



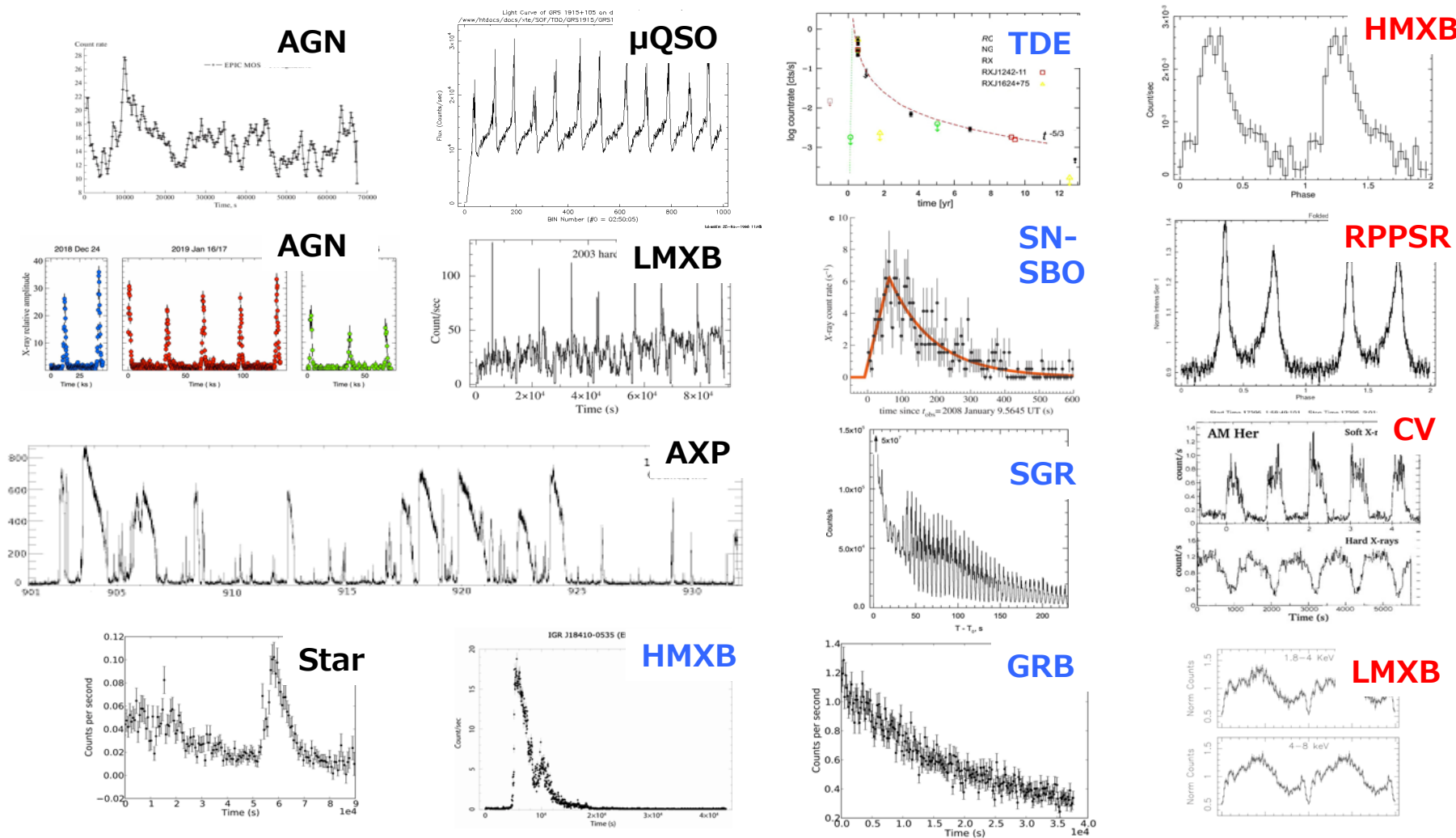
Exploring the X-ray Transient and variable Sky

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

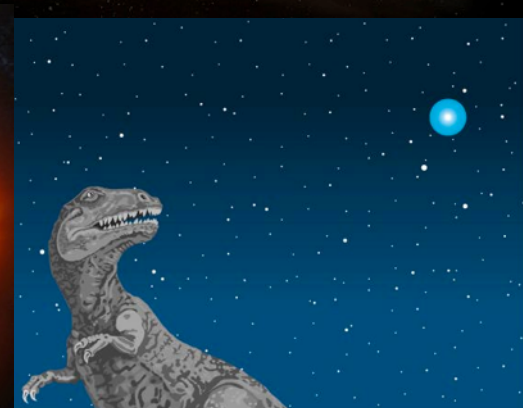
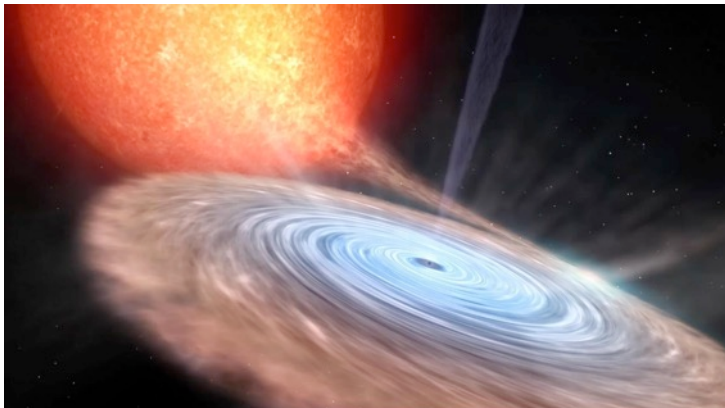
- radiation efficiency of accretion flows
- generation of winds and jets
- role of magnetic field

Strong gravity physics

Mechanisms behind massive stars explosions

Physics of B-field generation and dynamics

- in compact objects
- in normal stars



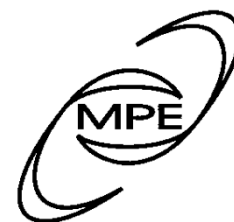
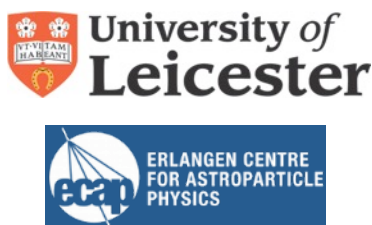
The EXTraS project



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](https://arxiv.org/abs/2105.02895)



Project coordination



A. De Luca

Based at IASF-Milano.

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

1. Aperiodic variability



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



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



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



S. Rosen

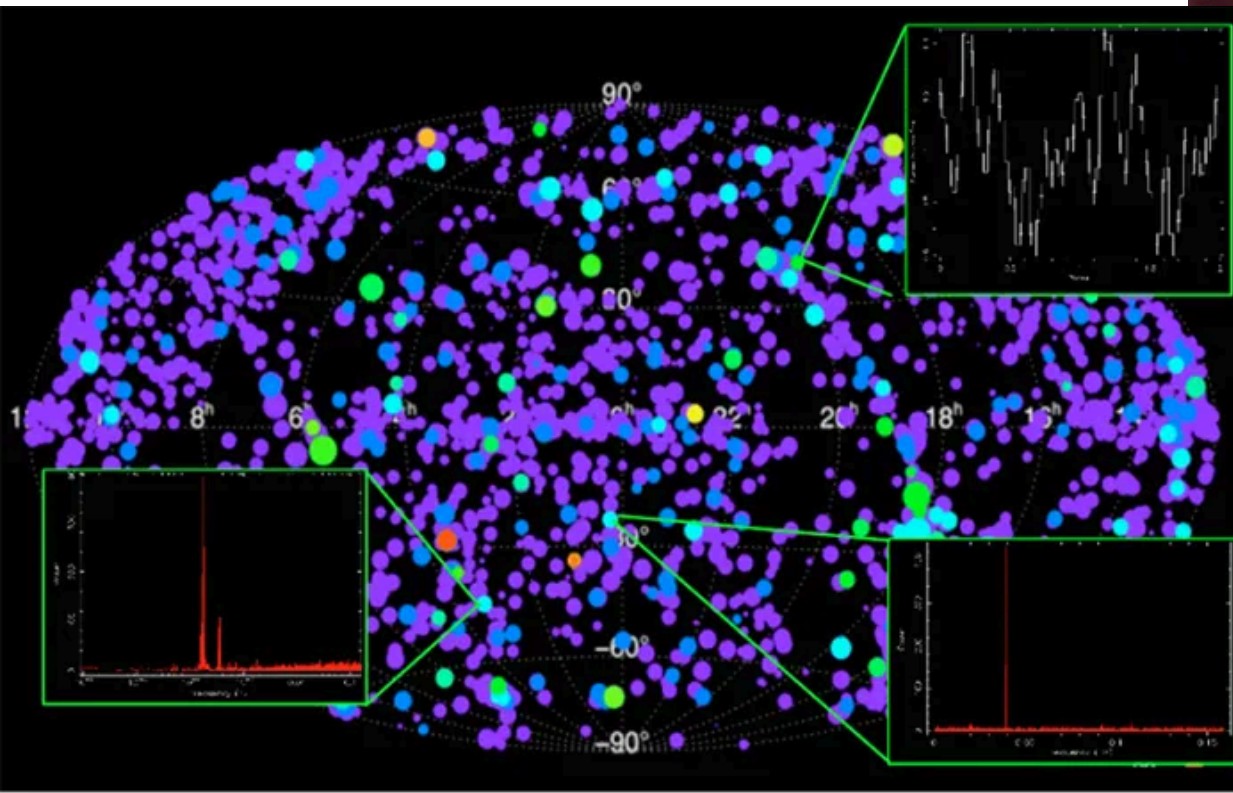
>400,000 XMM sources, between different observations

- 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

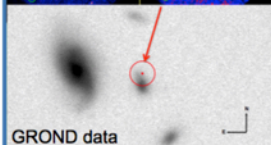
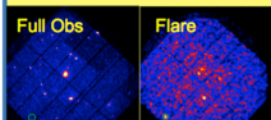
**Reference
for any current
and future
experiment in the
time domain**

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

Science with EXTras



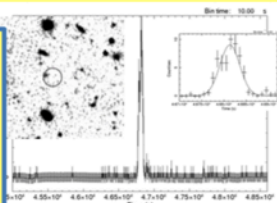
A distant SN shock breakout candidate



Novara et al., 2020, ApJ 898, 37

315s duration
 $z=0.092 \pm 0.003$
 (424 Mpc)
 Peak luminosity:
 $4.3 \times 10^{43} \text{ erg s}^{-1}$
 (0.3-10 keV)
 Total energy:
 $E \sim 1.7 \times 10^{46} \text{ erg}$
 Similar to SN2008D

A low-luminosity GRB at high redshift

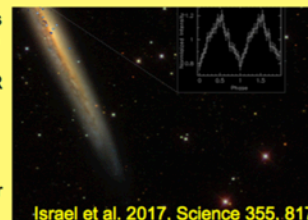


Salvaterra et al., in preparation

Flux \rightarrow
 $8 \times 10^{-12} \text{ erg/(cm}^2\text{s)}$
 Duration \rightarrow 80 s
 host spectroscopy
 $\rightarrow z > 2$
 $E \sim 10^{49} \text{ erg}$

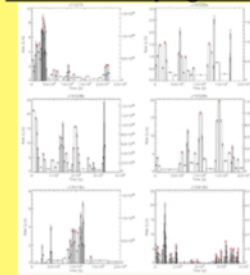
Discovery of pulsations in NGC 5907 ULX-1

$L_x \sim 1.6 \times 10^{41} \text{ erg/s}$
 (>500 Eddington)
 Brightest PSR
 ever detected
 Extreme Pdot
 A challenge for
 accretion theory



Israel et al. 2017, Science 355, 817

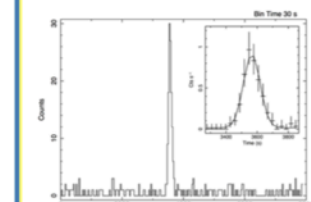
Flares from Supergiant Fast X-ray transients



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

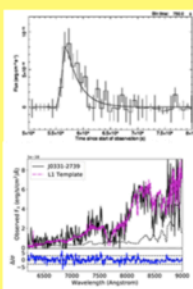


1-minute flare from globular
 cluster NGC 6540
 Peak luminosity:
 $L_f \sim 10^{34} \text{ erg/s}$ (0.3-10 keV)
 Properties defy any
 classification

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

A superflare from an L dwarf

$E \sim 2 \times 10^{33} \text{ erg}$
 No other flares in 3.5Ms
 of XMM data
 VLT/VIMOS Spectrum
 \rightarrow an L1 ultracool dwarf
 The coolest star ever
 detected in X-rays

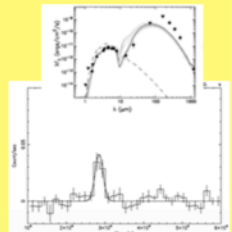


De Luca et al., 2020,
 A&A 634, L13

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

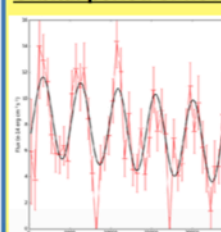
A flare from a very early protostar

Position \rightarrow CRBR51
 a known YSO
 Spectrum \rightarrow highly
 absorbed stellar flare
 SED \rightarrow
 class 0/I YSO !
 X-ray emission from
 such early proto-stars
 is poorly known



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

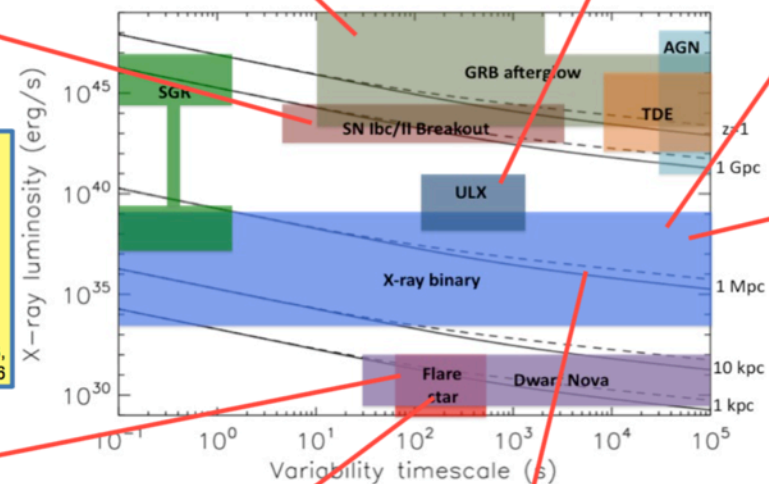
Orbital period of nova M31N 2013-01b



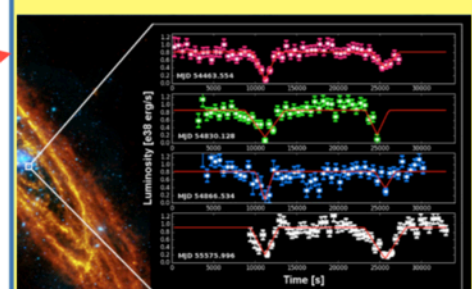
One of the most luminous
 and fastest novae ever
 detected in M31
 Discovered $P=1.28\text{h}$
 One of the few systems
 below 2-3h "period gap"

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

Marelli et al., 2018, ApJ 866, 155



Periodic dips and pulsations in the brightest source in M31



13 dips in 40 observations
 with $P \sim 4 \text{ hr}$

Most luminous LMXB
 dipper known

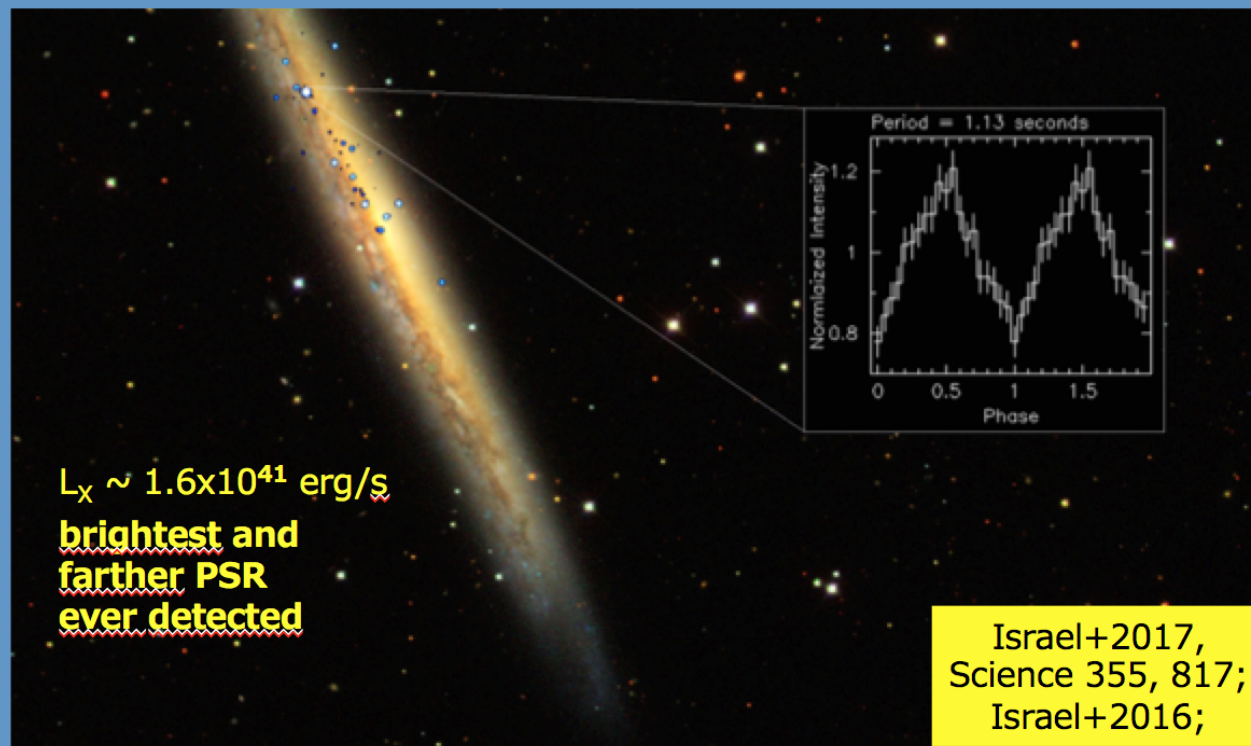
$L_x = 1-3 \times 10^{38} \text{ erg/s}$
 (0.2-12 keV)

It dominates hard X-ray
 emission of M31

(spin) Pulsations at $\sim 3 \text{ s}$
 4.15 h (orbital) modulation

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

NGC5907 ULX-1 & the *PULX* revolution



$L_x \sim 1.6 \times 10^{41}$ 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**

A low-luminosity GRB at high redshift

Flux \rightarrow
 8×10^{-12} erg/(cm²s)

Discovery of pulsations in NGC 5907 ULX-1

$L_x \sim 1.6 \times 10^{41}$ erg/s
 (>500 Eddington)

Flares from Supergiant Fast X-ray transients

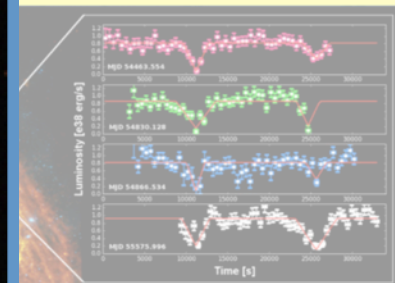
Using EXTraS
 Bayesian Blocks light
 curves

Sample of 144 flares
 from 9 sources

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

et al., 2019, MNRAS 487,420

Periodic dips and pulsations in the brightest
 in M31



in 40 observations
 4 hr

Most luminous LMXB
 dipper known

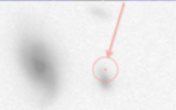
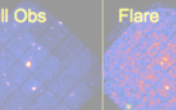
10^{38} erg/s
 keV)

It dominates hard X-ray
 emission of M31

pulsations at ~3 s
 (orbital) modulation

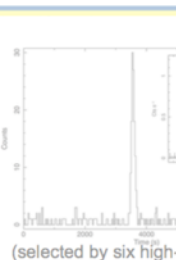
Marelli et al., 2017, ApJ 851, L27
 Rodriguez et al., 2018, ApJL 861, L26

A distant SN shock breakout candidate



GROND data

Novara et al., 2020, ApJ 8



A superflare from

$E \sim 2 \times 10^{33}$ erg

No other flares in 3.5
 of XMM data

VLT/VIMOS Spectrur
 \rightarrow an L1 ultracool dw

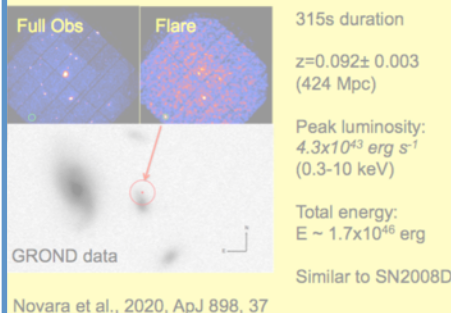
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A distant SN shock breakout candidate

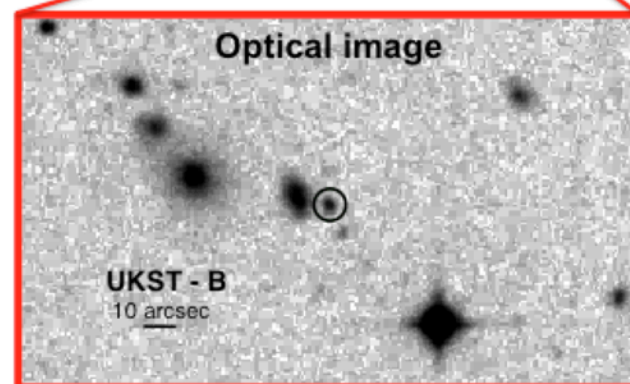
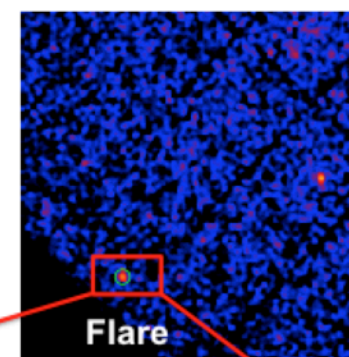
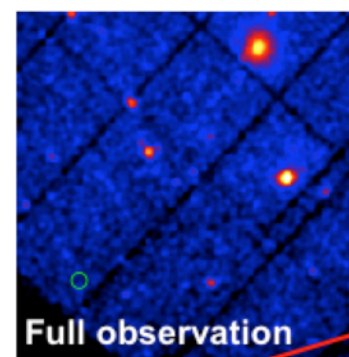
315s duration

$z=0.092$

Total energy:
 $1.7 \times 10^{46} \text{ erg}$

Similar to SN2008D
(Soderberg+ 2008)

Novara+2020,
ApJ 898, 37



The unknown

1-minute flare from globular cluster NGC 6540

Peak luminosity:
 $L_f \sim 10^{34} \text{ erg/s}$ (0.3-10 keV)

Properties defy any classification

Mereghetti et al.,
A&A 616

A superflare from an L dwarf

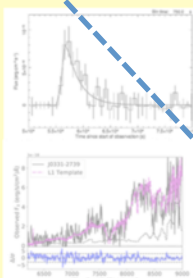
$E \sim 2 \times 10^{33} \text{ erg}$

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 mystery



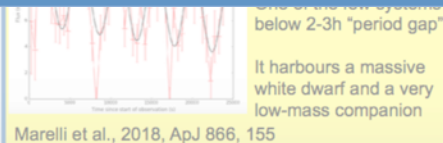
De Luca et al., 2020,
A&A 634, L13

A flare

Position
a known
Spectrum
absorbed

SED →
class 0/1 YSO !

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



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

Statistical properties of SFXT flares

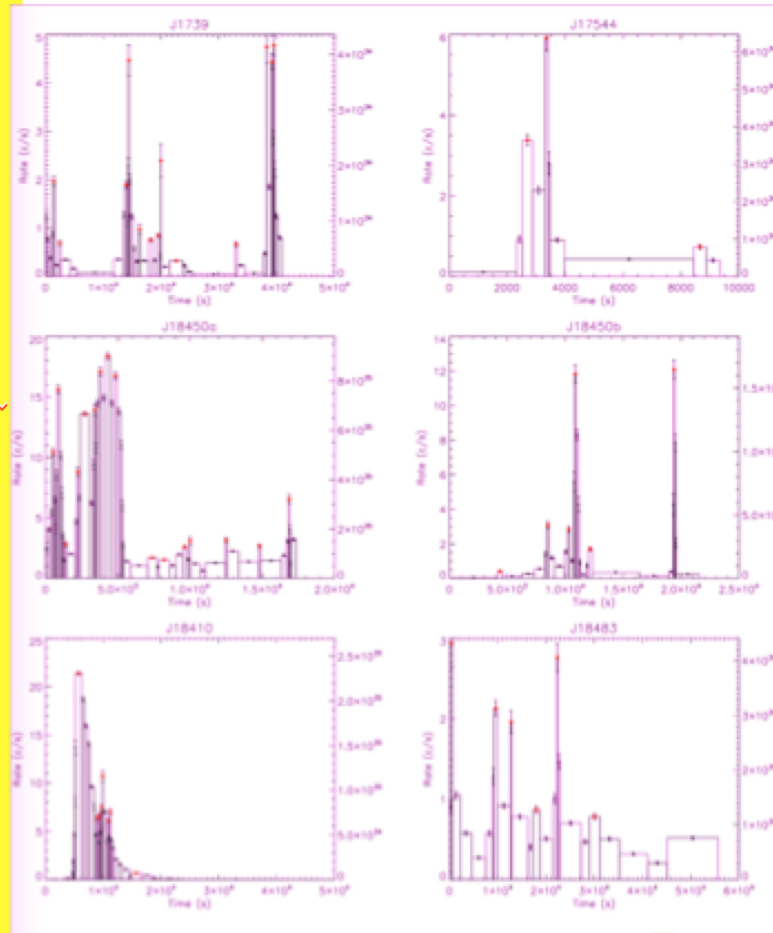
Based on Bayesian Blocks light curves

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



ULX-1



e 355, 817

z=1

1 Gpc

1 Mpc

10 kpc

1 kpc

5

b

at luminous

ae ever

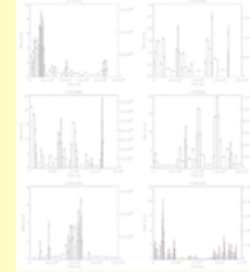
1

1.28h

systems

rod gap"

Flares from Supergiant Fast X-ray transients



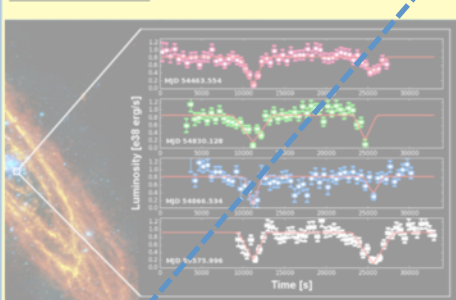
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Sample of 144 flares from 9 sources

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Sidoli et al., 2019, MNRAS 487,420

Periodic dips and pulsations in the brightest source in M31



13 dips in 40 observations with $P \sim 4$ h

$L_X = 1-3 \times 10^{38}$ 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 tiny star is a mystery

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

Marelli et al., 2018, ApJ 866, 155

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

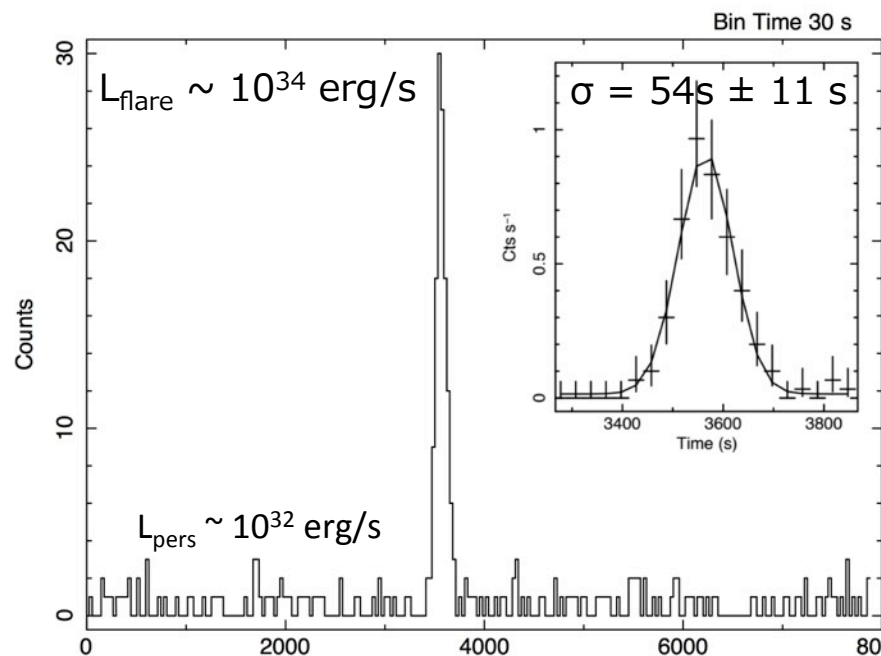
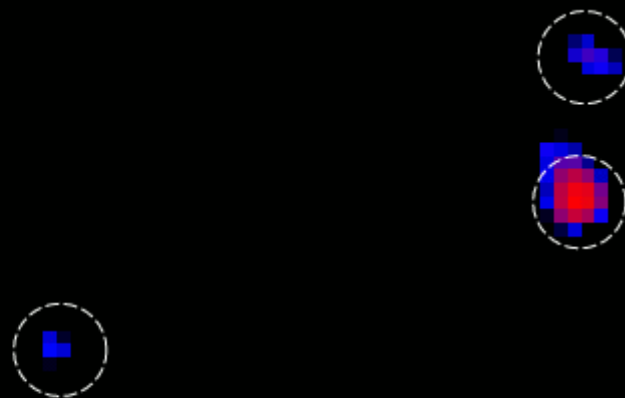
A puzzling flaring source



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



Missions

Show All Missions

Mission Home

Summary

Fact Sheet

STUDENTS DIGGING INTO DATA ARCHIVE SPOT MYSTERIOUS X-RAY SOURCE

10 August 2018

An enigmatic X-ray source revealed as part of a data-mining project for high-school students shows unexplored avenues hidden in the vast archive of ESA's XMM-Newton X-ray Observatory.



Universo INAF Sedi | Astrochannel | Progetti da Terra

HOME ASTRONOMIA SPAZIO FISICA

CON IL PROGETTO DI ALTERNANZA SCUOLA-LAVORO

Sorgente X scoperta da sei licei

L'identificazione della sorgente variabile di raggi X è stata scoperta da sei studenti del Liceo scientifico G.B. Grassi di Saronno nell'ambito del progetto X coordinato dall'Inaf. Il successo dell'esperienza nazionale di astrofisica

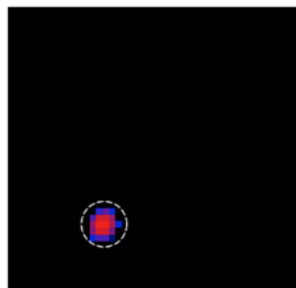
di Redazione Media Inaf Segui @mediainaf

Giovani scienziati crescono, anche grazie al progetto Alternanza scuola-lavoro, e realizzano scoperte di livello internazionale. È il caso di sei studentesse e studenti del Liceo scientifico G.B. Grassi di Saronno, Razvan Patrolea, Lorenzo Apollonio, Elena Pecchini, Cinzia

Torrenze, Bartolomeo Bottazzi-Baldi e Martino Giobbe. Il loro lavoro è stato pubblicato su Nature. Il progetto X coordinato dall'Inaf, indirizzato a studenti di liceo, ha dato così il via a una serie di indagini che si

nature > research highlights > article

nature International journal of science



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

ASTRONOMY AND ASTROPHYSICS 1
Teens stumble on a new class of X-ray object



HOME RESULTS PACKS PROJECTS & News

DE EN ES FR IT PL

Students open a new window on the universe

A group of high schoolers and researchers have discovered a new class of X-ray object. Their discovery could help us understand the nature of the universe.

SPACE

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

ASTRONOMY AND ASTROPHYSICS 1
Teens stumble on a new class of X-ray object



La scienza in classe

Il banco di prova

Quei liceali che studiano i raggi X

di TINA SIMONIELLO
Infografica di MANUEL BORTOLETTI

Sei ragazzi di uno scientifico di Saronno scoprono una sorgente variabile mai vista prima. E firmano l'articolo su una rivista di astrofisica

Sono appena usciti dal liceo, ma hanno già contribuito a individuare una sorgente celeste anomala di raggi X. Sono i sei studenti dello scientifico Giovanni Battista Grassi di Saronno che hanno partecipato a EXTrAS (Exploring the X-ray transient and variable sky), un progetto che studia la variabilità temporale delle sorgenti X coordinato dall'Inaf (Istituto Nazionale di Astrofisica).

«Dalle circa 500mila sorgenti "serendipity", cioè potenzialmente interessanti rilevate dalla missione Xmm-Newton dell'Agenzia spaziale europea, ne abbiamo selezionate 200 a emissione anomala. Un centinaio emettevano X a lampi (il cosiddetto "flame"), le altre seguendo un modello a eclissi. E le abbiamo affidate ai ragazzi», racconta Andrea De Luca, ricercatore all'Istituto di astrofisica spaziale e fisica cosmica di Milano (Ia-sf) che lo scorso anno li ha ospitati per due settimane. Studiare in che modo una sorgente astrofisica emette X nel tempo serve a comprendere la natura di quella sorgente, ad esempio se è una stella di neutroni o un buco nero. «La sorgente anomala, trovata da Razvan Florin Patrolea, Martino Giobbe, Lorenzo Apollonio, Cinzia Anna Torrenze, Elena Pecchini e Bartolomeo Bottazzi-Baldi, proviene da un ammasso globulare, un insieme di centinaia di migliaia di stelle e si trova nella nostra galassia», spiega De Luca, che è a capo di EXTrAS e ha seguito i ragazzi insieme al collega Ruben Salvaterra.

DE LUCA/ISTITUTO NAZIONALE DI ASTROFISICA



Razvan Florin Patrolea, 19 anni, (nella foto il quarto da sinistra) appena uscito dallo scientifico, studierà Fisica alla Statale: «Sono nato in Romania, ma vivo da anni a Cadorago, in provincia di Como. Sono appassionato di stelle da quando ho otto anni e ho desiderato moltissimo essere tra i sei dell'Inaf». E ci è riuscito. Razvan ha fatto parte del team di studenti del Grassi che hanno contribuito alla scoperta della nuova sorgente di radiazioni X anomala. «Se prima era un sogno, ora che ho visto come lavorano i ricercatori, so che vorrei studiare le stelle. C'è ancora così tanto da scoprire. Ecco, la ricerca ti permette di non mettere mai di mezzo il sogno. Lo so, questo è vero per ogni disciplina ma in più per l'astrofisica si ha la possibilità di farlo guardando il cielo. Io pensavo si trattasse di un'analisi "fredda", ma ho avuto la possibilità di vedere che non lo è affatto: ti fa capire moltissimo di un fenomeno».

Il progetto

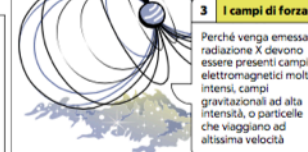
L'abc delle radiazioni cosmiche per svelare i misteri dell'universo



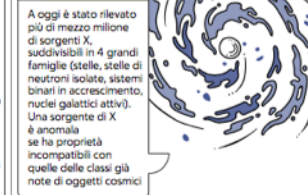
1 L'astronomia X
Nasce con Riccardo Giacconi (Nobel per la fisica nel 2002), che nel 1962 scopre Scorpius-X1, prima sorgente nota extraterrestre di raggi X.



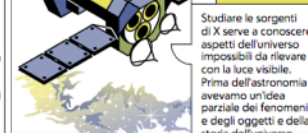
2 Gli emettitori
Tutti gli oggetti cosmici emettono radiazioni X, che è luce ad alta energia. Alcuni sono emettitori più potenti (come le stelle di neutroni e i buchi neri). La Terra è un emettitore molto debole di raggi X.



3 I campi di forza
Perché venga emessa radiazione X devono essere presenti campi elettromagnetici molto intensi, campi gravitazionali ad alta intensità, o particelle che viaggiano ad altissima velocità.



4 Le sorgenti
A oggi è stato rilevato più di mezzo milione di sorgenti X, suddivisibili in 4 grandi famiglie (stelle, stelle di neutroni isolate, sistemi binari in accrescimento, nuclei galattici attivi). Una sorgente di X è anomala se ha proprietà incompatibili con quelle delle classi già note di oggetti cosmici.



5 I dati raccolti
Studiare le sorgenti di X serve a conoscere aspetti dell'universo impossibili da rilevare con la luce visibile. Prima dell'astronomia X avevamo un'idea parziale dei fenomeni e degli oggetti e della storia dell'universo.

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
	<i>TD 0.6</i>	<i>TD 0.1</i>	<i>TD 0.0</i>
<i>Associates</i>	<i>TI 0.1</i>	<i>TI 0.1</i>	<i>TI 0.1</i>
	<i>TD 0.0</i>	<i>TD 0.0</i>	<i>TD 0.1</i>

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

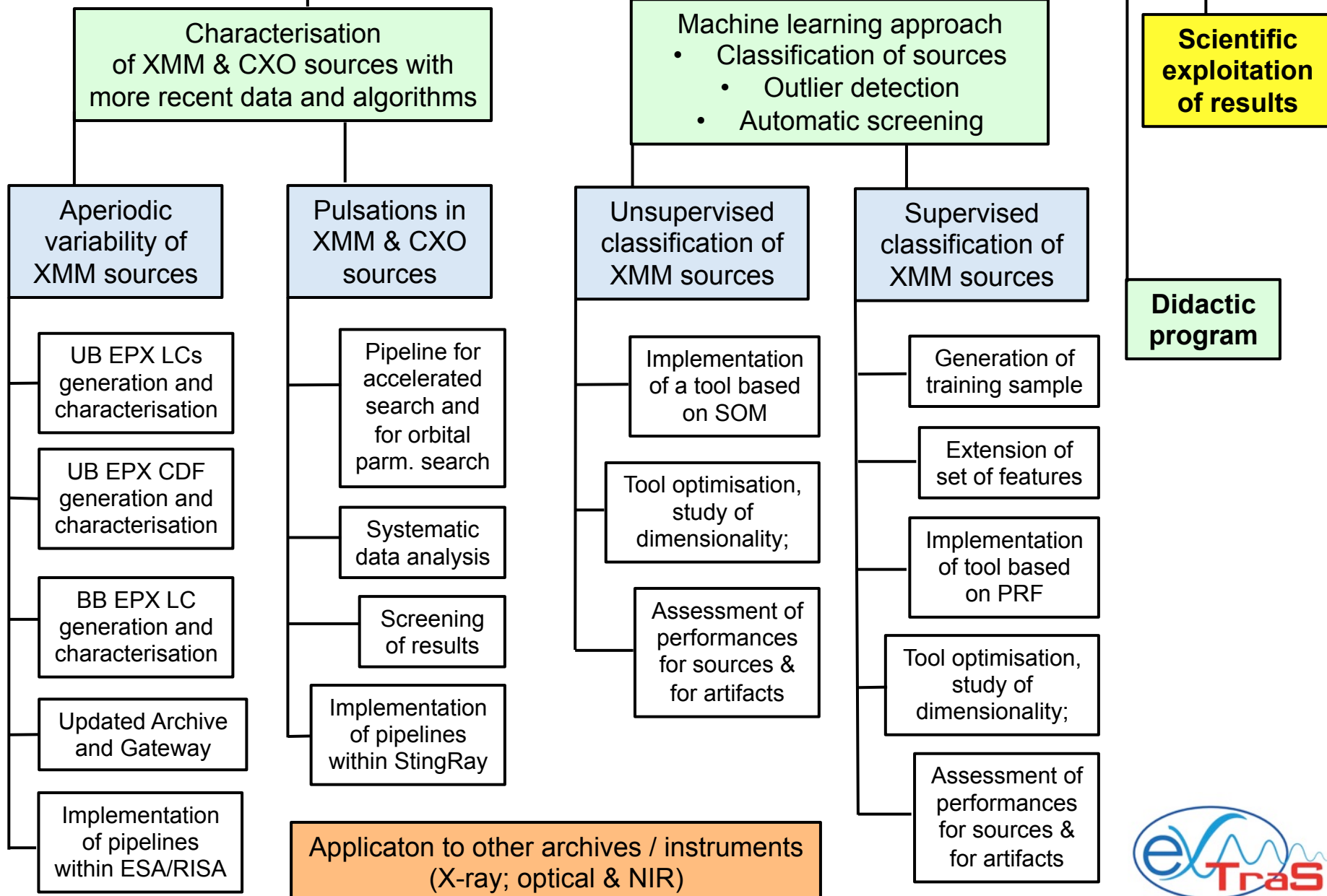
Interpretation of results

All team members are contributing

- 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

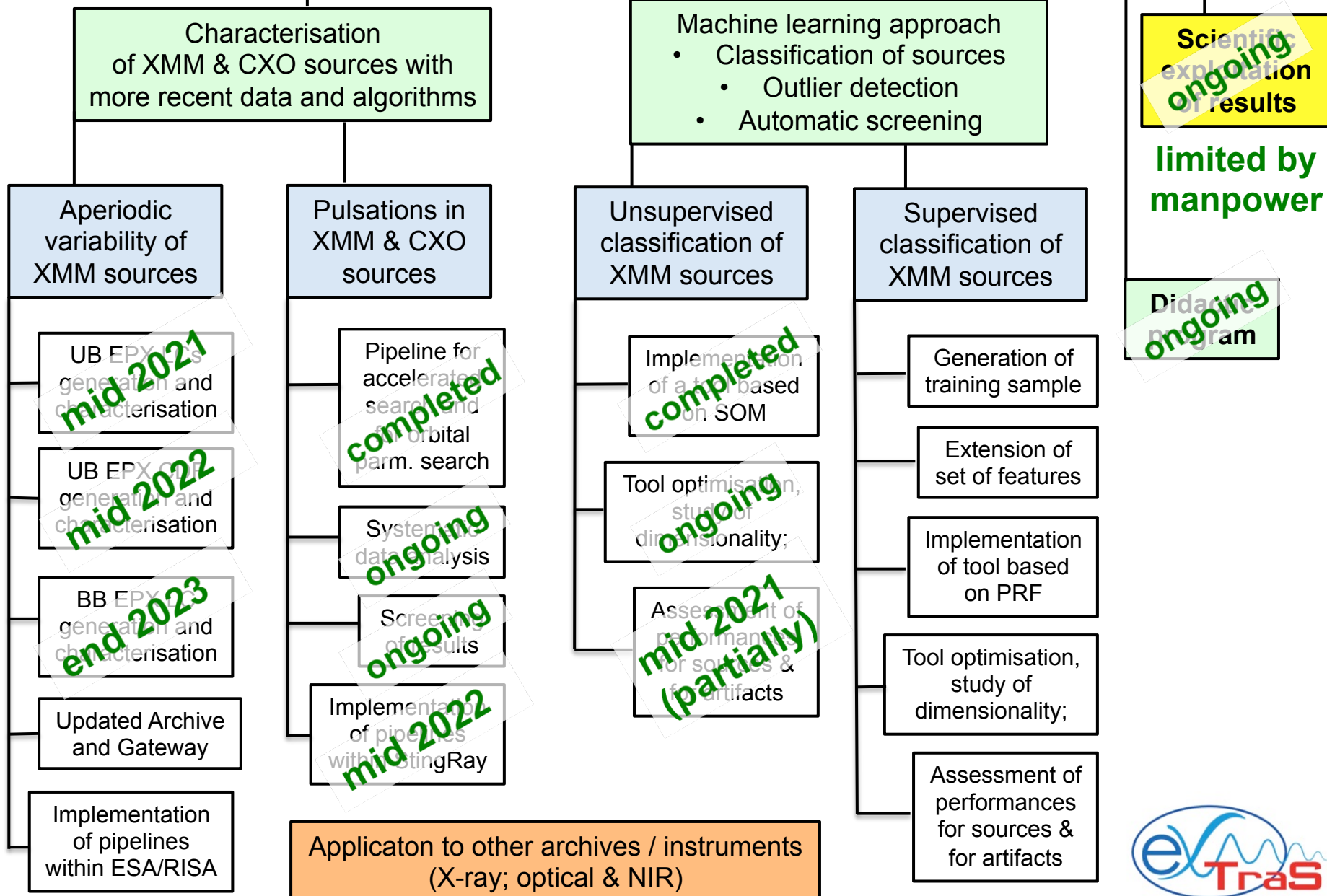
- INAF – IASF Milano in particular – had a key role in all phases of the XMM-Newton mission
- Such expertise was crucial for the success of the EXTraS project, led by INAF
- Our team has a lead position in (archival) time domain investigations (best software tools and expertise, huge set of results and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

Exploring the X-ray Transient and variable Sky



- 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.

Exploring the X-ray Transient and variable Sky



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

