The first unbiased survey of star-forming galaxies with eROSITA:

Scaling relations and a population of X-ray luminous starbursts

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& the eROSITA Normal Galaxies WG

"First Results from the SRG/eROSITA All-Sky Survey: From Stars to Cosmology"
September 20th 2024, Garching, Germany

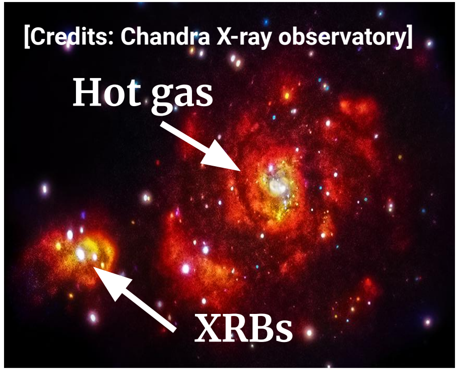
Studying the X-ray output of Normal Galaxies in the local Universe

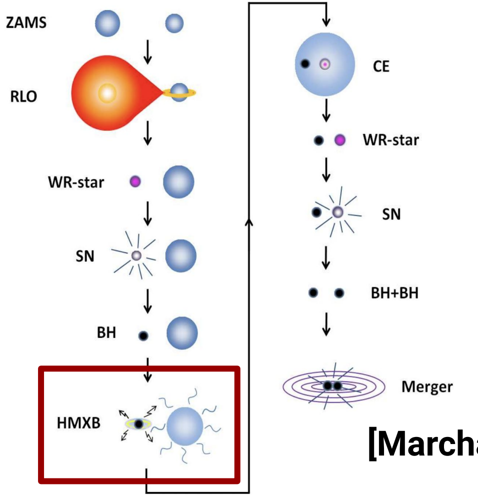
X-ray emission of normal galaxies is produced by:

X-ray Binaries (XRBs) & hot gas.

- ❖ **Constrain the evolutionary parameters** of XRBs by testing **different evolution scenaria** through population synthesis.
  - ➢ Orbital parameters, mass ratios
  - ➢ Stellar winds,SN kicks, CE ejection
- ❖ **Predict** the **formation rate** of GWs and/or sGRBs.
- ❖ **Study the effect of XRBs** on their **host galaxy** & the surrounding **IGM**.
- ❖ Study the **cosmological evolution of galaxies**.
  - ➢ First XRBs may affect the formation of the first galaxies in the Universe

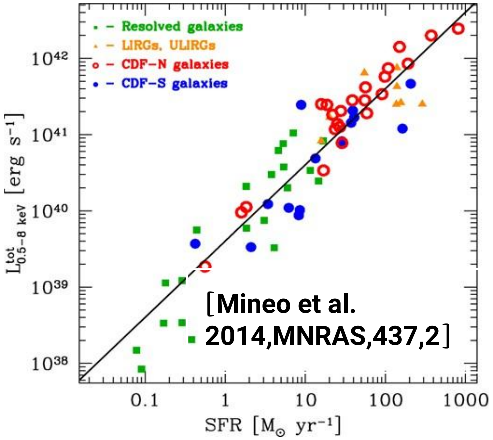
Lx – SFR– $M_\star$– Metallicity scaling relations

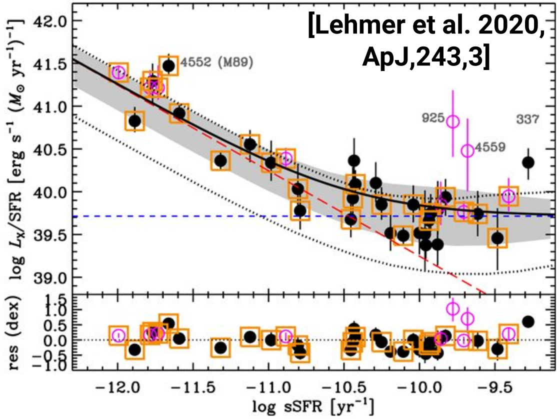




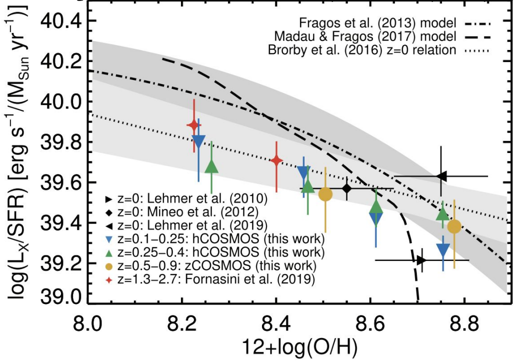
[Marchant+16]

Current state of the art & limitations

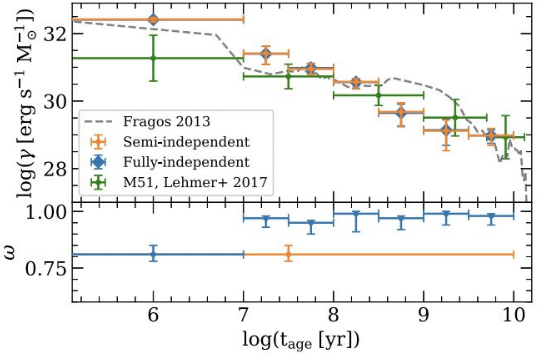




[Fornasini et al. 2020,MNRAS,495,1]



[Gilbertson et al. 2022,ApJ,926,1]



Current observational constraints

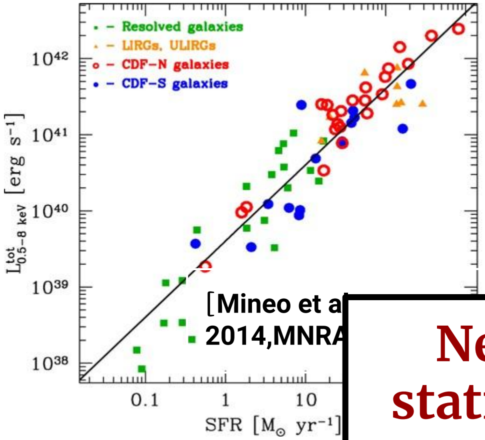
- ❖ X-ray output as a function of: **SFR**, **$M_\star$**, **Metallicity**
- ❖ Increased Lx correlates with:
  - ➢ Metallicity
  - ➢ Age of the stellar populations

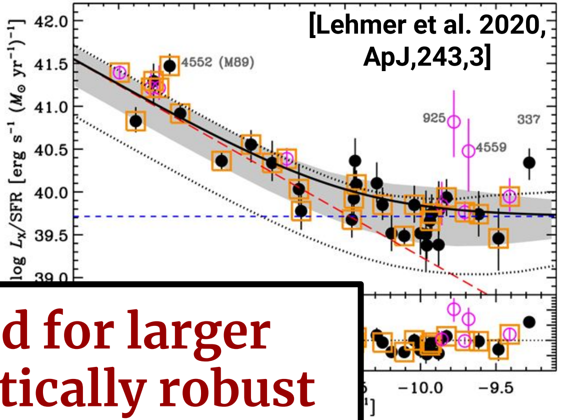
However…

Based on limited, non-representative samples.

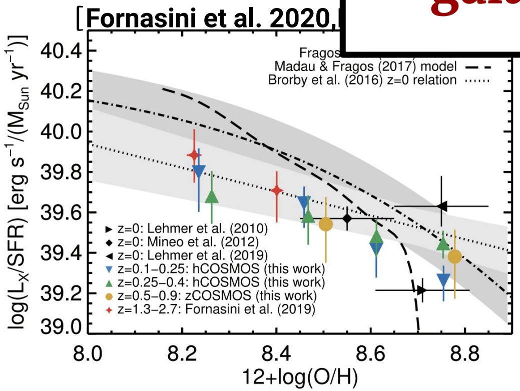
Small coverage of the SFR-$M_\star$-Metallicity parameter space from specially selected galaxy samples.

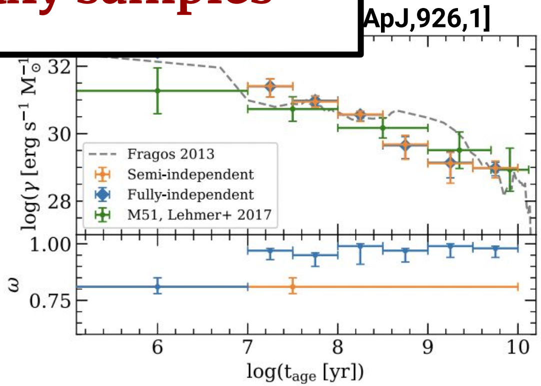
Current state of the art & limitations





Need for larger statistically robust galaxy samples





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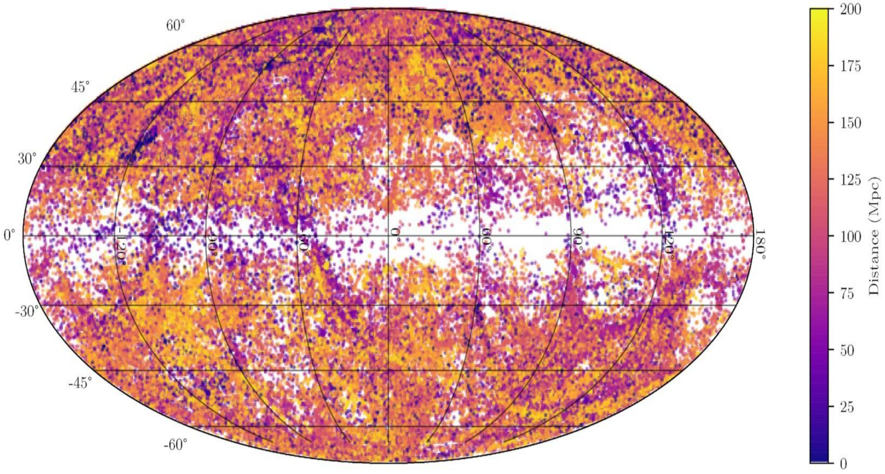
HECATEv2 + eRASS1: X-ray all sky survey

[Kovlakas et al. 2021, MNRAS,506,2; Kyritsis et al. in prep.]

[Predehl et al.2021,A&A 647, A1;Merloni et al. 2024, A&A, 687, A34]



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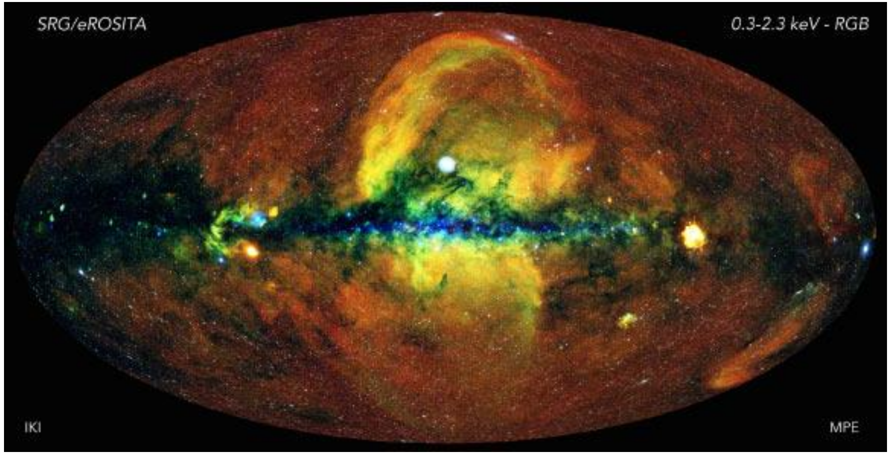

Table 6. Summary of performance characteristics of the eROSITA telescope and its survey sensitivity.

		Energy range	
		Soft band	Hard band
		0.2–2.3 keV	2.3–8 keV
FoV averaged effective area [cm^2]		1237 at 1 keV	139 at 5 keV
Total background [10^{-3} cts s^{-1} $arcmin^{-2}$]		≈3.7	≈2.1
Point source sensitivity eRASS:1			
Ecliptic Equatorial region	Total exposure = 200 s	5×10^{-14} erg s^{-1} cm^{-2}	7×10^{-13} erg s^{-1} cm^{-2}
Ecliptic Polar region	Total exposure = 4000 s	7×10^{-15} erg s^{-1} cm^{-2}	9×10^{-14} erg s^{-1} cm^{-2}
Point source sensitivity eRASS:1-8 (predicted)			
Ecliptic Equatorial region	Total exposure = 1600 s	1.1×10^{-14} erg s^{-1} cm^{-2}	2.5×10^{-13} erg s^{-1} cm^{-2}
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204733 galaxies at distance up to 200 Mpc (z~0.048)

✓**Basic properties:** position, Distance, Size
✓**Multi-wavelength data:** IR to Optical photometry & SDSS spectroscopic information
✓**Stellar population parameters:** SFR, $M_\star$, Metallicity
✓**Activity classification:** Star-Forming, AGN, Composite, LINER, Passive

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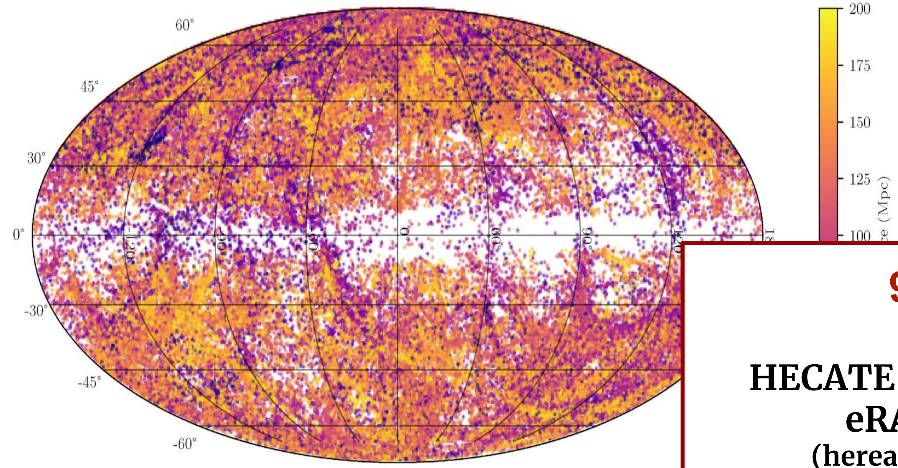

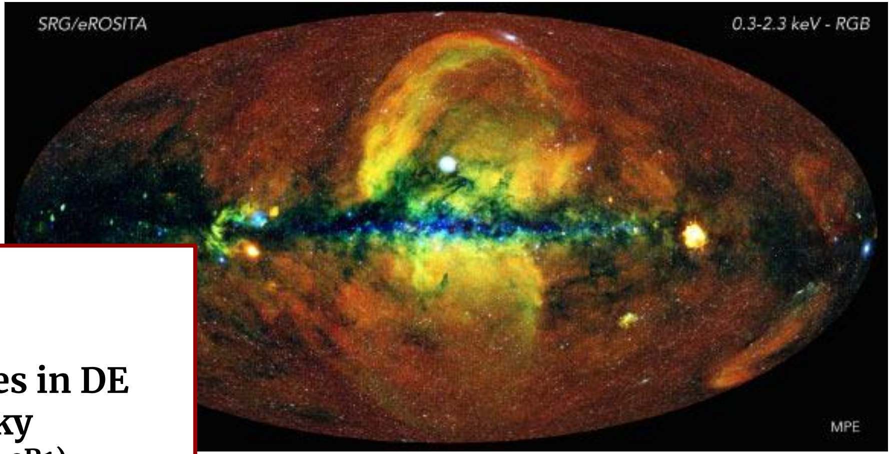

93806

HECATE galaxies in DE eRASS:1 sky
(hereafter HEC-eR1)

204733 galaxies at distance up to 200 Mpc (z~0.048)

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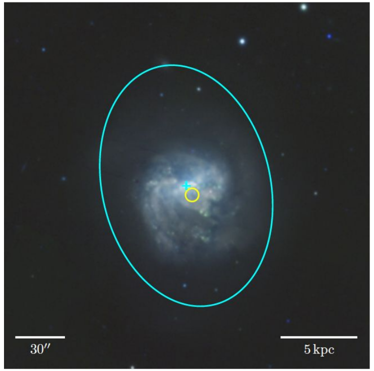
HEC -eR1: Normal Galaxy study
Methodology - X-ray photometry

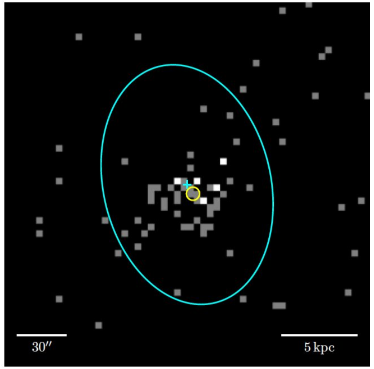
93806 HEC-eR1 galaxies

1. Extracted X-ray spectra
   - Accounting for extended emission; P. Weber, S. Hämmerich

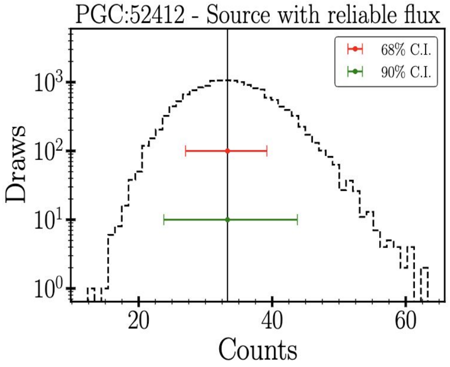
2. Measurement of source intensity
   - Posterior probability of the source's intensity
   - BEHR (Bayesian approach)

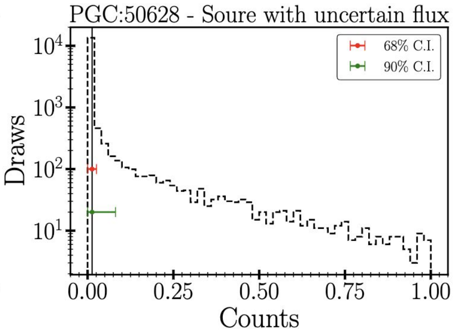


PanSTARRS



eRASS1 0.2-5 keV

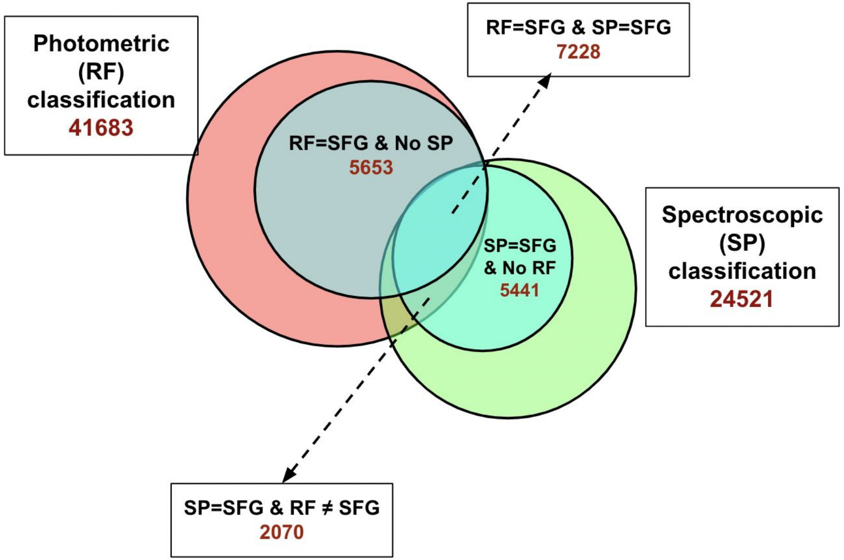




3. Calculate **Flux** & **Luminosity** based on the Posterior of the source's intensity and the distance of each galaxy.

HEC-eR1 sample construction

Selection of star-forming galaxies



Final Sample after screening

Reliable fluxes : **78**

Unreliable fluxes (Upper Limits): **18792**

Total: 18870 star-forming galaxies

Activity classification methods

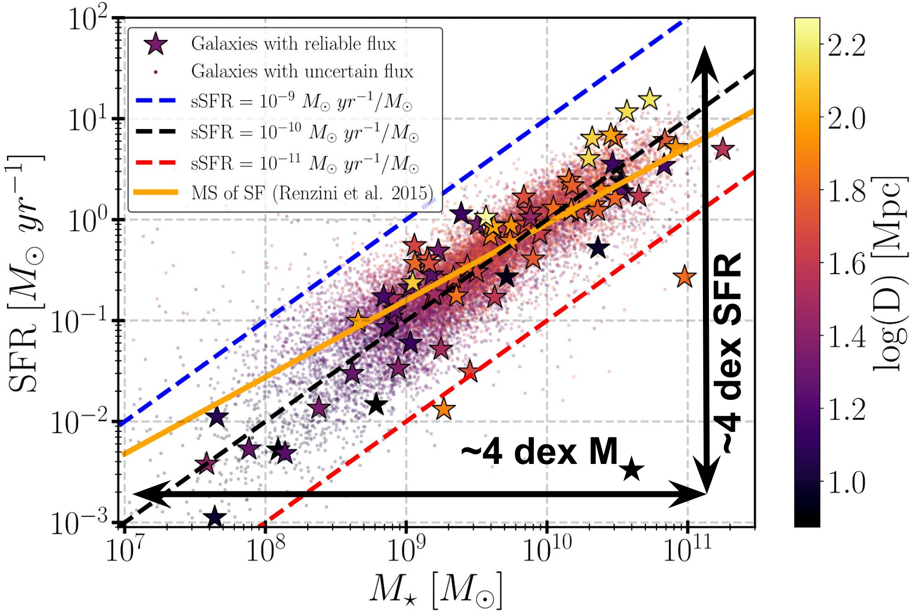
- ❖ Spectroscopic (SP) data (SDSS+Skinakas/TNG). [Stampoulis et al., A&A, 2019,486]
- ❖ Photometric mid-IR/optical data (RF).
  - ➢ **5-class activity classifier based on Random Forest machine learning algorithm** [C.Daoutis, E. Kyritsis et al., A&A,2023,679:A76]

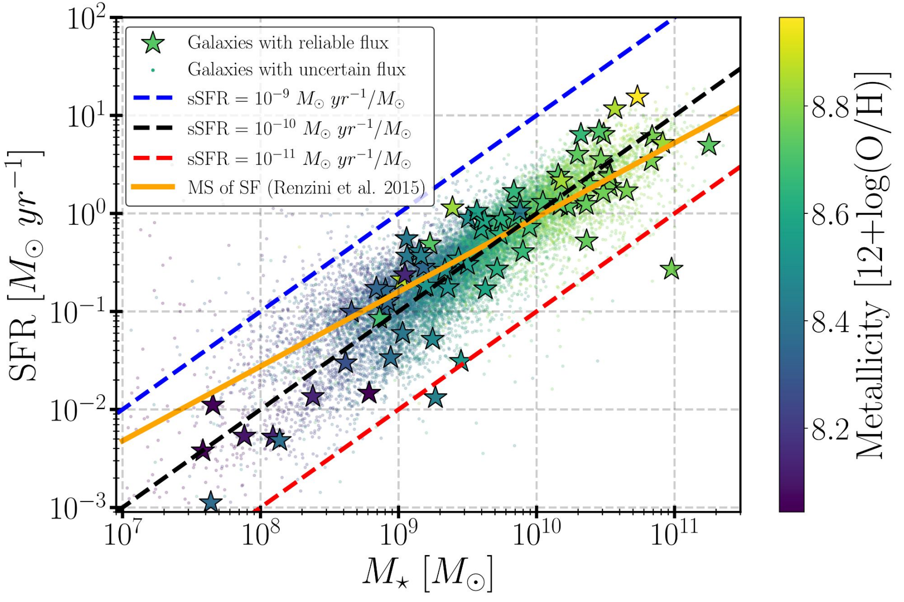
AGN & Galaxy Cluster screening

- AGN contamination (visual inspection; literature search)
- Hot-gas contamination from Galaxy Clusters
  - eROSITA Galaxy Cluster catalog (F.Harbel, E.Bulbul)
  - Abell Cluster catalog
  - Hickson Compact Group Galaxy
- UVOIR variability:
  - Cross-match with a sample of AGN identified by their UVOIR variability observed with eROSITA (Arcodia et al.2024, A&A, 681, A97)
- Hard X-ray colors

HEC-eR1 final sample of star-forming galaxies

SFR-$M_\star$-D-Metallicity parameter space

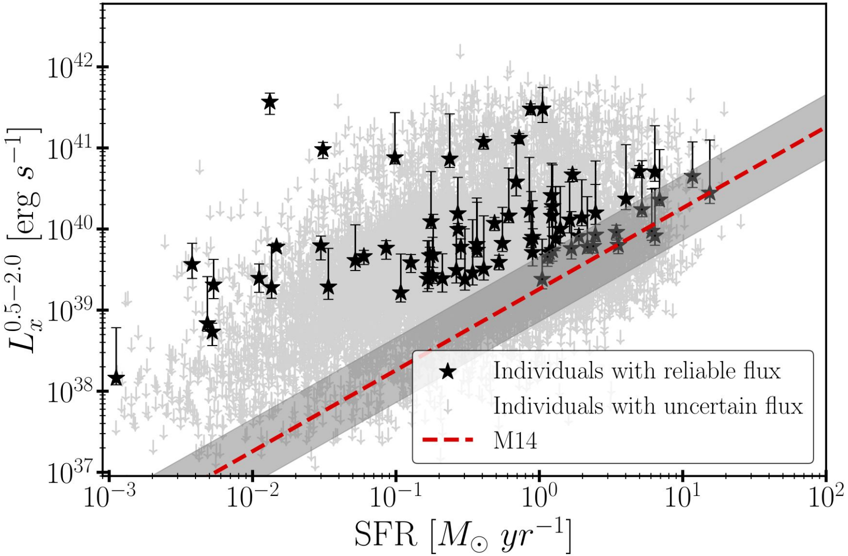


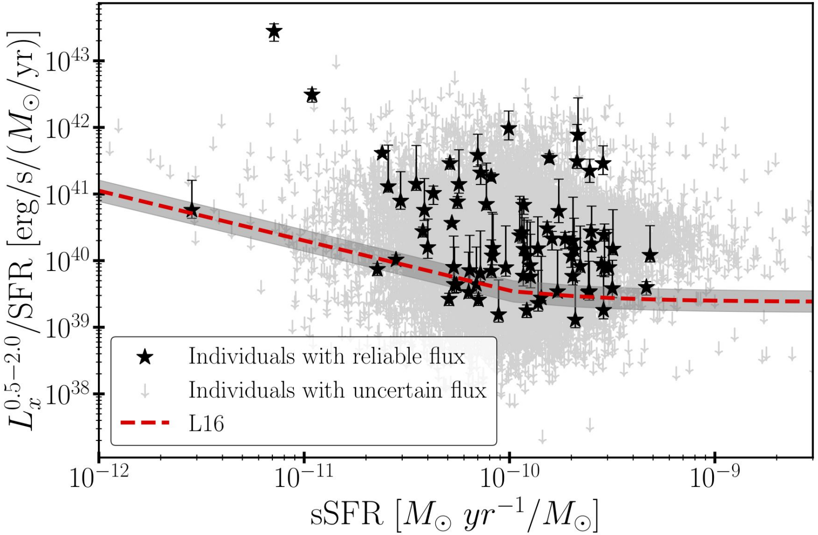


Our sample is well distributed in the galaxy Main Sequence plane and it covers a wide range of sub-solar to super-solar metallicities.

HEC-eR1 Normal Galaxy study

Scaling relations of individual galaxies

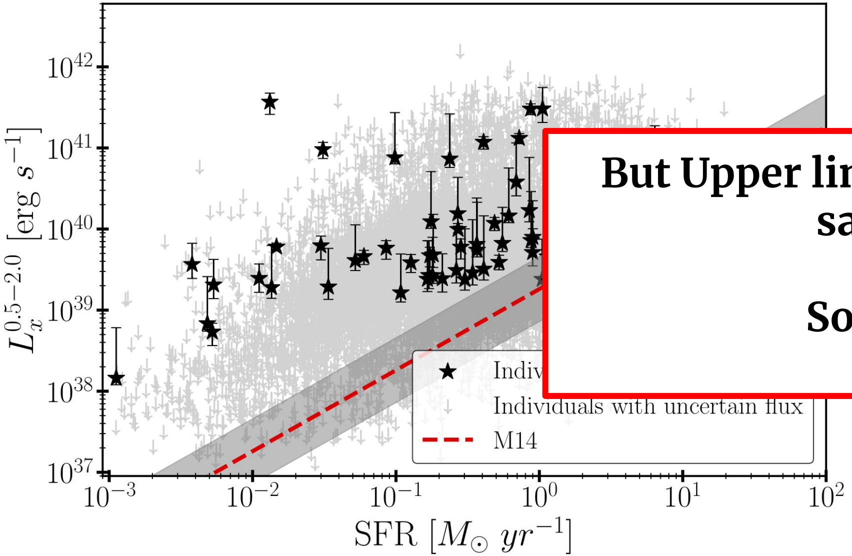


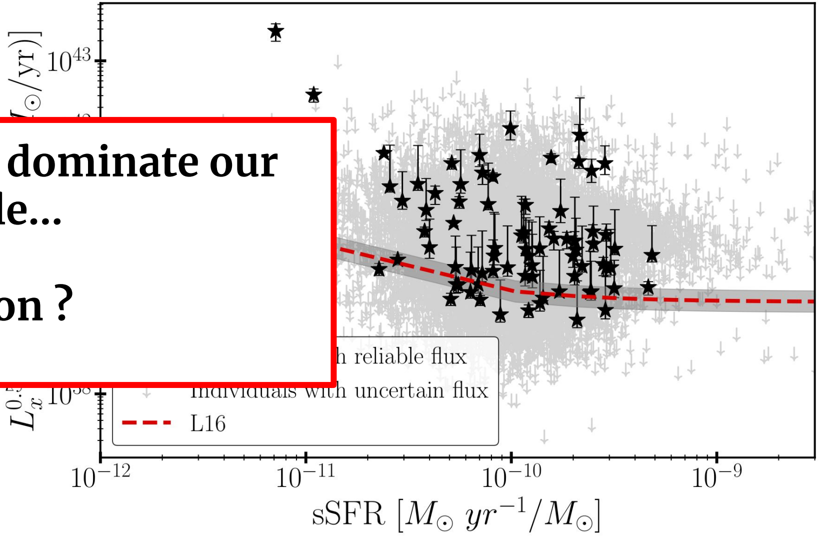


- ➢ **A population of extremely X-ray luminous galaxies is systematically above the Lx-SFR (M14) & Lx-SFR-$M_\star$ (L16) scaling relations !**
- ➢ **Increased scatter !**
- ➢ **Increased deviations for low SFRs !**

HEC-eR1 Normal Galaxy study

Scaling relations of individual galaxies





But Upper limits dominate our sample...

Solution ?

- ➢ **A population of extremely X-ray luminous galaxies is systematically above the Lx-SFR (M14) & Lx-SFR-$M_\star$ (L16) scaling relations !**
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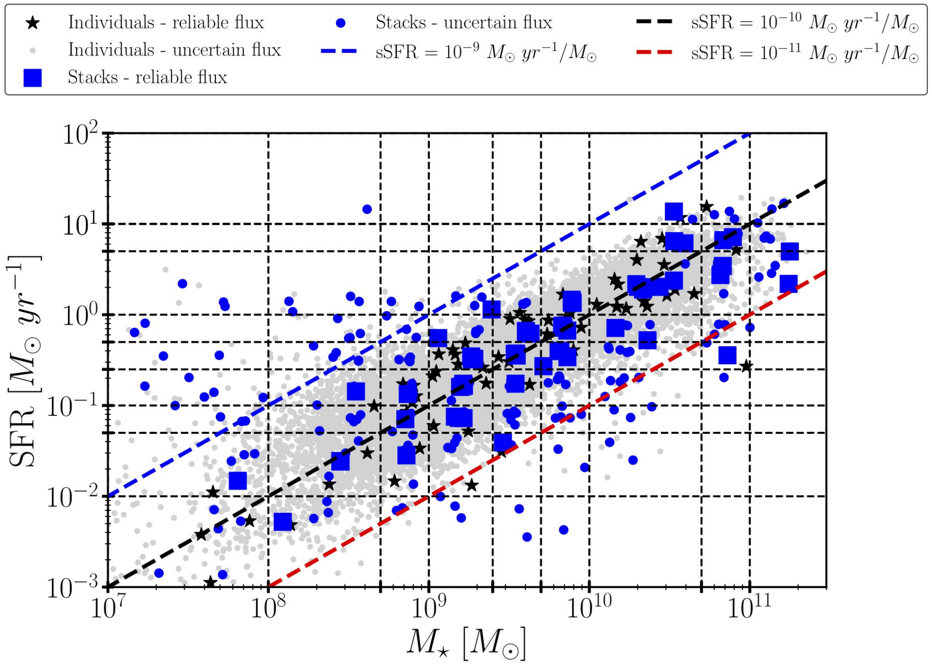
HEC-eR1 Normal Galaxy study

Stacking the galaxies per SFR - $M_\star$-D bin

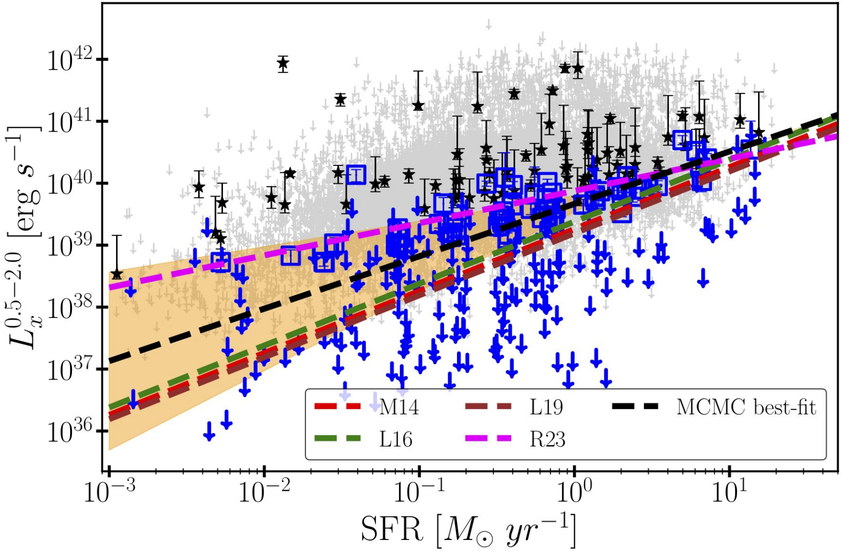


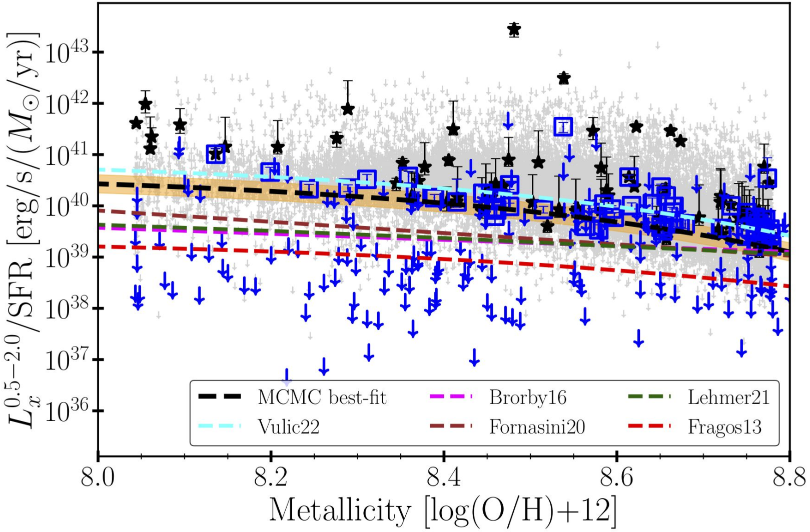
SFR- $M_\star$- D grid : **10x11x9**

- ➢ Select all the galaxies per bin following an adaptive binning: **239** bins
- ➢ **Reliable**: **58** bins & **Upper limits: 181** bins
- ➢ Calculation of the **<Lx>** of the galaxy population per SFR-$M_\star$-D bin

HEC-eR1 Normal Galaxy study

Updated Lx-SFR & Lx-SFR-Metallicity scaling relations



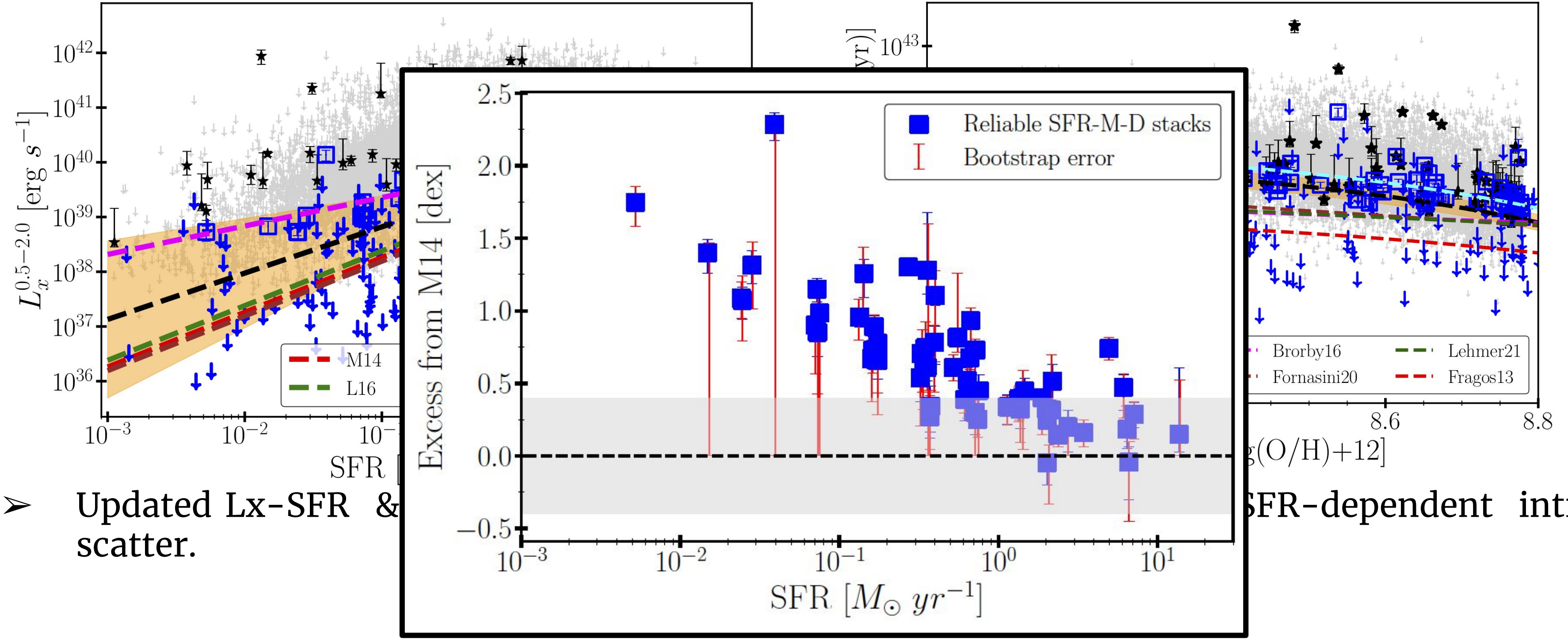


➢ Updated Lx-SFR & Lx-SFR-Z accounting for the Upper limits & the SFR-dependent intrinsic scatter.

$$log(L_X/\text{erg s}^{-1}) = A \cdot \log(\text{SFR}/\text{M}_\odot\,\text{yr}^{-1}) + B + \epsilon(\log(\text{SFR}))$$

$$log(L_X/\text{erg s}^{-1}) = \log(\text{SFR}/\text{M}_\odot\,\text{yr}^{-1}) + A \cdot (Z/Z_\odot) + B + \sigma$$

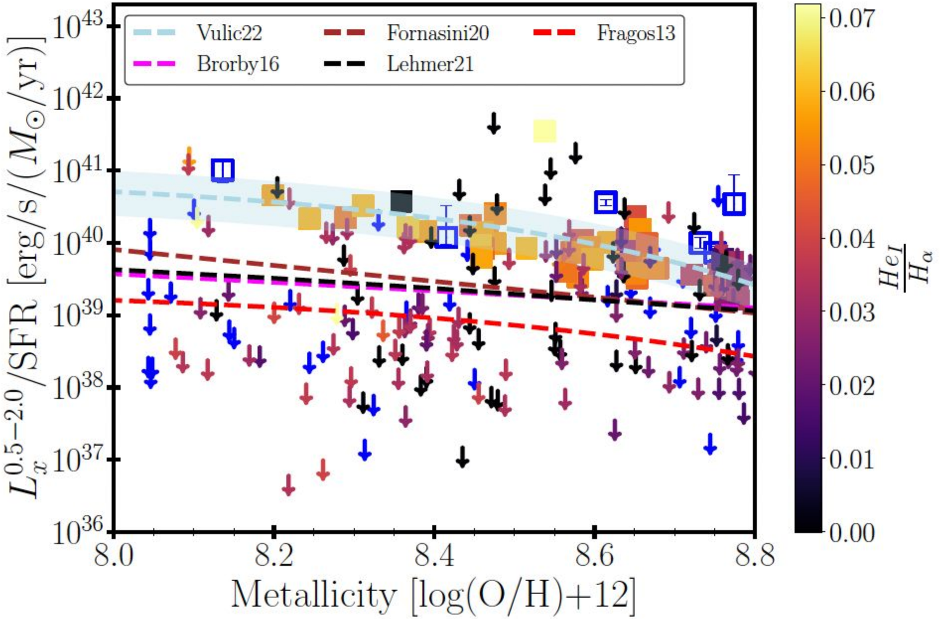
HEC-eR1 Normal Galaxy study
Updated Lx-SFR & Lx-SFR-Metallicity scaling relations



- ➢ Updated Lx-SFR & … SFR-dependent intrinsic scatter.
- ➢ The excess persists ! Stronger towards lower SFRs & higher sSFRs.
  - Up to ~**2 dex** for **SFR < 0.01 M$_{\odot}$/yr** .
  - Scatter **correlates** with SFR

HEC-eR1 Normal Galaxy study

Lx excess: Stellar population age or Metallicity ?



Partial correlation test accounting for the upper limit stacks .

- ➢ **Lx/SFR excess - Metallicity** → control for **HeI/Ha**
  - ○ Low variance
- ➢ **Lx/SFR excess - HeI/Hα** → control for **Metallicity**
  - ○ High variance

Stellar age is more strongly correlated with the Lx excess for stellar populations of age up to ~30 Myrs !

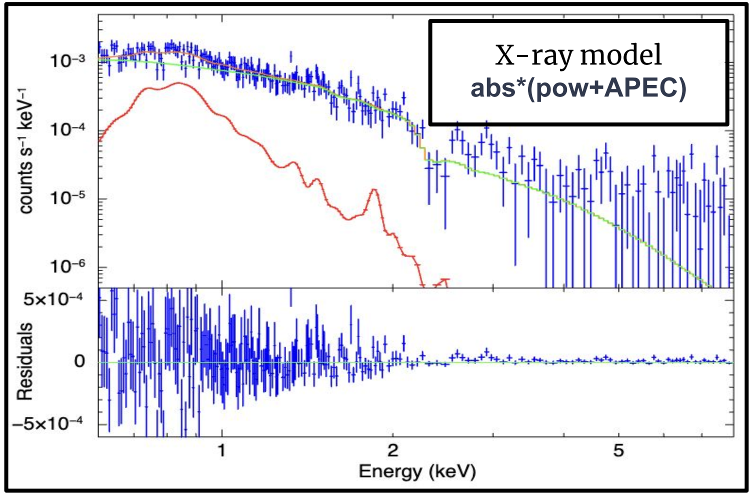
- ❖ HeI/5876 traces stellar populations of <8 Myrs
- ❖ Hα/6563 traces stellar populations of <30 Myrs

HEC-eR1 Normal Galaxy study

Lx excess: Hot-gas contribution or LMXBs ?

Is the excess due to hot-gas contribution ?

$$\text{Hot-gas contribution} = \frac{F_{0.5-2}^{APEC}}{F_{0.5-2}^{total}} \times 100\,\%$$ **= ~ 13 %**

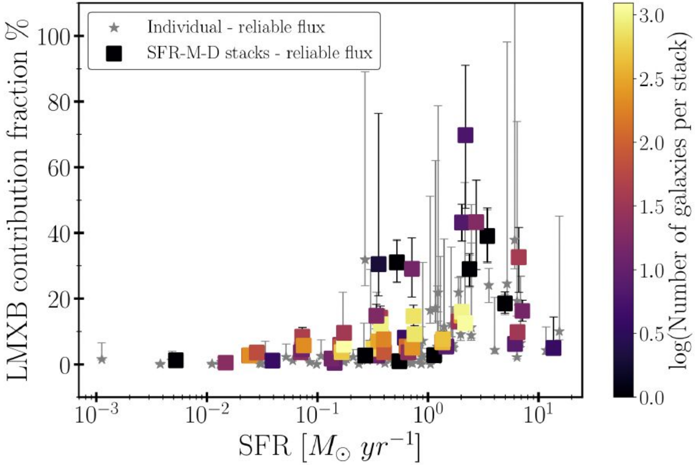


- ➢ Consistent with other works using eRASS4 data [Laktionov et al. 2024 in prep., See poster]

★ **Cannot explain the excess we measure.**

Is the excess at lower SFRs due to the contribution of the LMXBs in the integrated Lx ?

- ➢ Calculate the expected Lx based on LMXBs XLF from Lehmer+19



★ **LMXBs cannot explain the excess in lower SFRs.**

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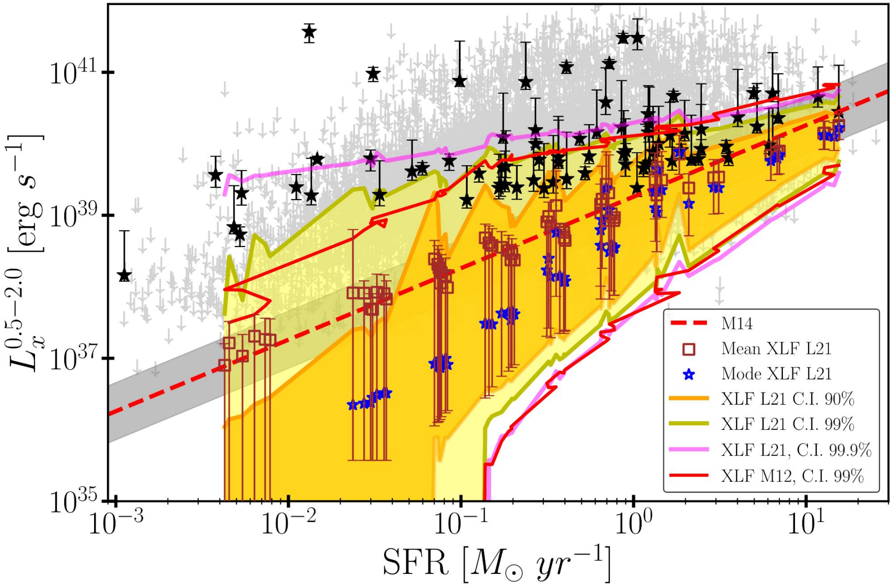
Lx excess: Stochasticity effect ?

Has the <Lx> excess a physical origin or it is the result of the stochastic sampling of the HMXBs XLF ?

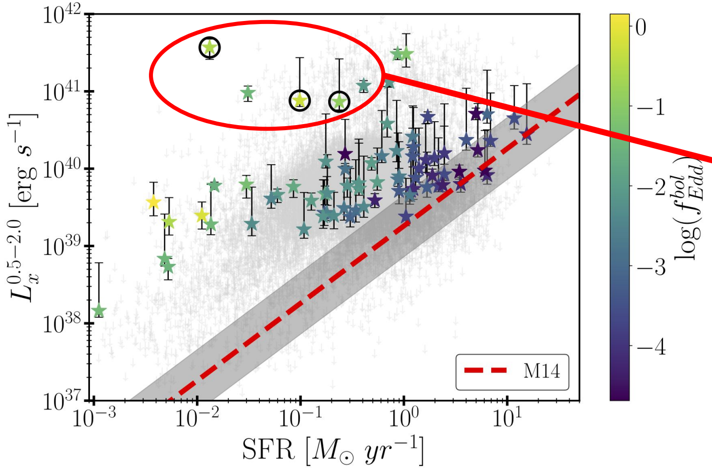


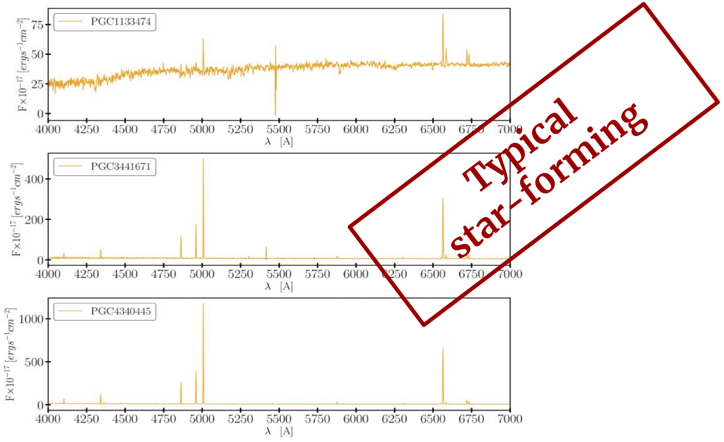
- Simulation of the expected Lx distribution due to stochastic sampling of HMXBs XLFs.
  - Solar-metallicity Mineo+12 (M12)
  - Metallicity-dependent Lehmer+21 (L21)
- L21 results in more luminous HMXBs in lower SFRs due to the lower metallicity.
- **$Prob_{stoch}$ < 0.05%**

Stochastic sampling is not adequate to explain the most X-ray luminous individual galaxies.

HEC-eR1 Normal Galaxy study

Lx excess: Low - luminosity AGNs or TDEs ?





If all the X-ray emission is due to accretion onto a SMBH how much powerful is it ?

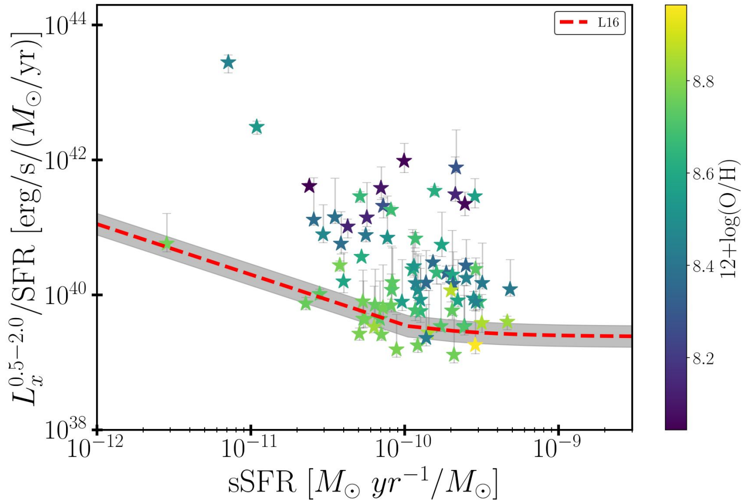
$M_\star \rightarrow M_{BH} \rightarrow L_{Edd} \rightarrow f^{Bol}_{Edd}$ is **typical of Seyfert 1**

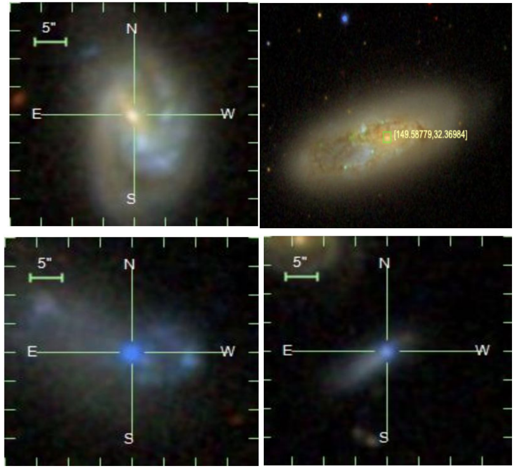
Are there **AGN signatures** in their **optical spectra** ?

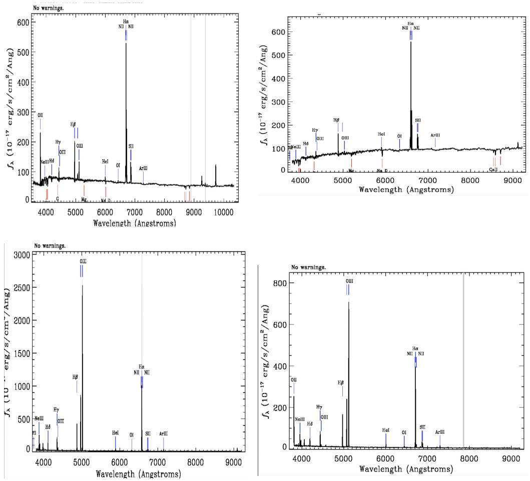
Tidal Disruption Events ?

TDE rate for SFGs x eR1-HEC sample of SFGs ~ **0.04 TDE yr^{-1}** or Prob. of observing **~ 1%**

HEC-eR1 Normal Galaxy study
Lx excess: Finally what ?







★ A subpopulation of galaxies with **high sSFRs**, **lower metallicities** & **very young stellar populations** due to a recent star-formation episode.

HEC-eR1 Normal Galaxy study

Conclusions

1. The 1st X-ray unbiased all-sky survey of star-forming galaxies with eROSITA.

2. Redefined the Lx-SFR & Lx-SFR-Metallicity scaling relations accounting for intrinsic scatter.

3. Discovery of a population of extremely X-ray luminous star-forming galaxies:
   a. Their star-forming nature is confirmed by their optical spectra.
   b. Driver of the Lx excess: high sSFRs, lower metallicities & very young stellar population.
   c. Stochasticity effects are very important.

4. Important implications for binary formation in low metallicity and high-z universe.

5. Stay tuned for updates based on eRASS:4.
   a. Better X-ray statistics, more detections.
   b. Extension to more distant lower metallicity galaxies.
   c. Normal Galaxy XLFs.

Paper submitted to A&A, available at **arXiv: 2402.12367**

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