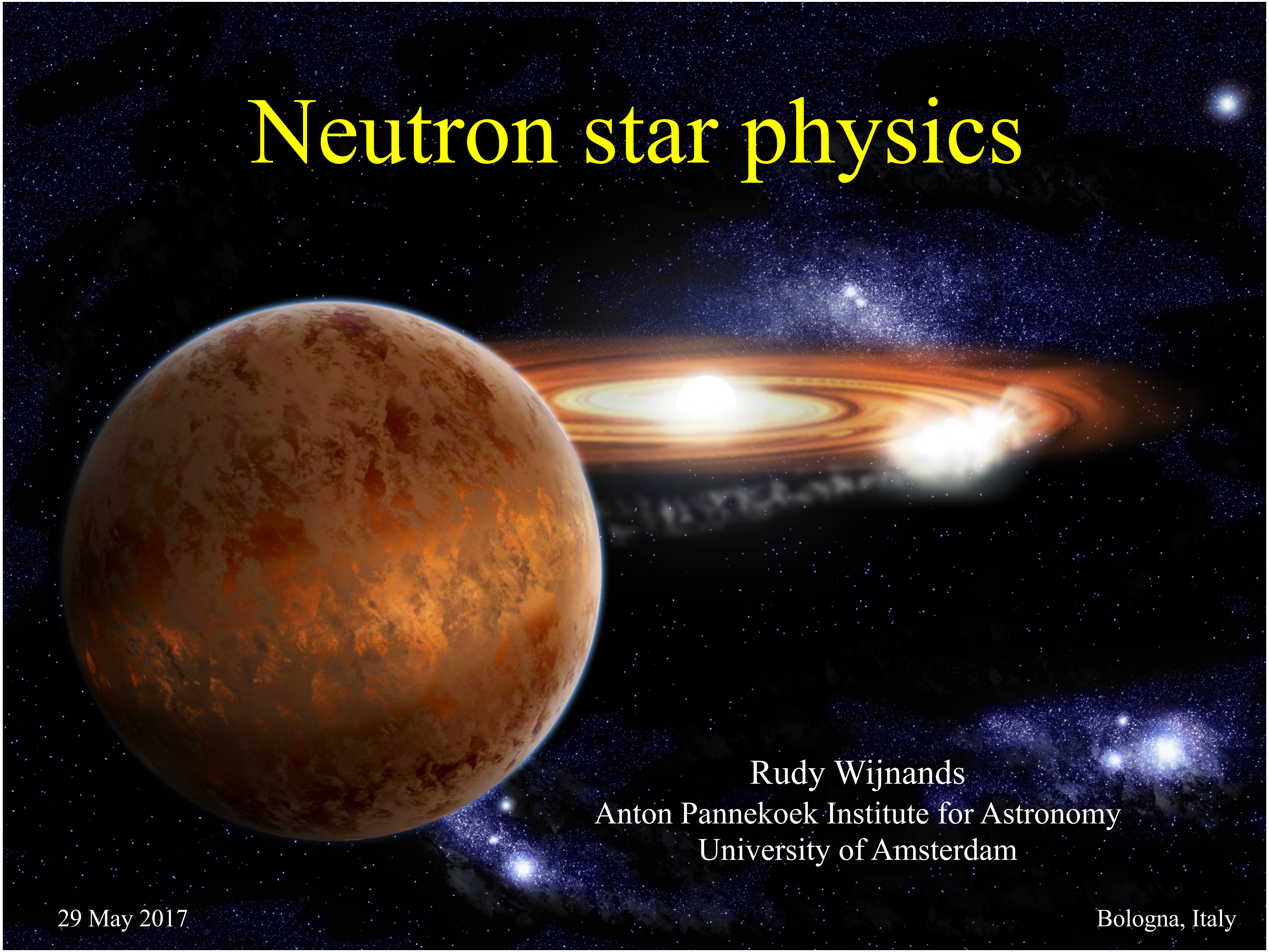
Neutron star physics



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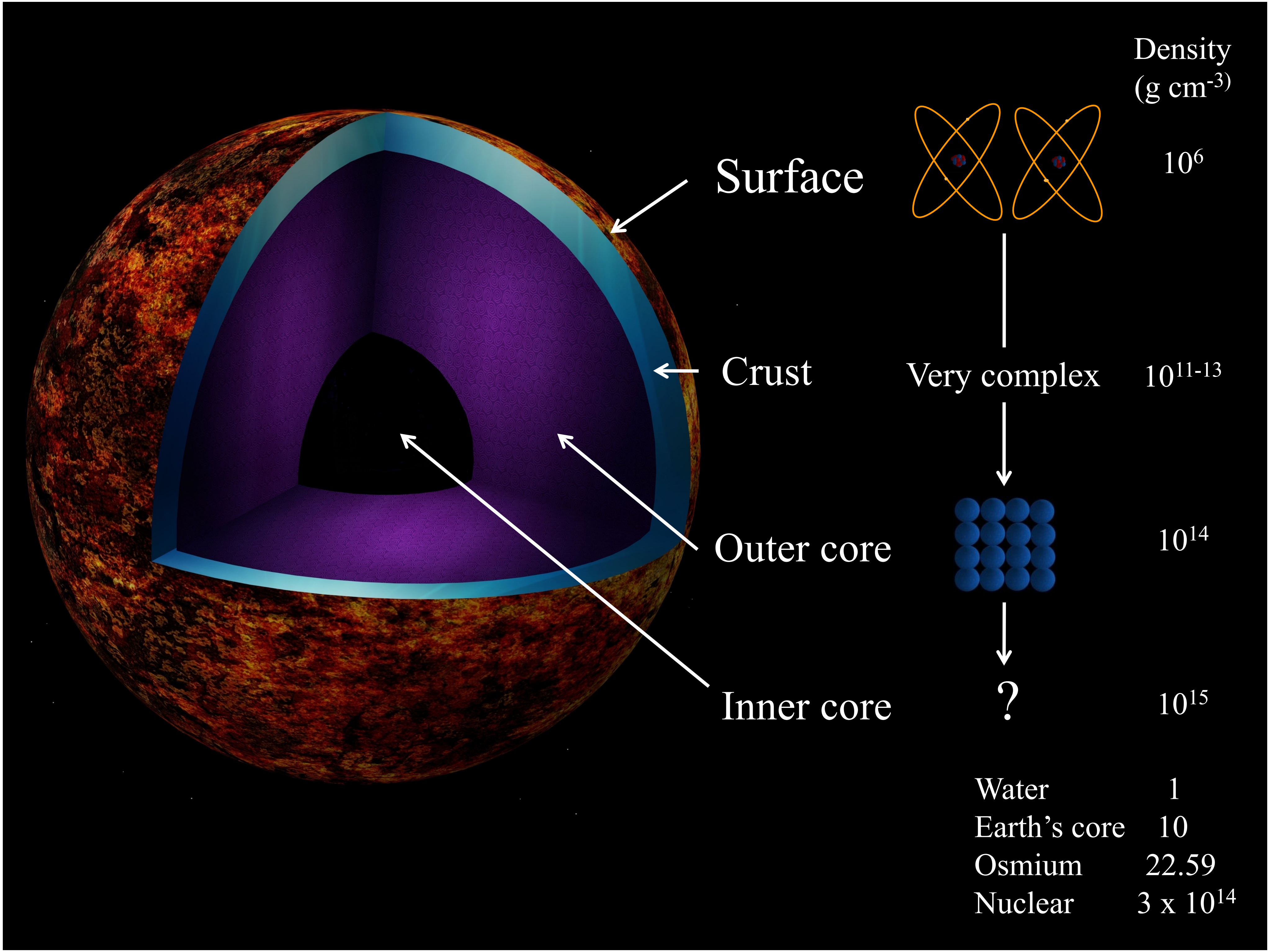
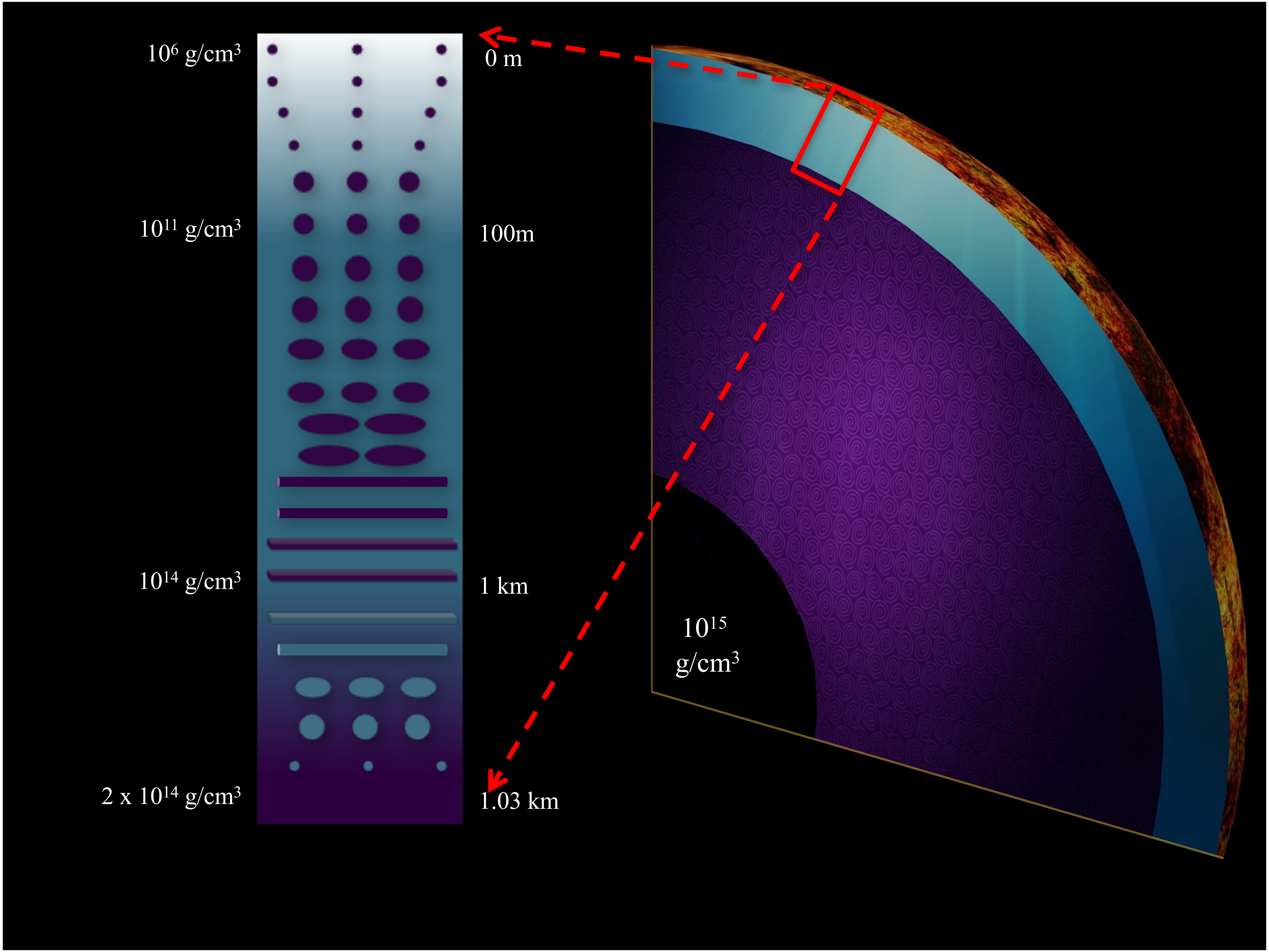
29 May 2017

Bologna, Italy

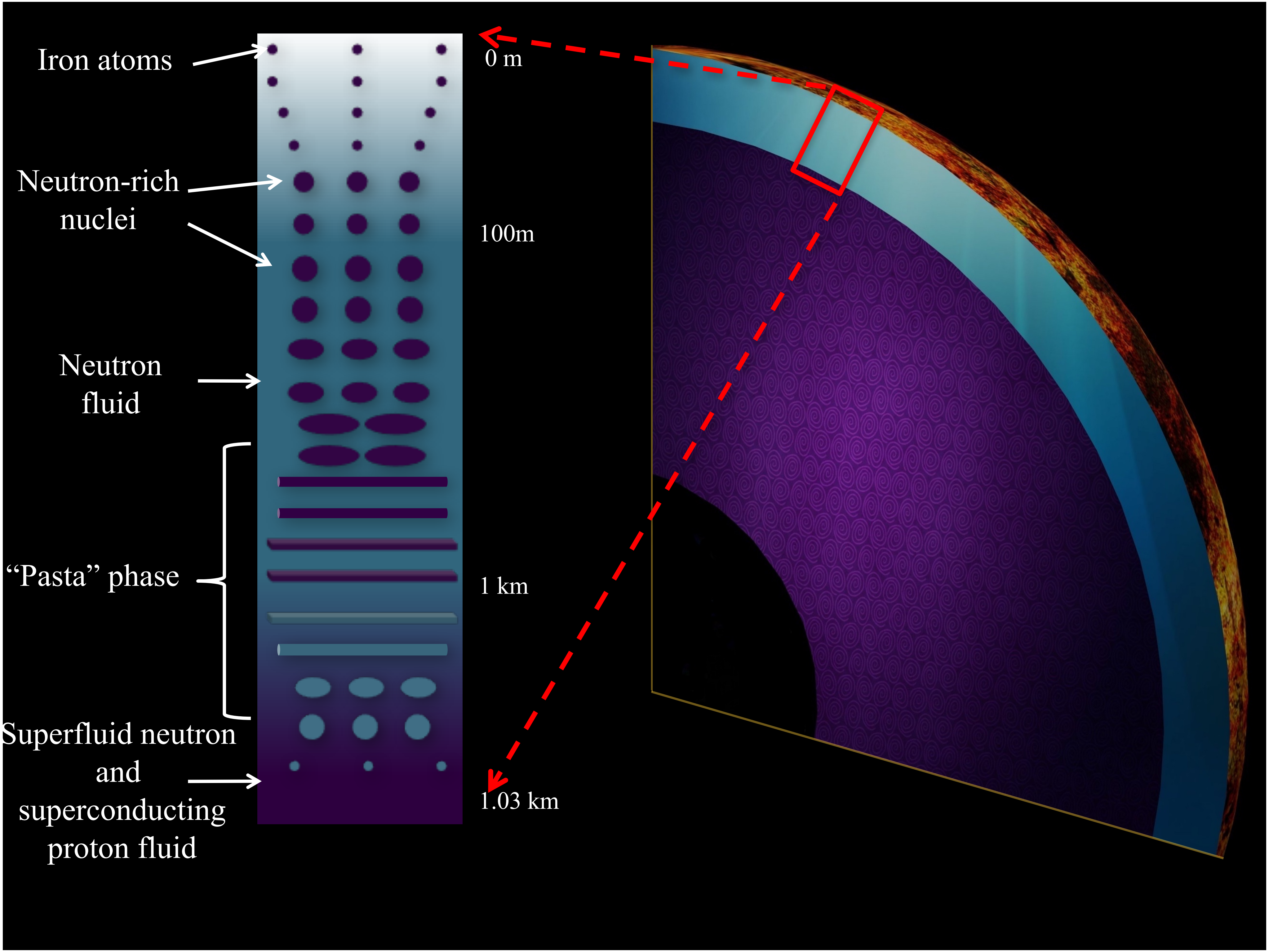
Lecture 2

- Some basic neutron star concepts
  - Born in supernovae → cool down within 10 milion years
  - Small mass (1.4-2 $M_\odot$), small radius (10-12 km), and strong magnetic field (10^{7-13} G)
- How does the neutron star affects the accretion?
  - Studying accretion physics (i.e., magnetic accretion)
  - Very complex → only some very basic concepts
- How does accretion affects neutron stars?
  - Studying neutron star physics
  - Dense matter physics → not possible on Earth

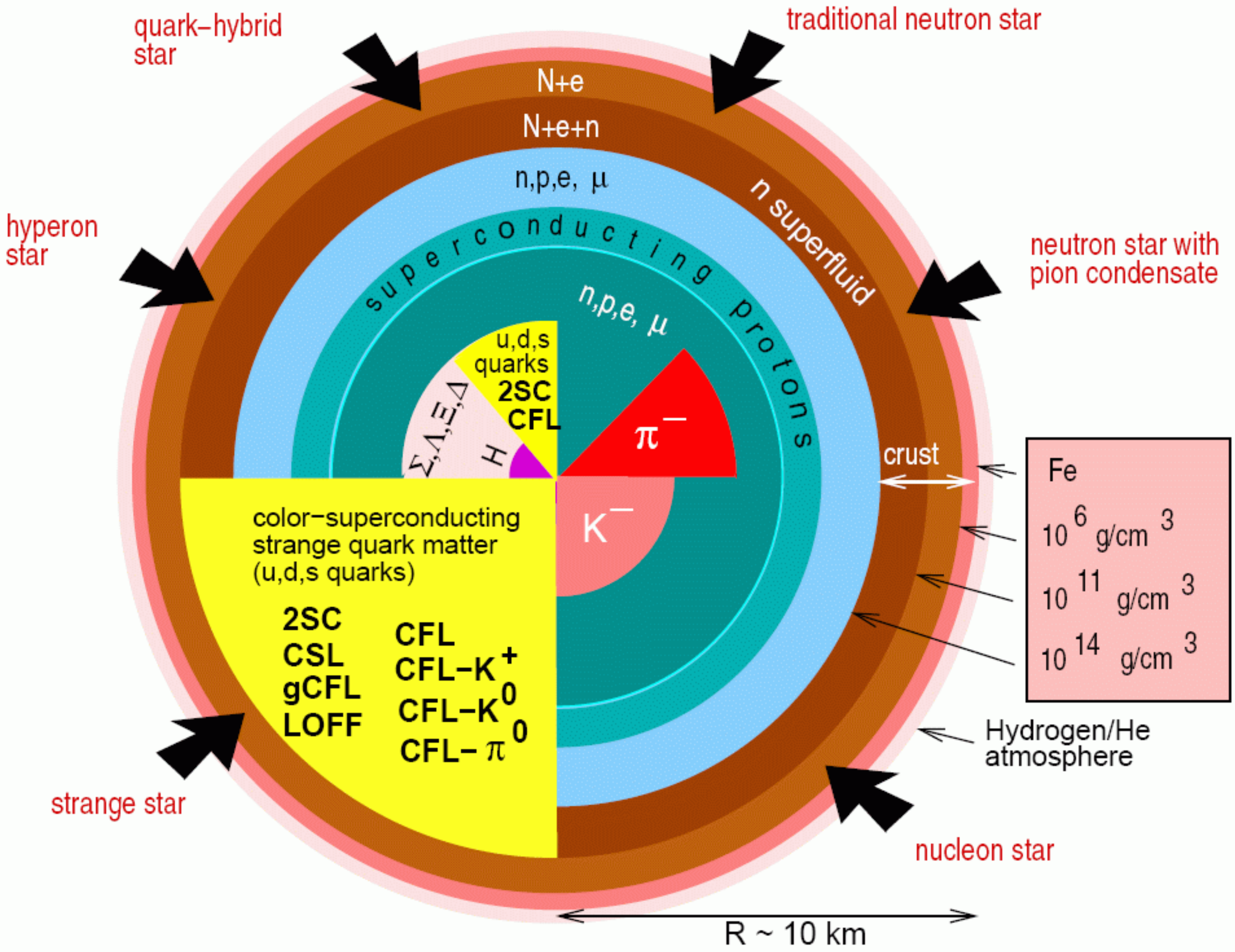

Density (g cm-3)
Surface
10^6
Crust
Very complex
10^11-13
Outer core
10^14
Inner core
?
10^15
Water 1
Earth's core 10
Osmium 22.59
Nuclear 3 x 10^14



10^6 g/cm^3
0 m
10^{11} g/cm^3
100m
10^{14} g/cm^3
1 km
2 x 10^{14} g/cm^3
1.03 km
10^{15}
g/cm^3



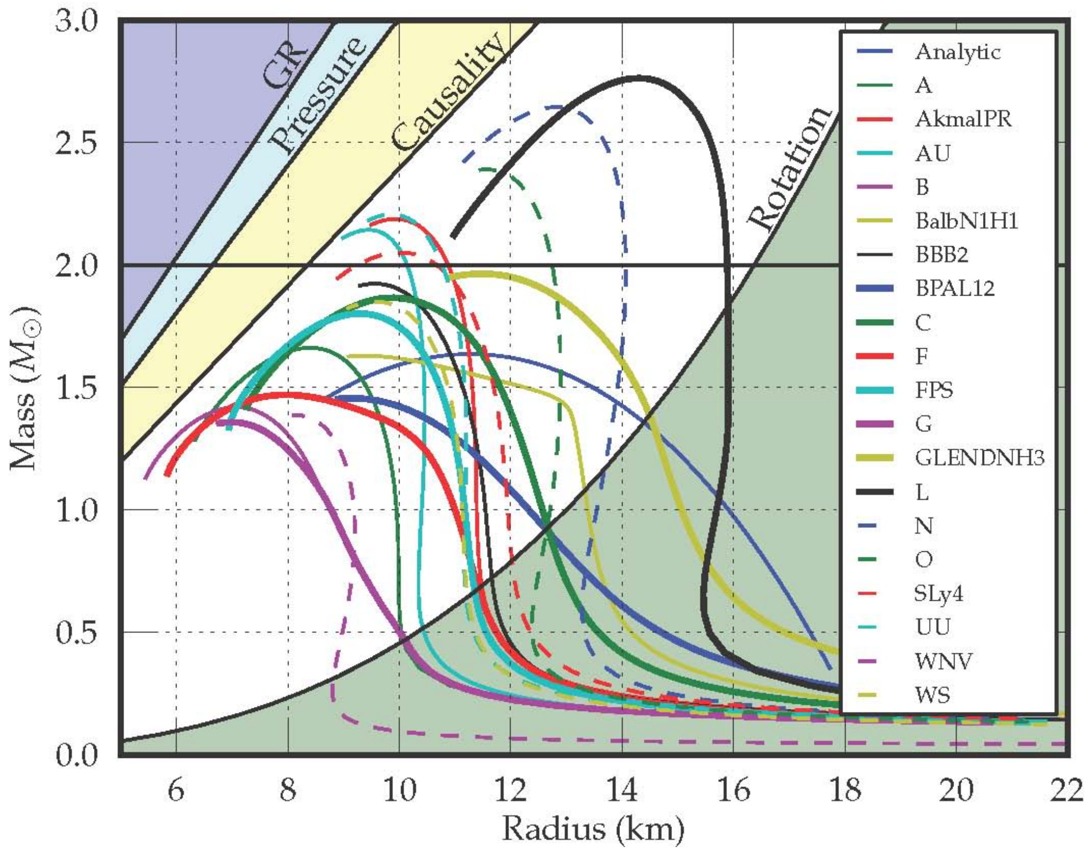
Iron atoms
Neutron-rich nuclei
Neutron fluid
"Pasta" phase
Superfluid neutron and superconducting proton fluid
0 m
100m
1 km
1.03 km



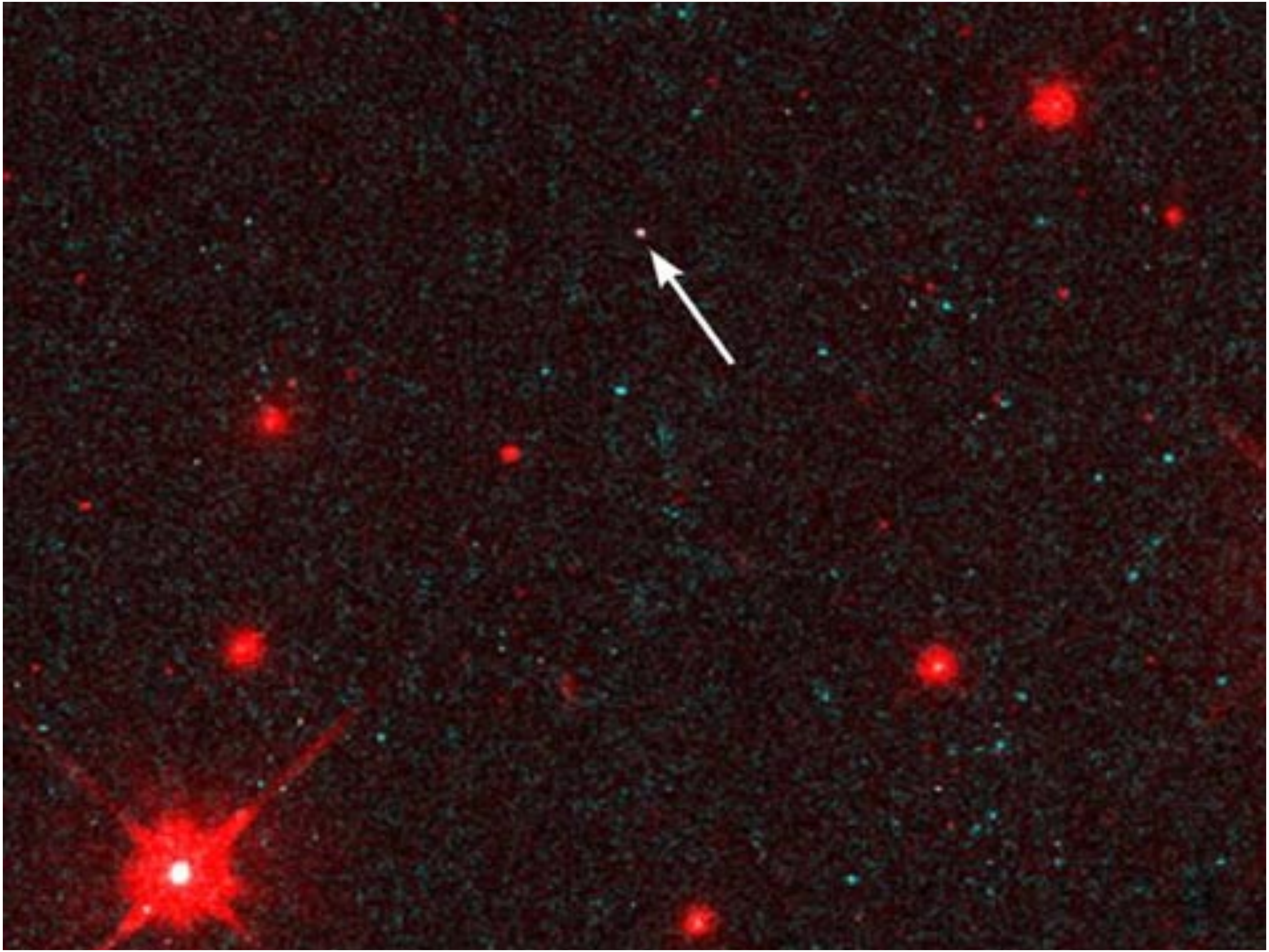
quark−hybrid star
traditional neutron star
N+e
N+e+n
n,p,e, μ
n superfluid
hyperon star
superconducting protons
neutron star with pion condensate
n,p,e, μ
u,d,s quarks
2SC
CFL
Σ,Λ,Ξ,Δ
H
π⁻
crust
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
K⁻
color−superconducting strange quark matter (u,d,s quarks)
2SC
CSL
gCFL
LOFF
CFL
CFL−K+
CFL−K0
CFL−π0
Hydrogen/He atmosphere
strange star
nucleon star
R ~ 10 km

How to constrain NS matter?

- Determining M and R



- Difficult, very weak sources



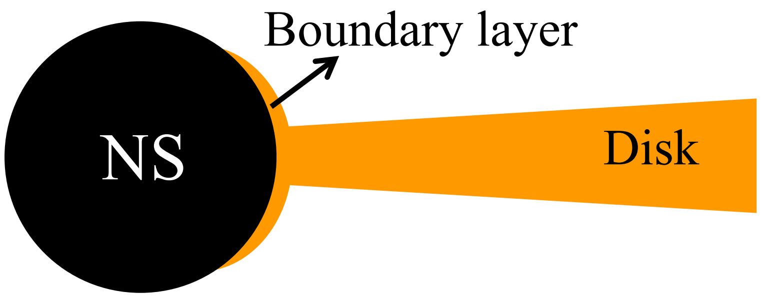
Use X-ray binaries

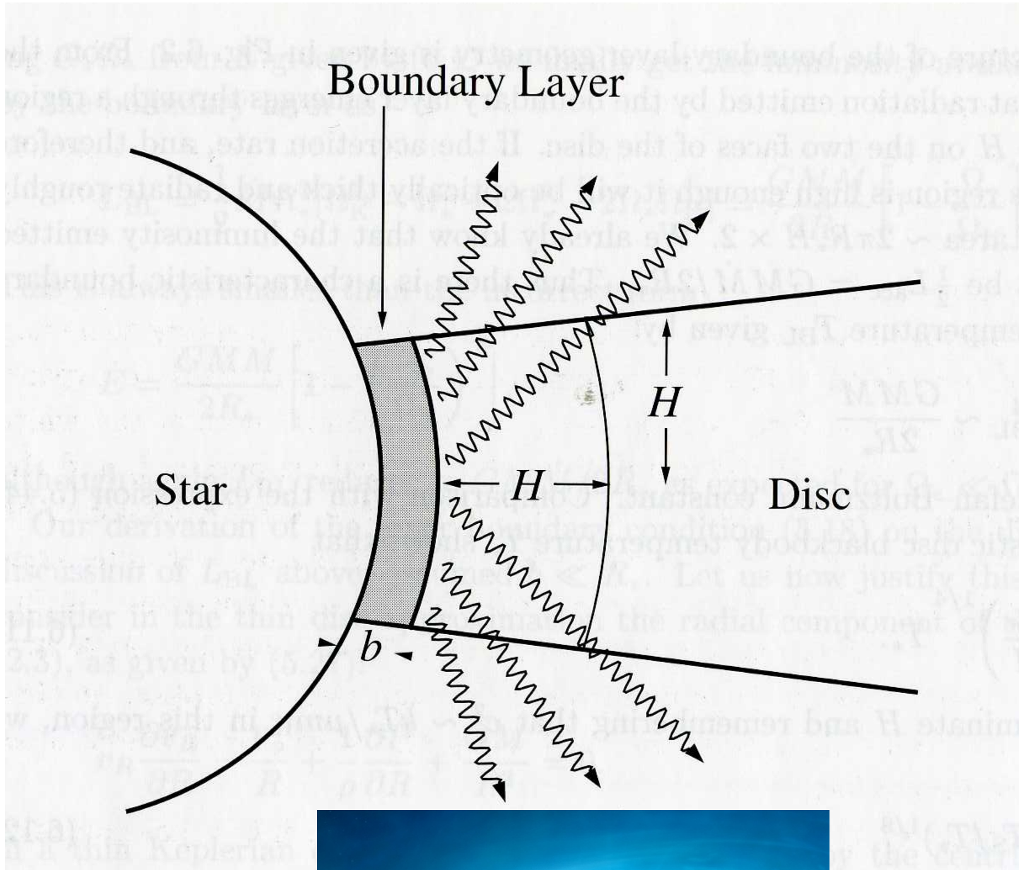
- Can be very bright in X-rays
- Neutron stars have strong magnetic fields
  - HMXBs: $B \sim 10^{12-13}$ G
  - LMXBs: $B \sim 10^{7-9}$ G

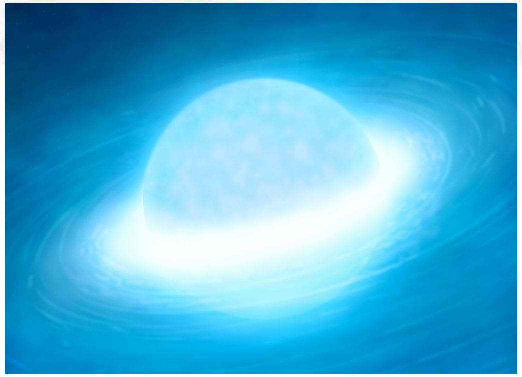
  ➔ Magnetic accretion ➔ M/R determination
- Heating and cooling of neutron stars due to the accretion of matter
  - Study physical processes in the core and crust

Non-magnetic accretion

- Boundary layer
  - – Unknown geometry







- One can prove
  - – See Frank, King and Raine (FKR)

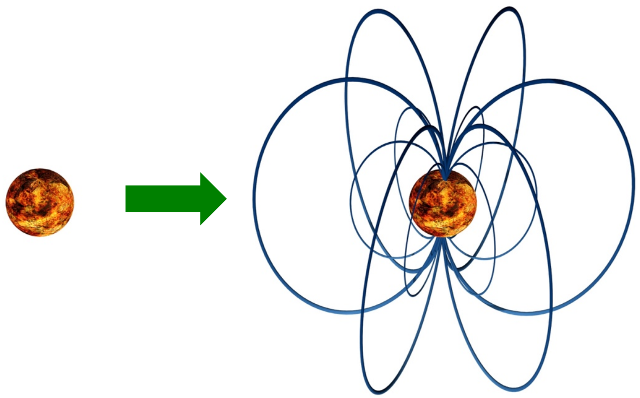
$$L_{BL} = \frac{GM\dot{m}}{2R}\left[1-\frac{\Omega_*}{\Omega_K}\right]^2 \Rightarrow L_{BL} = \frac{GM\dot{m}}{2R} = \frac{1}{2}L_{acc} \quad \text{if } \Omega_* << \Omega_K$$

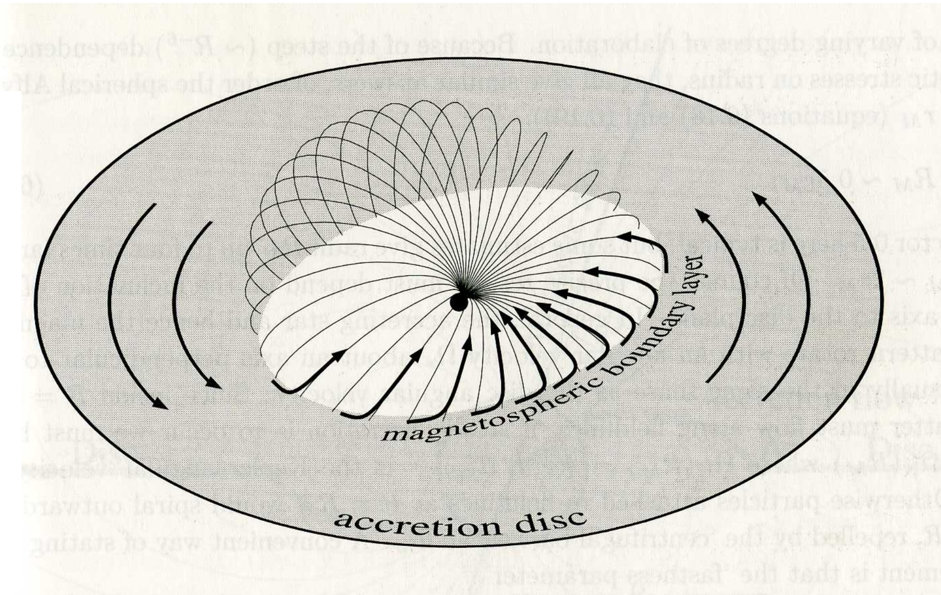
Magnetic accretion

- Most if not nearly all neutron stars will have a relevant magnetic fields
  - Although the range is large: 10^7-10^{13} Gauss
- Very complex to determine how exactly magnetic accretion occurs
  - Also relevant for other type of objects
    - White dwarfs, YSOs
- Neutron star information
- Basic concepts in magnetic accretion

Magnetic accretion

- If accretor has a significant magnetic field, there will be no boundary layer
- Disk is terminated at the magnetospheric boundary





- Disk-field interaction is very complex

Some quantities

- Magnetic moment $\mu = R^3 B$ so that $B \sim \mu/r^3$
- Magnetic pressure (cgs units):

$$P_{mag} = \frac{B^2}{8\pi} = \frac{\mu^2}{8\pi r^6}$$

Very steep dependence on *r*!

- Matter pressure (which is the ram + the gas pressure) $= \rho v^2 + \rho c_s^2 \approx \rho v^2$ for highly supersonic flows

Magnetospheric radius

- Magnetospheric radius is the radius at which the magnetic pressure equals the matter pressure
  - Thus the radius below which the magnetic field dominates the accretion flow (also called the Alfvén radius)
  - Since gas pressure << ram pressure, magnetic pressure = ram pressure

$$P_{mag}\left(r_M\right) = \rho \upsilon^2\Big|_{r_M} \Rightarrow \frac{\mu^2}{8\pi r_M^6} = \frac{\sqrt{2GM}\dot{m}}{4\pi r_M^{5/2}} \Rightarrow$$

$$r_M = 5.1\times 10^8 \dot{m}_{16}^{-2/7} m_1^{-1/7} \mu_{30}^{4/7} \ \text{cm} \Rightarrow$$

$$r_M = 2.9\times 10^8 m_1^{1/7} R_6^{-2/7} L_{37}^{-2/7} \mu_{30}^{4/7} \ \text{cm}$$

FKR

Note for $B = 10^{12}$ G and $R = 10^6$ cm, $\mu_{30} = 1$

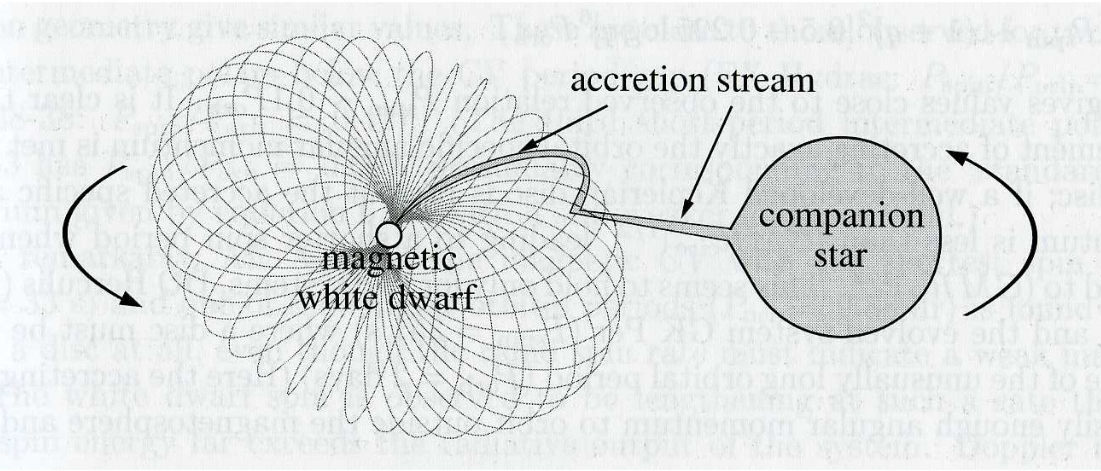
Disk accretion

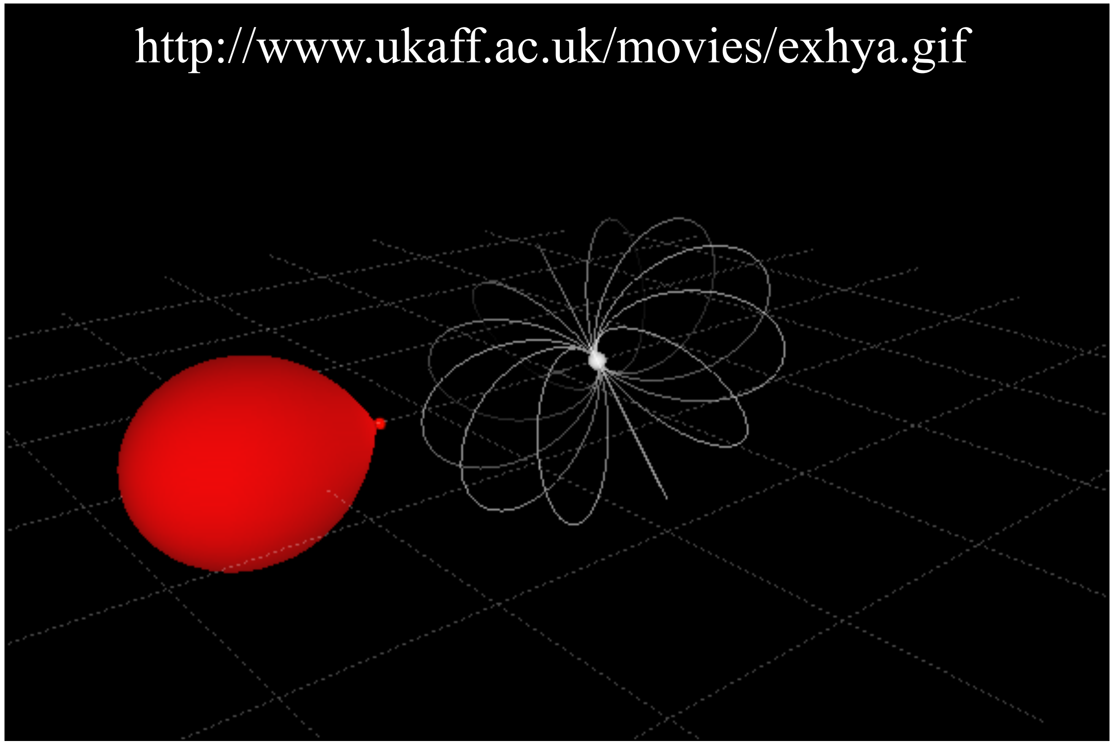
- At which radius R_M will the disk be disrupted by the field?
  - Very difficult problem to solve
  - Depends on
    - Configuration of B field
      - Is it dipole or not? How much distorted by the disk?
    - Inclination between B axis and rotation axis
- Typically $R_M \sim 0.5 r_M$, but other estimates suggest $R_M \sim 2 r_M$
- Inside $r = R_M$ the matter follows the field lines

How large is R_M?

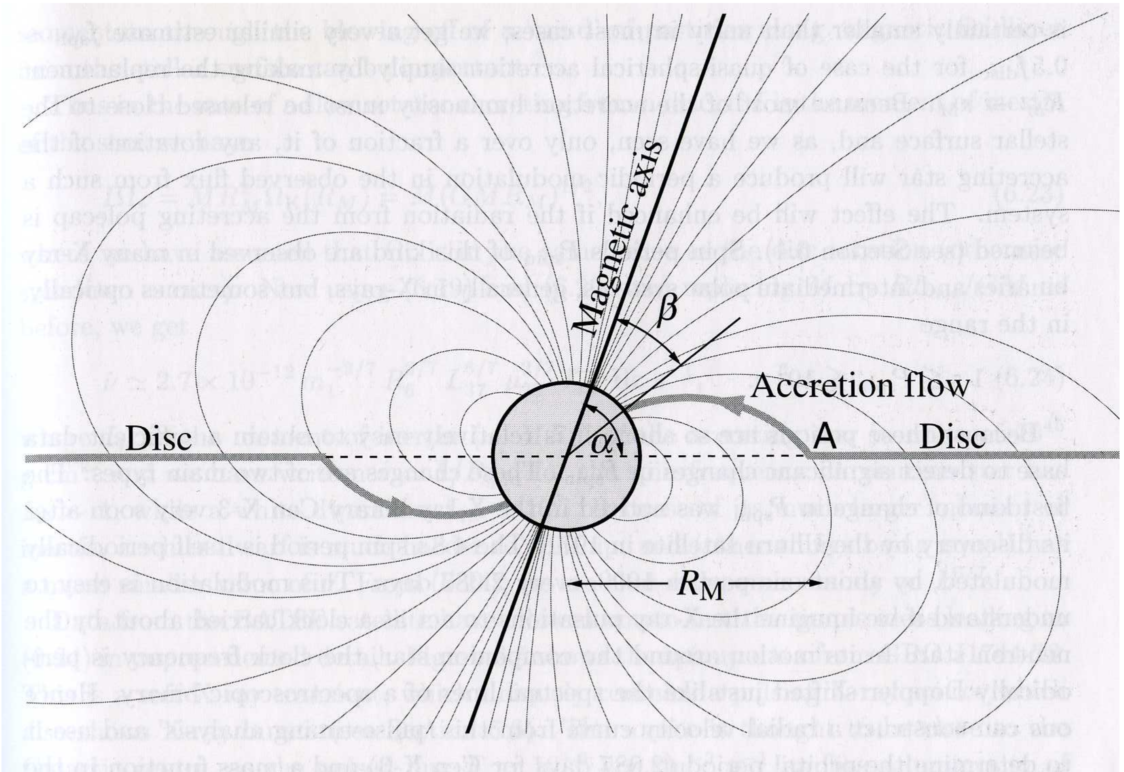
- For typical neutron star $R_M \sim 10^8$ cm >> $R_{NS} \sim 10^6$ cm
  - Thus R_M nearly always outside the star unless $B < 10^{7\text{-}8}$ G
    - In most case, accretion will be controlled by the field when coming close to the neutron star
  - Also, typically $R_M << R_{circ} \sim 10^{9\text{-}10}$ cm
    - Disk formation is not affected by the magnetic field in Roche-lobe overflow systems
      - In some white dwarf systems no disk is formed
    - For wind-accreting systems this is not so simple
      - We will focus on disk accreting systems

Polars = high B field WD





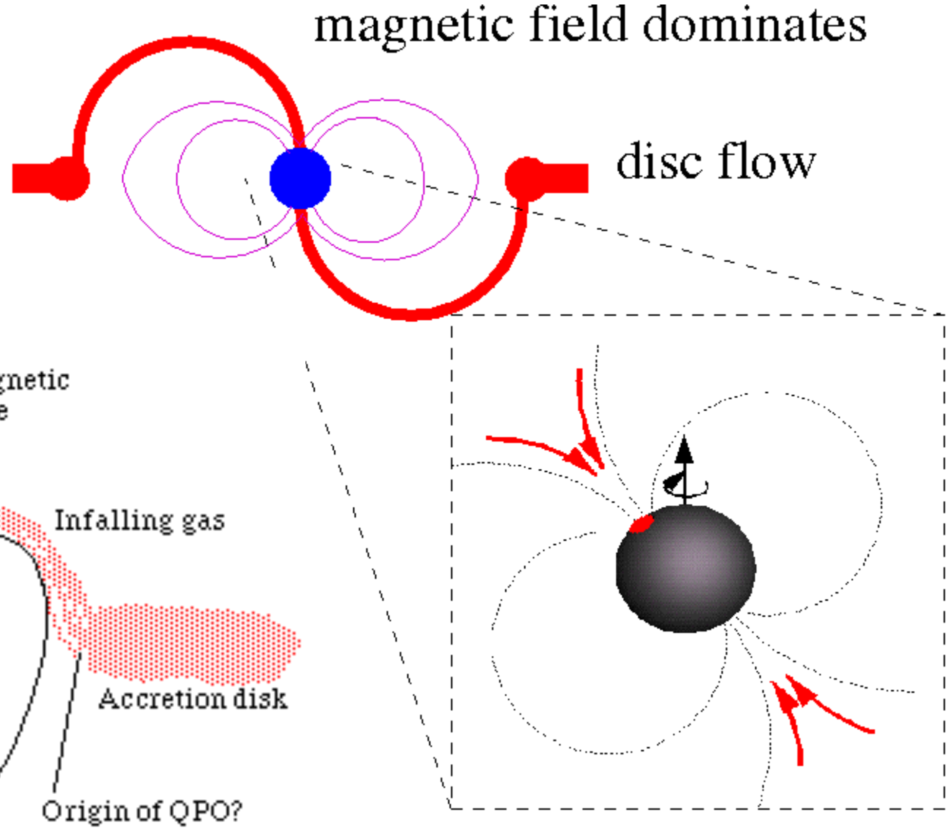
Accretion flow geometry

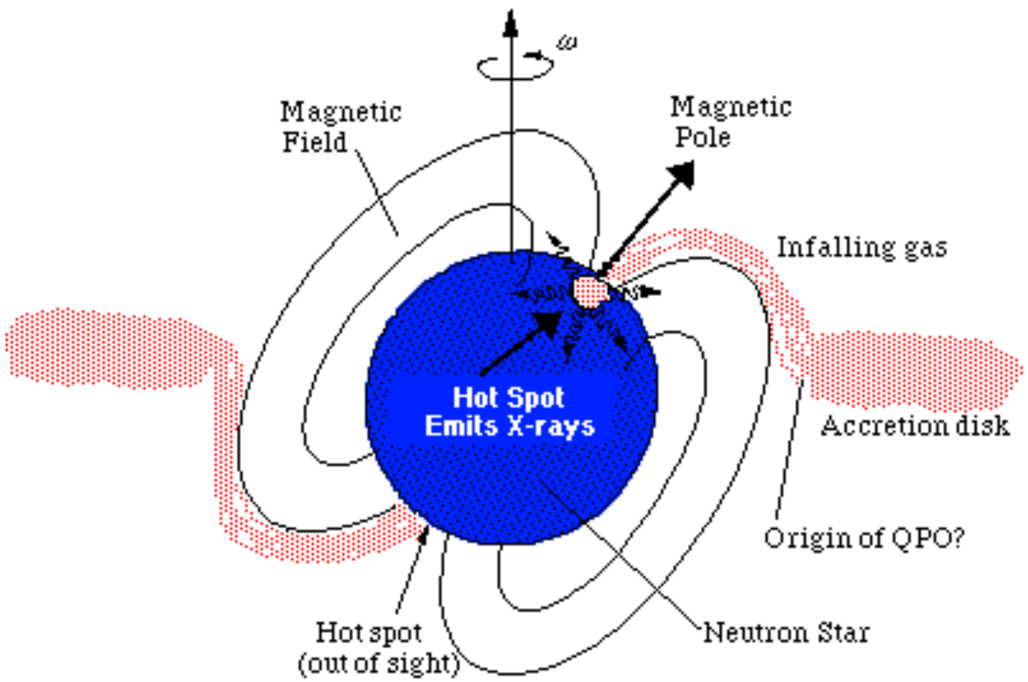


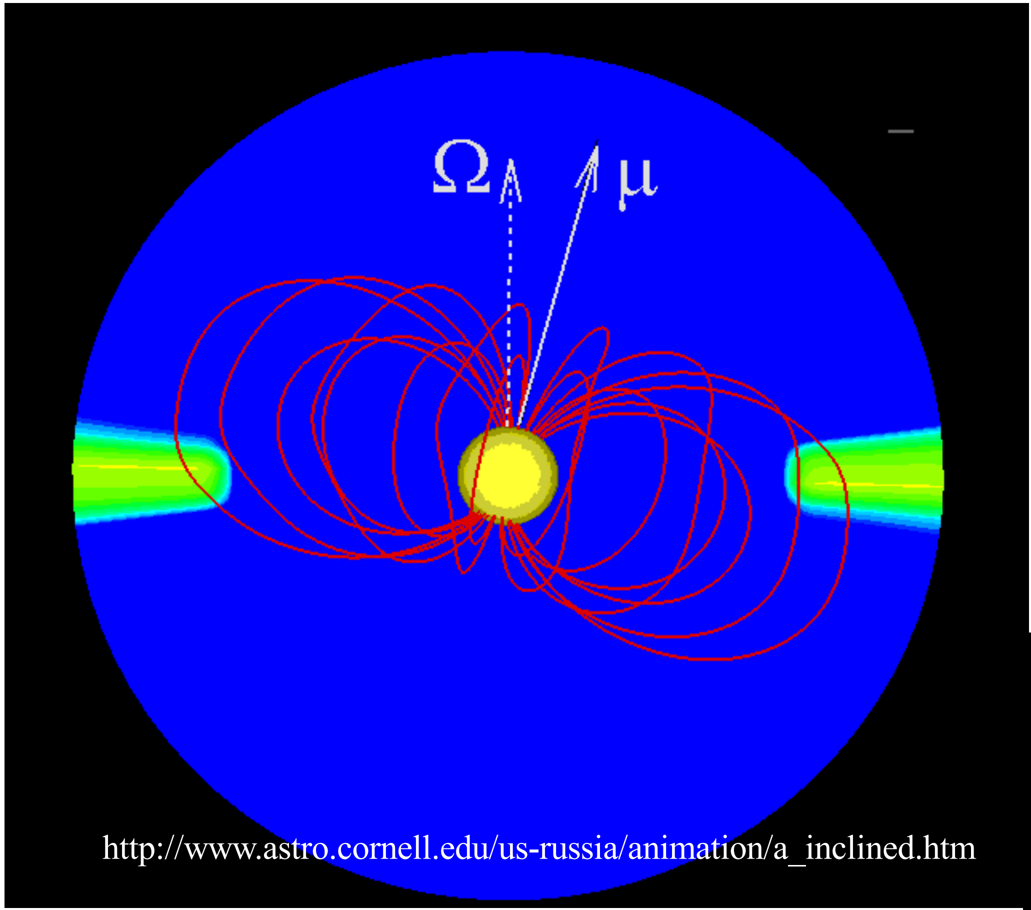
- Accretion can only occur at the polar caps, thus within β
  - All matter will be channeled to polar caps at $r = R_M$ at point A
  - Typically only a fraction of the surface receives matter

Observational effects

- Pulsations!
  - Often in X-rays, but also in optical
  - $1 \text{ ms} < P_{spin} < 10^4 \text{ s}$

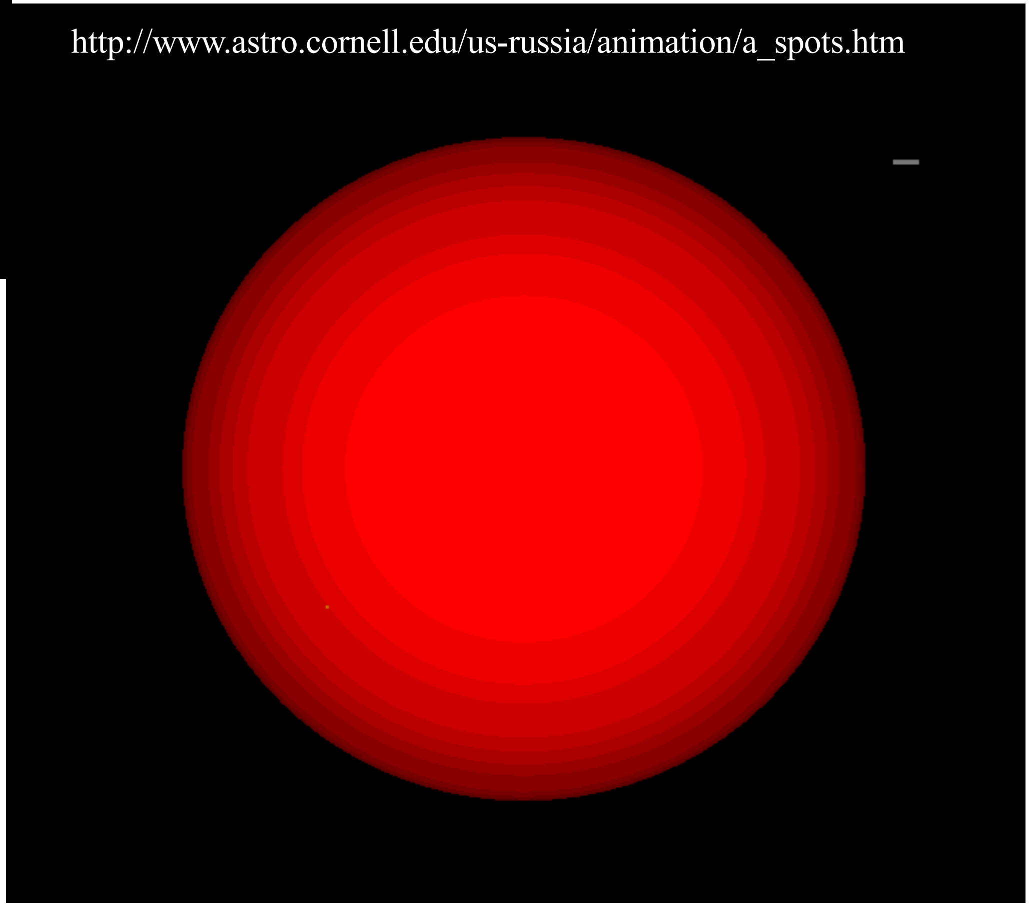






From Romanov et al.

http://www.astro.cornell.edu/~romanova/
http://www.astro.cornell.edu/us-russia/

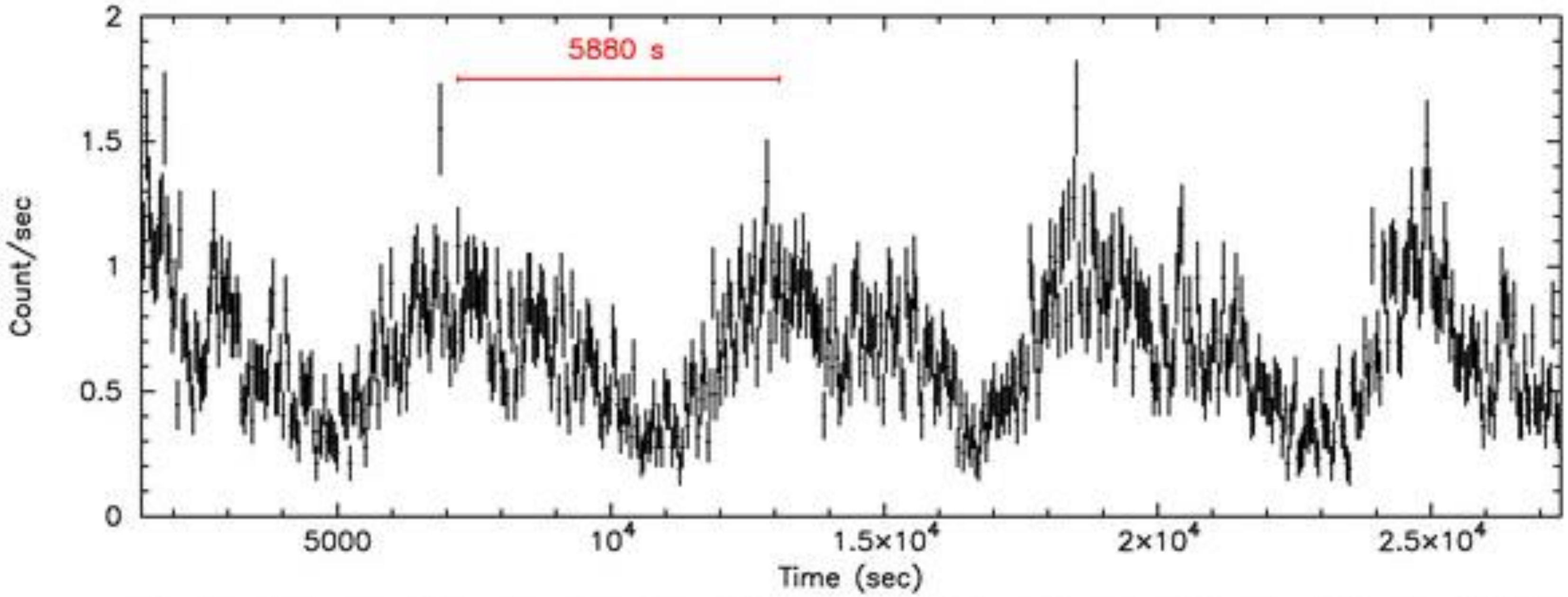


Θ = angle between magnetic field axis and rotation axis

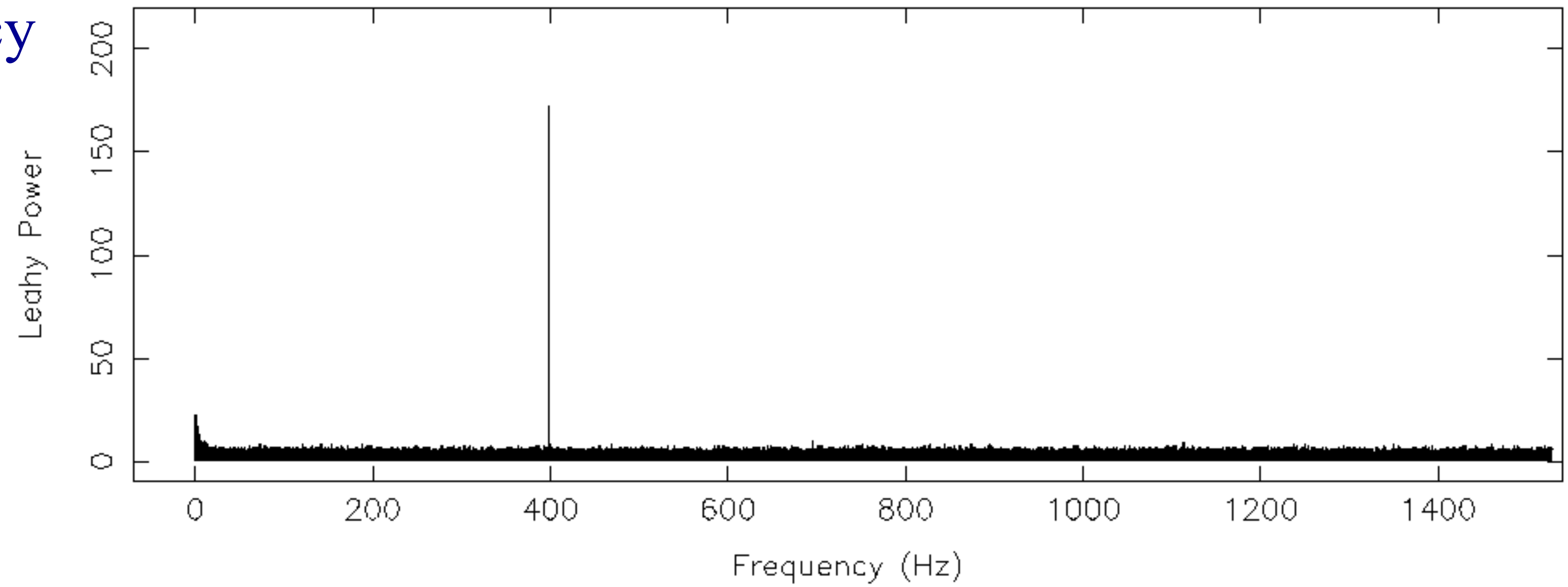
Hotspot

Pulsations

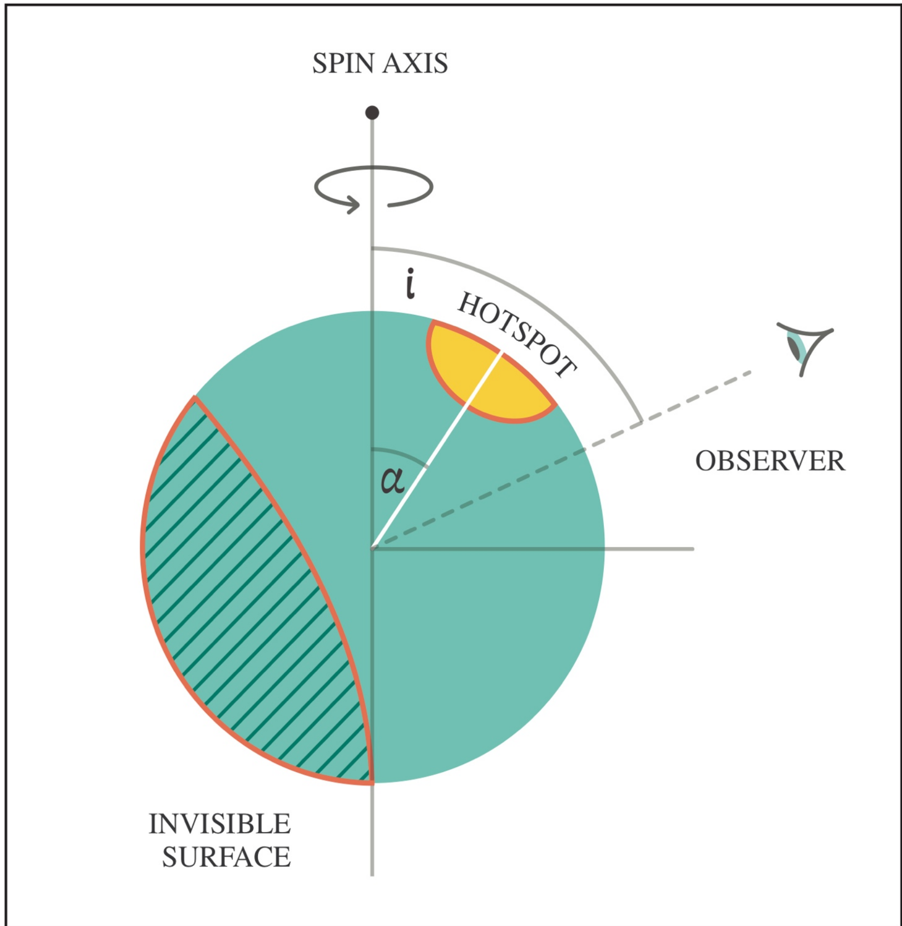
Time domain

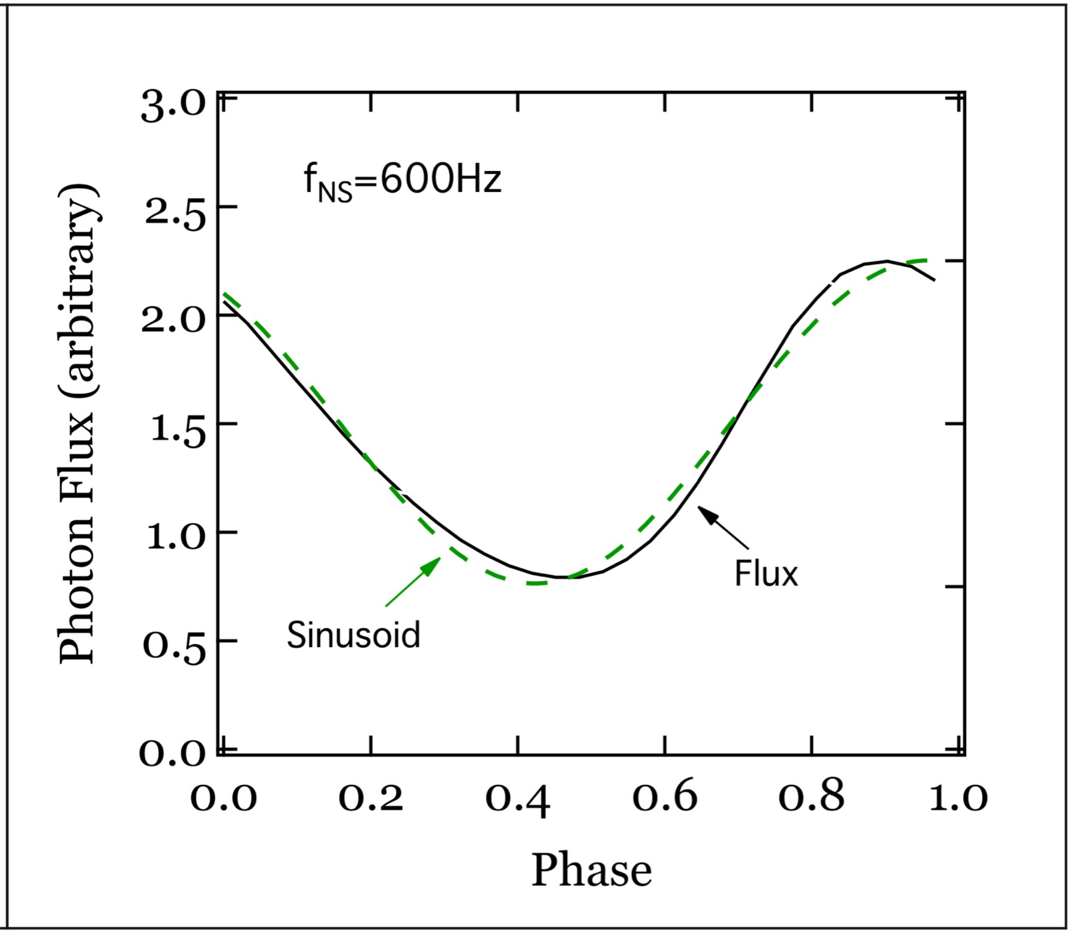


Frequency domain

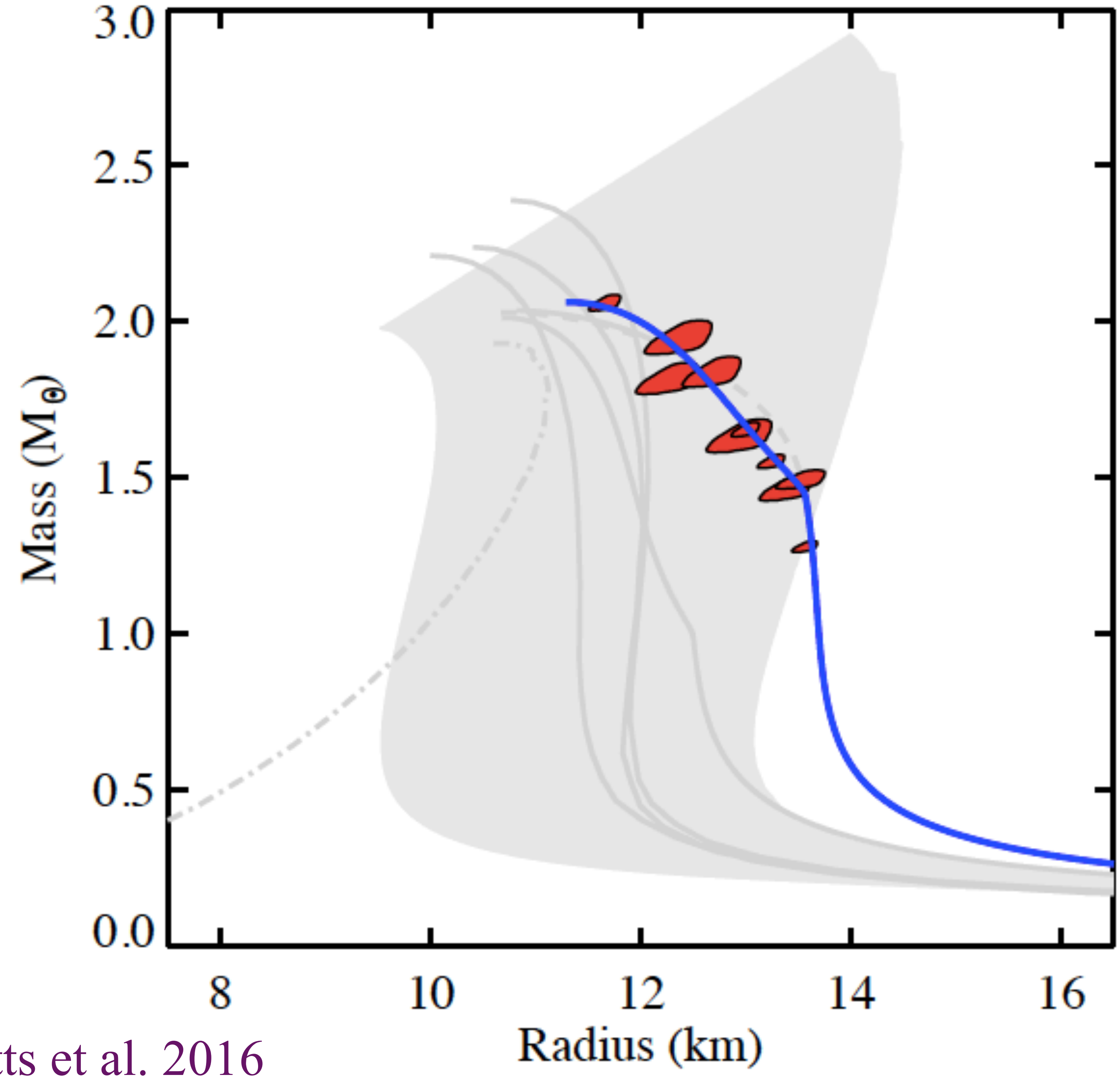


Pulse profile modelling



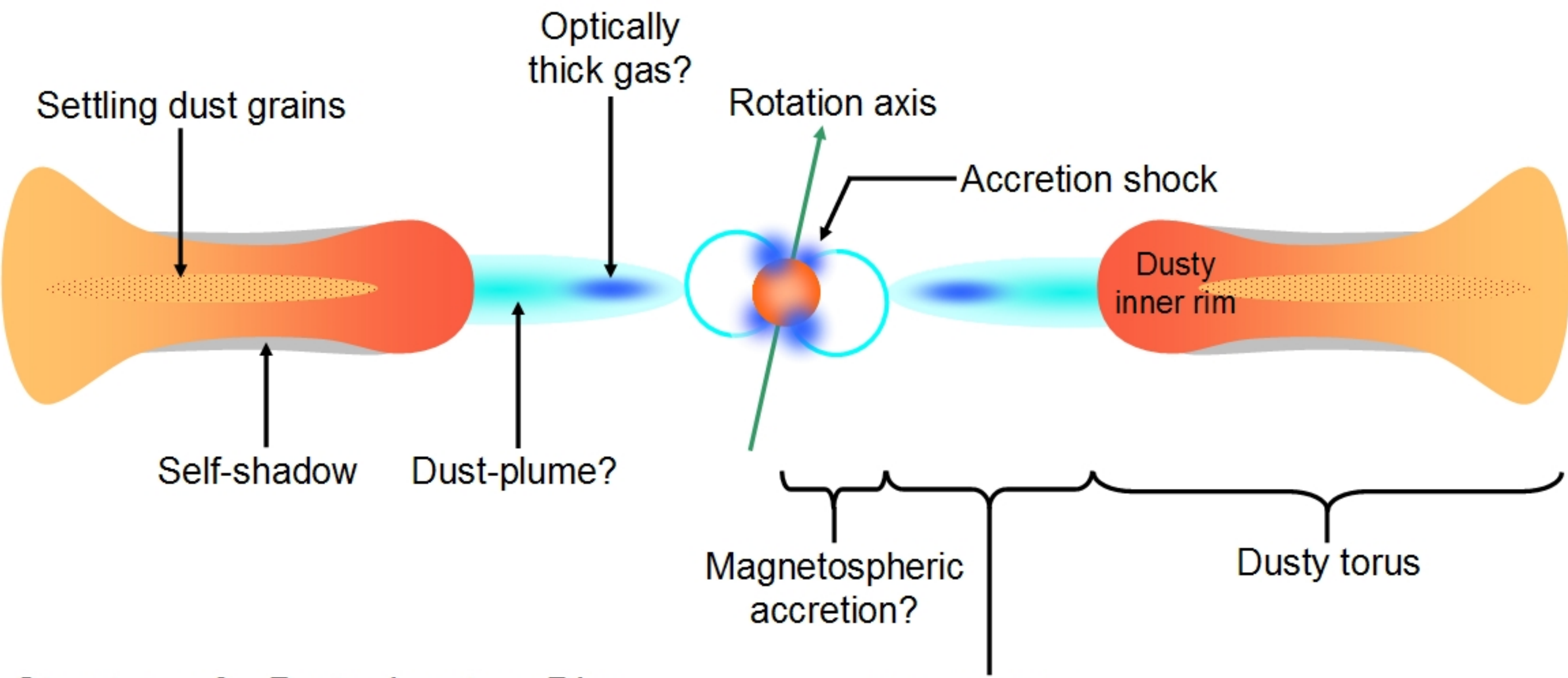


Psaltis et al. 2014; Watts et al. 2016

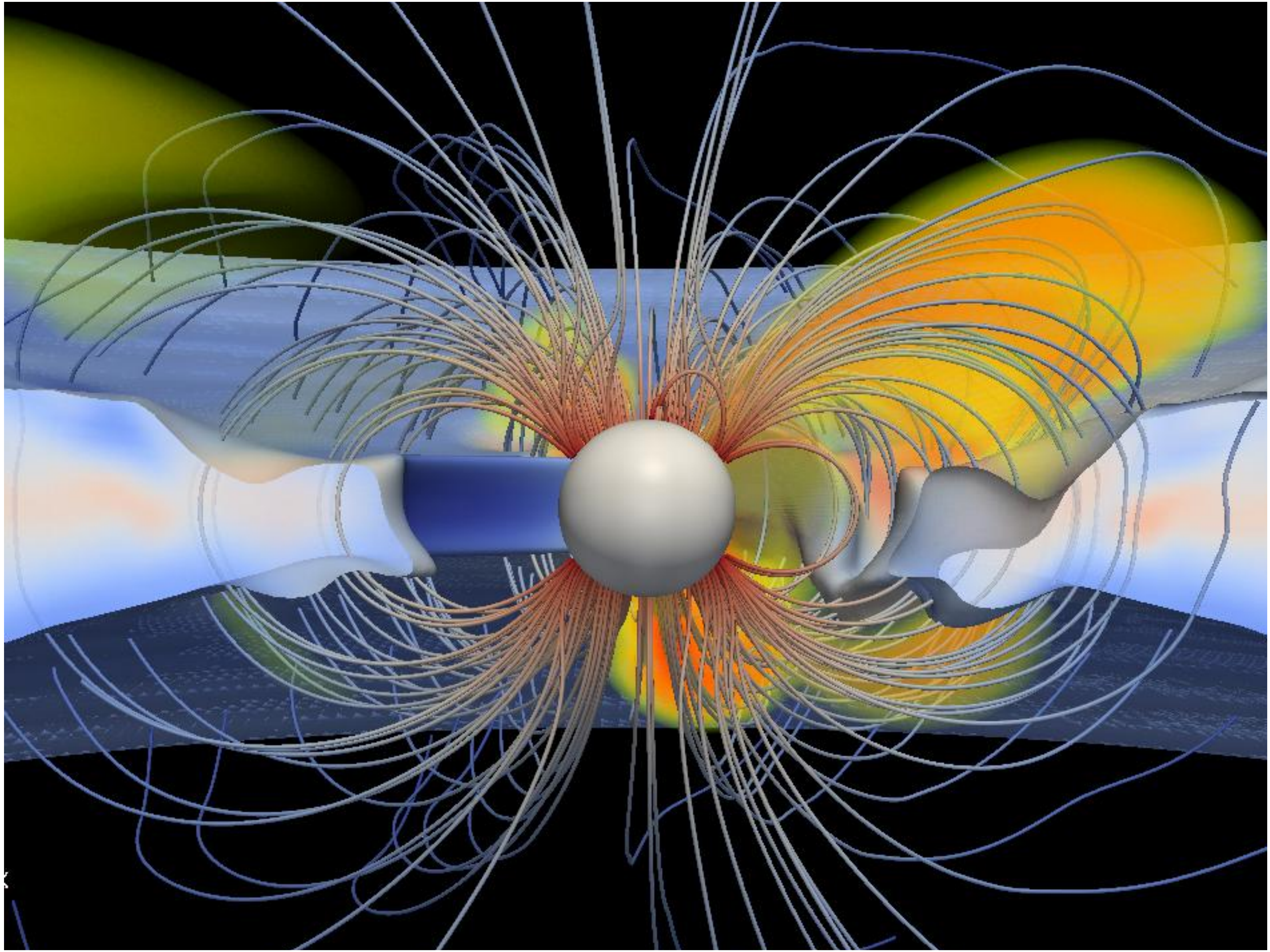


Watts et al. 2016

Also relevant to YSOs



Structure of a Protoplanetary Disc



Heating and cooling of accreting neutron stars

- Neutron stars are old & very cold when accretion starts
- A lot of energy is dumped on the neutron star
  - Release of gravitational energy (200 MeV/nucleon)
  - Thermonuclear reactions (1-5 MeV/nucleon)
  - Reactions in the deep crust (100's of meters)
    - *Electron caption, neutron emission, pycnonuclear reactions*
    - *1-2 MeV/nucleon*
- Will that heat up the neutron star?
- Can we observe that?
  - Yes! Cooling neutron stars in X-ray transients

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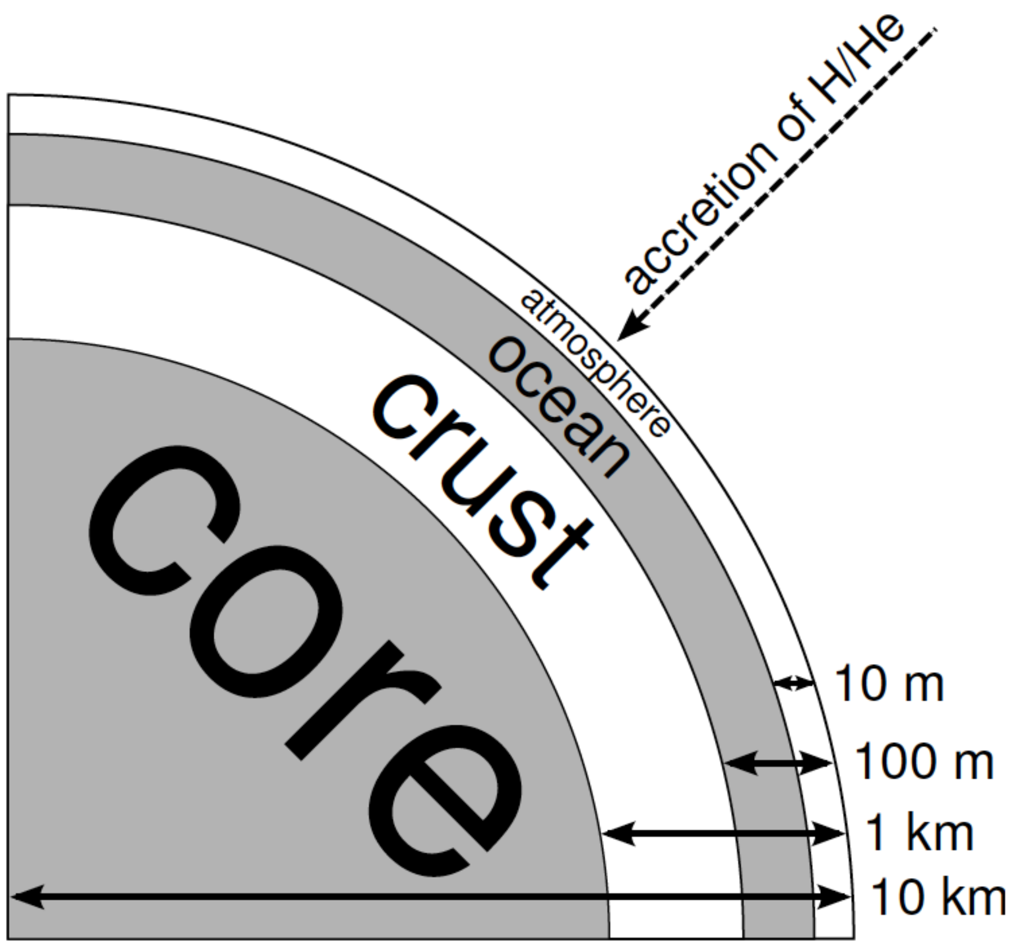
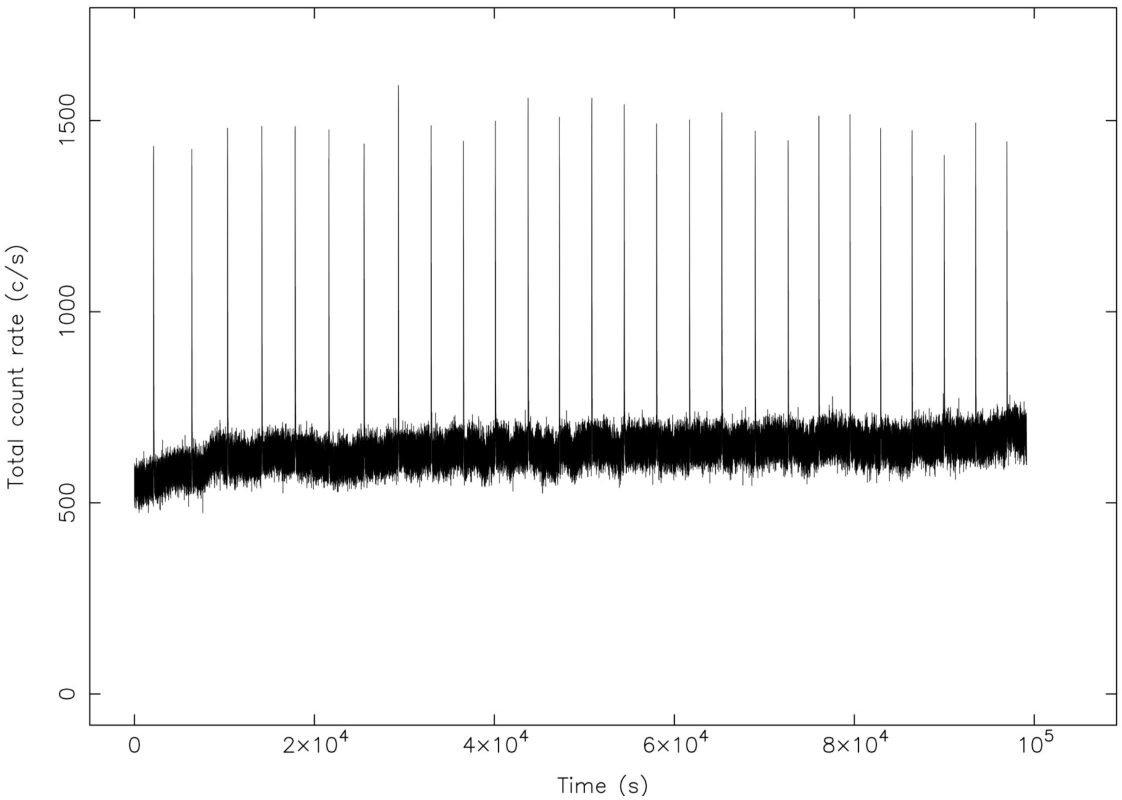
Igniting a thermonuclear burst

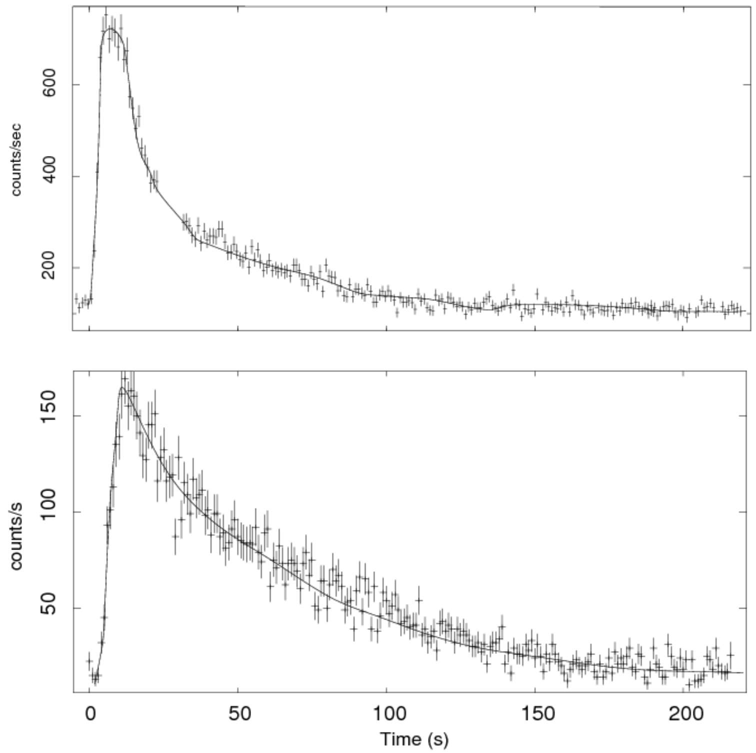


- Accreting H and He
- For Mdot > 1% Eddington, H burns stably on the surface
  - Layer of He produced
- After hours to days, pressure has build up sufficiently to allow unstable He burning → thermonuclear X-ray burst
  - Type-I X-ray burst
- A lot of nuclear physics involved

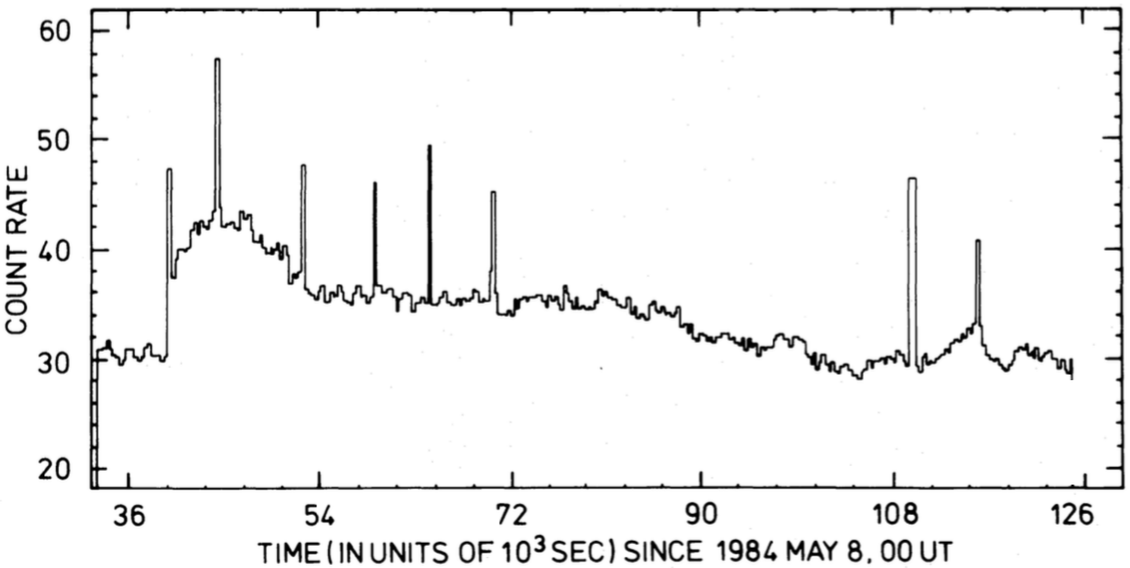
After slides by Nathalie Degenaar, Jean in ‘t Zand, Andrew Cumming



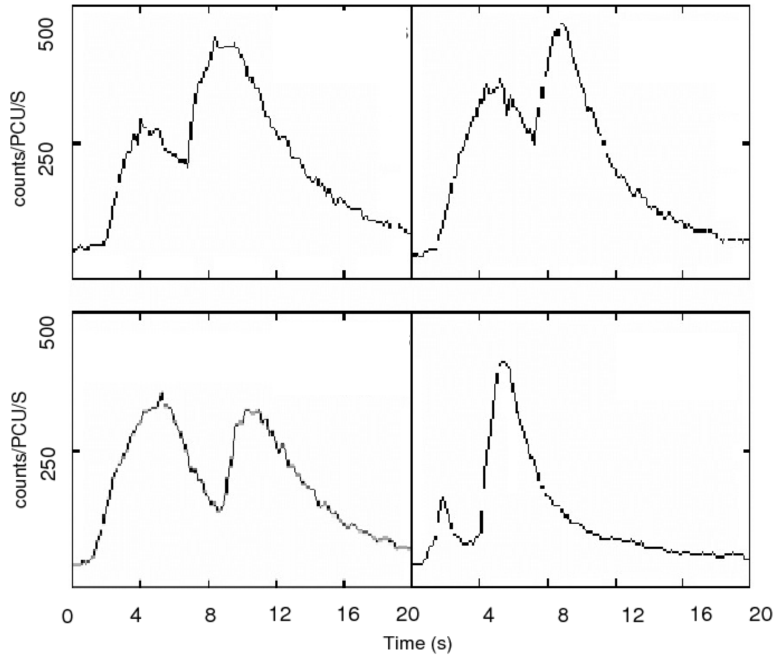
Total count rate (c/s)
0
500
1000
1500
0
2×10^4
4×10^4
6×10^4
8×10^4
10^5
Time (s)



counts/sec
200
400
600
counts/s
50
100
150
0
50
100
150
200
Time (s)



COUNT RATE
20
30
40
50
60
36
54
72
90
108
126
TIME (IN UNITS OF 10^3 SEC) SINCE 1984 MAY 8, 00 UT



counts/PCU/S
250
500
counts/PCU/S
250
500
0
4
8
12
16
20
4
8
12
16
20
Time (s)

http://www.nasa.gov/centers/goddard/mpeg/*97911main_Puff.0539.mpeg*

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Reheating of accreting neutron stars

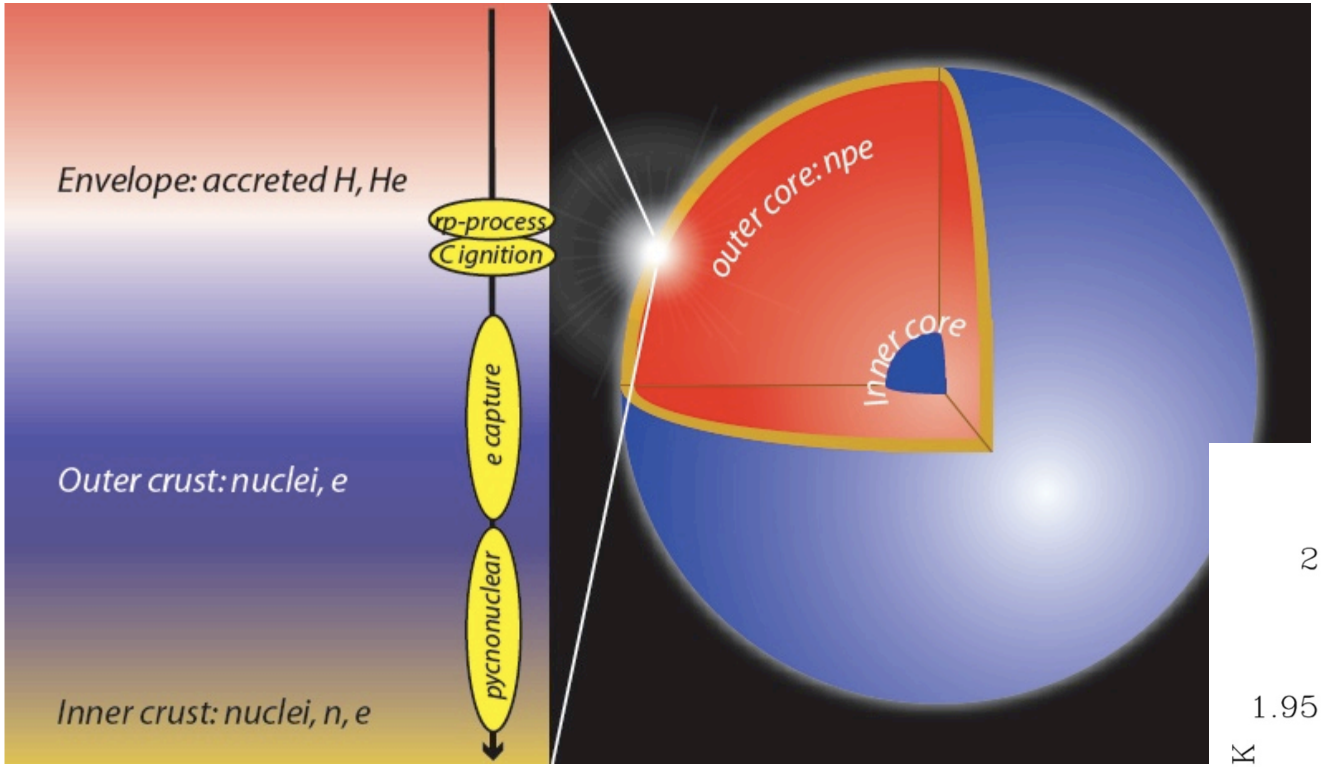
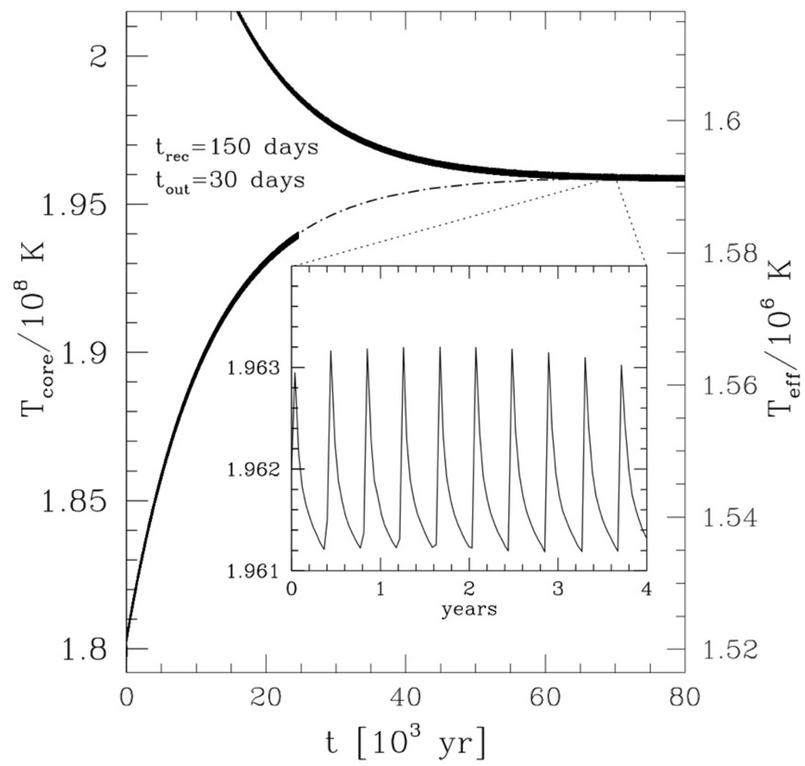


Figure provided by Ed Brown

Colpi et al. 2001



Heating mostly due to pycnonuclear reactions: about 1-2 MeV/nucleon

When accretion stops we can see the cooling emission from the surface

Crustal reactions

P (dyn cm^{-2})	ρ (g cm^{-3})	reactions	X_n	$\Delta\rho/\rho$ %	q (keV)
9.235×10^{25}	3.517×10^{08}	$^{106}\mathrm{Pd} \rightarrow {}^{106}\mathrm{Ru} - 2e^- + 2\nu_e$	0	4.4	5.7
3.603×10^{27}	5.621×10^{09}	$^{106}\mathrm{Ru} \rightarrow {}^{106}\mathrm{Mo} - 2e^- + 2\nu_e$	0	4.6	5.7
2.372×10^{28}	2.413×10^{10}	$^{106}\mathrm{Mo} \rightarrow {}^{106}\mathrm{Zr} - 2e^- + 2\nu_e$	0	4.9	5.6
8.581×10^{28}	6.639×10^{10}	$^{106}\mathrm{Zr} \rightarrow {}^{106}\mathrm{Sr} - 2e^- + 2\nu_e$	0	5.1	5.6
2.283×10^{29}	1.455×10^{11}	$^{106}\mathrm{Sr} \rightarrow {}^{106}\mathrm{Kr} - 2e^- + 2\nu_e$	0	5.4	5.5
5.025×10^{29}	2.774×10^{11}	$^{106}\mathrm{Kr} \rightarrow {}^{106}\mathrm{Se} - 2e^- + 2\nu_e$	0	5.7	5.5
9.713×10^{29}	4.811×10^{11}	$^{106}\mathrm{Se} \rightarrow {}^{106}\mathrm{Ge} - 2e^- + 2\nu_e$	0	6.1	5.5
1.703×10^{30}	7.785×10^{11}	$^{106}\mathrm{Ge} \rightarrow {}^{92}\mathrm{Ni} + 14n - 4e^- + 4\nu_e$	0.13	13.2	77.6
1.748×10^{30}	8.989×10^{11}	$^{92}\mathrm{Ni} \rightarrow {}^{86}\mathrm{Fe} + 6n2e^- + 2\nu_e$	0.19	6.9	39.2
1.924×10^{30}	1.032×10^{12}	$^{86}\mathrm{Fe} \rightarrow {}^{80}\mathrm{Cr} + 6n2e^- + 2\nu_e$	0.25	7.3	43.1
2.135×10^{30}	1.197×10^{12}	$^{80}\mathrm{Cr} \rightarrow {}^{74}\mathrm{Ti} + 6n2e^- + 2$[illegible]	[illegible]	[illegible]	[illegible]
2.394×10^{30}	1.403×10^{12}	$^{74}\mathrm{Ti} \rightarrow {}^{68}\mathrm{Ca} + 6n2e^- + 2$[illegible]	[illegible]	[illegible]	[illegible]
2.720×10^{30}	1.668×10^{12}	$^{68}\mathrm{Ca} \rightarrow {}^{62}\mathrm{Ar} + 6n2e^- + 2\nu_e$	0.42	8.5	57.7
3.145×10^{30}	2.016×10^{12}	$^{62}\mathrm{Ar} \rightarrow {}^{56}\mathrm{S} + 6n2e^- + 2\nu_e$	0.47	9.0	63.7
3.723×10^{30}	2.488×10^{12}	$^{56}\mathrm{S} \rightarrow {}^{50}\mathrm{Si} + 6n2e^- + 2\nu_e$	0.53	9.4	70.5
4.549×10^{30}	3.153×10^{12}	$^{50}\mathrm{Si} \rightarrow {}^{42}\mathrm{Mg} + 8n2e^- + 2\nu_e$	0.61	8.8	79.0
4.624×10^{30}	3.472×10^{12}	$^{42}\mathrm{Mg} \rightarrow {}^{36}\mathrm{Ne} + 6n2e^- + 2\nu_e$			
		$^{36}\mathrm{Ne} + {}^{36}\mathrm{Ne} \rightarrow {}^{72}\mathrm{Ca}$	0.66	10.6	251.8
5.584×10^{30}	4.399×10^{12}	$^{72}\mathrm{Ca} \rightarrow {}^{66}\mathrm{Ar} + 6n2e^- + 2\nu_e$	0.69	4.8	25.3
6.883×10^{30}	5.355×10^{12}	$^{66}\mathrm{Ar} \rightarrow {}^{60}\mathrm{S} + 6n2e^- + 2\nu_e$	0.72	4.7	27.3
8.749×10^{30}	6.655×10^{12}	$^{60}\mathrm{S} \rightarrow {}^{54}\mathrm{Si} + 6n2e^- + 2\nu_e$	0.75	4.6	29.2
1.157×10^{31}	8.487×10^{12}	$^{54}\mathrm{Si} \rightarrow {}^{46}\mathrm{Mg} + 8n2e^- + 2\nu_e$			
		$^{46}\mathrm{Mg} + {}^{46}\mathrm{Mg} \rightarrow {}^{92}\mathrm{Cr}$	0.79	4.0	139.6
1.234×10^{31}	9.242×10^{12}	$^{92}\mathrm{Cr} \rightarrow {}^{86}\mathrm{Ti} + 6n2e^- + 2\nu_e$	0.80	2.0	8.9
1.528×10^{31}	1.096×10^{13}	$^{86}\mathrm{Ti} \rightarrow {}^{80}\mathrm{Ca} + 6n2e^- + 2\nu_e$	0.82	1.9	9.0
1.933×10^{31}	1.317×10^{13}	$^{80}\mathrm{Ca} \rightarrow {}^{74}\mathrm{Ar} + 6n2e^- + 2\nu_e$	0.83	1.8	8.8
2.510×10^{31}	1.609×10^{13}	$^{74}\mathrm{Ar} \rightarrow {}^{68}\mathrm{S} + 6n2e^- + 2\nu_e$	0.85	1.7	10.2
3.363×10^{31}	2.003×10^{13}	$^{68}\mathrm{S} \rightarrow {}^{62}\mathrm{Si} + 6n2e^- + 2\nu_e$			
		$^{62}\mathrm{Si} + {}^{62}\mathrm{Si} \rightarrow {}^{124}\mathrm{Ni}$	0.86	1.7	70.3
4.588×10^{31}	2.520×10^{13}	$^{124}\mathrm{Ni} \rightarrow {}^{120}\mathrm{Fe} + 4n2e^- + 2\nu_e$	0.87	0.8	2.6
5.994×10^{31}	3.044×10^{13}	$^{120}\mathrm{Fe} \rightarrow {}^{118}\mathrm{Cr} + 2n2e^- + 2\nu_e$	0.88	0.9	2.4
8.408×10^{31}	3.844×10^{13}	$^{118}\mathrm{Cr} \rightarrow {}^{116}\mathrm{Ti} + 2n2e^- + 2\nu_e$	0.88	0.8	2.2

e^- capture

neutron emisson

Pycnonuclear reactions

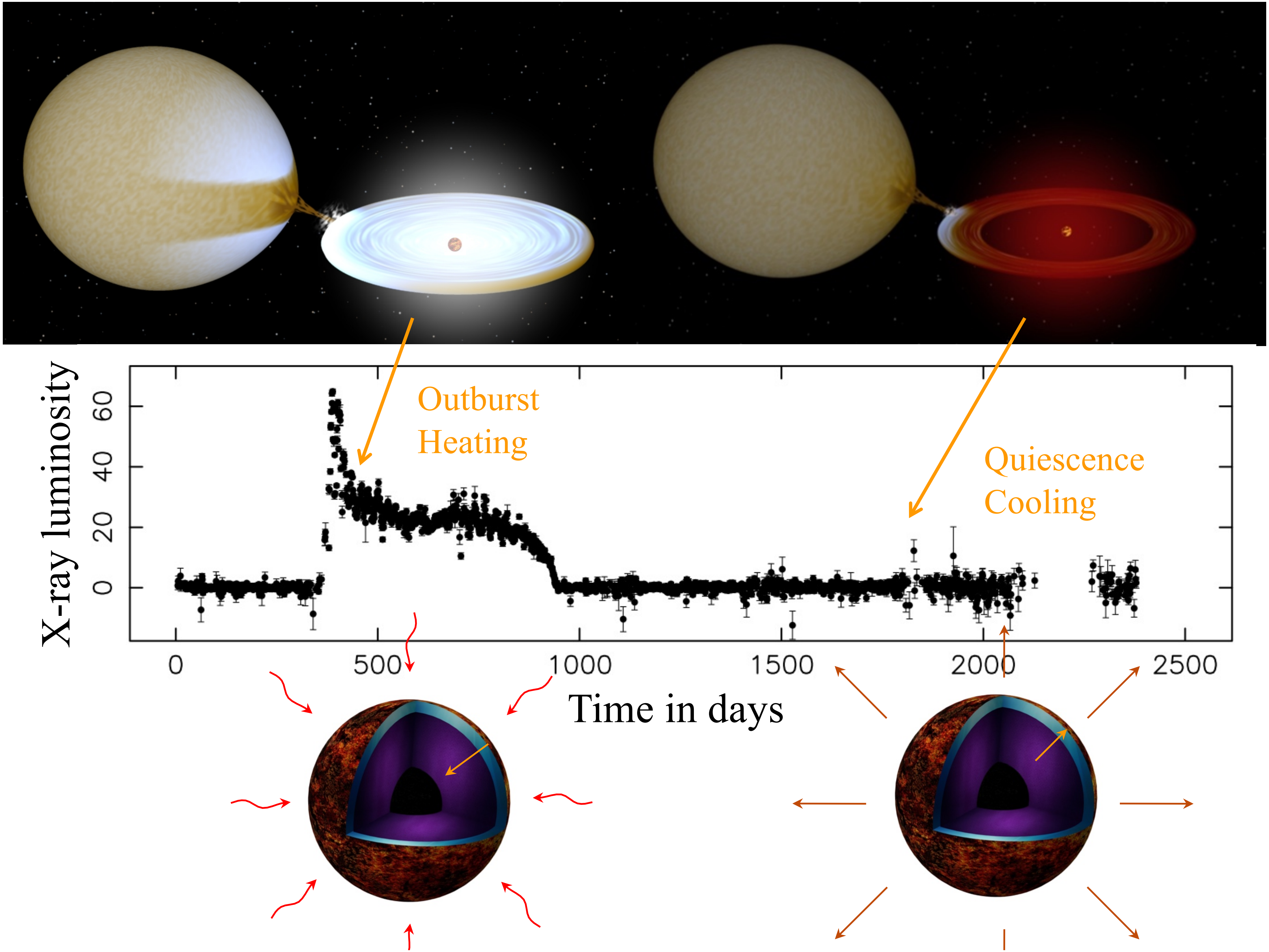
Reaction rate depends on density

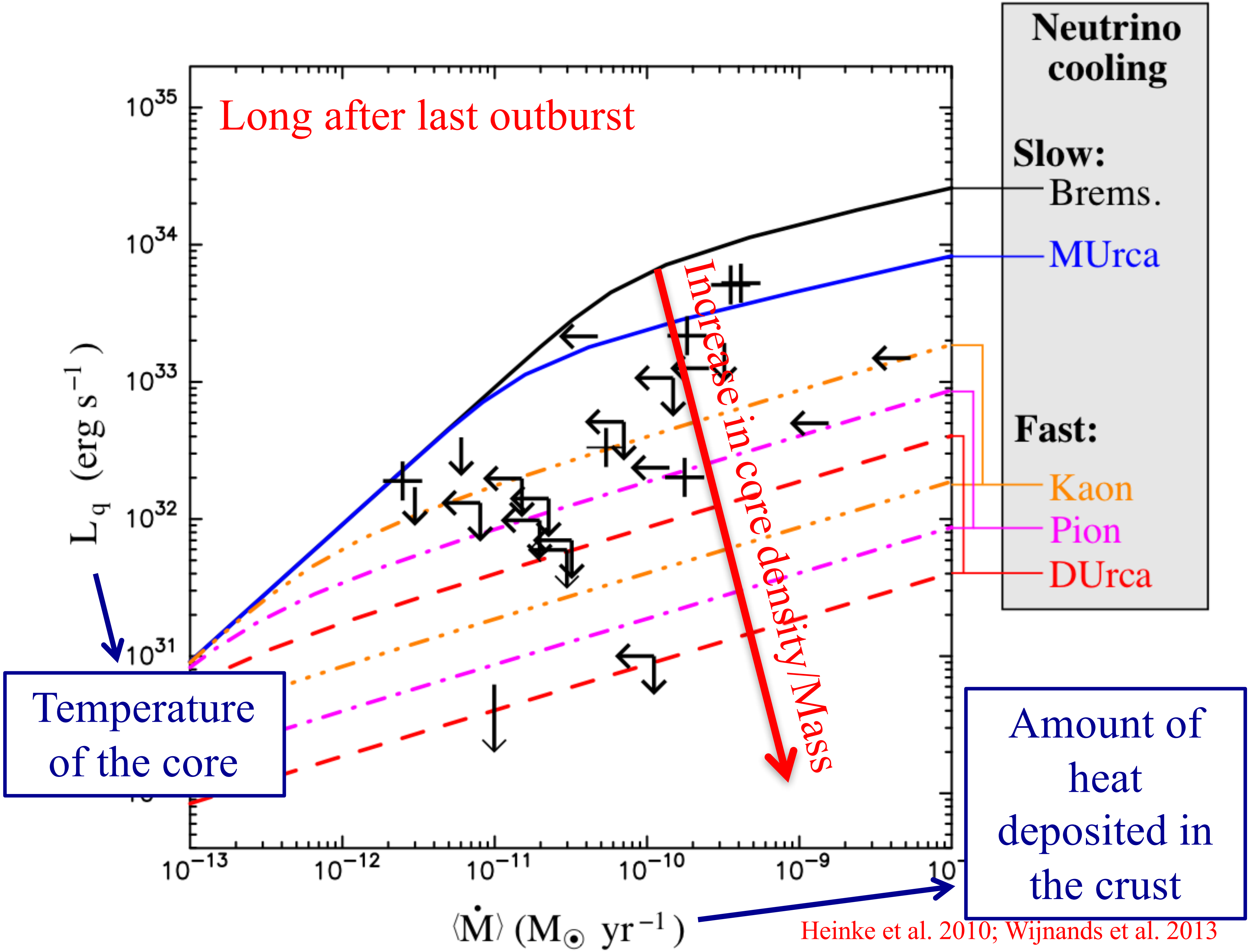
Exact rates and at which density they occur is not fully known

Haensel & Zdunik 2003

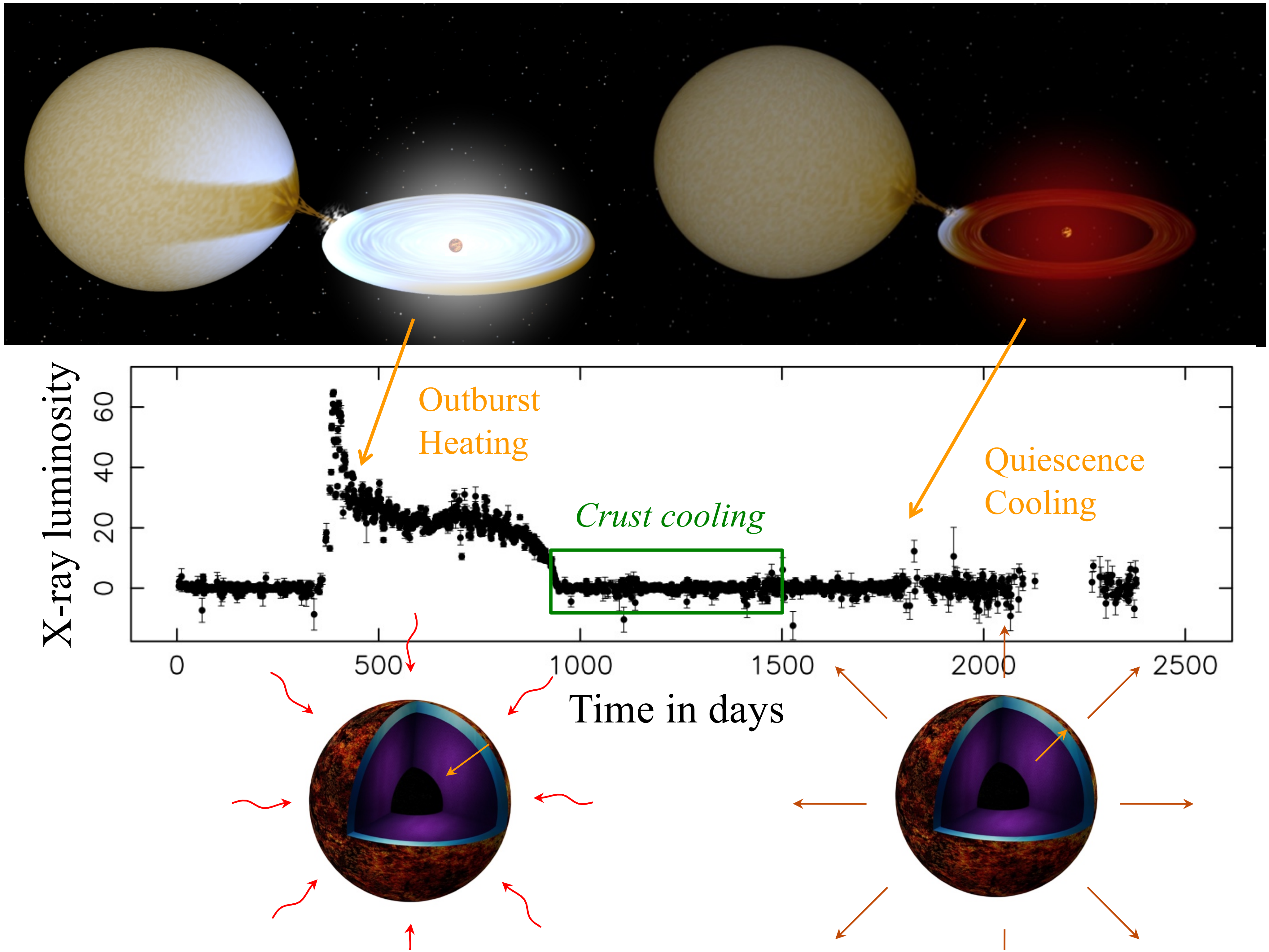
Heating and cooling of accreting neutron stars

- Neutron stars are old & very cold when accretion starts
- A lot of energy is dumped on the neutron star
  - Release of gravitational energy (200 MeV/nucleon)
  - Thermonuclear reactions (1-5 MeV/nucleon)
  - Reactions in the deep crust (100's of meters)
    - *Electron caption, neutron emission, pycnonuclear reactions*
    - *1-2 MeV/nucleon*
- Will that heat up the neutron star?
- Can we observe that?
  - Yes! Cooling neutron stars in X-ray transients


Outburst
Heating
Quiescence
Cooling
X-ray luminosity
0
20
40
60
0
500
1000
1500
2000
2500
Time in days

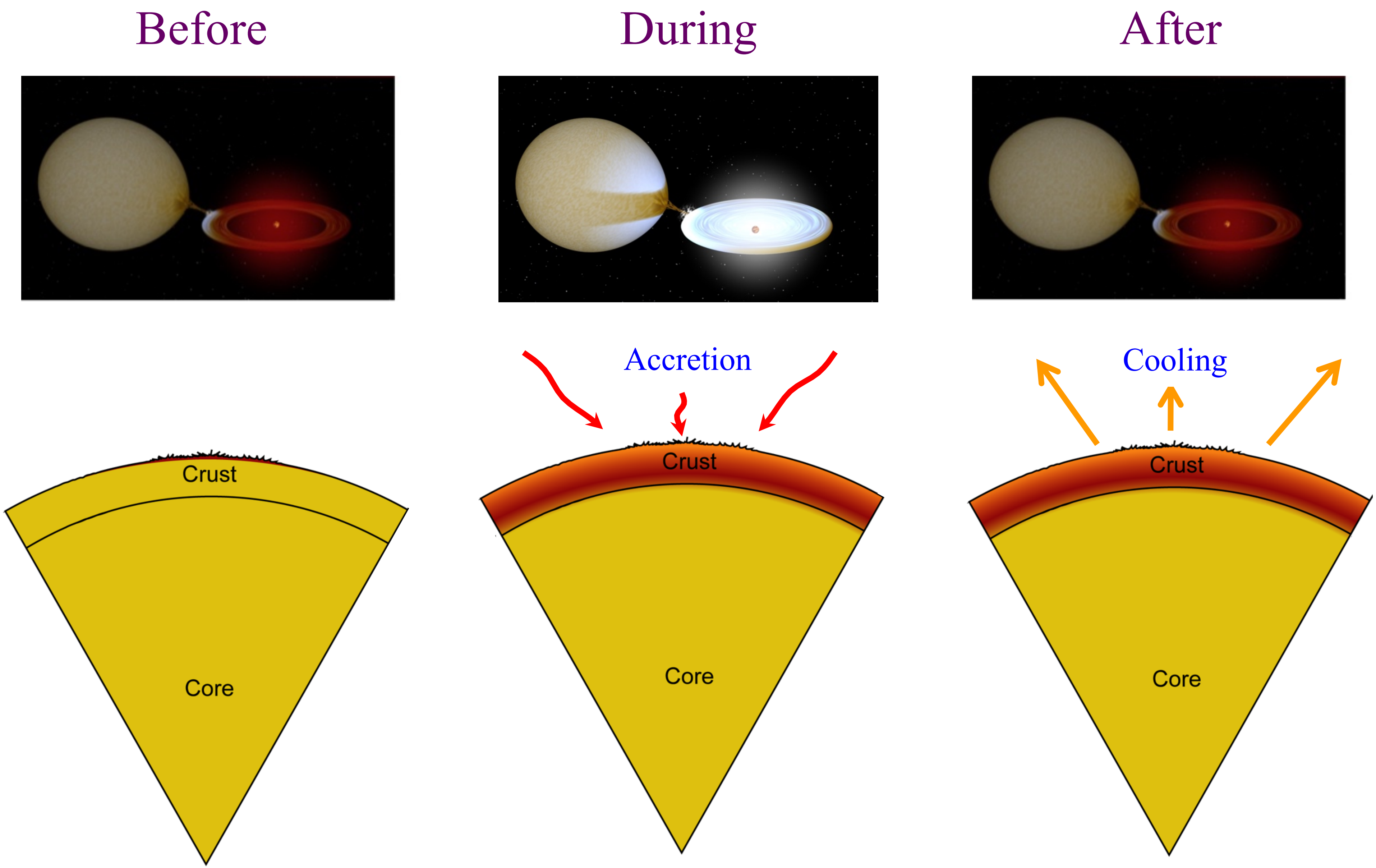


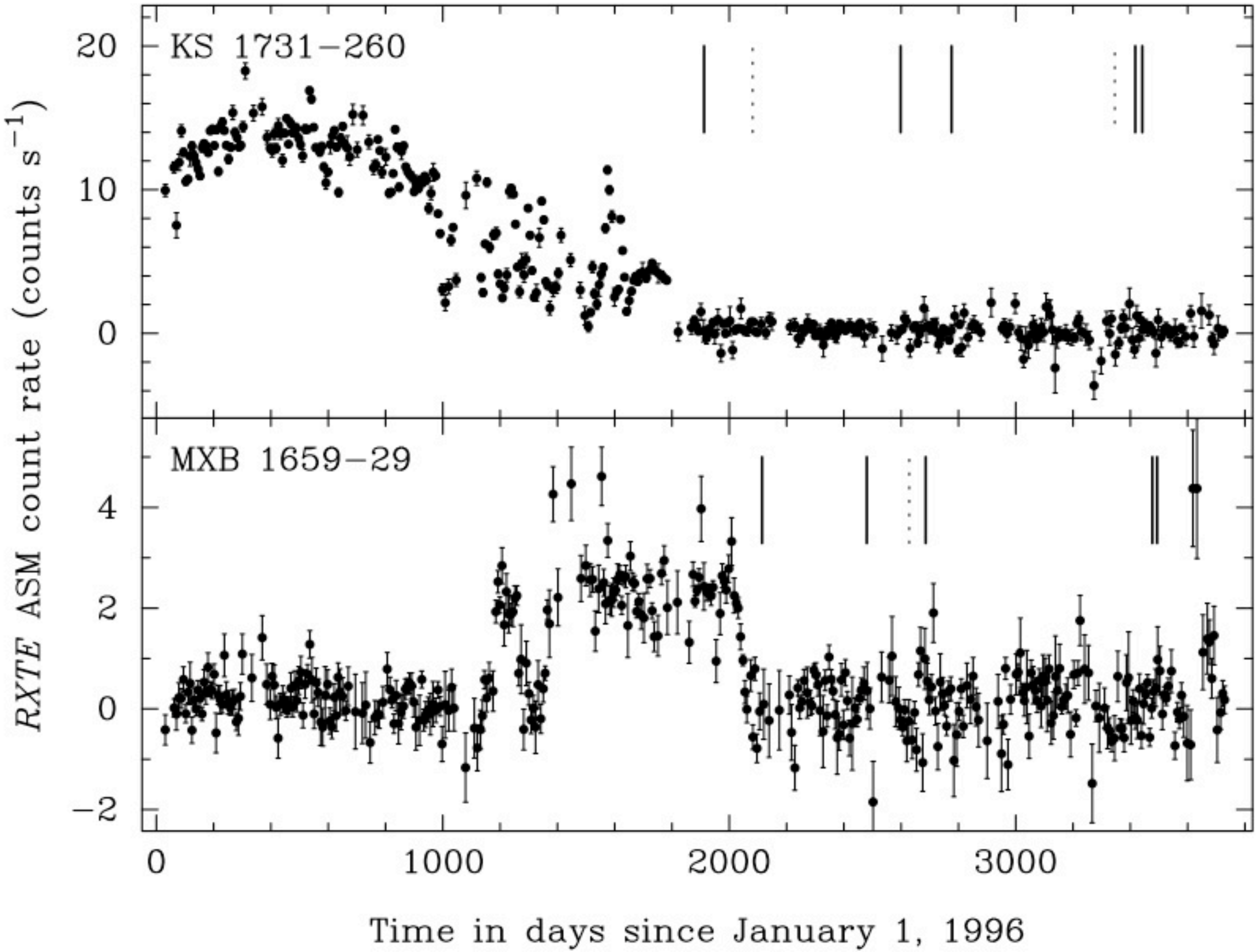
Neutrino cooling
Slow:
Brems.
MUrca
Fast:
Kaon
Pion
DUrca
Long after last outburst
Increase in core density/Mass
L_q (erg s^{-1})
$\langle\dot{M}\rangle$ ($M_\odot$ yr^{-1})
Temperature of the core
Amount of heat deposited in the crust
Heinke et al. 2010; Wijnands et al. 2013



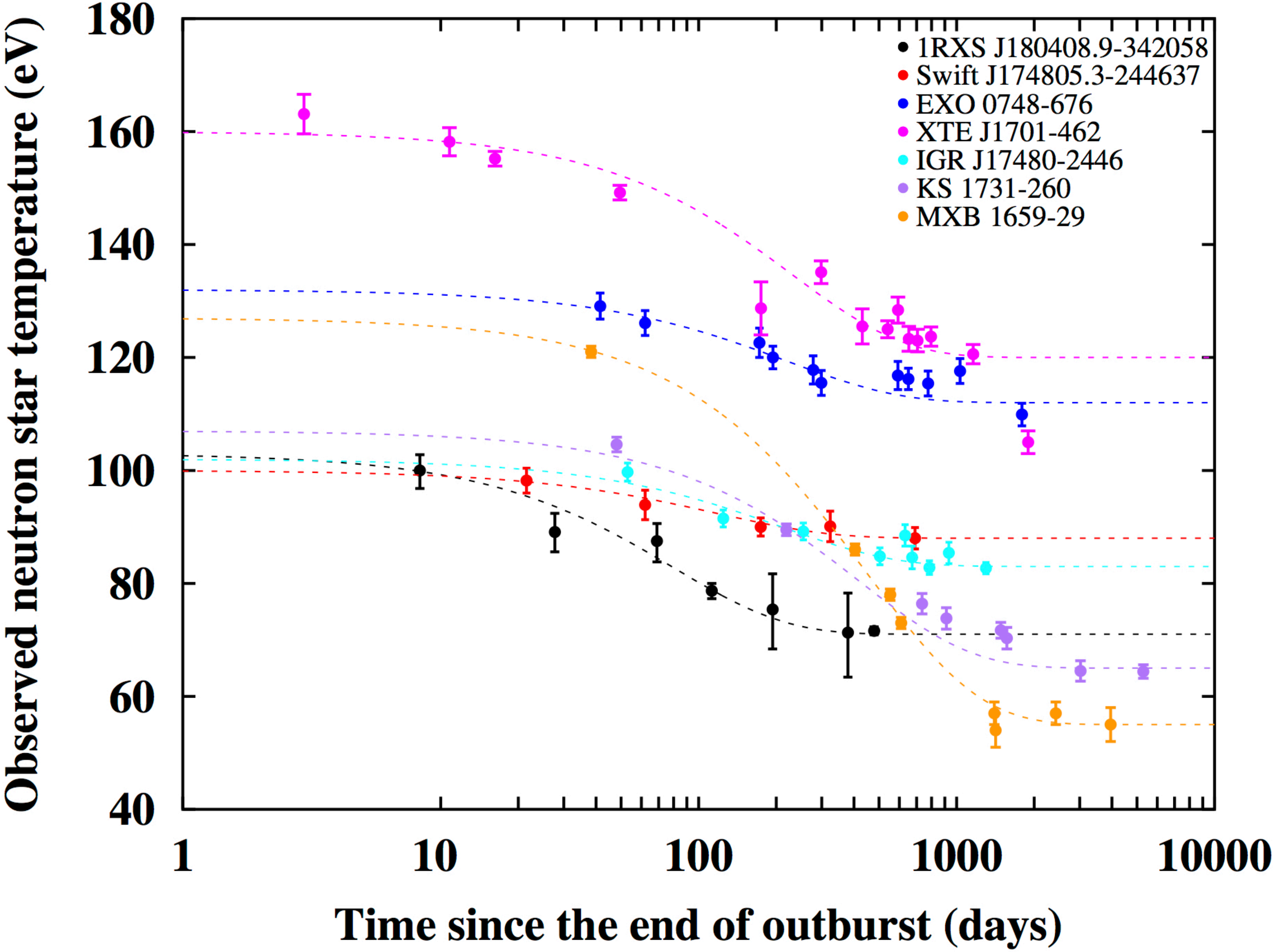
Outburst
Heating
Quiescence
Cooling
Crust cooling
X-ray luminosity
0
20
40
60
0
500
1000
1500
2000
2500
Time in days

Heating of the crust



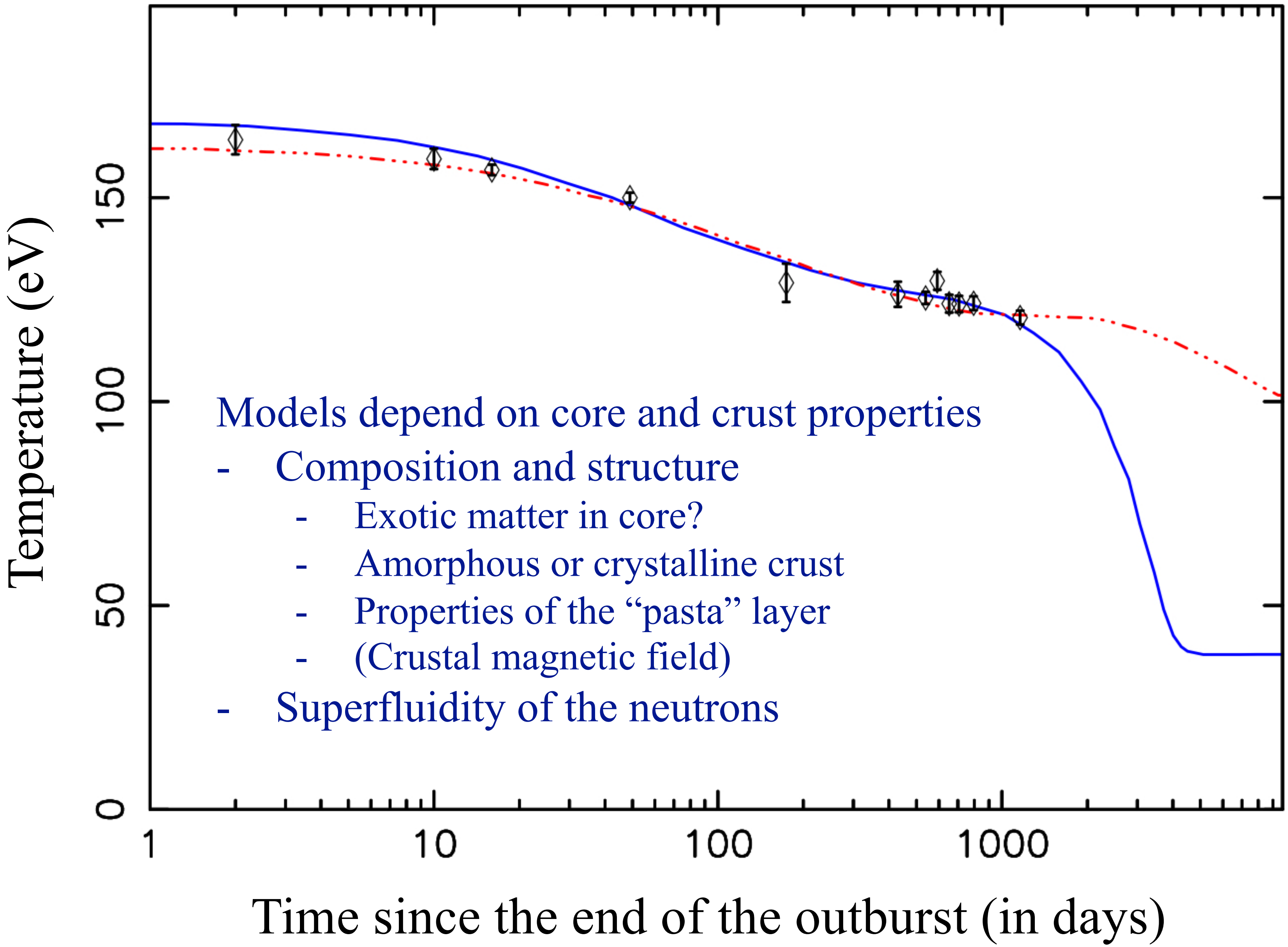


Wijnands et al. 2001, 2004; Cackett et al. 2006

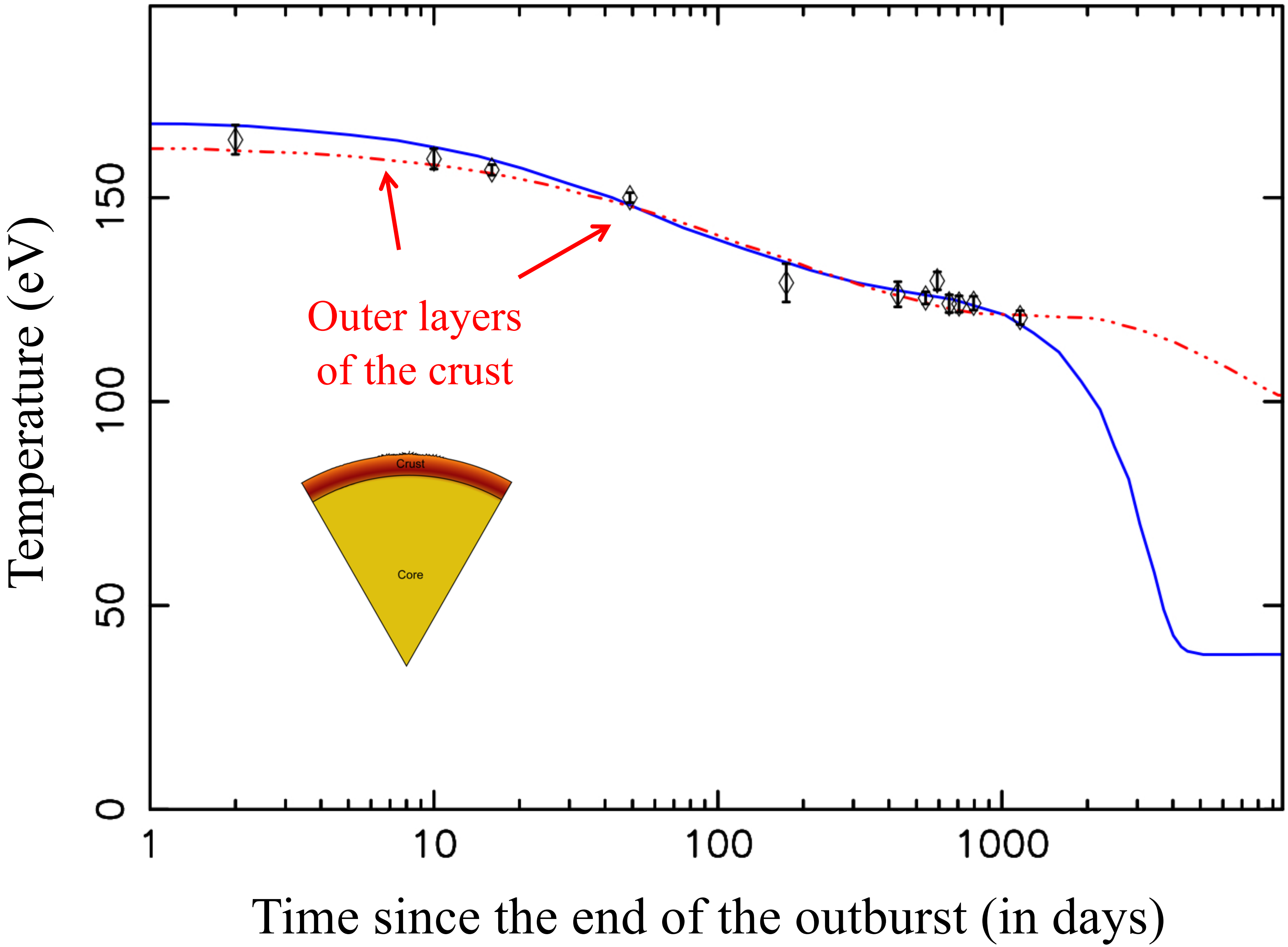


1RXS J180408.9-342058
Swift J174805.3-244637
EXO 0748-676
XTE J1701-462
IGR J17480-2446
KS 1731-260
MXB 1659-29
Observed neutron star temperature (eV)
180
160
140
120
100
80
60
40
1
10
100
1000
10000
Time since the end of outburst (days)

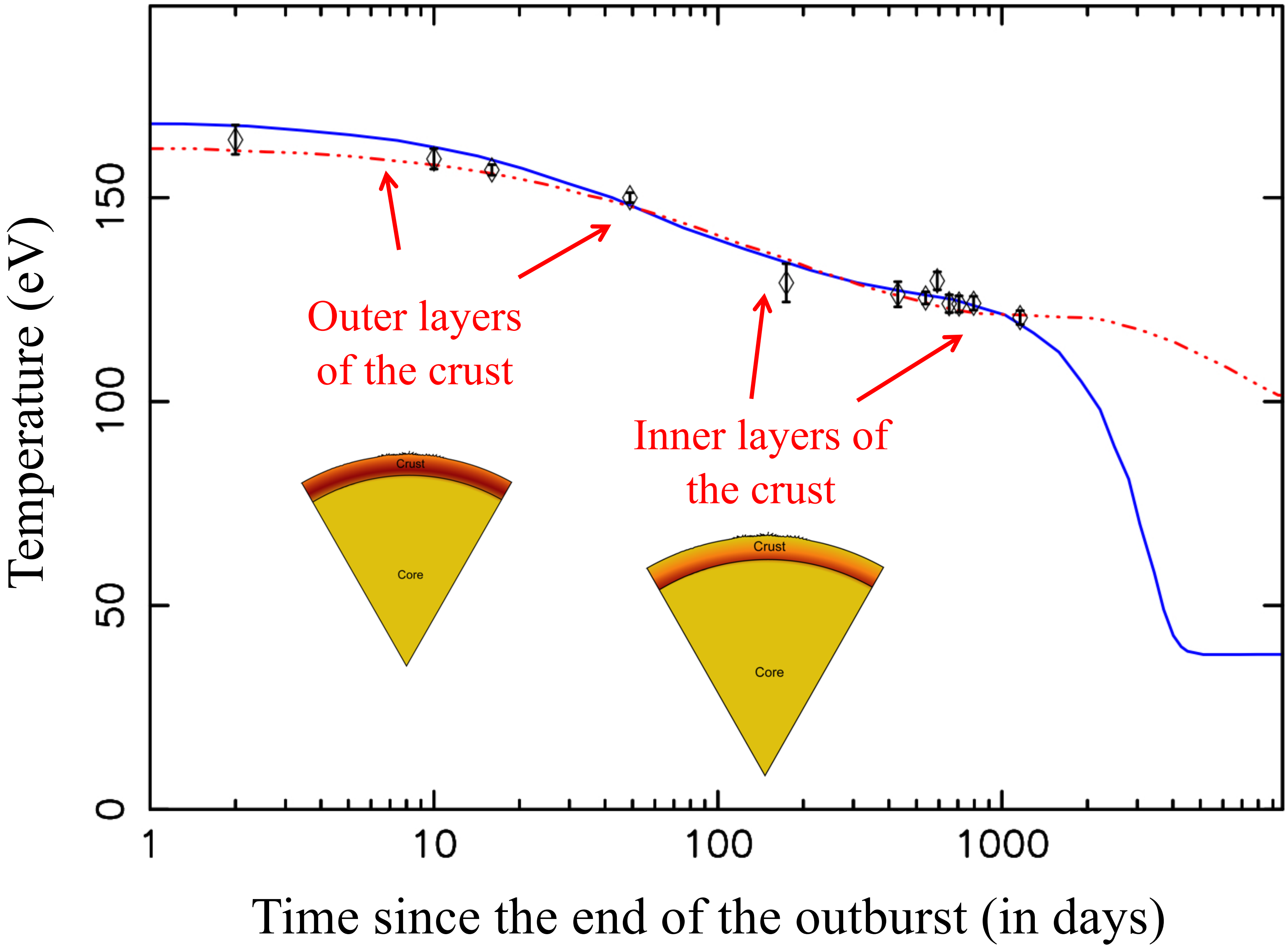
Probing the crust using cooling curves



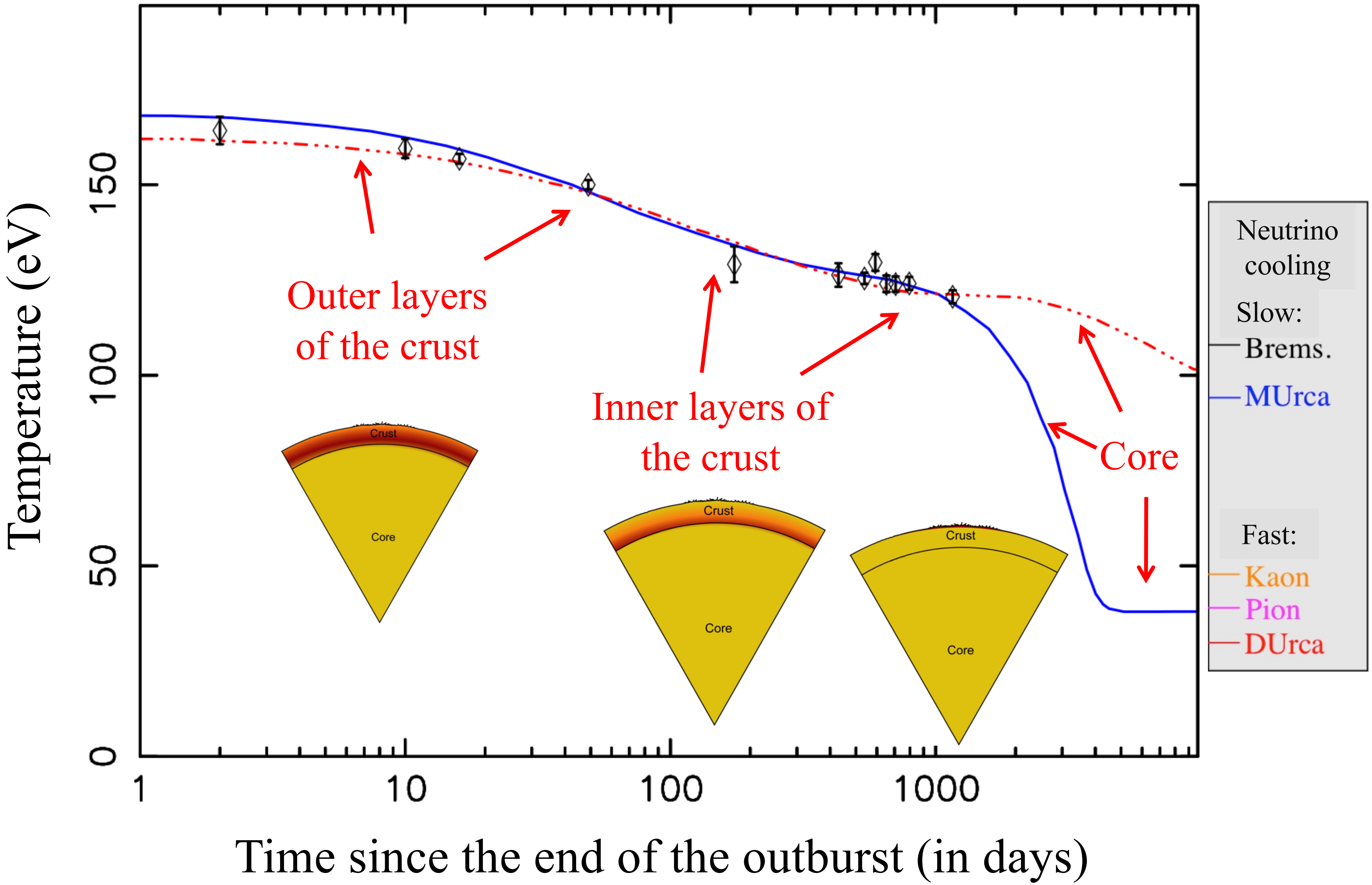
Probing the crust using cooling curves



Probing the crust using cooling curves



Probing the crust using cooling curves



Conclusions

- Neutron star strongly affects the accretion flow
  - Magnetic accretion → highly complex
- Potential to probe ultra-dense matter with accreting neutron stars
  - Pulse profile modelling
    - Need many photons → future generation of X-ray satellites
  - Cooling of accretion heated neutron stars
    - Has lead to new insights in neutron star cores and crusts but many uncertainties remain