Exploring the X-ray Transient and variable Sky

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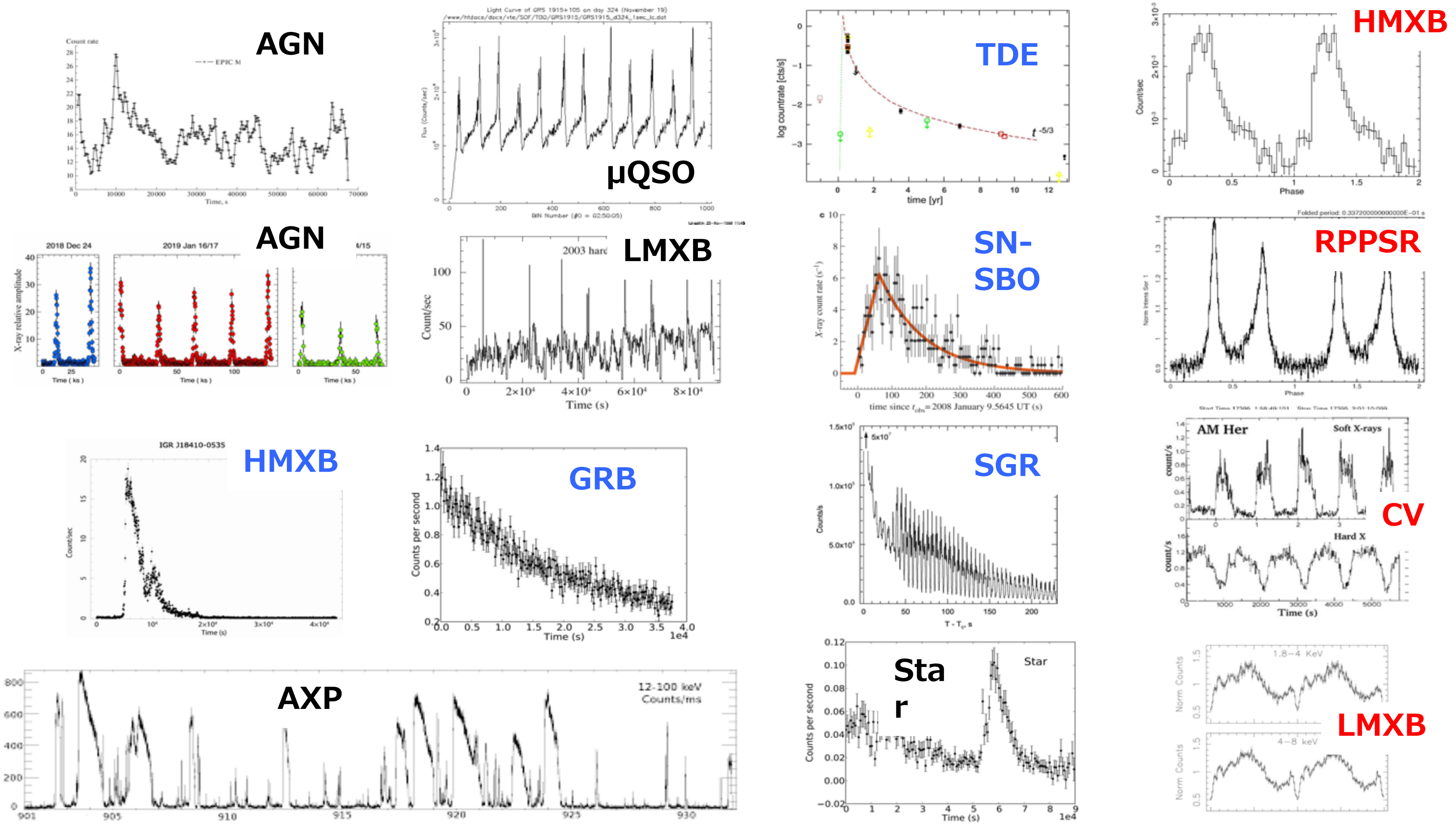
Outline

A talk about a past project, its outcome (yet to be fully explored) and some recent developments

1. Time domain astronomy, Serendipity, XMM-Newton
2. EXTraS (2014-2016): data analysis and products
   - aperiodic, short-term variability
   - search for periodicity
   - search for new transients
   - long-term variability
3. Recent work
4. Science highlights

Time-domain astronomy

Aperiodic, **transient**, **periodic** phenomena in the high-energy sky



From variability to physics

Accretion physics

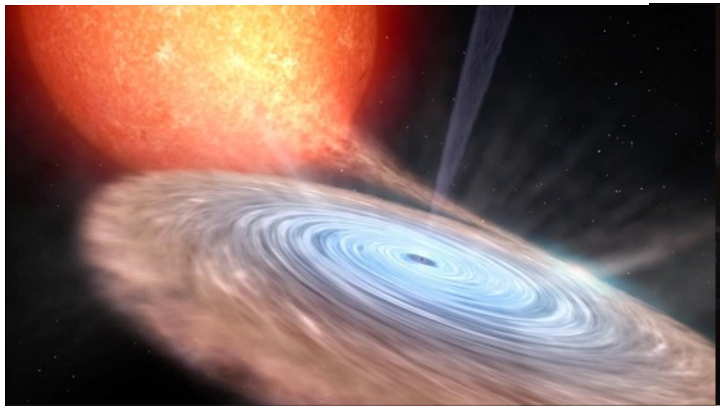
- radiation efficiency of accretion flows
- generation of winds and jets
- role of magnetic field

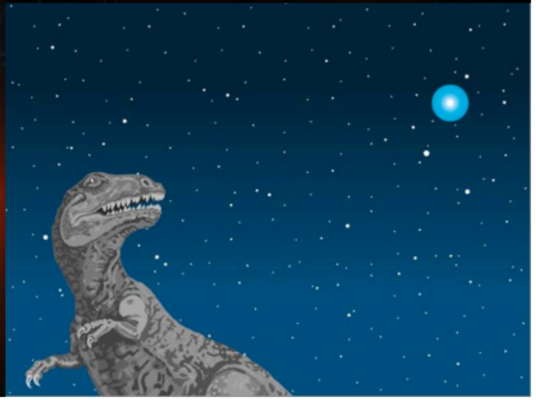
Strong gravity physics

Mechanisms behind massive stars explosions

Physics of B-field generation and dynamics

- in compact objects
- in normal stars





The EXTraS project (2014-2016)

XMM-Newton/EPIC

Most powerful tool to study variability in faint X-ray sources

Very large and growing archive of serendipitous data

EXTraS goals:

- extract all temporal domain information from EPIC data;
- characterise it;
- release it to the community in an easy-to-use form.

The EXTraS project

Funded by EU
FP7-Space-2013-1

2014-2016

as a service to the astronomical community

The EXTraS collaboration: A. De Luca, R. Salvaterra, A. Belfiore, S. Carpano, D. D'Agostino, F. Haberl, G. L. Israel, D. Law-Green, G.Lisini, M. Marelli, G. Novara, A. M. Read, G. Rodriguez-Castillo, S. R. Rosen, D. Salvetti, A. Tiengo, G. Vianello, M. G. Watson, C. Delvaux, T. Dickens, P. Esposito, J. Greiner, H. Hämmerle, A. Kreikenbohm, S.Kreykenbohm, M. Oertel, D. Pizzocaro, J. P. Pye, S. Sandrelli, B. Stelzer, J. Wilms, F. Zagaria

The EXTraS project

Data analysis: 4 pipelines

1. Aperiodic, short-term variability
2. Search for pulsations
3. Search for new, faint transients
4. Long-term variability

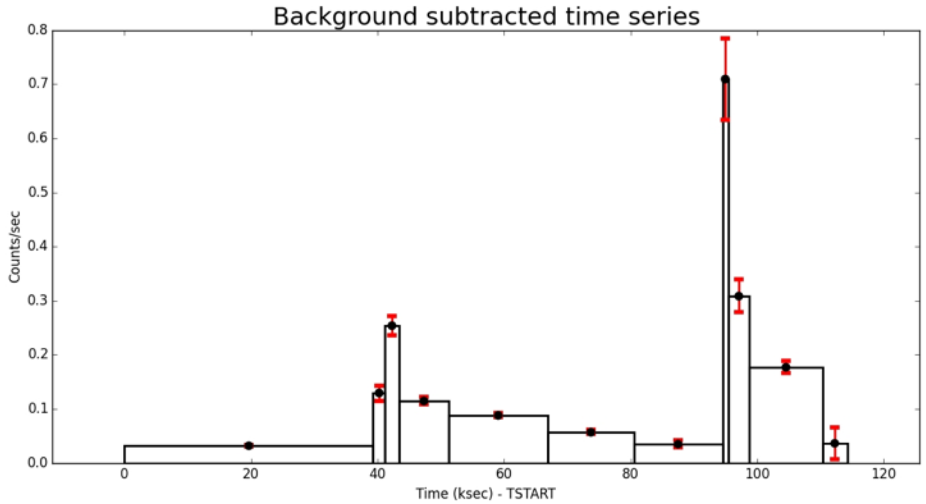
Run on all public data available at the time of the project (3XMM-DR4 / DR5)

The EXTraS project

Aperiodic variability

1. Largest possible fraction of sources, down to very faint fluxes;
2. all EPIC data, including time intervals affected by high bkg;
3. variability at the shortest time scales even in faint sources;
4. energy-resolved analysis and spectral variability;
5. full set of quantitative parameters to describe variability

We investigated **300,000 XMM un. sources**



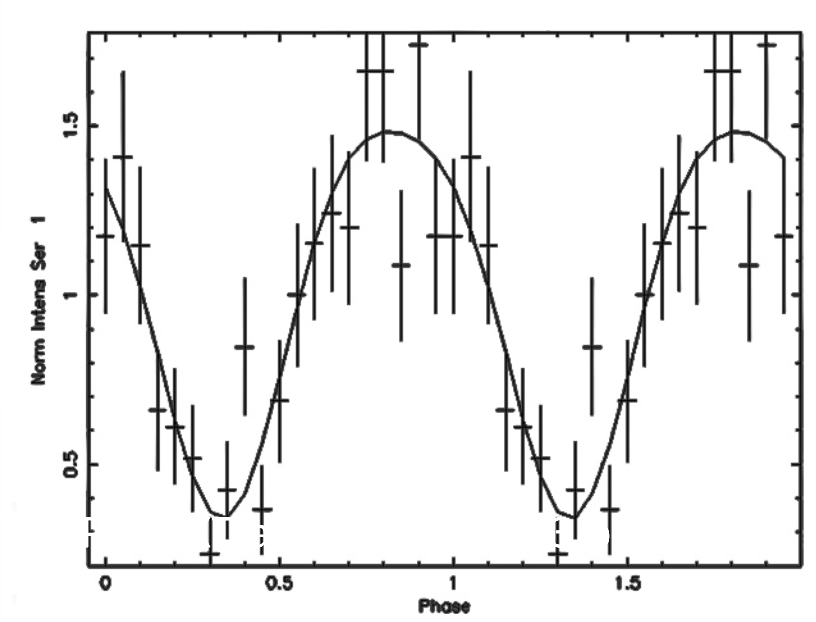
- **Light curves** (uniform time bins; Bayesian blocks) in 4 energy ranges; **CDFs**
- **Hardness ratios;**
- **FFT spectra;**
- Set of **temporal features** (best fit model parameters; moments of count rate distributions; quantile-based parameters; min/max gradient …)

De Luca+2021, A&A 650, 167

The EXTraS project

Periodicity

1. first systematic search for pulsations in EPIC sources
2. based on unbinned photon TOAs
3. all EPIC data, including time intervals affected by high bkg
4. large fraction of sources in the catalogue



Systematic study of **>300,000 sources**

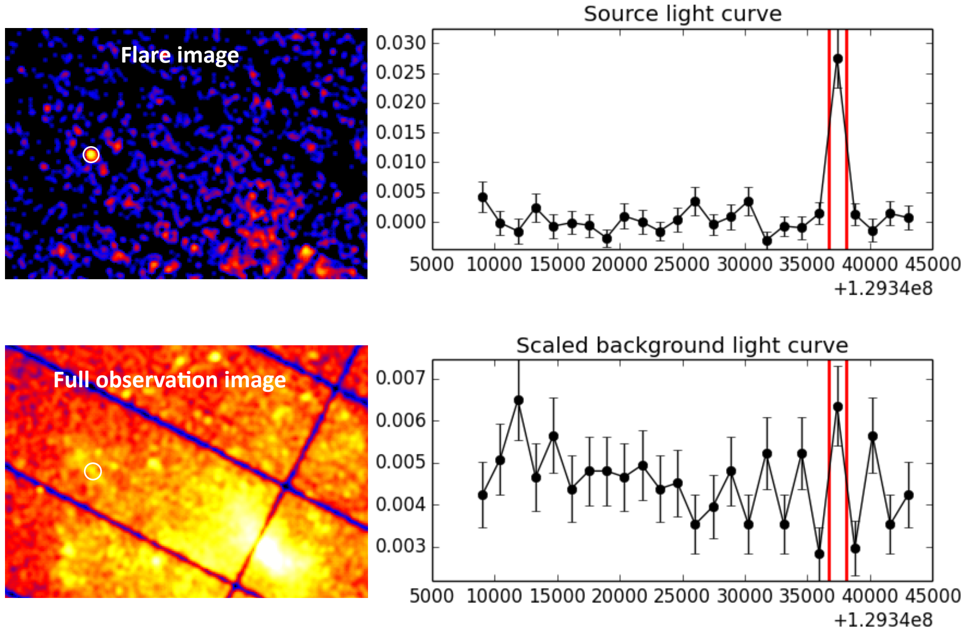
- Search based on **unbinned** photons TOAs
  - FFT-based à la Israel&Stella (1996)
  - taking into account properties of “colored” noise
  - Follow-up of candidates with Rayleigh test
- Period, significance, Folded LCs
- 3.5sigma U.L. on pulsed fraction

De Luca+2021, A&A 650, 167

The EXTraS project

New transients

1. first systematic search on all EPIC data
2. high bkg time intervals included in the analysis
3. transient search at all time scales



Missed by standard source detection

we investigated ~**7,800 observations**

2 approaches: Bayesian blocks; uniform bins

- Position, temporal properties
- Detection parameters in 3XMM energy bands

Catalogue of 136 "bright" transients

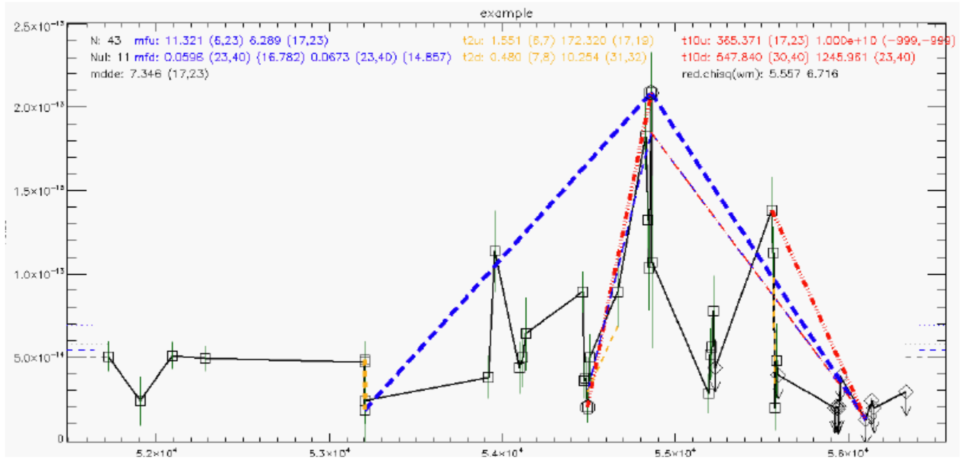
De Luca+2021, A&A 650, 167

The EXTraS project

Long-term variability

1. first systematic search on all EPIC data
2. Slew data included in our analysis
3. Larger slew dataset

- **long-term LCs** based on **flux** measurements & **upper limits** for all srcs. using all available data
- Test, quantification, characterization of variability
- Catalogue with 2 million photometric measurements **for >400,000 sources**

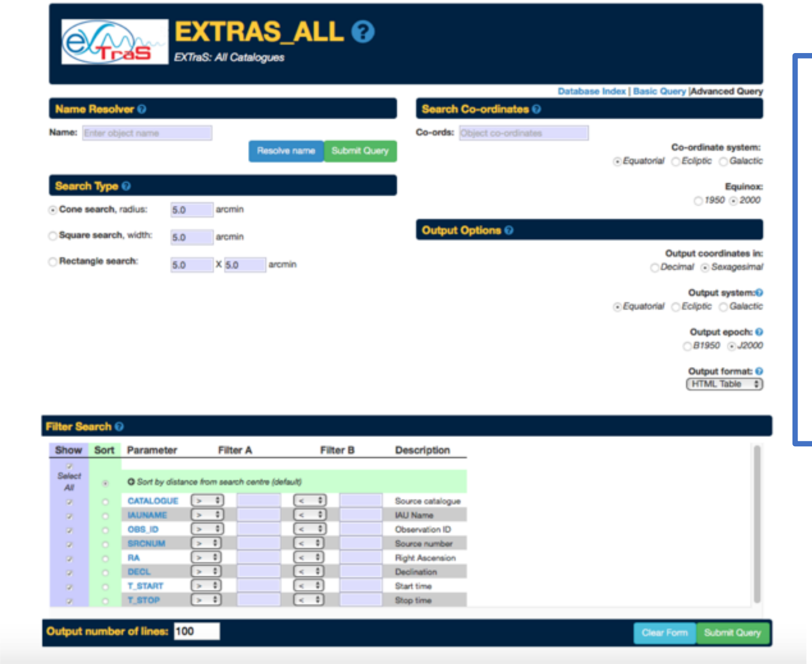


De Luca+2021, A&A 650, 167

(no more) Online resources

EXTraS
web site

Based at
CNR/IMATI

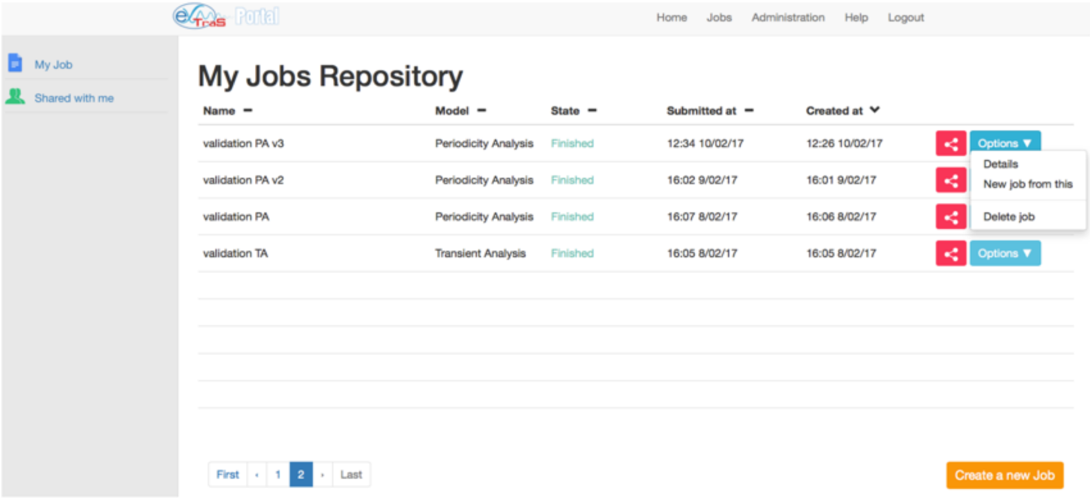


EXTraS
Public Data
Archive

Based at
Leicester
(LEDAS)

EXTraS
Science
gateway

Based at
CNR/IMATI,
running on EGI



Security issues after beginning of war

Discontinued because of lack of dedicated manpower

Products and results available

Recent developements

Limited by shortage of manpower

Short-term, aperiodic variability

1. Generation of **EPIC light curves** with uniform time bins **combining pn and MOSs**
2. Production of smoothed CDFs
3. Characterization of variability based on these new products

Run on all data collected up to the end of 2022

See e.g. Marelli+2017, ApJ 851, 27; Marelli+2018, ApJ 866, 125; Motta+2020, ApJ 898, 574; De Luca+2022, A&A 667, L7

Search for pulsations

1. Search for accelerated coherent signals
2. Search for coherent signals from binary systems (orbital parameters)
3. Search for pulsations accounting for both orbital and intrinsic Pdot variations

Run on several 10^4 LCs

See Israel+2022, MemSAIt 93, 34 and ref. therein

Work in progress

Exploring Machine learning

1) Classification of variability using machine learning (based on temporal features)

   a. **Unsupervised classification of all variable sources**
      using Self Organizing Maps

   b. **Supervised search for flares**
      XGBoost, NBMs

2) Search for faint transients in photon lists (preliminary)

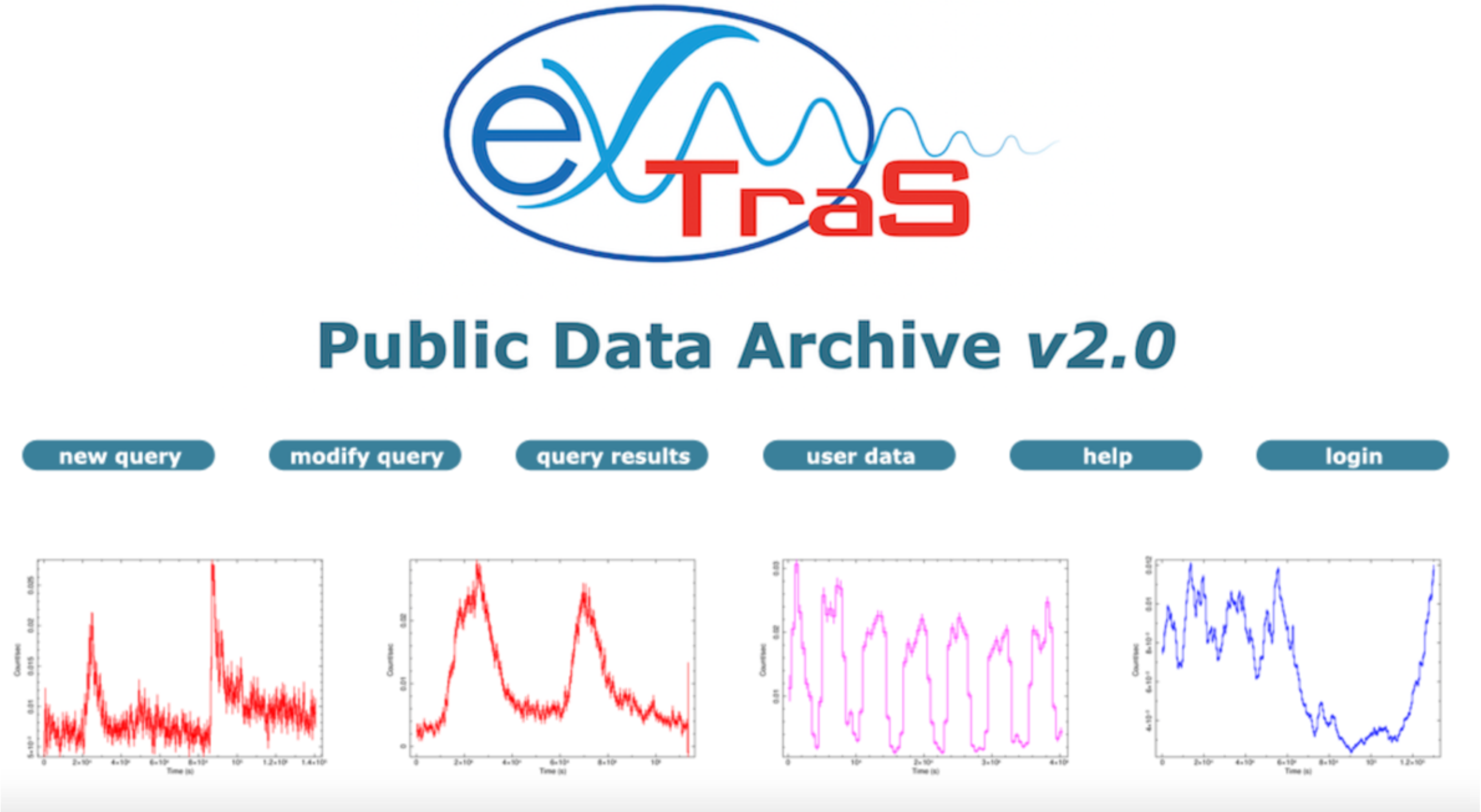
   Using Graph ANN with curriculum training

   Using message passing clustering

Kovacevic+2022, A&A 659, 66

Pasquato+2024, in prep

New online resources



New public data archive based at IASF-Milano – expected release in late spring 2024

Results of updated pipelines

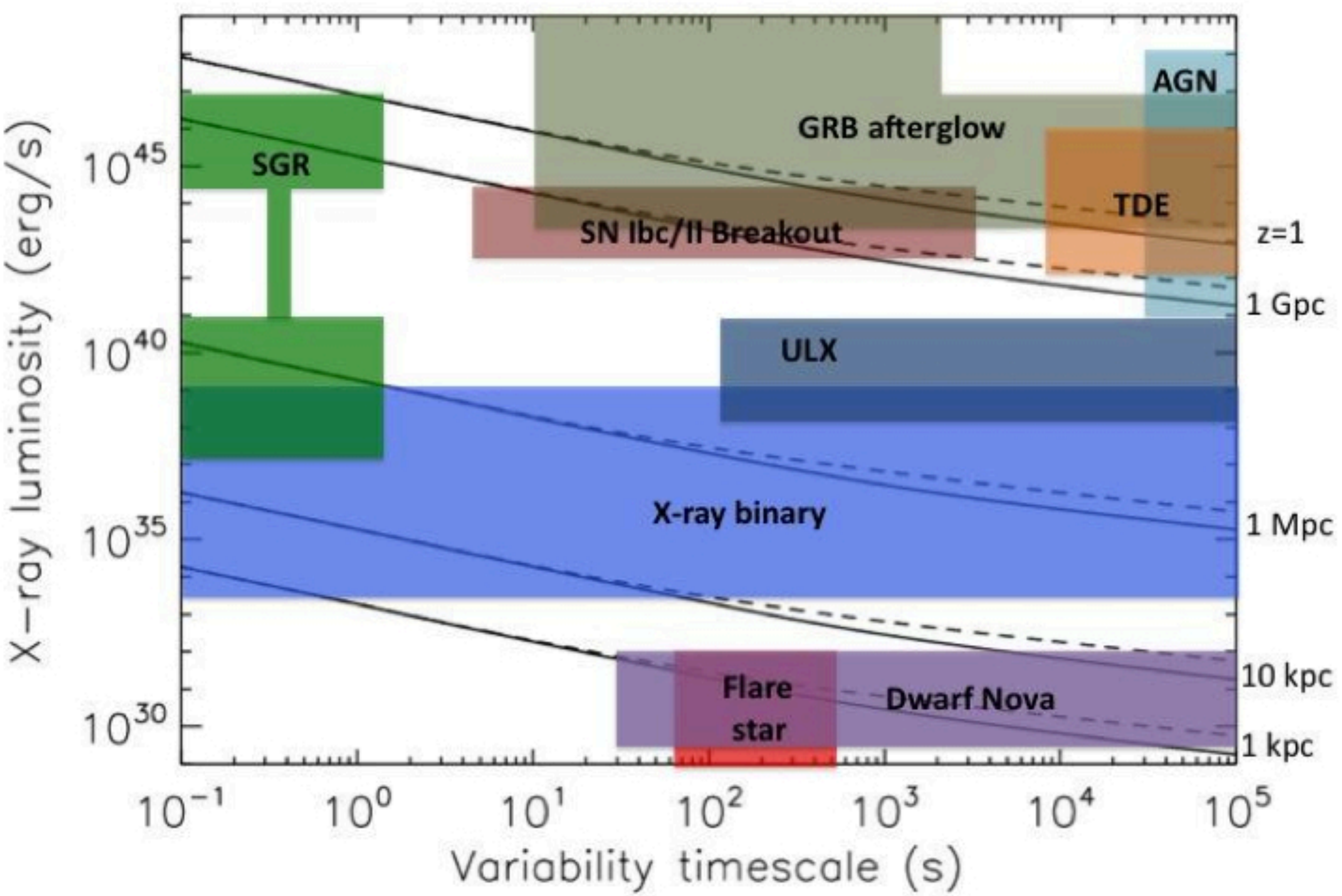
Aperiodic variability: EPIC LCs with 4 uniform time binning; single camera LCs with uniform & adaptive bins; smoothed CDFs; temporal features; flare flag

Complex queries on features

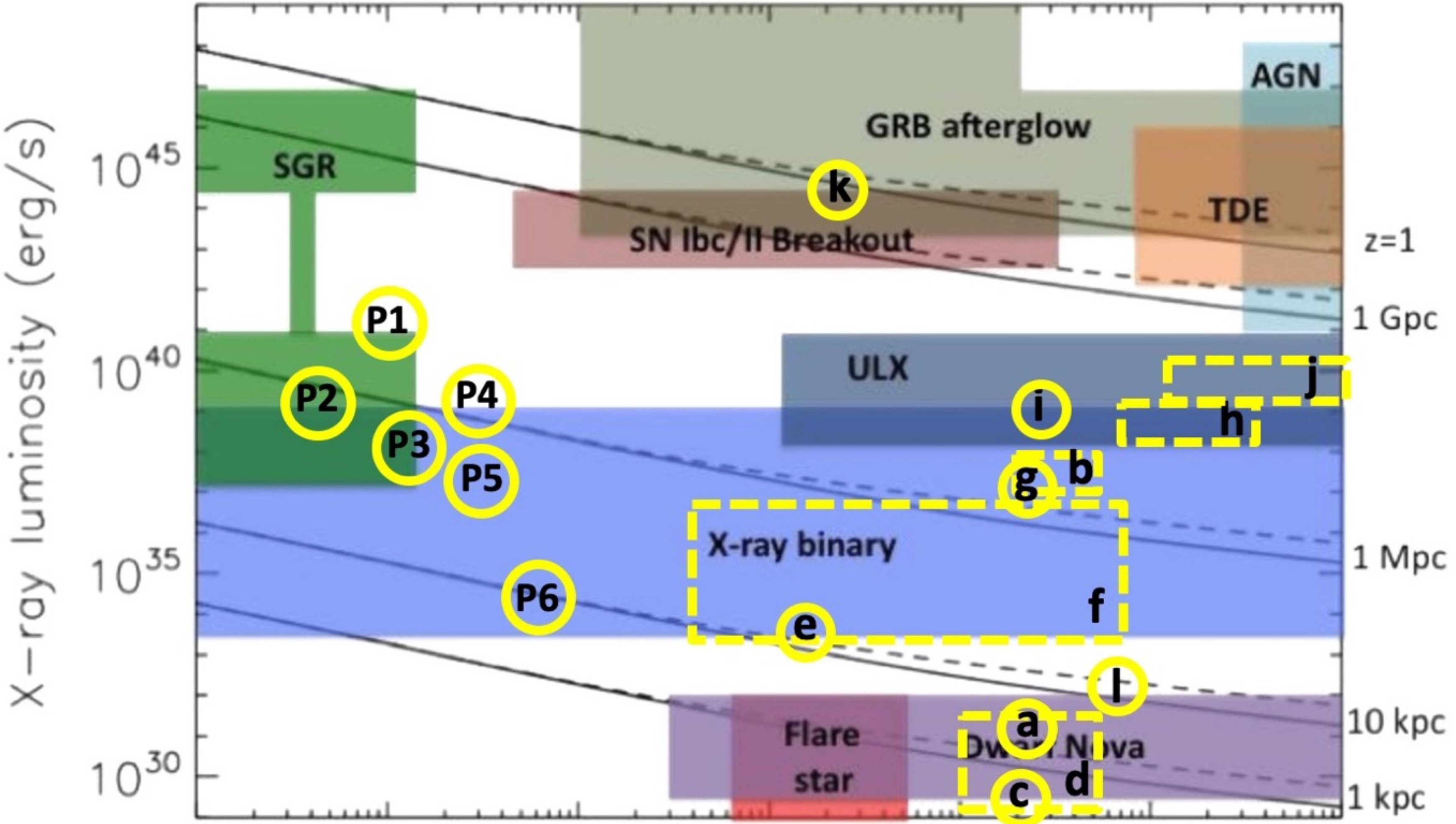
Interactive visualization of products

Download of products and catalogues

Science with EXTraS



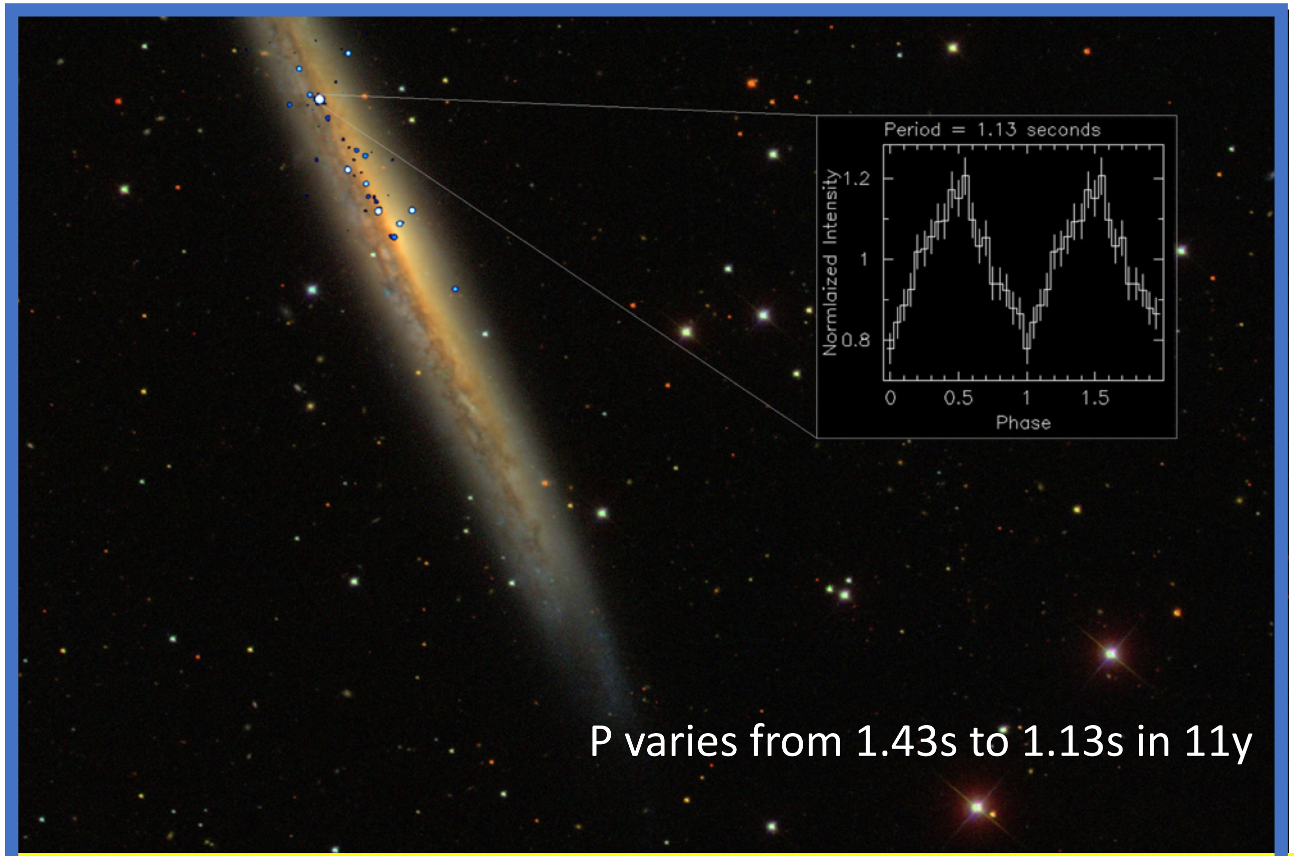
Aperiodic variability: a): a flare from a very early protostar (Pizzocaro+2016, A&A 587, A36); **b):** an extreme dipper in M31 (Marelli+2017, ApJ 851, L27); **c):** a superflare from an L dwarf (De Luca+2020, A&A 634, L13)**; d):** activity from a sample of A–M class Kepler stars (Pizzocaro+2019, A&A 628, A41); **e):** puzzling flare from the NGC6540 globular cluster (Mereghetti+2018, A&A 616, A36); **f):** flares from supergiant fast X-ray transients (Sidoli+2019, MNRAS 487, 420); **g):** periodic nova in M31 (Marelli+2018, ApJ 866, 125)**; h):** recurrent flares from a black hole candidate in NGC4472 (Tiengo+2022, A&A 661, A68); **i):** peculiar "heartbeat" oscillations in a ULX in NGC3621 (Motta+2020, ApJ 898, 174); **j):** variability of ULXs in NGC7456 (Pintore+2020, ApJ 890, 166); **k):** a supernova shock breakout candidate in a distant galaxy (Novara+2020, ApJ 898, 37); **l):** (quasi)periodic pulses from the black widow PSR J1311-3430 (De Luca+2022, A&A 667, L7).



Pulsators: P1): the extreme pulsar NGC5907 ULX-1 (Israel+2017, Science 355, 817); **P2):** 0.42 s pulsations in ULX NGC7793 P13 (Israel+2017b, MNRAS 466, L48); **P3):** 1.2 s pulsar in M31 (Esposito+2016, MNRAS 457, L5); **P4):** 2.8 s pulsations in M51 ULX-7 (Rodriguez-Castillo+2020, ApJ 895, 60) **P5):** pulsations from an extreme dipper in M31 (Rodriguez-Castillo+2018, ApJ 861, L26) **P6)**: 7.25 s pulsation from a candidate magnetar in the LMC (Imbrogno+2023, MNRAS 524, 5566)

Pulsations in NGC5907 ULX-1

Period. search



Israel+ 2017, Science 355, 817

L_X ~ 0.15-1.6x10^{41} erg/s
brightest PSR ever detected

"local" P_{dot}: several -10^{-9} s/s
"secular" P_{dot}=-8.1(1)x10^{-10} s/s
P/P_{dot} ~ 40 yr !!!

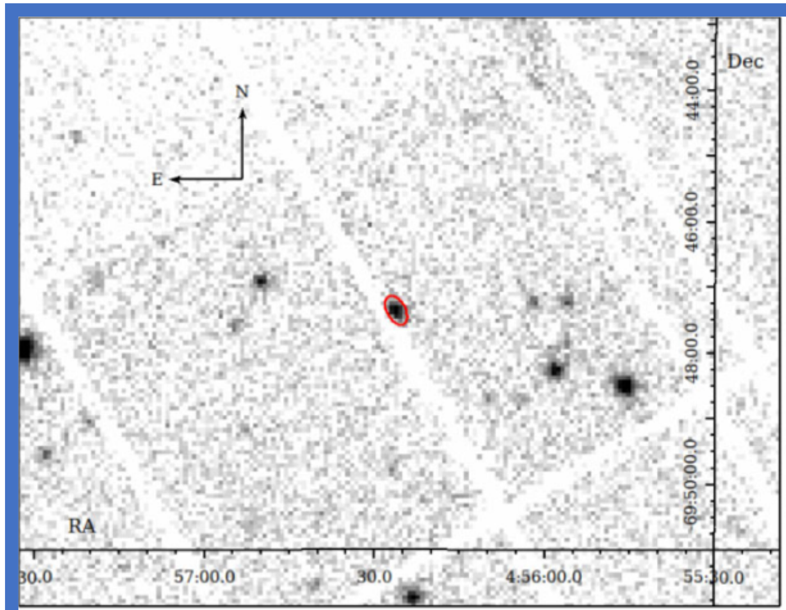
Porb=$5.3^{+2.0}_{-0.9}$ days (1□)
likelihood analysis (circular orbit)

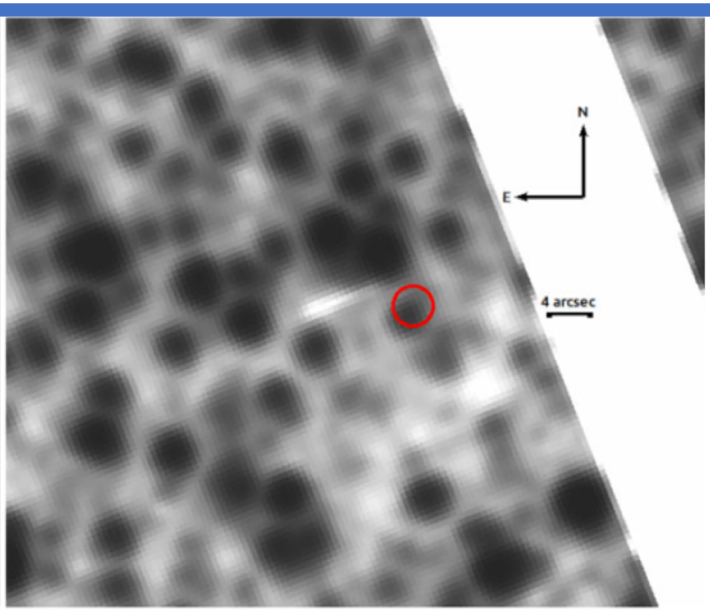
Dipolar B component
(~Magnetospheric boundary)
(0.7 – 3.0) x 10^{12} G @ b~1/10-1/7

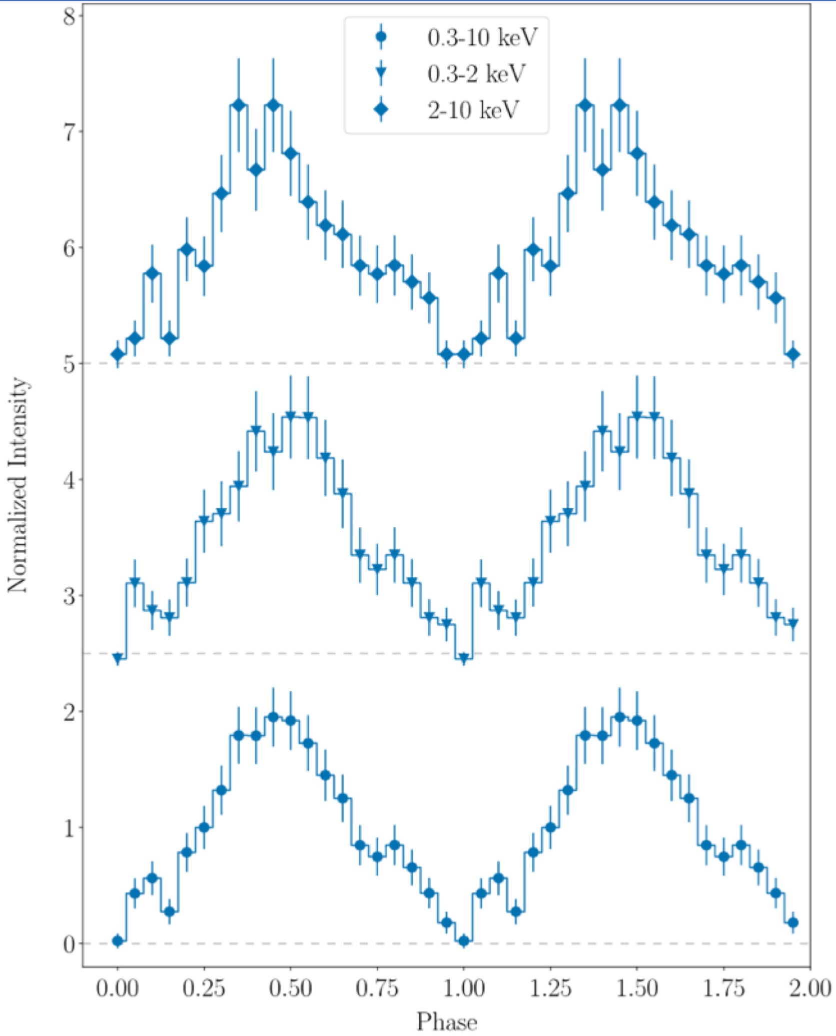
Multipolar B component
(~surface/bottom of
the accretion column)
(3-30) x 10^{13} G

A candidate magnetar in the LMC

Period. search







P = 7.25s – PF = 86%

$L_X \sim 2.7 \times 10^{34}$ erg/s

Detected in 1/6 observations

PL spectrum, Γ=1.9

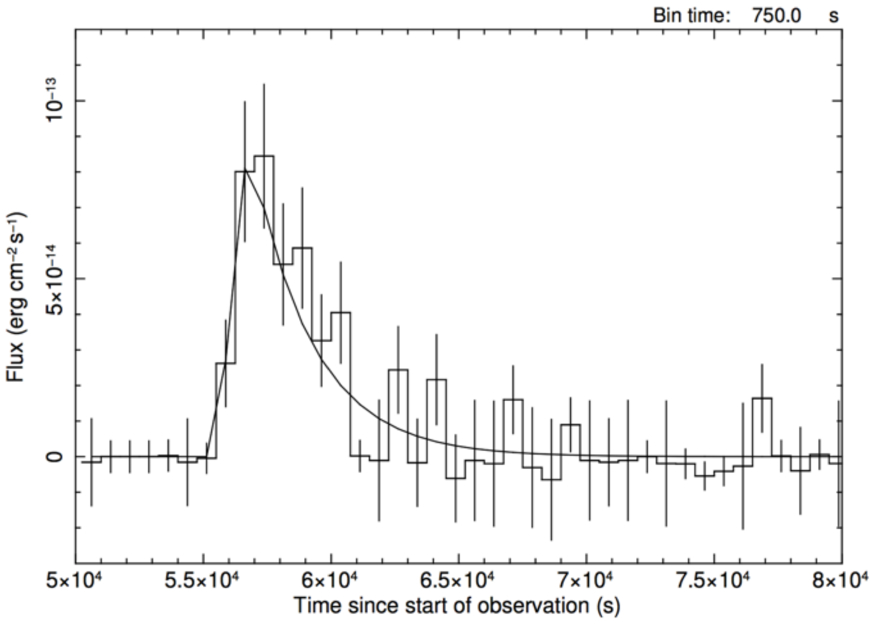
Possible counterpart G8-K3

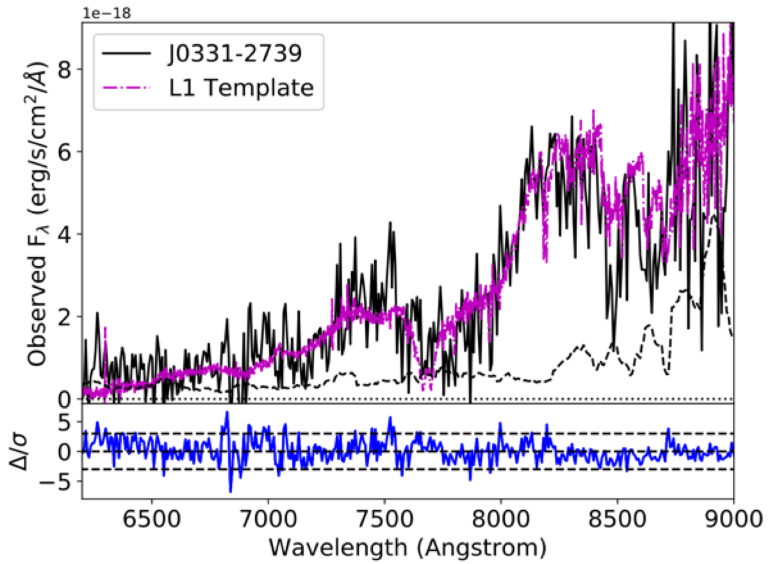
Properties best described by the magnetar interpretation

Imbrogno+2023, MNRAS 524, 5566

An X-ray superflare from a L dwarf

Short term Var.





located in the core of the CDFS !

VLT/VIMOS Spectrum → L1 ultracool dwarf

The coolest star ever detected in X-rays

E ~ $2x10^{33}$ erg

No other flares in 3.5Ms of XMM data

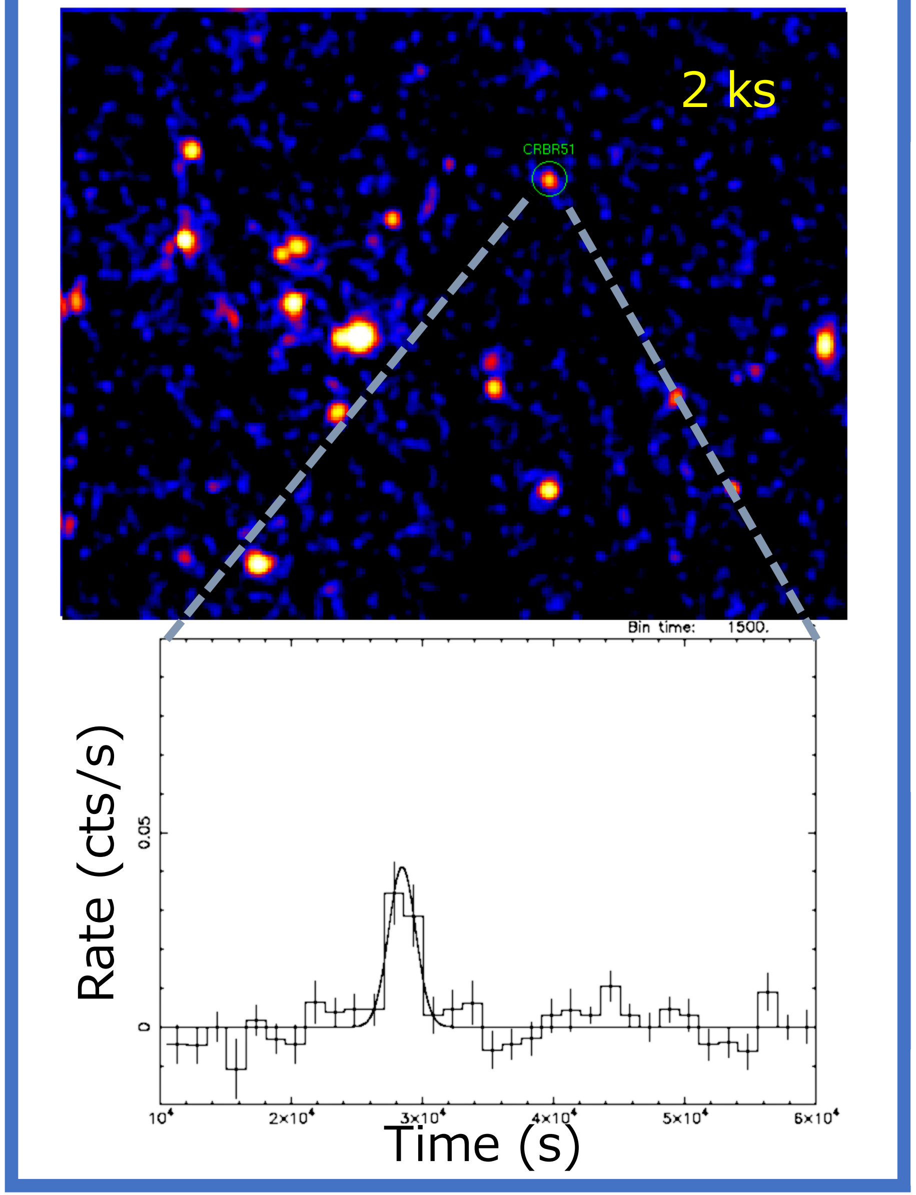
Mechanism to store and release such a dramatic amount of energy in such a tiny star is a mistery

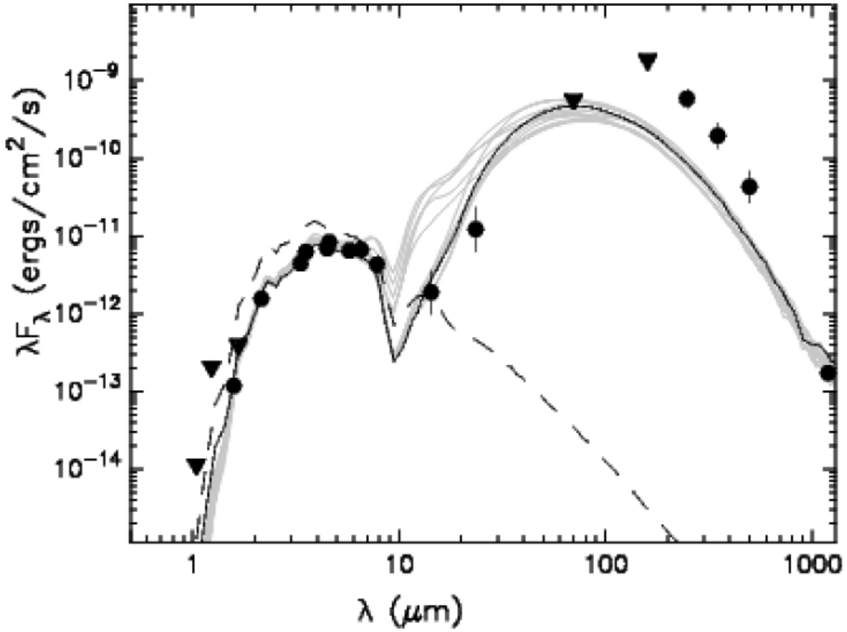
De Luca+2020, A&A 634, L13

A flare from a very early protostar

New transient

Pizzocaro+2016, A&A 587, 36





Position → CRBR51, a known YSO

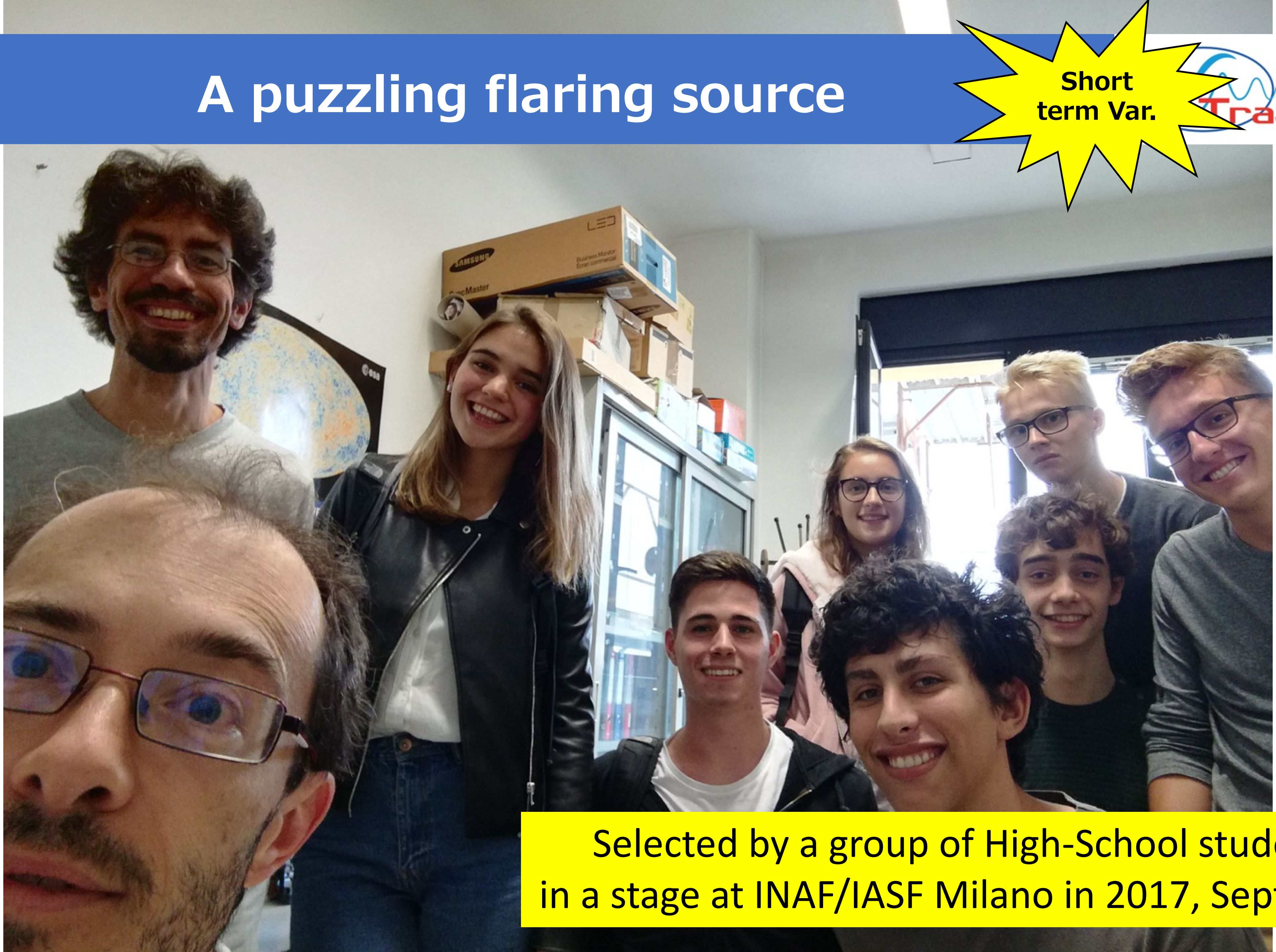
Spectrum → highly absorbed stellar flare

IR SED → class 1 YSO !

X-ray emission from such early proto-stars is poorly known

A puzzling flaring source

Short term Var.



Selected by a group of High-School students in a stage at INAF/IASF Milano in 2017, September

A puzzling flaring source

Short term Var.

nature › research highlights › article

a natureresearch journal

nature
International journal of science

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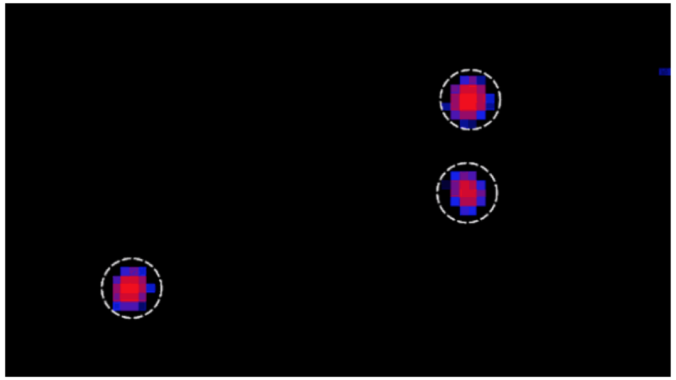


Three relatively steady X-ray sources (white circles) were outshone by a mysterious body (yellow arrow) that erupted with a large and sudden burst of X-rays. Credit: ESA/XMM-Newton, A. De Carlo/INAF

ASTRONOMY AND ASTROPHYSICS · 16 AUGUST 2018

Teens stumble on a new class of astronomical object

Students sifting through archived data find an X-ray flare too brief to belong to an ordinary star.

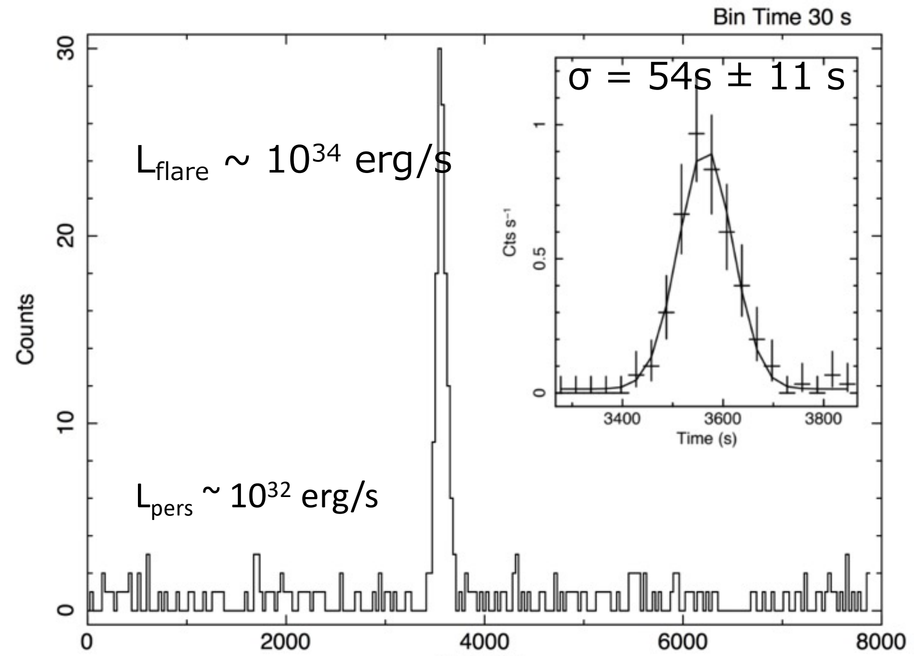
Secondary-school students have discovered a source of X-rays in the sky that appears to be a new type of astronomical object.

Stars can emit flares of intense X-ray radiation, and a star under the influence of a nearby black hole or neutron star can produce flares that are extremely bright and brief. In search of such objects, a team of students in their final year of secondary school in Saronno, Italy, analysed data from the XMM-Newton satellite, and identified an object that experienced a curious

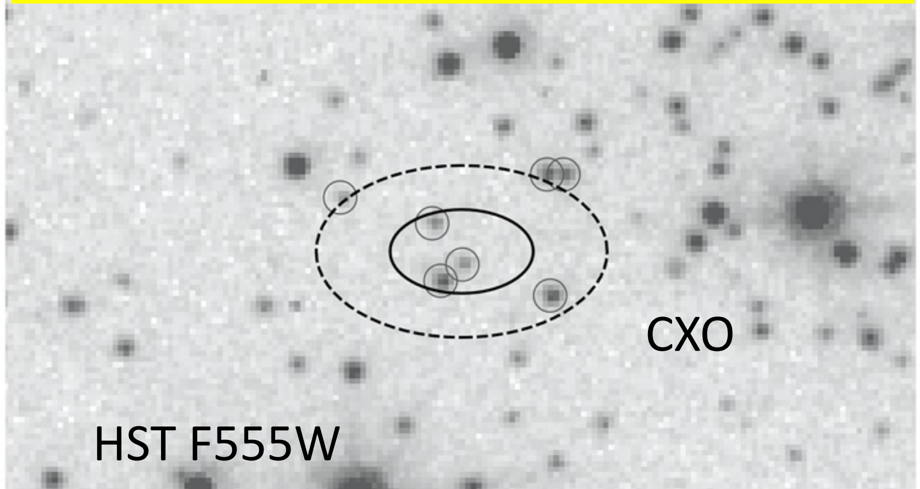
Selected by a group of High-School students
in a stage at INAF/IASF Milano in 2017, September

A puzzling flaring source

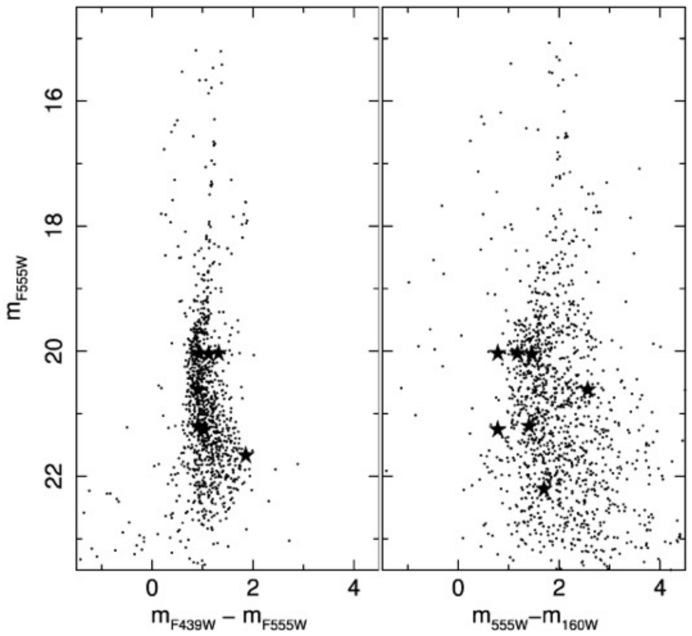
Short term Var.



Mereghetti+2018, A&A, 616, 36

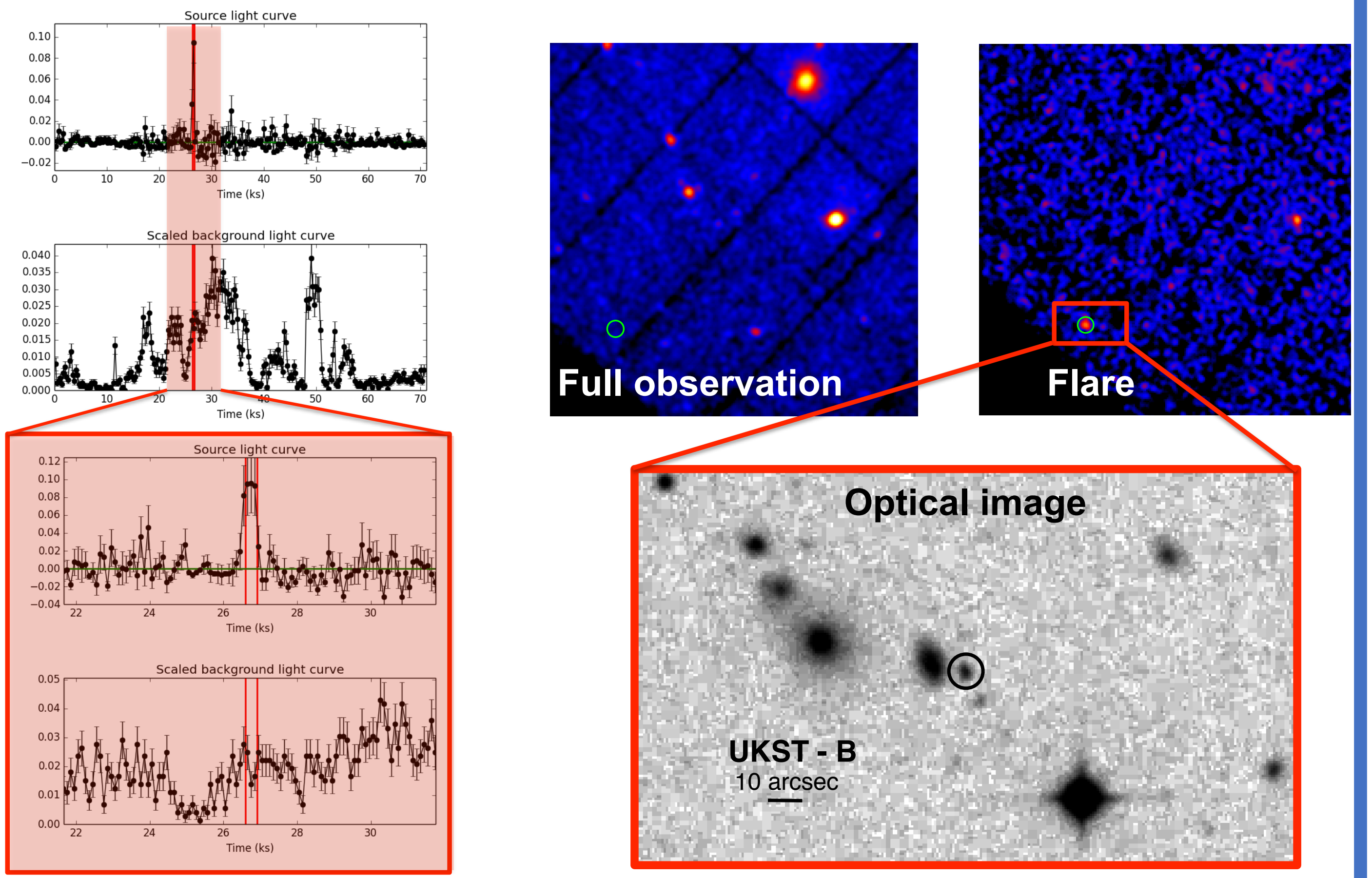


- Aligned with Globular Cluster NGC6540
- Type-I burst from a LMXB in NGC6540? *too faint*
- Flare from a G/K star in NGC6540? *too short*
- Flare from a foreground M dwarf? *ruled out by HST photometry*



A distant SN shock breakout

New transient



Novara+2020, ApJ 898, 37

315s duration

z=0.092± 0.003
(424 Mpc)

Peak luminosity:
4.3x10^{43} erg s^{-1}
(0.3-10 keV)

Total energy:
1.7x10^{46} erg

Similar to SN2008D
(Soderberg+ 2008)

Event rate broadly consistent with the one of ccSNe from optical data

Puzzling pulses from PSR J1311-3430

Short term Var.

Selected based on # of BBs and slope changes

An extreme Black Widow system, known to emit MWL flares

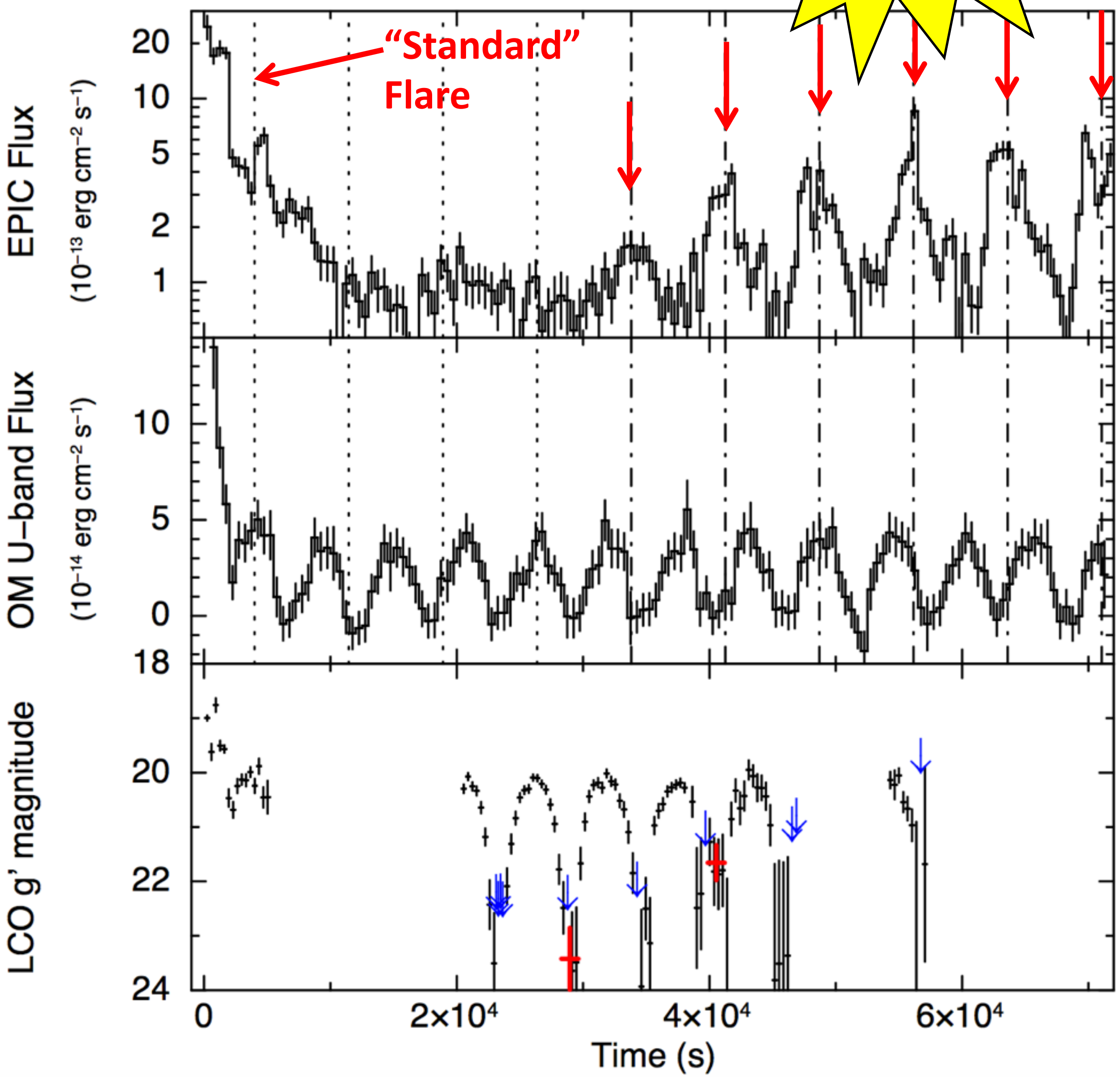
Six "pulses" with regular recurrence time

P = 7450±40 s (~124 min)
≠ P_{orb} ~5628 s (~ 94 min)

Pulses only seen in X-rays

Initial flare seen both in U and in g'

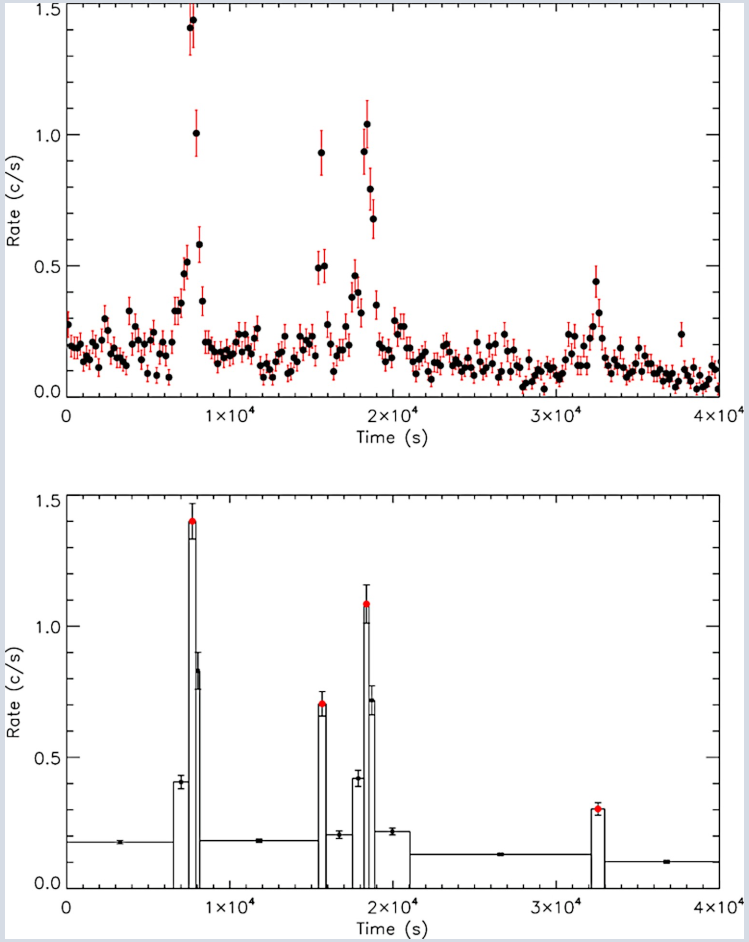
De Luca+2022, A&A 667, L7



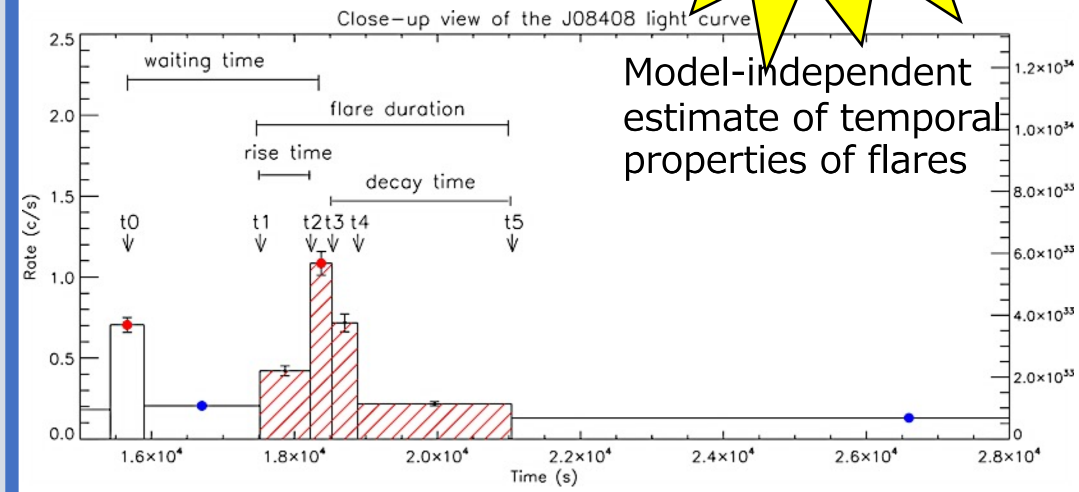
Statistical properties of SFXT flares

Short term Var.

Based on BB light curves:
144 flares from 9 sources

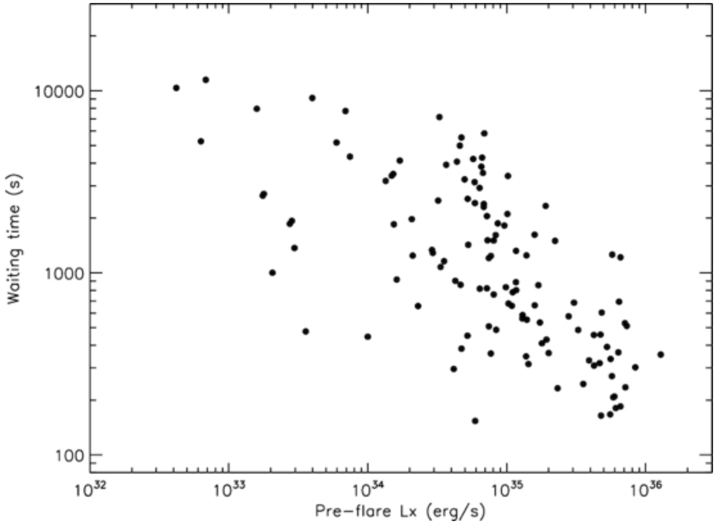


Sidoli+2019, MNRAS 487, 420



Model-independent estimate of temporal properties of flares

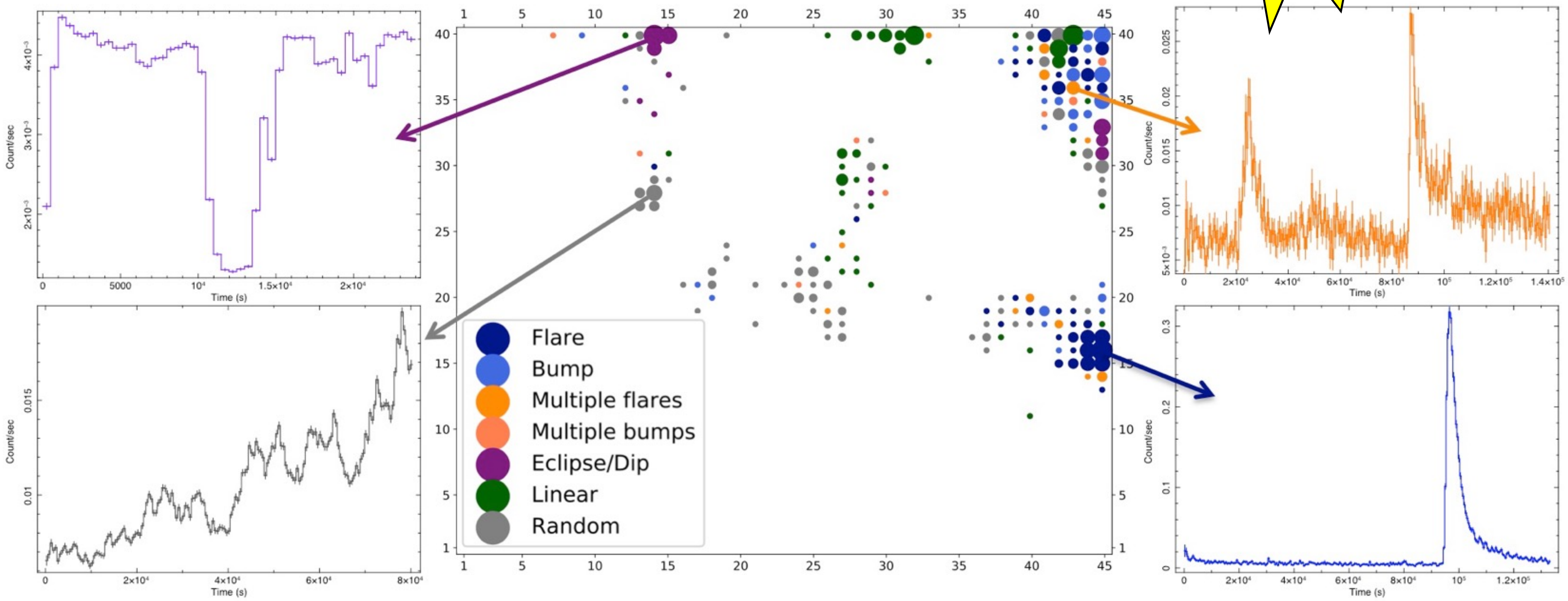
Correlation of flares temporal properties vs. other emission properties



Properties of SFXT flares consistent with onset of R-T instability in accreting plasma near the NS magnetosphere.

Classification of variability with SOM

Machine learning



Self Organizing Maps – dimensionality reduction and clustering

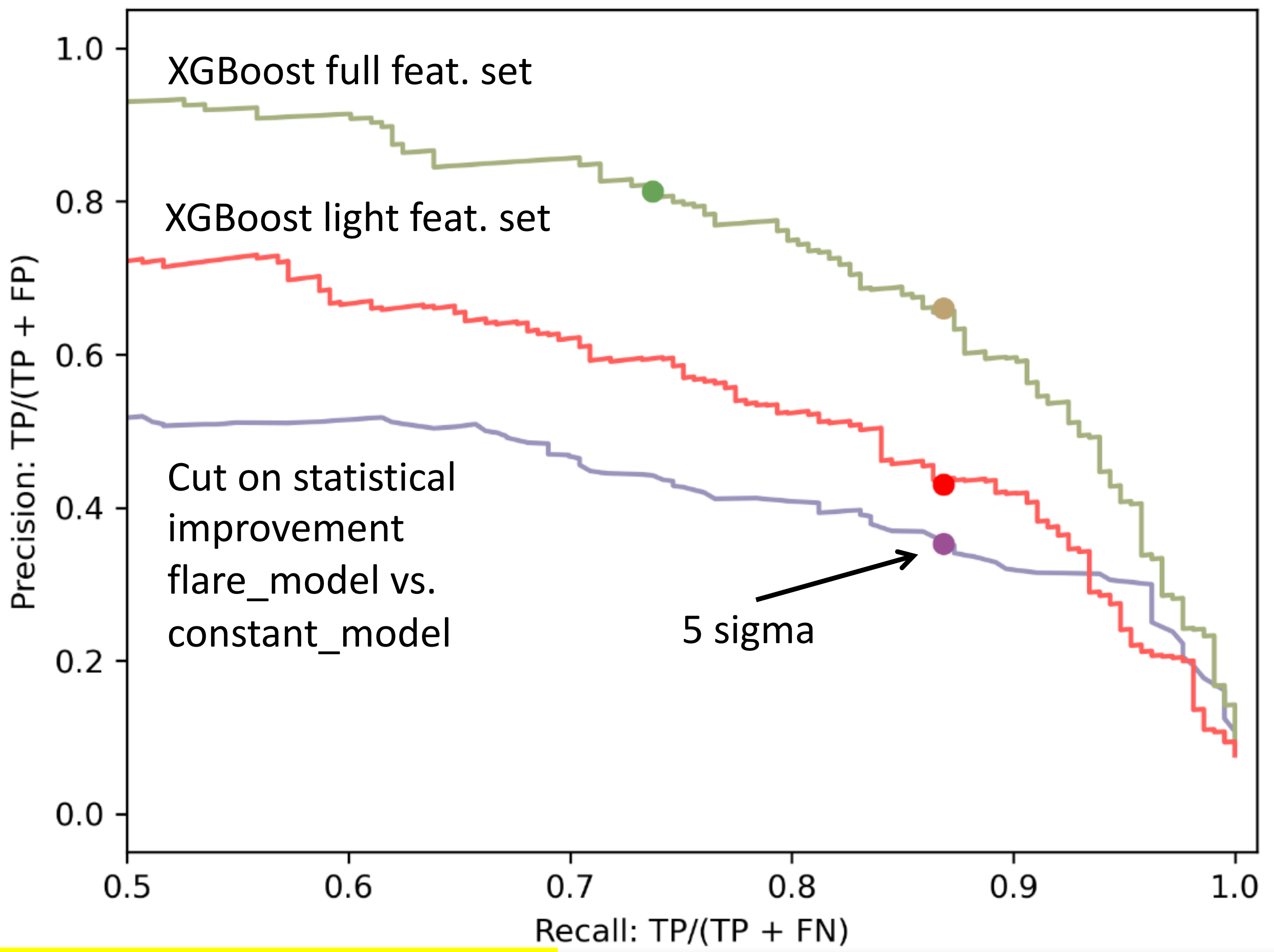
Based on 31 temporal domain features

Kovacevic+2022, A&A 659, A66

Variable sources are clustered -- distinctive regions of the SOM map associated with flares, eclipses, dips, linear light curves, and others.

Supervised search for flares

Machine learning



Pasquato+2024, in prep

Sample of stellar flares generated via visual inspection

Test different selection approaches

- XGBoost trained on full set of temporal features
- XGBoost trained on temporal features excluding model-dependent ones
- Simple cut on statistical improvement of flare model over constant model

Conclusions

- At the end of 2016, the EXTraS project had produced the most sensitive and thorough search for, and characterization of temporal variability in the soft X-ray sky.
- All results had been released to the community in a public archive. Archive discontinued in mid 2020; products available upon request
- EXTraS results and products are proving to be a very rich resource for investigations in almost all fields of astrophysics
- Updated pipelines for aperiodic variability and pulsations
- Machine learning approach is being tested to screen and classify results
- Deep learning approach is being tested to search for specific phenomena in time series

huge amount of information in serendipitous X-ray data in the time domain

very large space for discoveries

Lessons learnt from XMM will be crucial for a full exploitation of results from future experiments