25 years and counting
ILLUMINATING THE PROPERTIES OF RING GALAXIES THROUGH X-RAY AND MULTIWAVELENGTH OBSERVATIONS

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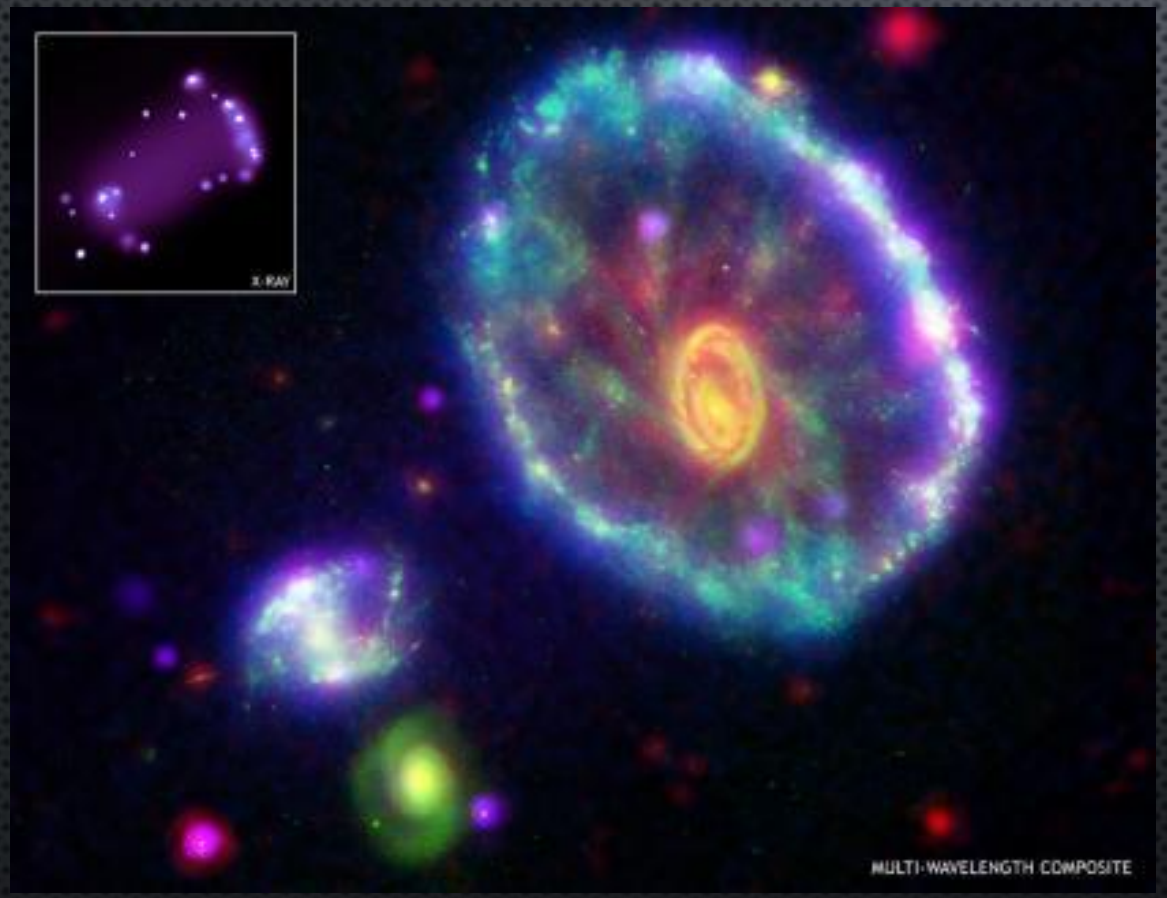
[Italy, USA, Check Republic, Greece]

COLLISIONAL RING GALAXIES – WHY?

Violent encounter between a ”bullet” galaxy and a target spiral (e.g. Theys & Spiegel 1979, Athanassoula+ 1997, Renaud+ 2018).

- Very few (0.02-0.2% of all spirals)
- Beautiful!
- Galaxy evolution studies: peculiar morphology that allows for an easier separation of the various galactic components – timing of unique wave of SF
- Fresh ”unpolluted” gas to make massive stars
- Test of alternate dynamics (MOND) predictions
- Total area of ring is smaller: less interlopers

CARTWHEEL GALAXY:
ASTRONOMERS DO FLIPS OVER CARTWHEEL GALAXY



- JAN, 11 2006
- COMPOSITE: NASA/JPL/CALTECH/P.APPLETON ET AL. X-RAY: NASA/CXC/A.WOLTER & G.TRINCHIERI ET AL.

HTTPS://CHANDRA.HARVARD.EDU/PHOTO/2006/CARTWHEEL/

ARP 147: GIANT RING OF BLACK HOLES

- FEBRUARY 9, 2011
- X-RAY: NASA/CXC/MIT/S.RAPPAPORT ET AL, OPTICAL: NASA/STSCI

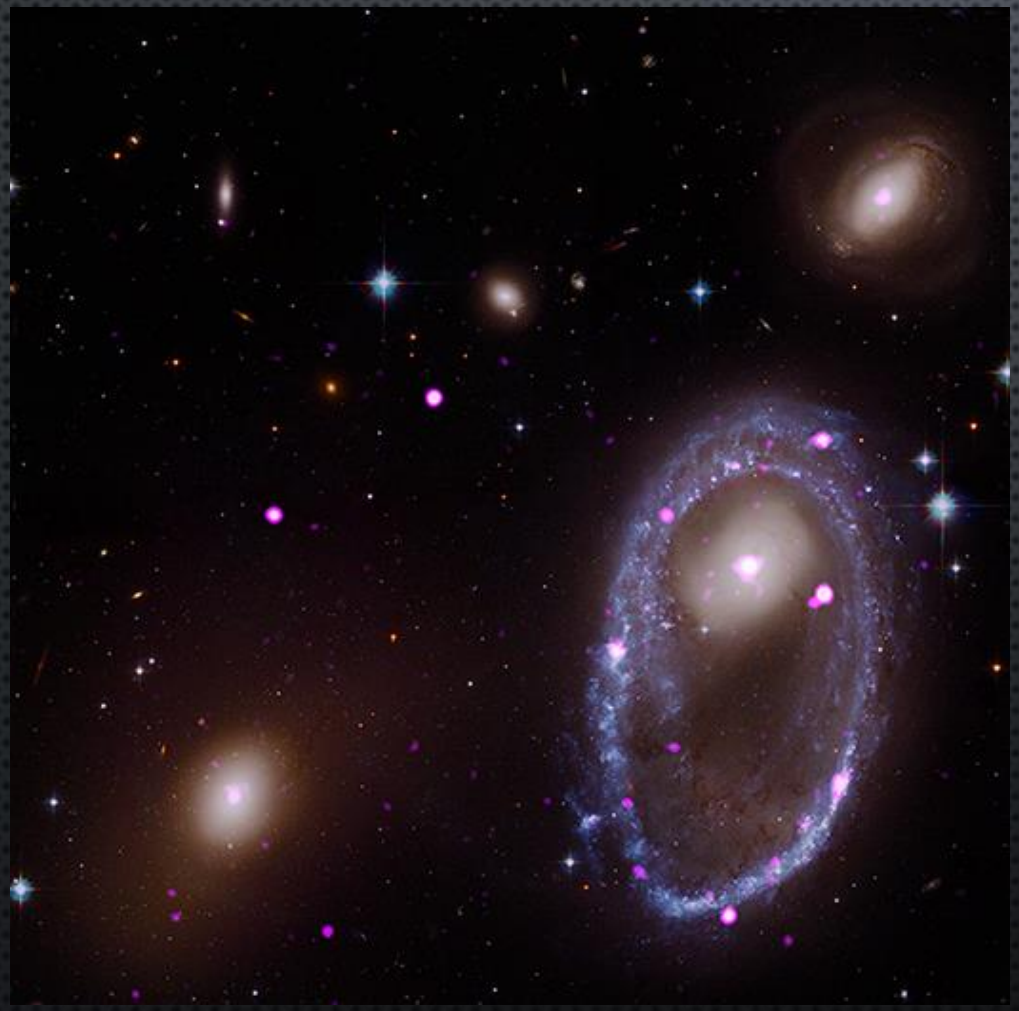
HTTPS://CHANDRA.HARVARD.EDU/PHOTO/2011/ARP147/

NGC 922:
SEARCHING FOR THE BEST BLACK HOLE RECIPE

- DECEMBER 6, 2012
- X-RAY (NASA/CXC/SAO/A.PRESTWICH ET AL); OPTICAL (NASA/STSCI)

HTTPS://CHANDRA.HARVARD.EDU/PHOTO/2012/NGC922/

AM 0644-741: Cosmic Collision Forges Galactic One Ring – In X-Rays



- September 6, 2018
- X-ray: NASA/CXC/INAF/A. Wolter et al; Optical: NASA/STScI

http://chandra.harvard.edu/photo/2018/ring/

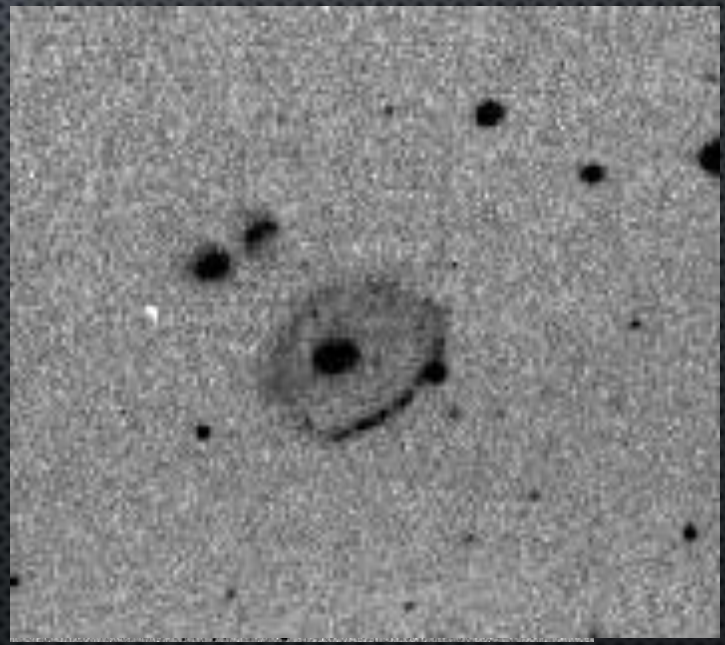
Cartwheel: NASA's Chandra Adds X-ray Vision to Webb Images

- October 4, 2022
- Credit: X-ray: NASA/CXC/SAO; IR (Spitzer): NASA/JPL-Caltech; IR (Webb): NASA/ESA/CSA/STScI

http://chandra.harvard.edu/photo/2022/chandrawebb/

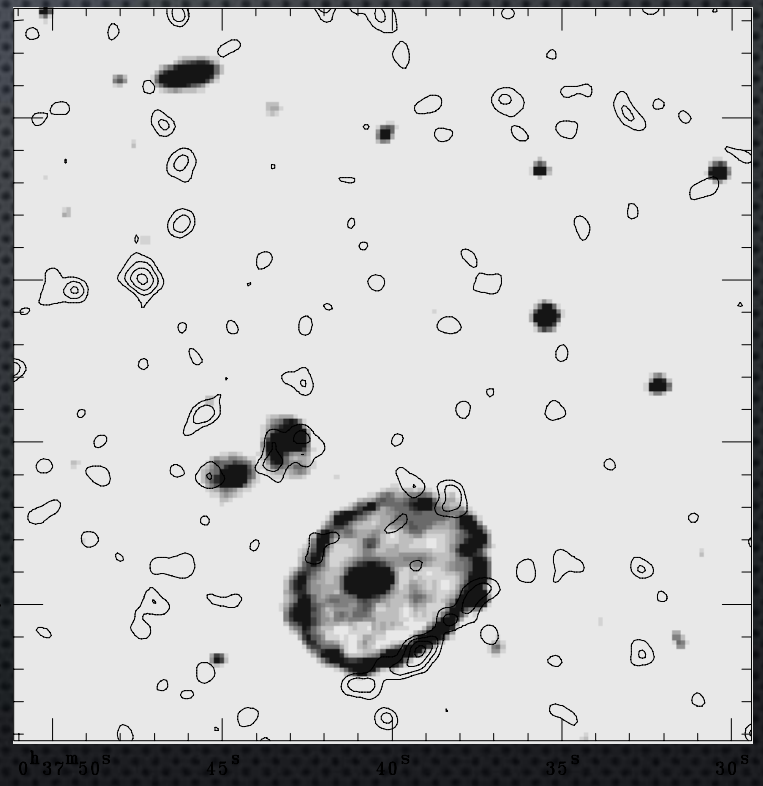
THE EPITOME – THE CARTWHEEL GALAXY

- Discovered by Zwicky (1941)
- One of the most prominent objects on Palomar Plates
- Member of a compact group (SCG 0035-3357; Iovino 2002)

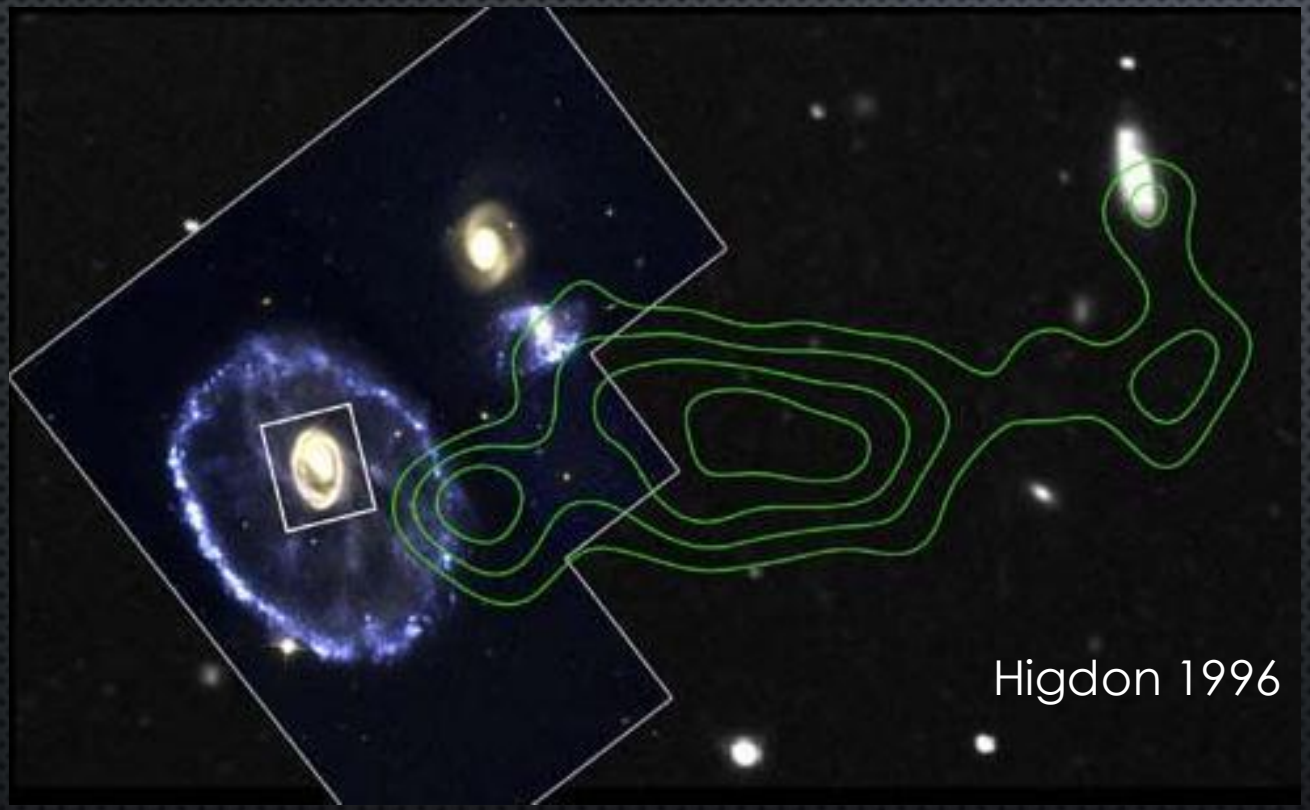


THE EPITOME – THE CARTWHEEL GALAXY

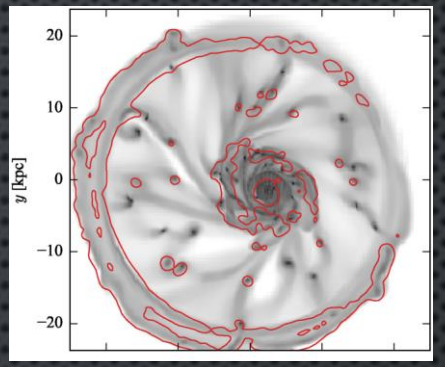
- Discovered by Zwicky (1941)
- One of the most prominent objects on Palomar Plates
- Member of a compact group (SCG 0035-3357; Iovino 2002)
- First X-ray observation to look for extended plasma emission from group (Wolter, Trinchieri, Iovino 1999)



THE TARGET AND THE BULLET



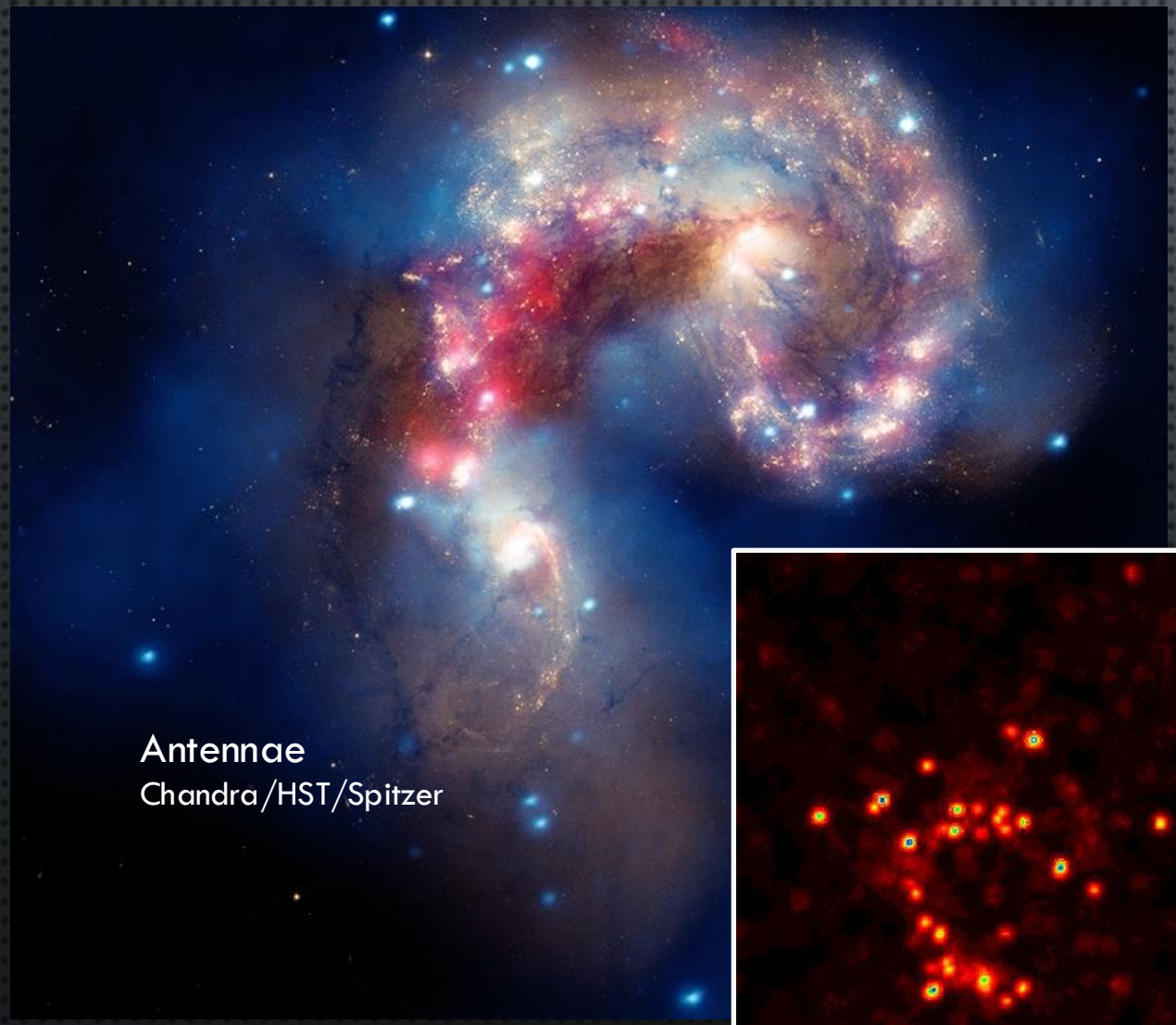
Chandra 25 Years - Anna Wolter

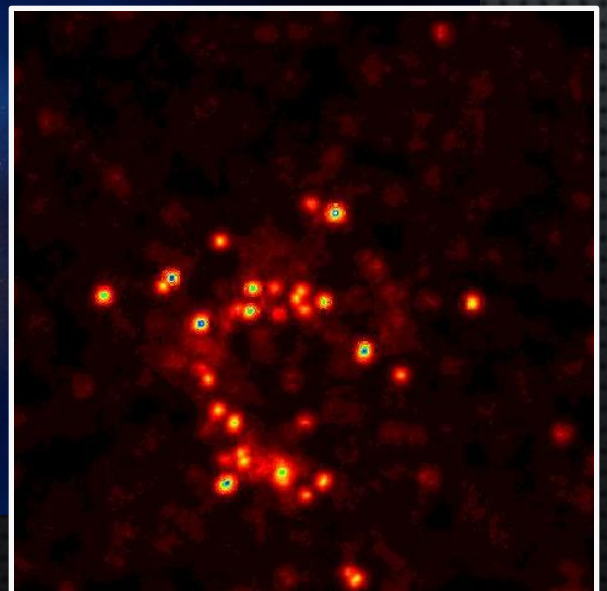


Renaud et al MNRAS **473**, 585–602 (2018)

- HEAD-ON HIGH-SPEED COLLISION ON A TARGET DISC GALAXY. WHICH IS THE BULLET? HI TRAIL – IS THE HI FROM THE "BULLET" RESPONSIBLE FOR NEW SF?
- TWO SCENARIOS:
  - THE GRAVITATIONAL ACCELERATION INDUCED BY THE COMPANION DRAGS THE MATTER OF THE TARGET TOWARDS THE CENTRAL IMPACT POINT. THEN THE SHOCK WAVE REBOUNDS, AND FORMS AN ANNULAR OVERDENSITY THAT TRAVELS RADIALLY.
  - THE SHOCK WAVE BRINGS THE MATERIAL (GAS AND STARS) TO THE OUTSKIRTS.

HIGH SFR OBJECTS – HIGH NUMBER OF ULXS



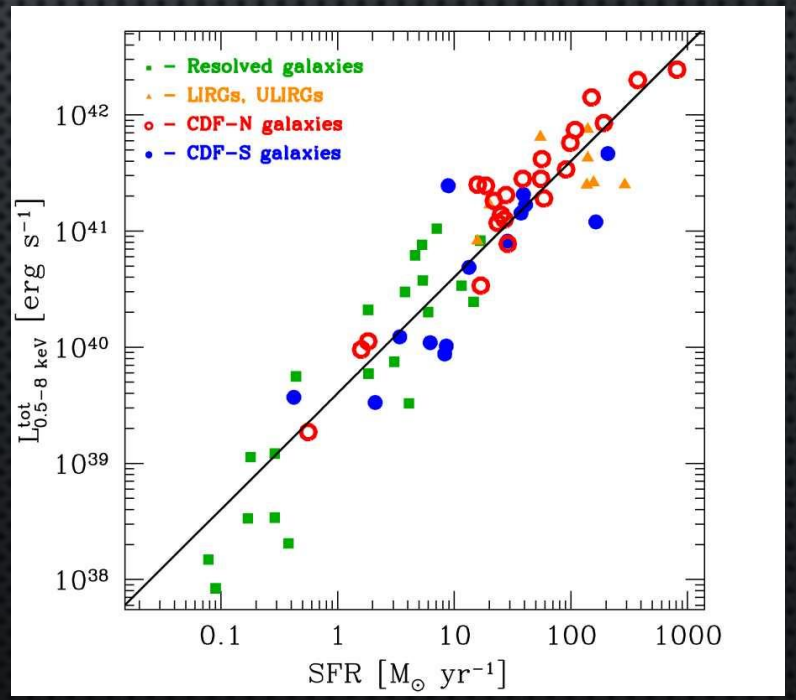


Zezas et al; Fabbiano et al.

WORKING DEFINITION OF ULTRA LUMINOUS X-RAY SOURCES (FABBIANO 1988)

- $L_{X(0.5\text{-}10KEV)}$ > 1-2 X 10^{39} ERG/S, = L_{EDD} (~10 M_{SUN}) UNRESOLVED & NON-NUCLEAR

LINK TO STAR–FORMATION (BAUER+ 2002, RANALLI + 2003, GRIMM+ 2003, MINEO+2012, GILFANOV+ 2023)

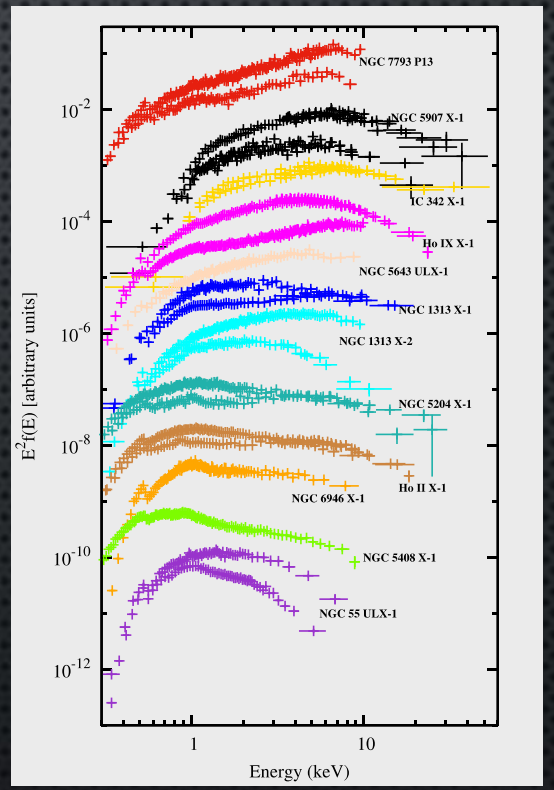


WHY ULXS ?

- Last stages of stellar evolution - collapse
- Evolution and life-span of unusual structures
- Progenitors of mergers -> gravitational waves
- Primordial ionization
  - Nebular HeII emission
- Tracer of low metallicity environment ?
  - Weaker stellar winds of low metallicity stars

WHAT POWERS THE BINARY?
HOW TO "WEIGH" THE COMPACT OBJECT?

High Mass BH	Stellar Mass BH	Neutron Star
Above Eddington?	Above Edd	Above Edd by orders
Stocastic variability	Stocastic variability	Pulsation (surface)
Soft spectrum		Hard spectrum

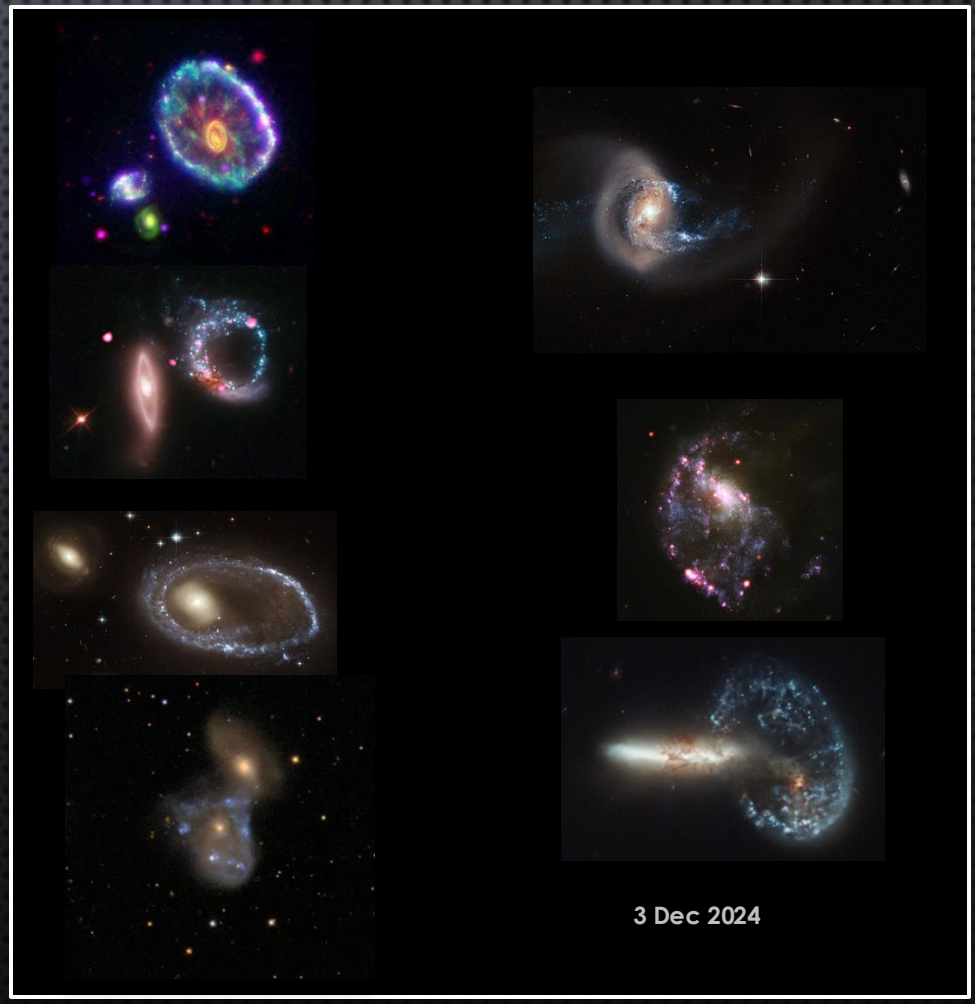


Pintore, ..Wolter, et al 2017

ULX IN COLLISIONAL RING GALAXIES (RIGS)

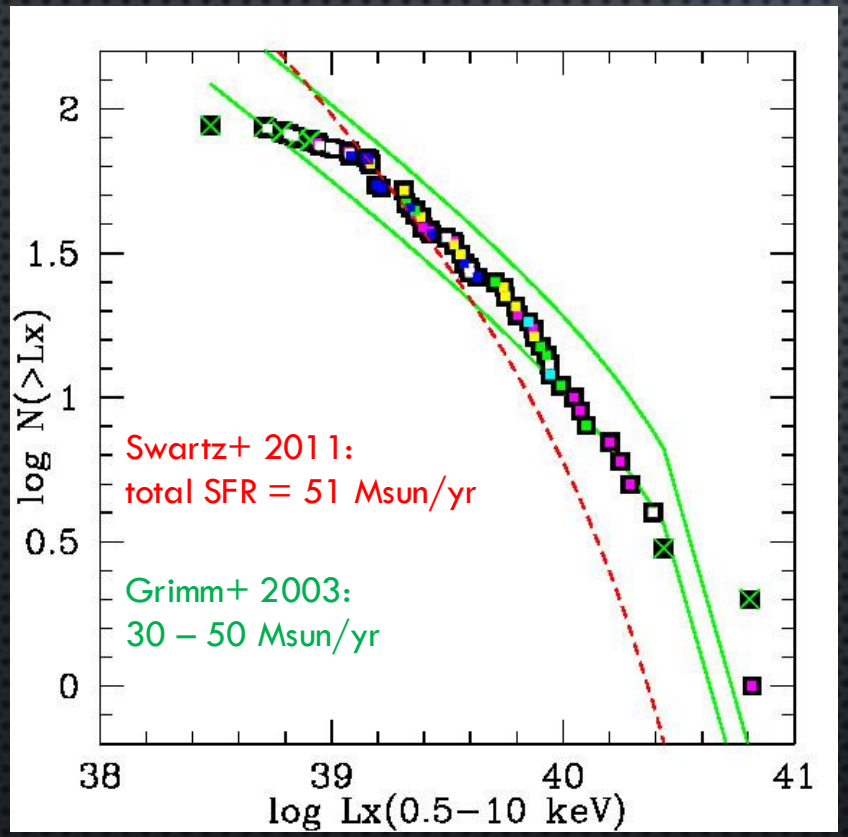
XLF OF RINGS IN WOLTER FRUSCIONE MAPELLI 2018

- CARTWHEEL (14+1) WOLTER ET AL. 2006
- ARP 284 (2+7) SMITH, STRUCK, & NOWAK (2005)
- ARP 147 (9+0) RAPPAPORT ET AL. (2010)
- NGC 922 (7+5) PRESTWICH ET AL (2012)
  KOUROUMPATZAKIS ET AL (2021)
- AM 0644-741 (7) WFM 2018
- ARP 148 (2) WFM 2018
- ARP 143 (9) WFM 2018



Chandra 25 Years - Anna Wolter

THE XLF OF RIGS



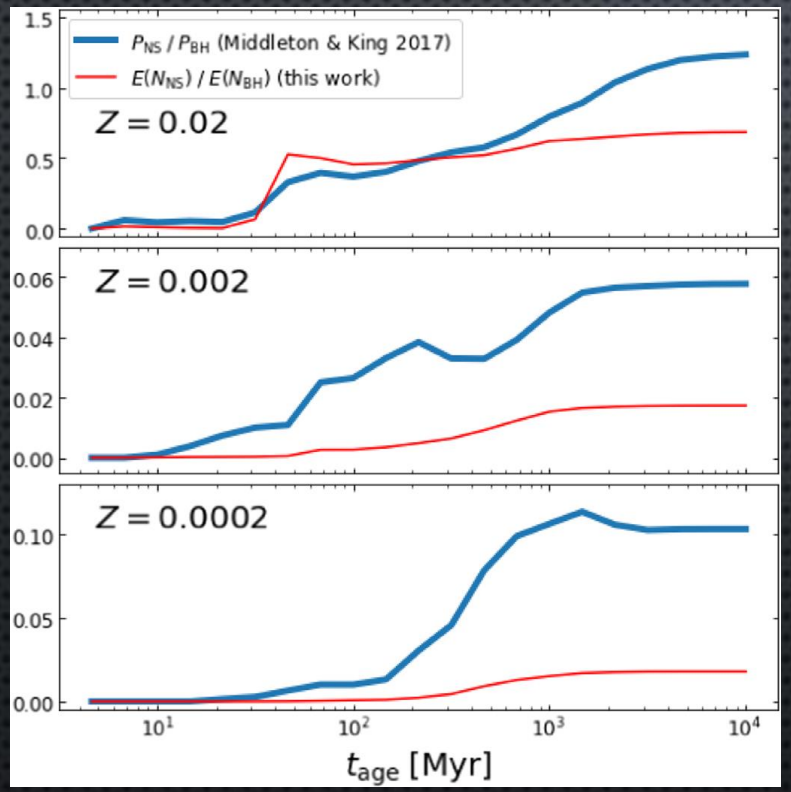
Wolter, Fruscione, Mapelli 2018

- 7 RiGs observed by Chandra (colors corresponds to different galaxies)
- We consider the population homogenous –single burst of SF – we sum all the sources IN THE RINGs
- 65 sources of which 50 are ULXs; SFR_{TOT} = 33 Msun
- Statistically consistent, with a tendency to be FLATTER – more high Lx src – and two outlier sources

- Age ~ few 100 Myr (Renaud+17) consistent with formation time of HMXB

  440 Myr Cartwheel (Higdon+1995)
  330 Myr NGC 922 (Wong+2006)
  80 Myr Arp 147 (Romano+2000)
  30 Myr Arp 143 (Higdon+1995)

ARE WE SEEING THE IMBH POPULATION?



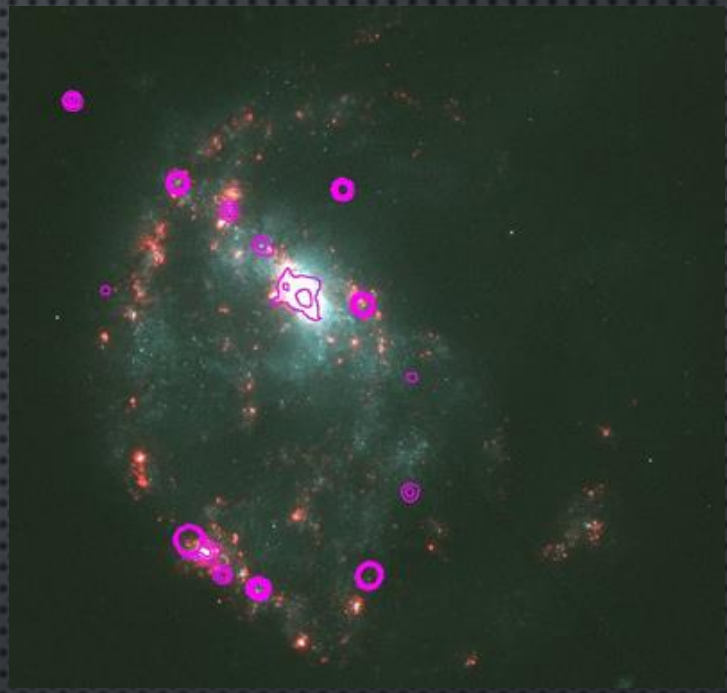
Wiktorowicz+2017

- From Wiktorowicz+2017 and Wiktorowicz+2020
- See also Spera, Mapelli, Bressan 2015
- Prediction of # of ULX based on StarTrack pop. synthesis (Belczynski+2002,+2003)

- Continuum SF -> after 100 Myr NS dominate
- Burst SF : BH dominate in low metallicity environments in young ULX

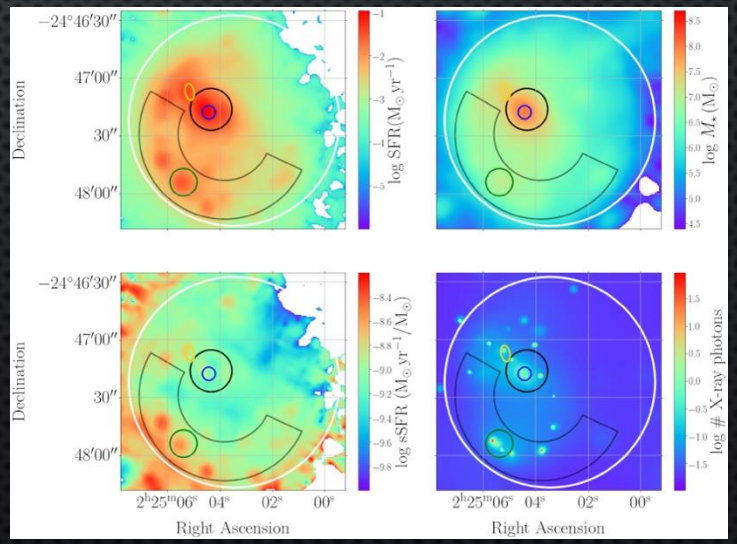
- It is tempting to conclude that the difference between RIGs and "normal" galaxies is due to the timing of the population and the flattening is due to the presence of BH-ULX.

METALLICITY – NGC 922 (SOLAR Z?)



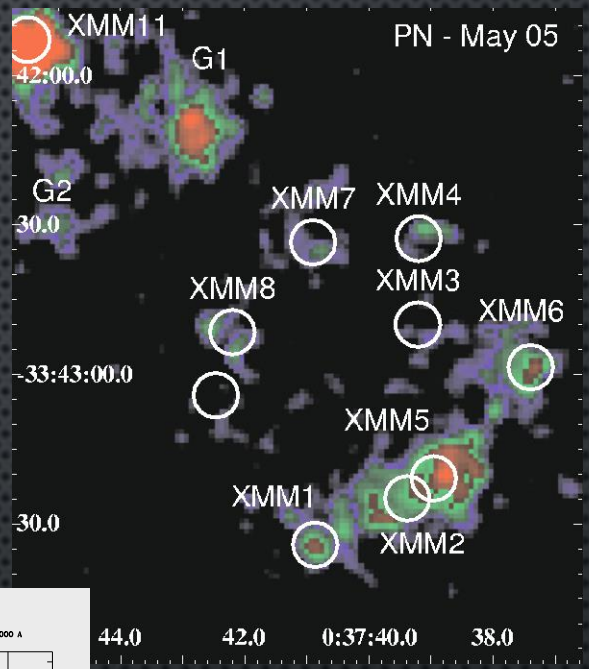
Kourourmpatzakis, Zezas, Wolter, Fruscione, Anastasopoulou, Prestwich 2021

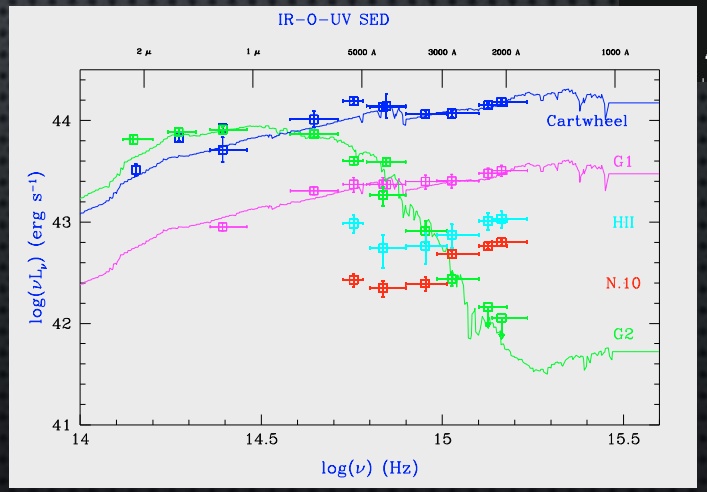
- ESO NTT spectra: He I emission -> ionization from recent stars clusters (Pellerin+2010)
- SFR (MIPS 24 um); Mstar (WISE1), sSFR; X-ray
- Lx ~ 1/Z in sub-galactic region: Less metals, More X-rays!
- Lx/Sfr = F(Z) (Brorby+2012, Fornasini+2020, Lehmer+2023)



CARTWHEEL WITH XMM-NEWTON

- XMM-Newton – 8 sources detected
- Variability of point sources (albeit confused) – especially N10 (see below)
- Transients (new sources)
- Low S/N detection of hot plasma at KT ~ 0.2 keV Lx (0.5-2) ~ 10^{40} erg/s
- Optical filters -> SED



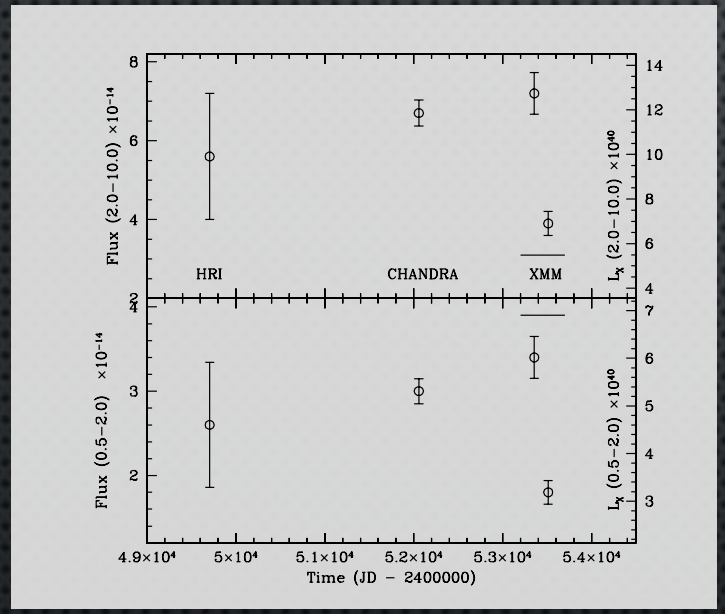


Crivellari, Wolter, Trinchieri 2009 A&A

THE HYPER-LUMINOUS X-RAY SOURCE (HLX): N10

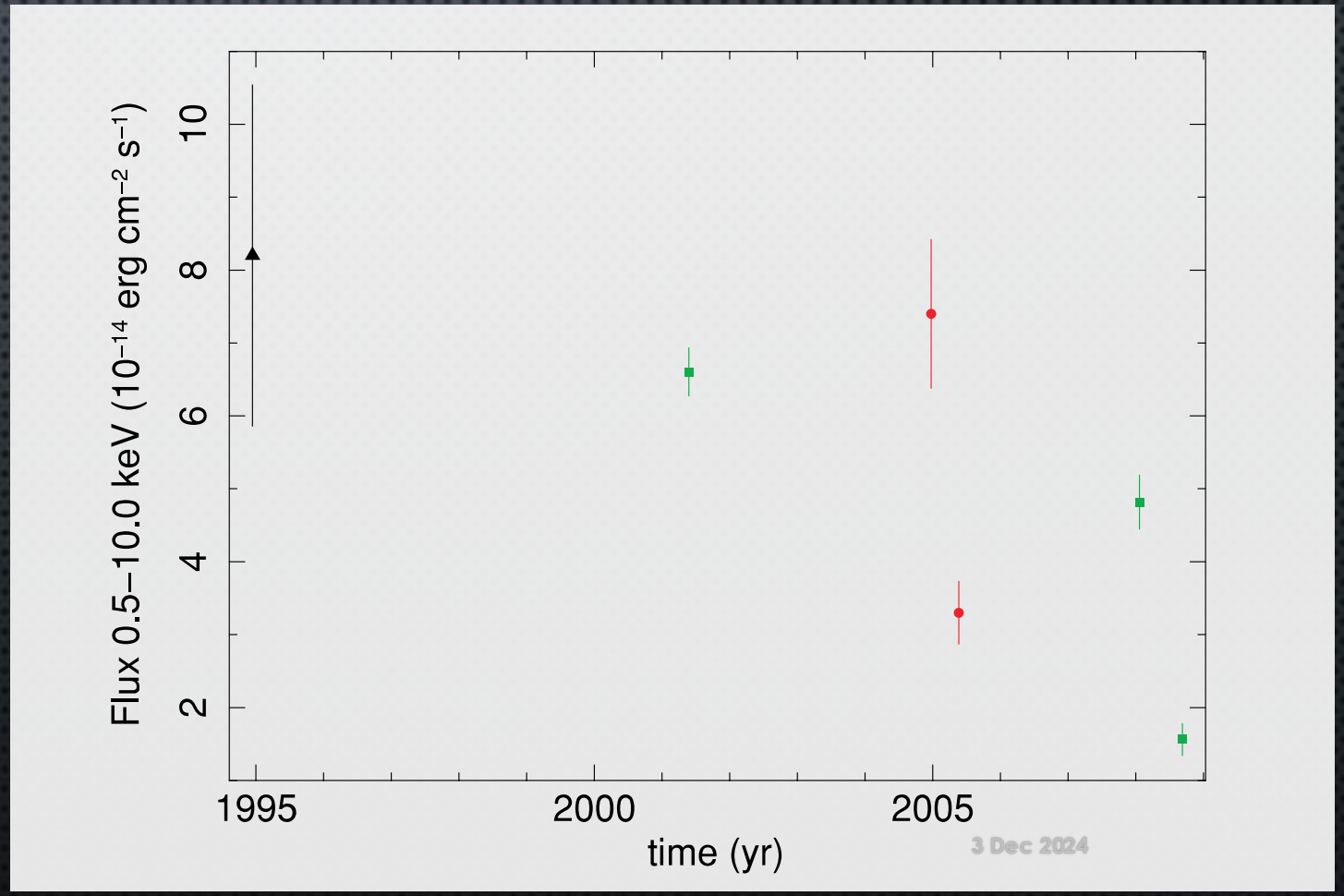
- N10 (Wolter, Trincheri 2004): Lx > 1-2 10^{41} erg/s – one of the few HLX
- Half Lx in 6 months in 2004-5 after 4 to 10 yrs of ~steady emission (Wolter, Trinchieri, Colpi 2006)

N10 LIGHT CURVE (ROSAT+XMM+CHANDRA)



Wolter, Trinchieri, Colpi 2006

Chandra 25 Years - Anna Wolter



Pizzolato, Wolter, Trinchieri 2010

THE HLX: N10 (XMM+CHANDRA)

- N10 (Wolter, Trincheri 2004): Lx > 1-2 10^{41} erg/s – one of the few HLX
- Half Lx in 6 months in 2004-5 after 4 to 10 yrs of ~steady emission (Wolter, Trinchieri, Colpi 2006); Again with Chandra in 2008
- Modeling of N10 variations (Pizzolato, Wolter, Trinchieri 2010)
  - Accretion on ~100 Msun BH (before the detection of GW)
  - NO hyper-accretion (king+2001) on stellar mass object (no $L \sim \kappa T^{-4}$)
  - Possibile also SN type IIn (young SN interacting with environ)

VARIABILITY - CHANDRA

"TIMING" IMAGE
RED: MAY 2001; GREEN: JAN 2008; BLUE: SEP 2008

- ALSO XMM-NEWTON (ALBEIT CONFUSION)
- 37 SOURCES INCLUDING G1 AND G2
- 1/3 VARIABLE BETWEEN OBSERVATIONS
- 5 SOURCES TRANSIENT (LMAX/LMIN > 10) -> NS?

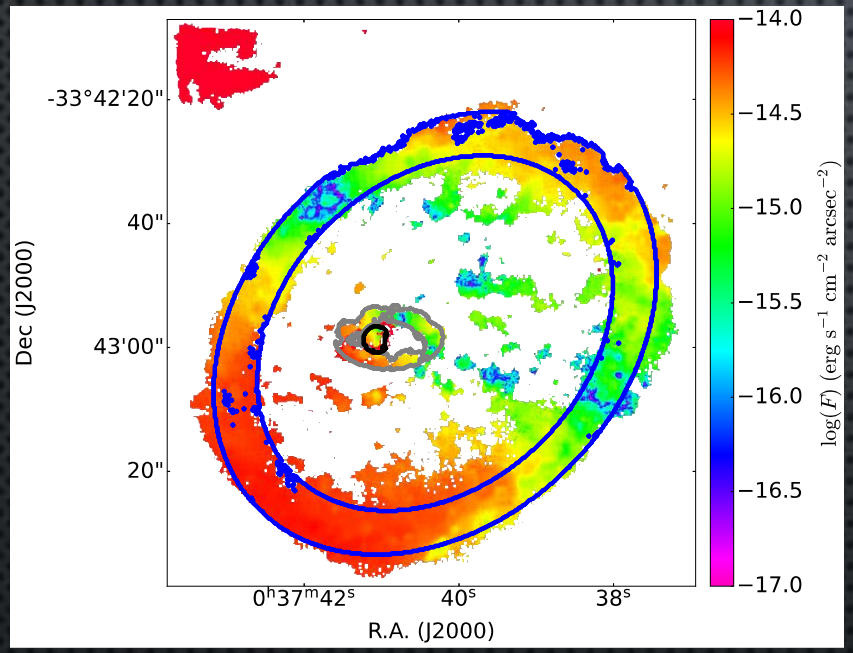
SALVAGGIO, WOLTER, BELFIORE, COLPI, 2023 MNRAS

POPULATIONS, METALLICITY, SFR

- MUSE DATA - MOSAIC OF 4 OBSERVATIONS WITH IFU

DITRANI, LONGHETTI, FOSSATI, WOLTER 2024 A&A

POPULATIONS, METALLICITY, SFR

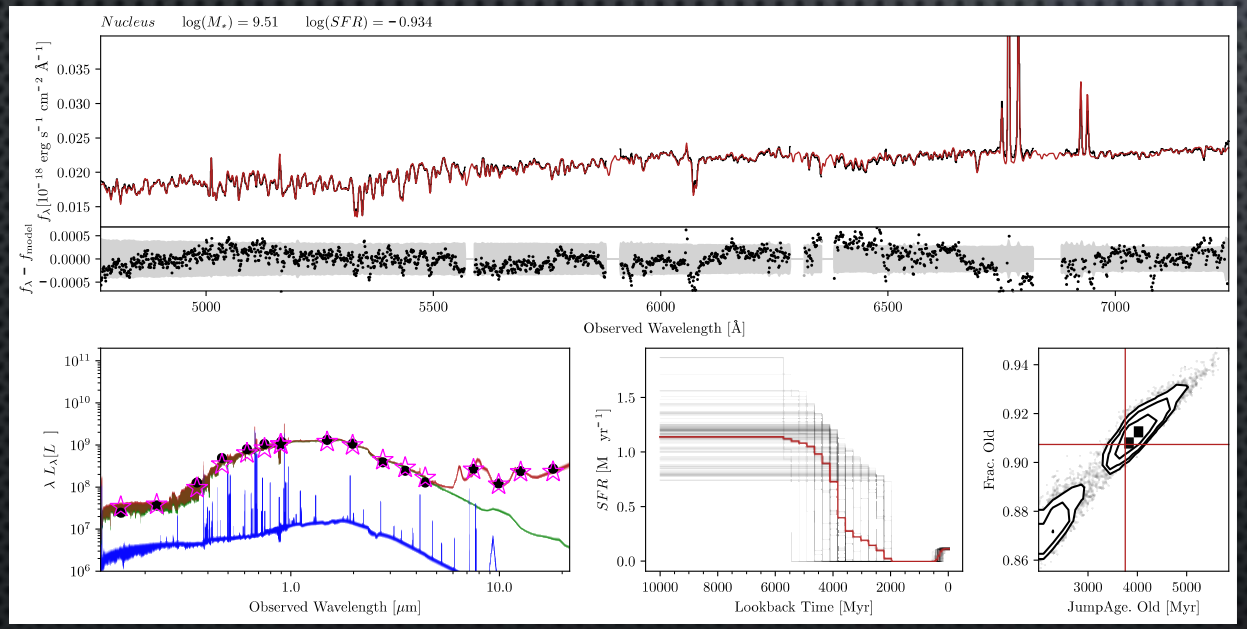


- MUSE DATA - MOSAIC OF 4 OBSERVATIONS WITH IFU
- DEFINE DIFFERENT REGIONS – EXTRACT SPECTRA (4 REGIONS)
- + JWST, VST… PHOTOMETRY
- FULL-INDEX FITTING OF THE STELLAR SPECTRA, ANALYSIS OF THE NEBULAR EMISSION, JOINT FULL SPECTRAL AND PHOTOMETRY FITTING
- STELLAR AGES, GAS AND STELLAR METALLICITIES, AND STAR FORMATION HISTORIES (SFHS)

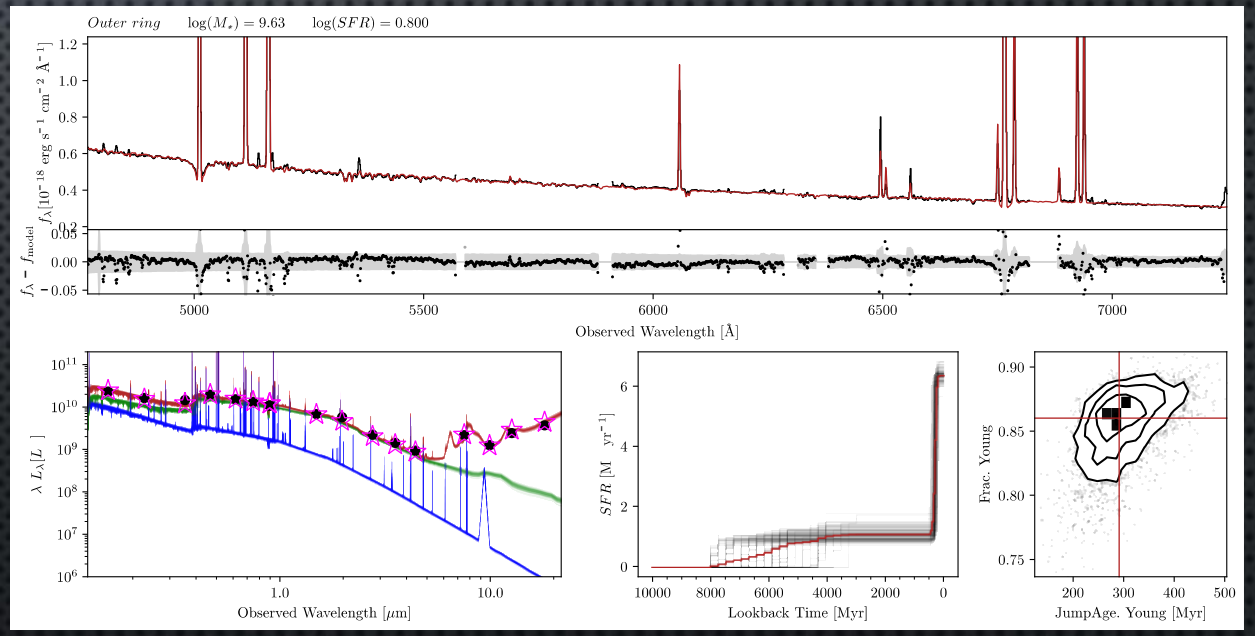
DITRANI, LONGHETTI, FOSSATI, WOLTER 2024 A&A

ASSUMING METALLICITY, DERIVE AGE/SFH

NUCLEUS



EXTERNAL RING

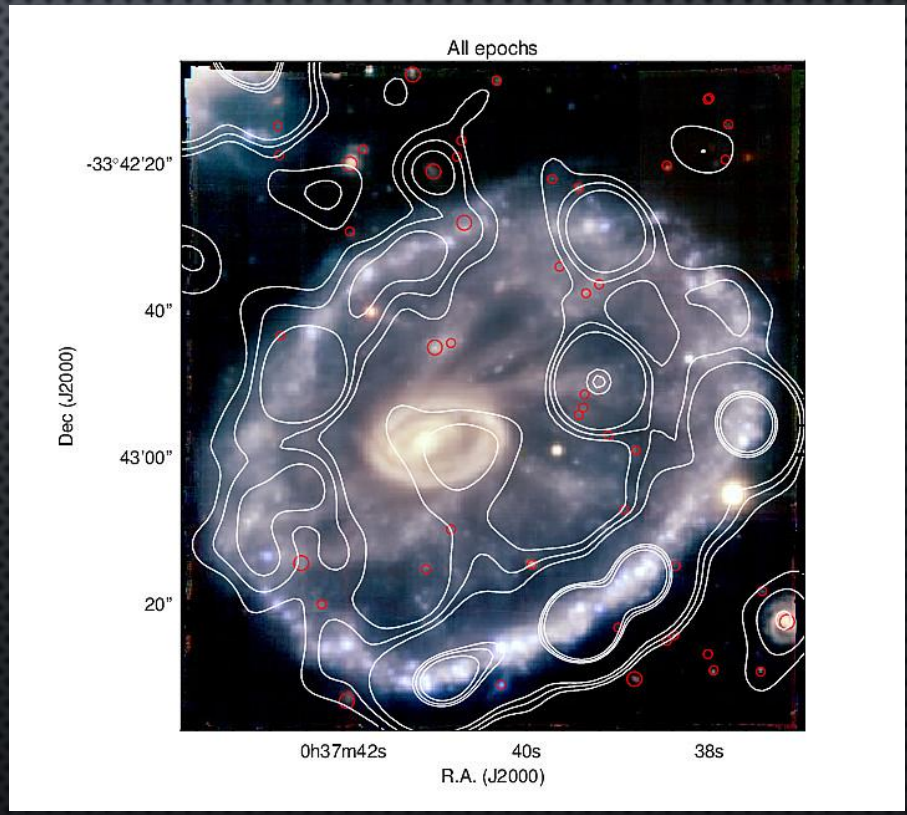


MULTINEST fit: Monte-Carlo Spectro-Photometric Fitter adapted from Fossati+ 2018

FROM STAR POPULATIONS TO ULXS

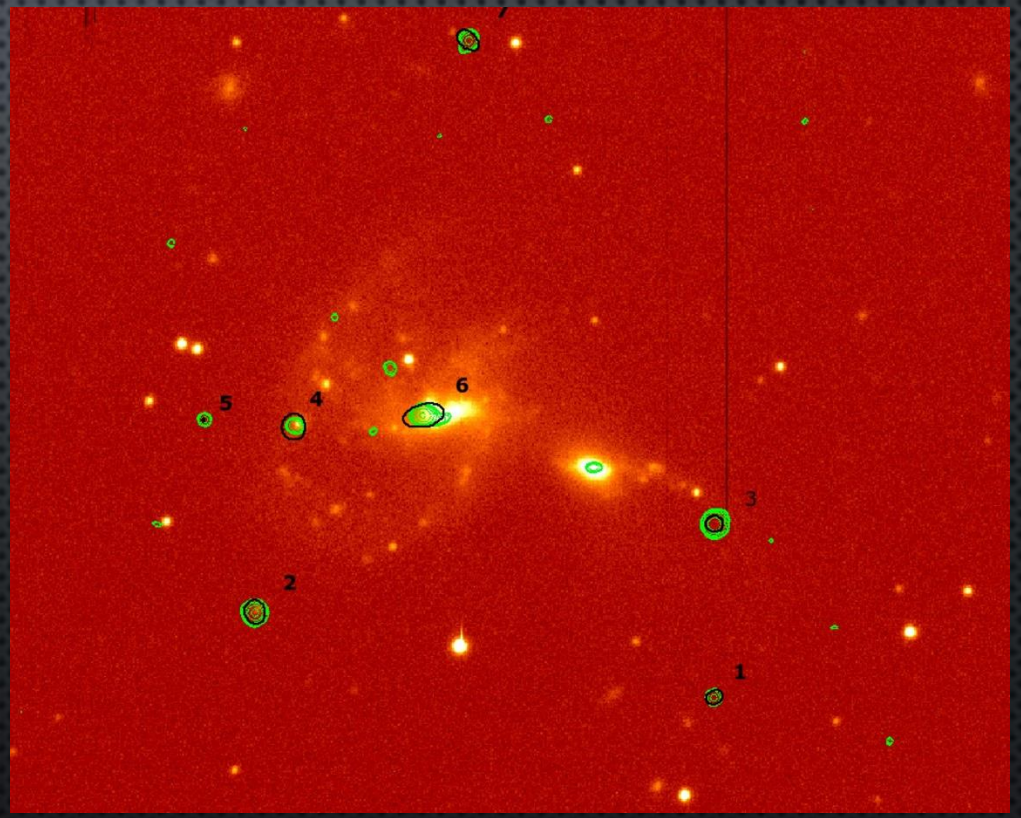
- THE "OLD" CARTWHEEL RETAINS CHARACTERISTICS OF SPIRALS
- A "YOUNG" POPULATION CONTRIBUTE A SMALL FRACTION OF THE MASS IN ALL REGIONS OUTSIDE THE NUCLEAR ZONE.
- THE OUTER RING IS VERY YOUNG <~ 400 MYR (CAVEAT FOR OLD STARS NOT EASY TO BE DETECTED)
- SHOCK WAVE DRAGS NEW STARS OUT
- EXPECT MOST ULXS POWERED BY BH; SOME MIGHT BE NS (PB: CAPTURE OF COMPANION?) WOLTER ET AL IN PREP.

Chandra contours; Circles: bkgd srcs



Future (near)

- Construct a comparison complete sample (Wolter, Fruscione, … in prep)
- 14 galaxies from Arp&Madore, z<0.02
  a number of observations in different bands (X-rays; Halpha etc)
- Less powerful than “Bright&Famous”
  - Lower Mass?
  - Shorter/Longer Time Scale from impact?
  - Different Metallicities?



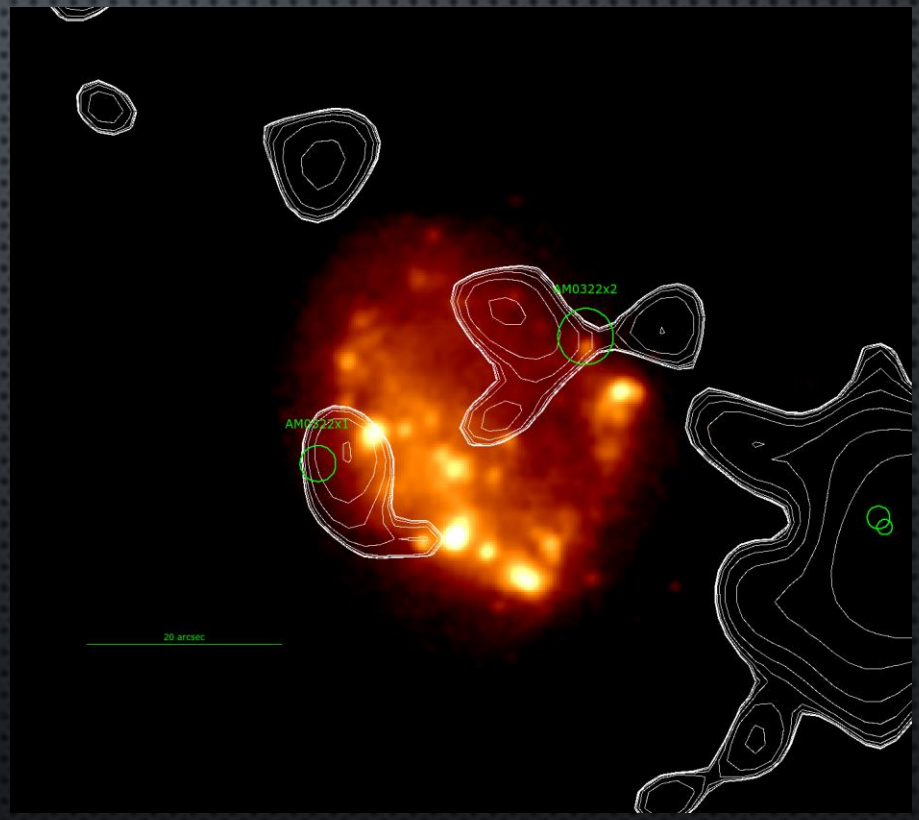
Future (near) – cont'd

- New Chandra Observations this AO

Seven objects:

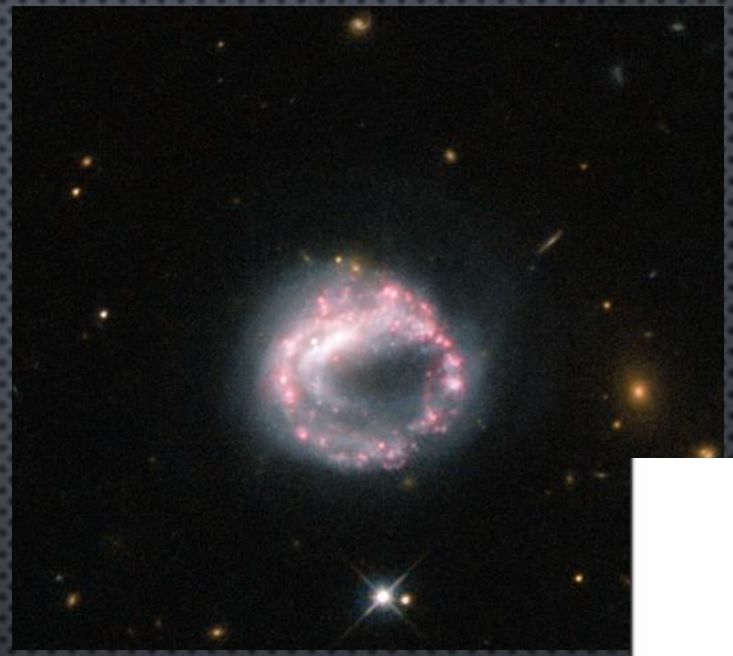
  - 3 with XMM-Newton detection, plus Halpha and spectral optical data;
  - 4 with no X-ray data and low Nh.

+ Optical data from Goodman spectrograph on SOAR telescope



FUTURE (FAR)

- A Northern Sample of RiGs
- Citizen Zoo Ring sample?



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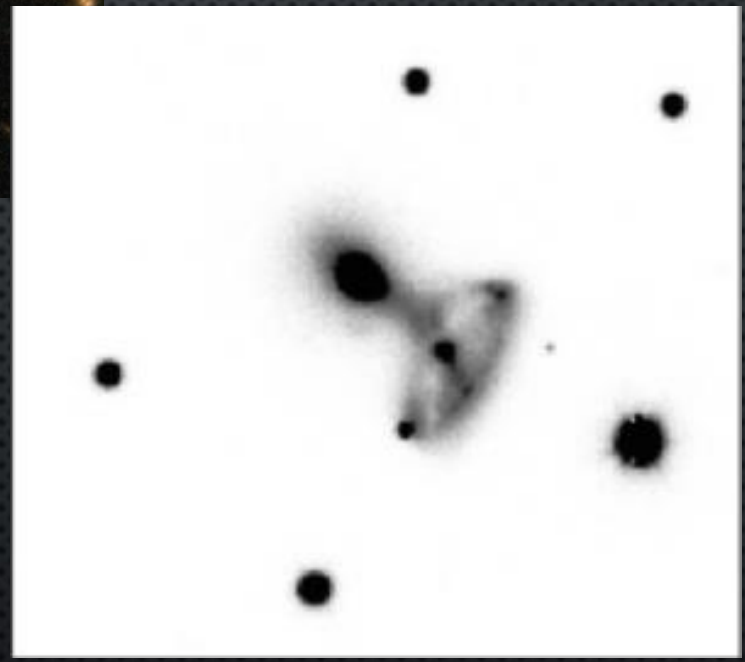

Auriga's Wheel

CONCLUSIONS

- RiGs are crowded – need eagle eye to resolve sources
- RiGs have young star population easy to disentangle – MultiLambda studies
- Variability -> to study emission mechanism in binaries & their nature
- Population of RINGS is young (at least Cartwheel – applying same analysis to others) -> possibly BH-powered ULXs
- Conclude the complete sample

… and do all this, and do it right …

Webb Captures Stellar Gymnastics in The Cartwheel Galaxy

NASA 2 Aug 22

https://www.nasa.gov/feature/goddard/2022/webb-captures-stellar-gymnastics-in-the-cartwheel-galaxy

Thank you

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