Time-domain astronomy

Francesco Coti Zelati

CTAO School - 1st edition, Bertinoro, 19/06/2024

ICE INSTITUT DE CIÈNCIES DE L'ESPAI
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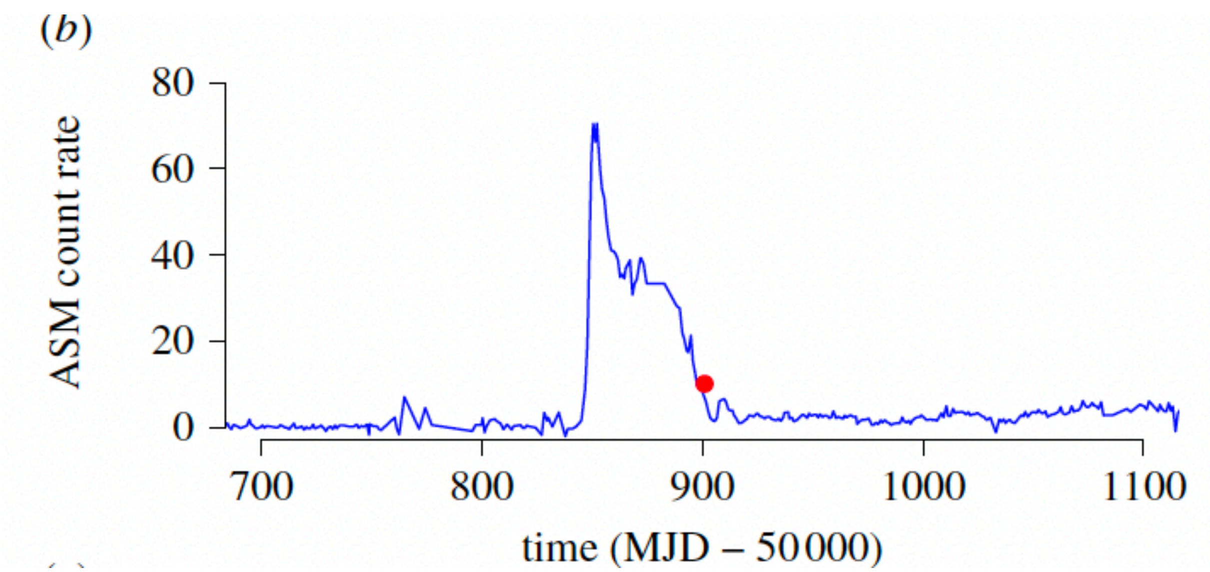
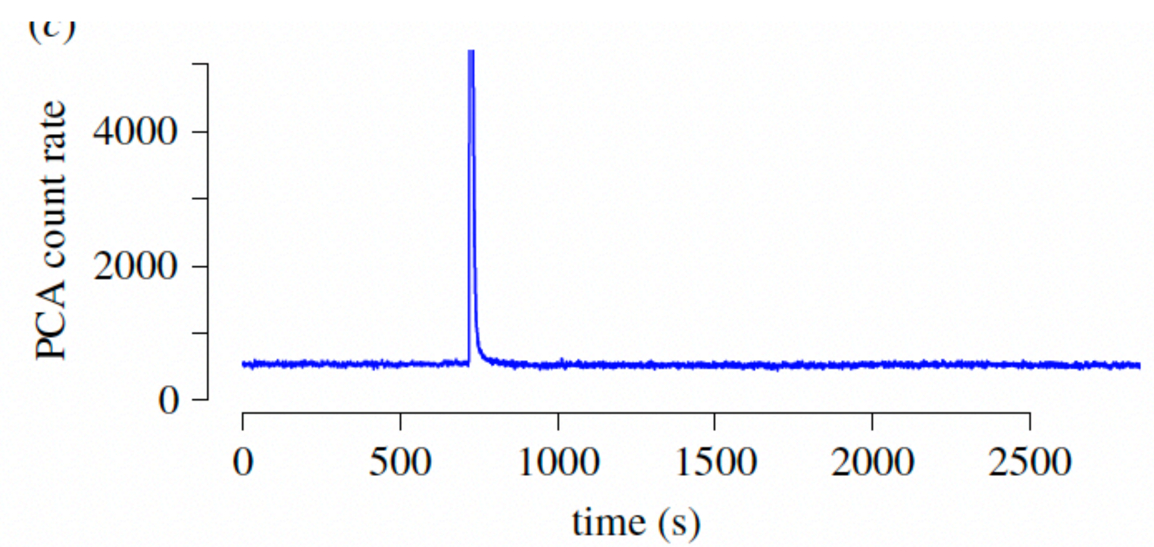
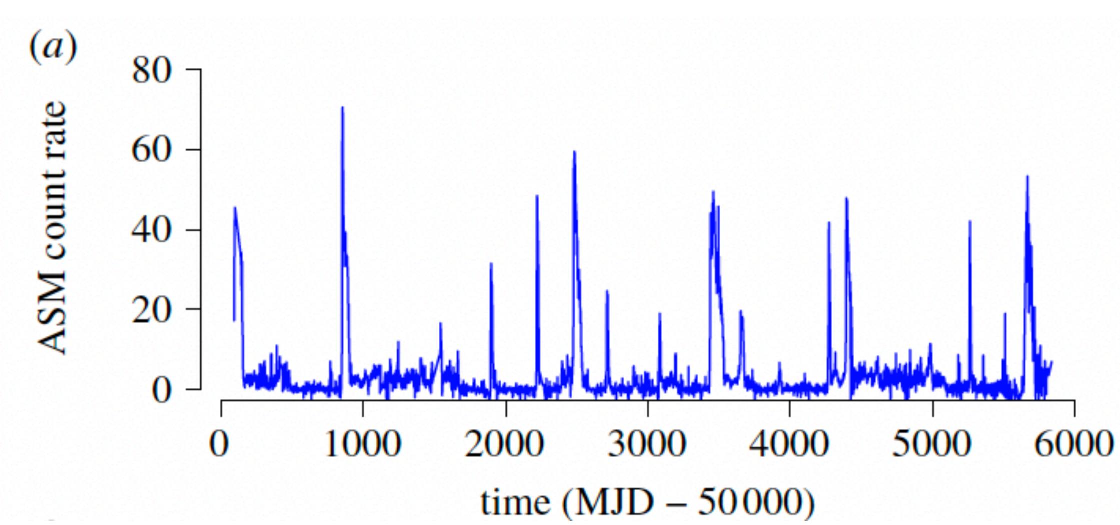
What is time domain astronomy?

- Study of astronomical objects and phenomena as they change over time.
- Involves monitoring the sky over various timescales from ms to tens of years.







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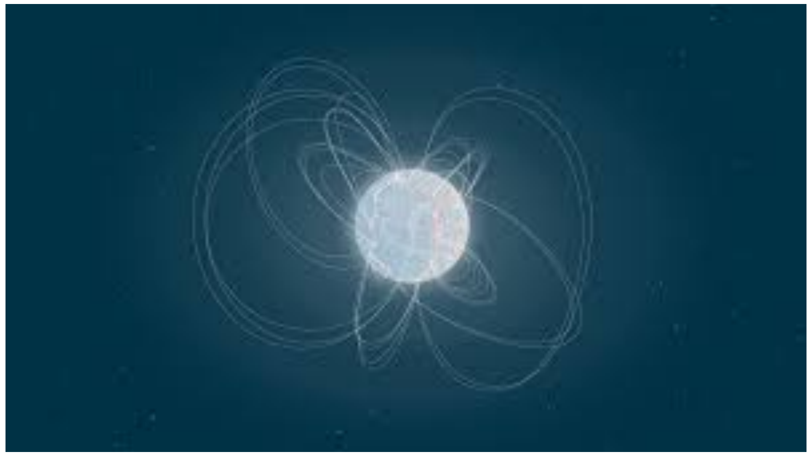
Why does it matter?

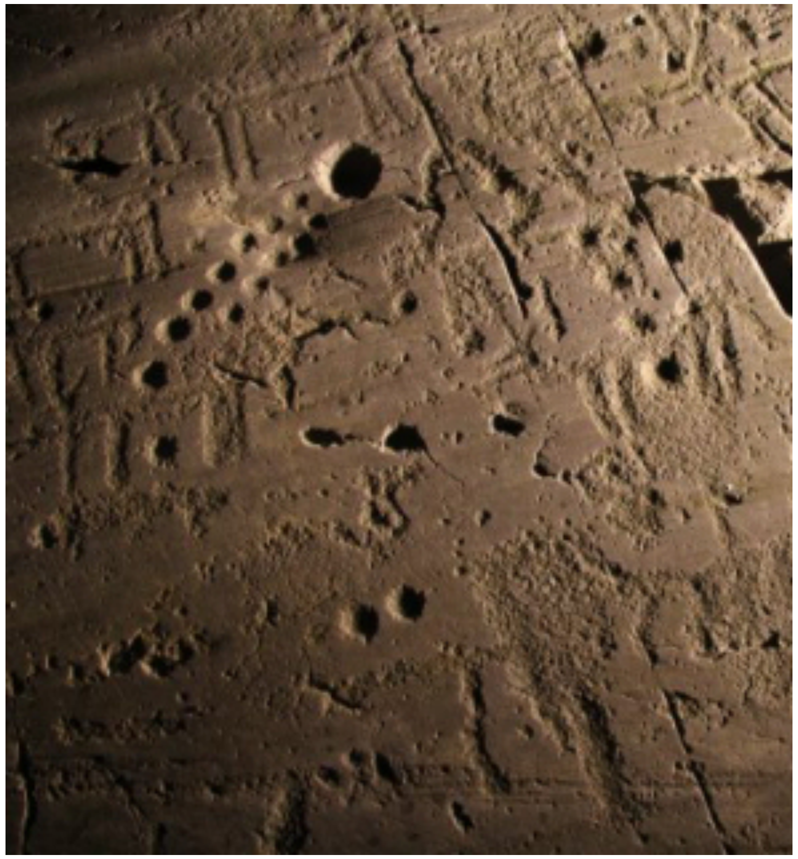
- Reveals key information about underlying physical processes
- Provides clues about exotic objects such as black holes and neutron stars.
- Helps in the discovery and study of transient phenomena (e.g. SNe, GRBs, outbursts from compact objects).



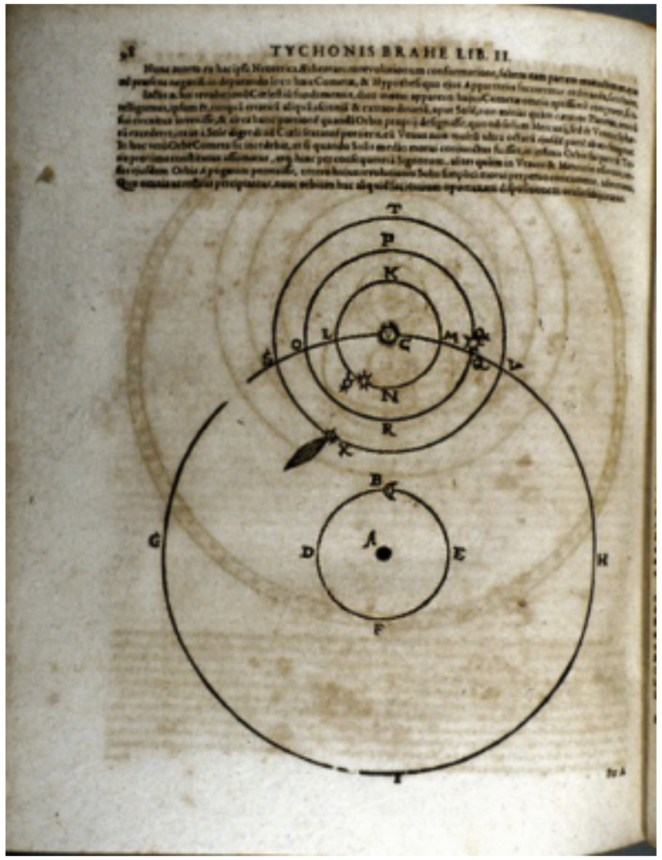
Historical origins of time domain astronomy

Time domain astronomy has its roots in antiquity, when ancient astronomers mapped the motion of the planets on the sky and timed the passage of comets.

Halley's Comet of 1066 represented in the Bayeux Tapestry



Comet symbol on Rock 35 from Area di Foppe, Nadro di Ceto (Brescia, Italy).



The path of the comet Tycho Brahe saw in 1577, in his geo/heliocentric model.

Types of variability

1. **Periodic variability**:

- Regular, repeating patterns.
- Examples: Pulsating stars (Cepheids, RR Lyrae), Eclipsing binaries.

2. **Aperiodic variability**:

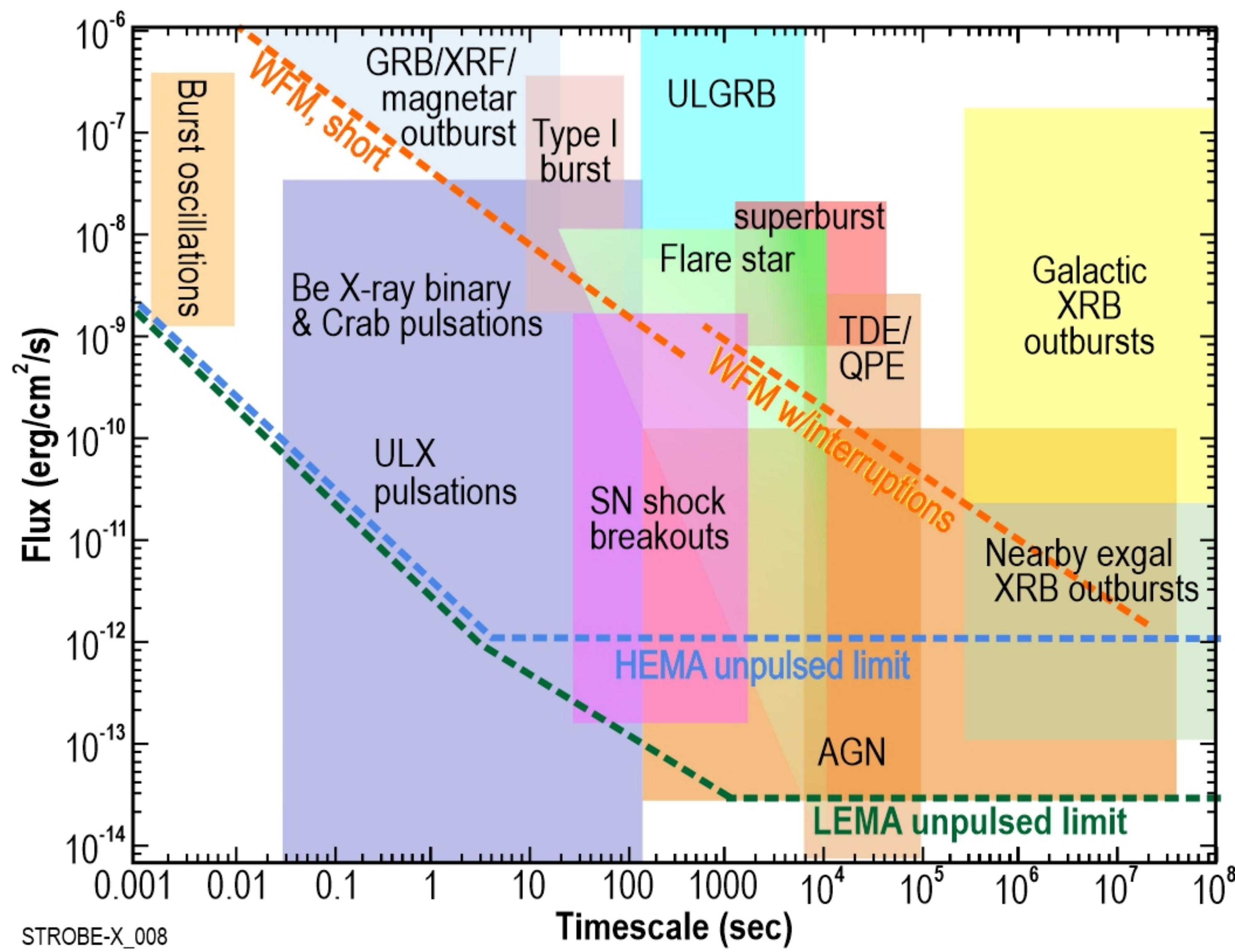
- Irregular, non-repeating patterns.
- Examples: Flares, outbursts, variable accretion rates in X-ray binaries.

3. **Transient variability**:

- Sudden, short-lived events.
- Examples: Supernovae, Gamma-Ray Bursts, Fast Radio Bursts.

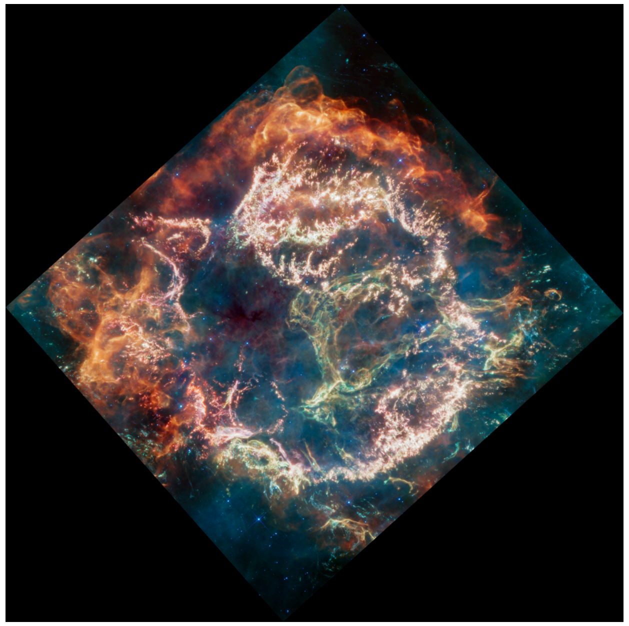
Sources of variability

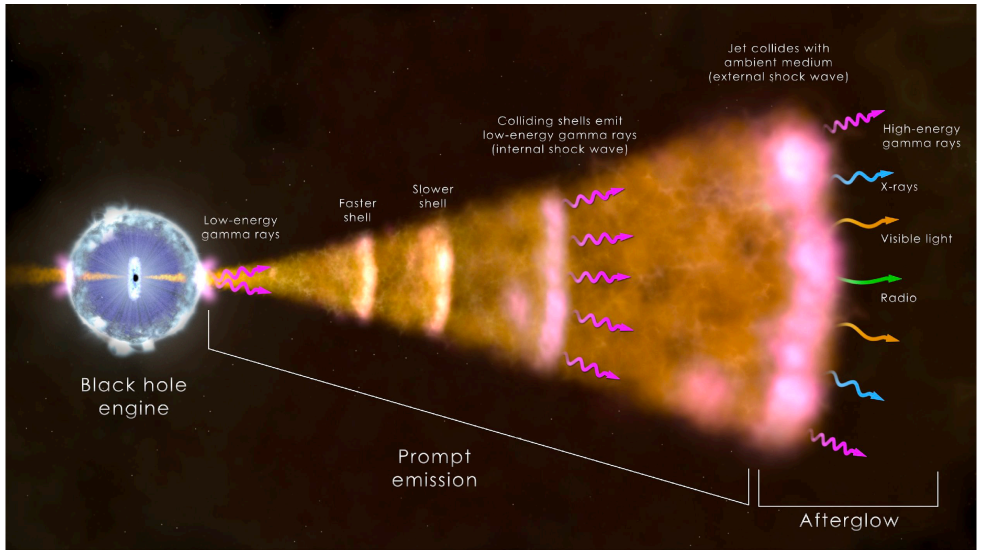
1. **Supernovae**: Explosive deaths of massive stars.
2. **Gamma-Ray Bursts**: Extremely energetic explosions in distant galaxies.
3. **Compact Objects**: Neutron stars (pulsars), stellar-mass BHs (X-ray binaries).
4. **Stars**: Pulsating stars, Eclipsing binaries, Flares.
5. **Active Galactic Nuclei**: SMBHs at the centers of galaxies with variable emission.
6. **Tidal Disruption Events**: Star getting too close to a SMBH and torn apart by tidal forces.
7. **Novae**: Outbursts due to a thermonuclear explosion on the surface of a white dwarf in a binary system.

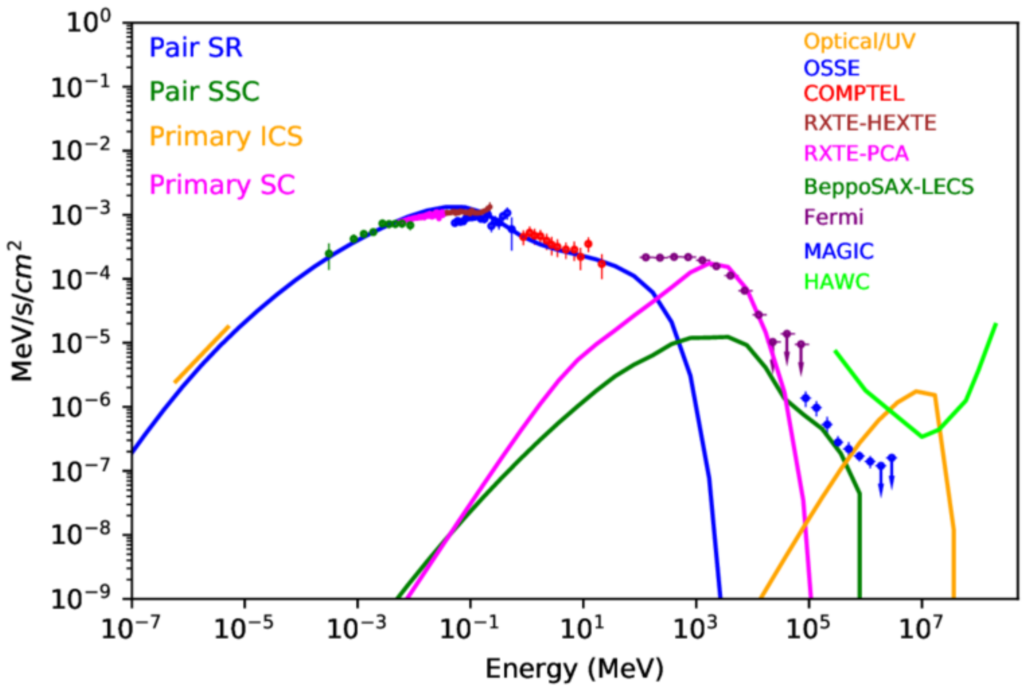


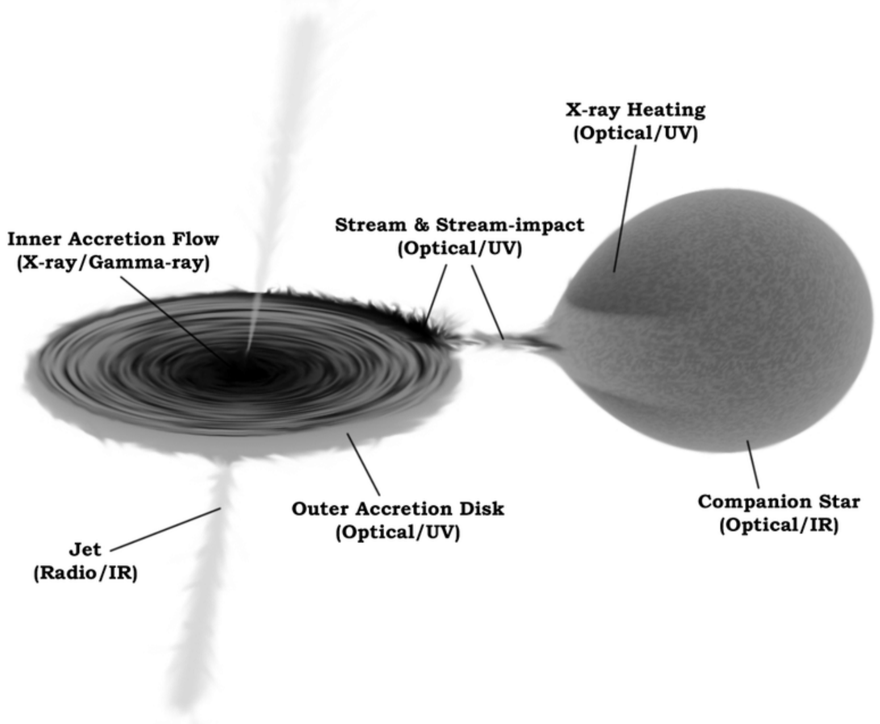
The importance of a multi band approach

- Different wavelengths probe different emission components and provide complementary information about astronomical objects.



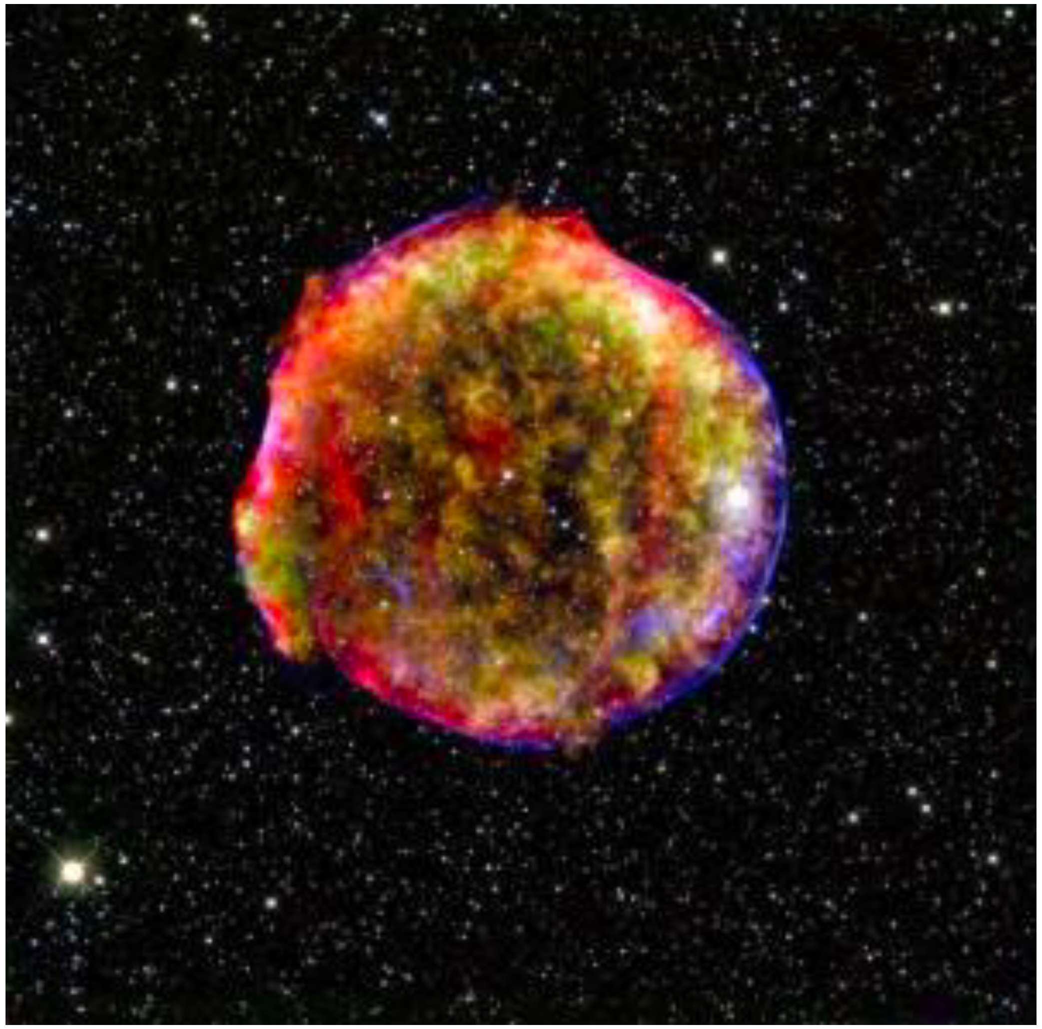


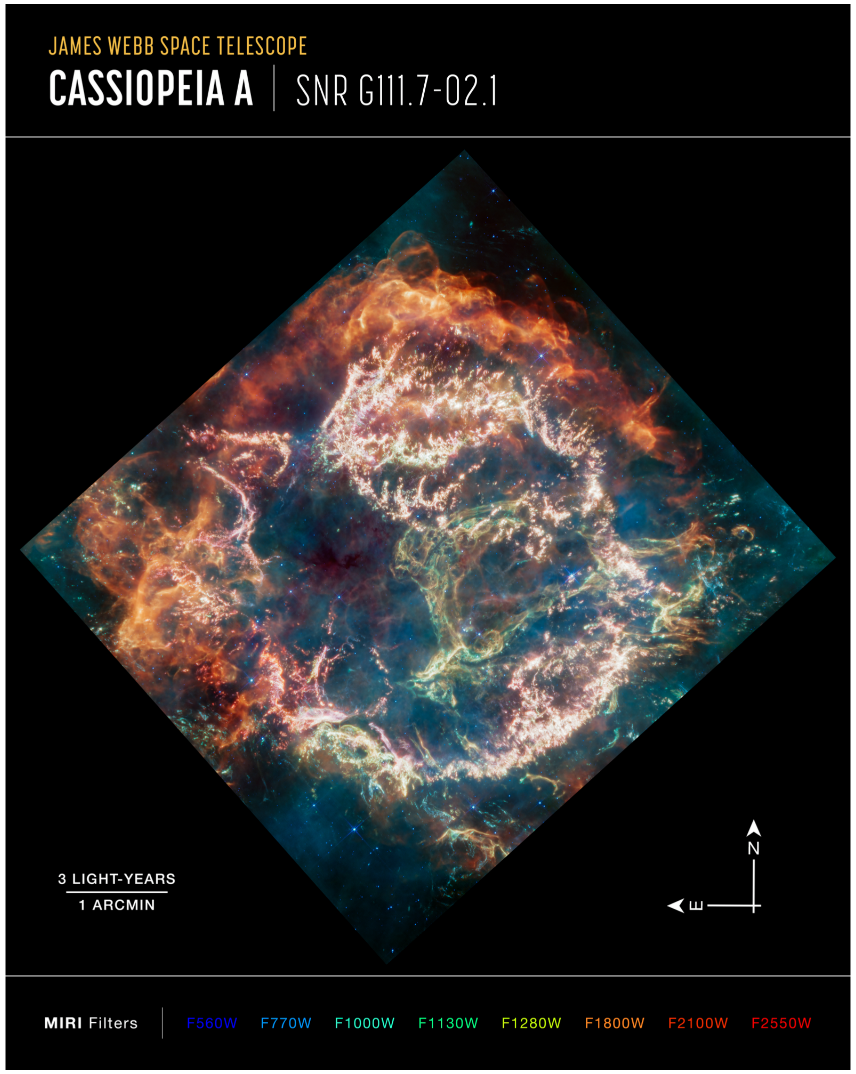




Supernovae

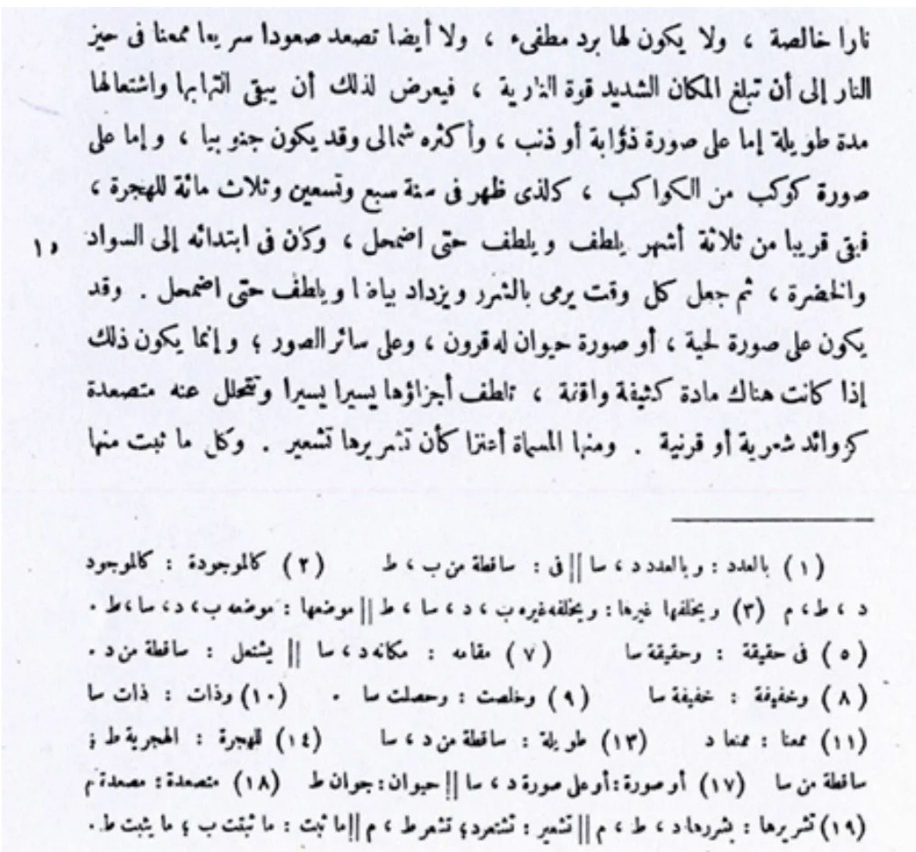
- Powerful and luminous explosion of a star.
- Transient events observable over periods ranging from days to months.
- Insights into stellar evolution, nucleosynthesis, and the dynamics of galaxies.





Supernovae

- Chinese astronomers have been the first to record a supernova.
- Over 20 historical candidates identified over the past 2000 years.
- Confirmed years: 185, 393, 1006 (brightest; also recorded in Egypt, Iraq, Italy, Japan and Switzerland), 1054 (Crab nebula remnant).
- In 1572 Tycho Brahe observed SN 1572 and argued it was very far from Earth.

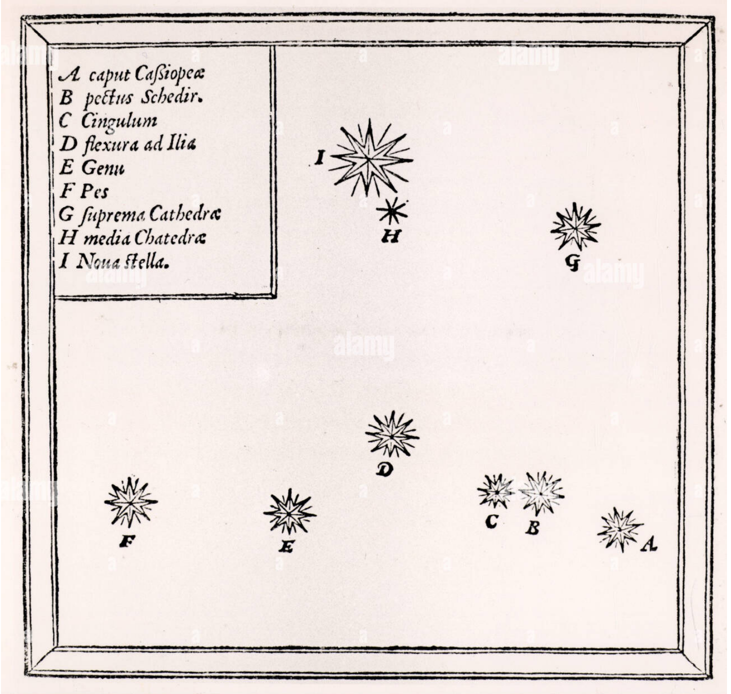


نارا خالصة ، ولا يكون لها برد مطفىء ، ولا أيضا تصعد صعودا سريعا ممعنا فى حيز النار إلى أن تبلغ المكان الشديد قوة النارية ، فيعرض لذلك أن يبقى التهابها واشتعالها مدة طويلة إما على صورة ذؤابة أو ذنب ، وأكثره شمالى وقد يكون جنوبيا ، وإما على صورة كوكب من الكواكب ، كالذى ظهر فى سنة سبع وتسعين وثلاث مائة للهجرة ، فبقى قريبا من ثلاثة أشهر يلطف ويلطف حتى اضمحل ، وكان فى ابتدائه إلى السواد والخضرة ، ثم جعل كل وقت يرمى بالشرر ويزداد بياضا ويلطف حتى اضمحل . وقد يكون على صورة لحية ، أو صورة حيوان له قرون ، وعلى سائر الصور ؛ وإنما يكون ذلك إذا كانت هناك مادة كثيفة واقفة ، تلطف أجزاؤها يسيرا يسيرا وتتحلل عنه متصعدة كزوائد شعرية أو قرنية . ومنها المسماة أعنزا كأن تشريرها تشعير . وكل ما ثبت منها

(١) بالعدد : وبالعدد د ، سا || ق : ساقطة من ب ، ط (٢) كالموجودة : كالموجود د ، ط ، م (٣) ويخلفها غيرها : ويخلفه غيره ب ، د ، سا ، ط || موضعها : موضعه ب ، د ، سا ، ط .
(٥) فى حقيقة : وحقيقة سا (٧) مقامه : مكانه د ، سا || يشتمل : ساقطة من د .
(٨) وخفيفة : خفيفة سا (٩) وخلصت : وحصلت سا . (١٠) وذات : ذات سا
(١١) ممعنا : ممنعا د (١٣) طويلة : ساقطة من د ، سا (١٤) للهجرة : الهجرية ط ؛ ساقطة من سا (١٧) أو صورة : أو على صورة د ، سا || حيوان : جوان ط (١٨) متصعدة : مصعدة م
(١٩) تشريرها : بشررها د ، ط ، م || تشعير : تشعرد ؛ تشعرط ، م || ما ثبت : ما ثبتت ب ؛ ما يثبت ط .

Passage from Ibn Sina’s Kitab al-Shifa describing the 1006 supernova

Crab nebula remnant



Tycho Brahe's drawing of the supernova of 1572

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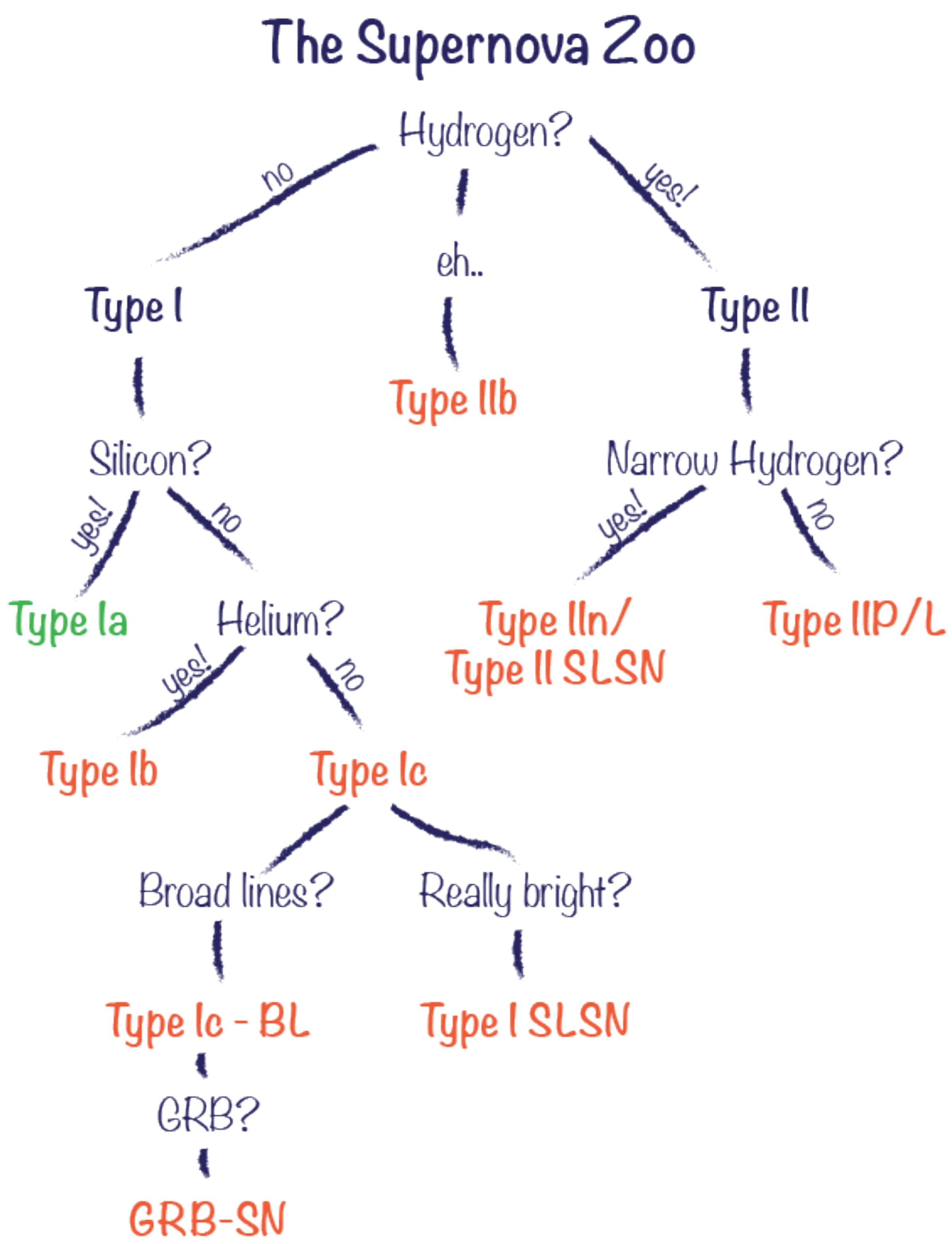
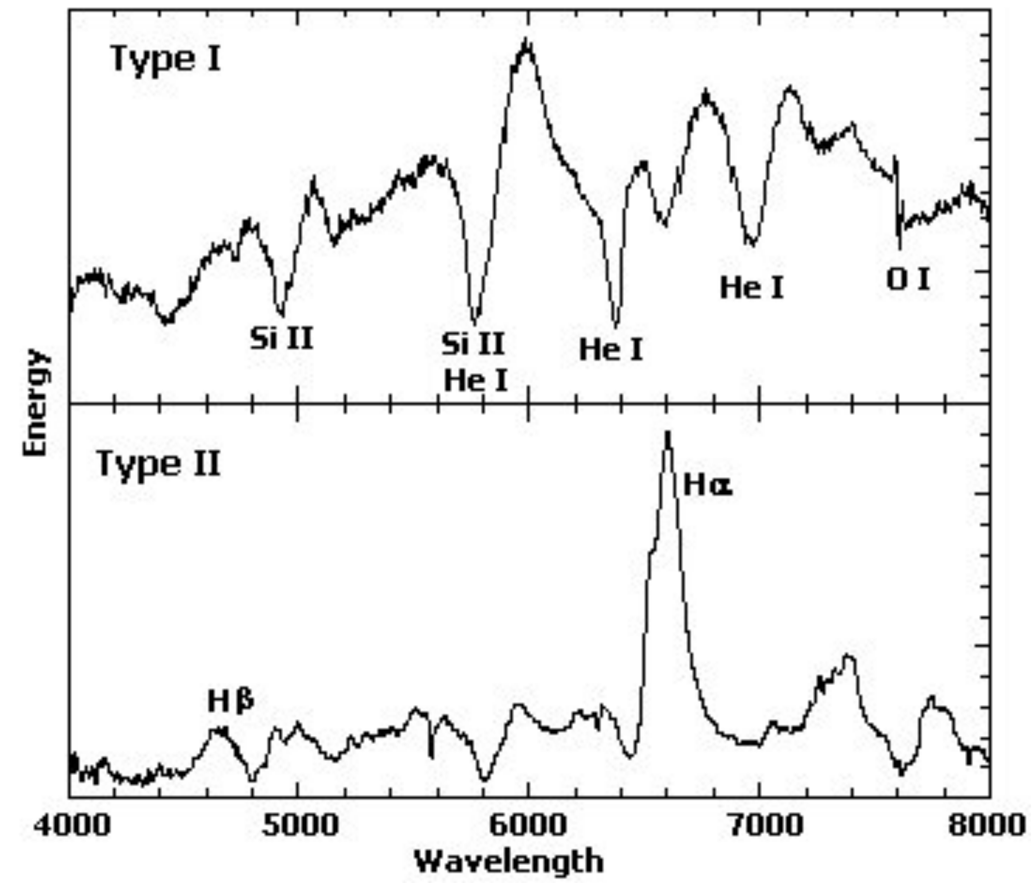
Types of supernovae



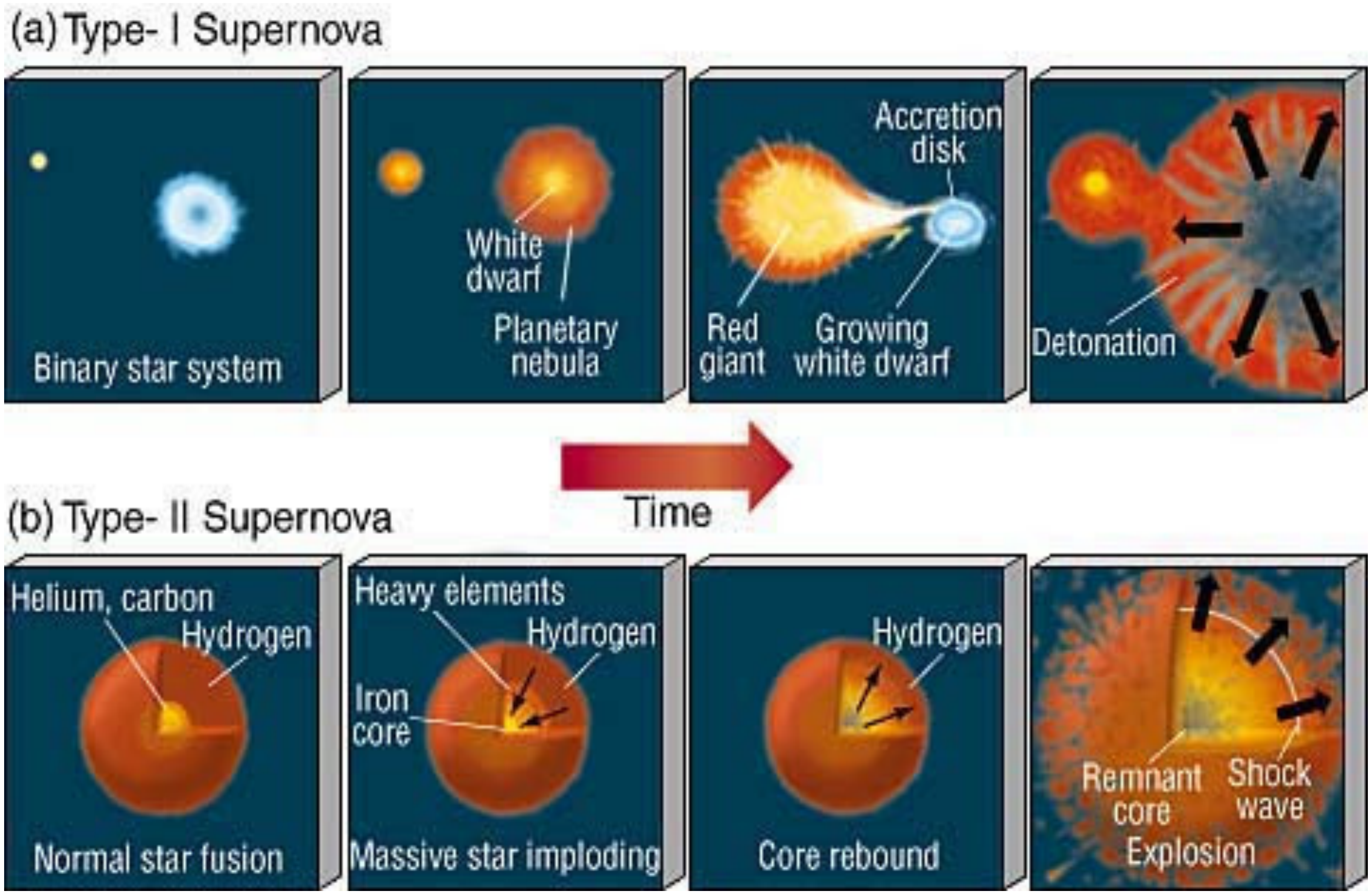
- Type I Supernovae (Subtypes: Ia, Ib, Ic)
- Lack of H lines in their spectra.

- Type II Supernovae:
- Presence of H lines in their spectra.



Types of supernovae

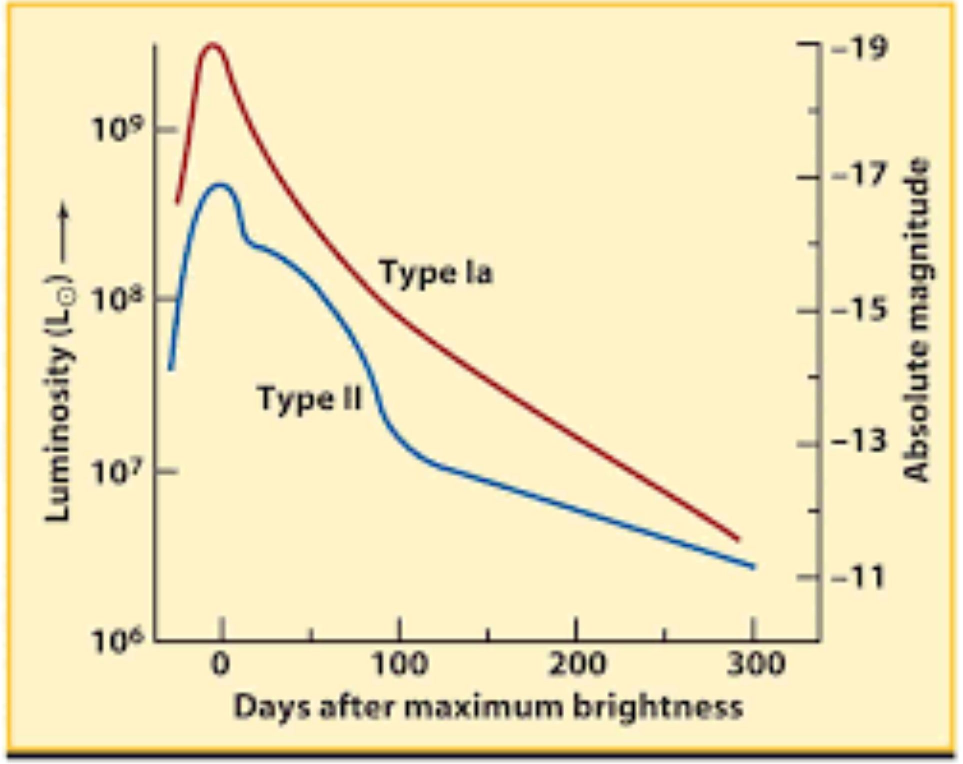
- Type I: occurs in binary systems when a WD accretes matter from its companion star until a thermonuclear explosion occurs.
- Type II: occurs when a massive star exhausts its nuclear fuel, leading to a core collapse and explosion.



Supernovae light curves

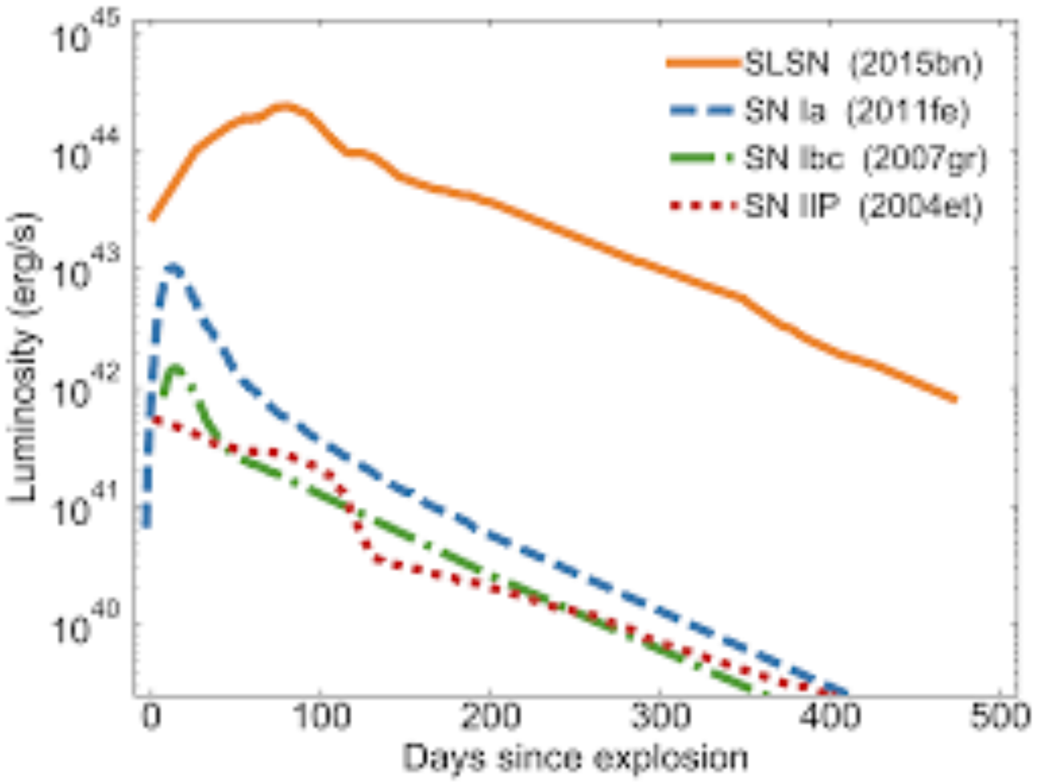
Type I: **Sharp, bright peak, followed by a steady decay.**

Emission primarily powered by the radioactive decay of nickel-56 to cobalt-56 and then to iron-56.



Type II : **Initial smooth peak followed (in some cases) by a distinctive plateau phase lasting for weeks/months, and a gradual decline.**

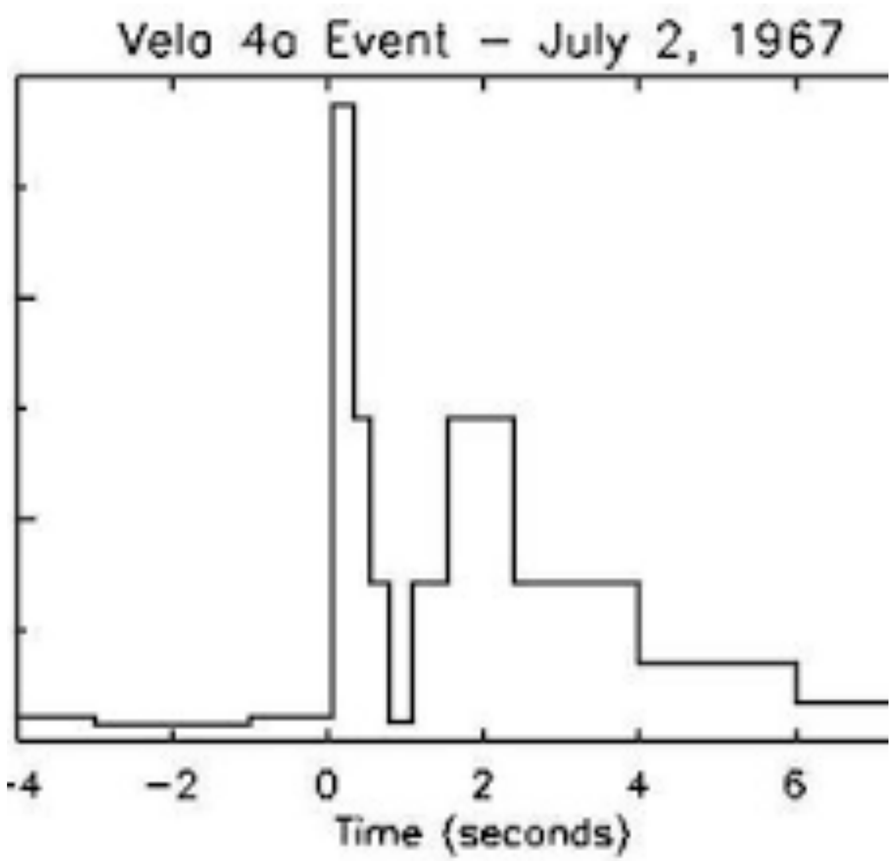
The plateau phase is powered by the recombination of hydrogen in the star outer layers



Gamma-ray bursts

- Extremely energetic explosions emitting gamma rays, releasing an energy comparable to a SN but in a timescale of seconds!
- Provide insights into the most energetic processes in the Universe.
- Key to understanding massive stars' deaths and black hole formation

The first GRB ever observed!



THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

"Since the beginning it was clear these were not terrestrial phenomena… then where did they come from?"

Gamma-ray bursts properties

Spectral Range: $\sim 10\,\mathrm{keV} - 10\,\mathrm{MeV}$

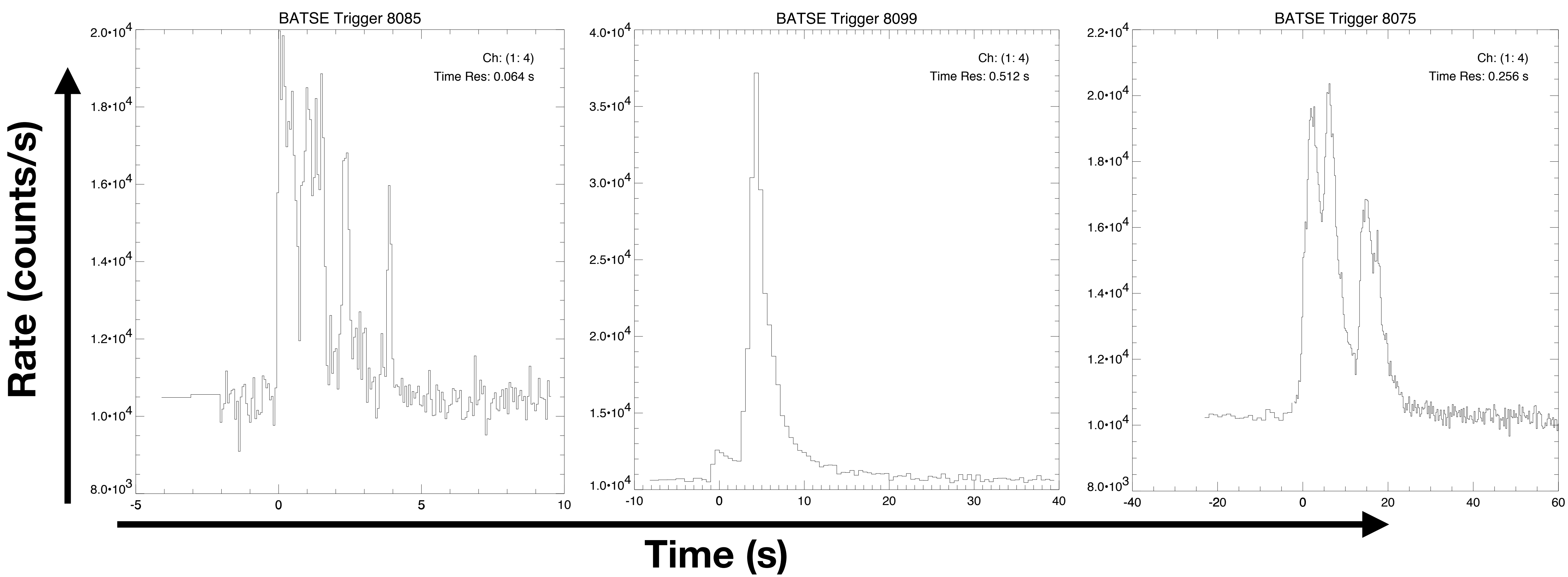
Duration: $\sim 1 - 1000\,s$

Isotropic Equivalent Energy: $\sim 10^{51} - 10^{54}\,\mathrm{erg}$

Rate: a few per week

Variability: $\sim 10\,\mathrm{ms} - 1\,\mathrm{s}$

Energy: $\sim 10^{50} - 10^{51}\,\mathrm{erg}$



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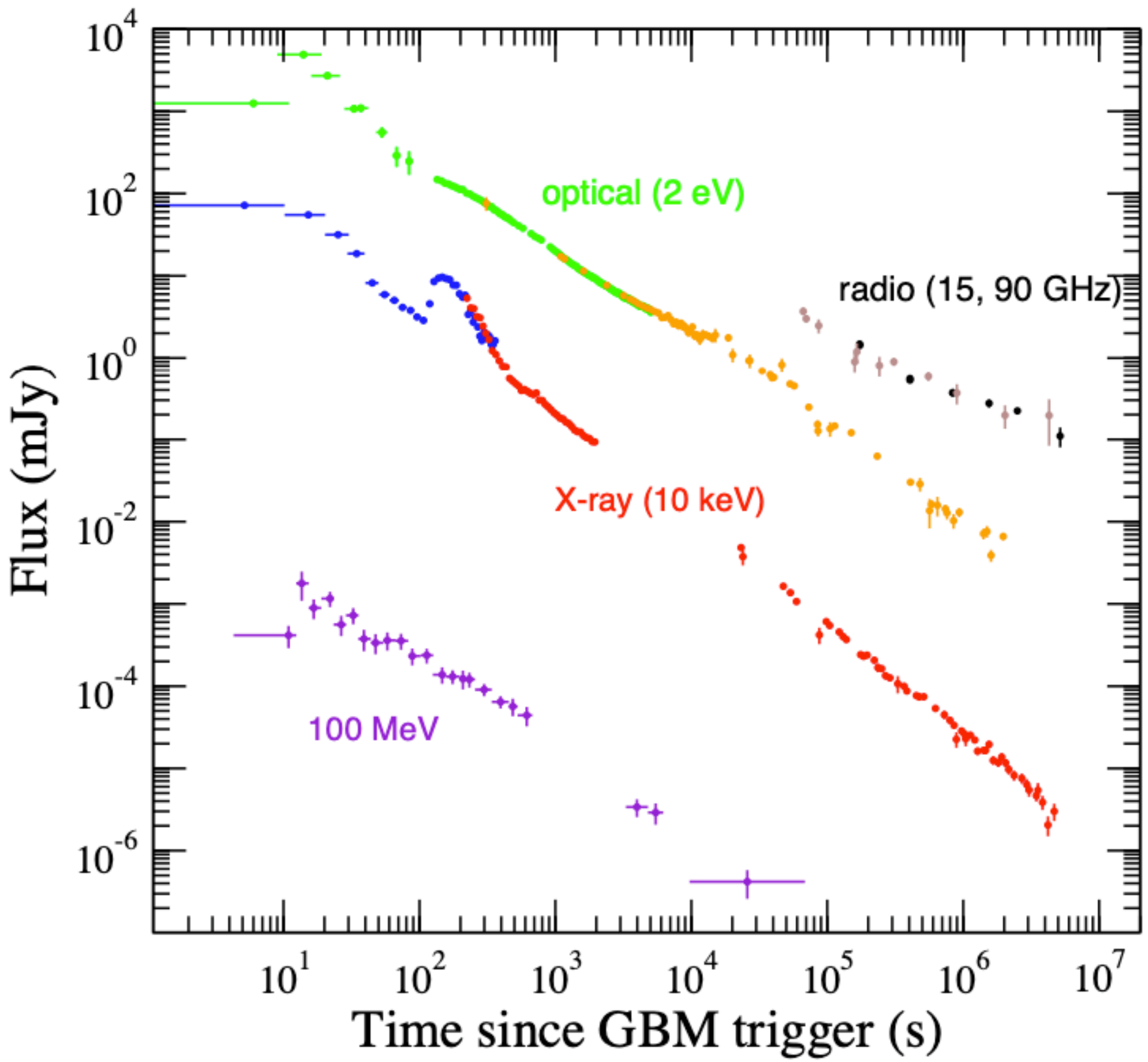
Gamma-ray bursts afterglows

GRB 130427A Panaitescu et. al. 2013



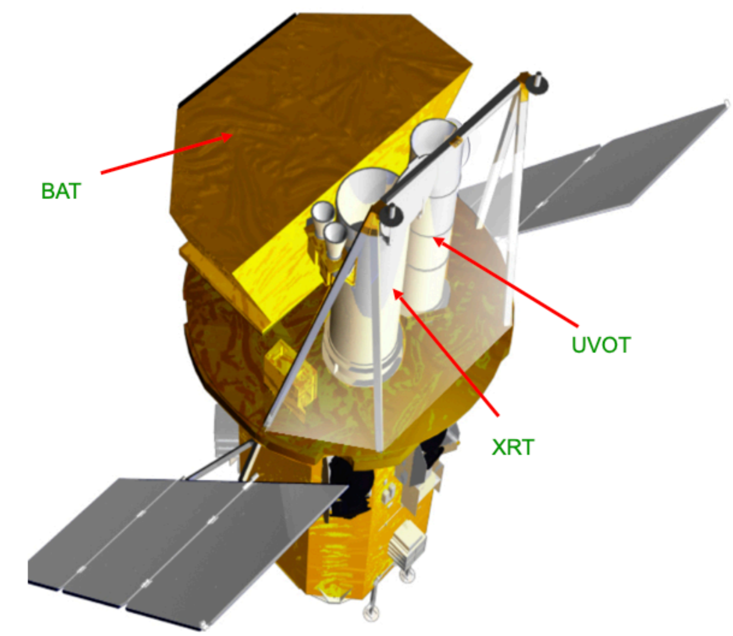
- Observed from radio to TeV
- Lasting days after the prompt emission
- Many different decay shapes

Neil Gehrels Swift Observatory

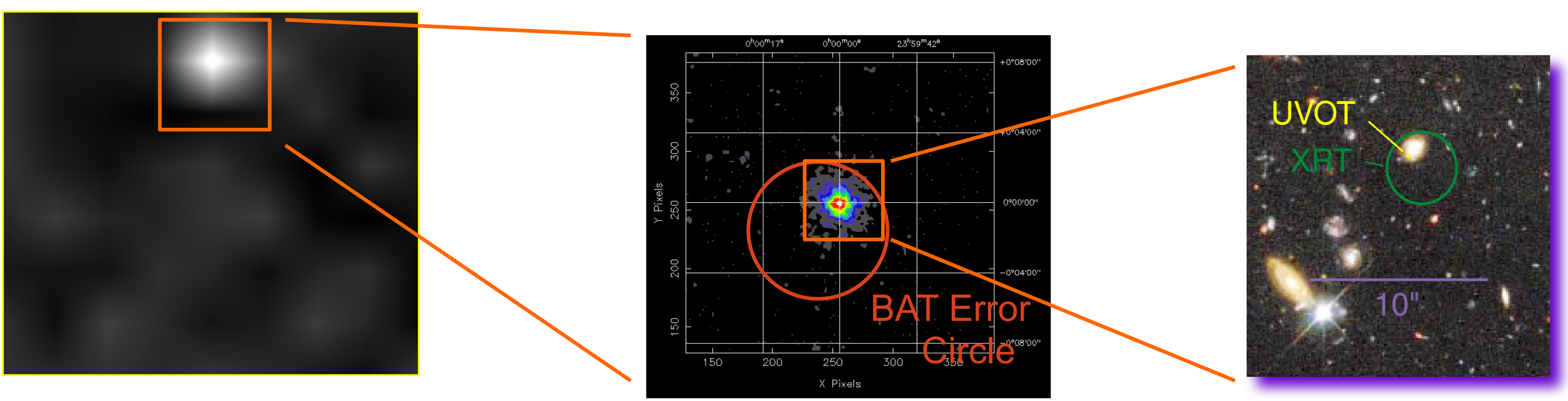
Wide-field hard X-ray detector (BAT)

Narrow field X-ray telescope with CCD detector (XRT)

Optical/UV telescope (UVOT)



BAT Burst Image | XRT Image | UVOT Image

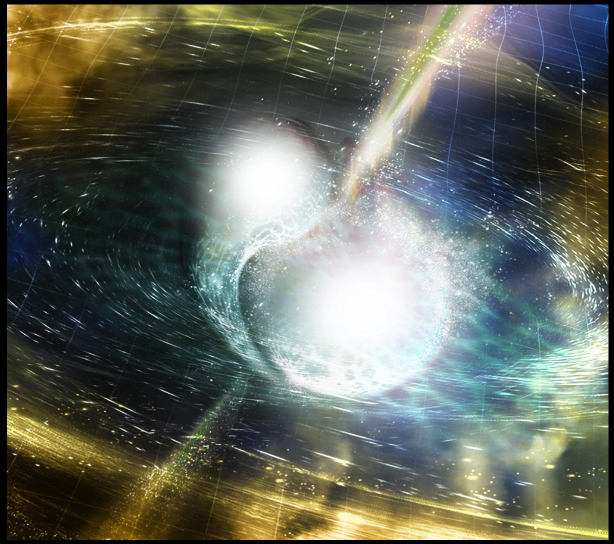


T~10 sec | *T~100 sec* | *T~300 sec*

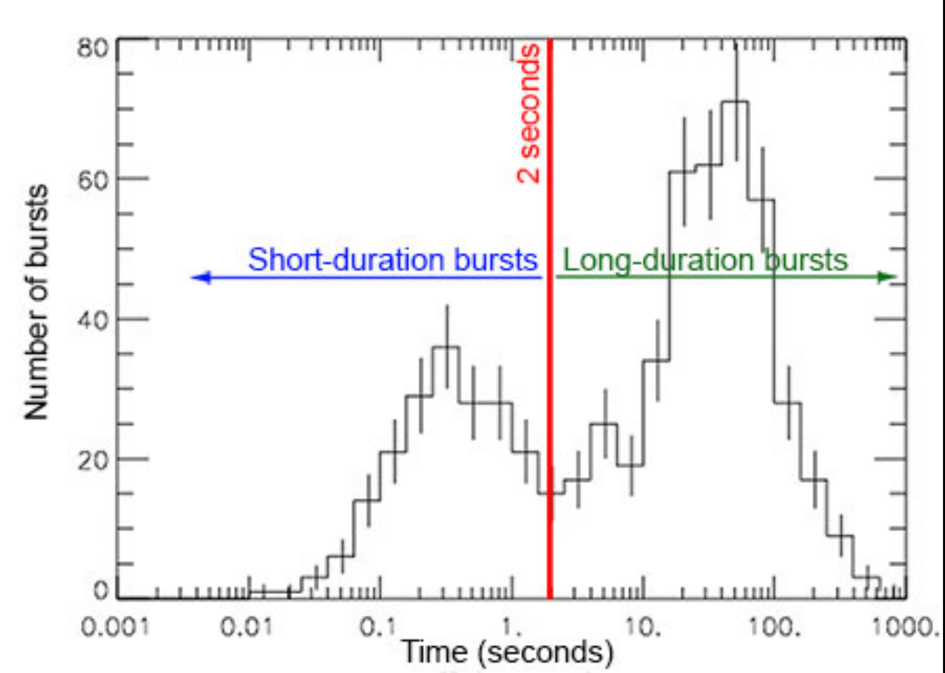
Gamma-ray bursts progenitors

Rapid variability allows to derive an estimate of the source size of the order of tens of km.

Short GRB

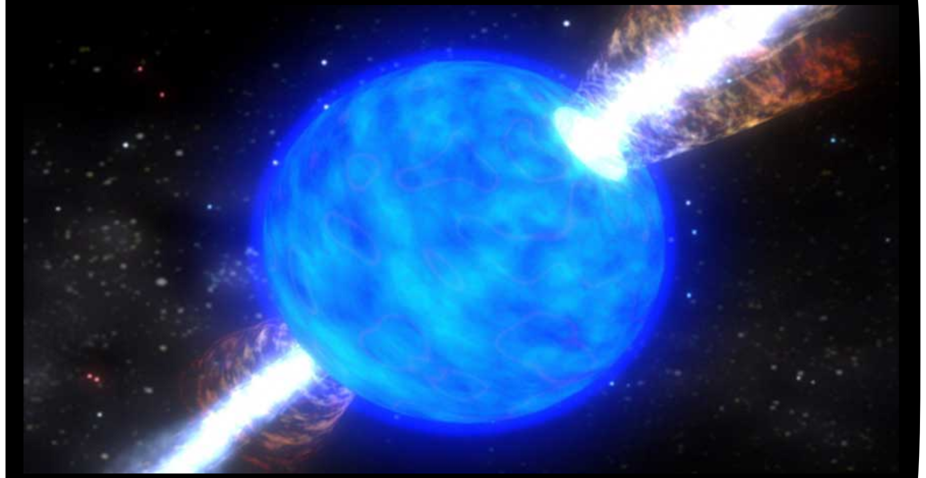


Compact Binary Merger



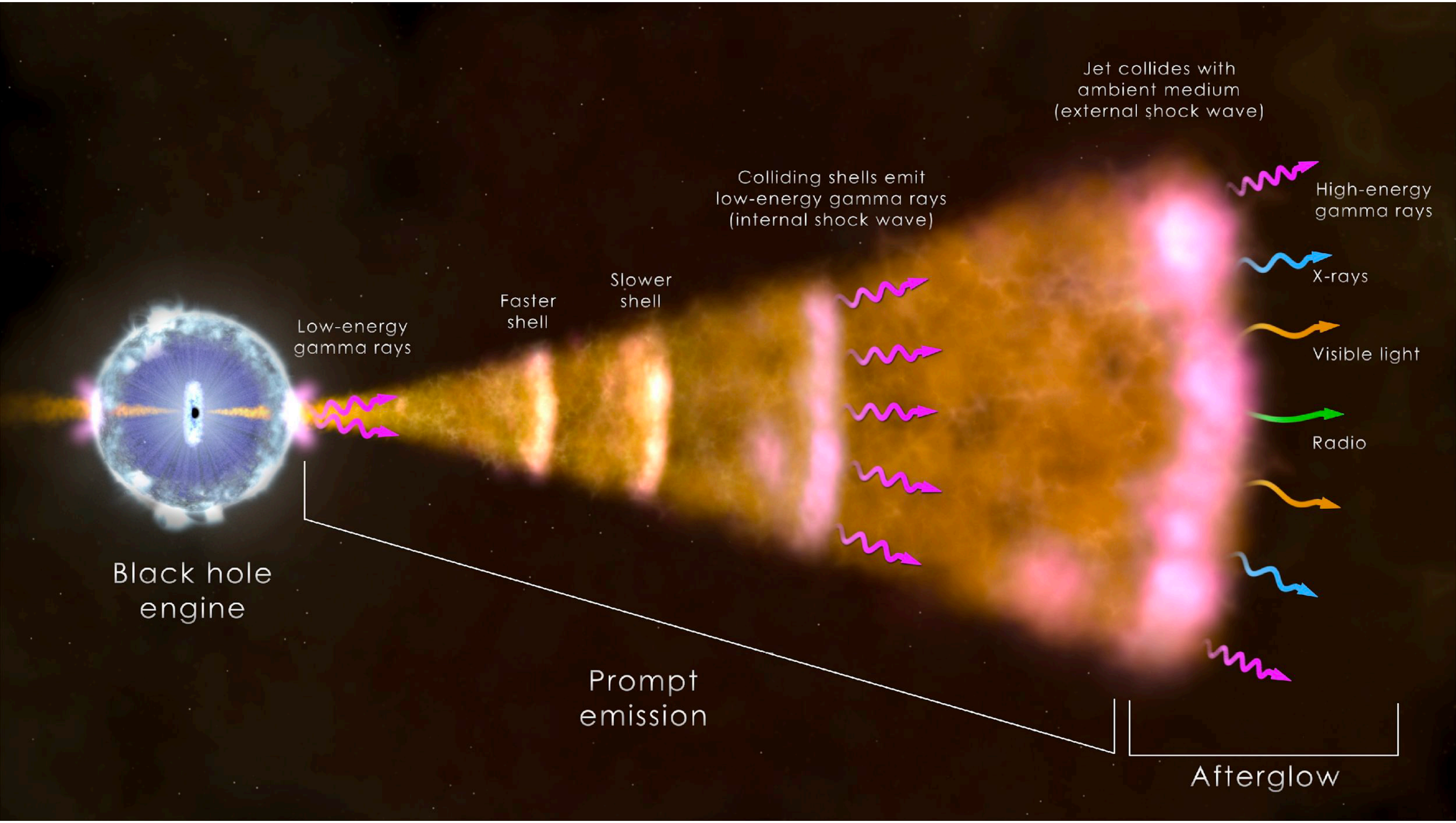
(https://imagine.gsfc.nasa.gov/science/objects/bursts1.html)

Long GRB



Collapsar

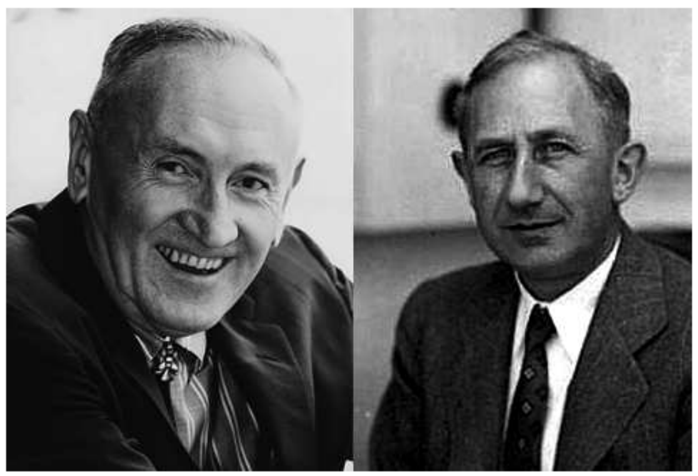
Gamma-ray bursts mechanisms

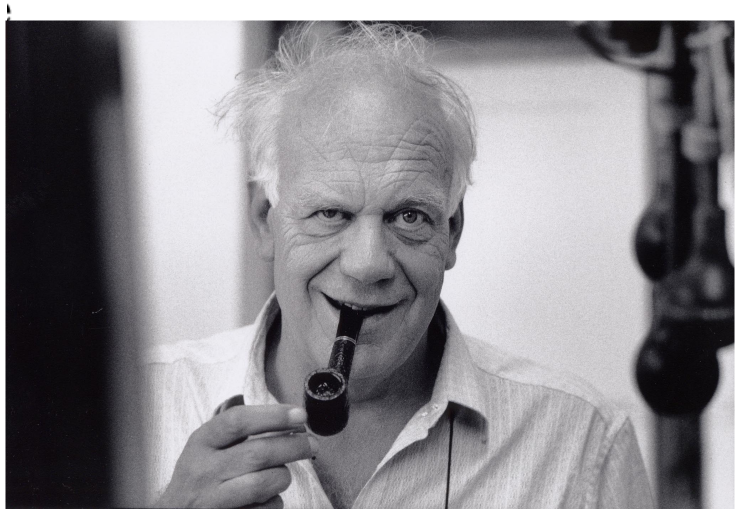


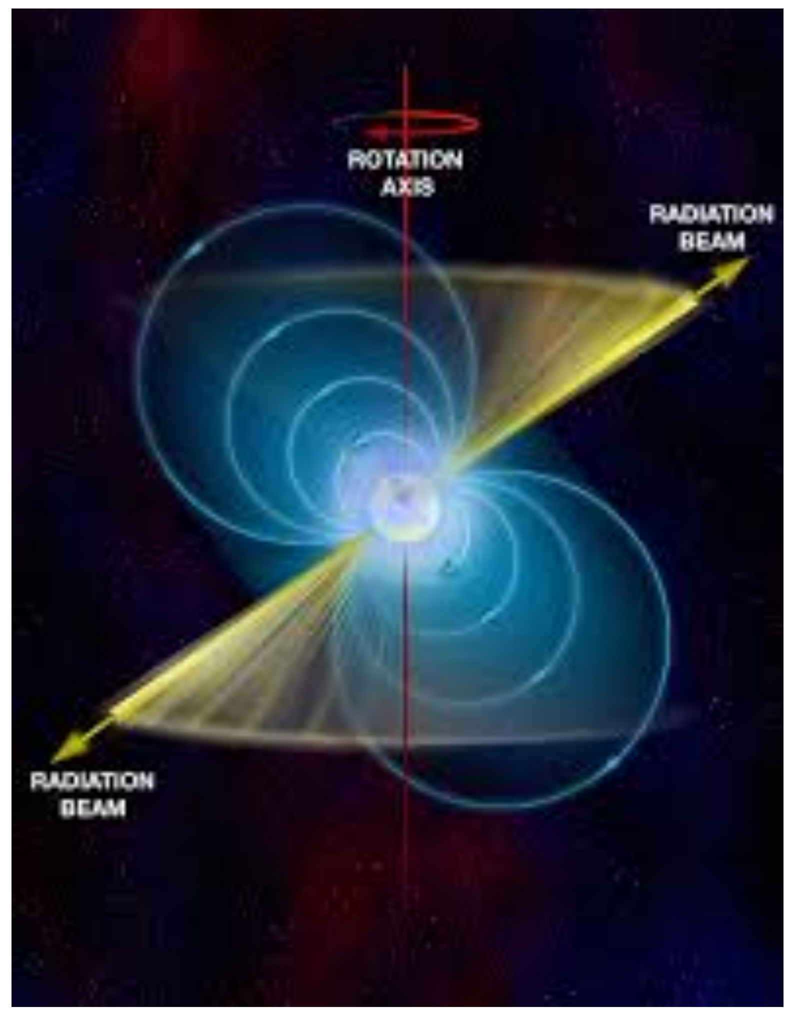
The discovery of pulsars

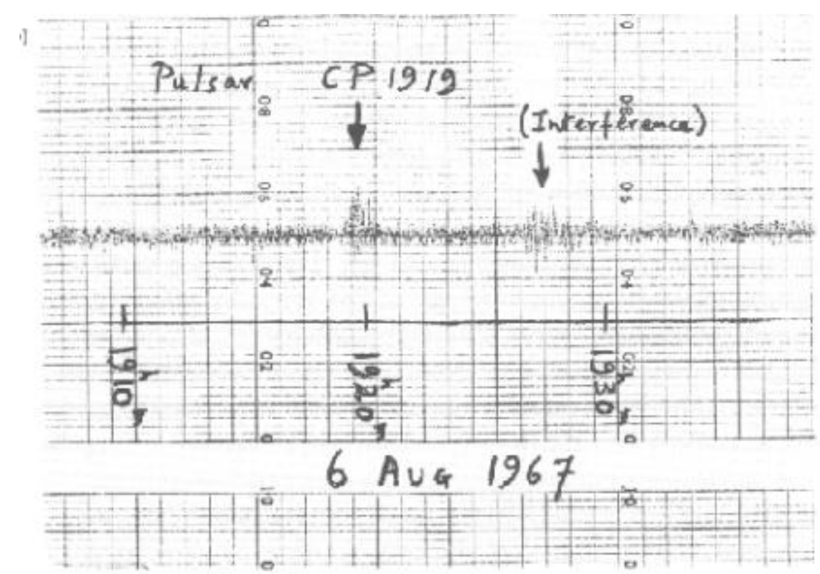
Rapidly rotating neutron stars emitting beams of electromagnetic radiation.

Discovered in 1967, they confirmed the predictions by Baade and Zwicky in 1934 on the existence of neutron stars and supported the theoretical model proposed by Pacini in 1967.

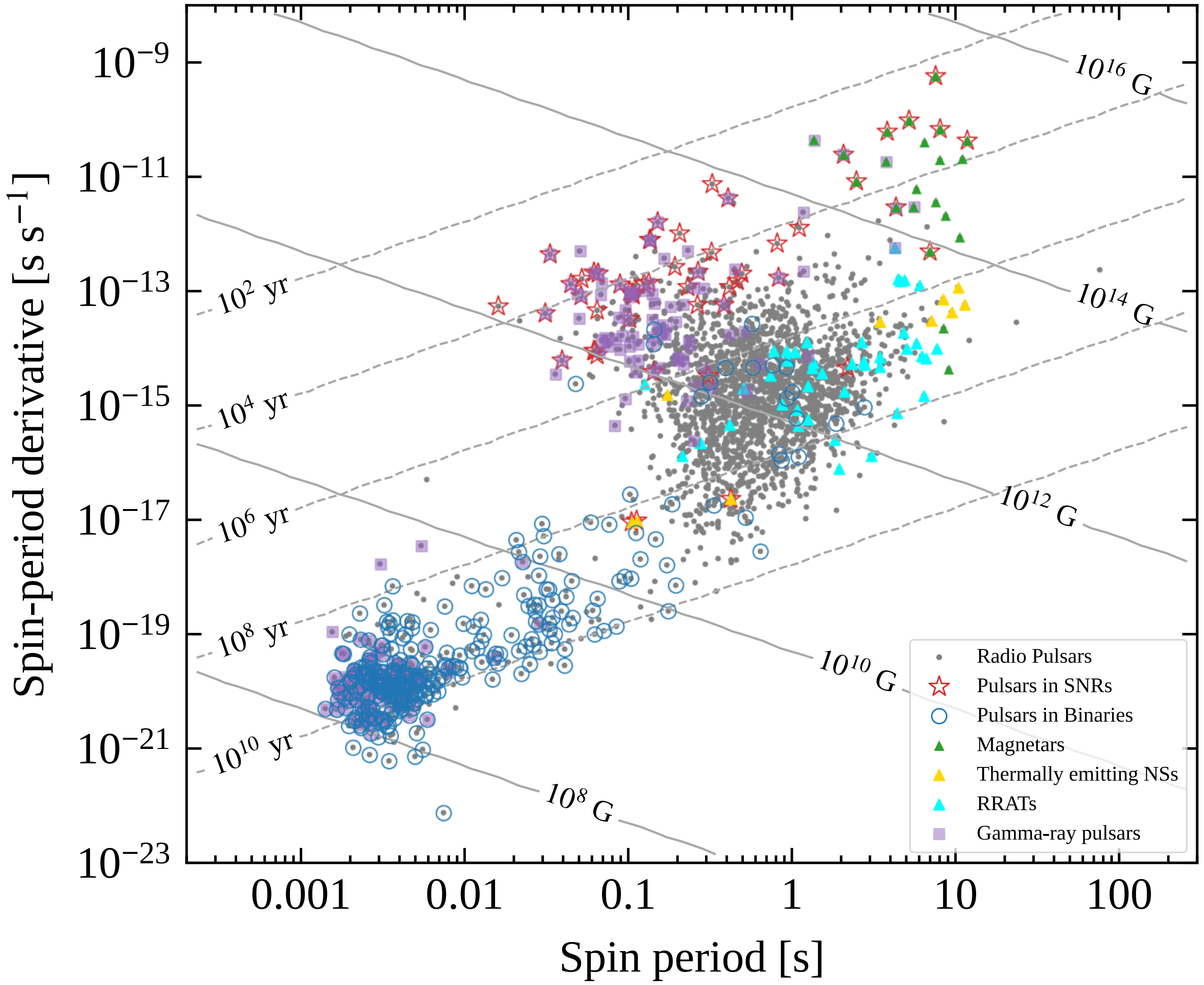








Pulsars as testbeds of fundamental physics

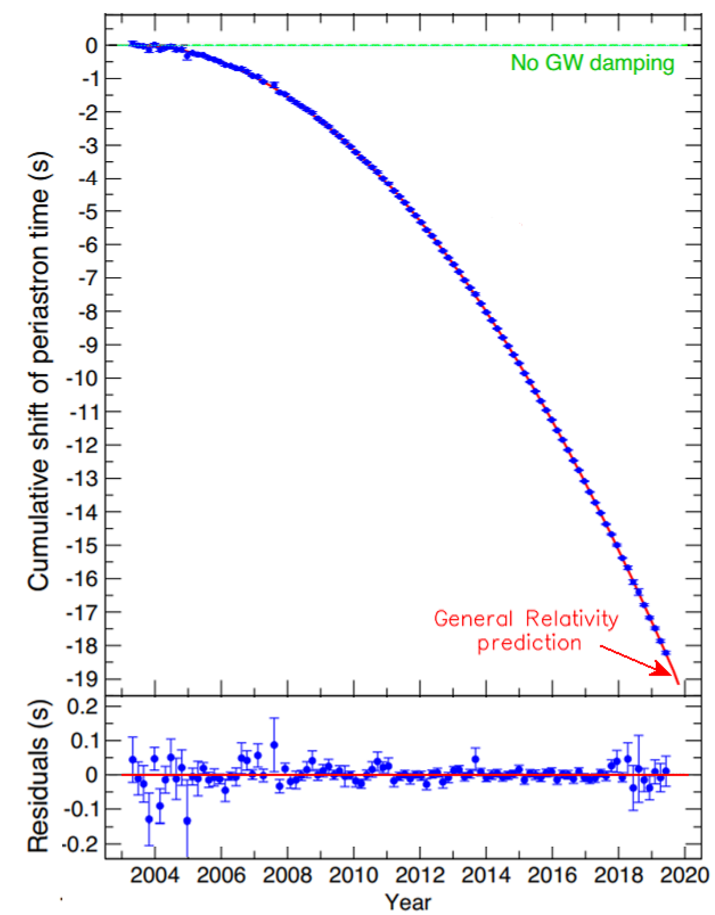


3500 pulsars are known (and counting)

- either isolated or in binary systems
- rotating at periods from ms to tens of s
- emitting from radio to gamma-rays and
- powered by different mechanisms

The **timing** of their regular pulses provides insight into:

- neutron star physics
- properties of dense matter within their interiors
- interstellar medium
- general relativity



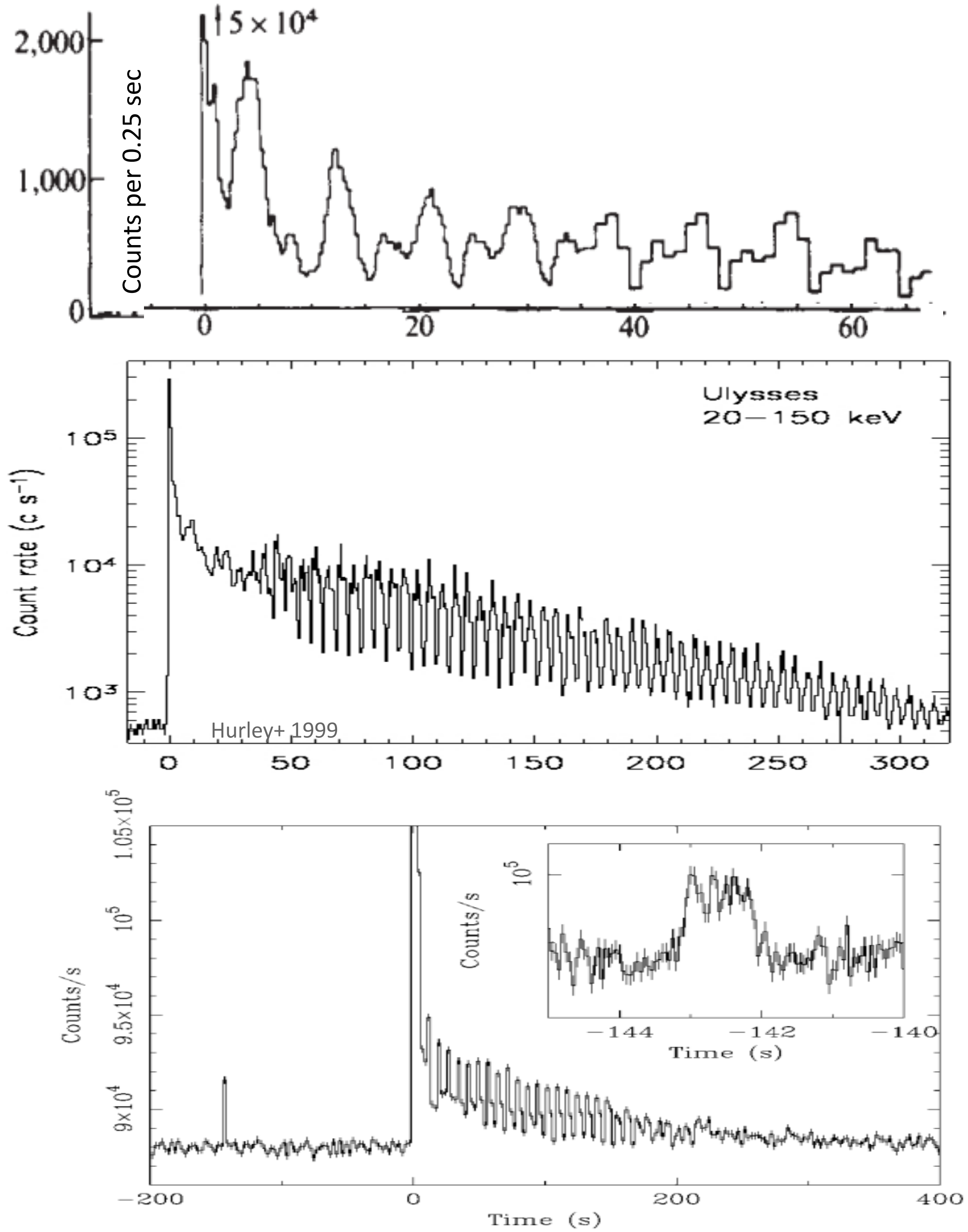
Parameter	Value
Right ascension (R.A.), α (J2000)	$07^h37^m51\overset{s}{.}248115(10)$
Declination (Dec), δ (J2000)	$-30°39'40\overset{''}{.}70485(17)$
Proper motion R.A., μ_α (mas yr^{-1})	$-2.567(30)$
Proper motion Dec., μ_δ (mas yr^{-1})	2.082(38)
Parallax, π_c (mas)	1.36(+0.12, −0.10)
Position epoch (MJD)	55045.0000
Rotational frequency (freq.), ν (Hz)	44.054 068 641 962 81(17)
First freq. derivative, $\dot{\nu}$ (Hz s^{-1})	$-3.4158071(11) \times 10^{-15}$
Second freq. derivative, $\ddot{\nu}$ (Hz s^{-2})	$-2.286(29) \times 10^{-27}$
Third freq. derivative, $\dddot{\nu}$ (Hz s^{-3})	$1.28(26) \times 10^{-36}$
Fourth freq. derivative, $\ddddot{\nu}$ (Hz s^{-4})	$4.580(86) \times 10^{-43}$
Timing epoch, t_0 (MJD)	55700.0
Orbital period, P_b (day)	0.102 251 559 297 3(10)
Projected semimajor axis, x (s)	1.415 028 603(92)
Eccentricity (Kepler equation), e_T	0.087 777 023(61)
Epoch of periastron, T_0 (MJD)	55 700.233 017 540(13)
Longitude of periastron, ω_0 (deg)	204.753 686(47)
Periastron advance, $\dot{\omega}$ (deg yr^{-1}) [c]	16.899 323(13)
Change of orbital period, $\dot{P}_b$	$-1.247920(78) \times 10^{-12}$
Einstein delay amplitude, γ_E (ms)	0.384 045(94)
Logarithmic Shapiro shape, z_s	9.65(15)
Range of Shapiro delay, r (μs)	6.162(21)
NLO factor for signal prop., q_{NLO}	1.15(13)
Derived parameters	
$\sin i = 1 - \exp(-z_s)$	0.999936(+9/−10)
Orbital inclination, i (deg)	89.35(5) or 90.65(5)
Total mass, M ($M_\odot$)[d]	2.587052(+9/−7)
Mass of pulsar A, m_A ($M_\odot$)[d]	1.338185(+12/−14)
Mass of pulsar B, m_B ($M_\odot$)[d]	1.248868(+13/−11)
Galactic longitude, l (deg)	245.2357
Galactic latitude, b (deg)	−4.5049
Proper motion in l, μ_l (mas yr^{-1})	−3.066(35)
Proper motion in b, μ_b (mas yr^{-1})	−1.233(31)
Distance from π_c, d (pc)	735(60)
Transverse velocity, v_T (km s^{-1})	11.5(10)

Magnetar giant flares

SGR 0526-66
1979 March 5
L_{peak} ~4x10^{44} erg/s
E_{tot}~5x10^{44} erg

SGR 1900+14
1998 August 27
L_{peak} >8x10^{44} erg/s
E_{tot}>3x10^{44} erg

SGR 1806-20
2004 December 27
L_{peak} ~2-5x10^{47} erg/s
E_{tot}~2-5x10^{46} erg



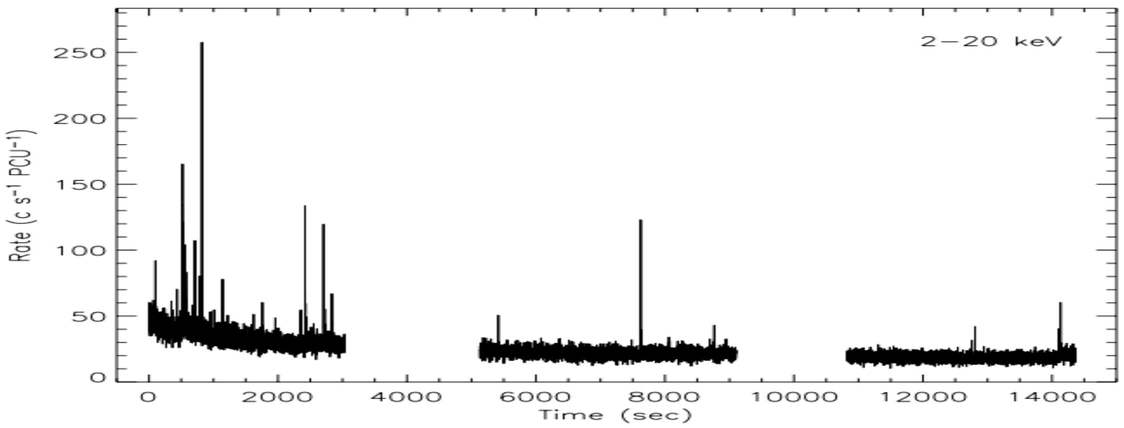
Initial spike (~0.1–0.2s) + long pulsating tail modulated at the NS spin period

Similar E_{tail}~10^{44} erg

Caused by large-scale rearrangements of the magnetic field

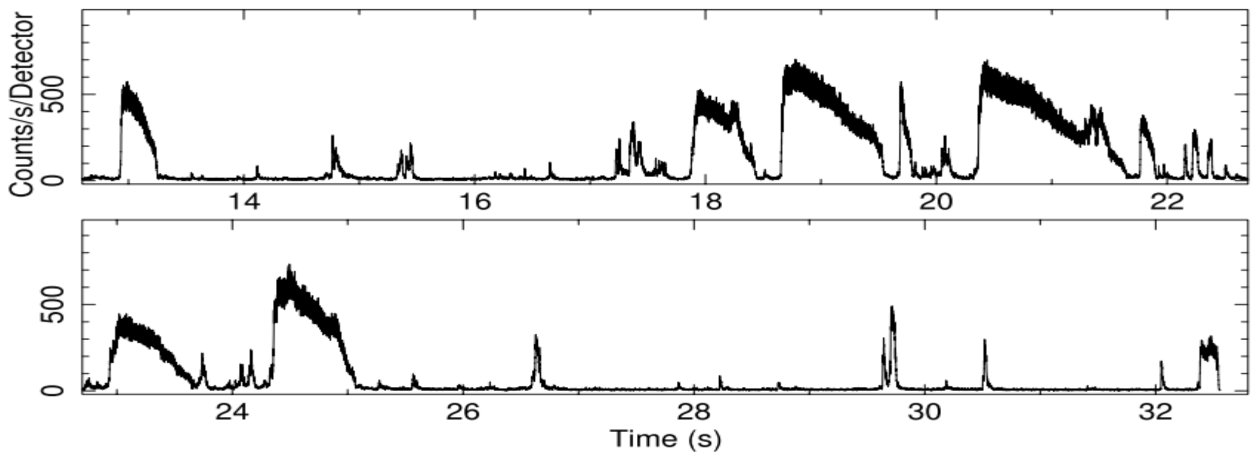
Magnetar bursts

Short bursts



$L_{peak} \sim 10^{39} – 10^{41}$ erg s^{-1}
duration ~ 0.01 – 1 s
sporadic or in storms

Intermediate bursts

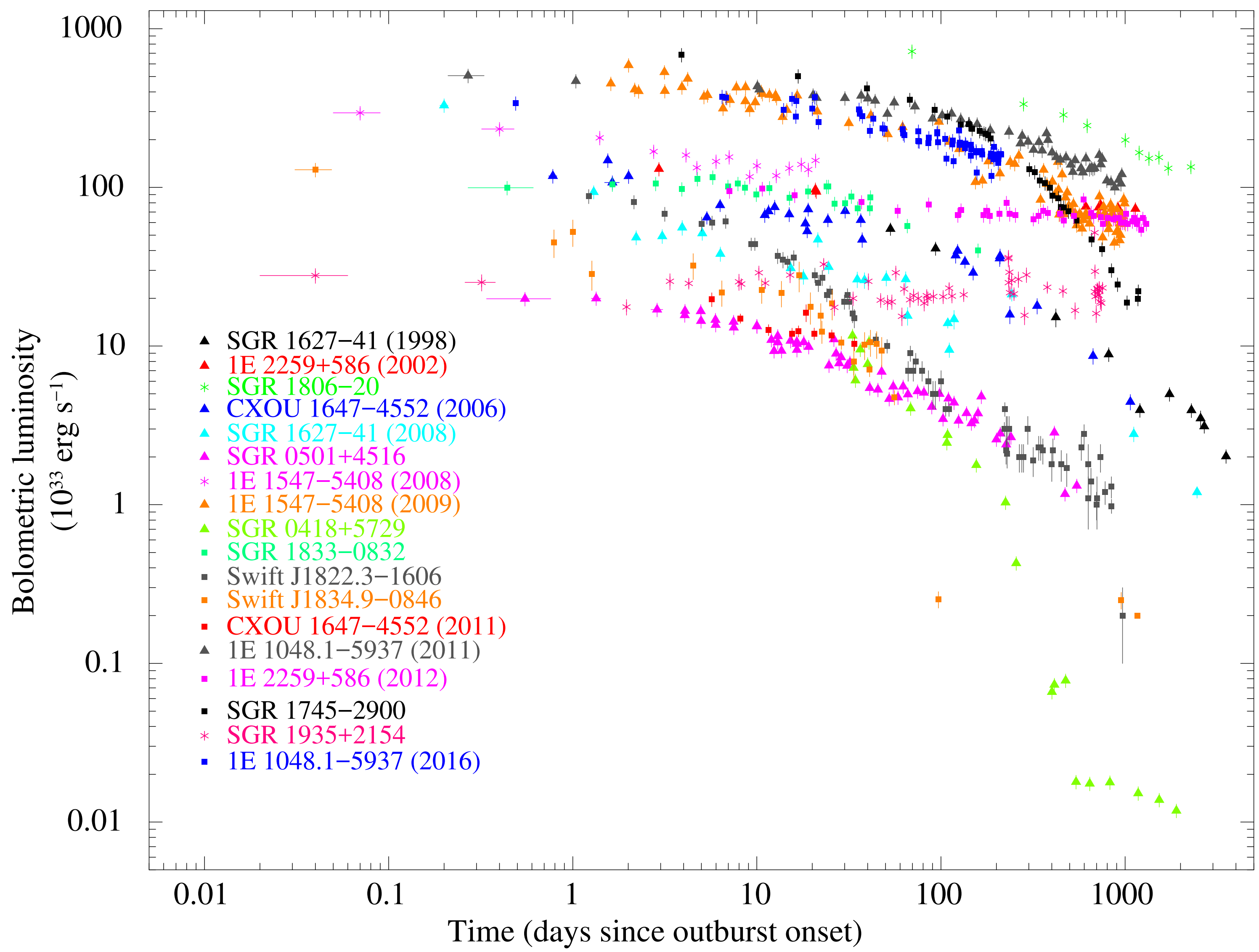


$L_{peak} \sim 10^{41} – 10^{43}$ erg s^{-1}
duration ~ 1 – 40 s
abrupt onset

They often announce an active phase

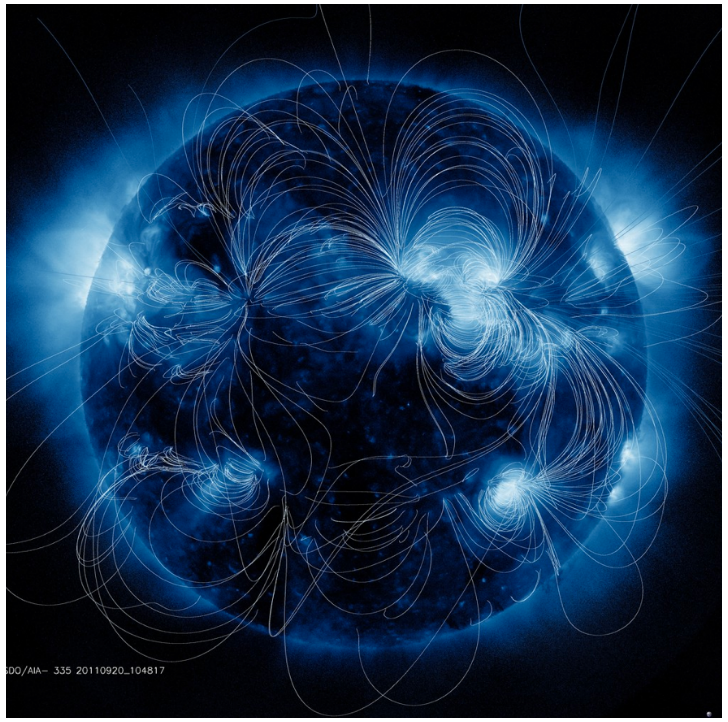
Magnetar outbursts

Coti Zelati et al. 2018
Magnetar Outburst Online Catalog
http://magnetars.ice.csic.es/



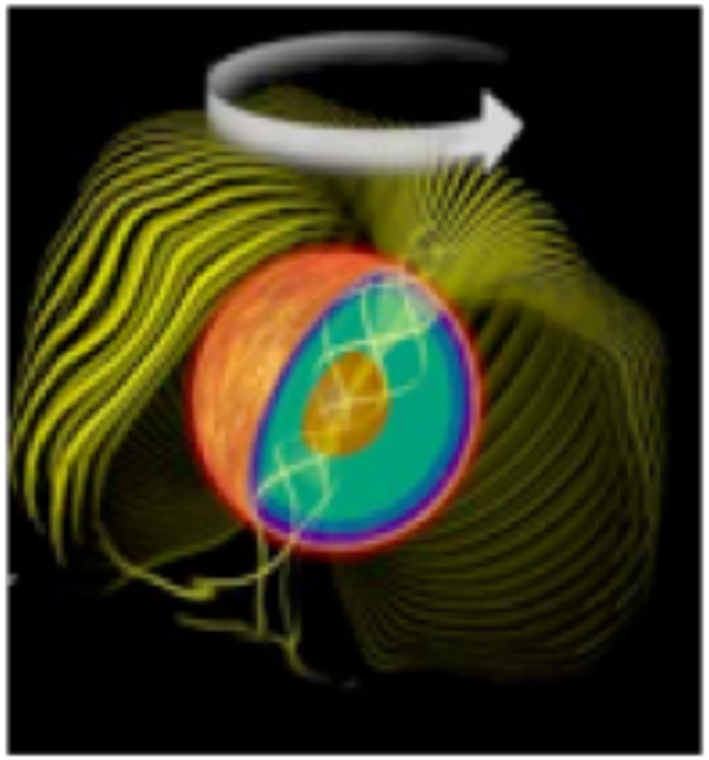
- About 1100 X-ray observations (12 Ms) between from 1998 to 2017
- Spectral fitting with empirical and more physically-motivated models
- Light curve modeling and estimate of energetics and decay time scale

Magnetar outbursts mechanisms



Internal source of heat?

- Plastic flows in the crust convert magnetic energy into heat
- Heat conducted up and radiated

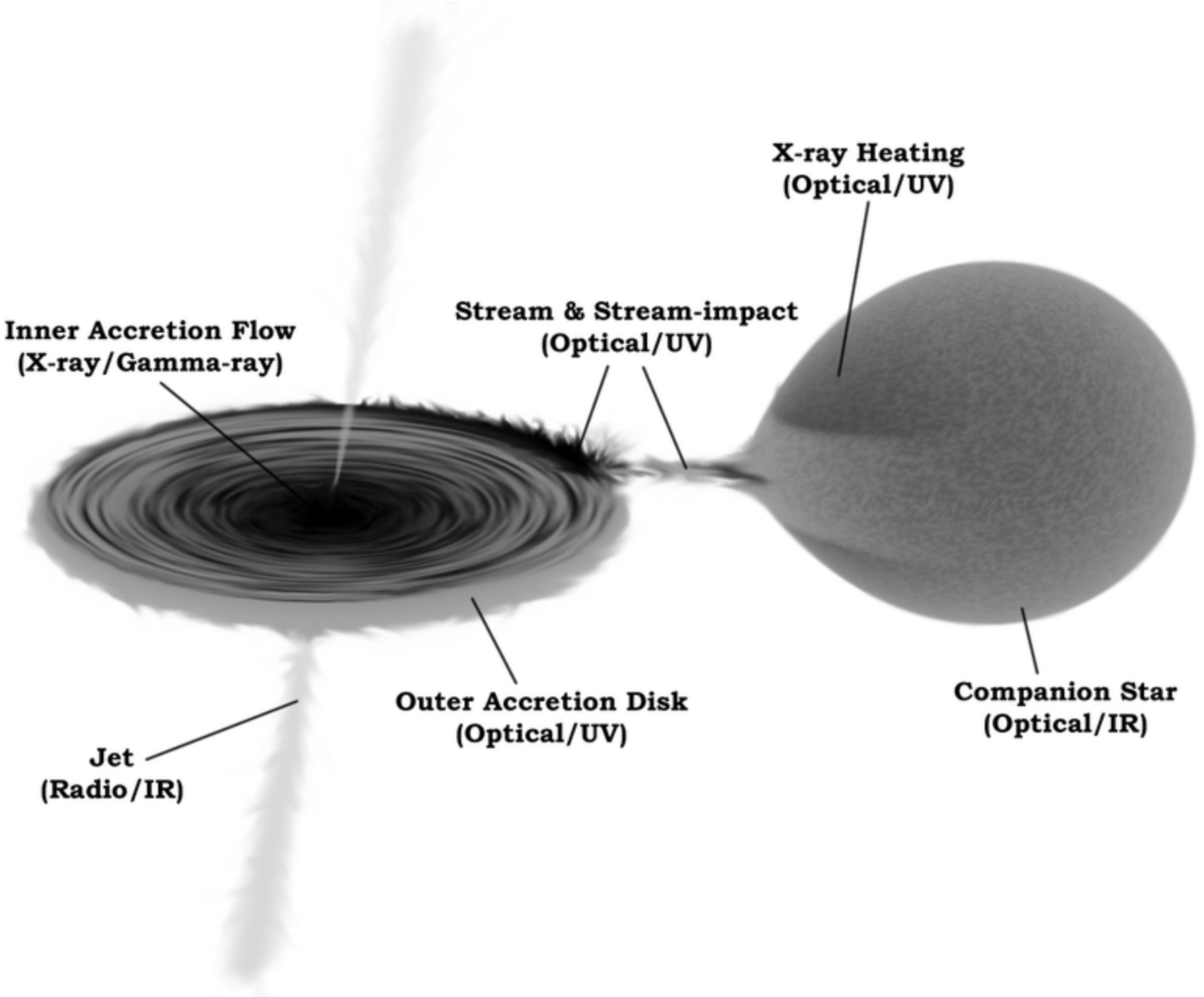


External source of heat?

- Crustal displacements twist up the external magnetic field
- Returning currents hit the surface

Low-mass X-ray binaries

- Systems where a NS or BH accretes matter from a companion star.

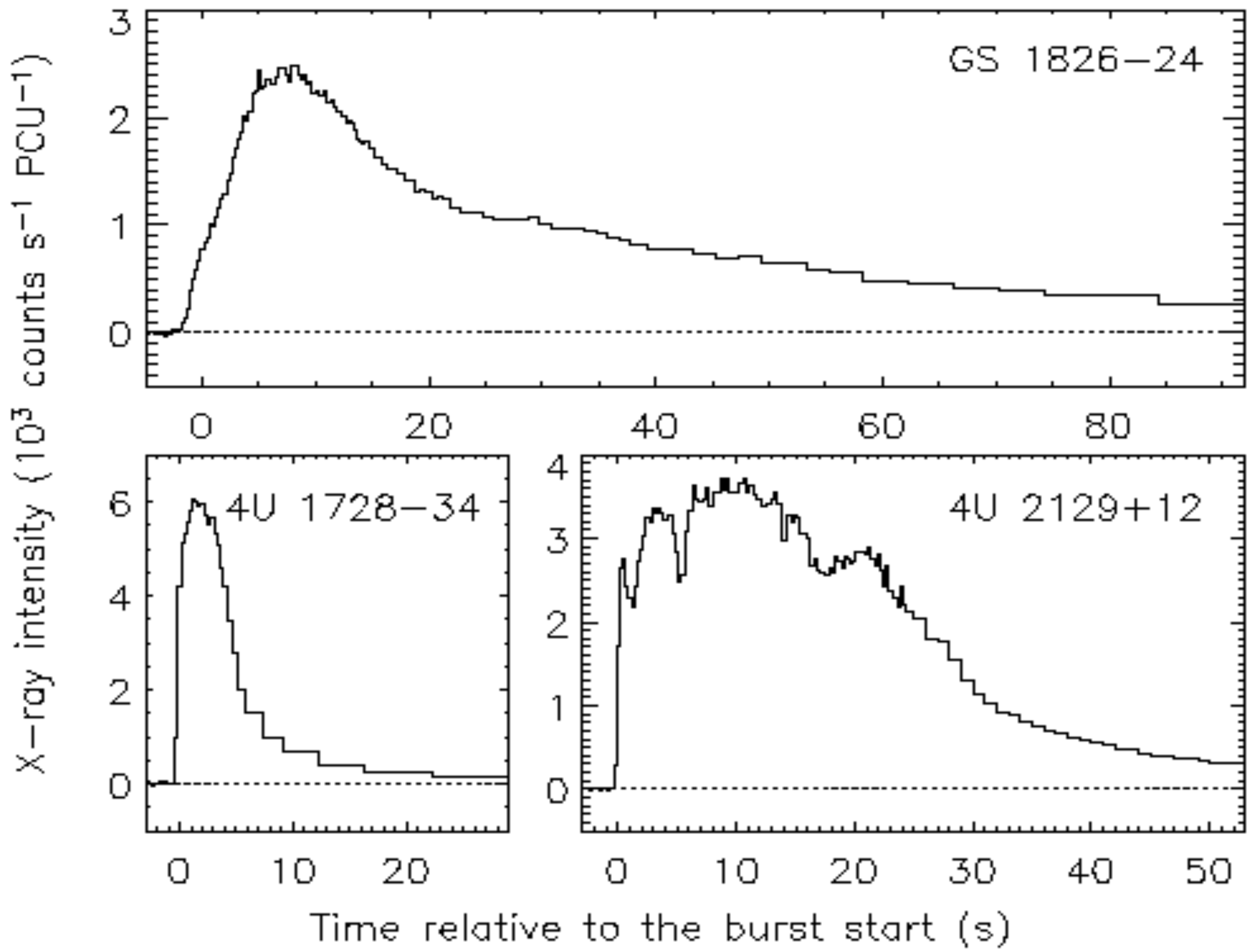


- Insights into accretion physics and binary star evolution.

NS-Low-mass X-ray binaries: bursts

Type I bursts:

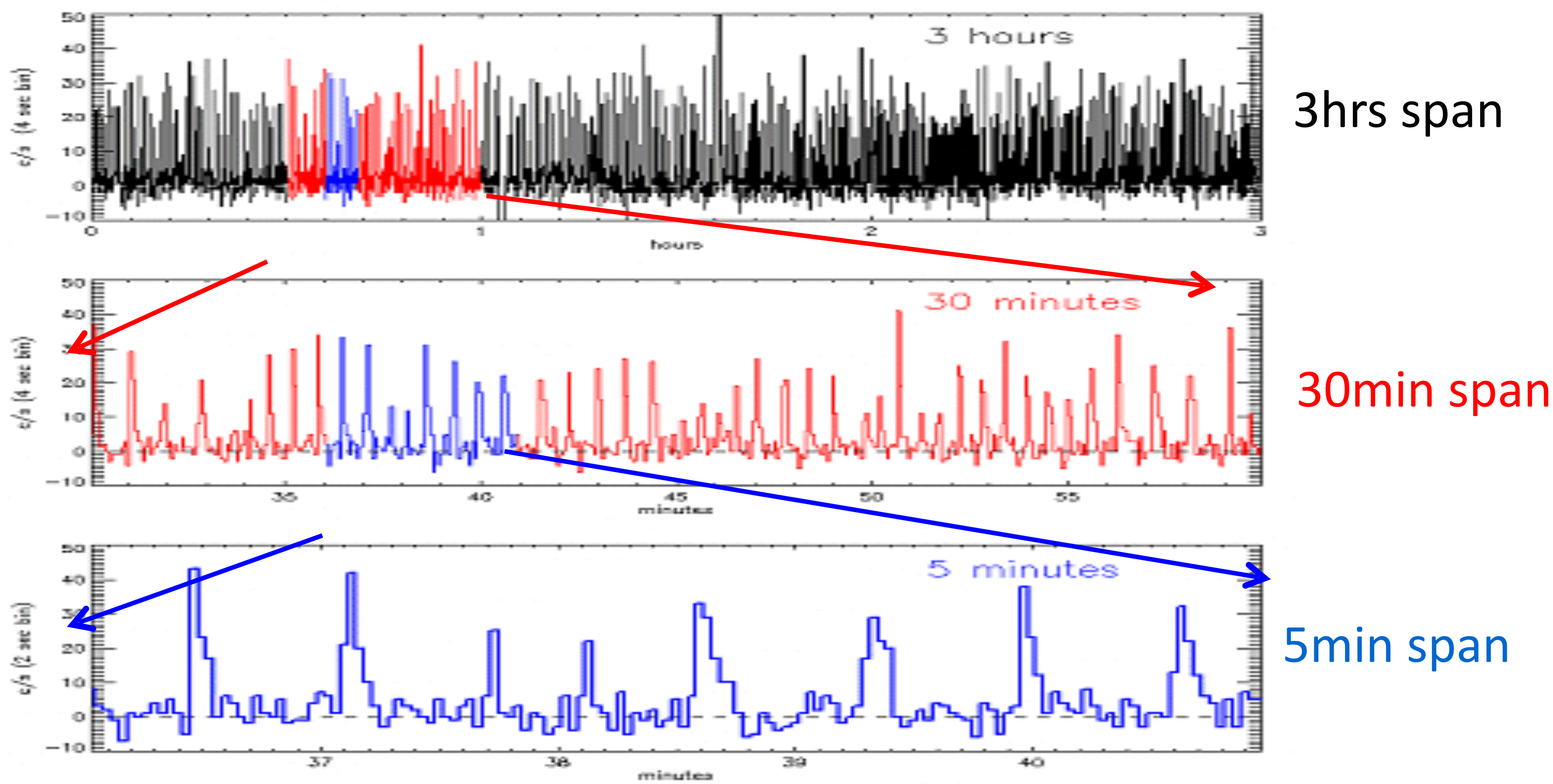
- Thermonuclear flashes on NS surface (H—>He burning – explosive)
- Rapid (few-sec) rise + expo decay (10-100sec) with $L_{peak} \approx 10\ L_{persistent}$
- Recurrence of hours-days during outbursts
- Total energy: 10^{39}-10^{40} erg
- Soft BB spectrum: kT ≈ 200 eV
- Sometimes expanding atmosphere



NS-Low-mass X-ray binaries: bursts

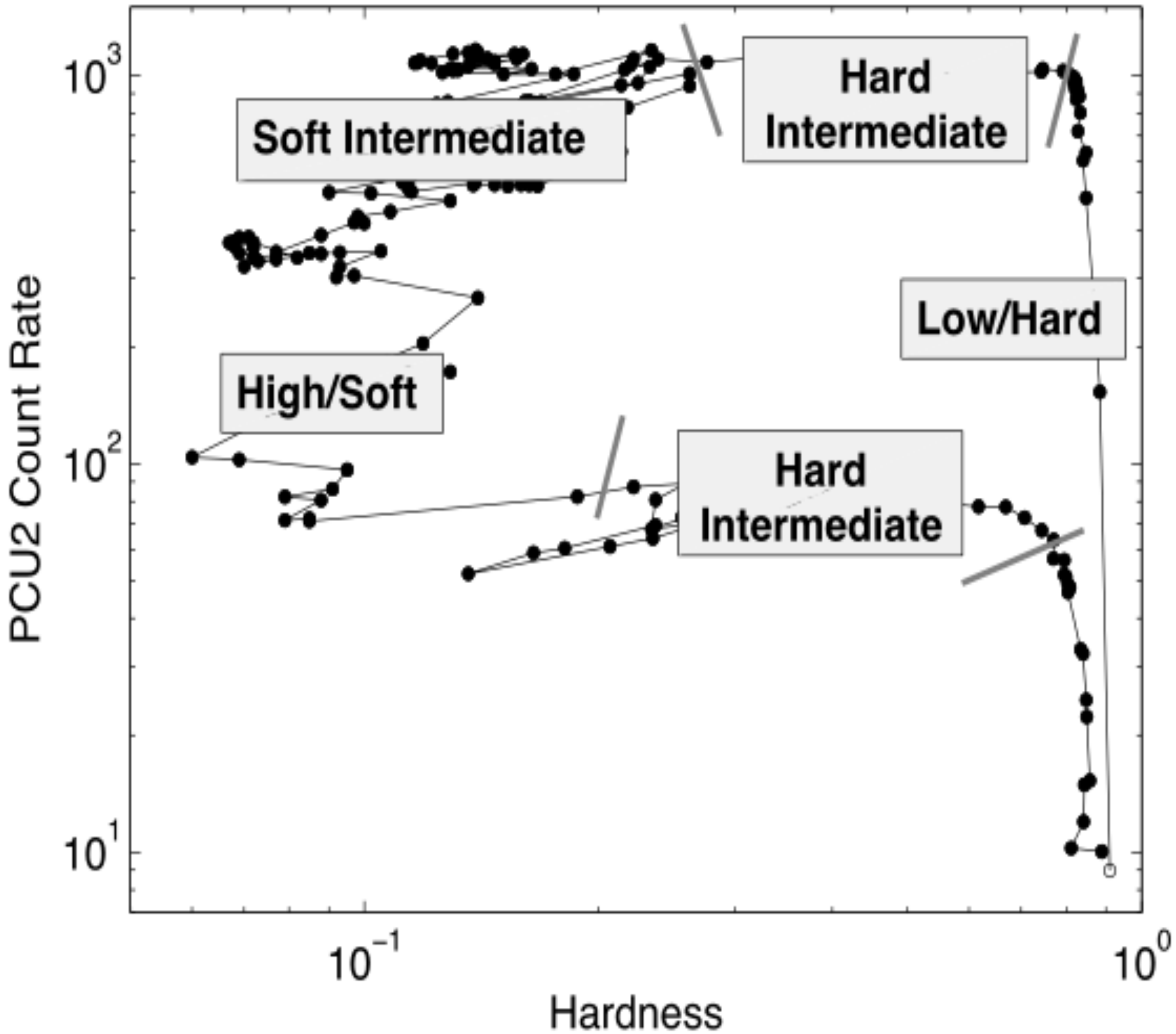
Type II bursts (Rapid):

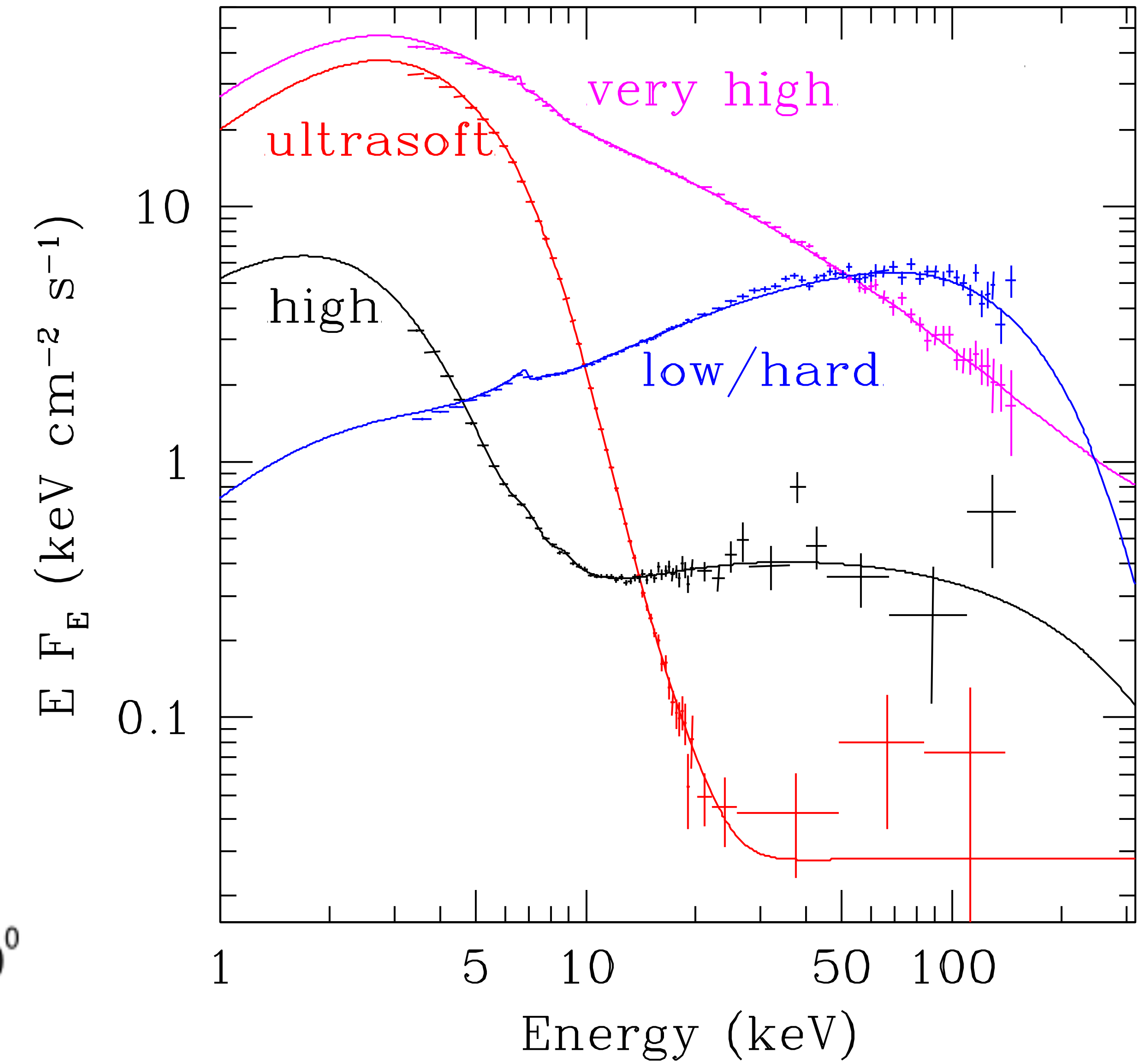
- Rapid rise (s) and decay (s-min)
- Recurrence ≈ 7 s
- No softening during decays kT ≈ 2 keV
- Energy in burst increases with waiting time
- Intermittent accretion due to disc instabilities



Low-mass X-ray binaries: variability

Complex spectral and variability behavior in outburst

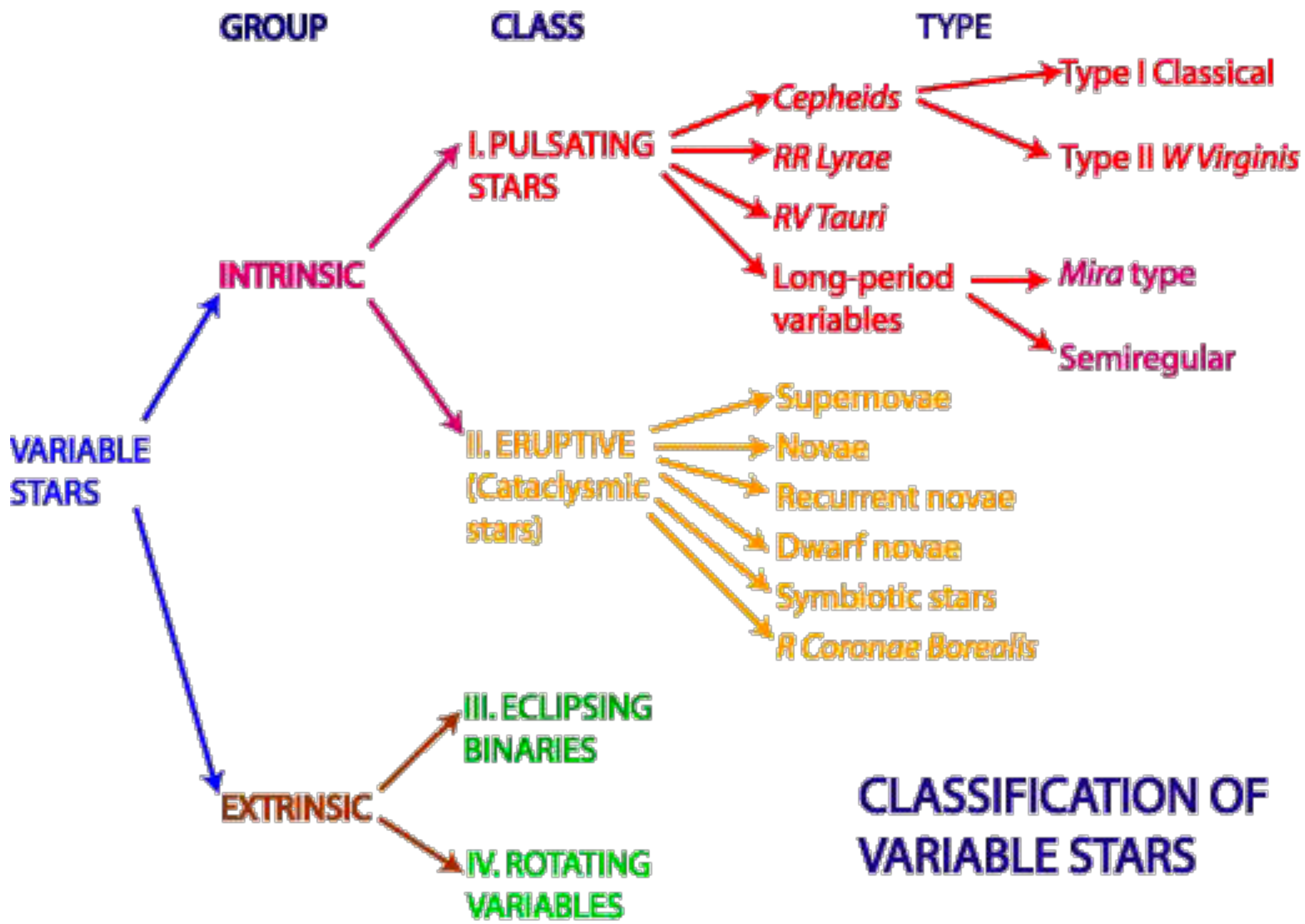




- About 25 NS-LMXBs have been seen to pulse at ms periods in outburst

Variable stars

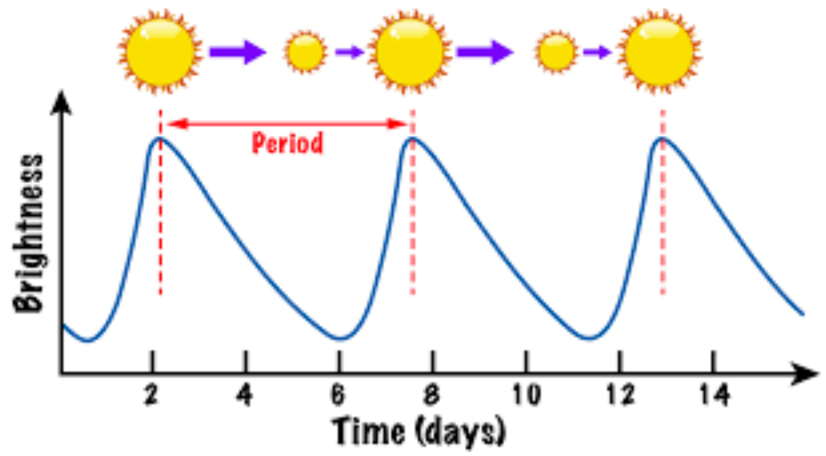
- Pulsating variables (e.g., Cepheids, RR Lyrae, RV Tauri), eruptive variables (e.g., novae, cataclysmic variables), eclipsing variables

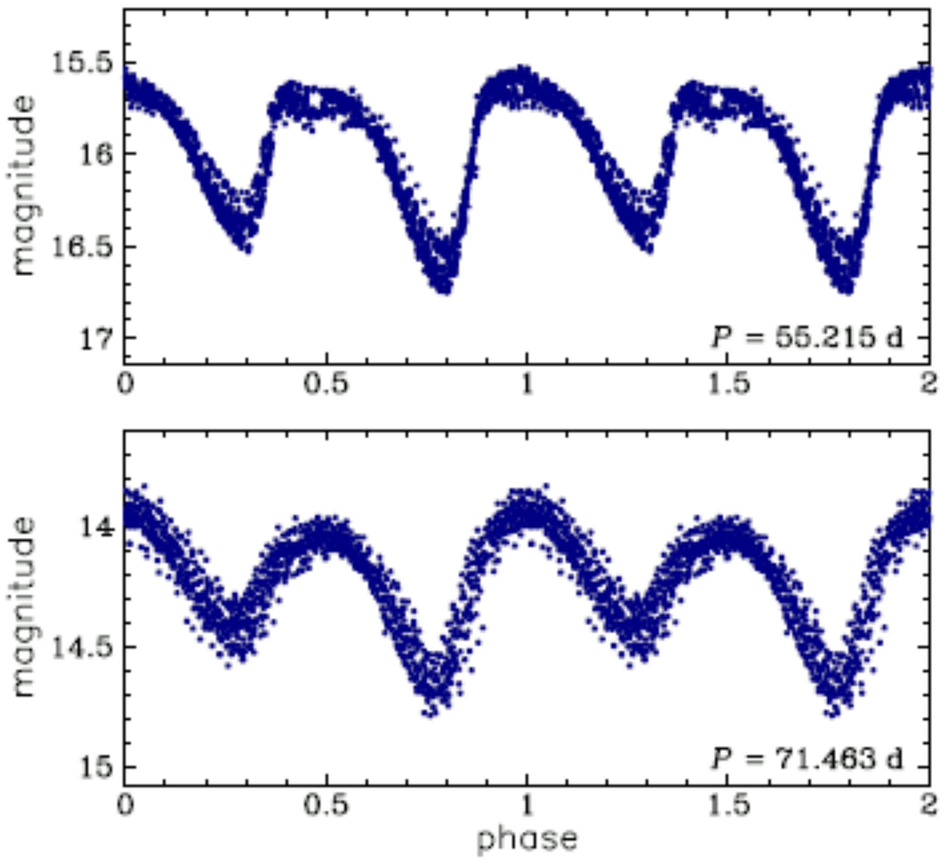


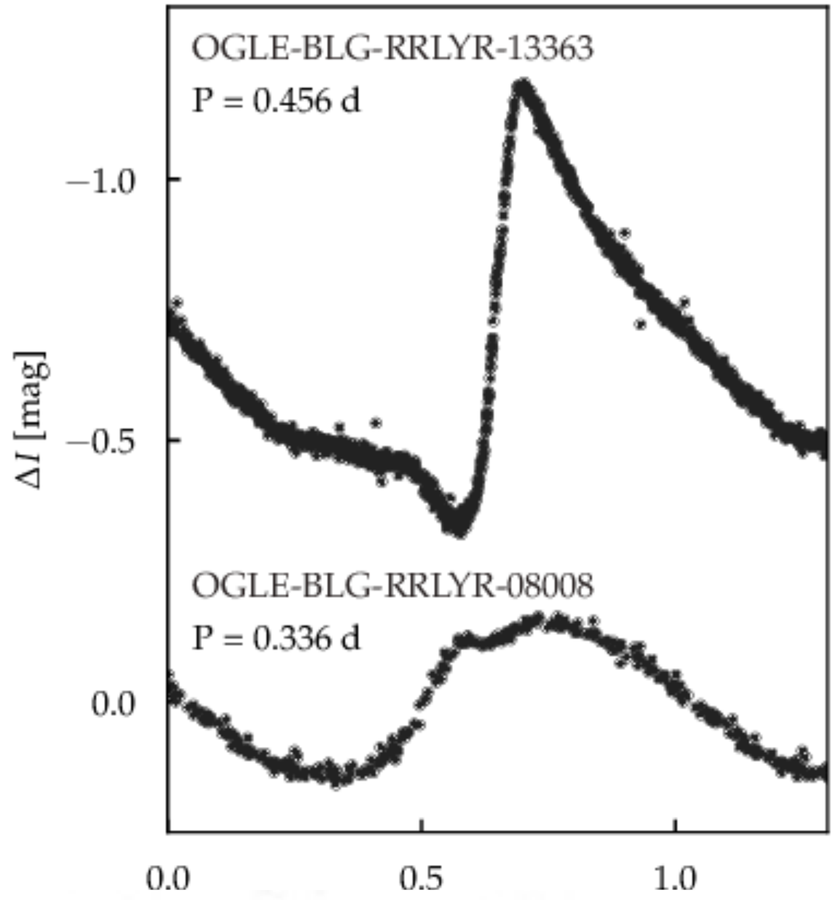
Pulsating variables: light curves

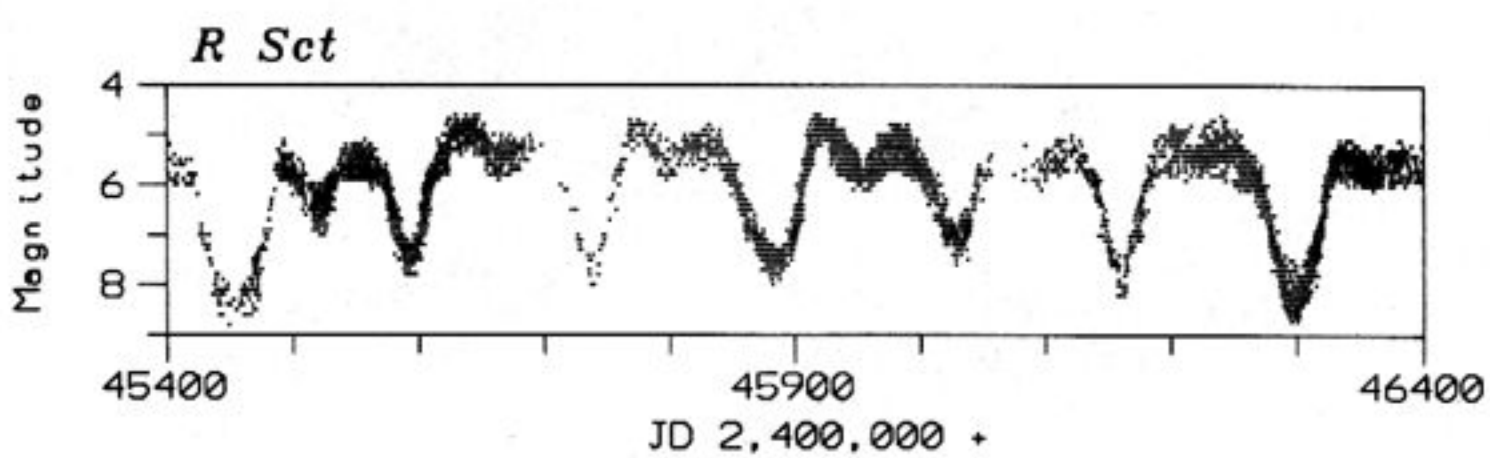
Regular variations in brightness due to periodic expansion and contraction of their outer layers.

Some stars are very regular, while others are irregular.









Erupting variables: novae

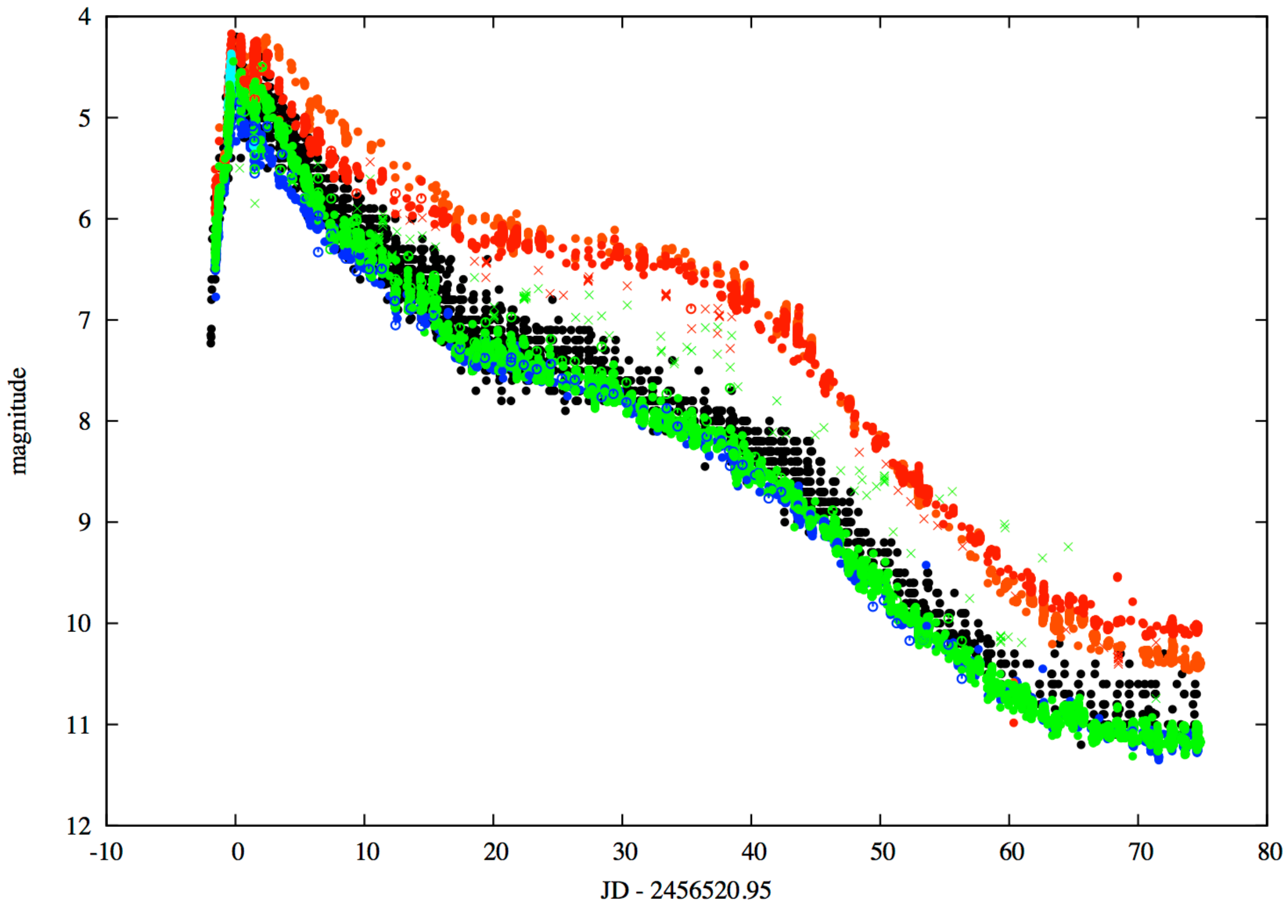
Sudden increase in brightness by several magnitudes due to sudden ignition of a hydrogen layer on the surface of a white dwarf in a binary system.

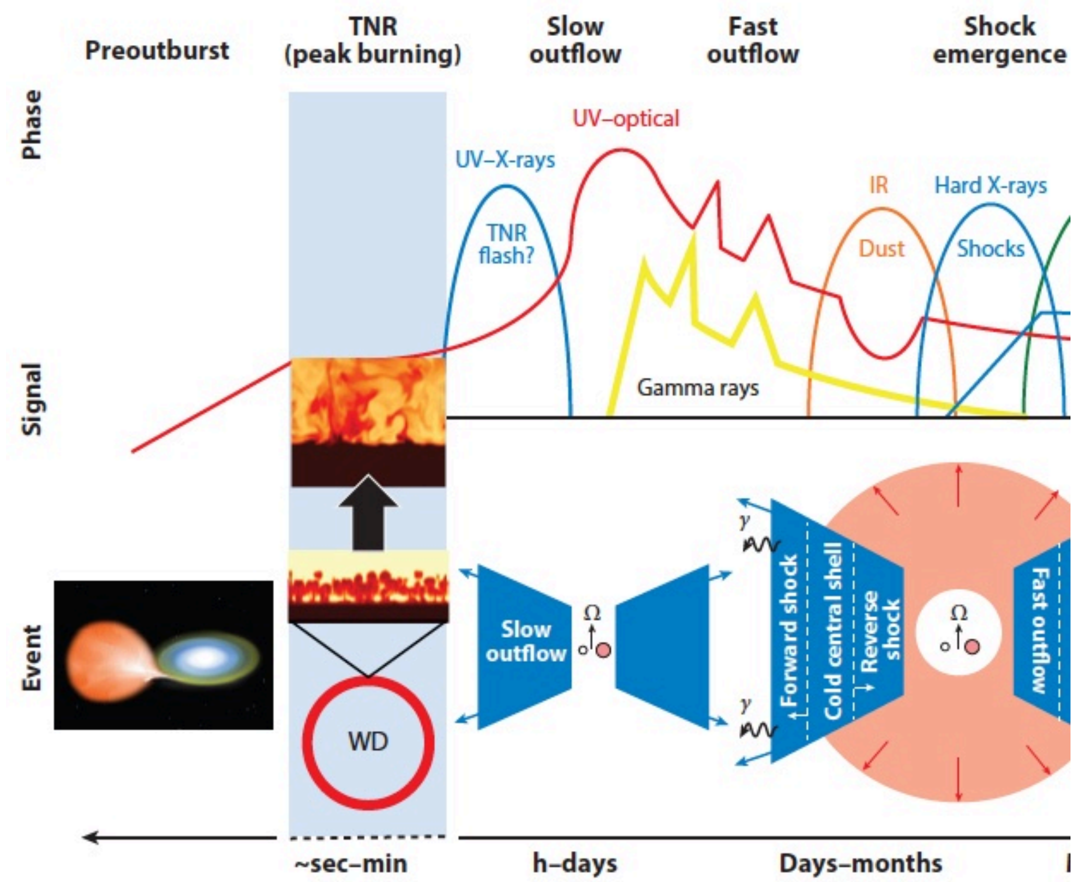
- **Classical Novae**: Single outburst observed.
- **Recurrent Novae**: Multiple outbursts observed over decades.
- **Dwarf Novae**: Smaller, more frequent outbursts due to instabilities in the accretion disc.

Novae light curves

Rapid rise to peak brightness followed by a gradual decline over weeks to months.

The amplitude of the outburst can be up to 10 mag or more.





Detection of a nova X-ray fireball

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

Published online: 11 May 2022

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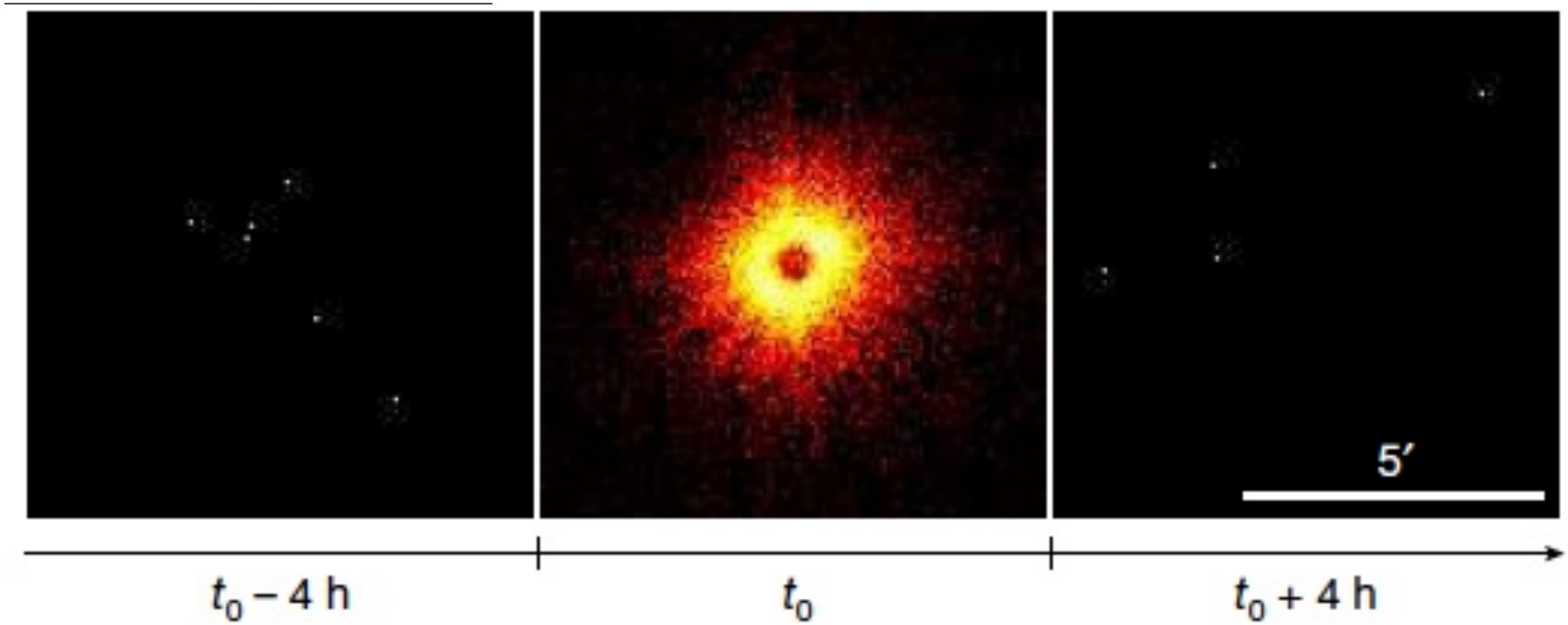


Observational confirmation of the existence of X-ray flash in a nova

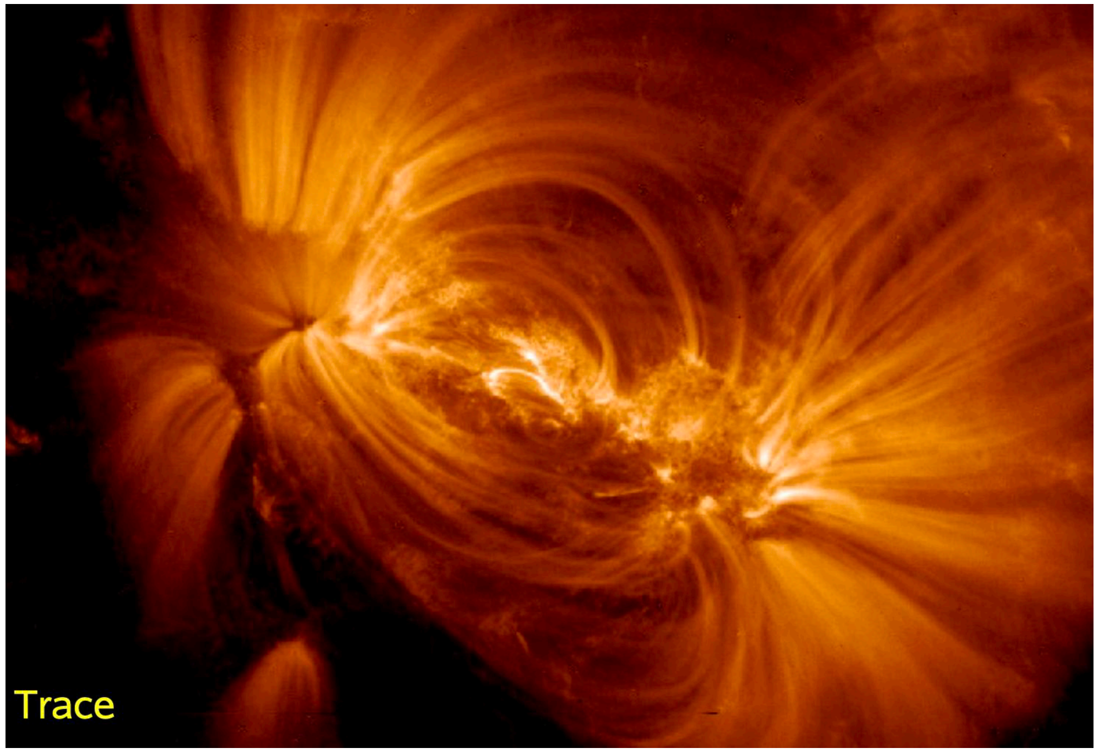
Stellar flares

Sudden bursts of energy and light emitted from the star surface from radio waves to X-rays.

Can last from a few minutes to several hours.

Many late-type stars (e.g. red dwarfs) frequently produce flares.

Probably produced due to reconnection of magnetic field lines in the corona.



Tidal disruption events

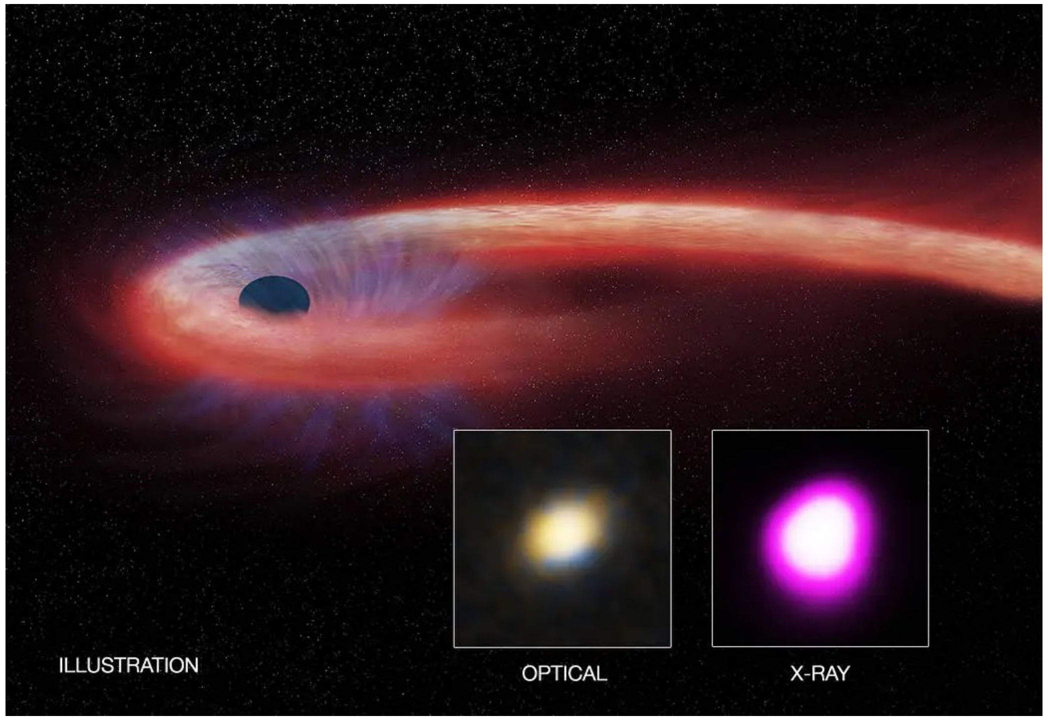
A star getting too close to a SMBH is stretched and compressed, eventually being torn apart by the BH tidal forces.

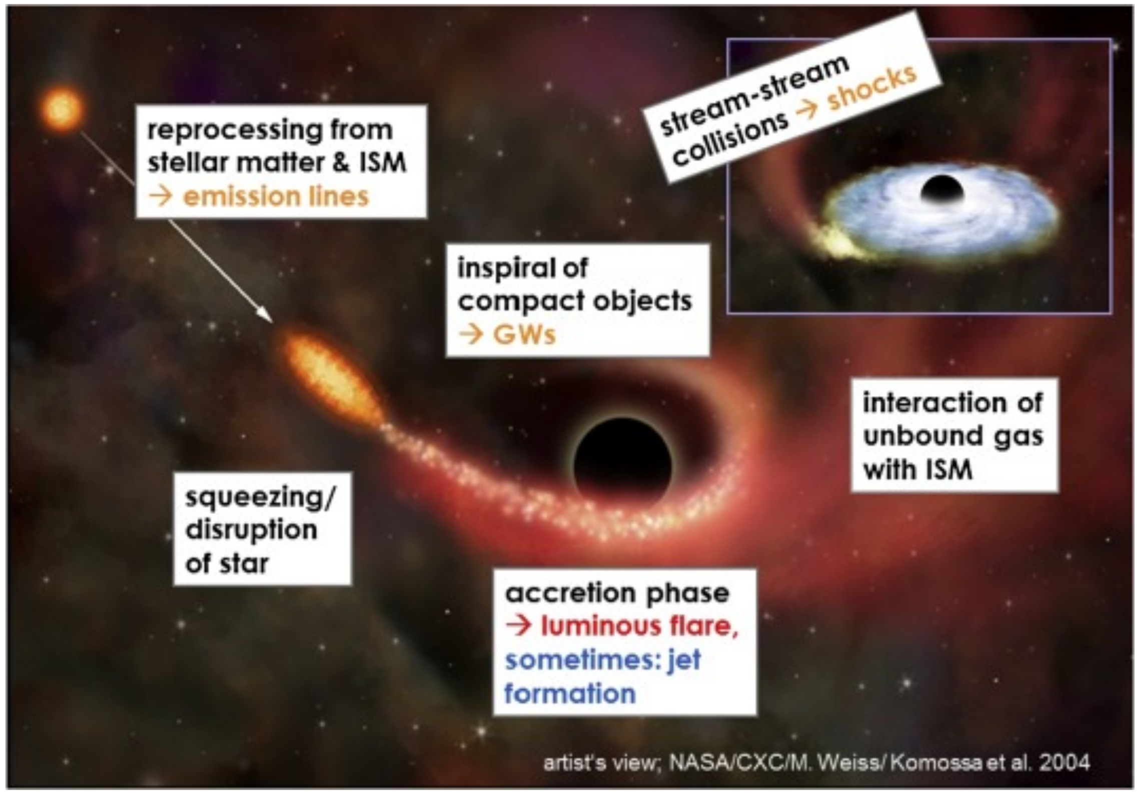
The stellar debris forms an accretion disc around the BH. Material heats up and radiates enhanced multi-band emission.

Later on, the debris continues to fall back onto the BH at a decreasing rate.

Unique opportunity to study black holes and the extreme physics of their surroundings.

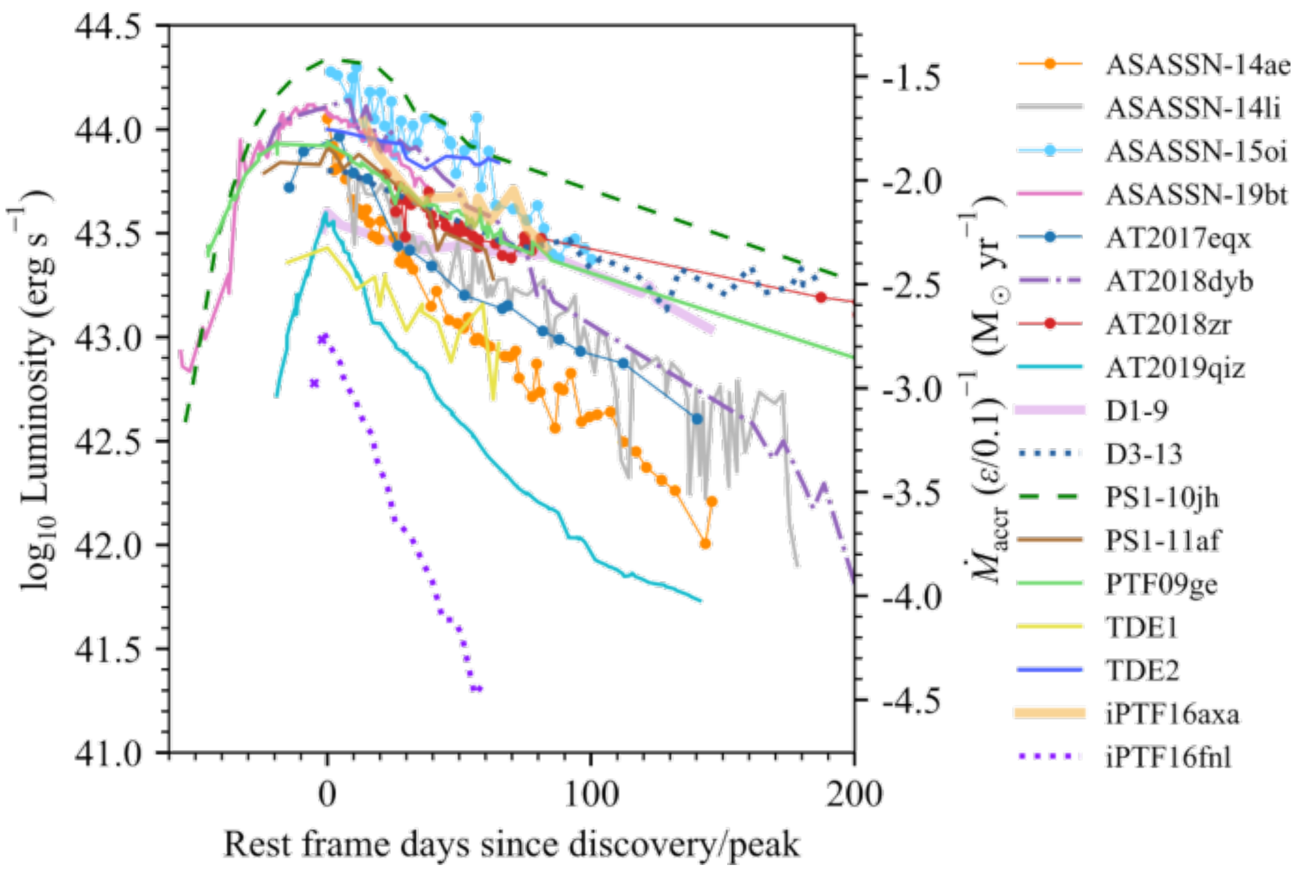
Estimated rate: one TDE per galaxy every 10,000 to 100,000 years.

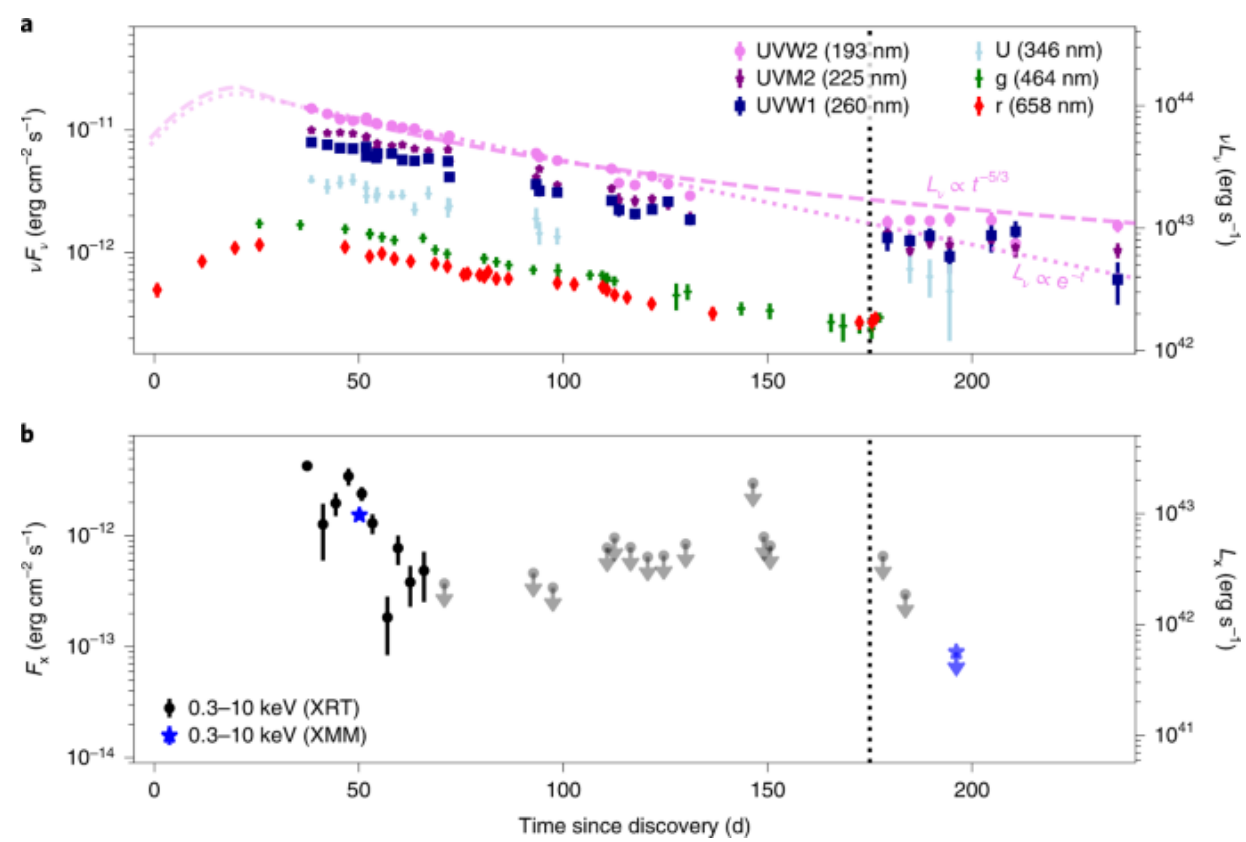




Tidal disruption events

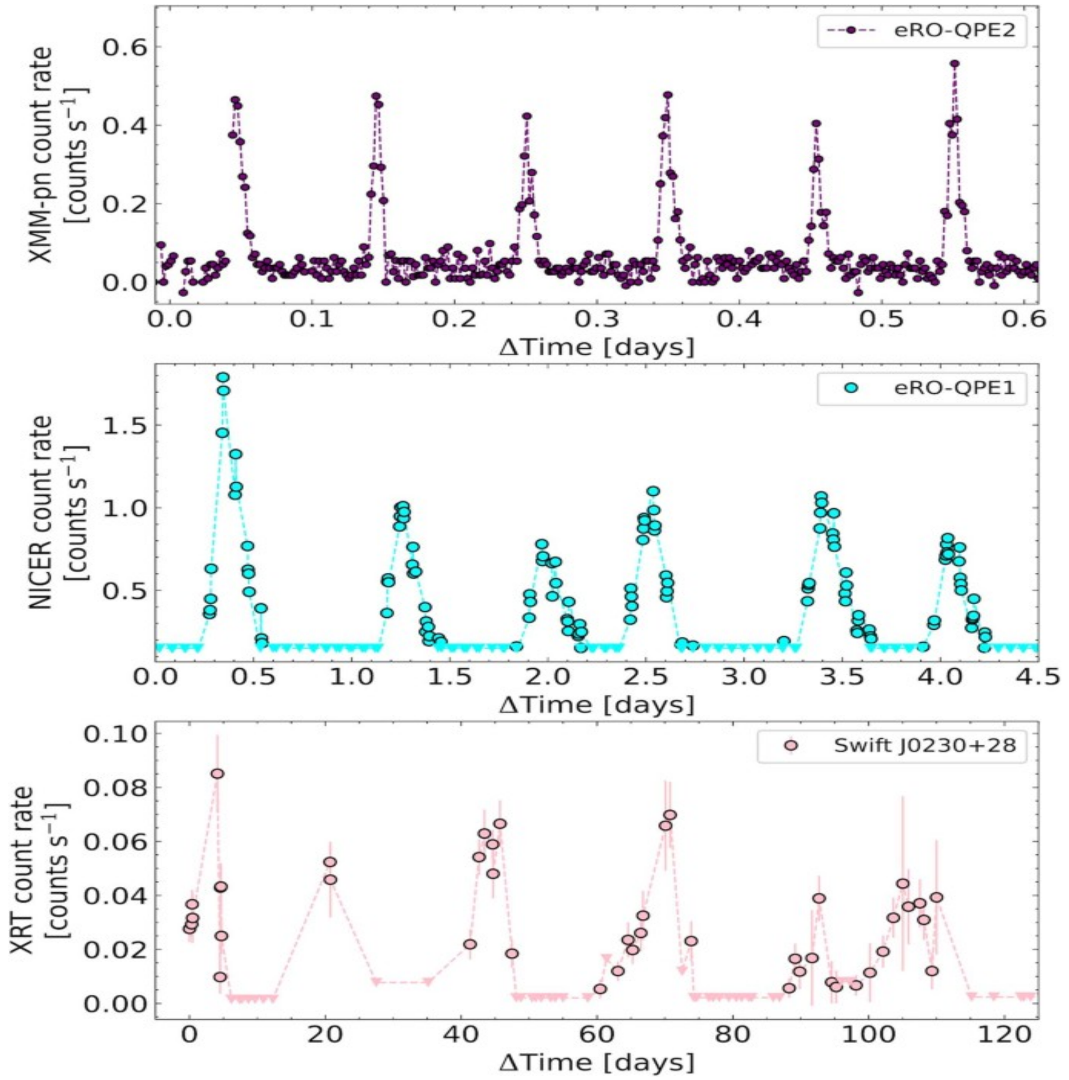
The light curve exhibits a rapid rise to peak brightness followed by a power-law decline





Quasi periodic eruptions

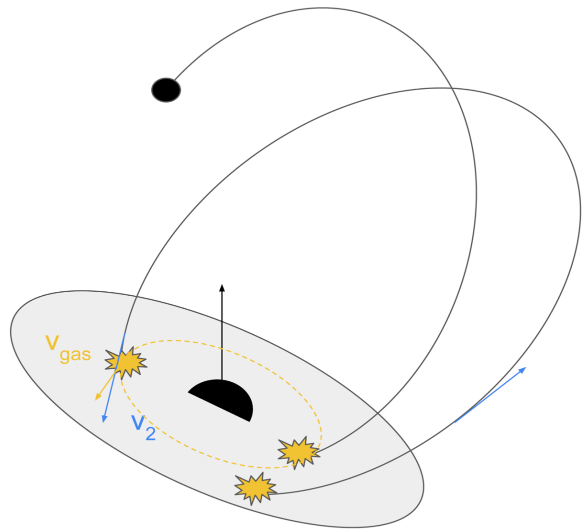
Regular sharp increases in luminosity from the vicinity of a SMBH, observed in some galactic nuclei at multiple wavelengths.



The period between eruptions can range from hours to days.

Leading scenarios:

- Partial disruptions of orbiting stars.
- Extreme mass-ratio inspiral system where the secondary intersects a precessing disc around the primary. At each impact, an adiabatically expanding gas cloud is expelled from the disc plane



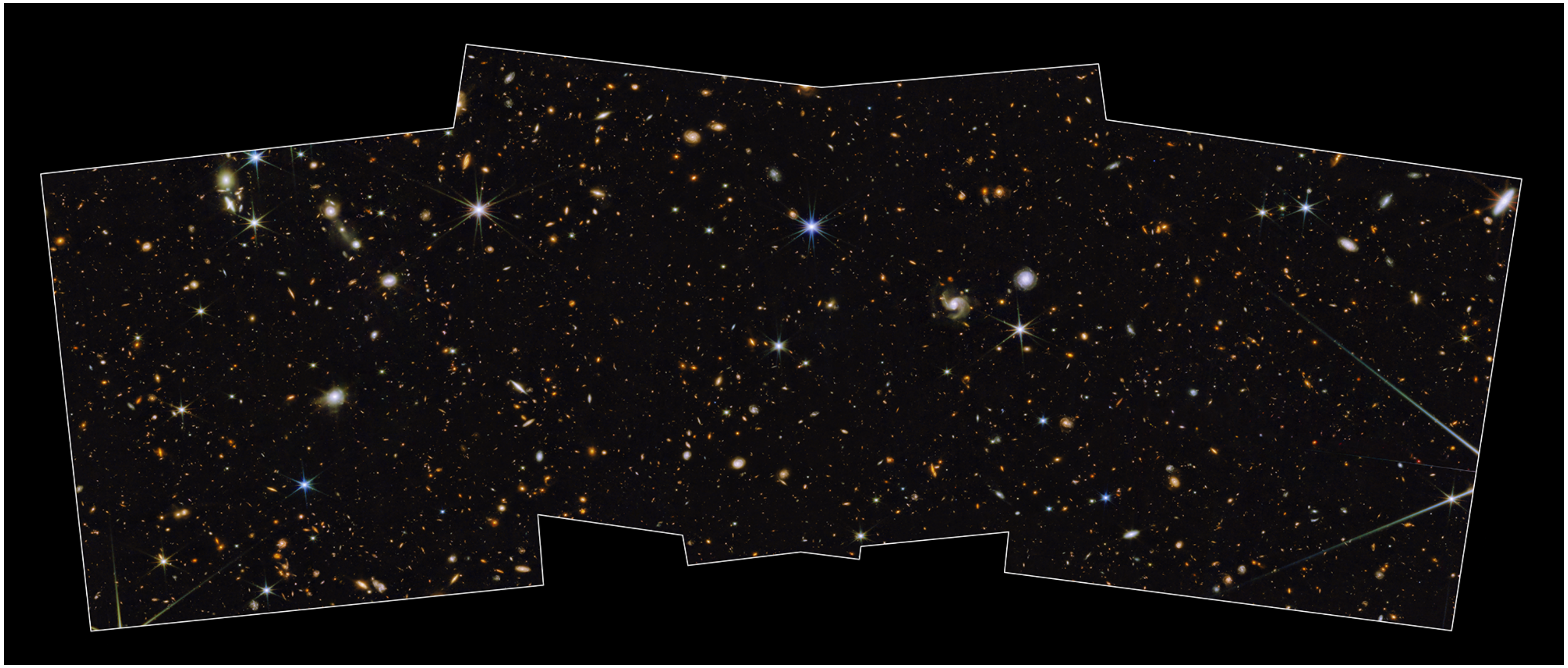
Time domain surveys

Regularly scan large portions of the sky to search for an monitor transient and variable events.

Often use robotic telescopes, automatic classification of transient events, rapid notification alerts.

Involve storing and transferring a huge amount of data due to large fields of view required.

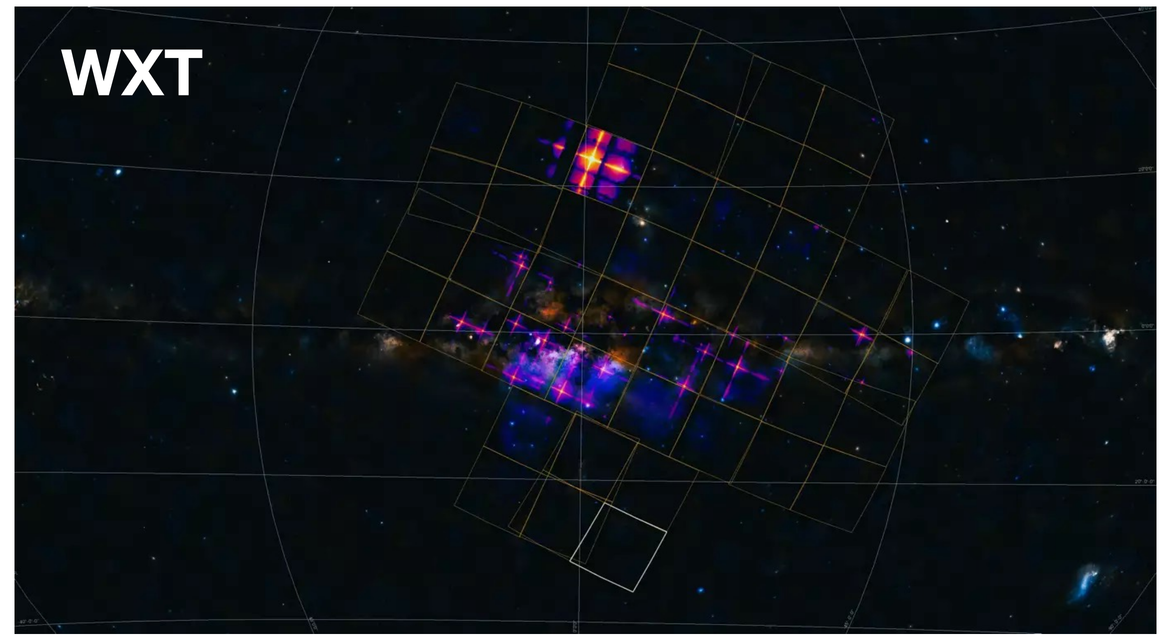
- Enable discovery and study of rare and short-lived phenomena.
- Provide statistical samples for understanding population characteristics.
- Provide triggers for follow-up observations.

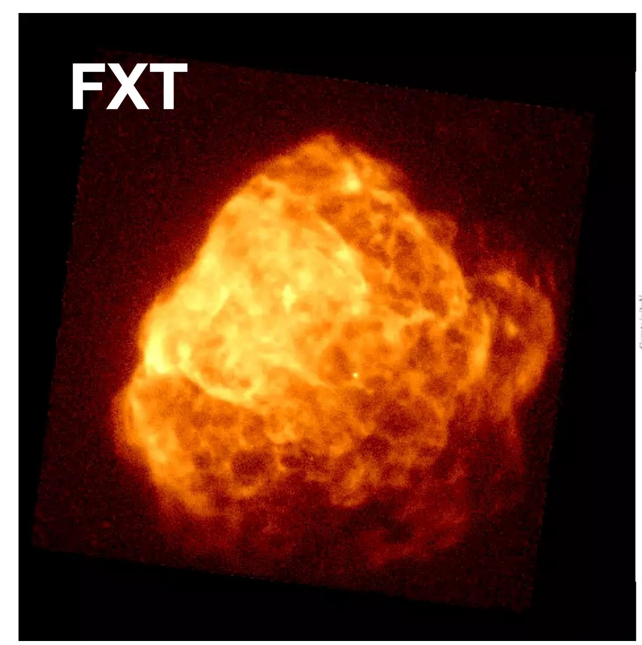


X-ray time domain surveys

INTEGRAL, MAXI, Fermi, Swift: searches for transients with wide-field sky monitors

Einstein Probe: a new X-tray transient hunter machine





Optical time domain surveys

Large Synoptic Survey Telescope @ Vera C. Rubin Observatory (Cerro Pachón)

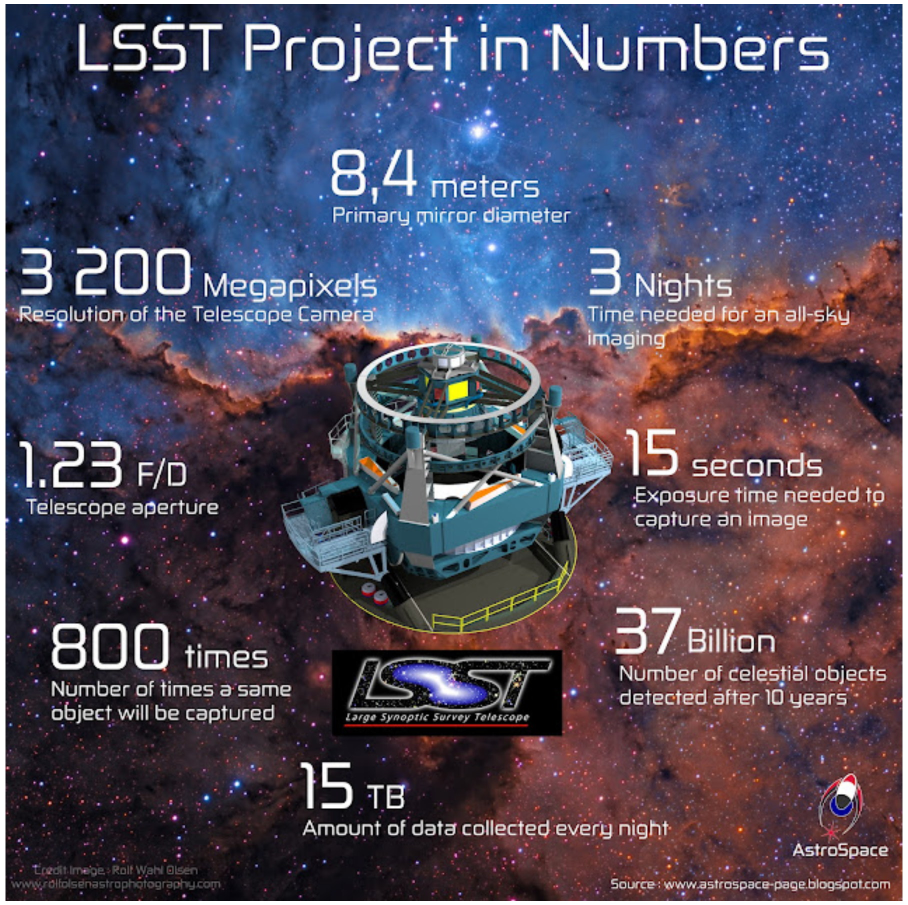
8.4-m primary mirror with a 3.2-gigapixel CCD imaging camera

Field of view: 9.6 square degrees.

Will cover the entire available sky every few nights

10 yr duration. First light in January 2025; fully operational in August 2025.

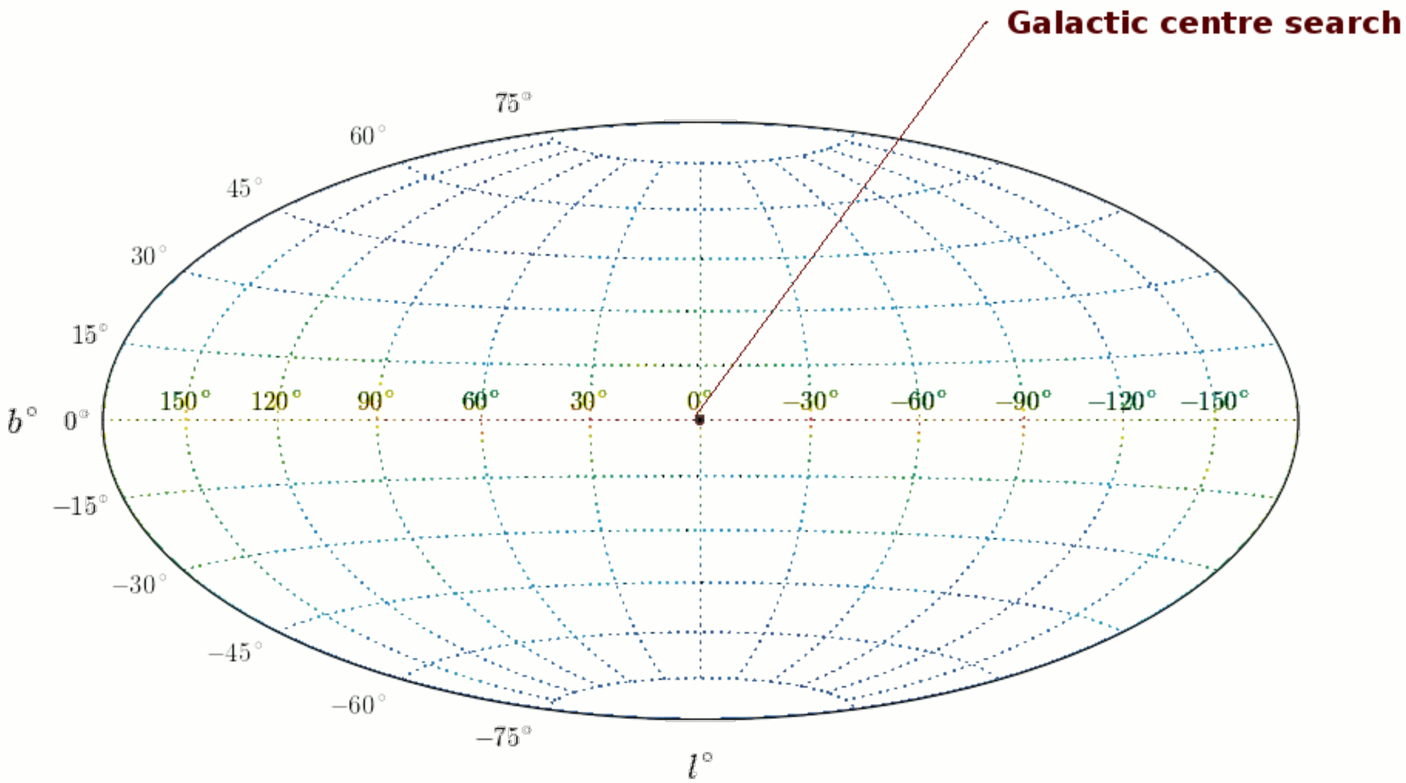
Generating unprecedented amounts of data for astronomical research.

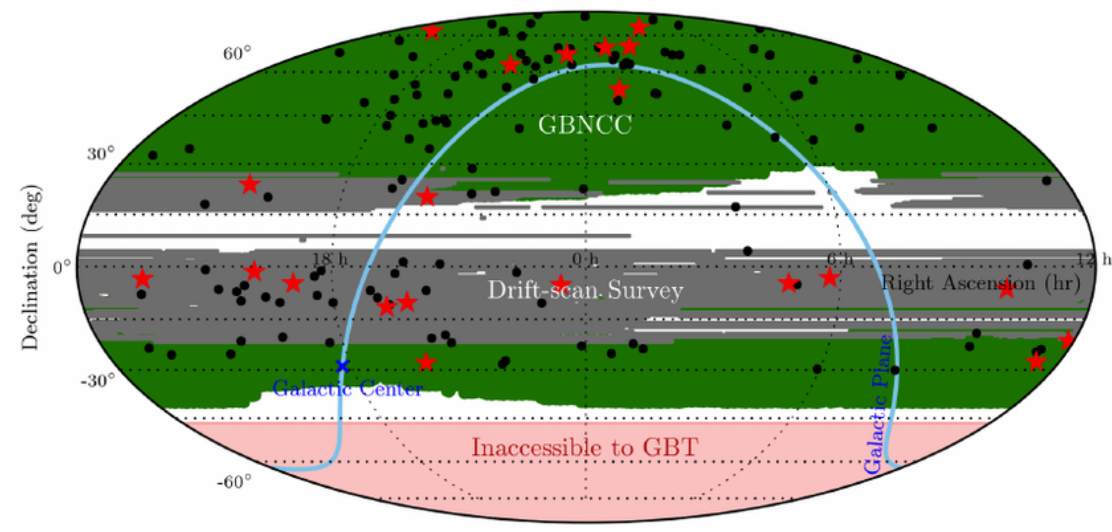


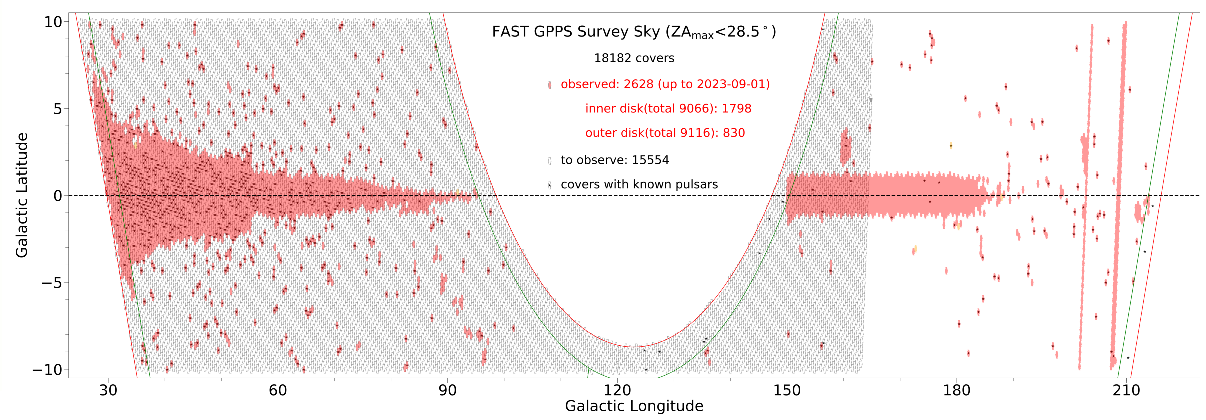
Category	ATLAS	ASAS-SN	Pan-STARRS	ZTF	LSST
Number of total sources	⋯	1×10^8	1×10^{10}	1×10^9	37×10^9
Number of total detections	1×10^{12}	1×10^{11}	1×10^{11}	1×10^{12}	37×10^{12}
Annual visits per source	1000[c]	180[d]	60[e]	300[a]	100[b]
Number of pixels	1×10^8	4×10^6 (×4)	1×10^9	6×10^8	3.2×10^9
CCD surface area (cm^2)	90	9	1415	1320	3200
Field of view (deg^2)	30	4.5	7	47	9
Hourly survey rate (deg^2)	3000	960	⋯	3760	1000
5σ detection limit in r	19.3	17.3	21.5	20.5	24.7
Nightly alert rate	⋯	⋯	⋯	1×10^6	1×10^7
Nightly data rate (TB)	0.15	⋯	⋯	1.4	15
Telescope (m)	0.5	4 × 0.14	1.8	1.2	6.5
No. of telescopes	2 (6)	5	2	1	1

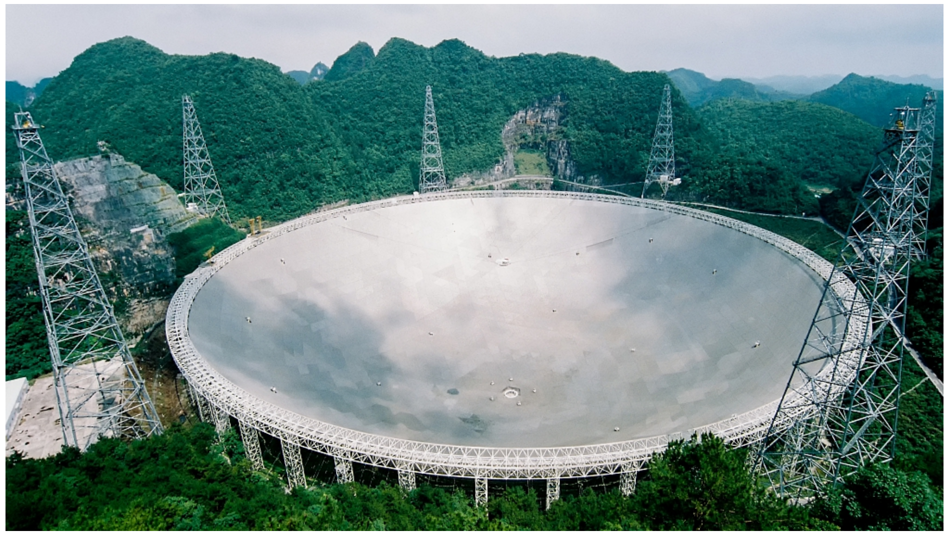
Radio time domain surveys: pulsars

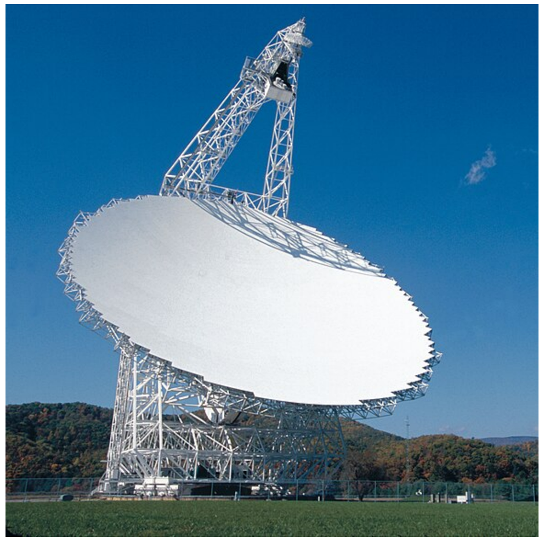
Arecibo, Parkers, Effelsberg, GBT, MeerKAT, FAST







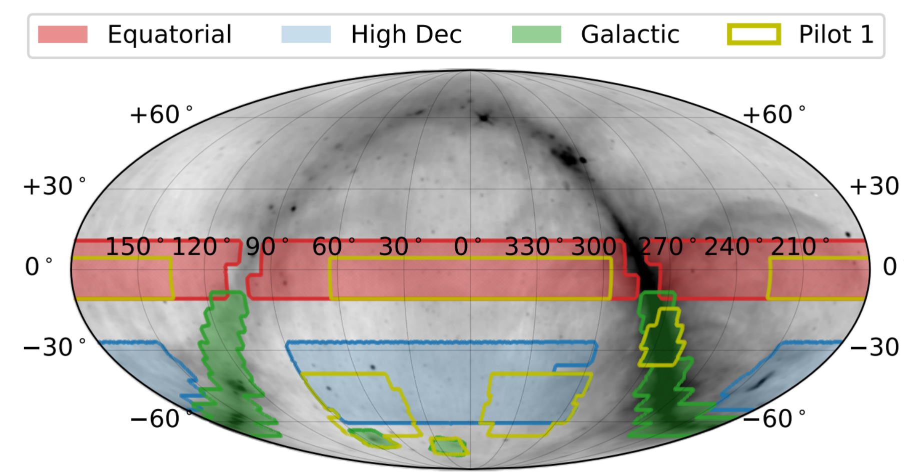




Radio time domain surveys: transients

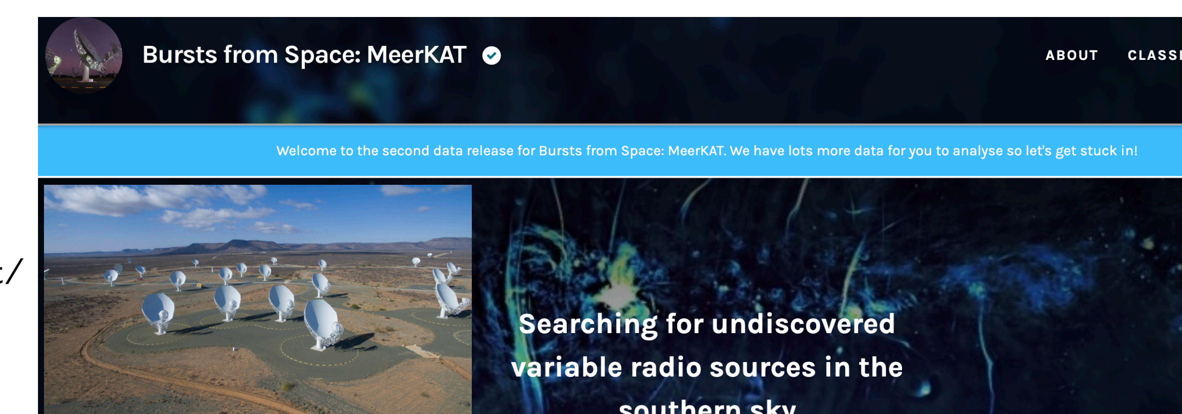
LOFAR transients key science project

ASKAP Variables and Slow Transients survey



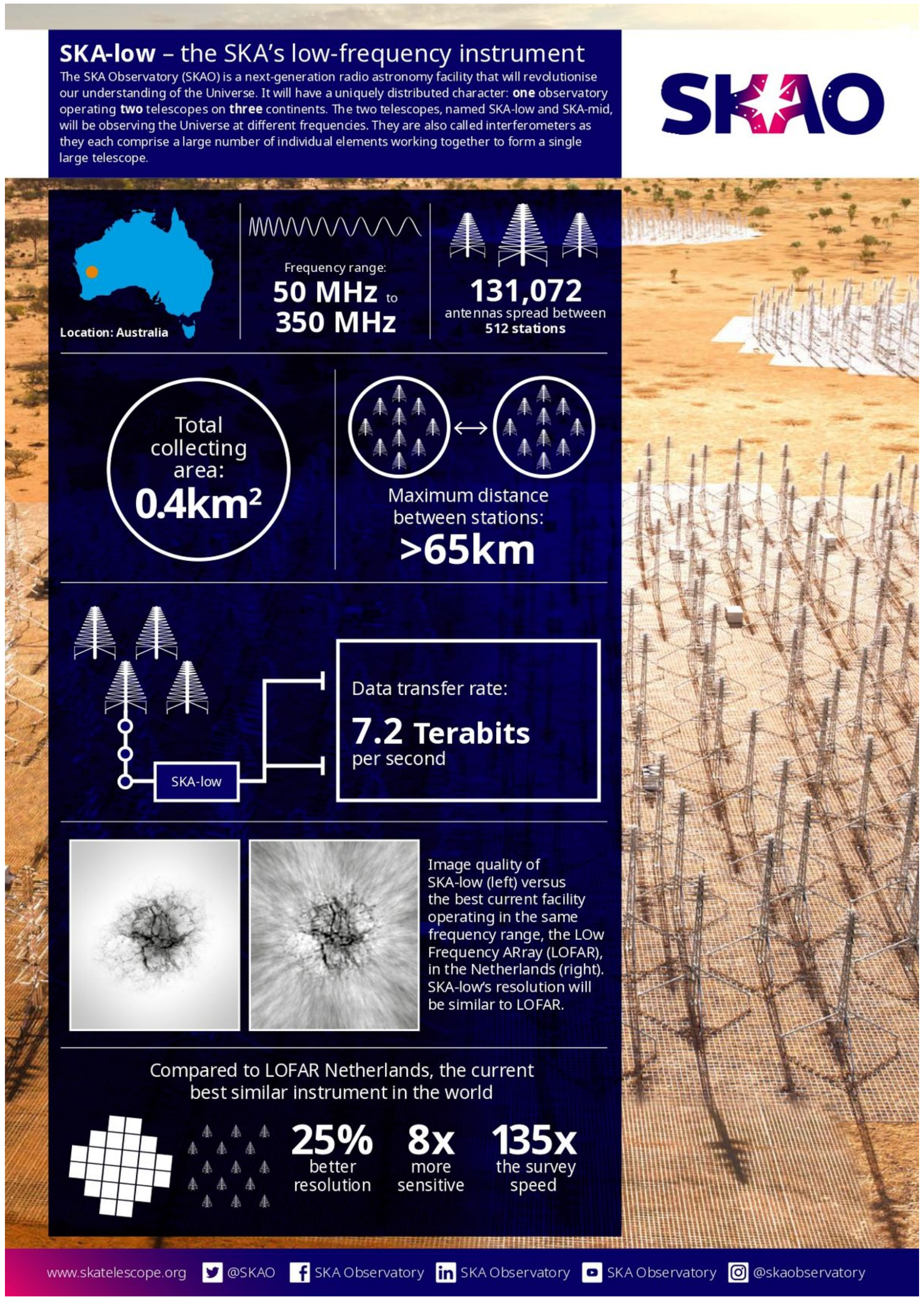
MeerKAT: bursts from space citizen science project

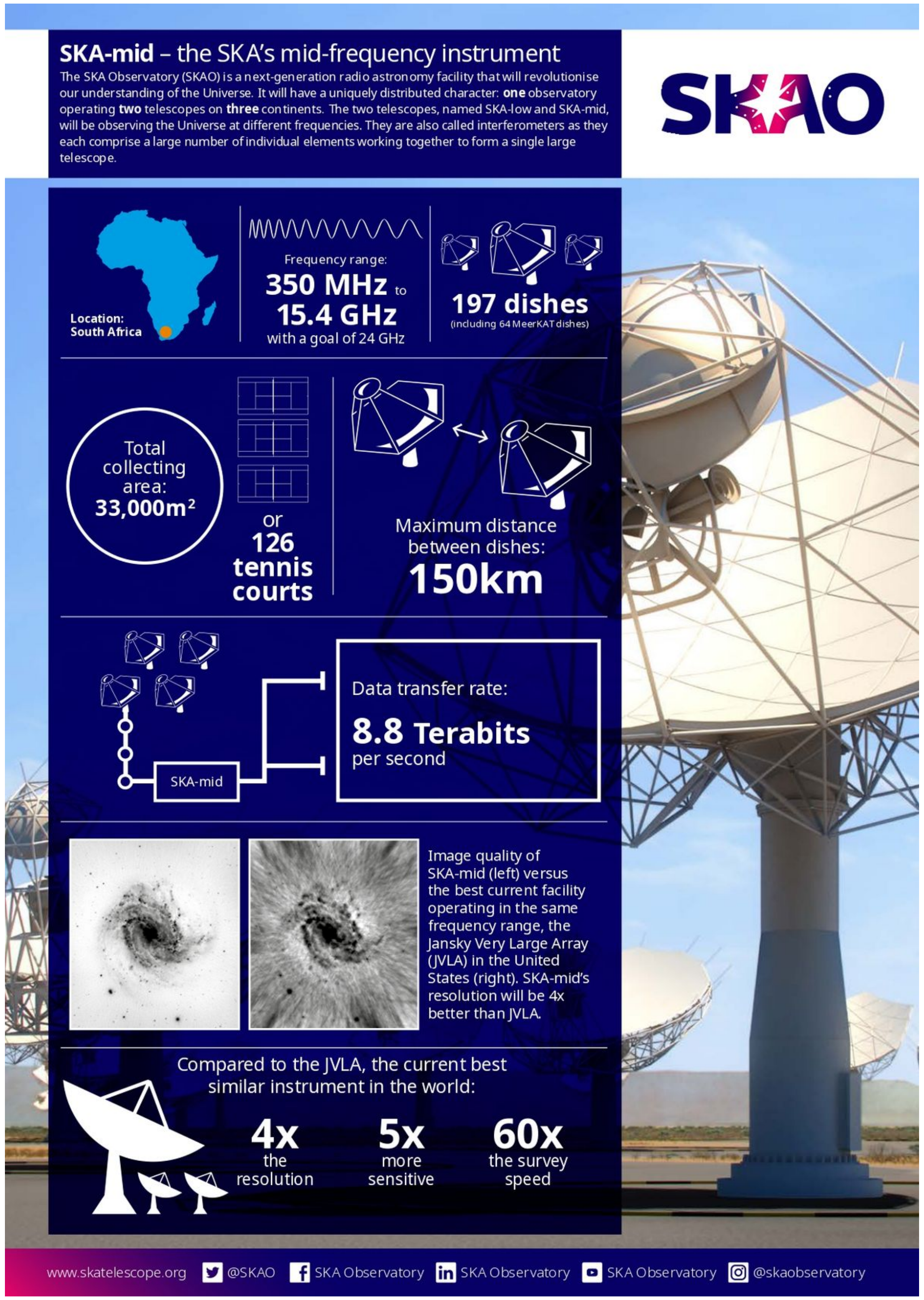
https://www.zooniverse.org/projects/alex-andersson/bursts-from-space-meerkat/



Radio time domain surveys: the future

- World's largest radio telescope, providing unprecedented sensitivity and resolution





Suggested reading

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