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Supernova remnant population in nearby galaxies

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	Distance (kpc)	Number of SNRs	References
LMC	50	59 (+15)	Maggi et al. (2016), Bozzetto et al (2017)
SMC	60	21 (+2)	Badenes et al. (2010), Haberl et al. (2012), Maggi et al. (2019)
M31	750	156	Sasaki et al. (2012), Lee & Lee (2014)
M33	800	217	Long et al. (2010), White et al. (2019)
M83	4600	211	Blair et al. (2015), Long et al. (2022)
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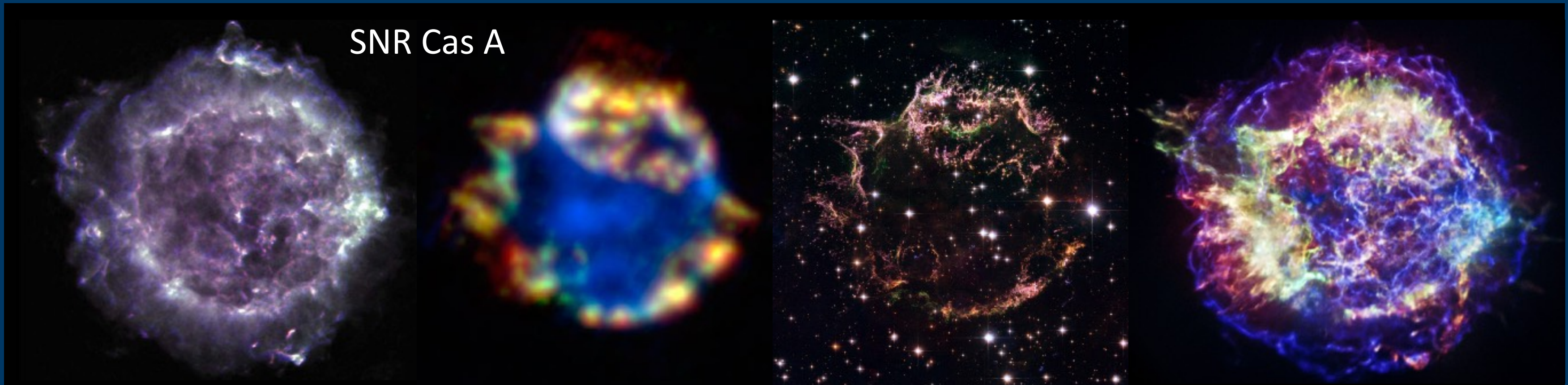
SNRs in another galaxy are approximately at the same distance.
Lower foreground absorption than to most of the SNRs in the Milky Way.

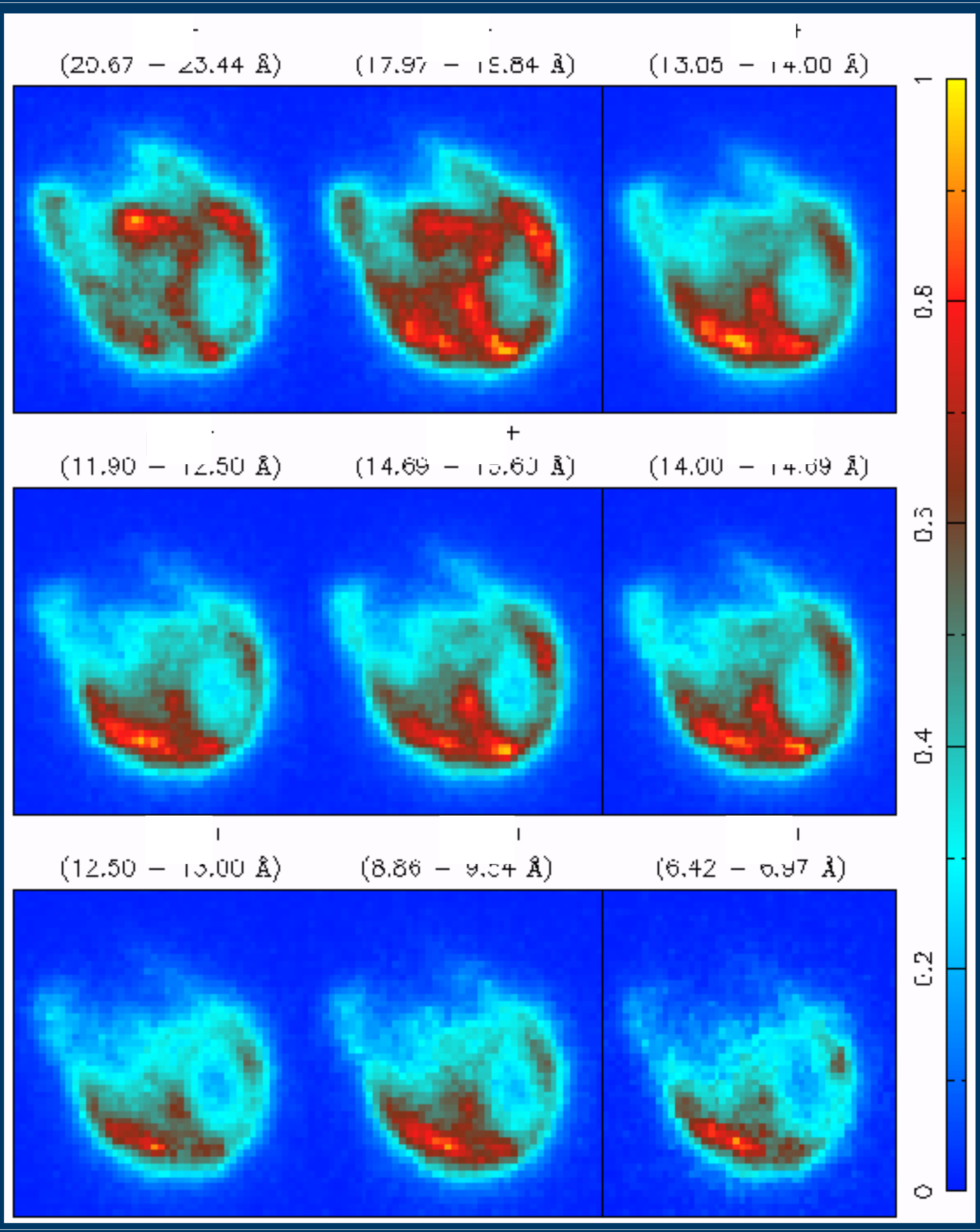
How to Find SNRs

- **Radio**: **Synchrotron** emission from **non-thermal electrons**. Flux density $S \sim \nu^{-\alpha}$ with about $\alpha = 0.5$.
- X-rays: **Thermal plasma** with continuum from free-free emission, recombination, two-photon emission. Line emission from electron-ion collisions. **Synchrotron** emission from **non-thermal electrons**.
- **Optical**: **Radiative shocks** in dense ISM. Optical **forbidden lines** from different ionization states (e.g., [O III] λλ 4959,5007, [O I] λλ 6300,6363, [N II] λλ 6549,6583, and [S II] λλ 6717,6731).
- **Infrared**: **Radiative shock**, e.g., [Fe II] λλ 1.27,1.64 μm. **Dust** emission.
- **Gamma-rays**: **Radioactive decay**, **cosmic rays**.



Radio (VLA, NRAO/AUI) IR (Spitzer, NASA/JPL-Caltech/J. Rho (Caltech-SSC) Optical (HST, NASA/ESA/Hubble X-rays (Chandra, NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.)

X-ray Emission of Hot Shocked Plasma

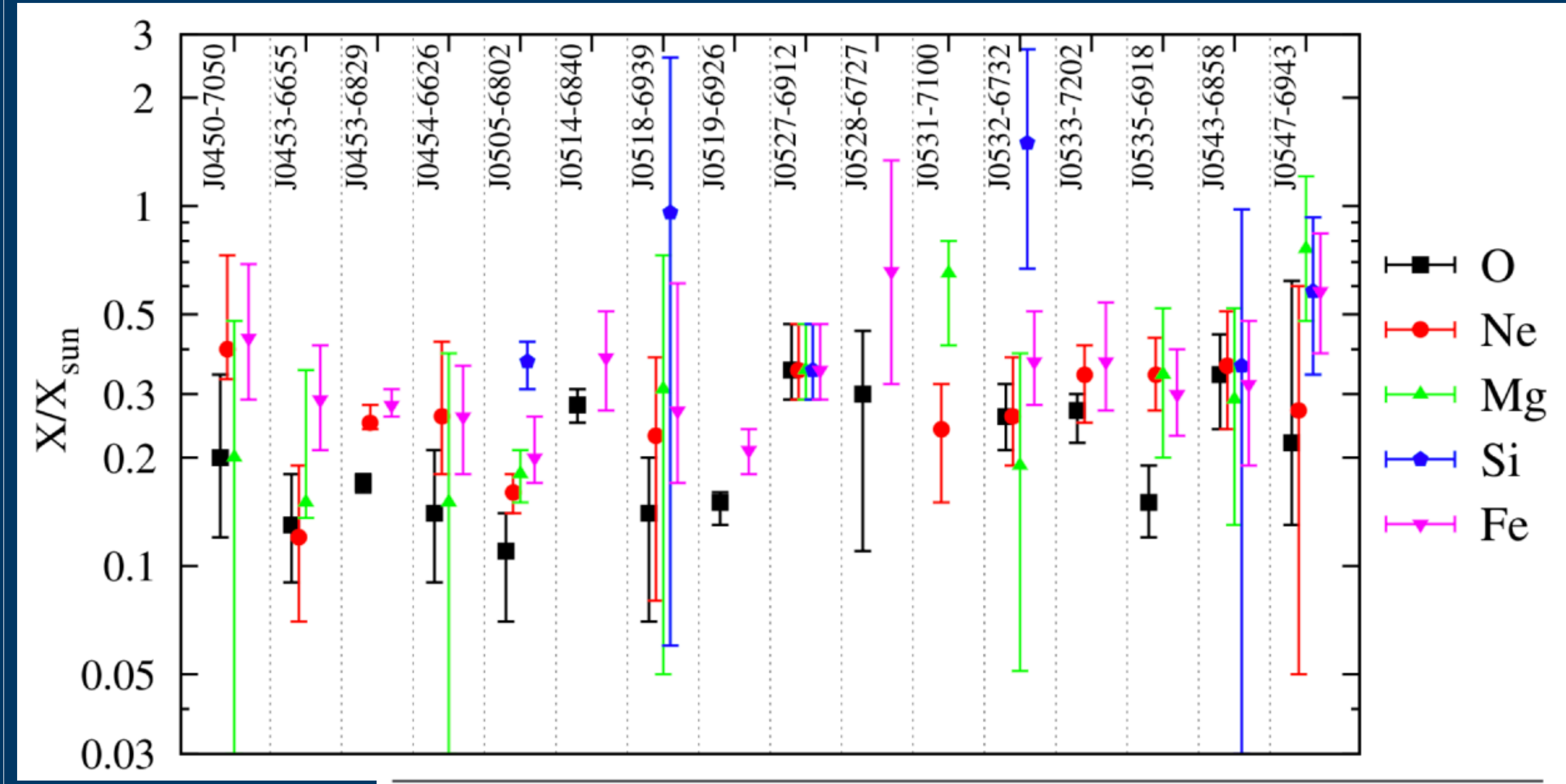


SNR N132D in the Large Magellanic Cloud

Behar et al. (2001)

SNRs and ISM Abundances

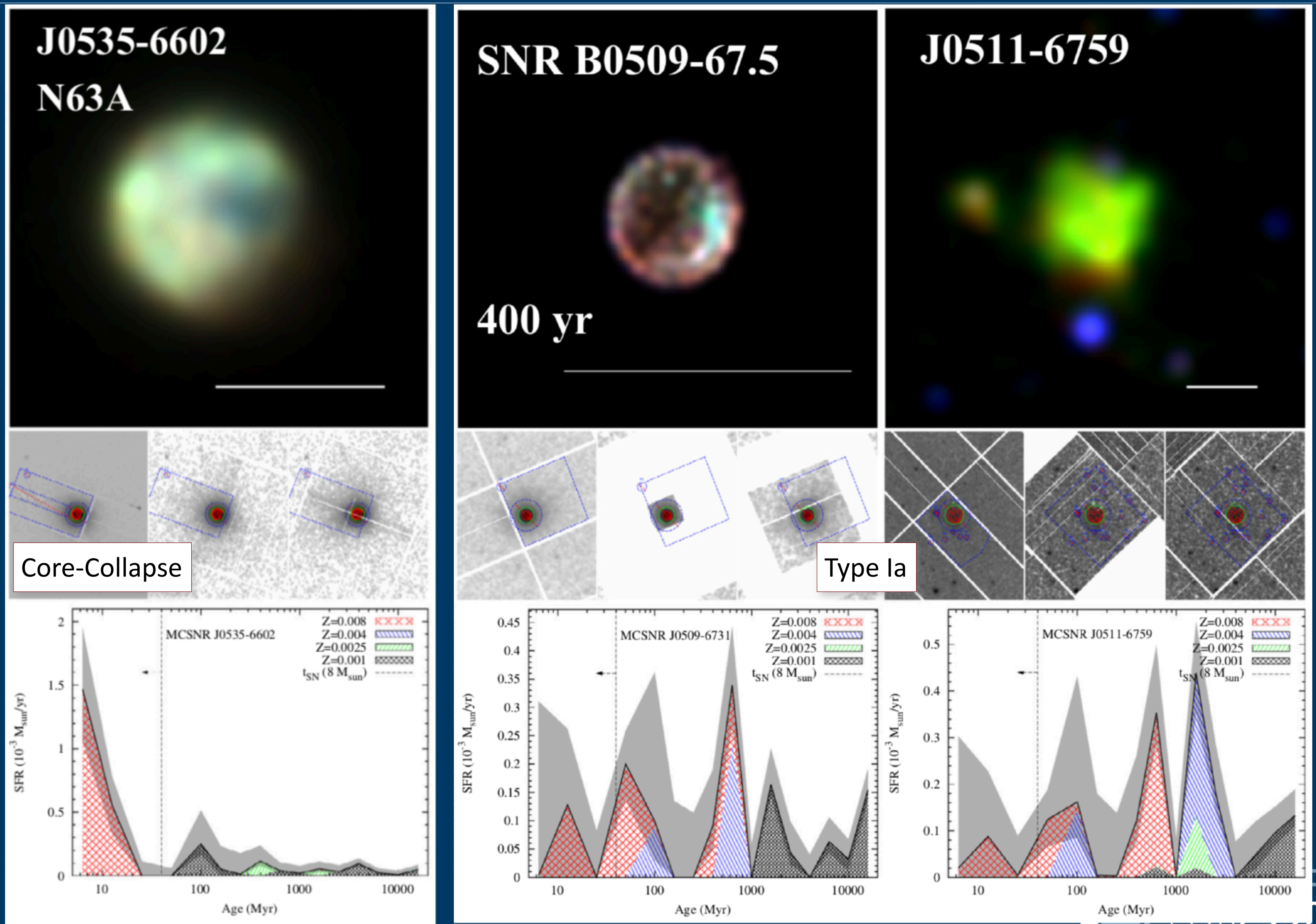
ISM abundances measured in XMM-Newton spectrum of LMC SNRs.



Element	$X/X_\odot$ (1)	N (2)	rms (3)	12 + log(X/H)	Hughes et al. (1998)	RD92
O	0.21	15	0.08	$8.01^{+0.14}_{-0.21}$	8.21 ± 0.07	8.35 ± 0.06
Ne	0.28	13	0.08	$7.39^{+0.11}_{-0.15}$	7.55 ± 0.08	7.61 ± 0.05
Mg	0.33	11	0.19	$6.92^{+0.20}_{-0.37}$	7.08 ± 0.07	7.47 ± 0.13
Si	0.69	6	0.42	$7.11^{+0.20}_{-0.41}$	7.04 ± 0.08	7.81[a]
Fe	0.35	15	0.12	$6.97^{+0.13}_{-0.18}$	7.01 ± 0.11	7.23 ± 0.14

Maggi et al. (2016)

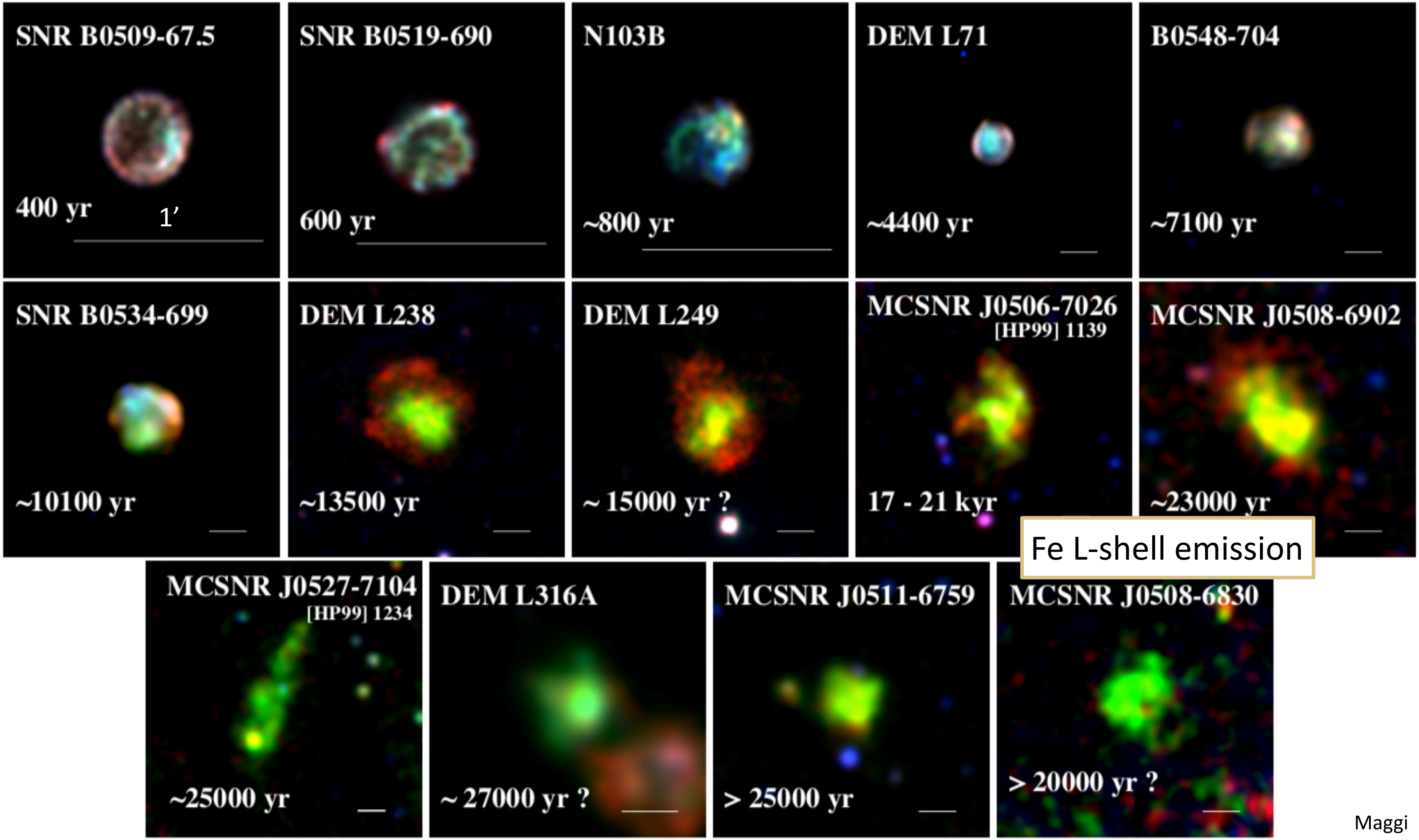
SNRs and Stellar Populations



Maggi et al. (2016)

SNR Evolution

Type Ia SNRs in the Large Magellanic Cloud



Maggi

SNR Morphologies

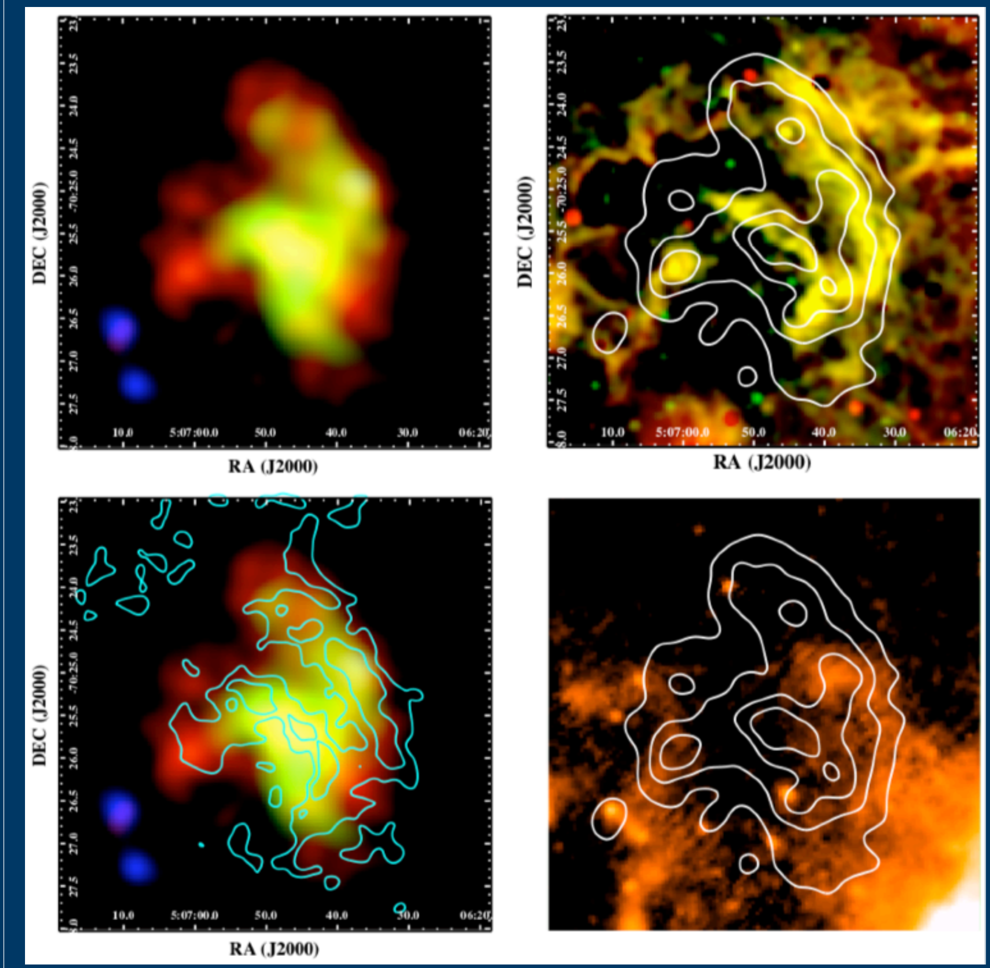
Core-collapse SNRs in the Large Magellanic Cloud

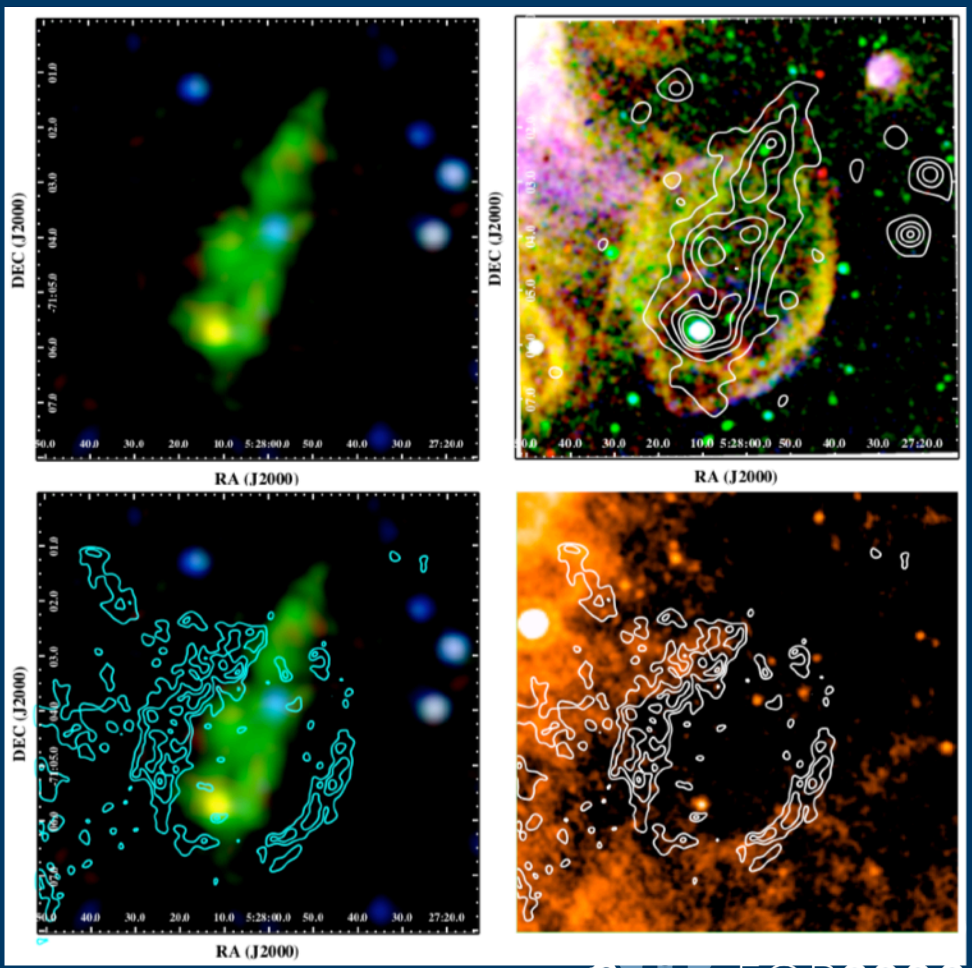
Maggi

Fe-rich Type Ia SNRs

SNRs J0506-7025 and J0527-7104 in the LMC (Kavanagh et al., 2016).

XMM-Newton EPIC (red: 0.3 - 0.7 keV, green: 0.7 - 1.1 keV, blue: 1.1 - 4.2 keV)	MCELS (red: Hα, green: [S II], blue: [O III]) with X-ray contours
XMM-Newton EPIC RGB with contours for [S II]/Hα > 0.67	Spitzer MIPS 24 µm image with contours for [S II]/Hα > 0.67





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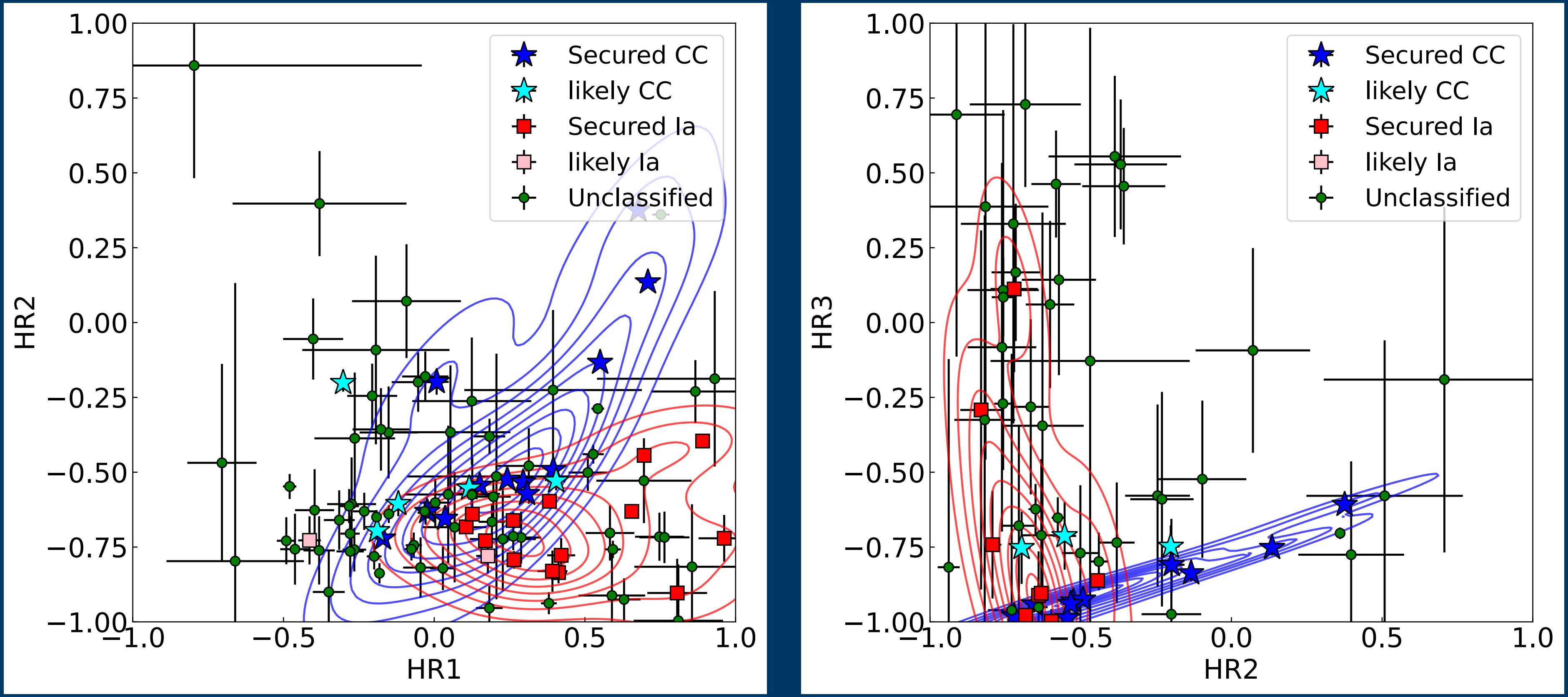
eROSITA LMC SNR Catalogue

Hardness ratios $HR_i = (B_{i+1} - B_i)/(B_{i+1} + B_i)$ for the count rates in the bands:

B1 = 0.3 - 0.7 keV, B2 = 0.7 - 1.1 keV, B3 = 1.1 - 2.3 keV, B4 = 2.3 - 8.0 keV

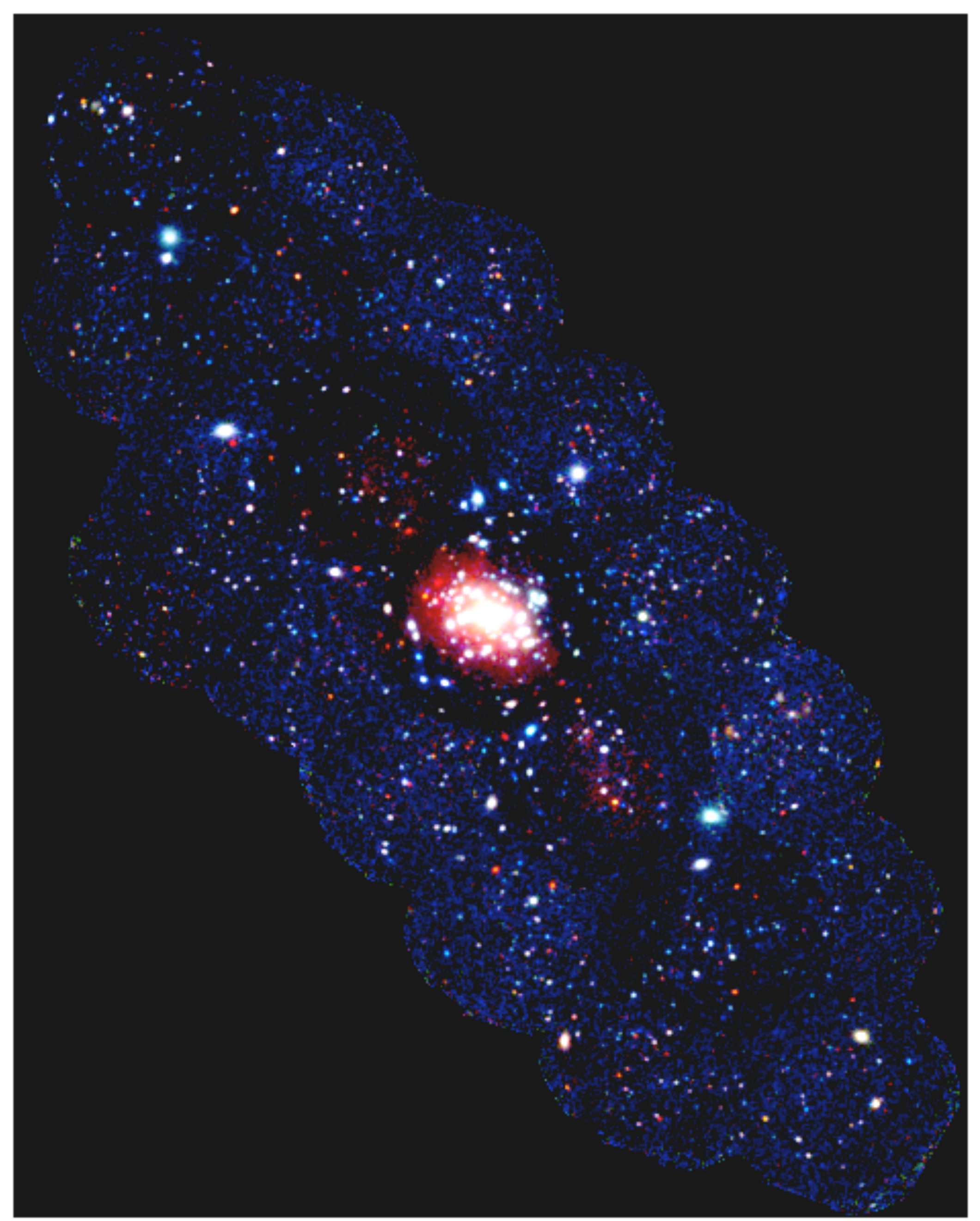
- Type Ia: hard in HR1 (> -0.2), soft in **HR2** (< -0.3), Fe L emission dominates.
- Core-collapse: hard in HR1 (> -0.5), soft in **HR3** (< -0.5), broader spectrum.



Zangrandi et al., submitted

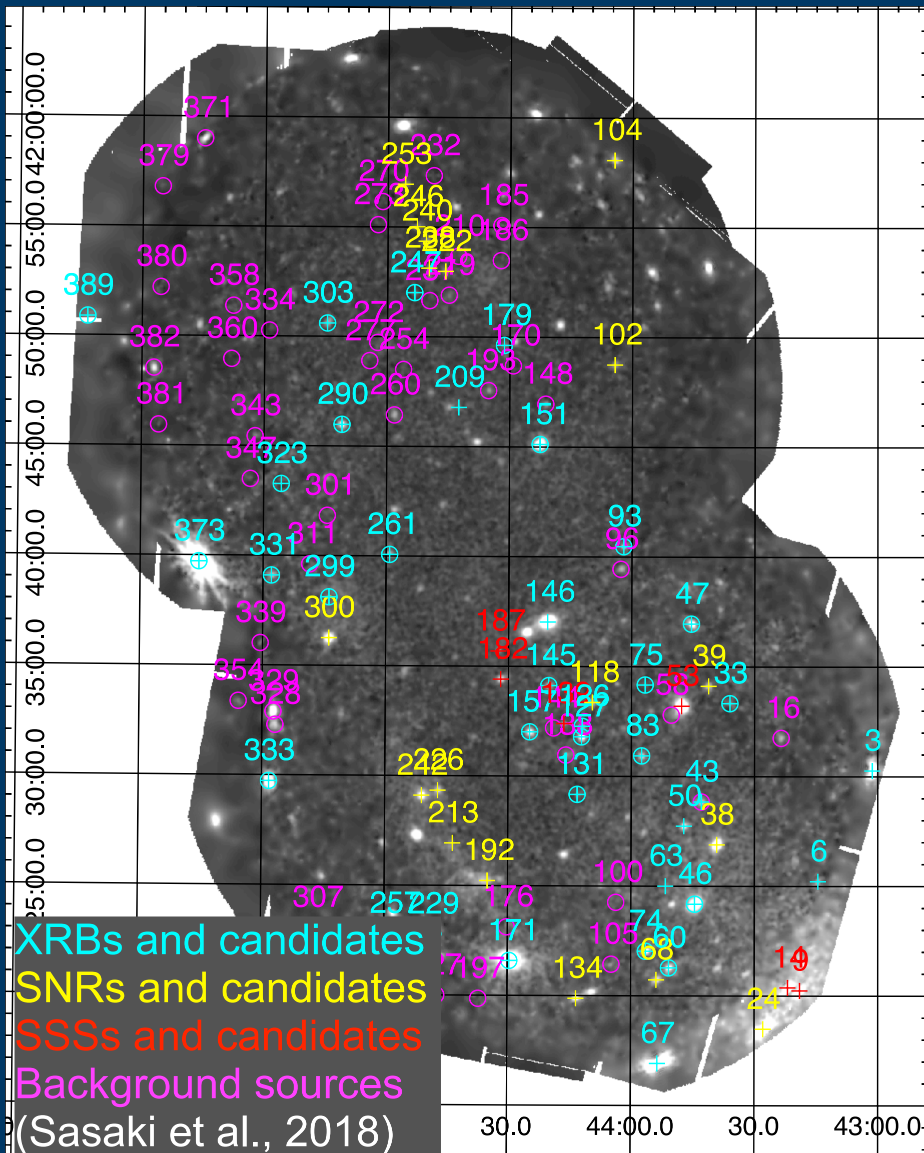
M31

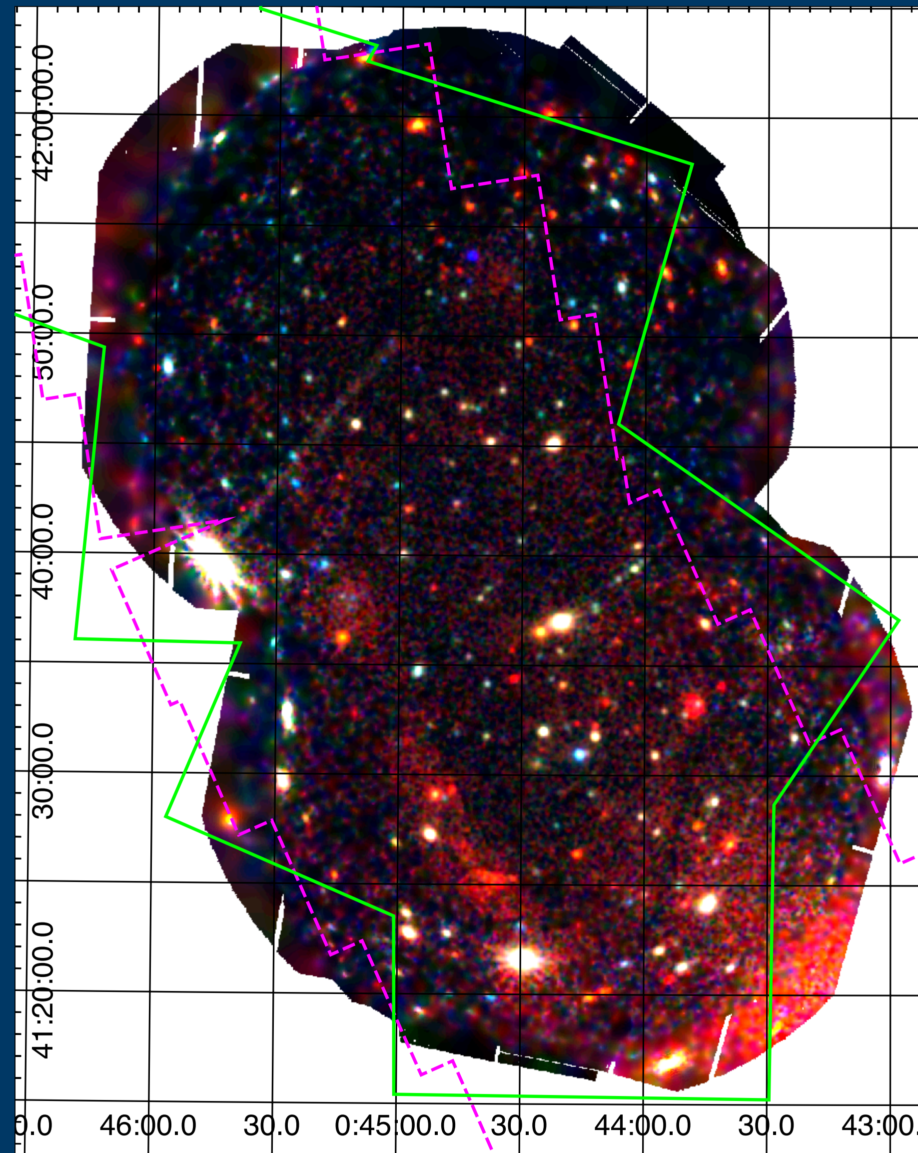
XMM-Newton survey (Pietsch et al., 2005, Stiele et al., 2011)



Northern Disk of M31

XMM-Newton, Chandra, and HST surveys





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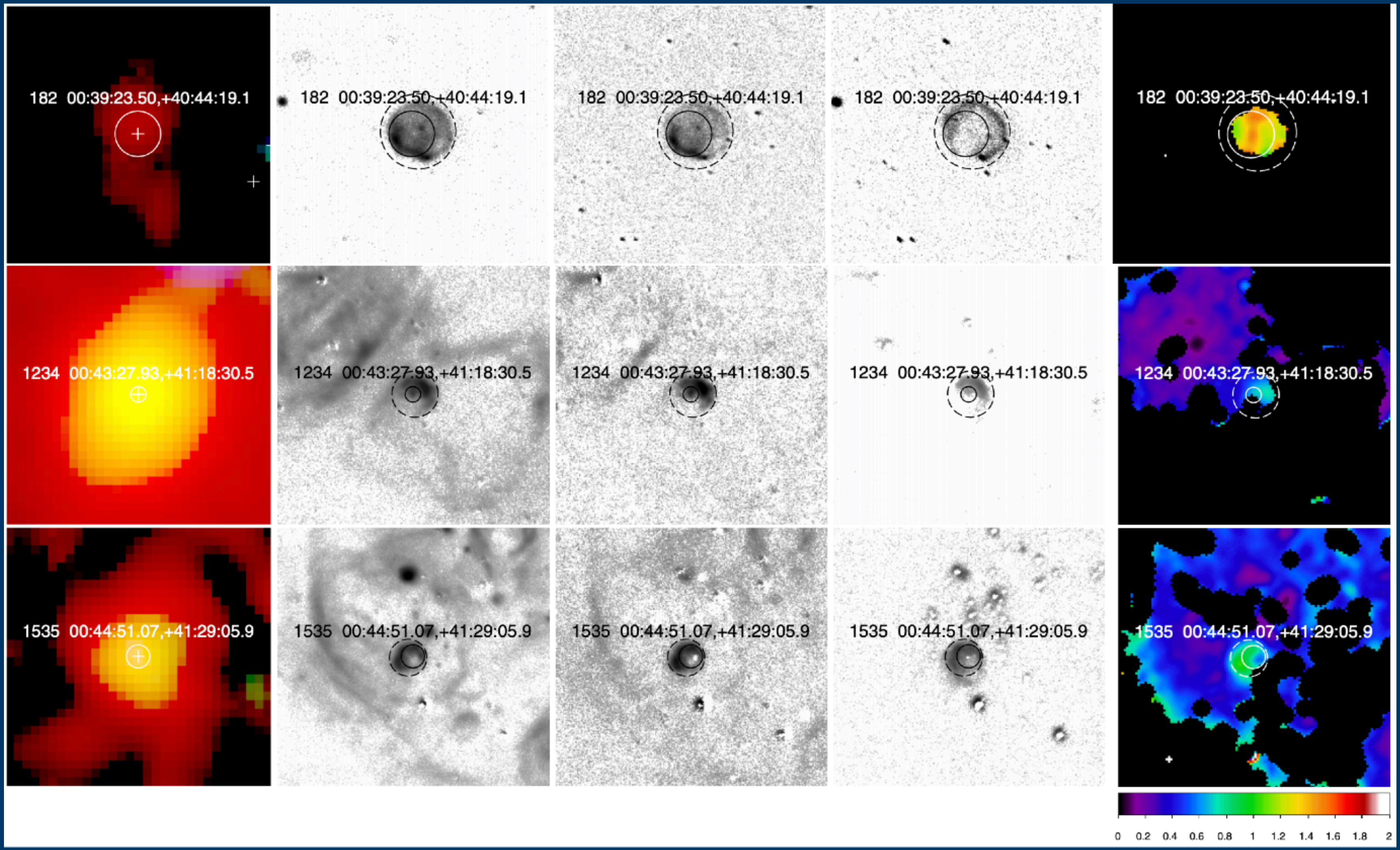
M31

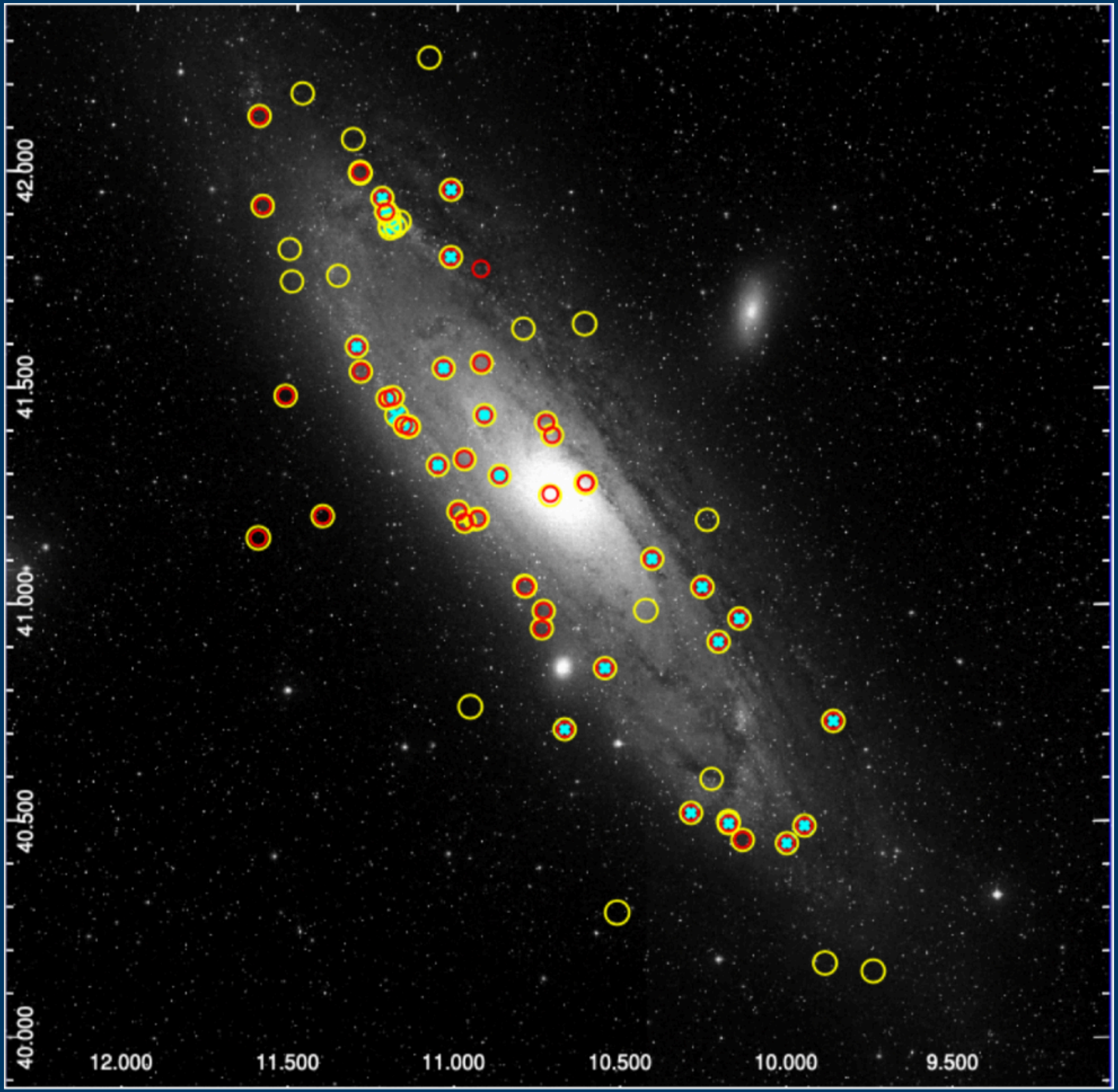


X-rays Halpha [S II] [O III] [S II]/H alpha

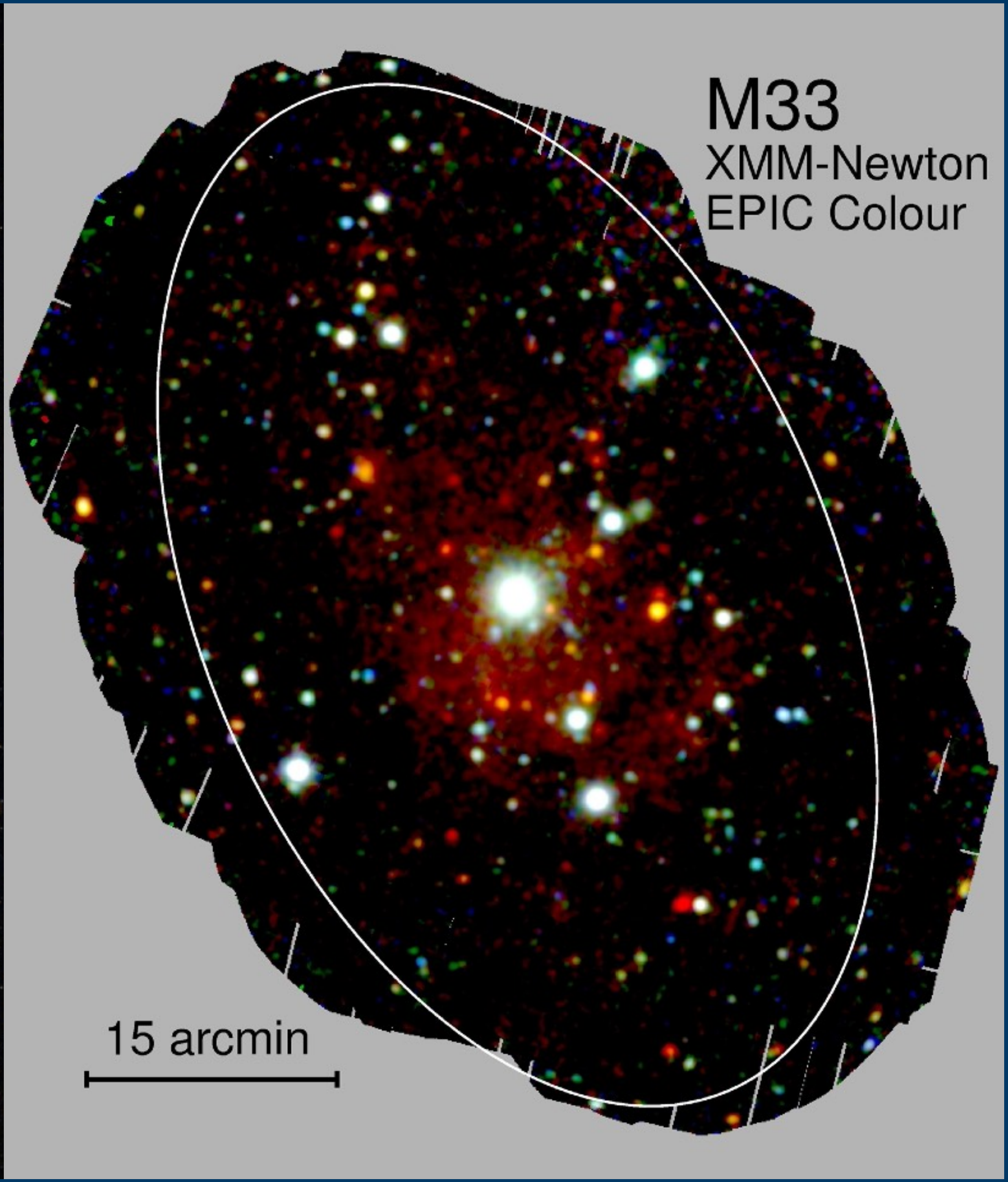
XMM-Newton and Local Group Galaxy Survey images (Massey et al. 2006), Sasaki et al. (2012)

M31

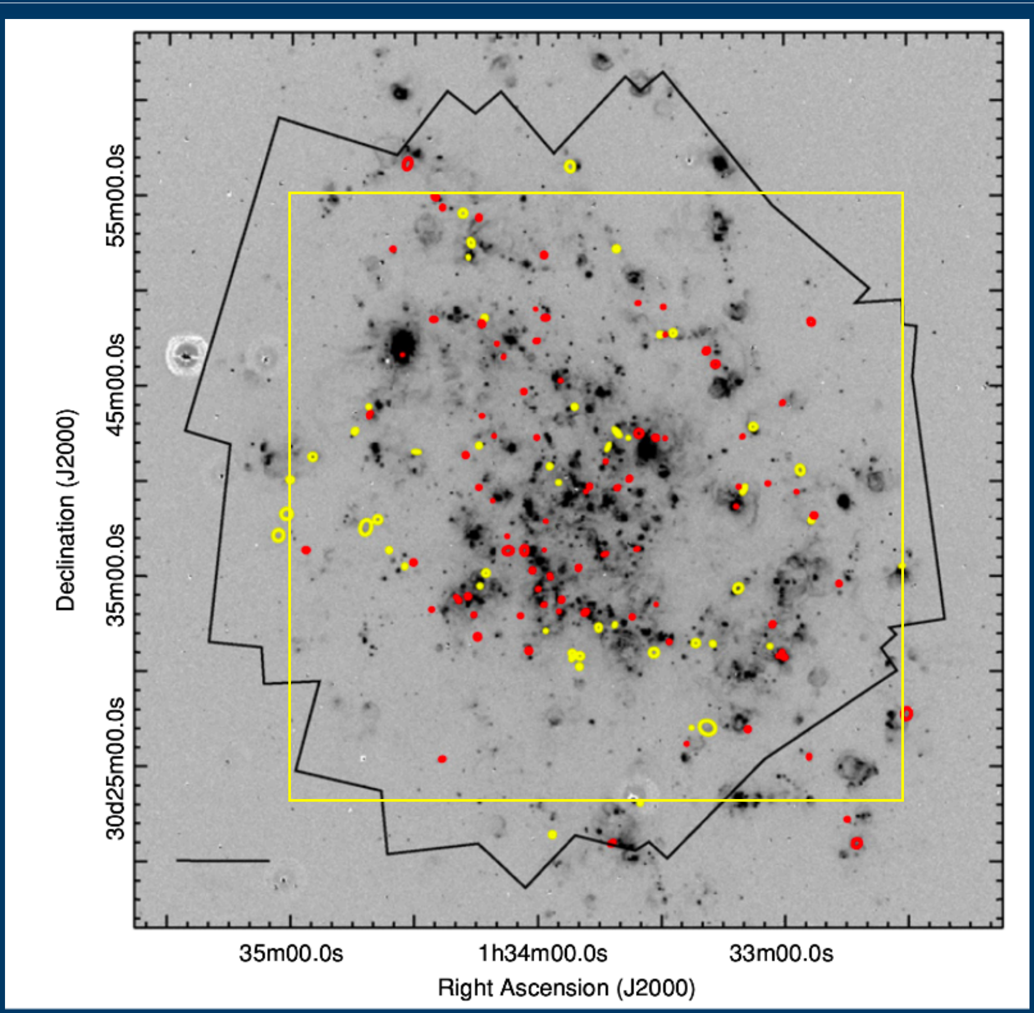
- Confirmed SNRs (yellow and red)
- New confirmation using **LOFAR** data (cyan)
- New **XMM-Newton** data of the Southern disk (Saeedi et al., in prep.)
- Optical catalog based on Local Group Galaxy Survey (Lee & Lee, 2014)

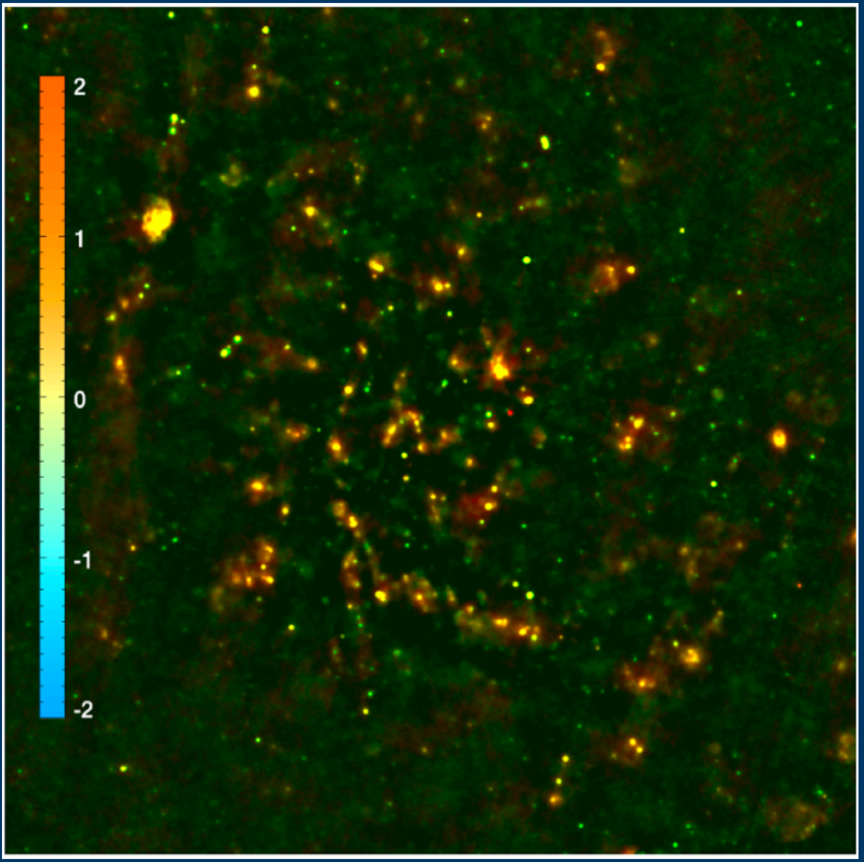


M33



M33





CHANDRA ACIS Survey of M33 (ChASeM33)

- Yellow: optical and X-ray detected SNRs
- Red: optical SNR candidates

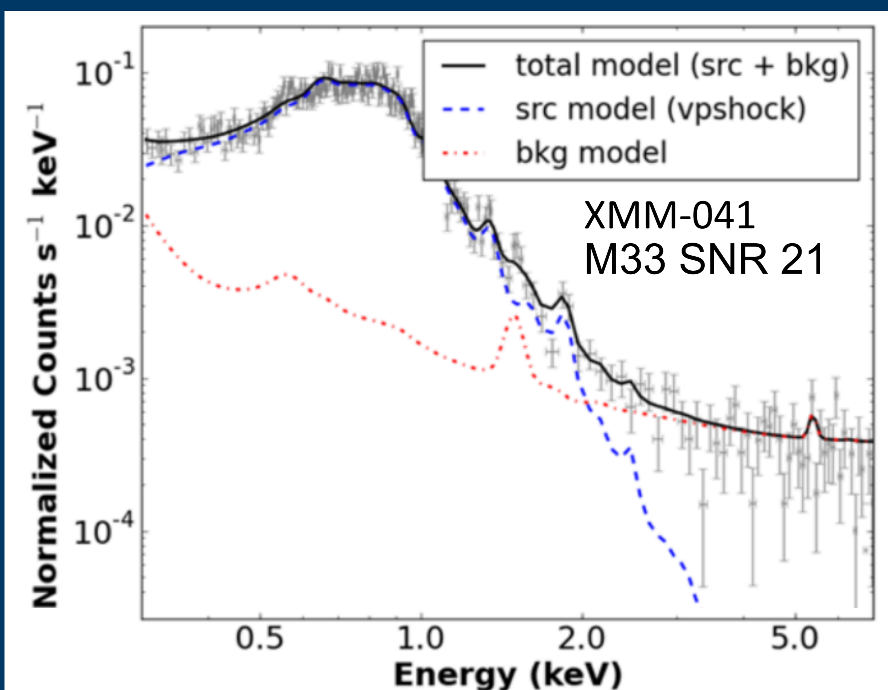
(Long et al. 2010)

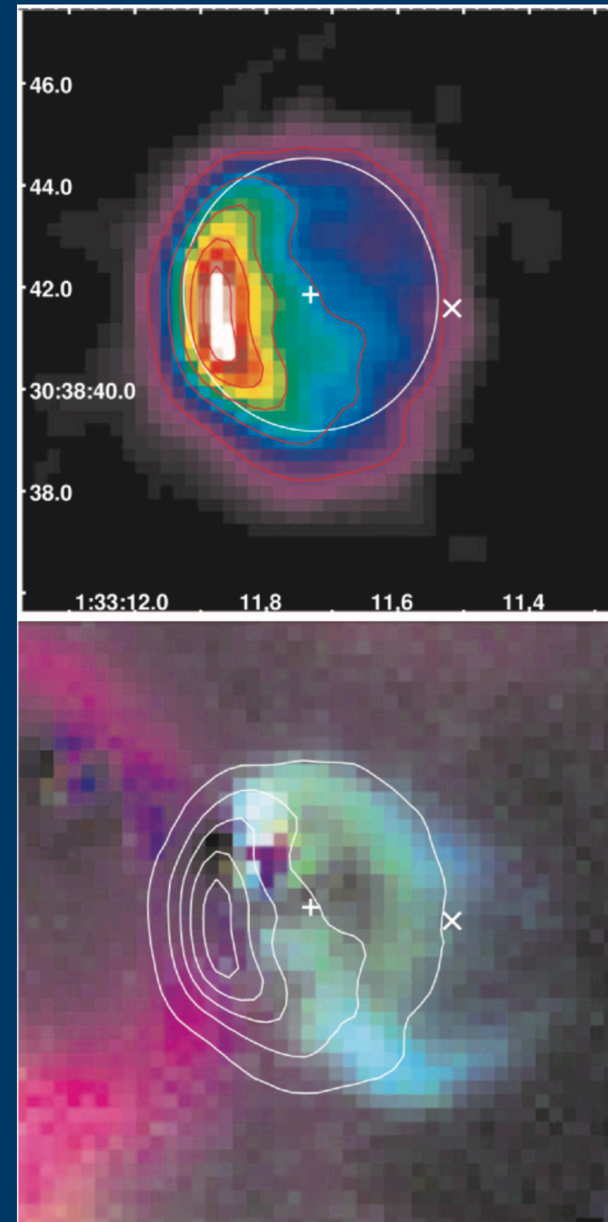
JVLA radio survey: radio spectral index (White et al. 2019)

M33

M33 SNR 21

- Resolved with Chandra, confirmed in the optical (red: Hα, green: [S II], blue: [O III], Gaetz et al., 2007).
- Spectral analysis with XMM-Newton (Garofali et al. 2017)





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Optical Line Ratios

Typically, **[S II]/Hα** to distinguish between shock-ionised and photoionised gas.

However, distinction between H II regions and SNRs becomes less obvious at low surface brightness (Long et al., 2018).

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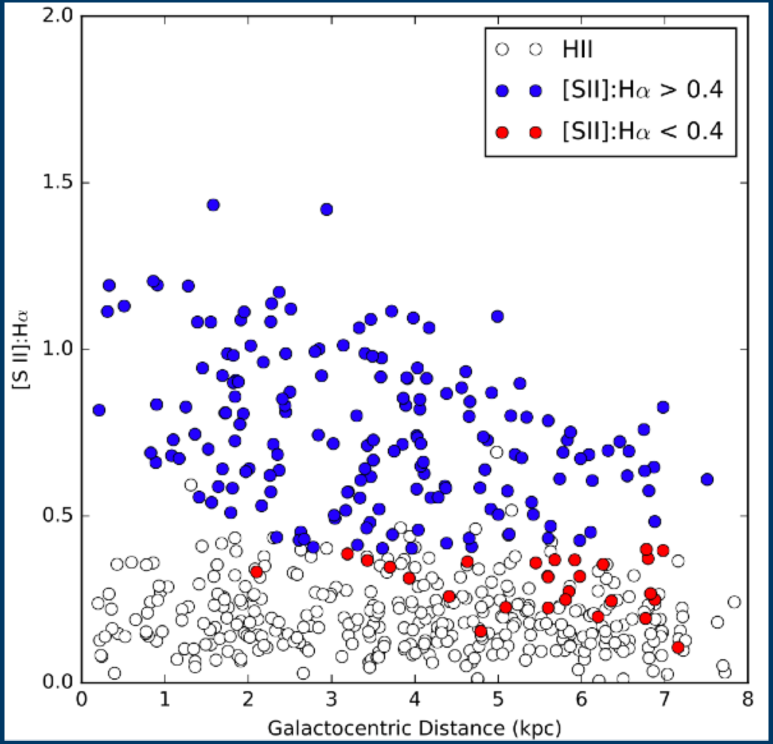
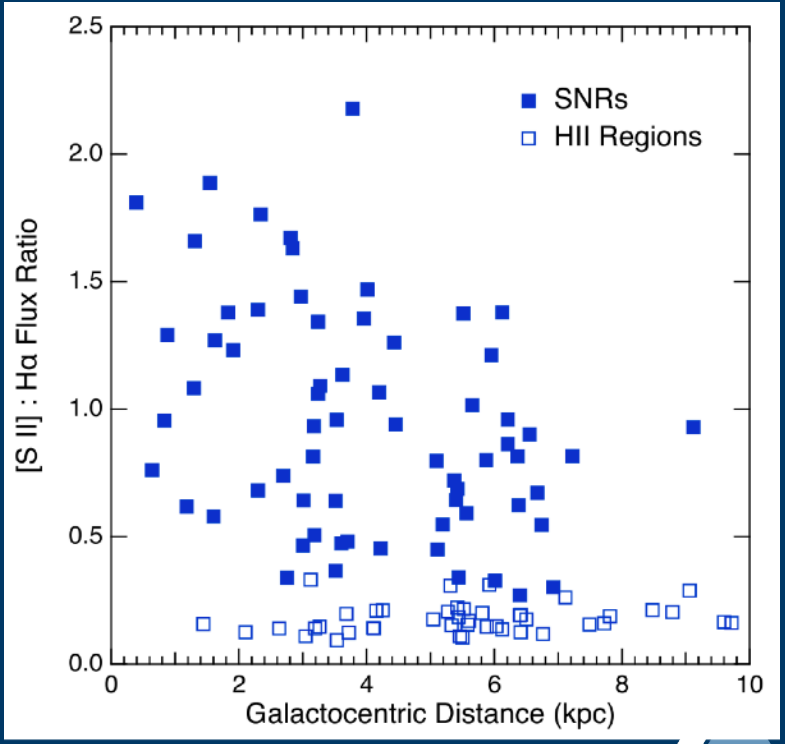


Long et al. (2018)



Winkler et al. (2021)

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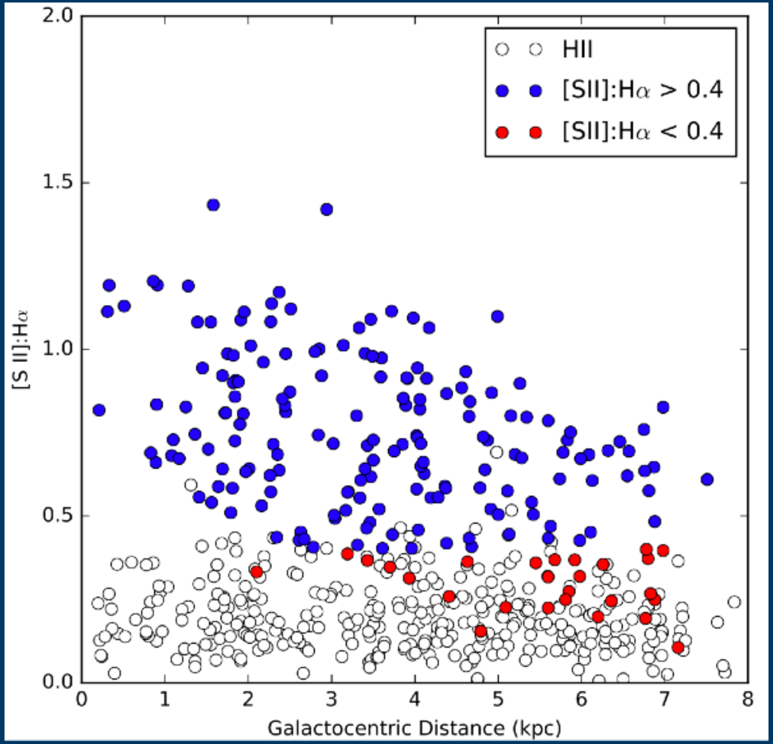
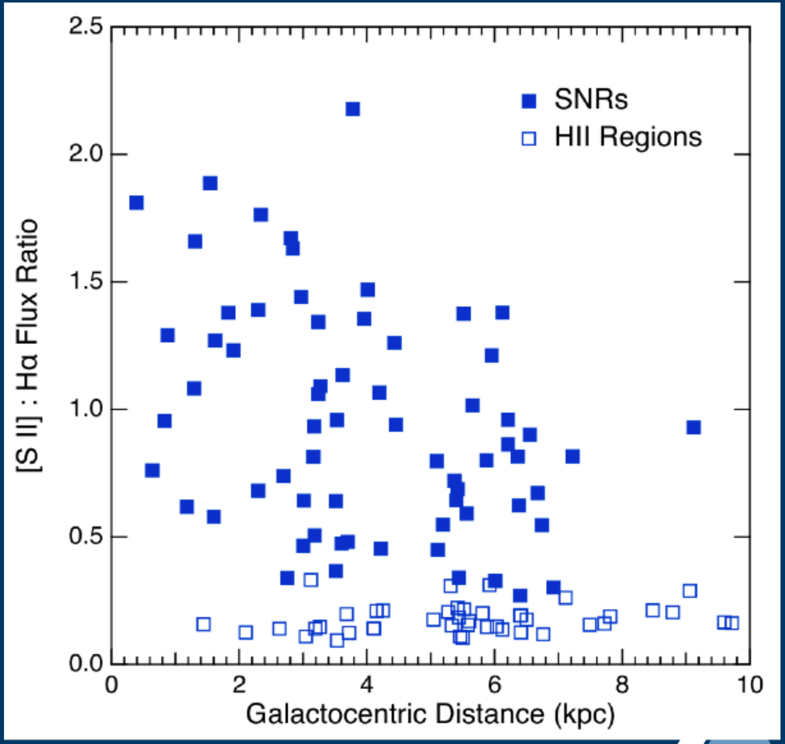
For identification of SNRs combination of radio, optical, and X-rays necessary!



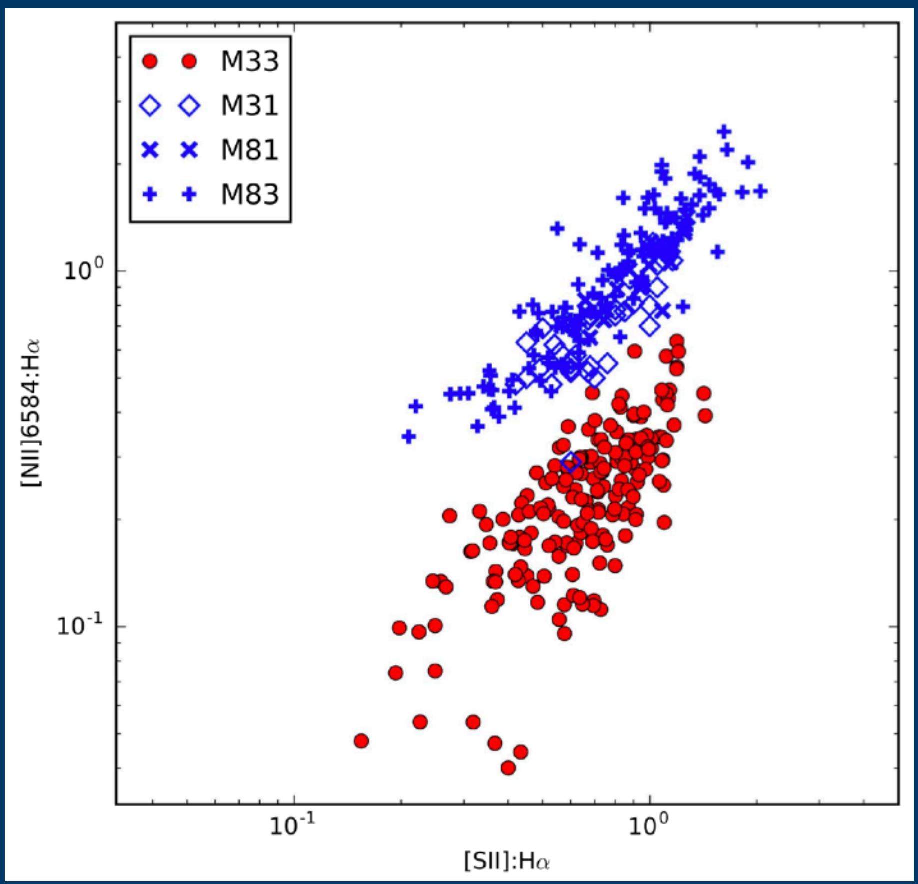
Long et al. (2018)



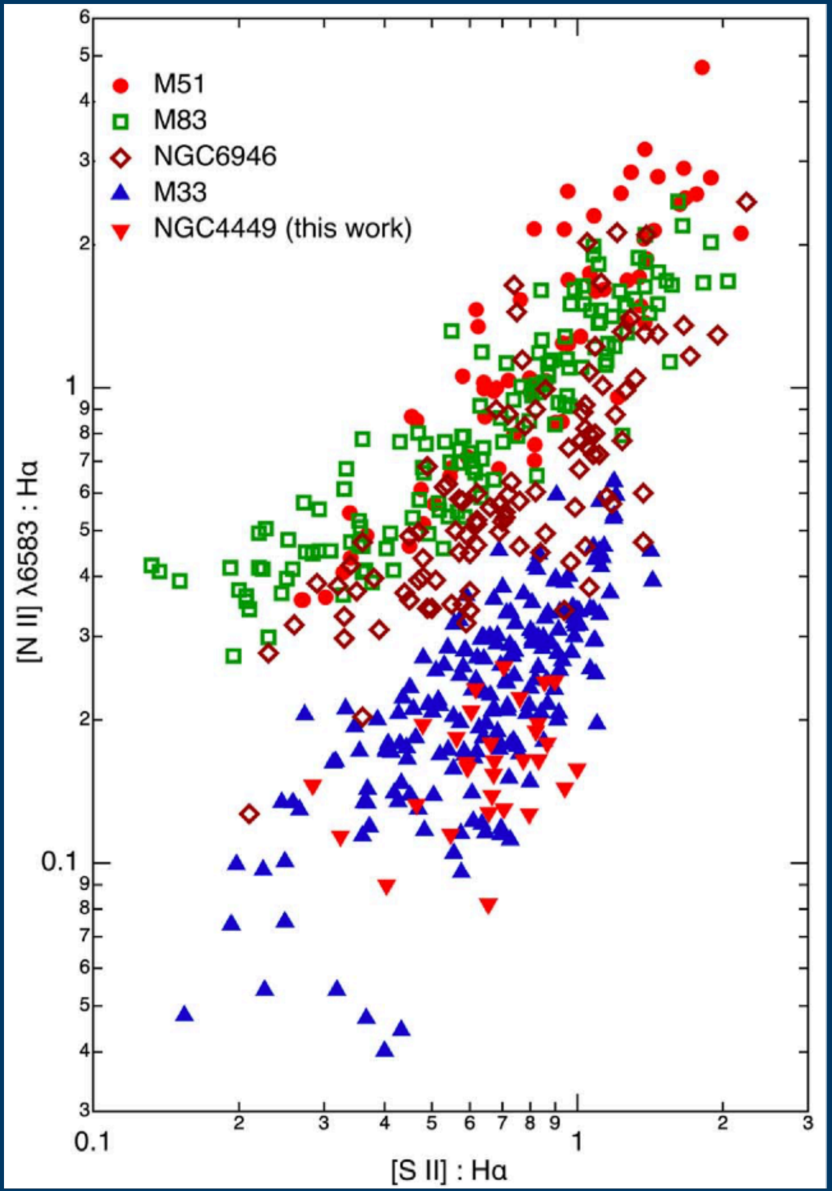
Winkler et al. (2021)

Optical Line Ratios

- [N II]/Hα higher for large spiral galaxies (M31, M51, M81, M83, NGC 6946) than for smaller star-forming galaxies (M33, NGC 4449).
- Depends on ISM metallicity.



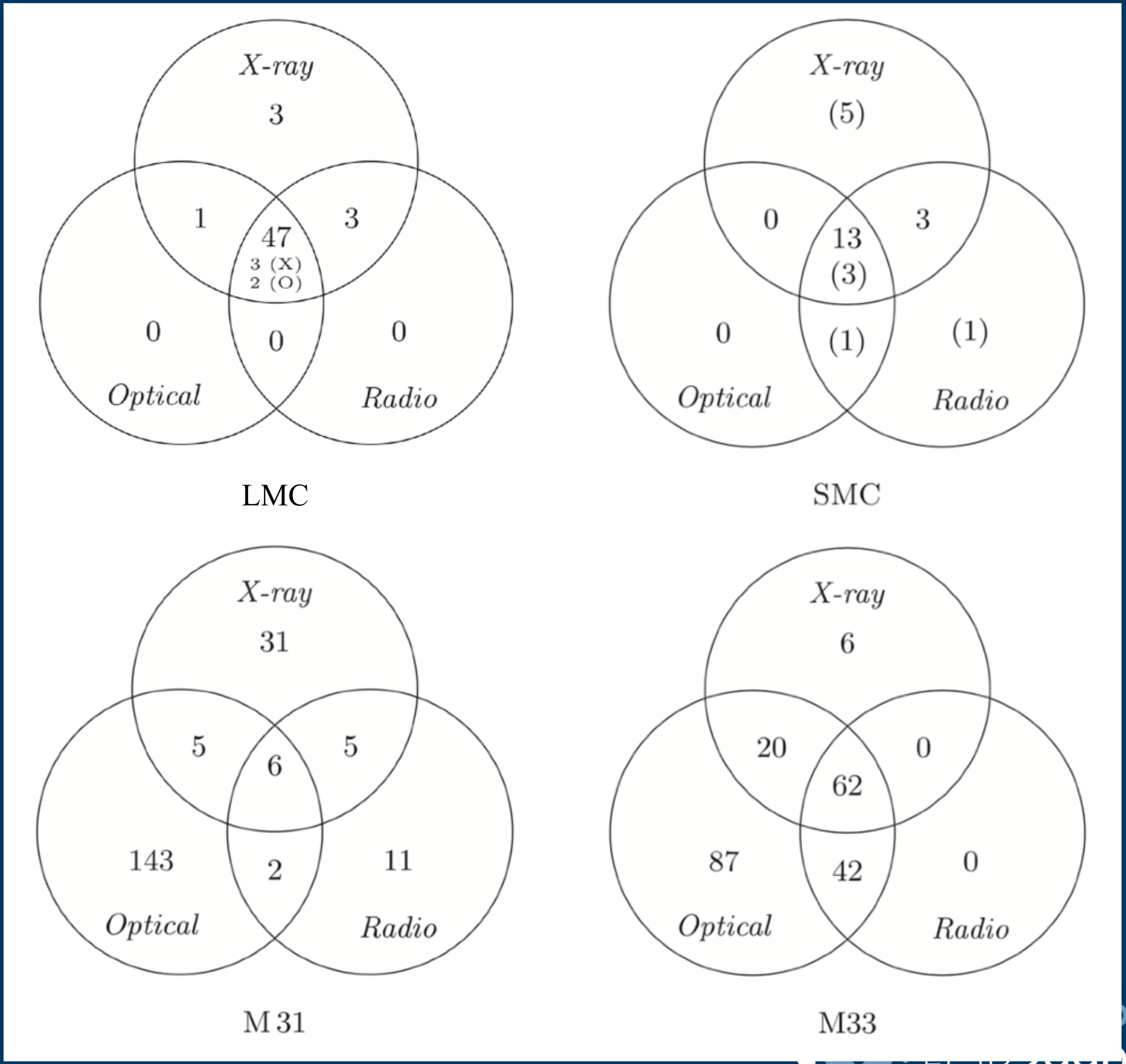
Long et al. (2018)



Winkler et al. (2023)

Number of Detections

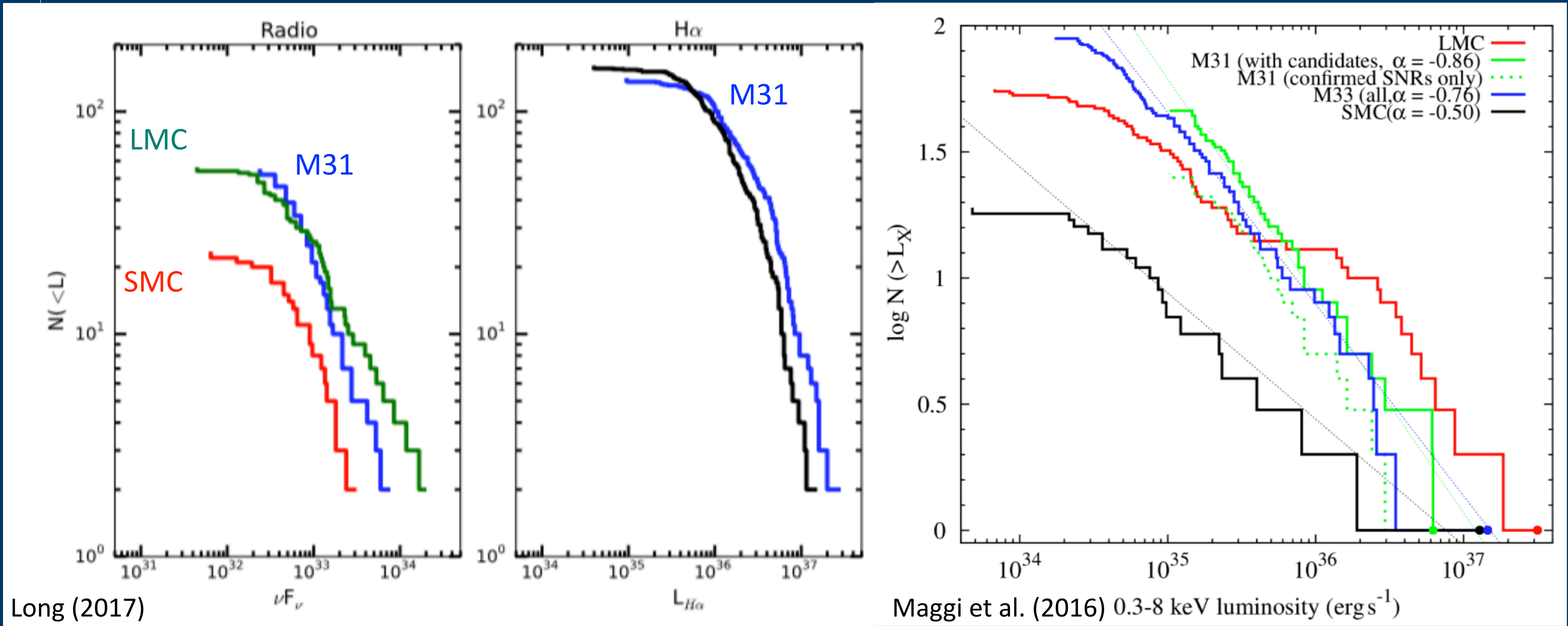
- Most of the SNRs in the Milky Way are detected in **radio**.
- SNRs in LMC and SMC can be detected in X-rays due to **low foreground absorption**.
- High number of **optical SNRs** in M31 and M33.
- X-ray and radio SNRs are embedded in and are often **confused with HII regions** in distant galaxies.



Bozzetto et al. (2017)

Luminosity Functions

- **Luminosity function** of SNRs in SMC and LMC **flatter** than in M33 or M31.
- LMC hosts **very bright SNRs**.
- Difference due to lower **metallicity** and difference in **ISM density**.
- Luminosity function in general proportional to **star-formation rate**.



Long (2017)

Maggi et al. (2016)

Questions to Be Answered

- Is the **number of SNRs** consistent with predictions of models for stellar evolution, supernova rate, and SNR evolution, taking into account the observational bias?
- What is the **fraction and spatial distribution of core-collapse SNRs vs. type Ia SNRs?** What can we learn about the explosion mechanisms? What can we learn about the environment?
- What is the **luminosity function (LFs) of SNRs**? How are the LFs of different galaxies related to the underlying stellar population, ISM, metallicity and SNR evolution?
- What is the **distribution of SNRs in comparison to that of the colder phases of the ISM?** Are SNRs correlated with large structures in the ISM or with star-forming regions? How many of the SNRs show correlations with molecular clouds?
- Can the SNR population explain the **cosmic ray density** in galaxies**?**

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Summary

Observations of **supernova remnants** will tell us about:

- type of **SN explosion** and structure and abundances in the **ejecta**,
- temperature, ionization, density distributions, element abundances in the **surrounding interstellar medium,**
- **mass loss** history of the progenitor,
- **time** since the explosion,
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Observed emission of SNRs also depends on **external factors**, especially on **absorption** and **distance**.

SNR populations in other galaxies are not affected by these external factors and can provide us with information about

- **stellar evolution** and **supernova explosion mechanisms**,
- **interstellar medium**, in particular, **metallicity**,
- **stellar population**,
- **star-formation history**.

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