Pulsars

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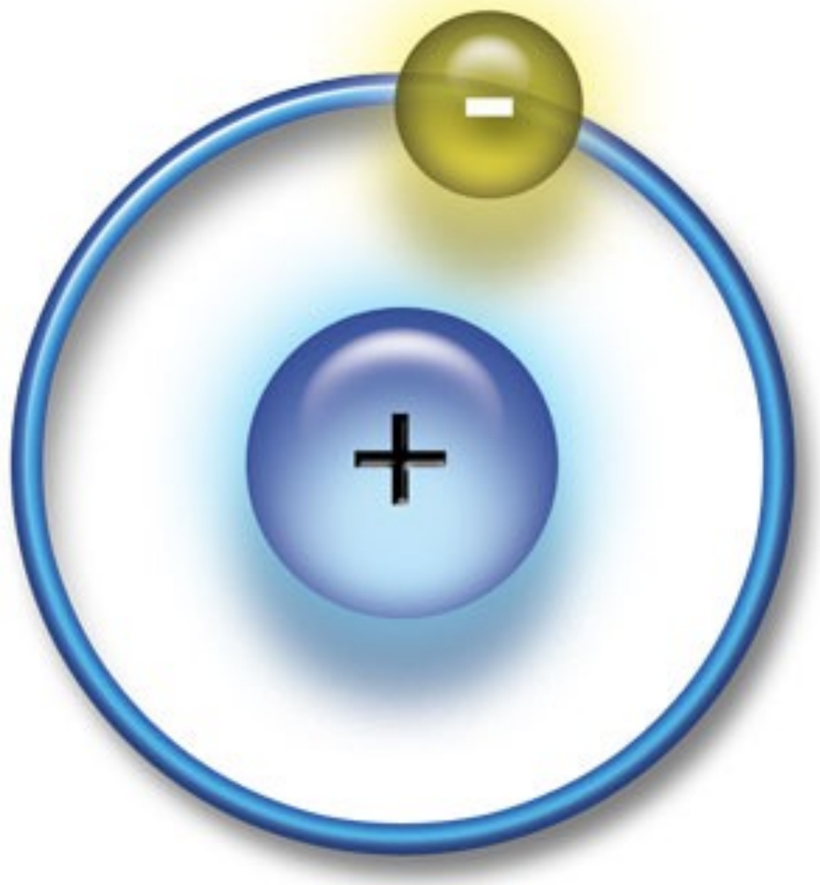
SEZIONE DI TORINO

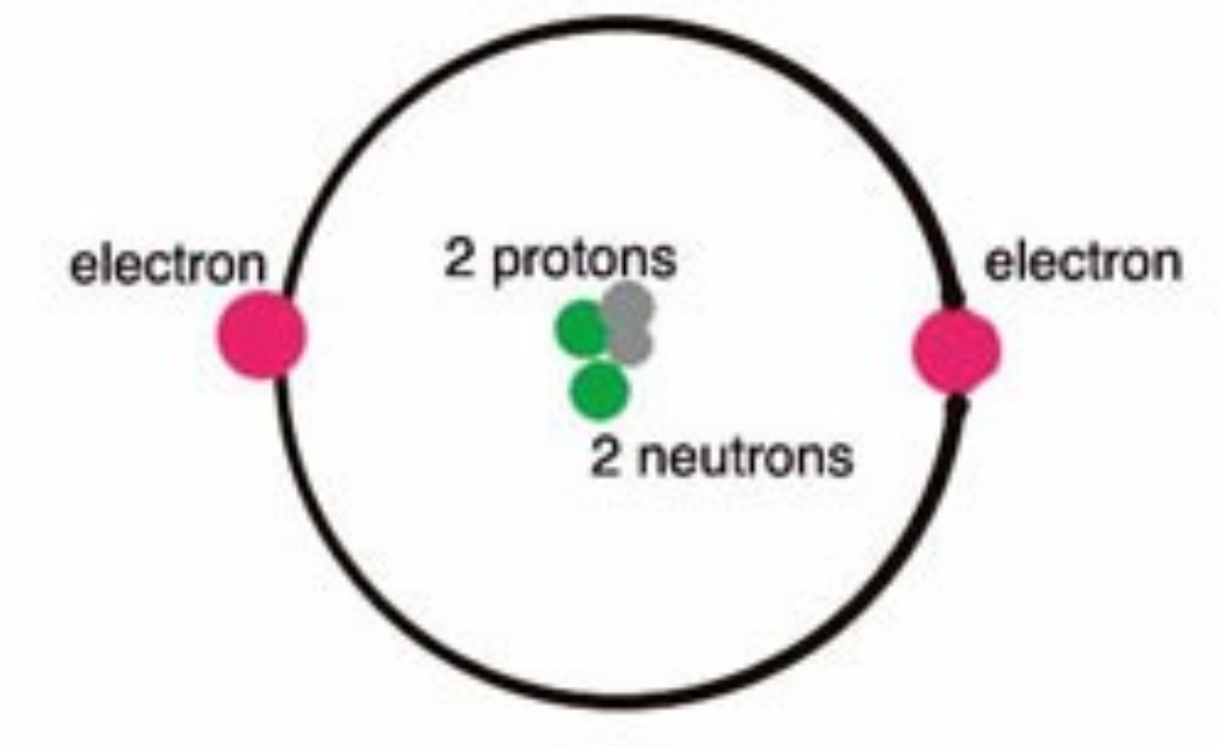
Fermi-LAT, Masterclass, April 5th

Main elements and particle in the Universe

Hydrogen

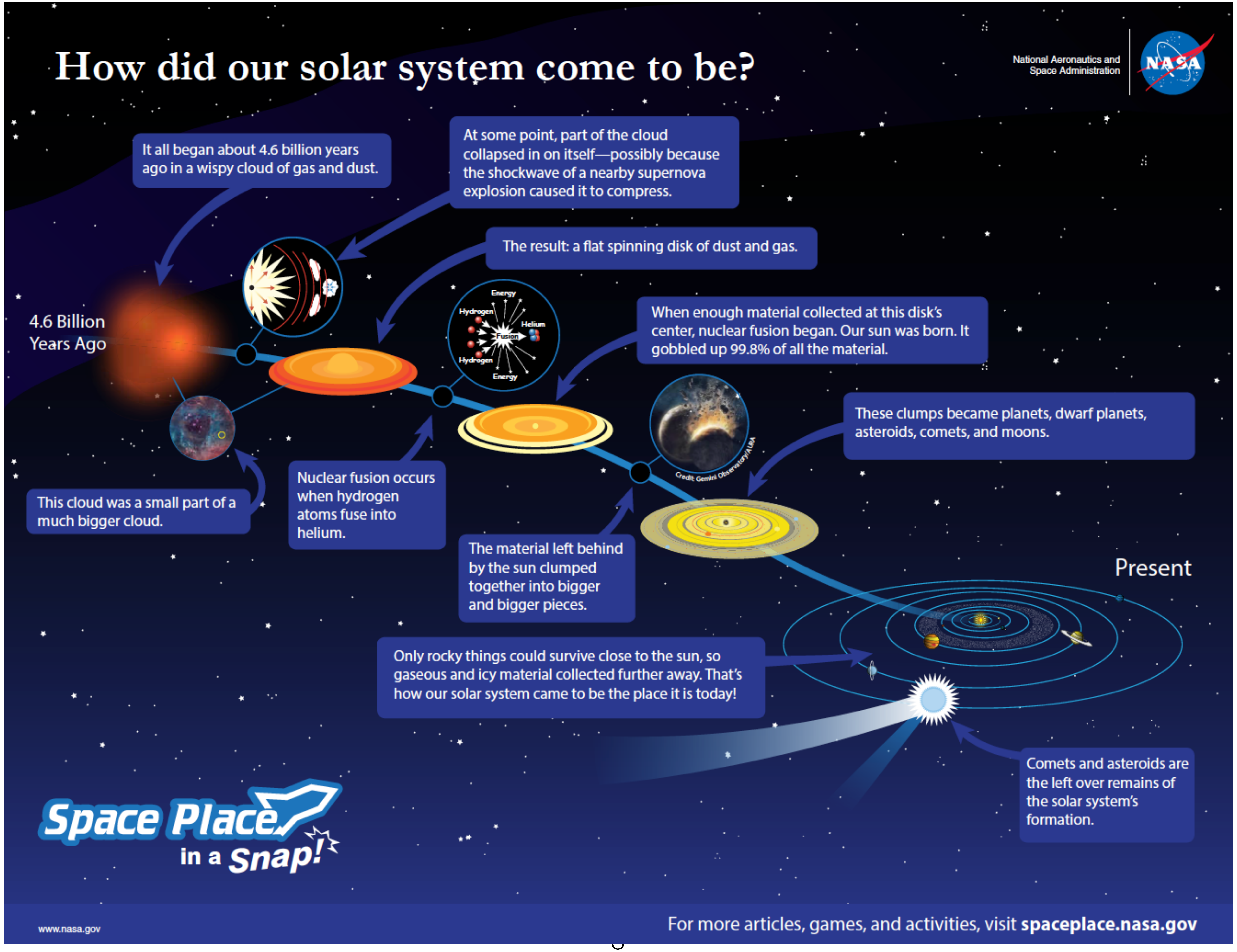


Helium



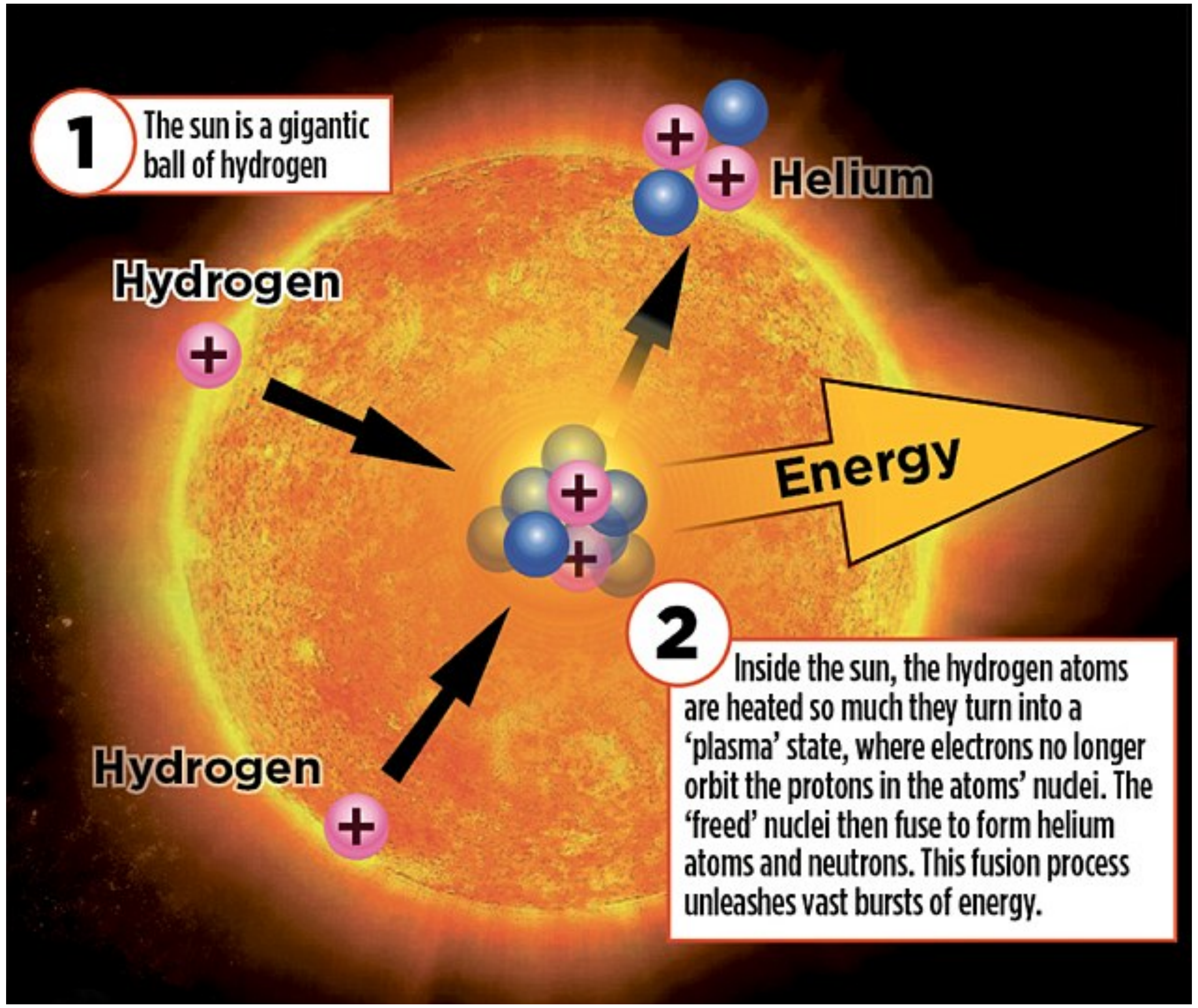
Photon

Formation of the solar system

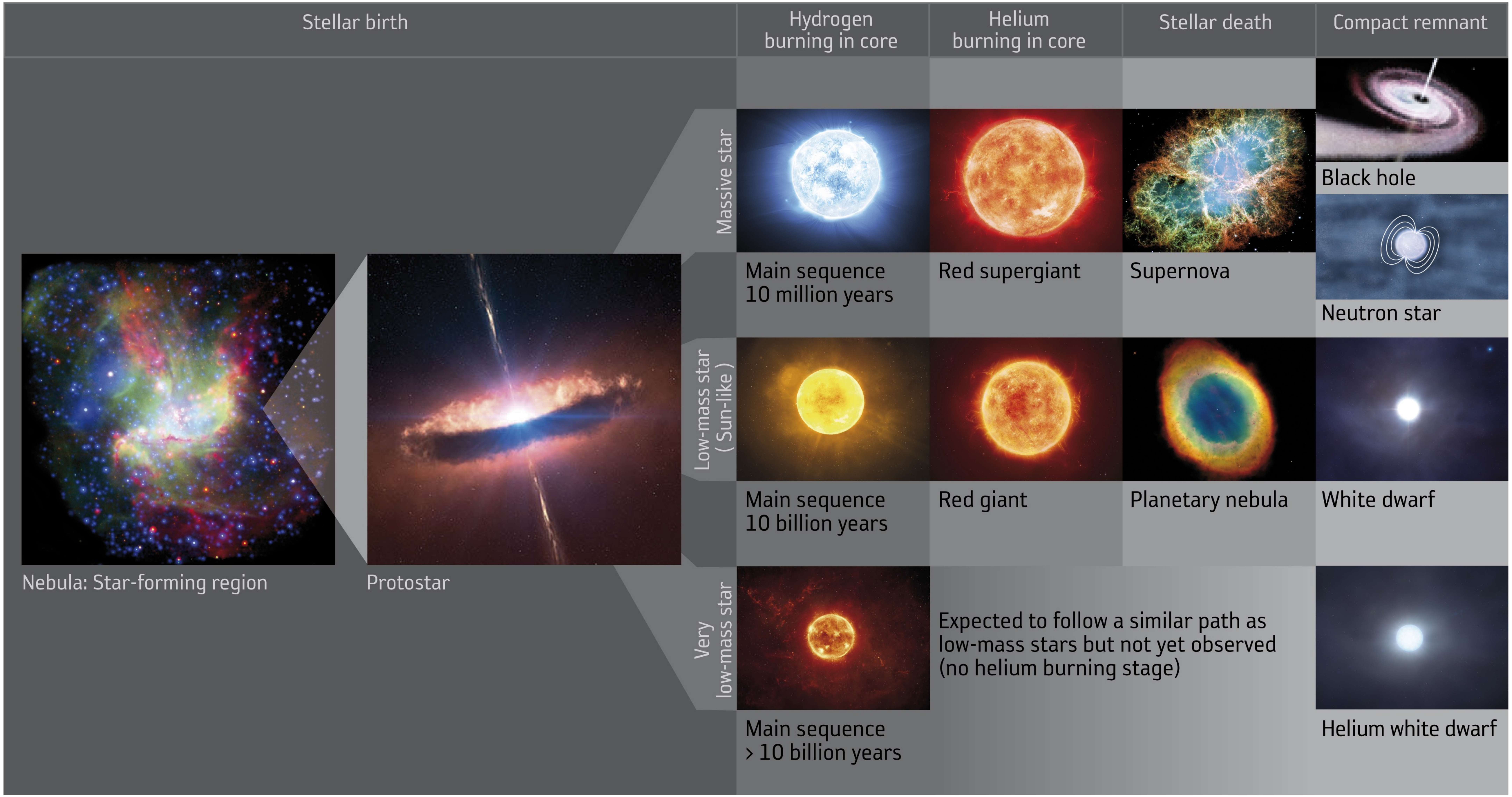


The Sun

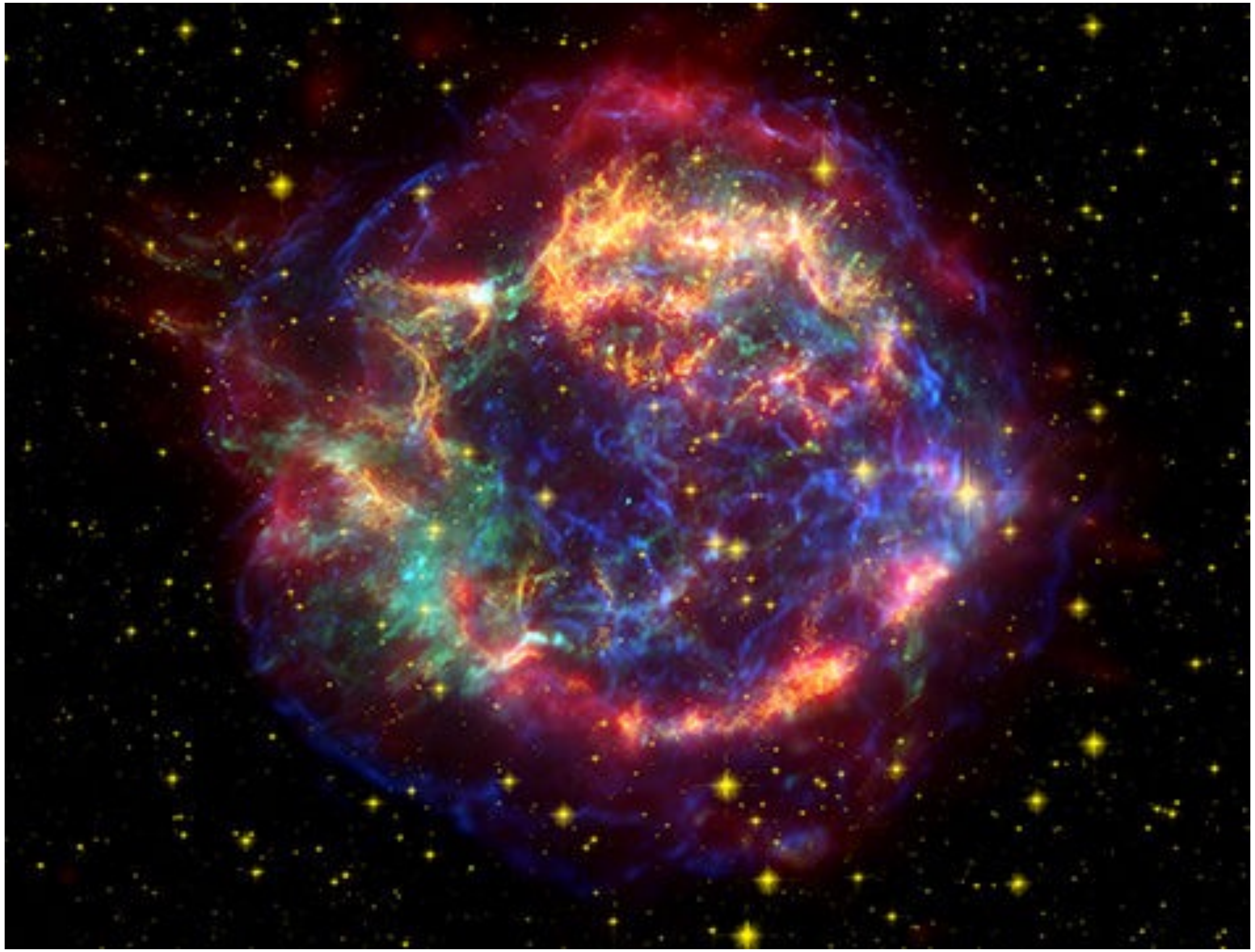
- The **Sun** is the star at the center of the Solar System. It is a nearly perfect sphere of hot plasma.
- It is by far the most important source of energy for life on Earth. Its **diameter is about 109 times that of Earth**, and its **mass is about 330,000 times that of Earth**, accounting for about **99.86% of the total mass of the Solar System.**
- **About three quarters of the Sun's mass consists of hydrogen (~73%); the rest is mostly helium (~25%).**
- The central mass became so hot and dense that it eventually initiated **nuclear fusion** in its core. It is thought that almost all stars form by this process.
- After hydrogen fusion in its core has stopped, the Sun will undergo severe changes and become a red giant. It is calculated that the Sun will become sufficiently large to engulf the current orbits of Mercury, Venus, and possibly Earth.



Life of a star



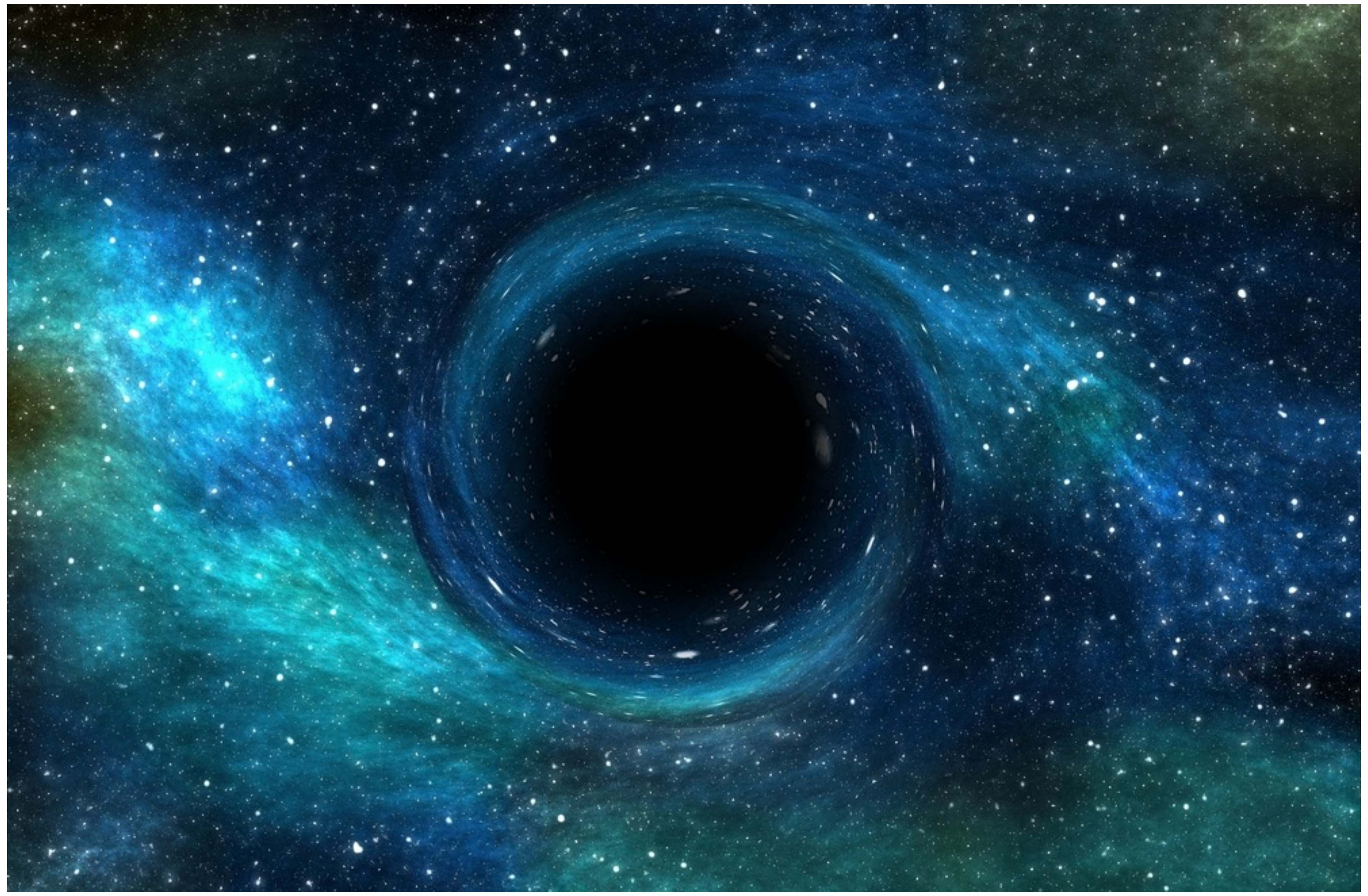
Supernova remnant



Cas A

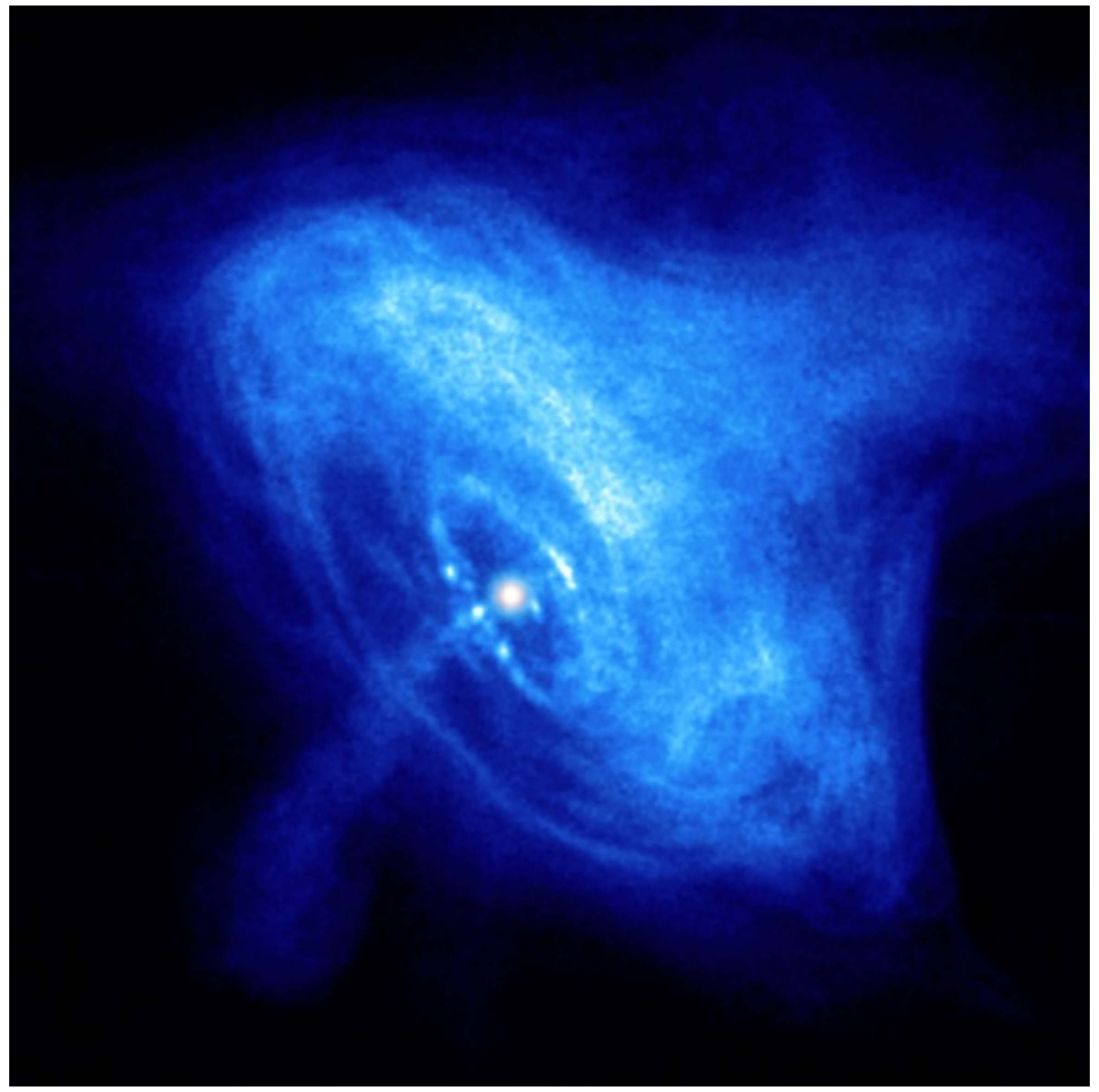
Black hole

A **black hole** is a region of spacetime exhibiting such strong gravitational effects that nothing—not even particles and electromagnetic radiation such as light—can escape from inside it.

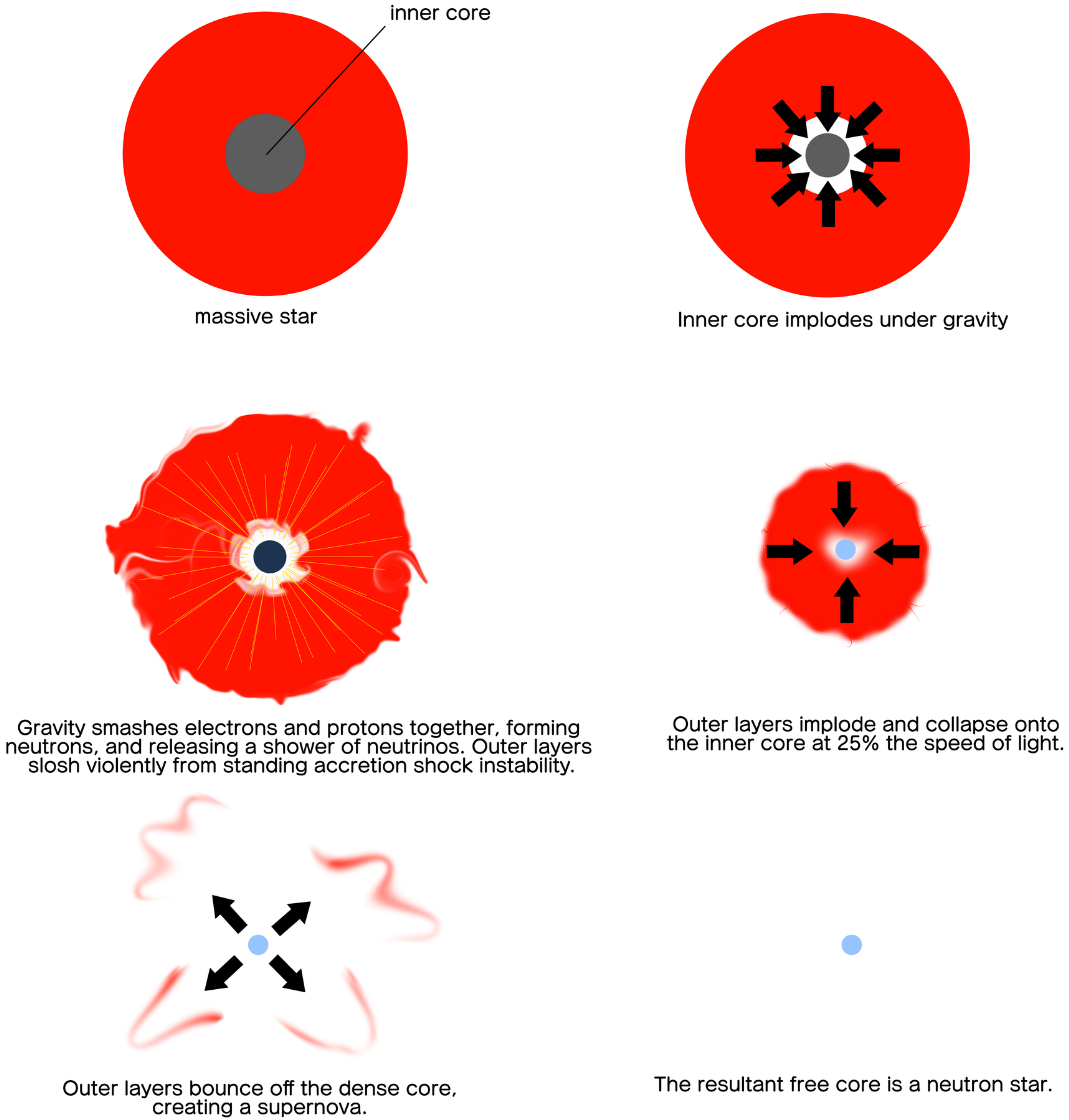


Wikipedia definition of a neutron star

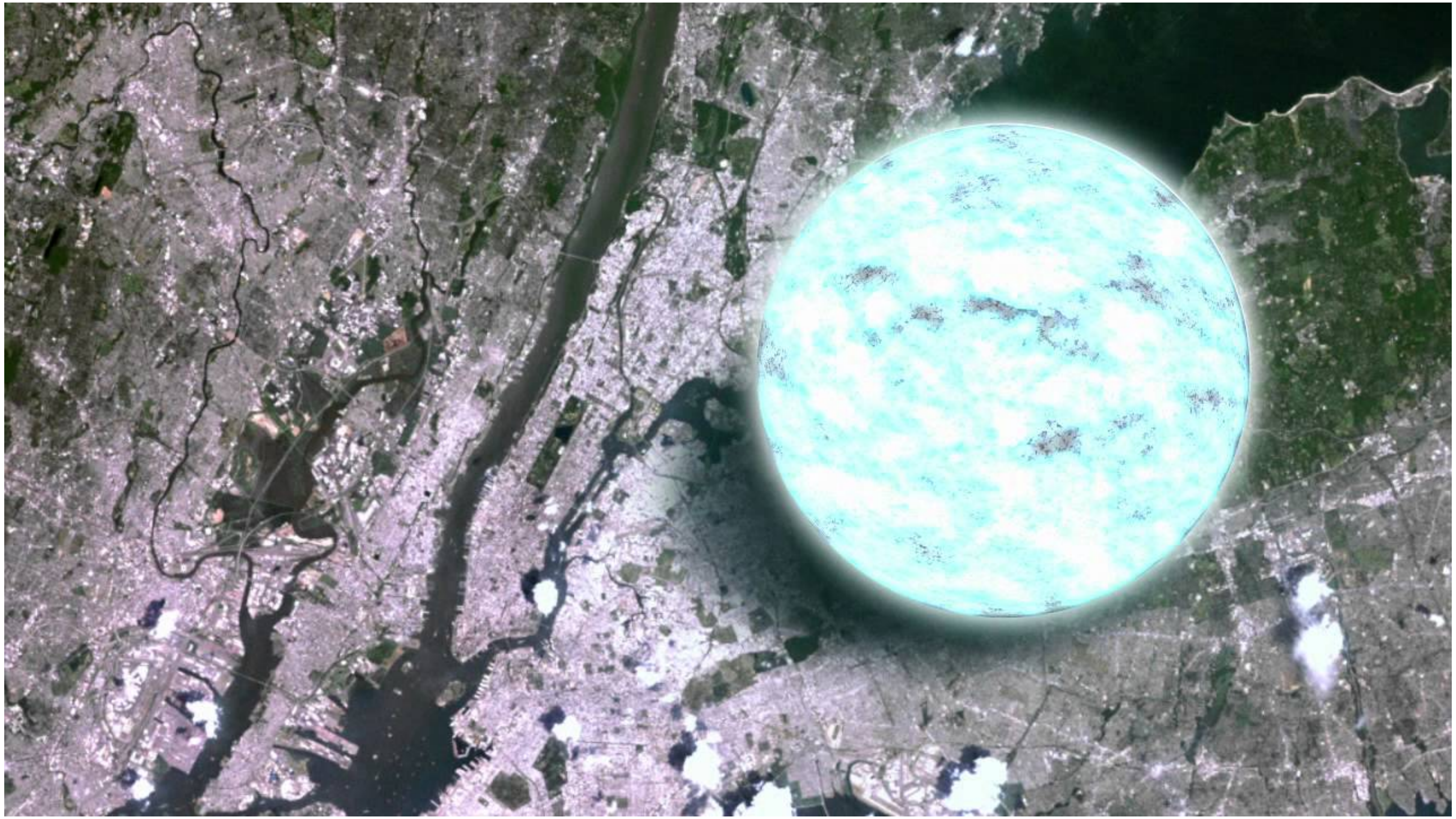
A **neutron star** is the collapsed core of a massive supergiant star, which had a total mass of between 10 and 25 solar masses, possibly more if the star was especially metal-rich.[1] Except for black holes and some hypothetical objects (e.g. white holes and quark stars), neutron stars are the smallest and densest currently known class of stellar objects.[2] Neutron stars have a radius on the order of 10 kilometres (6 mi) and a mass of about 1.4 solar masses.[3] They result from the supernova explosion of a massive star, combined with gravitational collapse, that compresses the core past white dwarf star density to that of atomic nuclei.



Neutron star formation



Pulsar size



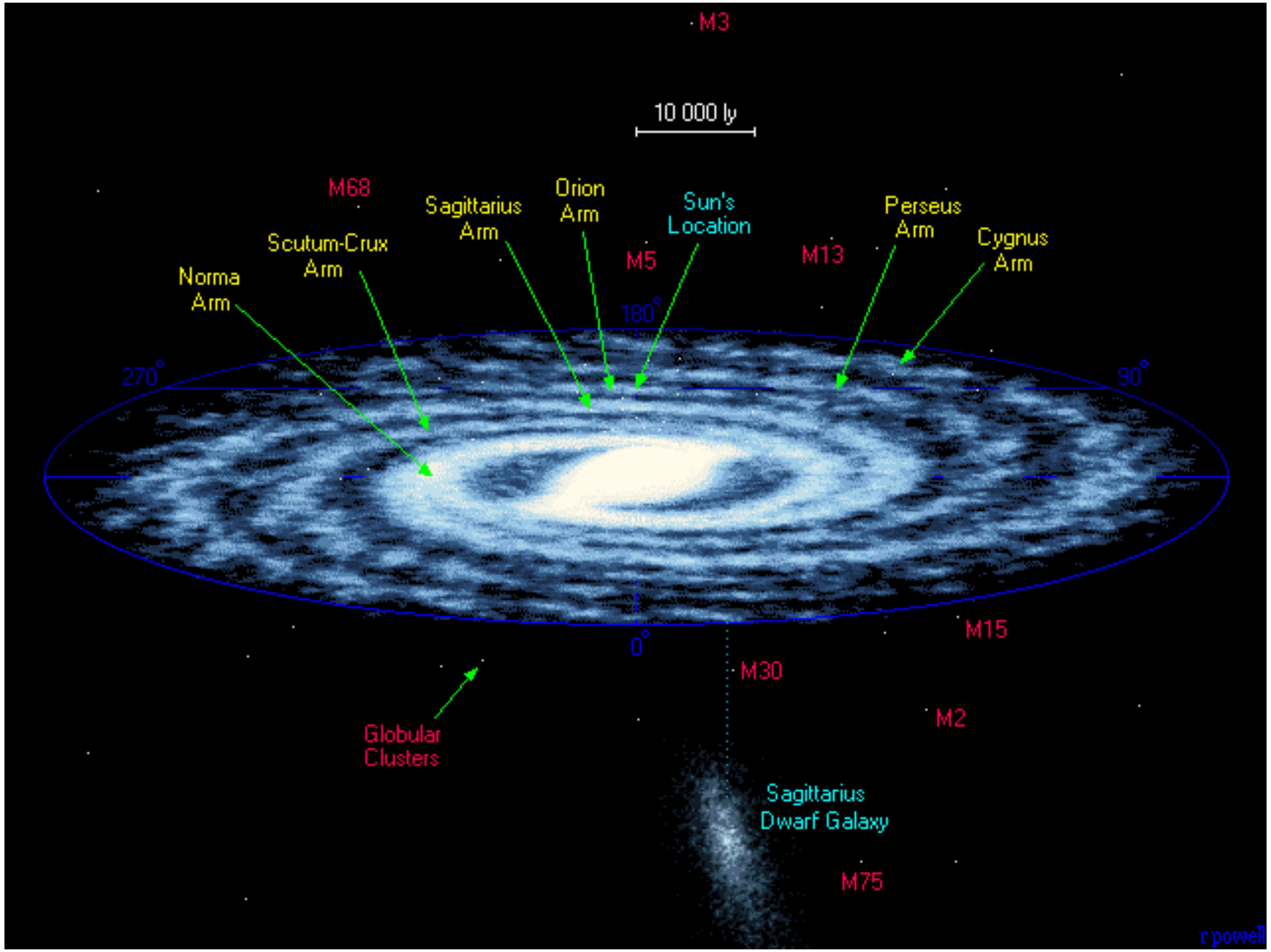
Further characteristics of a neutron star

- Most of the basic models for these objects imply that neutron stars are composed almost entirely of neutrons (subatomic particles with no net electrical charge and with slightly larger mass than protons).
- Neutron stars that can be observed are very hot and typically have a surface temperature of around 600000 K (sun temperature is 100 time smaller).
- Neutron star material is remarkably dense: a normal-sized matchbox containing neutron-star material would have a weight of approximately 3 billion tonnes, the same weight as a 0.5 cubic kilometre chunk of the Earth (a cube with edges of about 800 metres) from Earth's surface.
- Their magnetic fields are between 10^8 and 10^{15} (100 million and 1 quadrillion) times stronger than Earth's magnetic field. The gravitational field at the neutron star's surface is about 2×10^{11} (200 billion) times that of Earth's gravitational field. The magnetic field strength on the surface of neutron stars ranges from. These are orders of magnitude higher than in any other object: For comparison, a continuous 10^5 T field has been achieved in the laboratory.

Further characteristics of a neutron star

- As the star's core collapses, its rotation rate increases due to conservation of angular momentum, and newly formed neutron stars rotate at up to several hundred times per second.
- Some neutron stars emit beams of electromagnetic radiation that make them detectable as pulsars. Indeed, the discovery of pulsars by Jocelyn Bell Burnell and Antony Hewish in 1967 was the first observational suggestion that neutron stars exist.
- The radiation from pulsars is thought to be primarily emitted from regions near their magnetic poles.

Milky Way



M3
10 000 ly
M68
Sagittarius Arm
Orion Arm
Sun's Location
Perseus Arm
Cygnus Arm
Scutum-Crux Arm
Norma Arm
M5
M13
180°
270°
90°
0°
M15
M30
M2
Globular Clusters
Sagittarius Dwarf Galaxy
M75
r powell

View of another galaxy

This picture of the nearby galaxy NGC 6744, a Milky Way look-alike, was taken with the Wide Field Imager on the MPG/ESO 2.2-metre telescope at La Silla.
Credit: ESO

Milky Way structure

- The **Solar System** is located within the disk, about 27,000 light-years from the Galactic Center, on the inner edge of one of the spiral-shaped concentrations of gas and dust called the Orion Arm.
- The **stars in the inner ≈10,000 light-years** form a bulge and one or more bars that radiate from the bulge. The very center is marked by an intense radio source, named Sagittarius A*, which is likely to be a supermassive black hole.

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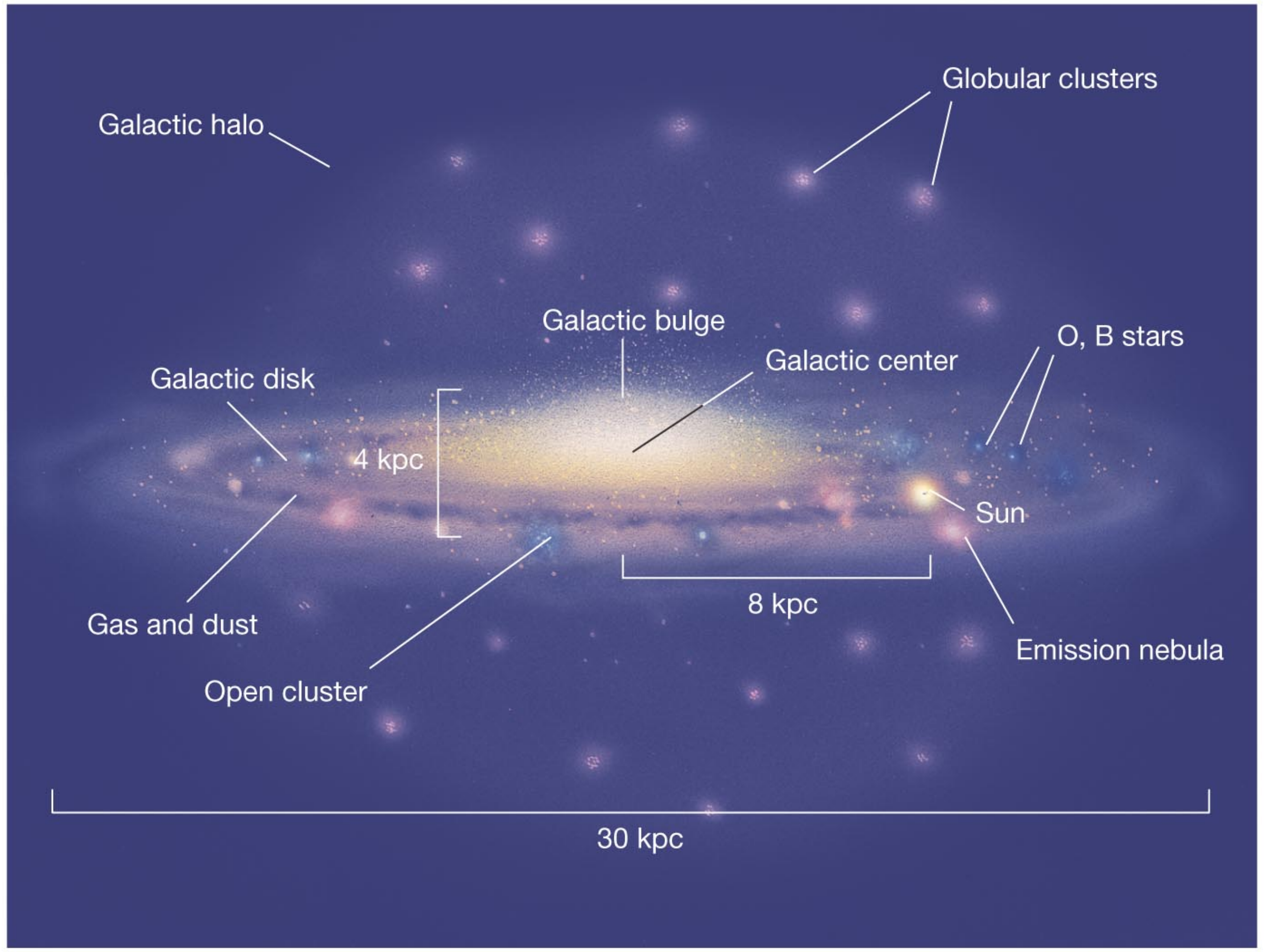
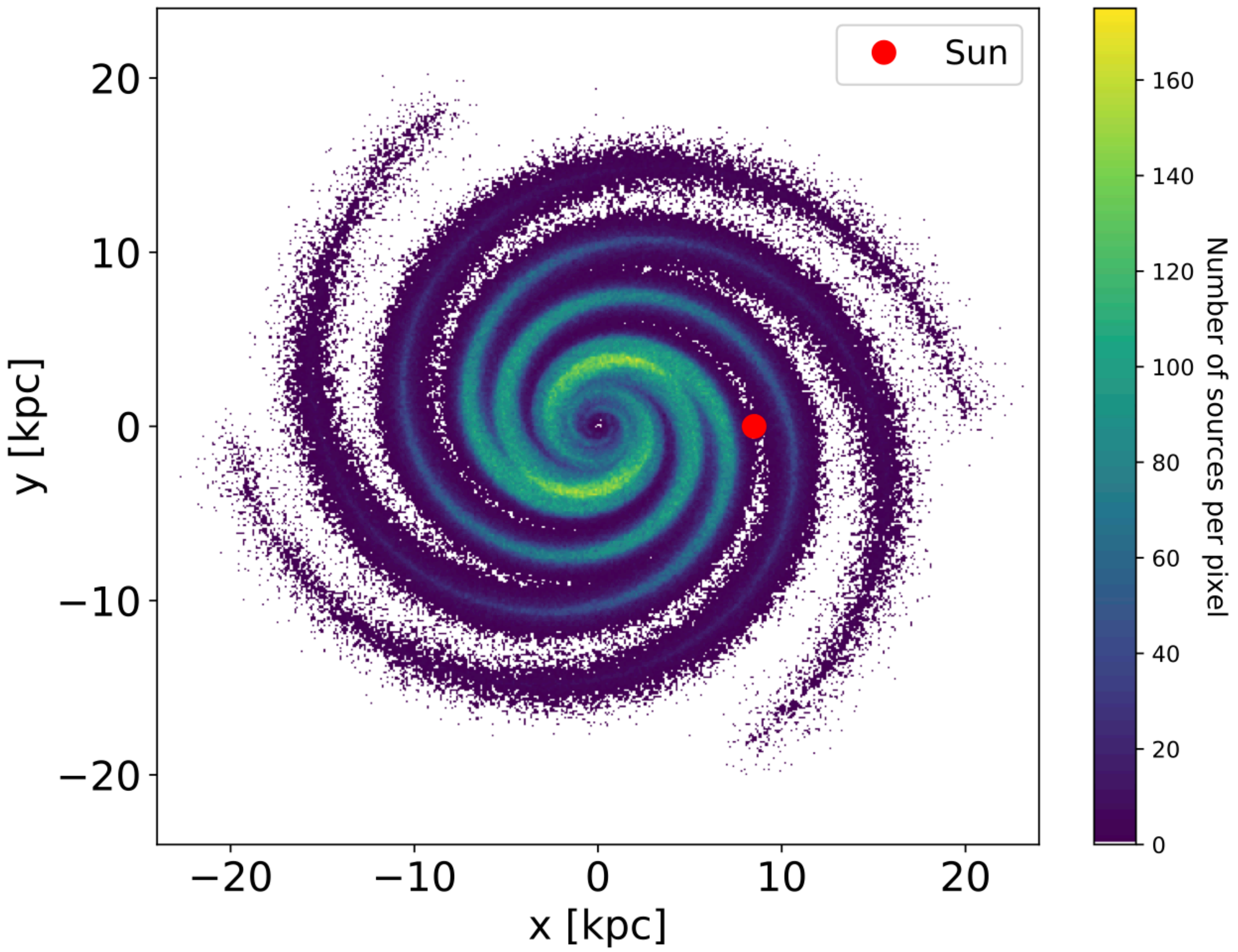
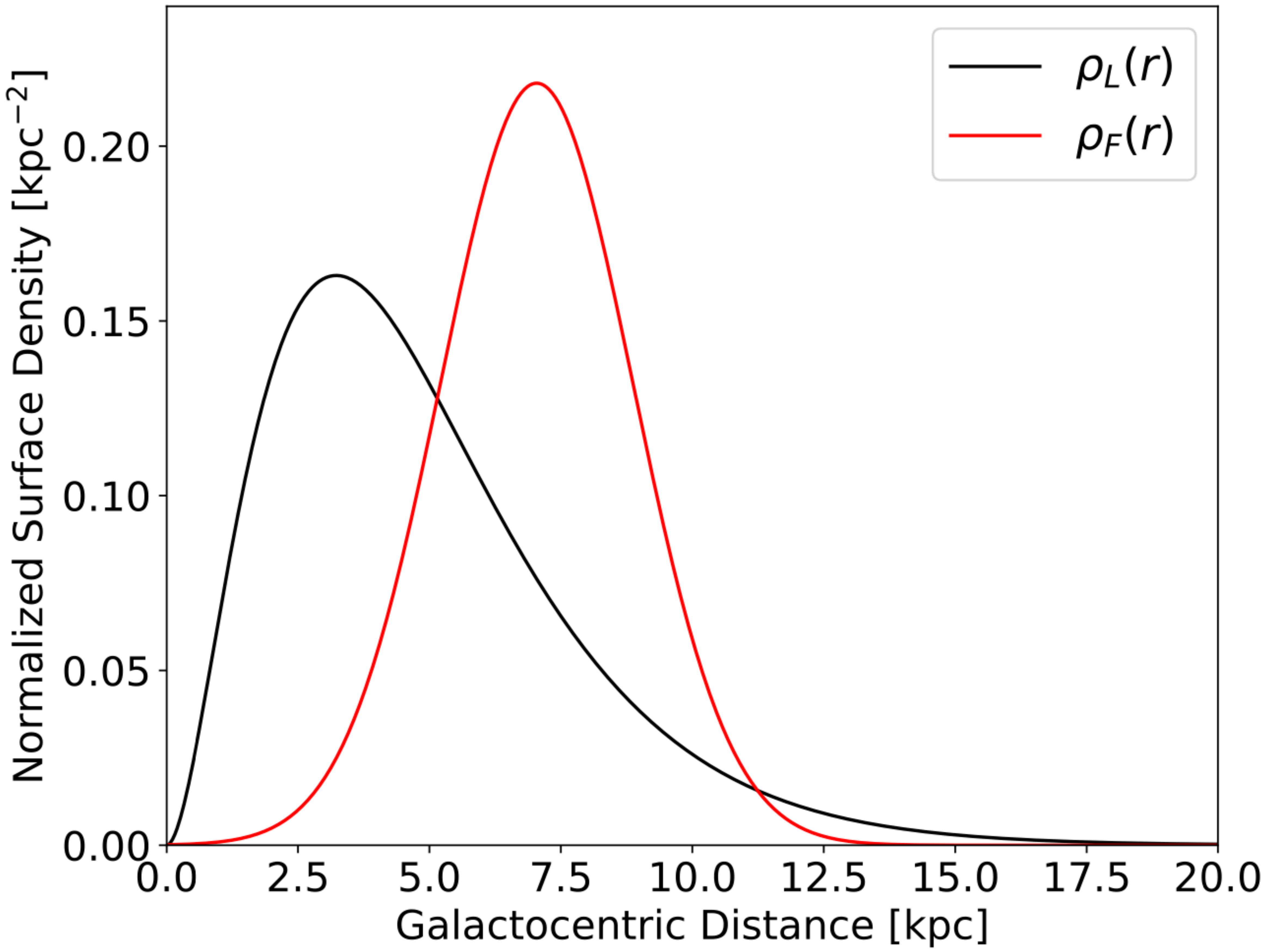


Distribution of pulsars





Wikipedia definition of a pulsar

A **pulsar** (from ***puls**ating **r**adio source*)[1][2] is a highly magnetized rotating neutron star that emits beams of electromagnetic radiation out of its magnetic poles.[3] This radiation can be observed only when a beam of emission is pointing toward Earth (similar to the way a lighthouse can be seen only when the light is pointed in the direction of an observer), and is responsible for the pulsed appearance of emission. Neutron stars are very dense and have short, regular rotational periods. This produces a very precise interval between pulses that ranges from milliseconds to seconds for an individual pulsar. Pulsars are one of the candidates for the source of ultra-high-energy cosmic rays. (See also centrifugal mechanism of acceleration.)

The periods of pulsars make them very useful tools for astronomers. Observations of a pulsar in a binary neutron star system were used to indirectly confirm the existence of gravitational radiation. The first extrasolar planets were discovered around a pulsar, PSR B1257+12 in 1992. In 1983, certain types of pulsars were detected that, at that time, exceeded the accuracy of atomic clocks in keeping time.[4]

First Discovery of a pulsar

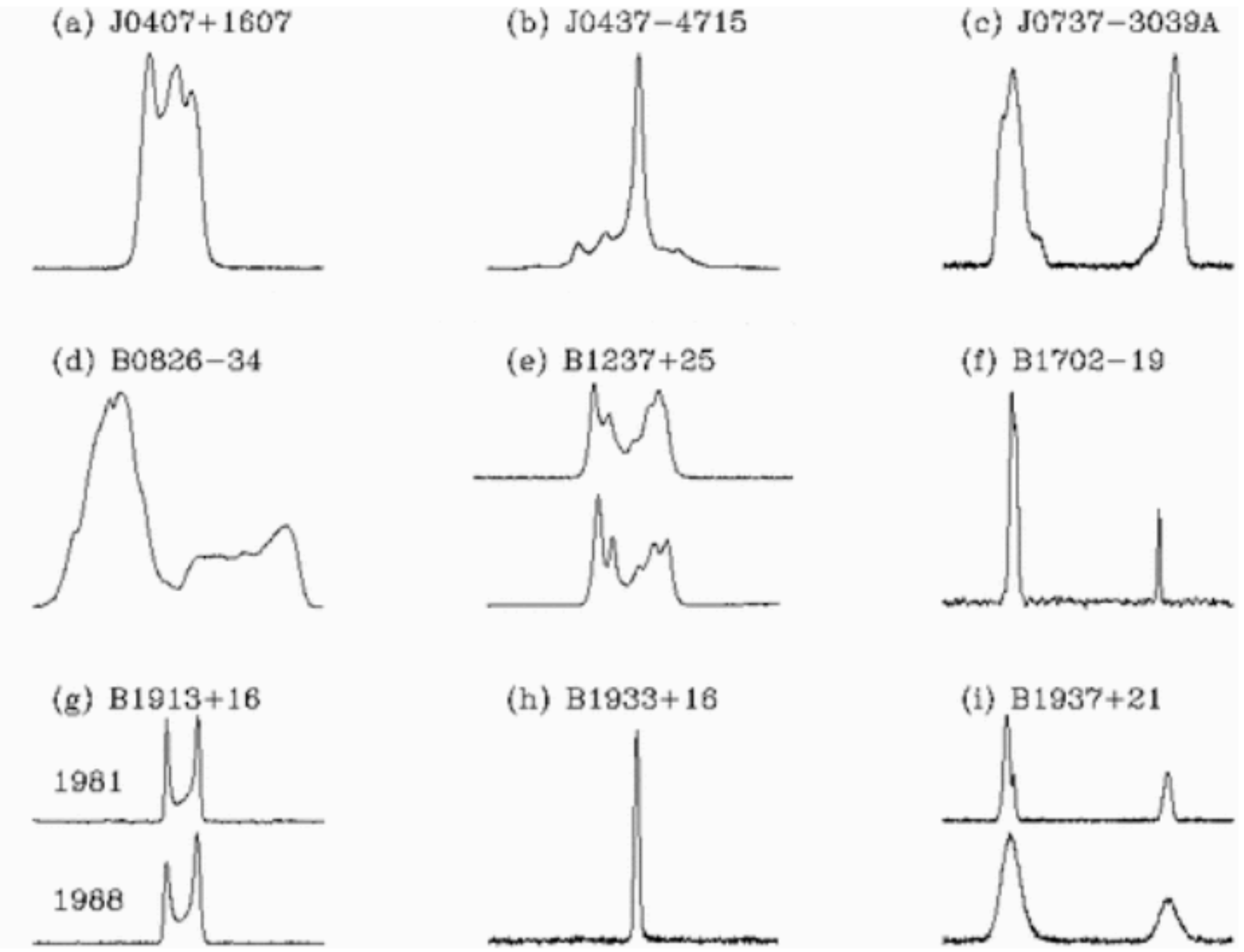
Published: 24 February 1968

Observation of a Rapidly Pulsating Radio Source

A. HEWISH, S. J. BELL, J. D. H. PILKINGTON, P. F. SCOTT & R. A. COLLINS

Nature **217**, 709–713 (1968) | Cite this article

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.



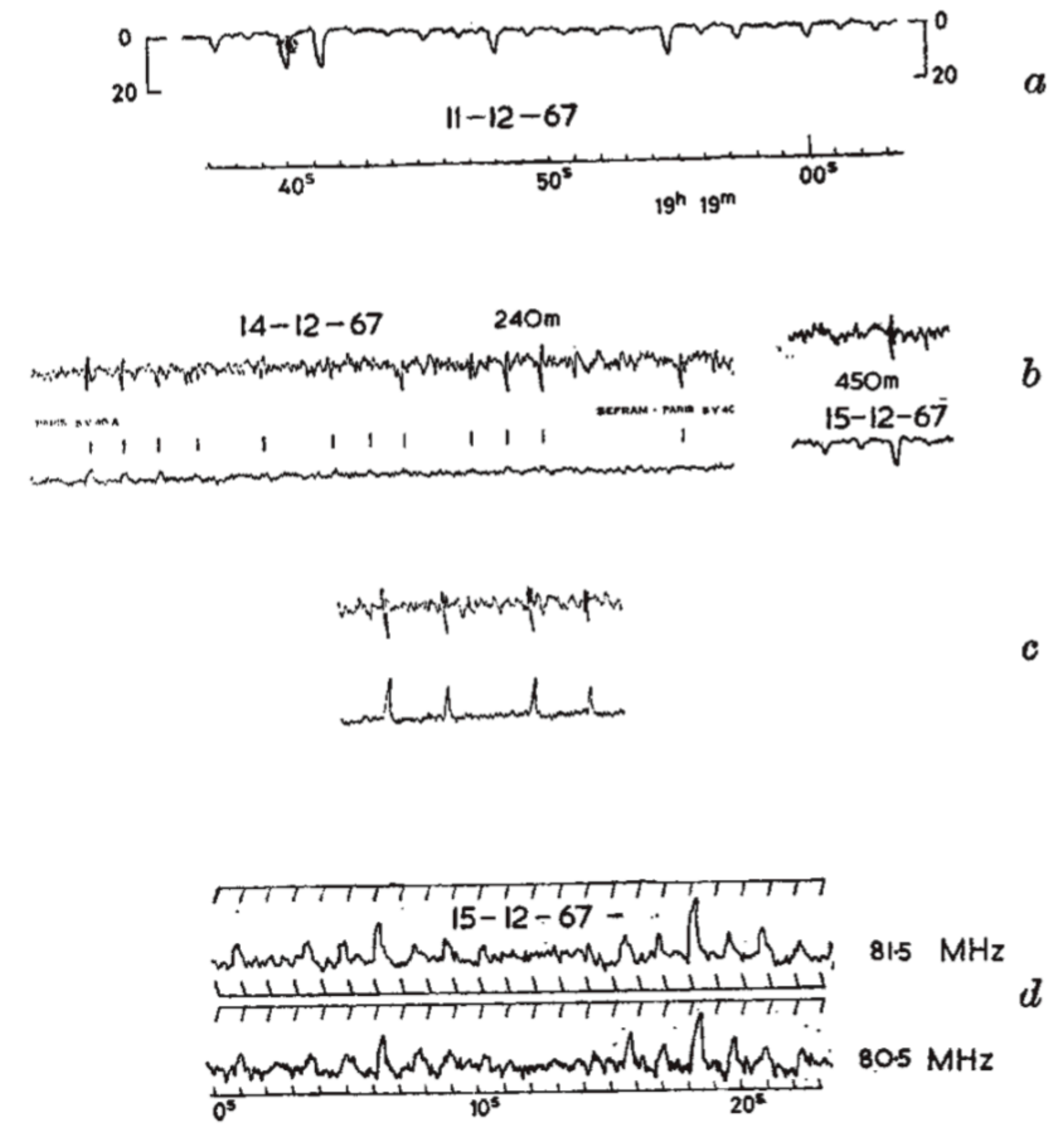
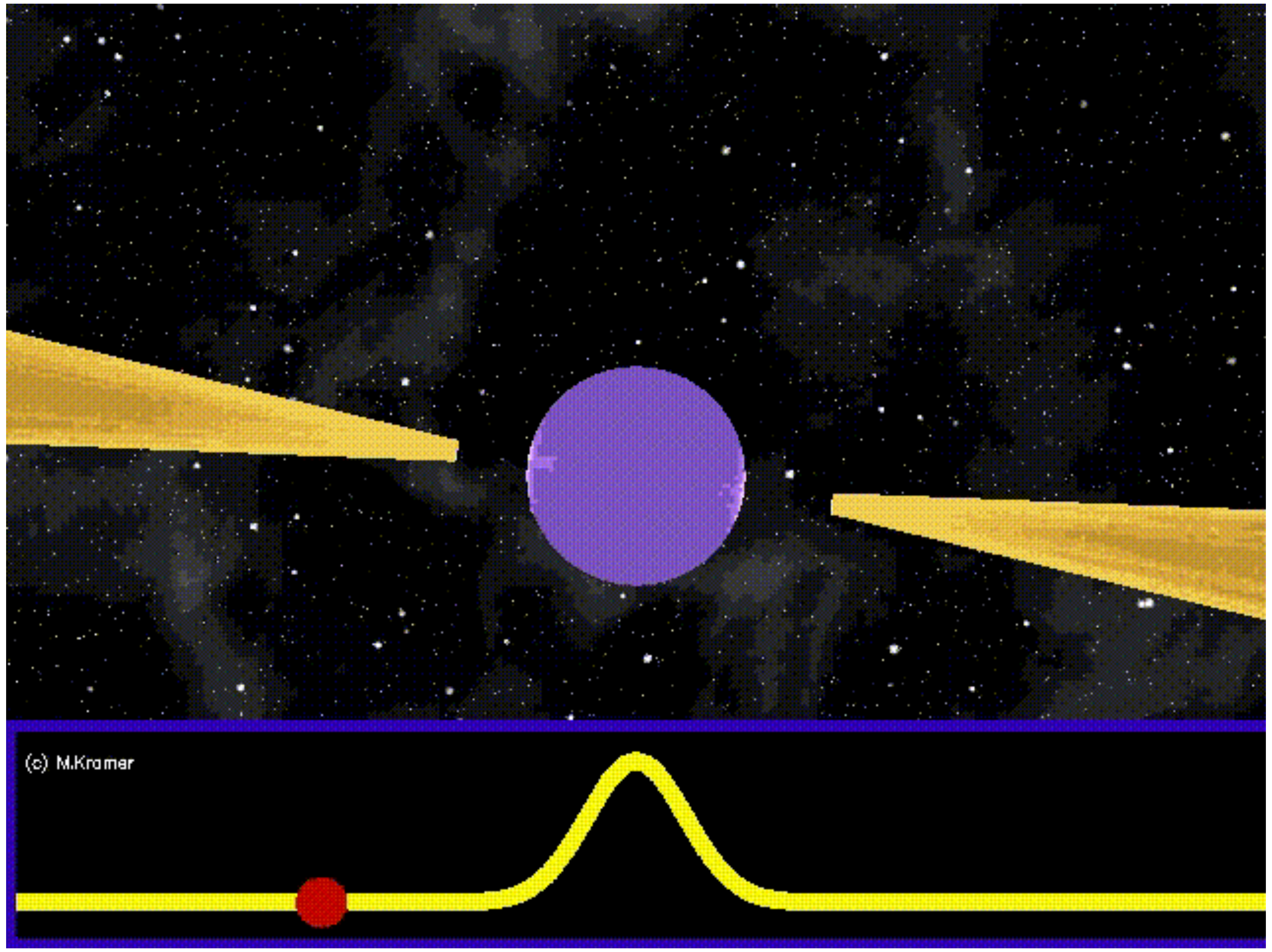


Fig. 1. *a*, A record of the pulsating radio source in strong signal conditions (receiver time constant 0·1 s). Full scale deflexion corresponds to 20×10^{-26} W m^{-2} Hz^{-1}. *b*, Upper trace: records obtained with additional paths (240 m and 450 m) in one side of the interferometer. Lower trace: normal interferometer records. (The pulses are small for $l = 240$ m because they occurred near a null in the interference pattern; this modifies the phase but not the amplitude of the oscillatory response on the upper trace.) *c*, Simulated pulses obtained using a signal generator. *d*, Simultaneous reception of pulses using identical receivers tuned to different frequencies. Pulses at the lower frequency are delayed by about 0·2 s.

Puslar electromagnetic radiation



Composite optical/X-ray image of the Crab Nebula, showing synchrotron emission in the surrounding pulsar wind nebula, powered by injection of magnetic fields and particles from the central pulsar.

Pulsar radiation emission

I (typically assumed to be 10^{45}g cm^2, as obtained from canonical neutron star values) and rotational frequency $\Omega_0 = 2\pi/P_0$:

$$W_0 = E_{\rm rot,0} = \frac{1}{2} I {\Omega_0}^2 \,. \tag{2.4}$$

The spin-down luminosity $\dot{E} = dE_{\rm rot}/dt$ of a pulsar is the rate at which the rotational kinetic energy is dissipated:

$$\dot{E} = \frac{dE_{\rm rot}}{dt} = I\Omega\dot{\Omega} = -4\pi^2 I \frac{\dot{P}}{P^3} \,. \tag{2.5}$$

Assuming a small deviation from the dipole nature of the magnetic field B of the pulsar, the evolution of the star may be parameterized as [55]:

$$P^{n-2}\dot{P} = ak(B\sin\alpha)^2 \,. \tag{2.6}$$

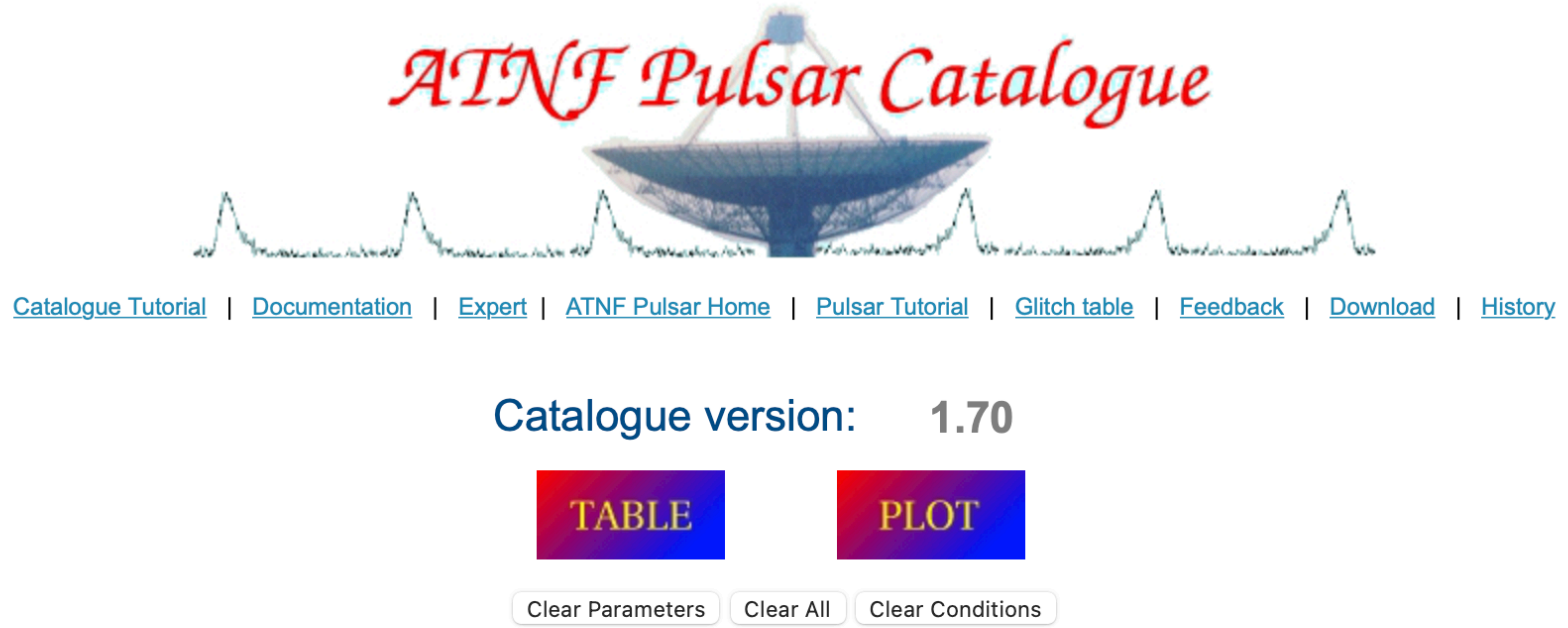
where the angle $\alpha > 0$ describes the inclination of the magnetic dipole with respect to the rotation axis, a is a constant of unit s^{n-3} and k takes the value of 9.76×10^{-40} s G^{-2} for canonical characteristics of neutron stars. The spin-down luminosity evolves with time t as in eq. 2.2:

$$\dot{E}(t) = \dot{E}_0 \left(1 + \frac{t}{\tau_0}\right)^{-\frac{n+1}{n-1}} \,. \tag{2.7}$$

From this equation, one can notice that the pulsar has roughly a constant energy output from its birth till $t = \tau_0$, when the energy output starts to decrease as $\dot{E} \sim t^{-(n+1)/(n-1)}$. Finally, the prediction on τ_0 is derived to be:

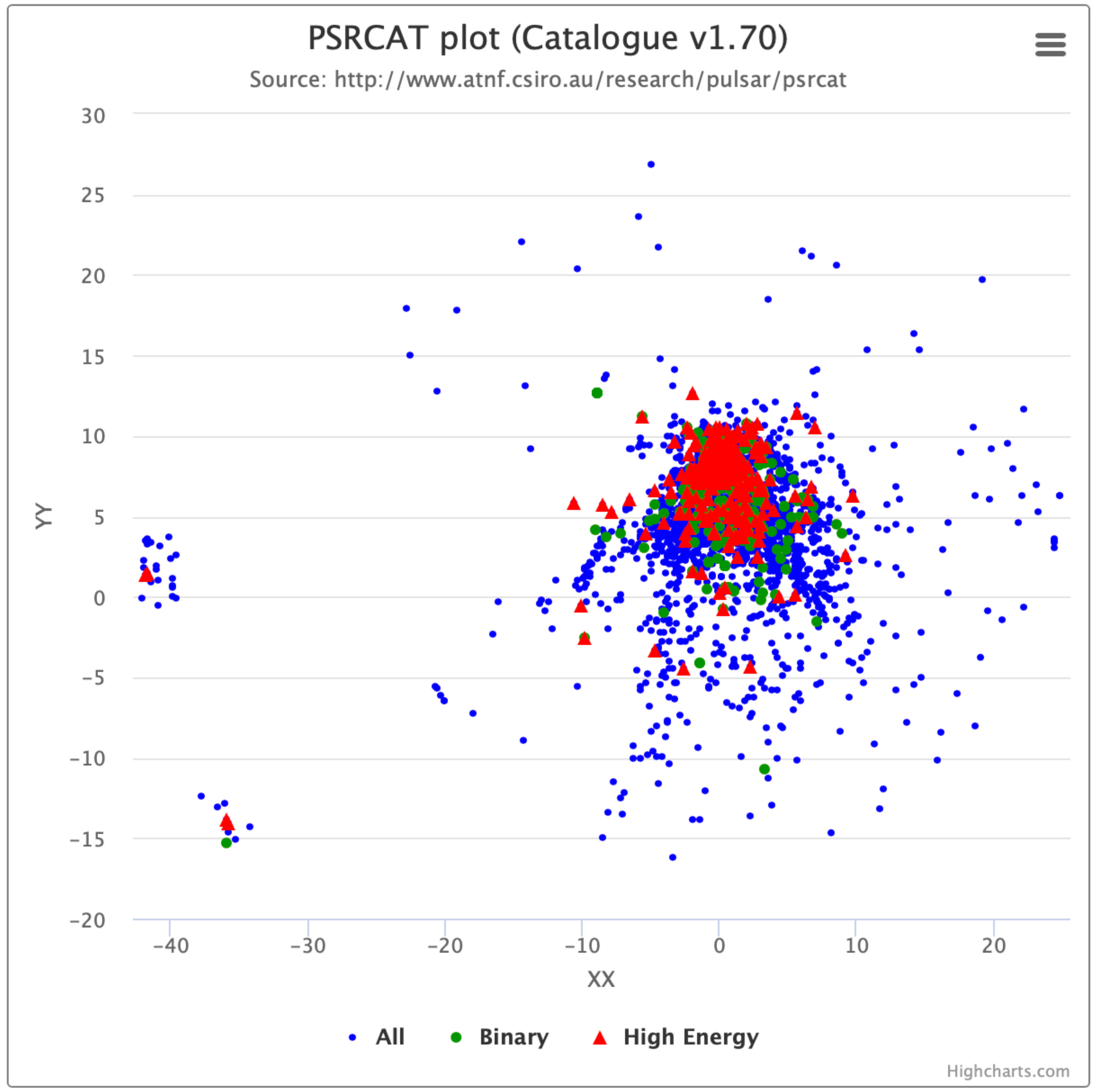
$$\tau_0 = \frac{P_0}{(n-1)\dot{P}_0} \,. \tag{2.8}$$

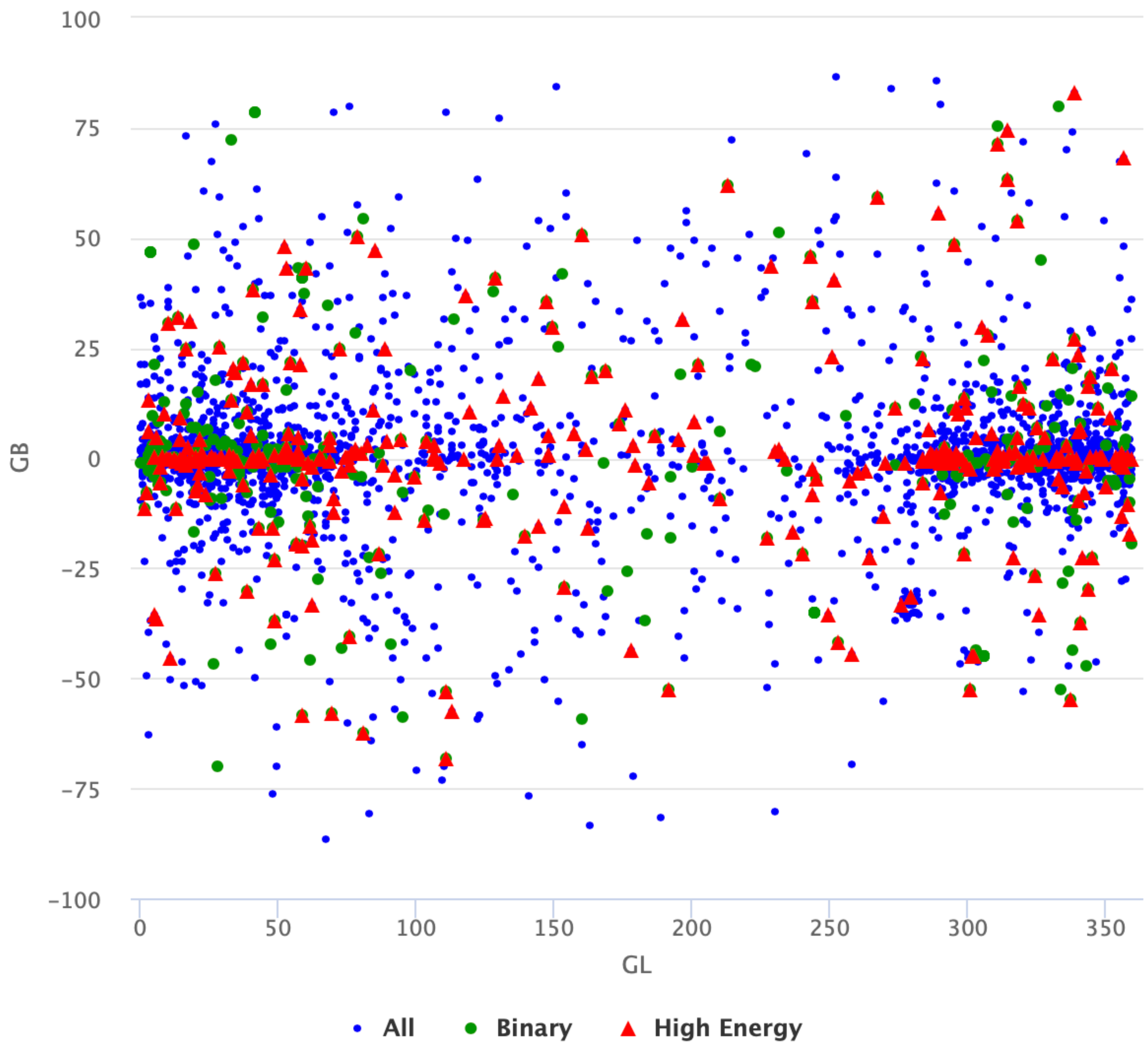
ATNF catalog



https://www.atnf.csiro.au/research/pulsar/psrcat/

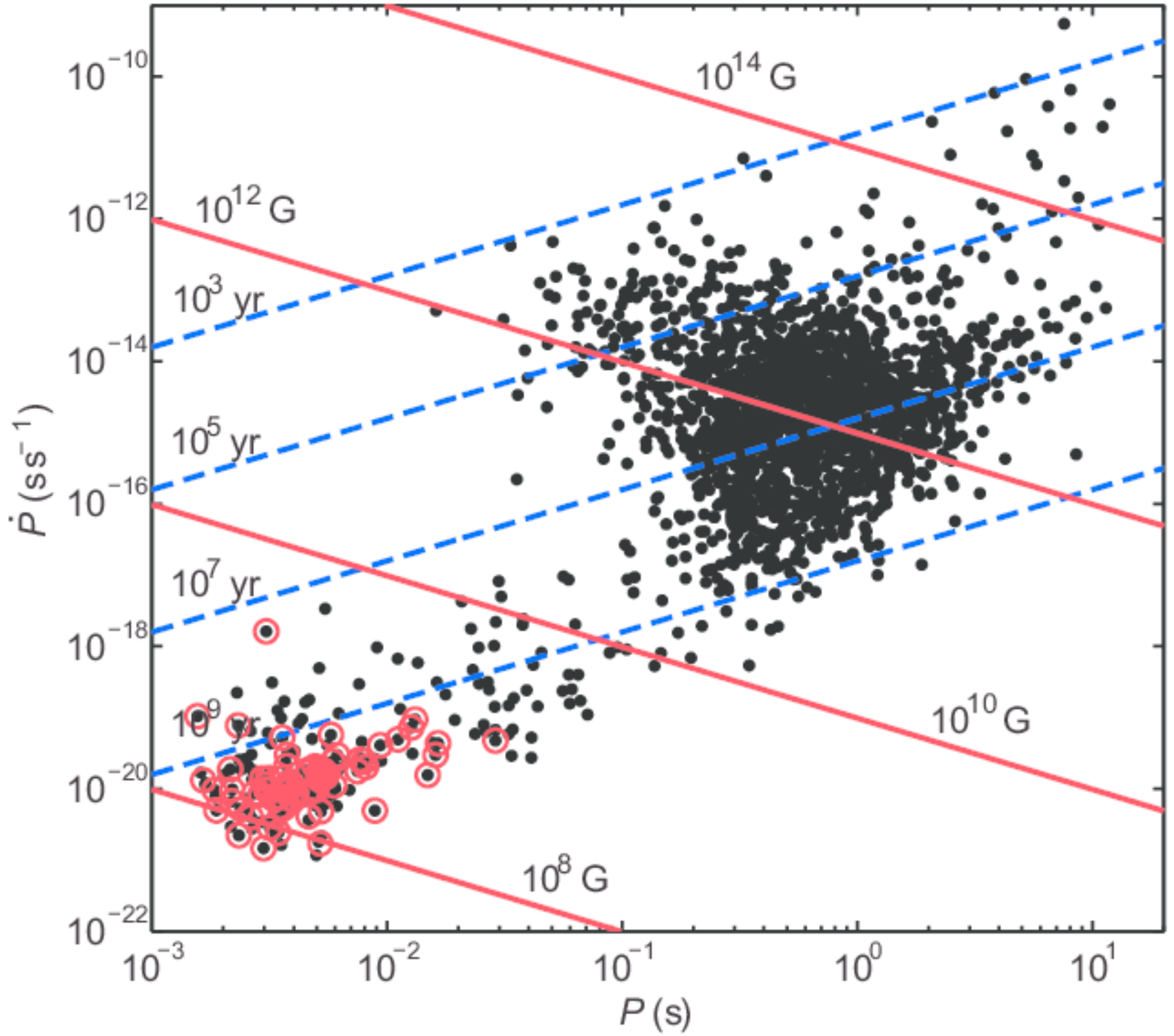
Distribution in the Galaxy

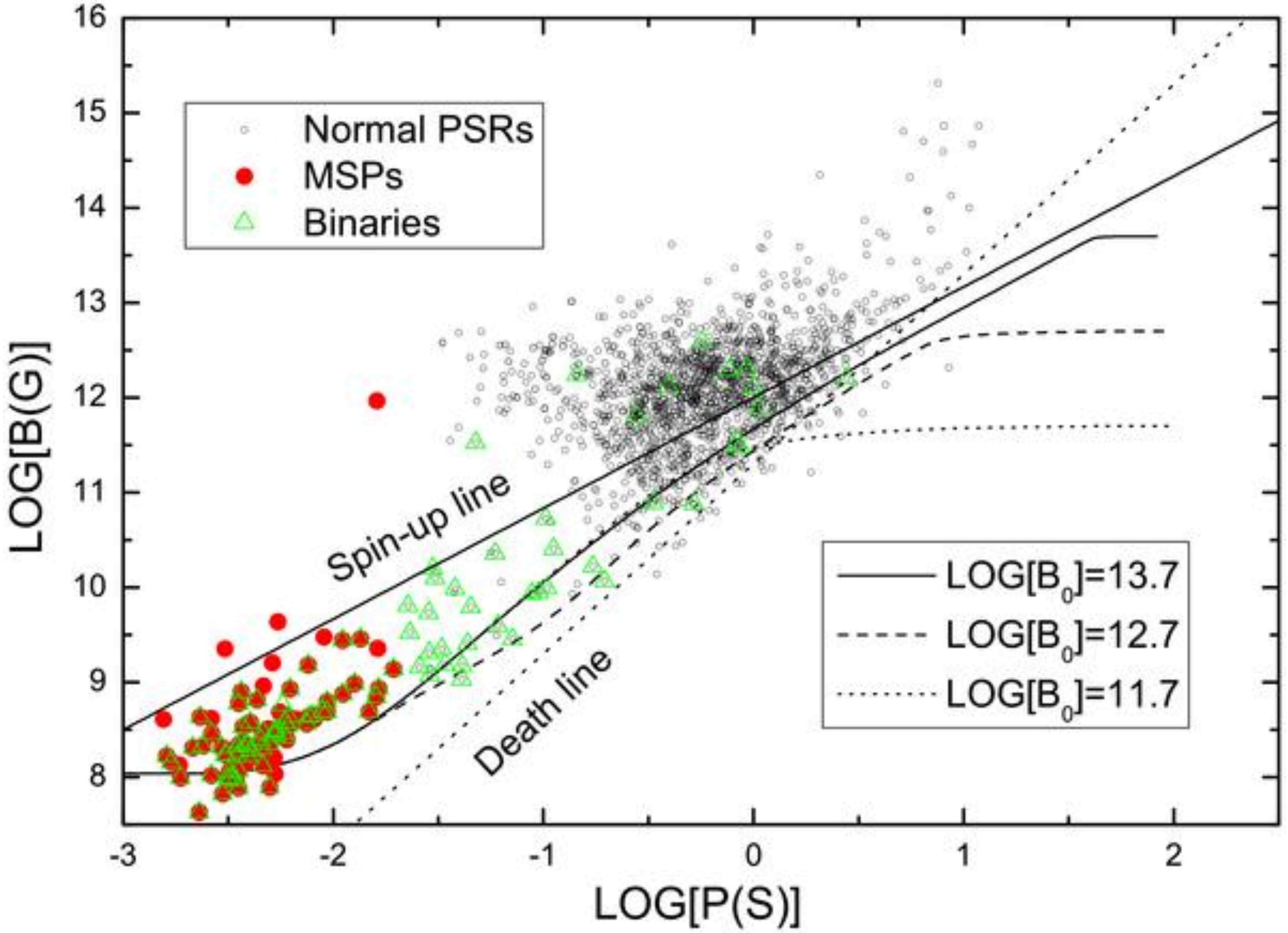




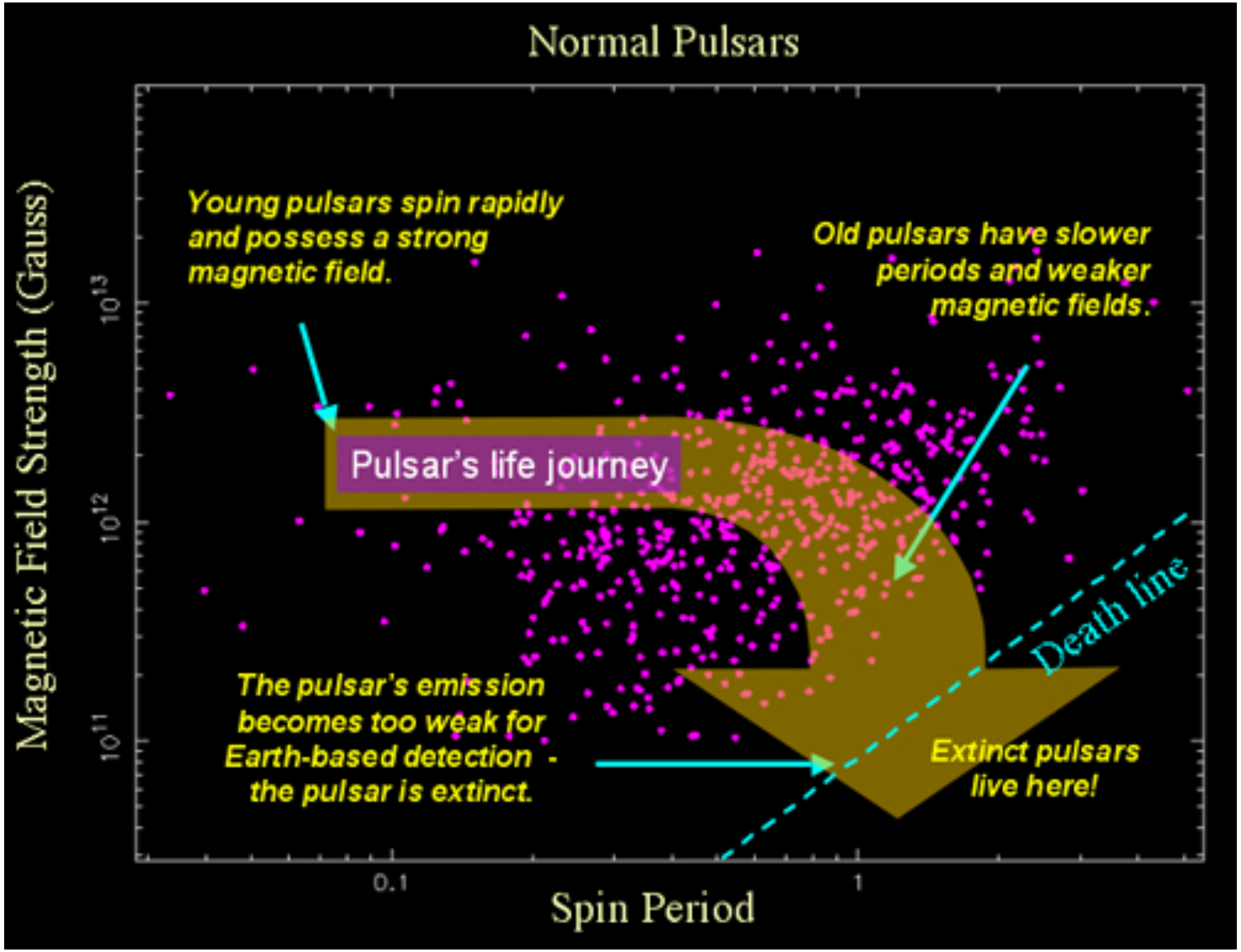
ZZ: Distance from the Galactic plane, based on Dist
XX: X-Distance in X-Y-Z Galactic coordinate system (kpc)
YY: Y-Distance in X-Y-Z Galactic coordinate system (kpc)

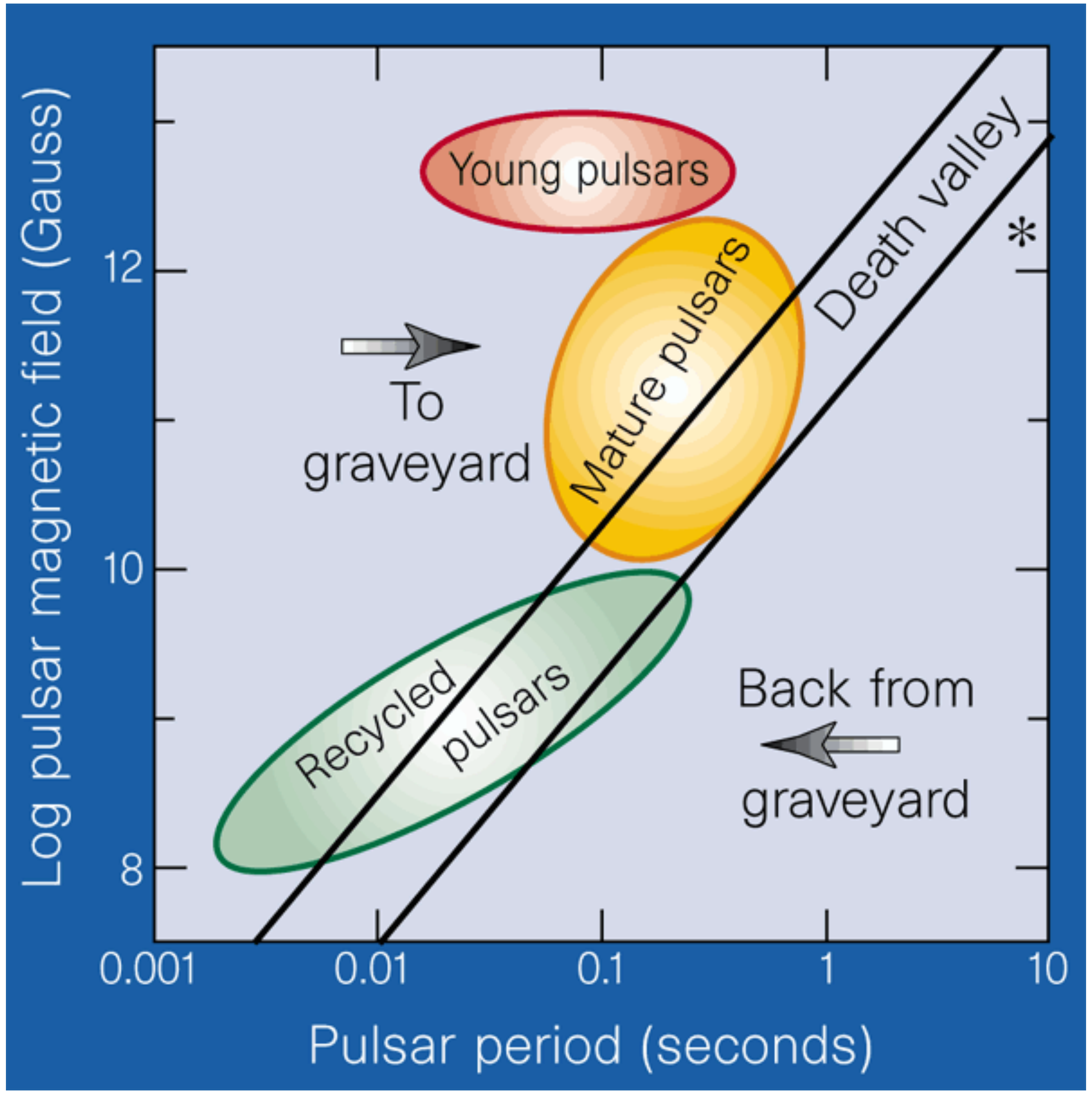
Period and spin down



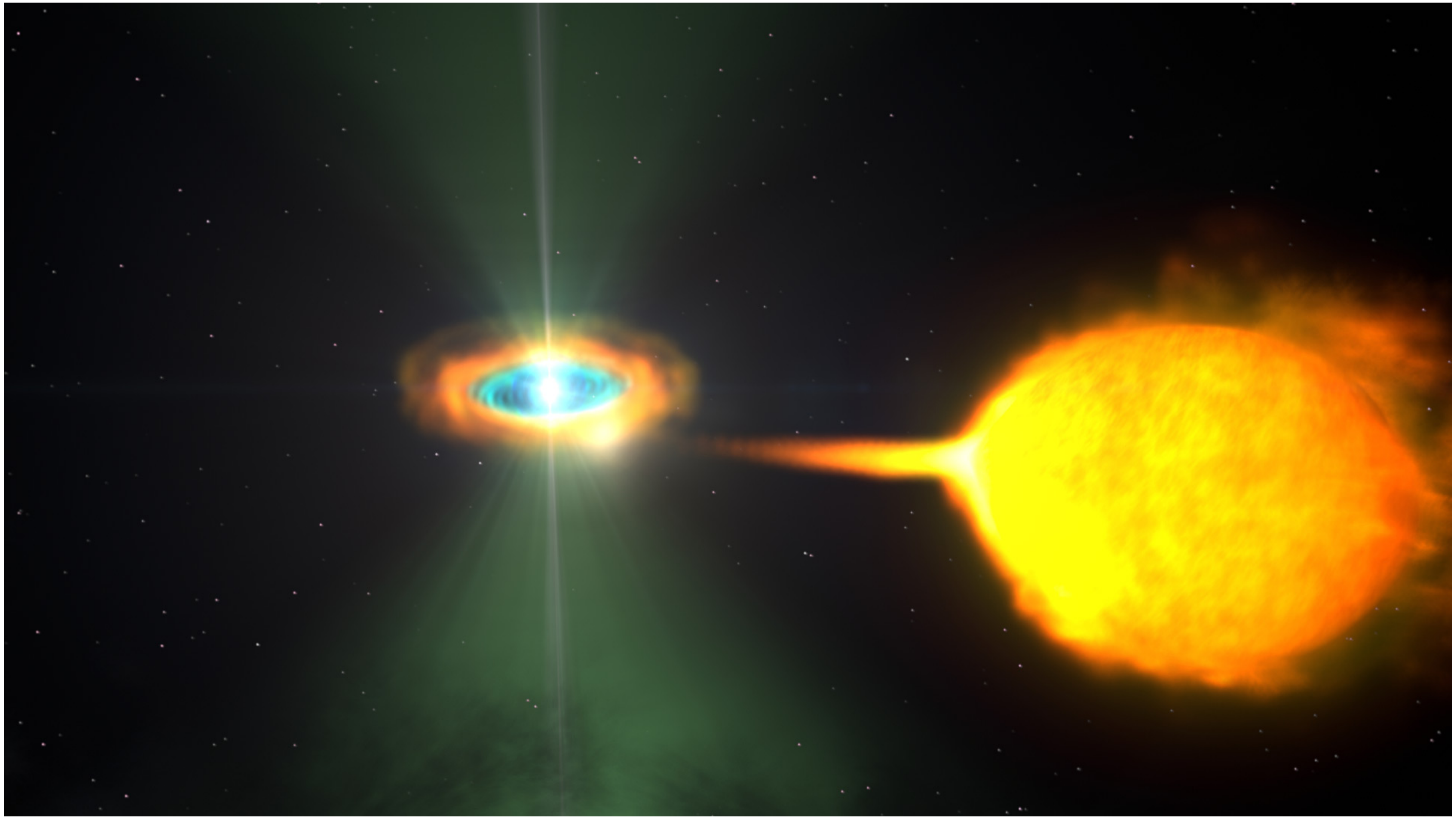


Pulsar evolution

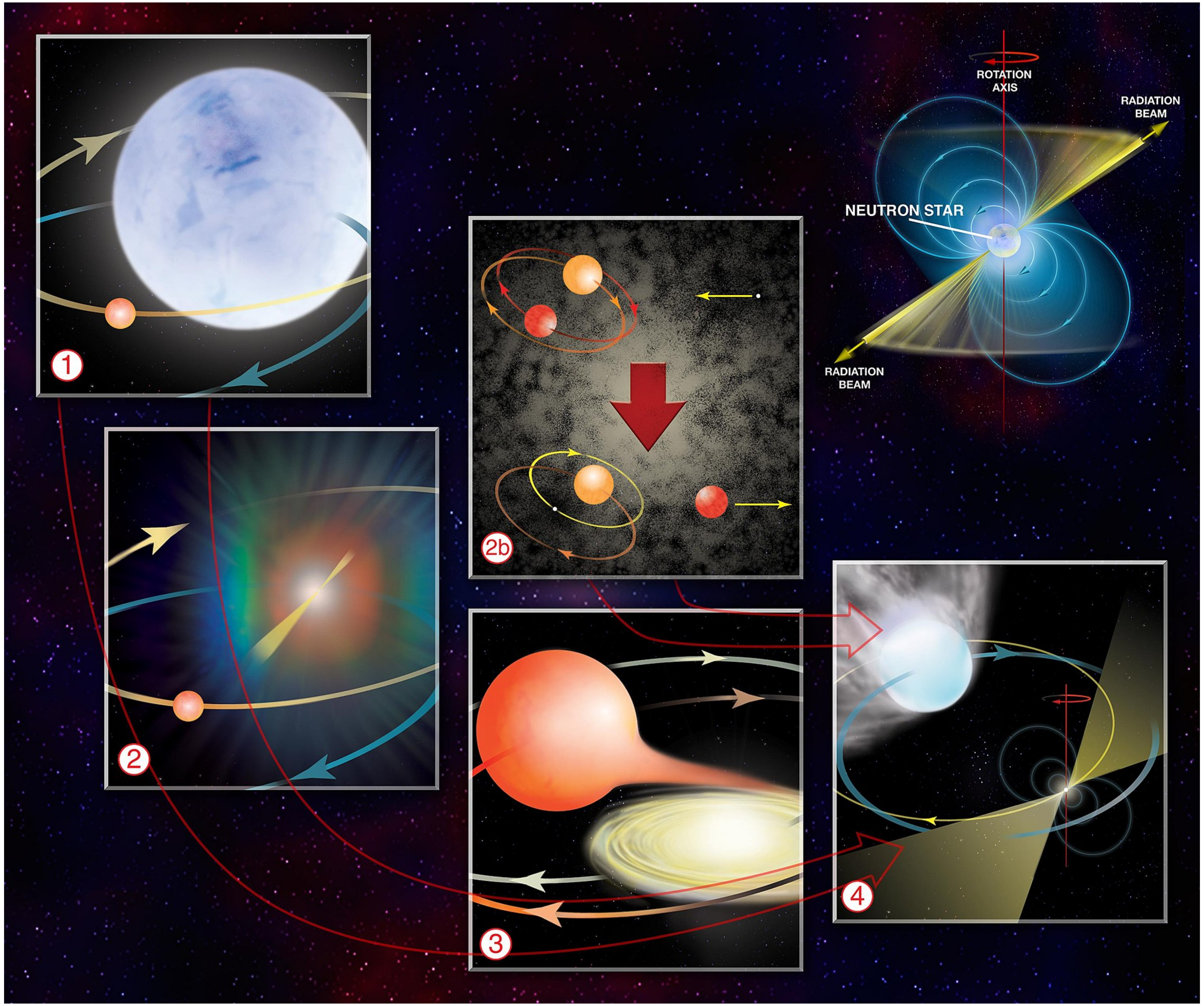




Millisecond pulsar

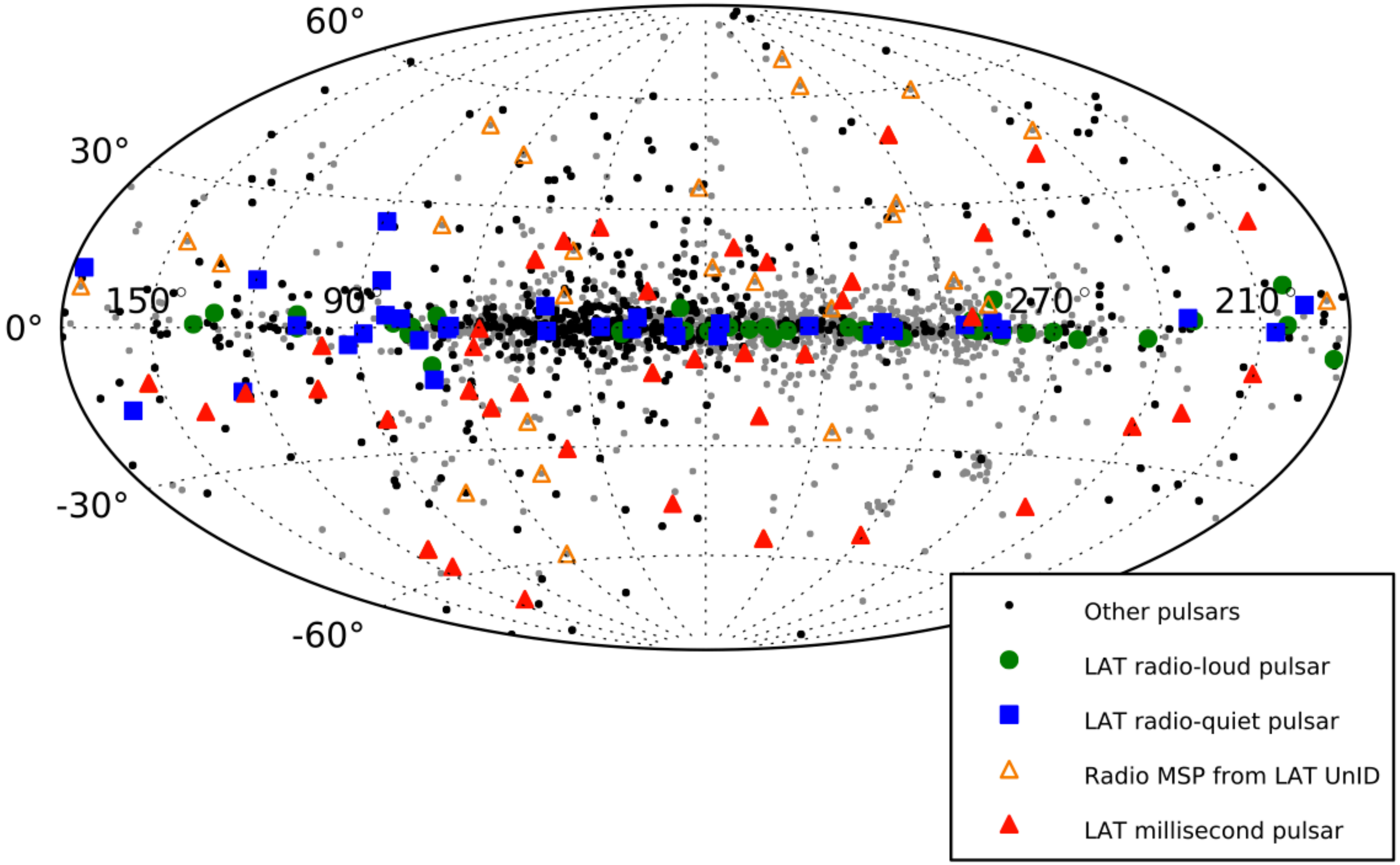


Millisecond pulsar

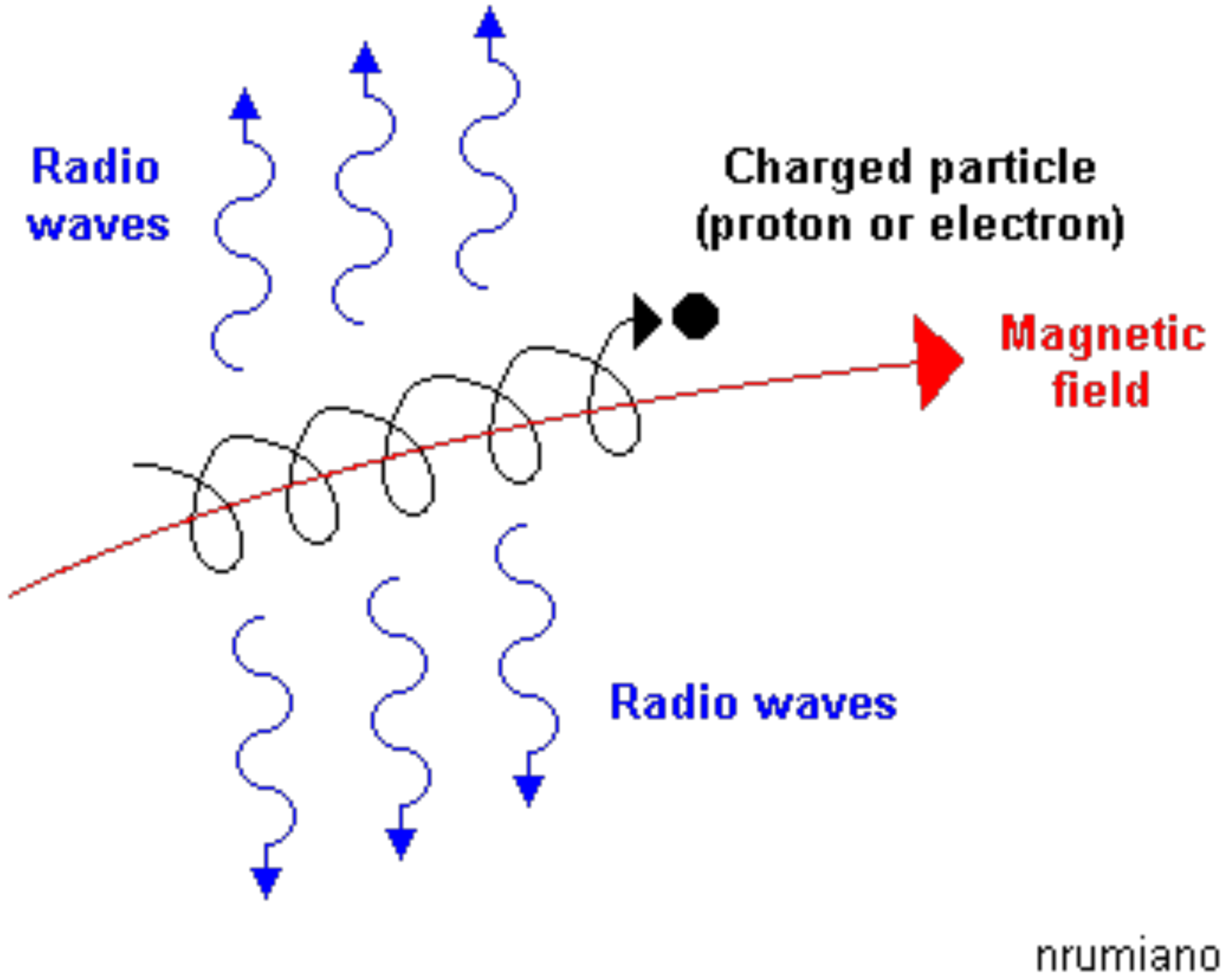


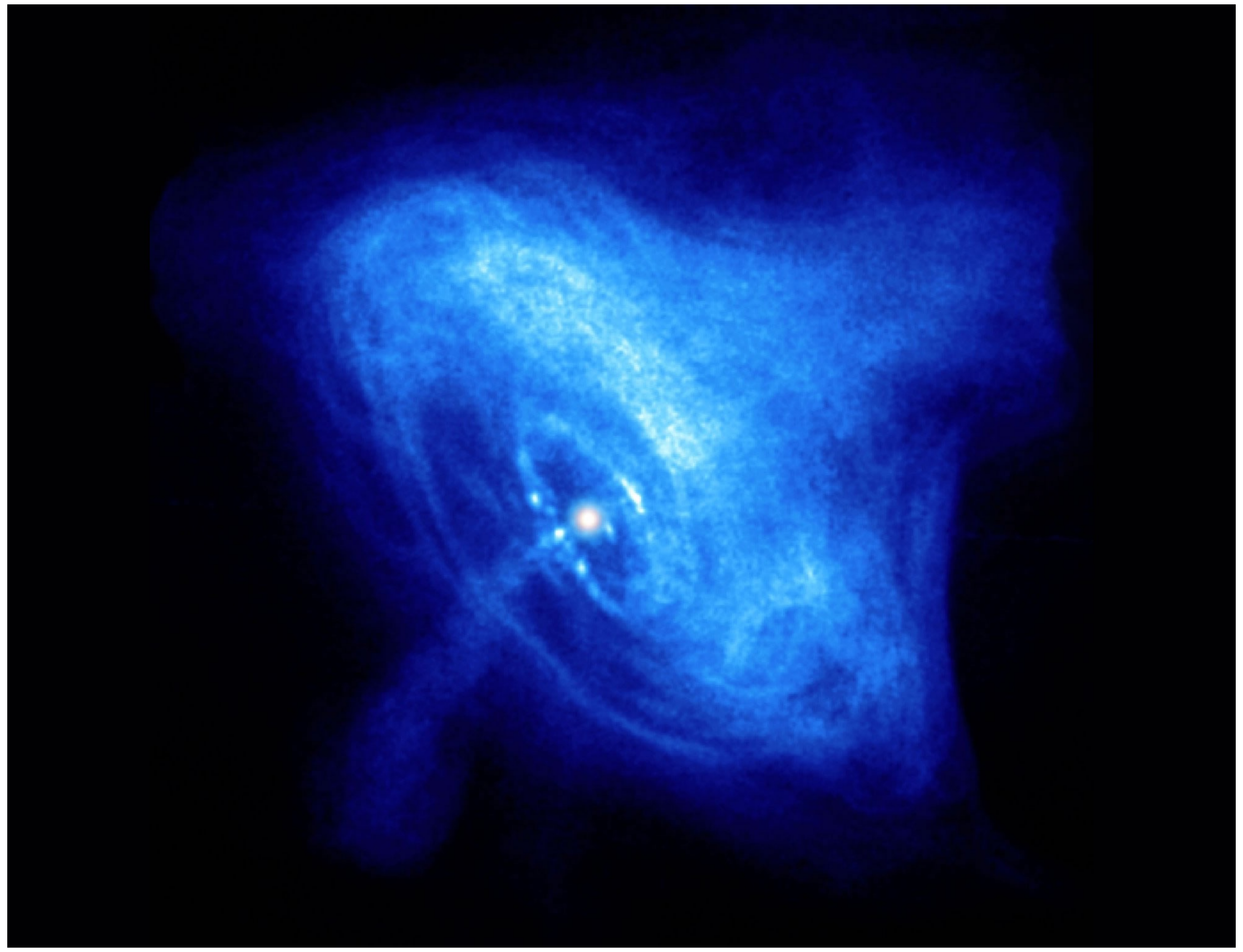
This diagram shows the steps astronomers say are needed to create a pulsar with a superfast spin. 1. A massive supergiant star and a "normal" Sun-like star orbit each other. 2. The massive star explodes, leaving a pulsar that eventually slows down, turns off, and becomes a cooling neutron star. 3. The Sun-like star eventually expands, spilling material on to the neutron star. This "accretion" speeds up the neutron star's spin. 4. Accretion ends, the neutron star is "recycled" into a millisecond pulsar. But in a densely packed globular cluster (2b)... The lowest mass stars are ejected, the remaining normal stars evolve, and the "recycling" scenario (3-4) takes place, creating many millisecond pulsars.

Fermi-LAT pulsar



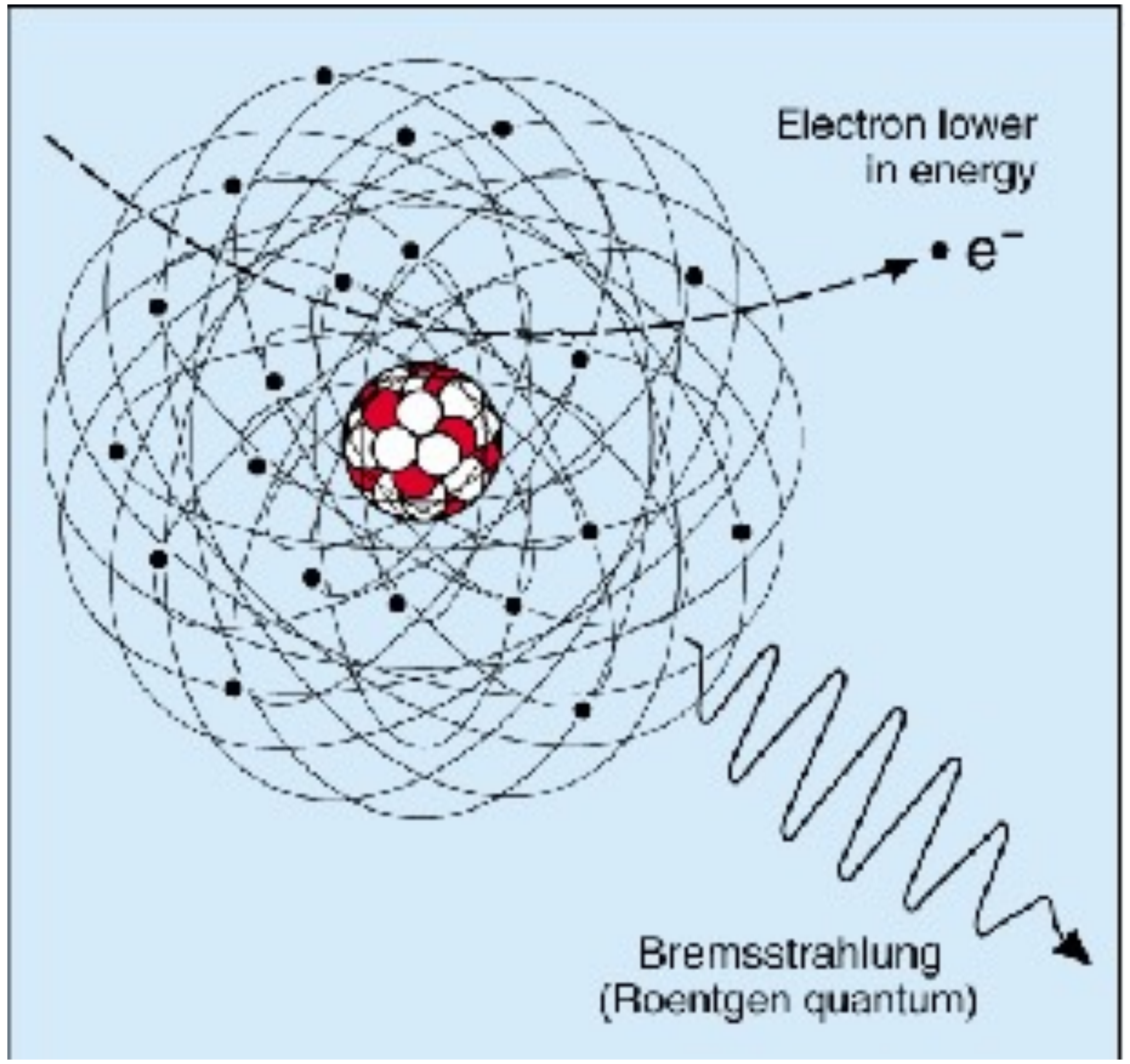
Production of radio emission (Synchrotron radiation)

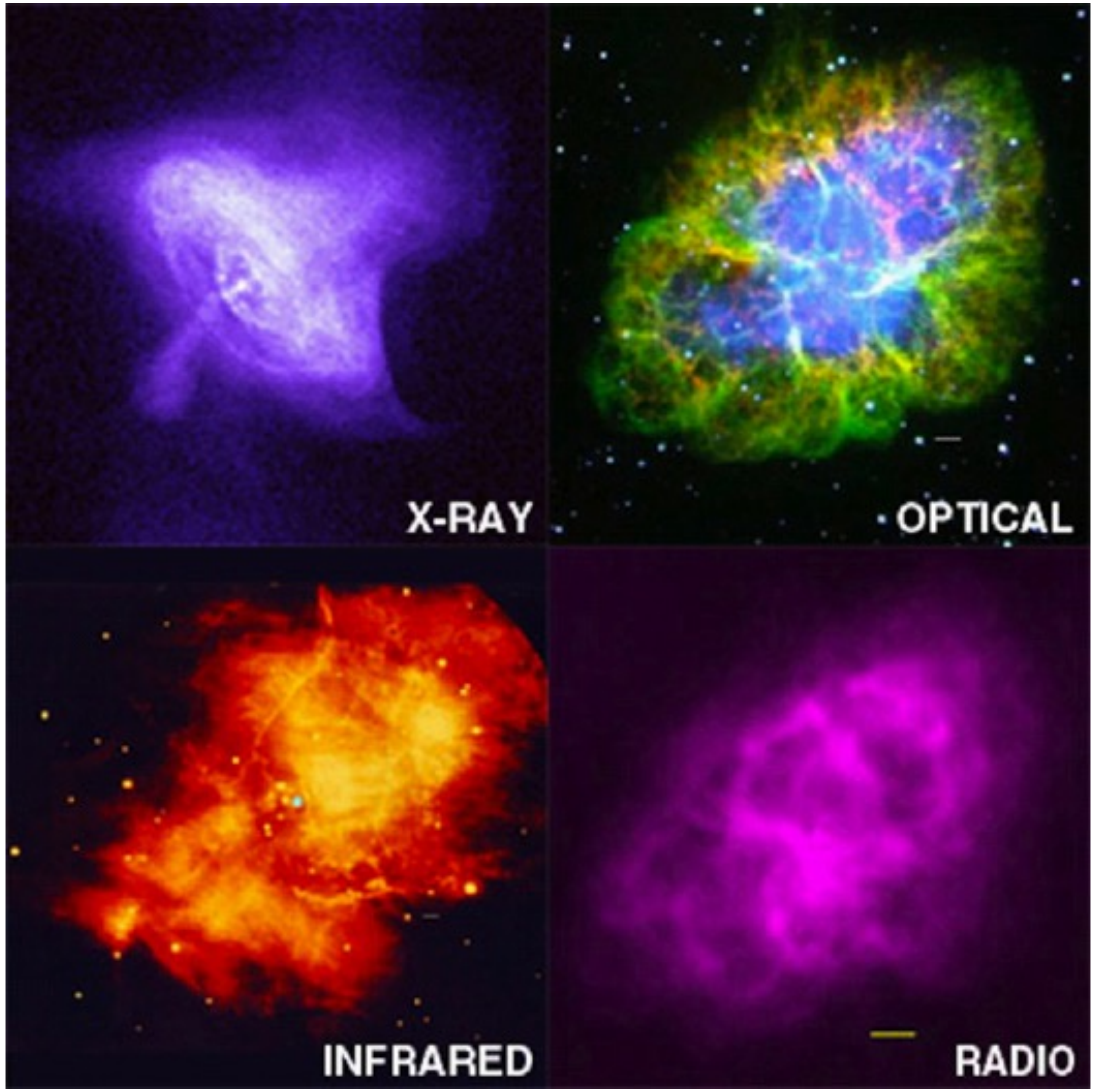




$$P = \frac{q^2}{6\pi\epsilon_0 m^4 c^5 r^2 \sin^2(\alpha)} E^4 \beta^4 = \frac{q^2}{6\pi\epsilon_0 m^4 c^5 r^2 \sin^2(\alpha)} (E^2 - m^2 c^4)^2.$$

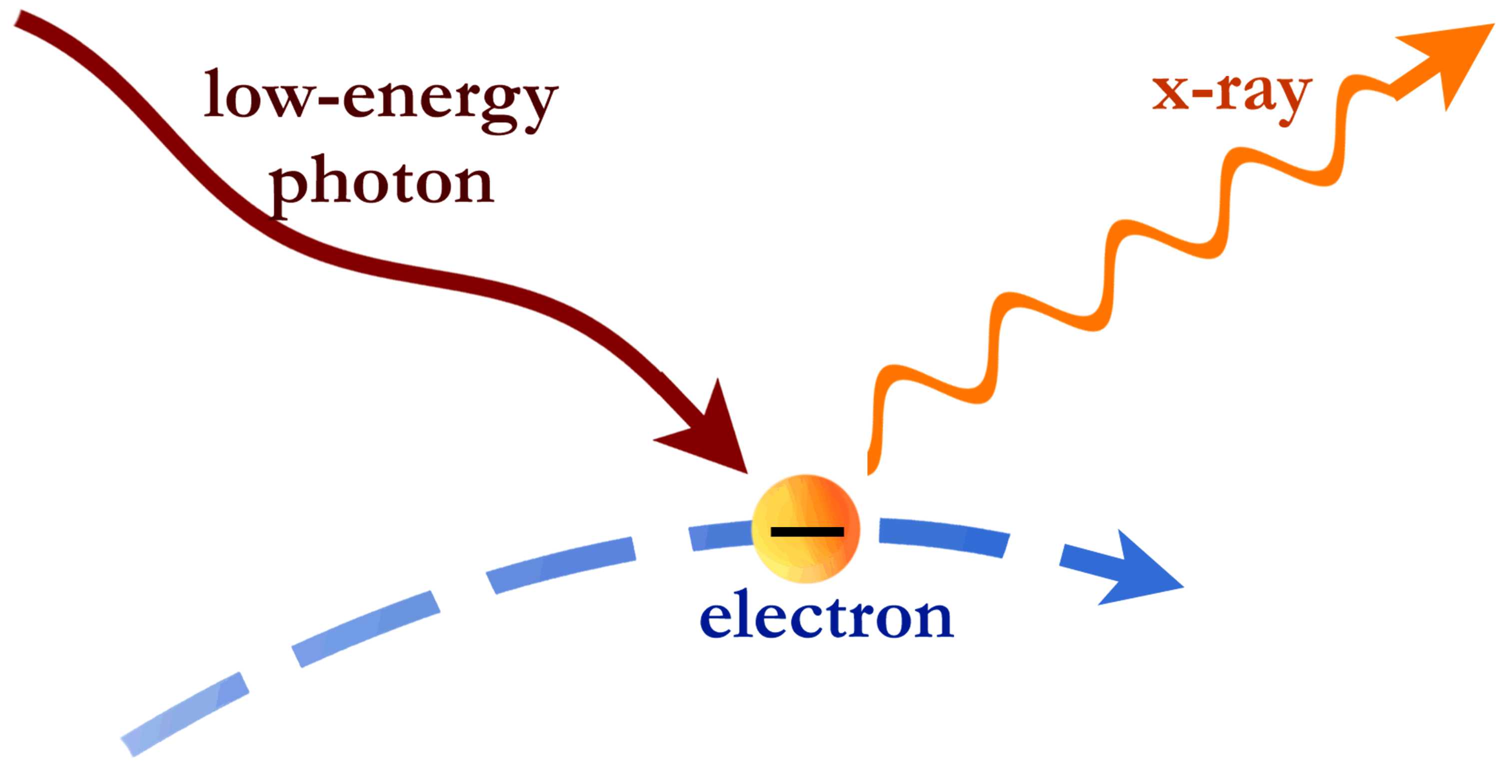
X-ray emission



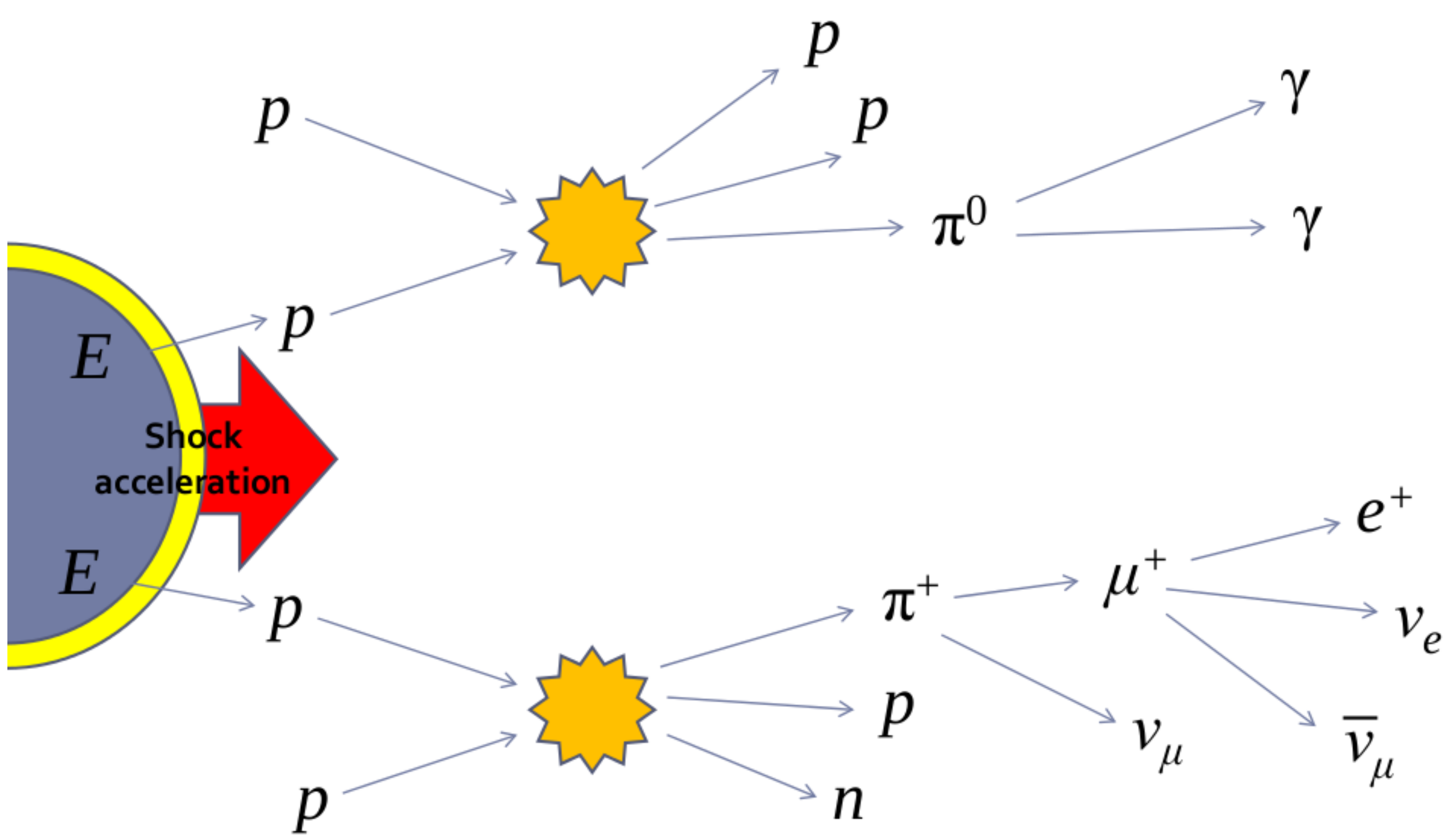


gamma-ray emission

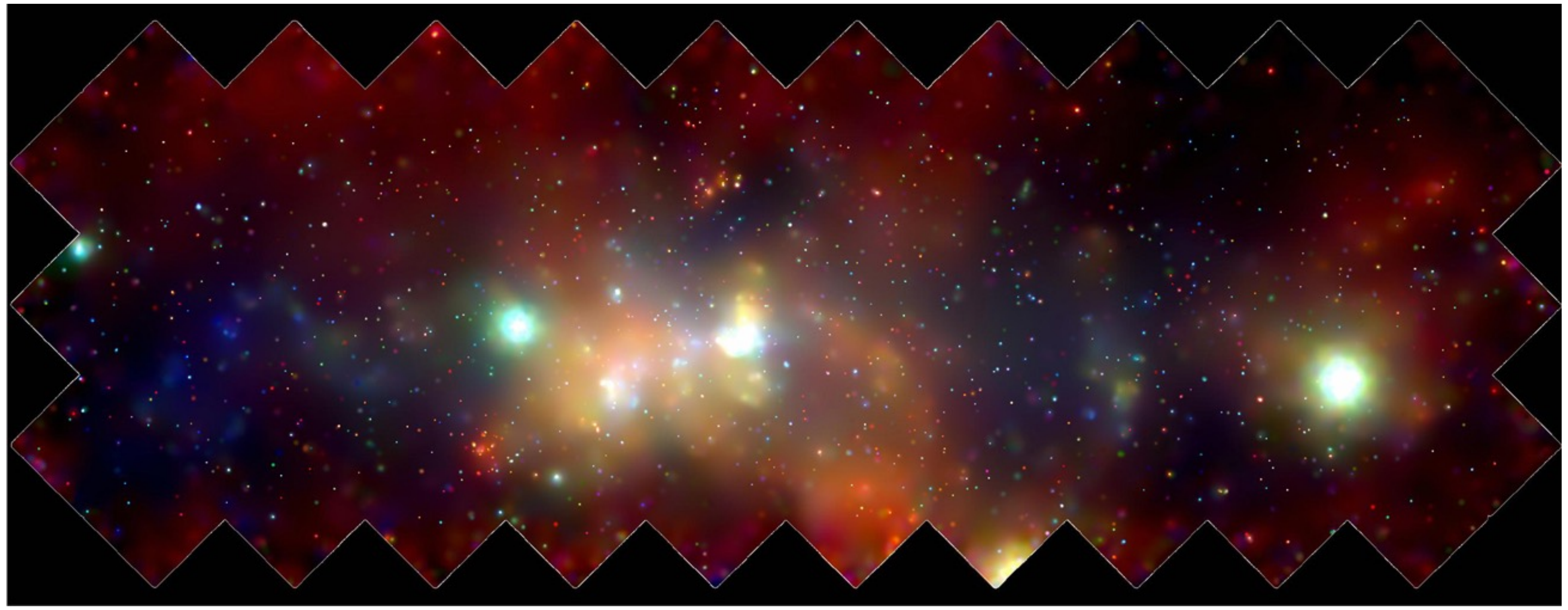
Inverse Compton scattering

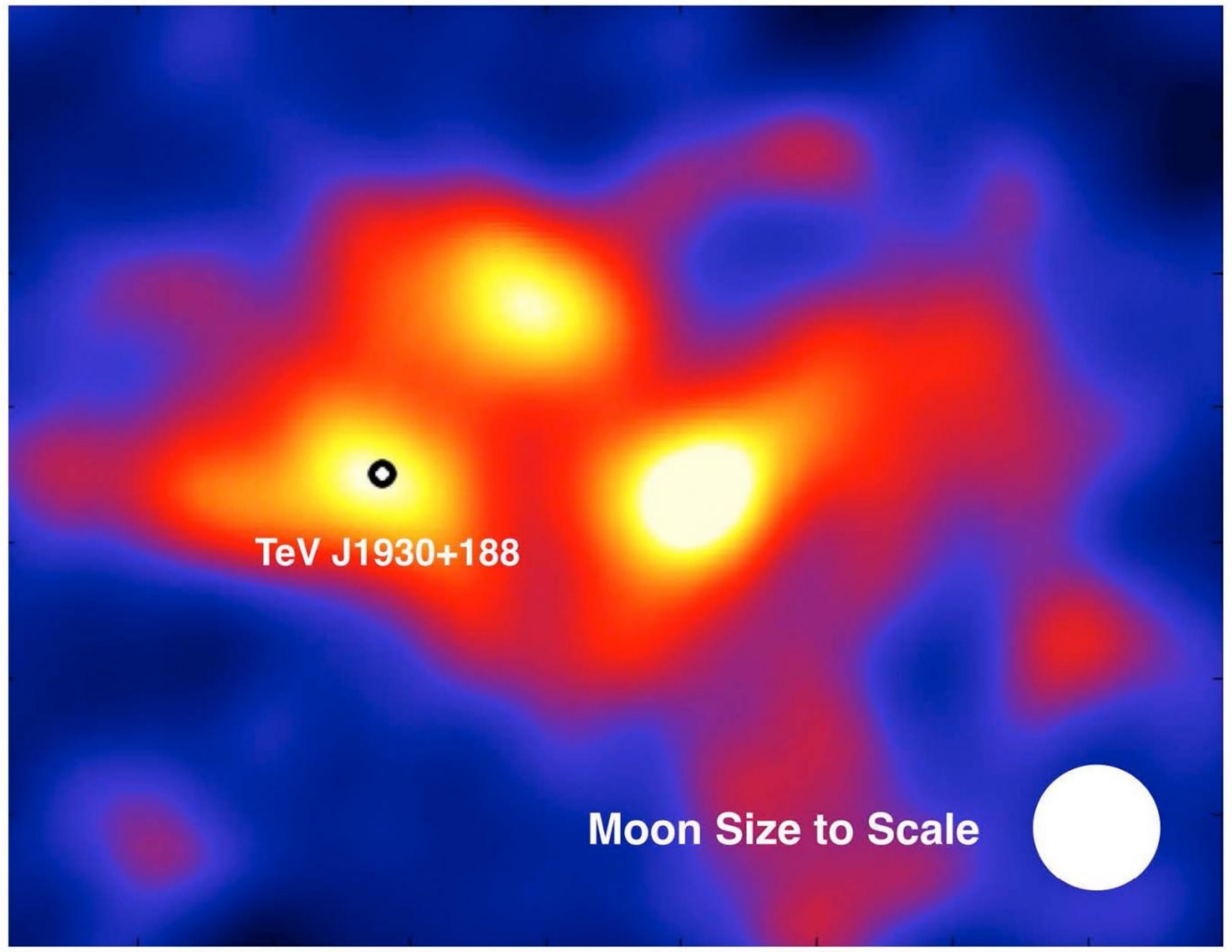


Pion decay

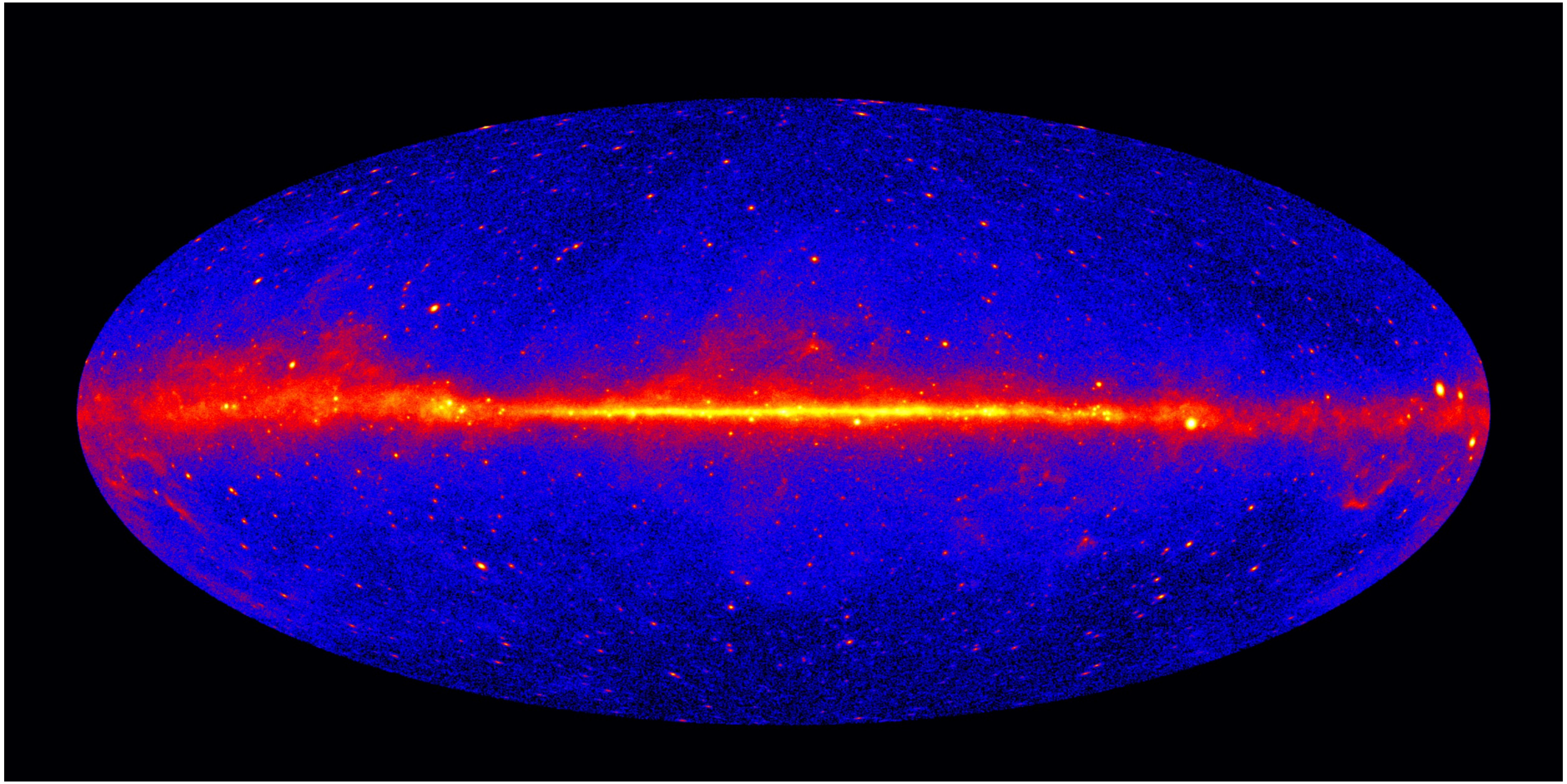


Optical, radio, X-ray and gamma rays from individual sources.



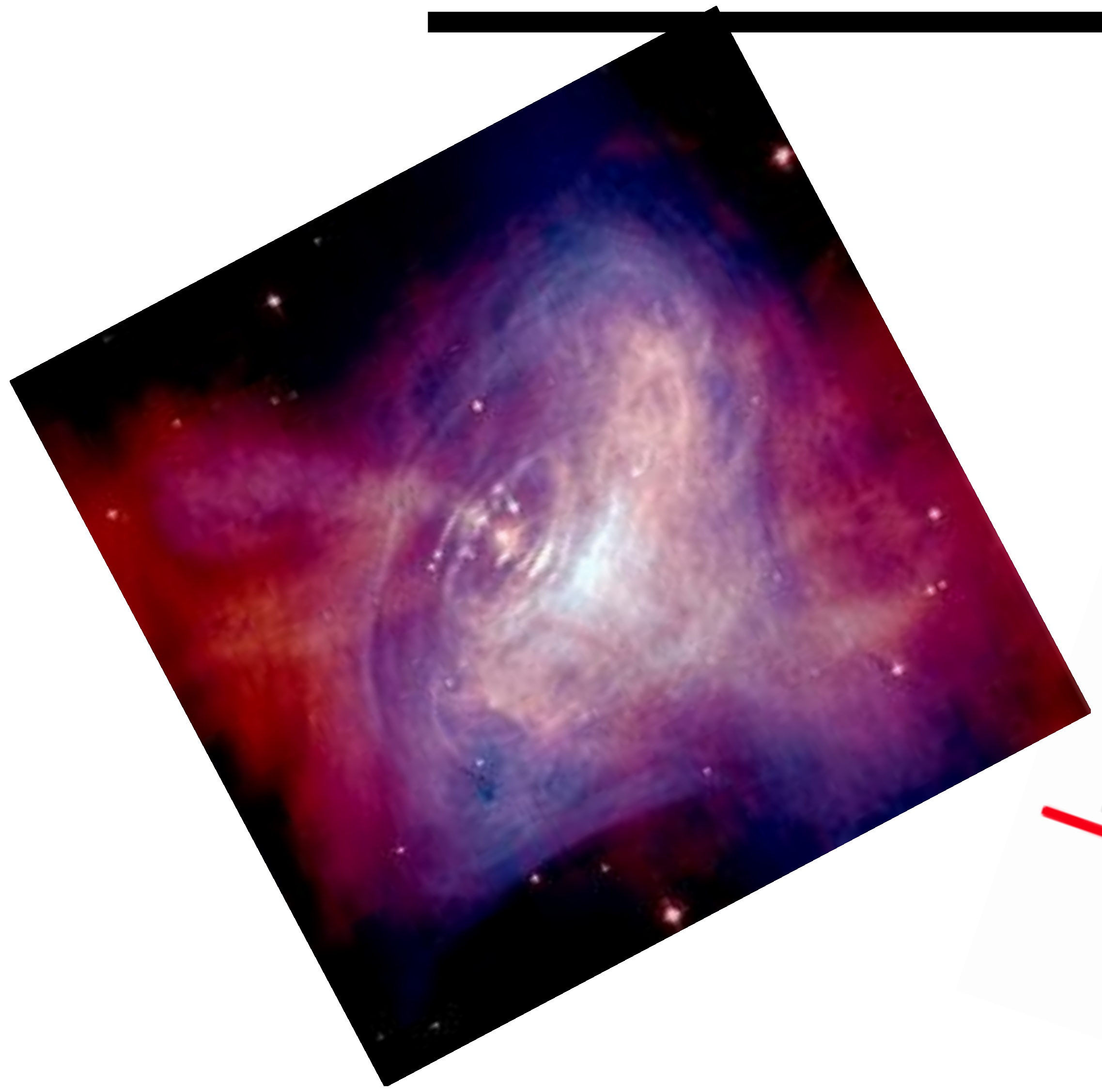


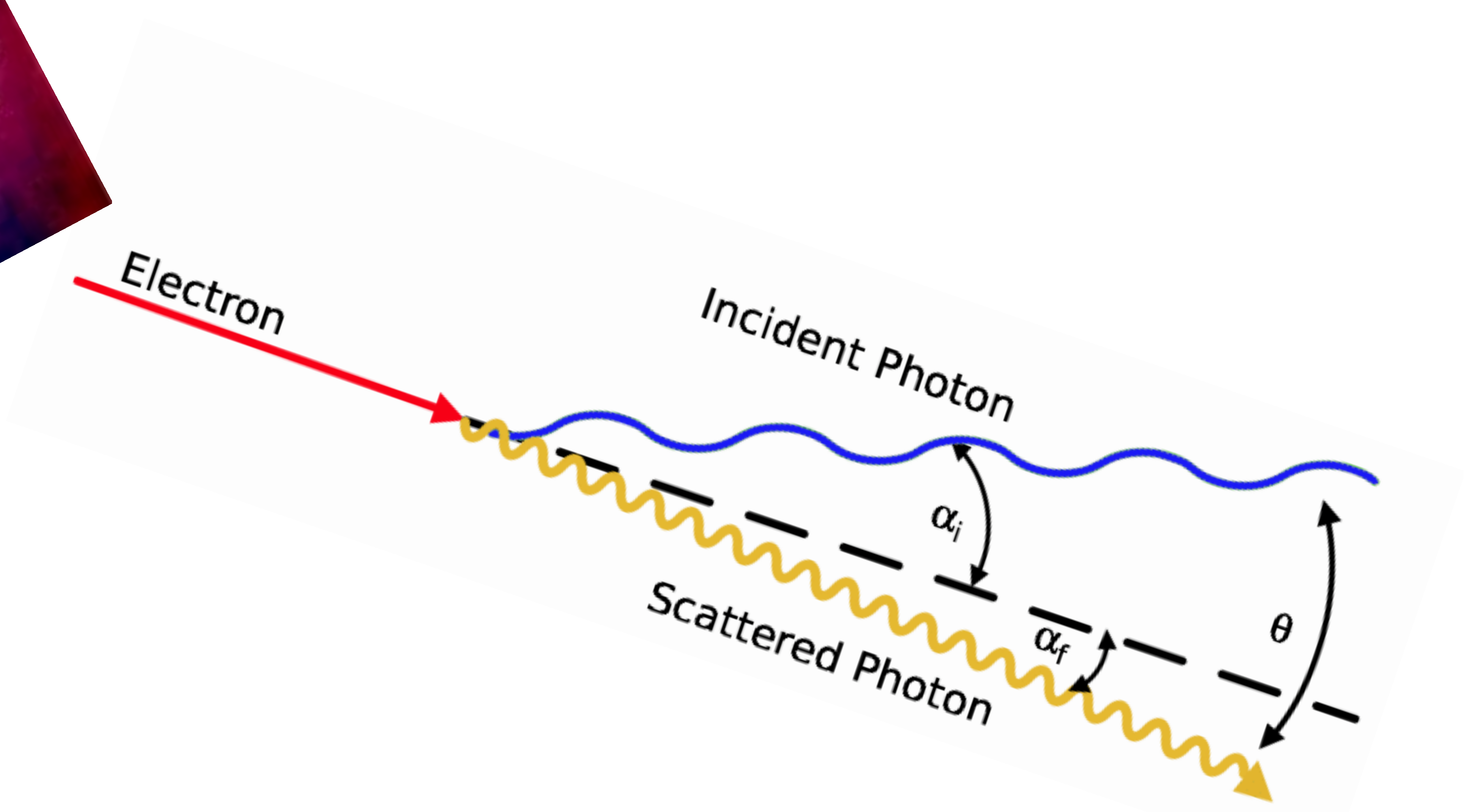
Fermi-LAT view of the Universe

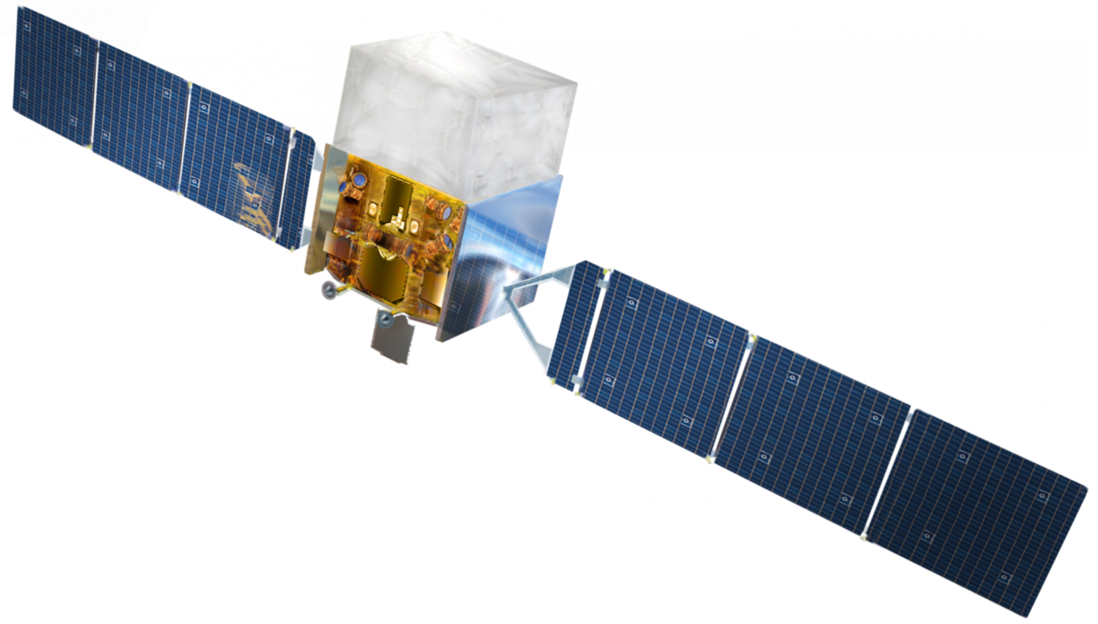


NASA/DOE/Fermi LAT Collaboration

Fermi-LAT

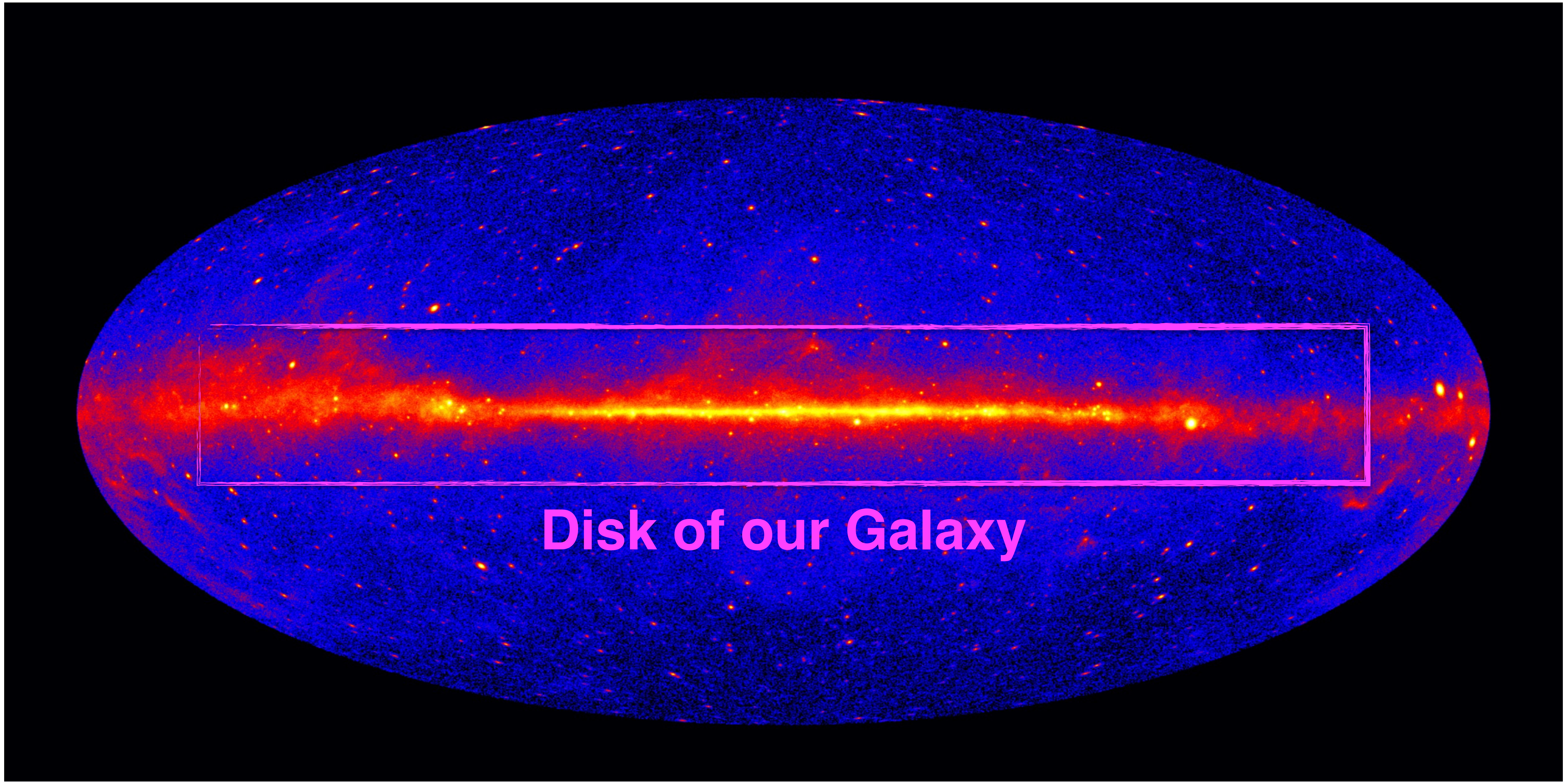






https://www.youtube.com/watch?v=G0dOoqeIczY

Milky Way: gamma rays



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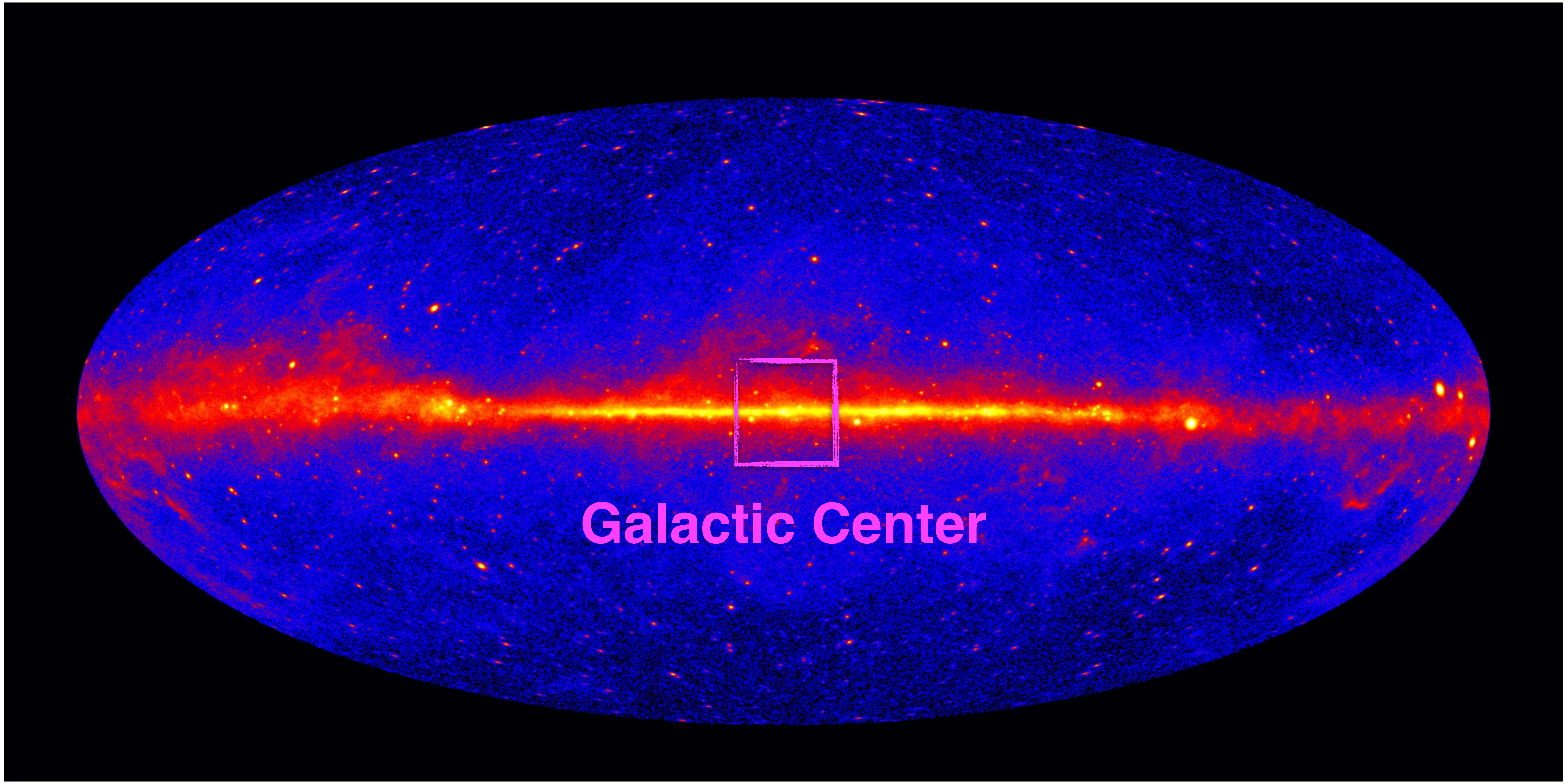
Milky Way: gamma rays



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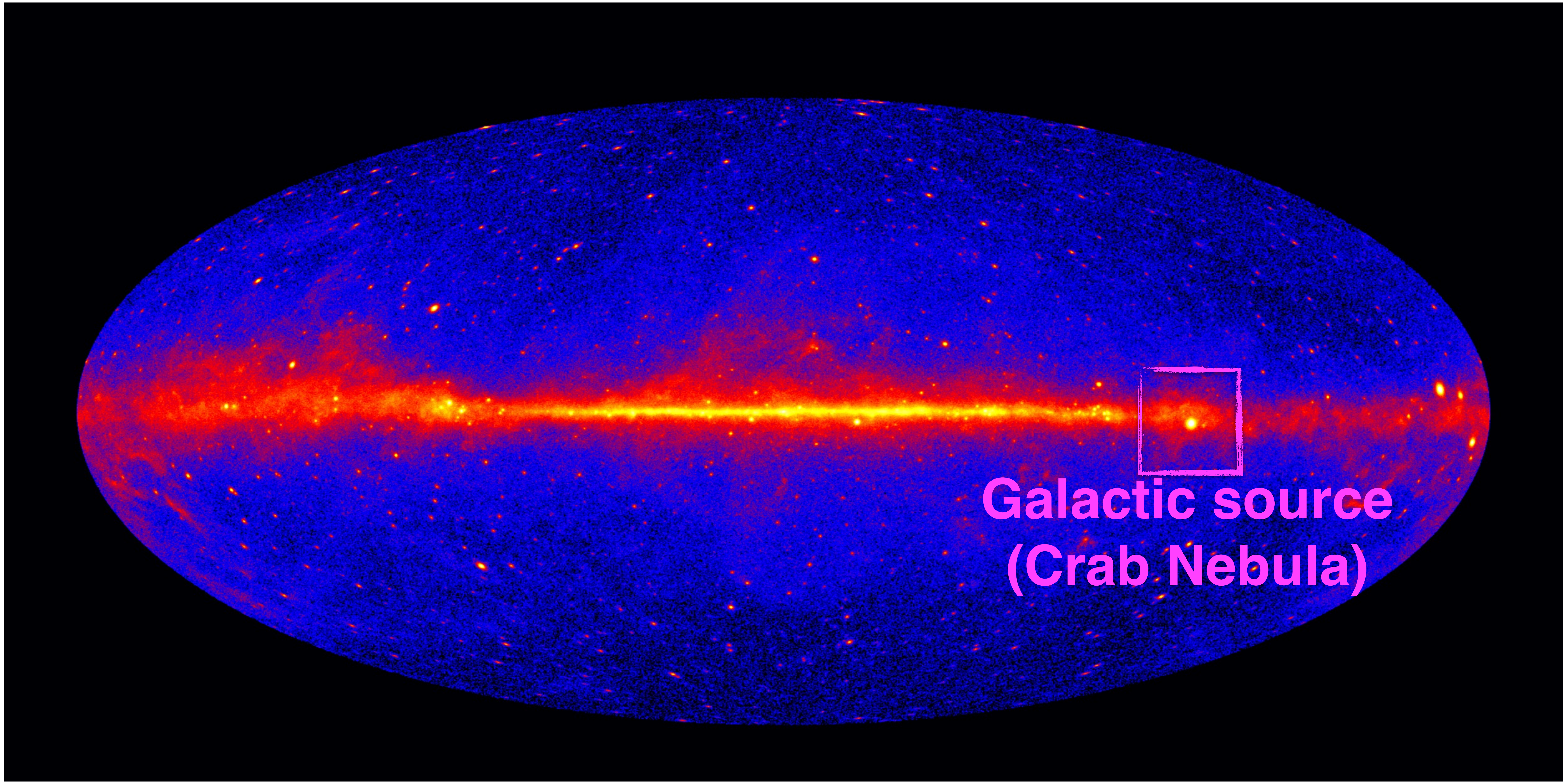
Milky Way: gamma rays



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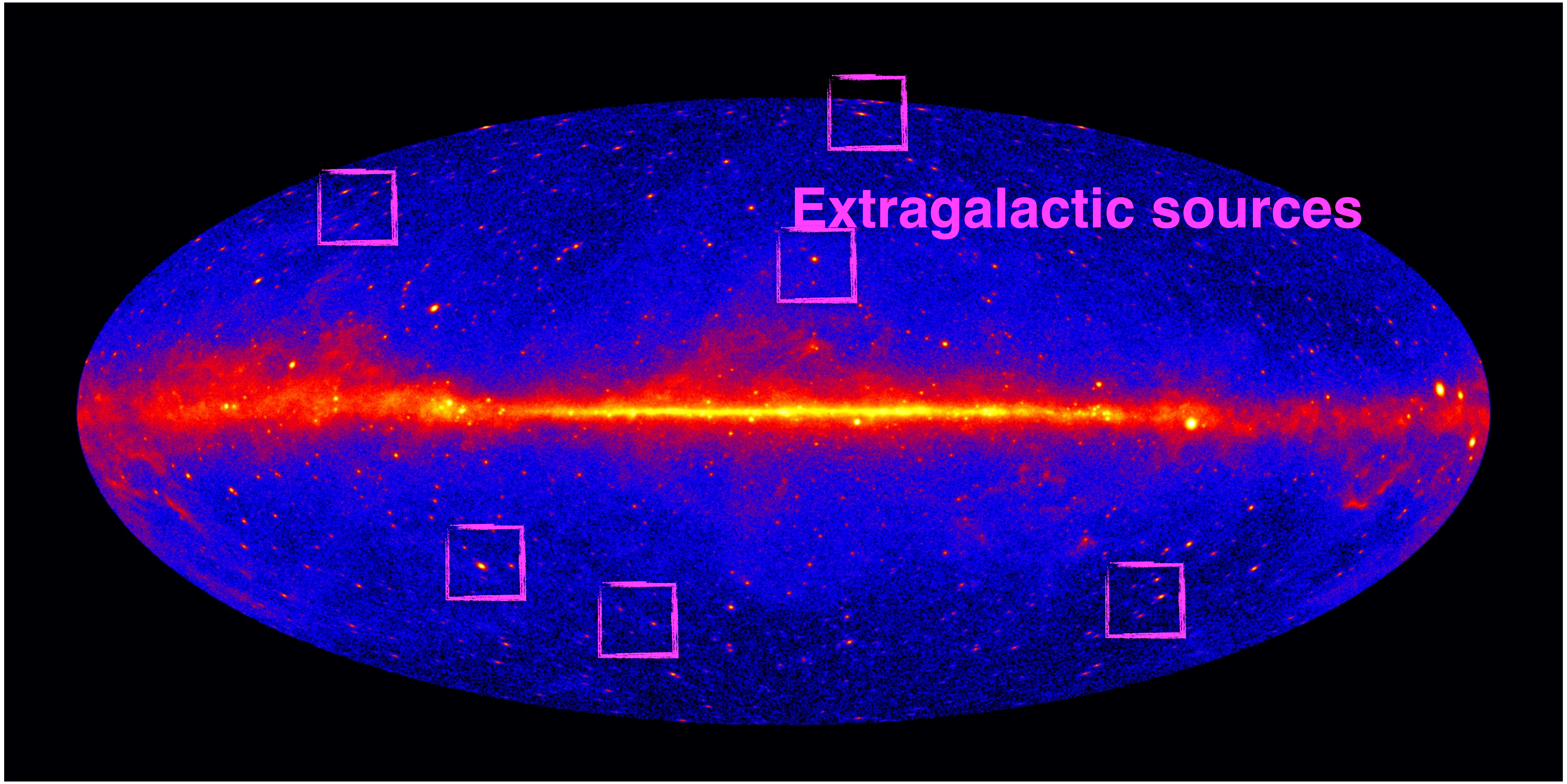
Milky Way: gamma rays



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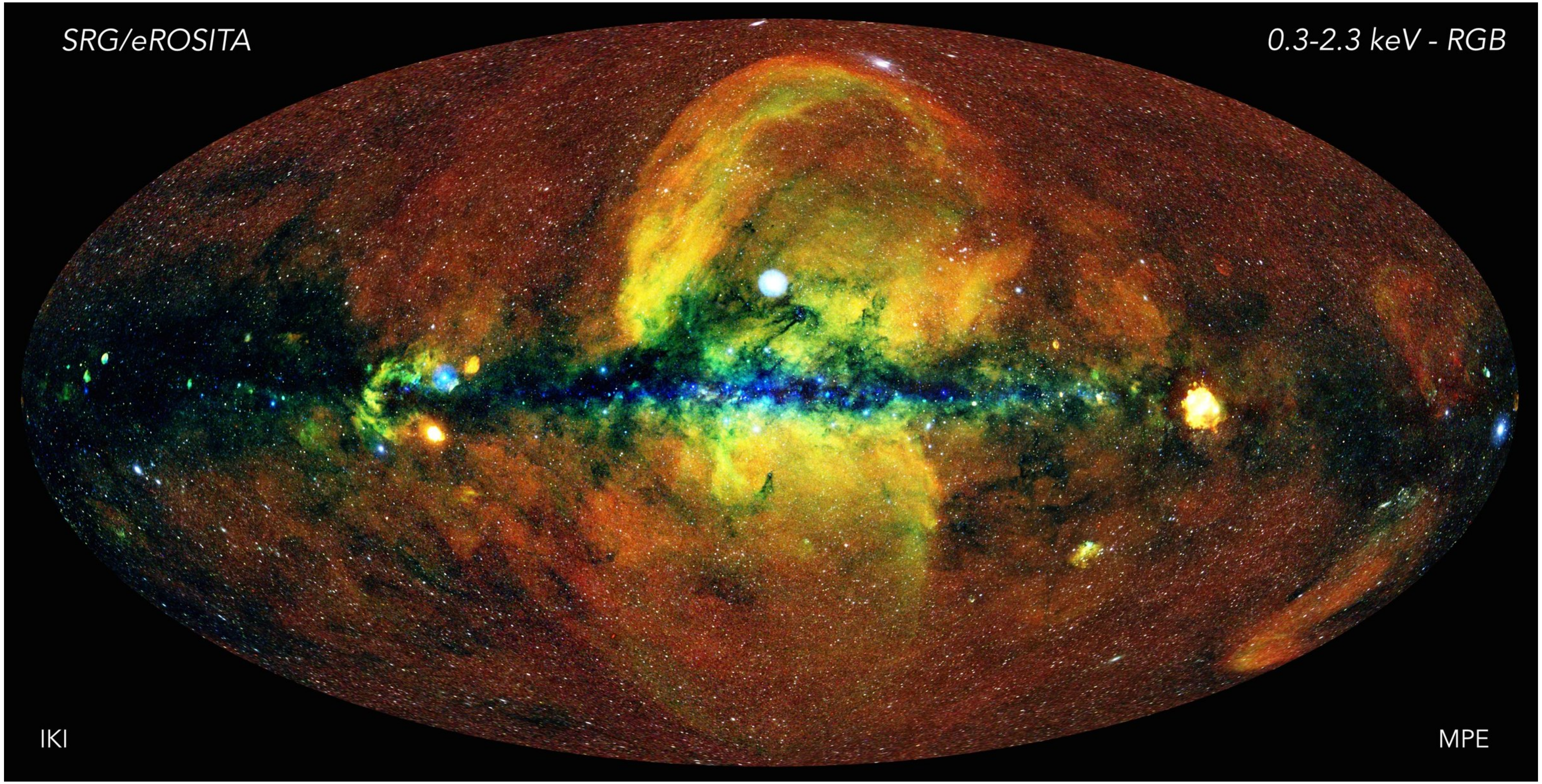
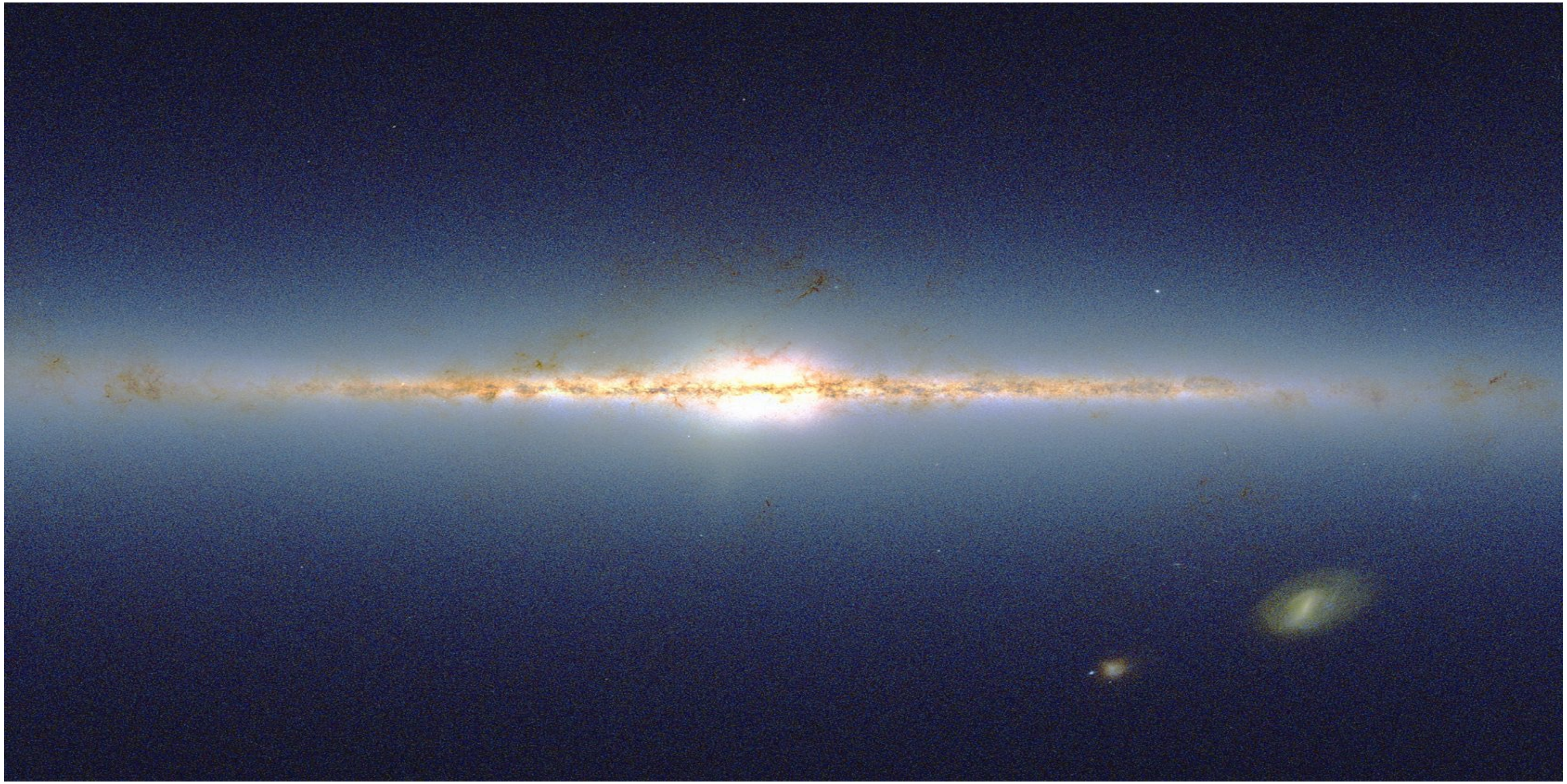
Milky Way: X-ray



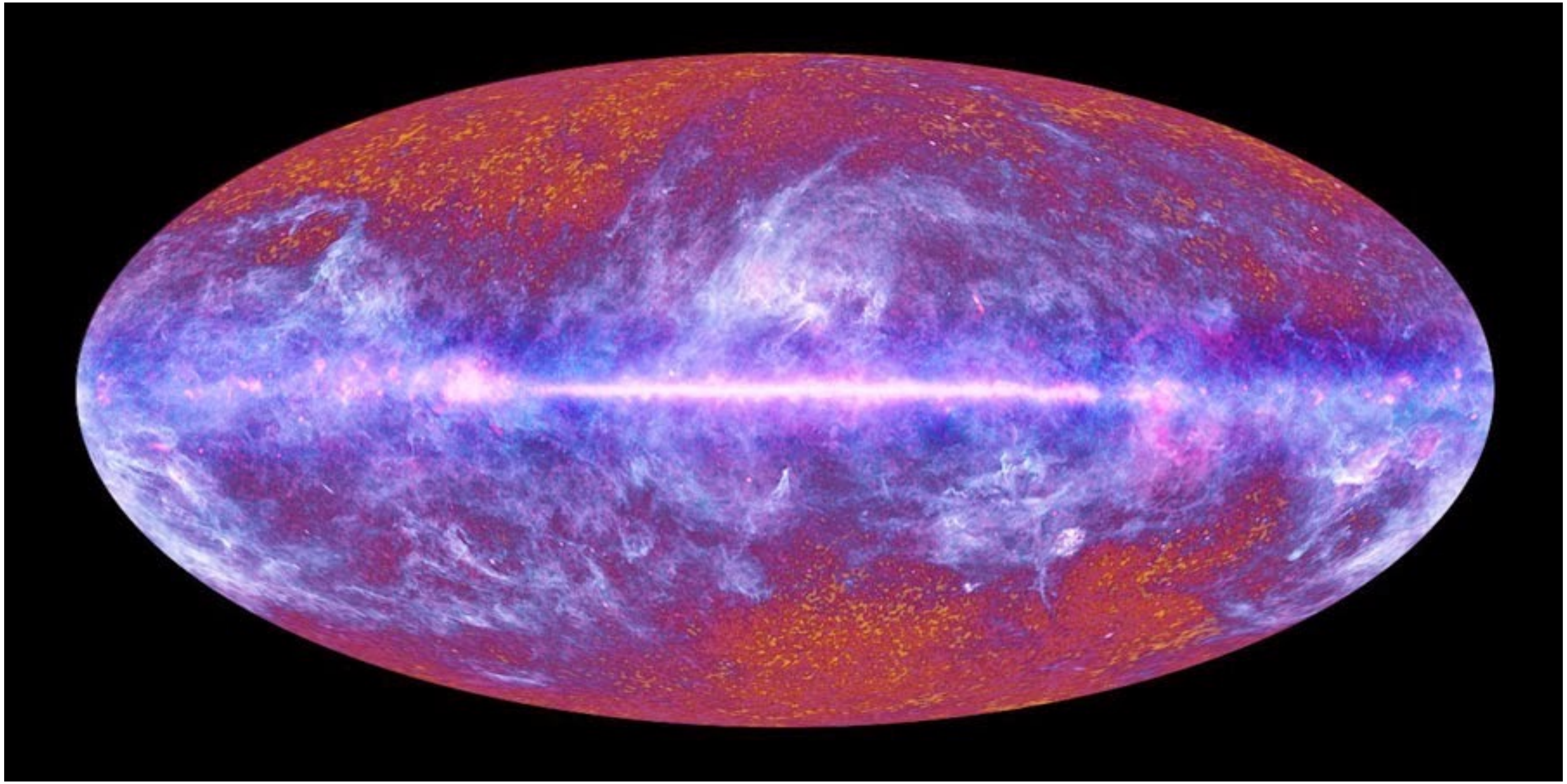
eRosita

Milky Way: Infrared



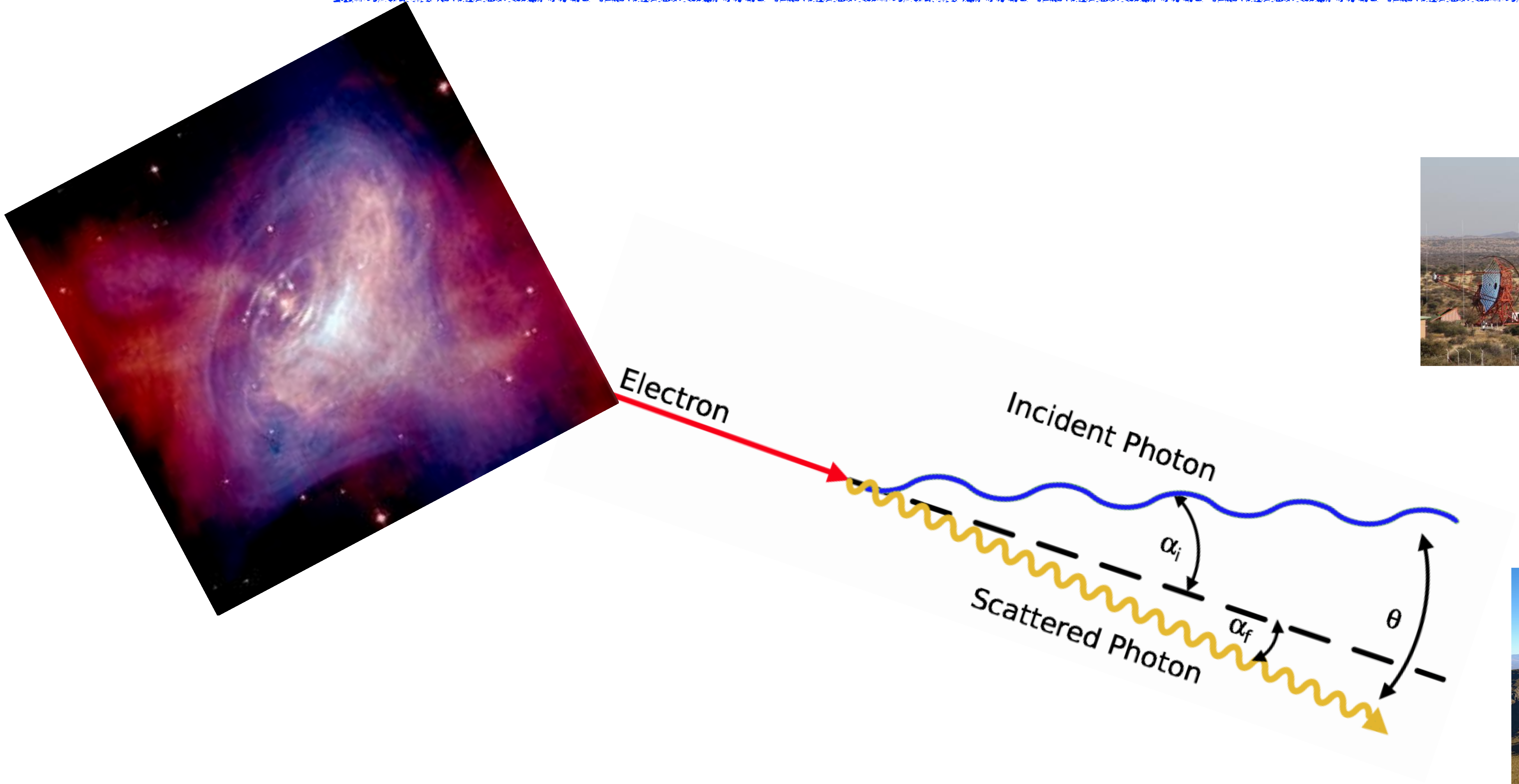
Milky Way: Optics

Milky Way: radio

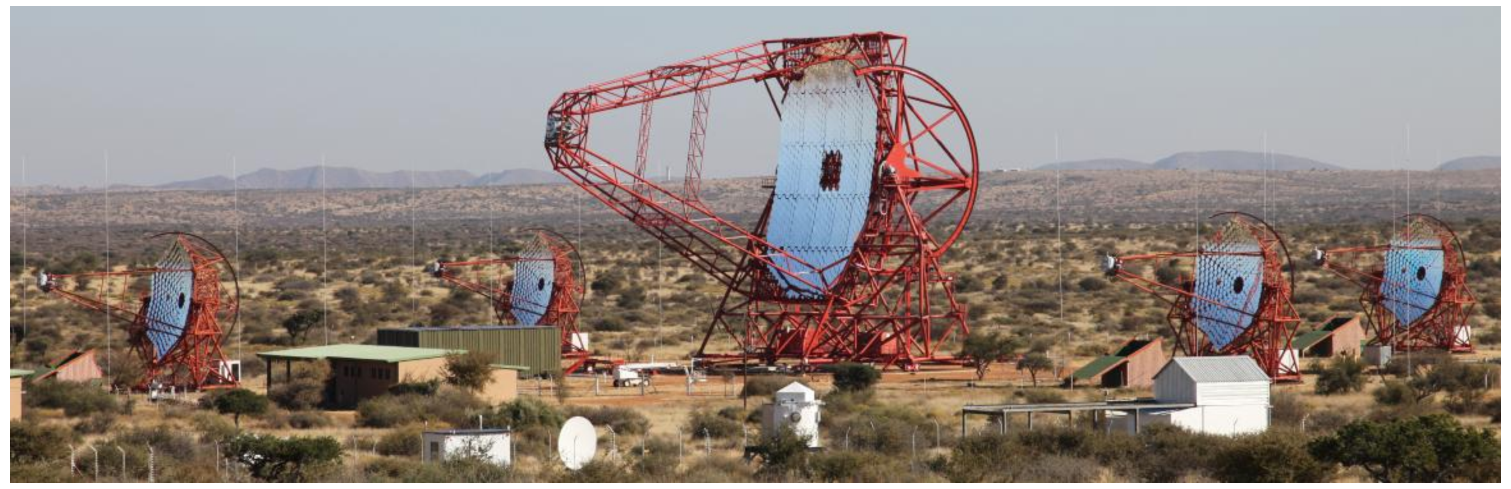


European Space Agency, HFI and LFI consortia

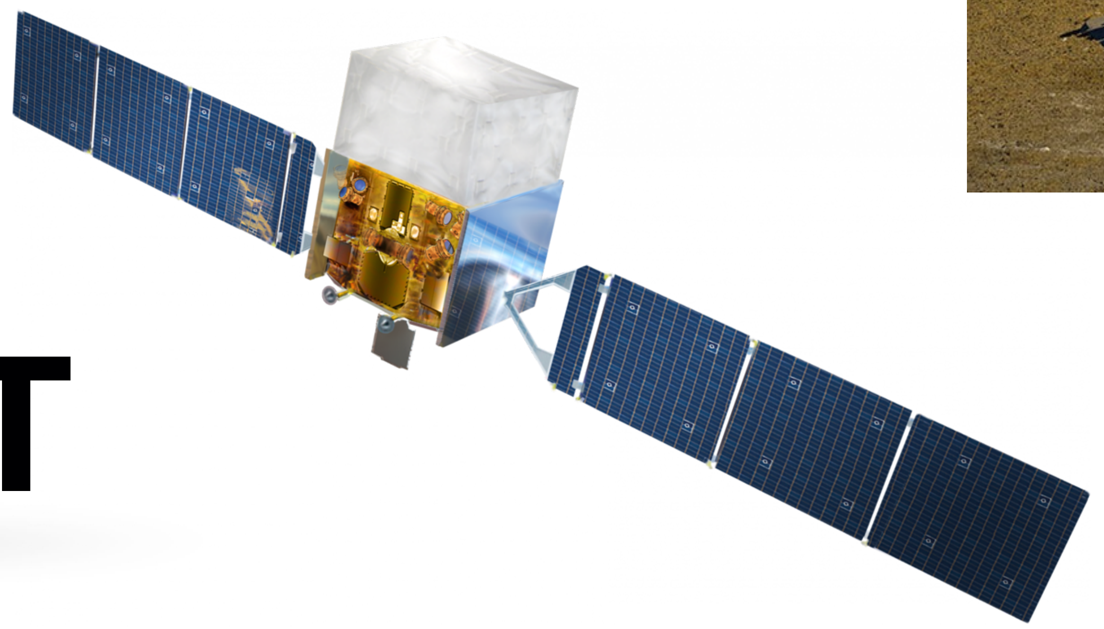
γ rays produced by inverse Compton scattering



IACTs



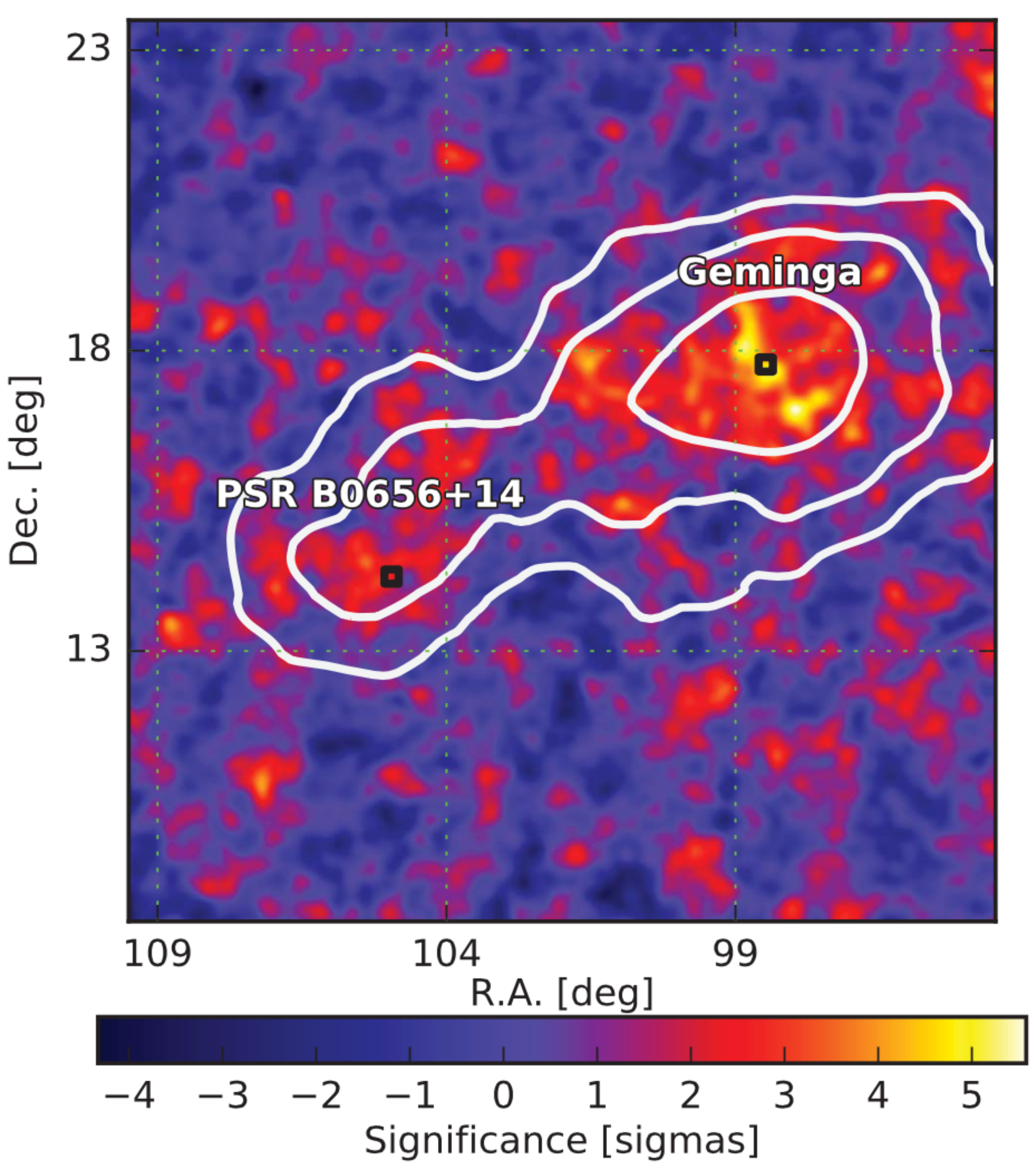
HAWC

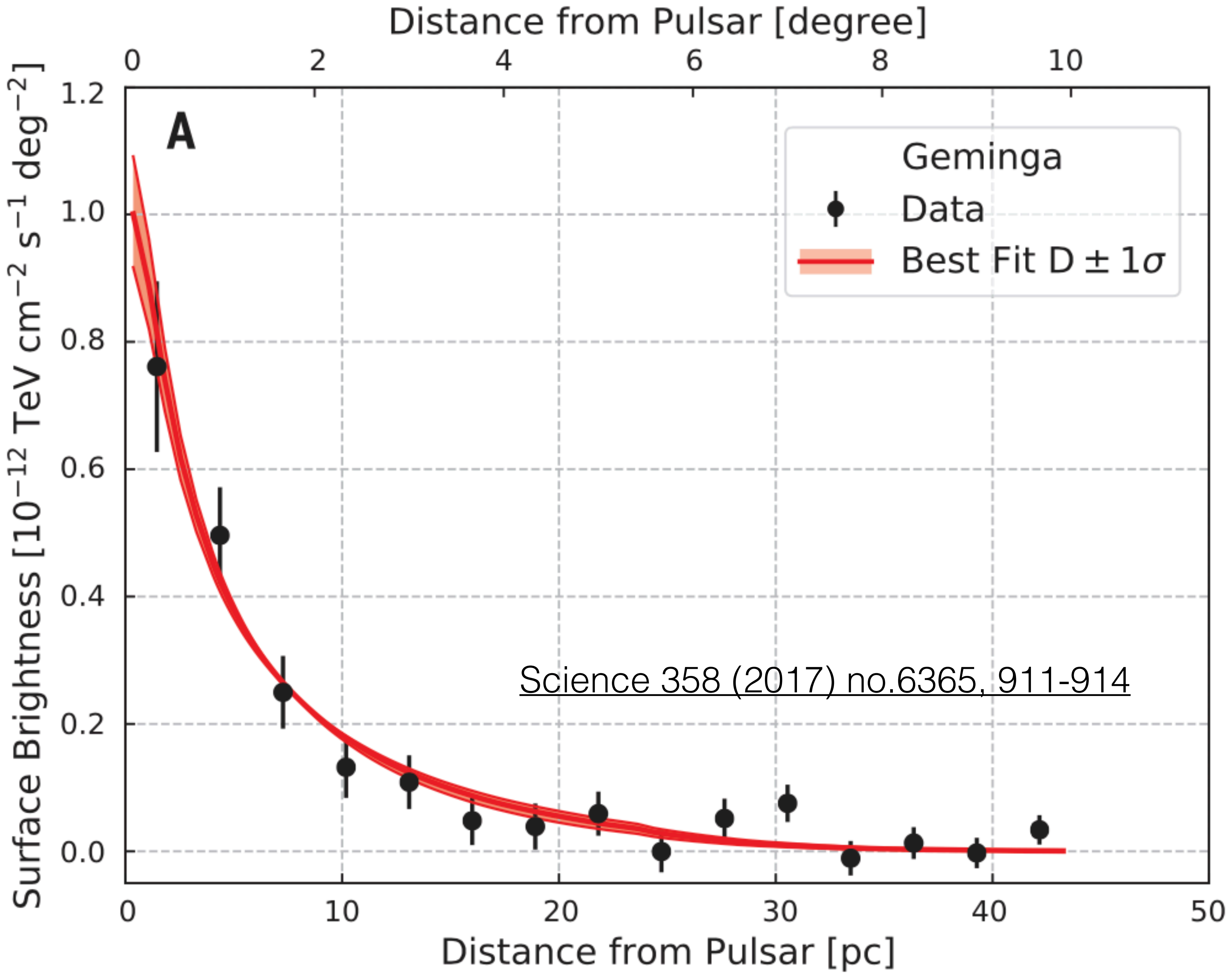


Fermi-LAT

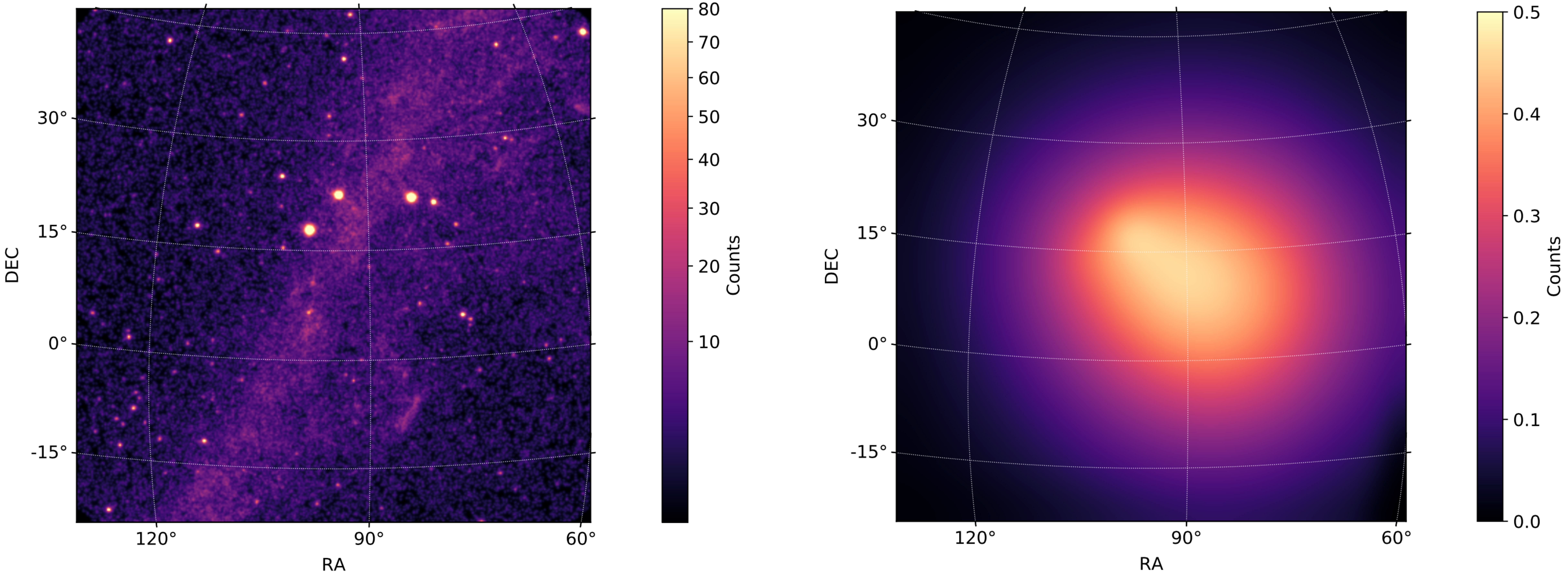
HAWC results for Geminga and Monogem PWNe

- HAWC detected an extended emission from Geminga and Monogem PWNe for **E>5 TeV**.
- ***In the vicinity of the PWN, the diffusion coefficient D must be about 500 times smaller than the average in the Galaxy.***



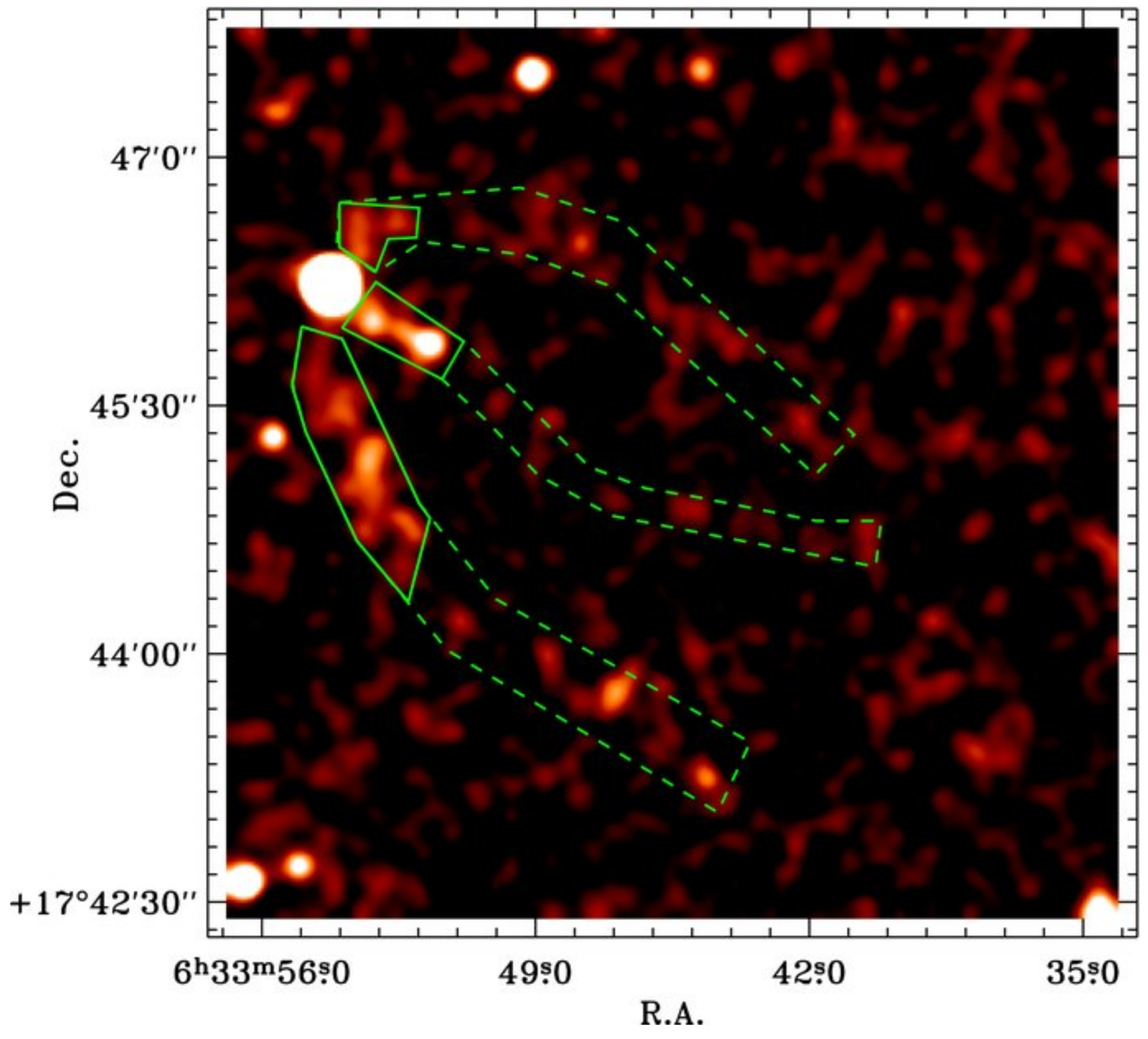


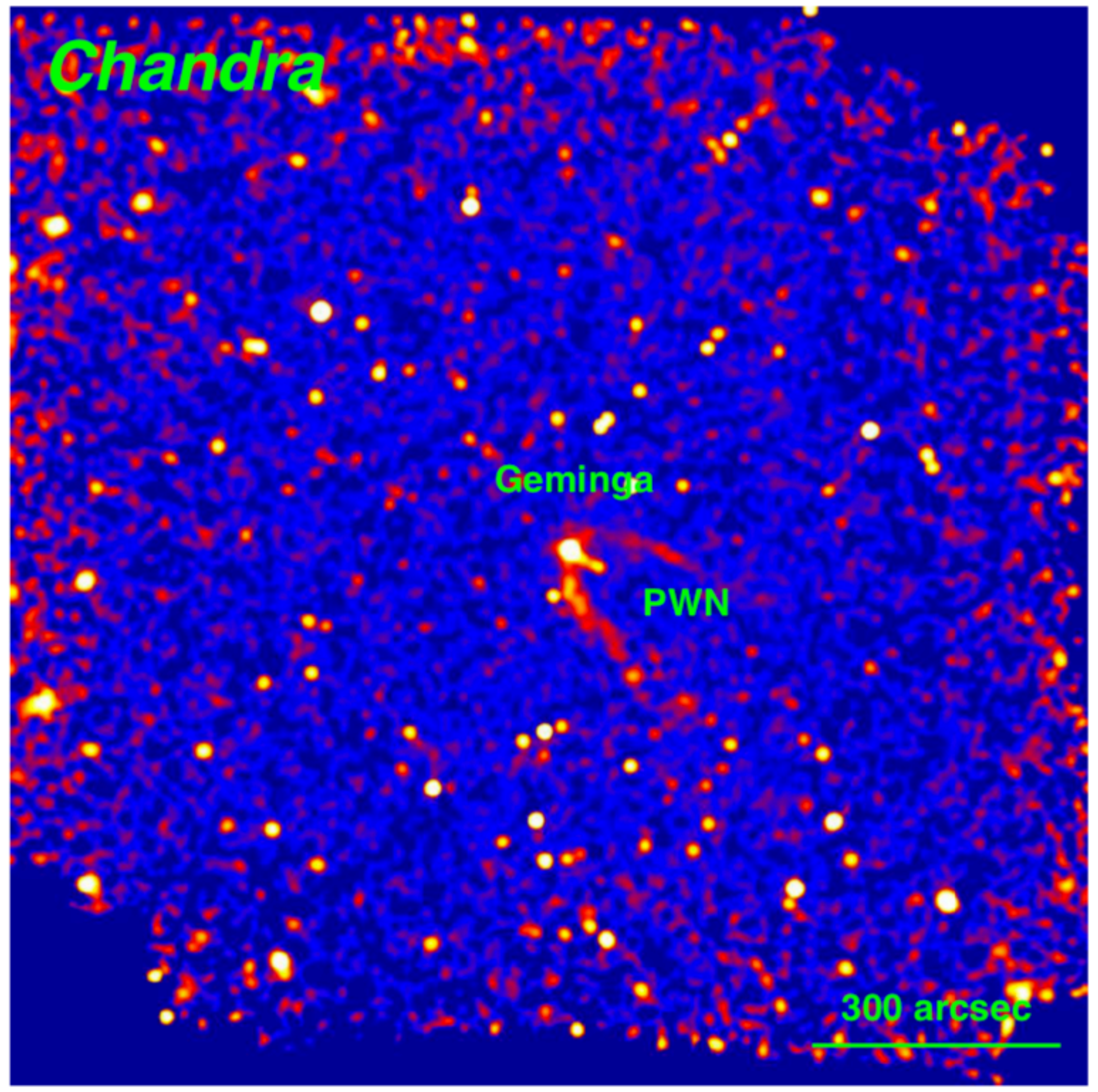
Analysis of Fermi-LAT data

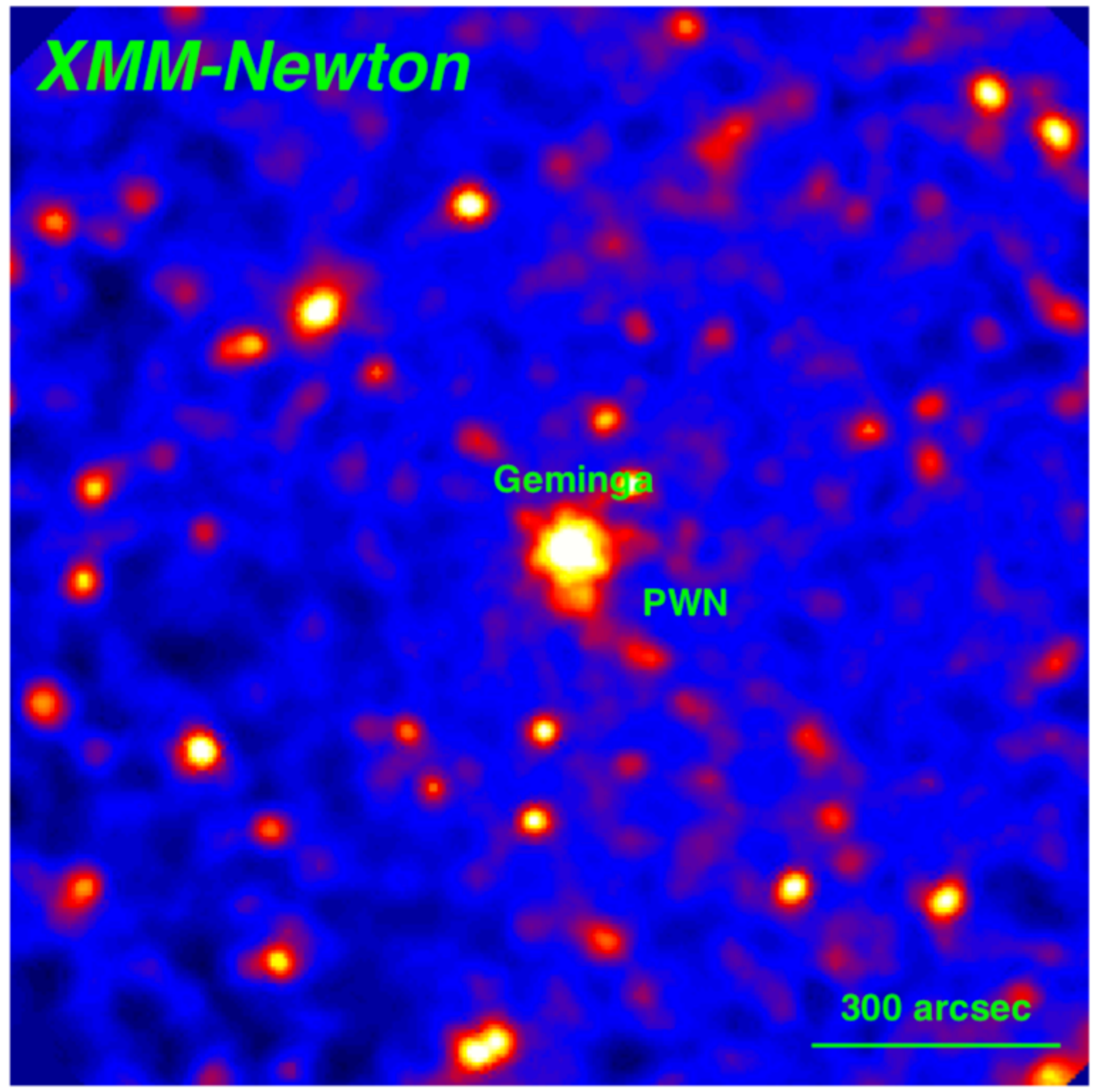


Di Mauro, Manconi, Donato PRD 100, 123015 (2019)

Current observations of pulsars and PWNe in X rays







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THANK YOU FOR LISTENING
ANY QUESTIONS?
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