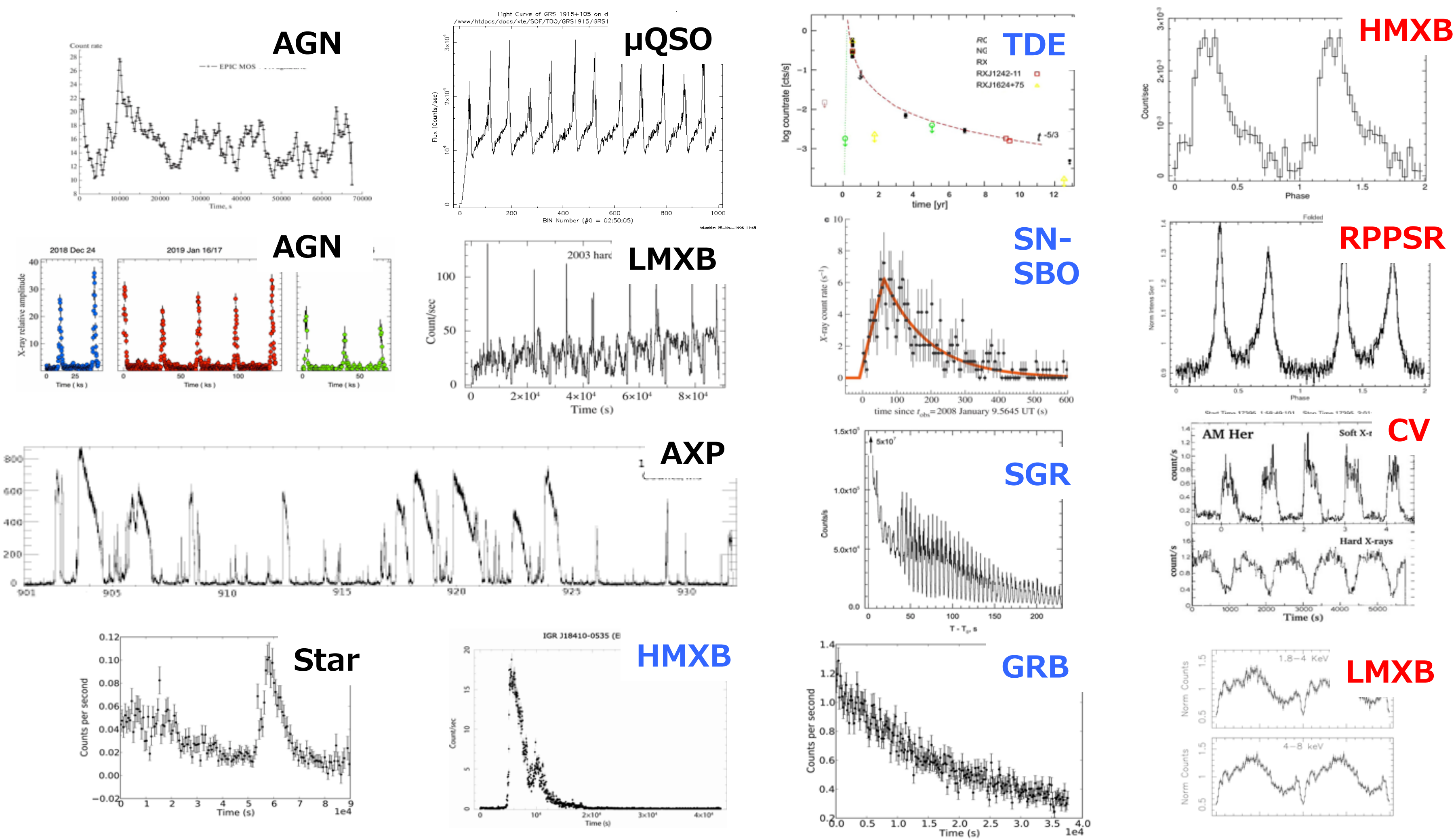
Exploring the X-ray Transient and variable Sky

Andrea De Luca
INAF/IASF Milano

Variability pervades the cosmos

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



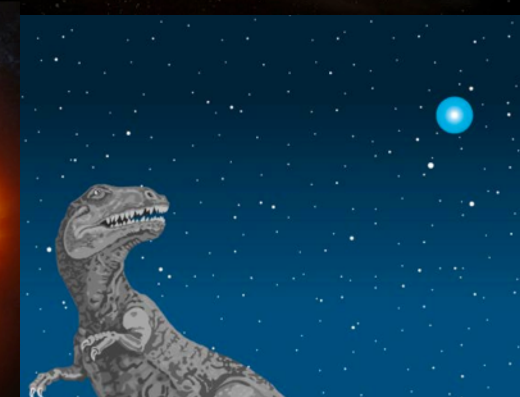
From variability to physics

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

EXTraS goals:

- extract all temporal domain information from XMM/EPIC data (mostly unexplored in ESA/XMM-SSC catalogues);
- characterise it;
- release it to the community in an easy-to-use form

→ ***new science***

Funded by EU
FP7-Space-2013-1
2014-2016

The EXTraS collaboration: A. De Luca (PI), 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

Full details: De Luca+2021, A&A in press, arXiv:2105.02895

Project coordination

INAF ISTITUTO NAZIONALE DI ASTROFISICA — A. De Luca

Based at IASF-Milano.

- 5 participating institutions.
- 370 person-months (96 INAF), 2014-2016

1. Aperiodic variability

INAF ISTITUTO NAZIONALE DI ASTROFISICA — A. Belfiore

400,000 XMM sources, time scales 1s – tens of hrs

- Light curves, hardness ratios, CDFs, power spectra
- set of parameters describing variability

2. Periodicity

INAF ISTITUTO NAZIONALE DI ASTROFISICA — G.L. Israel

>300,000 XMM sources, time scales <1s – hrs

- algorithm accounting for broad-band noise
- PDS, U.L. on pulsed fraction / folded light curves

3. New transients

IUSS — A. Tiengo

Missed by standard src detect. >7,800 XMM observations

- Bayesian Blocks, time scales <5,000 s
- time, duration, detect. params. in 5 energy ranges

4. Long-term variability

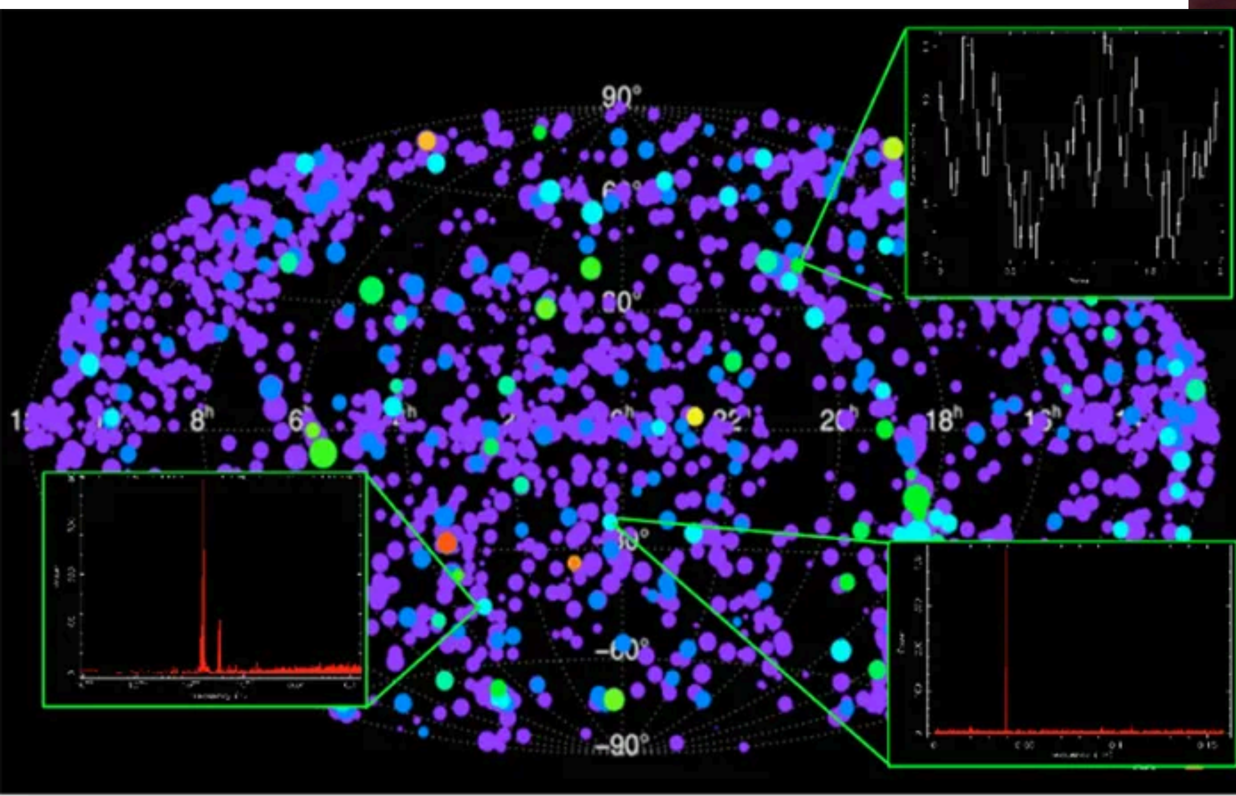
University of Leicester — S. Rosen

>400,000 XMM sources, between different observations

- LCs with detections & U.L. using pointed & slew data
- set of parameters describing variability

The CATS@BaR project

- Systematic search for pulsations in Chandra/ACIS data
- Started in 2012, led by G.L. Israel
- INAF project



- Same algorithm implemented in EXTraS
- Living project
- Analysis of **15 yr of data (430,000 time series)** published by Israel+2016, MNRAS 462, 4371

Results & products

- More than 30 refereed papers, several ESA and INAF PR
- 13 XMM-Newton proposals (3 LPs) totalling ~2.4 Ms
- 4 Chandra proposals totalling ~150 ks

Science highlights in next slides

- EXTraS Public Data Archive
  - results on temporal properties of >400,000 XMM sources in a fully searchable database
  - more than 20 million downloadable products
- results on >200,000 XMM sources based on more recent data (internal); >110 new pulsators (XMM and CXO data)

Scientific exploitation still preliminary

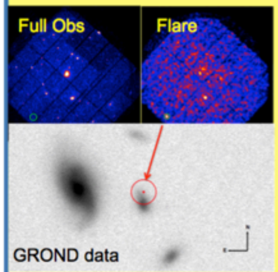
Recovered ~30% of XMM observing time discarded by standard analysis

Reference for any current and future experiment in the time domain

- large set of software tools (mostly released via the EXTraS web site)
- the EXTraS portal, a science gateway service

Science with EXTraS

A distant SN shock breakout candidate



315s duration

z=0.092± 0.003 (424 Mpc)

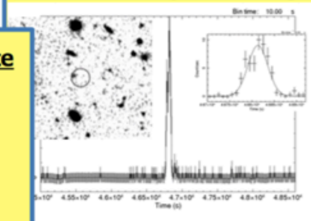
Peak luminosity: *4.3×10^{43} erg s^{-1}* (0.3-10 keV)

Total energy: E ~ 1.7×10^{46} erg

Similar to SN2008D

Novara et al., 2020, ApJ 898, 37

A low-luminosity GRB at high redshift



Flux → 8×10^{-12} erg/(cm^{2}s)

Duration → 80 s

host spectroscopy → z > 2

E ~ 10^{49} erg

Salvaterra et al., in preparation

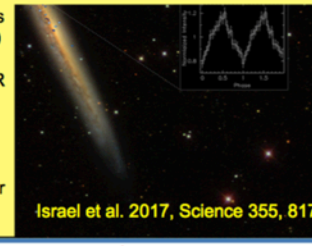
Discovery of pulsations in NGC 5907 ULX-1

Lx~1.6×10^{41} erg/s (>500 Eddington)

Brightest PSR ever detected

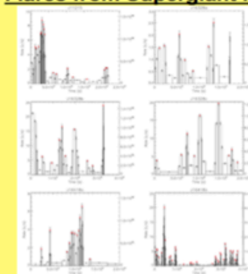
Extreme Pdot

A challenge for accretion theory



Israel et al. 2017, Science 355, 817

Flares from Supergiant Fast X-ray transients

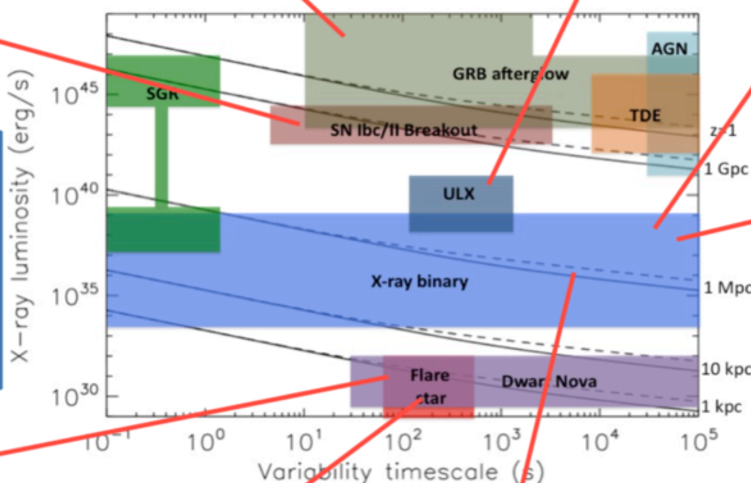


Using EXTraS Bayesian Blocks light curves

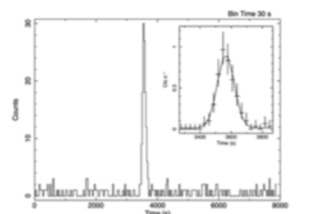
Sample of 144 flares from 9 sources

Statistical properties of flares point to Rayleigh-Taylor instability in accreting plasma

Sidoli et al., 2019, MNRAS 487,420



The unknown



(selected by six high-school students!)

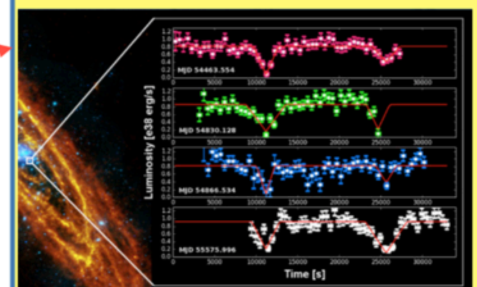
1-minute flare from globular cluster NGC 6540

Peak luminosity: L_f ~ 10^{34} erg/s (0.3-10 keV)

Properties defy any classification

Mereghetti et al. 2018, A&A 616, A36

Periodic dips and pulsations in the brightest source in M31



13 dips in 40 observations with P ~ 4 hr

L_X = 1-3 10^{38} erg/s (0.2-12 keV)

(spin) Pulsations at ~3 s
4.15 h (orbital) modulation

Most luminous LMXB dipper known

It dominates hard X-ray emission of M31

Marelli et al., 2017, ApJ 851, L27
Rodriguez et al., 2018, ApJL 861, L26

A superflare from an L dwarf

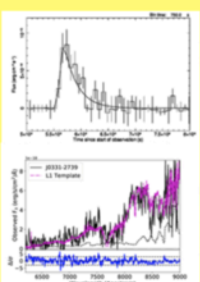
E ~ 2×10^{33} erg

No other flares in 3.5Ms of XMM data

VLT/VIMOS Spectrum → an L1 ultracool dwarf

The coolest star ever detected in X-rays

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



De Luca et al., 2020, A&A 634, L13

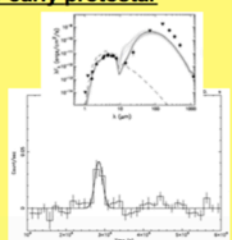
A flare from a very early protostar

Position → CRBR51 a known YSO

Spectrum → highly absorbed stellar flare

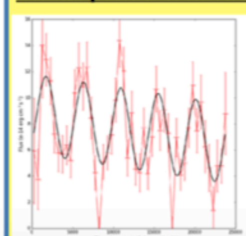
SED → class 0/1 YSO !

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



Pizzocaro et al., 2016, A&A 587, 36

Orbital period of nova M31N 2013-01b



One of the most luminous and fastest novae ever detected in M31

Discovered P=1.28h
One of the few systems below 2-3h "period gap"

It harbours a massive white dwarf and a very low-mass companion

Marelli et al., 2018, ApJ 866, 155

Science with EXTraS

A low-luminosity GRB at high redshift

Flux → 8x10^{-12} erg/(cm^{2}s)

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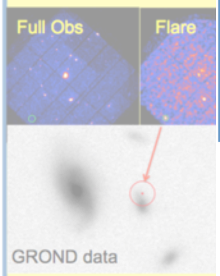
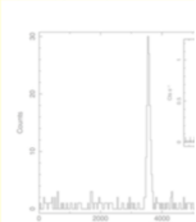


Novara et al., 2020, ApJ 8



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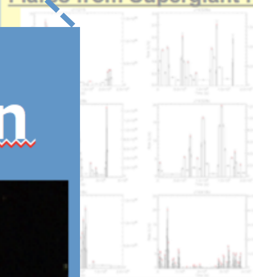

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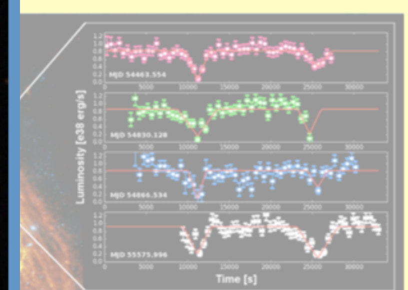


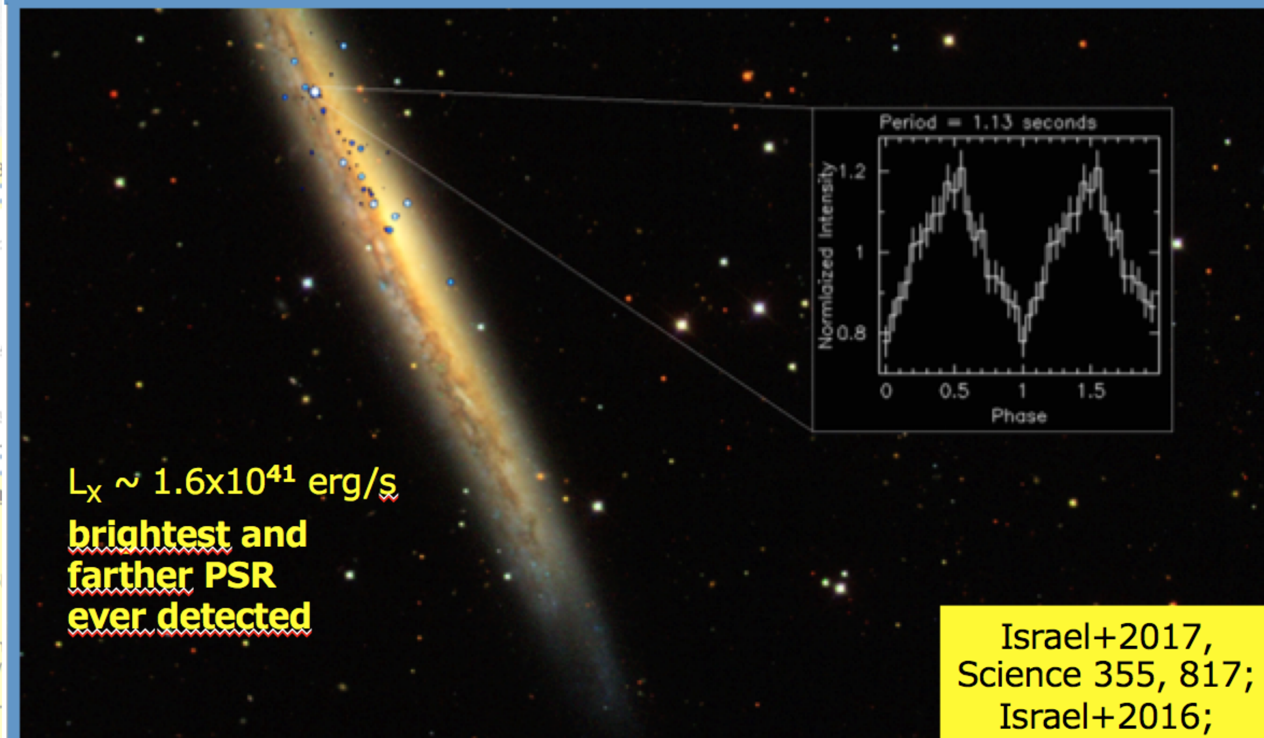
in 40 observations
4 hr
10^{38} erg/s
keV)
ulsations at ~3 s
orbital) modulation

Most luminous LMXB dipper known

It dominates hard X-ray emission of M31

Marelli et al., 2017, ApJ 851, L27
Rodriguez et al., 2018, ApJL 861, L26

NGC5907 ULX-1 & the *PULX* revolution



L_X ~ 1.6x10^{41} erg/s

brightest and farther PSR ever detected

Israel+2017, Science 355, 817; Israel+2016;

- **A further PULX was found (NGC7793 P13)**
- **Triggered a paradigm shift in ULX field**
- **Large boost to observational & theoretical efforts**

Science with EXTraS

A distant SN shock breakout candidate

315s duration

z=0.092

Total energy:
1.7×10^{46} erg

Similar to SN2008D
(Soderberg+ 2008)

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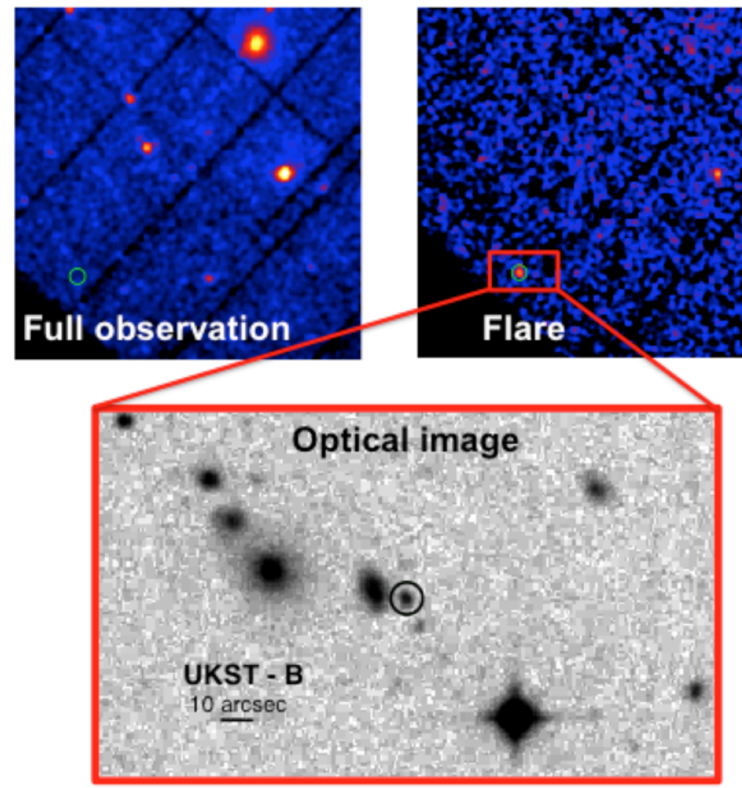
ApJ 898, 37



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Full Obs / Flare / GROND data

315s duration

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Salvaterra

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A flare

Position ... a known ...

Spectrum ... absorbed

SED → class 0/1 YSO !

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

Pizzocaro et al., 2016, A&A 587, 36

below 2-3h "period gap"

It harbours a massive white dwarf and a very low-mass companion

Marelli et al., 2018, ApJ 866, 155

Science with EXTraS

Statistical properties of SFXT flares

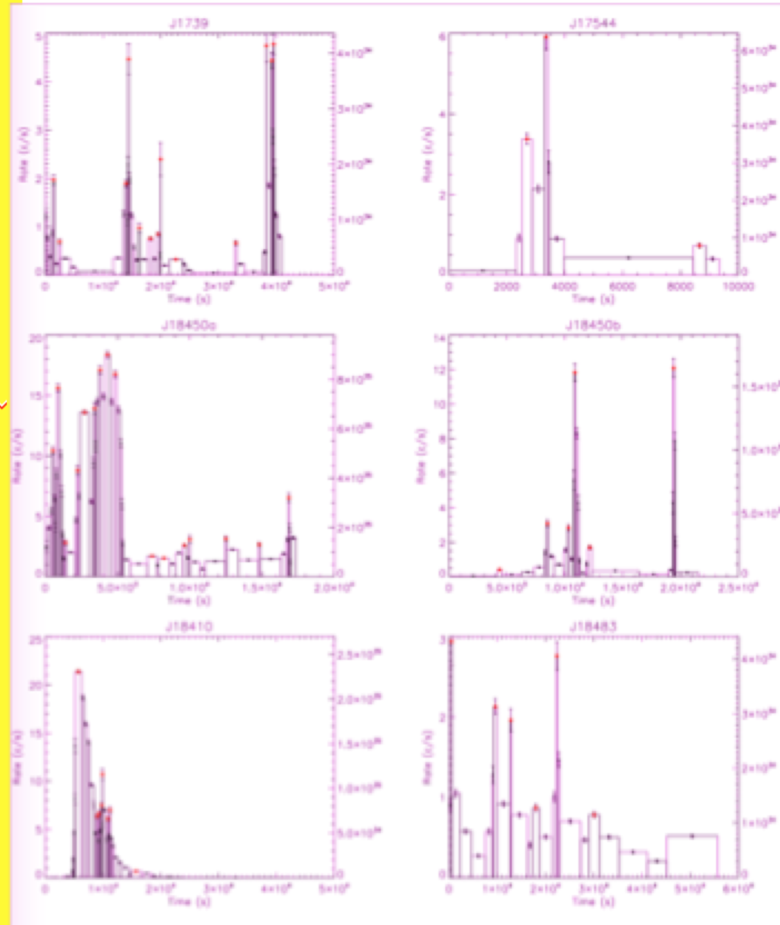
Based on Bayesian Blocks light curves

144 flares from 9 sources

Model-independent estimate of temporal properties of flares

Onset of R-T instability in accreting plasma near the NS magnetosphere.

Sidoli+2019, MNRAS 487, 420



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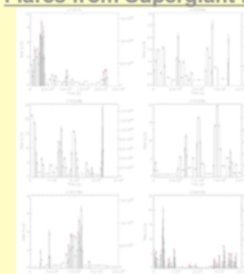

Using EXTraS Bayesian Blocks light curves

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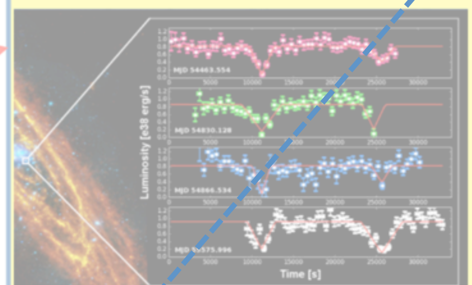

13 dips in 40 observations with P ~ 4 hr

Most luminous LMXB dipper known

L_X = 1-3 10^{38} erg/s (0.2-12 keV)

It dominates hard X-ray emission of M31

(spin) Pulsations at ~3 s

4.15 h (orbital) modulation

Marelli et al., 2017, ApJ 851, L27

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a tiny star is a mistery

De Luca et al., 2020, A&A 634, L13

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

Pizzocaro et al., 2016, A&A 587, 36

It harbours a massive white dwarf and a very low-mass companion

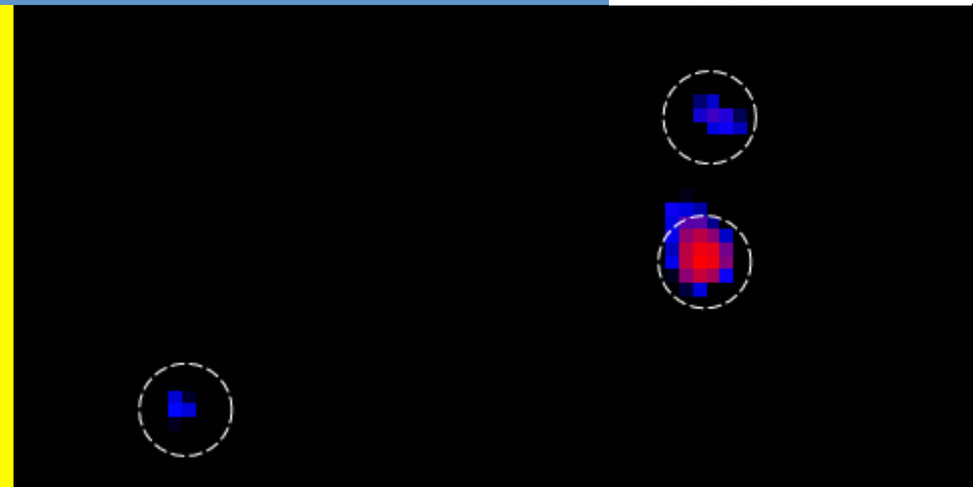
Marelli et al., 2018, ApJ 866, 155

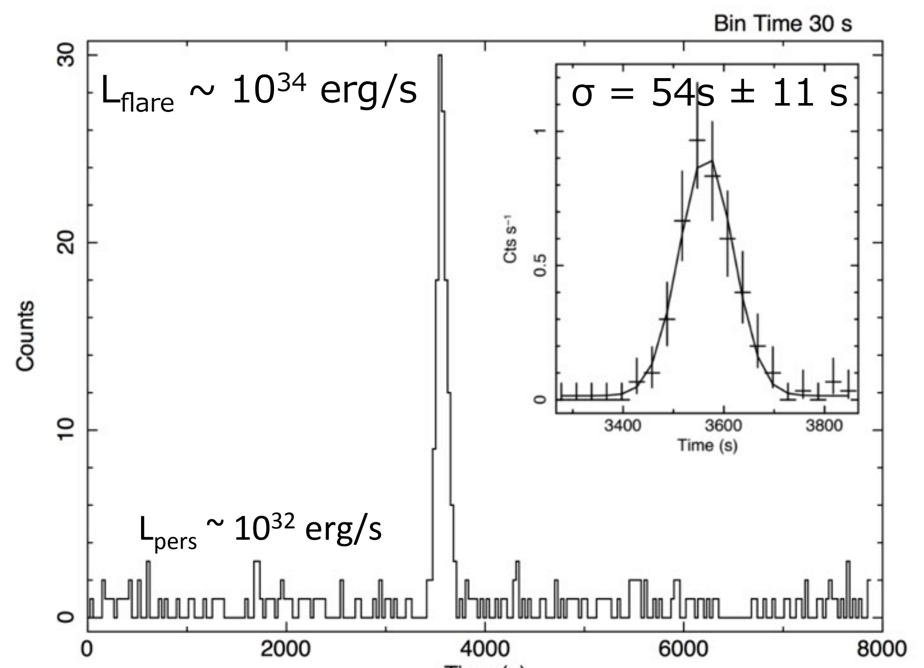
A puzzling flaring source

Selected by a group of high-school students during a stage at IASF Milano

Aligned with GC NGC6540, the flare defies any standard interpretation

Mereghetti+2018, A&A 616, A36





Didactic program developed within the EXTraS project and implemented within the Alternanza Scuola-Lavoro program.

Students are involved in screening and classification of light curves

Our educational activity could turn into an interesting citizen science experiment

Our team

IASF Milano
A. De Luca
M. Marelli
S. Mereghetti
R. Mignani
R. Salvaterra
L. Sidoli
A. Belfiore (TD)
M. Kovacevic (AdR)

OA-Roma
G.L. Israel
A. Miraval Zanon (Adr)

IASF Palermo
F. Pintore
G. Rodriguez

IUSS Pavia
A. Tiengo
P. Esposito (RTDB)

NYU Abu Dhabi
M. Pasquato

	FTE 2021	FTE 2022	FTE 2023
INAF	TI 2.05	TI 2.05	TI 2.05
	TD 0.6	*TD 0.1*	*TD 0.0*
Associates	TI 0.1	TI 0.1	TI 0.1
	TD 0.0	*TD 0.0*	*TD 0.1*

Coordination
A. De Luca

Aperiodic variability
A. De Luca
M. Marelli
S. Mereghetti
F. Pintore
R. Salvaterra
L. Sidoli
A. Belfiore
A. Tiengo

Search for pulsations
G.L. Israel
G. Rodriguez
L. Sidoli
A. Belfiore
A. Miraval Zanon
P. Esposito

Unsupervised Machine-Learning
A. De Luca
M. Marelli
R. Salvaterra
M. Kovacevic
M. Pasquato

Supervised Machine-Learning
A. De Luca
M. Marelli
R. Mignani
R. Salvaterra
M. Kovacevic
A. Tiengo
M. Pasquato

Interpretation of results
All team members are contributing

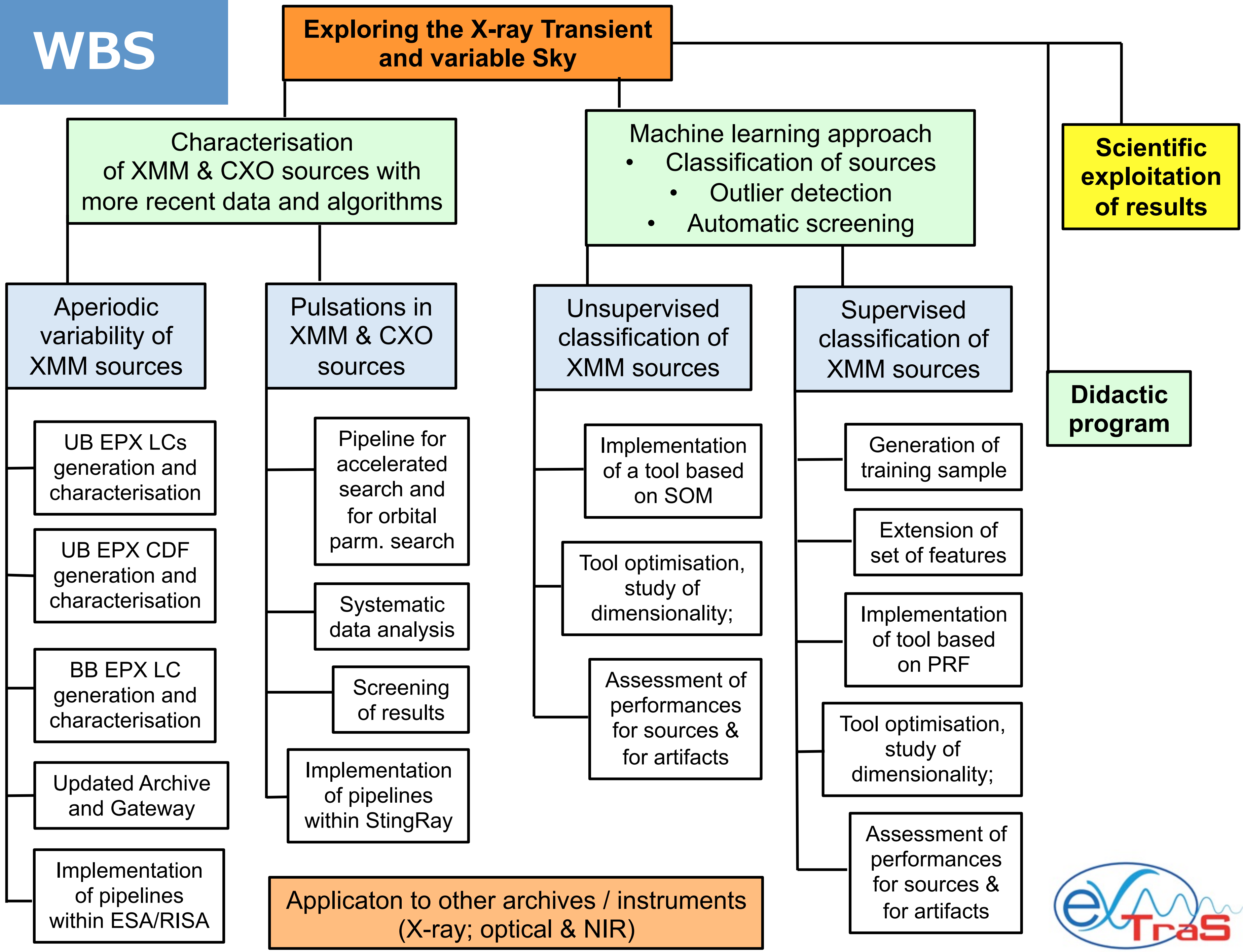
Fundings

- EXTraS funded by EC (FP7-SPACE GA 607452, 2014-2016)
  - EC contribution to the consortium 2.479 M€
  - INAF share: 507 k€
- Additional fundings within ASI-INAF AAE (2017-2019)
  - 1° call 80 k€ - ULTraS project (PI A. De Luca)
  - 2° call 122 k€ - PulsULTraS project (PI G.L. Israel)
- We have no fundings dedicated to the project
- We are seeking for opportunities in the future

INAF Leadership

- INAF – IASF Milano in particular – had a key role in all phases of the XMM-Newton mission
- Such expertise was crucial for the success of the EXTraS project, led by INAF
- Our team has a lead position in (archival) time domain investigations (best software tools and expertise, huge set of results and products)
- Lead position in science
- We firmly intend to continue this success story by extending our activities

WBS


Exploring the X-ray Transient and variable Sky
Characterisation of XMM & CXO sources with more recent data and algorithms
Machine learning approach
• Classification of sources
• Outlier detection
• Automatic screening
Scientific exploitation of results
Aperiodic variability of XMM sources
Pulsations in XMM & CXO sources
Unsupervised classification of XMM sources
Supervised classification of XMM sources
Didactic program
UB EPX LCs generation and characterisation
UB EPX CDF generation and characterisation
BB EPX LC generation and characterisation
Updated Archive and Gateway
Implementation of pipelines within ESA/RISA
Pipeline for accelerated search and for orbital parm. search
Systematic data analysis
Screening of results
Implementation of pipelines within StingRay
Implementation of a tool based on SOM
Tool optimisation, study of dimensionality;
Assessment of performances for sources & for artifacts
Generation of training sample
Extension of set of features
Implementation of tool based on PRF
Tool optimisation, study of dimensionality;
Assessment of performances for sources & for artifacts
Applicaton to other archives / instruments (X-ray; optical & NIR)
eXTraS

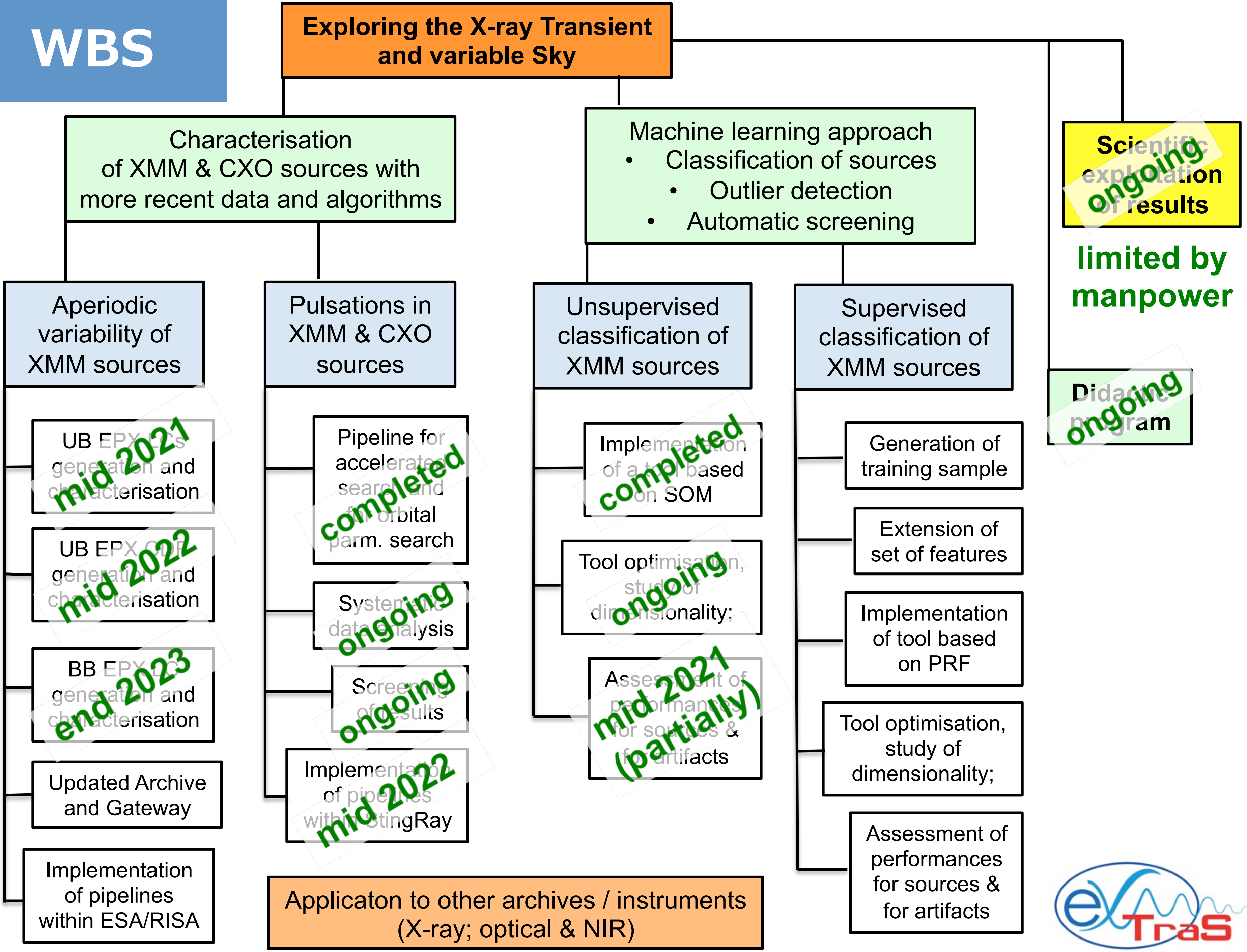
Criticalities

- No dedicated fundings
- Lack of manpower limits planned developments
- Expertise in machine learning approaches contributed by a young scientist (AdR) and by a collaborator (INAF associated).

  → Our team needs to be strengthened

- Computing time and storage. Availability of computing resources within the CHIPP initiative has been crucial. We were also awarded computing time at CINECA.

WBS



Exploring the X-ray Transient and variable Sky
Characterisation of XMM & CXO sources with more recent data and algorithms
Machine learning approach
• Classification of sources
• Outlier detection
• Automatic screening
Scientific exploitation of results
ongoing
limited by manpower
Didactic program
ongoing
Aperiodic variability of XMM sources
UB EPX LCs generation and characterisation
mid 2021
UB EPX CLR generation and characterisation
mid 2022
BB EPX LCs generation and characterisation
end 2023
Updated Archive and Gateway
Implementation of pipelines within ESA/RISA
Pulsations in XMM & CXO sources
Pipeline for accelerated search and for orbital parm. search
completed
Systematic data analysis
ongoing
Screening of results
ongoing
Implementation of pipelines within StingRay
mid 2022
Unsupervised classification of XMM sources
Implementation of a tool based on SOM
completed
Tool optimisation, study of dimensionality;
ongoing
Assessment of performances for sources & for artifacts
mid 2021 (partially)
Supervised classification of XMM sources
Generation of training sample
Extension of set of features
Implementation of tool based on PRF
Tool optimisation, study of dimensionality;
Assessment of performances for sources & for artifacts
Applicaton to other archives / instruments (X-ray; optical & NIR)

An invitation to the INAF community

Results and products on >400,000 sources are available online

New results and products on additional 200,000 sources (sample is growing)

Set of tools also available

Data access from www.extras-fp7.eu

Please contact us!

We would be glad to collaborate, to maximize science extraction from this gold mine