«From observation to discovery: data analysis with a human brain»
IUSS seminar, Lecture 3

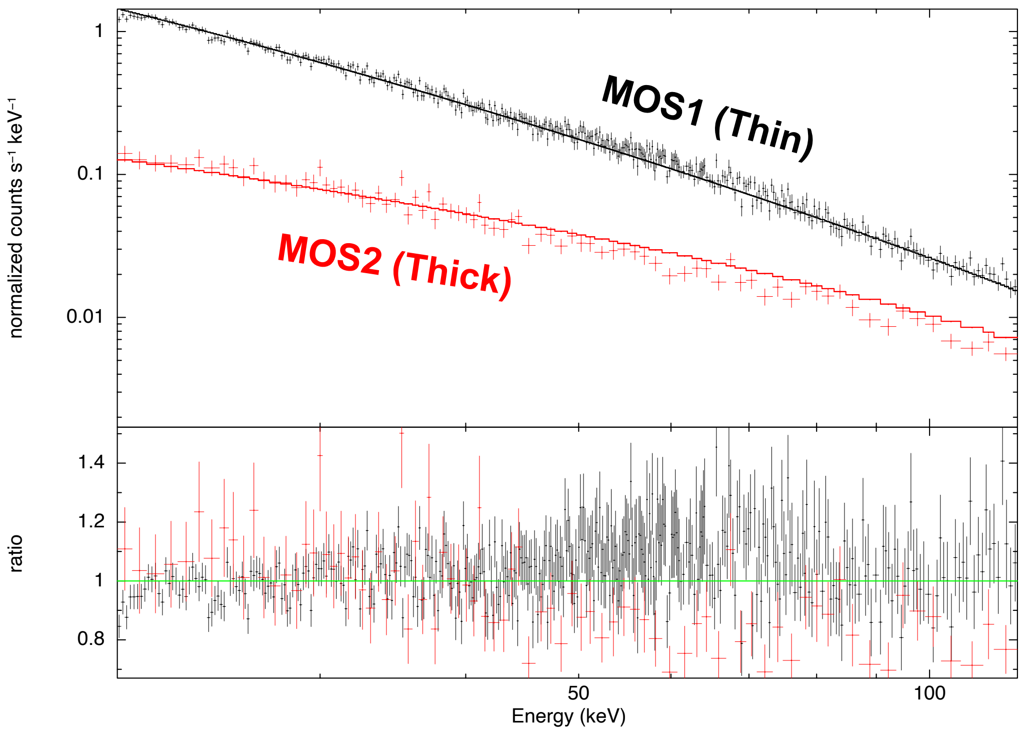
Pavia, 2023 March 20

The closest isolated neutron star

Andrea Tiengo

MOS spectra: simultaneous fit

- Background subtracted spectra with diagonal response matrix
- Restricted to **20-120 keV** band



Model:

$$F(E)=k\cdot(E+\Delta E)^{-\alpha}$$

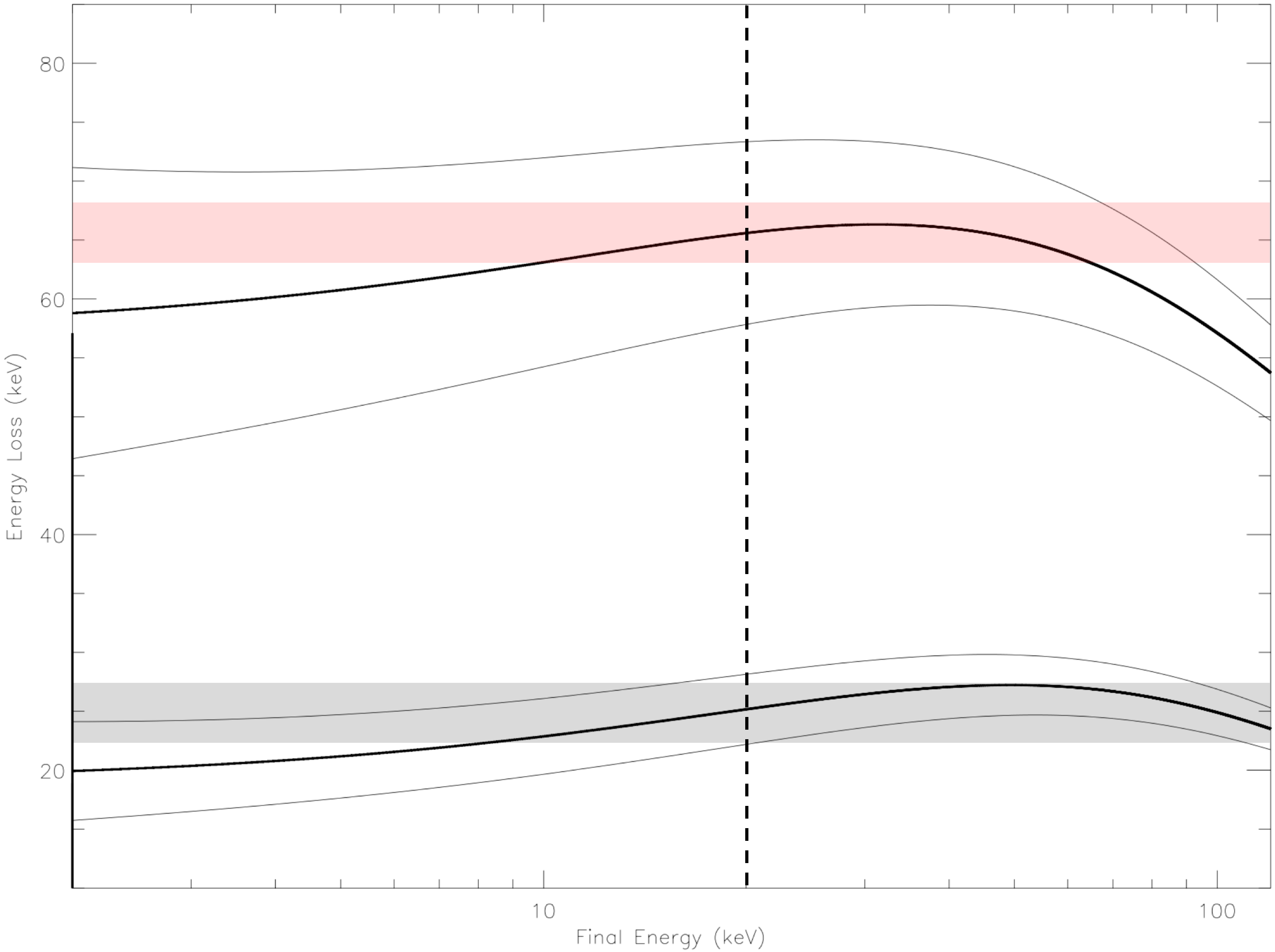
α = 3.9 ± 0.1,

ΔE_{thin} = 25.5 ± 2 keV,

ΔE_{thick} = 65.5 ± 2 keV,

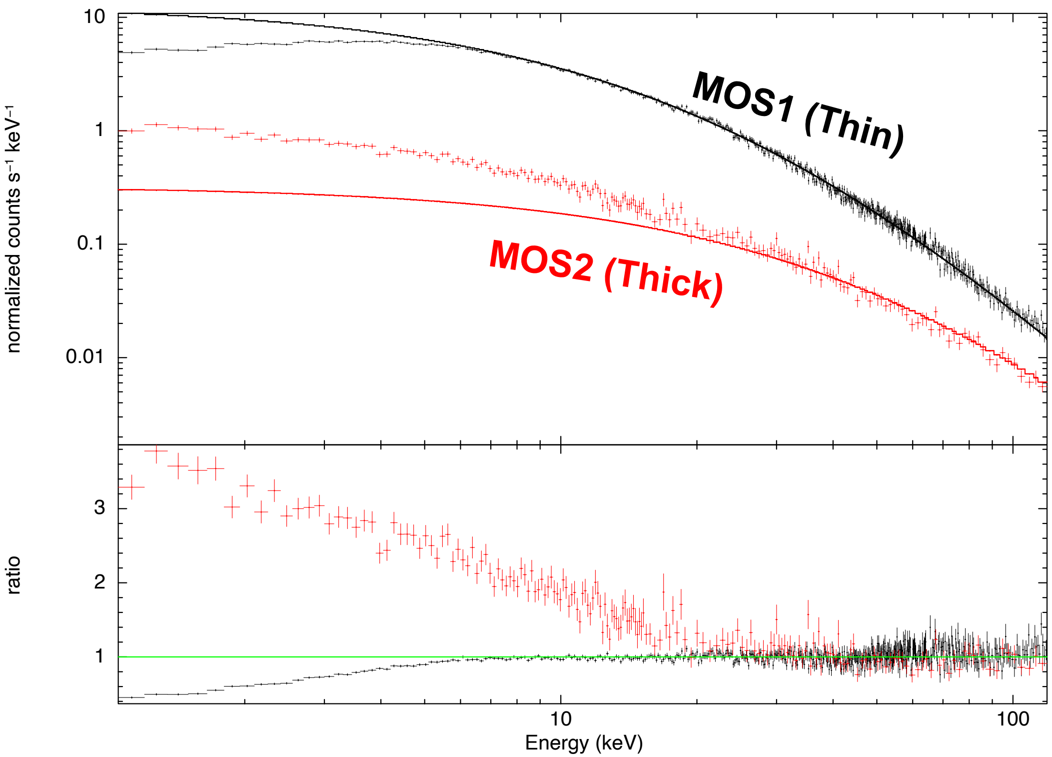
χ^2_{red}= 1.11 / 612 d.o.f.

Proton energy loss in filters



MOS spectra: simultaneous fit

- Background subtracted spectra with diagonal response matrix
- Extended to **1-120 keV** band



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ΔE_{thin} **= 25.5 keV,**

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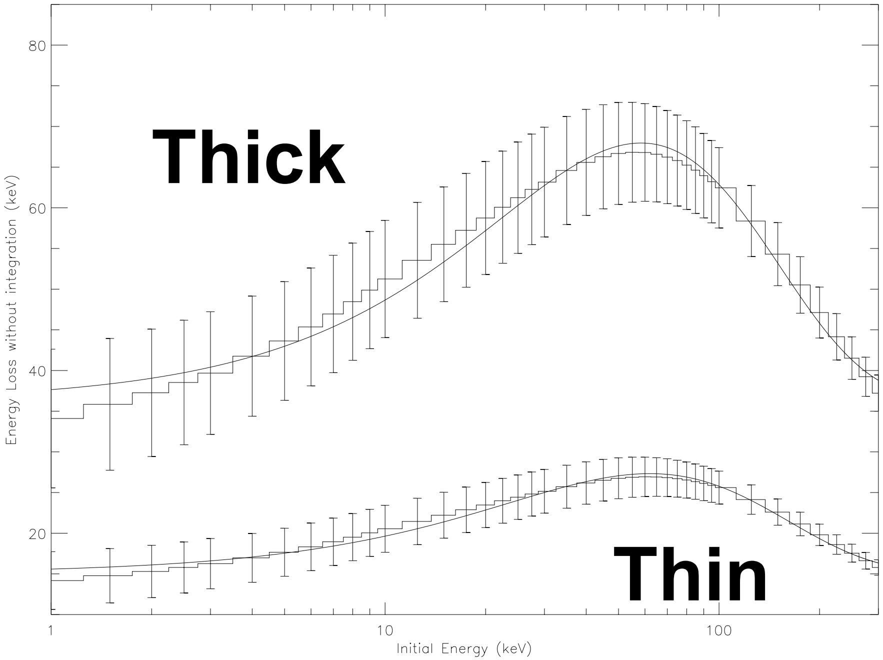
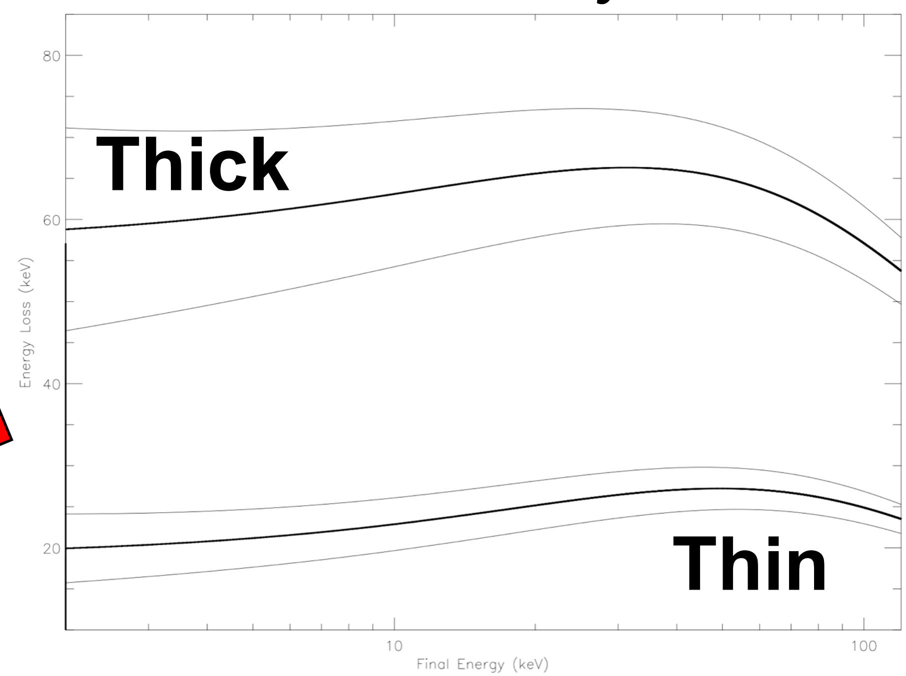
Proton energy loss in filters



$$dE(E_{initial}) = \Delta E_i + c_i \cdot E_{initial} \cdot exp(-E_{initial}/E_{f,i})$$

$\int$

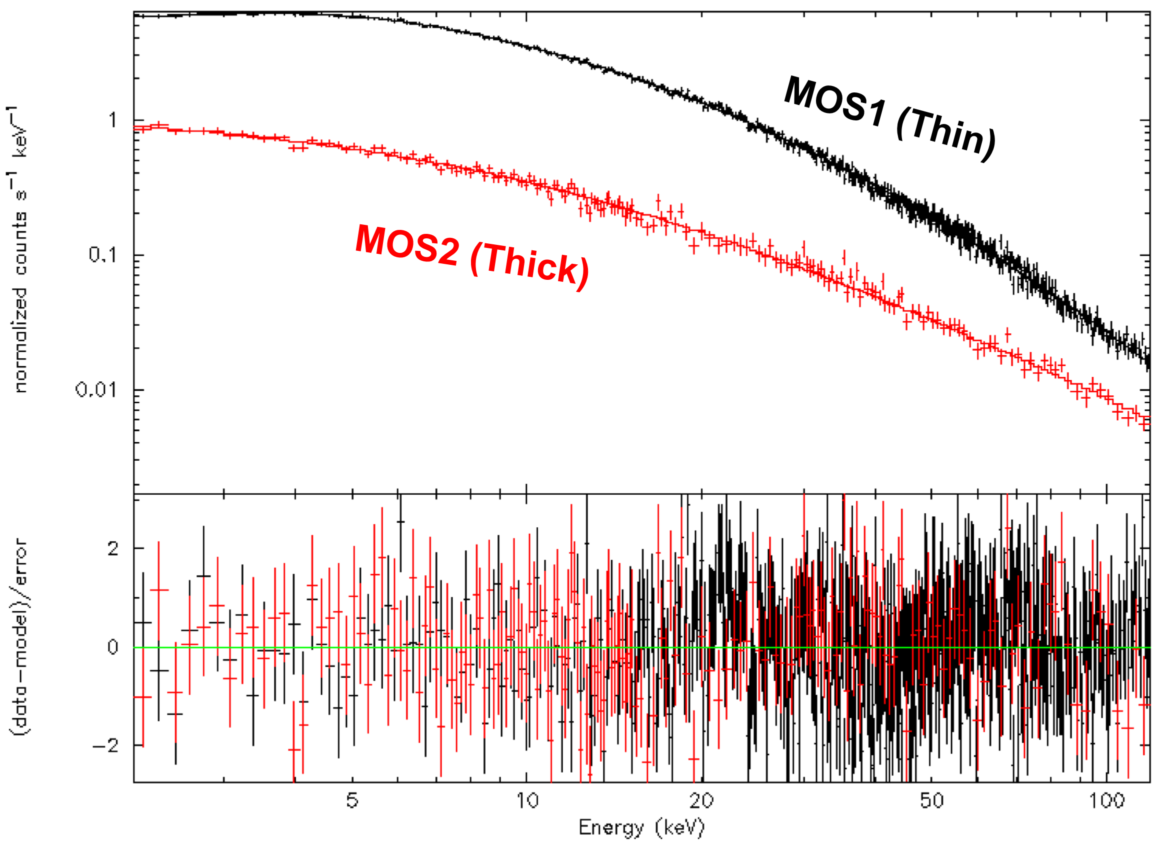


$$E_{initial} = E_{final} + \Delta E_f + c_f \cdot E_{final} \cdot exp(-E_{final}/E_{f,f})$$

Empirical model of energy loss

Model: $F(E)=k\cdot(E+\Delta E+c\cdot E\ \cdot exp(-E/E_f))^{-\alpha}$

Best-fit in the **2-120 keV** energy band:



α = 3.8 ± 0.1

ΔE_{thin} = 24 ± 2 keV

C_{thin}= 11 ± 3

$E_{f,thin}$= 1.1 ± 0.1 keV

ΔE_{thick} = 45 ± 2 keV

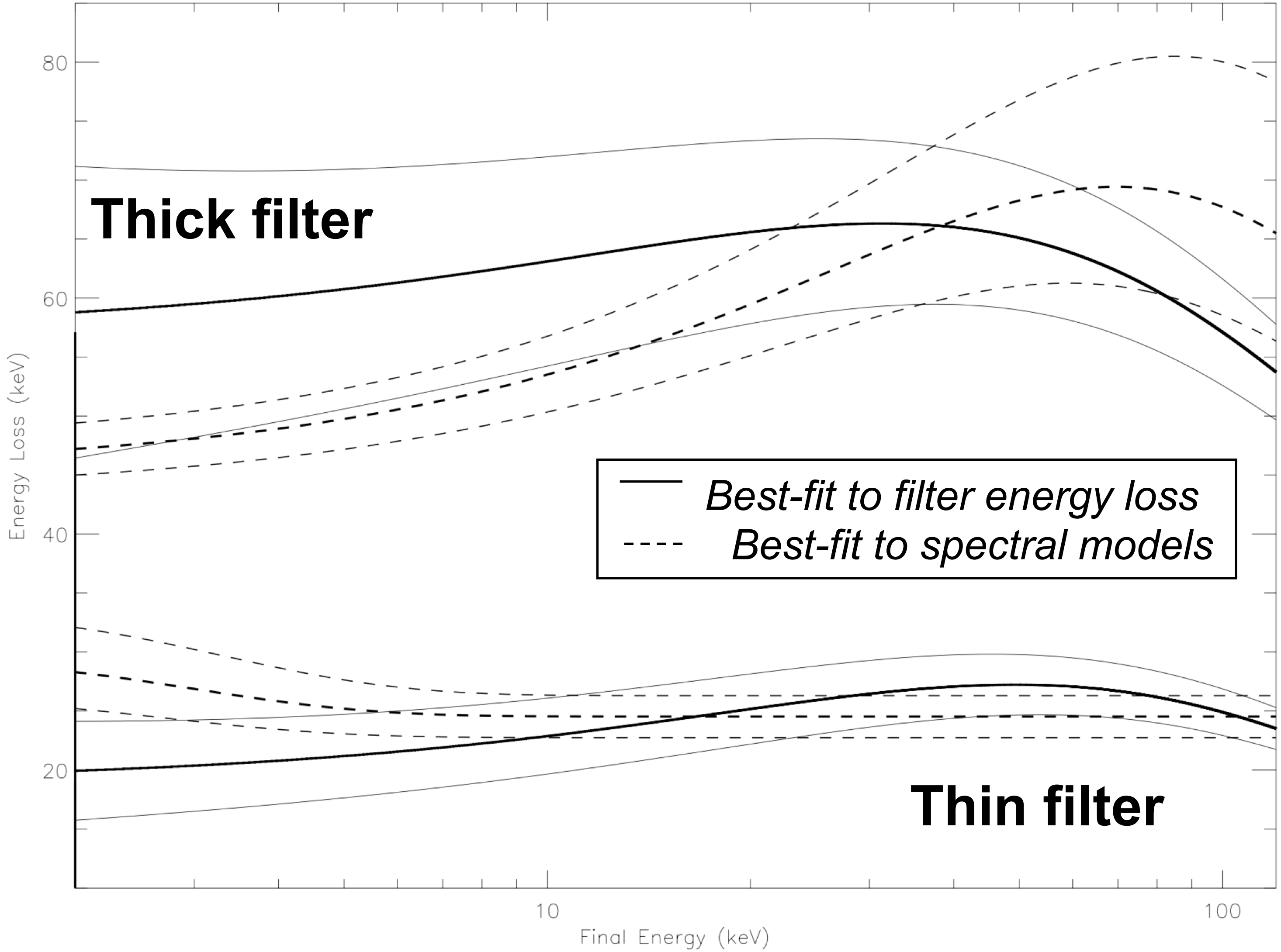
C_{thick}= 0.9 ± 0.1

$E_{f,thick}$= 70 ± 12 keV

χ^2_{red}=1.01 / 848 d.o.f.

Proton energy loss in filters

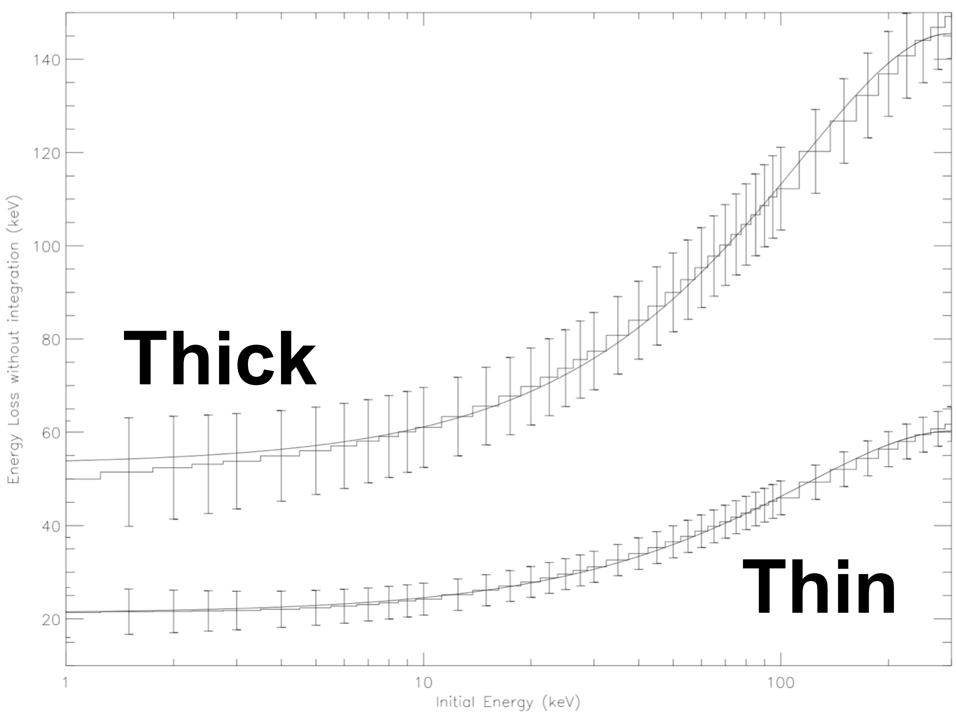
$$F(E)=k\cdot(E+\Delta E+c\cdot E\cdot exp(-E/E_f))^{-\alpha}$$



Alpha energy loss in filters

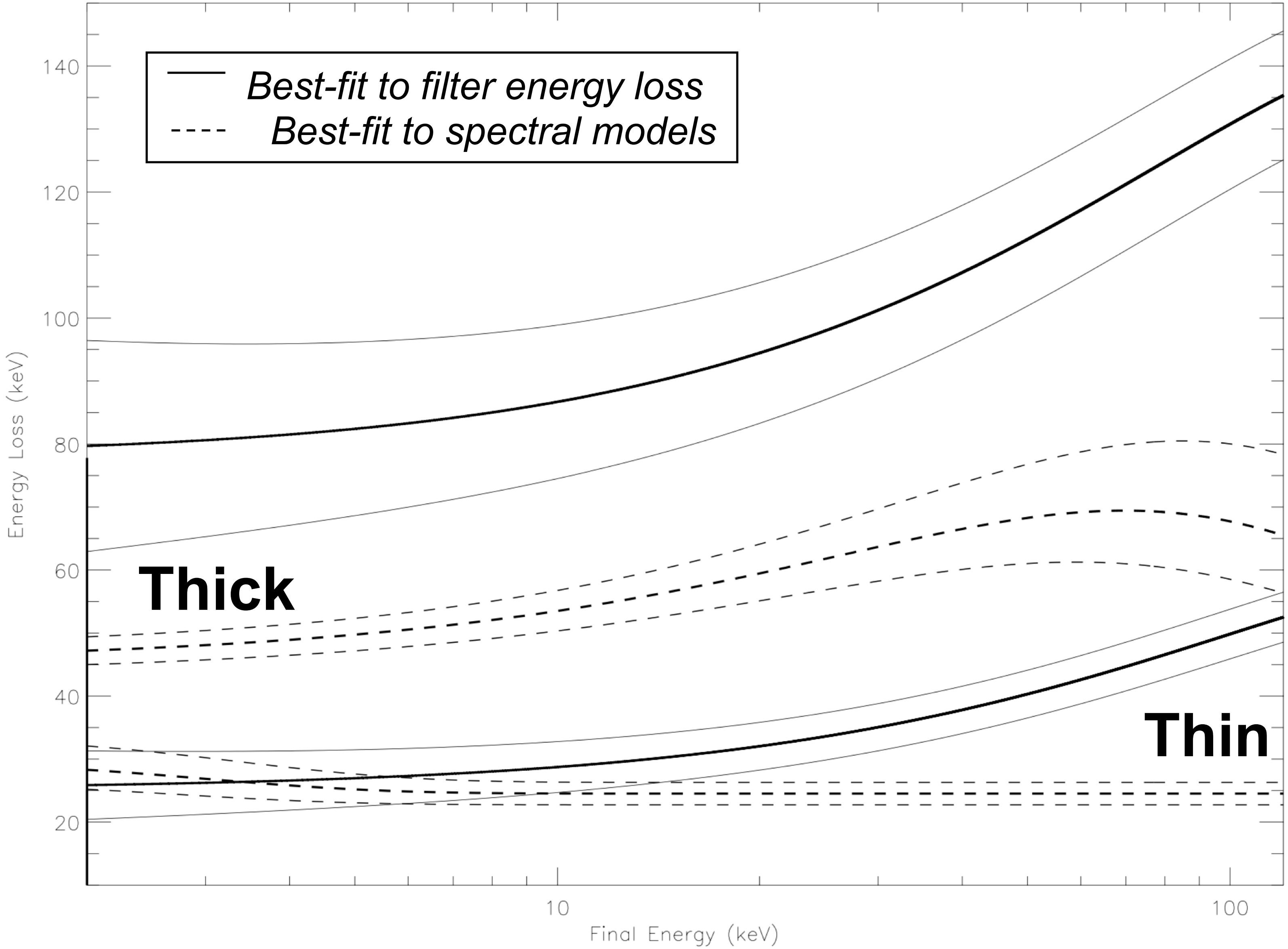
- Constructing the **energy loss for each filter** as if protons keep the same energy across the filter (only valid for small energy losses, i.e., **short tracks**)
- Empirical **model** of energy loss for each filter using:

$$dE(E)=\Delta E+c\cdot E\cdot exp(-E/E_f)$$



ΔE_{thin} = 21 ± 3 keV,
C_{thin} = 0.35 ± 0.1,
$E_{f,thin}$ = 300 ± 100 keV,
ΔE_{thick} = 53 ± 8 keV,
C_{thick} = 0.8 ± 0.3,
$E_{f,thick}$ = 300 ± 100 keV

Alpha energy loss in filters



The origin of background flares

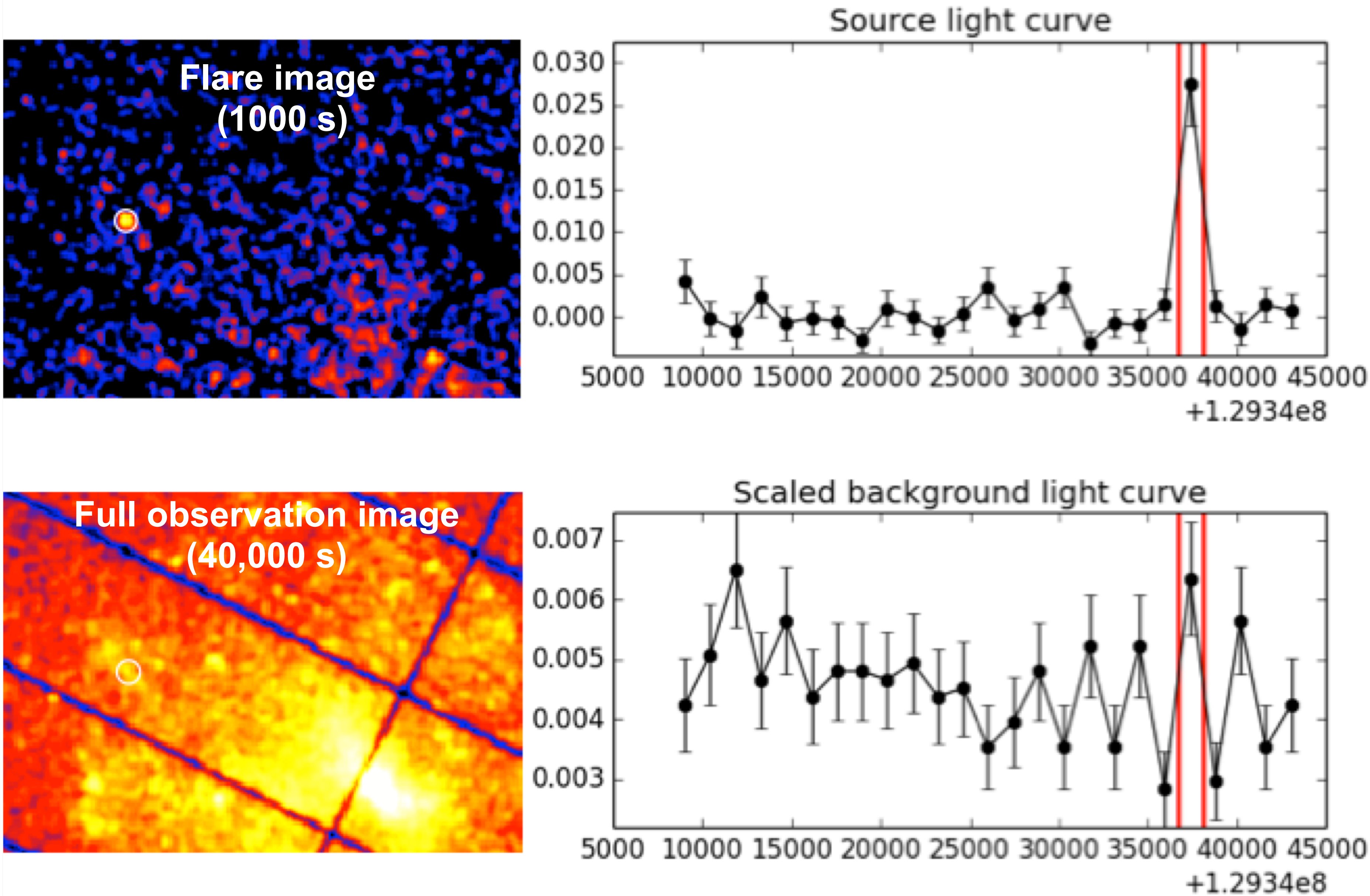
Difference in energy between detectors is consistent with difference in **energy loss** expected for **protons** passing through thin and thick filter

$\Rightarrow$ background flares in *XMM-Newton* data are due to soft (E<100 keV) <u>protons</u> focused by the X-ray mirrors

How could we minimize this problem in **future** X-ray missions?

- **Different orbit** (LEO or L2)
- **Magnetic diverter** (immediately after the mirrors or above the detectors)

Detecting X-ray transients



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A Supernova Candidate at $z^{*} = 0.092$ in XMM–Newton Archival Data

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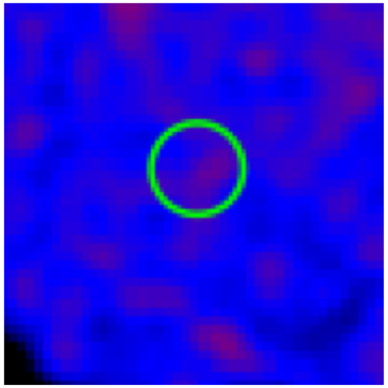
Abstract

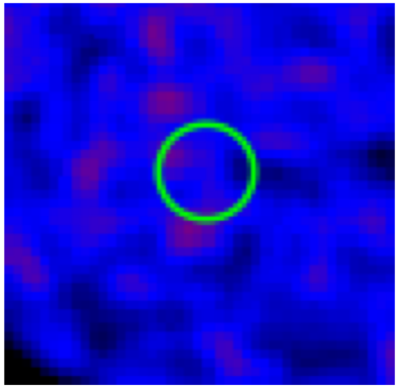
During a search for X-ray transients in the XMM–Newton archive within the EXTraS project, we discovered a new X-ray source that is detected only during an $\sim$5 min interval of an $\sim$21 hr-long observation performed on 2011 June 21 (EXMM 023135.0–603743, probability of a random Poissonian fluctuation: $\sim 1.4 \times 10^{-27}$). With dedicated follow-up observations, we found that its position is consistent with a star-forming galaxy (SFR = 1–2 $M_{\odot}$ yr^{-1}) at redshift $z = 0.092 \pm 0.003$ ($d = 435 \pm 15$ Mpc). At this redshift, the energy released during the transient event was 2.8×10^{46} erg in the 0.3–10 keV energy band (in the source rest frame). The luminosity of the transient, together with its spectral and timing properties, make EXMM 023135.0–603743 a gripping analog to the X-ray transient associated to SN 2008D, which was discovered during a Swift/XRT observation of the nearby ($d = 27$ Mpc) supernova-rich galaxy NGC 2770. We interpret the XMM–Newton event as a supernova shock break-out or an early cocoon, and show that our serendipitous discovery is broadly compatible with the rate of core-collapse supernovae derived from optical observations and much higher than that of tidal disruption events.

* **Redshift** to distance conversion: http://www.astro.ucla.edu/~wright/CosmoCalc.html

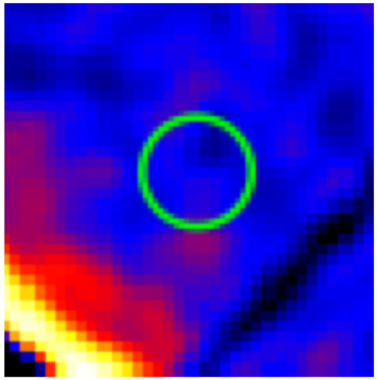
X-ray image of the full observation



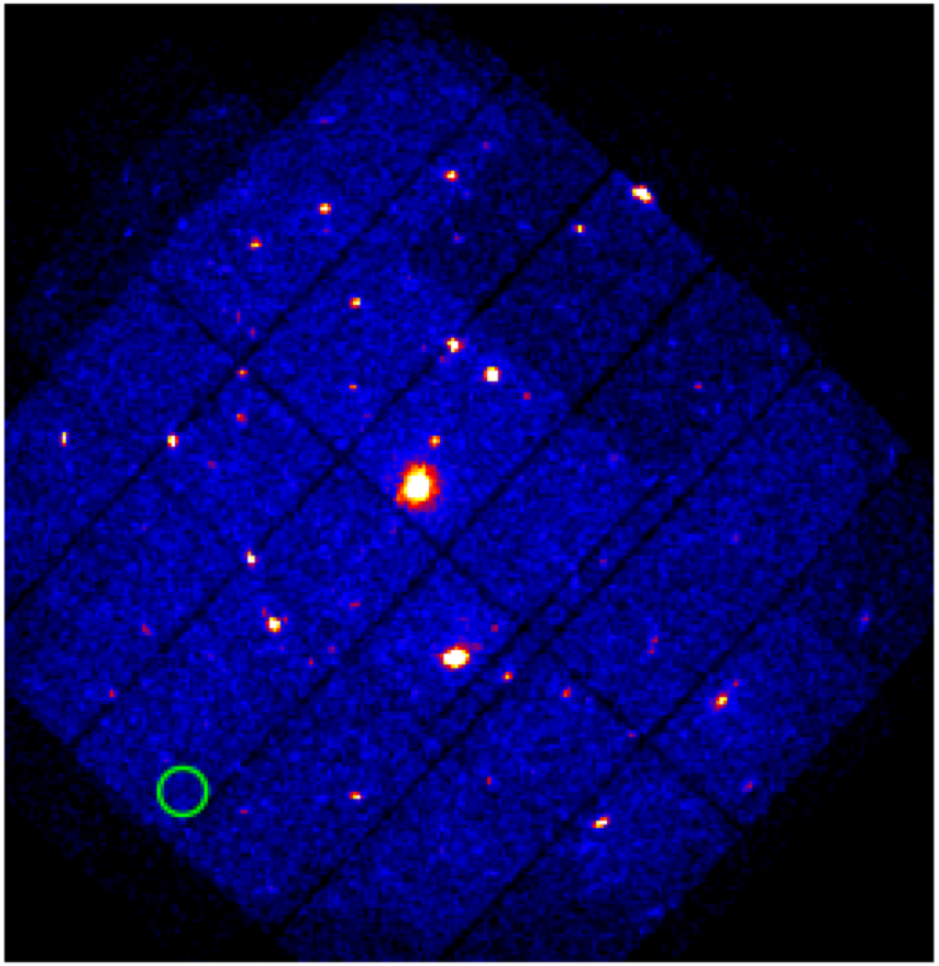
MOS1



MOS2



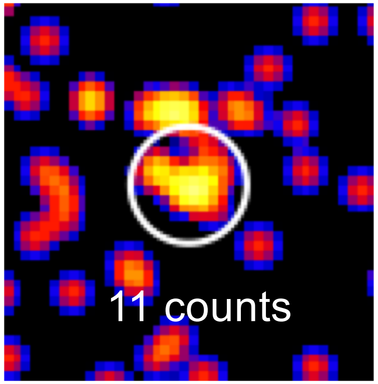
PN



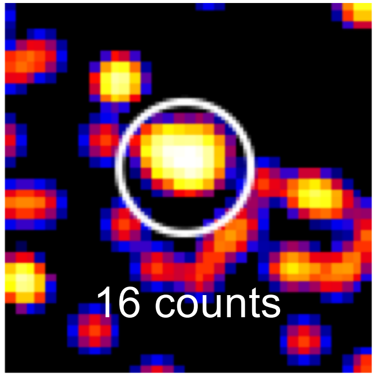
Entire observation (net exposure >20 ks)

The new transient is NOT visible in the whole observation

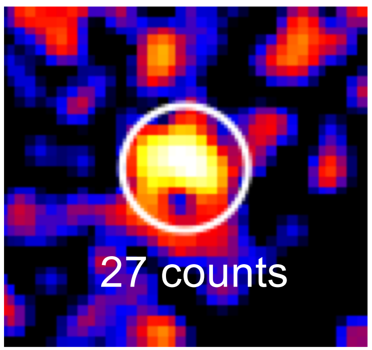
X-ray image during the X-ray flare



MOS1



MOS2



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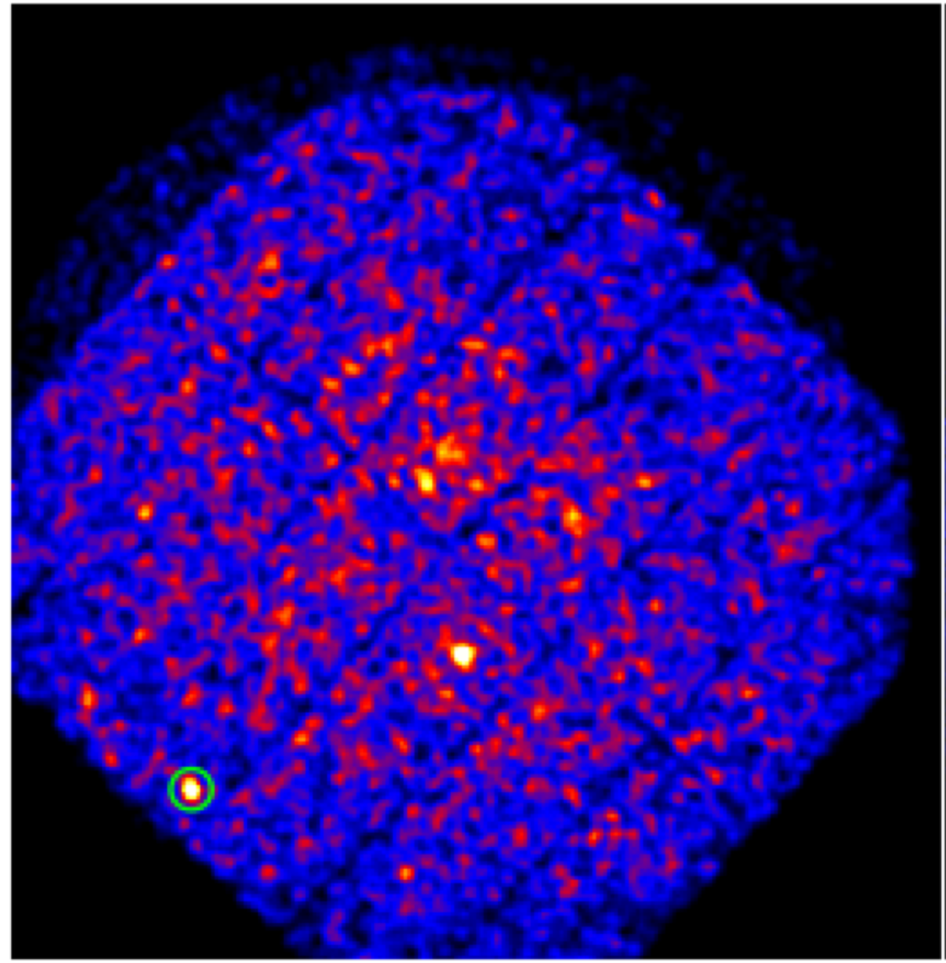
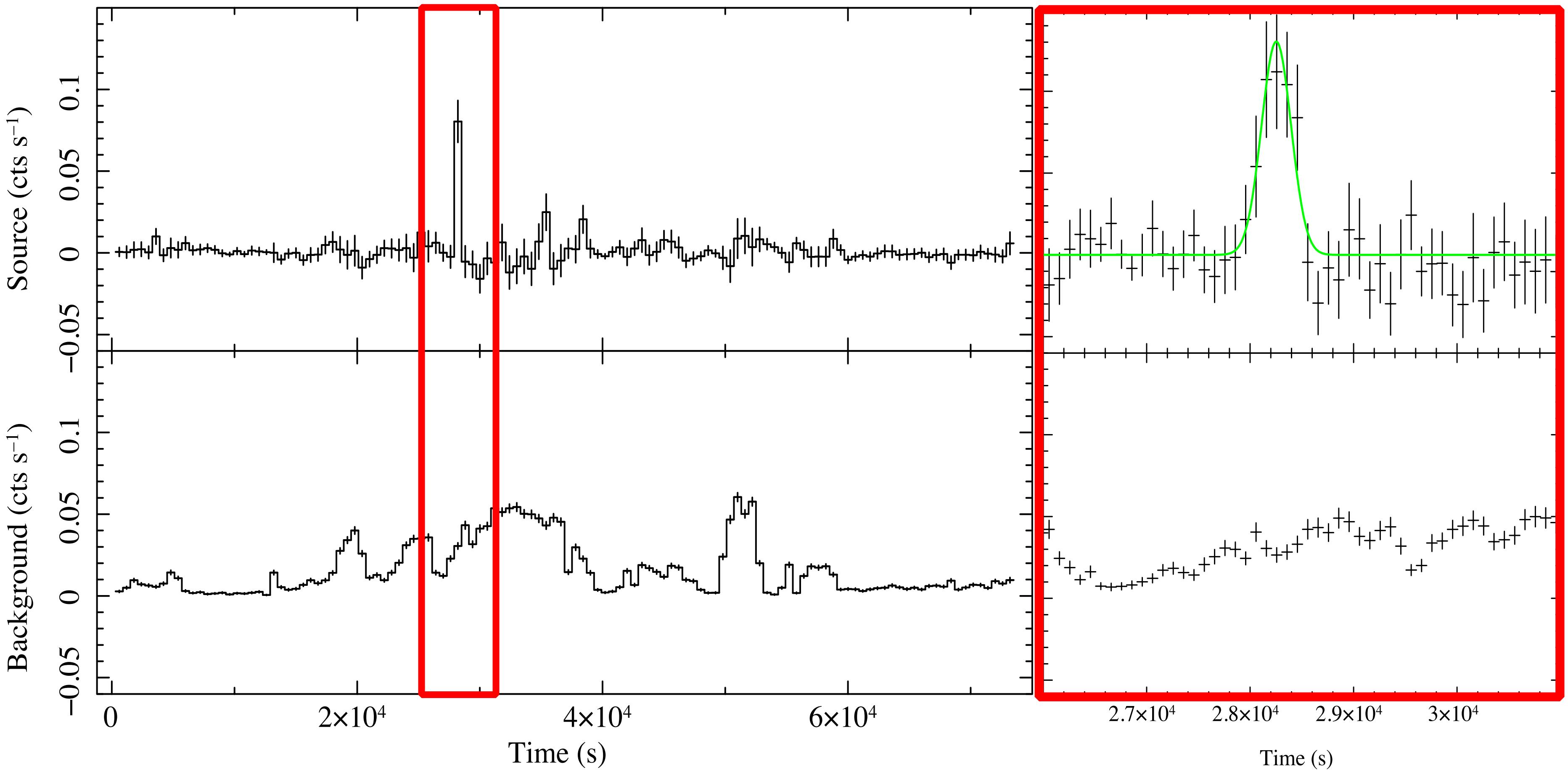


Time interval: 315 s

1σ **position error**: 1.9”

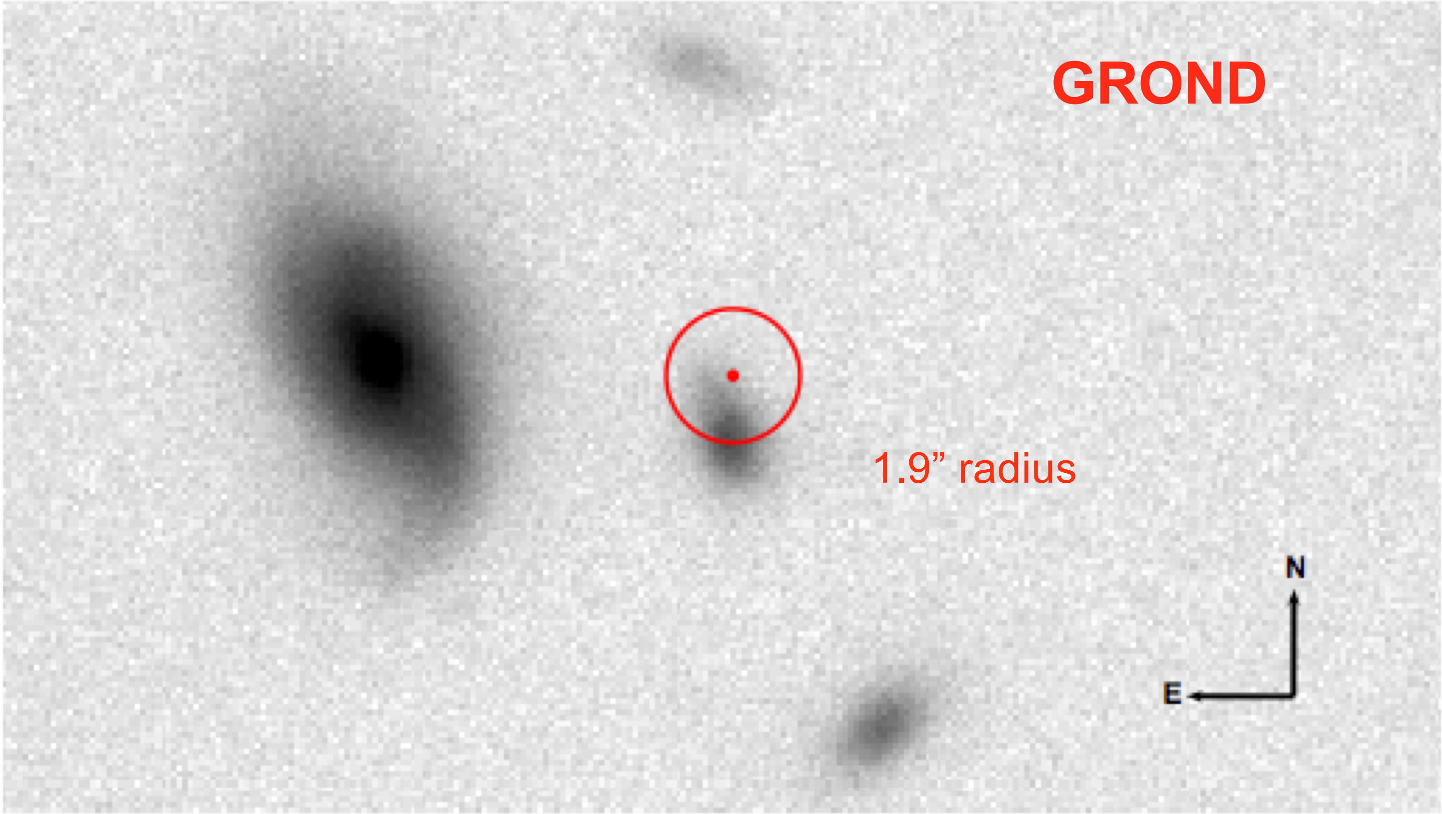
X-ray light curve



47 net counts by integrating the Gaussian profile

Follow-up optical observations

From CTIO* optical high resolution spectrum we derive:
- **$z = 0.092 \pm 0.003$**, corresponding to a distance of 424 Mpc;
- galaxy $M=3\times10^{8}\ M_{\odot}$ and $SFR=1\ M_{\odot}\ yr^{-1}$ $\Rightarrow$ **small and star-forming**

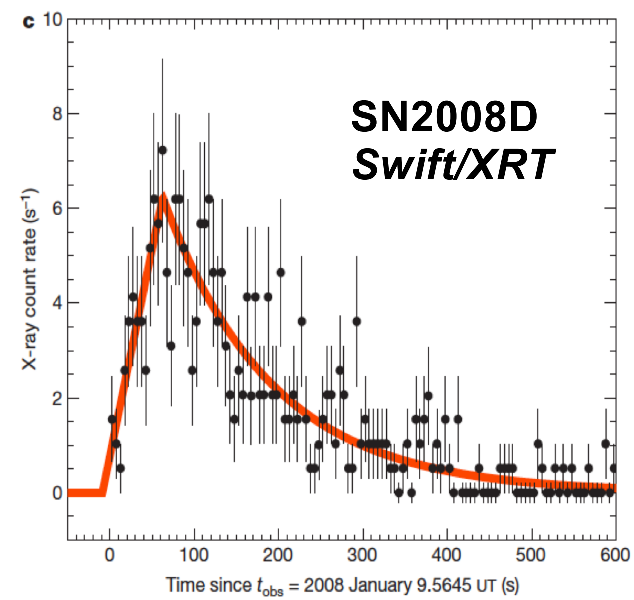


* (COSMOS spectrograph at the Blanco Telescope of the Cerro Tololo Inter-American observatory)

Comparison with SN2008D

The flare energy and duration are very similar to those of the X-ray transient associated to **SN2008D** *(Soderberg et al.,2008)*, interpreted as the emission from the **shock break-out** of a core-collapse supernova

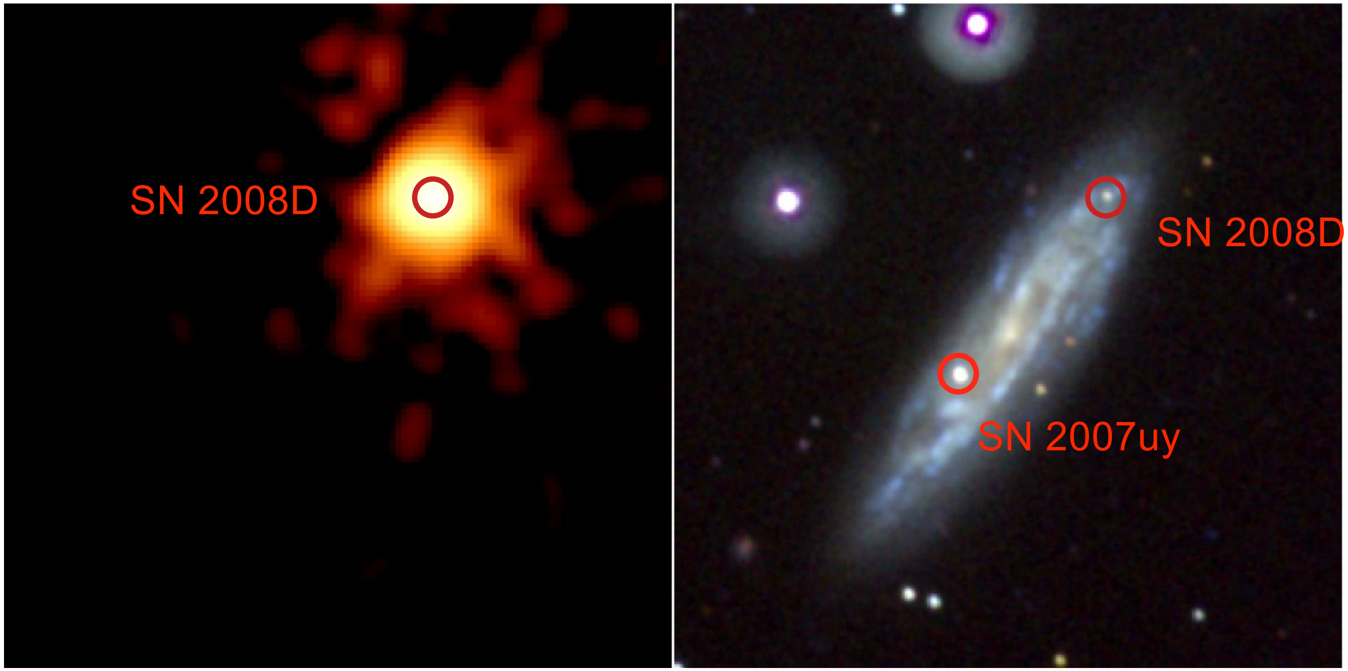
	SN 2008D	***EXTraS transient***
d	*27 Mpc (z=0.006494)*	*424 Mpc (z=0.092)*
Fluence	*2.3×10^{-7} erg cm^{-2}*	*8×10^{-10} erg cm^{-2}*
Total energy	*2×10^{46} erg*	*1.7×10^{46} erg*
Peak luminosity	*6.1×10^{43} erg s^{-1}*	*4.3×10^{43} erg s^{-1}*



Supernova association

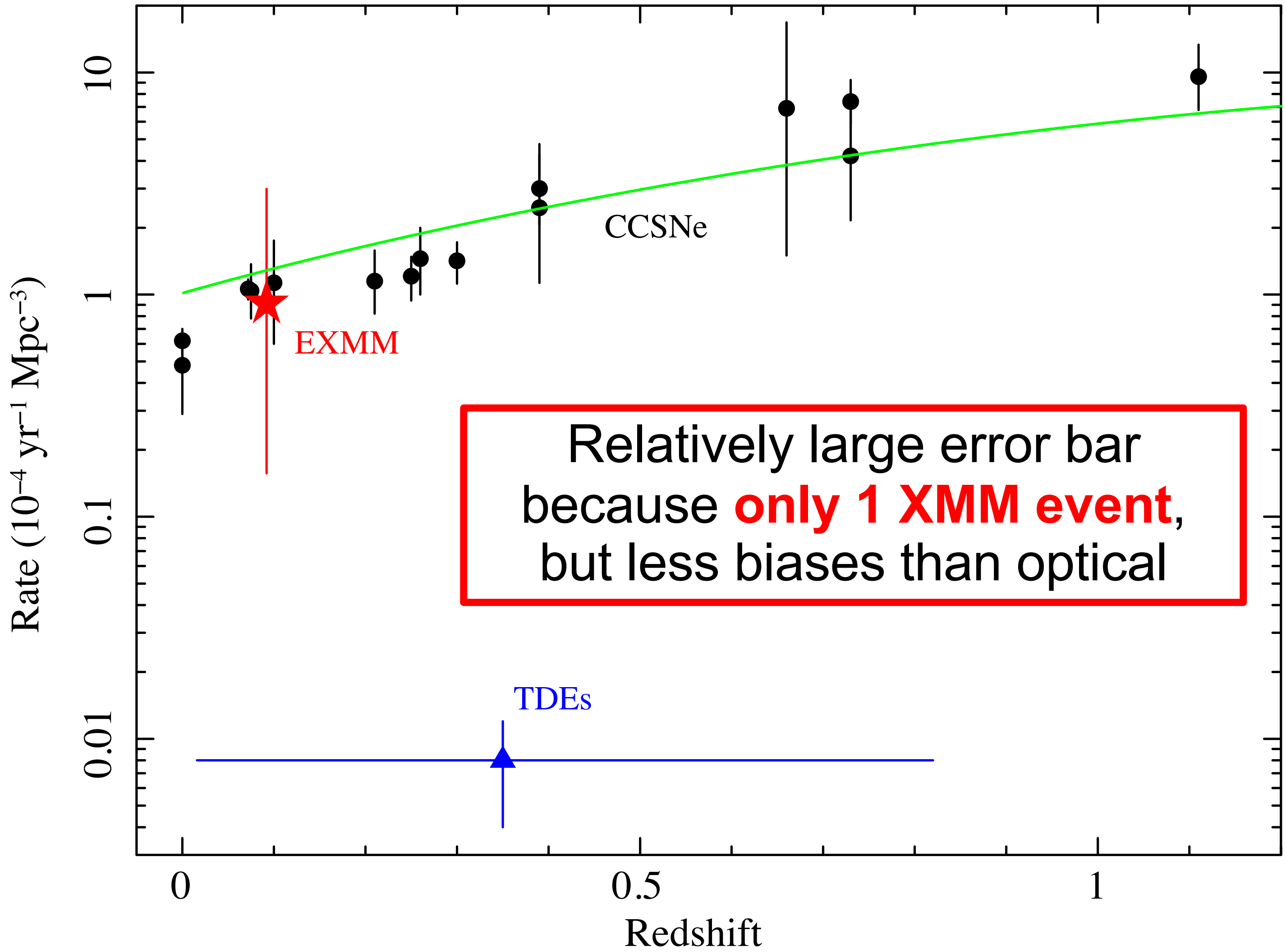
Being discovered in archival data, no follow-up optical observations to **search for a supernova**; no sufficiently deep archival optical observations; outside OM FoV during *XMM-Newton* observation

SN2008 was discovered in a SN-rich galaxy, whereas our discovery is **serendipitous**



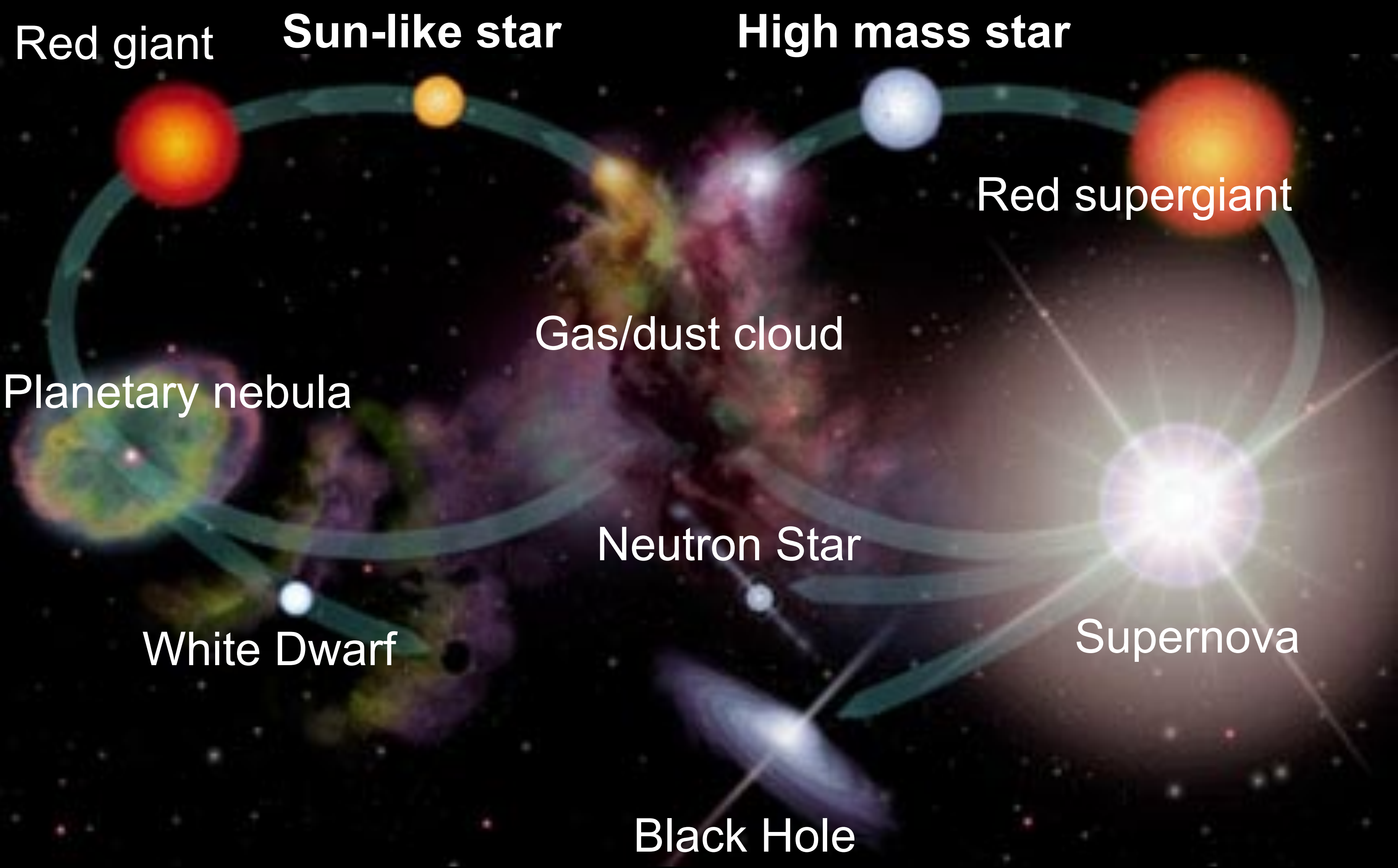
http://www.nasa.gov/centers/goddard/news/topstory/2008/swift_supernova.html

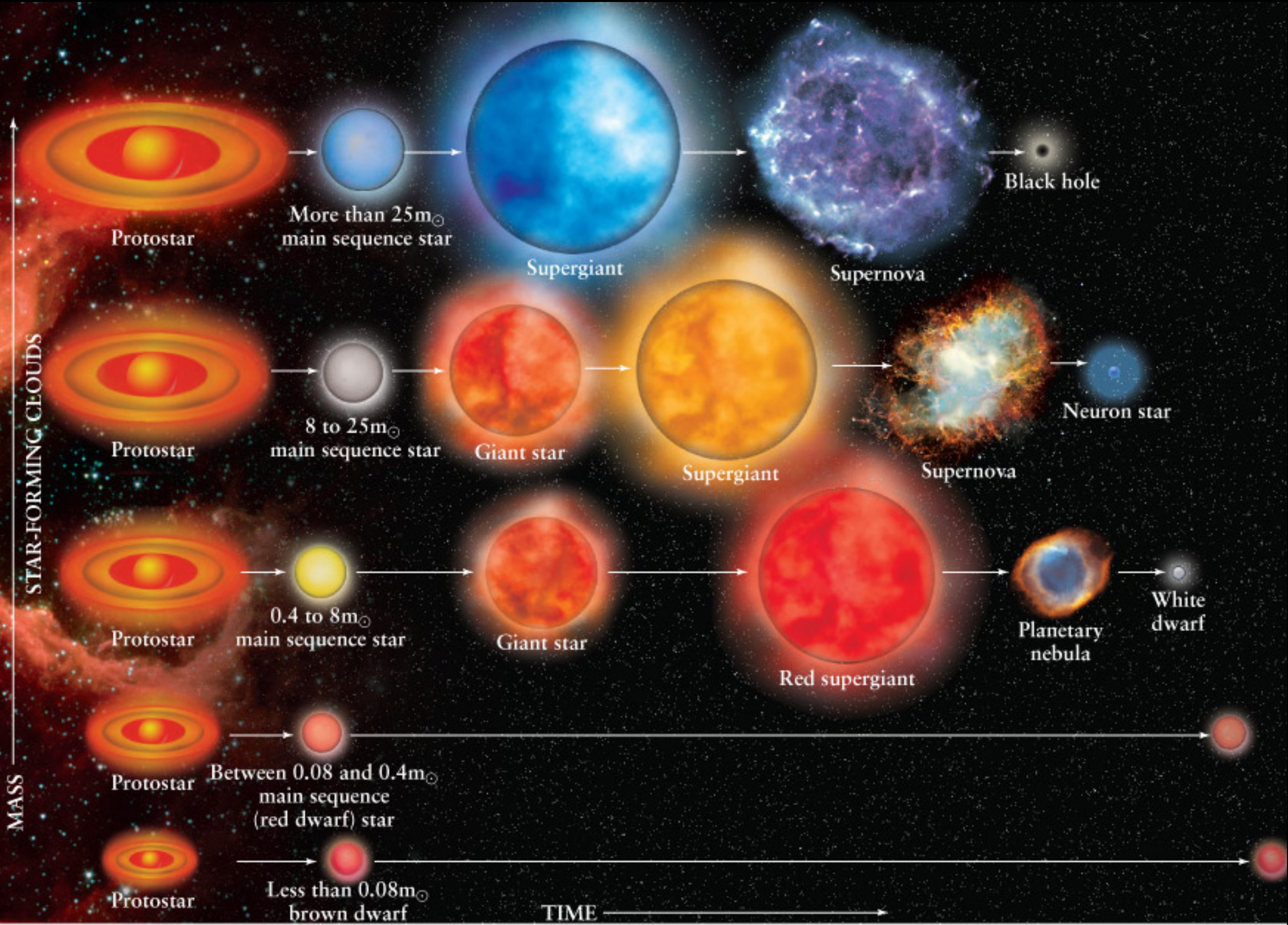
Event Rate



Larger FoV (**THESEUS**) to detect **low-z** events, larger effective area (**ATHENA**) to detect events at **higher redshift**

Stellar evolution




Protostar
More than 25m⊙
main sequence star
Supergiant
Supernova
Black hole
Protostar
8 to 25m⊙
main sequence star
Giant star
Supergiant
Supernova
Neuron star
Protostar
0.4 to 8m⊙
main sequence star
Giant star
Red supergiant
Planetary
nebula
White
dwarf
Protostar
Between 0.08 and 0.4m⊙
main sequence
(red dwarf) star
Protostar
Less than 0.08m⊙
brown dwarf
TIME
MASS
STAR-FORMING CLOUDS

Neutron star properties

The collapse of its core amplifies some properties of the exploded star:

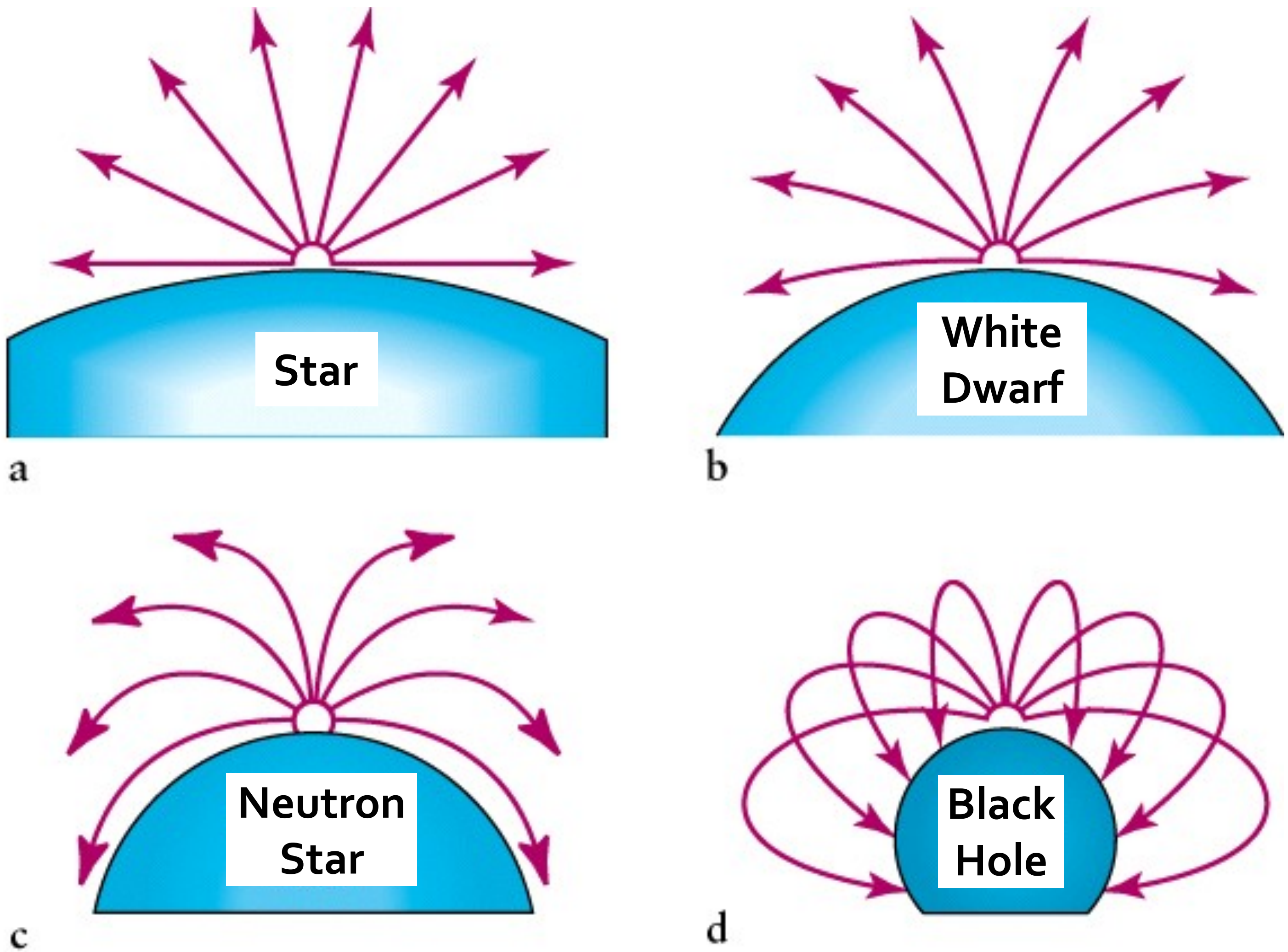
- **Density** (the mass of the Sun in a sphere of ~10 km radius)


A White Dwarf has about
the same mass as the Sun and
the same radius as the Earth

Neutron Star

Mass~1.5 M_{Sun}
Radius~12 km

Light bending



Radius of a non-rotating Black Hole: $R_S = \frac{2GM}{c^2} \approx \boxed{3\frac{M}{M_{Sun}}\ km}$

Neutron star properties

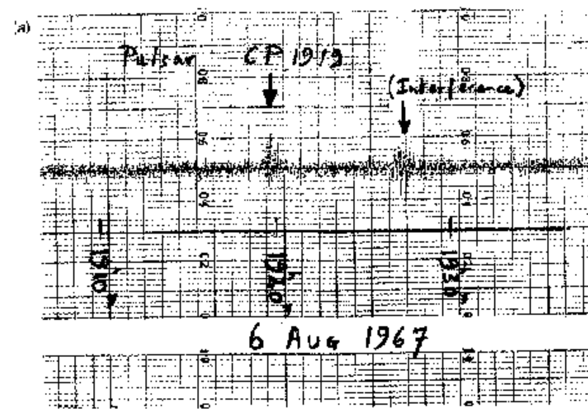
The collapse of its core amplifies some properties of the exploded star:

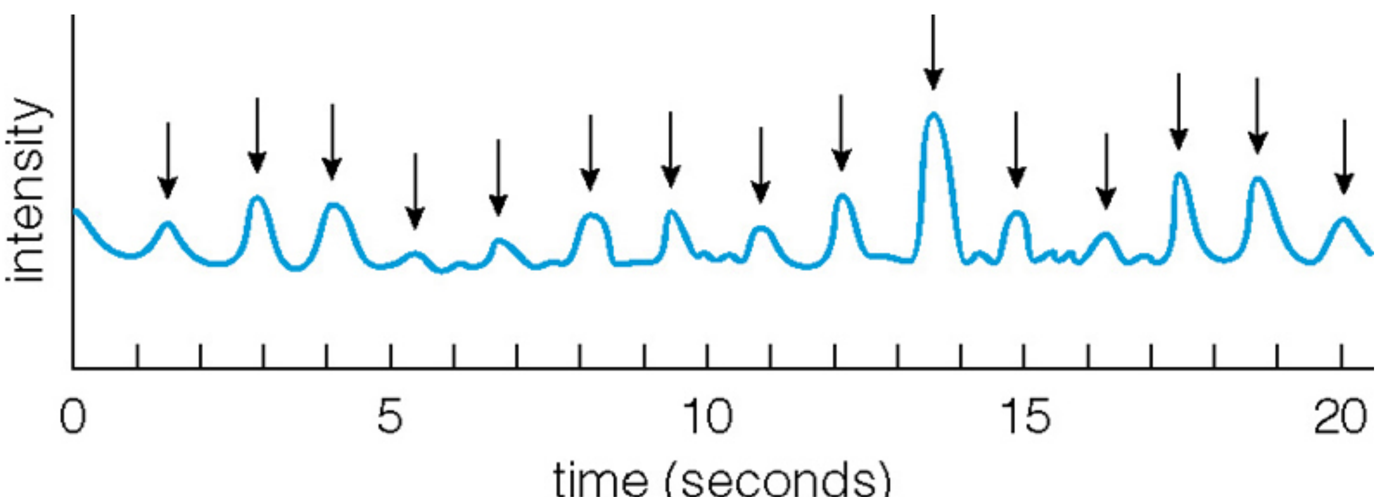
- **Density** (the mass of the Sun in a sphere of ~10 km radius)
- **Rotation rate** (up to hundreds of rotations per second)

Only a very **dense** object can rotate so fast (otherwise it would be destroyed by **centrifugal forces**)

The discovery radio pulsars

- In **1967**, graduate student **Jocelyn Bell** and her advisor Anthony Hewish accidentally discovered a **radio source** in *Vulpecula* (**LGM1**).
- Sharp **pulse** recurred every 1.3 sec.
- Determined it was **300 pc** away.
- More **“pulsars”** with similarly short periods

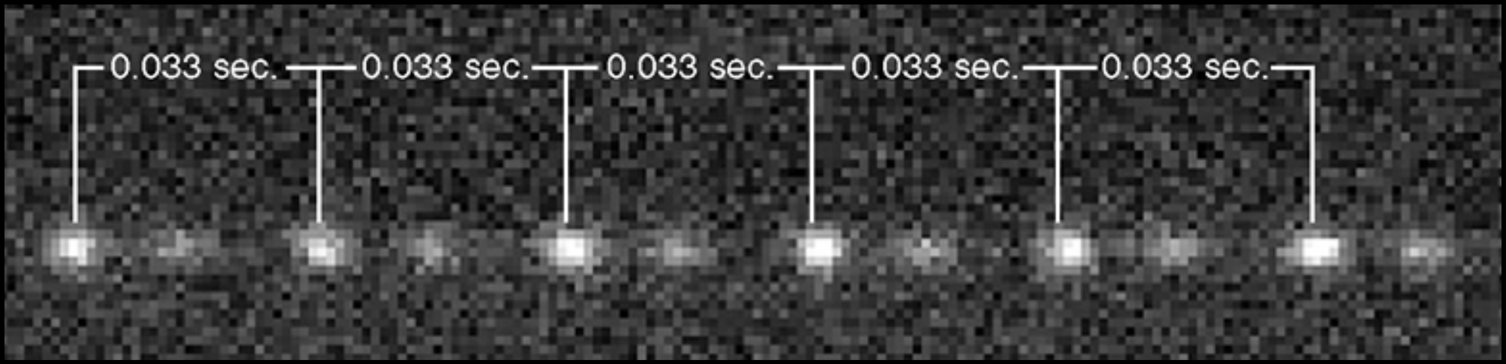




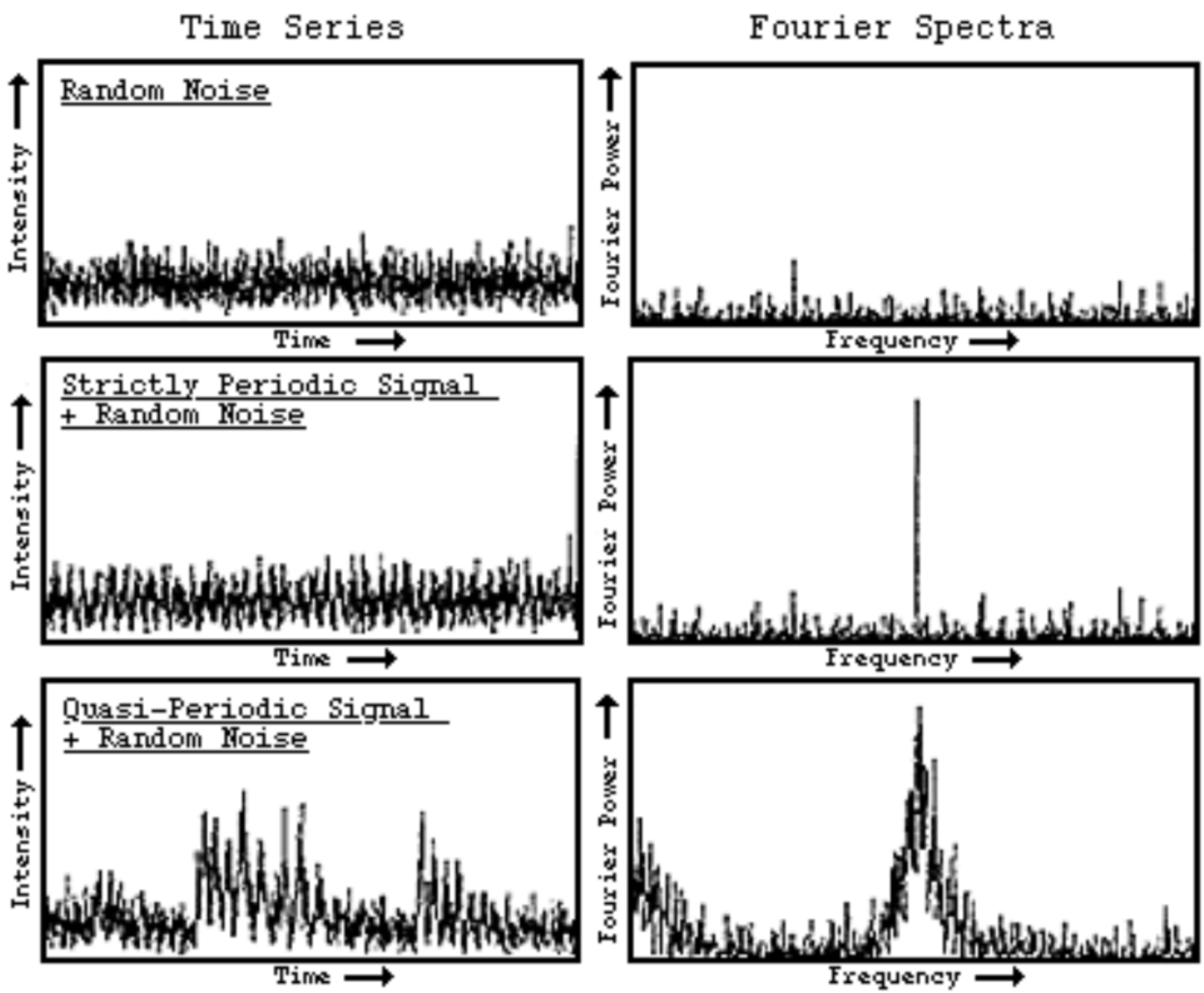
Pulsars = rotating neutron stars

Neutron stars were expected as remnants of supernovae: a pulsar was soon discovered in the **Crab Nebula**, where a supernova exploded in 1054.

The Crab pulsar also pulses in visual light

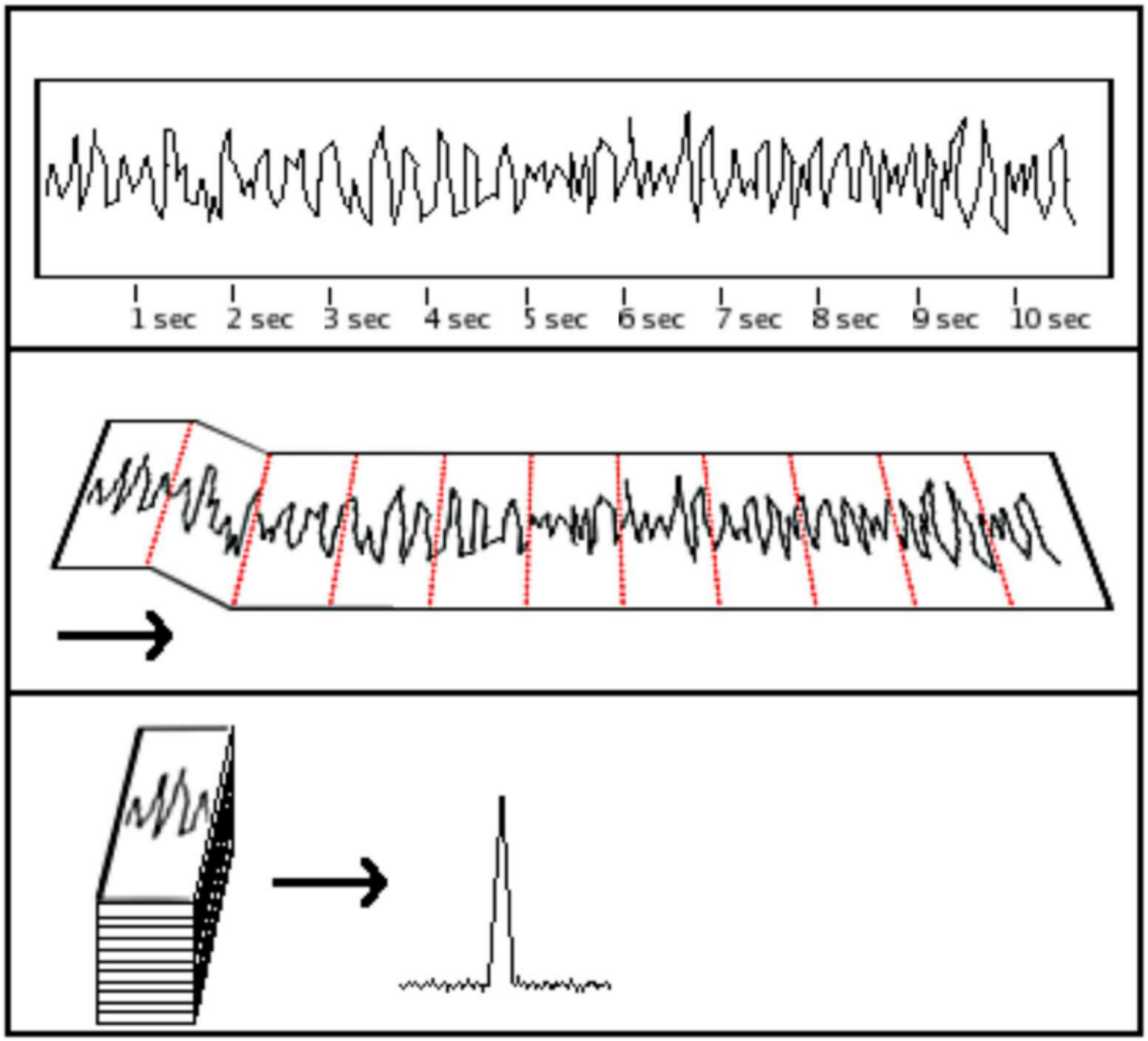


Search for pulsations



Search for pulsations

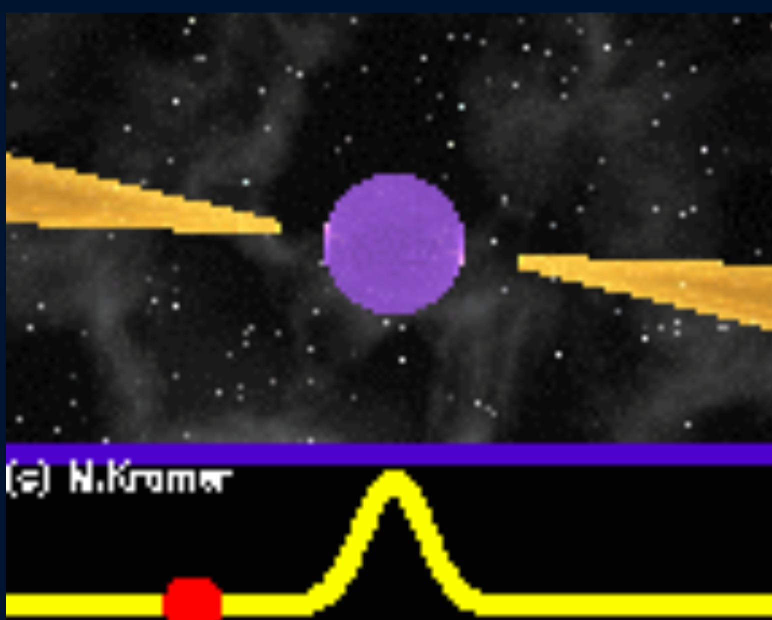
Folding (if the period is known)



Neutron star properties

The collapse of its core amplifies some properties of the exploded star:

- **Density** (the mass of the Sun in a sphere of ~10 km radius)
- **Rotation rate** (up to hundreds of rotations per second)
- **Magnetic field** (up to ~10^{15} times larger than Earth field)



Pulsar parameters from P and $\dot{P}$

Crab: P=33 ms, $\dot{P}$=4.3 x 10^{-13} s s^{-1}

Rotational energy loss: $\dot{E}_{rot} = \frac{d}{dt}\left(\frac{1}{2}I\omega^2\right) = I\omega\dot{\omega} = I\frac{4\pi^2}{P}\frac{d}{dt}\left(\frac{1}{P}\right) = -4\pi^2 I\dot{P}P^{-3}$

$$\Rightarrow \dot{E}_{rot,Crab} \approx 5\times10^{38} \text{ erg s}^{-1}$$

Rotating magnetic dipole in vacuum: $\dot{E} = -(32\pi^4/3c^3)B_\perp^2 R^6 P^{-4}$

$$\Rightarrow B_\perp = \sqrt{\frac{3c^3 IP\dot{P}}{8\pi^2 R^6}} \approx 3.2\times10^{19}\left(\boxed{P\dot{P}}\right)^{1/2} \text{ G}$$

$$\Rightarrow B_{Crab} \approx 4\times10^{12}\ G$$

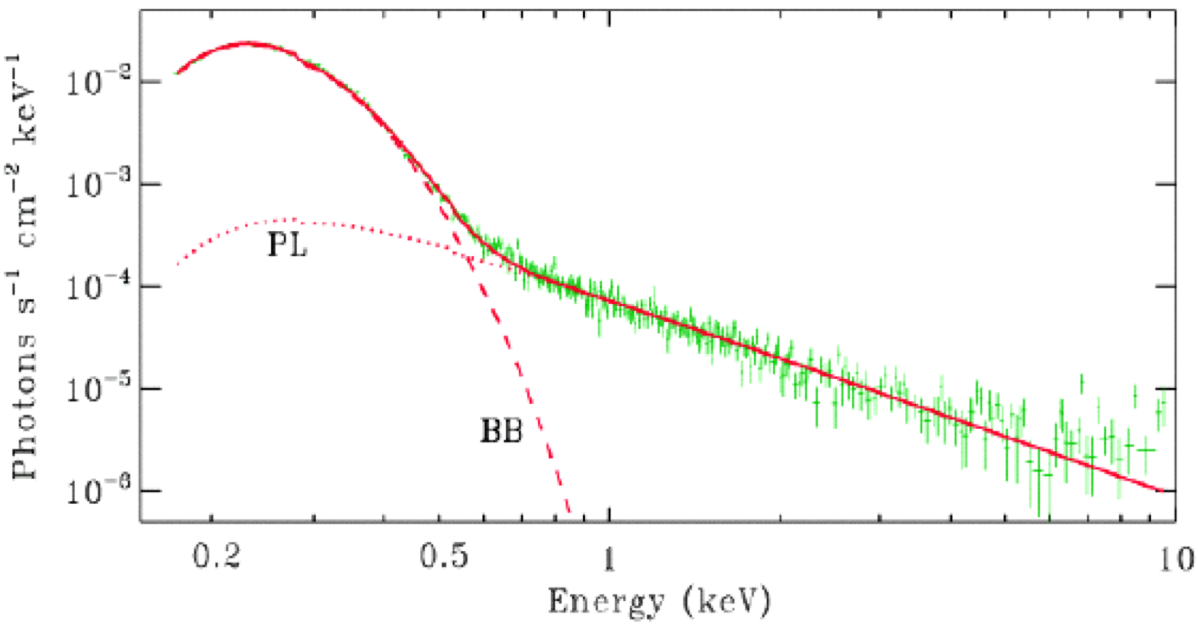
Characteristic age: $\tau = P/2\dot{P}$

$$P\dot{P} = P\frac{dP}{dt} \Rightarrow \int_0^\tau PdP = \int_0^\tau \boxed{P\dot{P}}dt \Rightarrow \frac{1}{2}\left(P^2 - P_0^2\right) = P\dot{P}\tau \Rightarrow \tau \approx \frac{P}{2\dot{P}} \text{ if } P_0 << P$$

$$\Longrightarrow \tau_{\text{Crab}} \approx 1218 \text{ yrs} \approx 2023 - 1054 = 969 \text{ yrs}$$

Rotation-powered pulsars at X-rays

- **Crab-like:** $\tau < 10^4$ years. In SNR and thermal emission well below non-termal PL emission (only upper limits on T)
- **Vela-like:** $\tau \sim 10^4$-10^5 years. Thermal emission emerging from non-thermal emission ($T_\infty \sim 1$ MK)
- **Geminga-like:** $\tau \sim 10^5$-10^6 years. At X-rays, thermal emission and non-thermal tail



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- **Geminga-like:** $\tau \sim 10^5$-10^6 years. At X-rays, thermal emission and non-thermal tail
- **Old pulsars:** $\tau > 10^6$ years. Weak non-thermal emission, but also low temperature $\Rightarrow$ faint sources
- **Msec pulsars:** $\tau > 10^8$ years. P~few ms and B ~10^8-10^{10}, as result of accretion in binary system. Non-thermal spectra and, in some cases, thermal X-rays from heated polar cap

The Magnificent Seven (M7)
(or XDINS: X-ray Dim Isolated Neutron Stars)

- Discovered by the *ROSAT* satellite as soft X-ray sources with no optical counterpart

- Thermal spectrum, low interstellar absorption, X-ray pulsations with P=3-12 s (but no radio emission) ⇒ nearby (~100 pc) **neutron stars**

- Among >2,000 NSs, **only** the M7 have pure thermal spectra (in some cases, broad absorption lines) ⇒ we directly observe the hot (~10^6 K) NS surface

- Ideal objects to study the Equation of State of NSs

RXJ1856 before 2007

- RXJ1856 is the **brightest** and the **closest** of the Magnificent Seven ⇒ the best target to study EoS
- Despite 10 years of searches, **no pulsation** (pulsed fraction<1.2%)

Why?

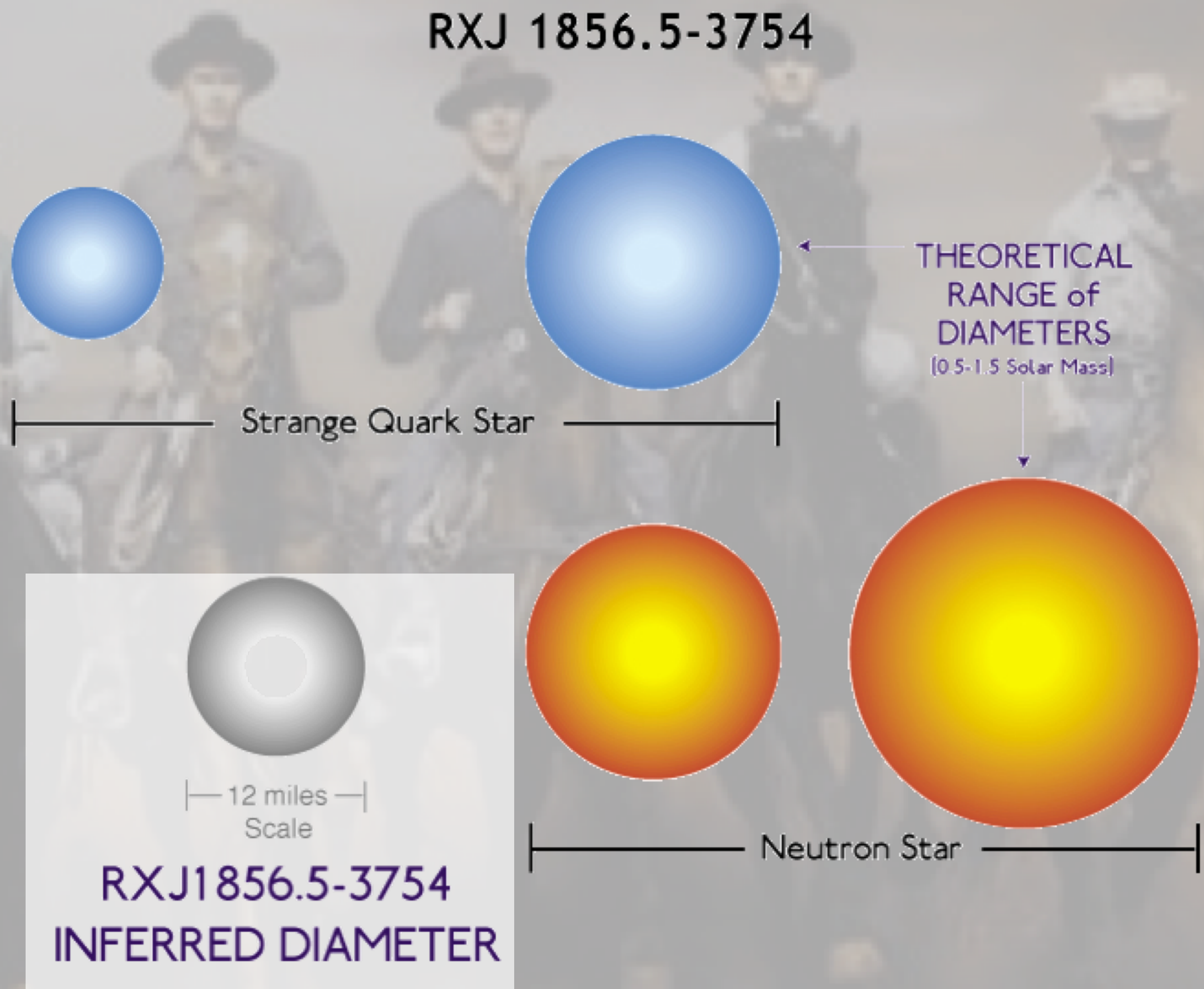
✓ Fast (or slow) rotator?

✓ Aligned rotator?

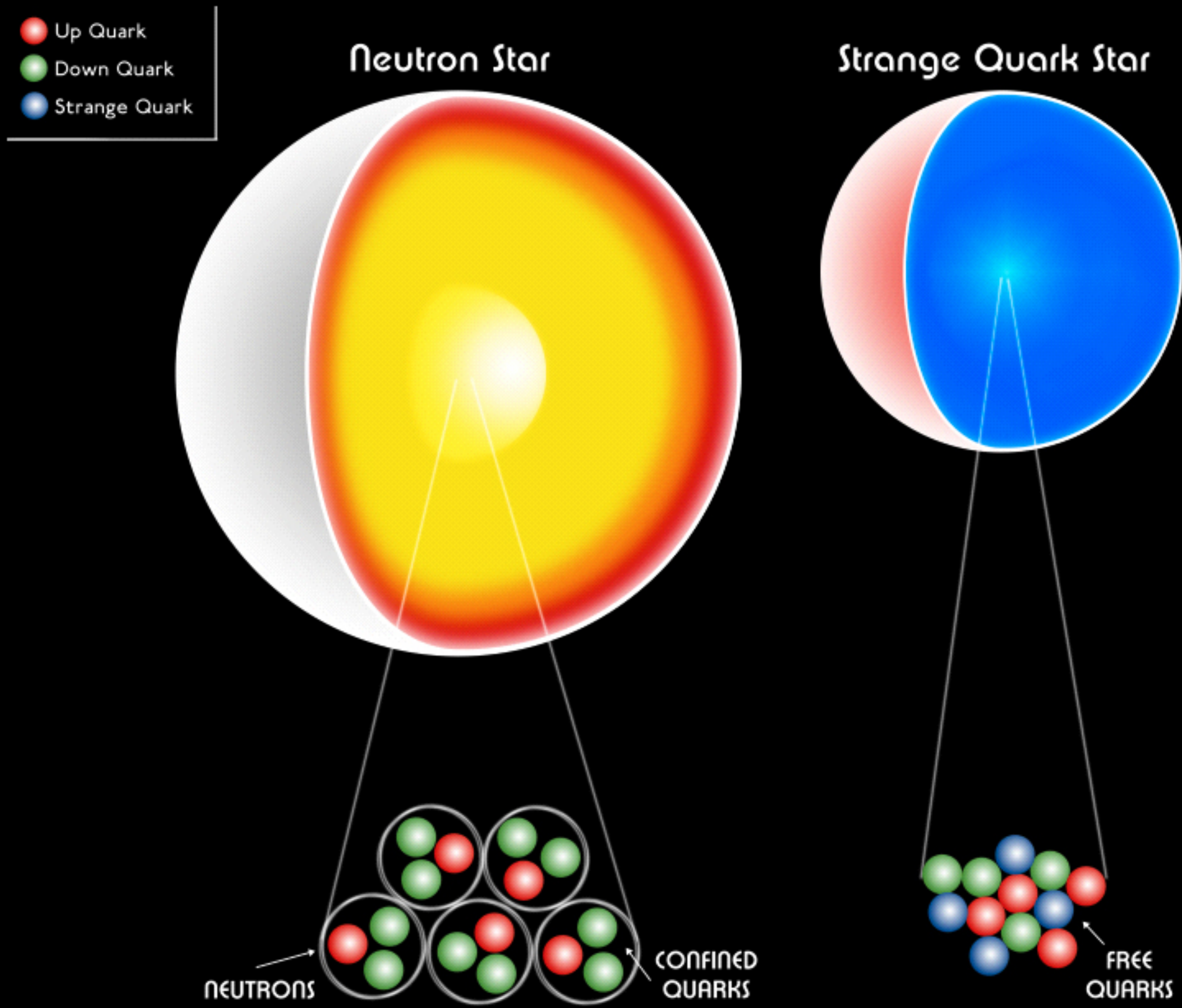
✓ Perfectly uniform temperature?

Is RXJ1856 too small to be a NS?

No pulsations and BB **radius < 5 km** ⇒ assuming uniform BB from whole NS surface, it must be smaller than a NS ⇒ **quark star**!

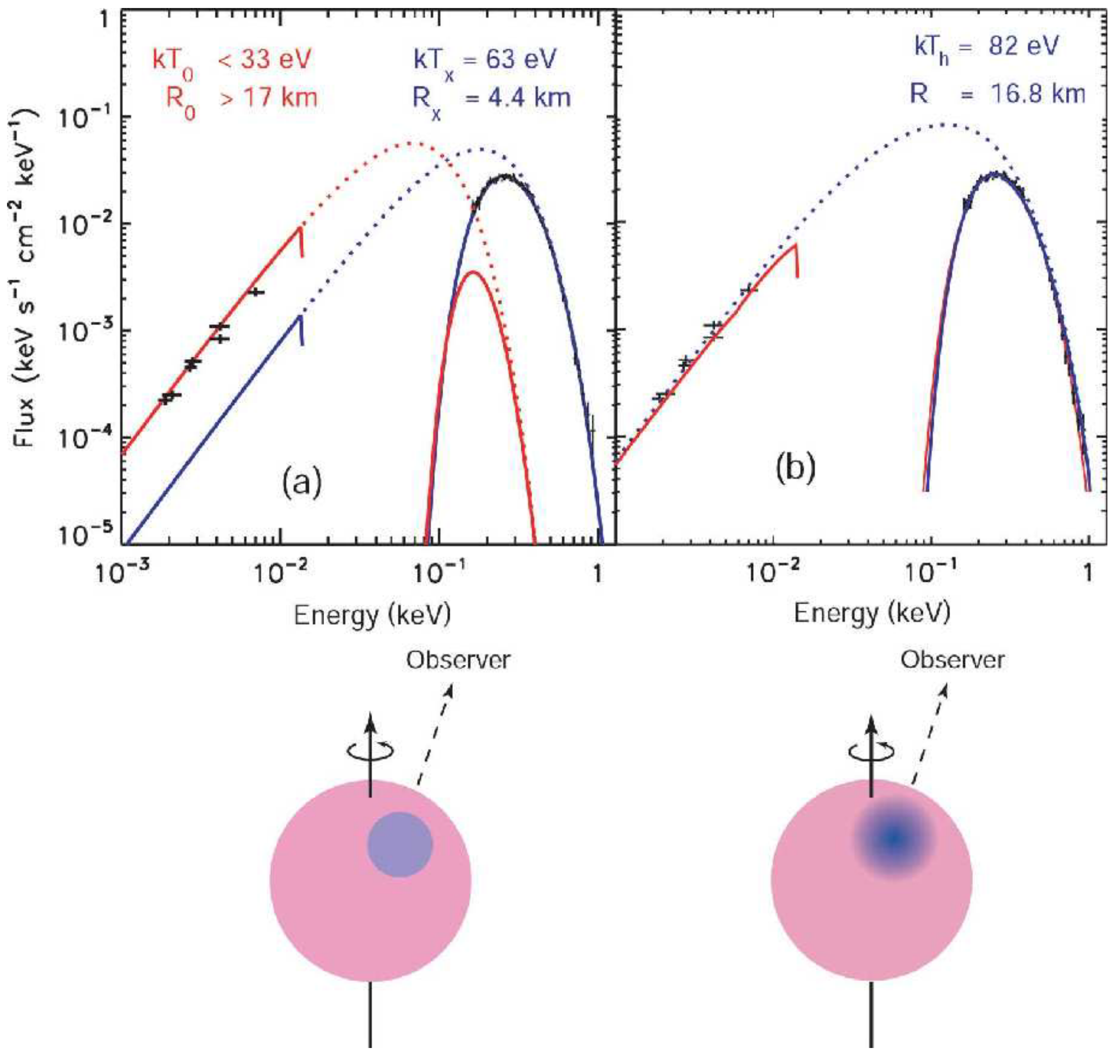


Neutron star vs. quark star



How robust is the radius measure?

Optical/UV excess suggests X-rays emitted by a **hot spot** ⇒ the rest of the surface is much cooler ⇒ **larger** (and model-dependent) NS **radius**



A&A 399, 1109–1114 (2003)
DOI: 10.1051/0004-6361:20021747

Astronomy & Astrophysics

The thermal radiation of the isolated neutron star RX J1856.5–3754 observed with Chandra and XMM-Newton

V. Burwitz, F. Haberl, R. Neuhäuser, P. Predehl, J. Trümper, and V. E. Zavlin

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Abstract. We present results of the analysis of data collected in 57-ks *XMM-Newton* and 505-ks *Chandra* observations of the nearby ($\simeq$120 pc) isolated neutron star RX J1856.5–3754. We confirm most of the statements made by Burwitz et al. (2001) who discussed the original 55-ks *Chandra* data. Detailed spectral analysis of the combined X-ray and optical data rules out the currently available nonmagnetic light and heavy element neutron star atmosphere (LTE) models with hydrogen, helium, iron and solar compositions. We find that strongly magnetized atmosphere models also are unable to represent the data. The X-ray and optical data show no spectral features and are best fitted with a two-component blackbody model with $kT^{\infty}_{\rm bb,X} \simeq 63.5$ eV and $R^{\infty}_{\rm bb,X} \simeq 4.4\,(d/120\,{\rm pc})$ km for the hot X-ray emitting region, and $kT^{\infty}_{\rm bb,opt} < 33$ eV and $R^{\infty}_{\rm bb,opt} > 17\,(d/120\,{\rm pc})$ km for the rest of the neutron star surface responsible for the optical flux. The large number of counts collected with *XMM-Newton* allows us to reduce the upper limit on periodic variation in the X-ray range down to 1.3% (at a 2σ confidence level) in the 10^{-3}–50 Hz frequency range. In an attempt to explain this small variability, we discuss an one-component model with $kT^{\infty}_{\rm bb} \simeq 63$ eV and $R^{\infty}_{\rm bb} \simeq 12.3\,(d/120\,{\rm pc})$ km. This model requires a low radiative efficiency in the X-ray domain, which may be expected if the neutron star has a condensed matter surface.

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XMM-NEWTON DISCOVERY OF 7 s PULSATIONS IN THE ISOLATED NEUTRON STAR RX J1856.5−3754

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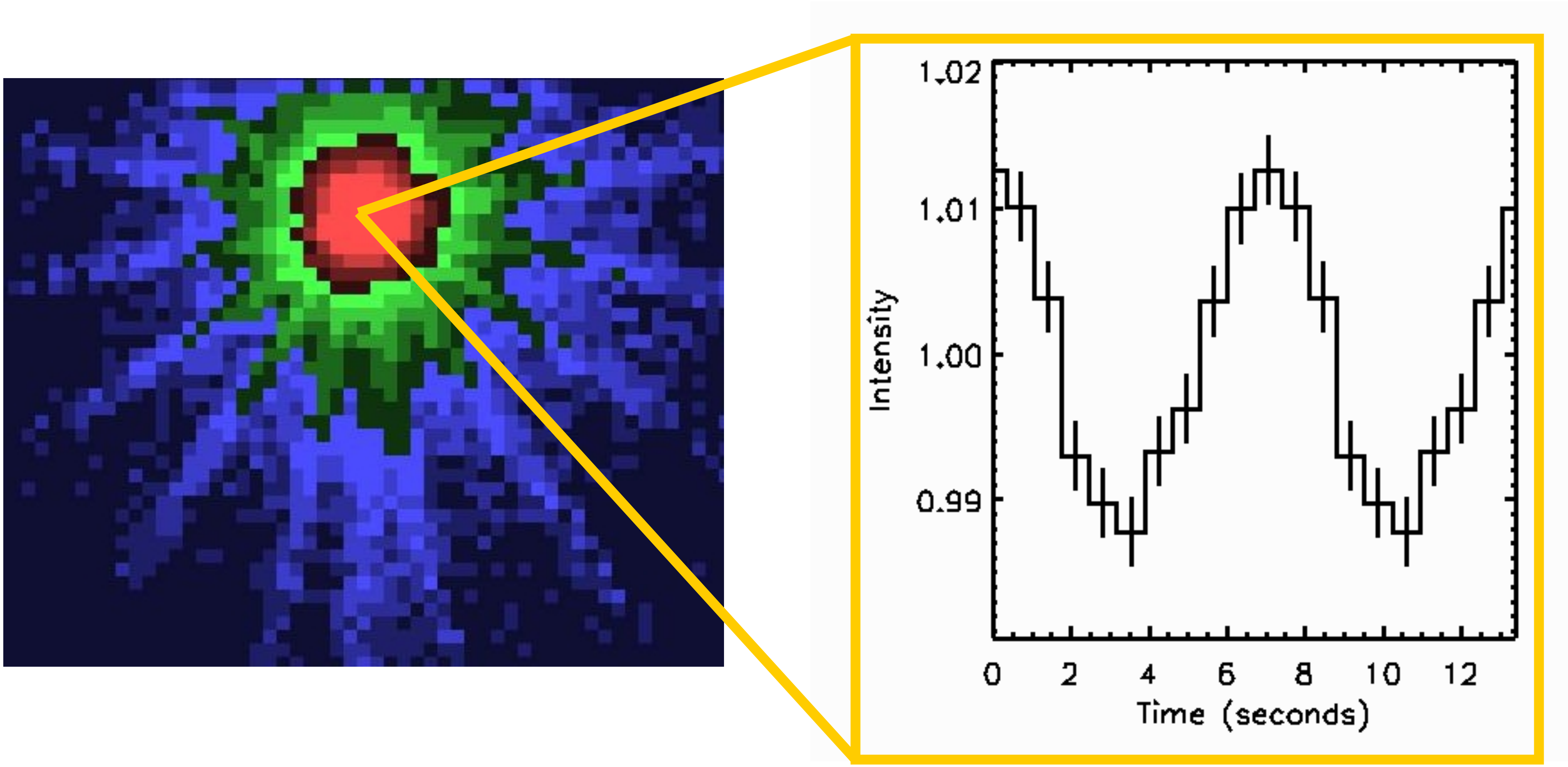

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Two decades of X-ray observations of the isolated neutron star RX J1856.5 − 3754: detection of thermal and non-thermal hard X-rays and refined spin-down measurement

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ABSTRACT

The soft X-ray pulsar RX J1856.5 − 3754 is the brightest member of a small class of thermally emitting, radio-silent, isolated neutron stars. Its X-ray spectrum is almost indistinguishable from a blackbody with $kT^\infty \approx 60$ eV, but evidence of harder emission above ~ 1 keV has been recently found. We report on a spectral and timing analysis of RX J1856.5 − 3754 based on the large amount of data collected by *XMM-Newton* in 2002–2022, complemented by a dense monitoring campaign carried out by *NICER* in 2019. Through a phase-coherent timing analysis we obtained an improved value of the spin-down rate $\dot{\nu} = -6.042(4) \times 10^{-16}$ Hz s^{-1}, reducing by more than one order magnitude the uncertainty of the previous measurement, and yielding a characteristic spin-down field of 1.47×10^{13} G. We also detect two spectral components above ~ 1 keV: a blackbody-like one with $kT^\infty = 138 \pm 13$ eV and emitting radius 31^{+8}_{-16} m, and a power law with photon index $\Gamma = 1.4^{+0.5}_{-0.4}$. The power-law 2–8 keV flux, $(2.5^{+0.7}_{-0.6}) \times 10^{-15}$ erg cm^{-2} s^{-1}, corresponds to an efficiency of 10^{-3}, in line with that seen in other pulsars. We also reveal a small difference between the 0.1–0.3 keV and 0.3–1.2 keV pulse profiles, as well as some evidence for a modulation above 1.2 keV. These results show that, notwithstanding its simple spectrum, RX J1856.5 − 3754 still has a non-trivial thermal surface distribution and features non-thermal emission as seen in other pulsars with higher spin-down power.