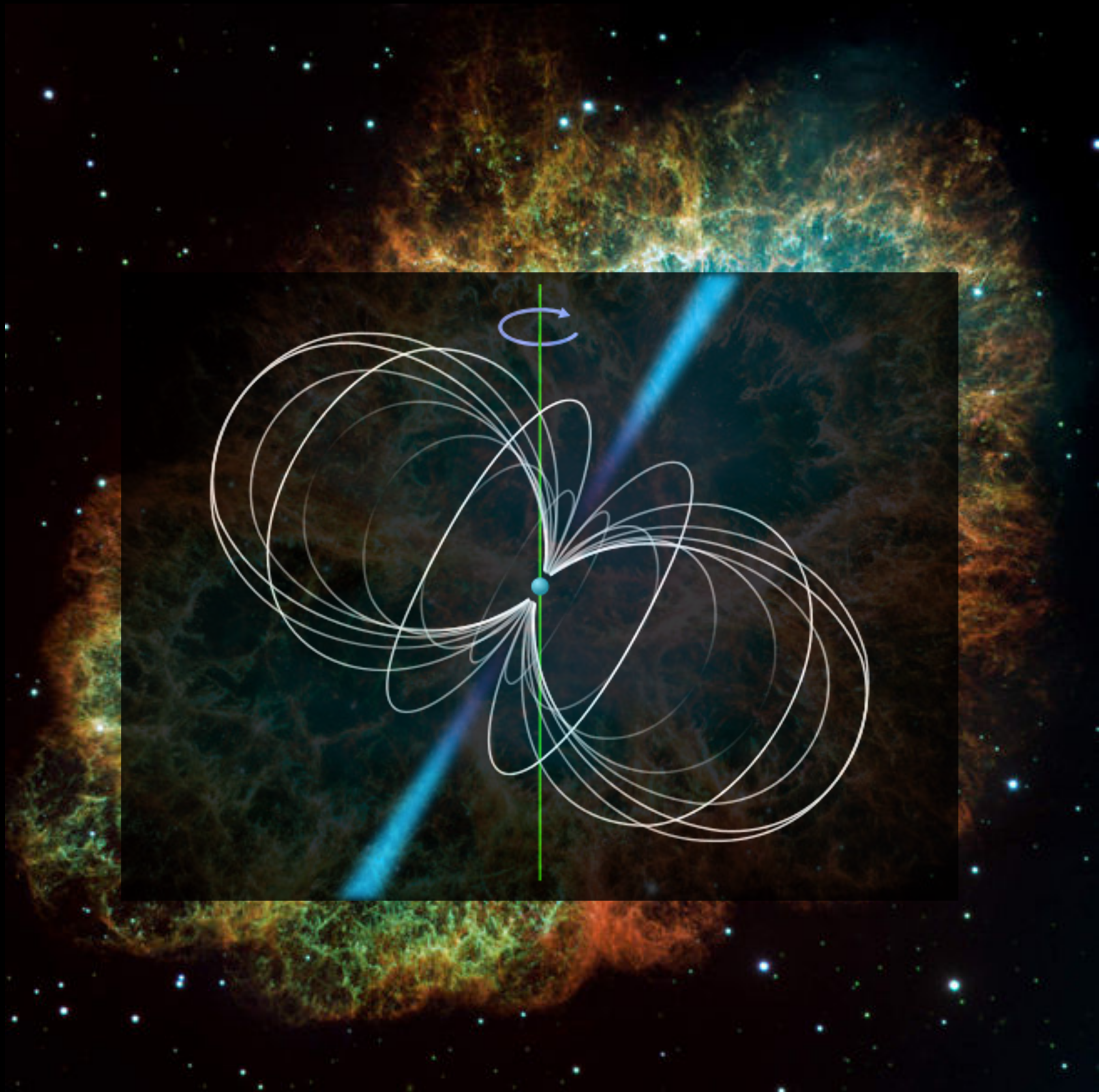
Pulsar
CP 1919
(Interference)
6 Aug 1967



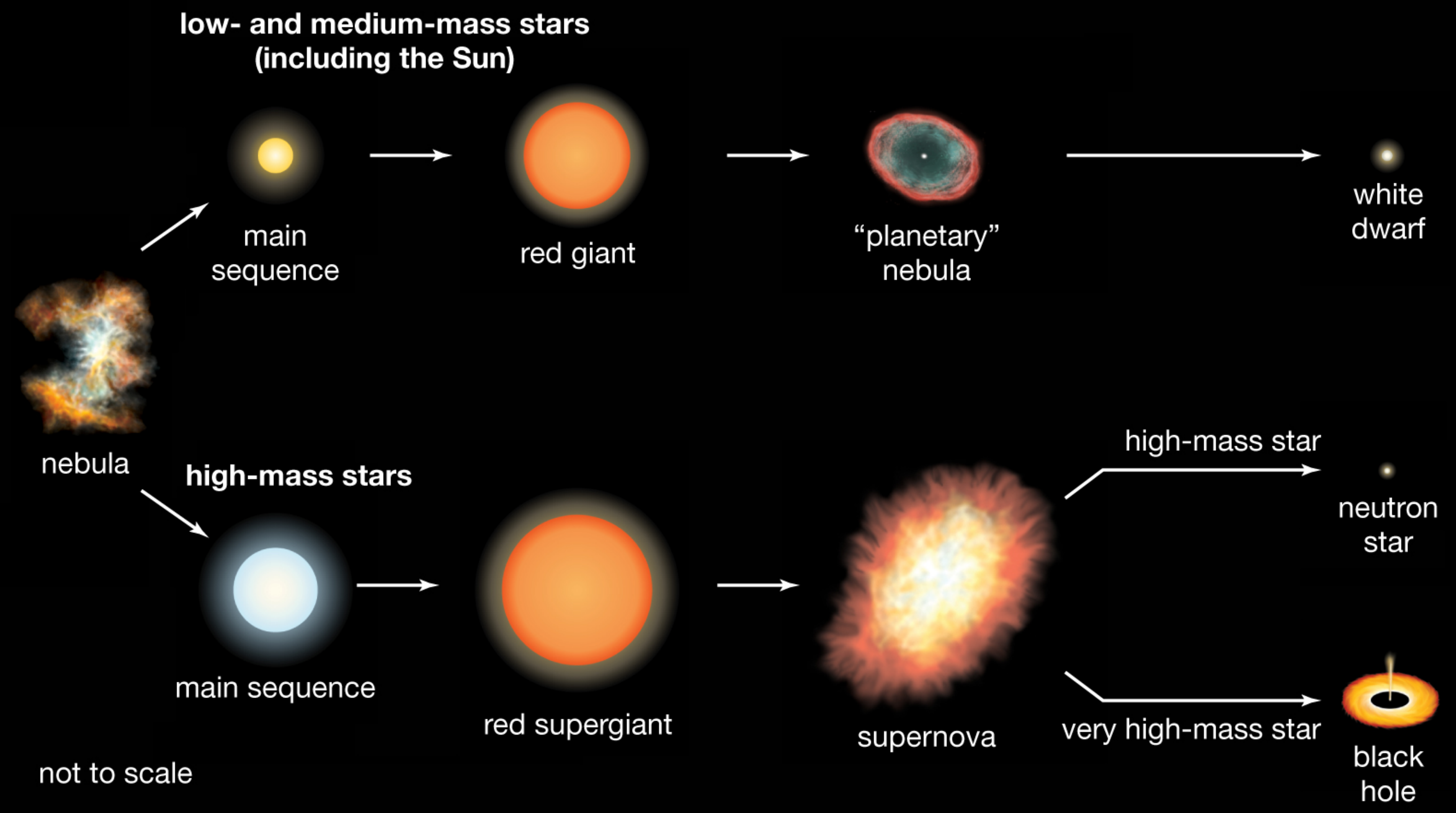
Pulsar
CP 1919
6 Aug 196



(a)
Pulsar
CP 1919
(Interference)
6 Aug 1967
(b)
SEFRAM - PARIS
First observation of pulses
from CP 1919
28 November 1967



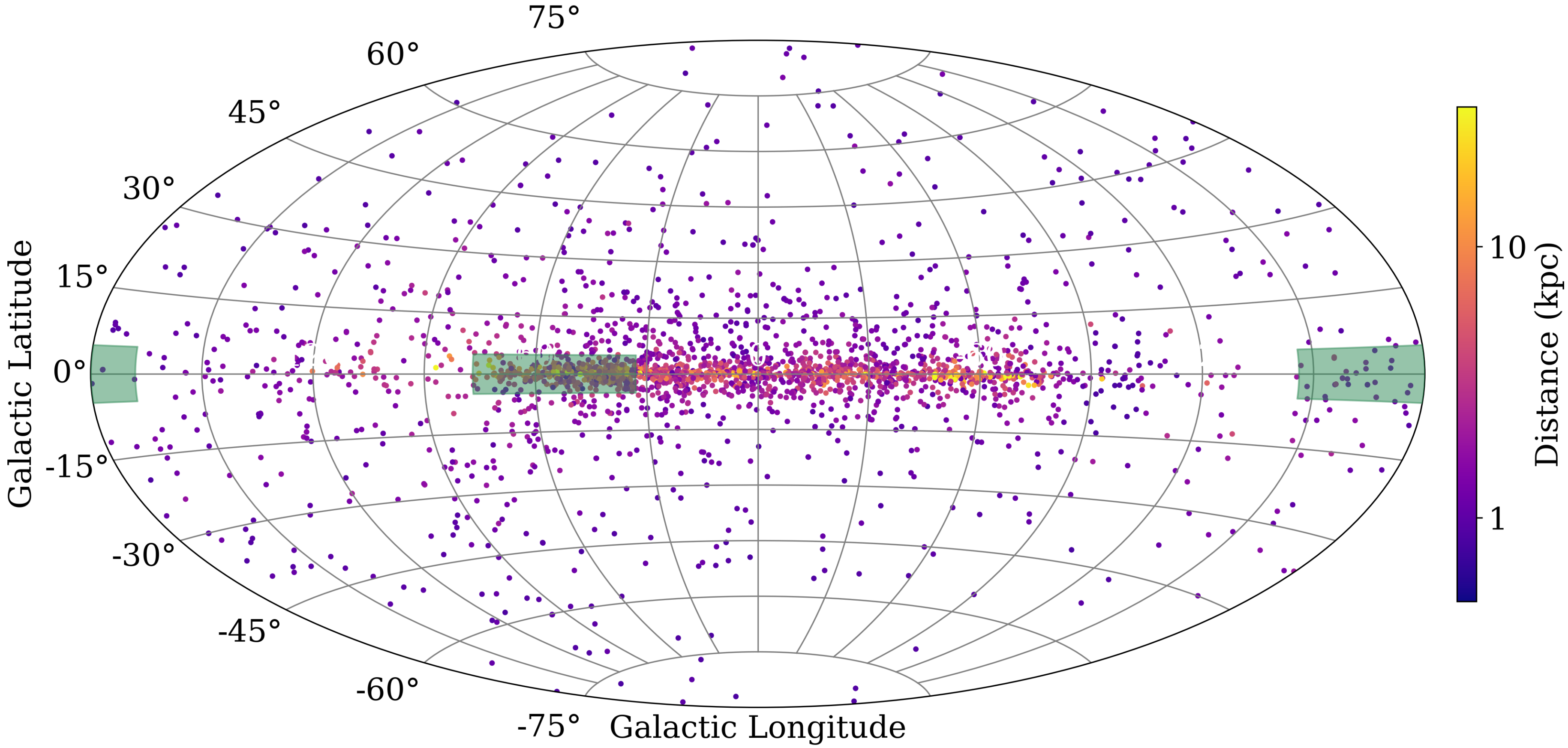
Stellar evolution

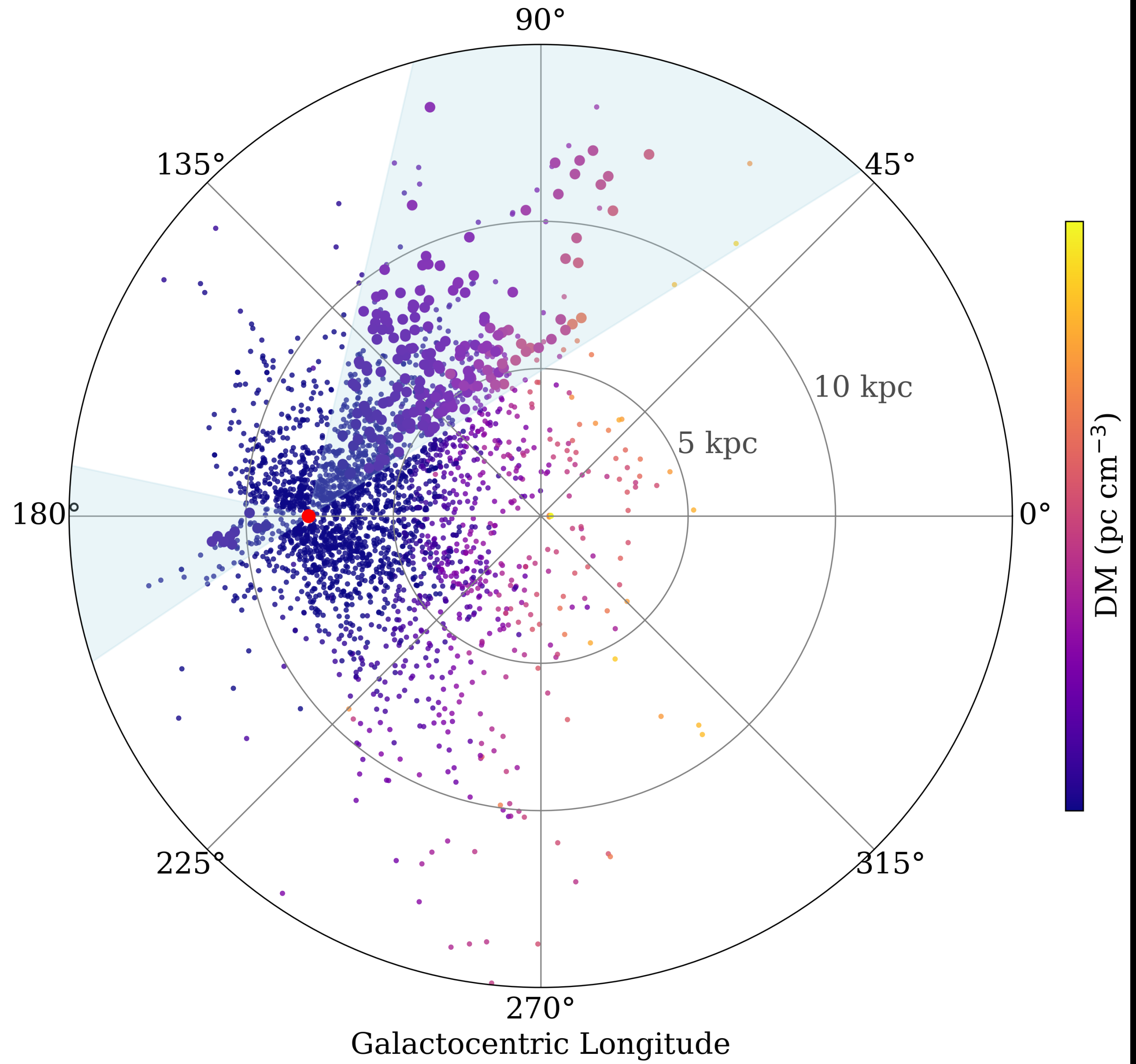


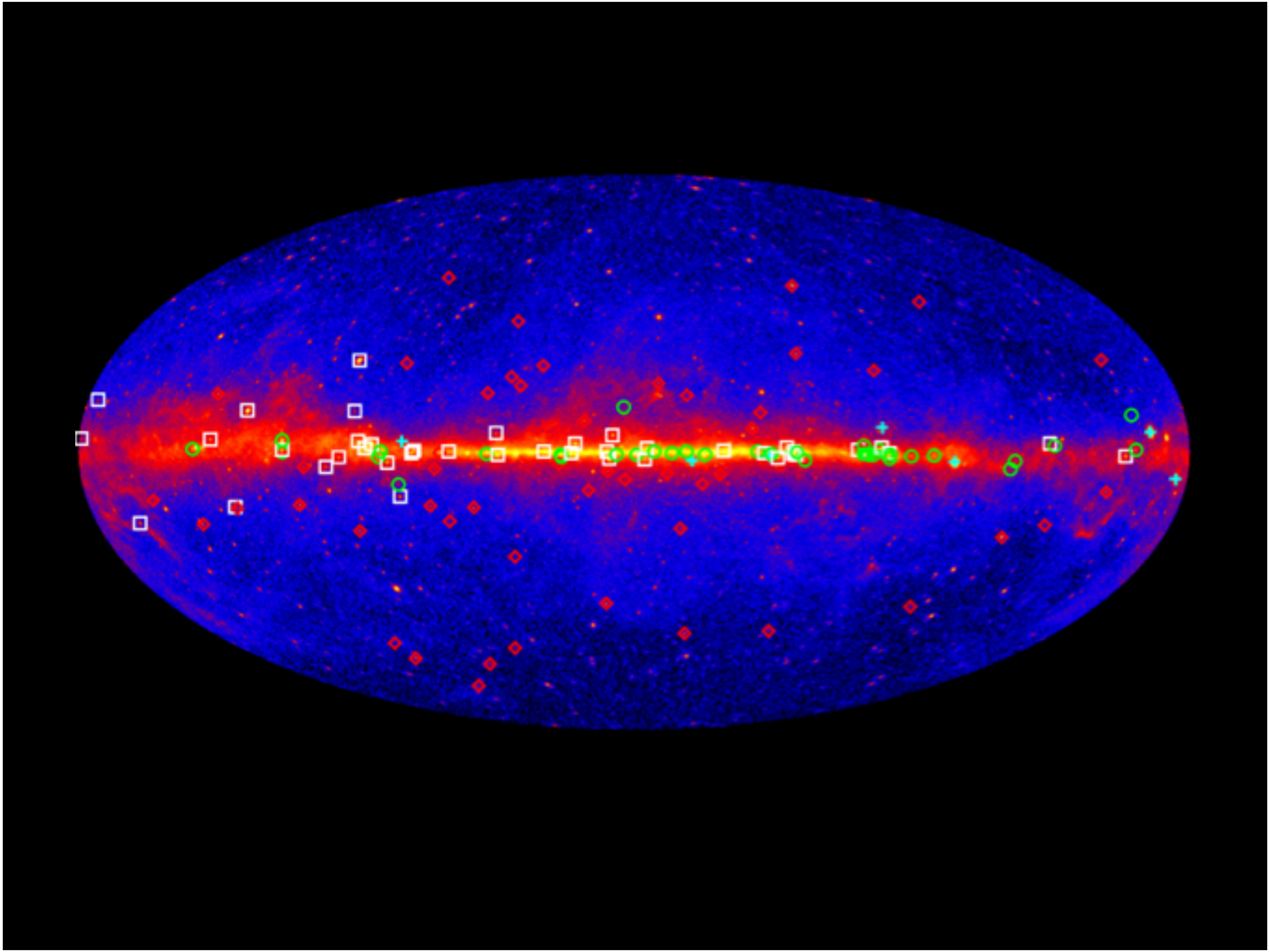


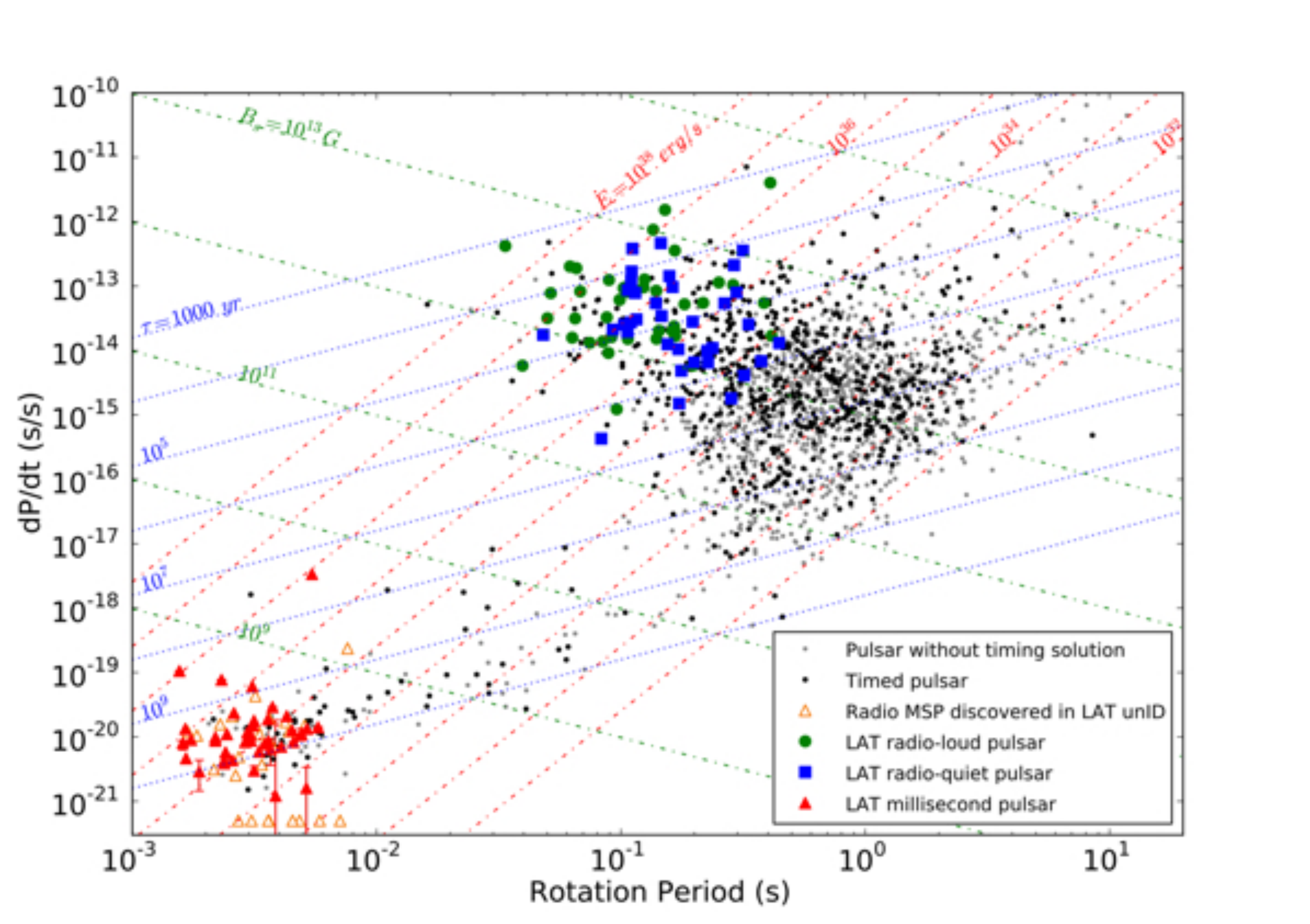


NASA

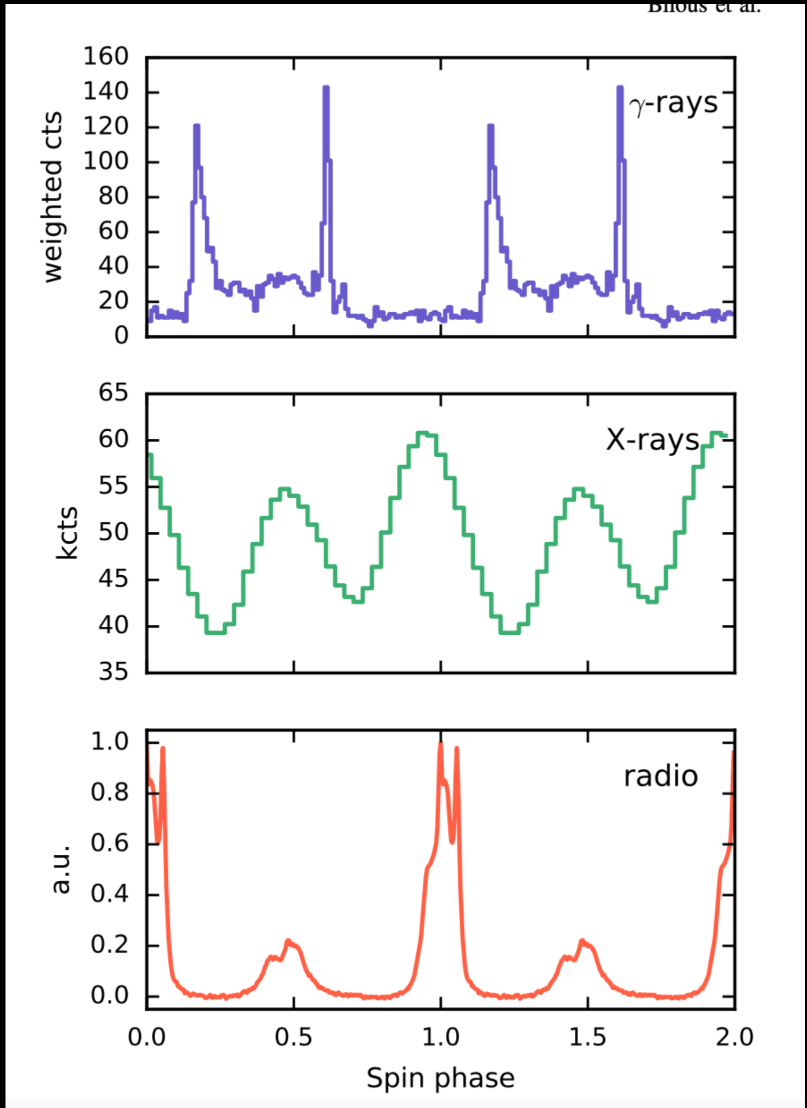

75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Galactic Latitude
Galactic Longitude
10
1
Distance (kpc)

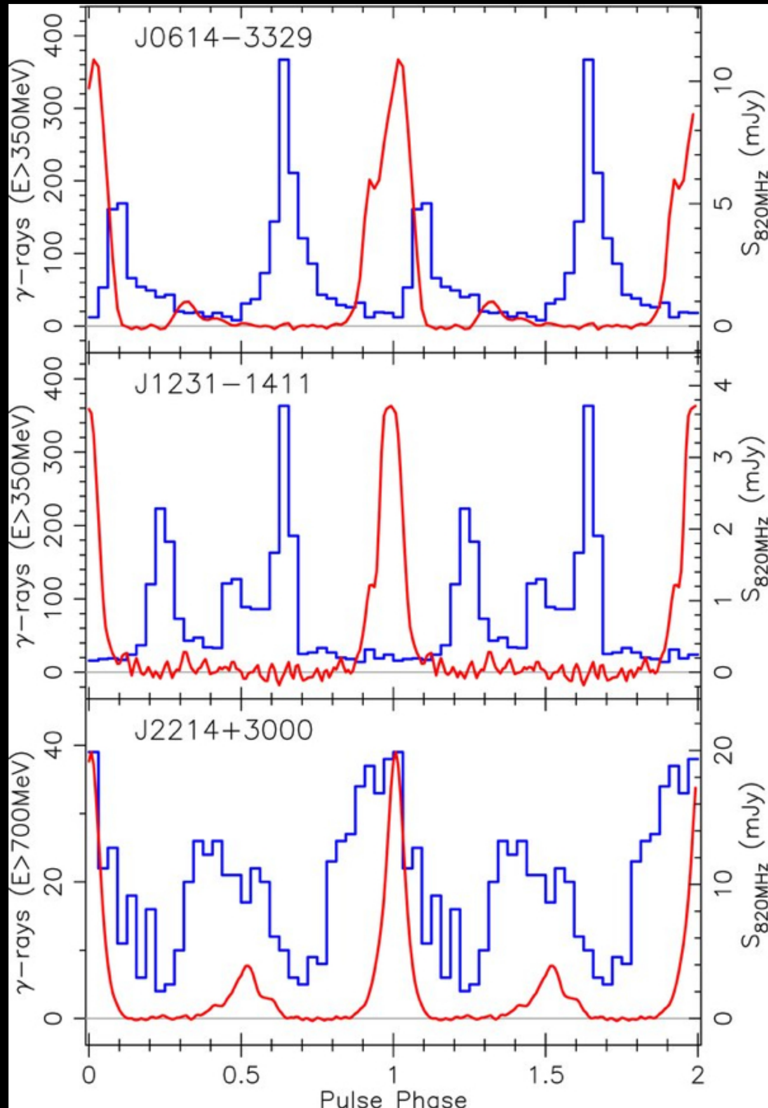

90°
135°
45°
10 kpc
5 kpc
180°
0°
225°
315°
270°
Galactocentric Longitude
DM (pc cm^{-3})

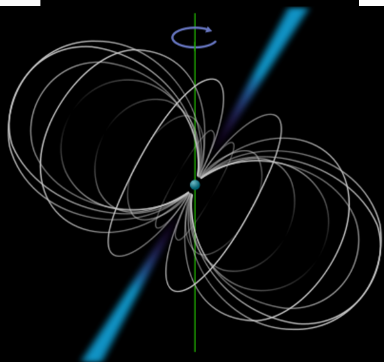




dP/dt (s/s)
Rotation Period (s)
$B_s = 10^{13}$ G
10^{11}
10^{9}
$\dot{E} = 10^{38}$ erg/s
10^{36}
10^{34}
10^{32}
$\tau = 1000$ yr
10^{5}
10^{7}
10^{9}
Pulsar without timing solution
Timed pulsar
Radio MSP discovered in LAT unID
LAT radio-loud pulsar
LAT radio-quiet pulsar
LAT millisecond pulsar

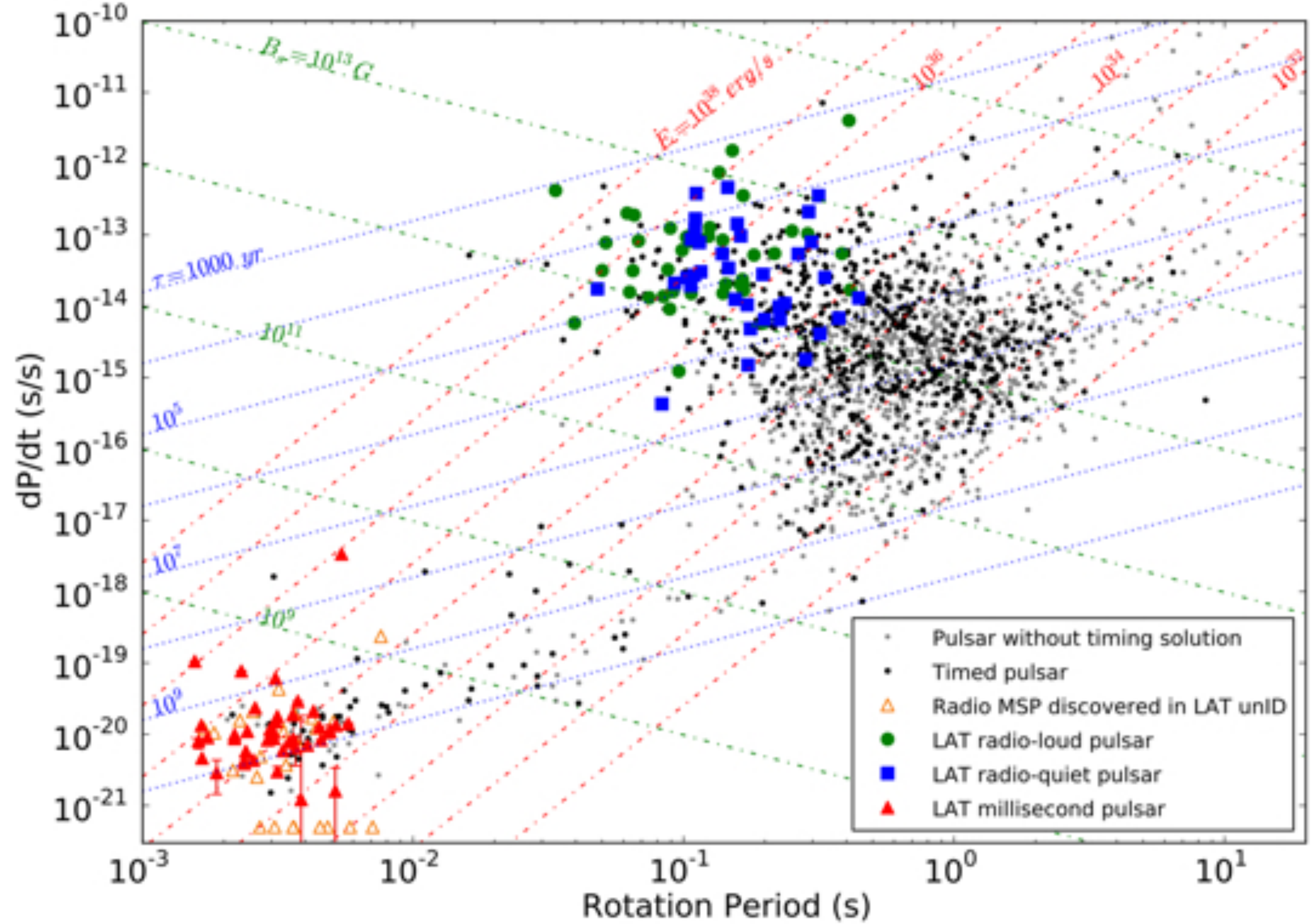






PSR J0030+0451
Bilous et al. 2019

Ransom et al.



dP/dt (s/s)
Rotation Period (s)
Pulsar without timing solution
Timed pulsar
Radio MSP discovered in LAT unID
LAT radio-loud pulsar
LAT radio-quiet pulsar
LAT millisecond pulsar

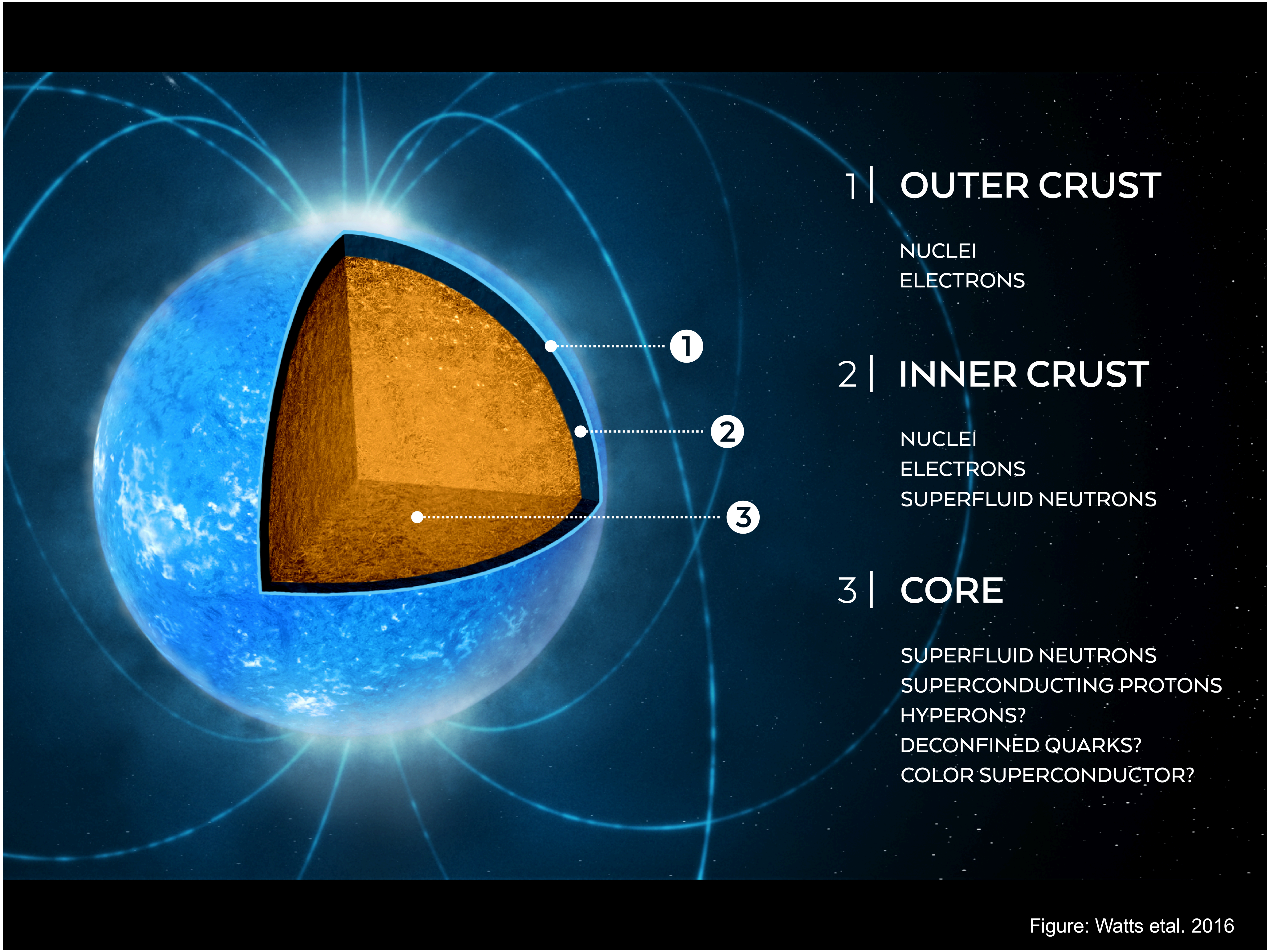
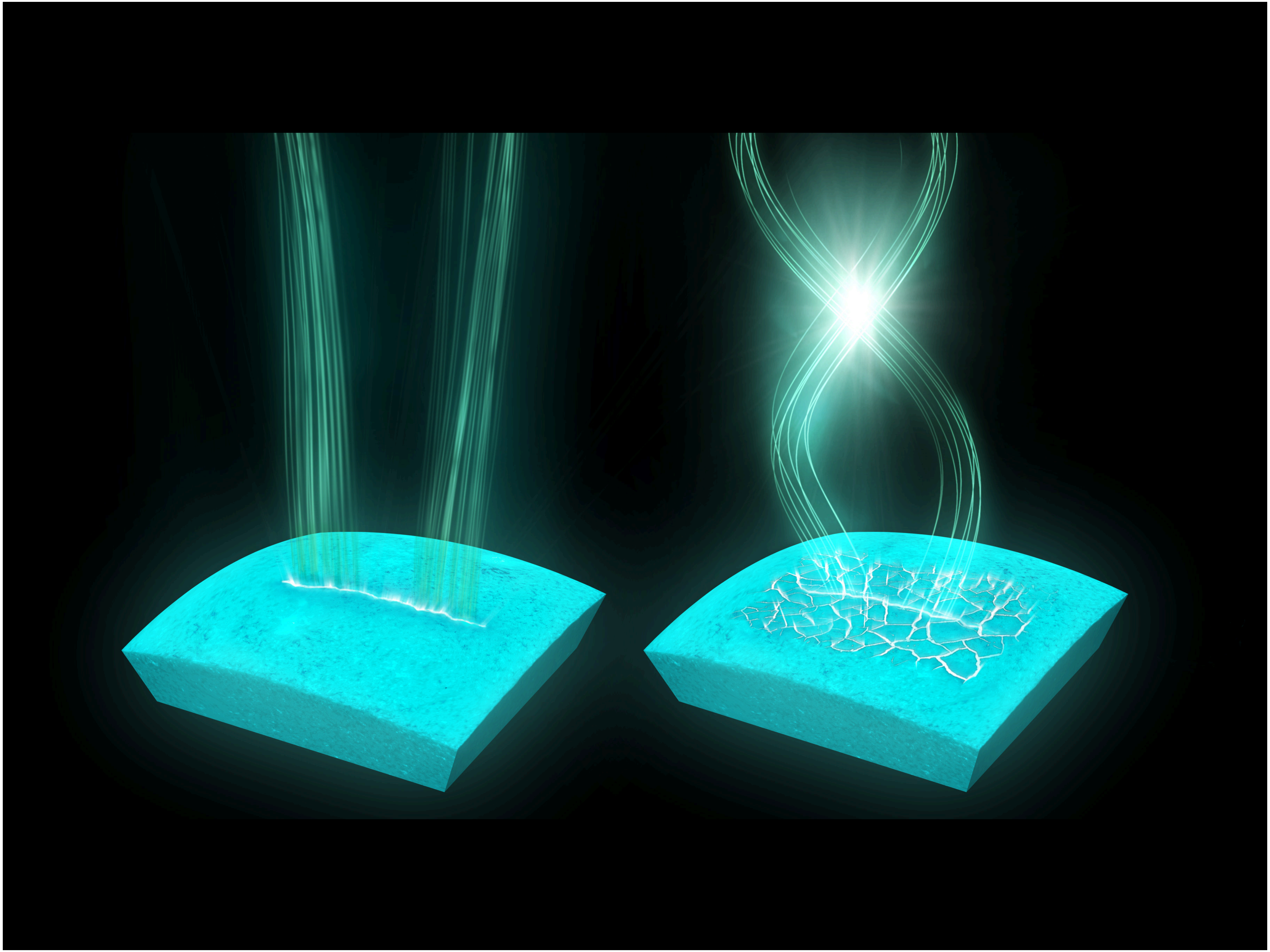
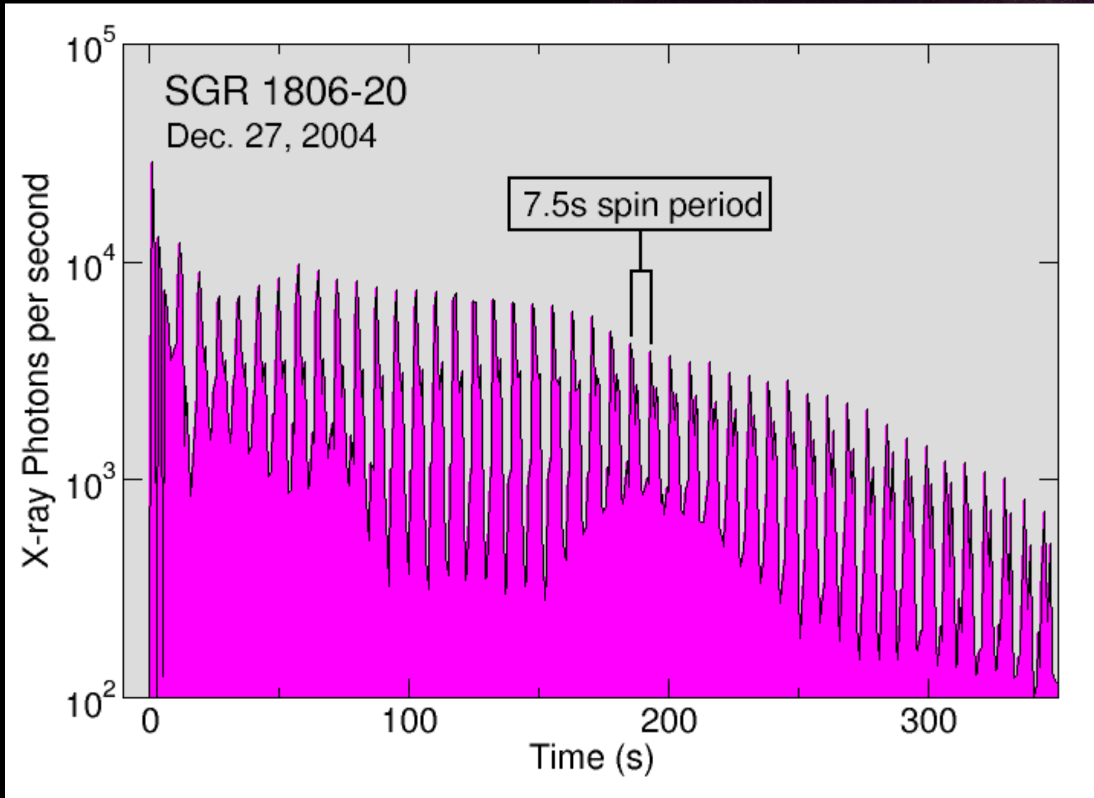
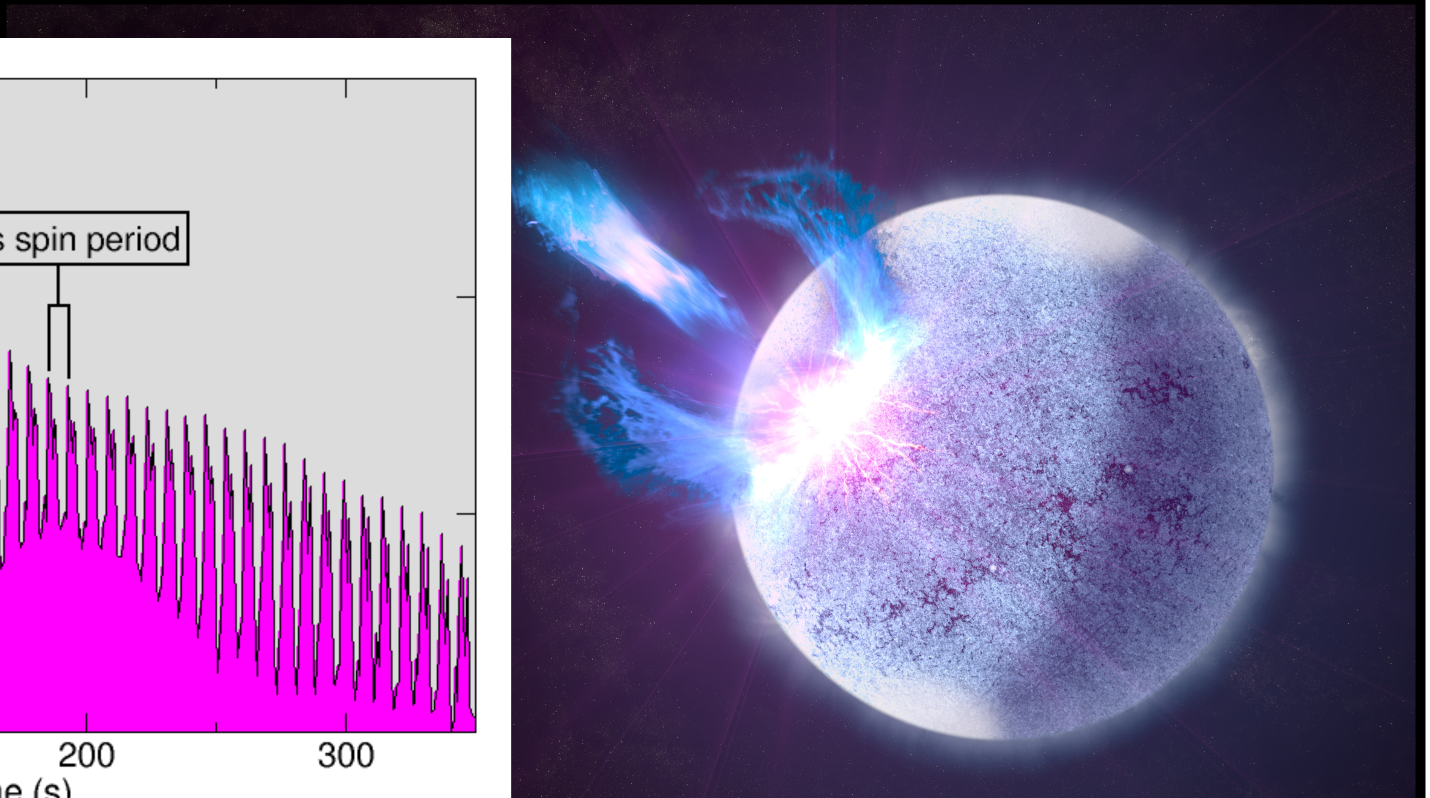
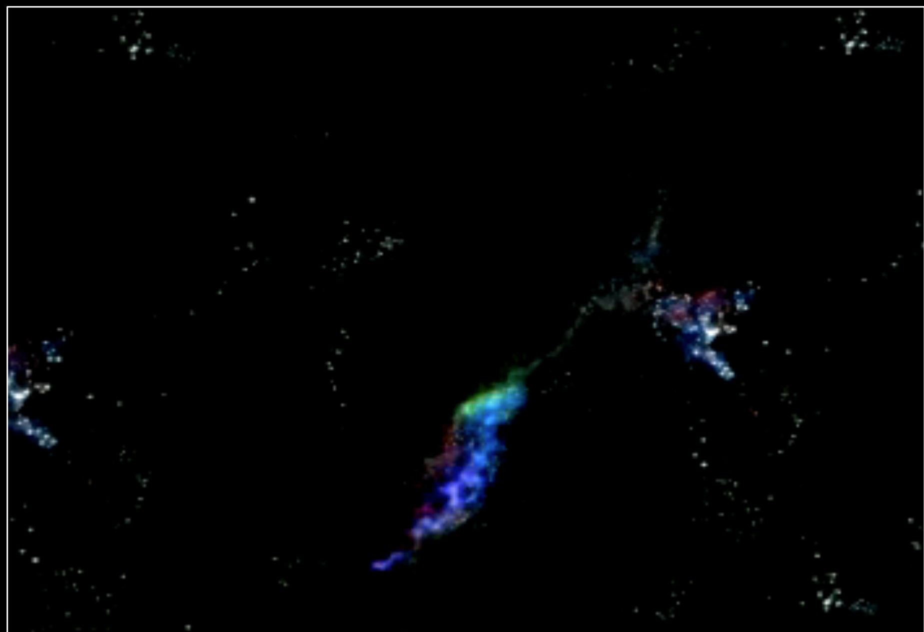
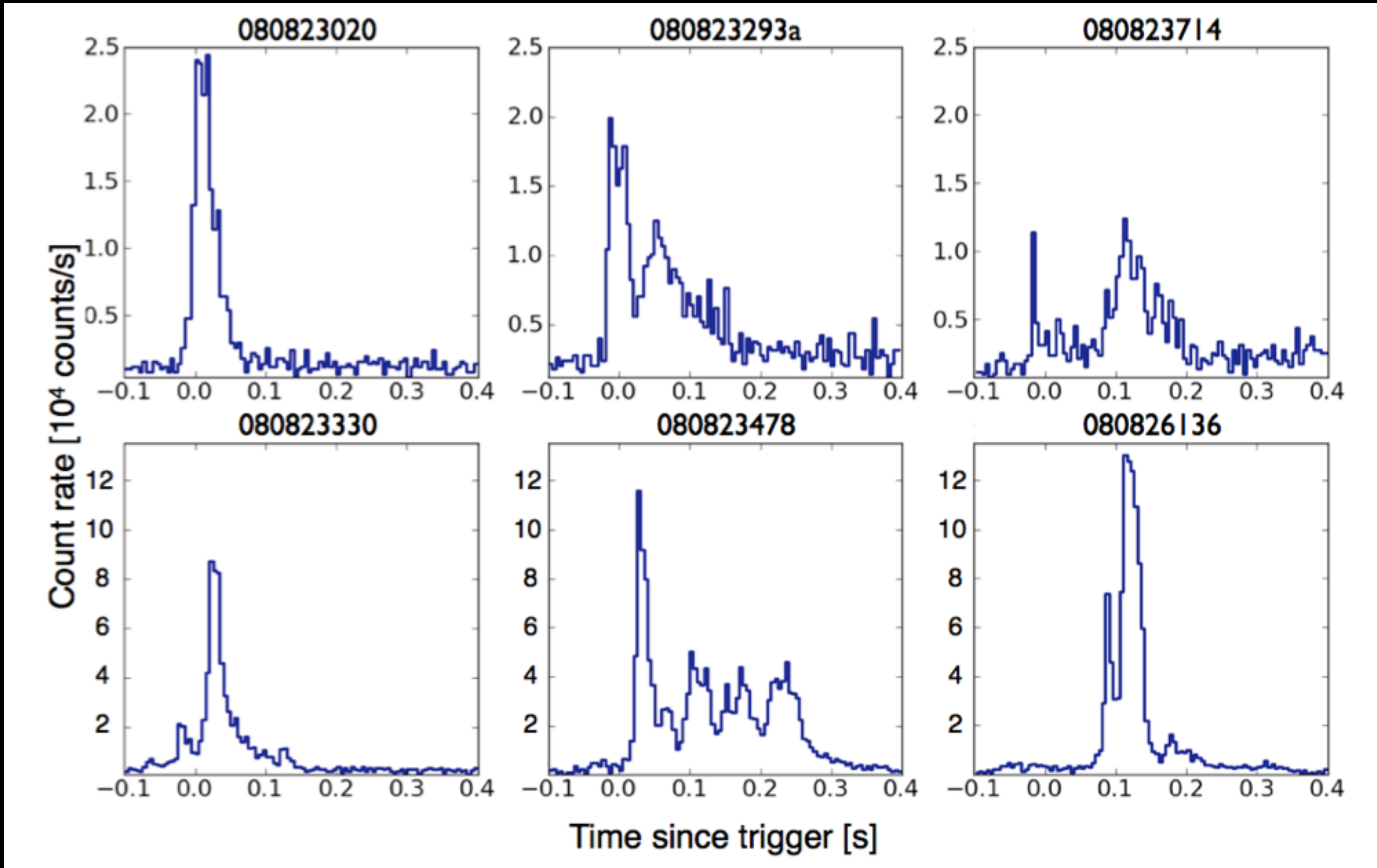


Figure: Watts etal. 2016

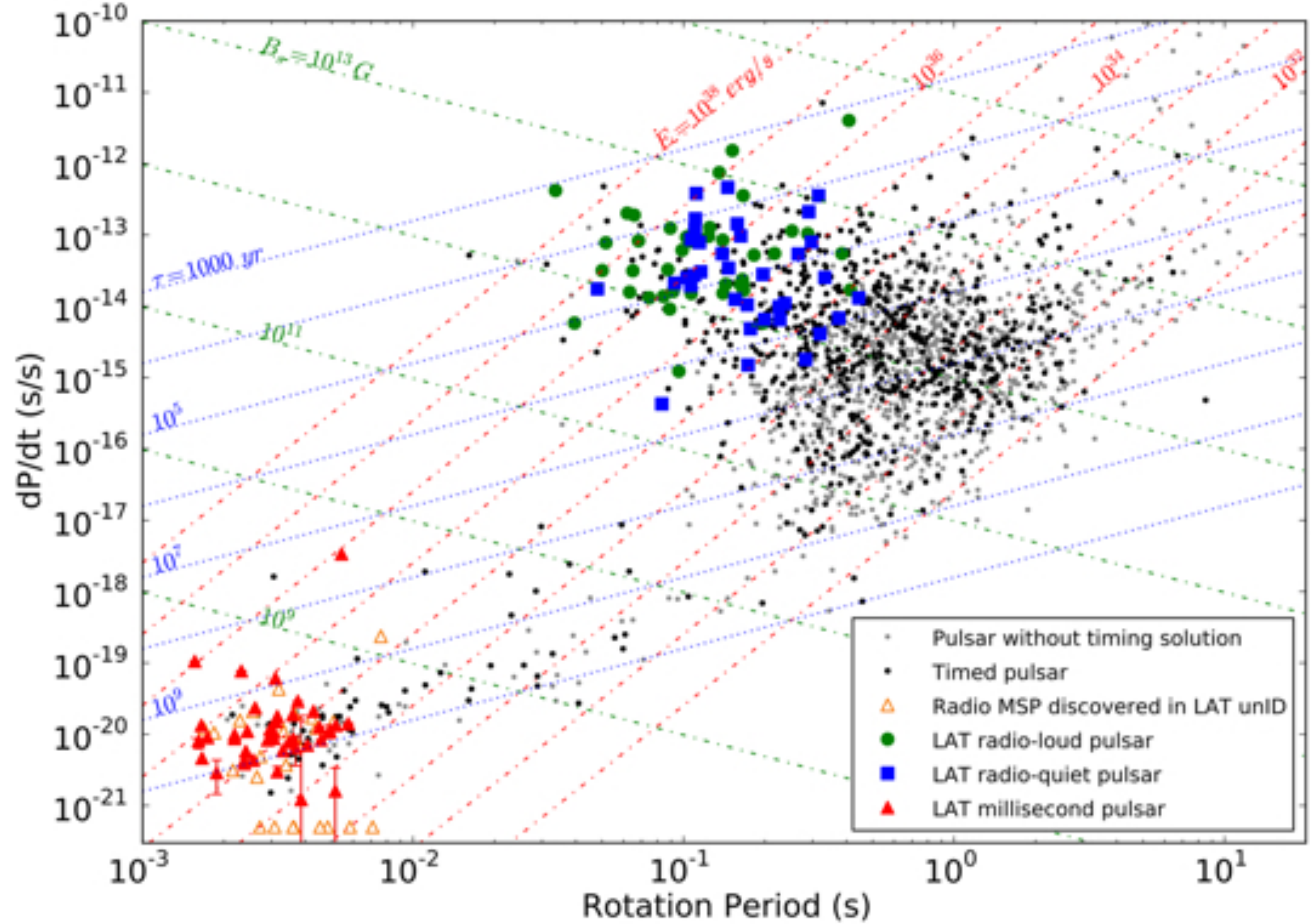



SGR 1806-20
Dec. 27, 2004
7.5s spin period
X-ray Photons per second
10^5
10^4
10^3
10^2
0
100
200
300
Time (s)



SMALL MAGNETAR BURSTS



Fermi GBM bursts from SGR 0501+4516 (Huppenkothen et al. 2013)



dP/dt (s/s)
Rotation Period (s)
$B_s = 10^{13}$ G
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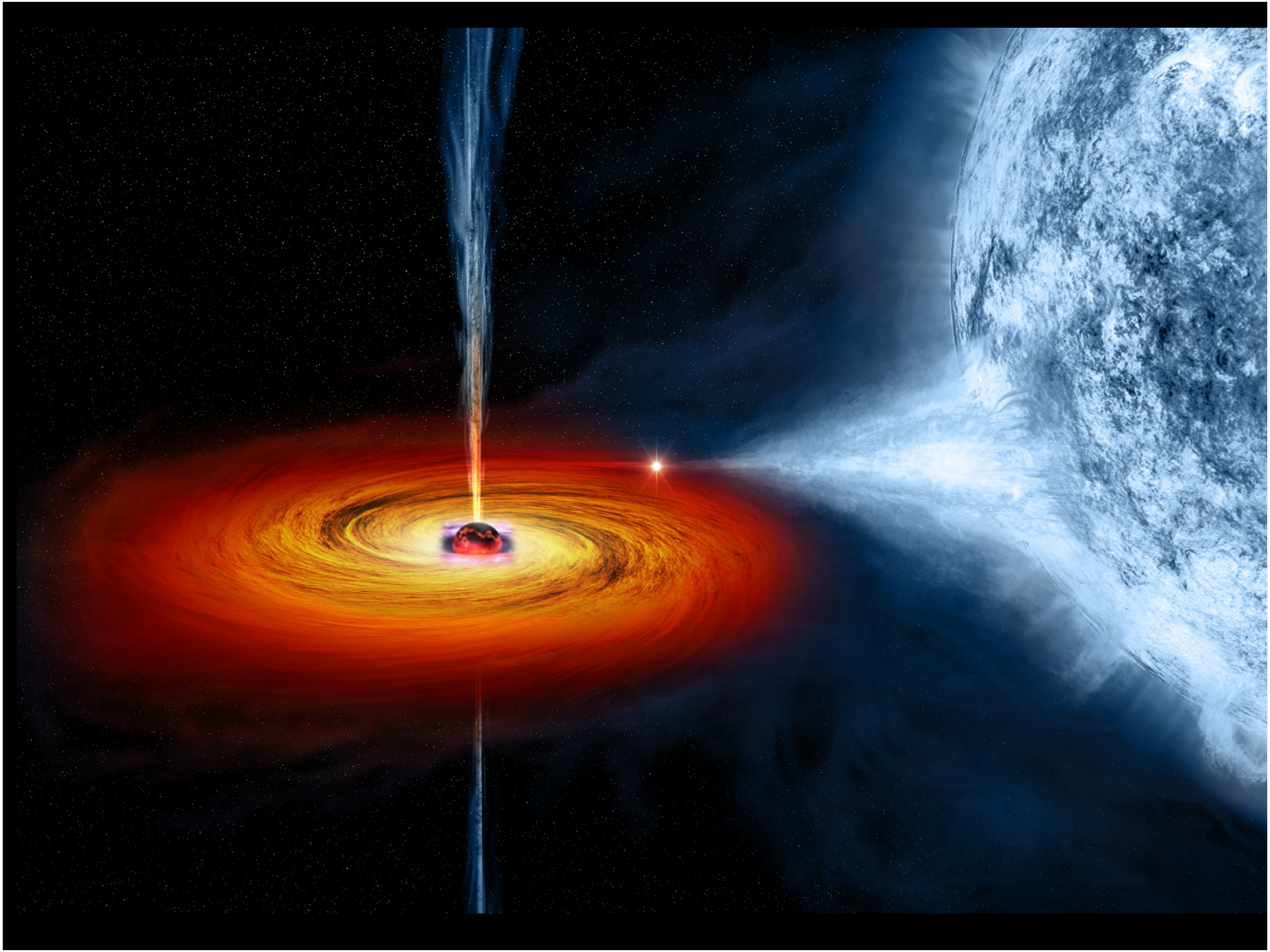
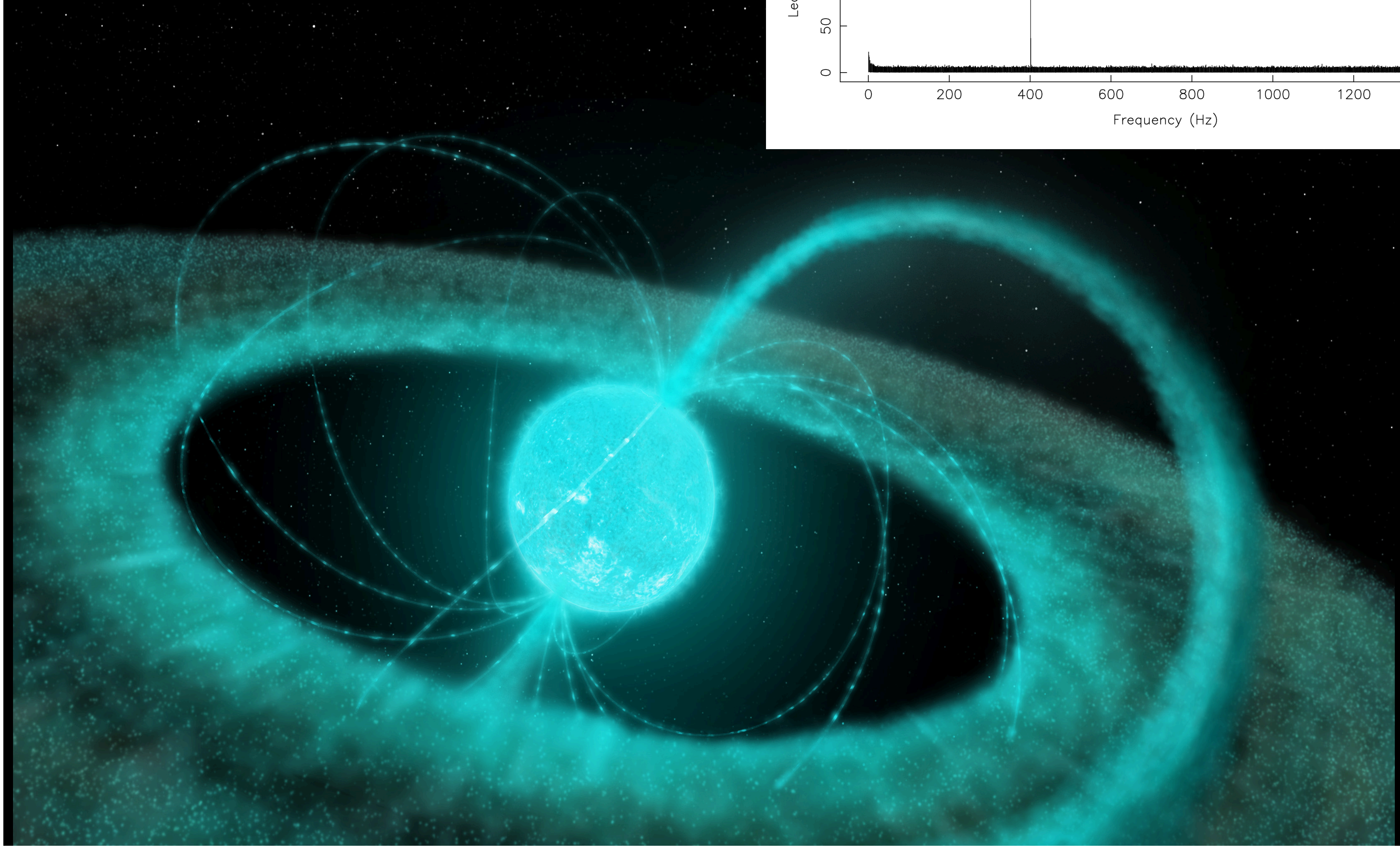
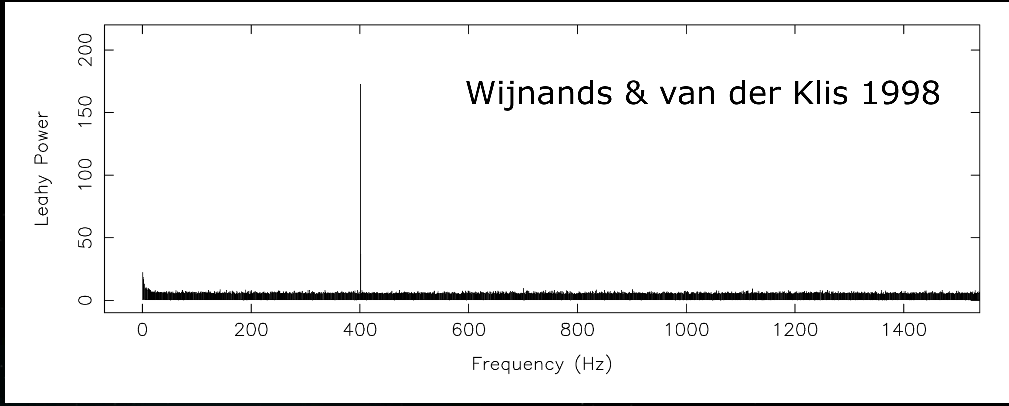
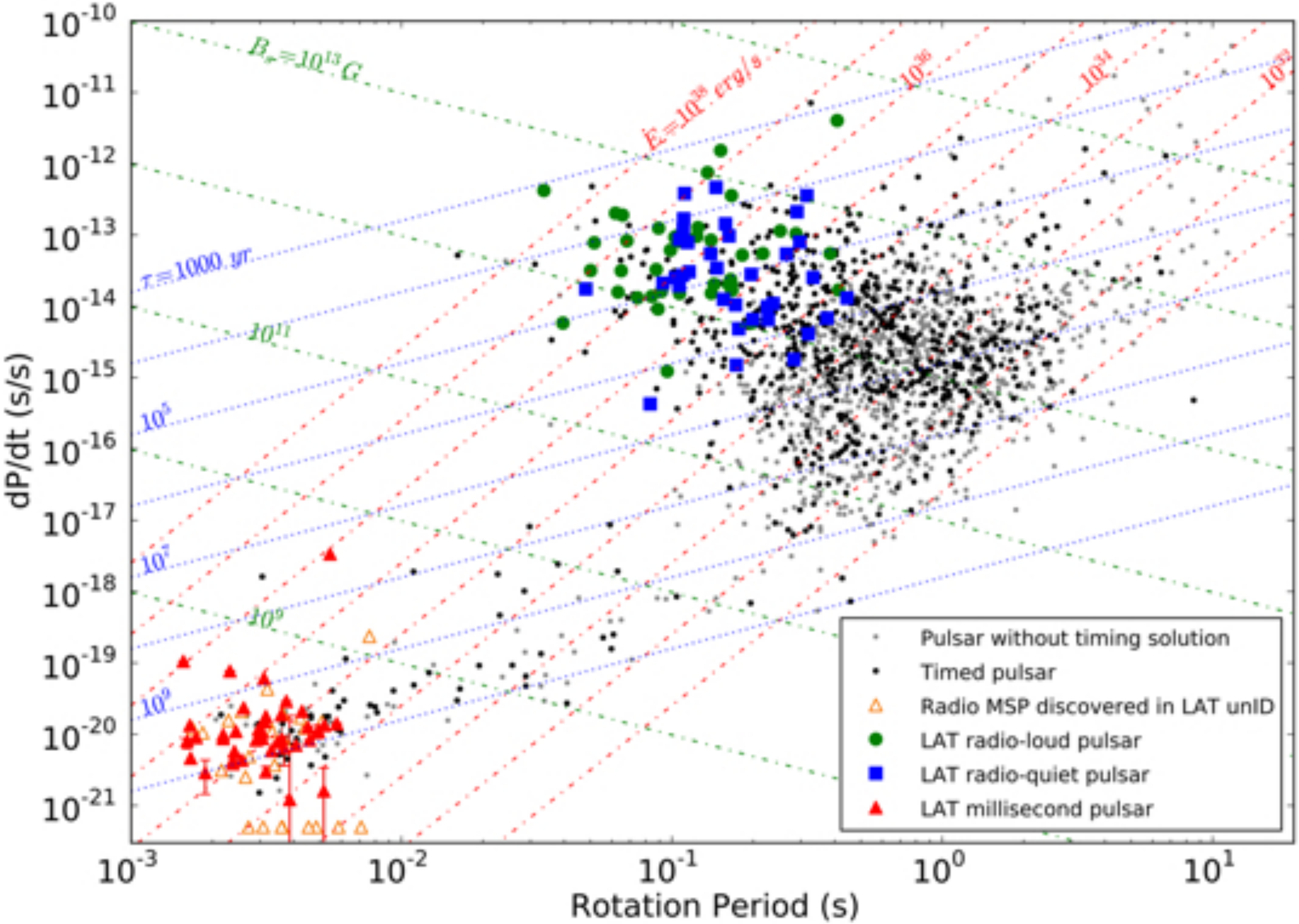


ACCRETING PULSARS







dP/dt (s/s)
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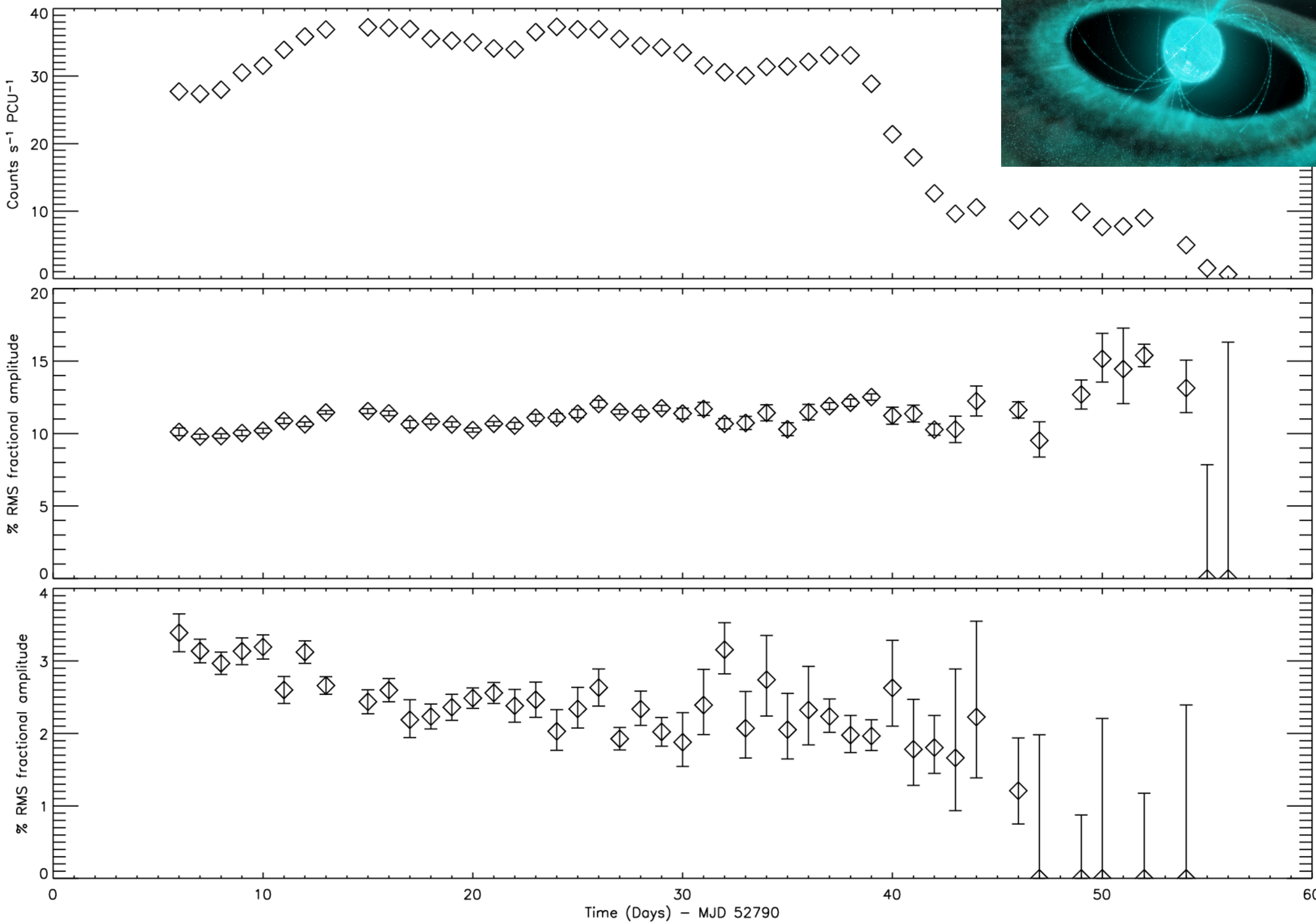
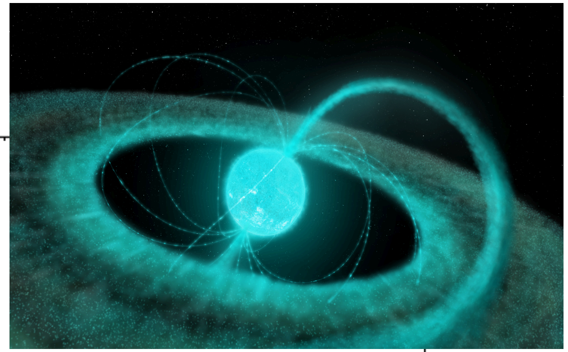
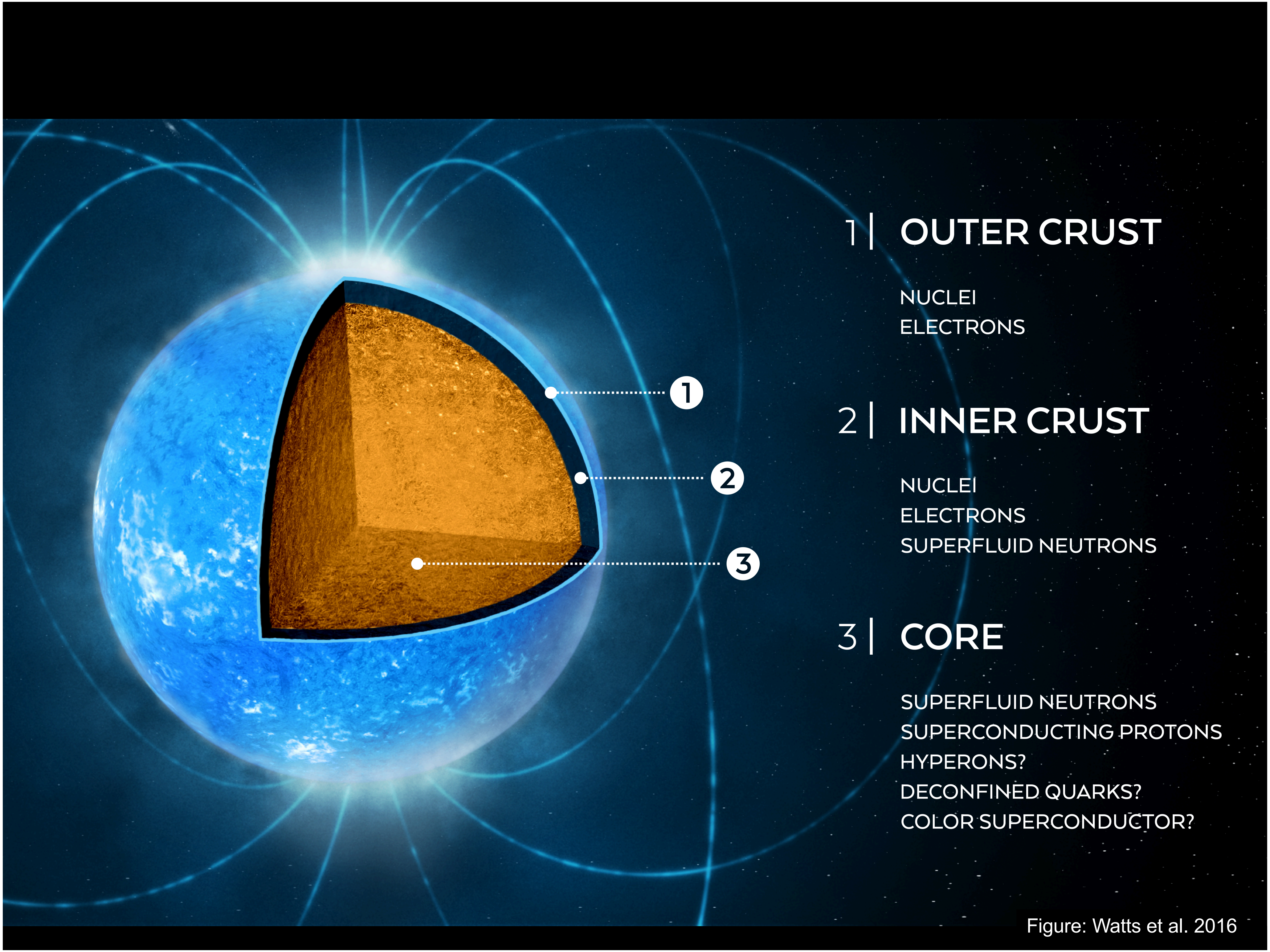
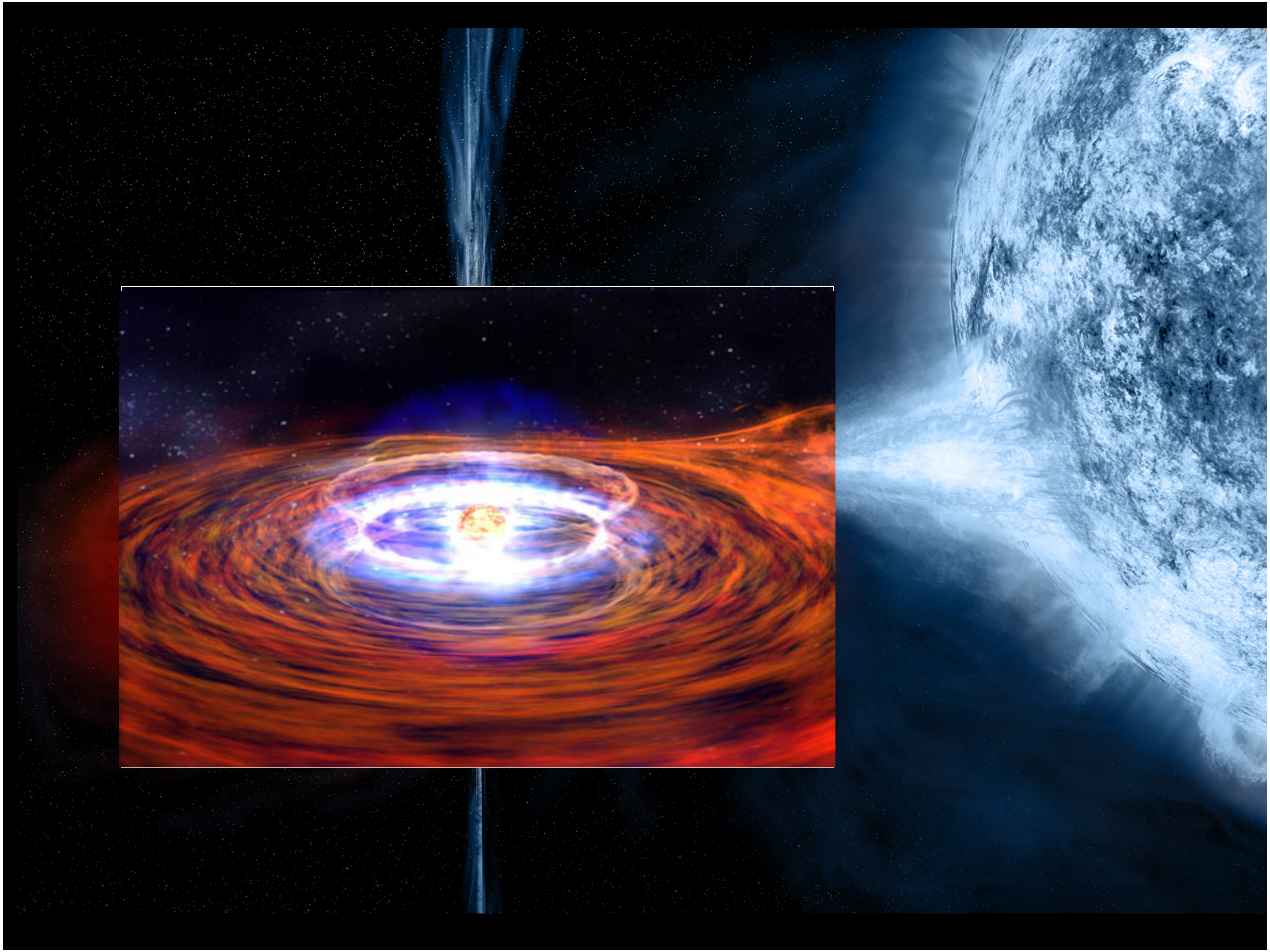
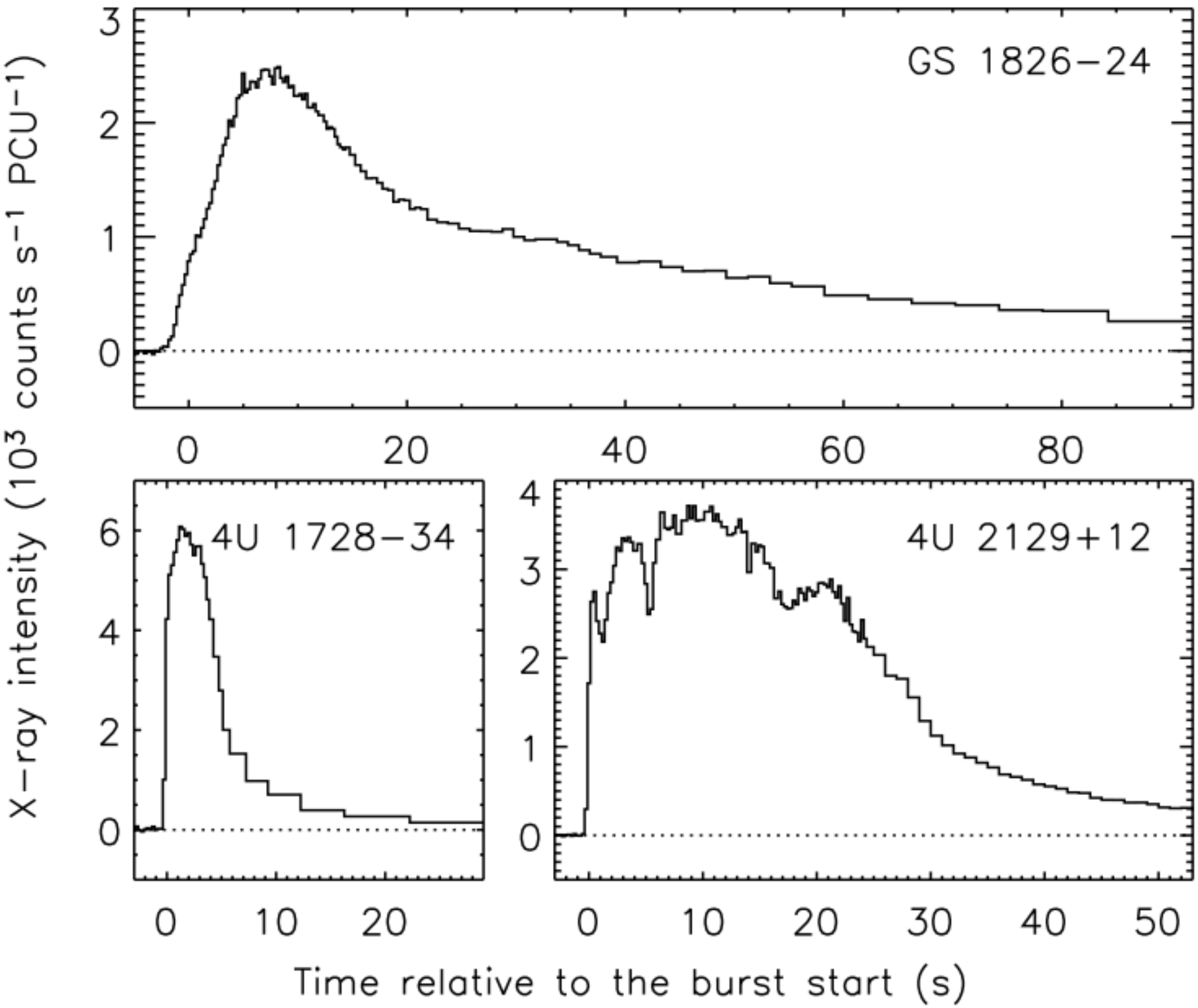




XTE J1814-338, Watts et al. 2005

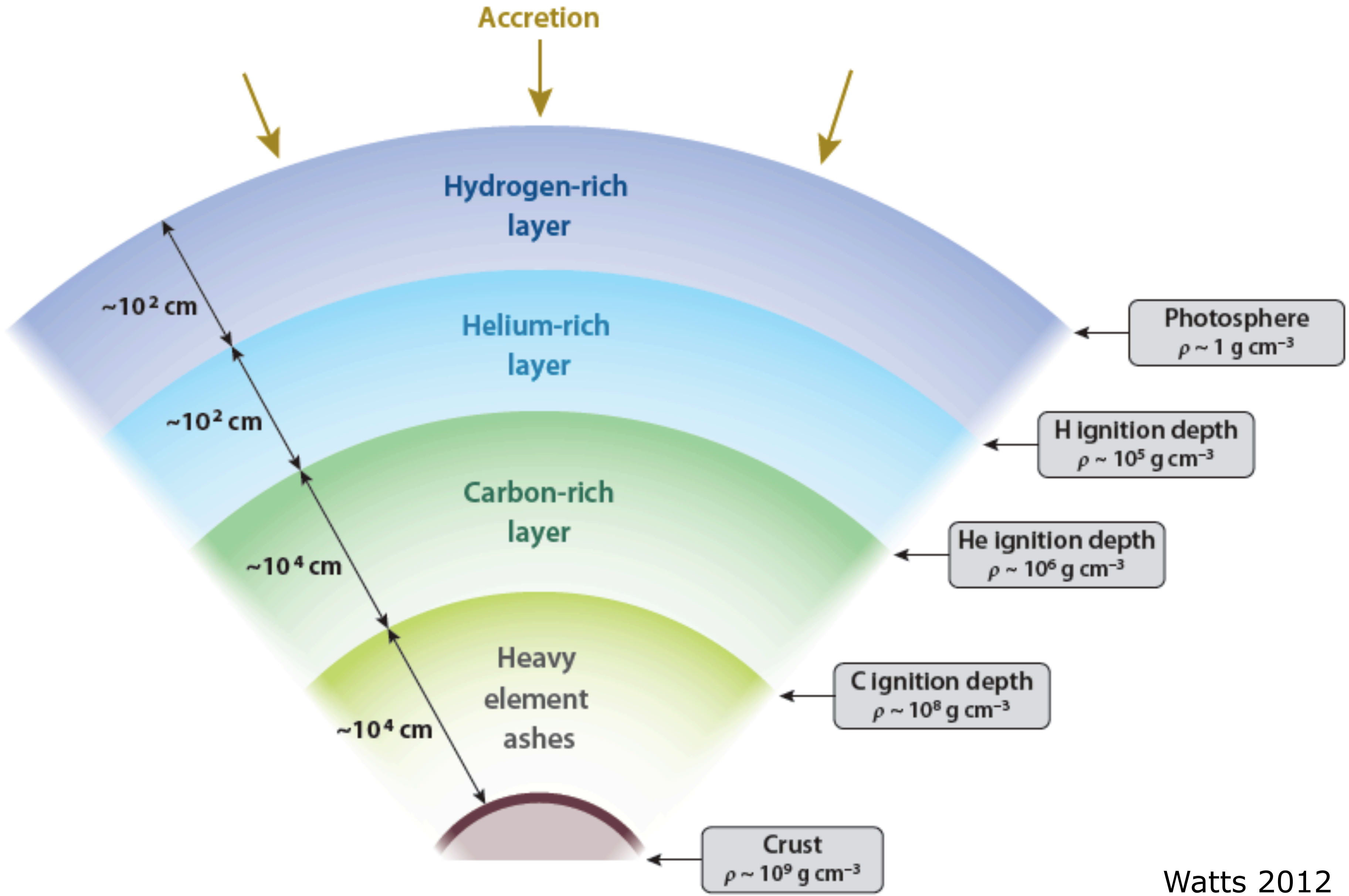

1
2
3
1 | OUTER CRUST
NUCLEI
ELECTRONS
2 | INNER CRUST
NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS
3 | CORE
SUPERFLUID NEUTRONS
SUPERCONDUCTING PROTONS
HYPERONS?
DECONFINED QUARKS?
COLOR SUPERCONDUCTOR?
Figure: Watts et al. 2016





Some typical thermonuclear X-ray bursts: Galloway et al. 2008

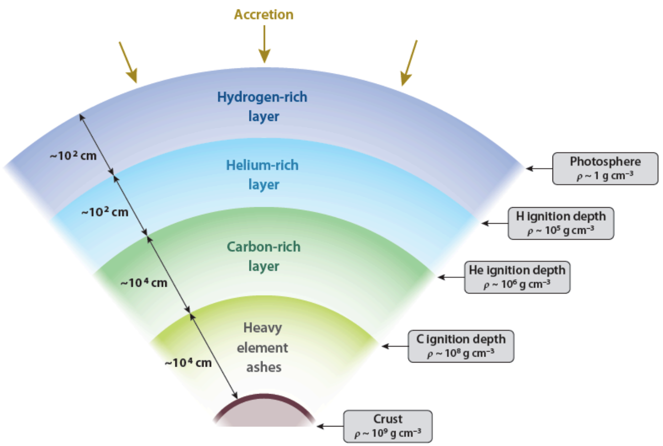
The X-ray burst mechanism

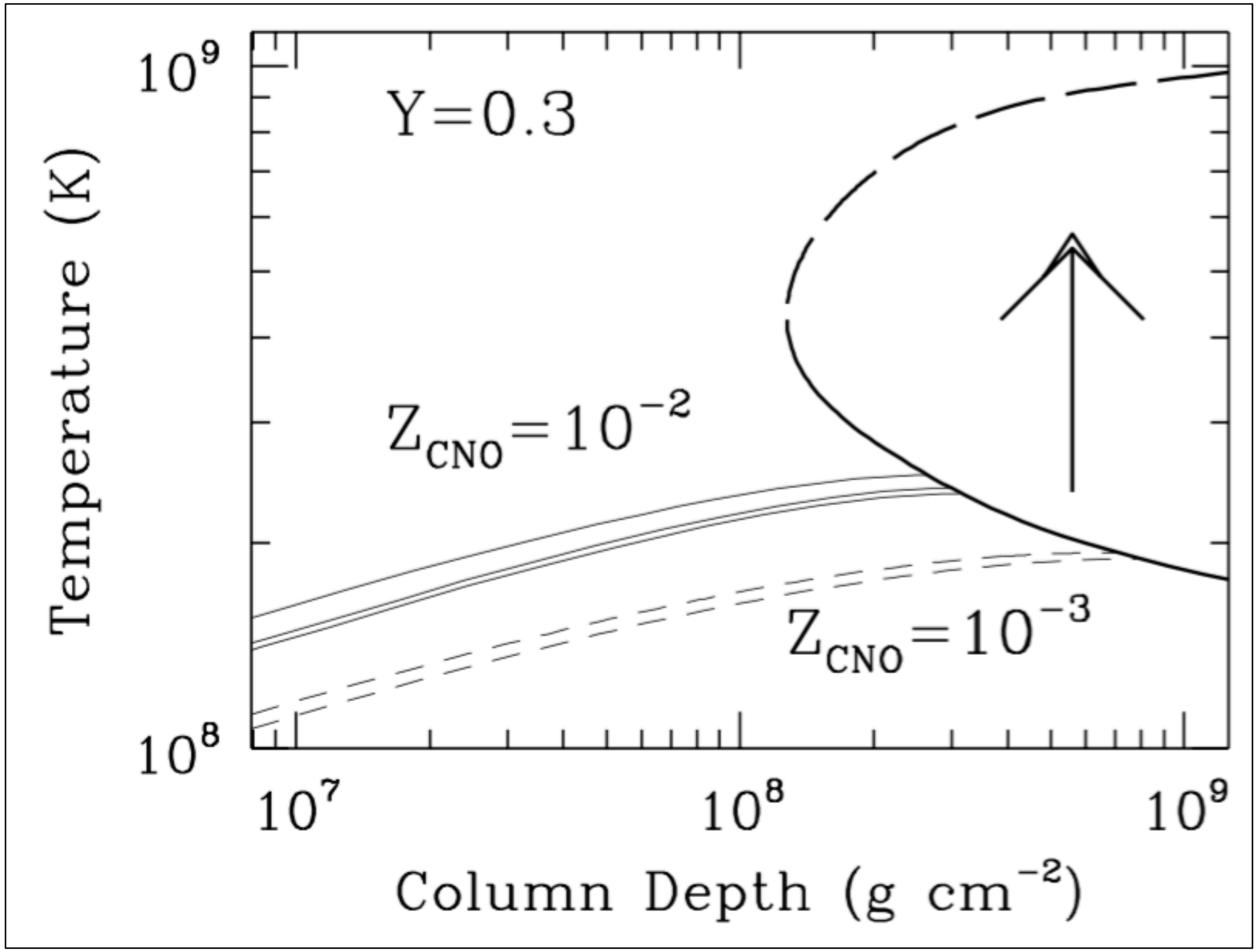


Watts 2012

The X-ray burst mechanism

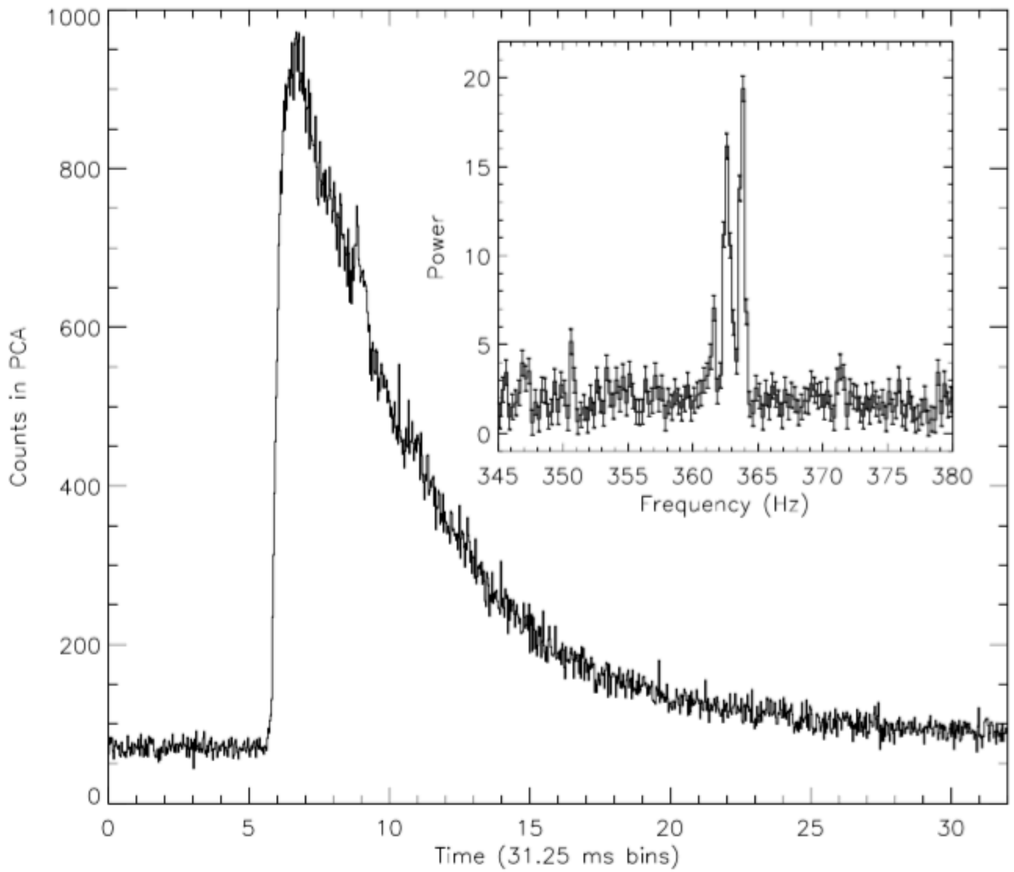
$$\frac{d\epsilon_{3\alpha}}{dT} = -\frac{d\epsilon_{cool}}{dT} \qquad \epsilon_{3\alpha} = 5.3 \times 10^{21} \frac{\rho_5^2 Y^3}{T_8^3} \exp\left(\frac{-44}{T_8}\right) \text{ergs g}^{-1}\text{ s}^{-1}.$$

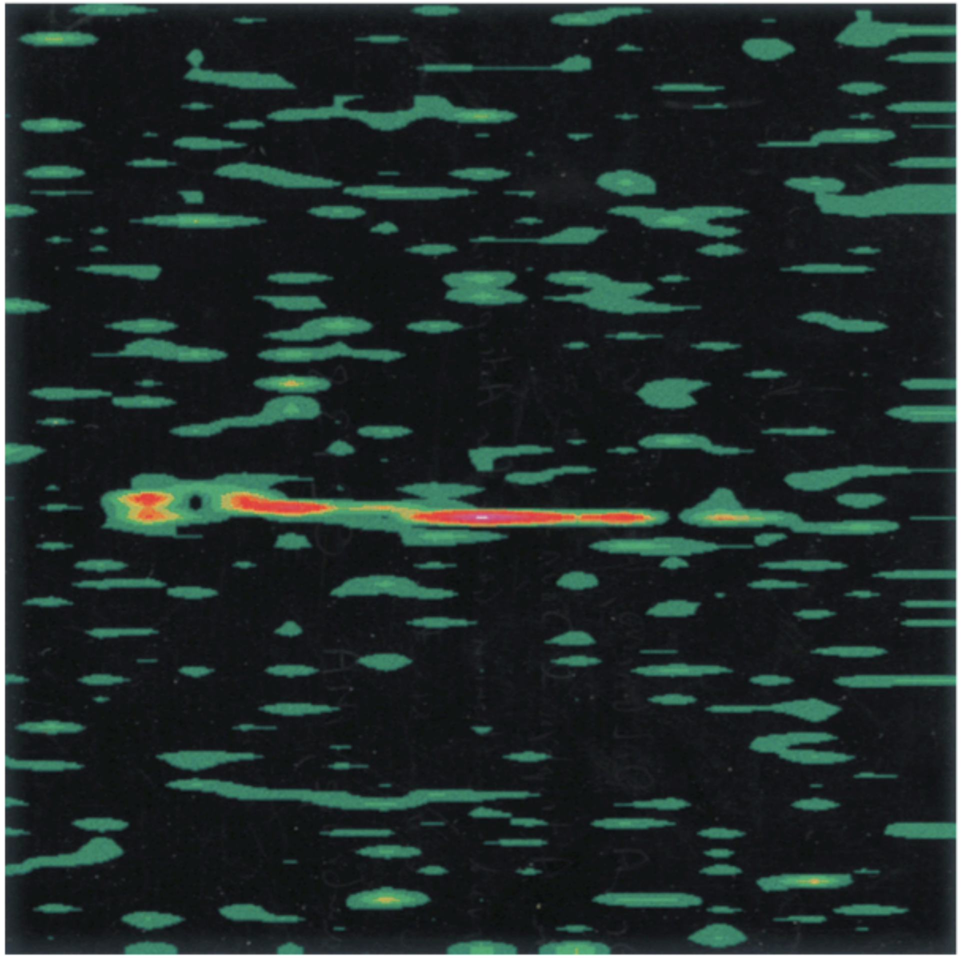




Bildsten 1998

The discovery of 'burst oscillations'

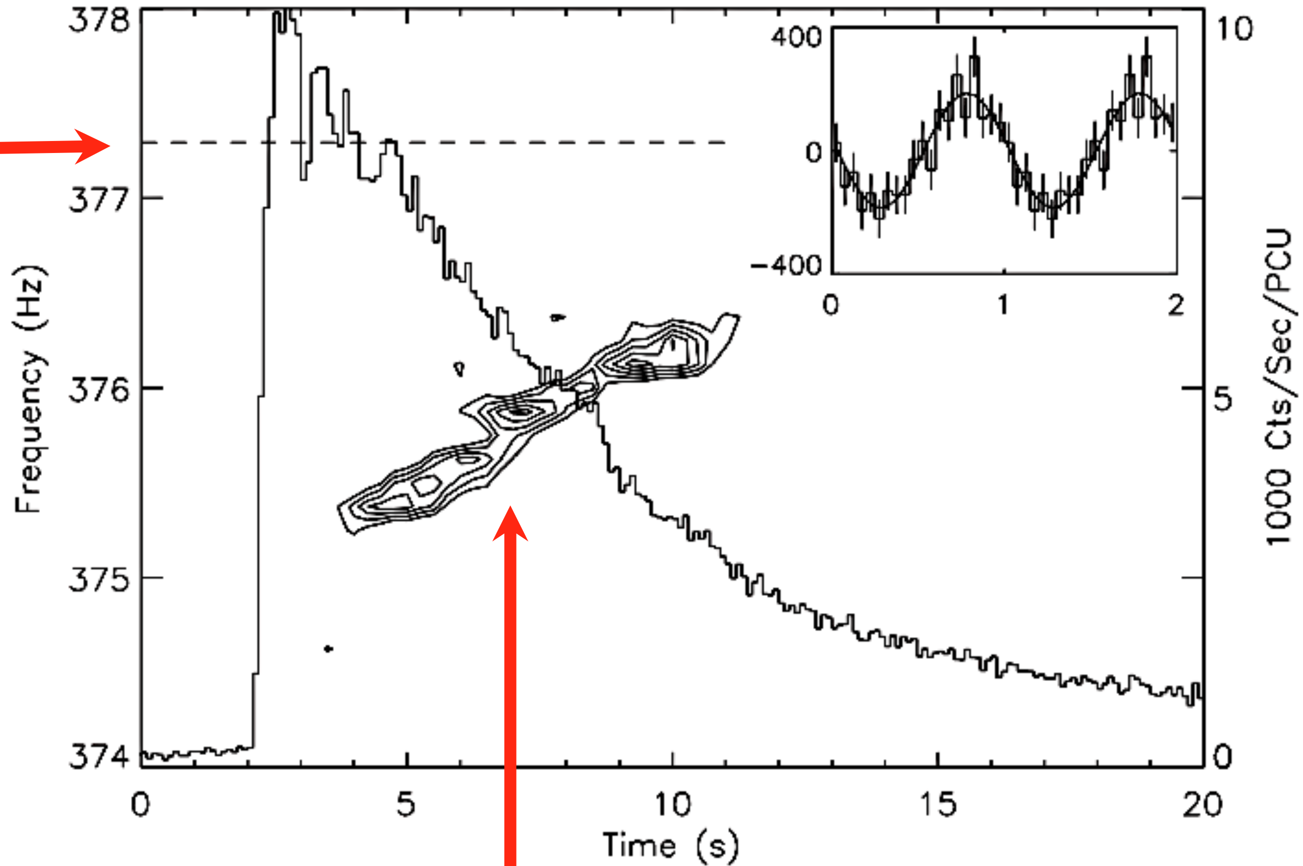




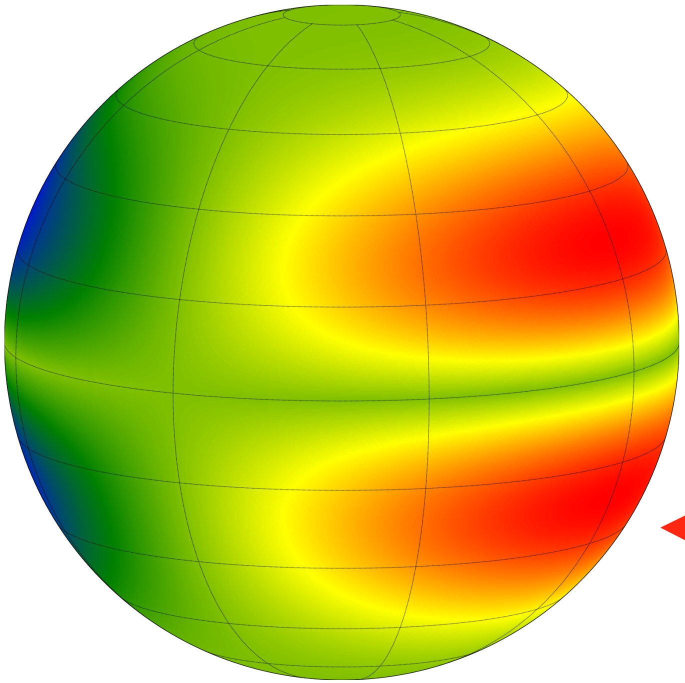
Strohmayer et al. 1996

Relation to spin frequency

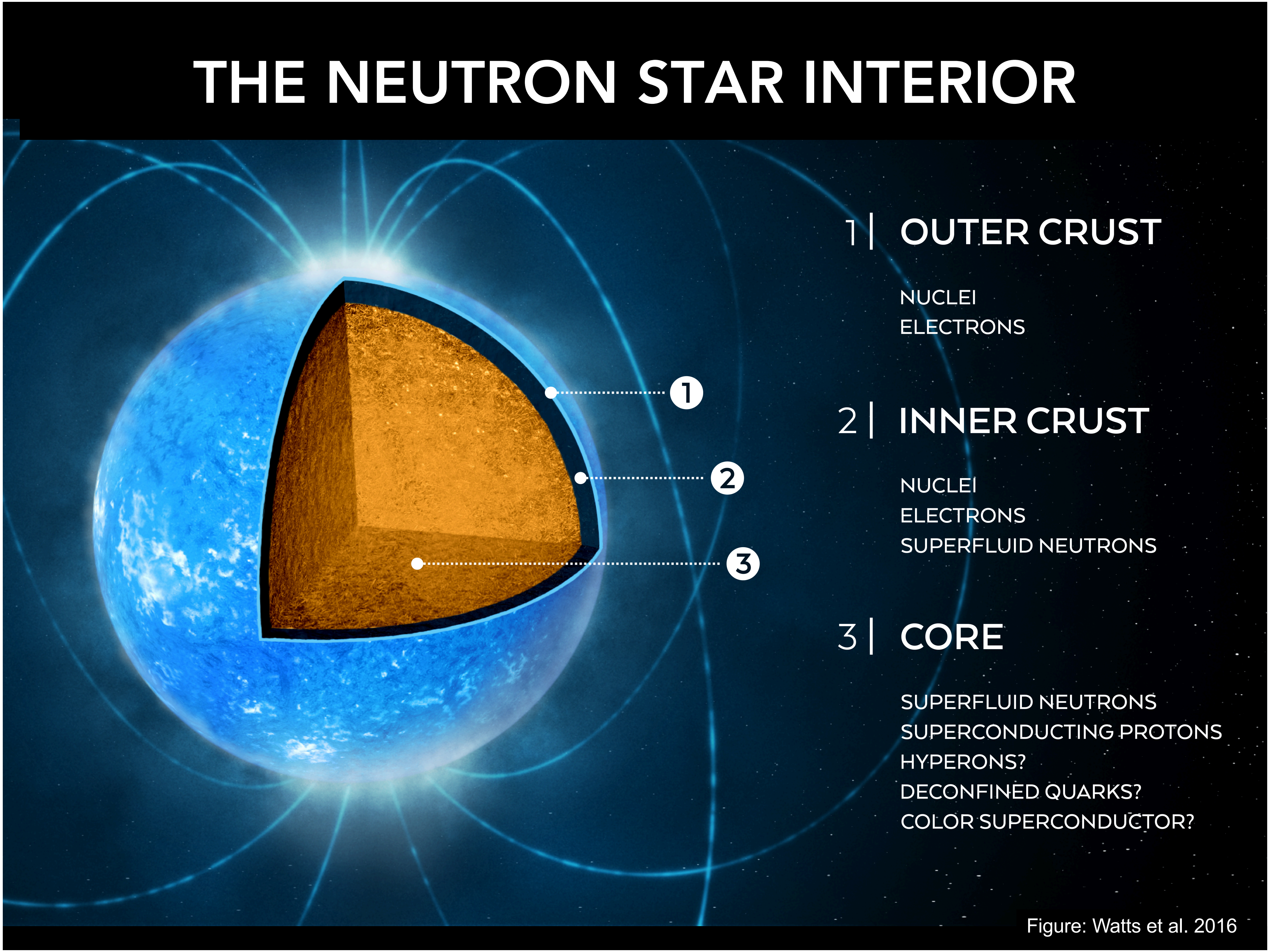
Spin frequency



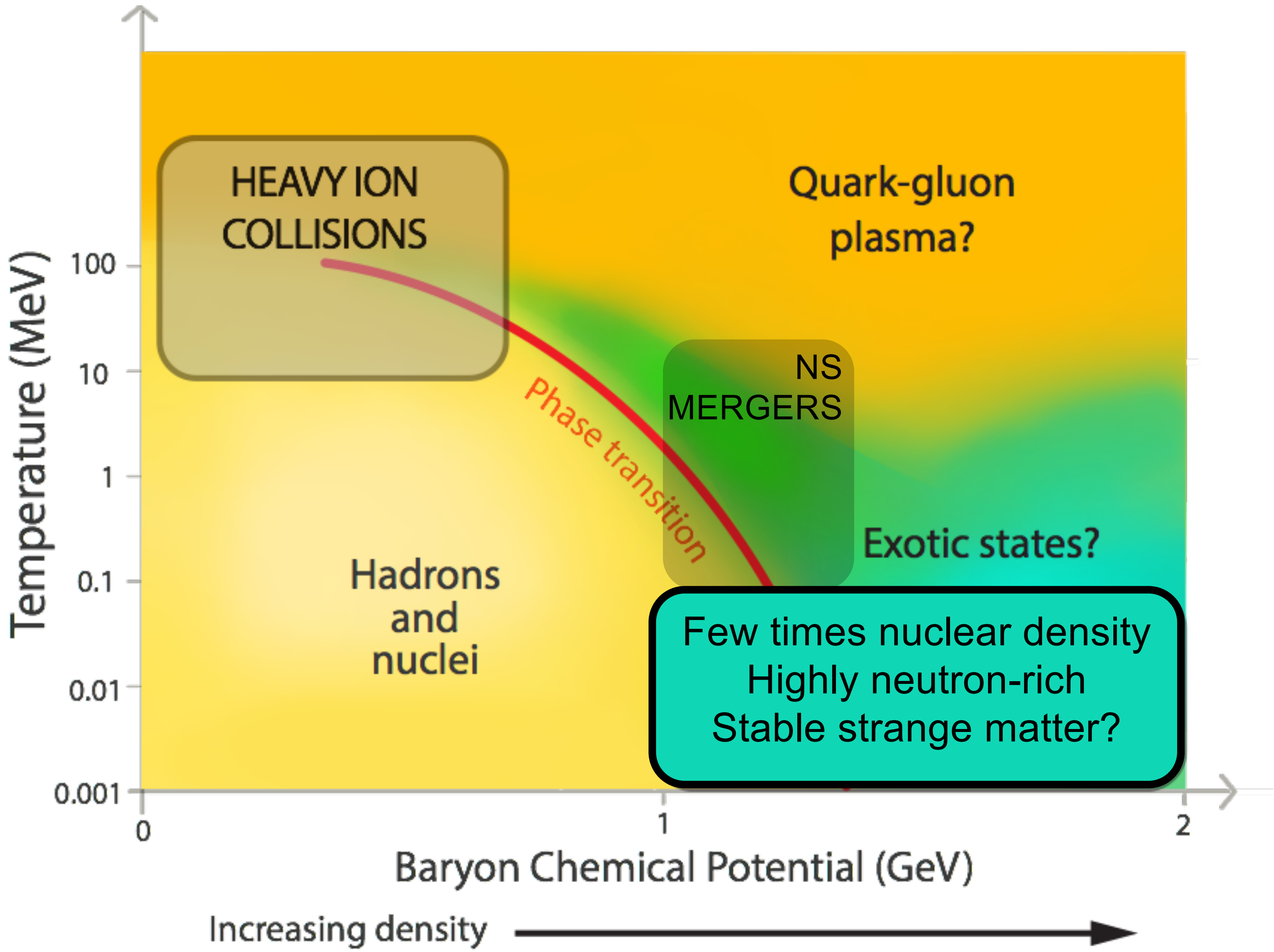
Watts et al. 2009



Drifting hotspot(s)


THE NEUTRON STAR INTERIOR
1
2
3
1 | OUTER CRUST
NUCLEI
ELECTRONS
2 | INNER CRUST
NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS
3 | CORE
SUPERFLUID NEUTRONS
SUPERCONDUCTING PROTONS
HYPERONS?
DECONFINED QUARKS?
COLOR SUPERCONDUCTOR?
Figure: Watts et al. 2016

UNKNOWNS IN STRONG FORCE PHYSICS



FROM NUCLEAR PHYSICS TO TELESCOPE

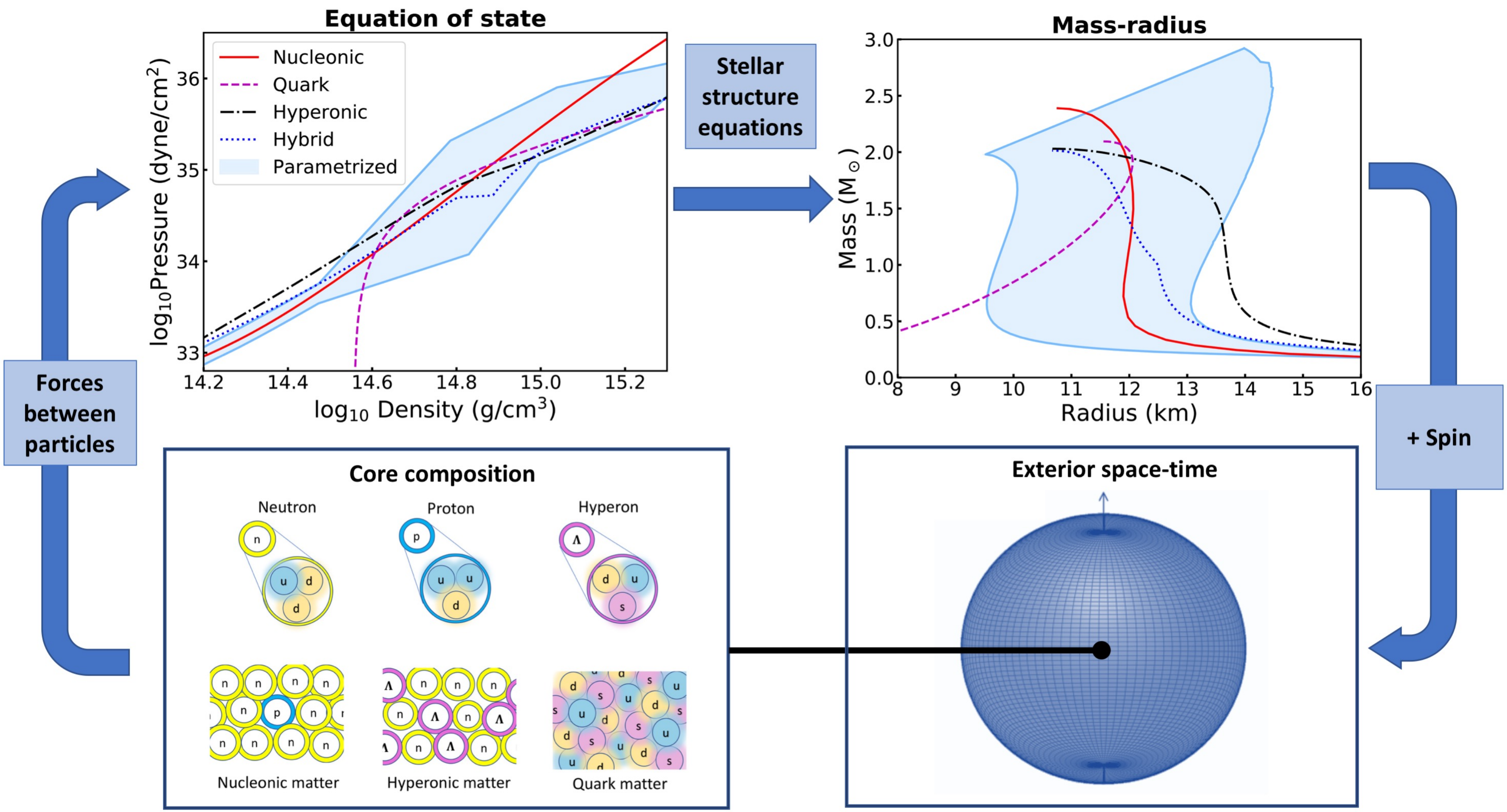


Figure: Adapted from Ray et al. 2019