Compact Objects in the Milky Way

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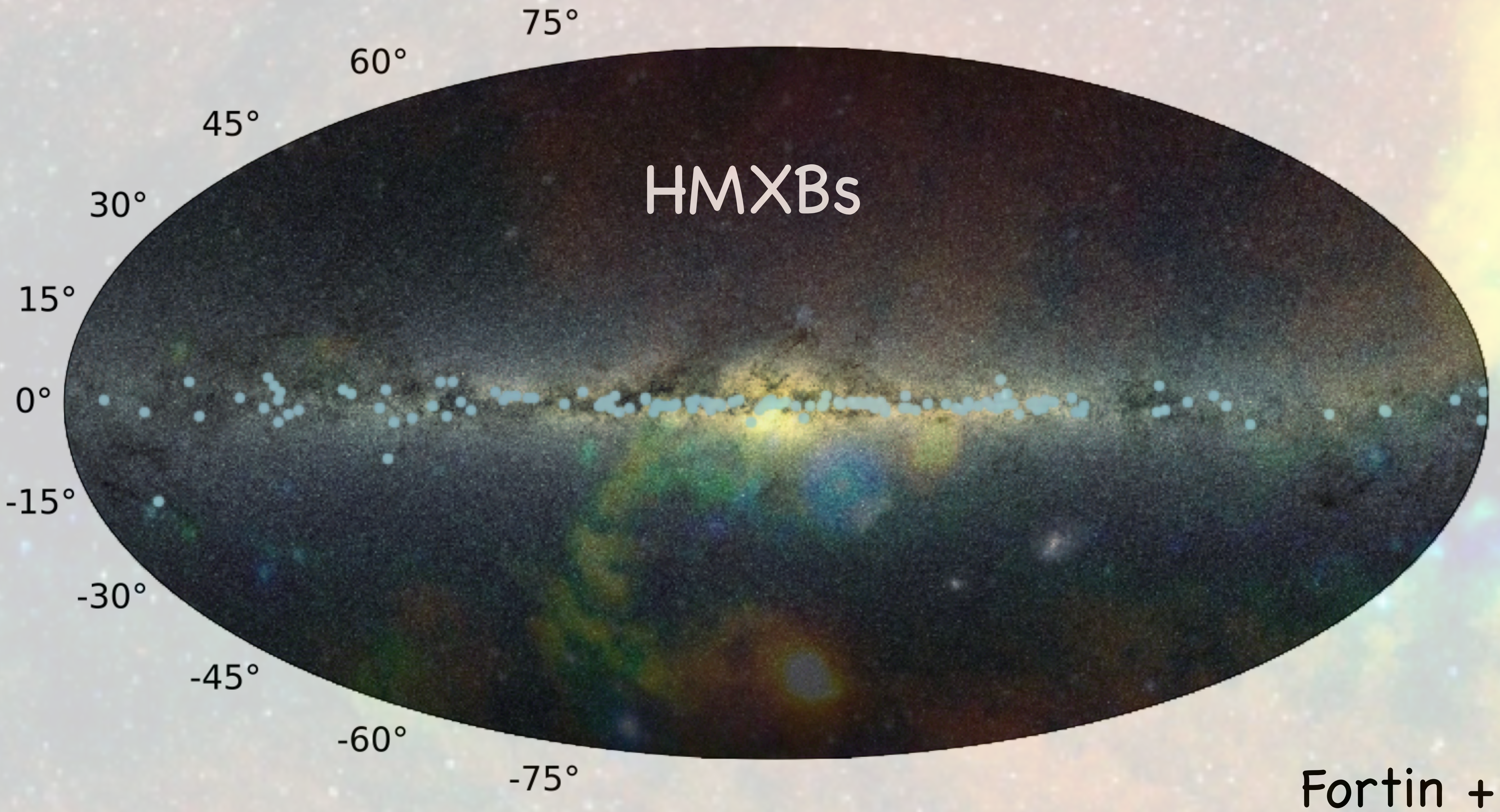
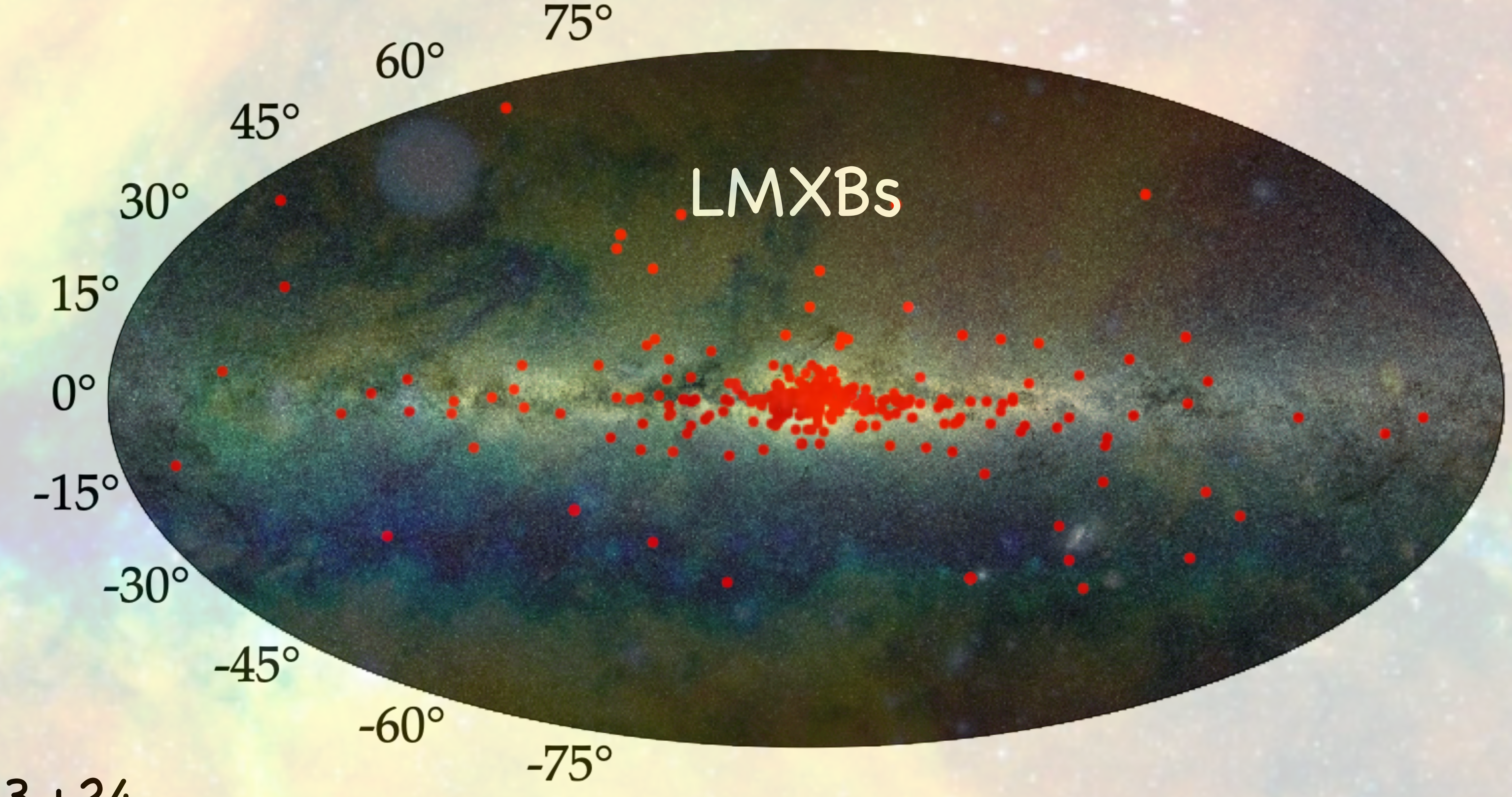
Extraterrestrial Physics, Germany

Brightest compact objects are accreting!





Fortin +23,+24
Also Neumann+23, Avakyan+23

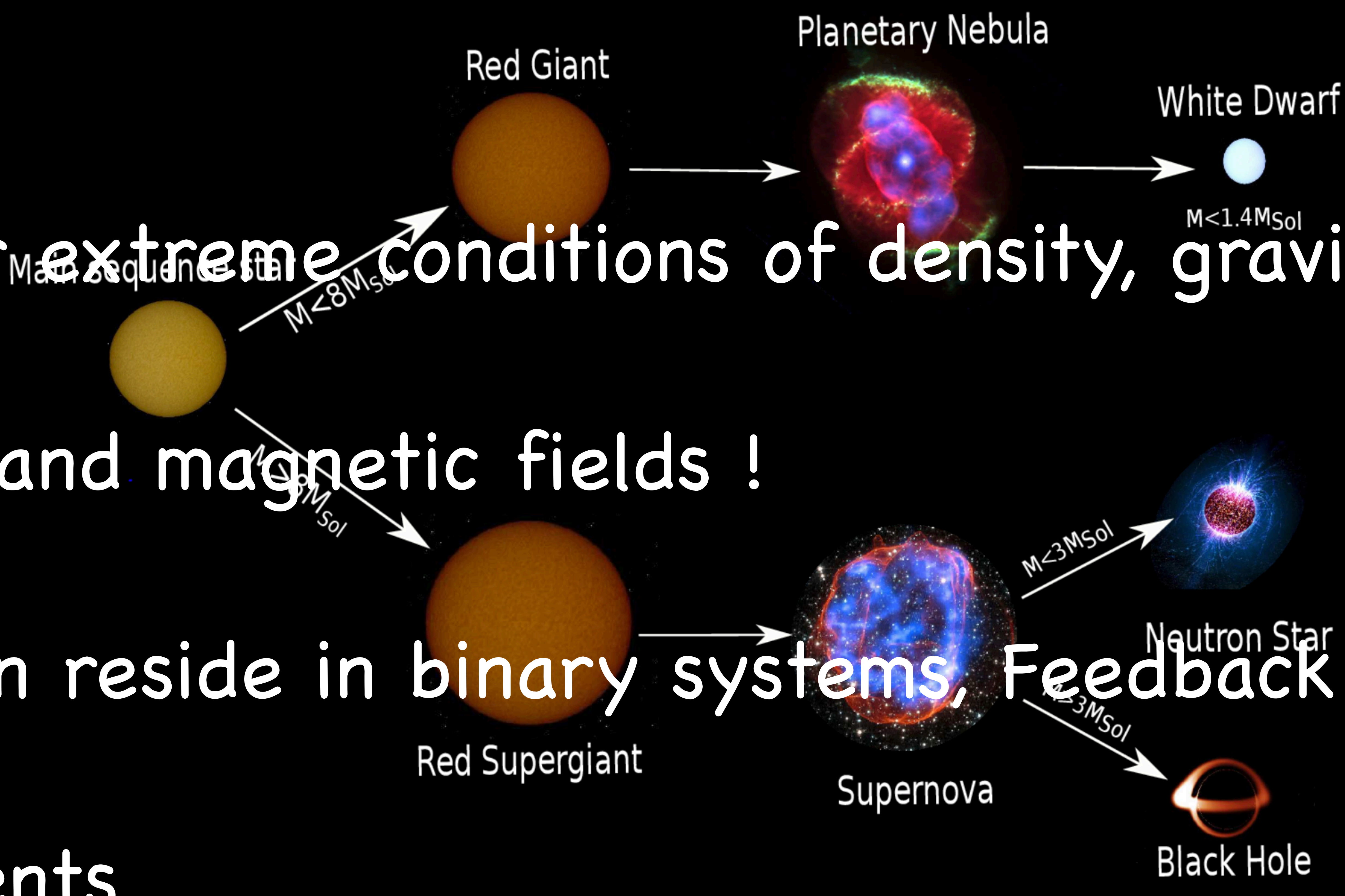
η_{acc}= accreting efficiency can be as high as 10-40% compare to 0.7% for nuclear burning

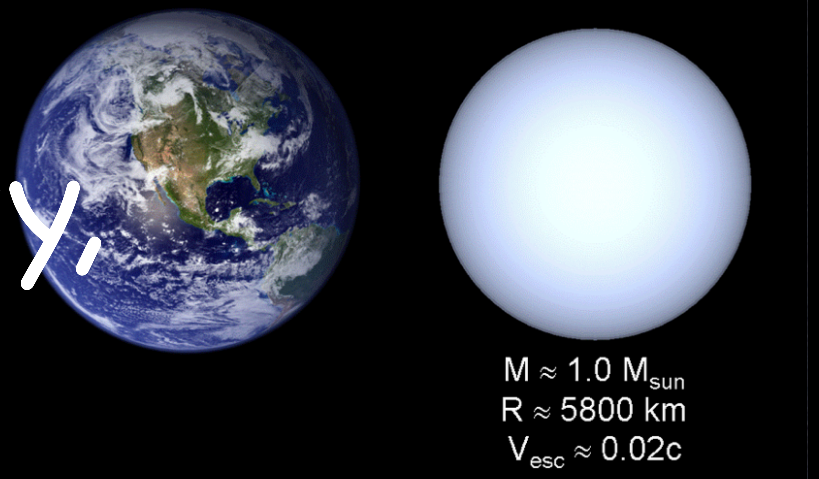
Neutron stars & Black holes

L_x 10^{35}-10^{39} erg/s

What are compact objects and why do we care?

‘Compact’ objects





NASA's Goddard Space Flight Center/Conceptual Image Lab

- Matter under extreme conditions of density, gravity, temperature and magnetic fields !
- Large fraction reside in binary systems, Feedback to ISM, exotic transients

Object	M	R
–	$M\odot$	cm
White Dwarf	≤ 1.4	10^9
Neutron Stars	~ 1.4	10^6
Black holes	> 3	$3 \times 10^{-5} \frac{M}{M\odot}$

ρ ~10^6 gm/cm³
g ~10^8 m/cm²

White dwarf

ρ ~10^{14} gm/cm³
g ~10^{14} m/cm²

Neutron star

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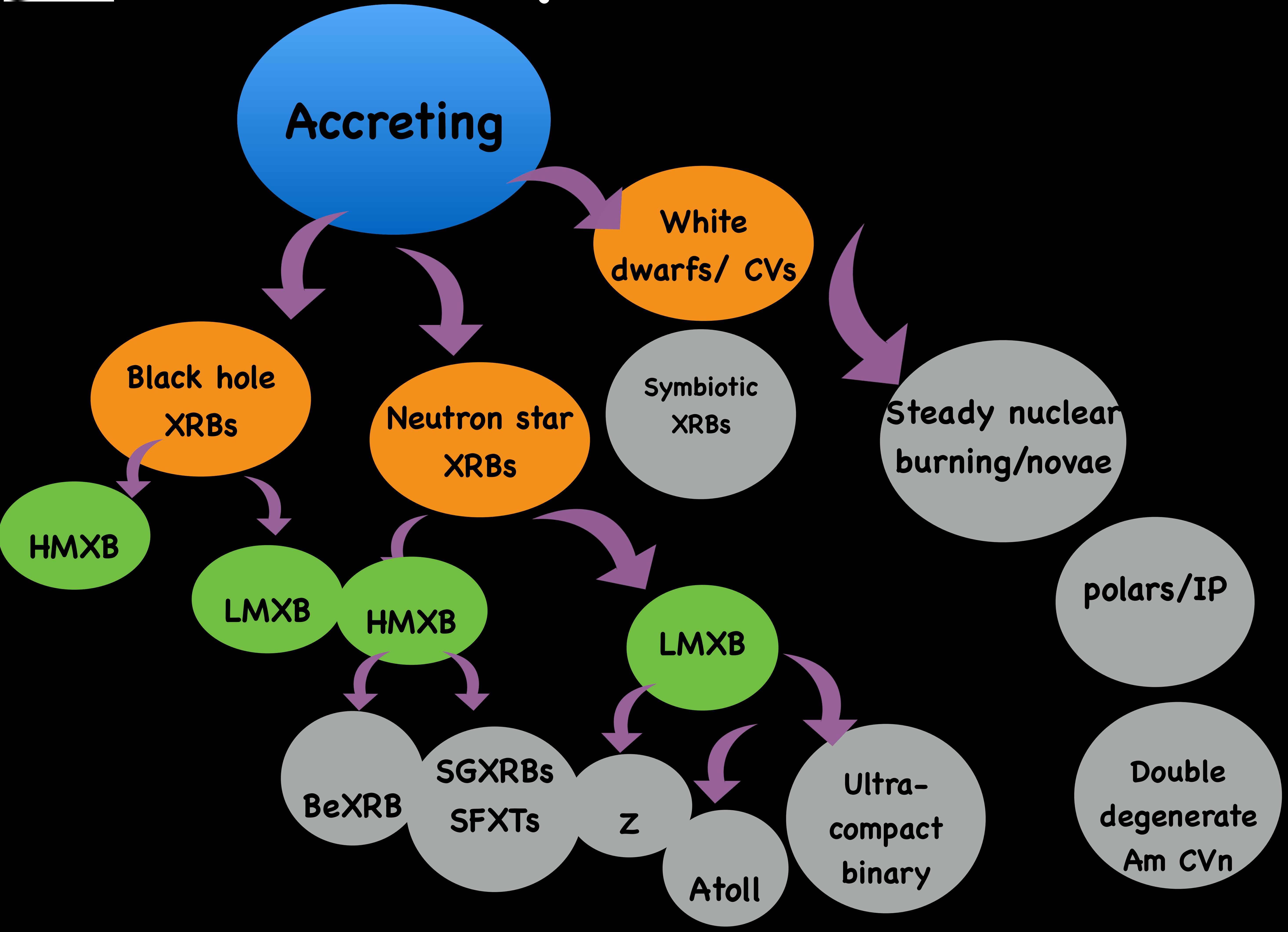
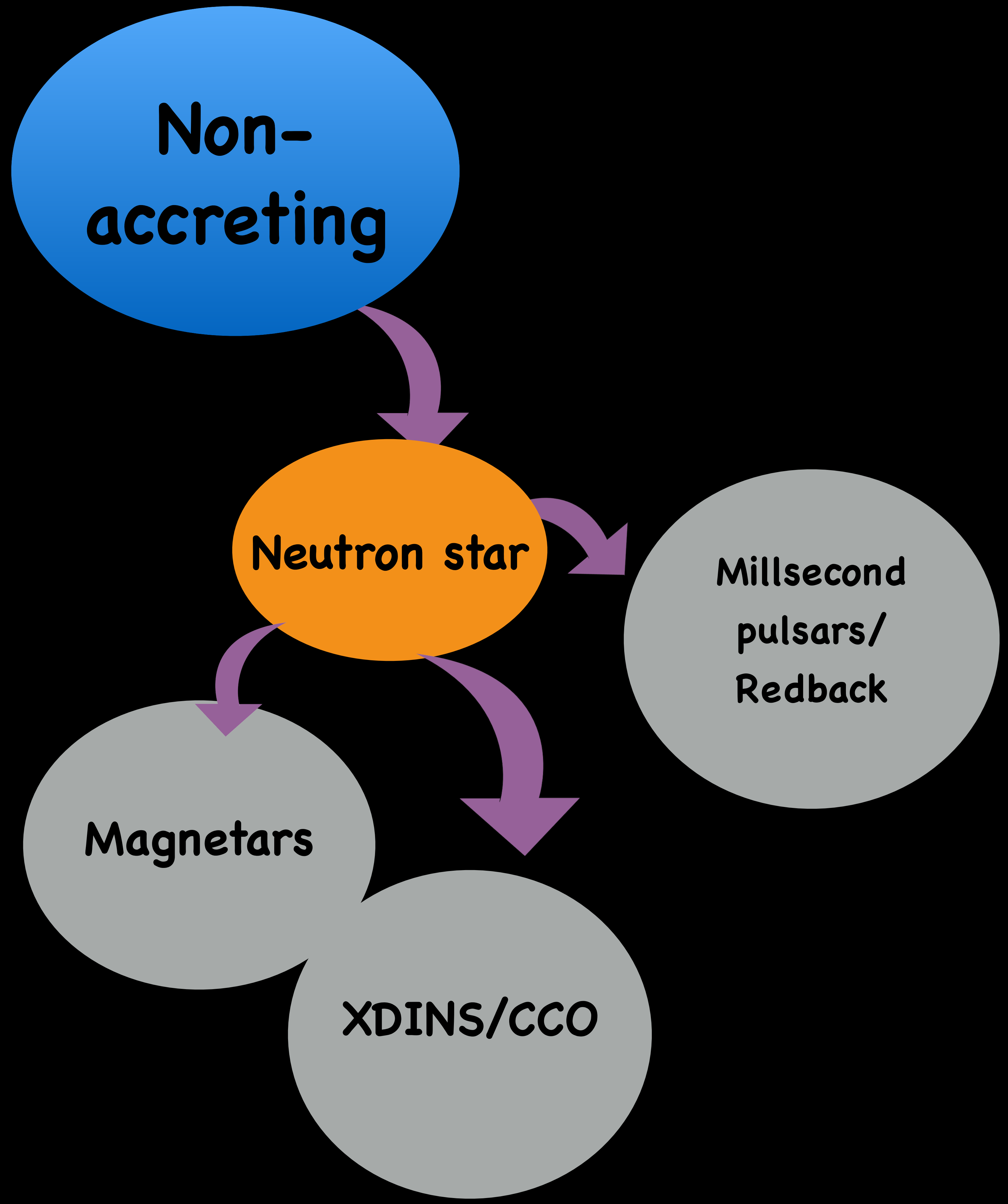
Compact Object Zoo in X-rays



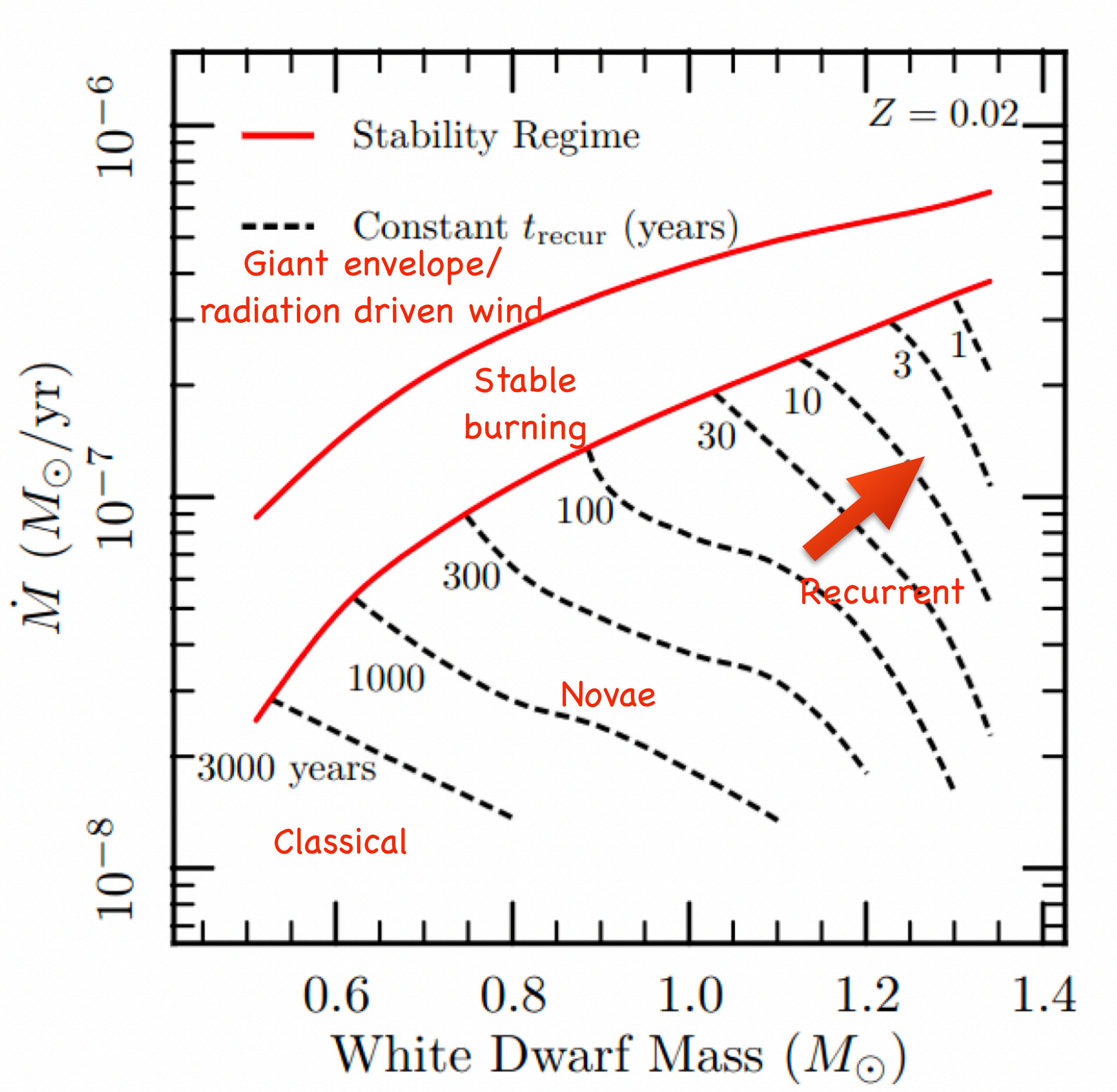
- Accreting
  - Black hole XRBs
    - HMXB
    - LMXB
  - Neutron star XRBs
    - HMXB
      - BeXRB
      - SGXRBs SFXTs
    - LMXB
      - Z
      - Atoll
      - Ultra-compact binary
  - White dwarfs/ CVs
    - Symbiotic XRBs
    - Steady nuclear burning/novae
    - polars/IP
    - Double degenerate Am CVn



- Non-accreting
  - Neutron star
    - Millsecond pulsars/ Redback
    - Magnetars
    - XDINS/CCO

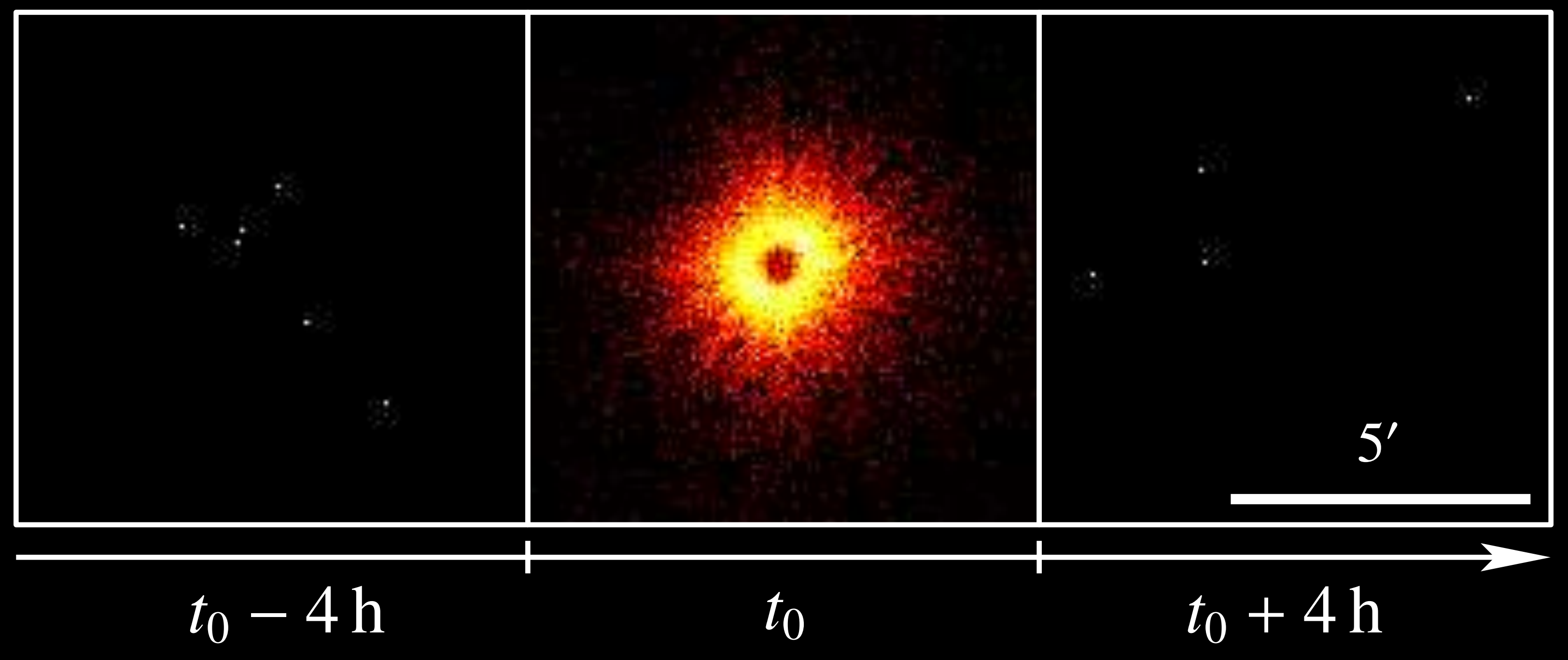
Key questions & breakthroughs

White dwarfs, Novae, & Type Ia Supernovae



Wolf+13

Discovery of a Nova ignition flash



Article

X-ray detection of a nova in the fireball phase

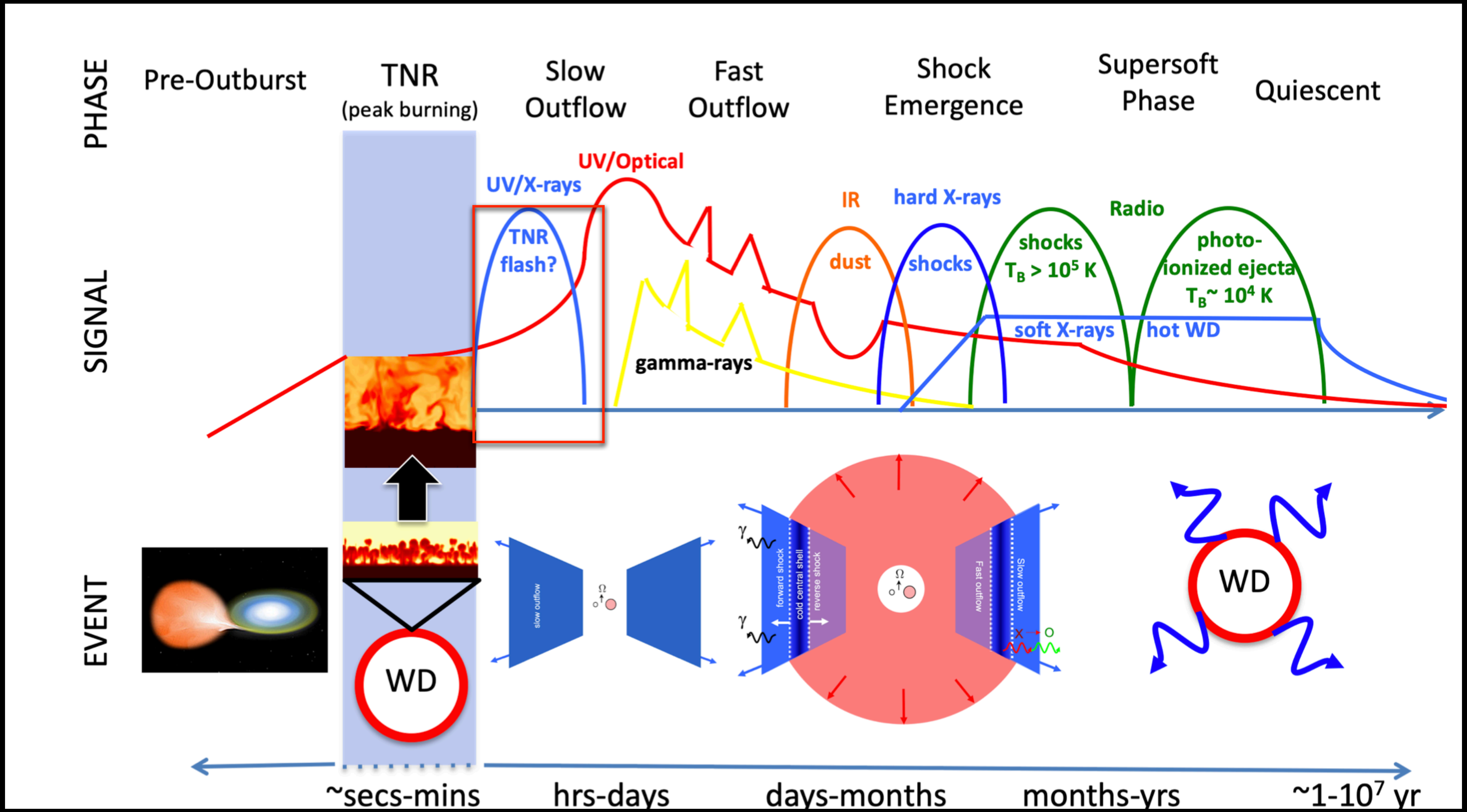
https://doi.org/10.1038/s41586-022-04635-y
Received: 11 January 2022
Accepted: 14 March 2022

Ole König[1]✉, Jörn Wilms[1]✉, Riccardo Arcodia[2], Thomas Dauser[1], Konrad Dennerl[2], Victor Doroshenko[3], Frank Haberl[2], Steven Hämmerich[1], Christian Kirsch[1], Ingo Kreykenbohm[1], Maximilian Lorenz[1], Adam Malyali[2], Andrea Merloni[2], Arne Rau[2], Thomas Rauch[3], Gloria Sala[4,5], Axel Schwope[6], Valery Suleimanov[3], Philipp Weber[1] & Klaus Werner[3]

Novae are caused by runaway thermonuclear burning in the hydrogen-rich envelopes of accreting white dwarfs, which leads to a rapid expansion of the envelope and the ejection of most of its mass[1,2]. Theory has predicted the existence of a 'fireball' phase following directly on from the runaway fusion, which should be observable as a short, bright and soft X-ray flash before the nova becomes visible in the optical[3–5]. Here we report observations of a bright and soft X-ray flash associated with the classical Galactic nova YZ Reticuli 11 h before its 9 mag optical brightening. No X-ray source was detected 4 h before and after the event, constraining the duration of the flash to shorter than 8 h. In agreement with theoretical predictions[4,6–8], the source's spectral shape is consistent with a black-body of $3.27^{+0.11}_{-0.33} \times 10^5$ K ($28.2^{+0.9}_{-2.8}$ eV), or a white dwarf atmosphere, radiating at the Eddington luminosity, with a photosphere that is only slightly larger than a typical white dwarf.

König, Wilms, et al. Nature+22

Timeline of physical processes & EM radiation in nova

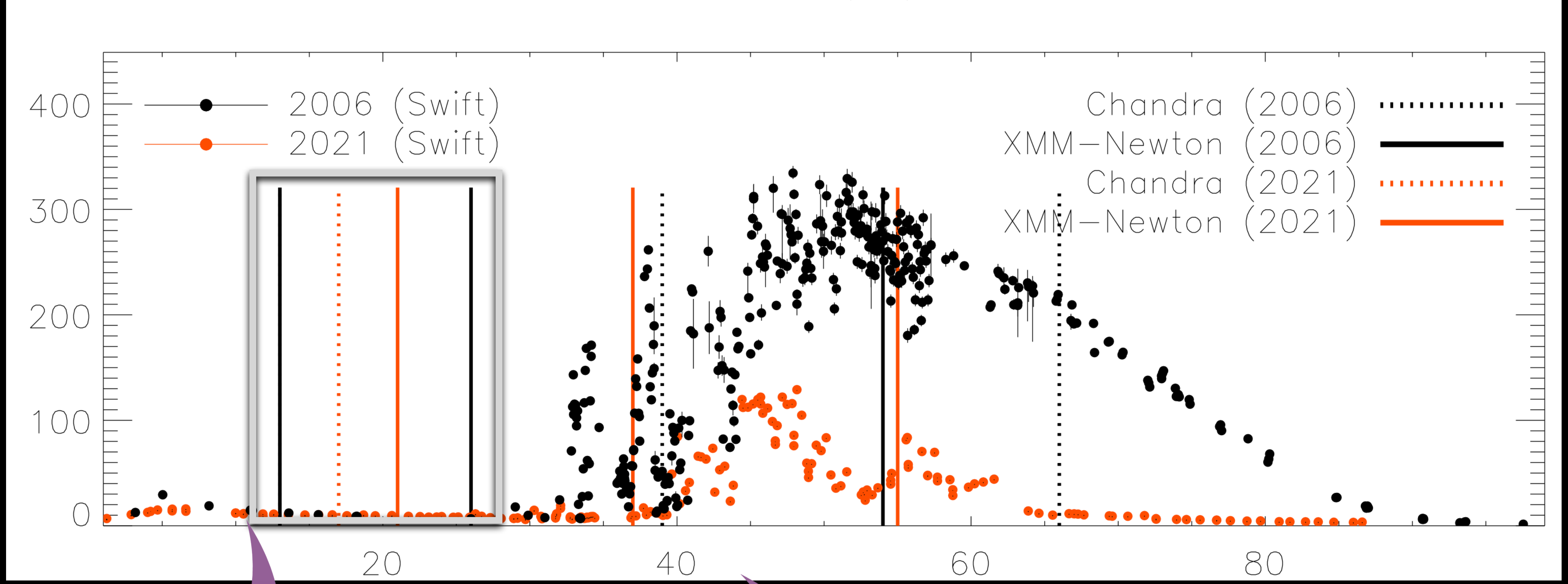


Chomiuk+20

20-70 novae/yr in Galaxy (Shafter+17)

RS Ophiuchi: A recurrent symbiotic nova

The recurrent nova RSOphuichi (RSOph) consists of a massive WD and an RG donor star in a binary orbit with a period of 453.6 ± 0.4 days

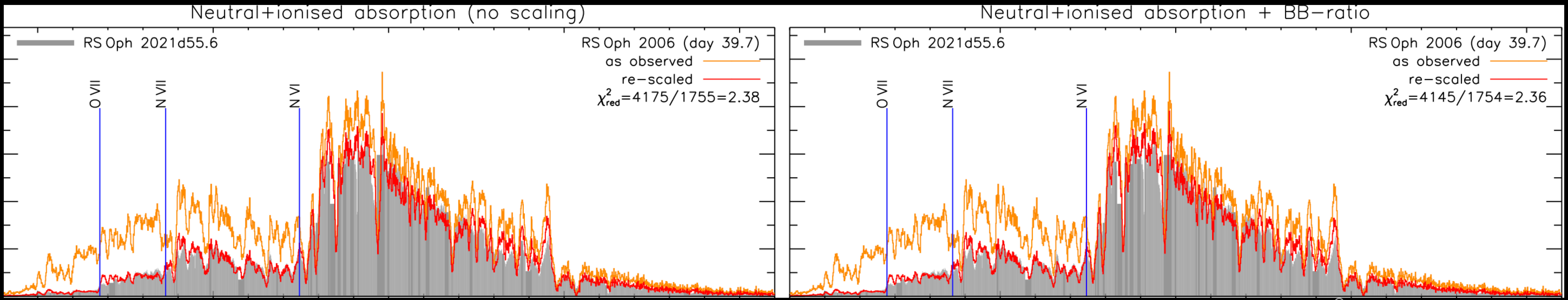


Tref.

Page+22

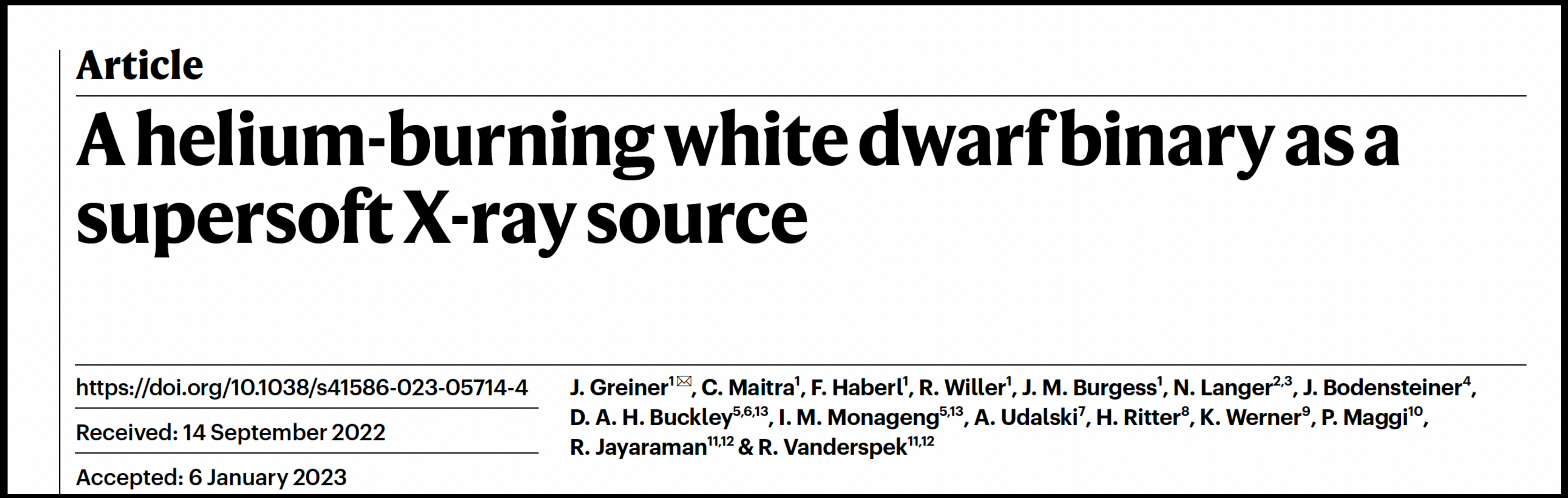
high-velocity ejecta from the TNR runs into its dense stellar wind, giving rise to X-ray emission from hot, shocked gas (Orio+22, Islam+23)

Central engine same, variable absorber between 2006 & 2021



(Ness+23)

Smoking gun of SN 1a single degenerate scenario



Article

A helium-burning white dwarf binary as a supersoft X-ray source

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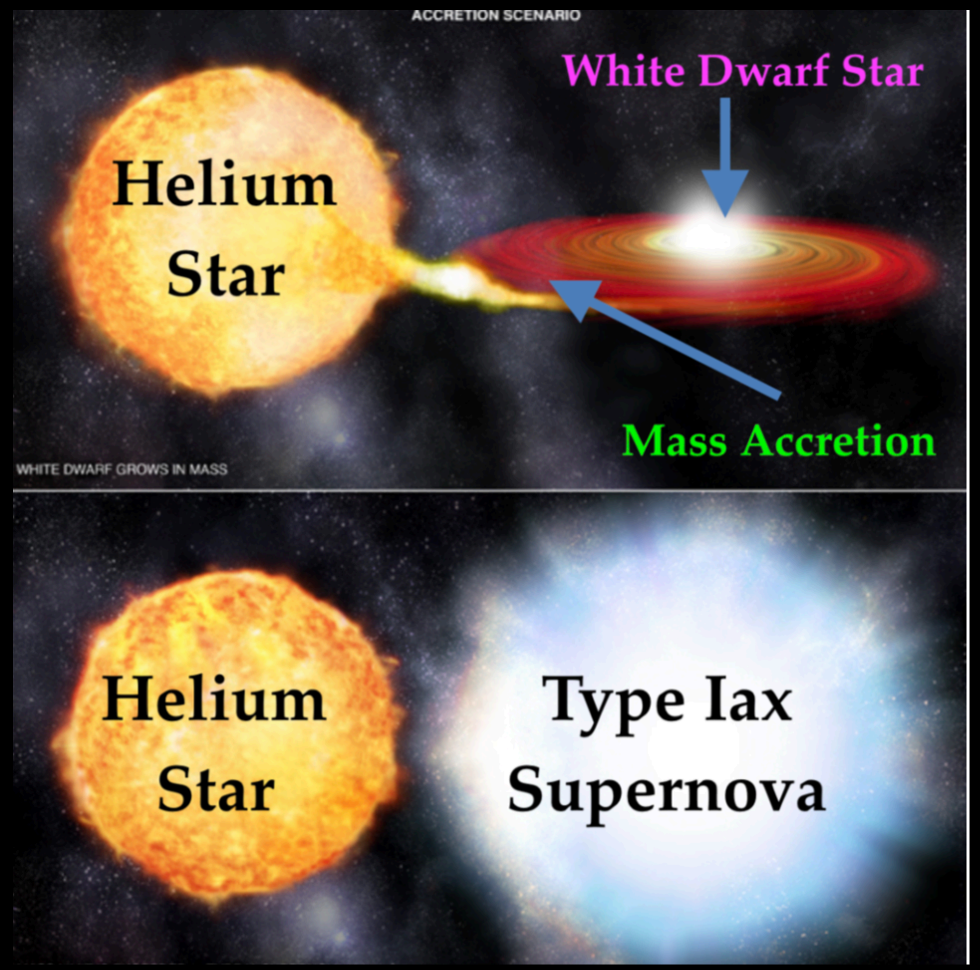
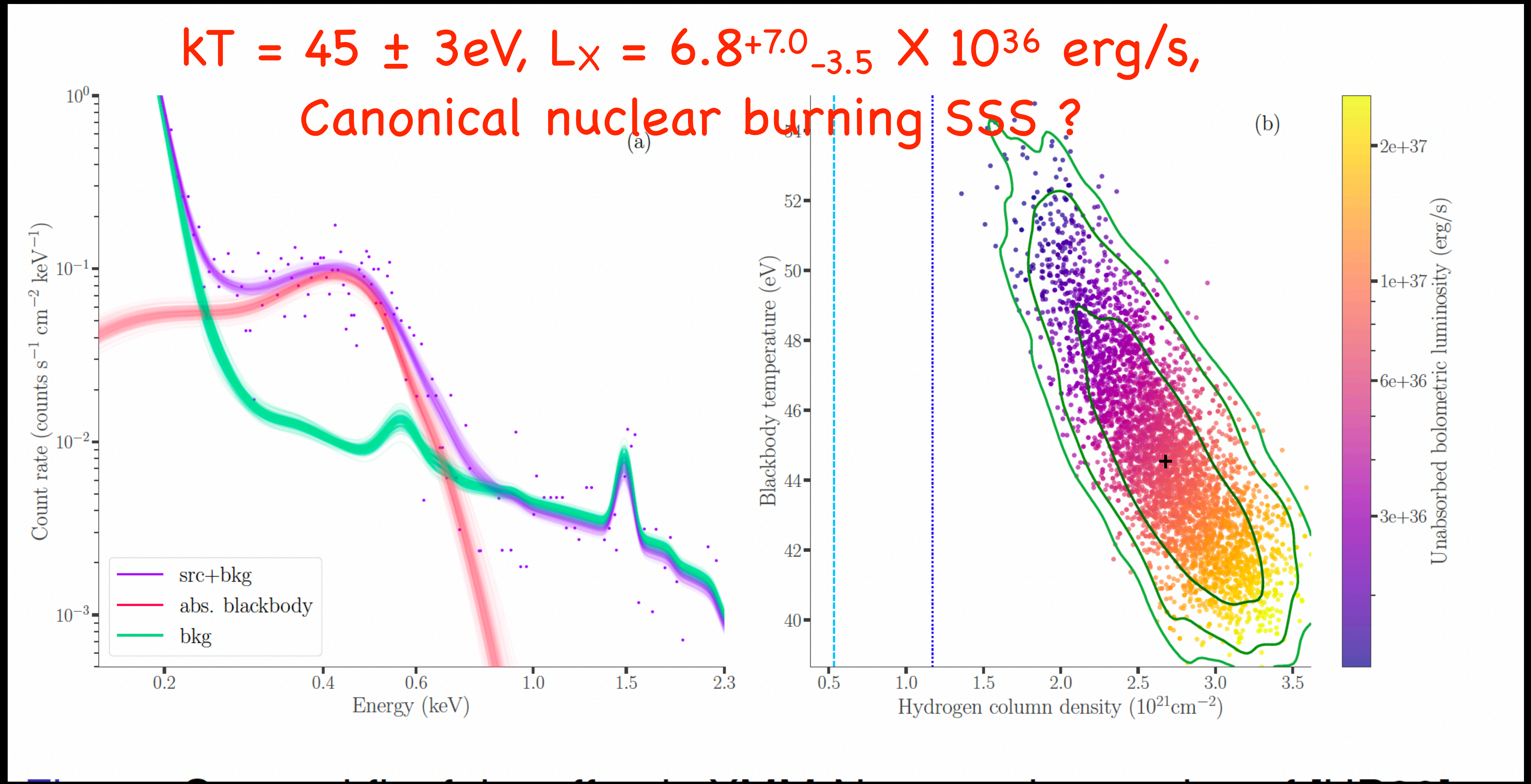
Received: 14 September 2022

Accepted: 6 January 2023

J. Greiner[1]✉, C. Maitra[1], F. Haberl[1], R. Willer[1], J. M. Burgess[1], N. Langer[2,3], J. Bodensteiner[4], D. A. H. Buckley[5,6,13], I. M. Monageng[5,13], A. Udalski[7], H. Ritter[8], K. Werner[9], P. Maggi[10], R. Jayaraman[11,12] & R. Vanderspek[11,12]

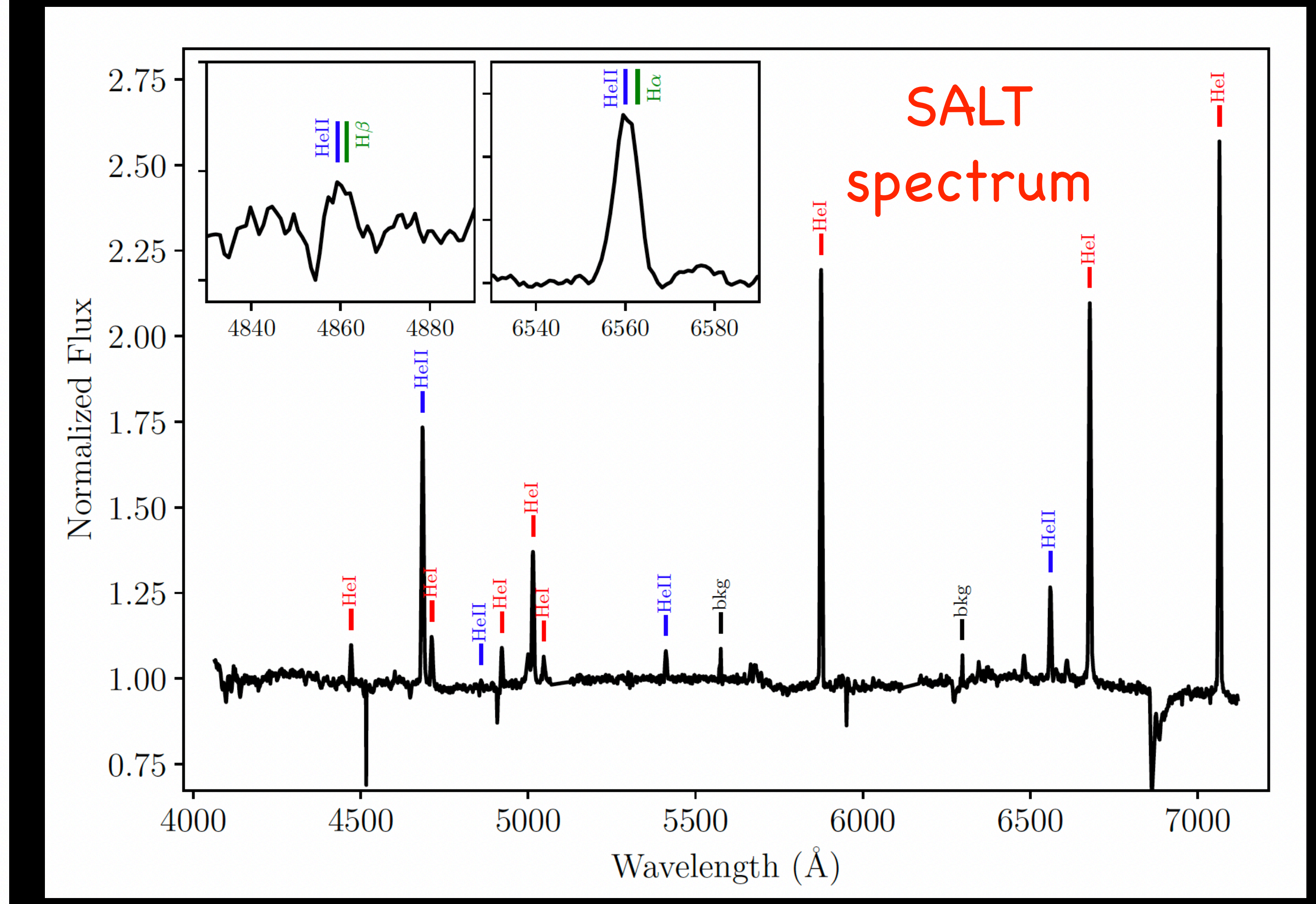
Greiner, Maitra, et al.
Nature+23





$kT = 45 \pm 3$eV, $L_X = 6.8^{+7.0}_{-3.5} \times 10^{36}$ erg/s,

Canonical nuclear burning SSS ?

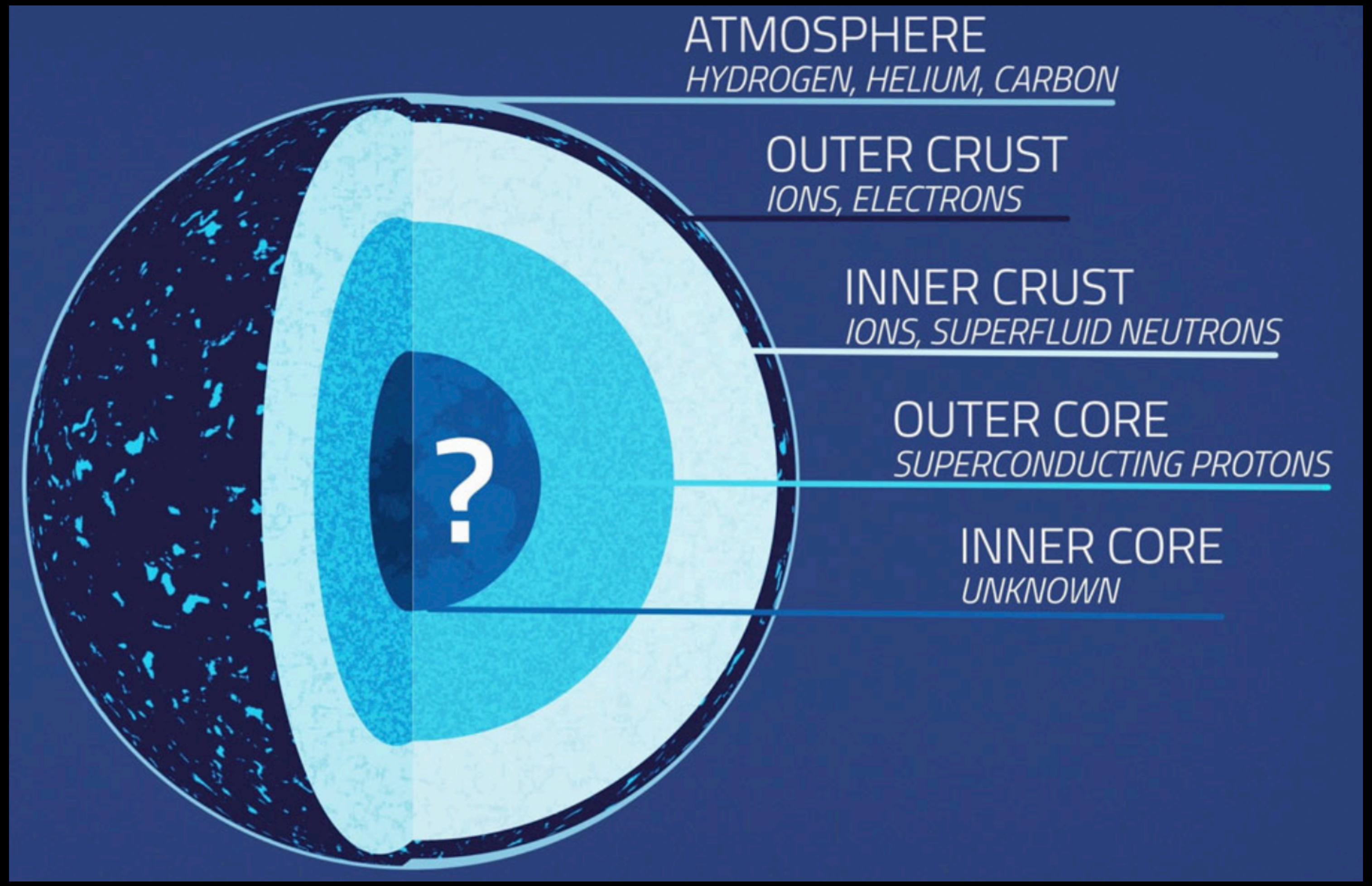


SALT spectrum

[HP99] 159 aka eRASSU J052015.3-654429 is a canonical SSS, burning He instead of H -

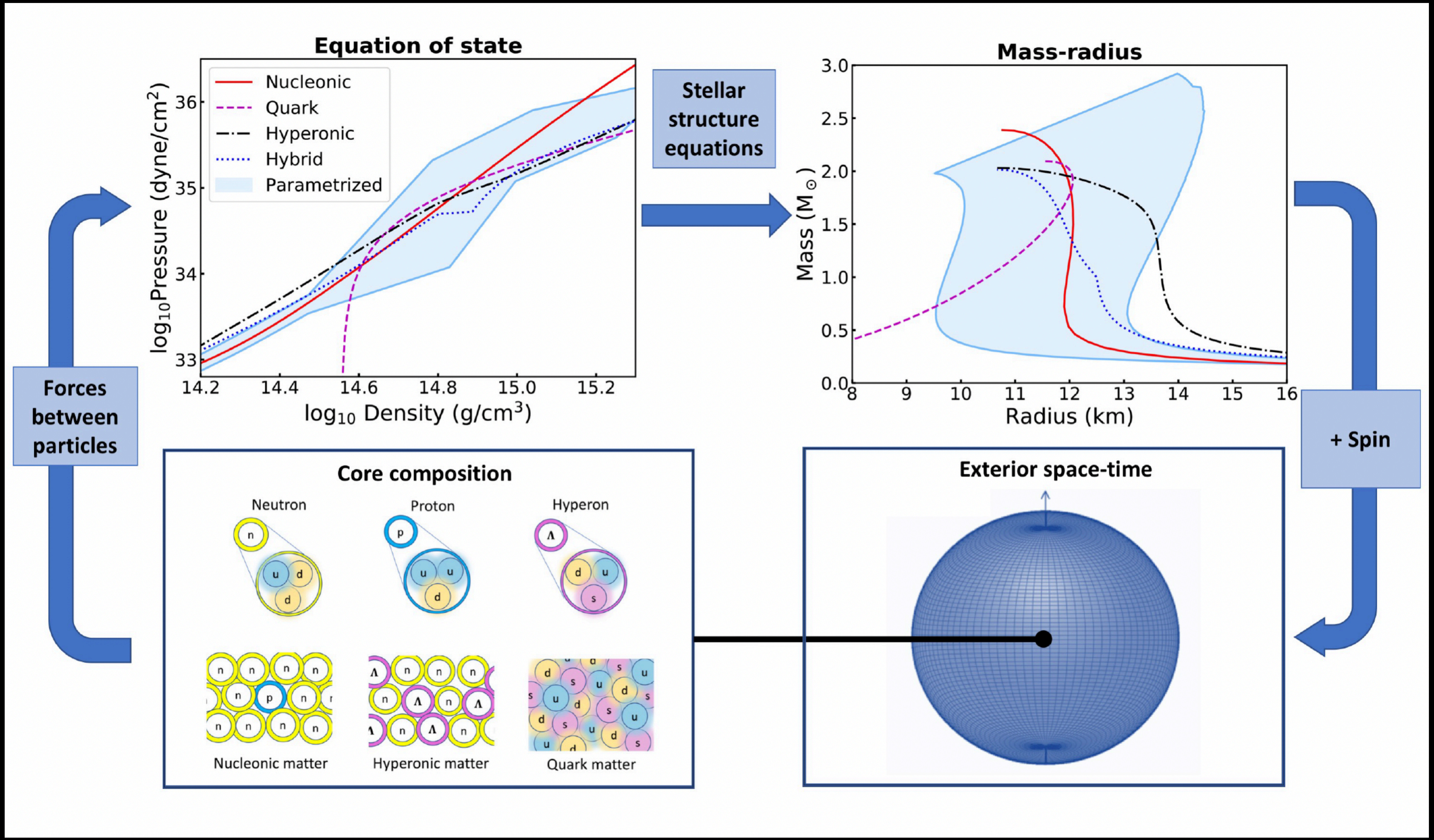
Pathway for - SN 1ax

Neutron star composition: equation of state (EOS)



NASA's Goddard Space Flight Center /
Conceptual Image Lab

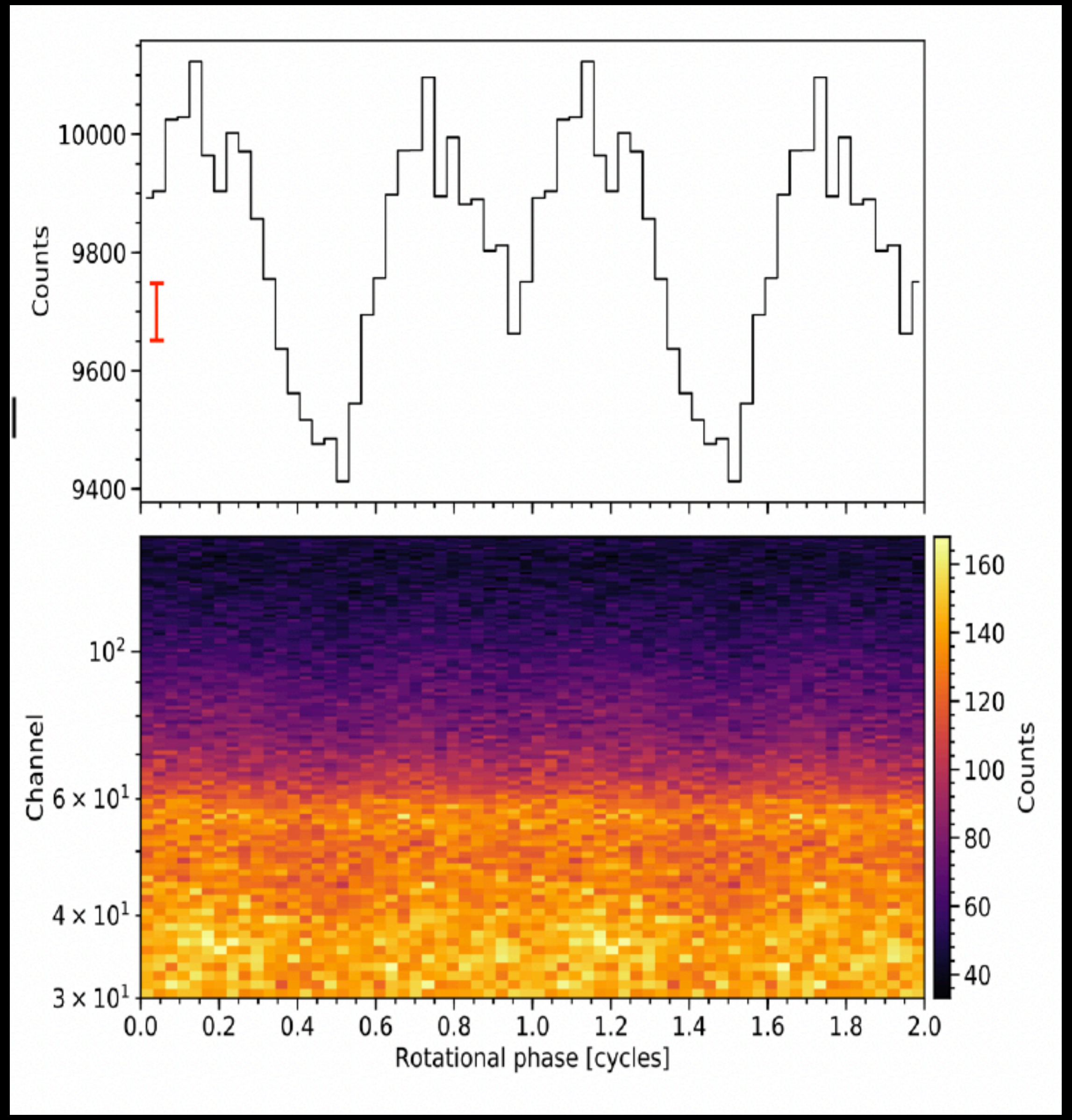
- EOS probes pressure density relation for ultra-dense matter at low temperatures ($n \sim 6n_0$)
- At some high density: transition from nucleons to quark and gluon degrees of freedom (phase transition) & exotic states expected



Solved given equation of state P(ε) for (M,R)-relation and tidal deformability Λ

Image credits A. Watts, Ray et al. 2019

Pulse profile modelling of millisecond X-ray pulsars

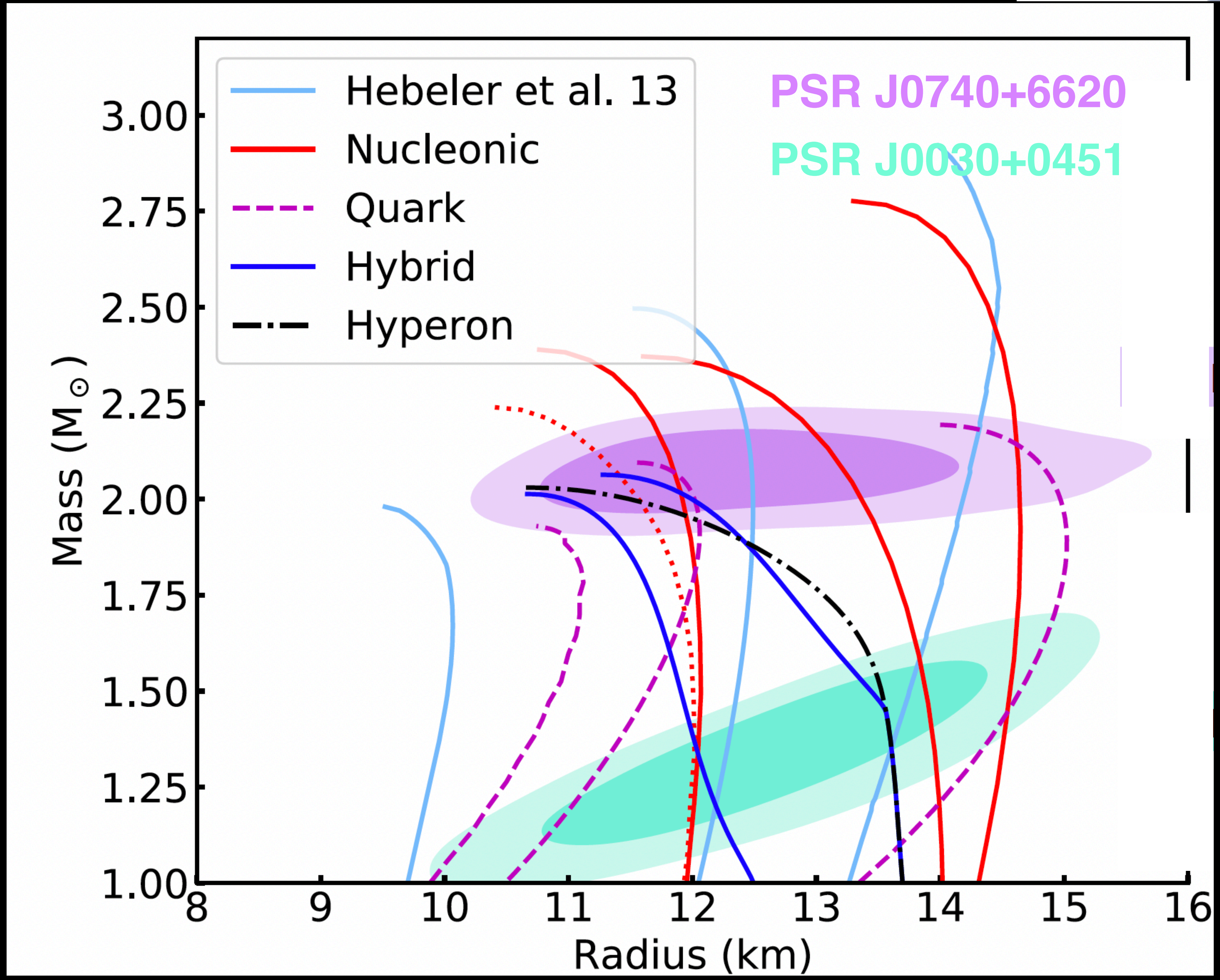


PSR J0740+6620: pulse profile modelling of XMM-Newton & NICER data

NICER team J0740 papers: Wolff et al. 2021, Riley et al. 2021, Raaijmakers et al. 2021, Miller et al. 2021, Dittmann et al 2024

M = 2.08±0.07 M⊙ R = $13.7\pm^{2.6}_{1.5}$ R⊙

NICER team J0030 papers: Bogdanov et al. 2019a,b, 2021 (data and supporting analysis); X-PSI (Riley et al. 2019, Raaijmakers et al. 2019, Bilous et al. 2019);



Webb & Barret 2007

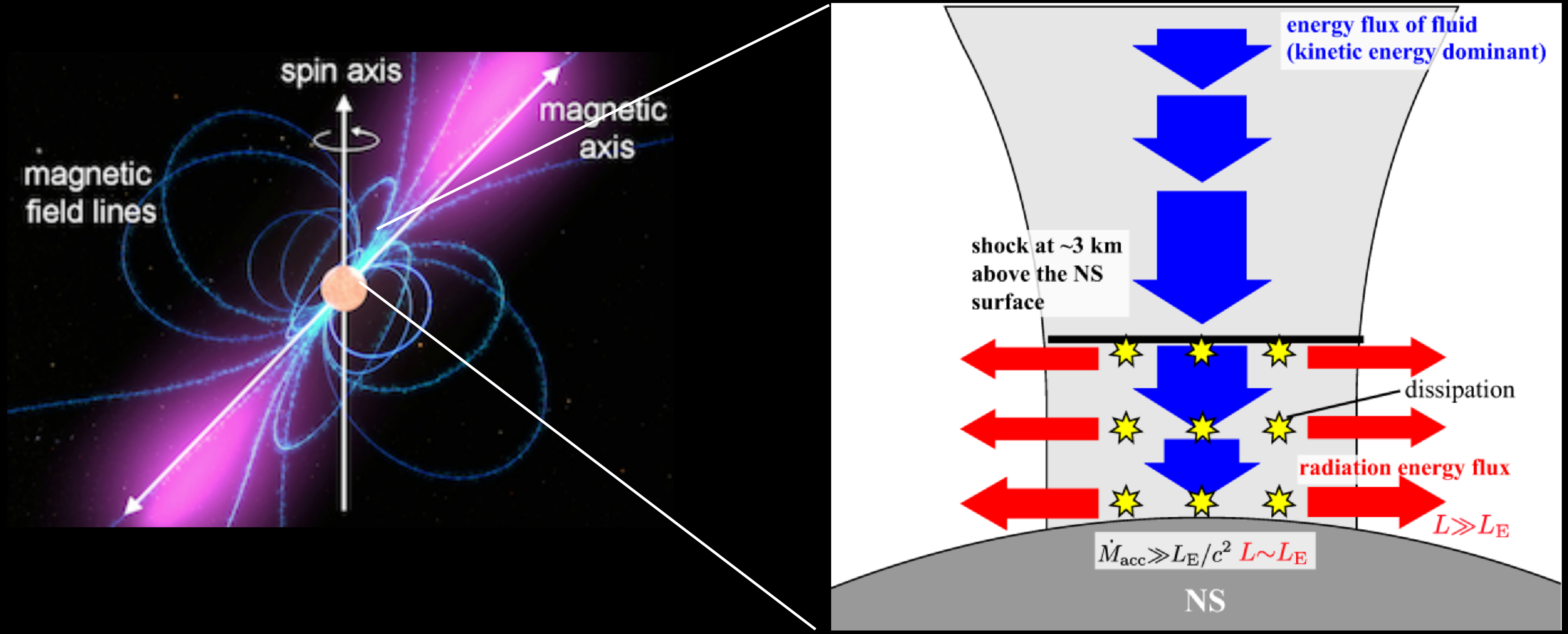
Adaped from A. Watts, 2022

Also NS atmosphere modelling of quiescent XRBs in globular clusters ωCen, M13, and NGC 2808

-> The EOSs that are satisfied by all NS includes the EOSs of normal nucleonic matter and one strange quark matter model (R>8km M unto 2.4M⊙)

See NS radii constraints from reflection models in LMXB (Ludlam+22)

Accretion at extreme regimes:
Swift J0243.6+6124 the first Galactic ultra-luminous pulsar



$$\sigma_{\perp}(E,B) \simeq \begin{cases} \sigma_T (E/E_{cyc})^2 & \text{for } E \lesssim E_{cycl} \\ \sigma_T & \text{for } E \gtrsim E_{cycl} \end{cases}$$

$$\sigma_{II}(E,B) \simeq \begin{cases} \sigma_T [(1-u^2) + u^2 (E/E_{cyc})^2 \;] & \text{for } E \lesssim E_{cycl} \\ \sigma_T & \text{for } E \gtrsim E_{cycl} \end{cases}$$

◆ Maximum accretion luminosity for a neutron star $L_{39} \approx 0.35 B_{12}^{3/4}$ erg s^{-1} (Mushtukov+2015)

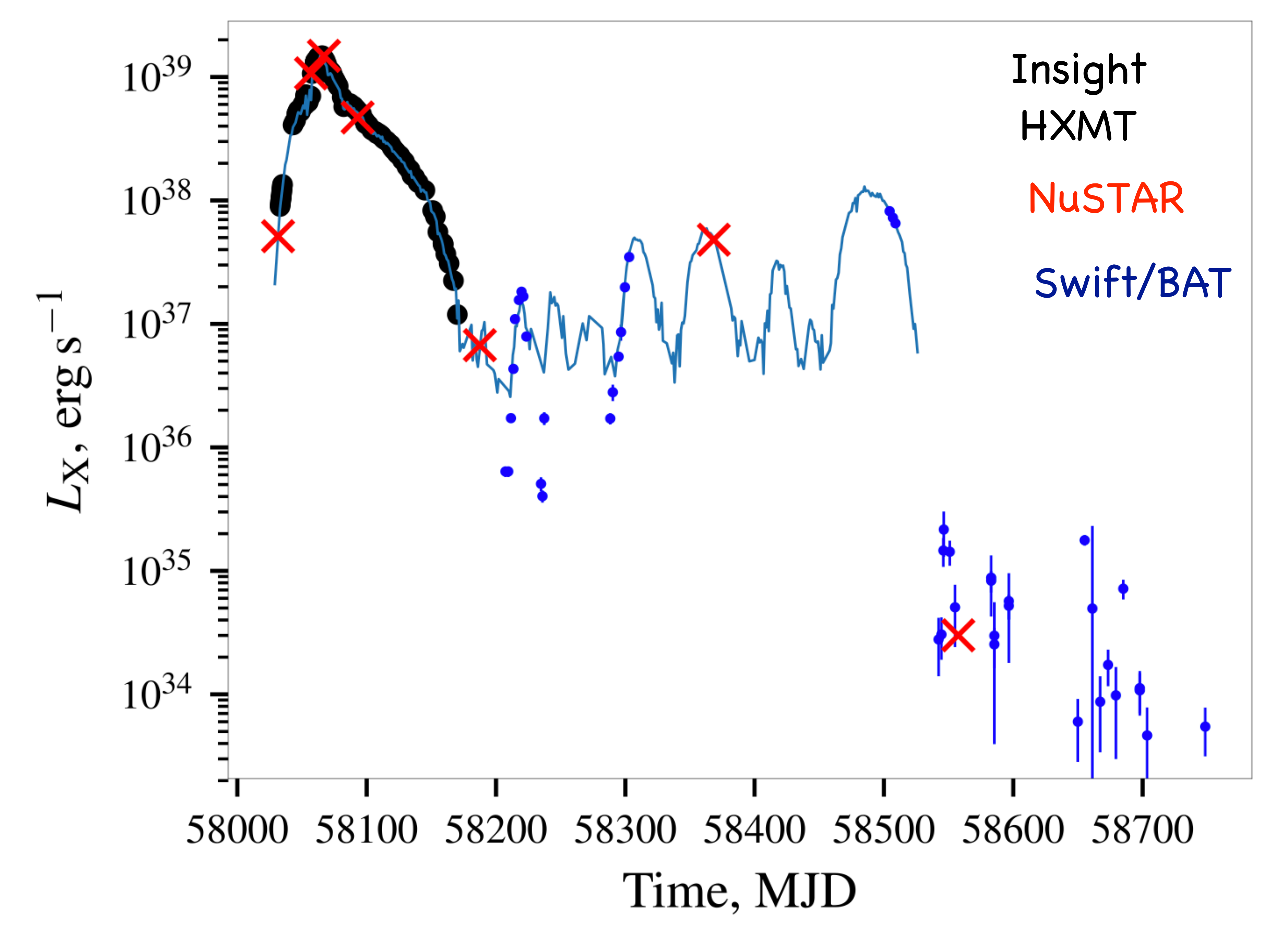
NS are able to radiate at 100 x Eddington limit (M82 X-2 Bachetti+14)

◆

Swift J0243.6+6124 is a link between Super Eddington XRBs and ULXs

(Kennea+17, Jenke & Wilson-Hodge +17, 18, Doroshenko+18)

Debate of the Magnetic field



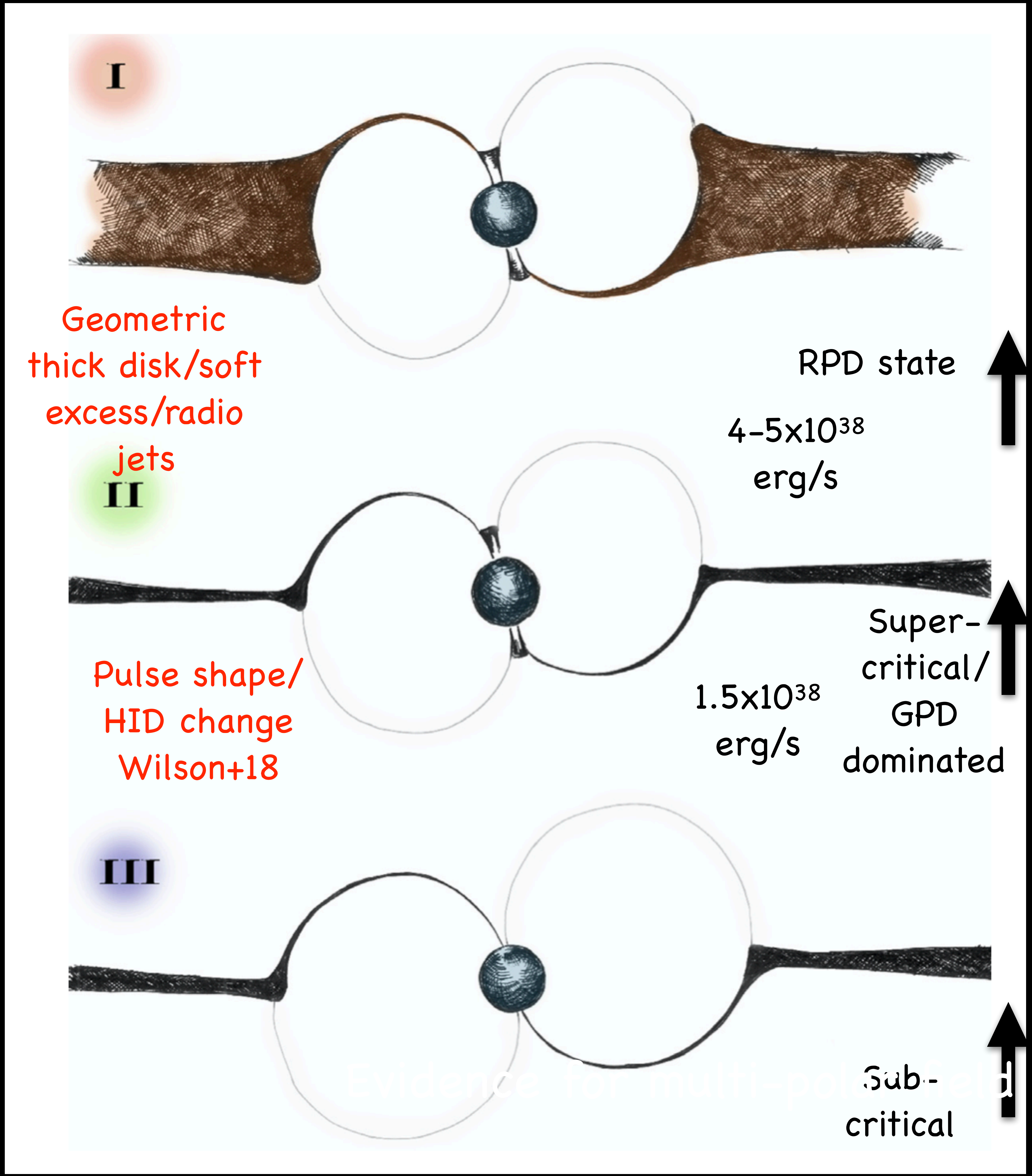
Doroshenko+20

Evidence for multi-polar field

Insight-HXMT detection of CRSF at 120-146 keV

-> B~ 1.6 × 10^{13} G

Kong+22,



Geometric thick disk/soft excess/radio jets

RPD state

4-5x10^{38} erg/s

Pulse shape/ HID change Wilson+18

1.5x10^{38} erg/s

Super-critical/ GPD dominated

Sub-critical

Accretion at lower Lx 10^{34} erg/s

-> dipole magnetic fiel of B~ 3 × 10^{12} G

Multipole component?

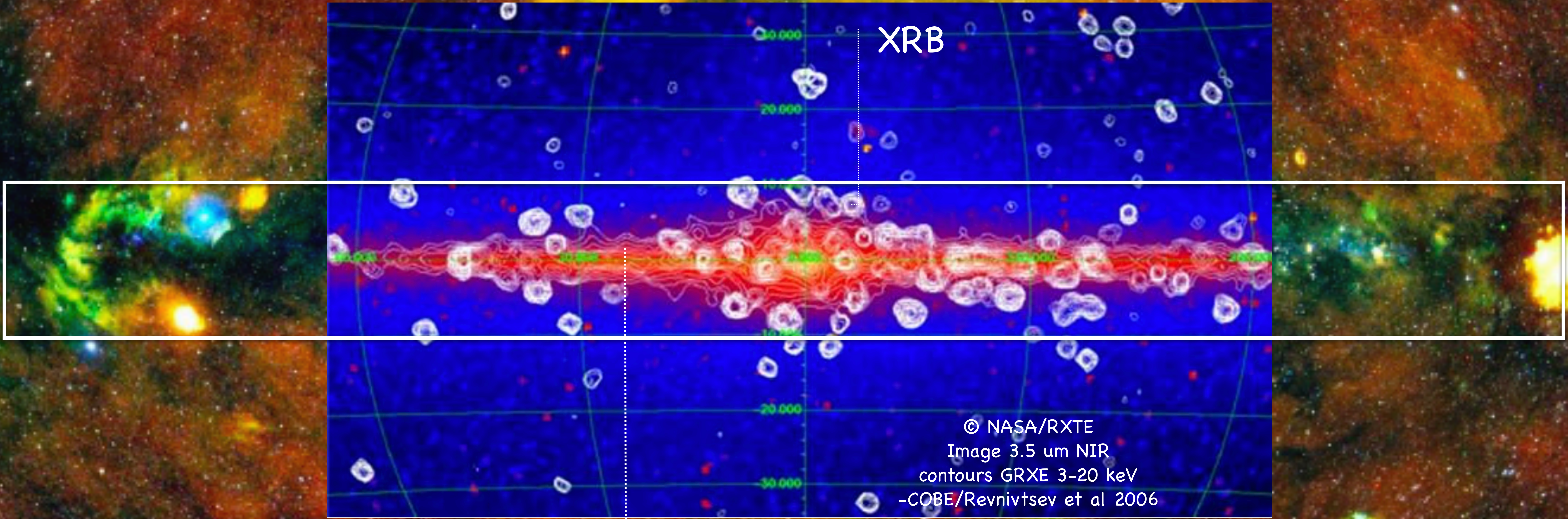
Jaisawal+19, Wilson-Hodge+18, Doroshenko+20

NOTE!

-> Future lies in X-ray polarisation measurements (IXPE, Tsygankov+22; Malacaria+23; Forsblom+23)

Understanding the population in the Milky Way

Constitutes large fraction of Galactic Ridge X-ray emission



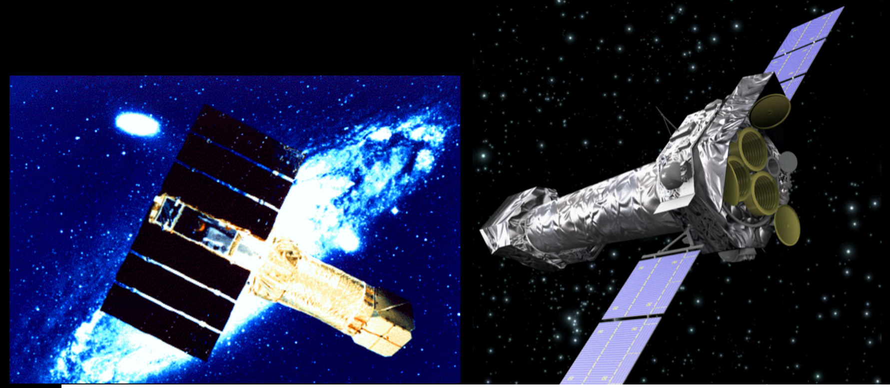
© NASA/RXTE
Image 3.5 um NIR
contours GRXE 3-20 keV
-COBE/Revnivtsev et al 2006

Catacyclysmic Variables
Polars
Intermediate polars (Mondal+24)
Dwarf novae
Quiscent LMXBs (Muno+2005) + quiescent
magnetars (Coti Zelati+2018) stars (Schmitt+22)

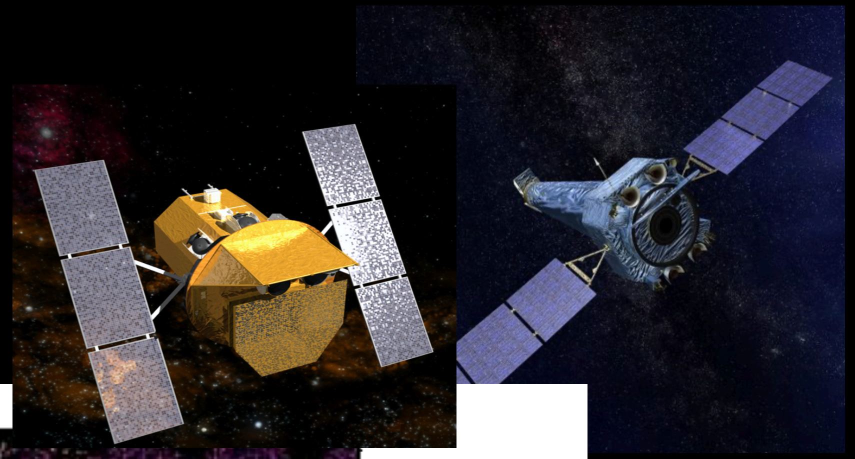
White dwarfs

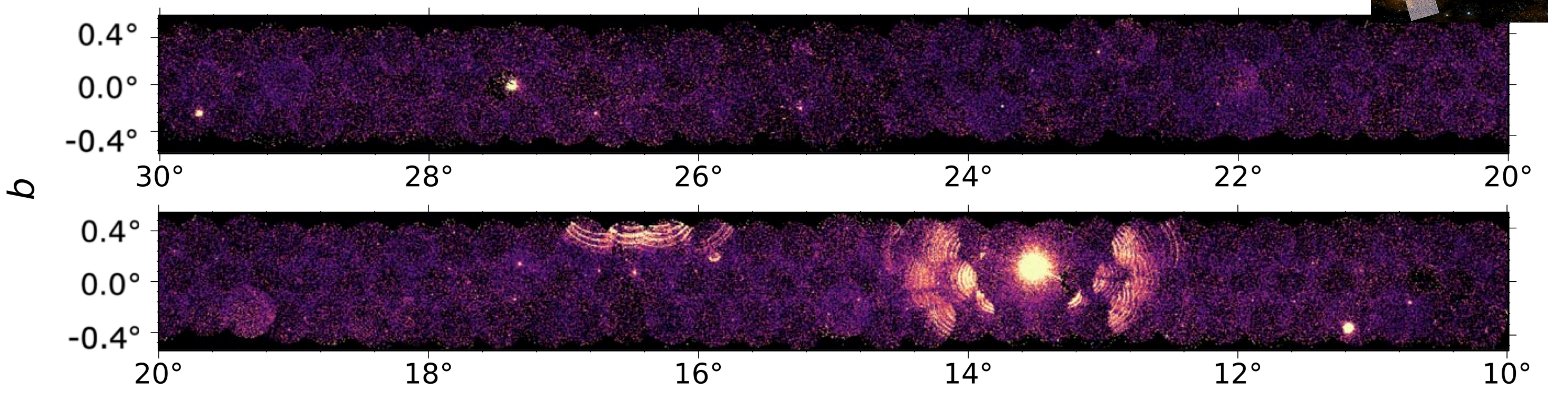
Neutron stars

70-80% GRXE can be resolved into
Point sources (RevnivsteV+09, Nature)
L_x 10^{27}-10^{34} erg/s



Galactic Plane & Bulge surveys





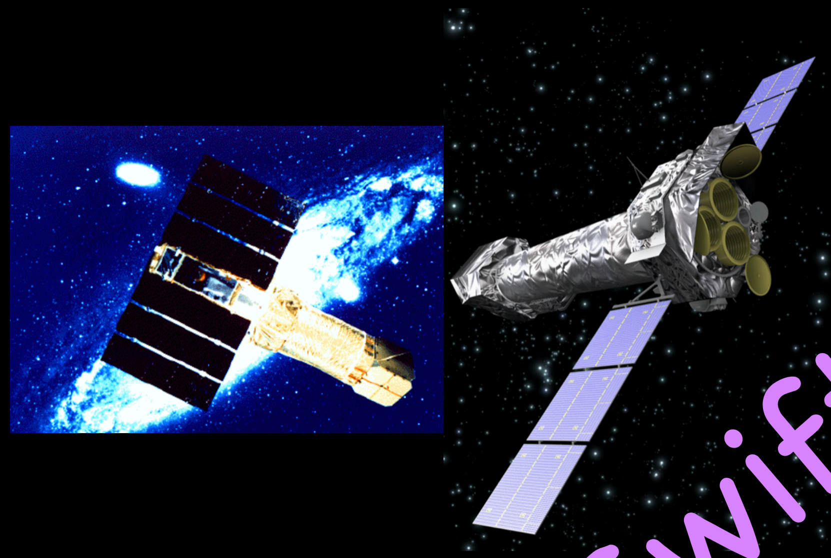
SDGPS: Connor+23 (380 unique paintings with ~5 ks exposure) -40deg2

ASCA Galactic plane survey 0.7-10 keV (Sugizaki+01)

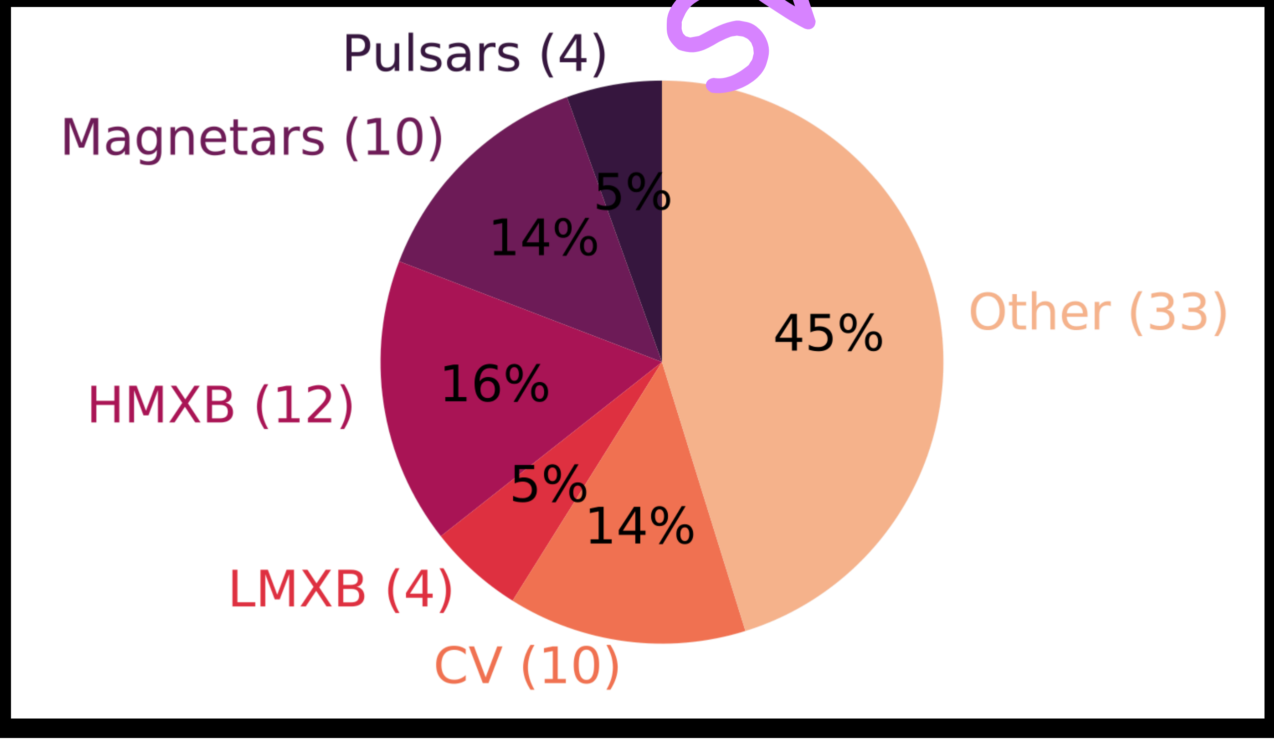
XMM-Newton survey of Galactic plane 0.5-12 keV (Motch+10, Moran+13), XMM-Newton Heritage Survey of the inner Galactic disk (Mondal,Ponti+24,Ponti et al. in prep)

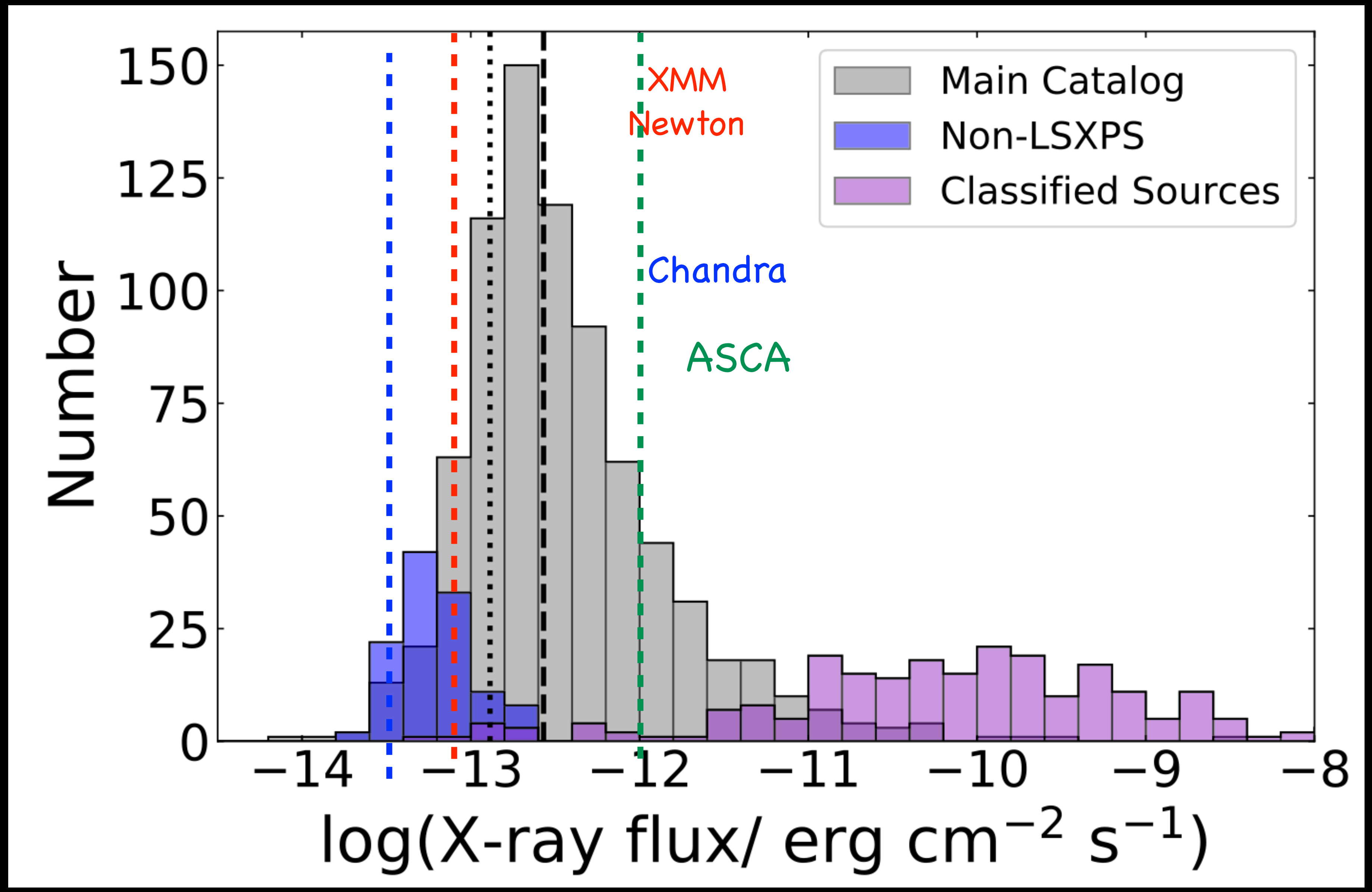
Chandra ChaMPlane survey (Grindlay+05, Rogel+06), Chandra Galactic Bulge Survey 0.5-10 keV (Jonker+11,14, Wevers+16)

Galactic Plane & Bulge surveys



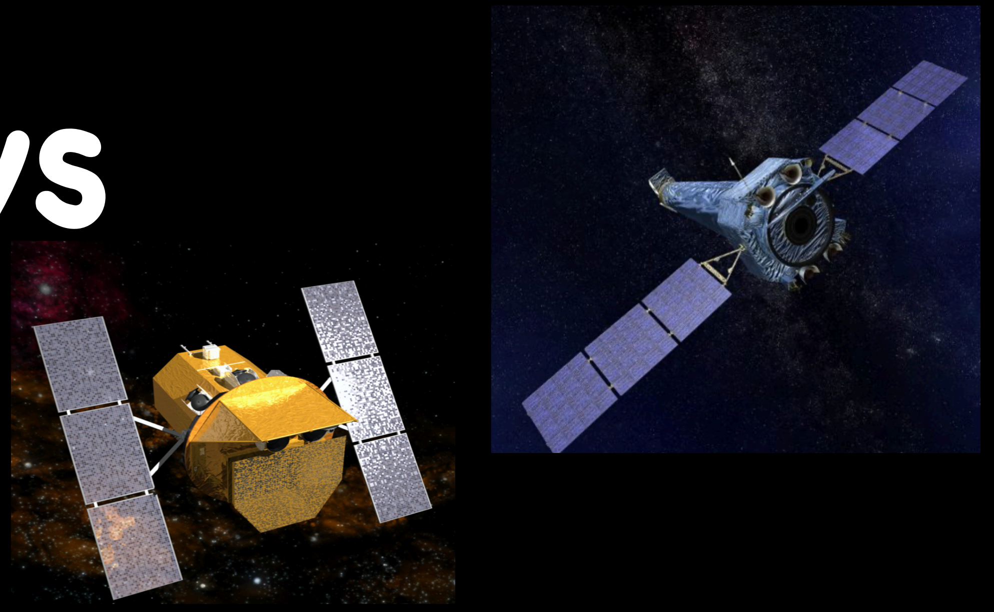
Swift GP

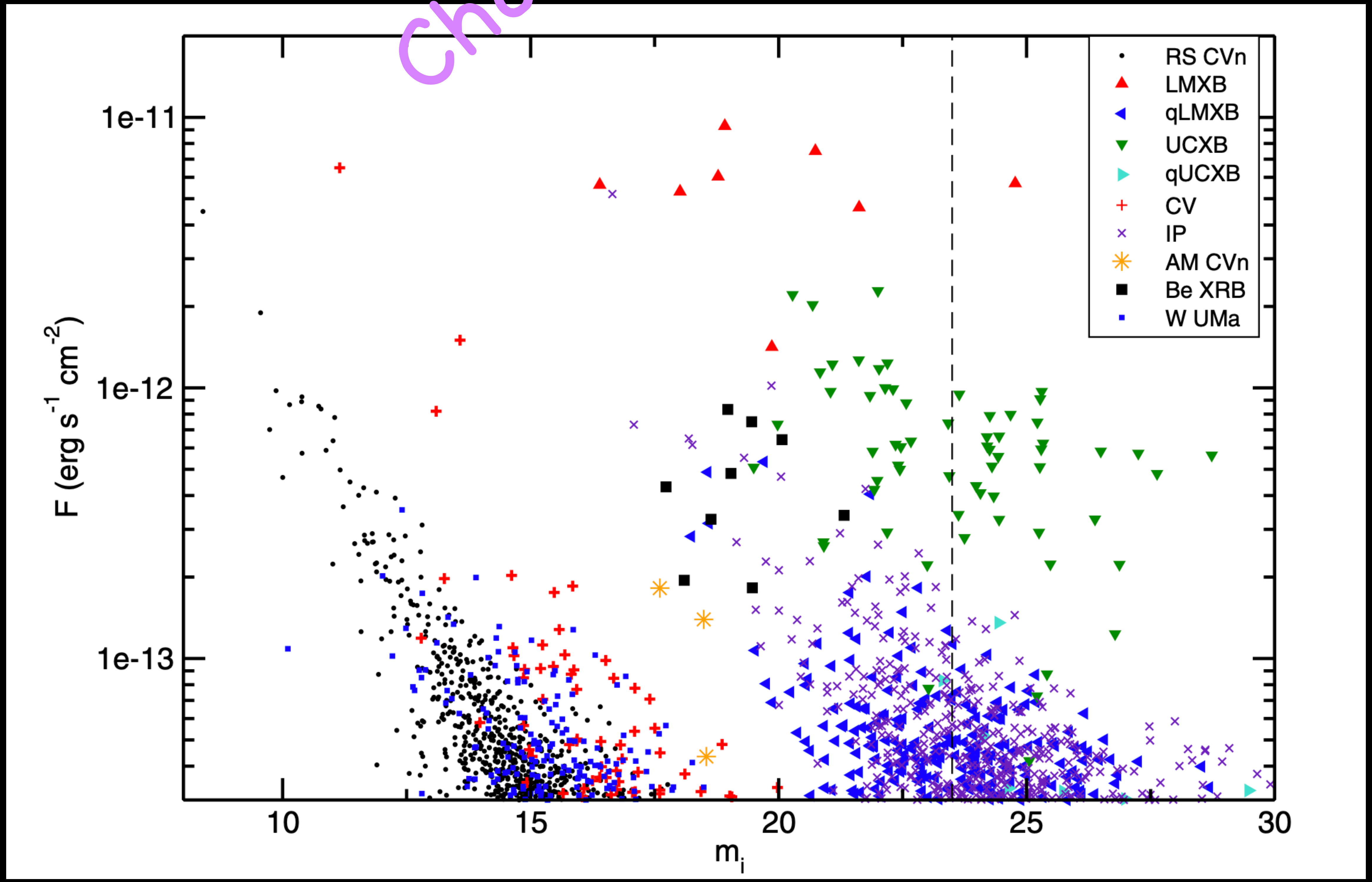




Swift GPS: Connor+23 (380 unique paintings with ~5 ks exposure) -40deg2

Chandra GB

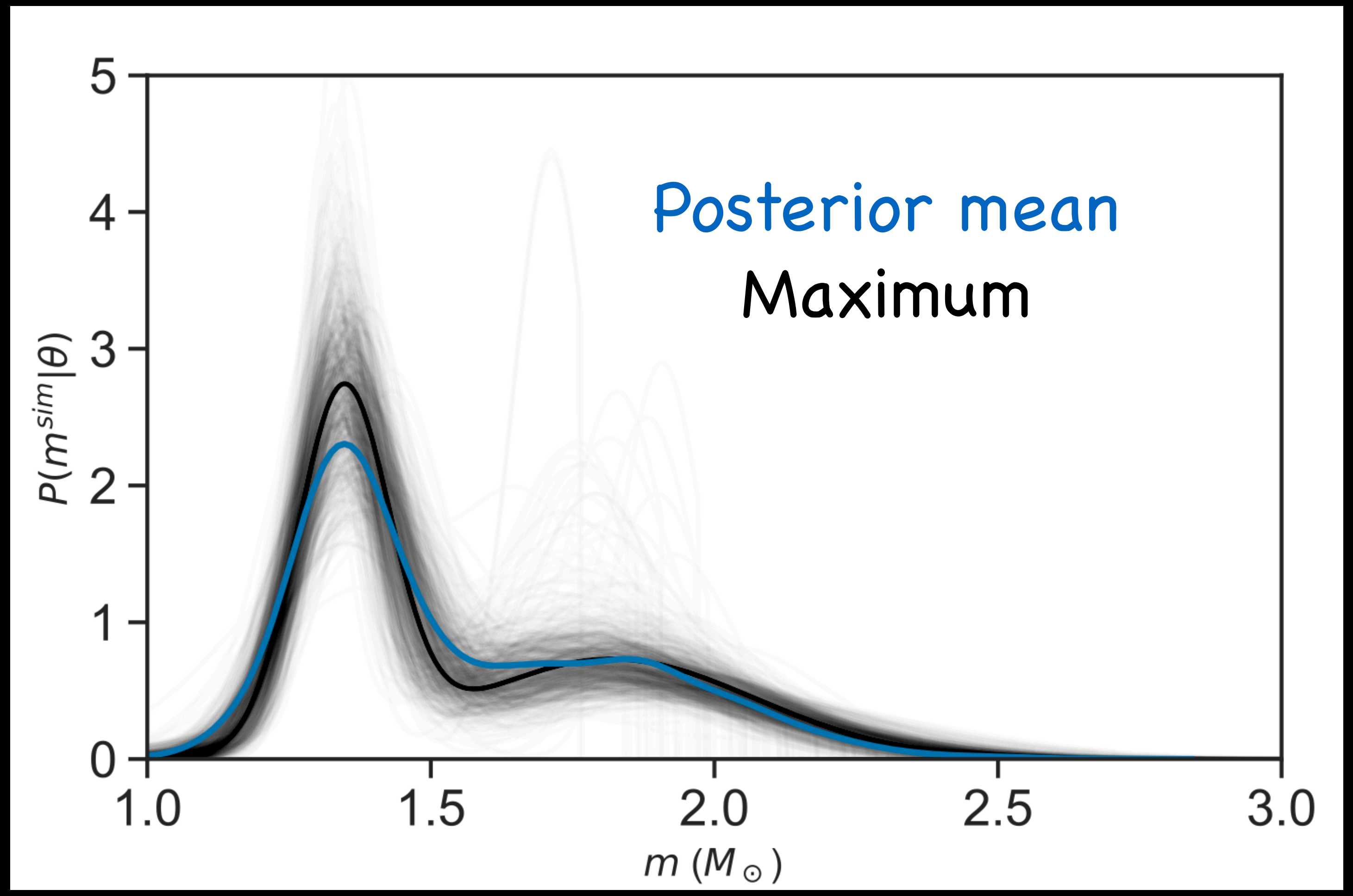




Xray flux vs i' band mag for sources in the Chandra GBS (jonker+11)

Importance of Galactic Plane & Bulge surveys

- Compact object masses – NS and BH mass gap, NS mass distribution & equation of state (Ozel+10, Lattimer & Prakash 04) - dynamical mass measurements & eclipsing quiescent XRBs



1000 posterior samples drawn from original shows

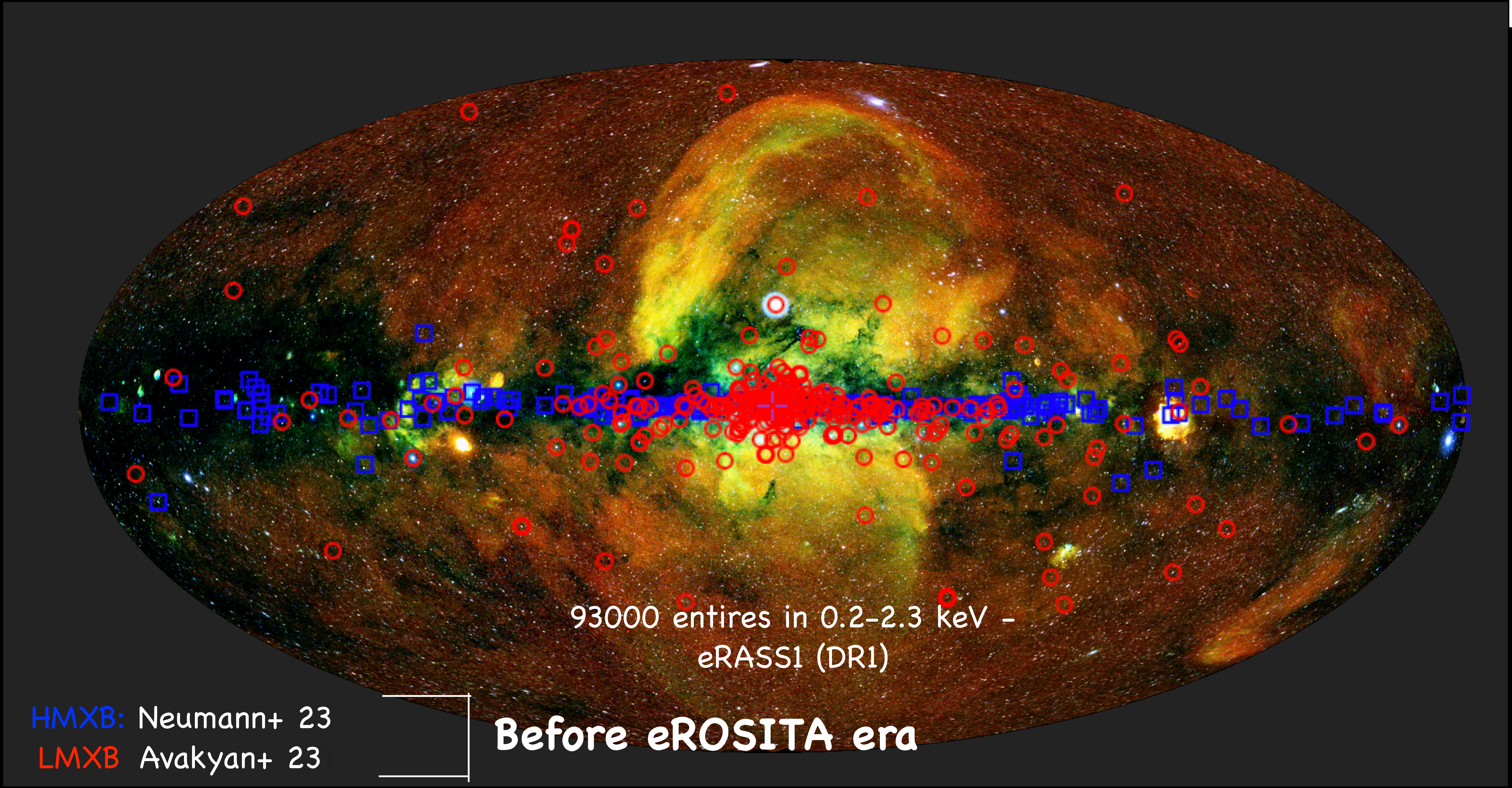
μ_1 =1.351 M⊙

μ_2 =1.756 M⊙

Horvath+22, Lucas M. de Sá+23

- Spatial distribution of CO, NS kick distribution, orbits, spectra at diff Lx -> inputs to population synthesis models

Compact objects in the Milky Way in the eROSITA era



93000 entires in 0.2-2.3 keV - eRASS1 (DR1)

HMXB: Neumann+ 23

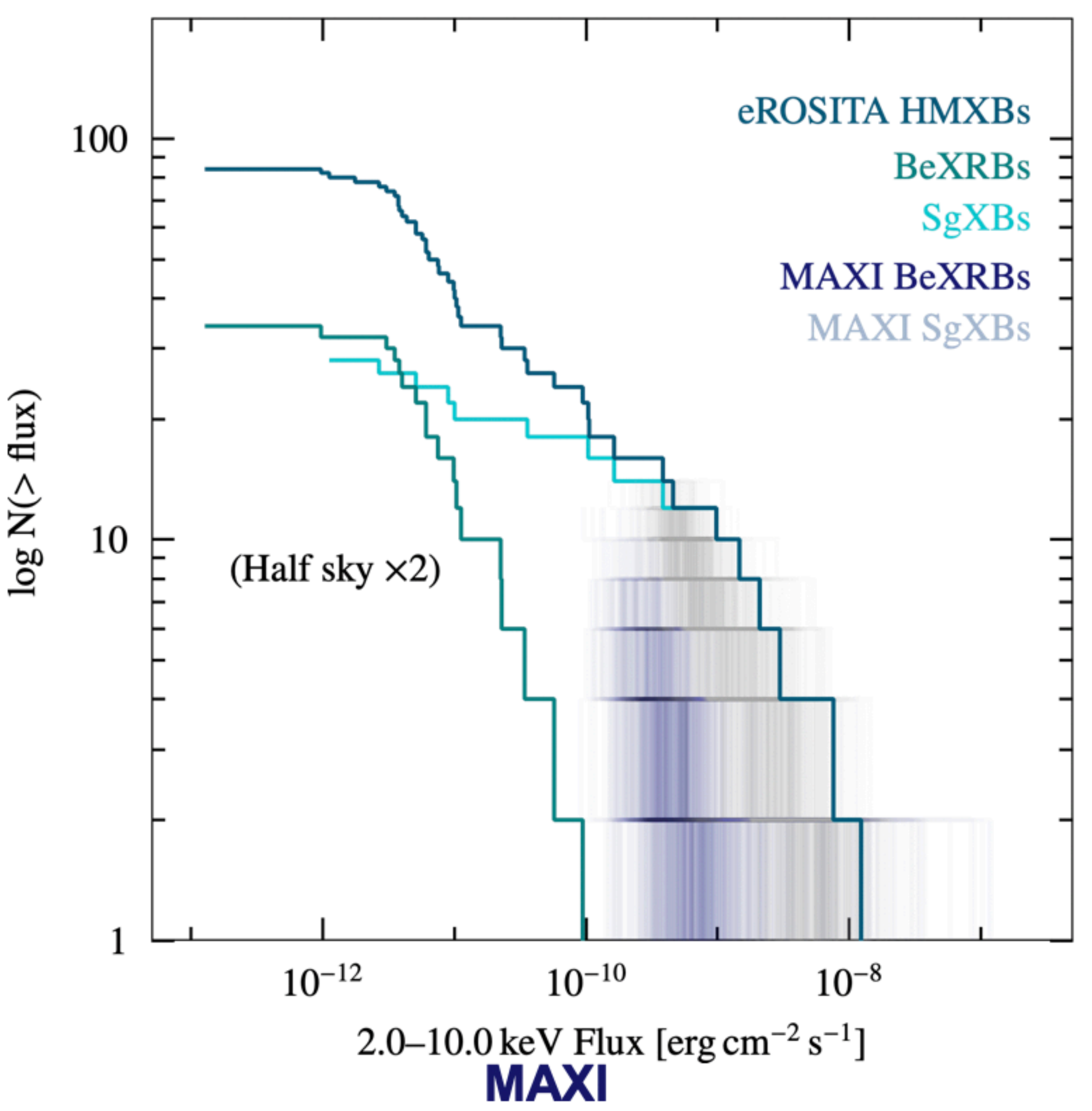
LMXB Avakyan+ 23

Before eROSITA era

http://astro.uni-tuebingen.de/~xrbcat/

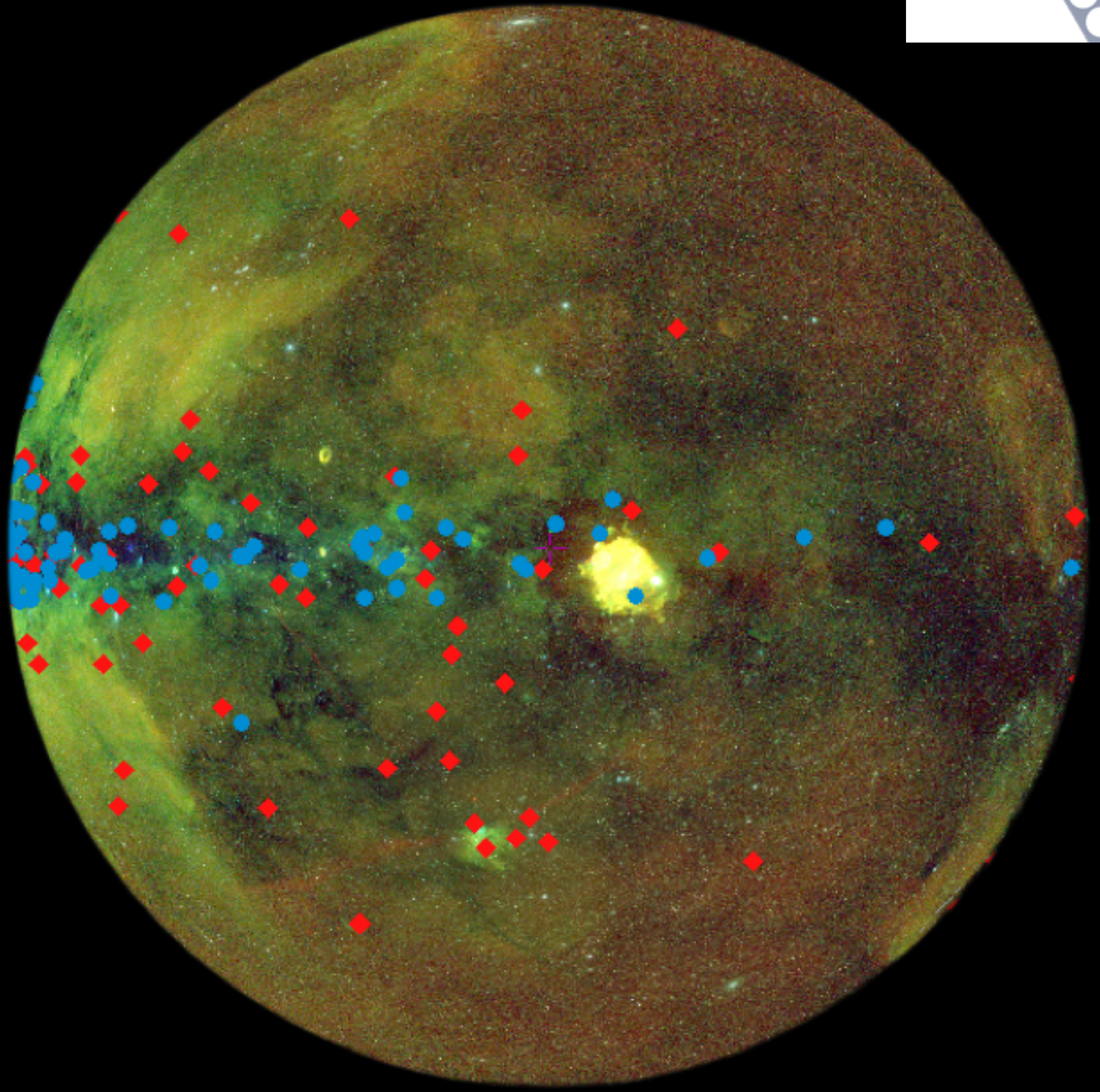
SRG/eROSITA MPE/IKI

XRBs in the Milky Way in the eROSITA era



- The low flux end populated by BeXRBs while SgXBs show higher fluxes
- MAXI do not detect BeXRBs at fluxes detectable by eROSITA

Zainab et al. in prep



HMXB, & LMXB:
Avakyan+ in prep)

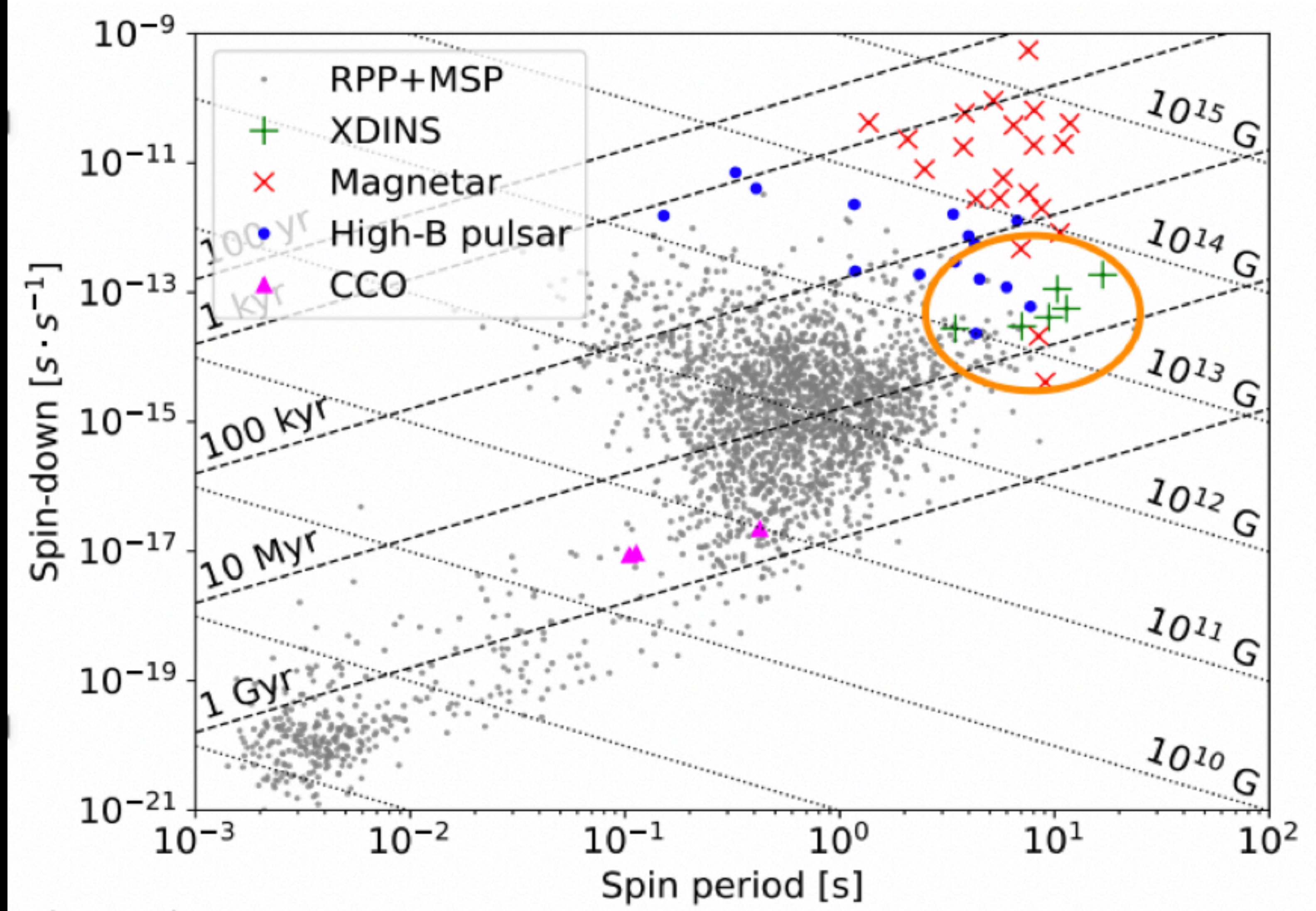
Completeness = 0.7

Purity = 0.83

XRB Candidates: 185

Credit: Avakyan, Zainab

Isolated neutron stars in the Milky Way in the eROSITA era



Magnificant seven (Haberl+06, Bogdanov+24:)
A group of isolated young cooling **neutron stars** -
None discovered after ROSAT

- Selected 33 candidates (Kurpas+24)

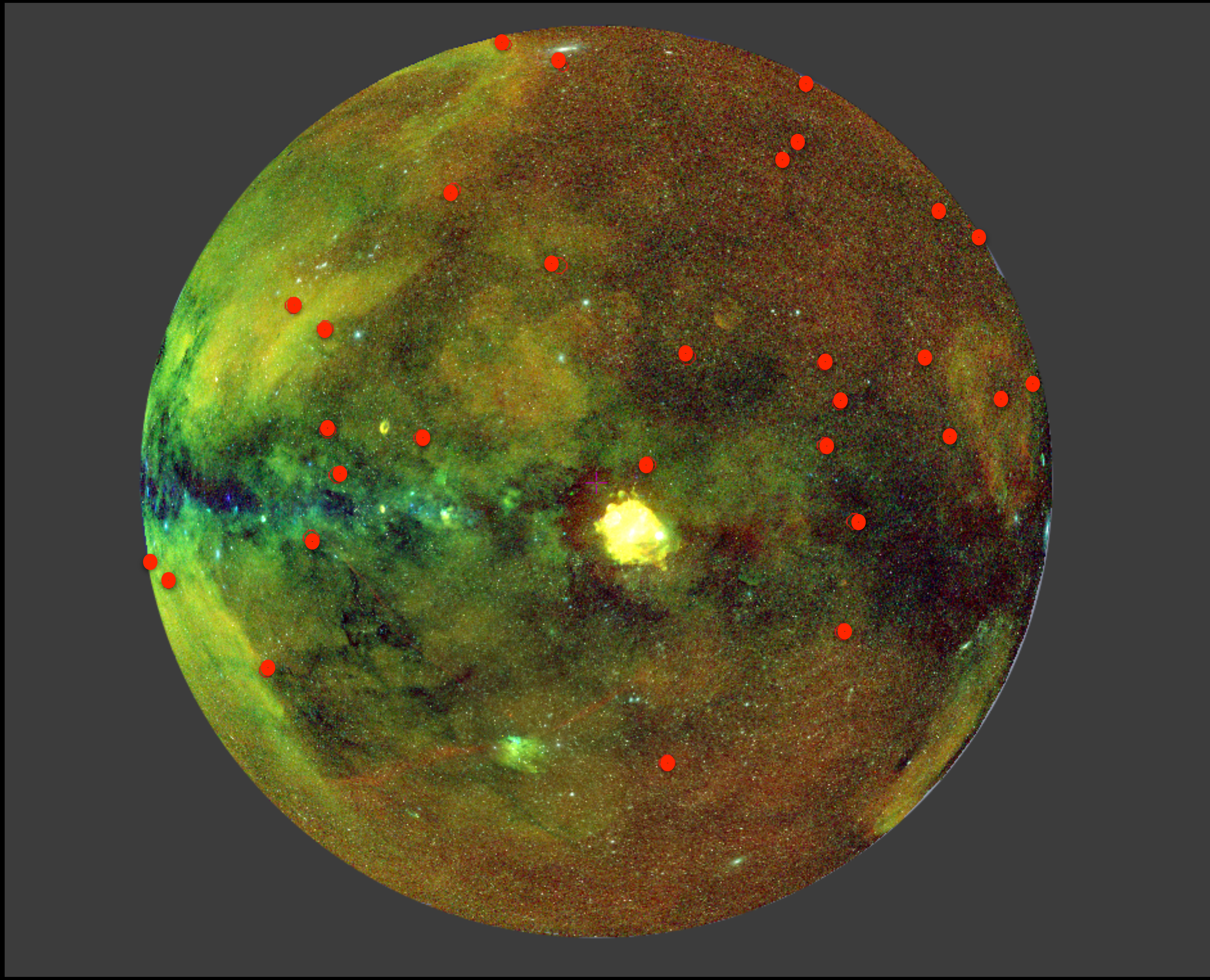
- Soft thermal spectrum
- Absence of non-X-ray counterparts

- Follow-up

- X-ray: position, spectrum, pulsations
- Optical: f_X/f_{opt}

→ Six new isolated neutron stars (1 XDINS: Kurpas+24, A&A, 683, A164)

What next ?



Candidate XDINS: Kurpas+ 24)

See talks on novae in MW by Gloria Sala & symbiotic stars by Sara Saeedi

Summary & key questions

White dwarfs

- Understanding the physics of (recurrent) novae (fireball, super-soft phase) , nuclear burning & environments, progenitors of SN 1a, binary evolution, common envelope , role of binary companion

Neutron stars

- Neutron star mass distribution, mass-gap, EOS, magnetic fields, accretion geometry, super-Eddington accretion

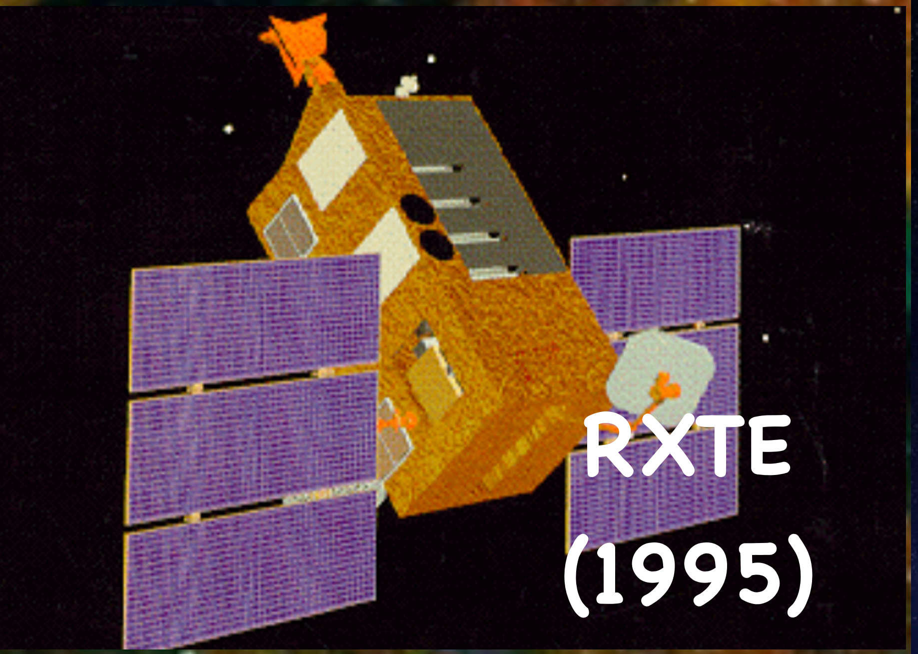
Population studies

- What comprises the GRXE?, hidden CVs? population synthesis models, stellar evolution, luminosity functions

Compact Objects in the Milky Way

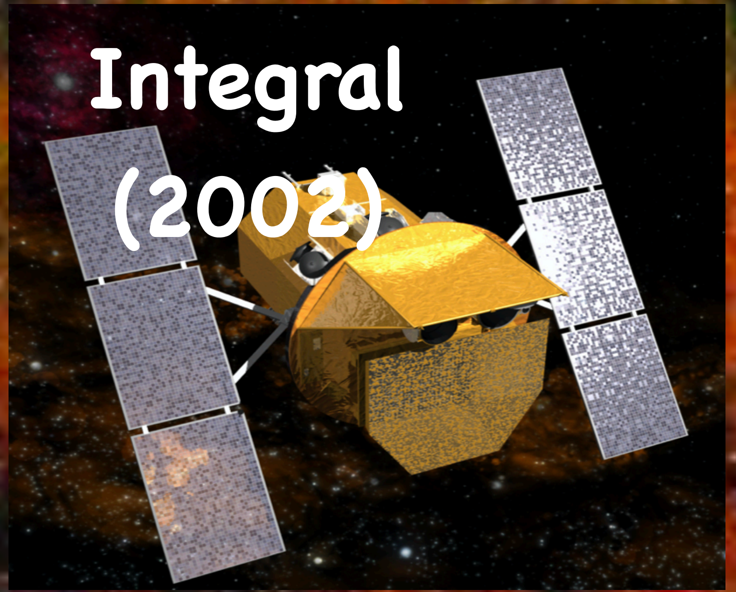
Past


ROSAT
(1990)


RXTE
(1995)

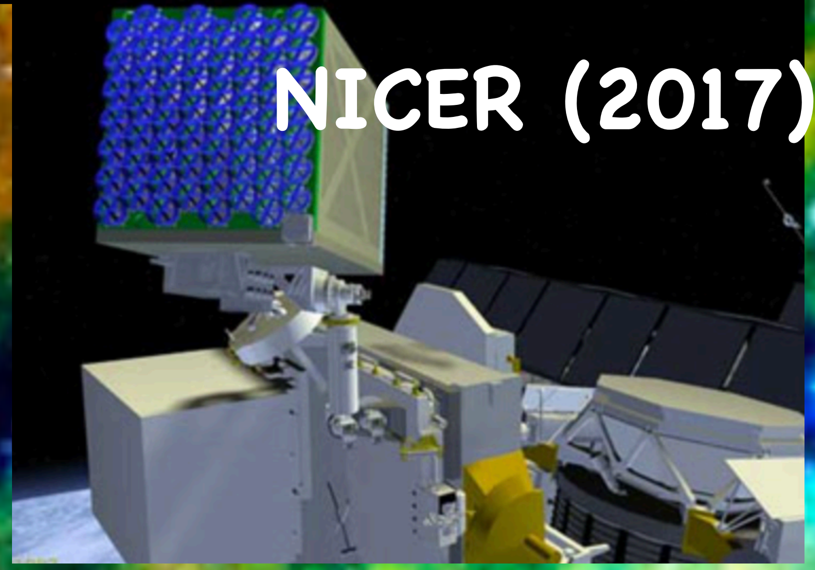

XMM-newton
(1999)


Chandra
(2000)

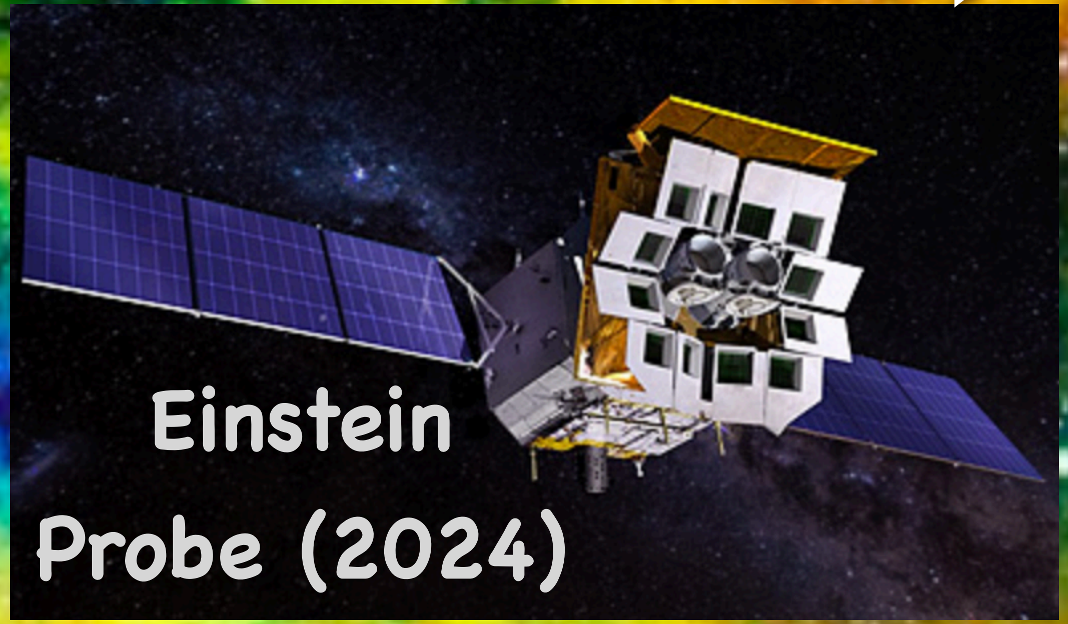

Integral
(2002)

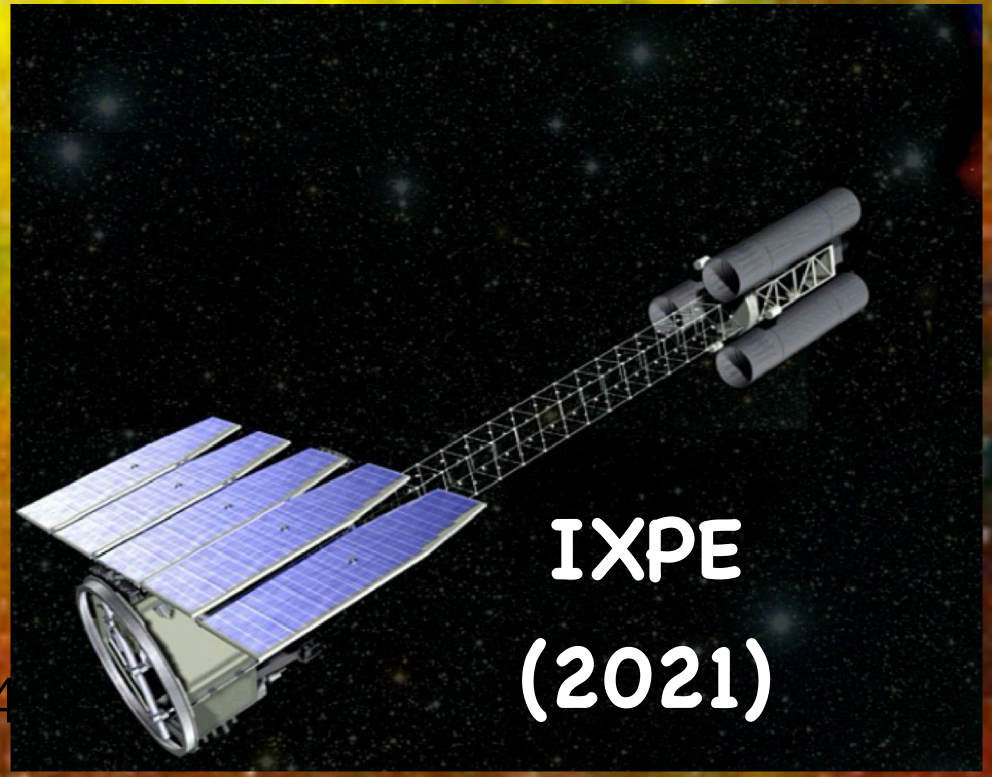
Present


SRG/eROSITA
(2019)

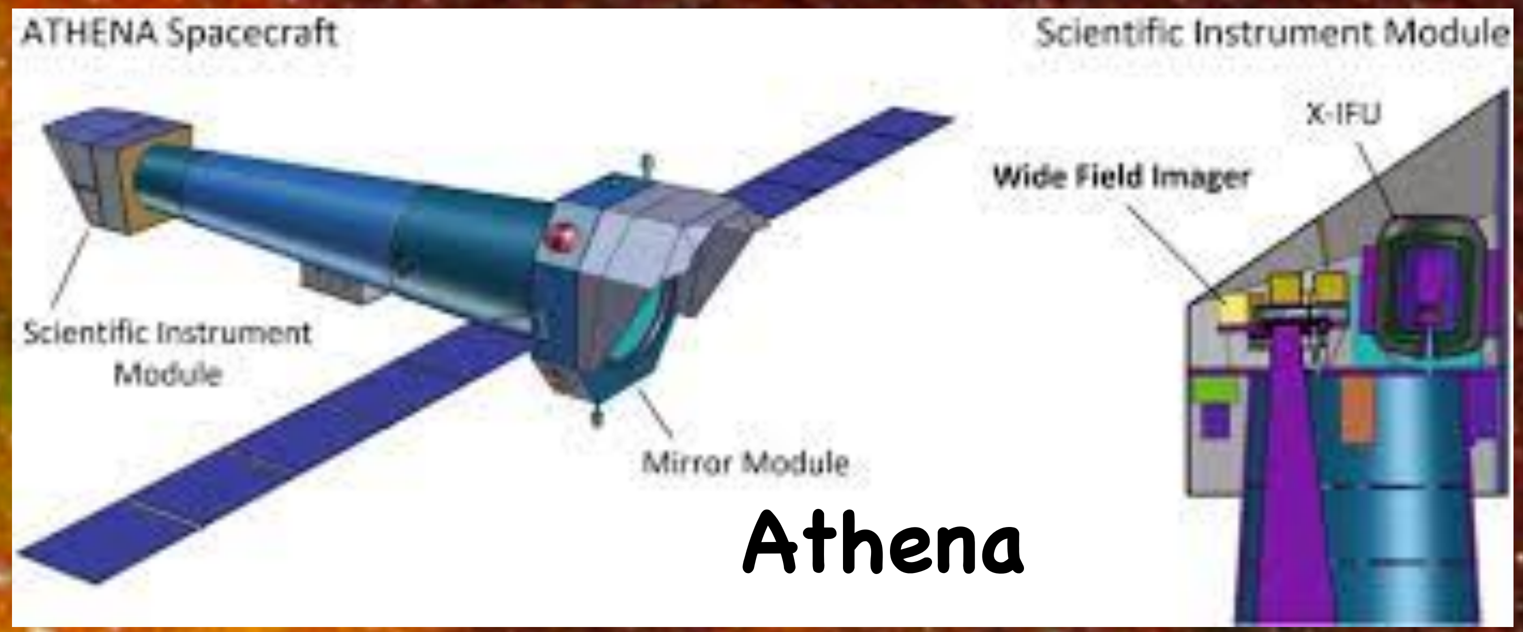

NICER (2017)


NuSTAR
(2013)


Einstein
Probe (2024)


IXPE
(2021)

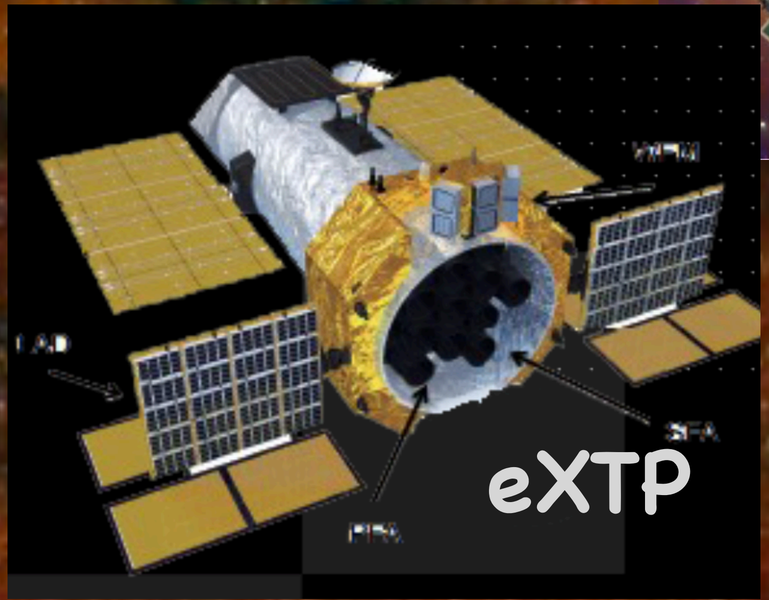
Future



Athena


HEX-P


STROBE-X


eXTP