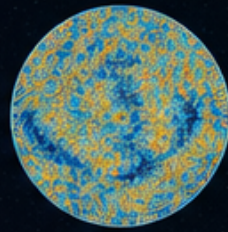
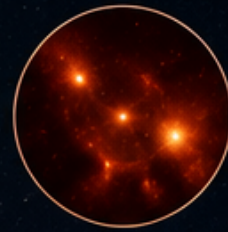




RADIO



MICROWAVE



INFRARED



OPTICAL



ULTRAVIOLET



X-RAY

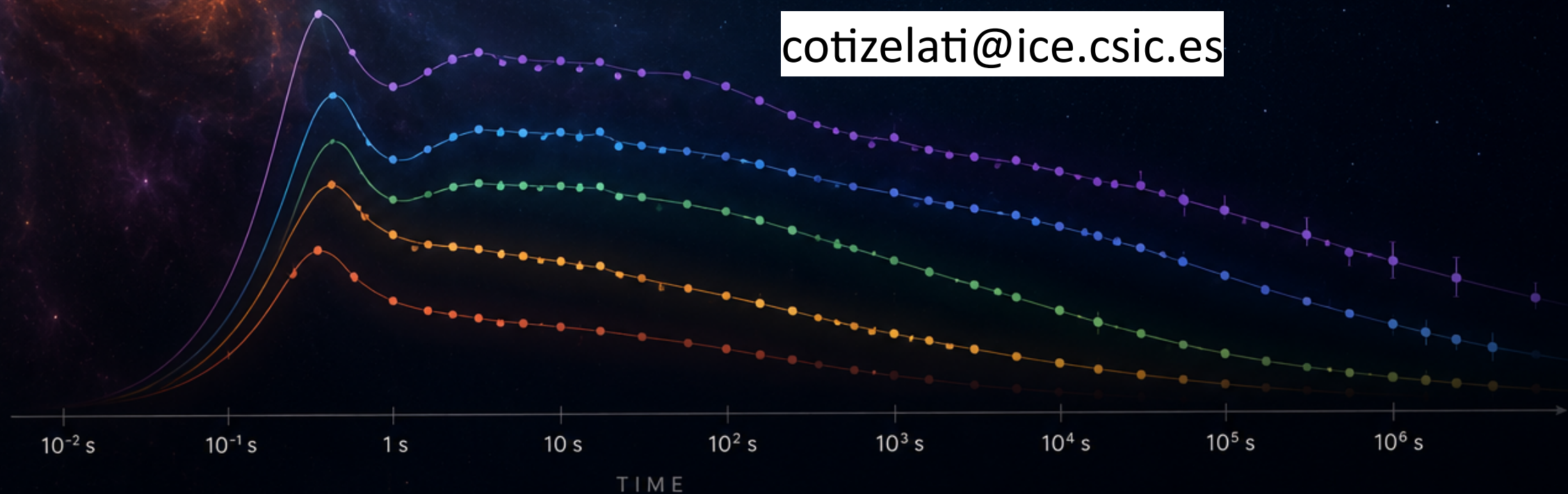


GAMMA-RAY

Multi-Wavelength Transients

Francesco Coti Zelati

cotizelati@ice.csic.es

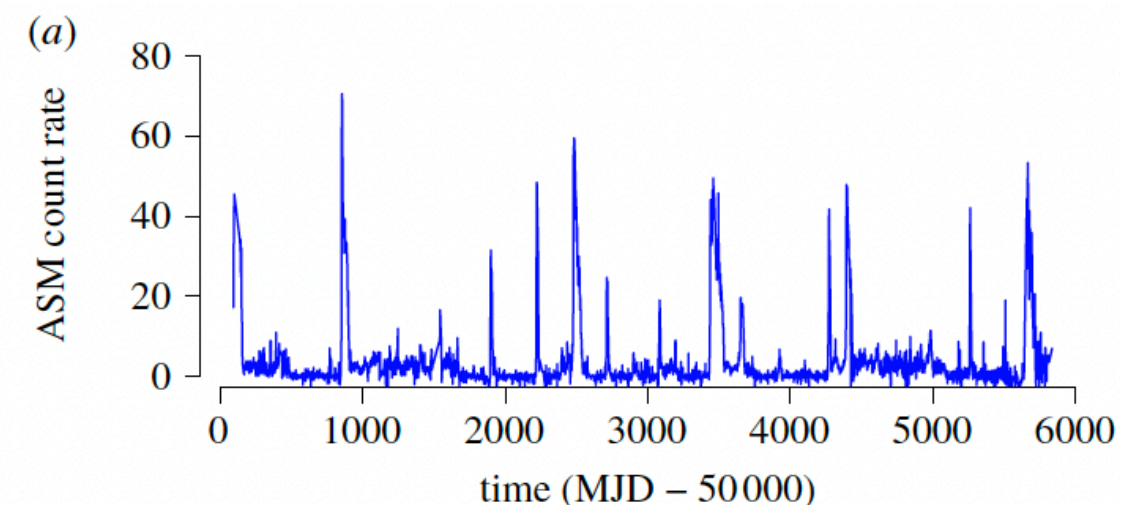
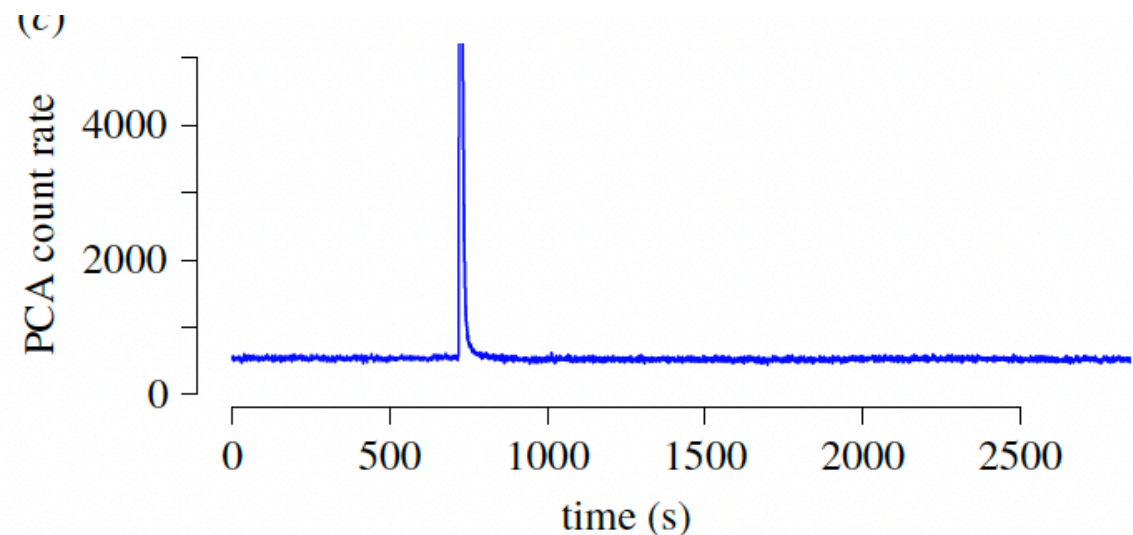
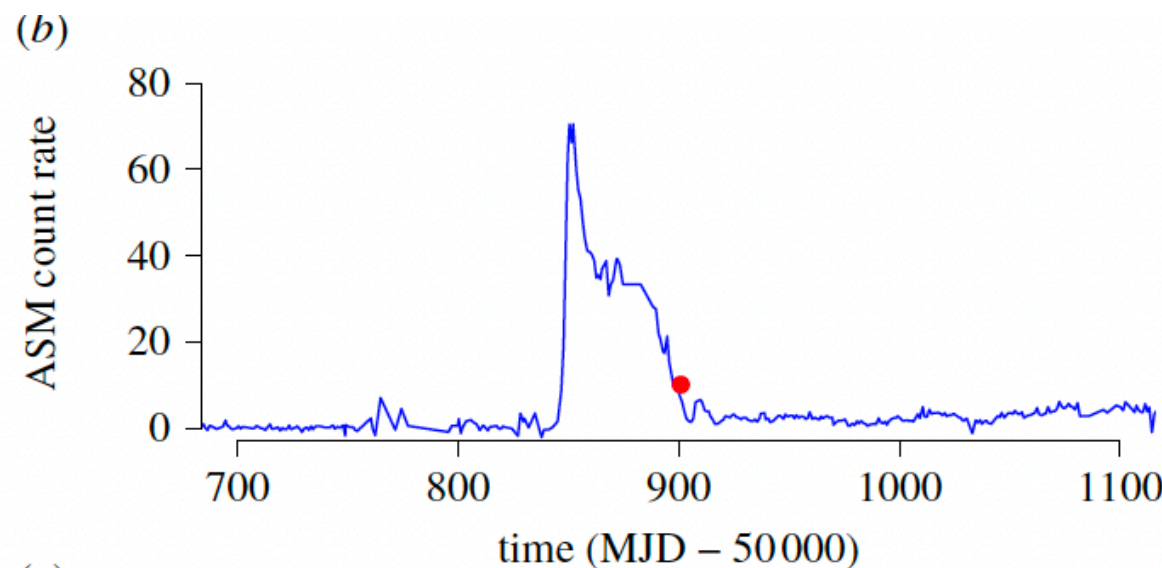


Outline

- Time domain astronomy: definition and importance
- Types of variability
- Sources of variability
 - Supernovae
 - Gamma-ray bursts
 - TDEs
 - Fast X-ray transients
 - Pulsars and magnetars and connection with FRBs
 - LMXBs
 - Novae
 - QPEs
- Time domain surveys

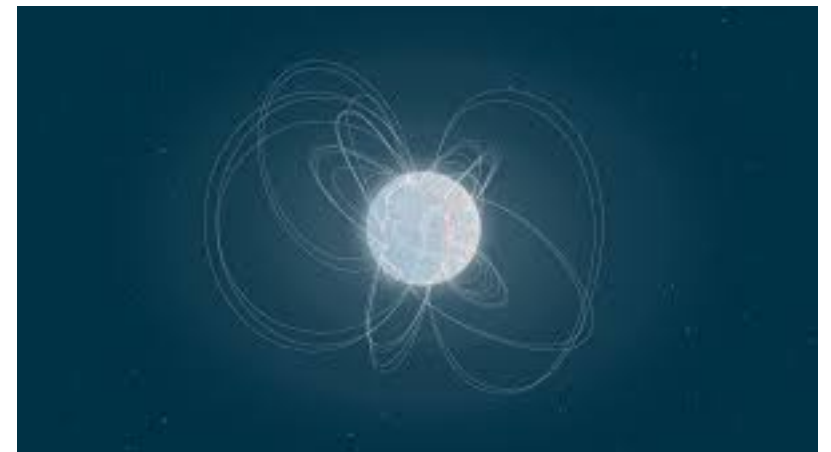
What is time domain astronomy?

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



Why time-domain astronomy 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. Supernovae, GRBs, outbursts from compact objects).

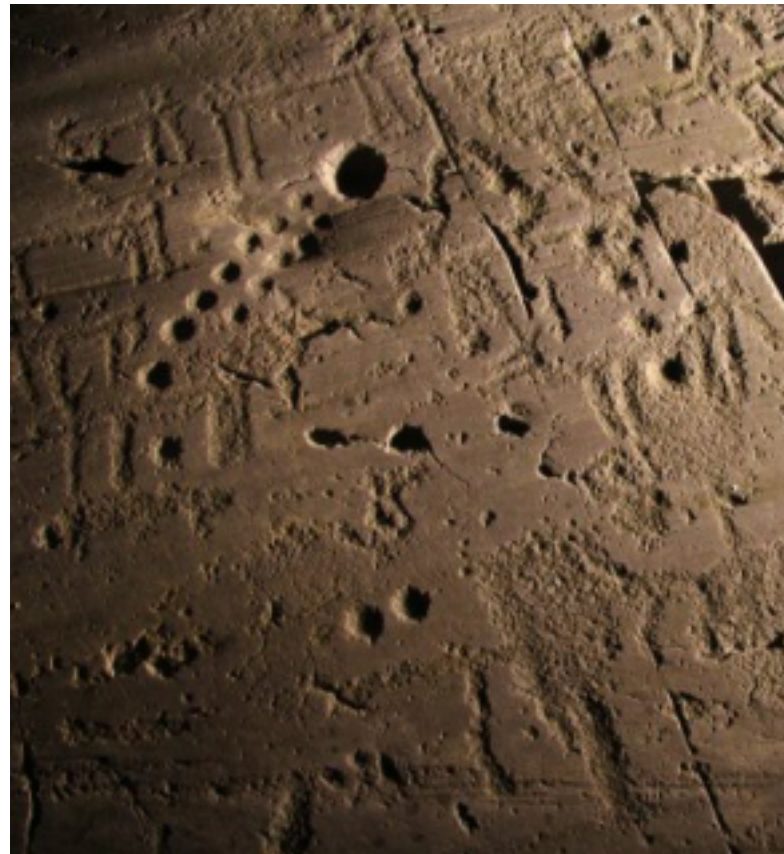


Historical origins of time domain astronomy

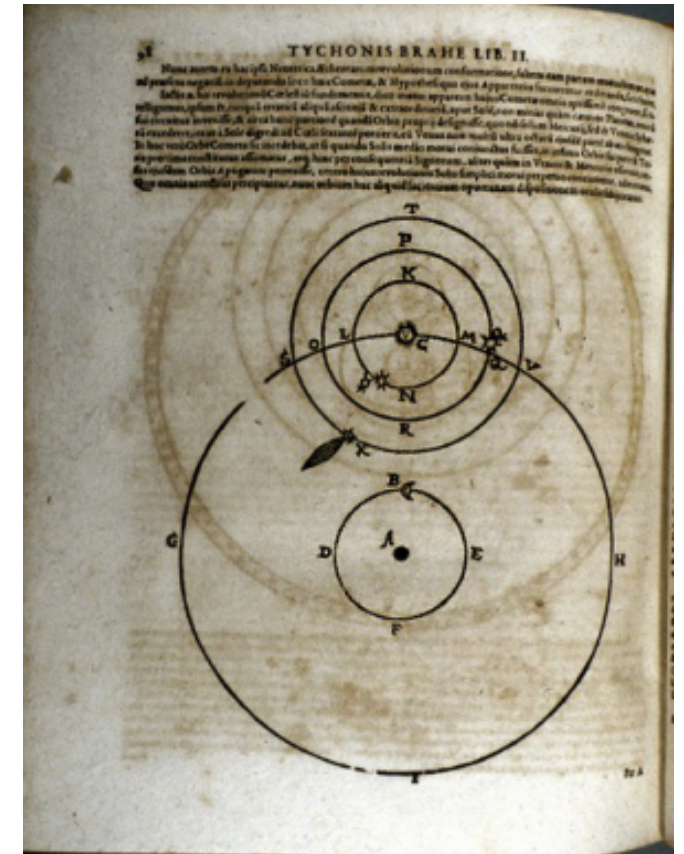
Time domain astronomy has its roots in antiquity, when ancient astronomers mapped the motion of the planets on the sky and timed the passage of comets.



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. Transient variability:

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

2. Periodic variability:

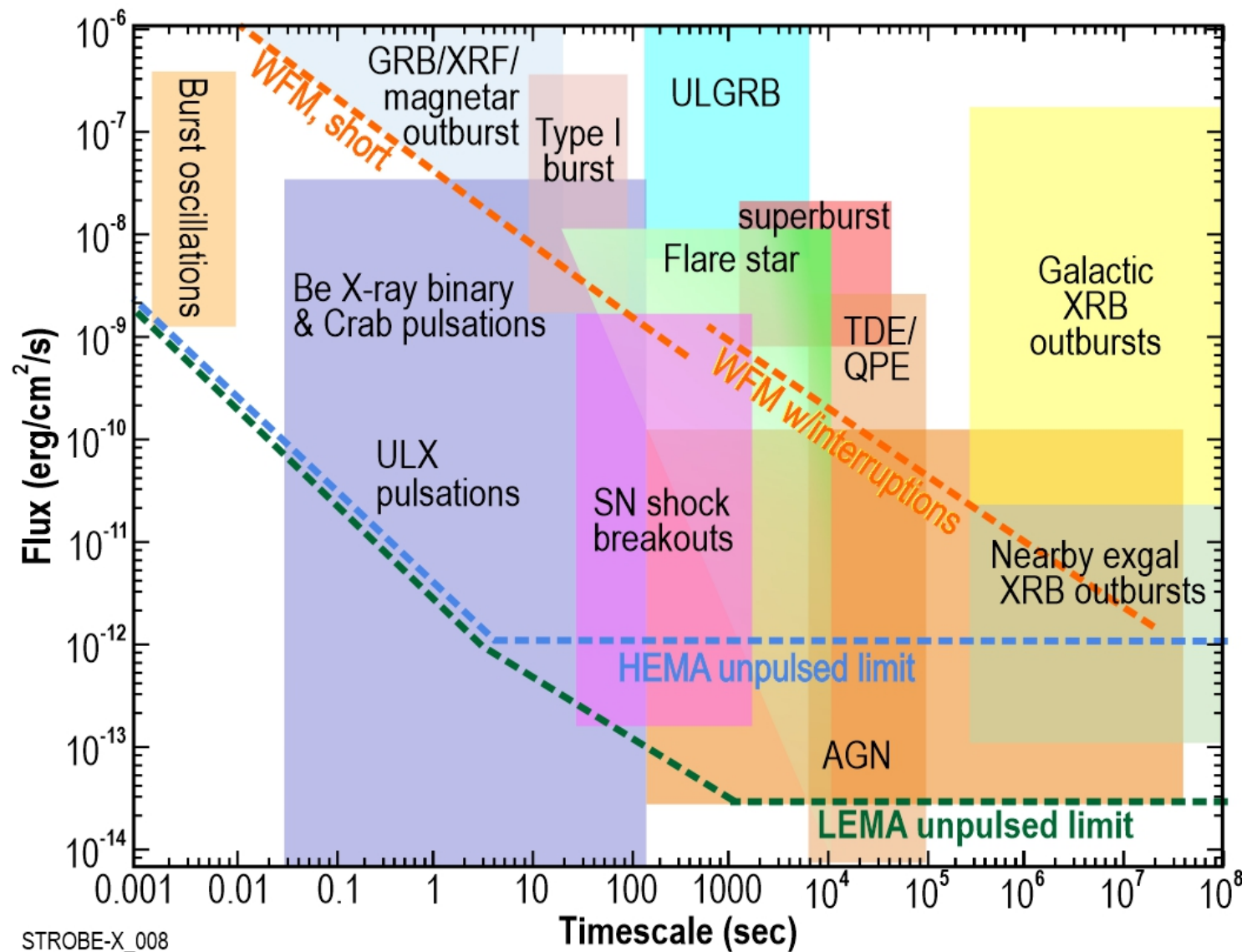
- Regular, repeating patterns.
- Examples: Pulsating stars (Cepheids, RR Lyrae), Eclipsing binaries.

3. Aperiodic variability:

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

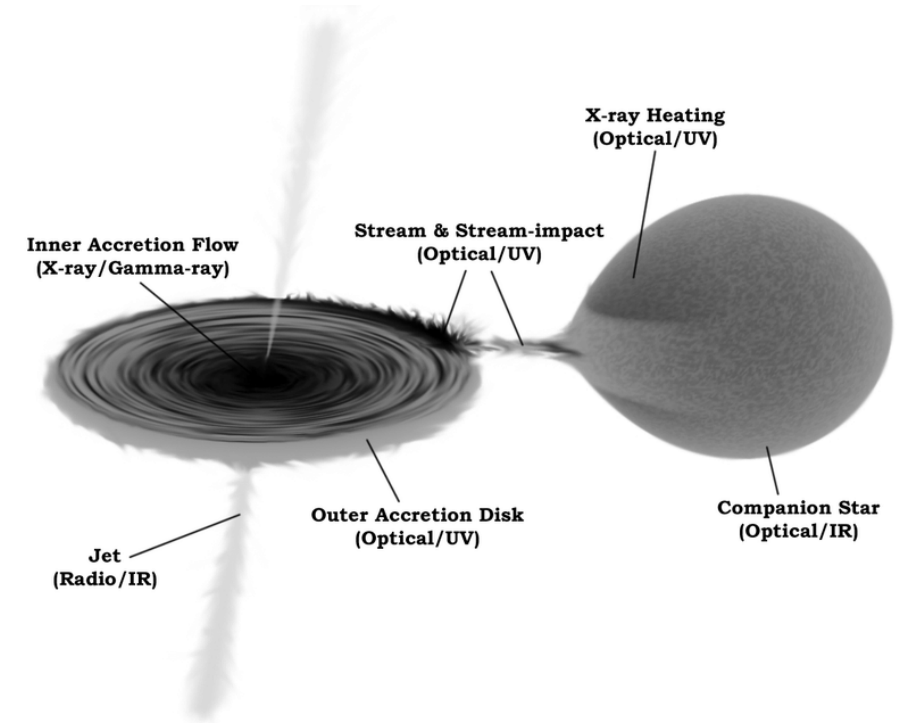
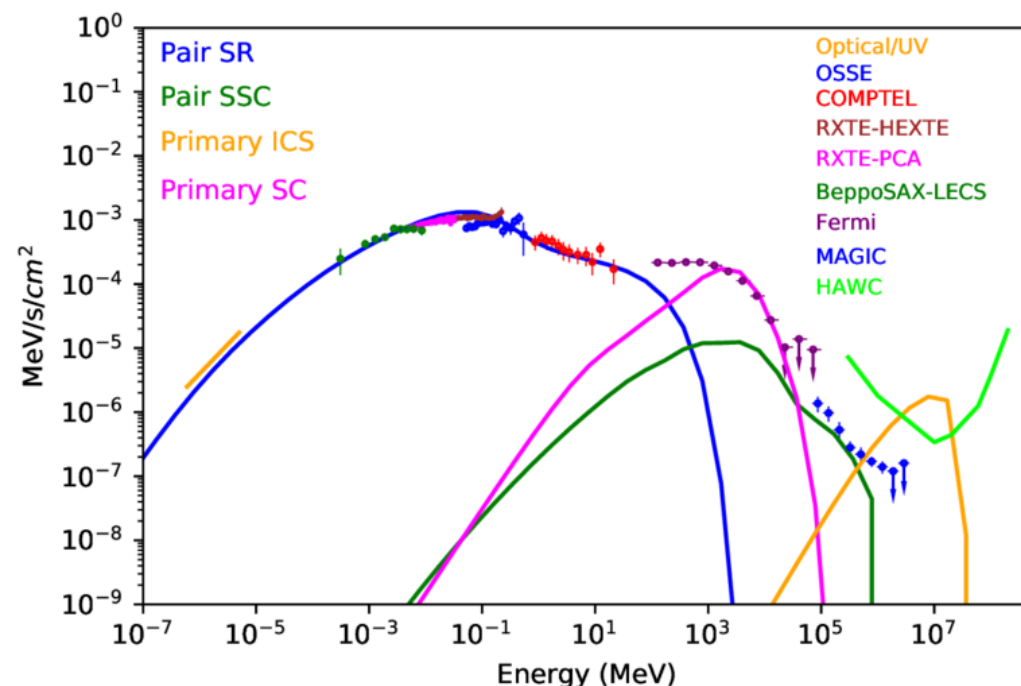
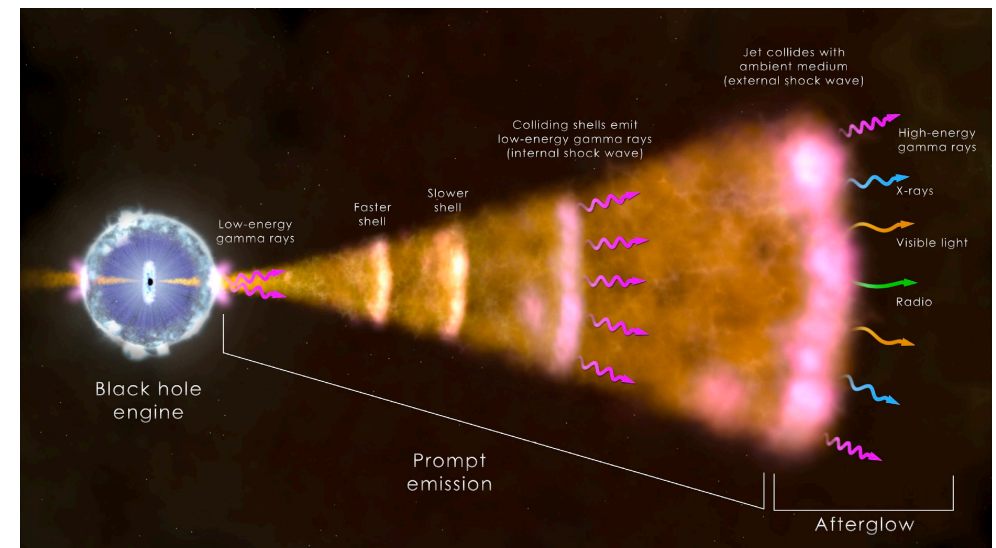
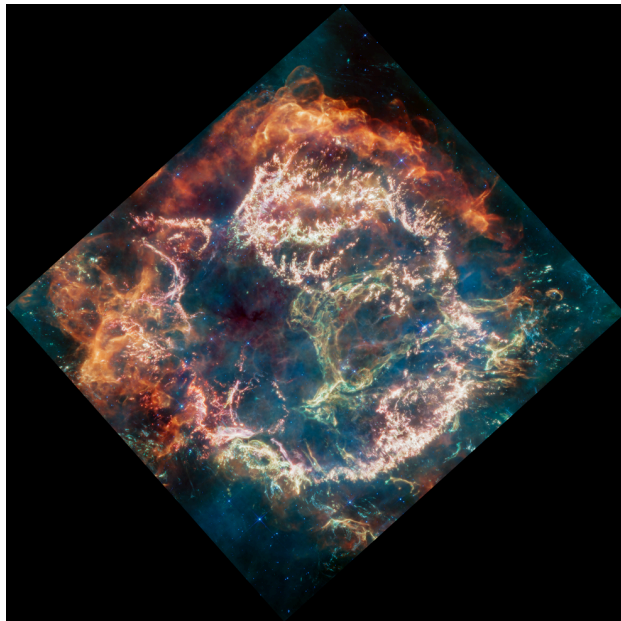
The transient sky spans huge scales

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), accreting white dwarfs
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

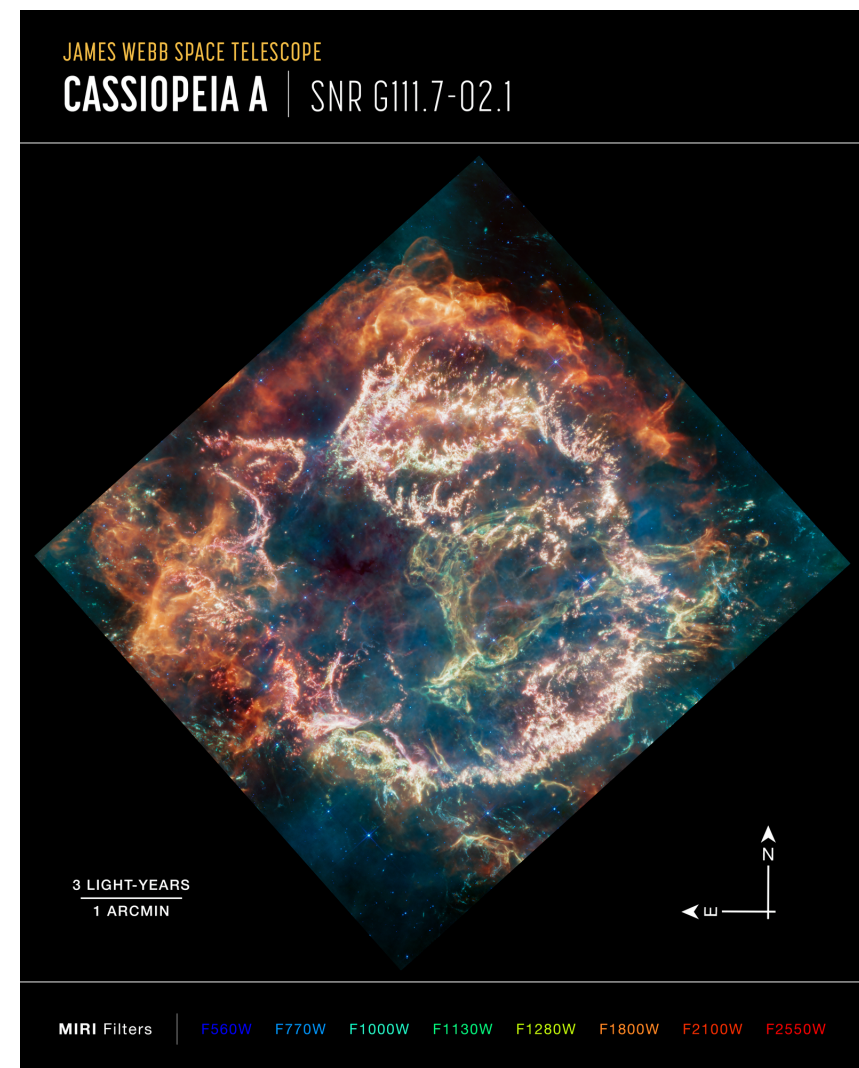
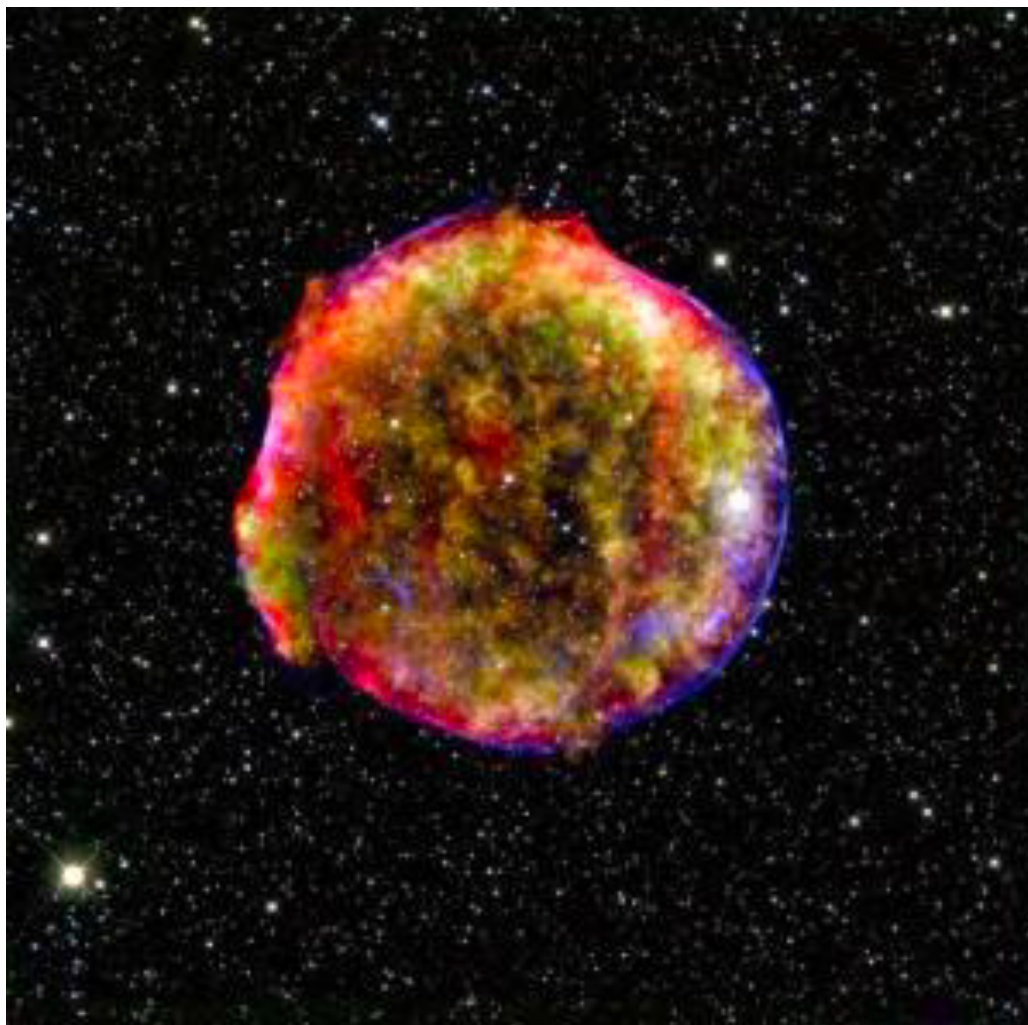
- Different wavelengths probe different emission components and provide complementary information about astronomical objects.



Francesco Coti Zelati (ICE, CSIC)

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.

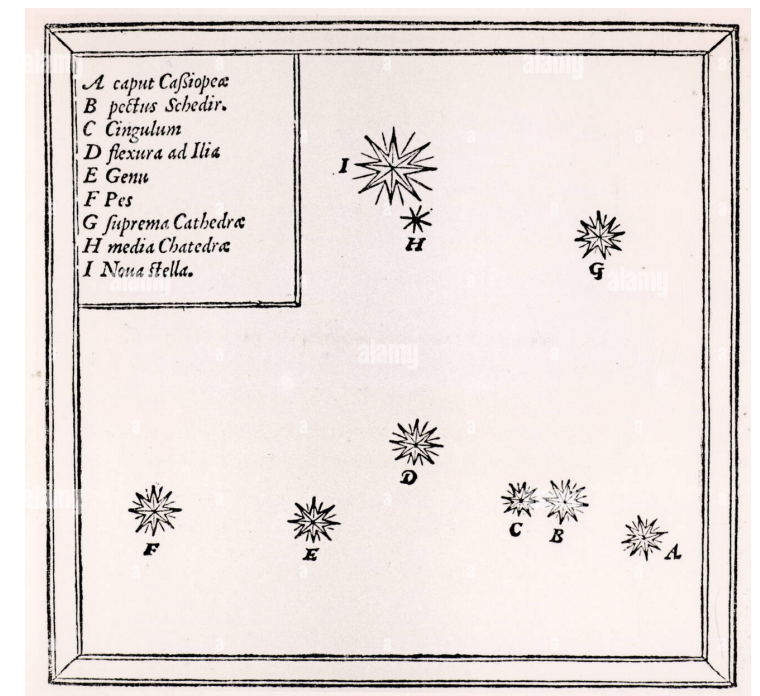
نارا خالصة ، ولا يكون لها برد مطفى ، ولا أيضا تصعد صعودا سريعا ممعنا في حيز النار إلى أن تبلغ المكان الشديد قوة النارية ، فيعرض لذلك أن يبقى التهابها واشتعالها مدة طويلة إما على صورة ذؤابة أو ذنب ، وأكثره شمالى وقد يكون جنوبيا ، وإما على صورة كوكب من الكواكب ، كالذى ظهر في سنة سبع وتسعين وثلاث مائة للهجرة ، فبقى قريبا من ثلاثة أشهر يطفئ ويلطف حتى اضمحل ، وكان في ابتدائه إلى السواد والخضرة ، ثم جعل كل وقت يرى بالثمر ويزداد يابا ويلطف حتى اضمحل . وقد يكون على صورة لحية ، أو صورة حيوان له قرون ، وعلى سائر الصور ؛ وإنما يكون ذلك إذا كانت هناك مادة كثيفة واقنة ، تطفئ أجزاؤها يسيرا يسيرا وتحتل عنه متصعدة كروائد شمعية أو قرنية . ومنها المسماة أعترا كان تشريرها تشعير . وكل ما ثبت منها

(١) بالعدد : وبالعدد ، سا || فى : ساقطة من ب ، ط (٢) كالموجود : كالموجود
 د ، ط ، م (٣) ويختلفها غيرها : ويختلفه غيره ب ، د ، سا ، ط || موضعها : موضع ب ، د ، سا ، ط .
 (٥) فى حقيقة : وحقيقة سا (٧) مقامه : مكانه د ، سا || يشتعل : ساقطة من د .
 (٨) وخفيفة : خفيفة سا (٩) وخلعت : وحصلت سا . (١٠) وذات : ذات سا
 (١١) ممعنا : ممعنا د (١٣) طويلة : ساقطة من د ، سا (١٤) للهجرة : الهجرة ط ؛
 ساقطة من سا (١٧) أو صورة : أو على صورة د ، سا || حيوان : حيوان ط (١٨) متصعدة : متصعدة م
 (١٩) تشريرها : بشردها د ، ط ، م || تشعير : تشعير د ، تشعير ط ، م || ما ثبت : ما ثبت ب ، د ، ما ثبت ط .

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

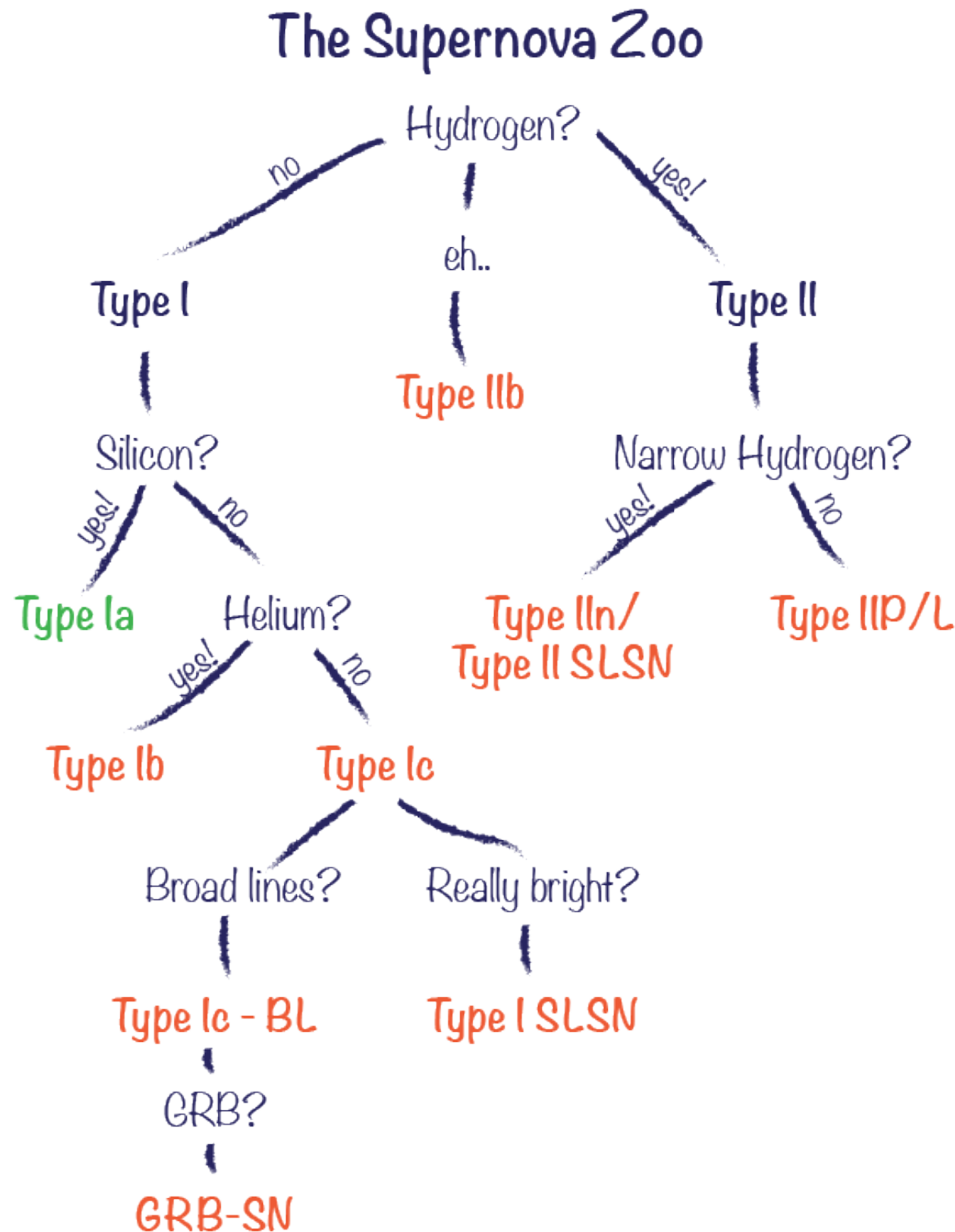


Crab nebula remnant

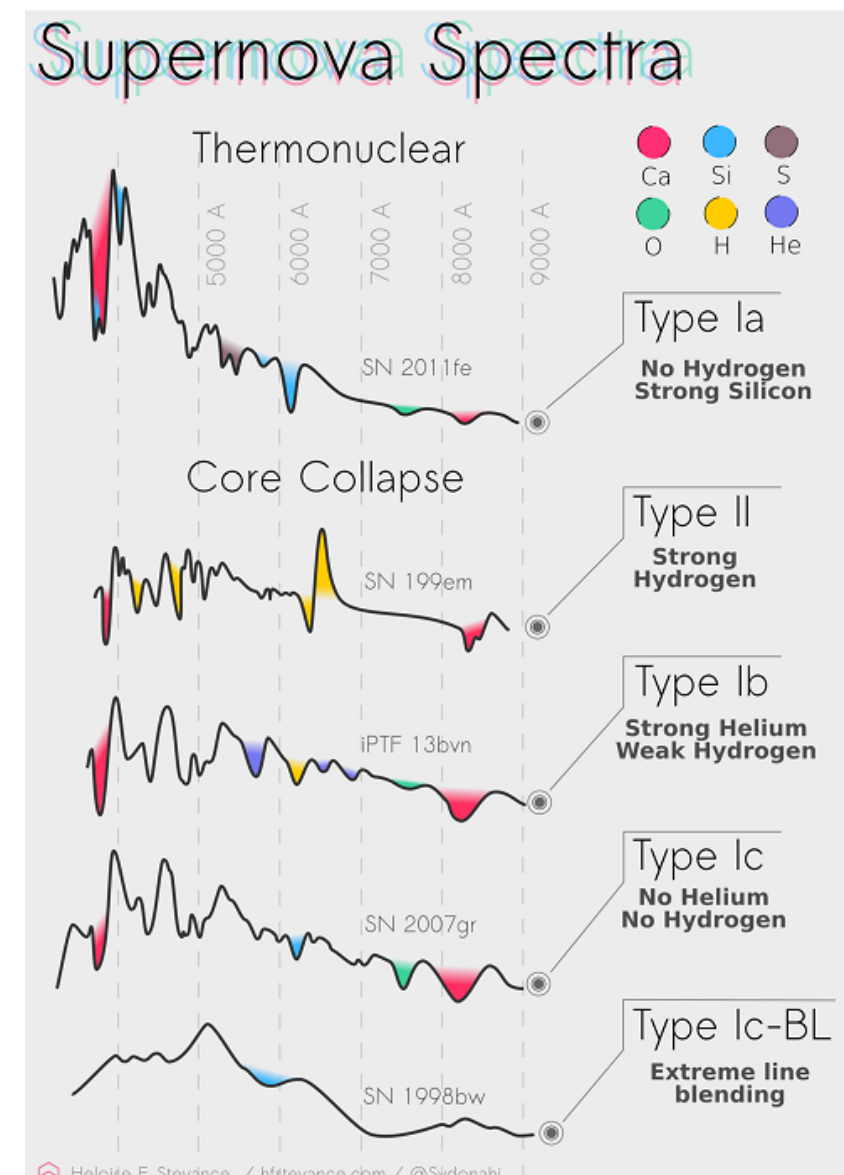


Tycho Brahe's drawing of the supernova of 1572

Types of supernovae



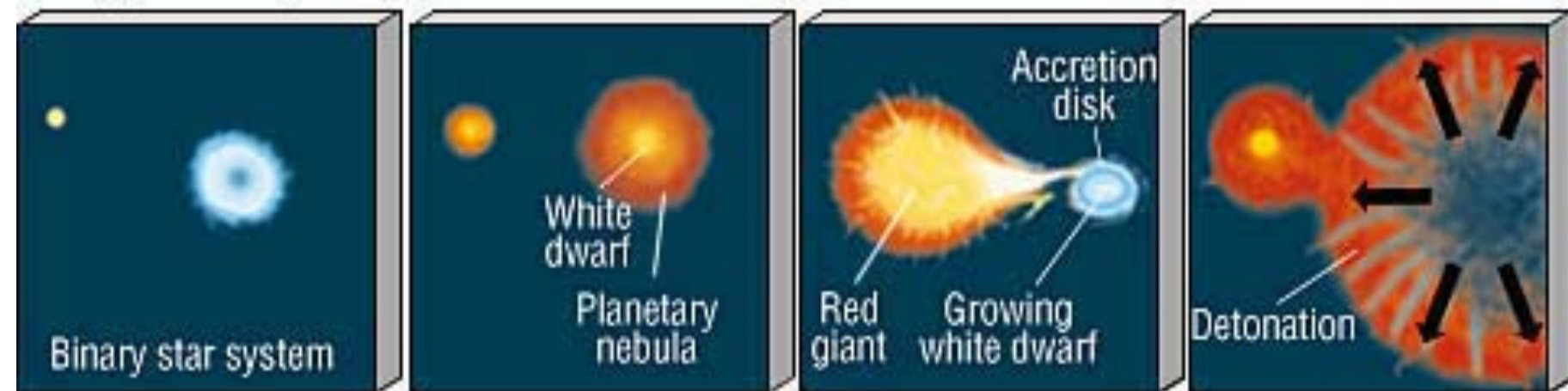
- Type I Supernovae (Subtypes: Ia, Ib, Ic)
Lack of H lines in their spectra.
- Type II Supernovae:
Presence of H lines in their spectra.



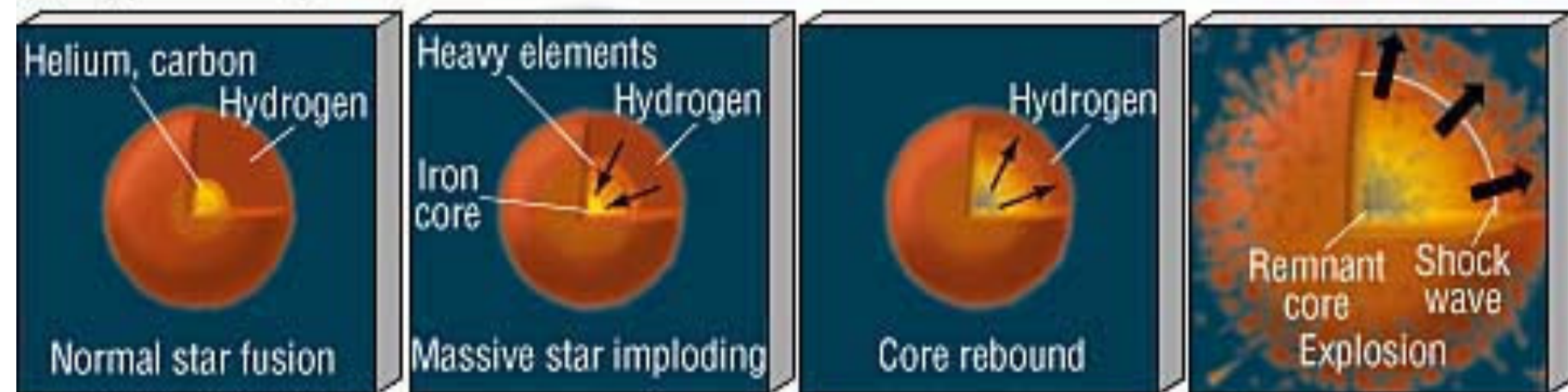
Two engines dominate supernovae

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

(a) Type- I Supernova



(b) Type- II Supernova



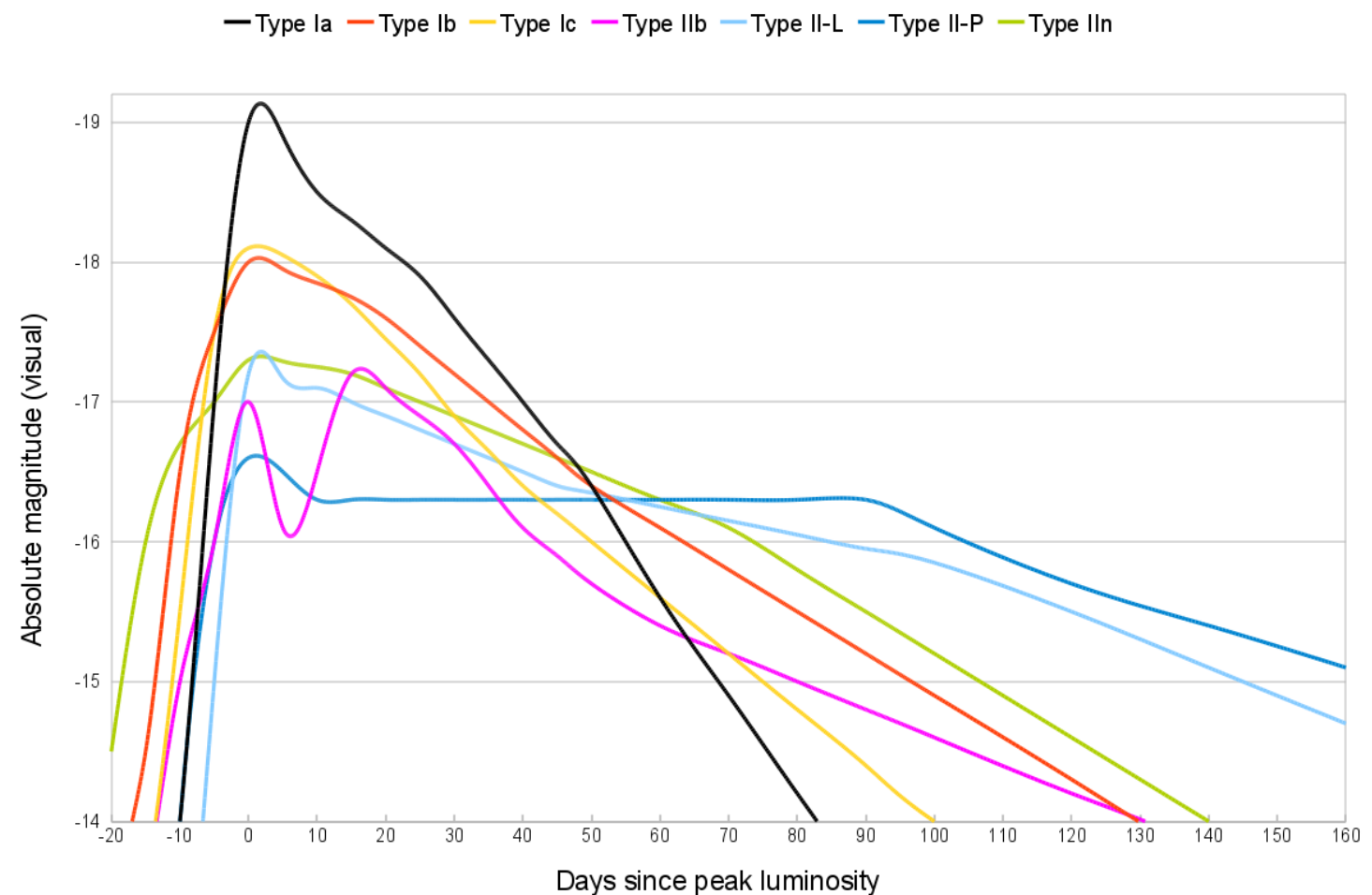
Supernovae light curves

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

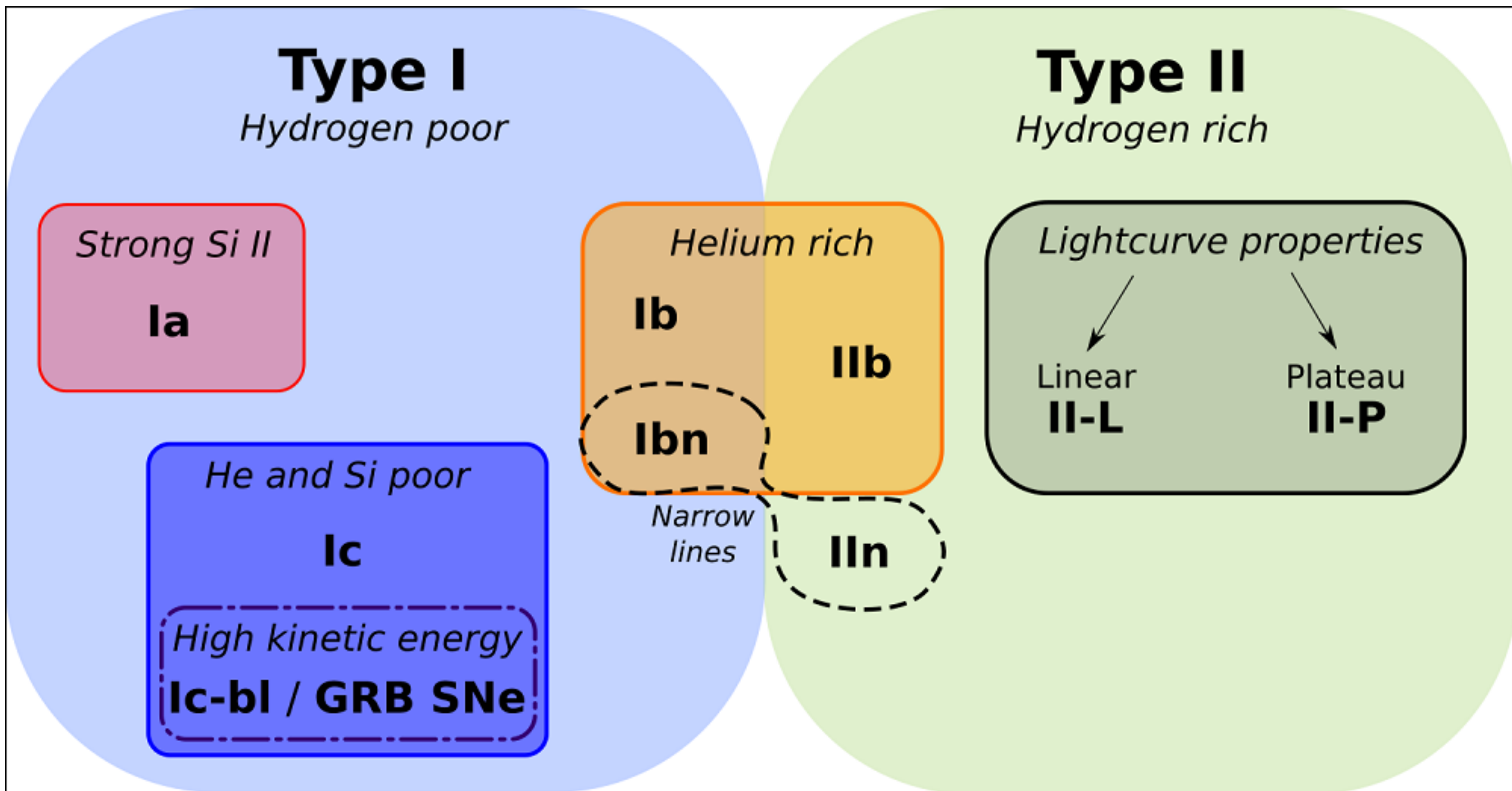
Emission primarily powered by the radioactive decay of nickel-56 to cobalt-56 and then to iron-56.

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

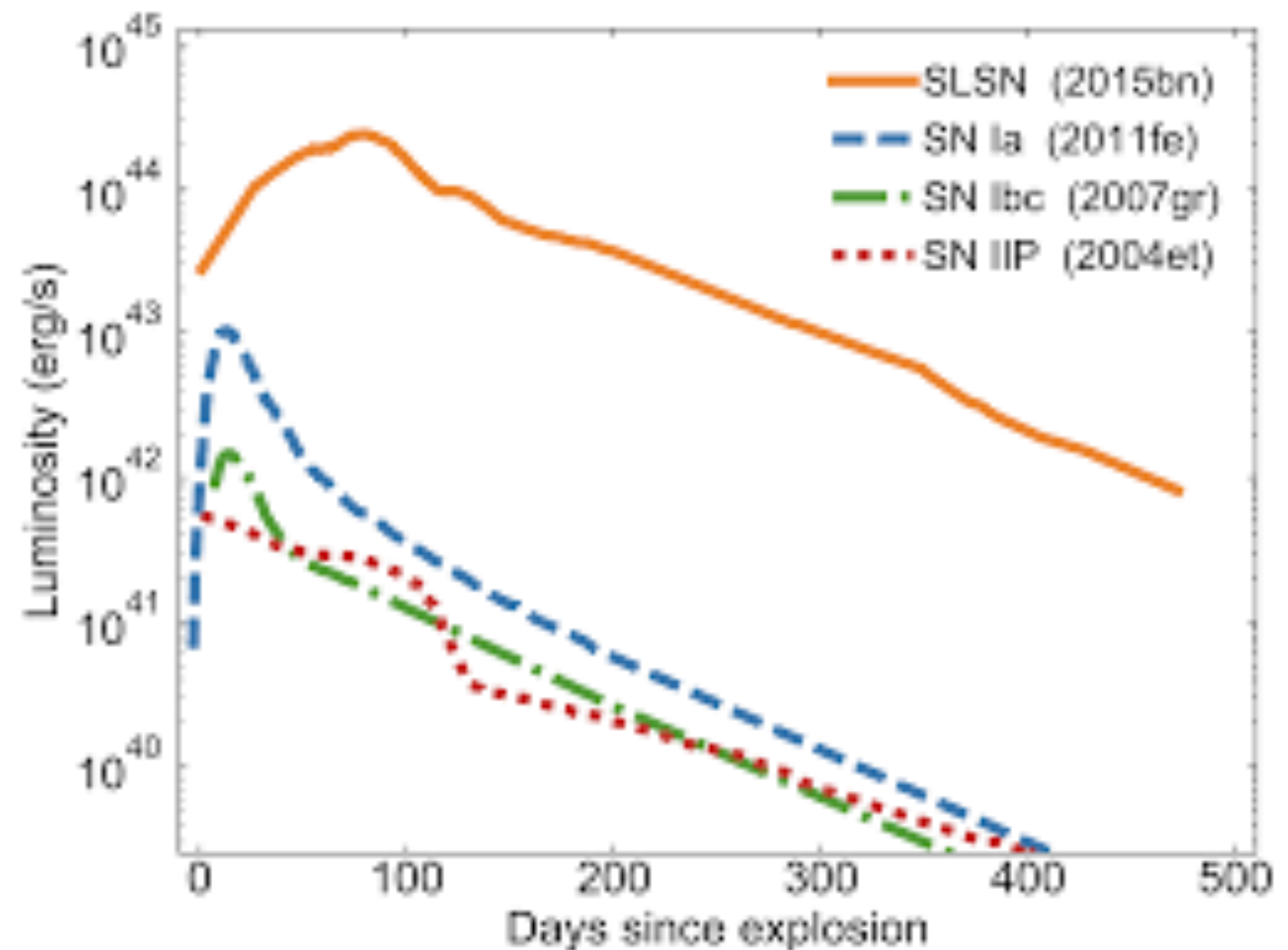


Types of supernovae



Superluminous Supernovae (SLSNe)

- Peak luminosity up to $\sim 10\text{--}100\times$ that of normal SNe.
- Main classes:
 - SLSN-I: H-poor
 - SLSN-II: H-rich, often interacting with dense CSM
- Possible power sources:
 - Spin-down of a newborn magnetar (favoured)
 - Ejecta–CSM interaction

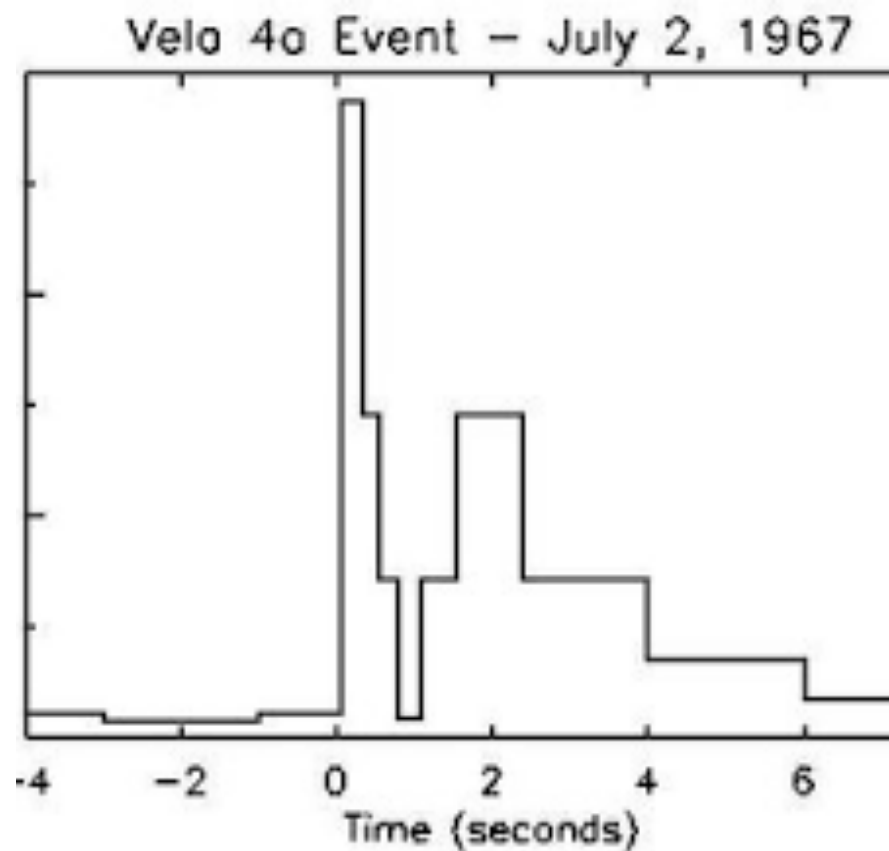


Gamma-ray bursts

- Extremely energetic explosions emitting gamma rays, releasing an energy comparable to a SN (10^{54} erg) 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
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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

Vela satellites detected flashes that were neither terrestrial nor solar... then where did they come from?

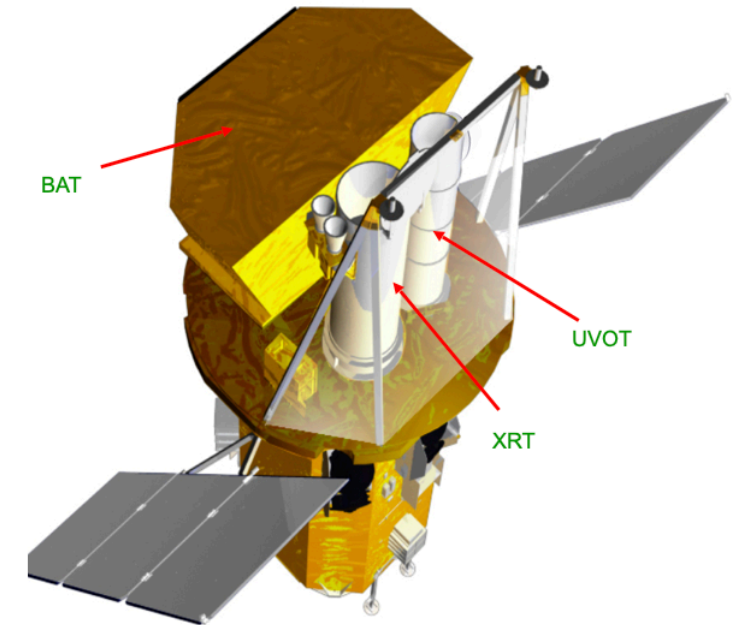
We now have observed more than 10 000 GRBs!

Neil Gehrels Swift Observatory

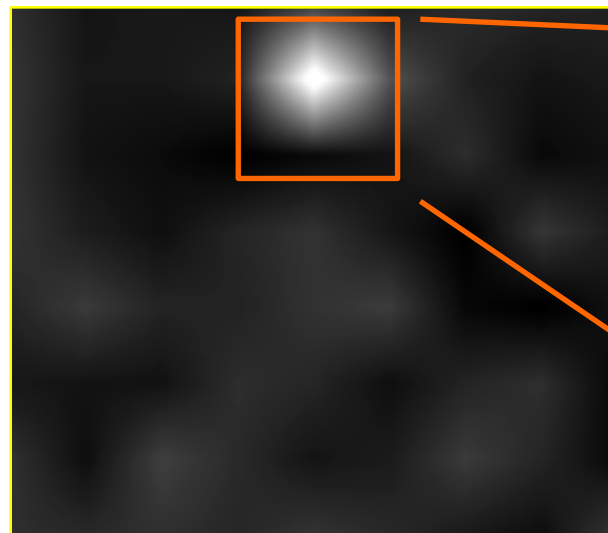
Wide-field hard X-ray detector (BAT)

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

Optical/UV telescope (UVOT)

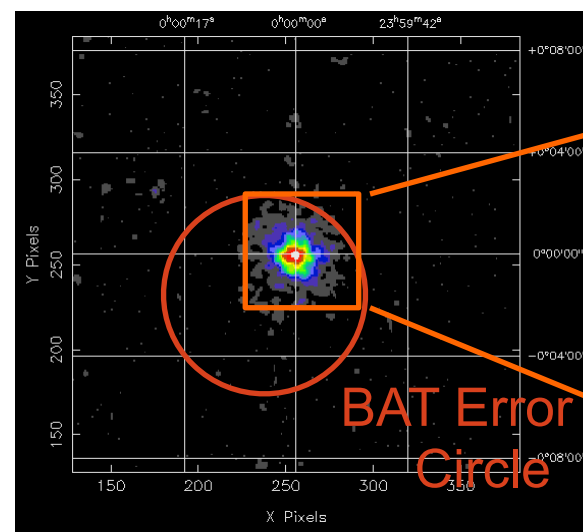


BAT Burst Image



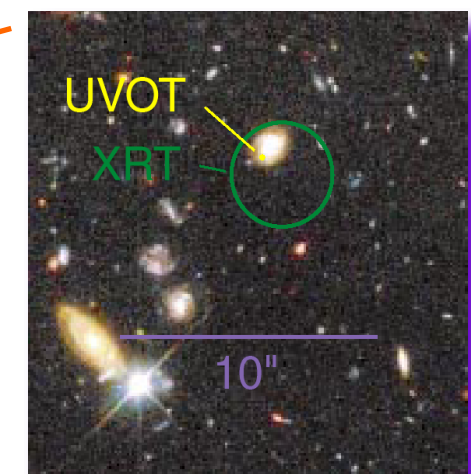
$T \sim 10$ sec

XRT Image



$T \sim 100$ sec

UVOT Image



$T \sim 300$ sec

Francesco Coti Zelati (ICE, CSIC)

Gamma-ray bursts properties

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

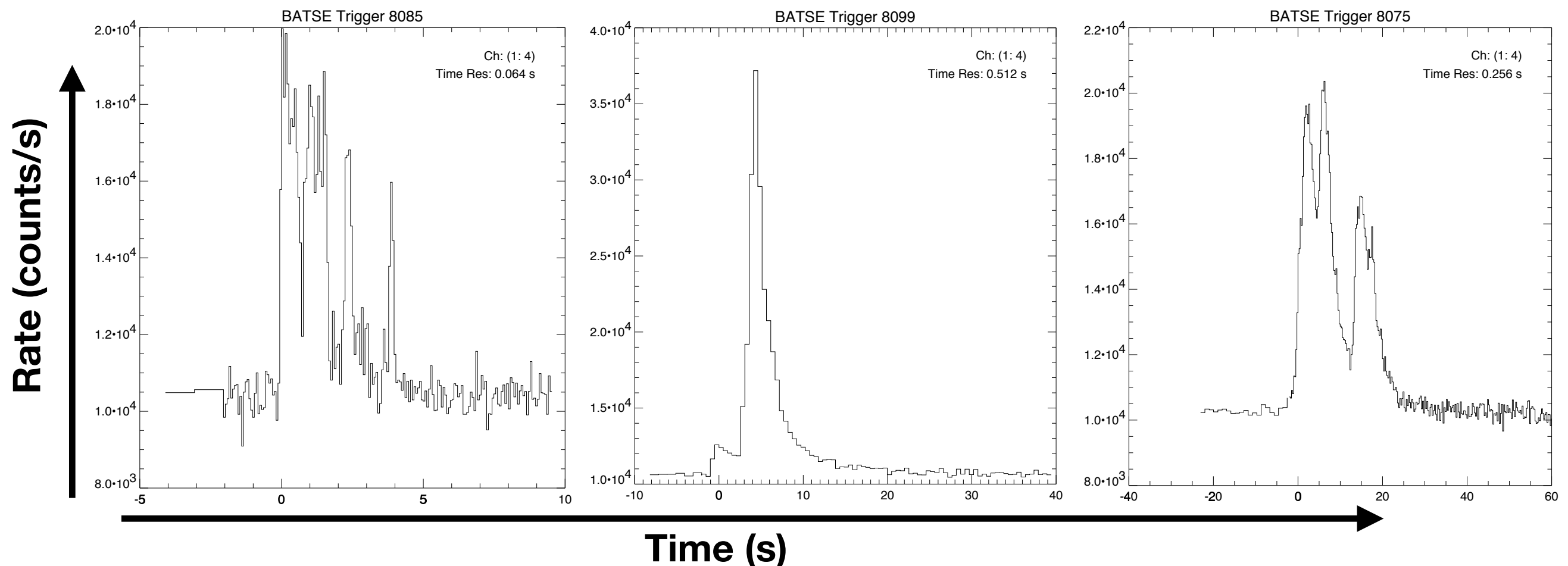
Duration: $\sim 1 - 1000 \text{ s}$

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

Rate: a few per week

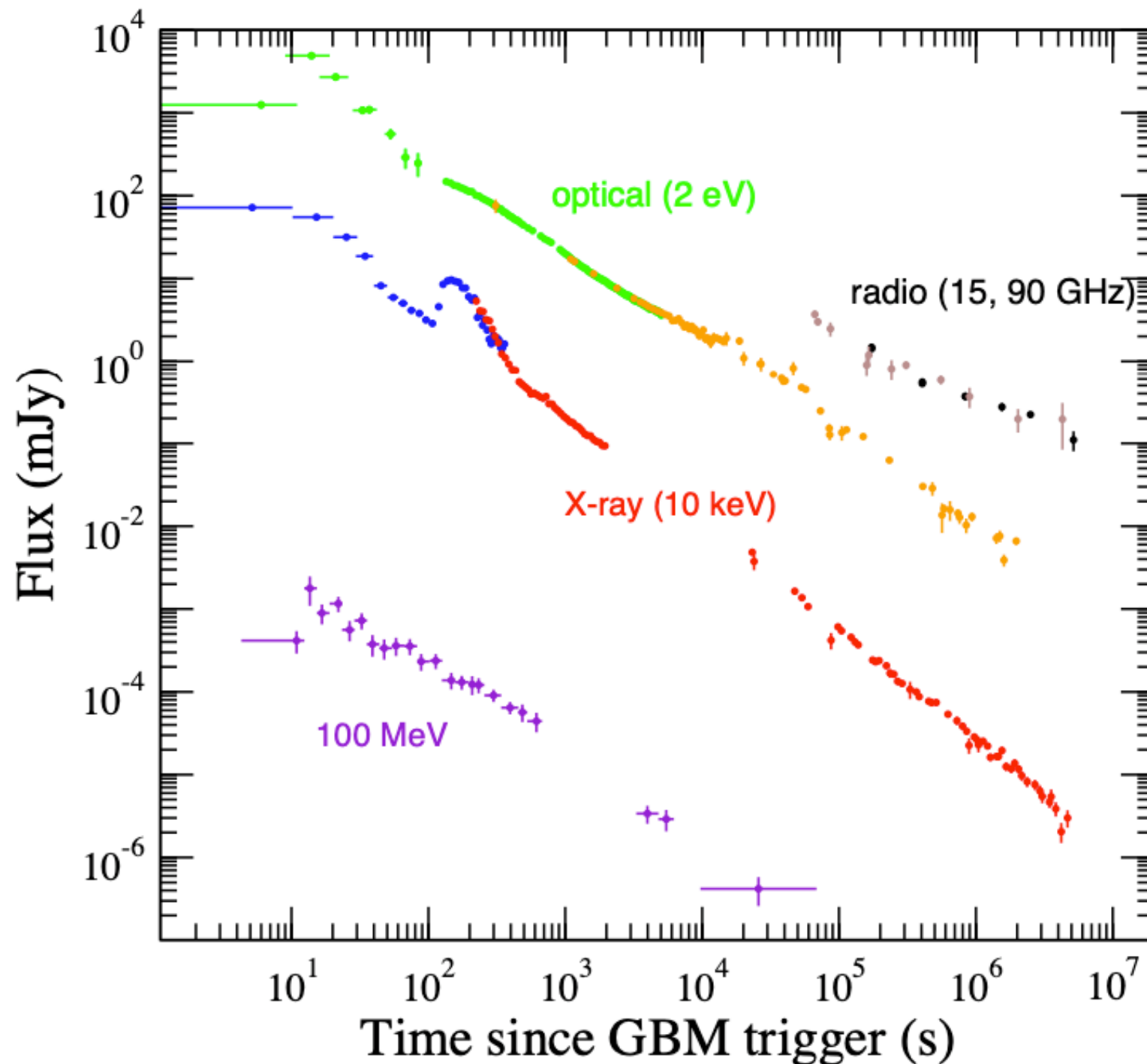
Variability: $\sim 10 \text{ ms} - 1 \text{ s}$

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



Gamma-ray bursts afterglows

GRB 130427A Panaitescu et. al. 2013

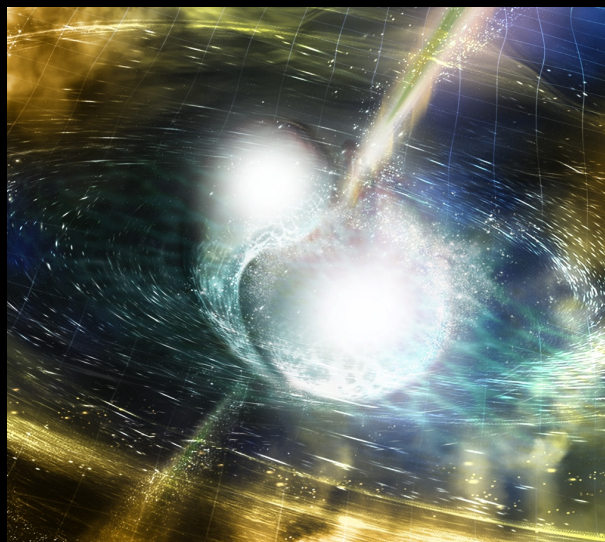


- Decelerating shock between ejecta and surrounding medium
- Observed from radio to TeV
- Lasting from minutes to years after the prompt emission
- Many different decay shapes
- Optical spectrum provide distance estimate
- SED modeling is a proxy of jet physics and geometry, magnetic field, energetics and environment

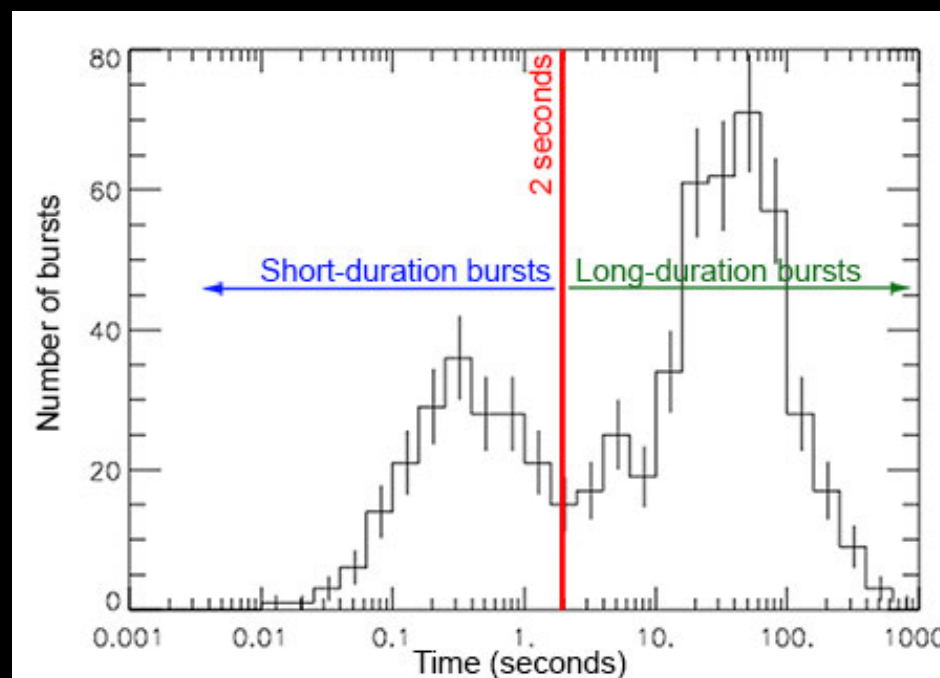
Gamma-ray bursts progenitors

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

Short GRB

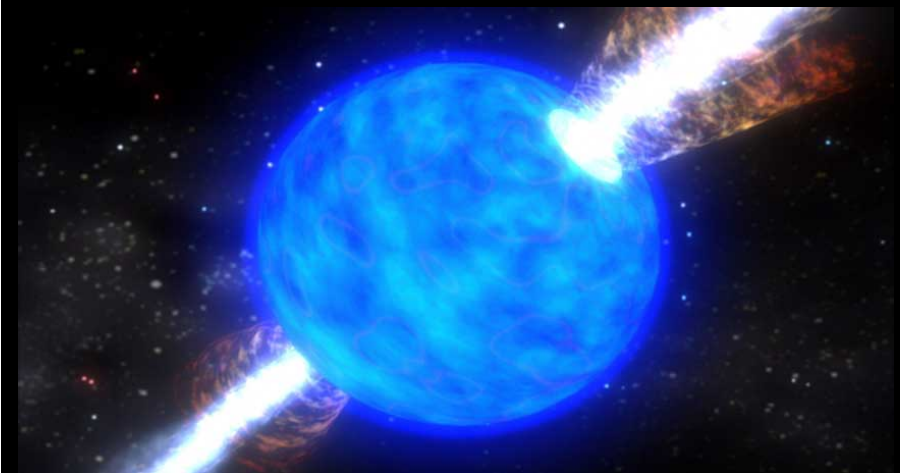


**Compact Binary
Merger**



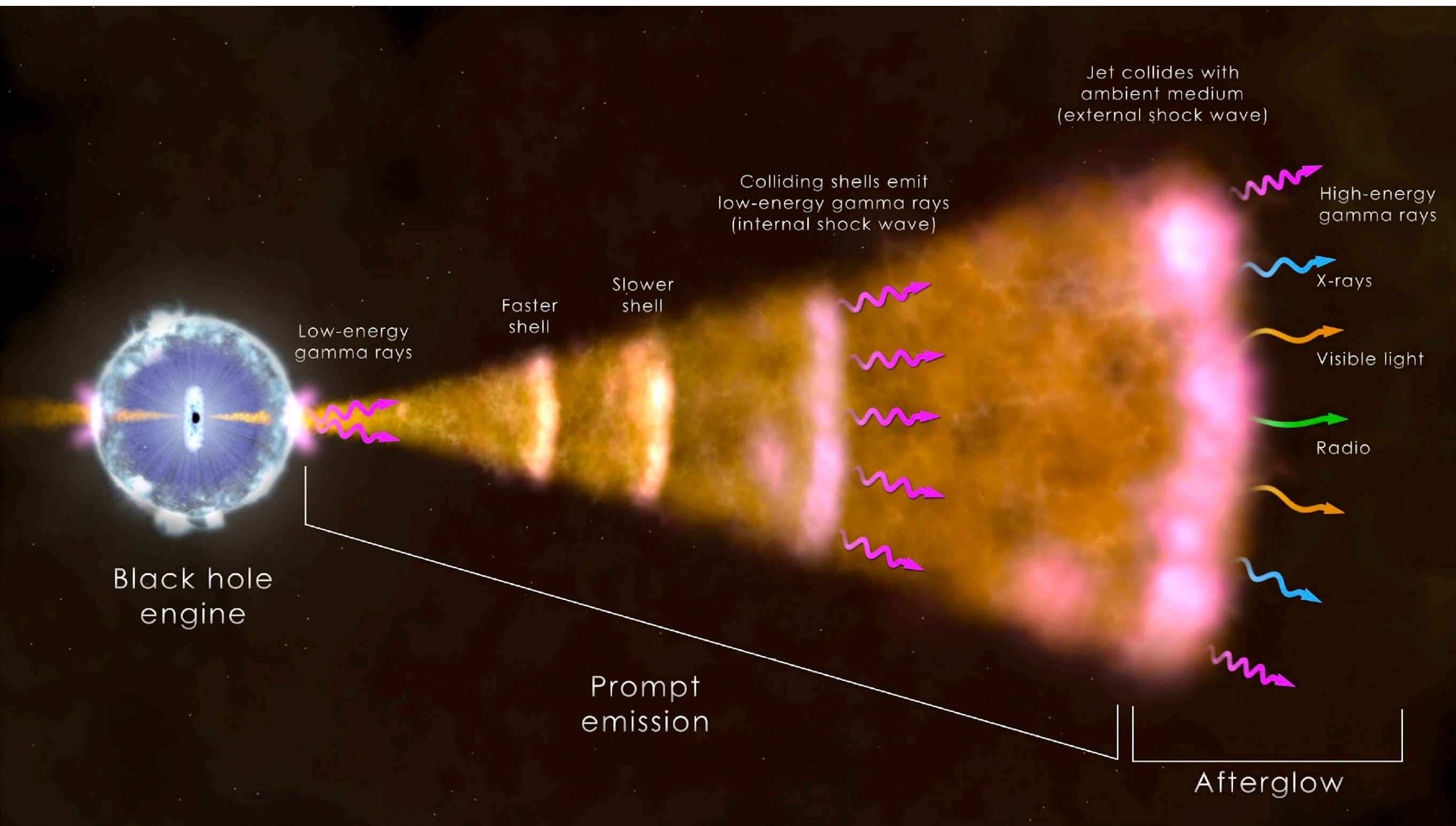
(<https://imagine.gsfc.nasa.gov/science/objects/bursts1.html>)

Long GRB



Collapsar

Gamma-ray bursts mechanisms



Tidal disruption events

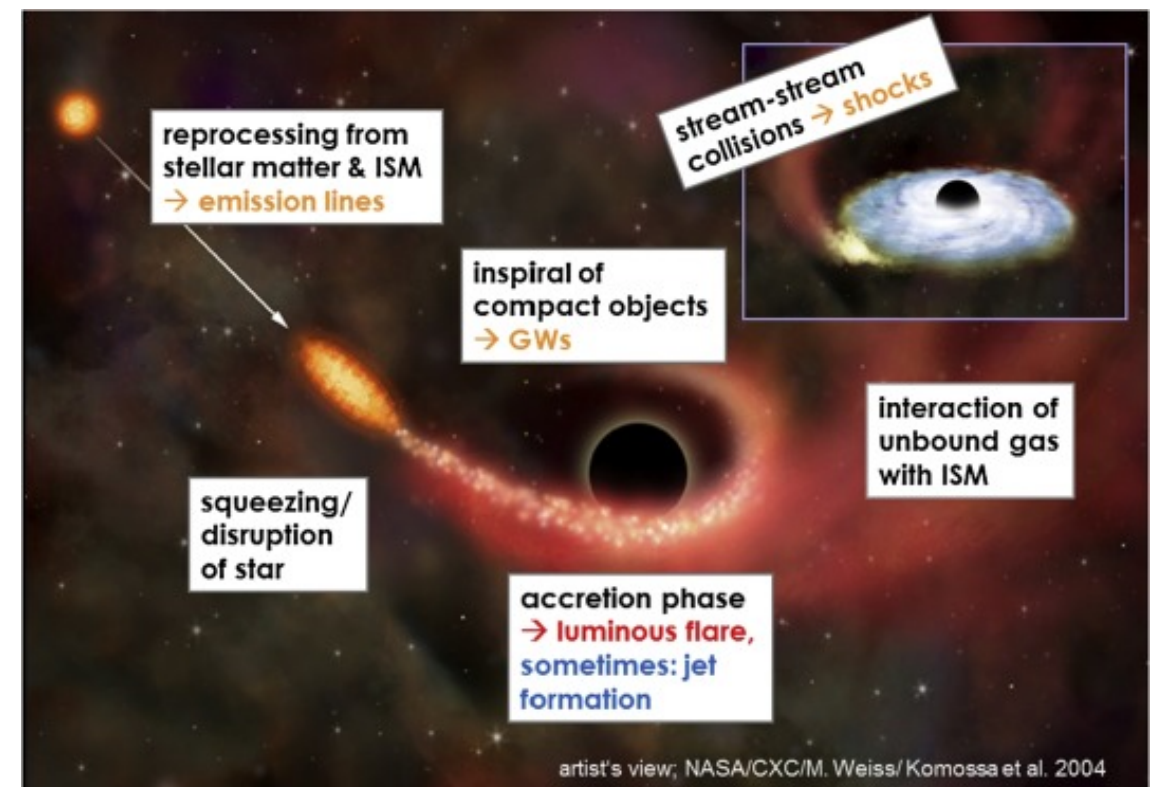
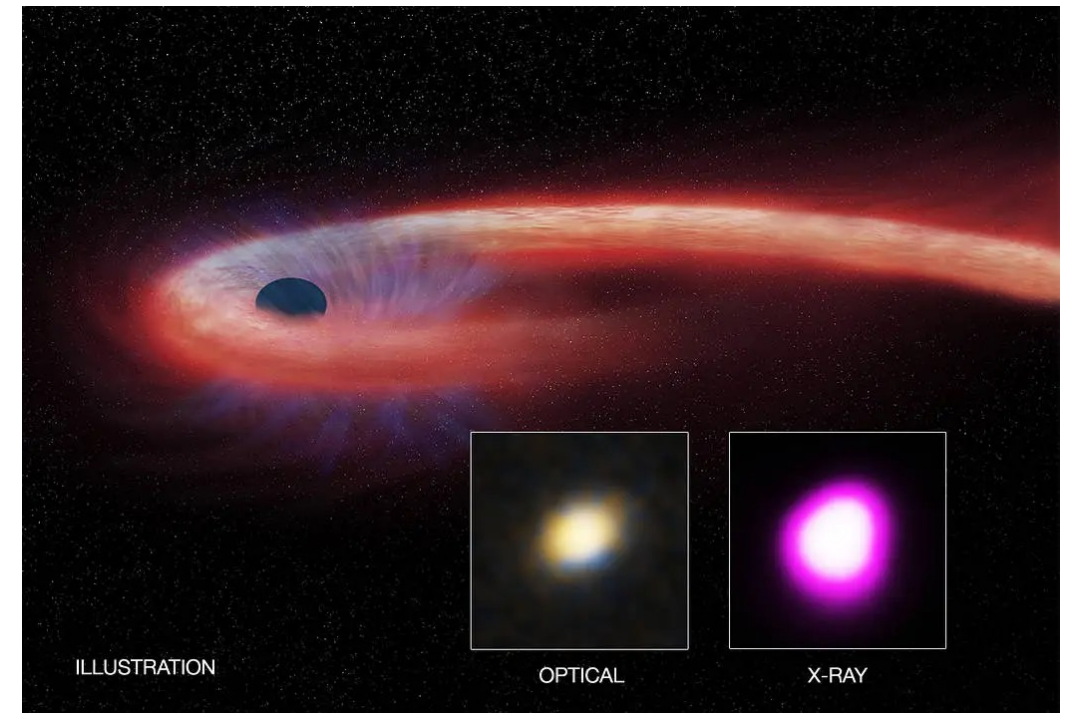
A star passing within the tidal radius of a massive BH is torn apart by tidal forces.

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

The debris then continues to fall back onto the BH at a decreasing rate.

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

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



Tidal disruption events

A star passing within the tidal radius of a massive BH is torn apart by tidal forces.

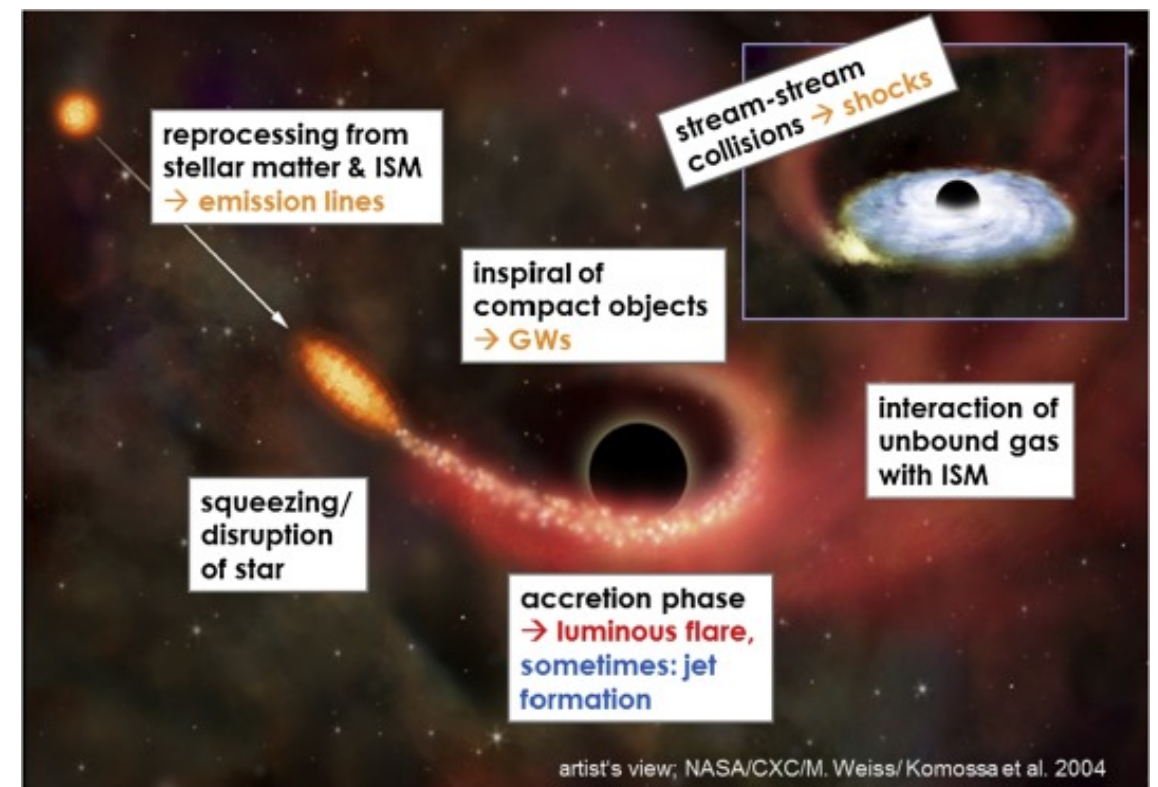
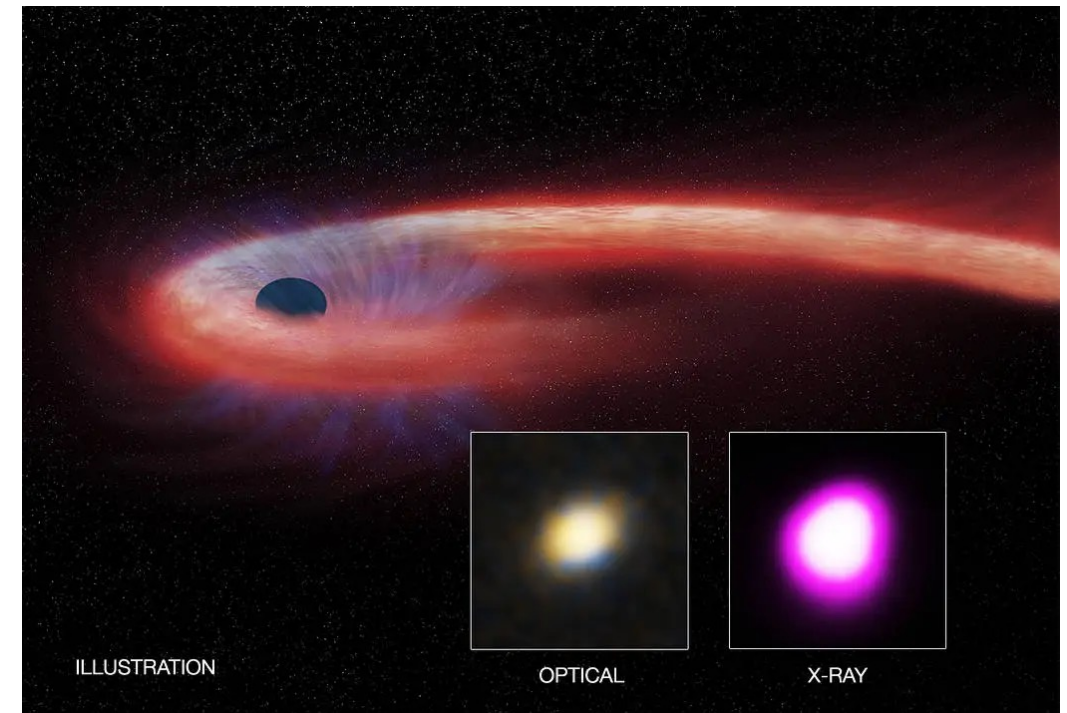
Roughly half of the stellar debris becomes unbound. The remaining debris forms an accretion disc around the BH.

Material heats up and radiates enhanced multi-band emission.

The debris then continues to fall back onto the BH at a decreasing rate.

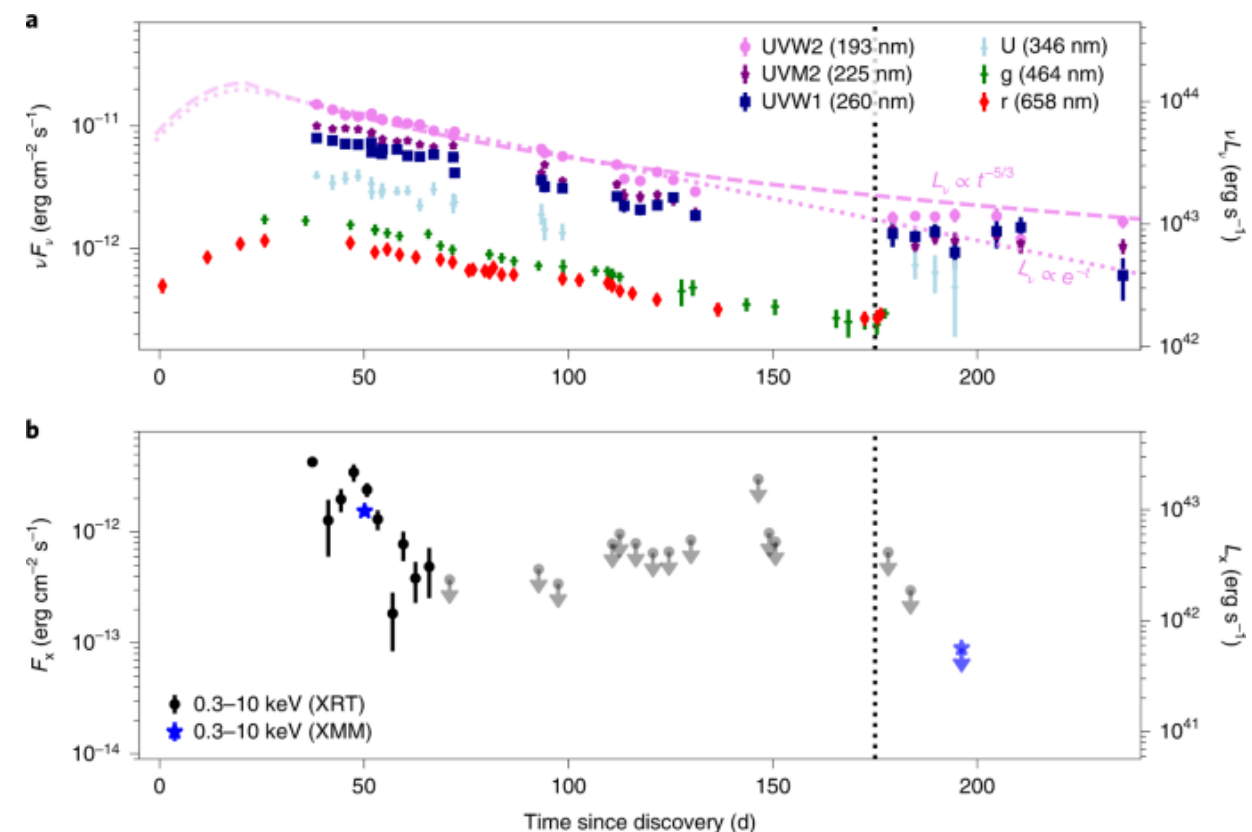
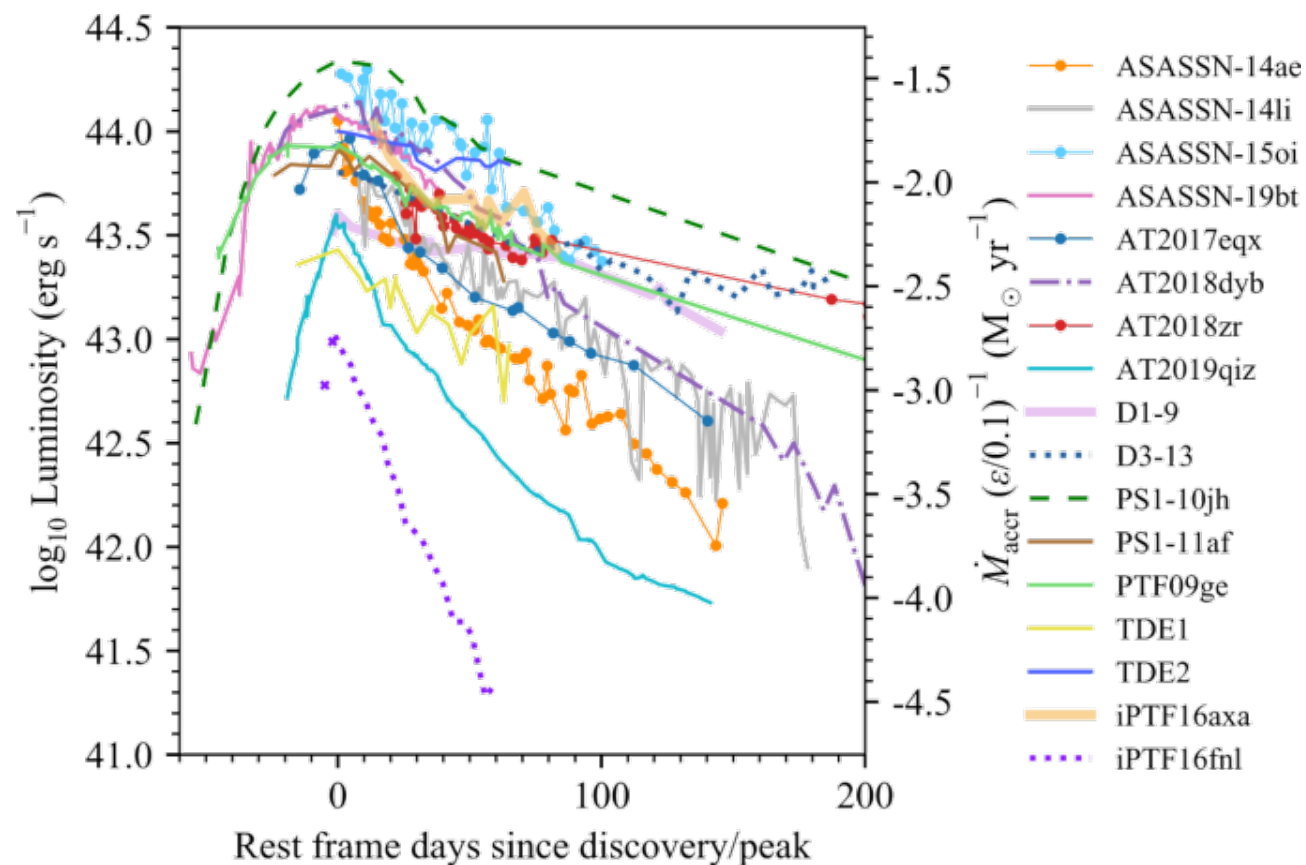
Unique opportunity to study BHs and the extreme physics of their surroundings.

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



Tidal disruption events: light curves

Rapid rise to peak brightness followed by a power-law decline



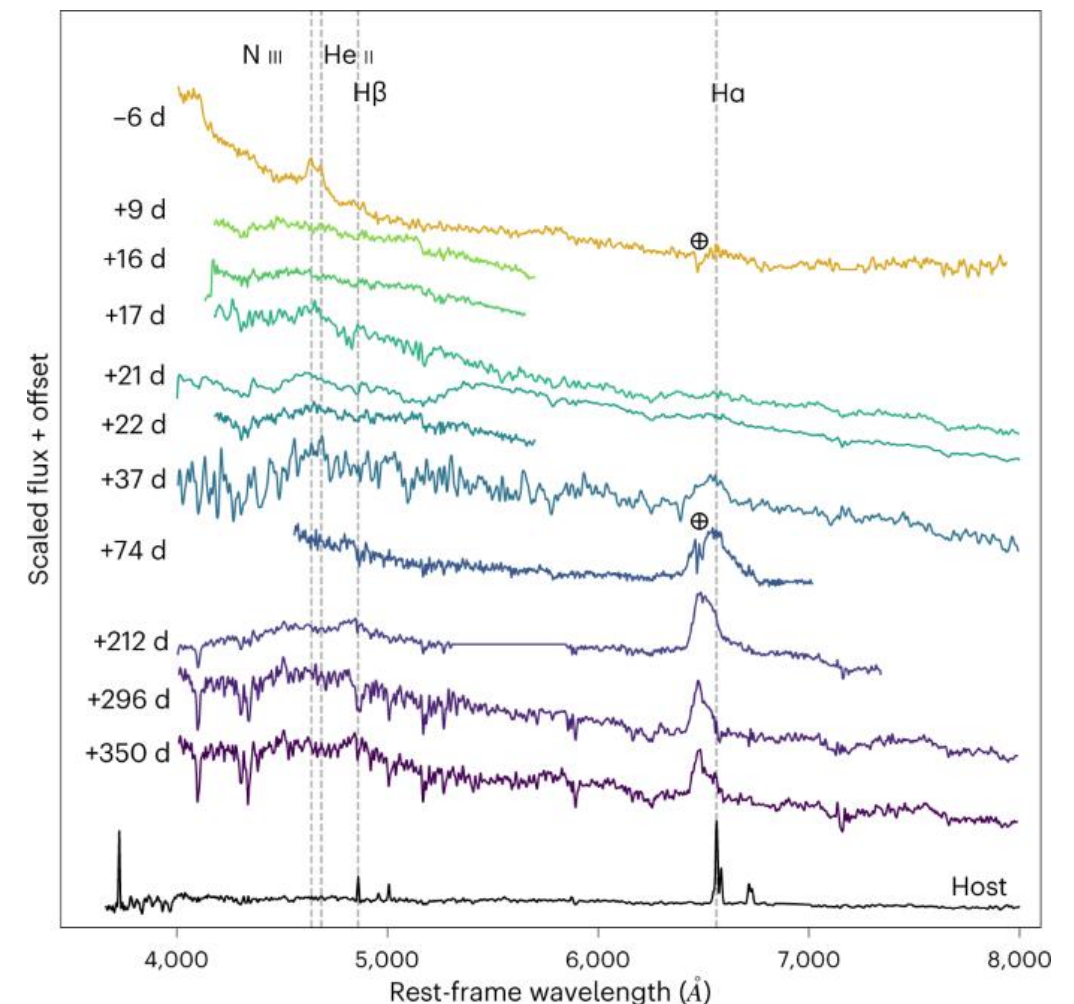
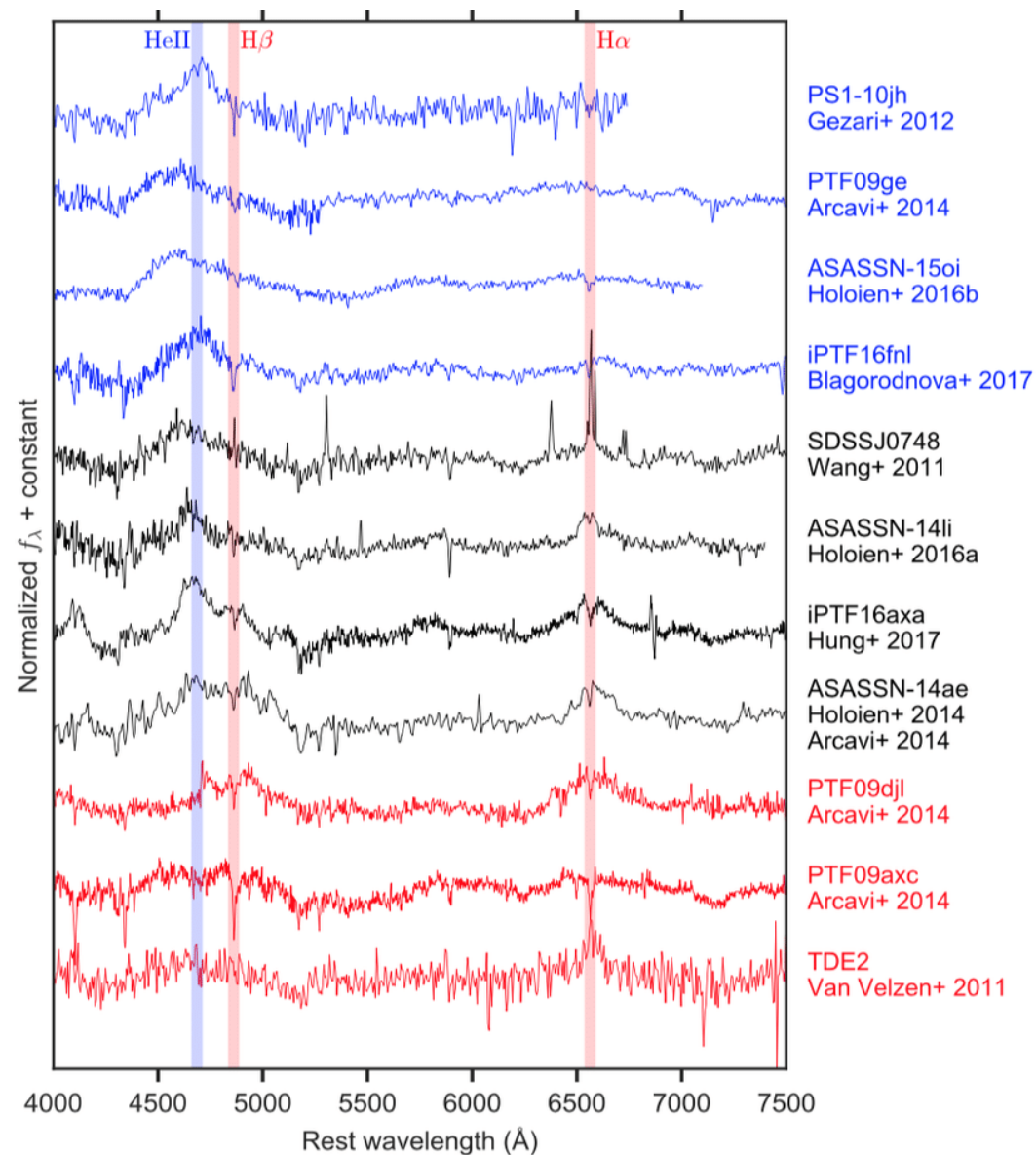
Francesco Coti Zelati (ICE, CSIC)

Tidal disruption events: spectra

Blue thermal continuum (T of a few 10^4 K)

Broad H Balmer lines ($H\alpha$ and $H\beta$) from moving, ionized debris or outflows

He II $\lambda 4686$ from strongly ionized gas



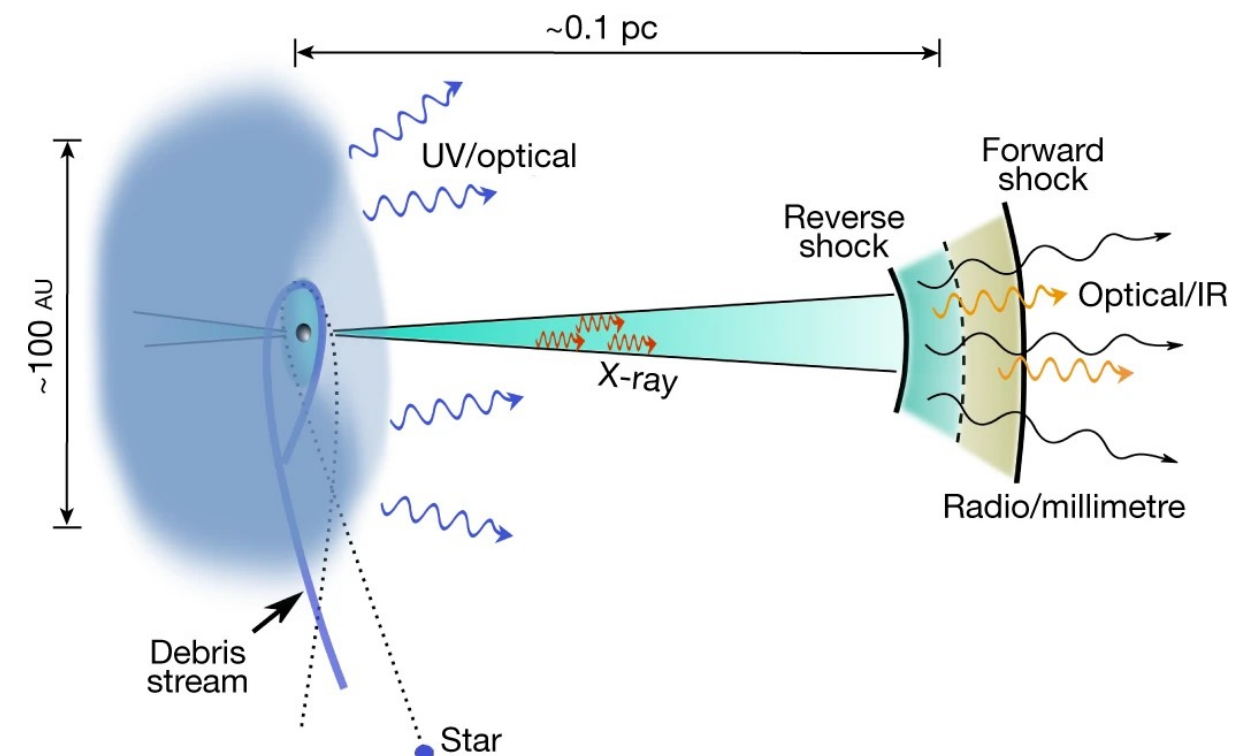
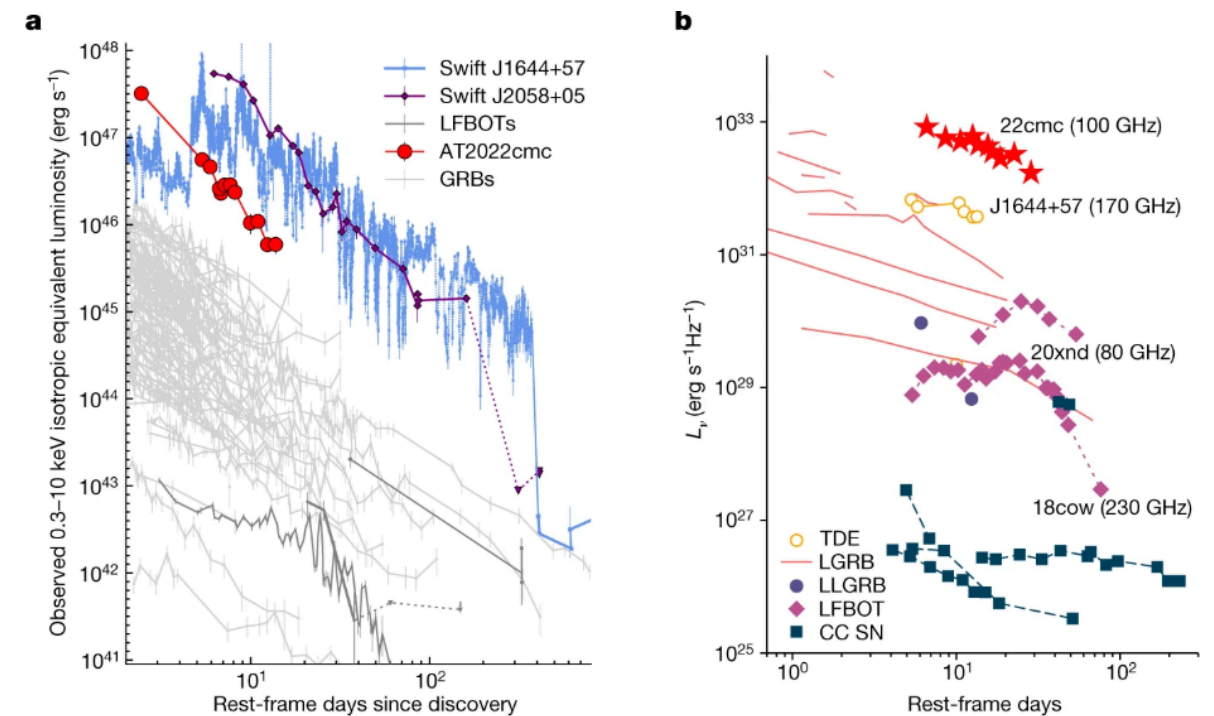
Relativistic (jetted) tidal disruption events

Rare class of TDEs (<1%) launching relativistic collimated jets.

Observed nearly on-axis $\rightarrow$ relativistic beaming.

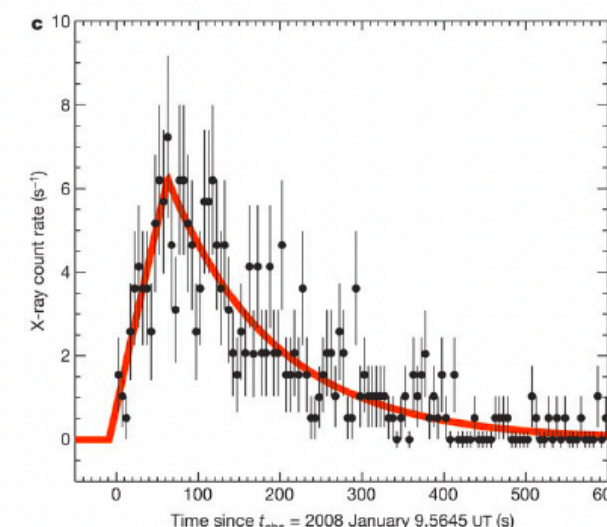
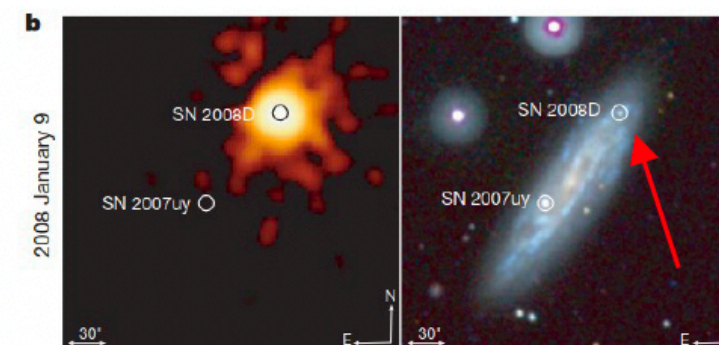
Bright ($L_x \approx 10^{48}$ erg s $^{-1}$), variable non-thermal X-rays.

Long-lived radio synchrotron afterglow from jet-ISM interaction.

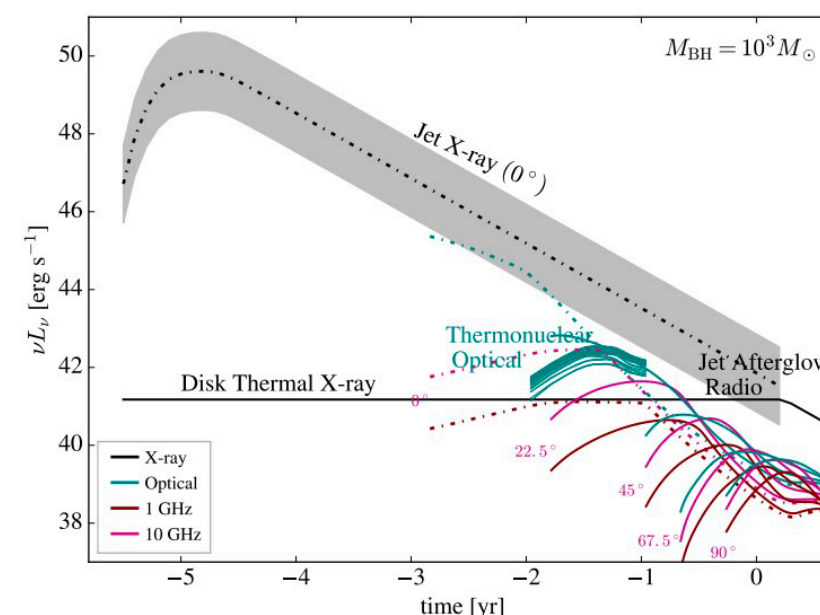


Fast X-ray transients

- A shock breakout (SBO) from a core-collapse SN.
- Generated from the SN explosion shock as it crosses the surface of a star (e.g., Soderberg et al. 2008).
- In 2008 Swift/XRT captured an X-ray flash coinciding with the Type Ibc SN 2008D.



- A TDE involving a WD and an IMBH
- The X-rays are produced by the tidal disruption and accretion of the compact WD in the gravitational field of the IMBH (e.g., Jonker et al. 2013).



- Orphan emission related to cocoon jet breakout of massive star. Long GRBs seen slightly off-axis

- Sub-luminous GRBs

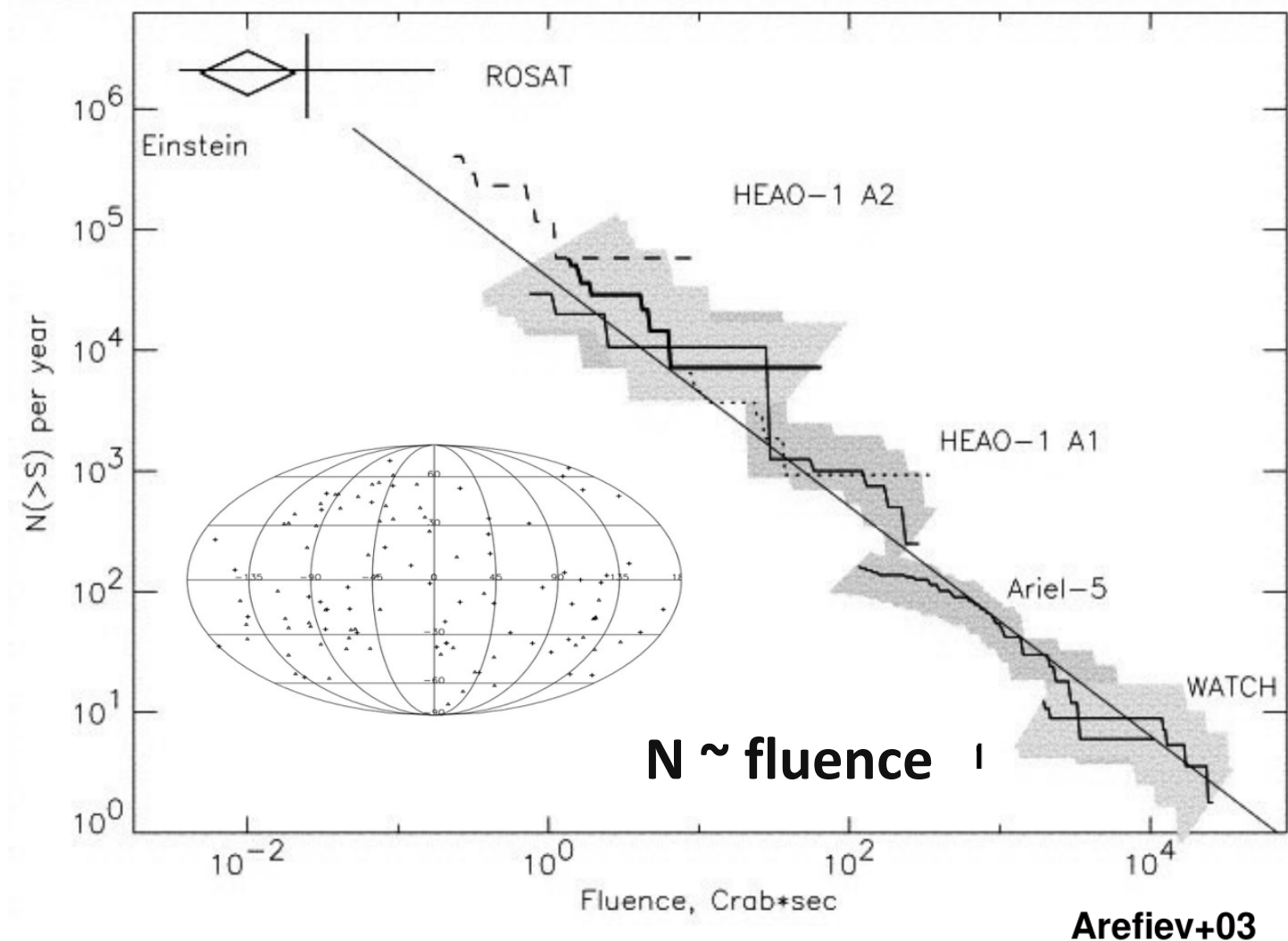
Brief History of FXTs (pre-2000)

Ariel 5 27 FXTs (Pye+McHardy83)
HEAO 1 A-1 10 FXTs (Ambruster+Wood86)
HEAO 1 A-2 8 FXTs (Connors+86)
ROSAT 141 FXTs (Vikhlinin98)
Einstein 18 FXTs (Gotthelf+96)

Poor localization, largely archival searches

Little/no division here between
Galactic/Extragalactic

**Significant contamination from flare stars
some confirmed GRBs**

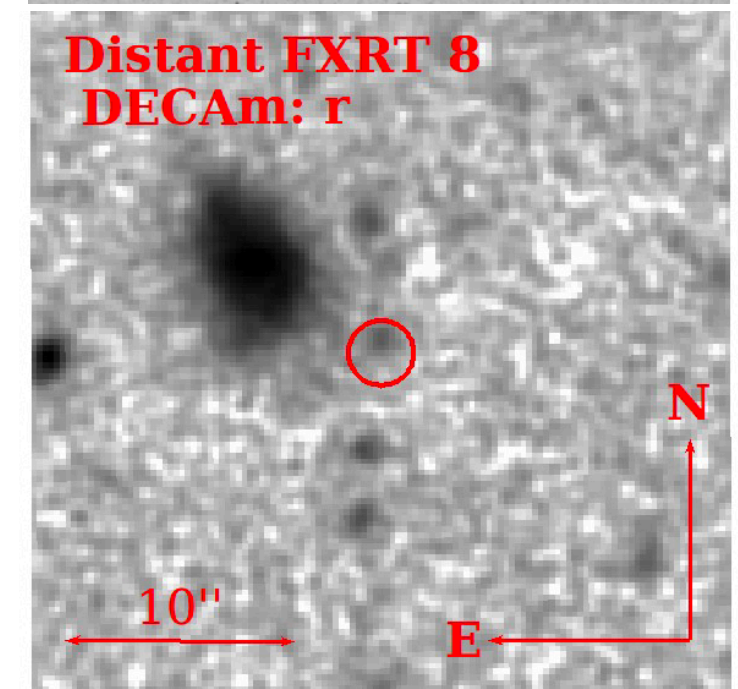
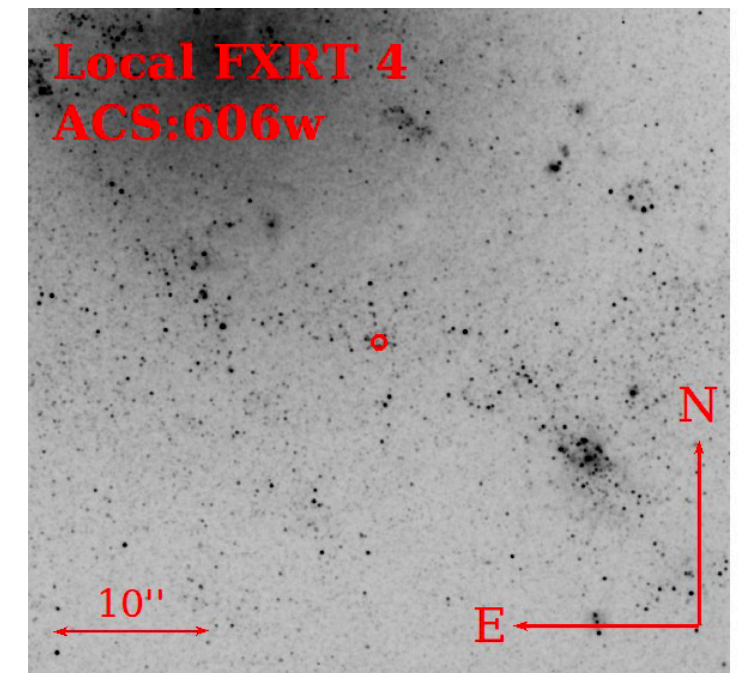


Brief History of FXTs (post-2000)

22 FXTs identified by Chandra (2000-2022)

- Five FXTs appear related with galaxies (called *Local FXTs*) at <100 Mpc ($L_{X,\text{peak}} \approx 10^{39-40}$ erg/s), rate ≈ 34.3 deg $^{-2}$ yr $^{-1}$ at *Chandra* depth.

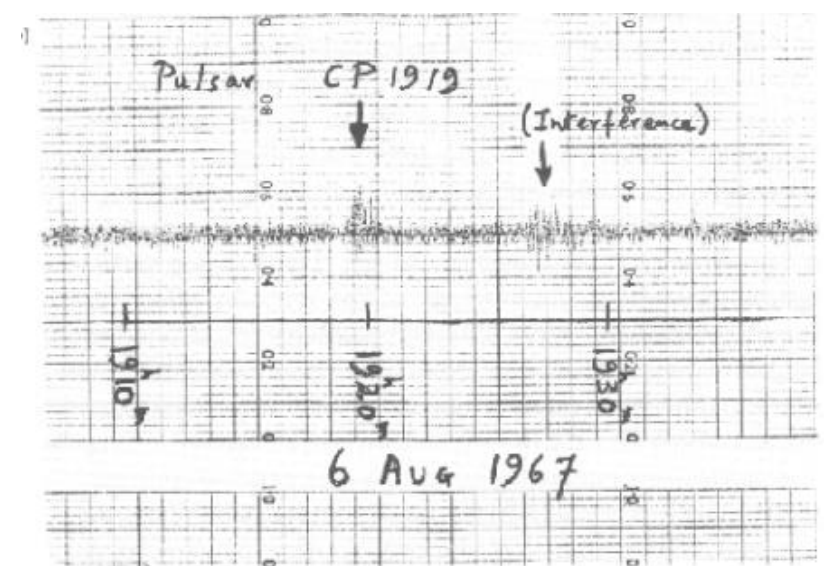
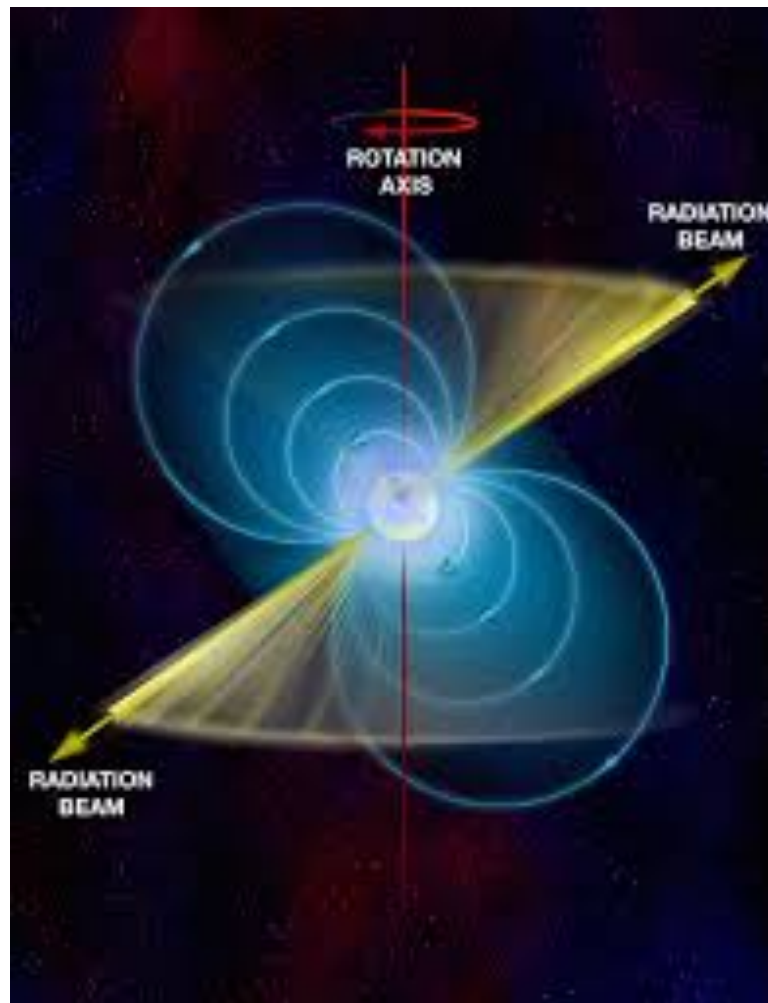
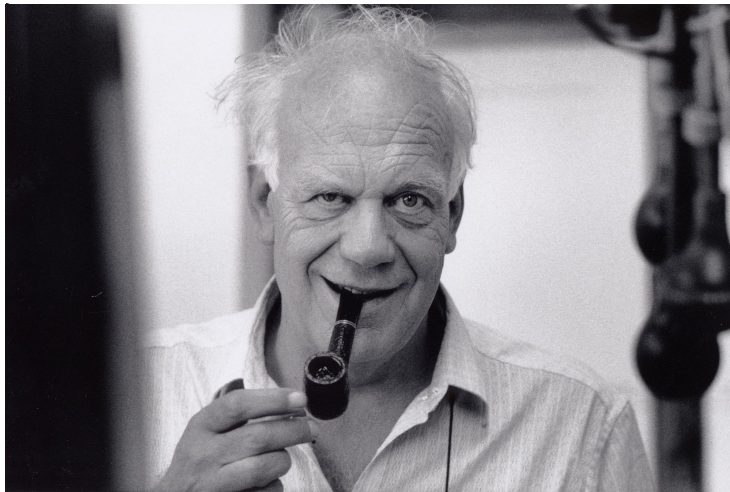
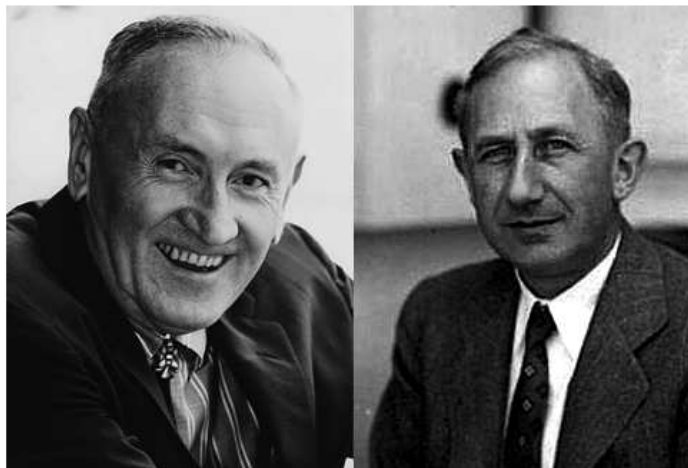
17 FXTs are non-local events (>100 Mpc, called *Distant FXTs*). 7 of them have extended sources with $z_{\text{photo/spec}} \sim 0.7-3.5$, so $L_{X,\text{peak}} \approx 10^{44-47}$ erg/s; rate ≈ 36.9 deg $^{-2}$ yr $^{-1}$ at *Chandra* depth.



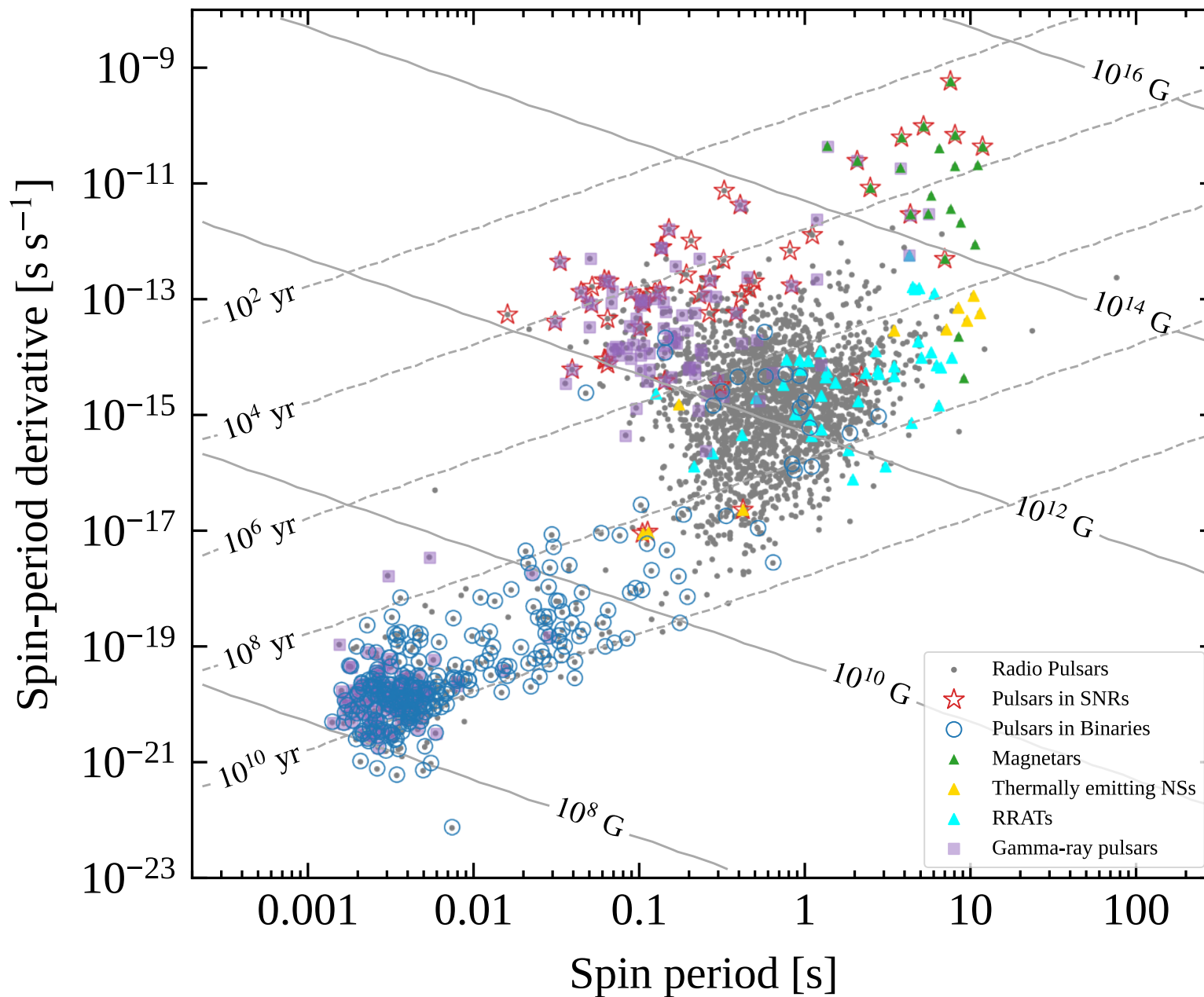
The discovery of pulsars

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



4500 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

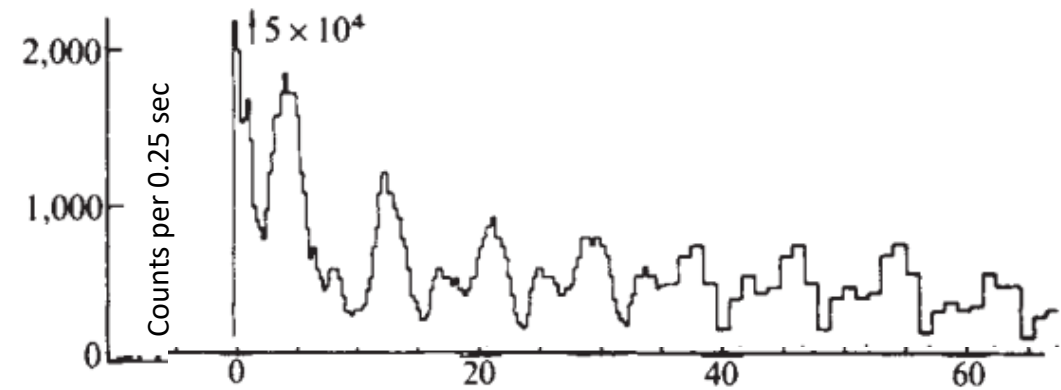
Magnetar giant flares

SGR 0526-66

1979 March 5

$$L_{\text{peak}} \sim 4 \times 10^{44} \text{ erg/s}$$

$$E_{\text{tot}} \sim 5 \times 10^{44} \text{ erg}$$



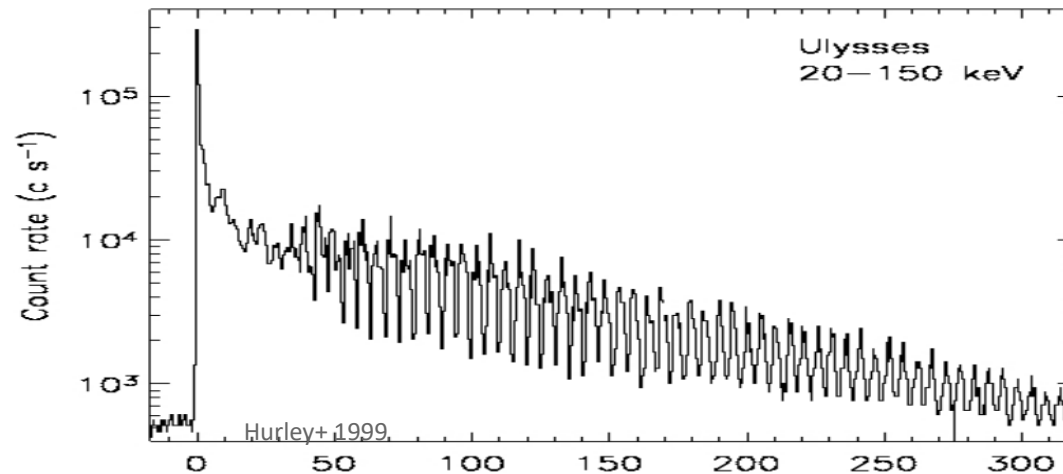
Initial spike ($\sim 0.1\text{--}0.2\text{s}$)
+ long pulsating tail
modulated at the NS spin
period

SGR 1900+14

1998 August 27

$$L_{\text{peak}} > 8 \times 10^{44} \text{ erg/s}$$

$$E_{\text{tot}} > 3 \times 10^{44} \text{ erg}$$



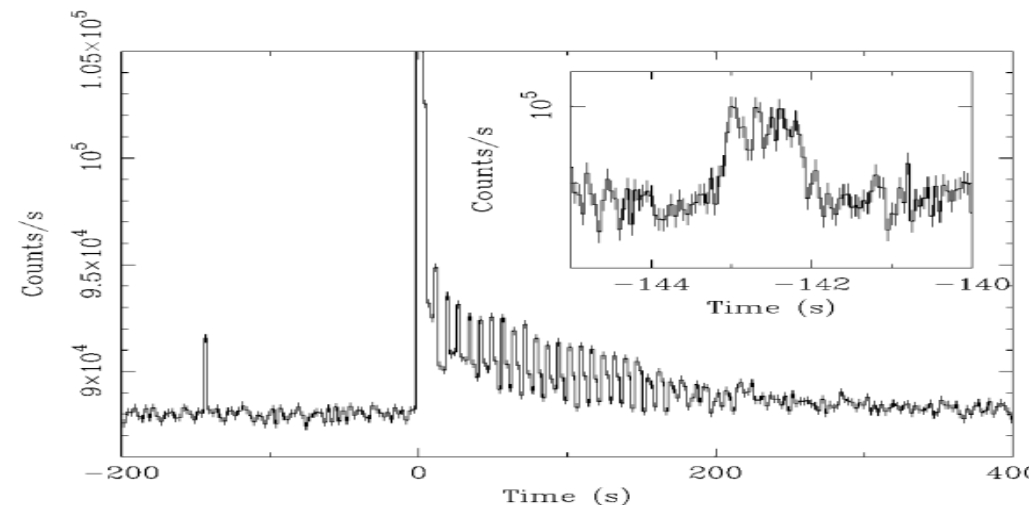
Similar $E_{\text{tail}} \sim 10^{44} \text{ erg}$

SGR 1806-20

2004 December 27

$$L_{\text{peak}} \sim 2\text{--}5 \times 10^{47} \text{ erg/s}$$

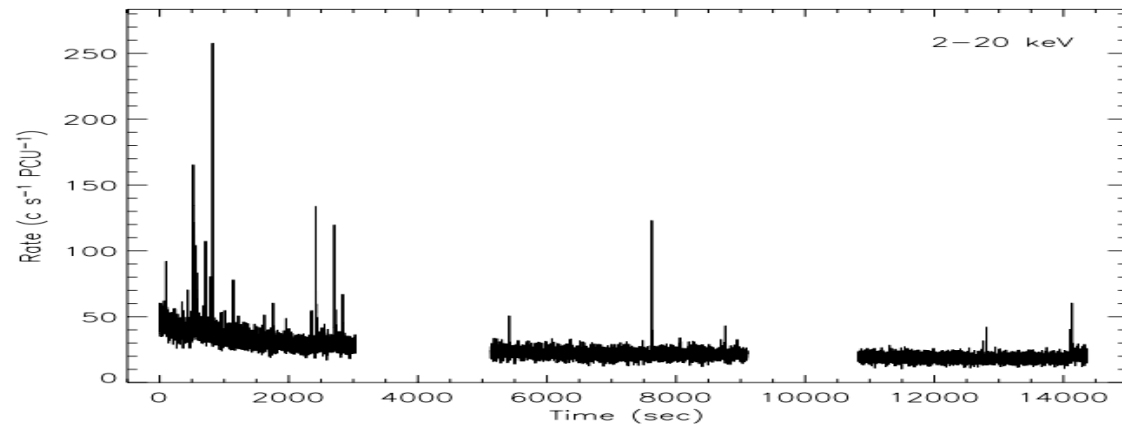
$$E_{\text{tot}} \sim 2\text{--}5 \times 10^{46} \text{ erg}$$



Caused by large-scale
rearrangements of the
magnetic field

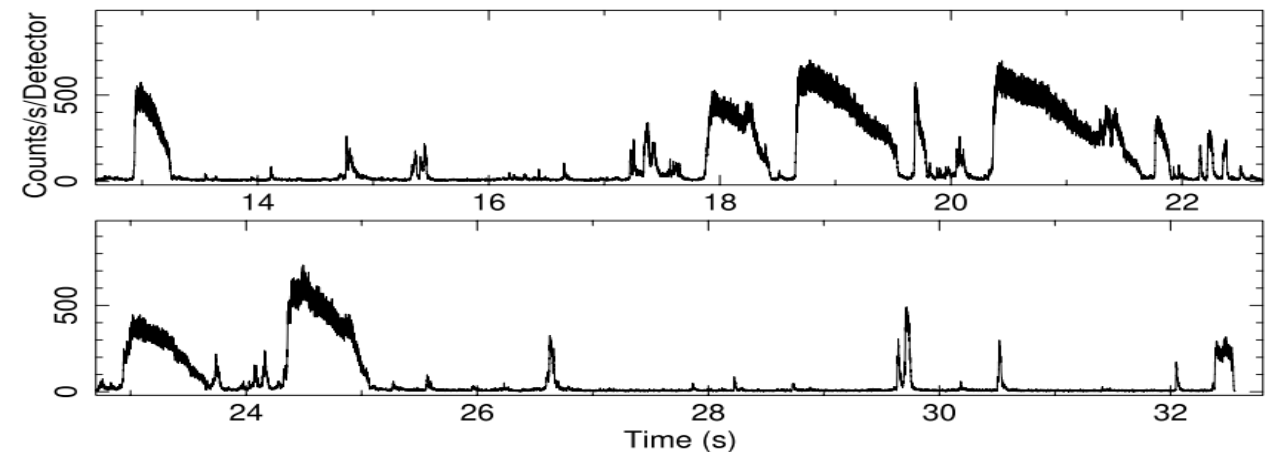
Magnetar bursts

Short bursts



$L_{\text{peak}} \sim 10^{39} - 10^{41} \text{ erg s}^{-1}$
duration $\sim 0.01 - 1 \text{ s}$

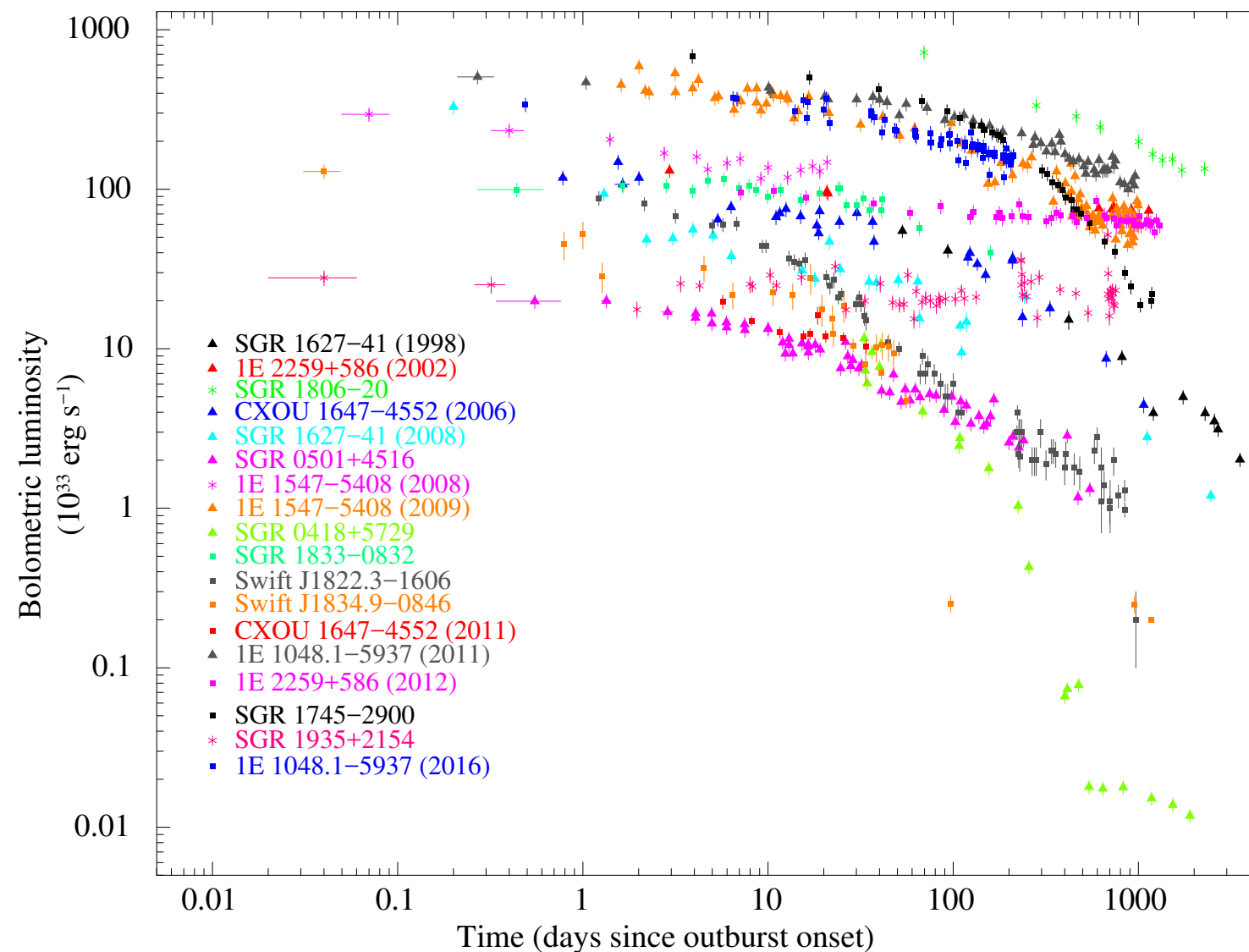
Intermediate bursts



$L_{\text{peak}} \sim 10^{41} - 10^{43} \text{ erg s}^{-1}$
duration $\sim 1 - 40 \text{ s}$

They often announce an active phase

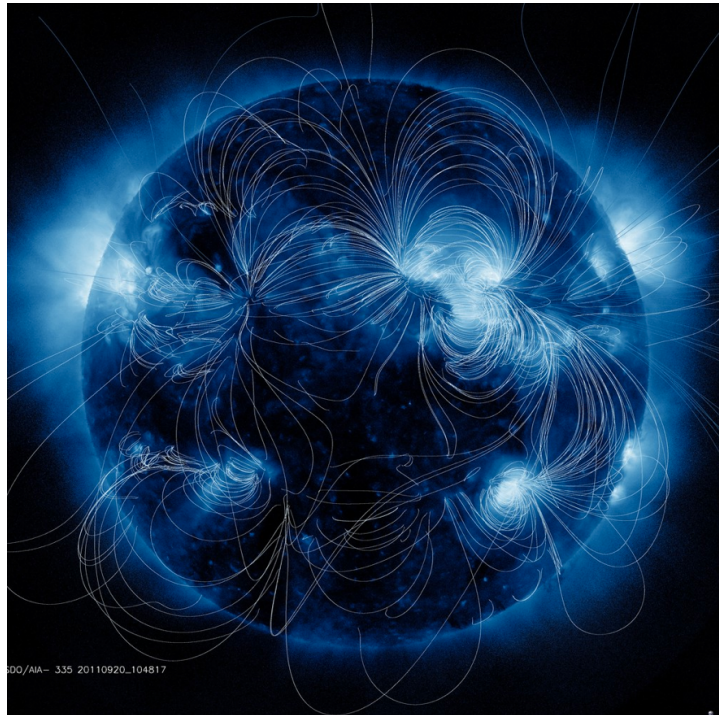
Magnetar outbursts



- ▶ 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

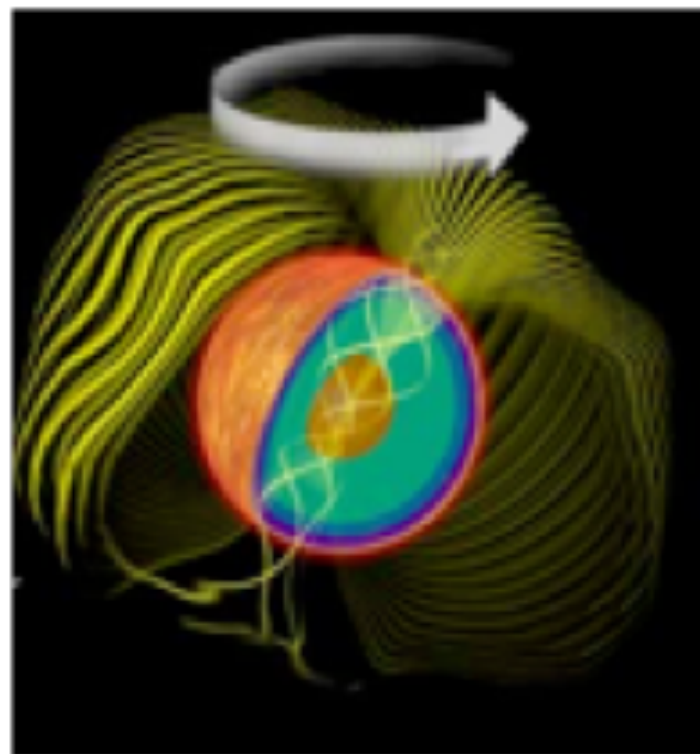
Francesco Coti Zelati (ICE, CSIC)

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?

SGR MAXE

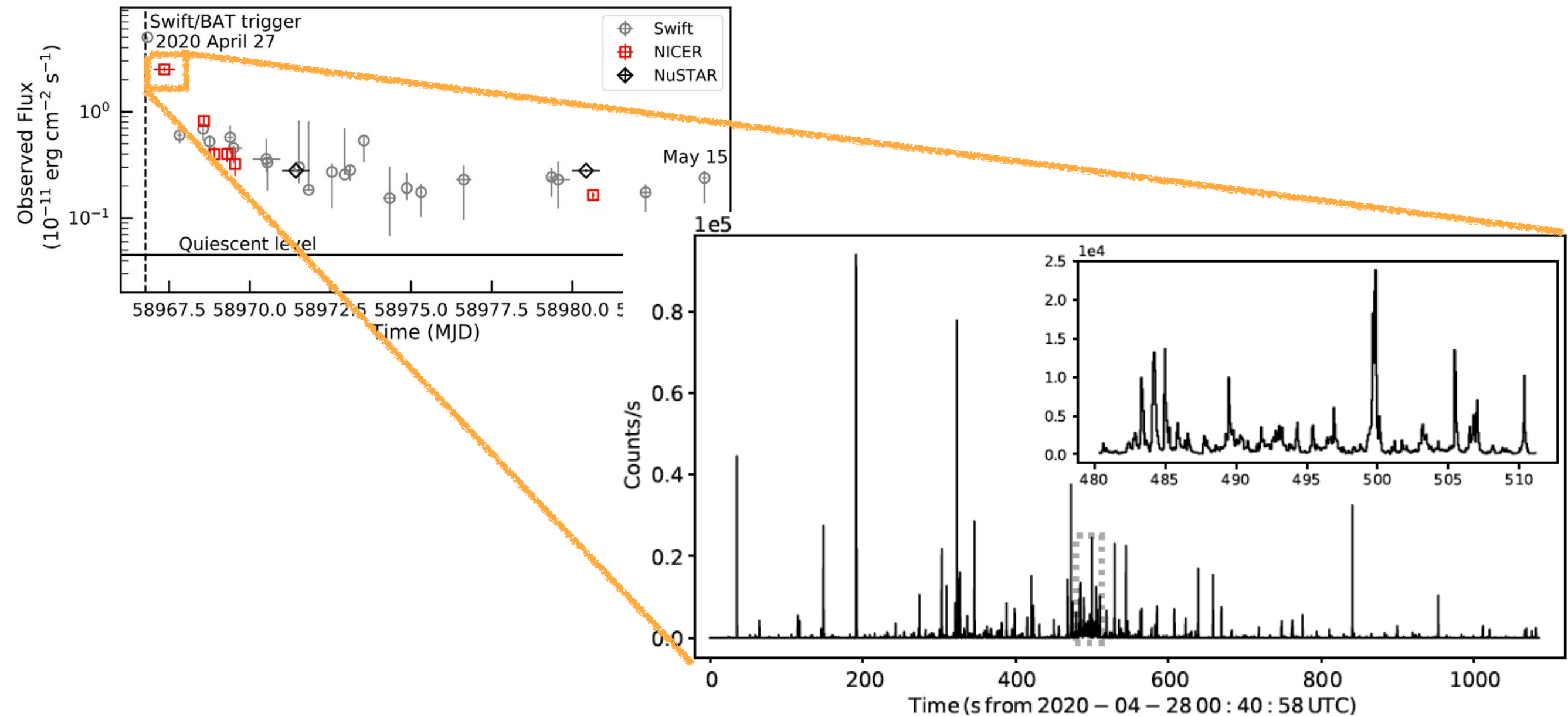
- ▶ Crustal displacements twist up the external magnetic field
- ▶ Returning currents hit the surface

SGR J1935+2154: the 2020 reactivation

Discovered in outburst in 2014. Six outbursts detected since then.

A new X-ray outburst in 2020 with an initial rapid decay

A burst forest (217 short X-ray bursts in 20 min, six hours after the outburst onset)



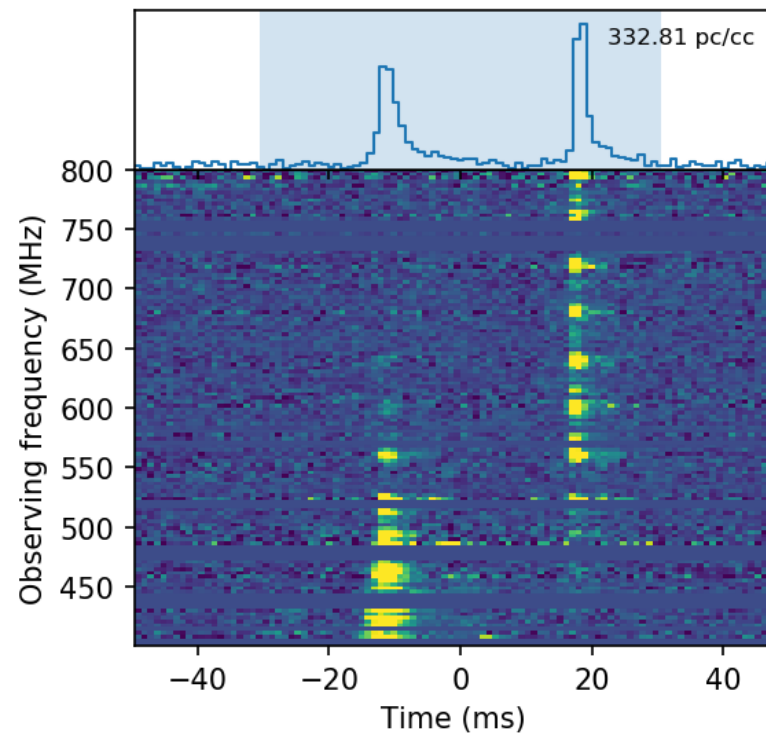
Borghese et al. 2020, Younes et al. 2020

Francesco Coti Zelati (ICE, CSIC)

A bright FRB-like radio burst

A bright millisecond-timescale radio burst from the direction of the Galactic magnetar SGR 1935+2154

ATel #13681; *Paul Scholz (UToronto) on behalf of CHIME/FRB Collaboration*
on 28 Apr 2020; 20:45 UT



Two bursts (0.6 / 0.3 ms)
separated by 29 ms.

~480 / ~220 kJy ms

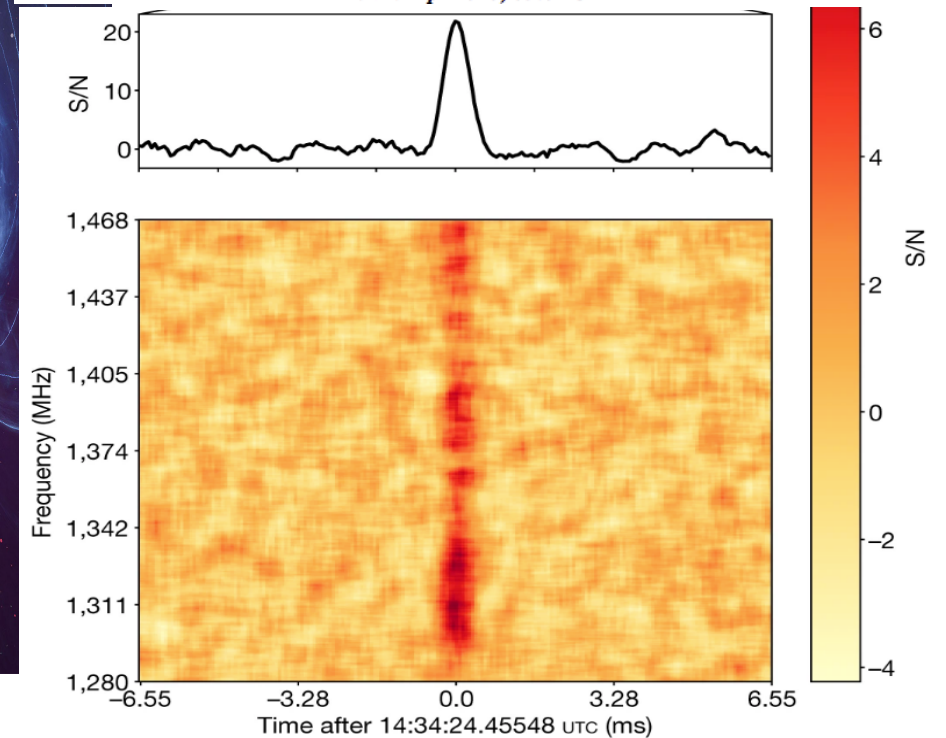
$E_{\text{iso}} \sim 3 \times 10^{34}$ ergs



The brightest ms radio
burst ever from a
Galactic source

Independent detection of the radio burst reported in ATel #13681 with STARE2

ATel #13684; *C. Bochenek, S. Kulkarni, V. Ravi, D. McKenna, G. Hallinan (Caltech), & K. Belov (JPL)*
on 29 Apr 2020; 03:04 UT



Single-peaked burst.

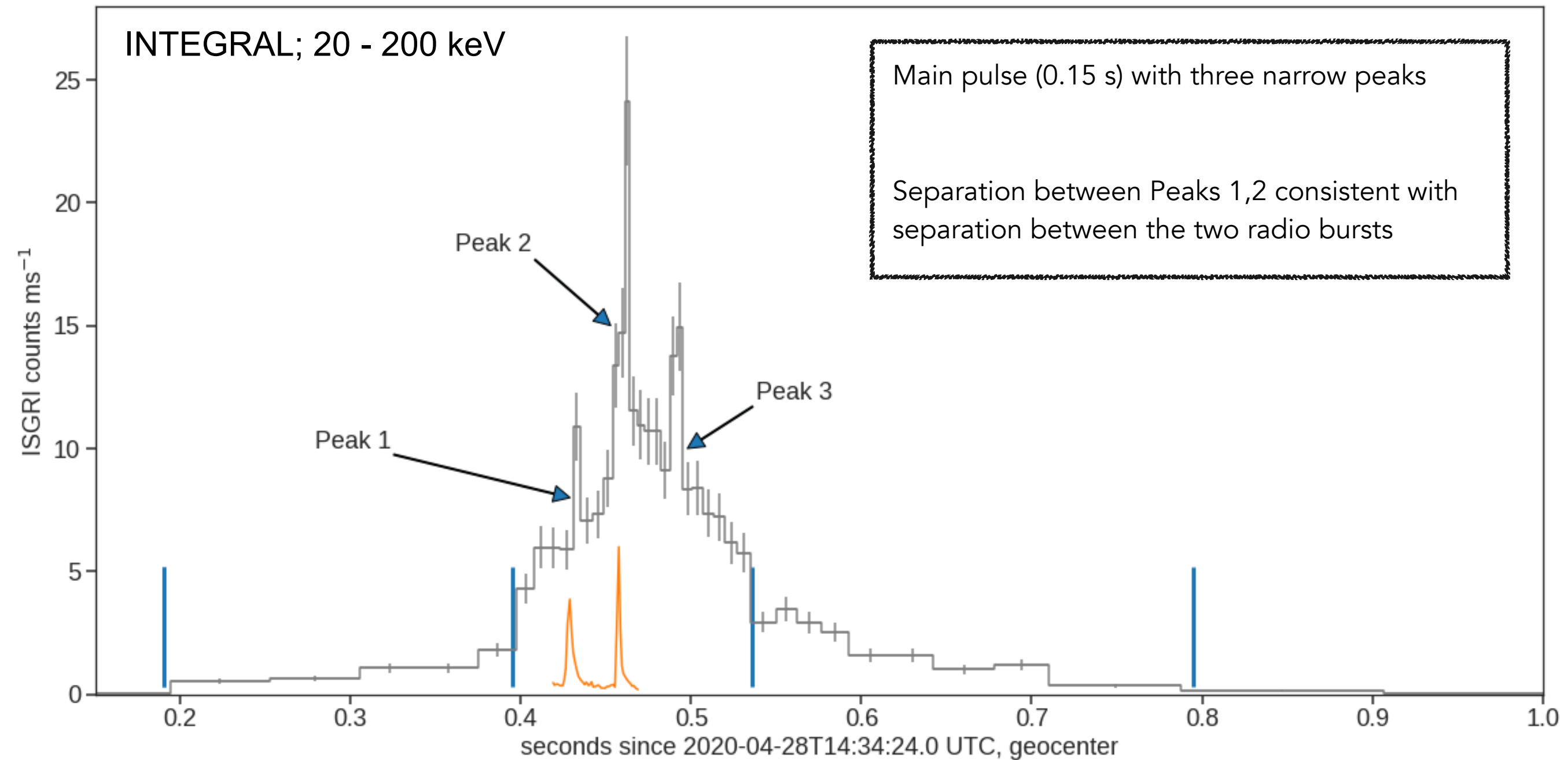
~1.5 MJy ms

$E_{\text{iso}} \sim 2 \times 10^{35}$ ergs

Andersen et al. 2020, Bochenek et al. 2020

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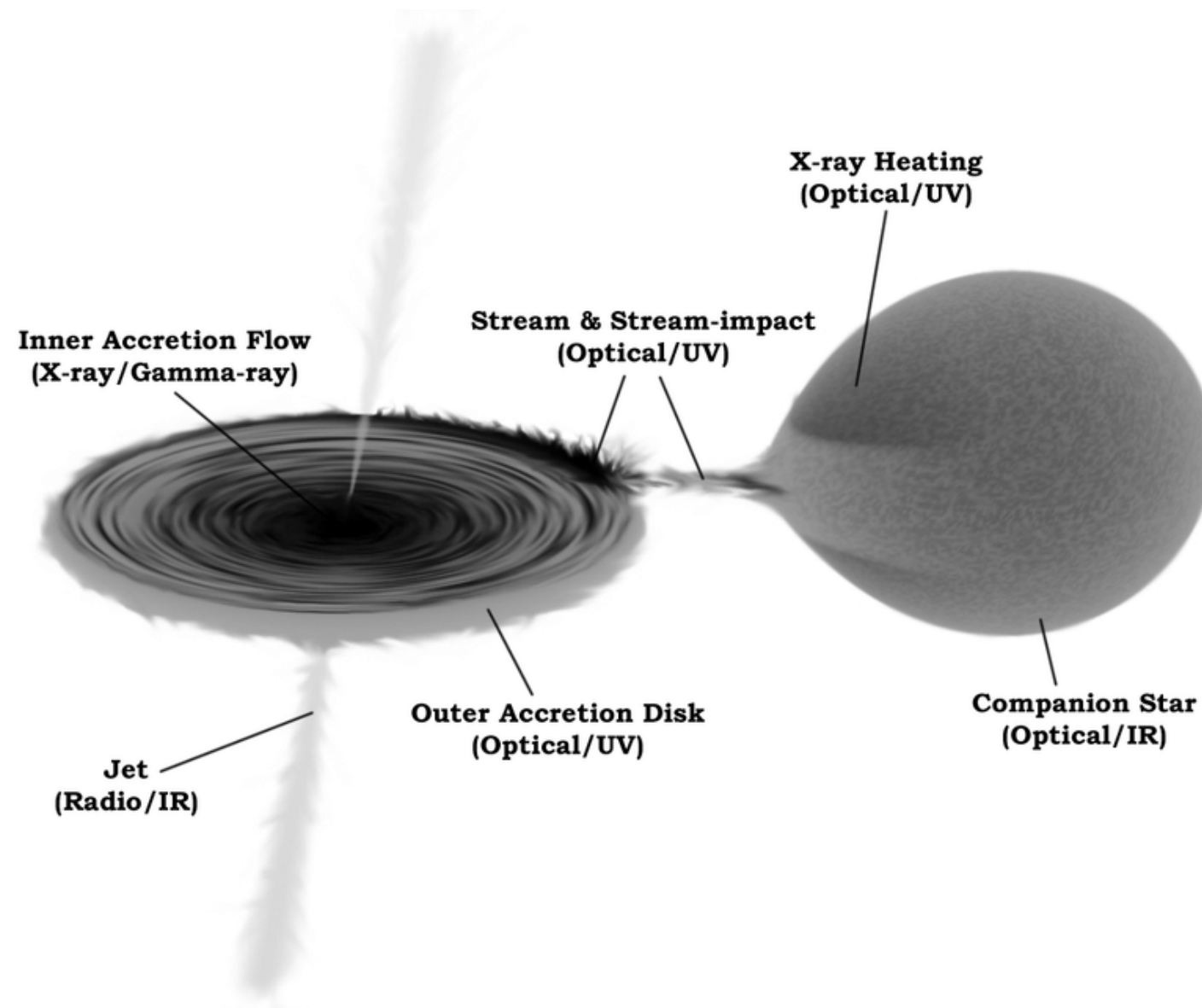
A bright FRB-like radio burst associated with a X-ray burst



Mereghetti et al. 2020; see also Li et al. 2021, Ridnaia et al. 2021; Tavani et al. 2021

Low-mass X-ray binaries

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

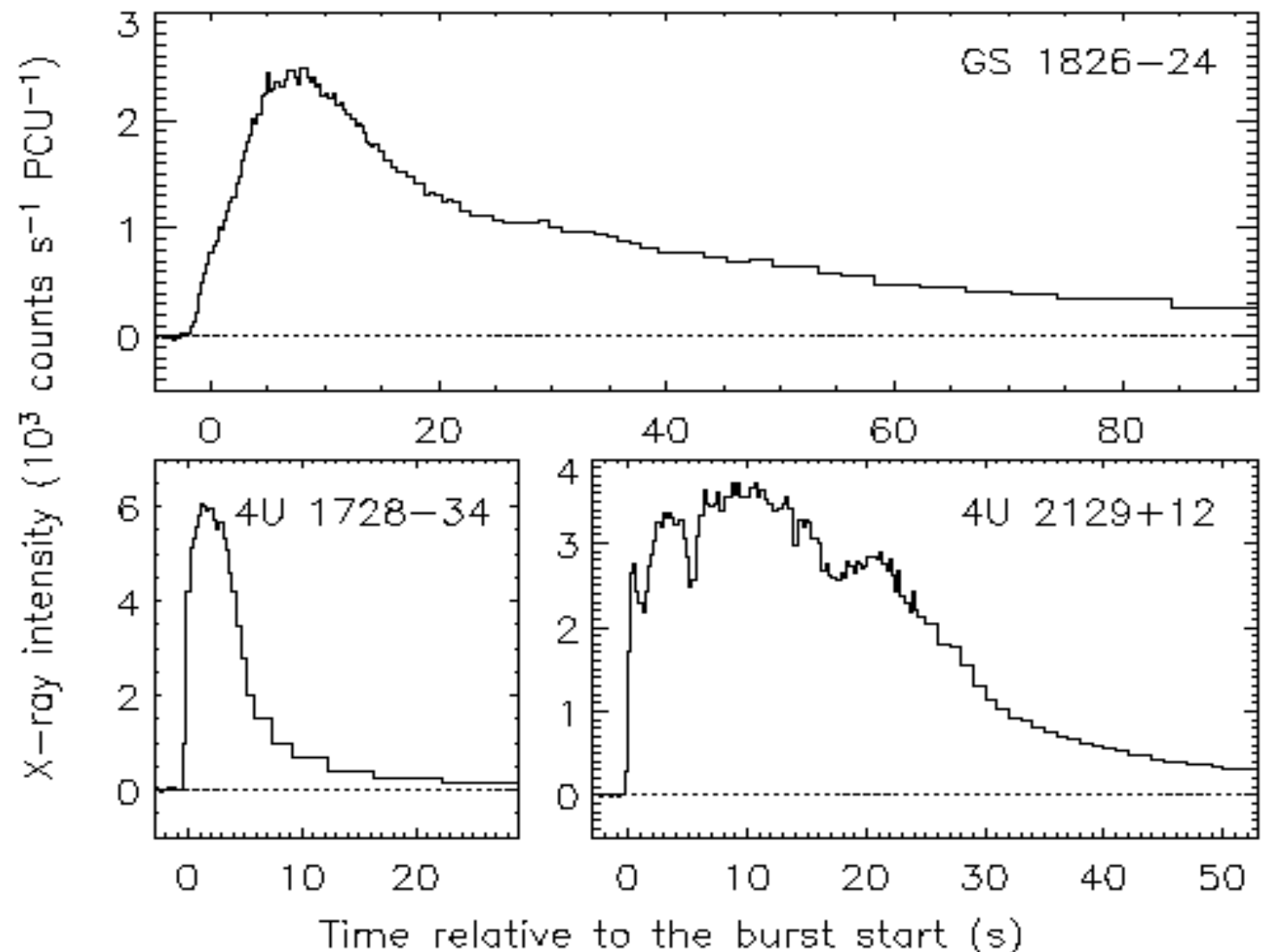


- Insights into accretion physics and binary star evolution.

NS-Low-mass X-ray binaries: bursts

Type I bursts:

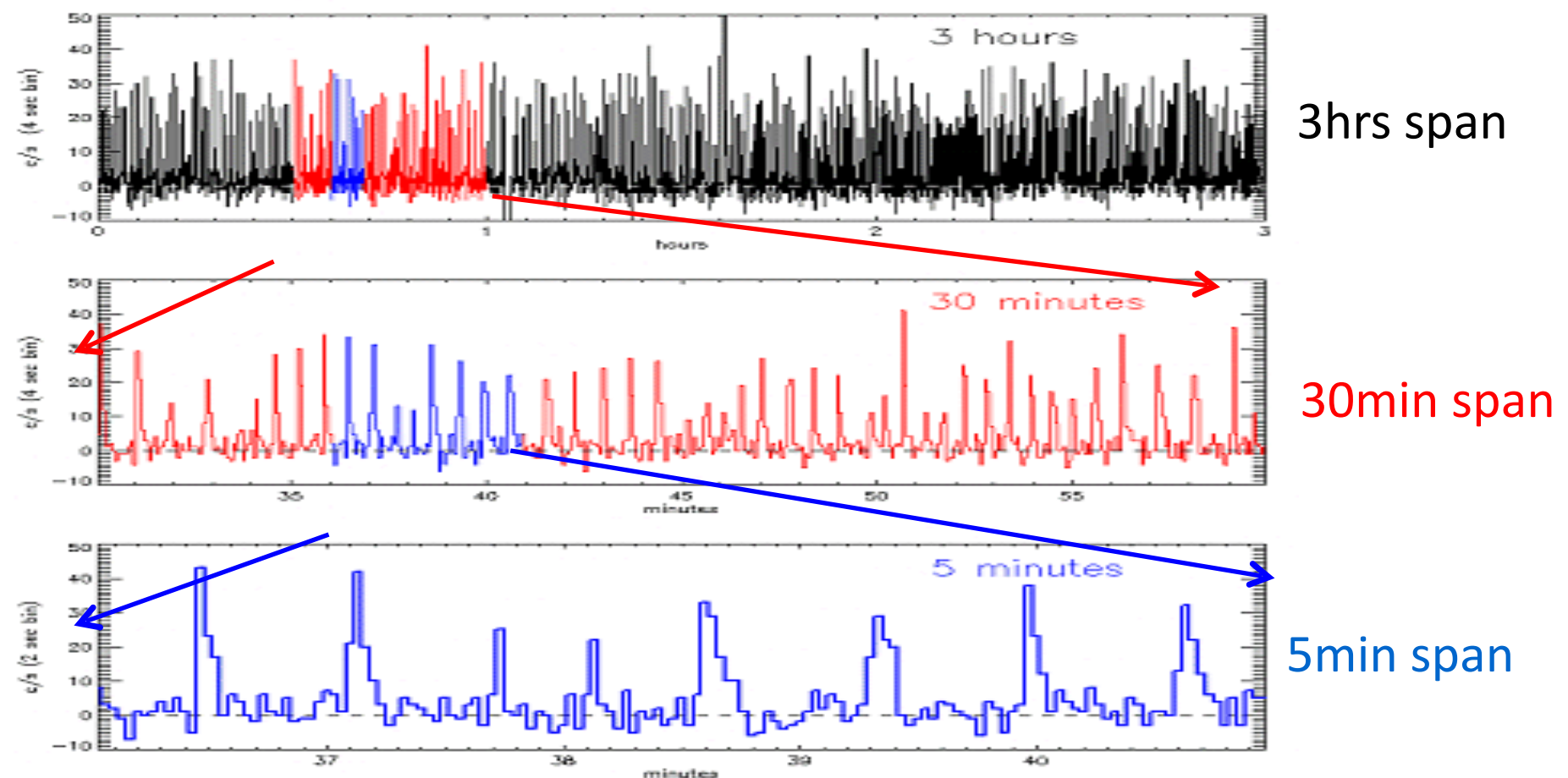
- Thermonuclear flashes on NS surface (H $\rightarrow$ He burning – explosive)
- Rapid (few-sec) rise + expo decay (10-100sec) with $L_{\text{peak}} \approx 10 L_{\text{persistent}}$
- Recurrence of hours-days during outbursts
- Total energy: 10^{39} - 10^{40} erg
- Soft BB spectrum: $kT \approx 200$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



NS-Low-mass X-ray binaries: bursts

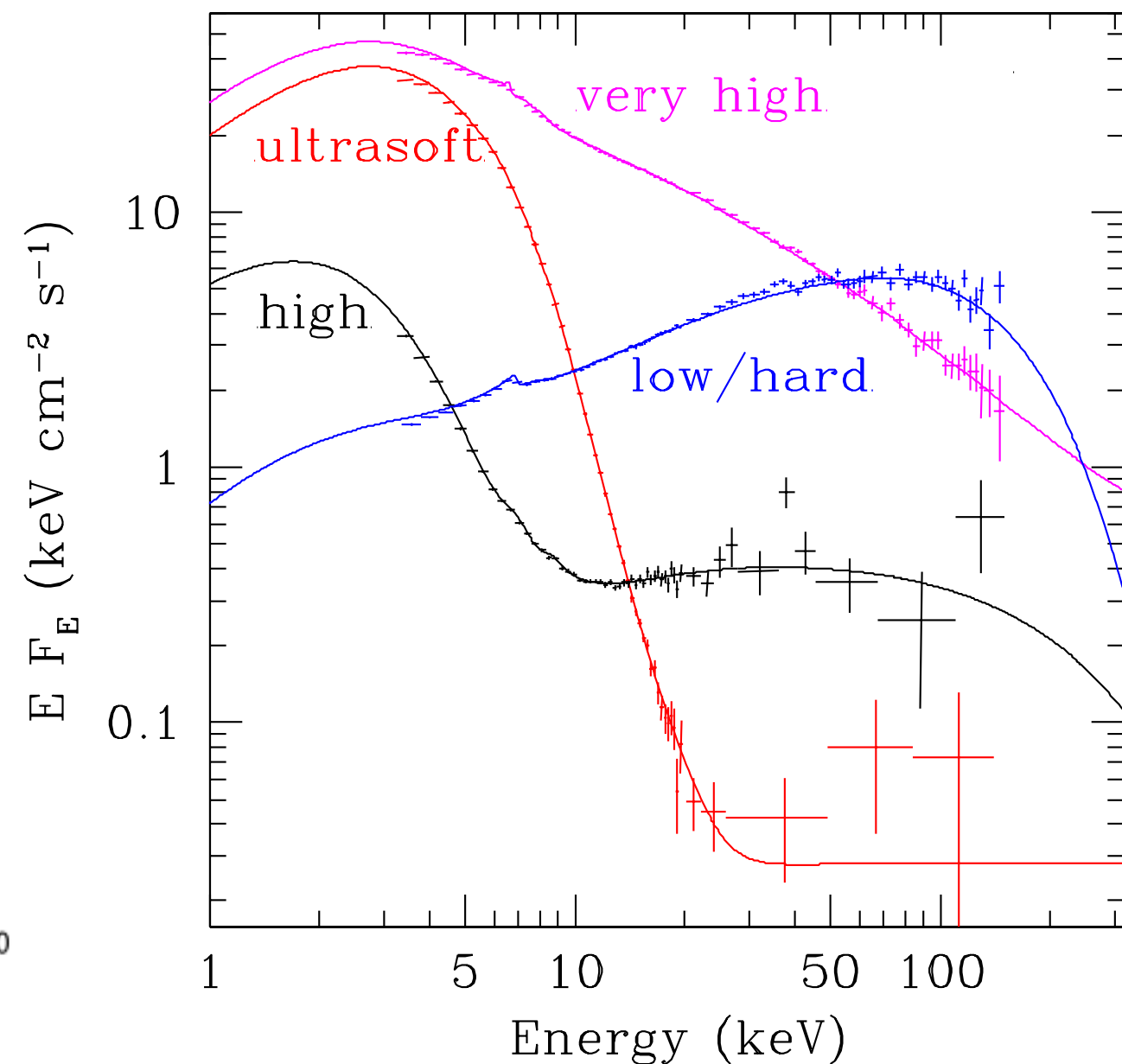
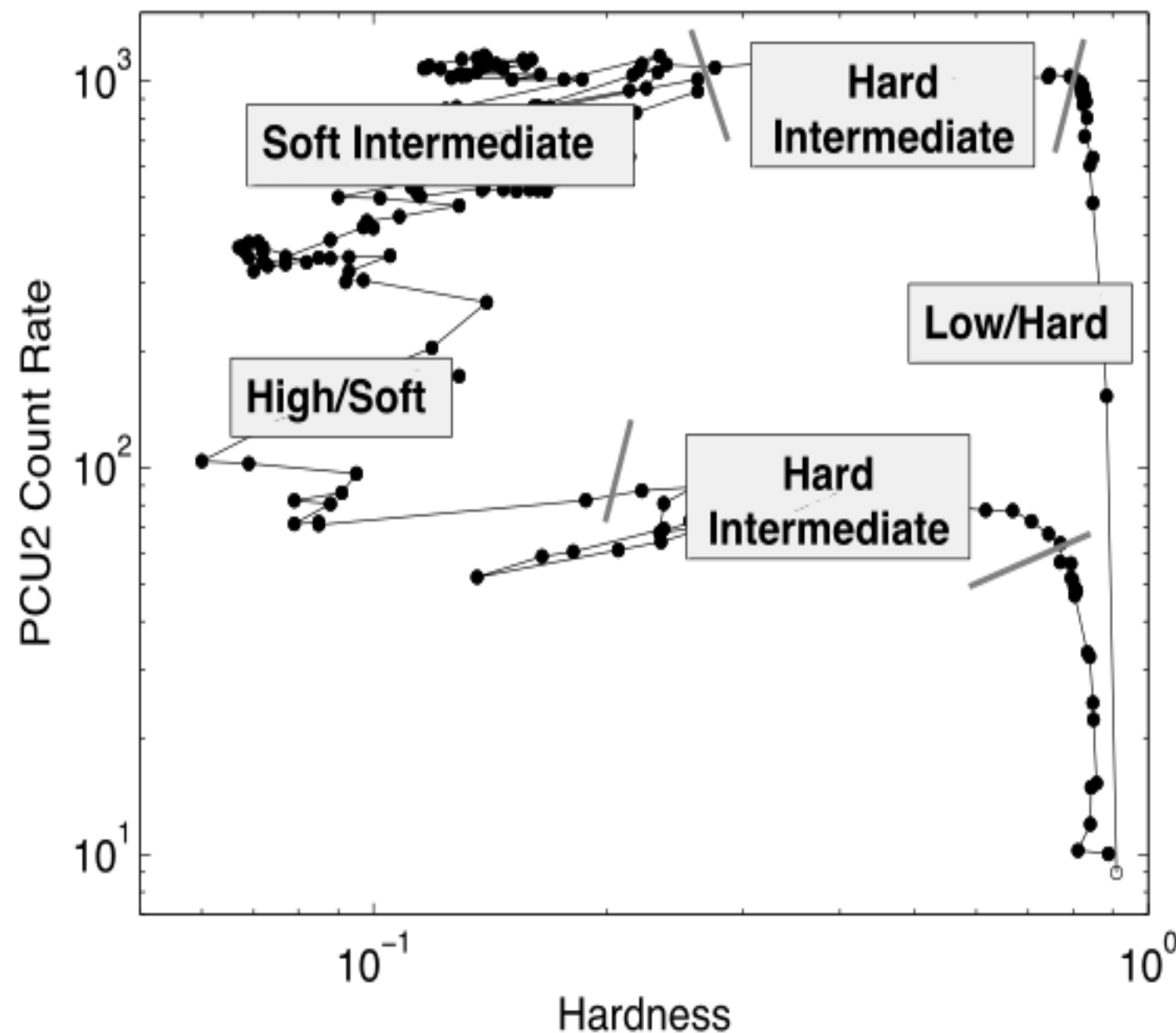
Type II bursts (Rapid):

- Rapid rise (s) and decay (s-min)
- Recurrence ≈ 7 s
- No softening during decays $kT \approx 2$ 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

Erupting variables: novae

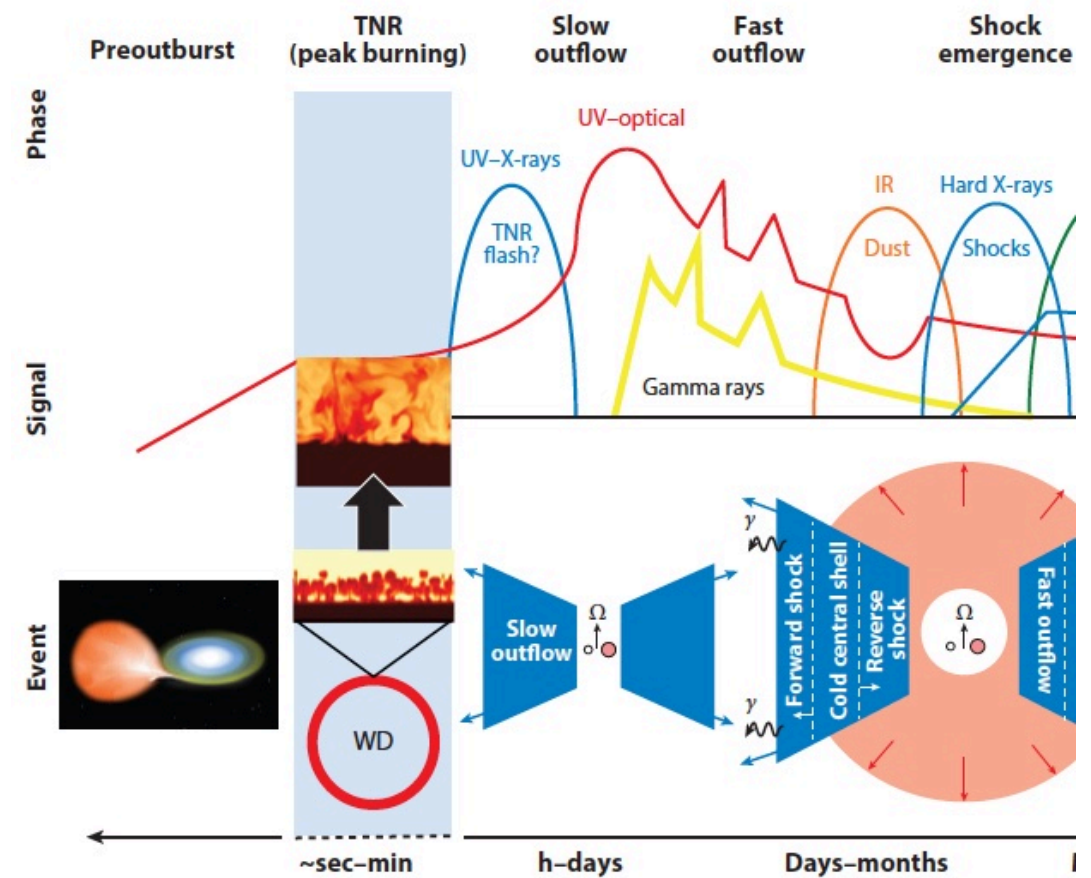
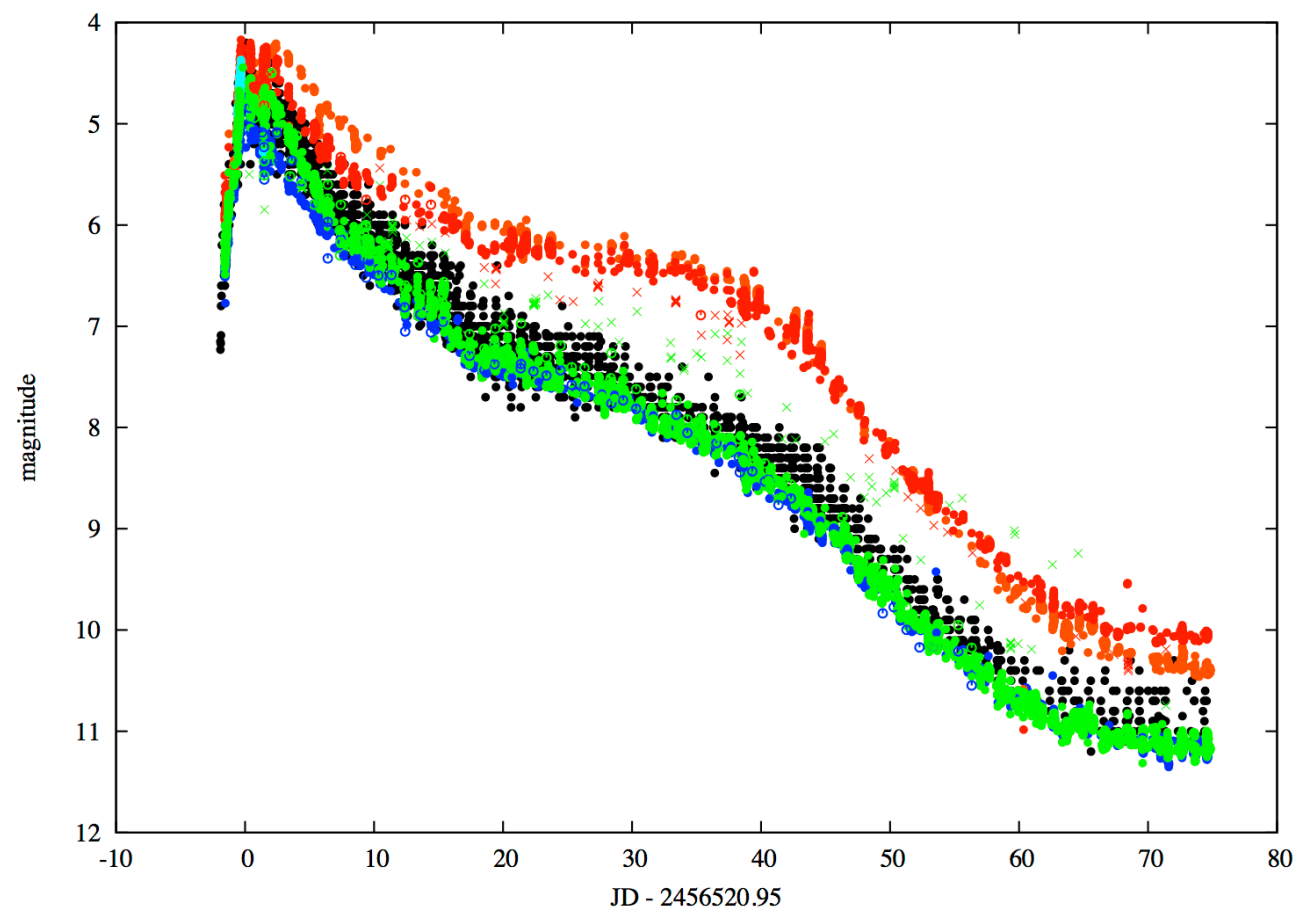
Sudden increase in brightness by several magnitudes due to sudden ignition of a hydrogen layer on the surface of a white dwarf in a binary system.

- **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

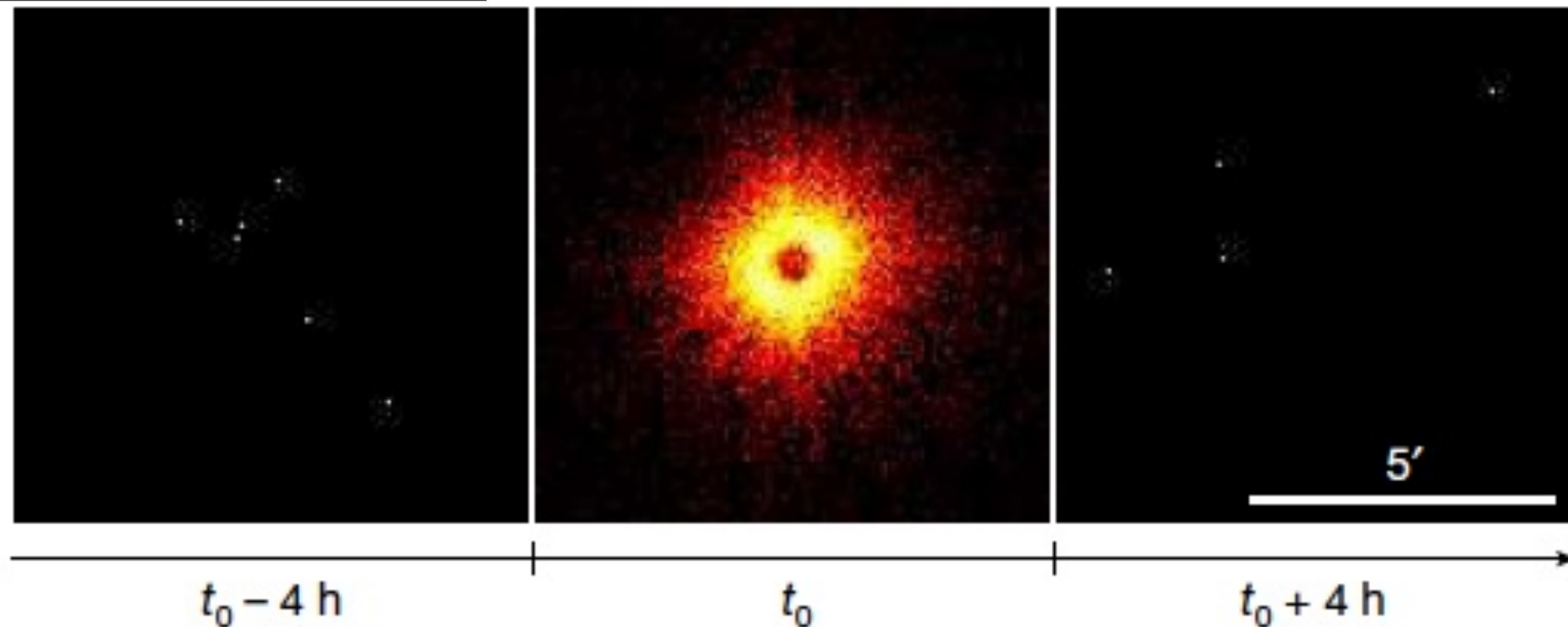
<https://doi.org/10.1038/s41586-022-04635-y>

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Ole König^{1✉}, Jörn Wilms^{1✉}, Riccardo Arcodia², Thomas Dauser¹, Konrad Dennerl², Victor Doroshenko³, Frank Haberl², Steven Hämmerich¹, Christian Kirsch¹, Ingo Kreykenbohm¹, Maximilian Lorenz¹, Adam Malyali², Andrea Merloni², Arne Rau², Thomas Rauch³, Gloria Sala^{4,5}, Axel Schwope⁶, Valery Suleimanov³, Philipp Weber¹ & Klaus Werner³



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

Francesco Coti Zelati (ICE, CSIC)

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

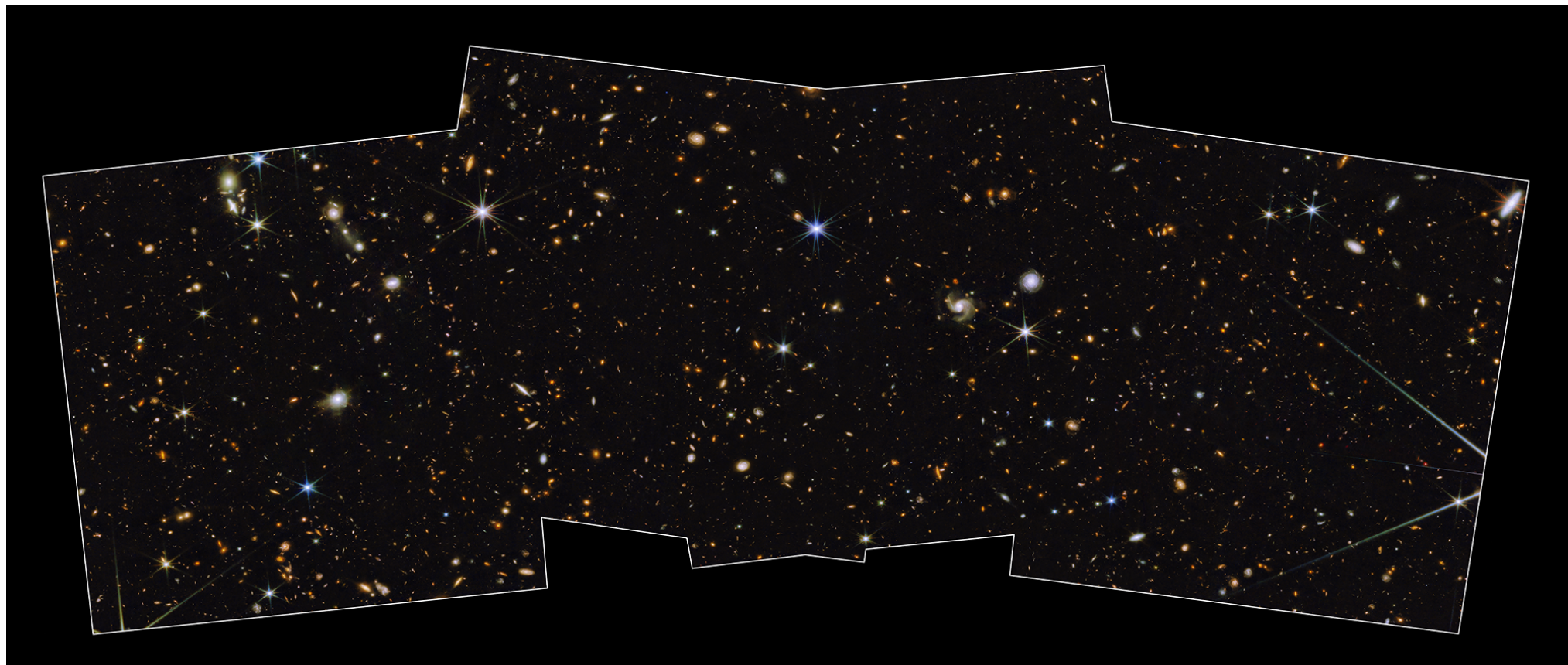
**Institute of
Space Sciences**

**EXCELENCIA
MARIA
DE MAEZTU**

MaX
MARCO DE
AUTOEVALUACIÓN DE LA
EXCELENCIA

Time domain surveys

- Regularly scan large portions of the sky to search for and 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-ray transient hunter machine



中国科学院
CHINESE ACADEMY OF SCIENCES

MPE

esa

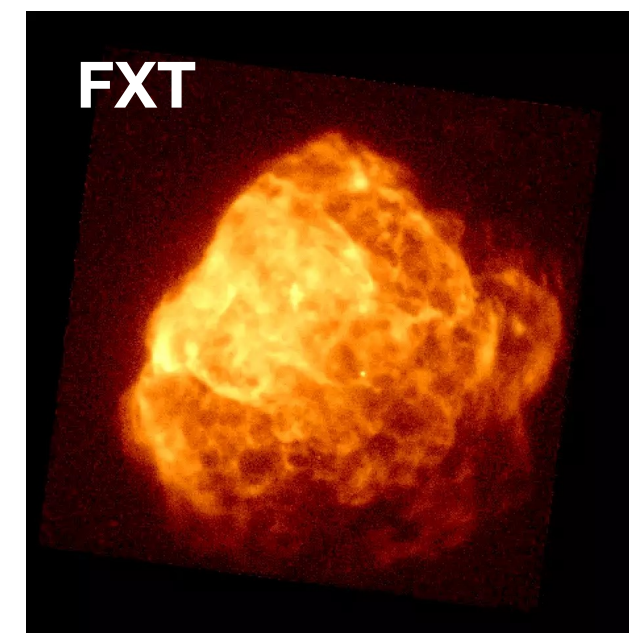
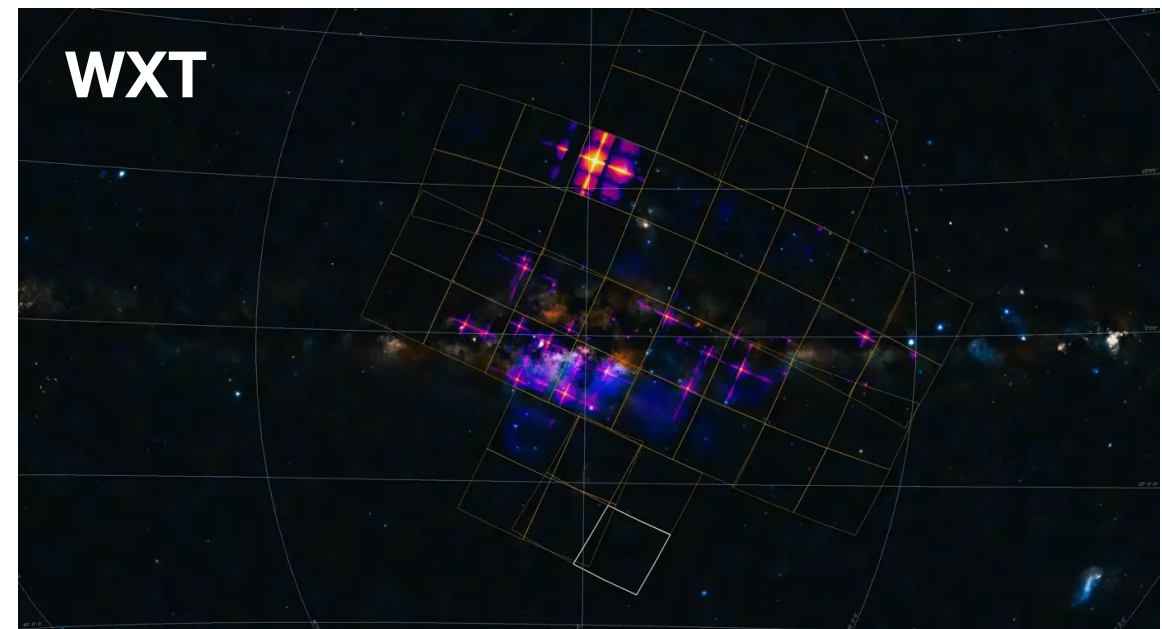
Two science instruments

Wide-field X-ray Telescope (WXT): provides a large field of view and uses novel lobster-eye optics to observe a large portion of the sky at any given time

Follow-up X-ray Telescope (FXT): homes in on X-ray sources found with WXT with a much higher resolution and larger light-collecting power

Key questions

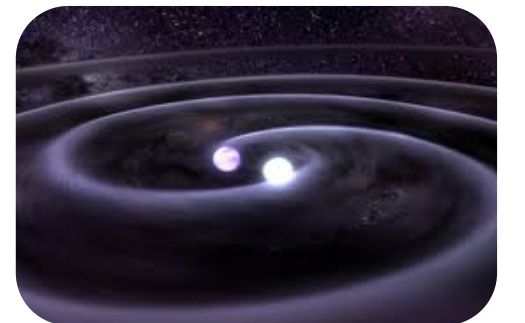
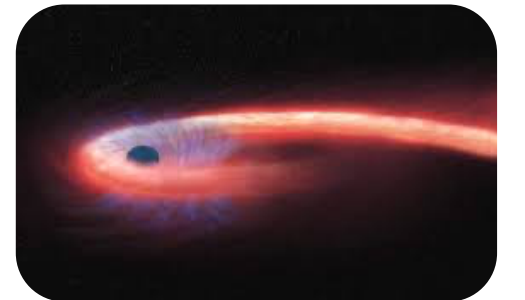
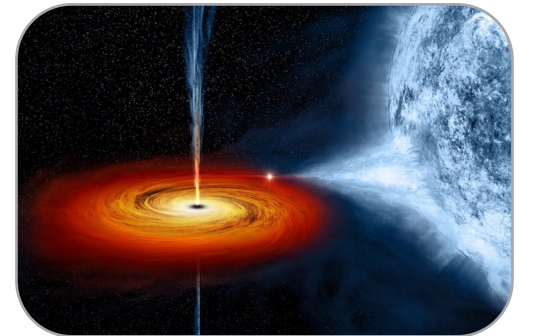
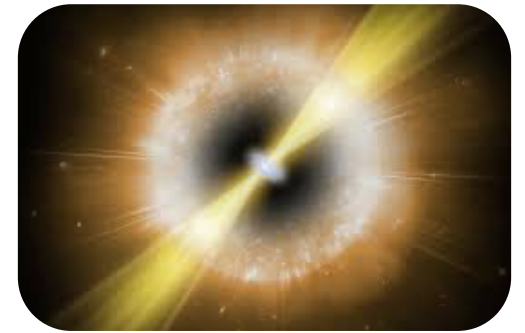
- How common are **black holes**, how do they swallow matter, and what powers their jets?
- What kind of events produce **gravitational waves**, and how?
- What happens when a star explodes and goes **supernova**?



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Einstein Probe: science goals

- Discover faint, distant and rare soft X-ray transients
- Characterise transients/variables by quick X-ray follow-up
- Disseminate transient alerts to astro community in time
- Detect and localize the electromagnetic counterpart to GWs and neutrino events



Yuan et al. 2022, Handbook of X-ray and Gamma-ray
Astrophysics; Yuan et al. 2025, Science China Physics, Mechanics
& Astronomy

Milestones and mission profile

- Mission concept proposed in 2012 and adopted in 2017
- Joined by ESA & MPE (2018), CNES (2022)
- Launched: January 9, 2024
- Altitude: 592km
- Circular orbit: period ~ 97min
- Maneuver ability: $20^{\circ} \text{ min}^{-1}$



Instruments and spacecraft



Follow-up X-ray Telescope (FXT - 2 detectors)

Wolter-I type CCD
FoV: 1 deg (diameter)
Energy: 0.3-10 keV
Eff. Area: $2 \times 300 \text{ cm}^2$ @1keV
Energy resol: 100eV @1keV
Time resol: 50ms, 2ms, 40μs
Position accuracy: 10"

Wide-field X-ray

Lobster-eye MPO + CMOS
FoV: 3600 sq deg (1.1 sr)
Energy: 0.5-4 keV
Eff. Area: $\sim 3 \text{ cm}^2$ @1keV
Energy resol: 120eV @1keV
Time resol: 50ms
Position accuracy: $< 3'$

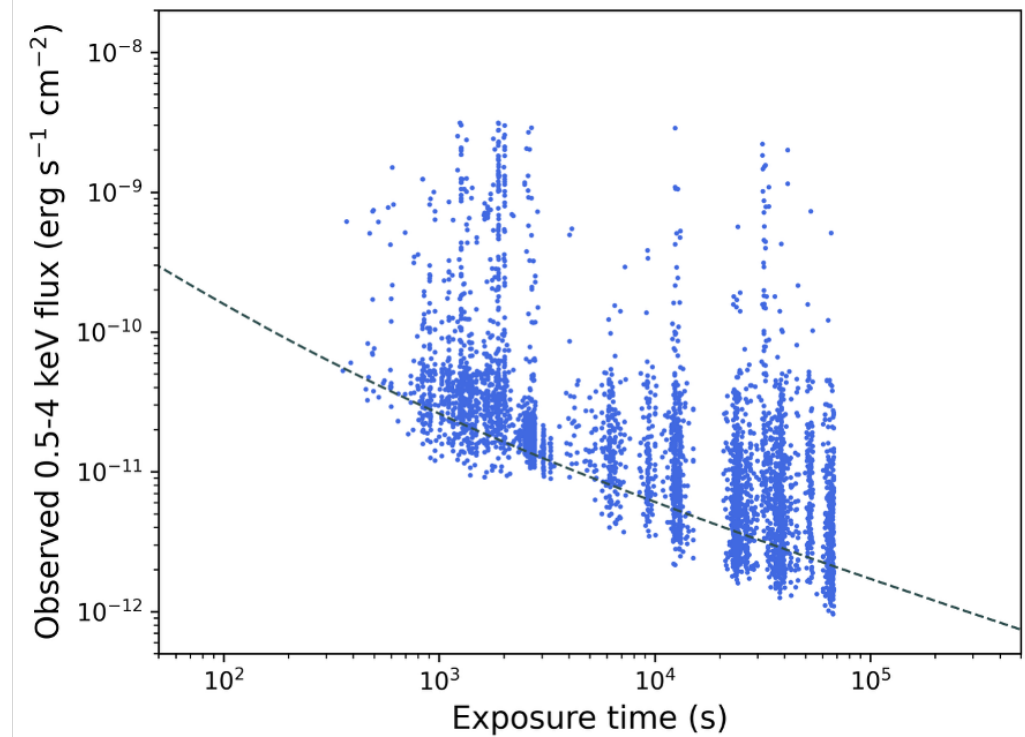
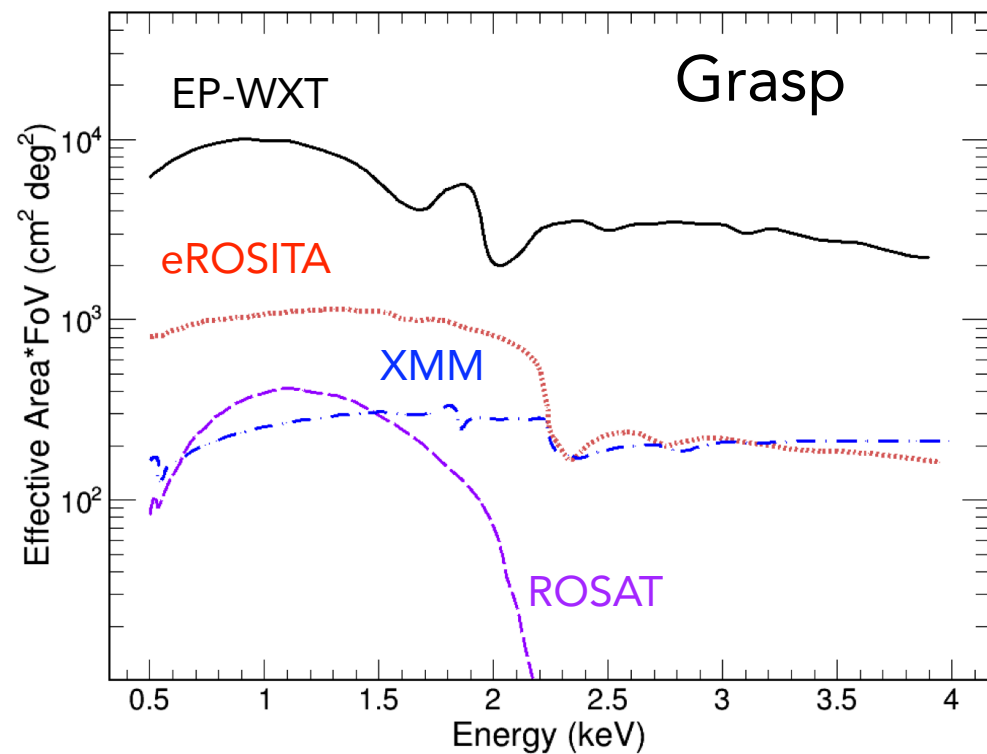
Onboard automated system

- Autonomous slew in 3-5 min
- Fast Alert distribution & ToO upload

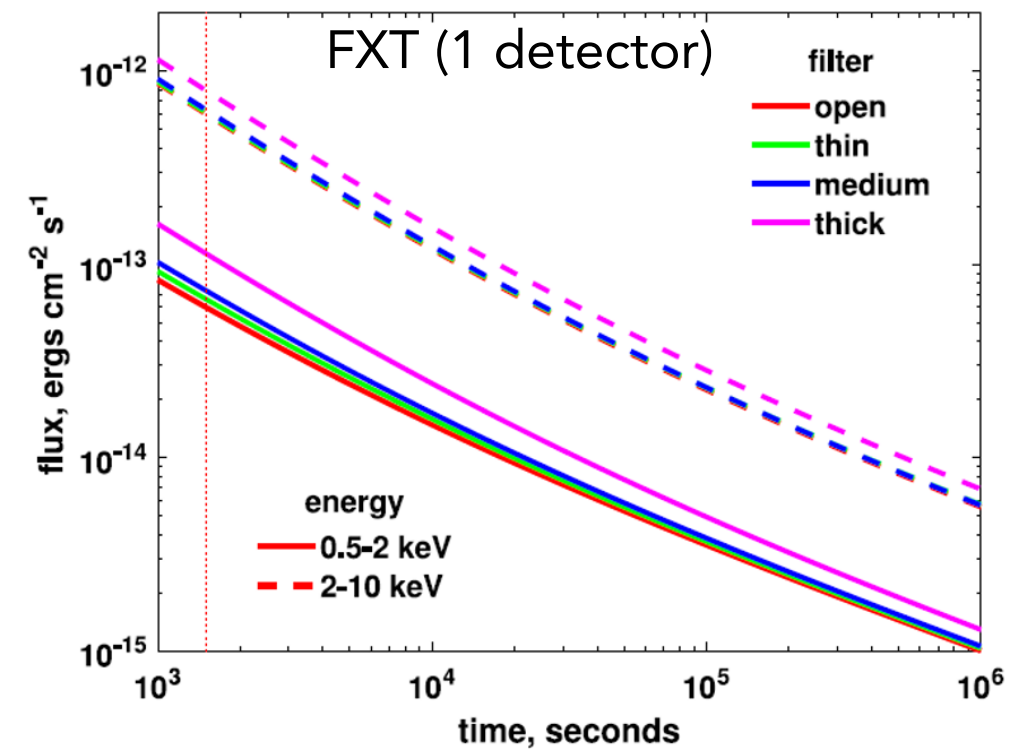
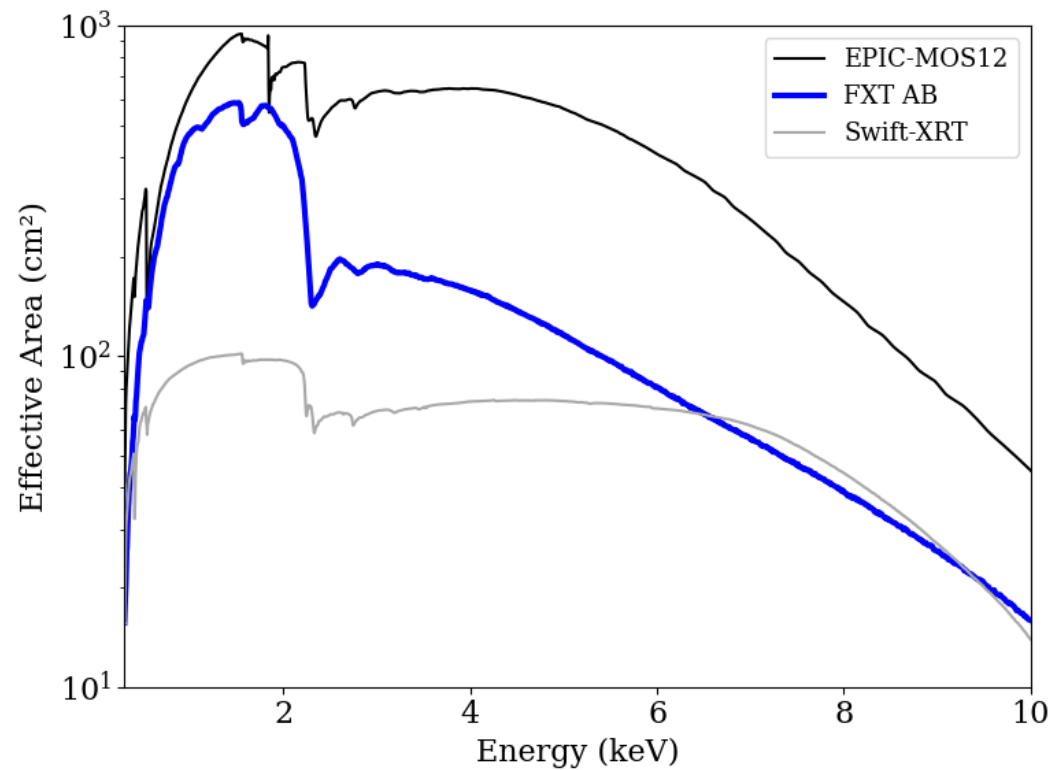
Yuan et al. 2025

Instrument sensitivity

WXT

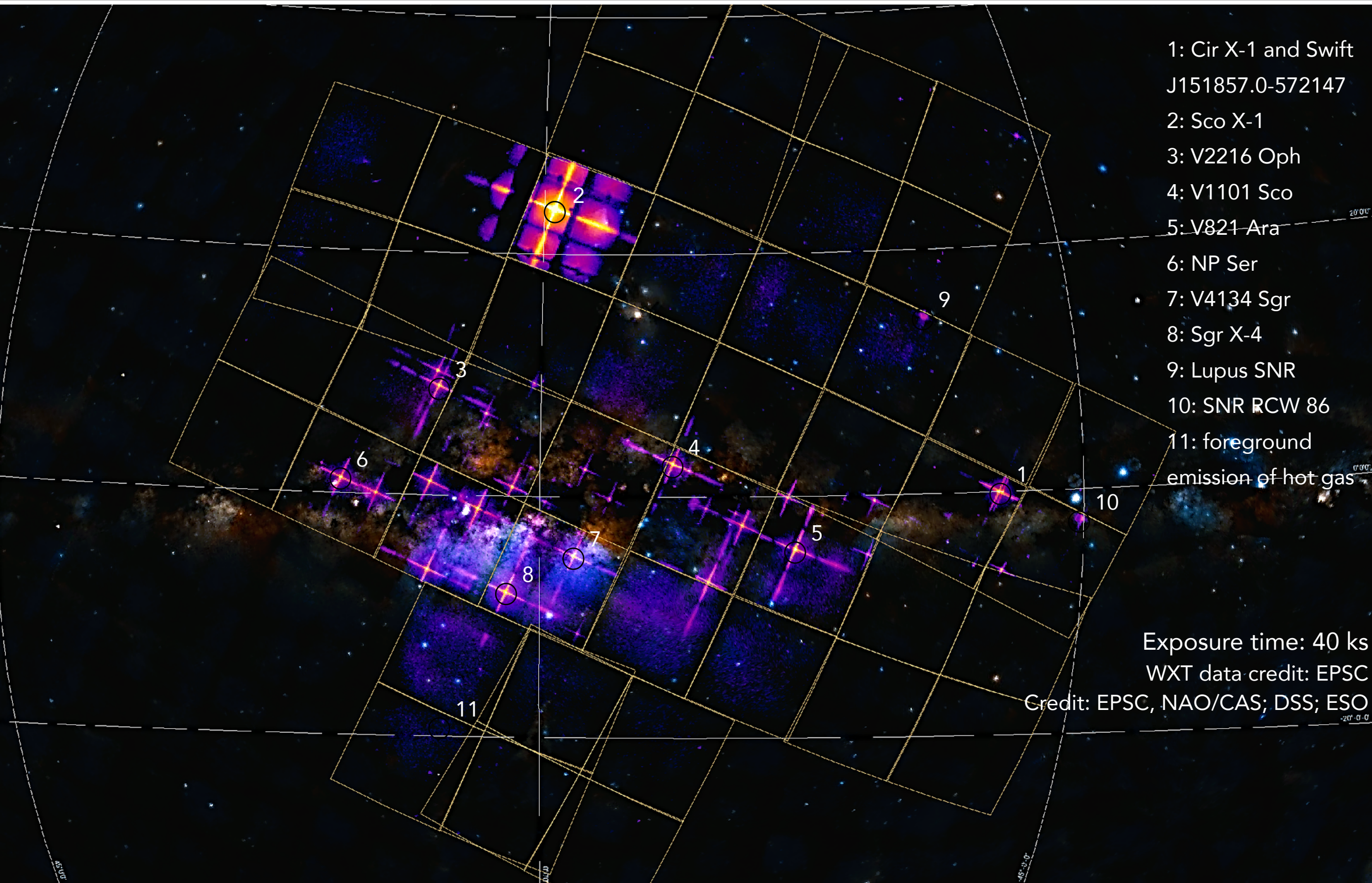


FXT



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"Pointed" mode: the Galactic Center

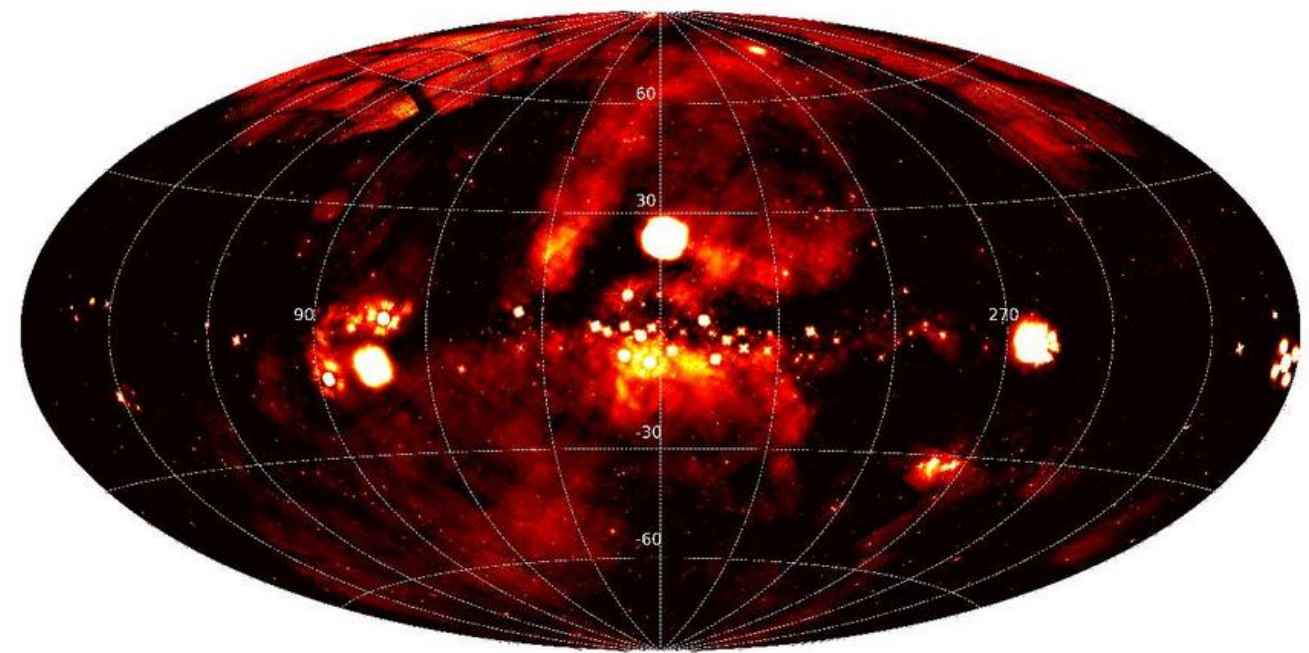
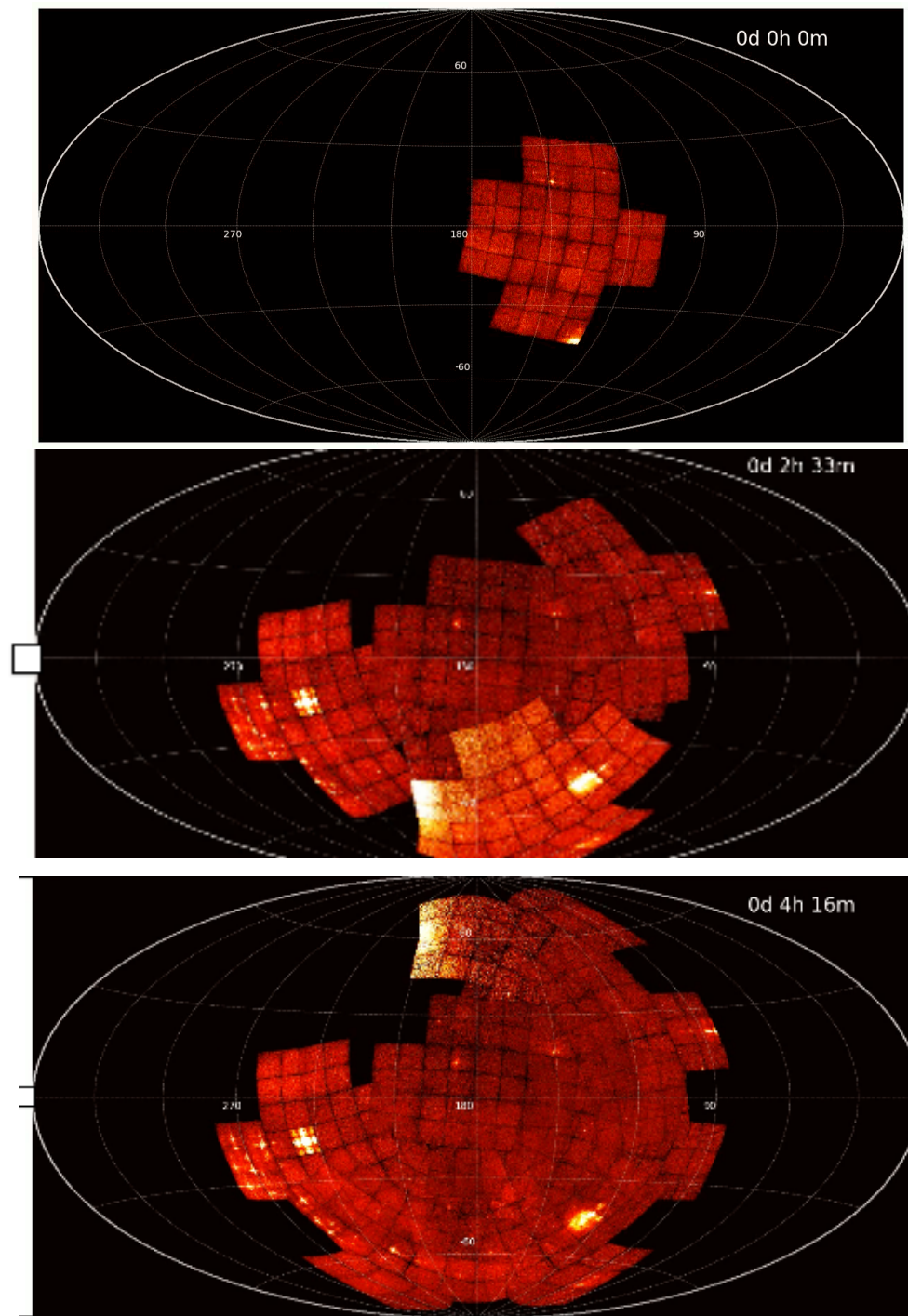


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Survey mode

Three 20-min pointings per orbit
Covers all night-sky in 3 orbits (5 hours)

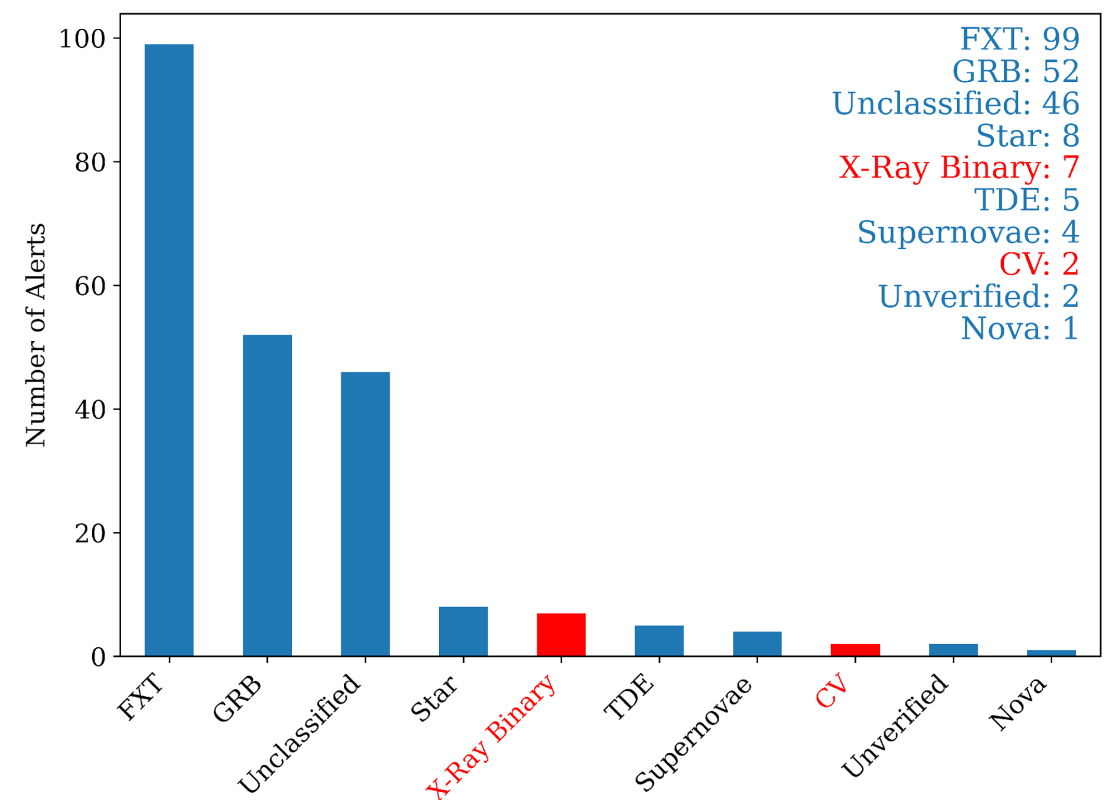
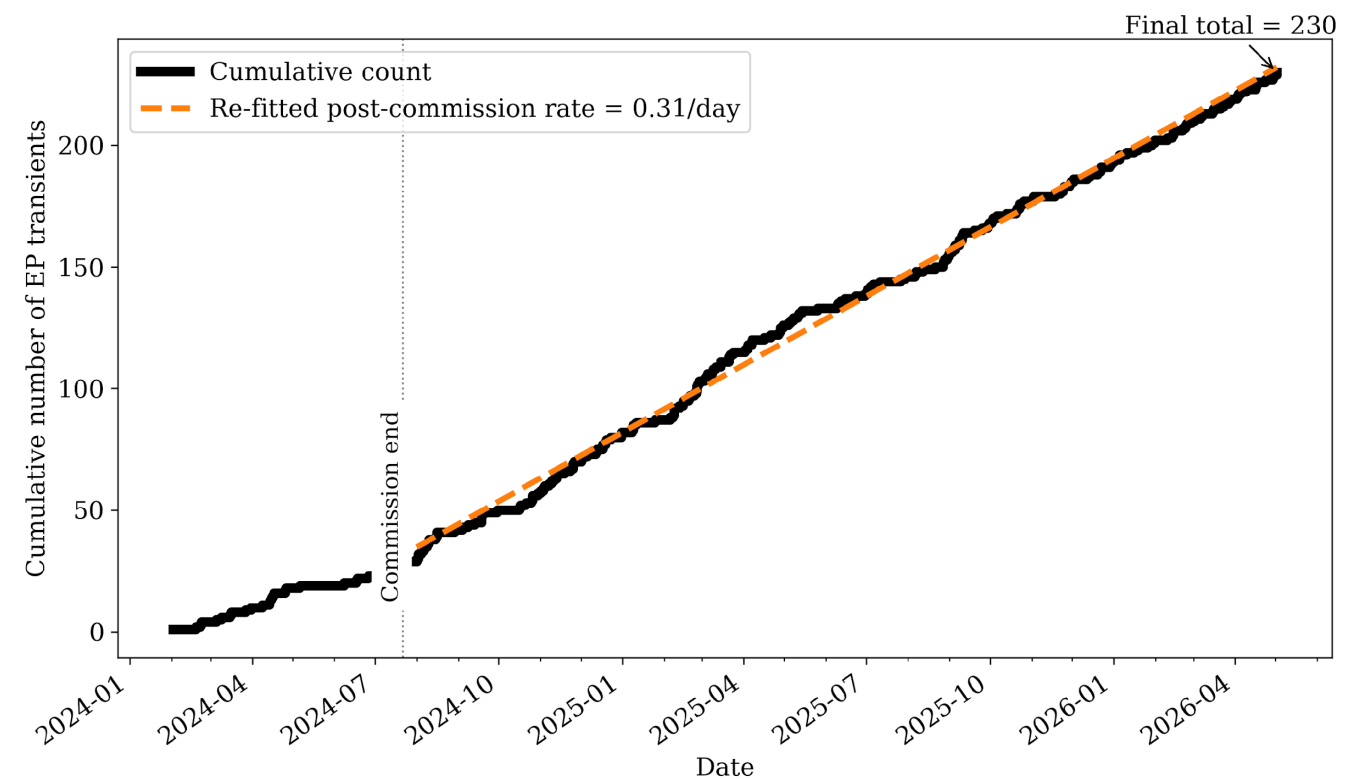
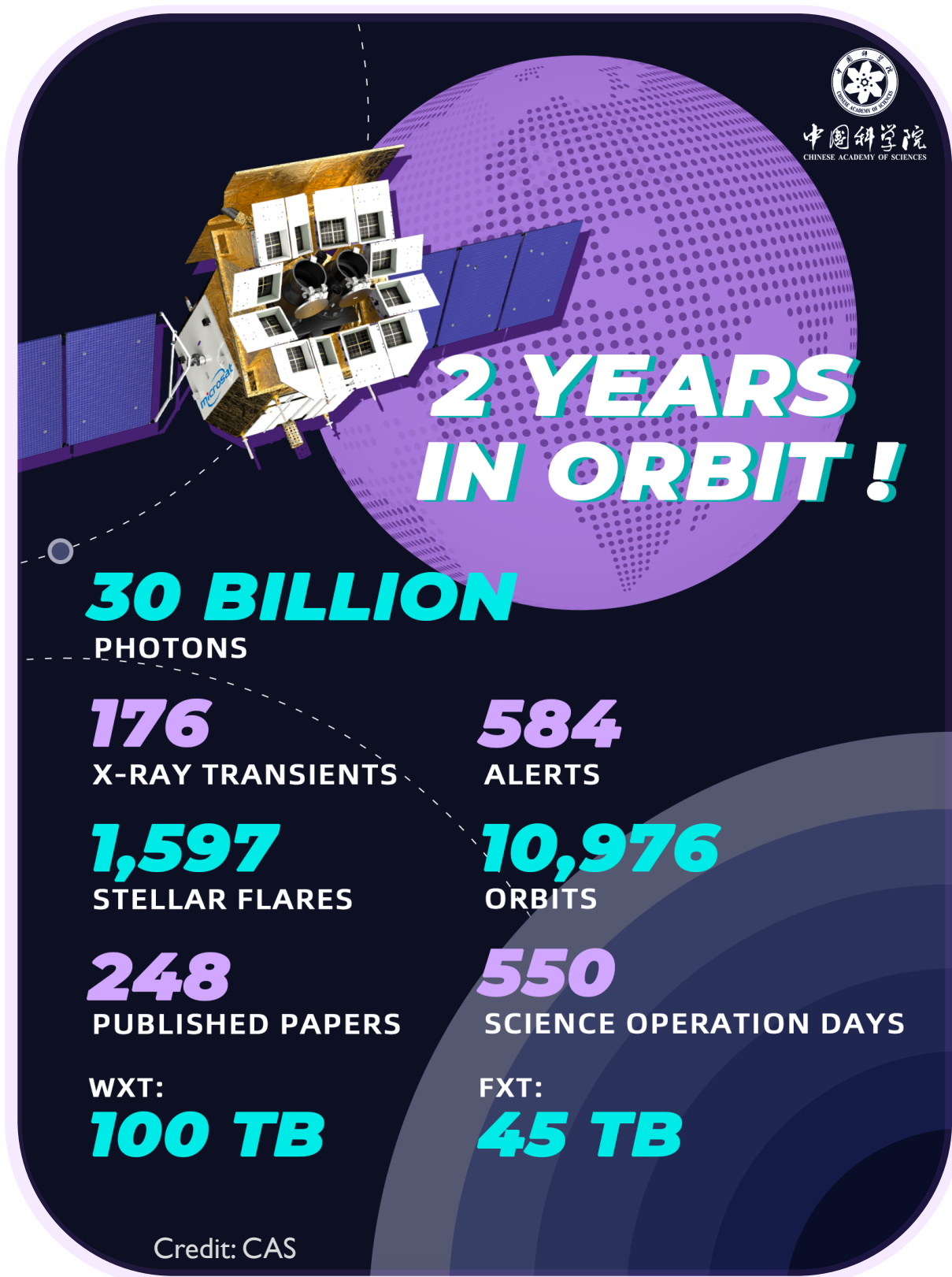
Covers whole soft X-ray sky in half year



20 billion X-ray photons

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New transients

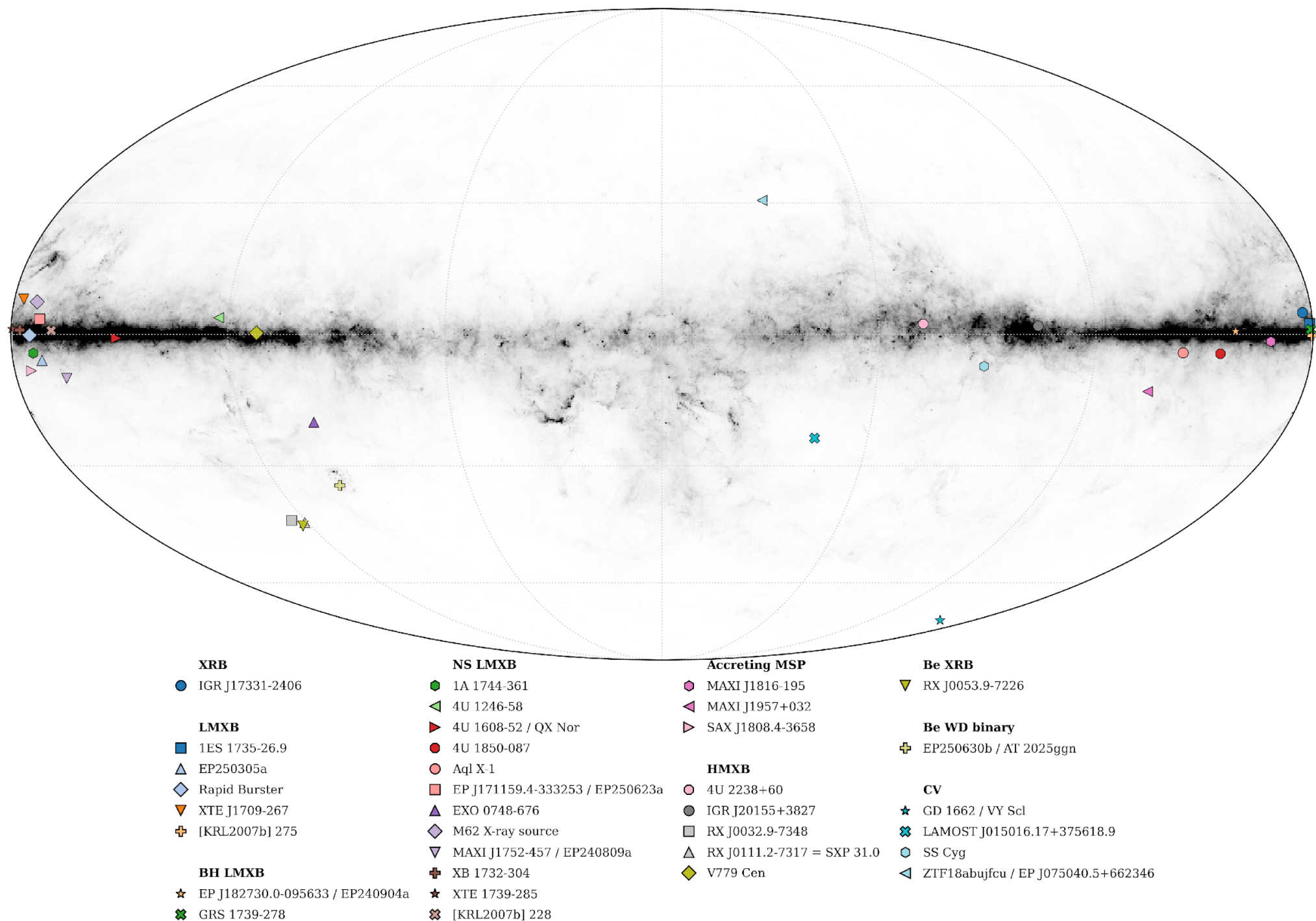


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Known active Galactic transients

>26000 known X-ray sources

X-ray activity from tens known Galactic XRBs (1/3 first detected by EP)



Francesco Coti Zelati (ICE, CSIC)

Optical time domain surveys

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

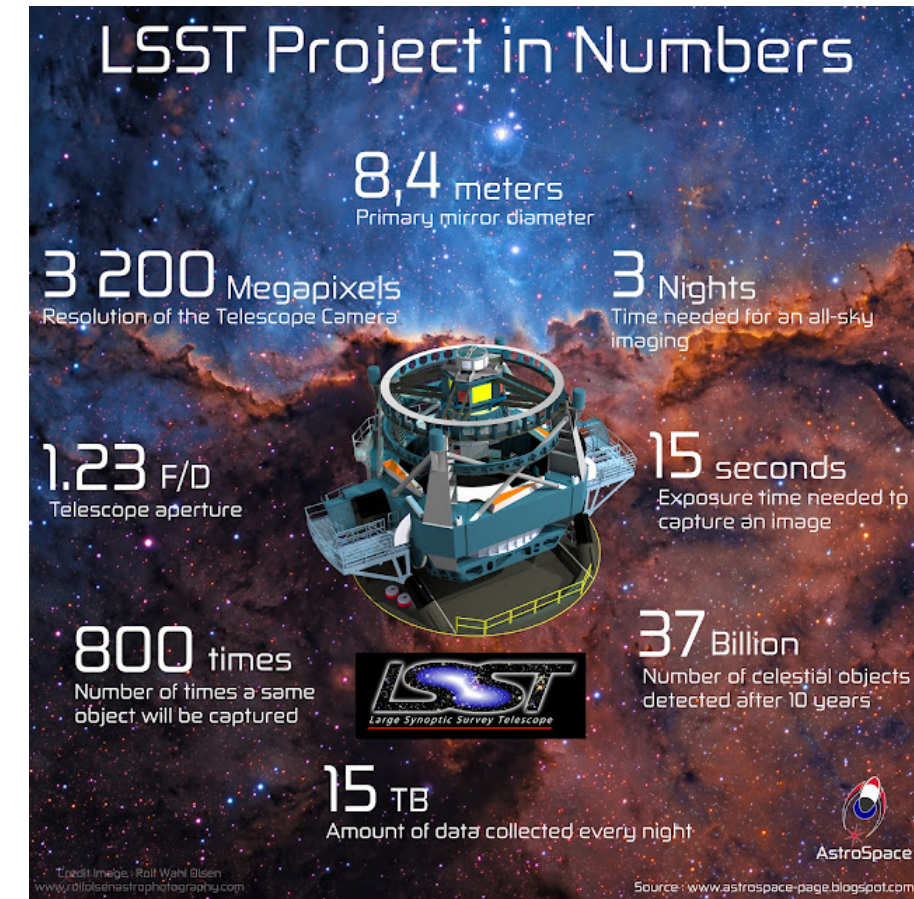
8.4-m primary mirror with a 3.2-gigapixel CCD imaging camera

Field of view: 9.6 square degrees.

Will cover the entire available sky every few nights

The ten-year Legacy Survey of Space and Time is now underway.

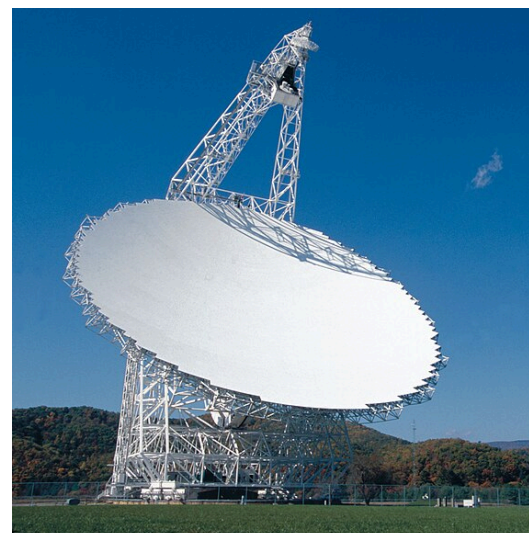
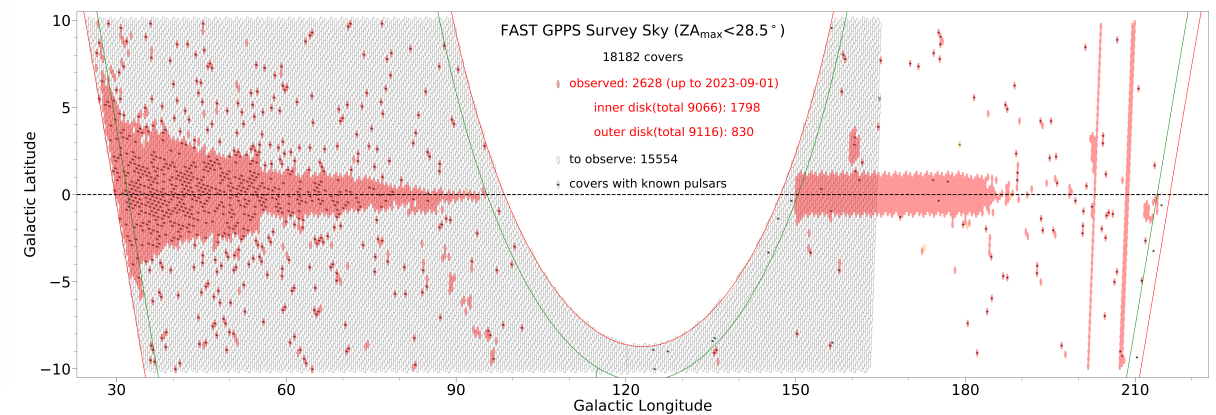
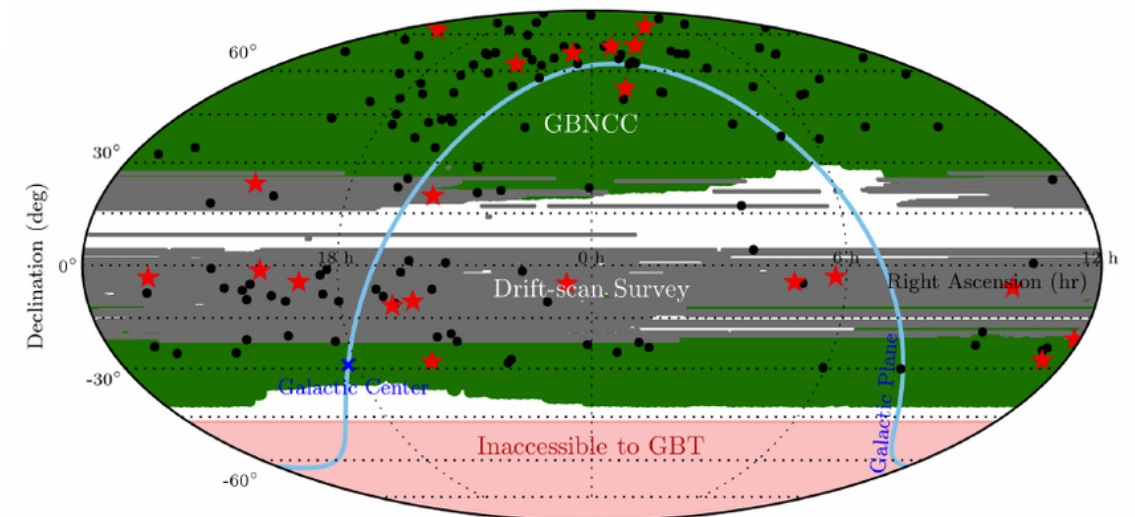
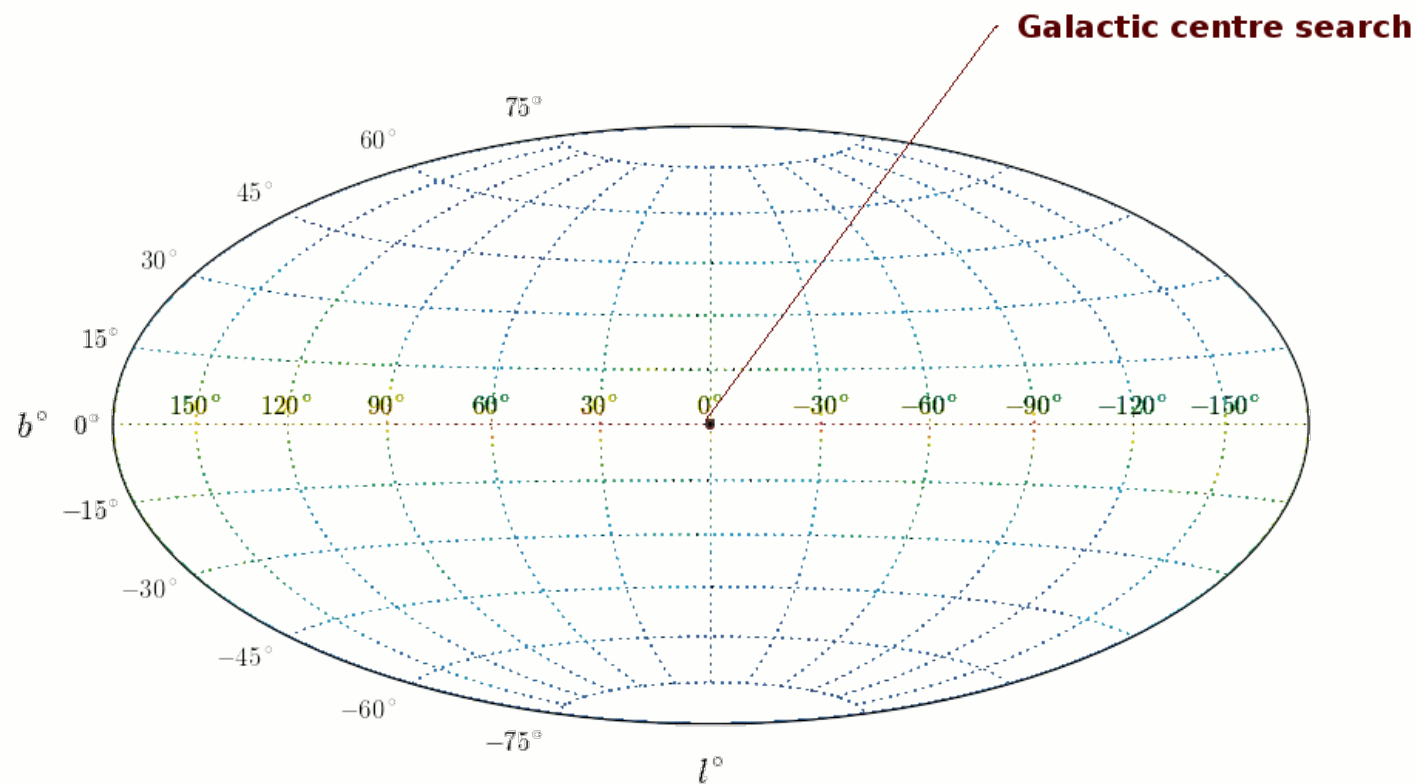
Generating unprecedented amounts of data for astronomical research.



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	$4 \times 10^6 (\times 4)$	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
5 σ 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

Parkers, Effelsberg, GBT, MeerKAT, FAST



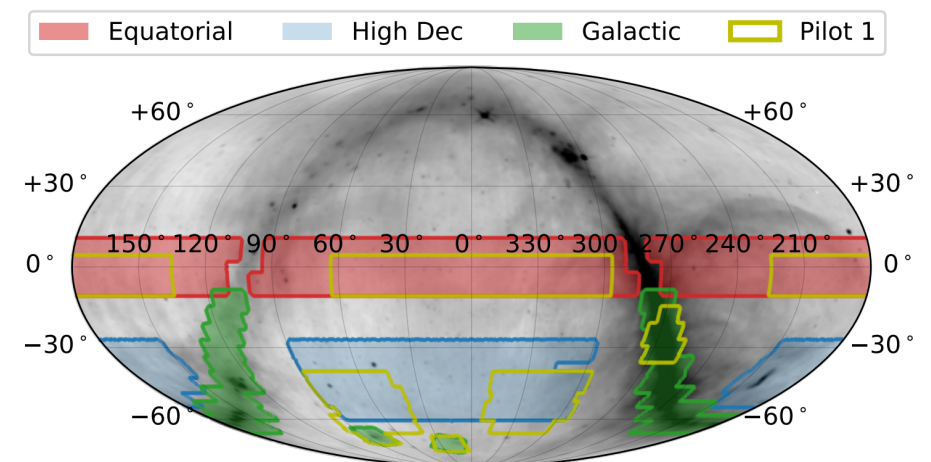
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Radio time domain surveys: transients

LOFAR transients key science project

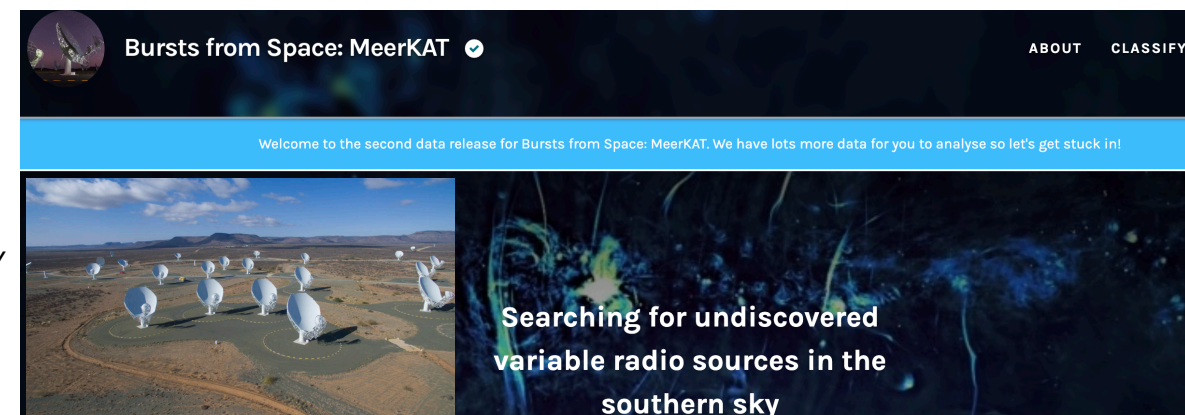


ASKAP Variables and Slow Transients survey



MeerKAT: bursts from space citizen science project

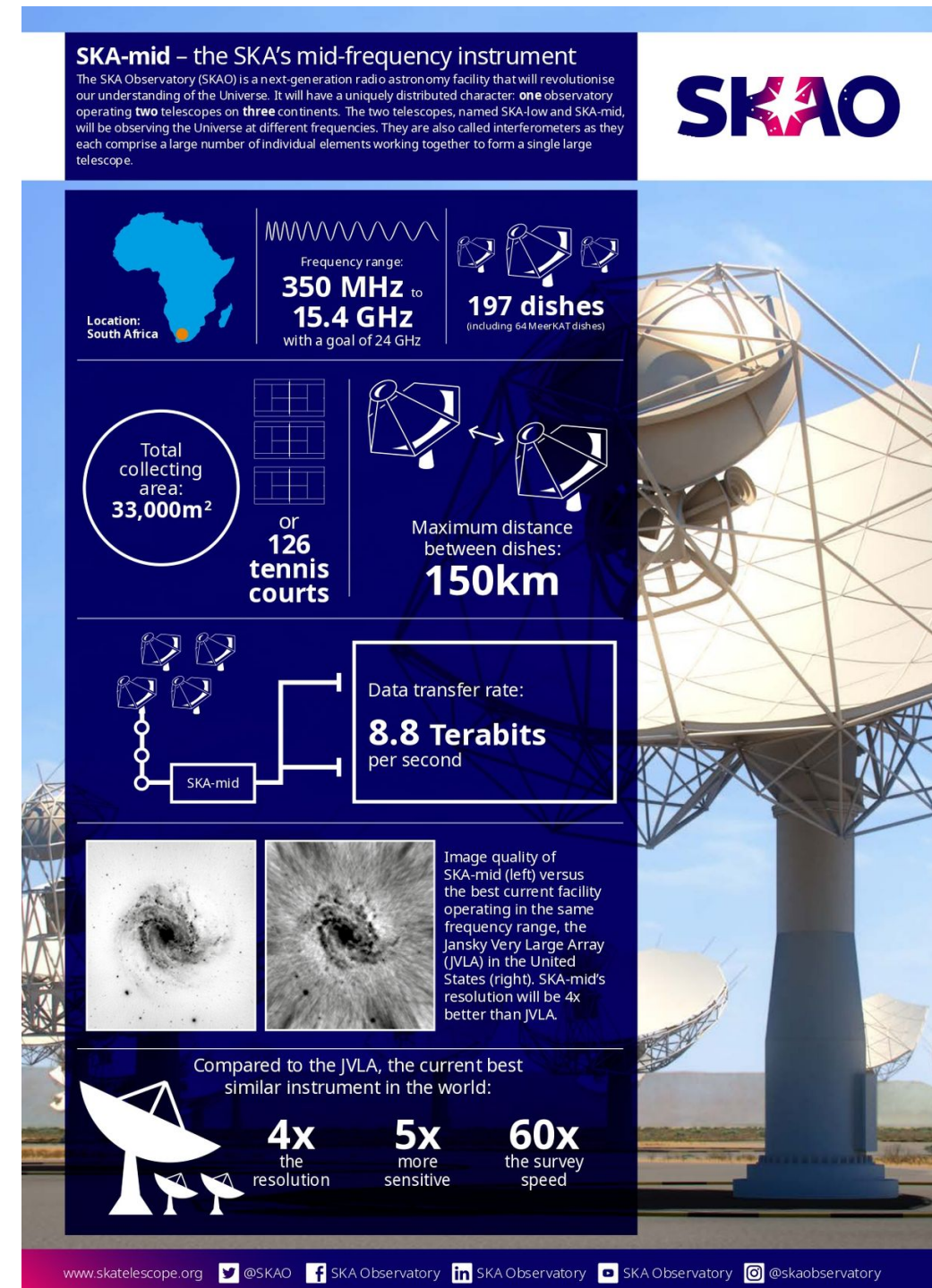
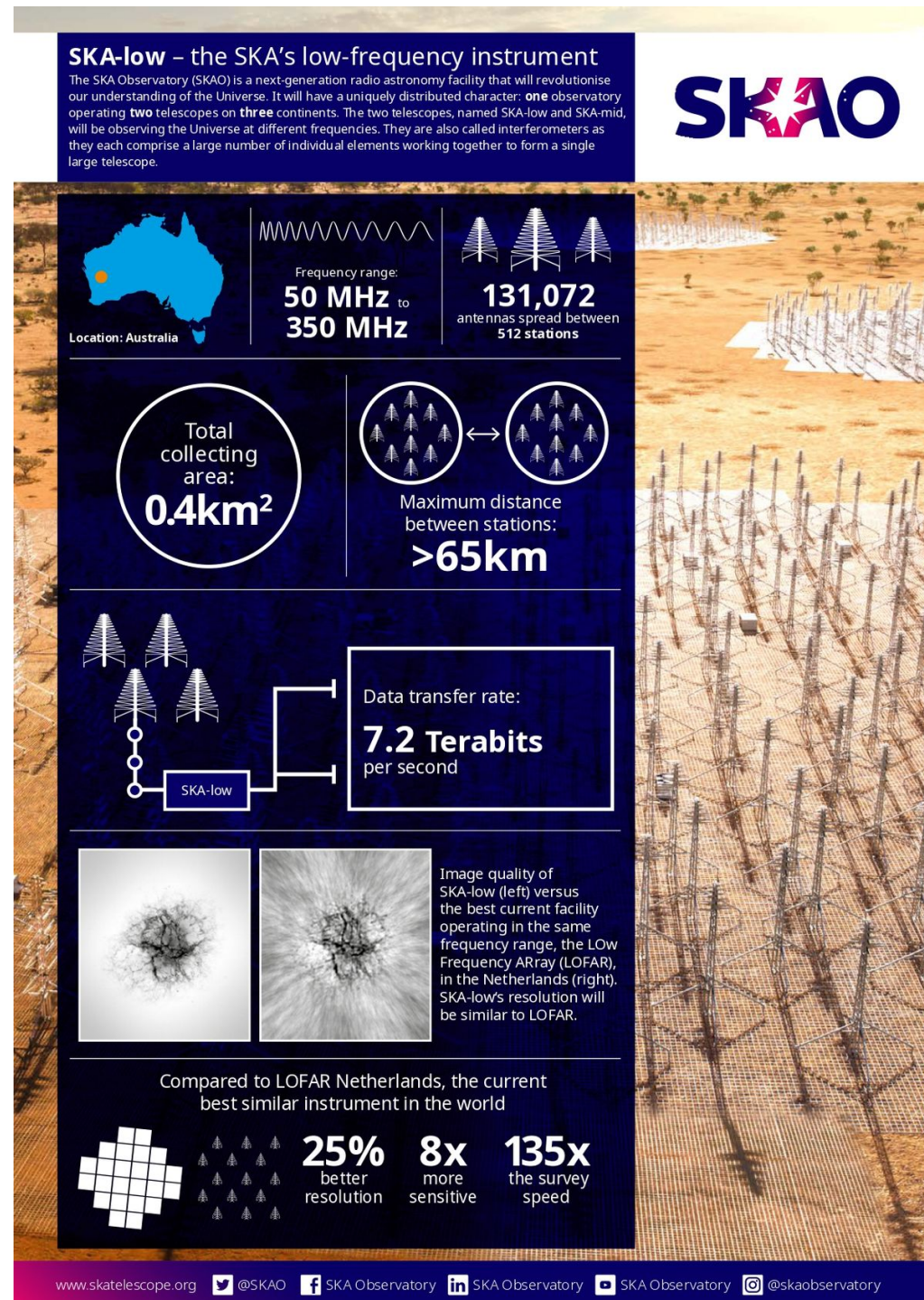
<https://www.zooniverse.org/projects/alex-andersson/bursts-from-space-meerkat/>



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Radio time domain surveys: the future

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



Suggested reading

- Athem W. Alsabti, Paul Murdin, *“Handbook of Supernovae”*, Springer
- Piran, T., *“The physics of gamma-ray bursts”*, Reviews of Modern Physics
- Levan A., *“Gamma-ray bursts”*, Encyclopedia of Astrophysics, Elsevier
- Wex, N. & Kramer, N., *“Gravity Tests with Radio Pulsars”*, Universe
- Kaspi, V. & Beloborodov, A., *“Magnetars”*, Annual review of Astronomy and Astrophysics
- Coti Zelati, F. et al., *“Systematic study of magnetar outbursts”*, MNRAS
- Bahamian, A. & Degenaar, N., *“Low-Mass X-ray Binaries”*, Handbook of X-ray and Gamma-ray Astrophysics
- Galloway, D. et al., *“The Multi-INstrument Burst ARchive (MINBAR)”*, ApJS
- Chomiuk, L. et al., *“New Insights into Classical Novae”*, Annual review of Astronomy and Astrophysics
- Gezari, S., *“Tidal Disruption Events”*, Annual review of Astronomy and Astrophysics
- Miniutti, G., et al., *“Nine-hour X-ray quasi-periodic eruptions from a low-mass black hole galactic nucleus”*, Nature

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