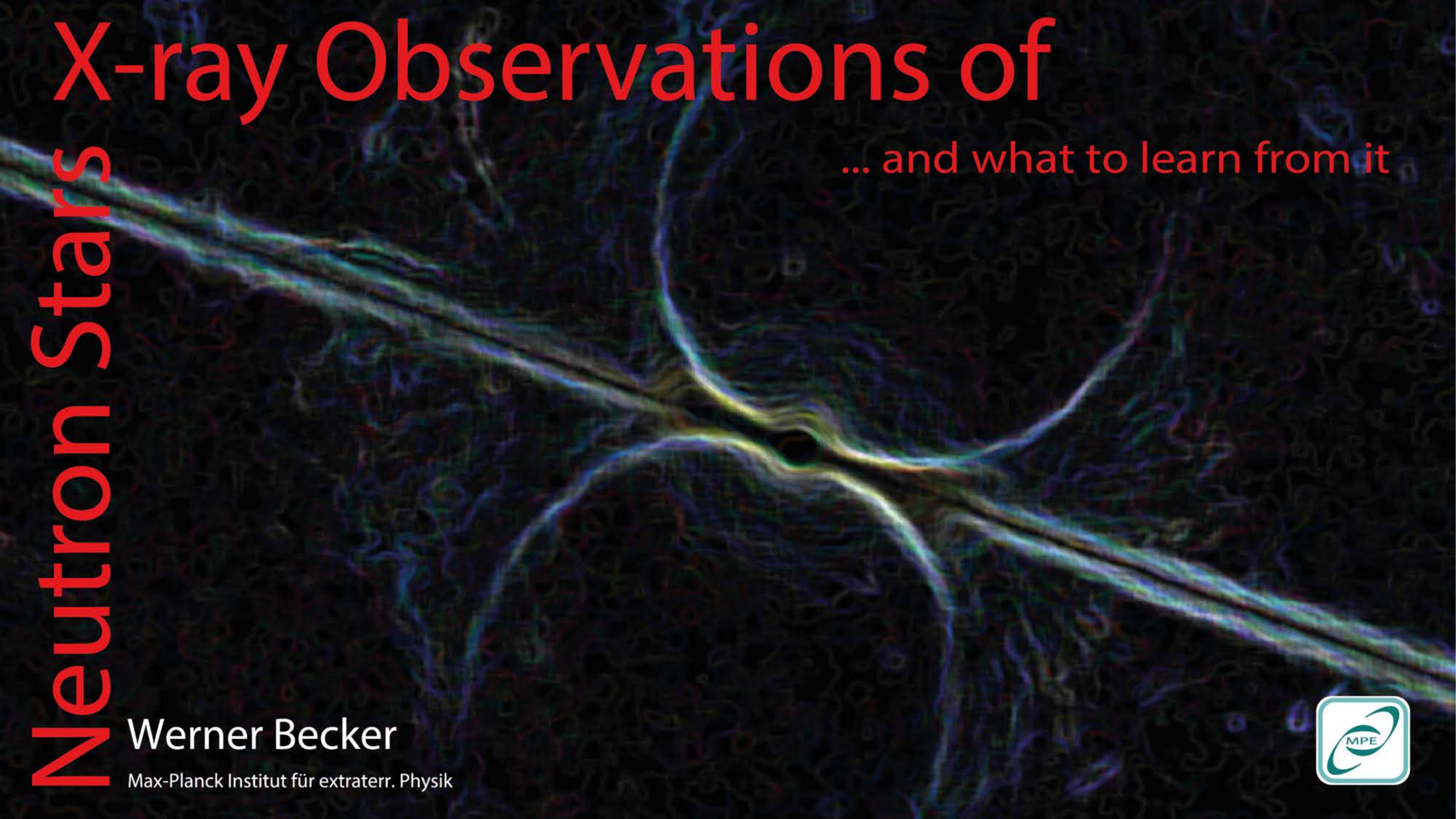


X-ray Observations of Neutron Stars

... and what to learn from it

Werner Becker

Max-Planck Institut für extraterr. Physik

What will I talk about:

- The end state of stellar evolution: How are Neutron Stars formed ?
- What are the unique properties of Neutron Stars
- What are the high energy emission properties of Neutron Stars
- X-ray observatories and the observation of Neutron Stars and Pulsars
- NS EOS: Equation of state of super dense and *cold* nuclear matter
- Measurements of Neutron Star masses and radii
- Thermal evolution of Neutron Stars: The details of Neutron Star cooling and constraints following from it

The end-state of stellar evolution depend only on the initial star mass!

- $M = 1 – 8\ M_{\odot}$: The star will evolve to become a white dwarf or will explode in a nuclear C-detonation (Typ Ia Supernova)
- $M > 8 - 30\ M_{\odot}$: The star will undergo a gravitational collapse, observable as Type Ib, Ic or Type II supernova, to form a Neutron Star
- $M > 30\ M_{\odot}$: The star will undergo a gravitational collapse to form a Black Hole

Some days to go:

The further contraction of the star results in central temperatures of more than 3 billion degrees. At the center Silicon and Sulfur fusion into Iron, which forms a very dense sphere of about 1 - 3 $M_\odot$

As the fusion of Iron does not release energy, the final state of fusion is reached.

Hydrogen / Helium

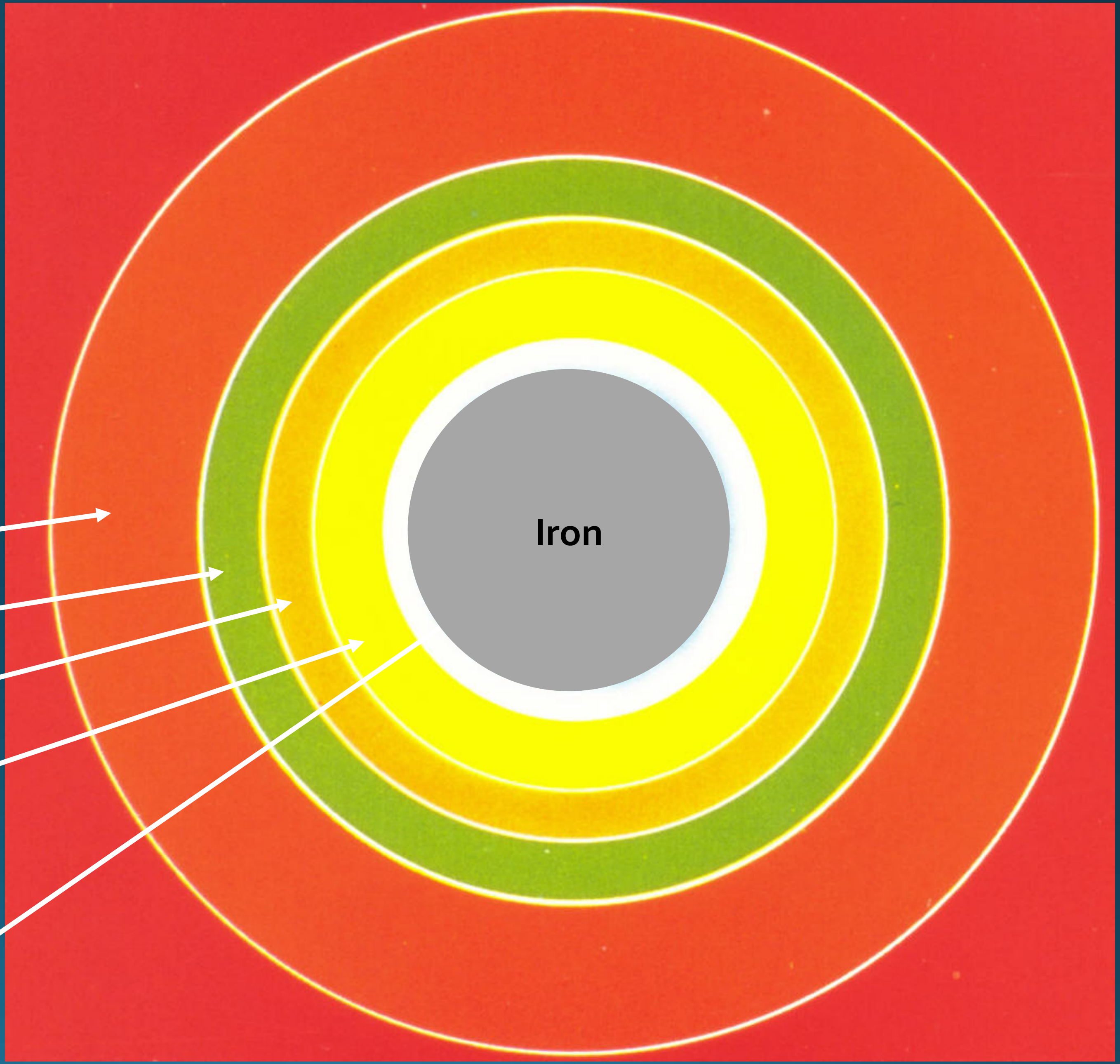
Carbon

Neon / Magnesium

Magnesium / Oxygen

Iron

Silicon and Sulfur → Iron

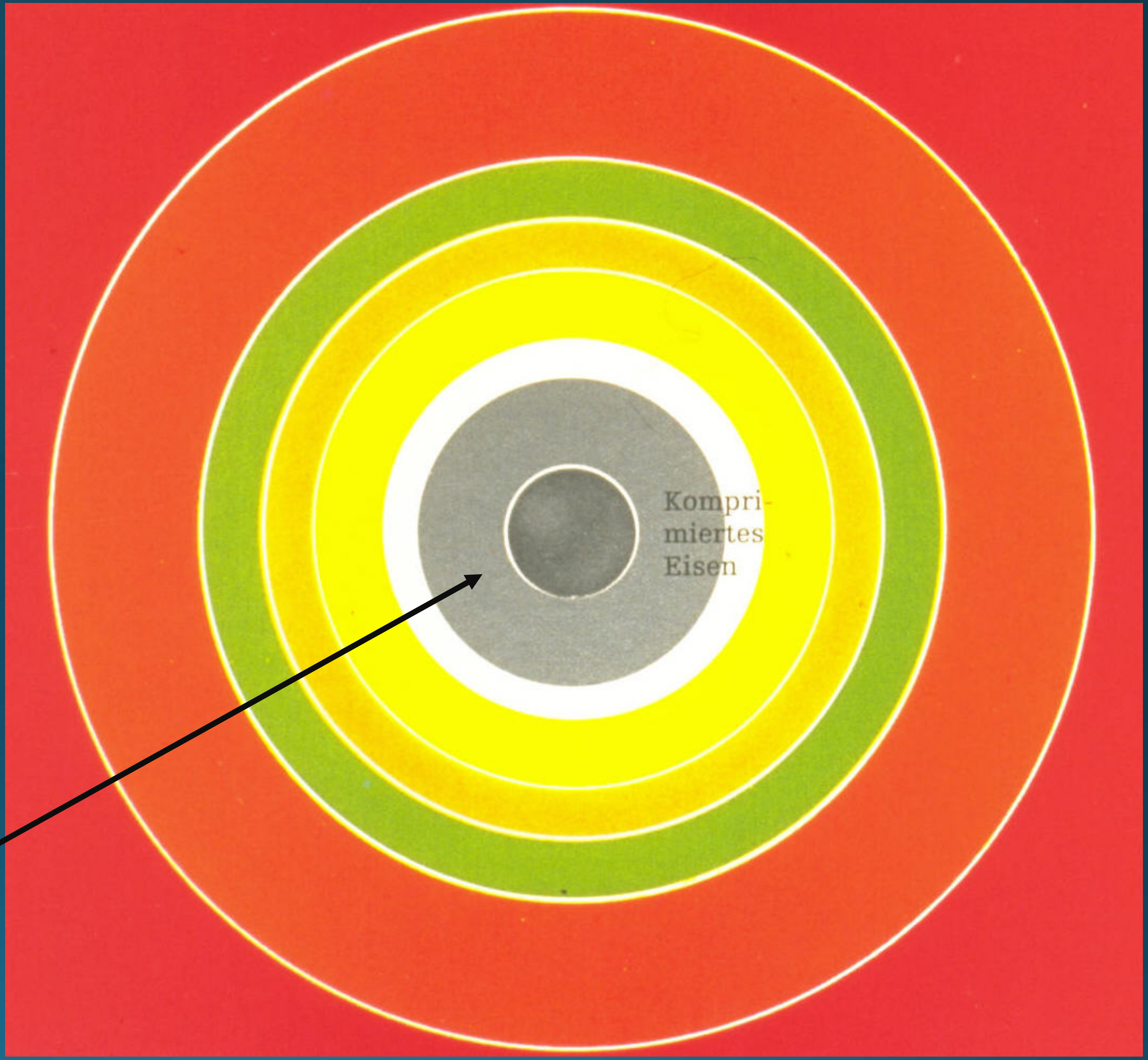


Tenths of a second before the collapse:

The end of the central fusion process is the start of the gravitational core collapse. The Iron in the core is falling towards the center with almost a quarter of the velocity of light. The temperature increases to 100 billion degrees, while the initially earth-size Iron sphere is merged to become a ~20 km diameter small Neutron Star.

The atomic nuclei of the Iron atoms are merging into each other.

This will produce an almost infinite amount of Neutrinos whose pressure will cause the star to explode.

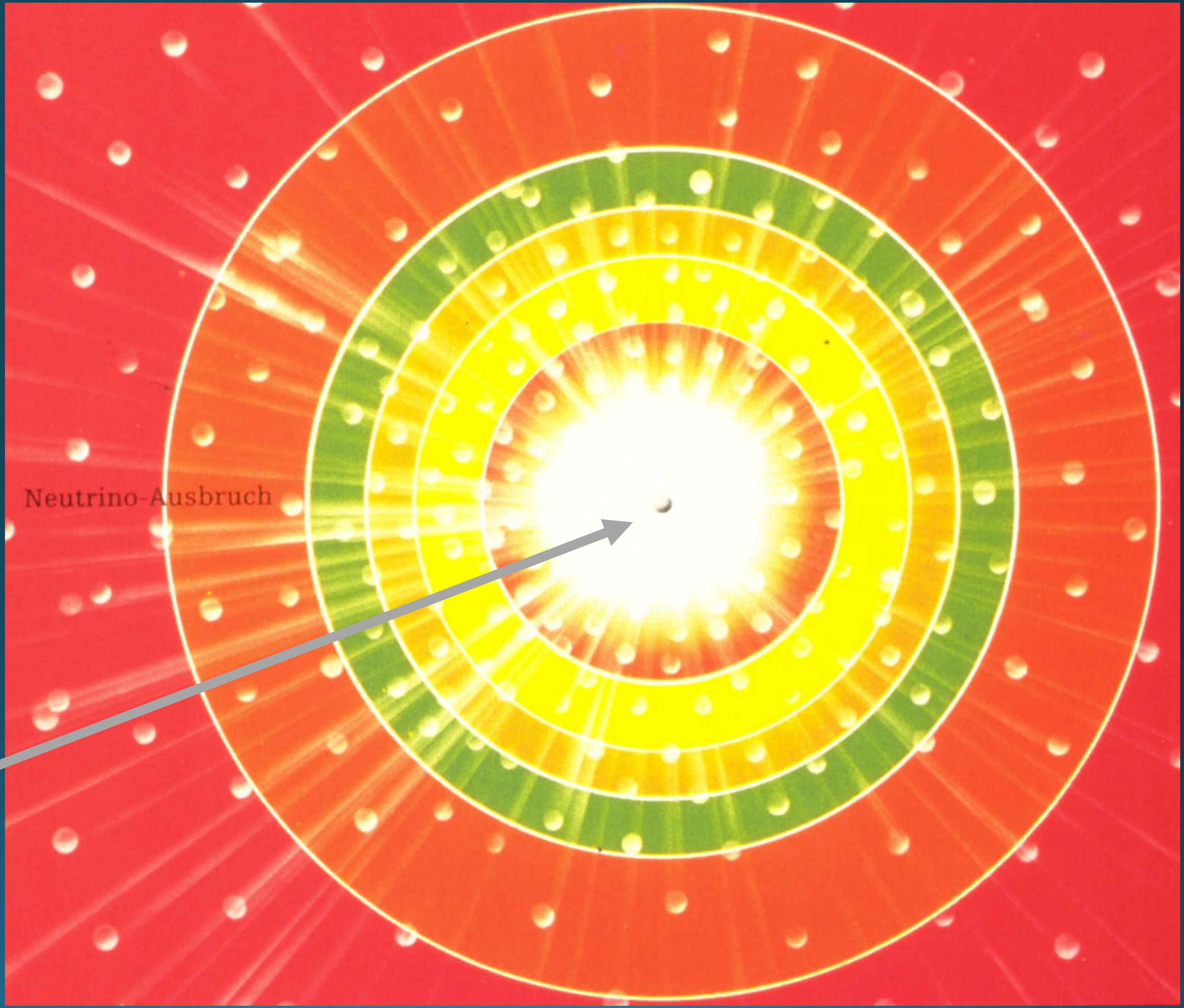


Compressed Iron core

Seconds after:

The explosion energy is emitted by 99.5% in the form of Neutrinos.

As a first indication of the explosion they are passing through the outer shells of the star.



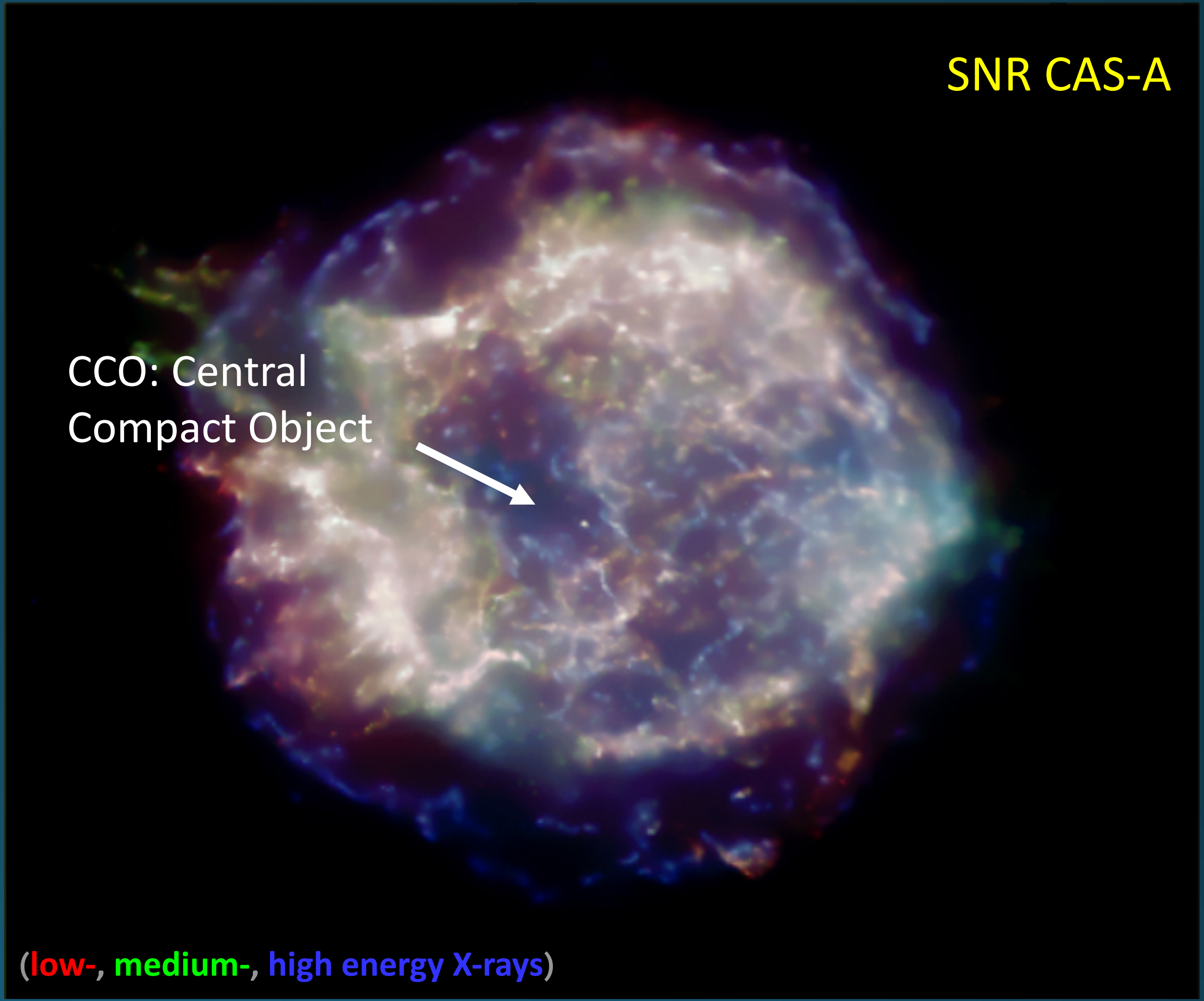
Neutron Star

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$p + e^{-} \rightarrow n + \nu_e$$

Supernova remnant Cassiopeia A (CAS-A)

- In this scenario: Neutron Stars are formed at a temperature of about 1 billion degrees in a core-collapse supernova event.



Historical SN of 1667 AD (distance about 11 000 LJ)

What are the unique properties of Neutron Stars?

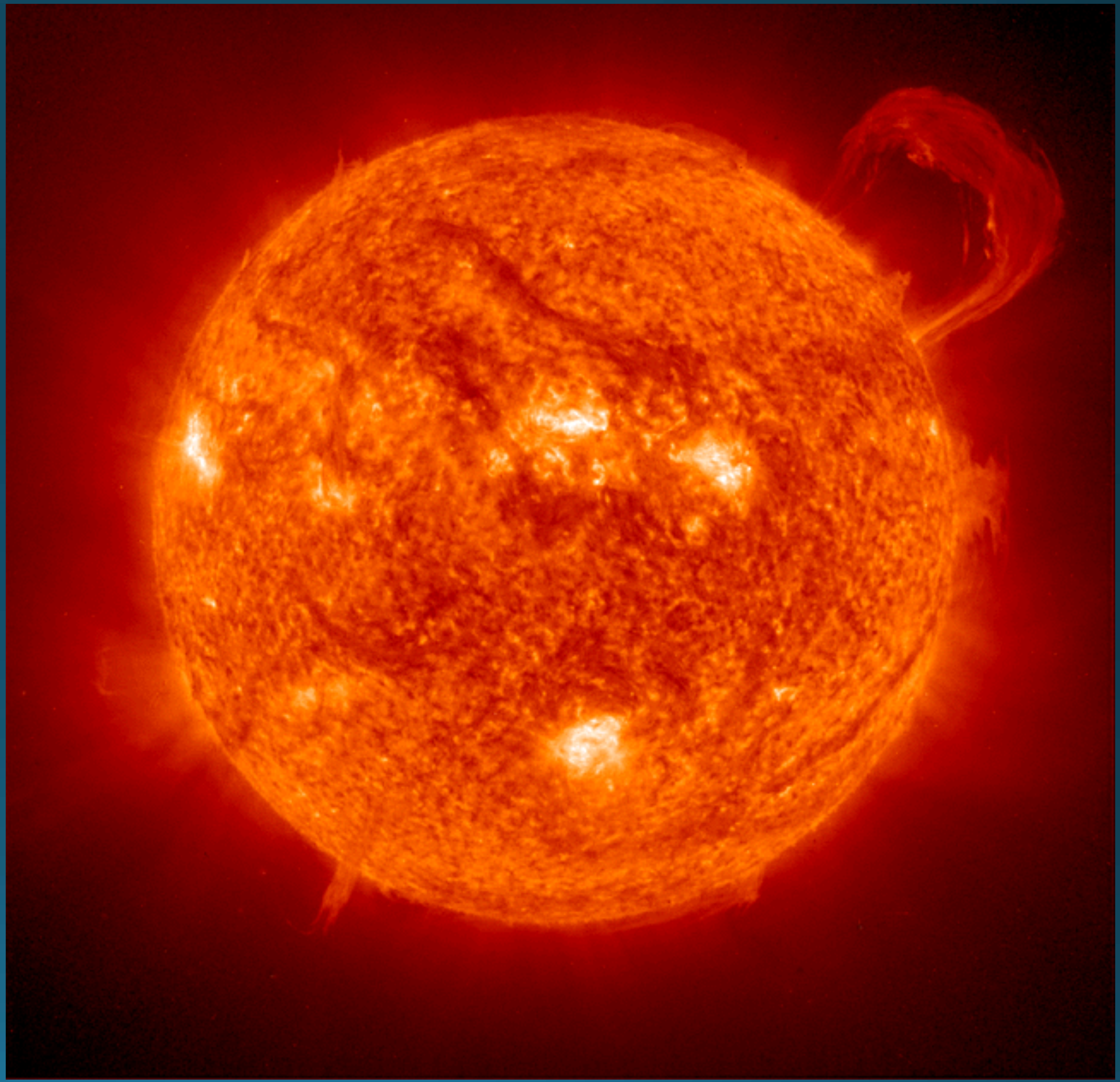
Extreme stellar parameters:

Mass	1-3 Solar masses
Radius	10 km
Density	1 billion tons per cm^3
Gravitation	10 trillion g
Magnetic field	100 million Tesla
Rotation periods	up to milliseconds
Temperature	several billion degrees (in statu nascendi)

- Neutron Stars are quasi gigantic atomic nuclei in the universe
- They consist of ca. 10^{56} Neutrons
- Landau 1932: Neutron Stars –> weird stars

How to understand the strong magnetic fields and fast rotation periods?

- What happens with the rotation period of the sun (28d) if its radius shrinks down to 10 km?



Conservation of angular momentum: → Rotation period of the Neutron Star

$$(I\,\Omega)_\odot = (I\,\Omega)_{\rm NS}$$

$$\boxed{P_{\rm NS} = P_\odot \left(\frac{R_{\rm NS}}{R_\odot}\right)^2 \approx 5 \times 10^{-4}\ \mathbf{s}}$$

The rotation period is of the order of milliseconds

Conservation of magnetic flux: -> Neutron Star magnetic field

$$B\,R^2 = const.,\ B_\odot \sim 1\mathbf{G}$$

$$\boxed{B_{\rm NS} = B_\odot \left(\frac{R_\odot}{R_{\rm NS}}\right)^2 \approx 5 \times 10^9\ \mathbf{G}}$$

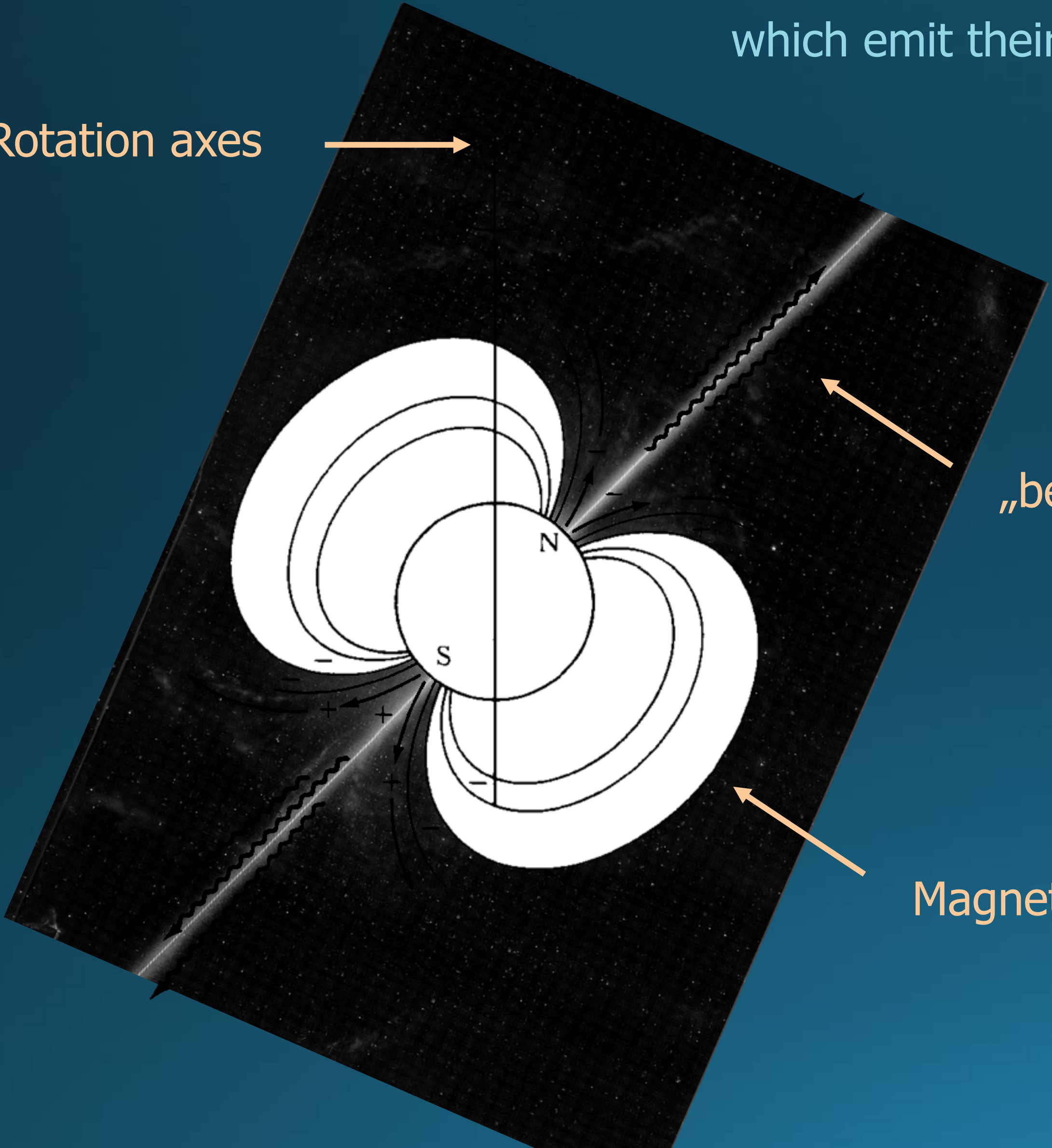
Magnetic field strength are of the order of $10^9 - 10^{13}$ Gauss

>> The magnetic field in Neutron Stars is frozen in ! <<

Neutron stars are observable as pulsars

- Pulsars are strongly magnetized and fast rotating compact objects which emit their radiation along narrow radiation cones.

Rotation axes



„beamed“ radiation

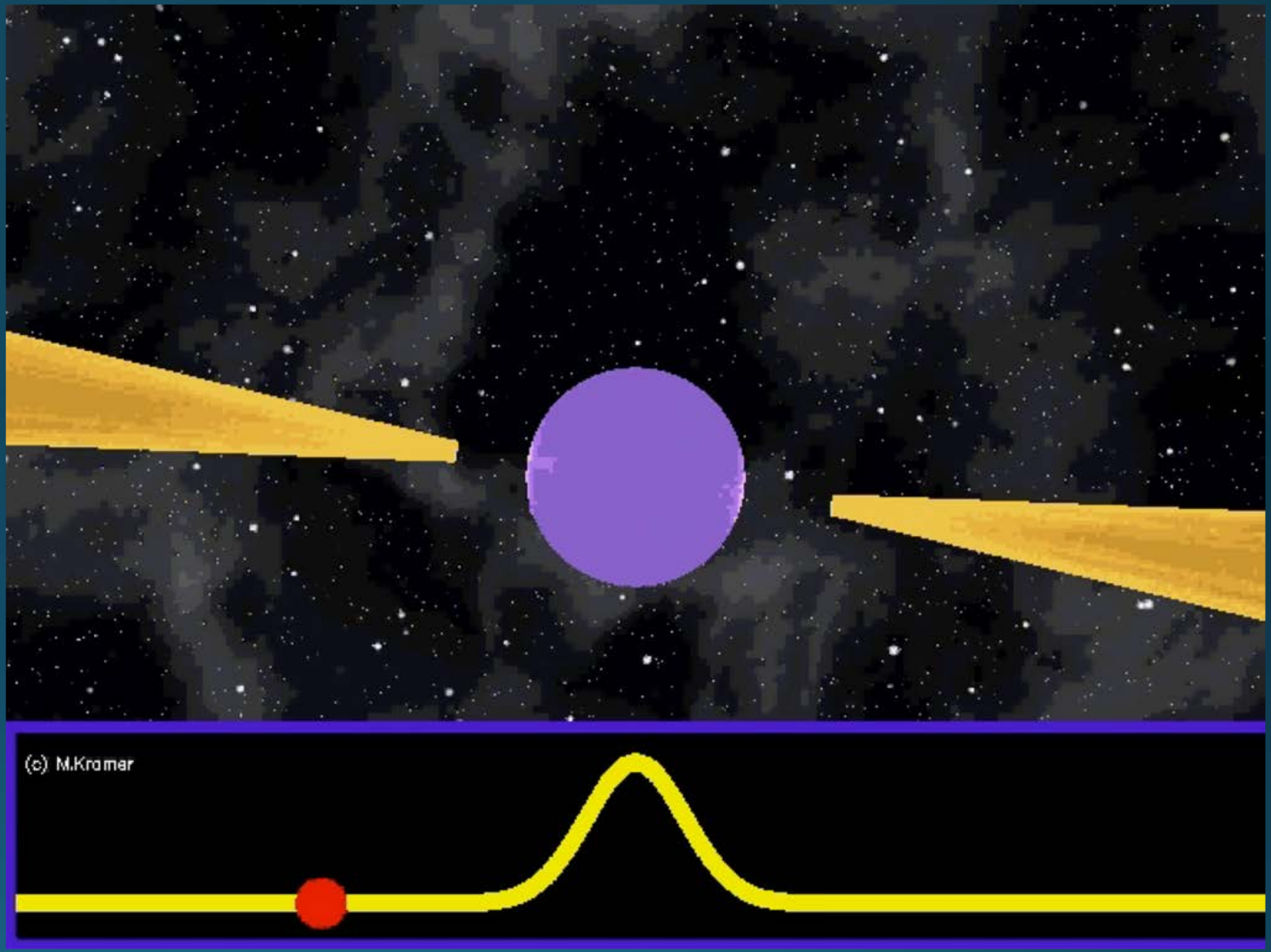
Magnetic field lines

How is the beamed radiation formed?

Vela-Pulsar (P=89 ms)

Crab-Pulsar (P=33 ms)

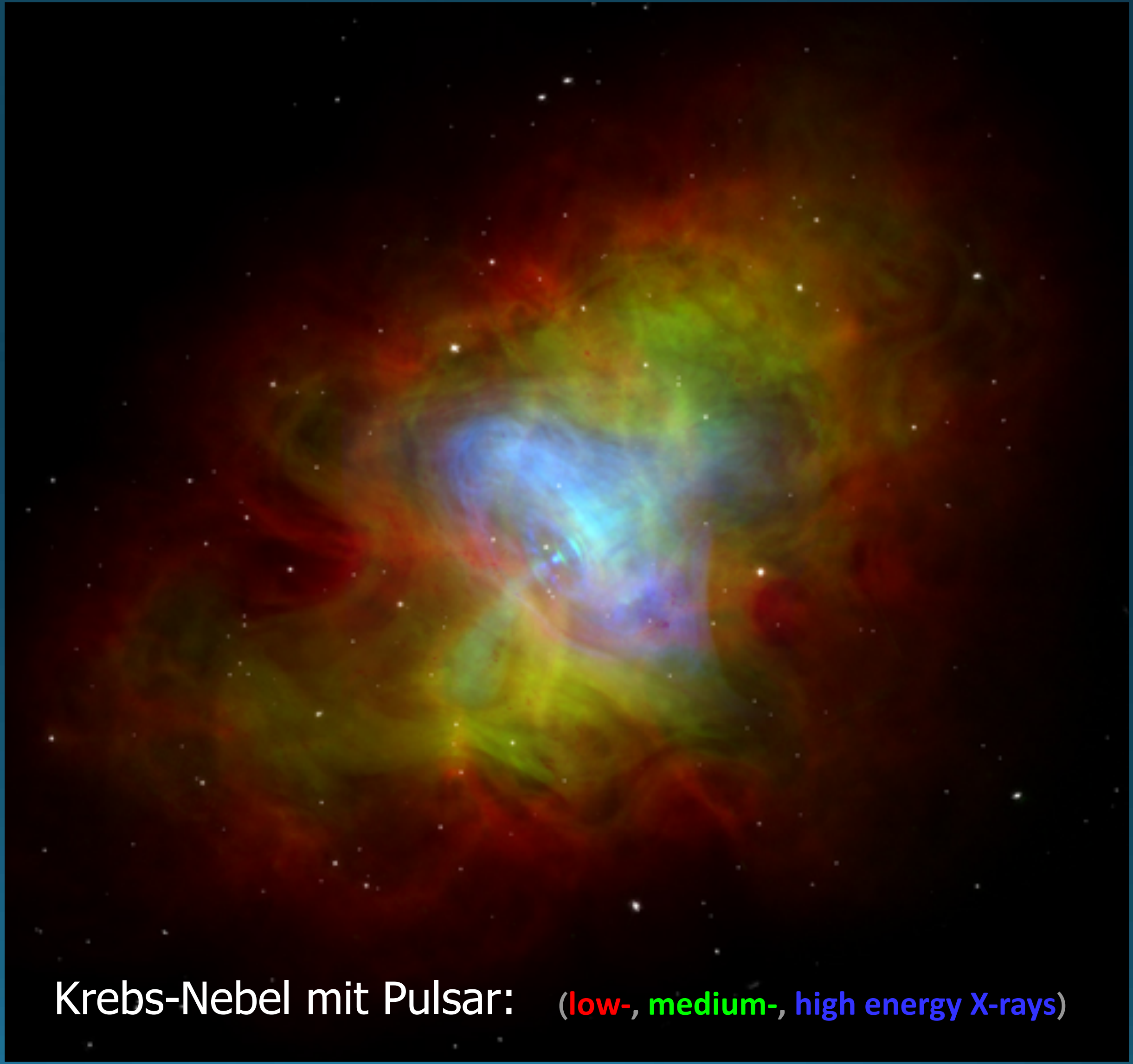
ms-Pulsar (P=1.6 ms)



Pulsars are rotation-powered, i.e. the radiated energy corresponds to the decrease of the rotational energy (Gold 1967; Pacini 1967,68)

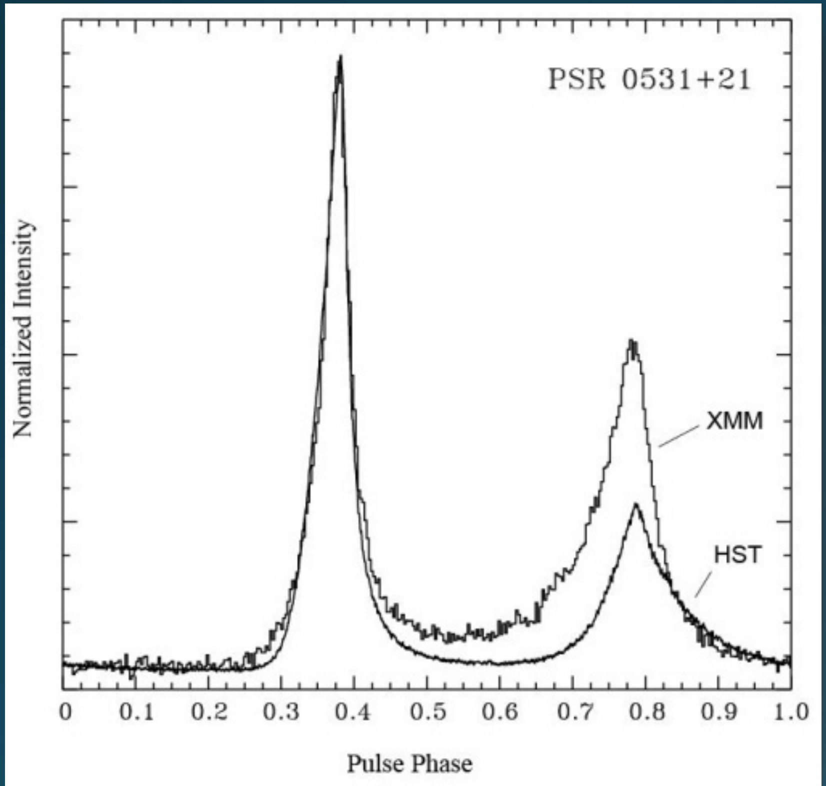
- The Crab Pulsar in the Supernova remnant: SN 1054

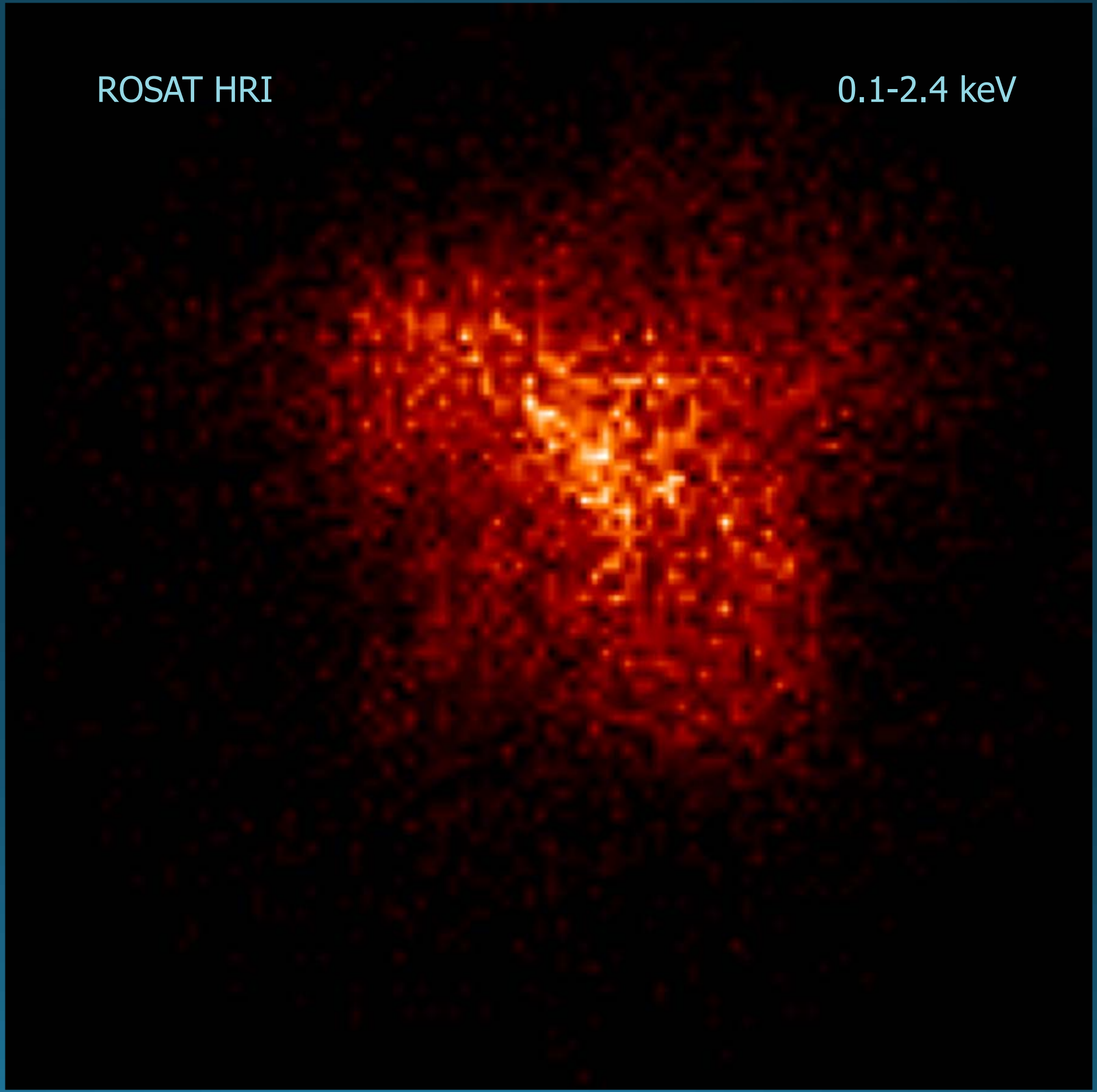
* $I = 10^{45}$ g cm^2
* $\Omega = 188.11$ rad s^{-1}
* $\dot{\Omega} = -2.37 \times 10^{-9}$ rad s^{-2}
* $E_{rot} = \frac{1}{2}\, I\, \Omega^2 \sim 2 \times 10^{49}$ erg
* $\dot{E} = I\, \Omega\, \dot{\Omega} \sim 4 \times 10^{38}$ erg/s
* $|\, \vec{m}\, | = \frac{1}{2}\, B_p\, R^3$
* $\dot{E} = -\frac{2}{3\, c^3}\ \ |\, \ddot{\vec{m}}\, |^2$
* $\dot{E} = -\frac{1}{6\, c^3}\, B_p^2\, R^6\, \Omega^4\ \sin^2 \alpha$
* $B_p = 2.1 \times 10^{20} \sqrt{\dot{\Omega}\, /\, \Omega^3}$
* $\tau \equiv -\frac{1}{2}\, \Omega\, /\, \dot{\Omega}$



- The Crab Pulsar in the Supernova remnant: SN 1054

  - Rotation period 33 ms
  - Distance 6000 Lj





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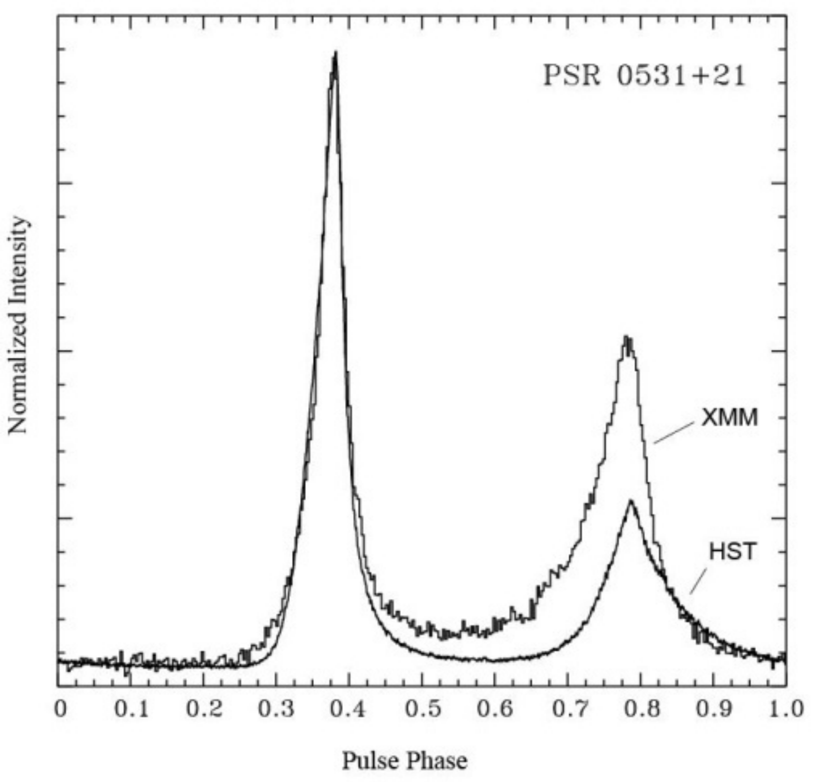
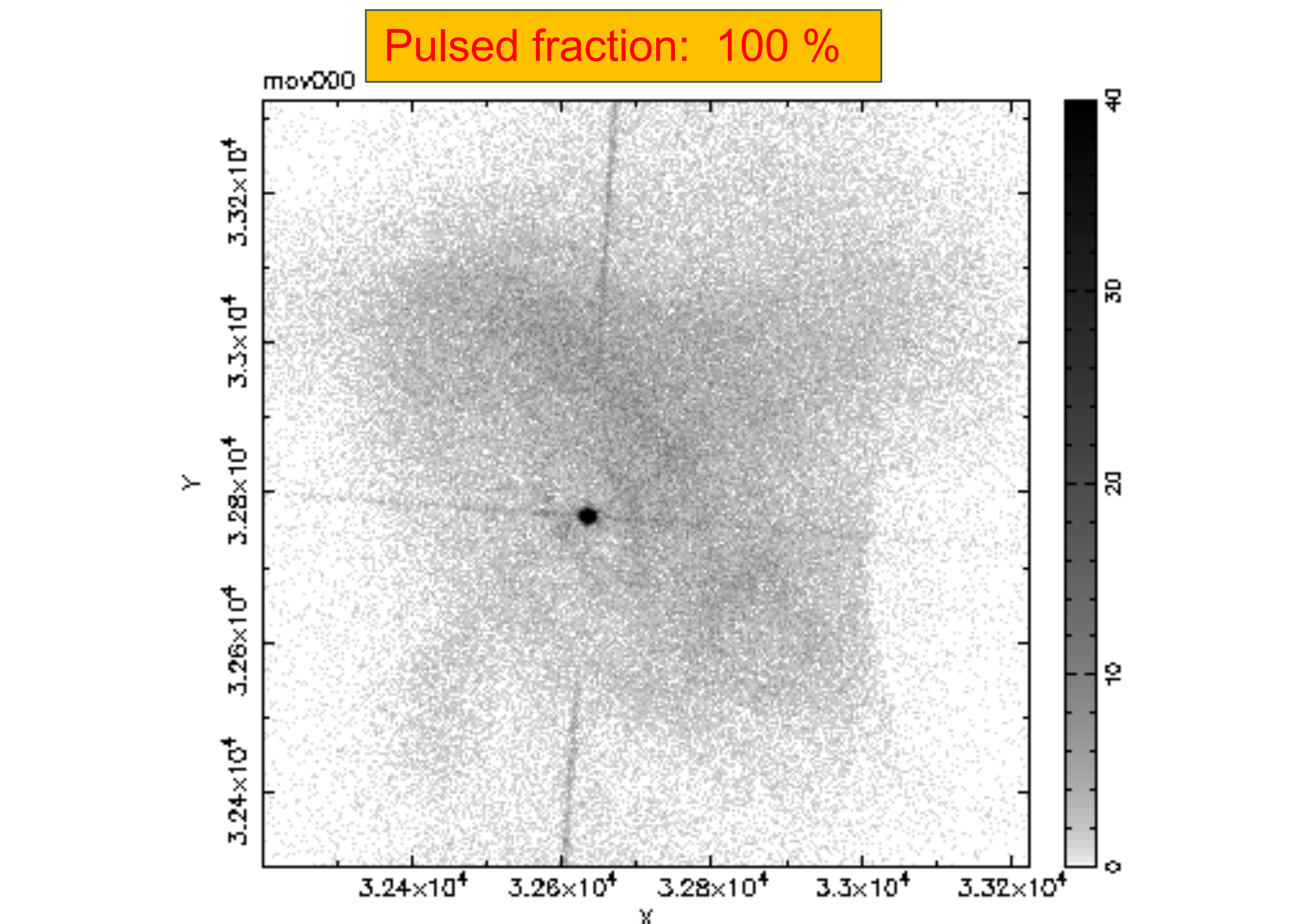
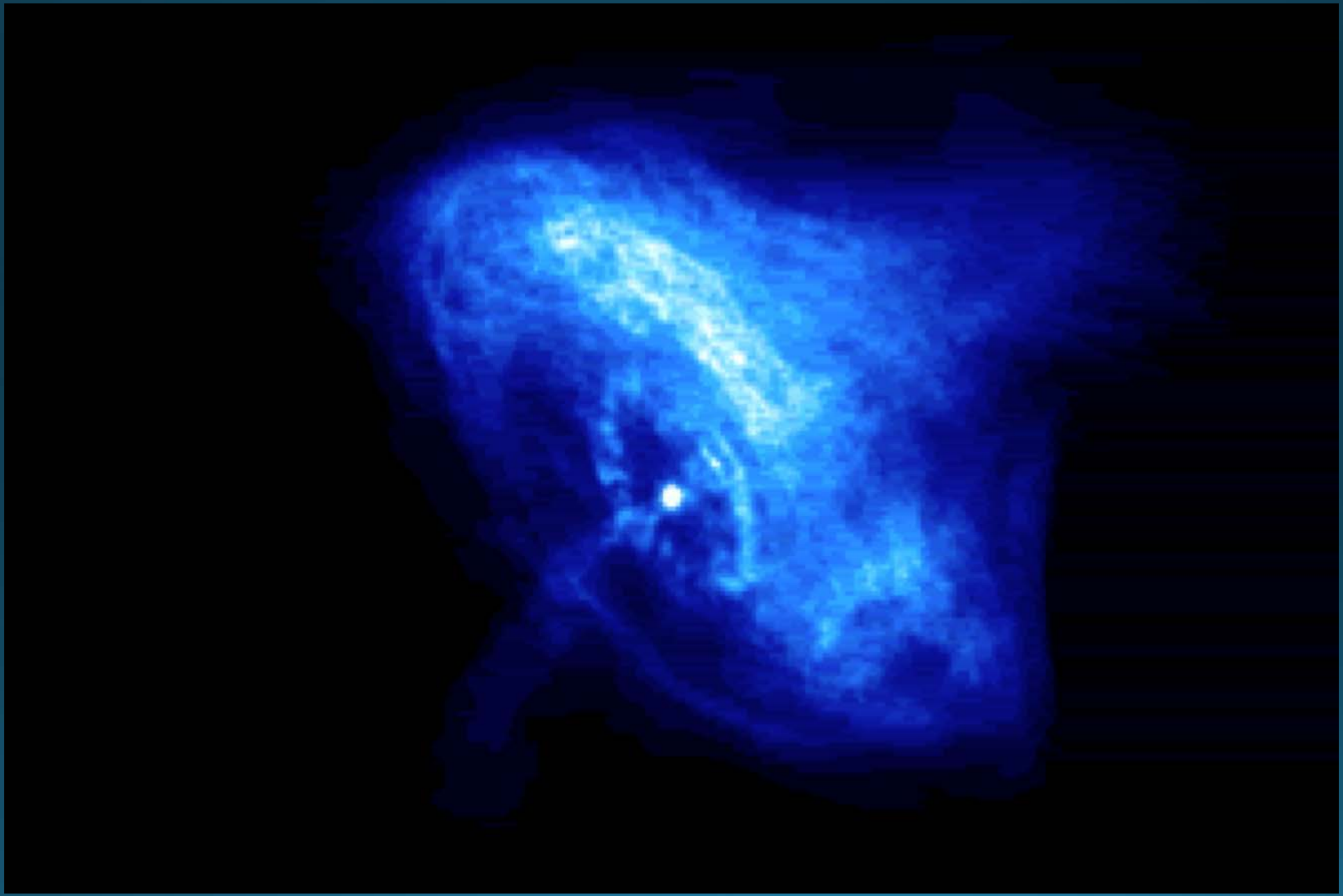


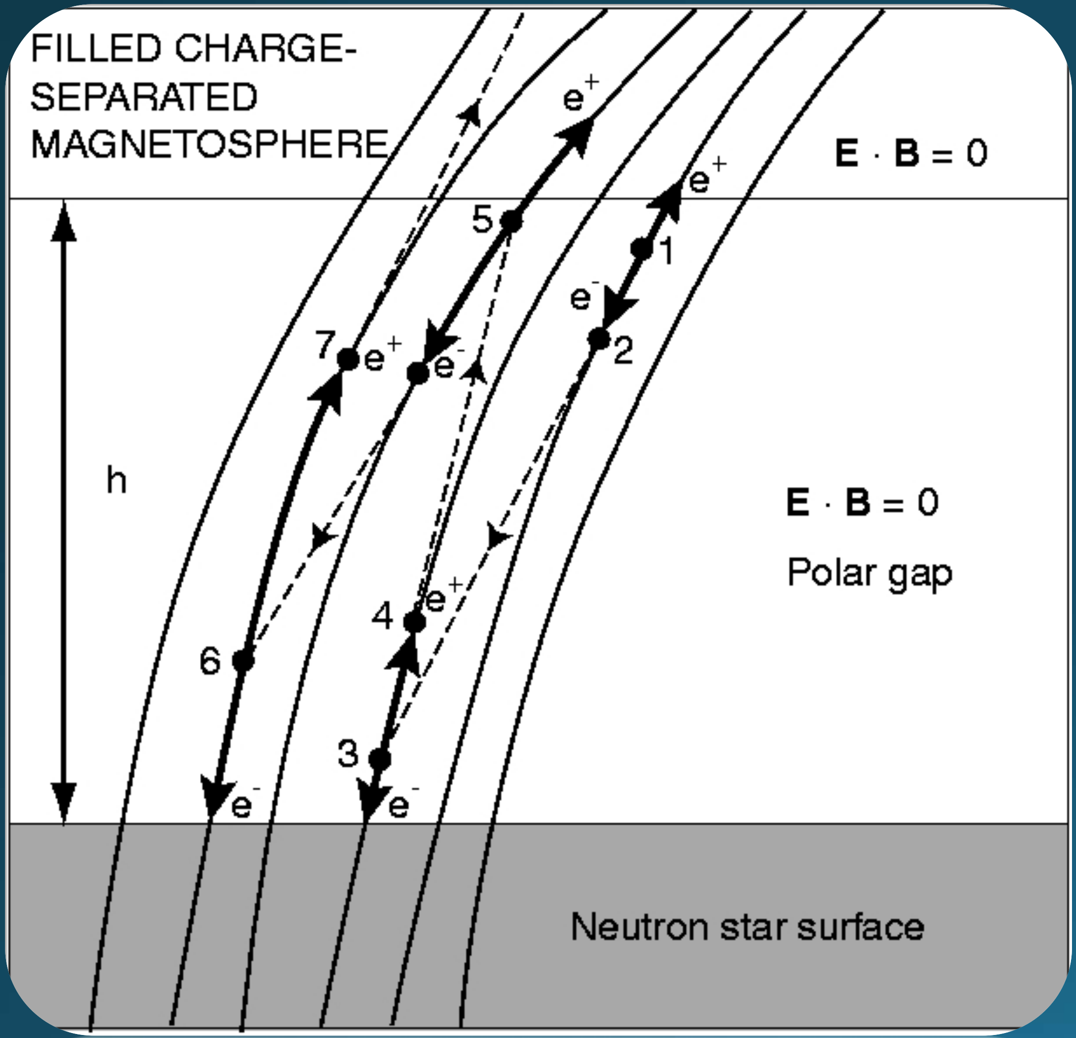


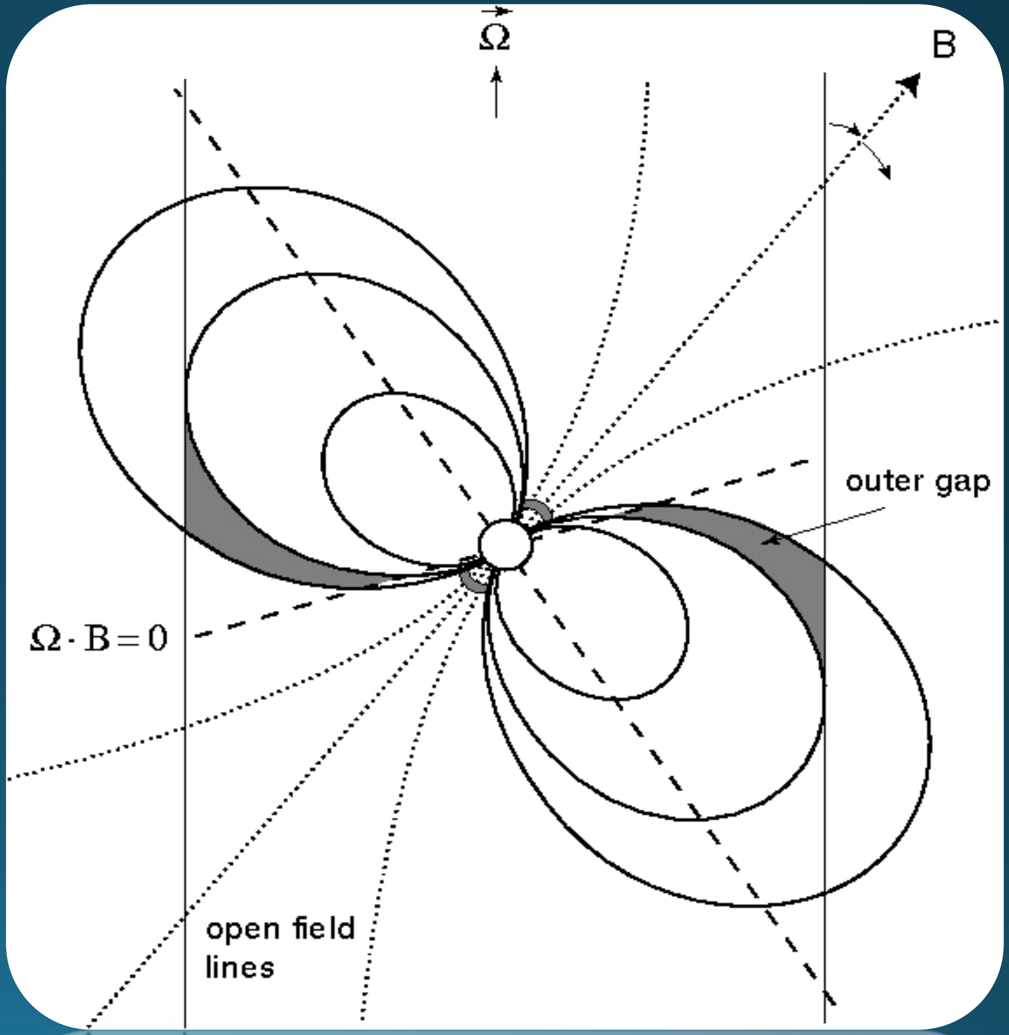
Weisskopf et al. 2011

- The Crab Pulsar in the Supernova remnant: SN 1054

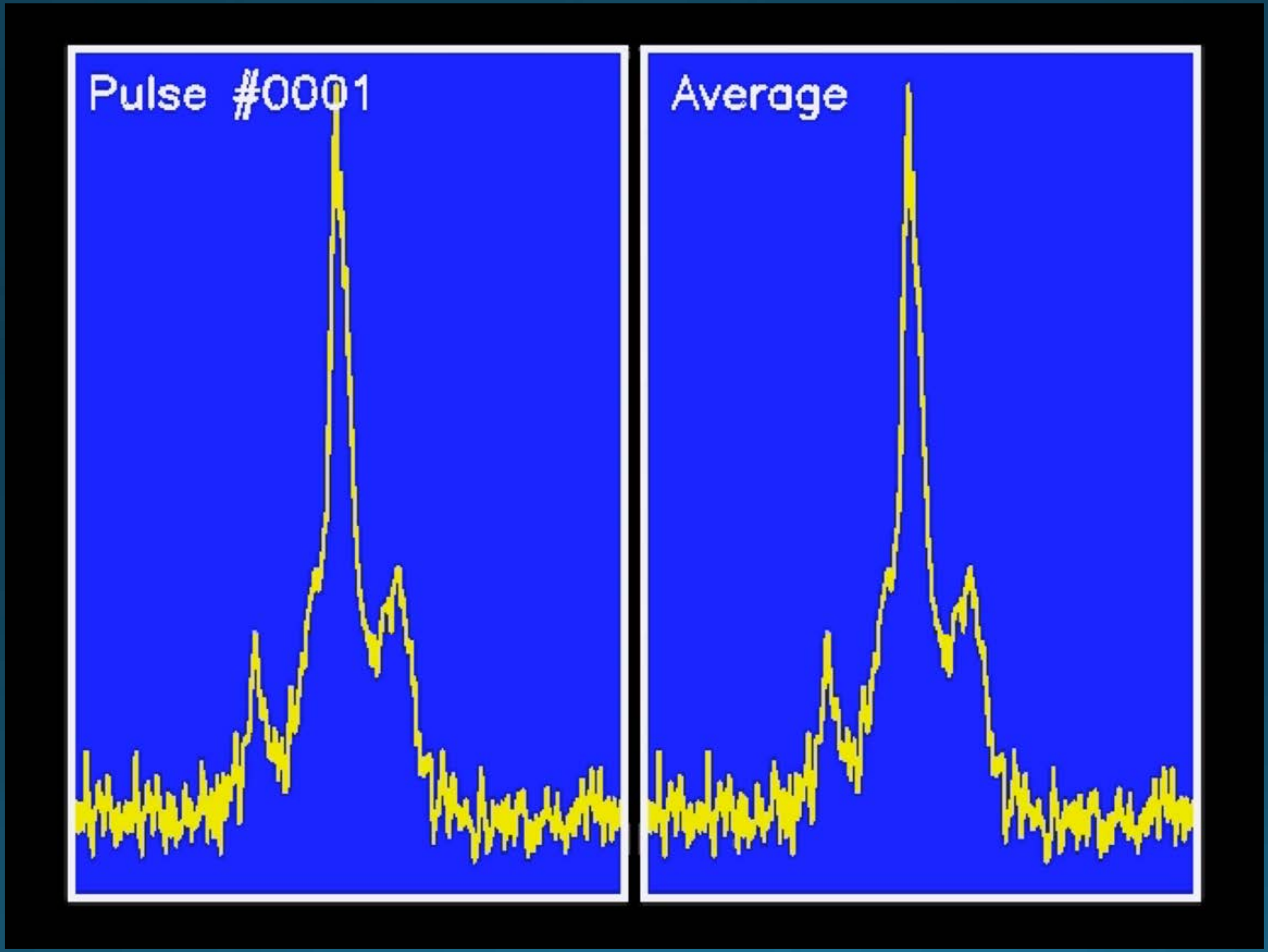


Non-Thermal Pulsar radiation





Single pulses might be different from the averaged pulse profile!

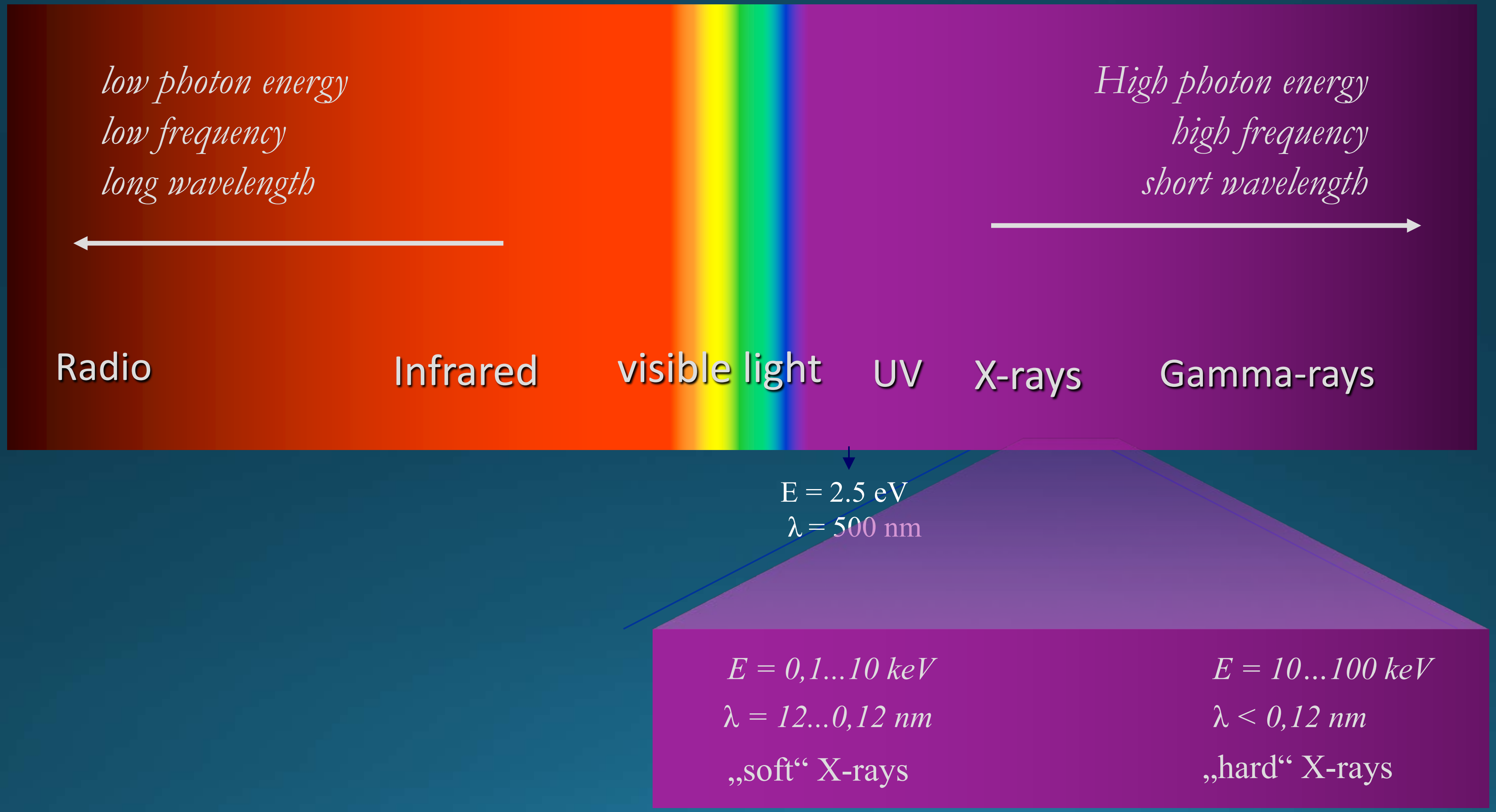


Kramer et al.

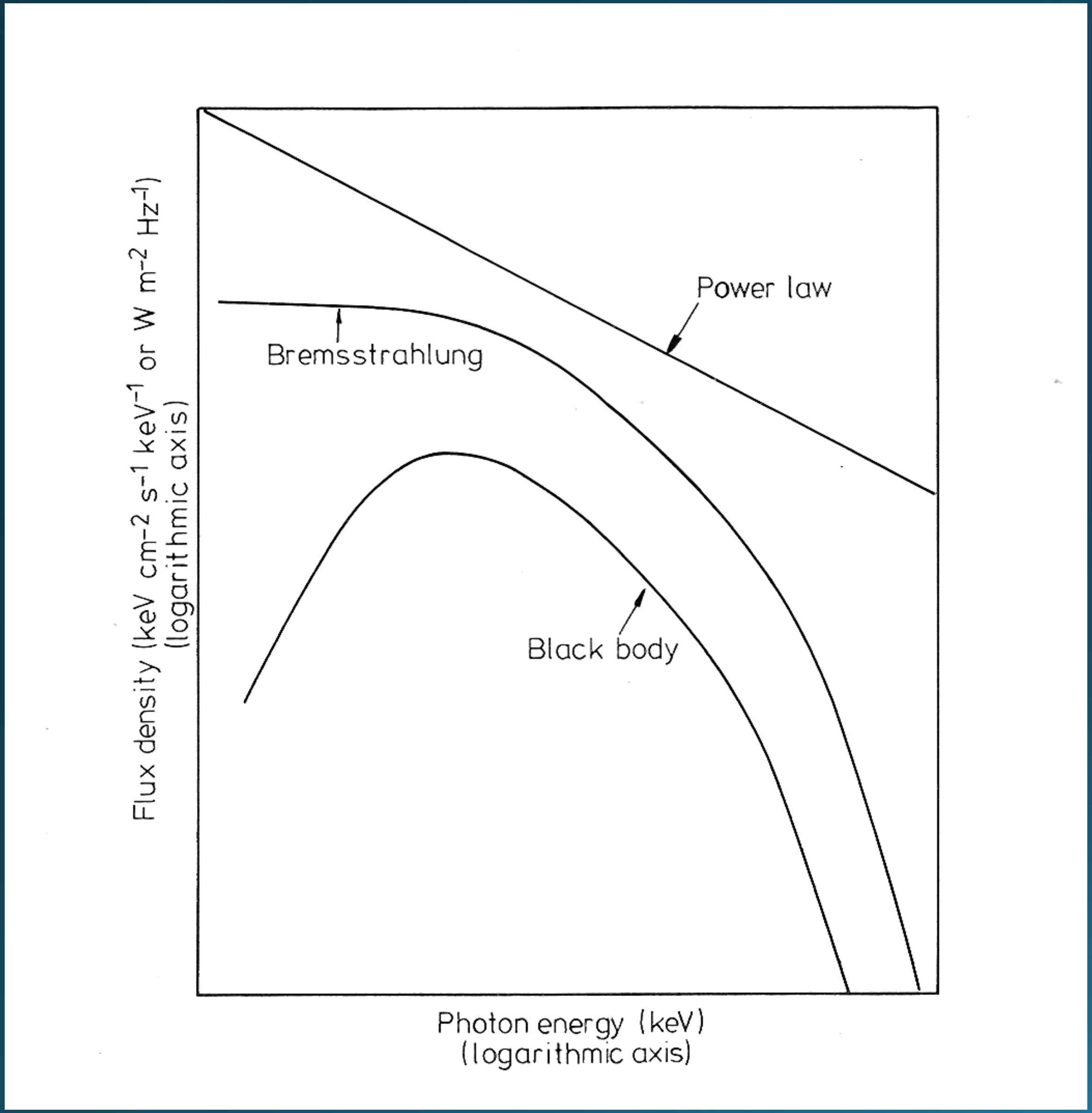
Single pulses

Averaged pulse profile

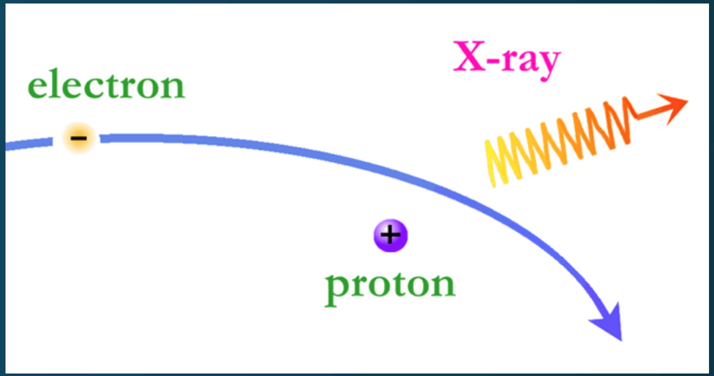
Astronomical observations at all frequencies!



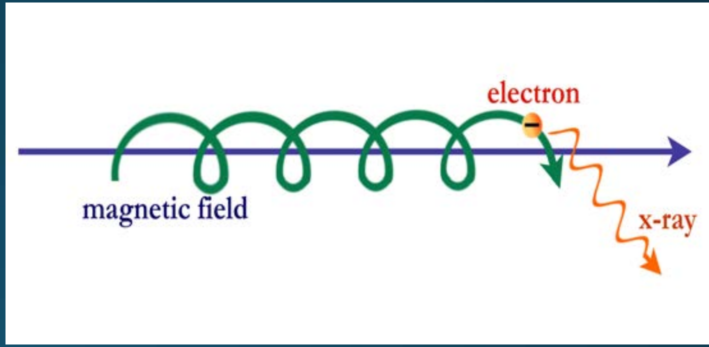
X-ray emitting processes in Neutron Stars:



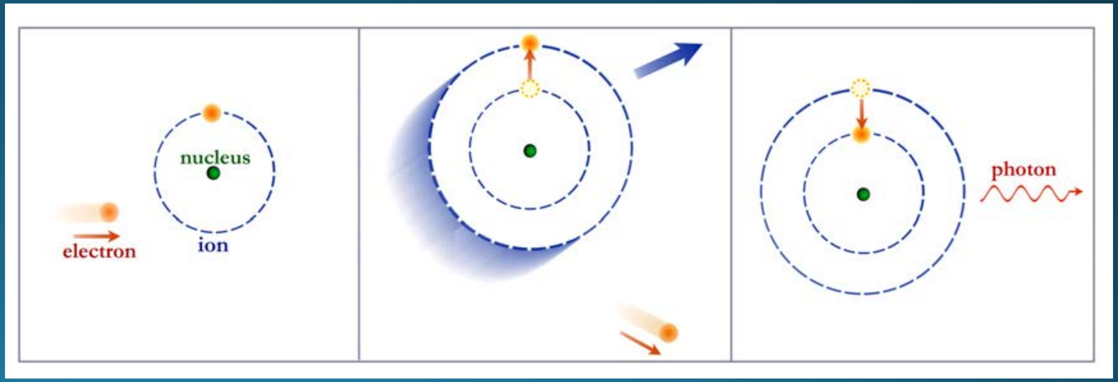
Bremsstrahlung

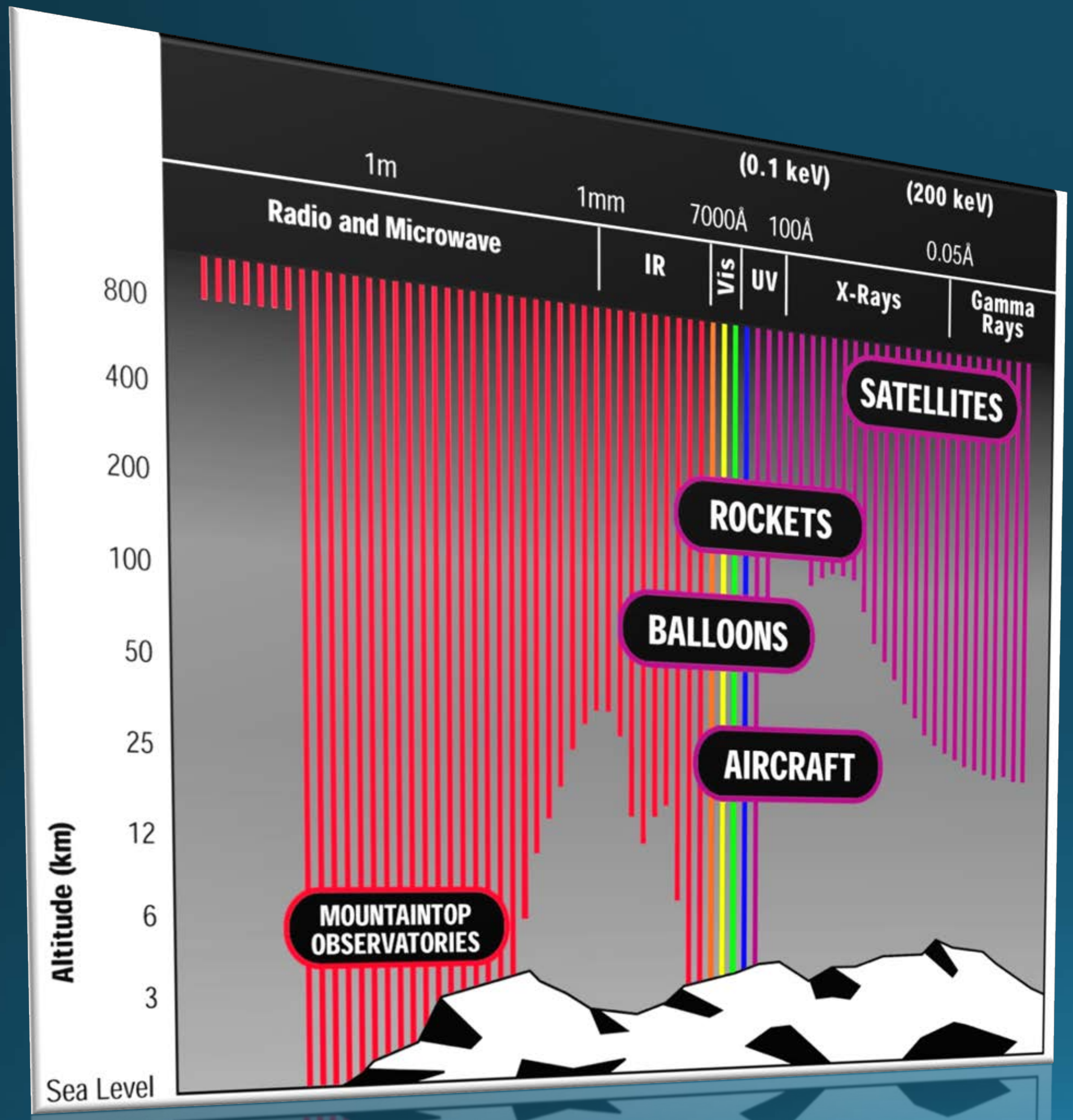


Synchrotron- and cyklotron radiation



Collisional excitation



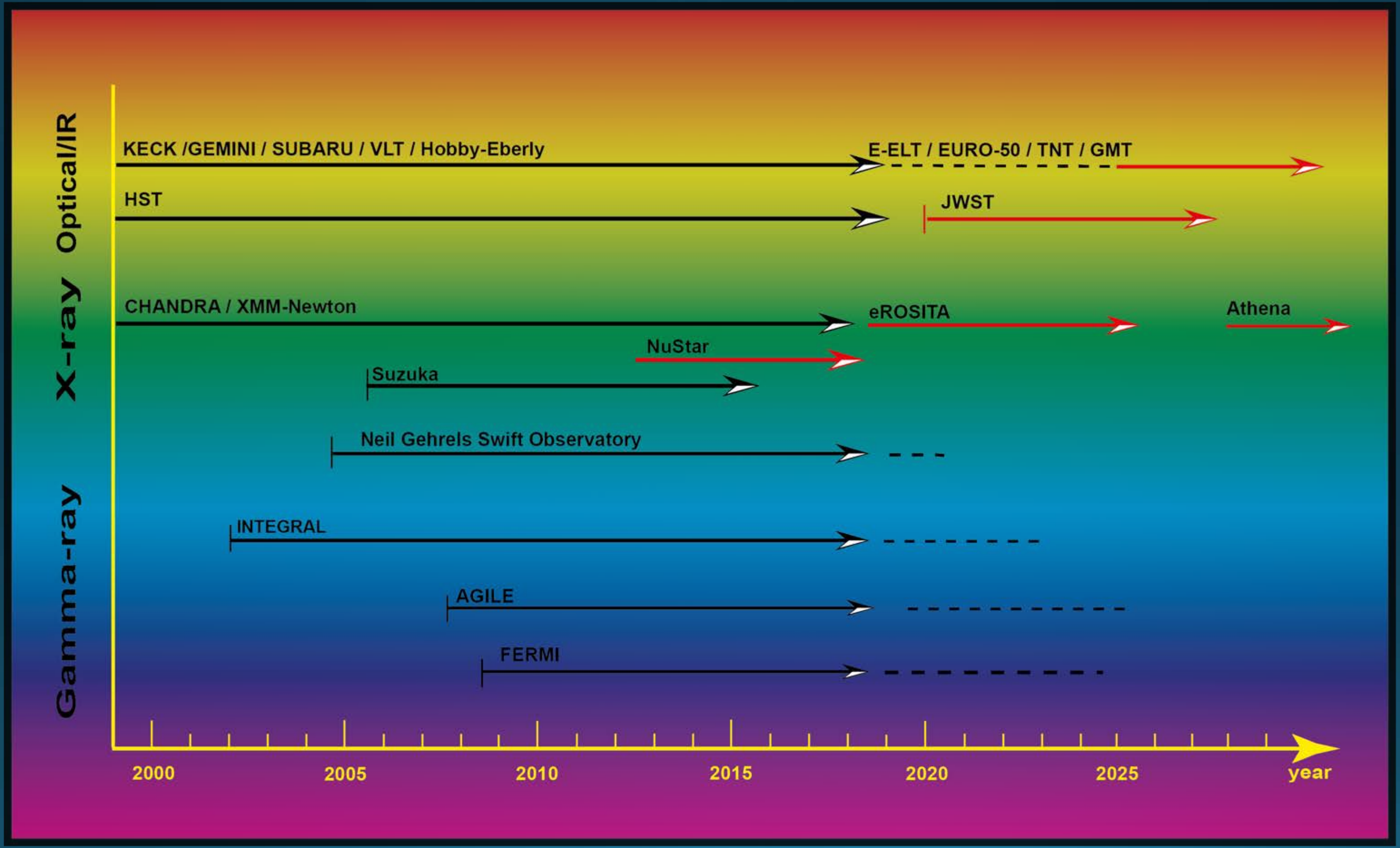


X-ray astronomy

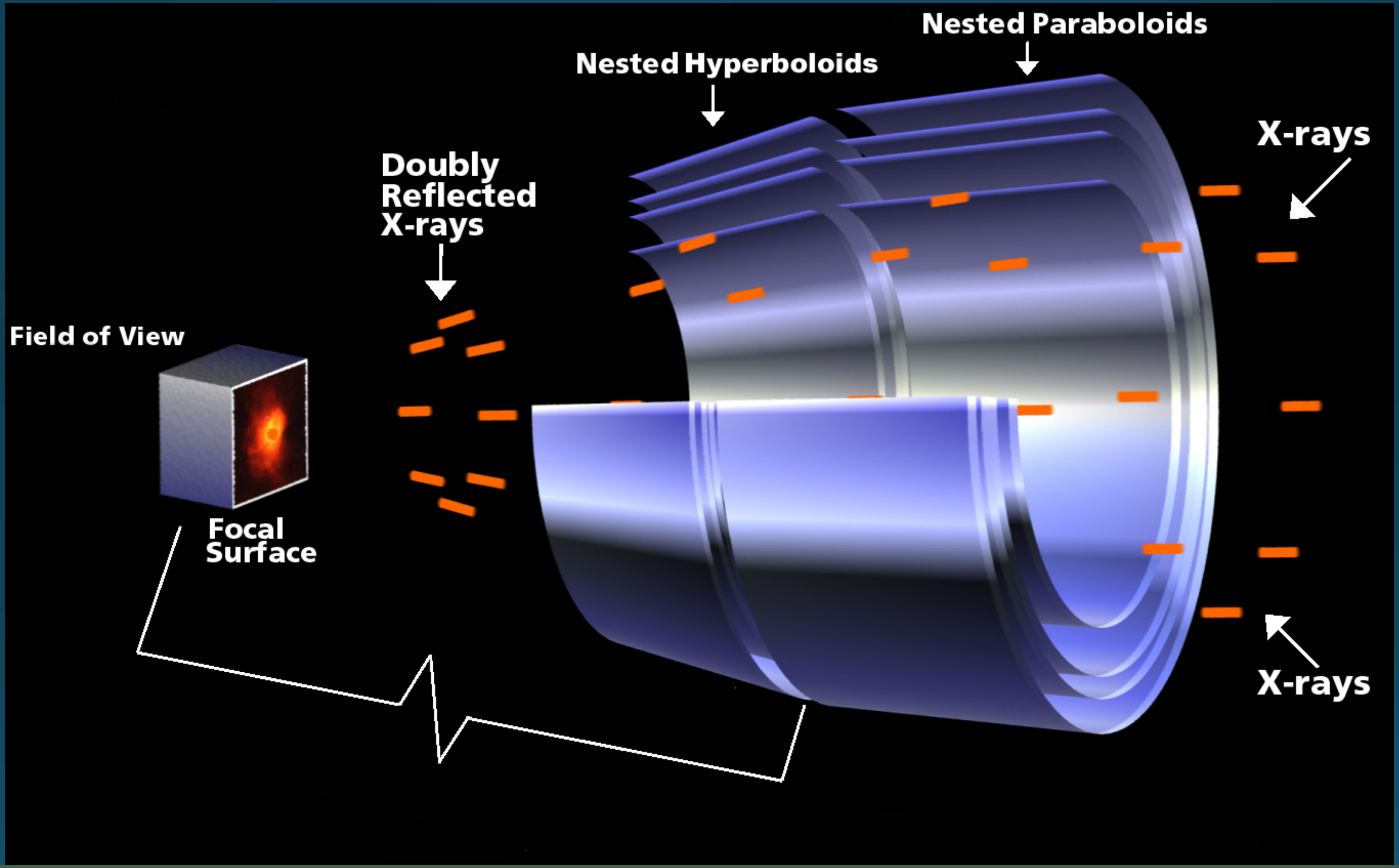
X-ray radiation is absorbed in the earth's atmosphere

The observation of stellar X-ray sources is only possible by X-ray satellites or balloon experiments

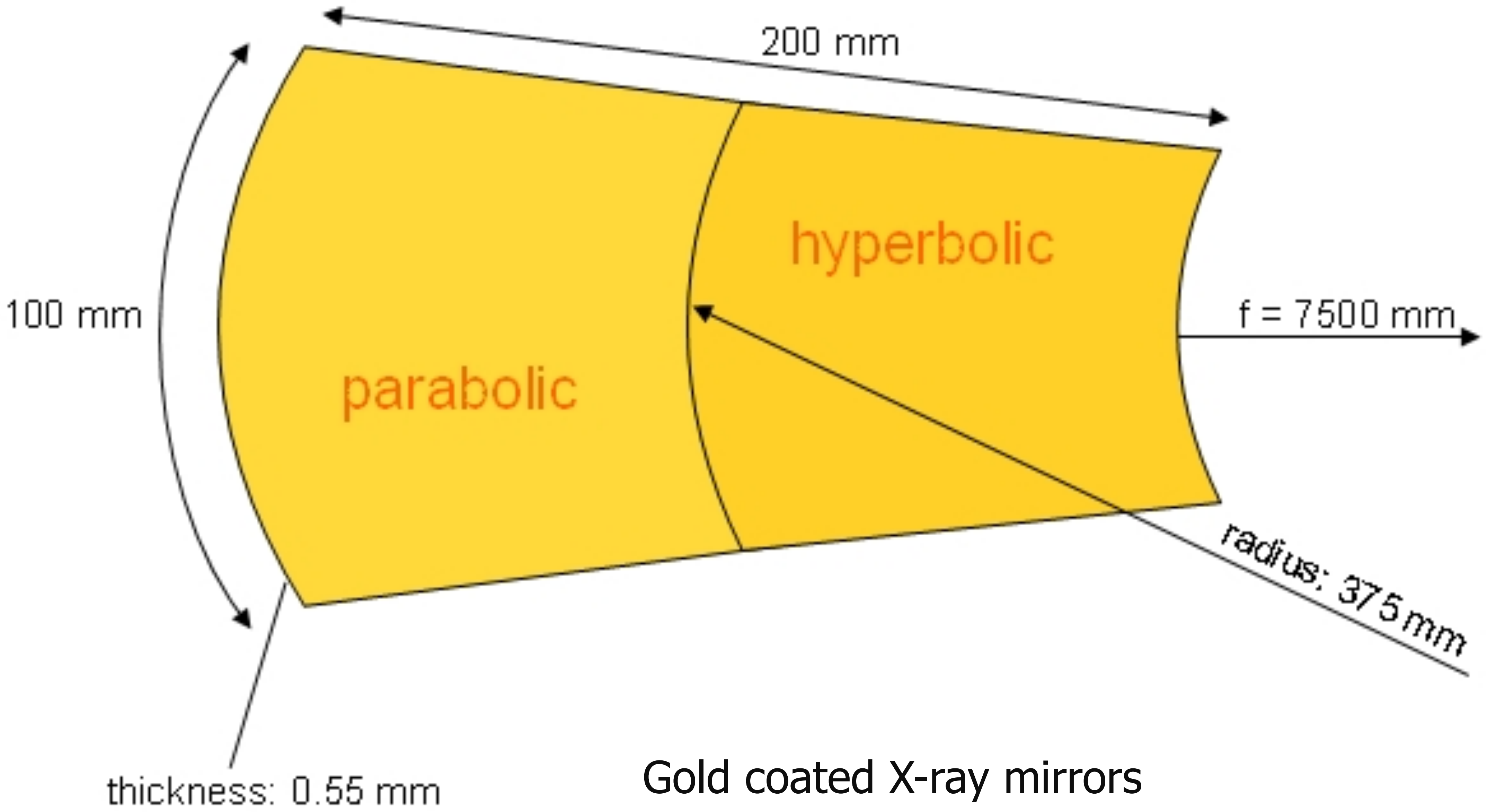
Recent and future High Energy Observatories



Focusing X-rays

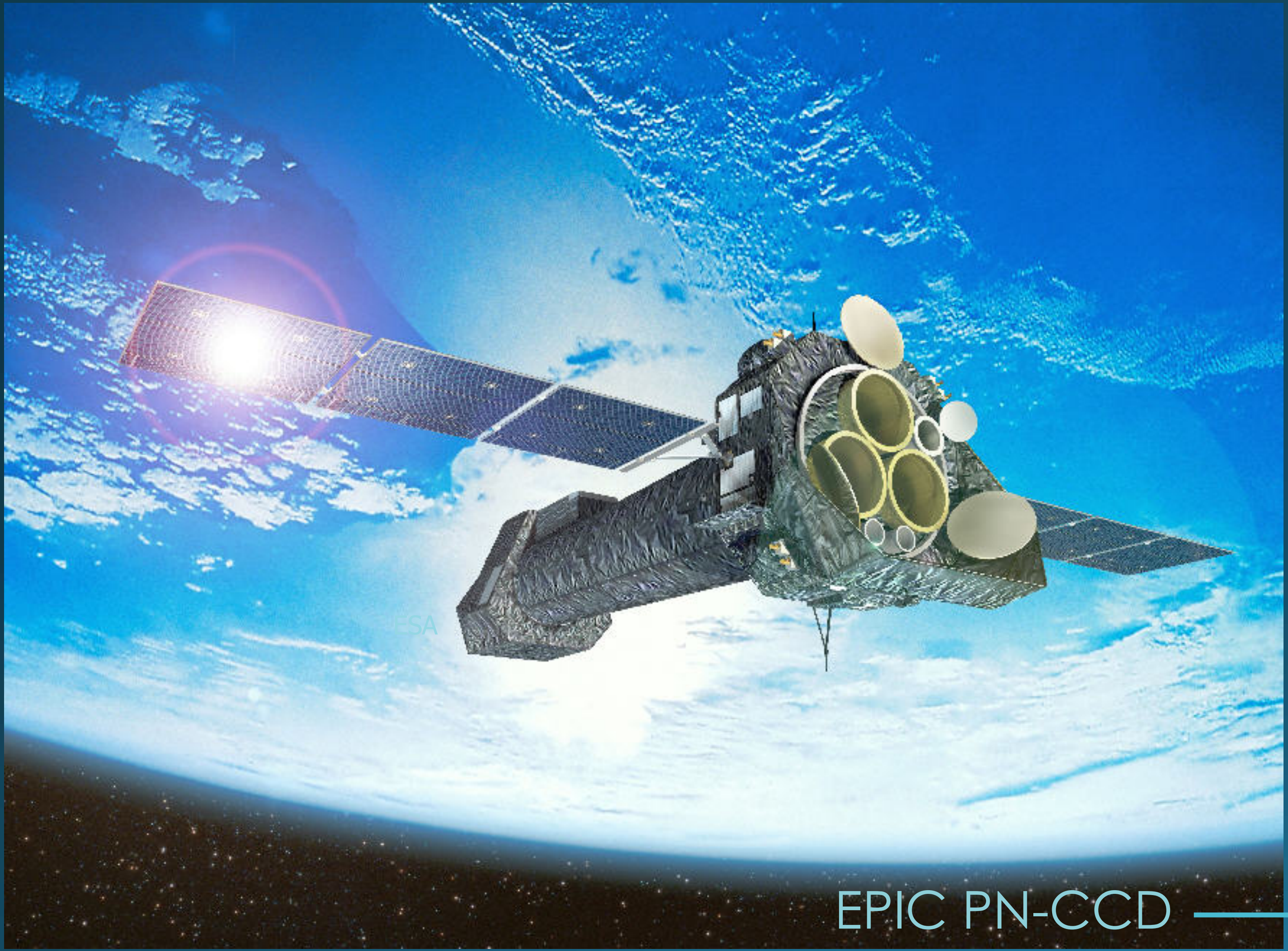


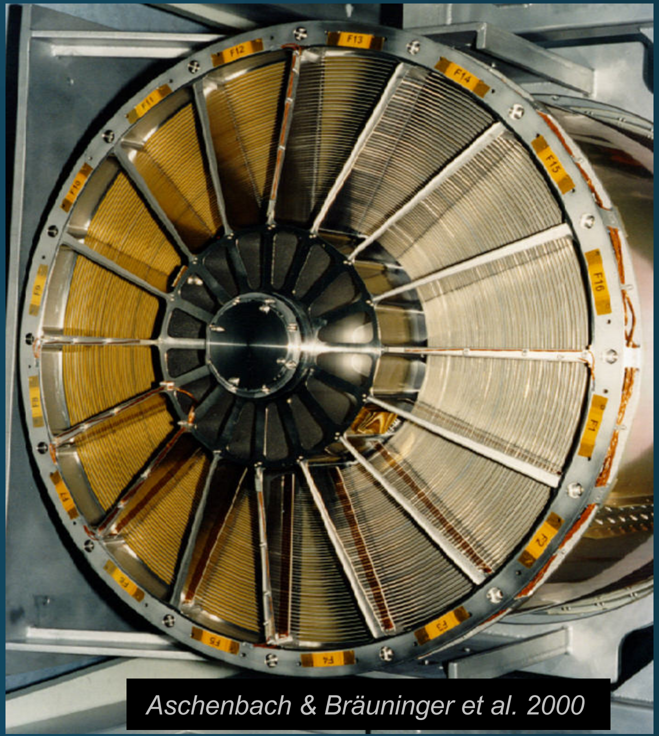
X-rays are focused by double reflection in a type-I Wolter telescope which consists of nested paraboloids and hyperboloids



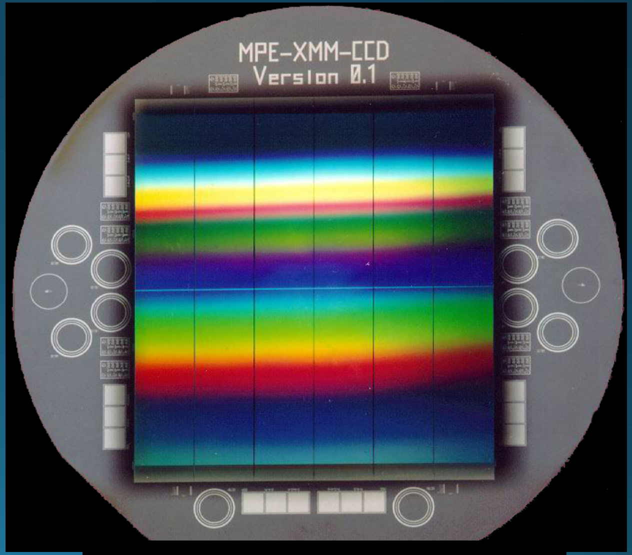
Gold coated X-ray mirrors

XMM-Newton (0.2 -15 keV)



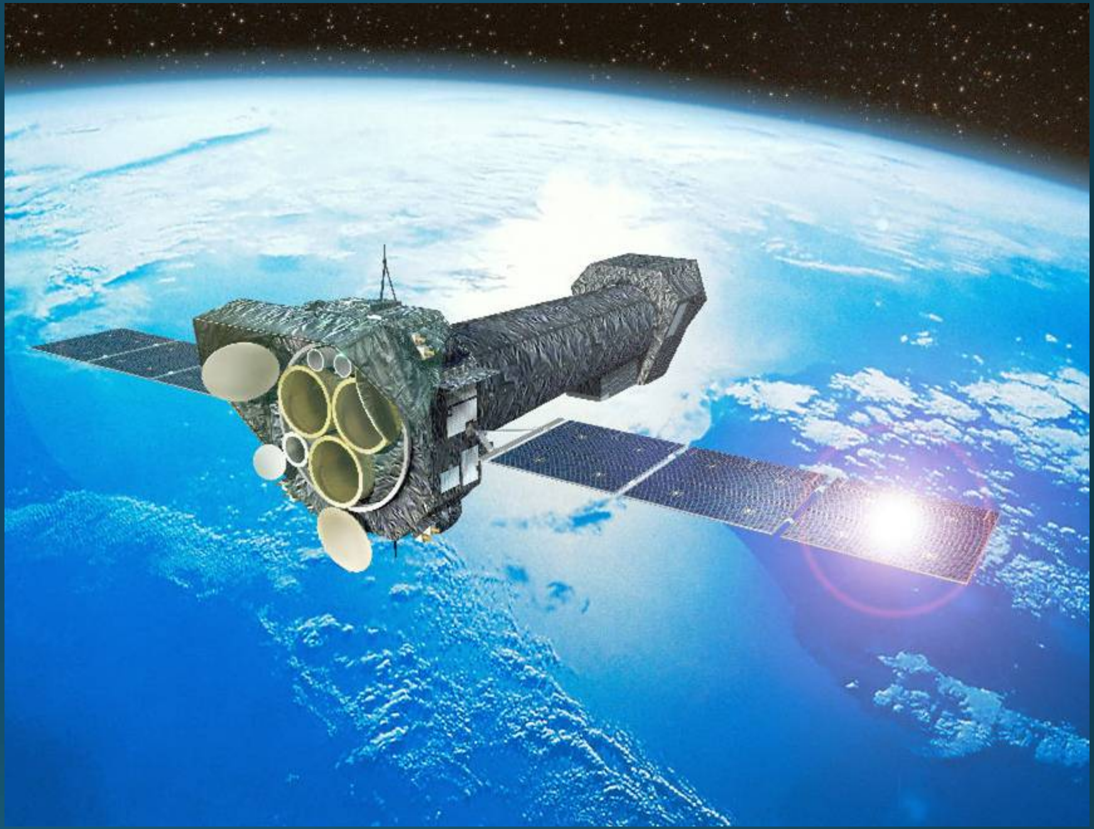


Aschenbach & Bräuninger et al. 2000



Strüder et al 2000

Performance of recent X-ray observatories



Chandra (NASA):

- Effective mirror area 0.08 m^2
- Angular resolution 0.5″ HEW
- Sensitivity : 10^{-16} erg cm^{-2} s^{-1}

XMM-Newton (ESA):

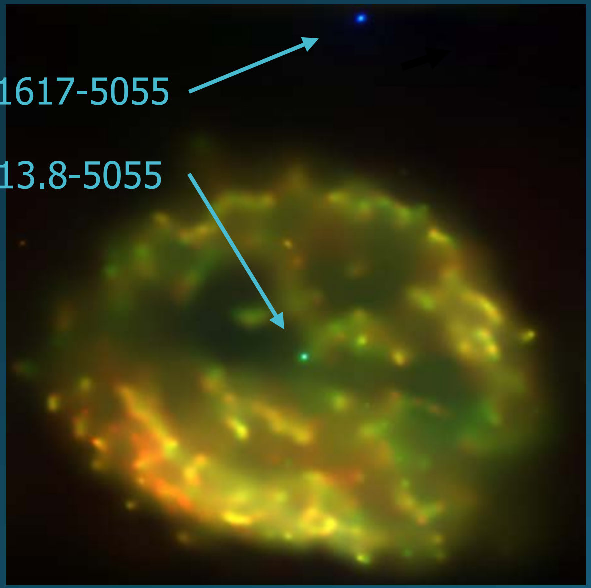
- Effective mirror area 0.4 m^2
- angular resolution 15″ HEW
- Sensitivity : 10^{-17} erg cm^{-2} s^{-1}

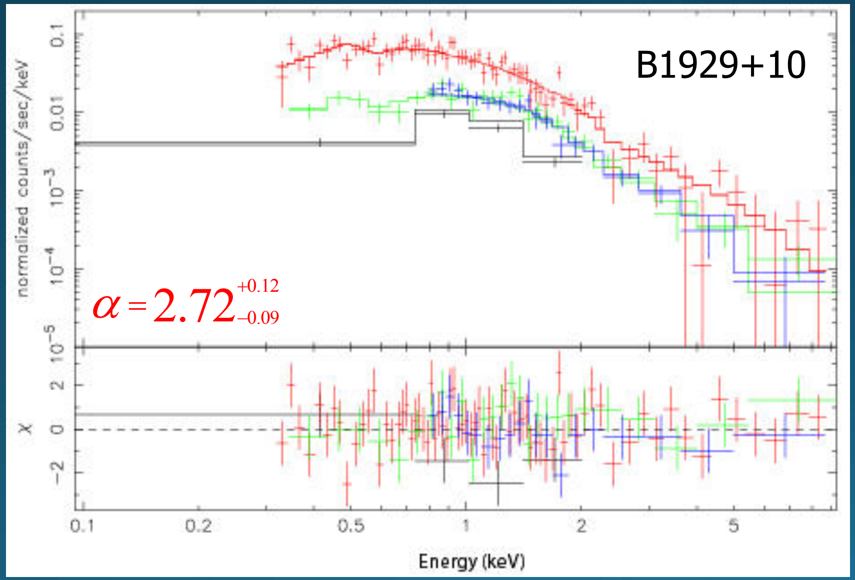
X-ray data contain...

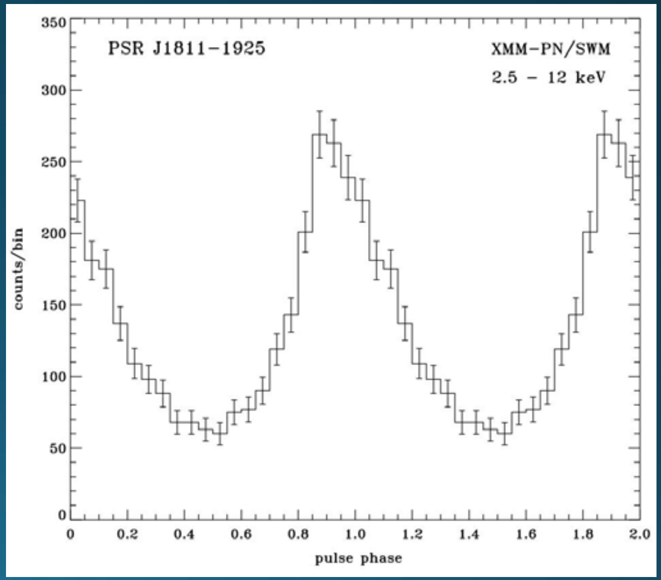
- Image information
- Spectral information of each X-ray photon
- Time information on the X-ray photon‘s arrival time

PSR J1617-5055

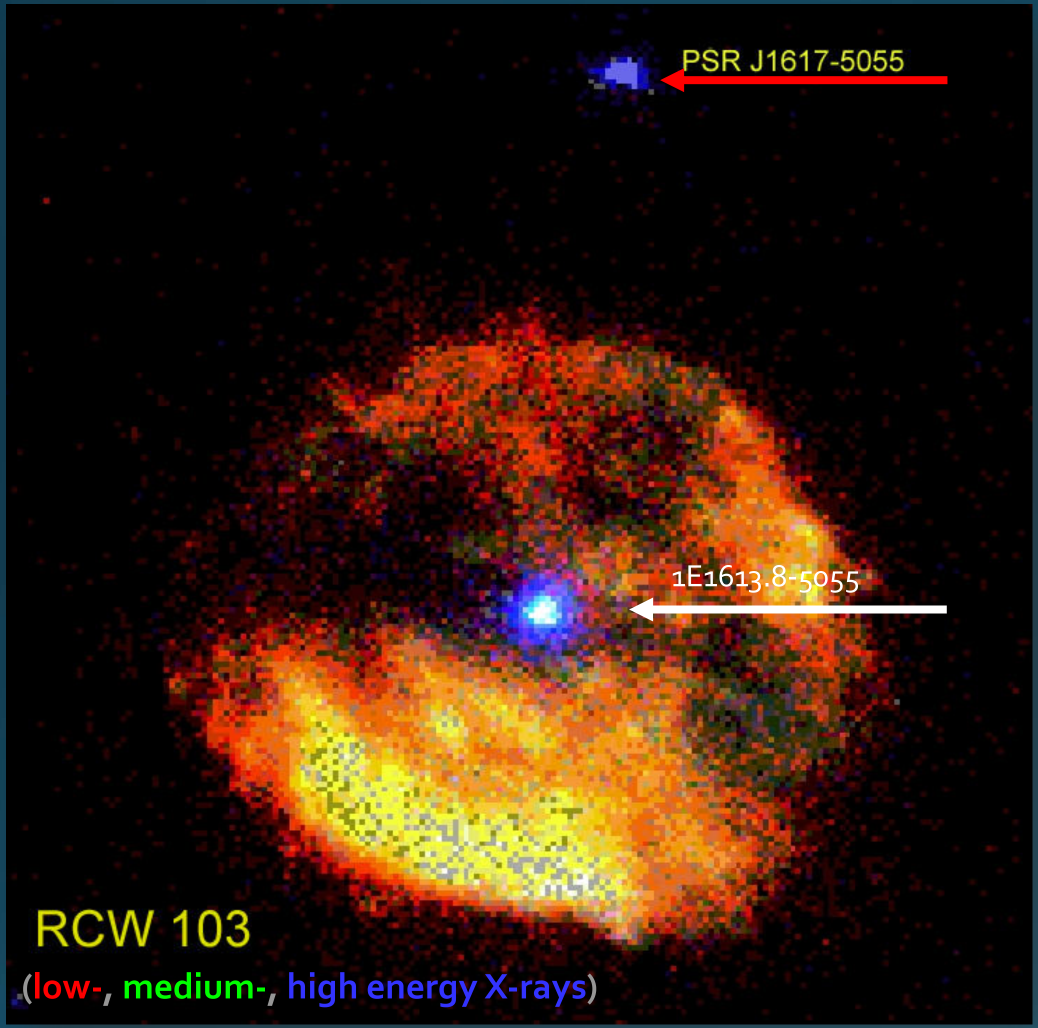
1E 1613.8-5055







Historical Supernova remnant: RCW 103 (SN 300BC)



Becker & Aschenbach 2002

Age ~ 2000 yrs

Distance = 10 000 LJ

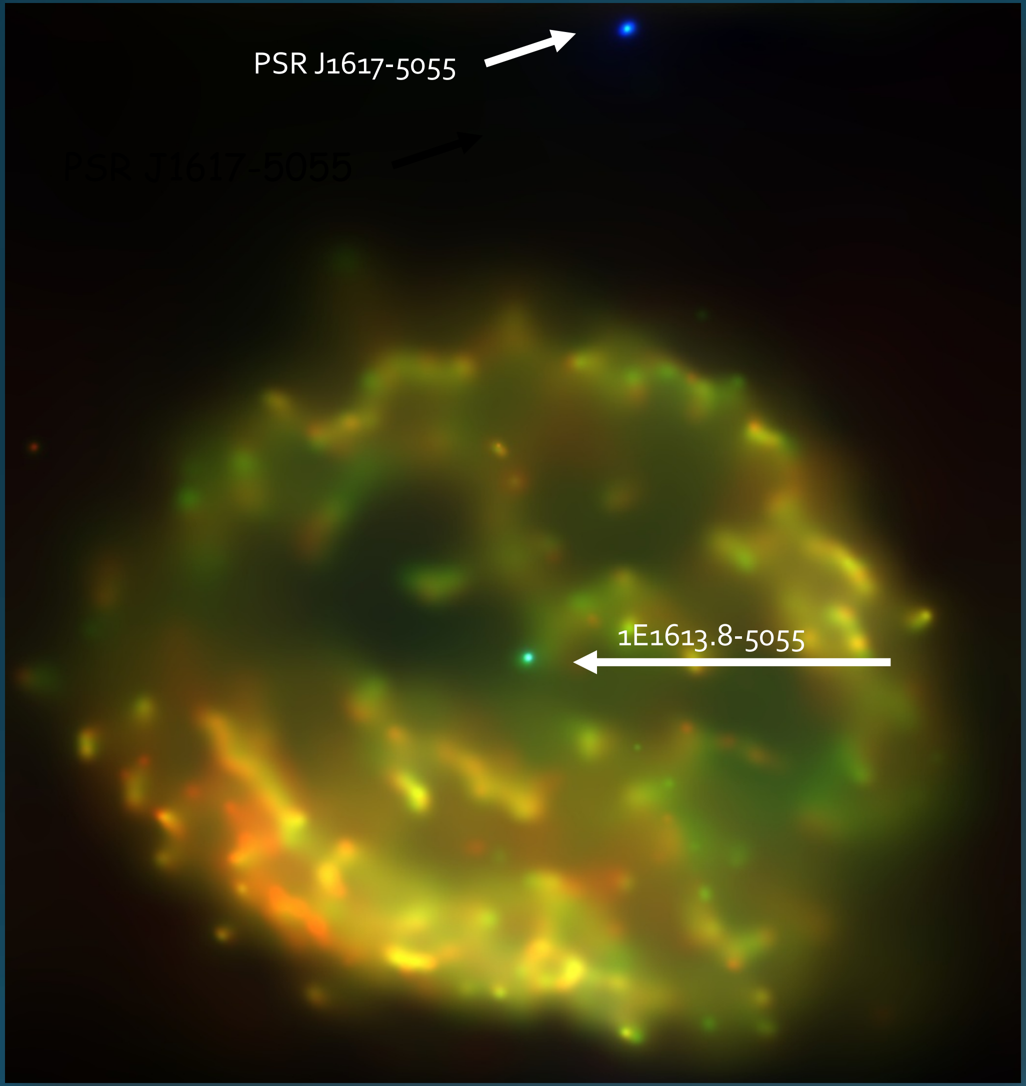
Central point source with black-body like X-ray spectrum → T~ 4-5 10^6 K

Cooling Neutron Star

Strong flux variability in ROSAT + ASCA Data

Angular resolution is essential!

Historical Supernova remnant: RCW 103 (SN 300BC)



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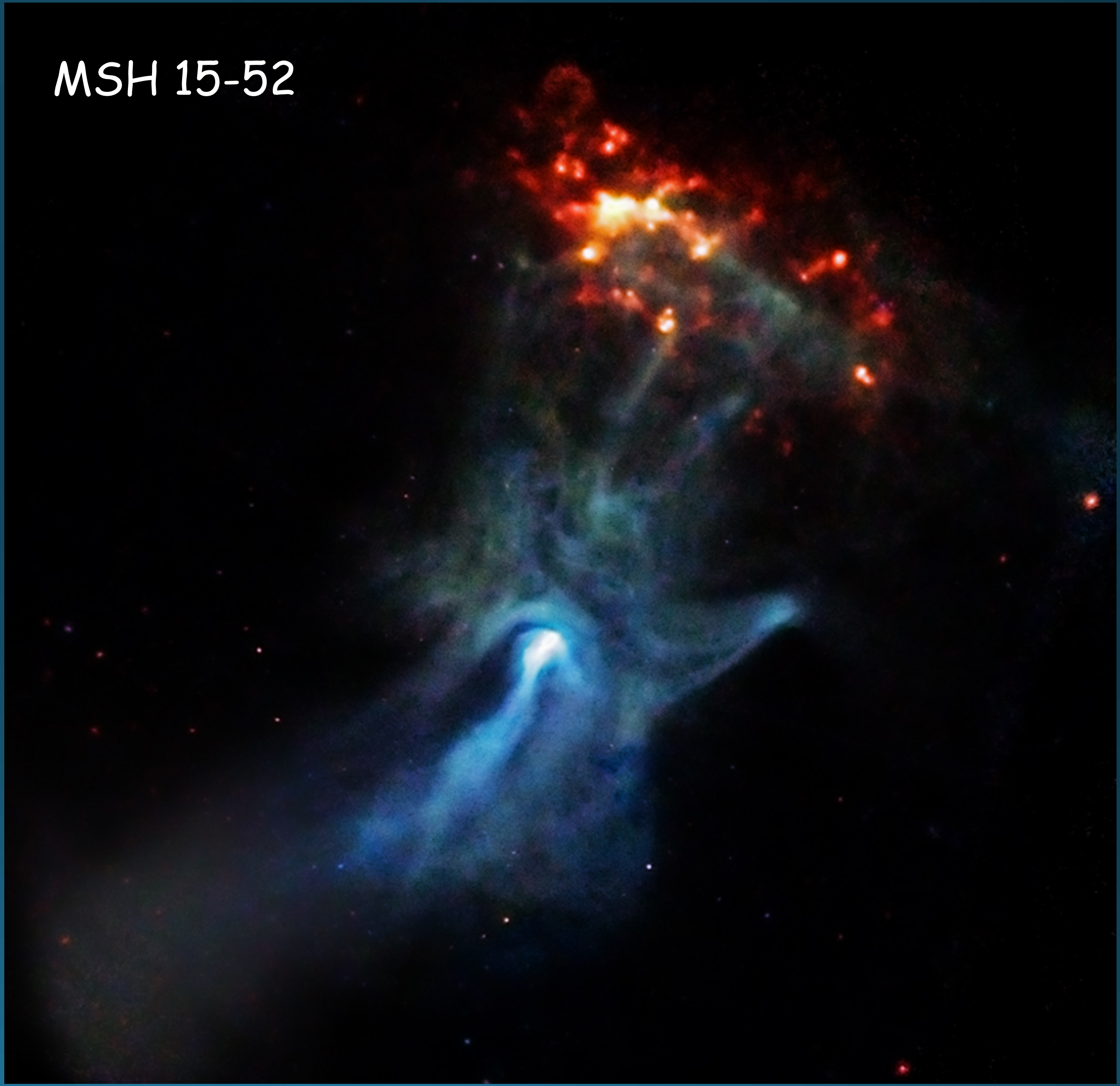
Central point source with black-body like X-ray spectrum → T~ 4-5 10^6 K

Cooling Neutron Star

Strong flux variability in ROSAT + ASCA Data

Pulsar wind nebula

Neutron stars sometimes indicate their existence also by the formation of pulsar wind nebula!

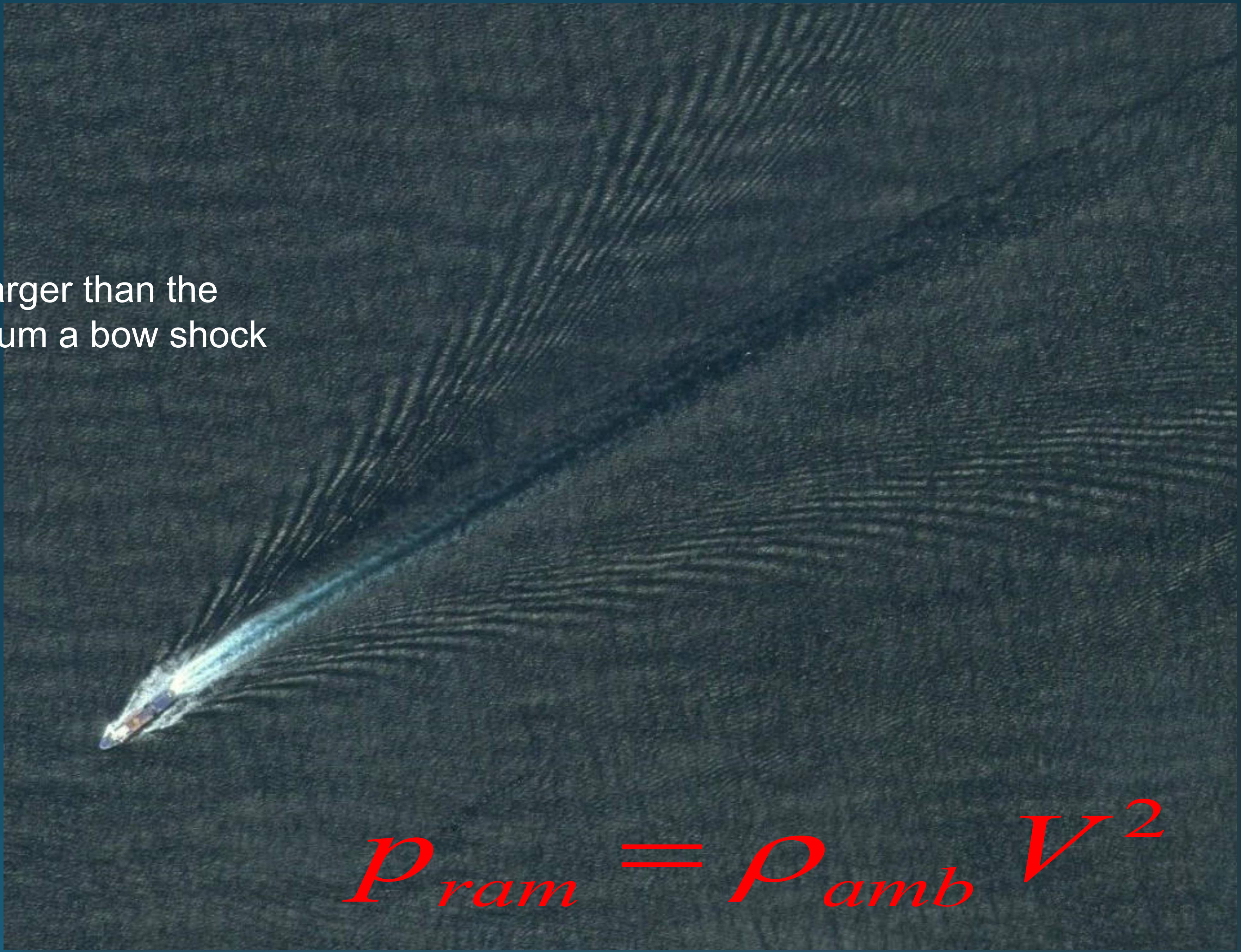


Slane et al. 2008

Bow shock nebula of Pulsars

Bow shocks from Neutron stars

If the pressure at the ram is larger than the pressure of the ambient medium a bow shock is formed

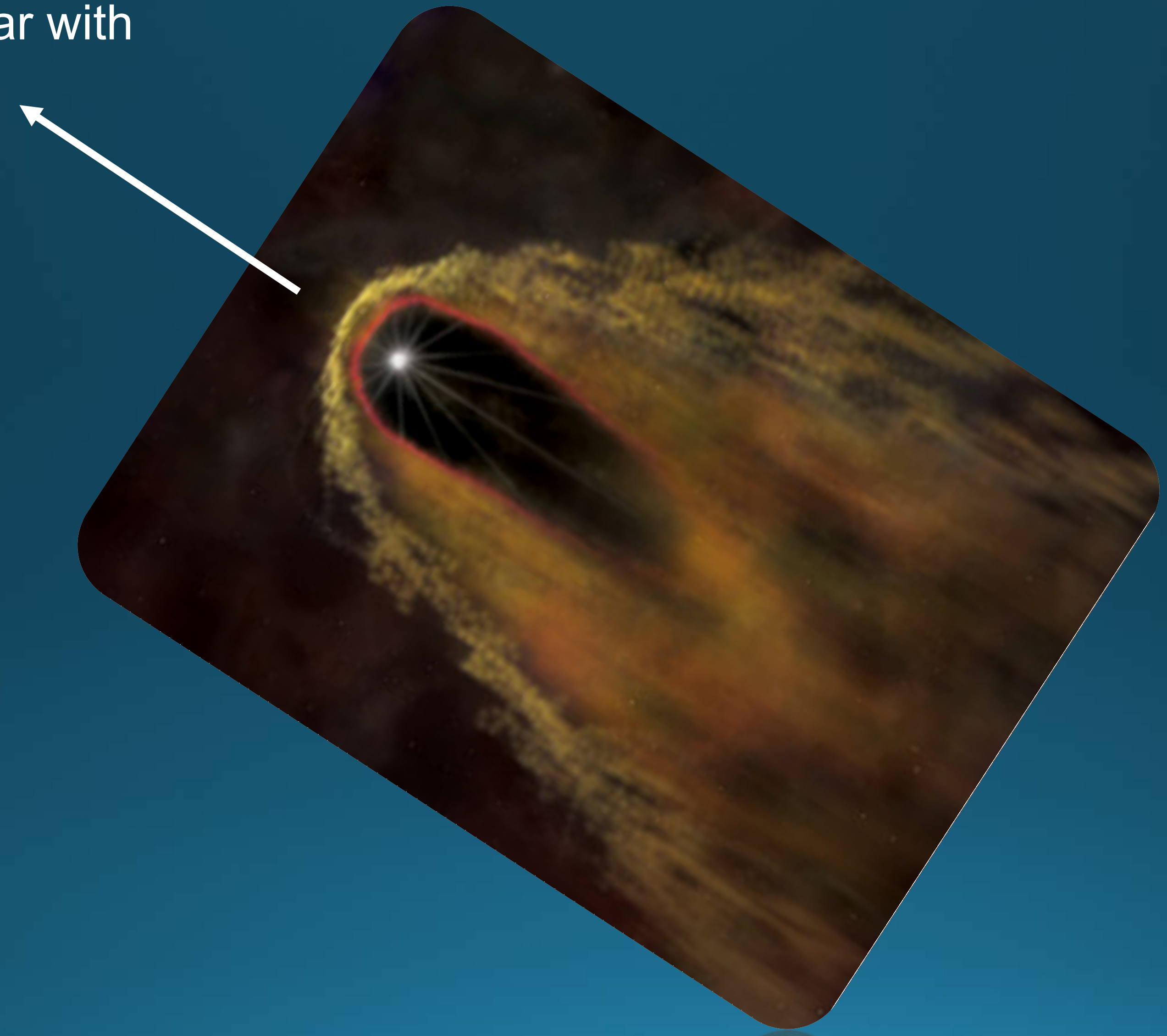


$$p_{ram} = \rho_{amb} V^2$$

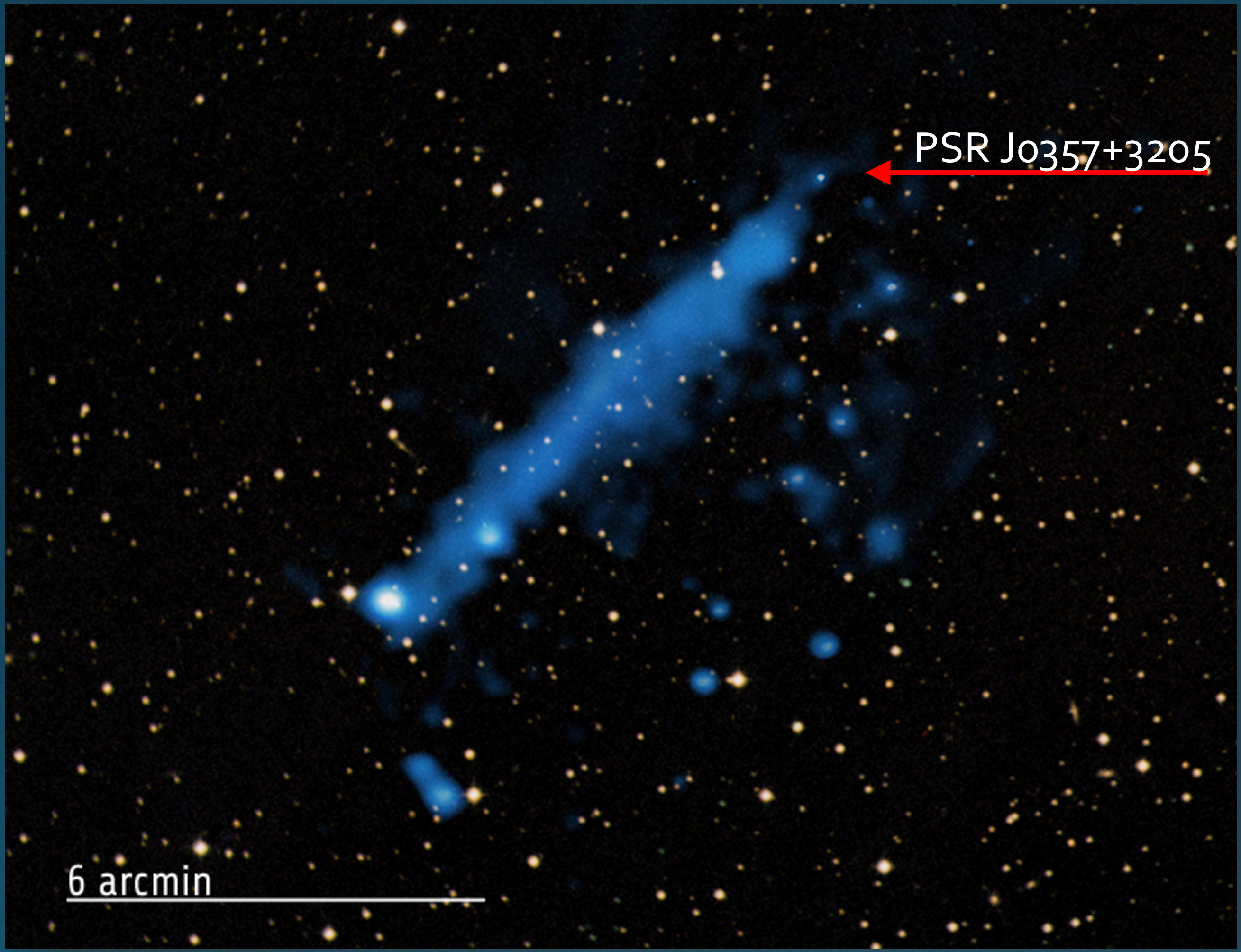
Bow shock of Neutron stars

Proper motion of the pulsar with

Velocity V



The X-ray tail of the pulsar PSR J0357+3205



de Luca et al.(2011)

length of the tail > 9 arcmin, width 1.2 arcmin

The Neutron Star Zoo

Accretion powered pulsar	$\Rightarrow$	X-ray Pulsare
Rotation powered pulsar:	$\Rightarrow$	radio, optical, X-, γ-ray
$\hookrightarrow$ Pulsar wind nebula:	$\Rightarrow$	radio, optical, X-, γ-ray, TeV
XDINs (X-ray dim isolated neutron stars):	$\Rightarrow$	optical, X-ray
Soft Gamma-ray Repeater (SGRs):	$\Rightarrow$	optical, X-, γ-ray
Anomalous X-ray Pulsare (AXPs):	$\Rightarrow$	optical, X- ray, (radio)
Central Compact Objects in SNRs (CCOs):	$\Rightarrow$	X- ray

Magnetars

Summary of the rotation-powered pulsars in a P-Pdot diagram

2636 Radio pulsars

188 X-ray PSRs

23 Crab-like

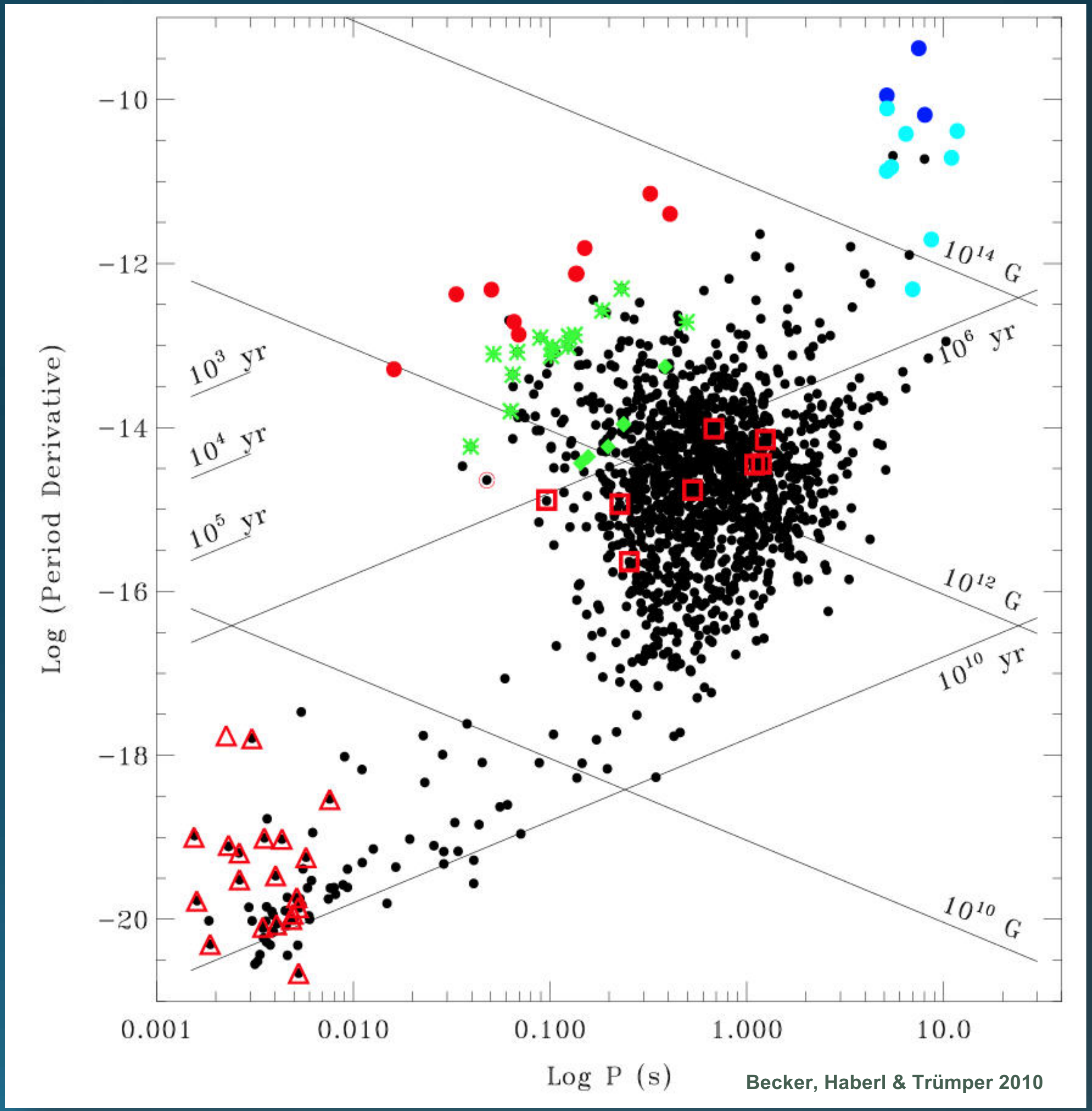
17 Cooling

13 old

62 ms-PSRs

123 γ-ray PSRs

Spectral – and timing information are available only for ~2/3 of this pulsars

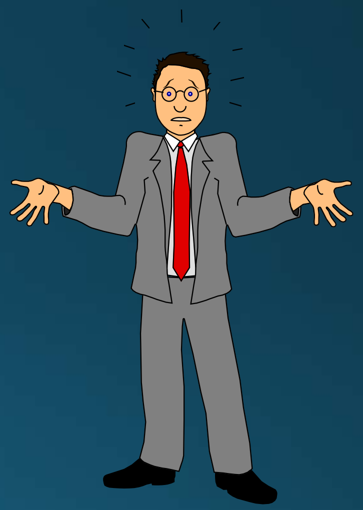


More than 50 years after the discovery of Pulsars, many questions are unsolved ….

- How are the different manifestations of neutron stars related to each other?
- What are the physical parameters which differentiate between AXPs/SGRs/CCOs/XDINs/PSRs ?
- Is there a relation between AXPs/SGRs und high B-field radio pulsars?
- What decides that a collapsing star will end in a Crab-like pulsar, a Magnetar or a CCO ?

❖ EOS:

- What is the maximal upper bound for a neutron star mass ?
- What is the range of possible neutron star radii ?
- Is there any exotic matter in neutron stars (do strange stars exist) ?



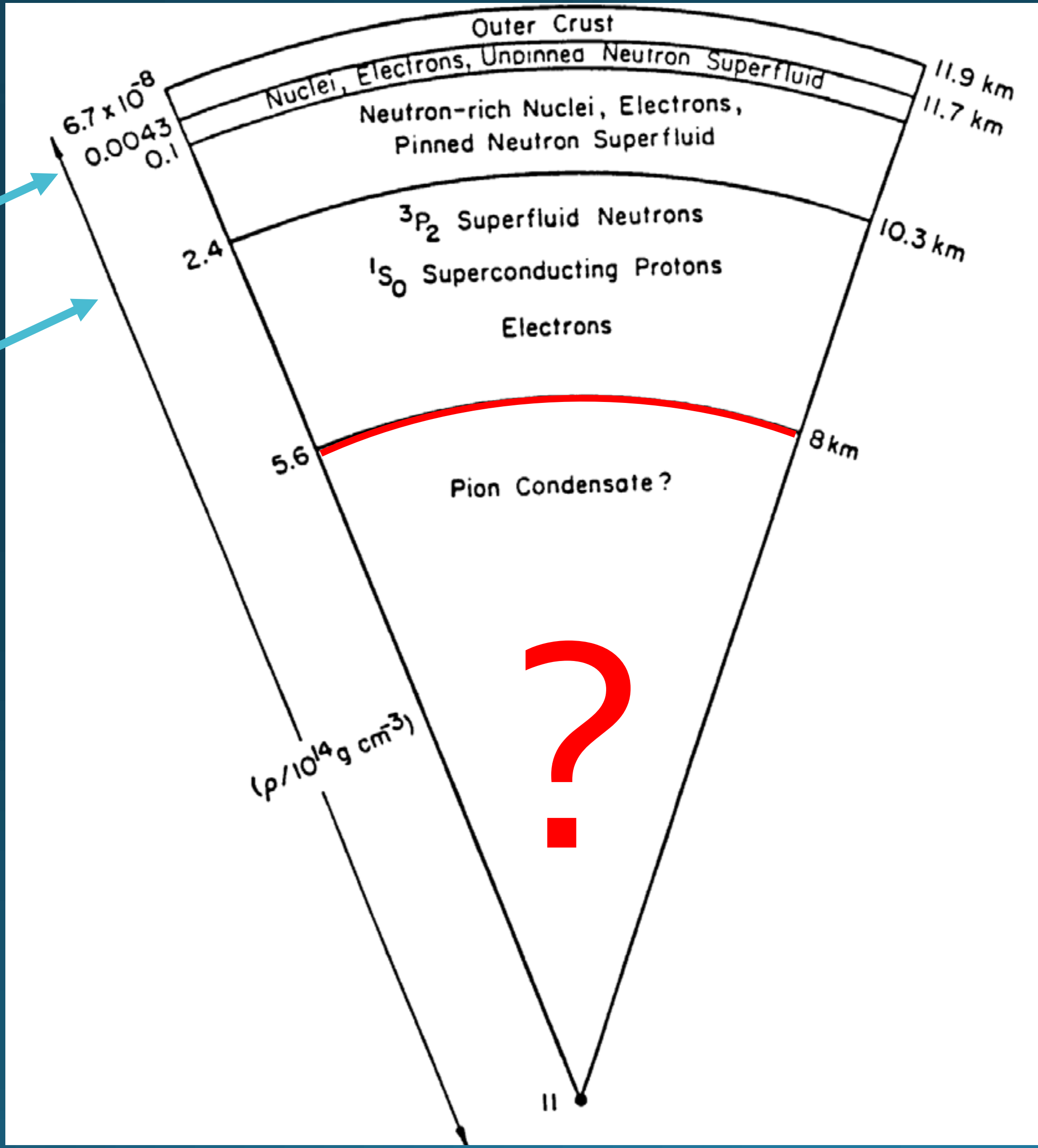
❖ Emission Process:

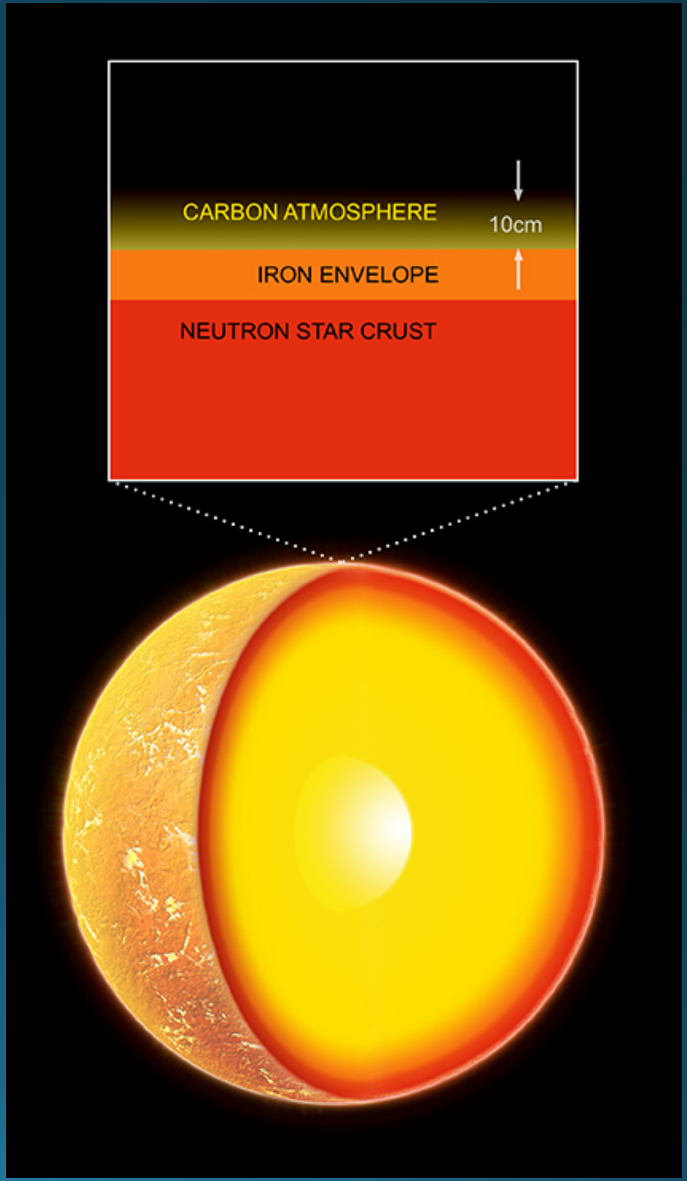
- How can we relate e.g. the spectra observed at radio, optical, X- and gamma-rays to get a general understanding of the emission processes operating in the neutron star’s magnetosphere ?

The structure of Neutron Stars: Slice through a 1.4 Mo Neutron Star

Neutron drip point

Atomic nuclei density

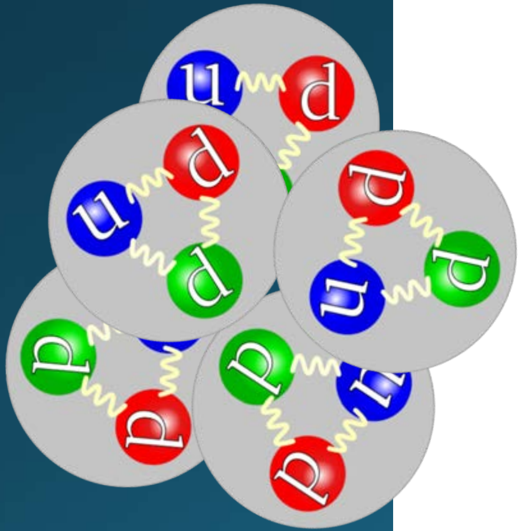


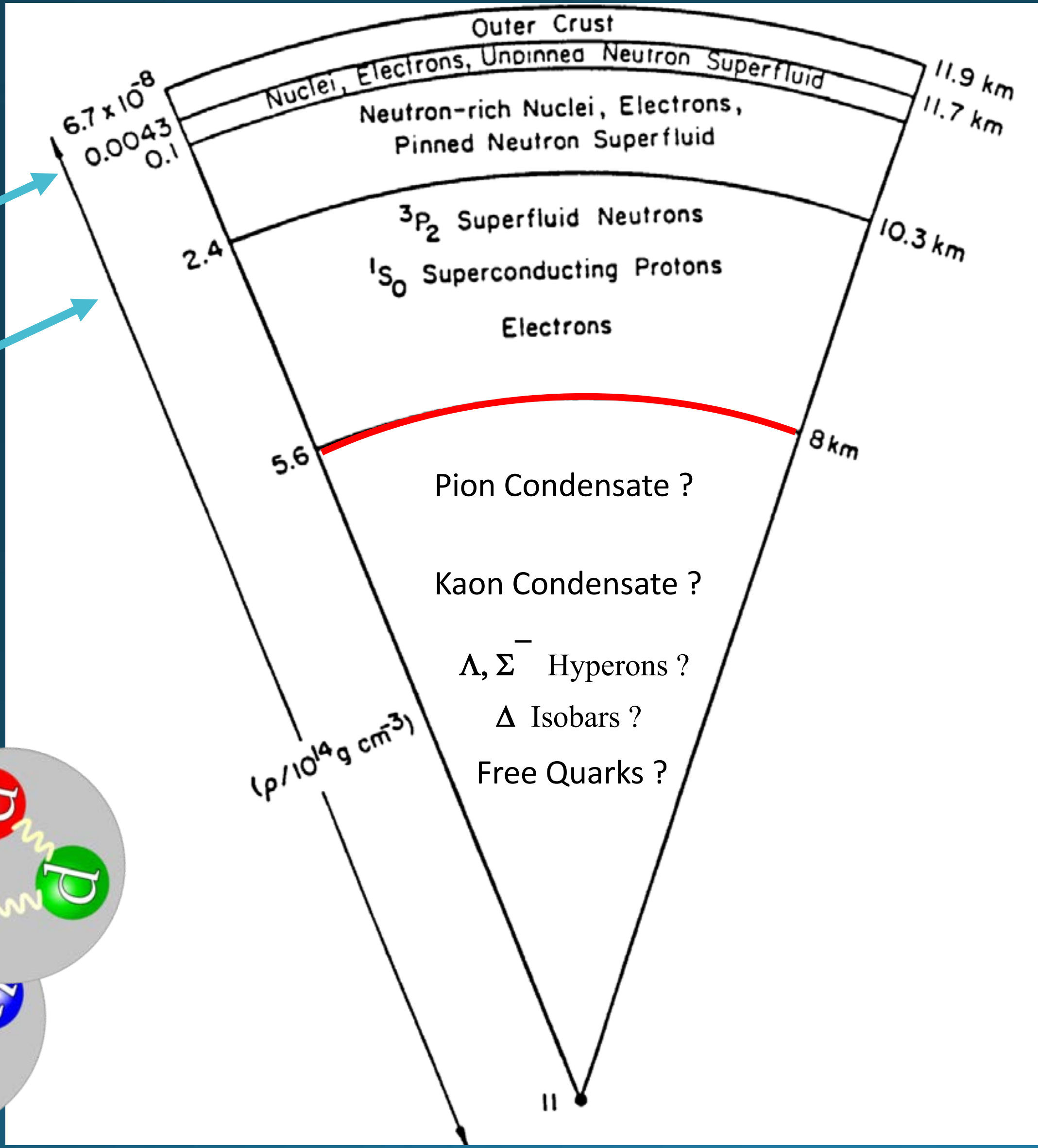


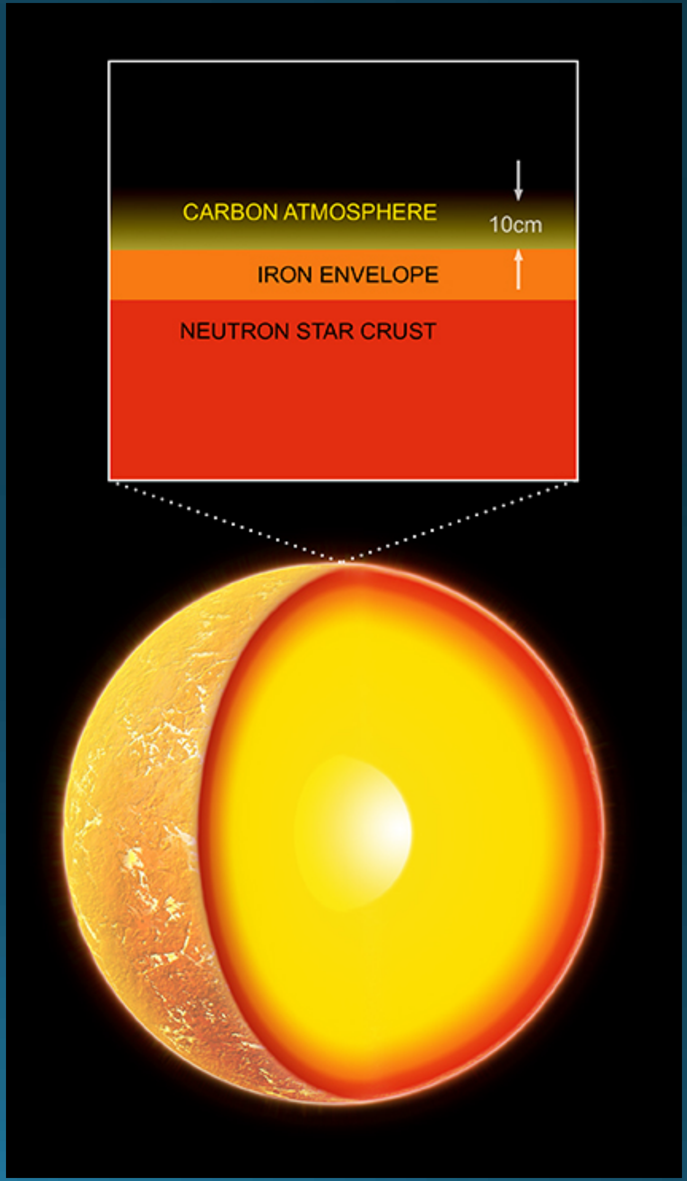
Innerer Aufbau von Neutronensternen: Schnitt durch einen 1.4 Mo Neutronenstern

Neutron drip point

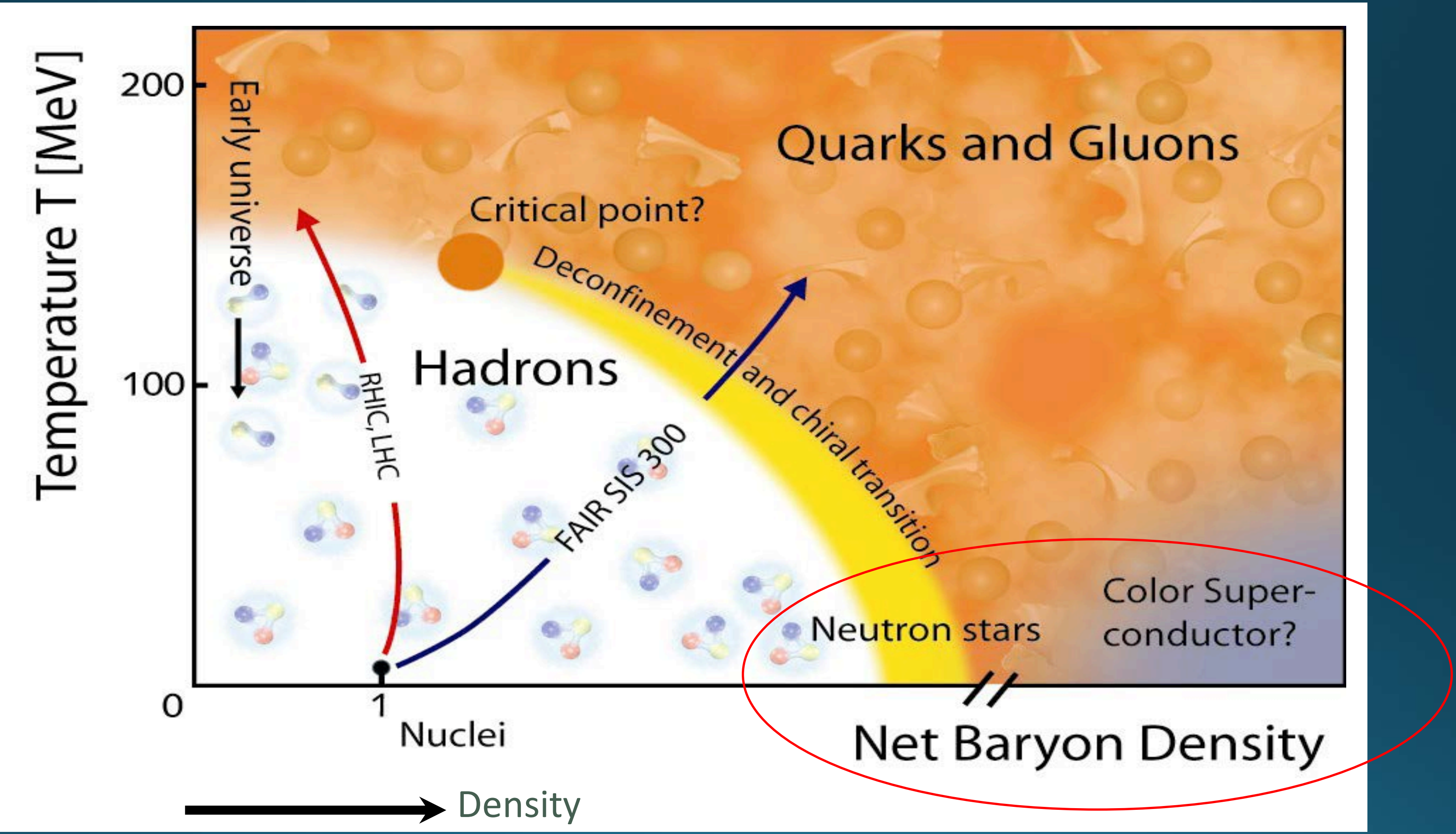
Atomic nuclei density







Neutron Stars allow to test the high density – low temperature range of the QCD phase diagram



→ Equation Of State (EOS) of cold nuclear matter at ultra high density

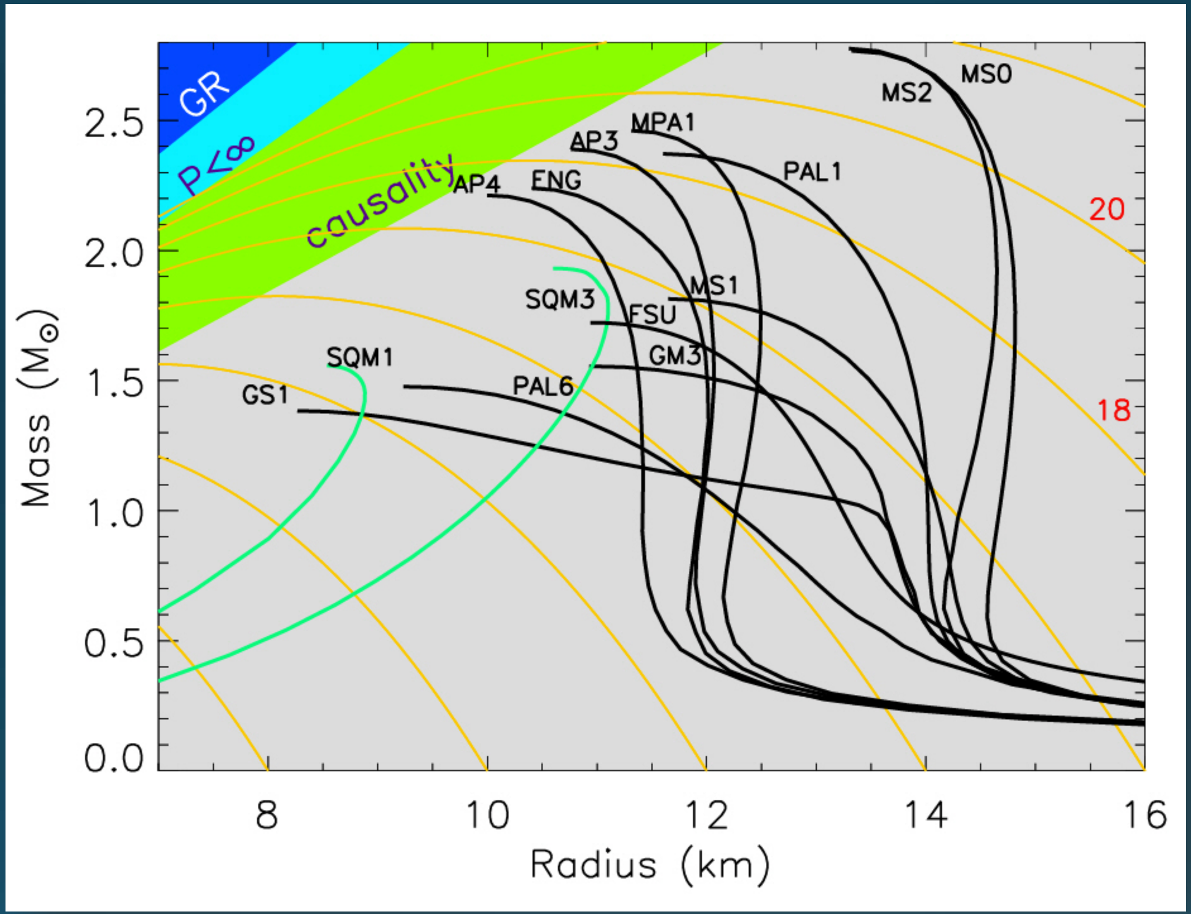
Equation of state (EOS) of nuclear matter

The key to understand the structure of neutron stars is its Equation Of State

The EOS is not just one equation but is a set of several coupled and non-linear differential equations which couple mass, density, pressure and temperature

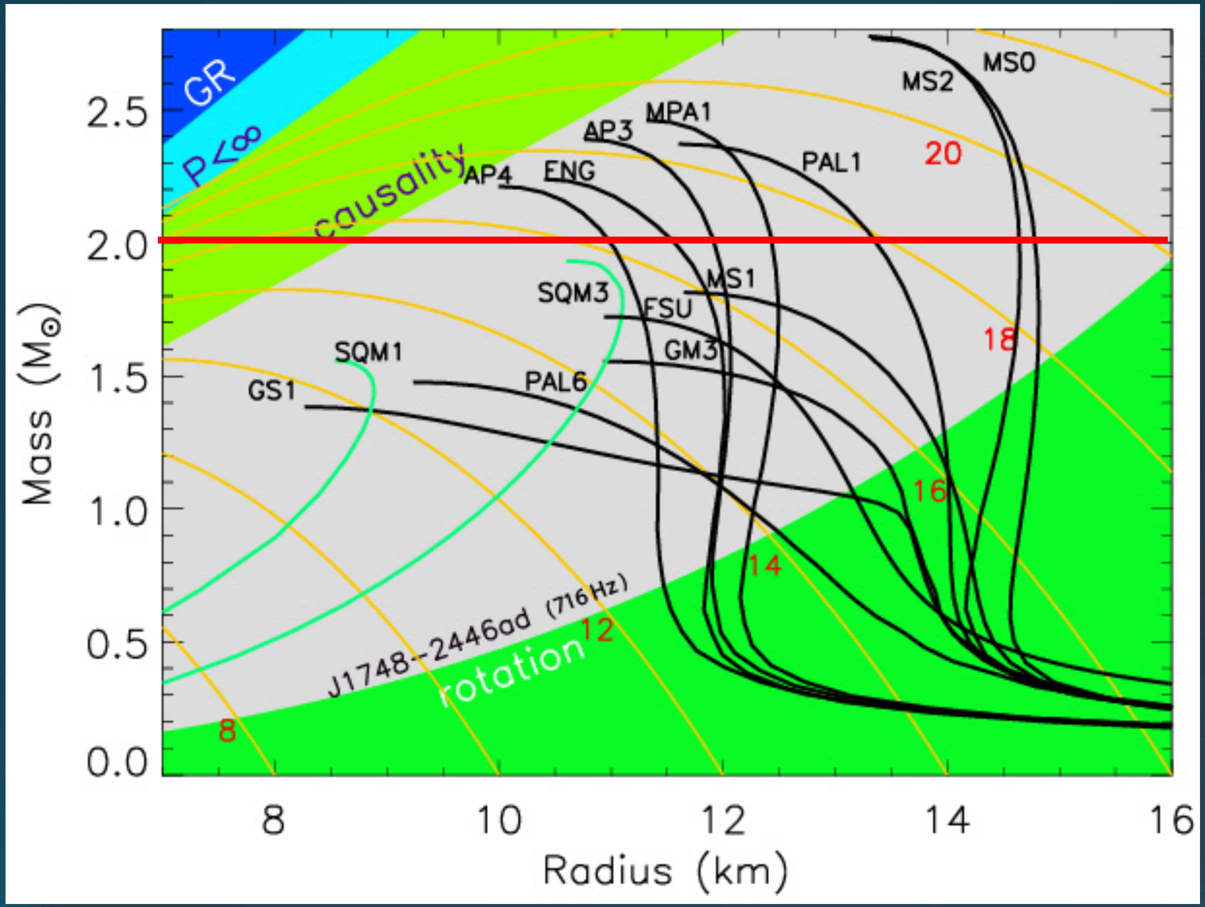
Irrelevant of all details, it is important to note that this relation can be translated into a mass-radius relation: ***M = M(R)***

EOS: Equation of state of nuclear matter



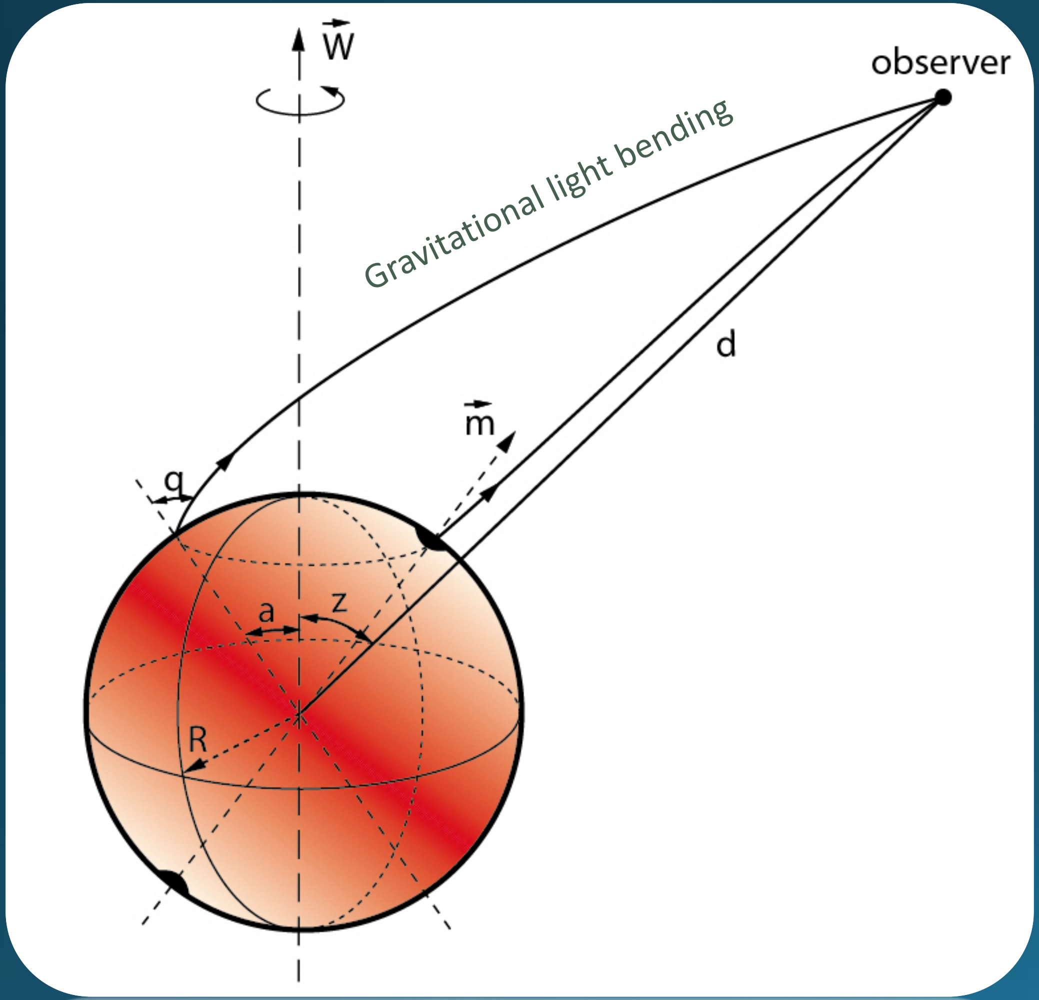
It is important to measure the mass and radius of a Neutron Star in order to restrict its equation of state

EOS: Equation of state of nuclear matter



It is important to measure the mass and radius of a Neutron Star in order to restrict its equation of state

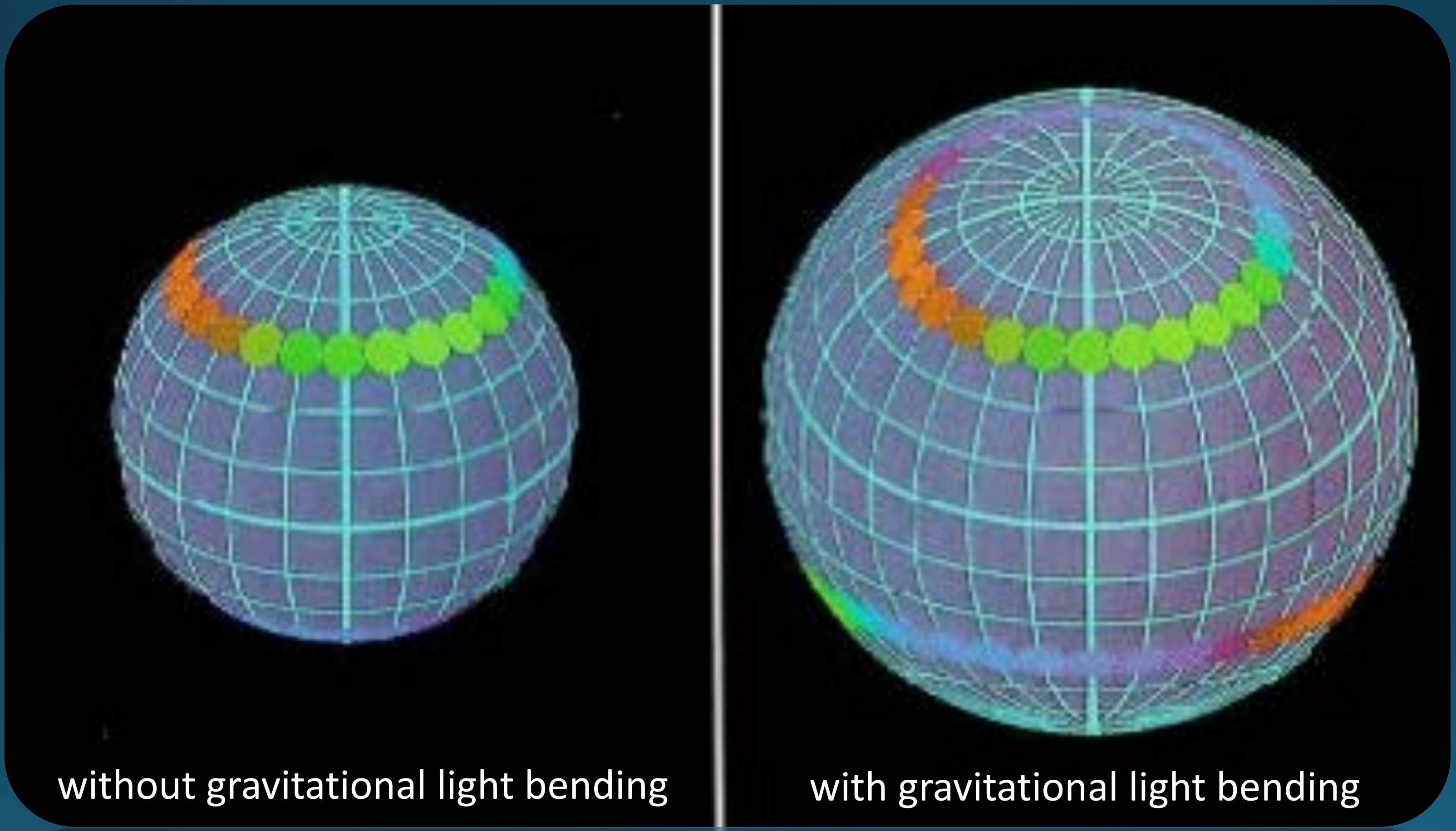
Gravitational light bending depends on the ratio of M/R



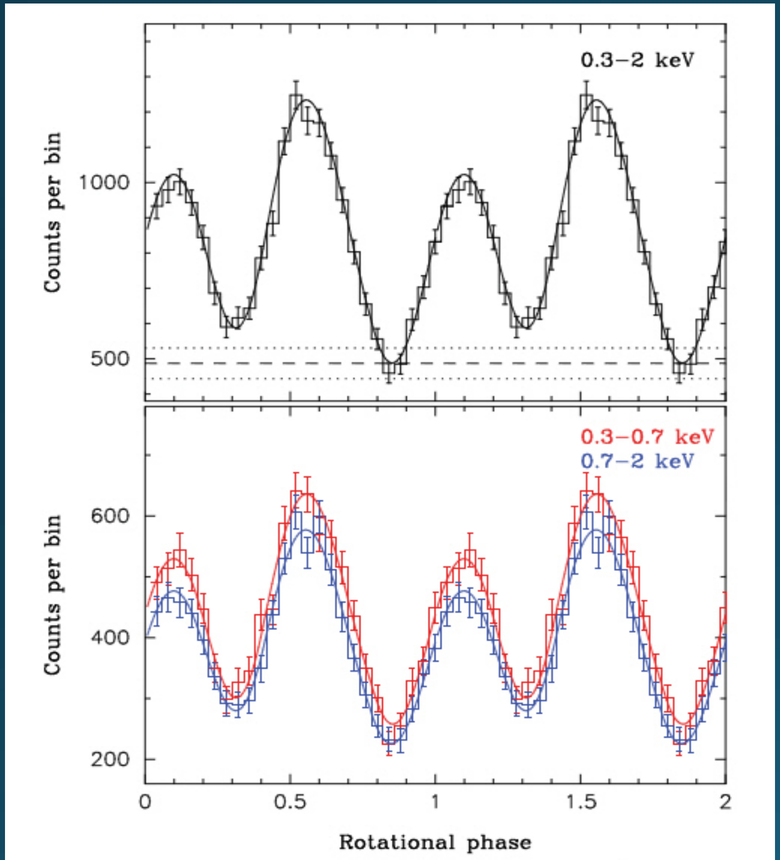
The details depend on **M/R** and have a measurable influence on the observed pulse profile

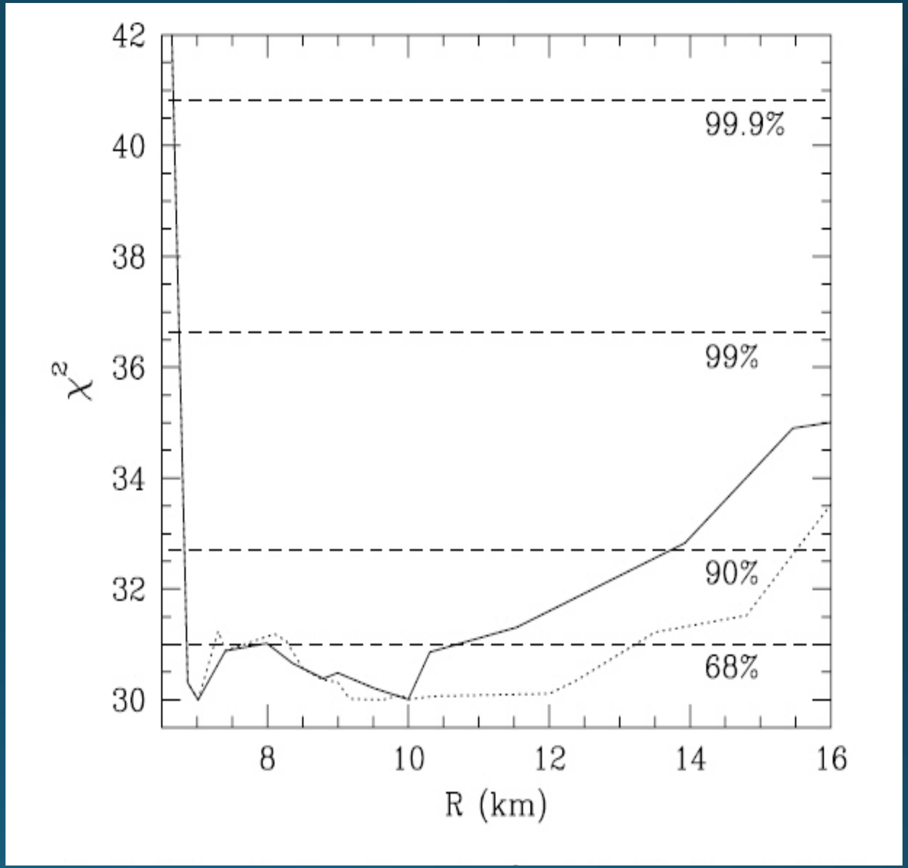
Becker 2009

Gravitational light bending depende on M/R ab and has a measureable influence on the pulse profile



Pulsar waveform fitting is sensitive to the neutron star's M/R





Requires an extremely good photon statistics

Significant results → next generation of X-ray observatories

Measuring M/R with NICER by fitting the Pulsars' waveform

NICER: The Neutron Star Interior Composition ExploreR

- 56 optical elements use grazing incidence optics to focus light onto silicon detectors
- Planed mission duration: 18 Month
- Goals: Measure neutron star masses and radii to within 5% by monitoring X-ray pulse profiles of several nearby pulsars
- Search for periodic pulsations from transient and steady systems
- Determine the physical properties of the neutron-star crust via astro-seismology

Thermal evolution of rotation powered pulsars

Neutron stars are born at a temperature of billions of degrees and cool thereafter!

Thermal evolution of rotation powered pulsars

The cooling of Neutron Stars depends strongly on the equation of state,

i.e. on the nuclear interaction potential at ultra high matter densities

The X-ray emission properties of Pulsars is changing with their age

Crab like Pulsars

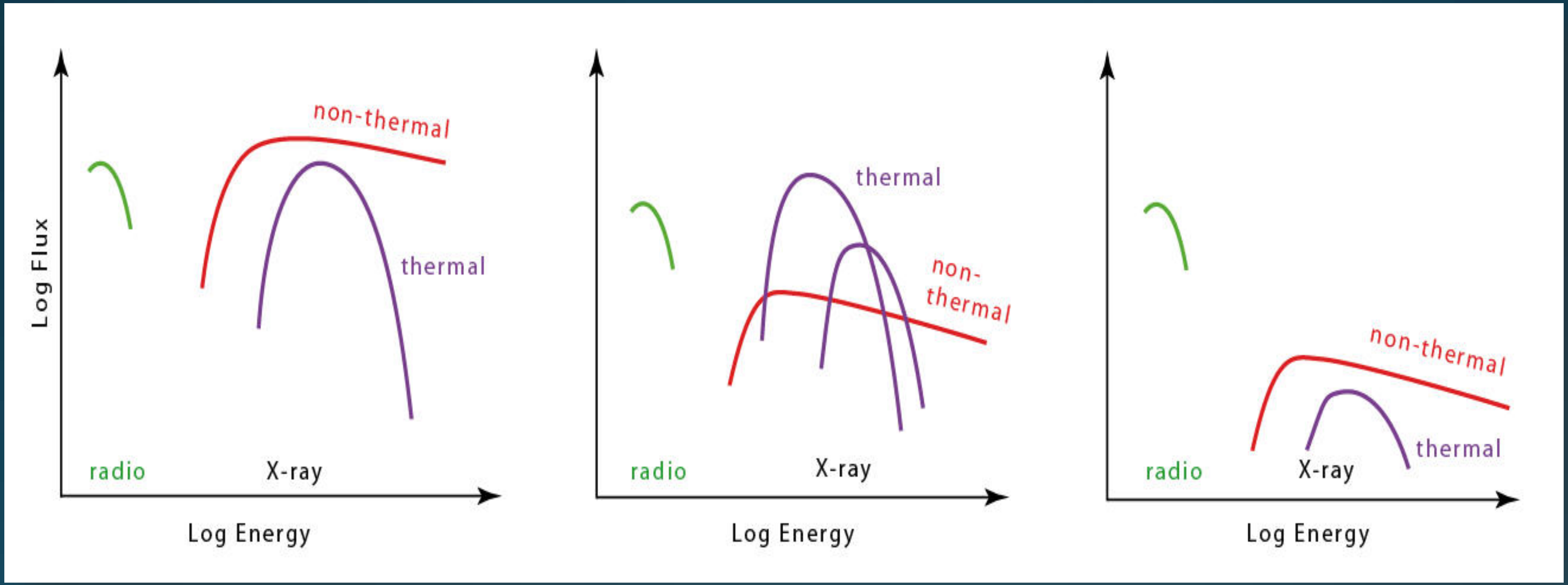
(< 10^4 Jahre)

Cooling Neutron Stars

(~10^5 - 10^6 Jahre)

Old Pulsars

(10^6 - 10^8 Jahre)

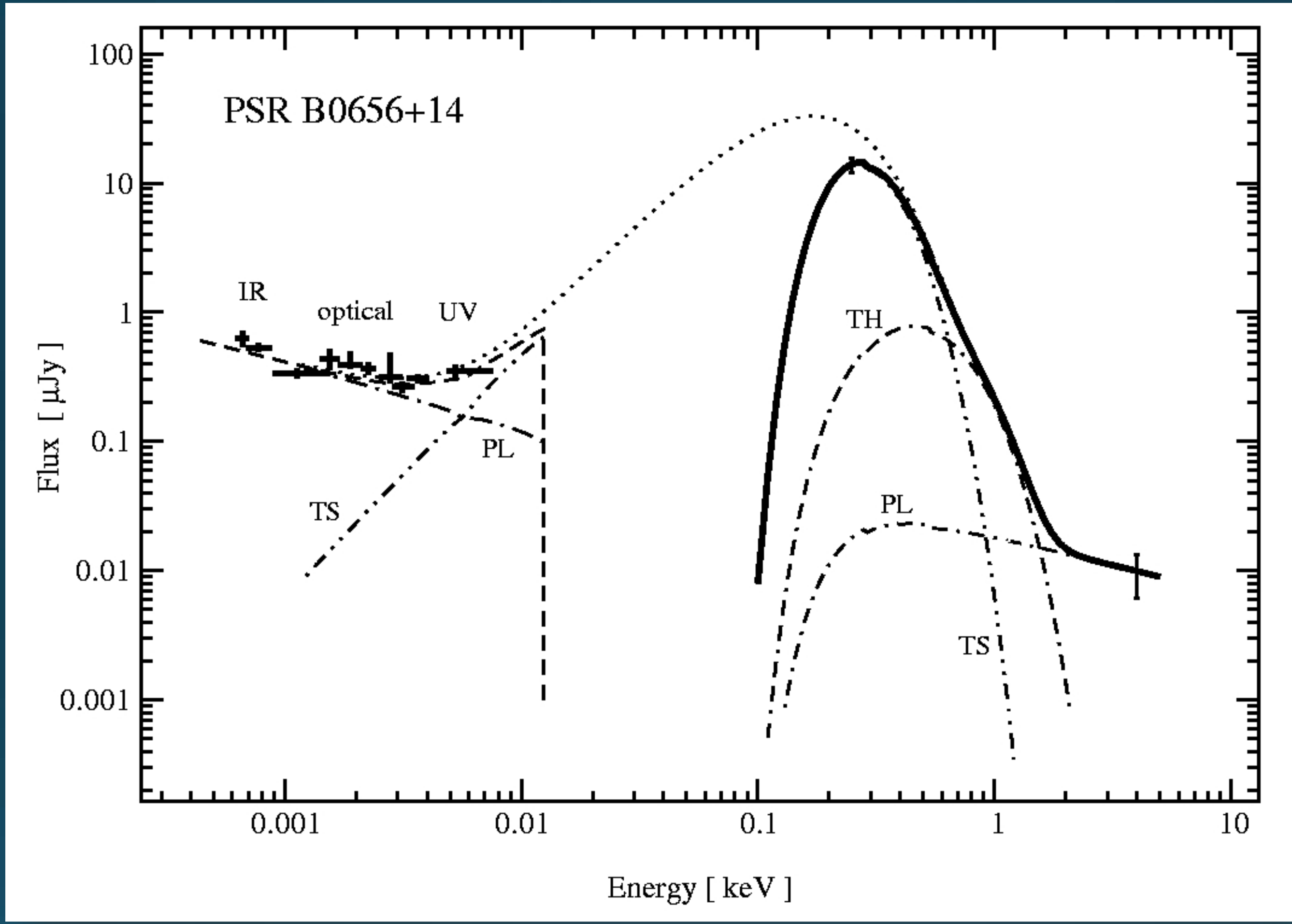


Pulsed emission~ 100%

Pulsed emission ~ 20-50%

Pulsed emission ~ 40%

Exploring cooling Neutron Stars: PSR 0656+14



X-ray observatories allow us to measure the source's X-ray spectrum from which it is possible to obtain the Neutron star's surface temperature (blackbody temperature TS and TH)

Thermal Evolution of Neutron Stars

Cooling of Neutron Stars:

$$C(T_i)\,\frac{\mathrm{d}\,T_i}{\mathrm{d}\,t} = -L_\nu(T_i) - L_\gamma(T_s) + \sum_k H_k$$

C_ν : Specific heat capacity

L_ν : Neutrino luminosity

L_γ : Emission of thermal photons form the neutron star's surface

$\sum_k H_k$: Sum of all heating controbutions

Thermal Evolution of Neutron Stars

TABELLE 2.1 Neutrinoemissivität der Neutronenstern-Kühlungsmodelle

Reaktionsprozeß	Darstellung	Emissivität (erg/s/cm³)
Direkter URCA-Prozeß	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27} \times T_9^6$
π-Kondensat	$n + \pi^- \to n + e^- + \bar{\nu}_e$ $n + e^- \to n + \pi^- + \nu_e$	$\sim 10^{26} \times T_9^6$
Quark-URCA-Prozeß	$d \to u + e^- + \bar{\nu}_e$ $u + e^- \to d + \nu_e$	$\sim 10^{26}\, \alpha_c\, T_9^6$
K-Kondensat	$n + K^- \to n + e^- + \bar{\nu}_e$ $n + e^- \to n + K^- + \nu_e$	$\sim 10^{24} \times T_9^6$
Modifizierter URCA-Prozeß	$n + n \to n + p + e^- + \bar{\nu}_e$ $n + p + e^- \to n + n + \nu_e$	$\sim 10^{20} \times T_9^8$
Direkt gekoppelte Elektron-Neutrino-Prozesse	$\gamma + e^- \to e^- + \nu_e + \bar{\nu}_e$ $\gamma_{plasmon} \to \nu_e + \bar{\nu}_e$ $e^+ + e^- \to \nu_e + \bar{\nu}_e$	$\sim 10^{20} \times T_9^8$
Neutron-Neutron und Neutron-Proton-Bremsstrahlung	$n + n \to n + n + \nu + \bar{\nu}$ $n + p \to n + p + \nu + \bar{\nu}$	$\sim 10^{19} \times T_9^8$
Elektron-Ion-Neutrino-Bremsstrahlung	$e^- + (Z, A) \to$ $e^- + (Z, A) + \nu_e + \bar{\nu}_e$	$\propto T_9^6$

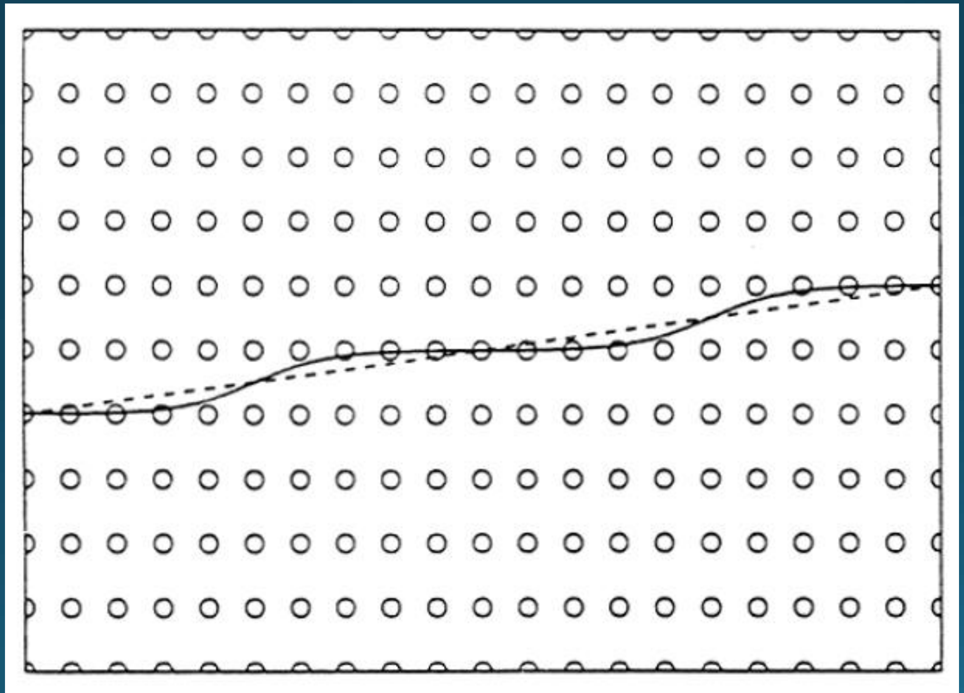
Becker 1994

Possible thermal reactions taking place in a neutron star and being important for its thermal evolution

Thermal Evolution of Neutron Stars: Frictional heating

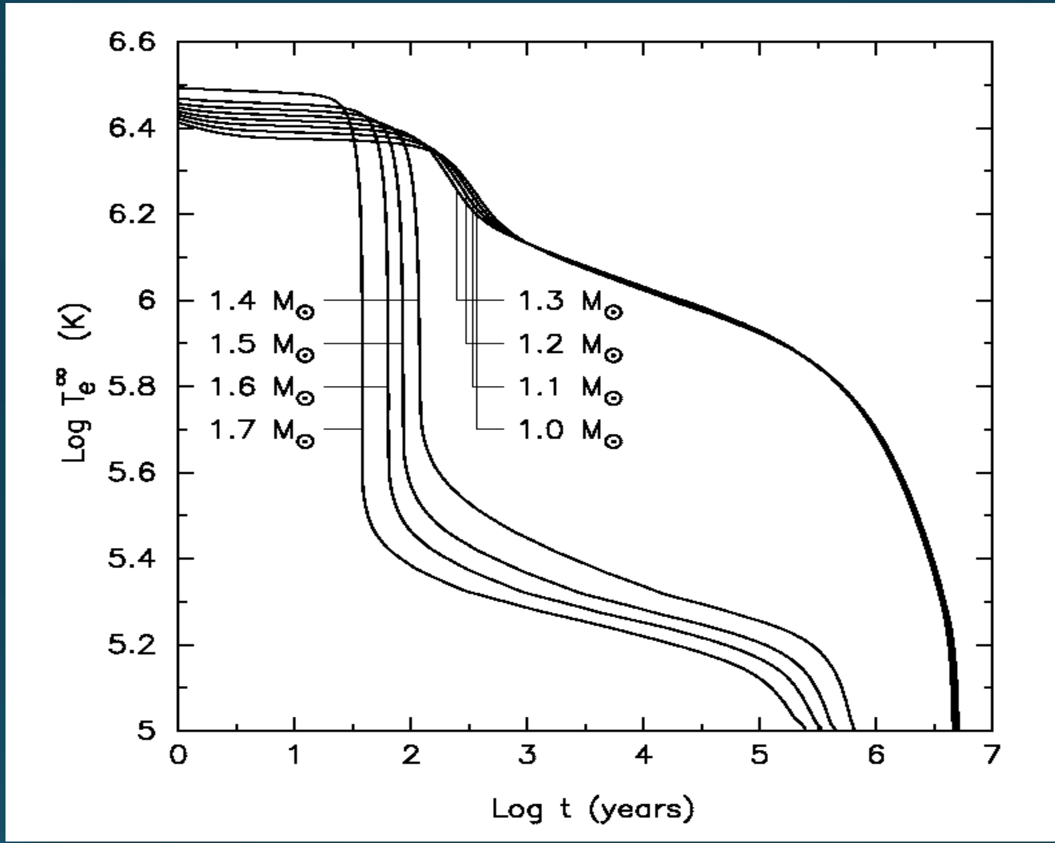
→ **Heating:**

The superfluid and solid parts of a Neutron star rotate with a different angular velocity. Dissipative interaction (friction) at their interface leads to a frictional heating during the Pulsars spin-down.



Other heating mechanisms in Neutron Stars are e.g. Vortex-Pinning / Vortex-Creaping

Neutron Star Cooling ← → EOS of cold dense nuclear mater



Observing thermal spectra from neutron stars yields the surface temperature AND the emitting area and hence its radius → R

(if the distance to the Neutron Star is known)

Studying cooling Neutron Stars

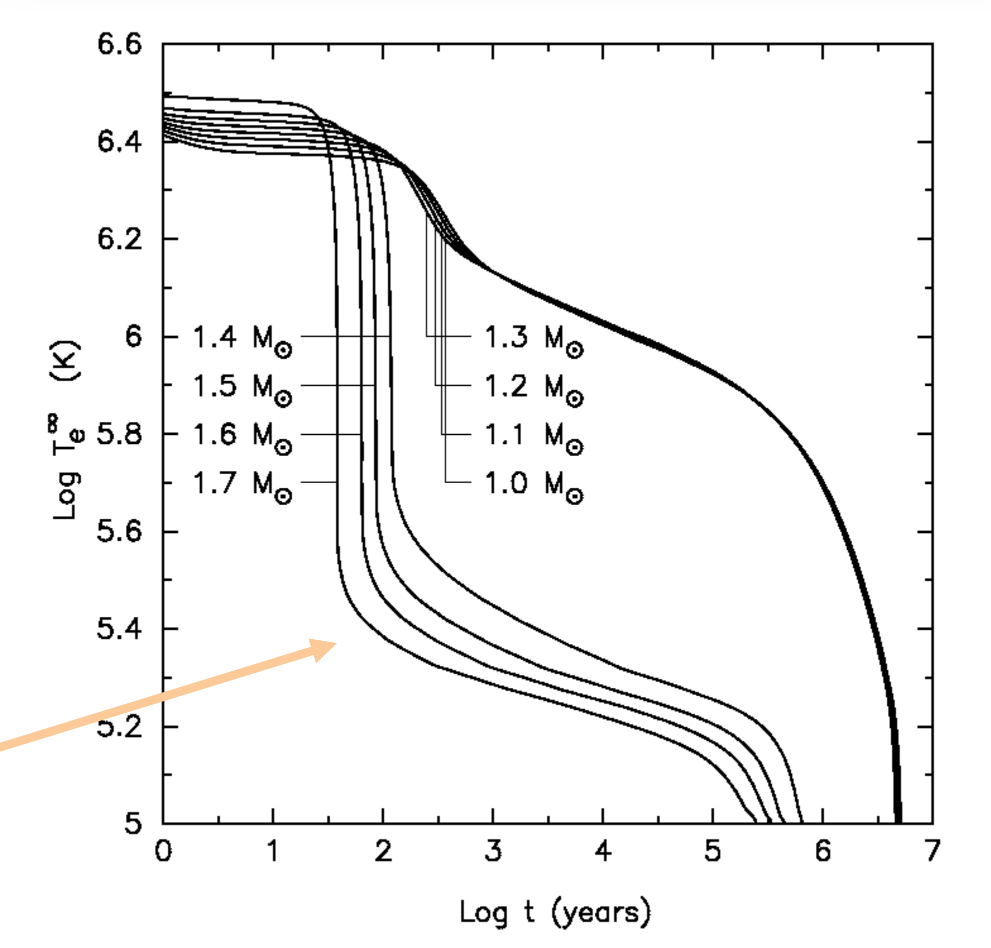
$$C(T_i)\,\frac{\mathrm{d}\,T_i}{\mathrm{d}\,t} = -L_\nu(T_i) - L_\gamma(T_s) + \sum_k H_k$$

- Neutrino cooling is the dominant cooling process during the first ~100 000 years in the lifetime of a Neutron Star.

- After this time the emission of thermal photons from the Neutron Star surface becomes the dominant cooling mechanism.

- The details of the thermal evolution depend strongly on the physical properties of the matter at ultra high densities, which are only badly know.

- Fast cooling in the case of an increased Neutrino luminosity (temperature inversion!).



Studying cooling Neutron Stars

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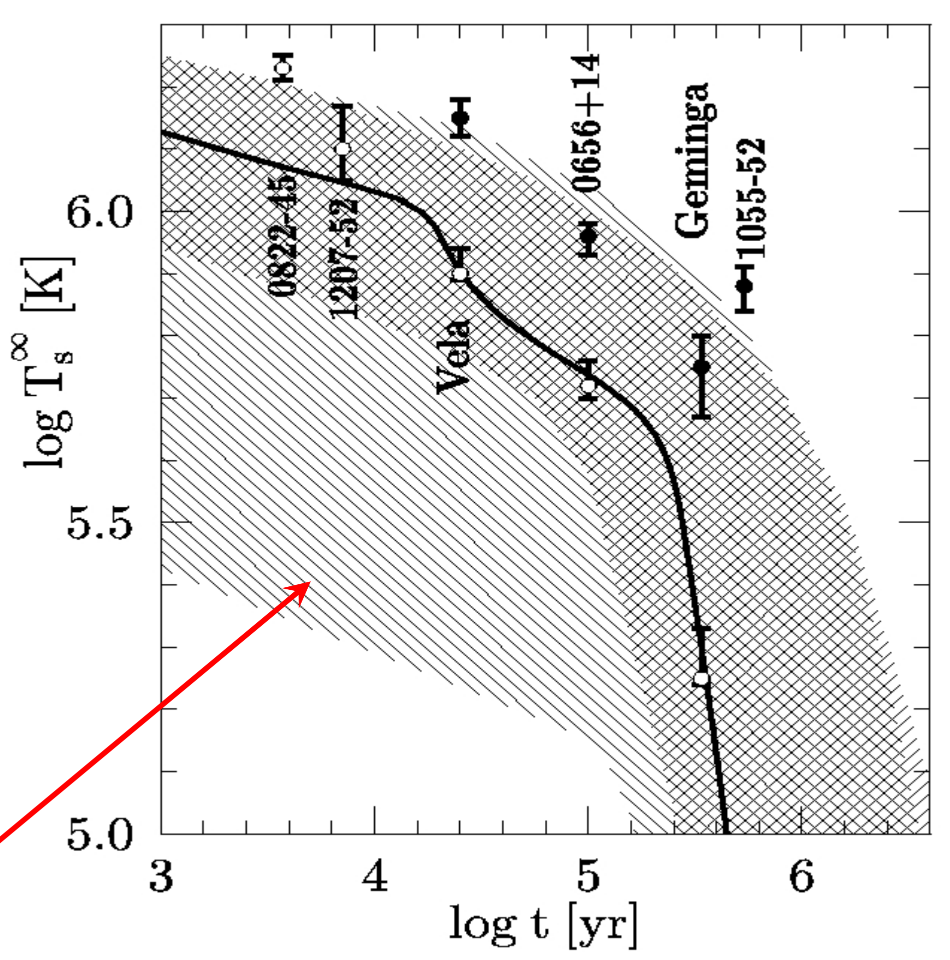
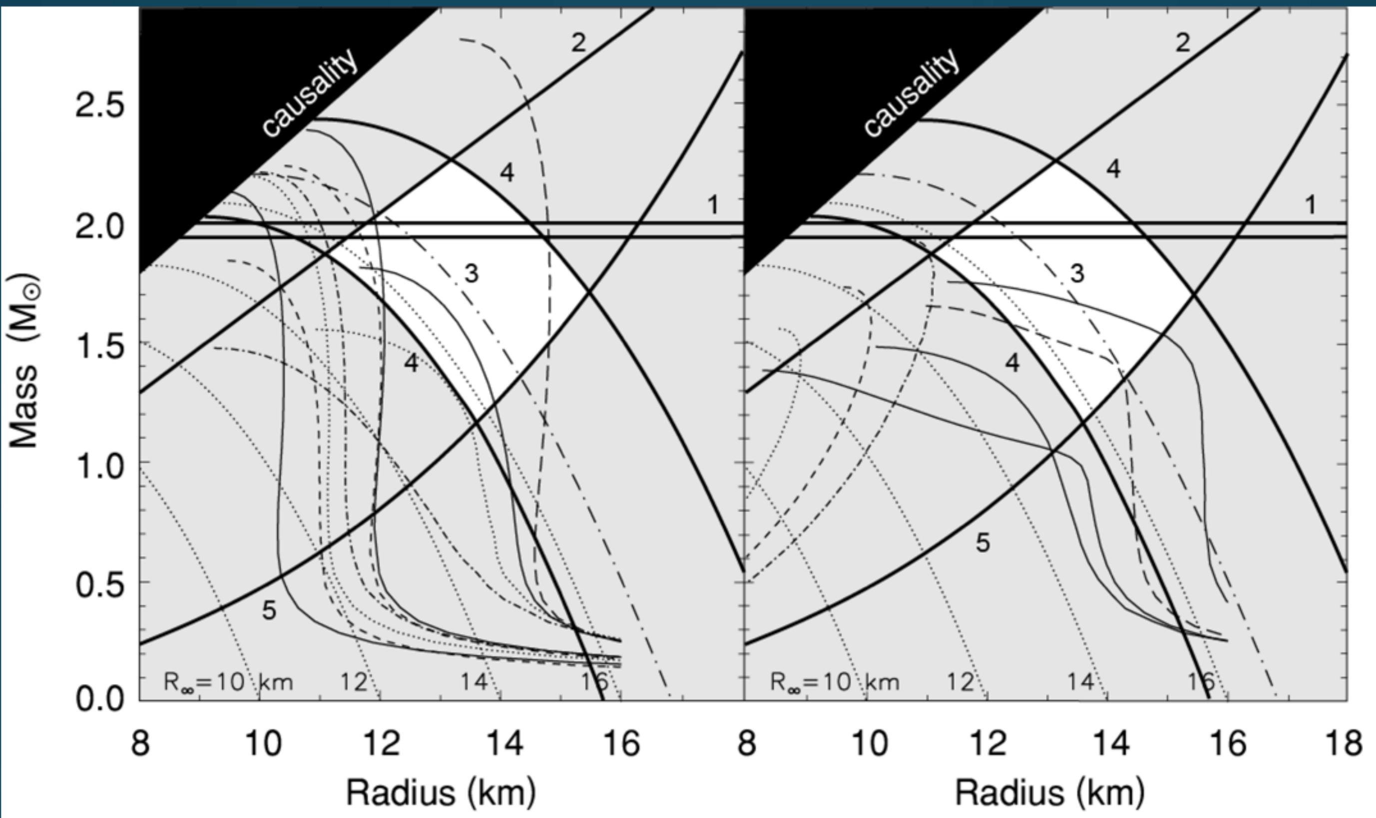


Comparison of predicted Neutron Star surface temperatures and those which have been measured by an X-ray observatory

>>> NO INDICATION FOR FAST COOLING <<<



1 Largest mass J1614 - 2230
(Demorest et al. 2010)

2 Maximum gravity XTE 1814 – 338
(Bhattacharyya et al. 2005)

3 Minimum radius RXJ1856 - 3754
(Trümper et al. 2004)

4 Radius, 90% confidence limits LMXB 47 Tuc
(Heinke et al. 2006)

5 Largest spin frequency J1748 – 2446
(Hessels et al. 2006)

Summary:

- Observations of Neutron Stars provide important restrictions for the EOS of super-dense and cold nuclear matter
- Observations of Neutron Stars strongly suggest that the EOS of Neutron Stars is ‘stiff’
- The observations of cooling Neutron Stars provide *no* evidence for the existence of Hyperons, Kaons-, Pion-Condensate and quasi free Quarks in the central region of Neutron Stars
- Observations restrict the Neutron Star radii to $R \geq$ 11-16 km for a Neutron Star mass in the range of 1.1 - 2.2 $M_{\odot}$
- Up to now there is no observational evidence for the existence of „Strange Stars“

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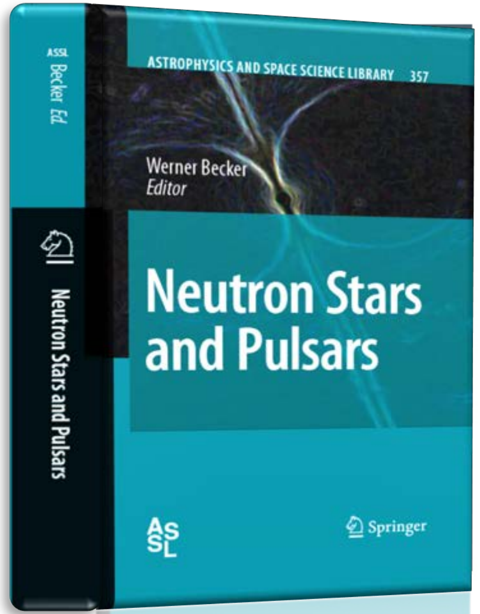

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Neutron Stars and Pulsars

Keywords:

- Gravitational Waves from Spinning Neutron Stars
- Isolated Neutron Stars and Millisecond Pulsars
- Neutron Star Cooling and Magnetic Field Evolution
- Particle Acceleration and Interactions in Pulsar Magnetospheres
- Pulsar Wind Nebulae
- Radio and high Energy Emission from Rotation-Powered Pulsars
- Soft Gamma-ray Repeaters and Magnetars
- Structure of Neutron Stars and EOS

"What have we learned about the subject and how did we learn it?"

"What are the most important open questions in this area?"

"What new tools, telescopes, observations, and calculations are needed to answer these questions?".