FORTH Foundation for Research & Technology - Hellas

SNR populations in our Galaxy and beyond: bridging the gap

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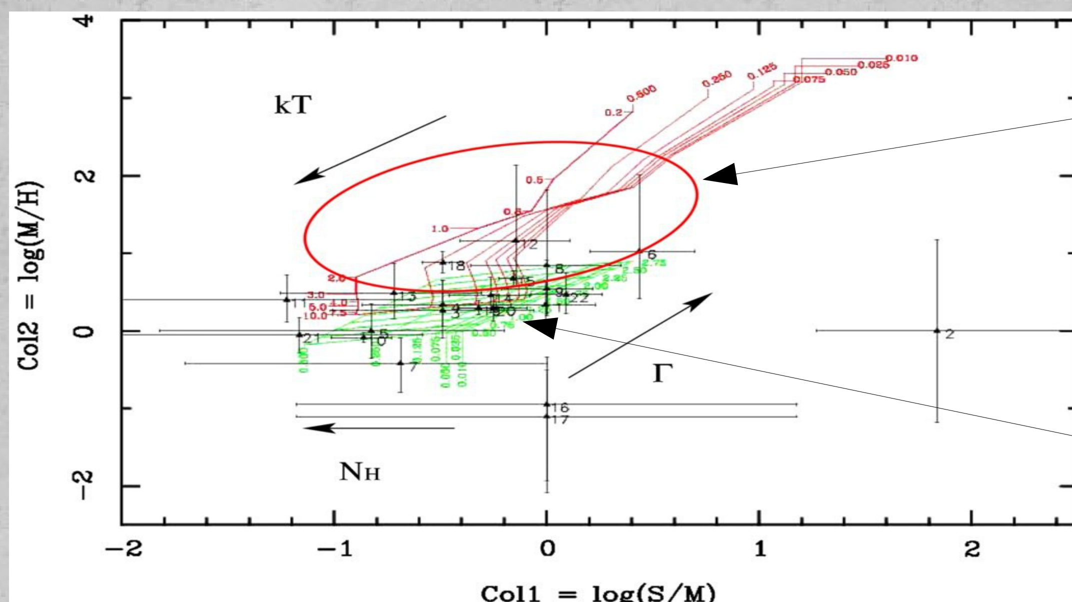
Photo credit: Prof. Andreas Zezas

3-8 June 2019, Chania, Crete, Greece

Selection Criteria for detecting SNRs

1. **Optical: [SII]/Hα ≥ 0.4** (Mathewson & Clarke 1973)

2. **X-rays**: ***soft*** *(≤ 2 keV) sources with* ***thermal*** *emission*



SNRs

XRBs

Leonidaki et al. (2010)

3, Radio: Non-thermal emission

4. [FeII] (1.644 μm) (e.g. Blair et al. 2014)

Caveats in the optical

- Subtraction...hard work

(e.g. different seeing conditions, stars with different spectral types)

- Researchers adopt different criteria

(e.g. visual inspection of Hα-[SII] emission, certain morphology, exclude nebulae with interior blue stars)

- Contamination of [N II] λλ 6548, 6583 lines adjacent to Hα

(thus lowering the [S II] :Hα ratio)

- Confusion near the [S II] : Hα = 0.4 criterion

(especially for fainter objects. Diffuse ionized gas (DIG) can also have a high [S II] : Hα ratio)

Is the [S II] : Hα criterion alone completely reliable...?

Oxygen lines as a new diagnostic...

A diagnostic tool for the identification of Supernova Remnants

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We present new diagnostic tools for distinguishing supernova remnants (SNRs) from HII regions. Up to now, sources with flux ratio [S II]/Hα higher than 0.4 have been considered as SNRs. Here, we present the combinations of three or two line ratios as more effective tools for the separation of these two kinds of nebulae, depicting them as 3D surfaces or 2D lines. The diagnostics are based on photoionization and shock excitation models (MAPPINGS III) analysed with Support Vector Machine (SVM) models for classification. The line-ratio combination that gives the most efficient diagnostic is: [O I]/Hα - [O II]/Hβ - [O III]/Hβ. This method gives 98.95% completeness in the SNR selection and 1.20% contamination. We also suggest the [O I]/Hα line ratio as a more effective 1D diagnostic for the photometric selection of SNRs.

Key words: SNRs – HII regions – Diagnostic tool – shock models – starburst models

(talk by Maria Kopsacheili)

1 INTRODUCTION

Study of SNR demographics and their physical properties (density, temperature, shock velocities) is very important in order to understand their role in galaxies. Their feedback to the Interstellar Medium (ISM), and consequently to the entire galaxy, is of high importance since they provide significant amounts of energy that heat the ISM and they enrich it with heavy elements. They are fundamentally related to the star-forming process in a galaxy, inasmuch as the compression of the ISM by the shock wave, under appropriate conditions, can lead to the formation of new stars. Having a complete census of SNR populations can also give us a picture of the on-going massive star formation rate (SFR) since

with 225 photometric SNRs; (Blair et al. 2013; Blair et al. 2012), M33 with 220 (Long et al. 2018), M31 with 150 (Lee & Lee 2014). The small number of observed extragalactic SNRs compared to those in our Galaxy, is the result of different sensitivity limits and also different selection criteria. The identification of SNRs in our Galaxy or the Magellanic clouds is generally based on the detection of extended non-thermal radio sources, or X-ray sources, while studies in other galaxies rely on photometric or spectroscopic measurements of diagnostic spectral lines.

The most common mean of identifying SNRs in the optical regime, is the use of the flux ratio of the [S II] ($\lambda\lambda$6717, 6731) to Hα (λ6563) emission lines, as first sug-

Selection Criteria for detecting SNRs

MNRAS **000**, 1–10 (2015) Preprint 27 May 2019 Compiled using MNRAS LaTeX style file v3.0

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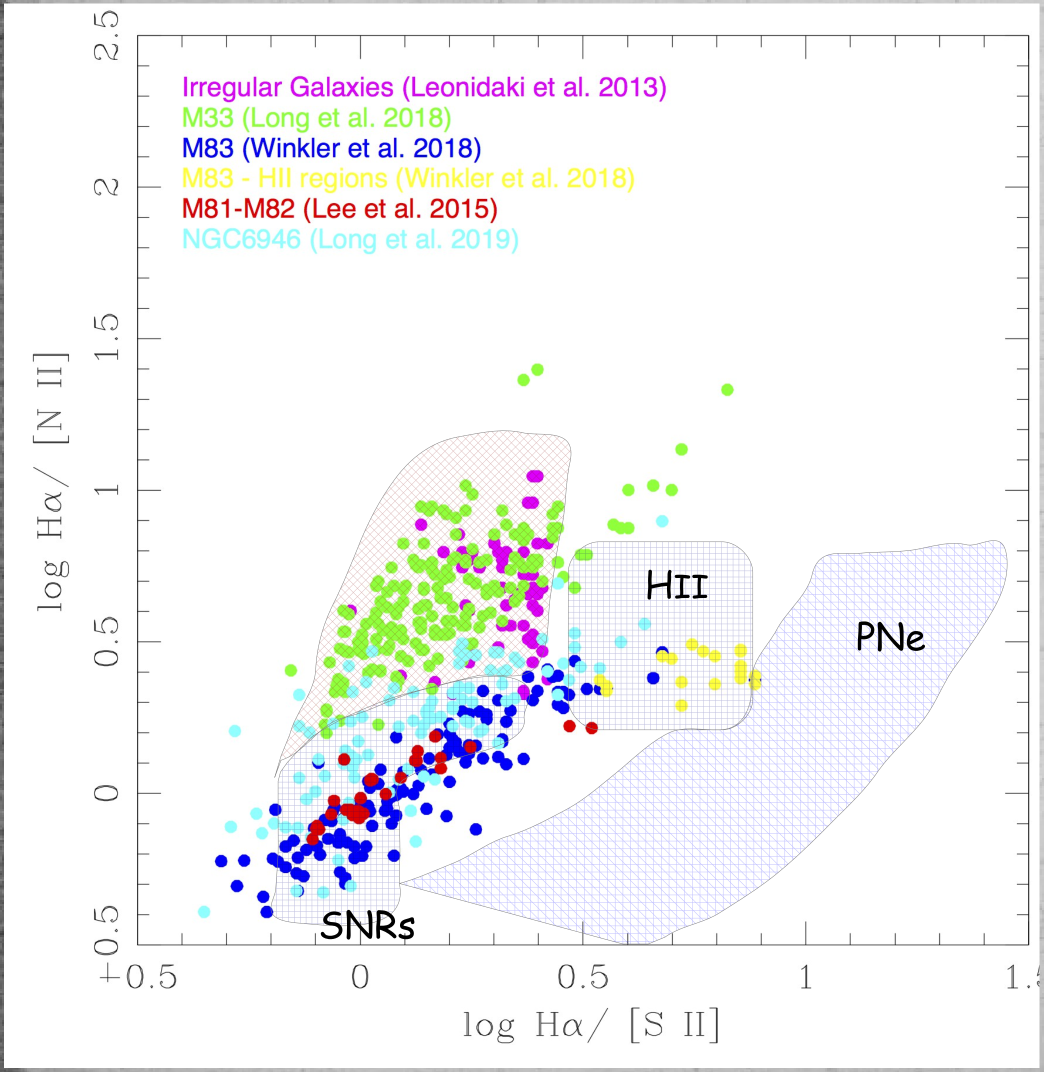
SNRs in the optical: Emission line diagnostics

[NII]/Ha: metallicity and shock-heated gas indicator



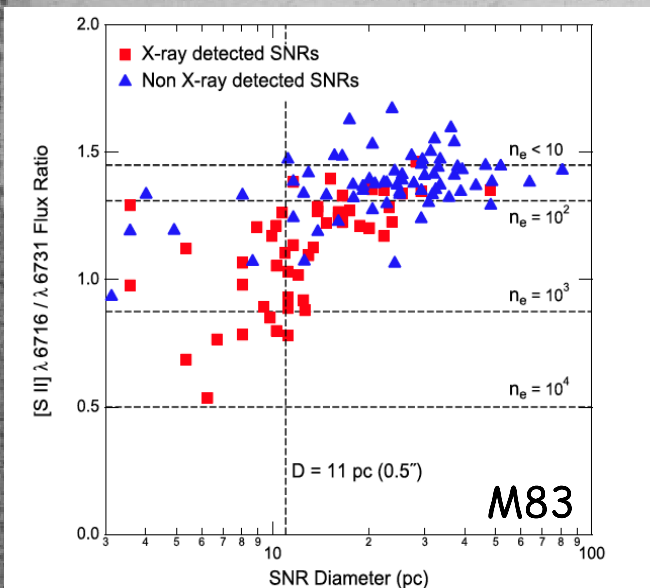
Leonidaki et al. 2019 (in preparation)

Metallicity gradient → linked to star formation mechanism

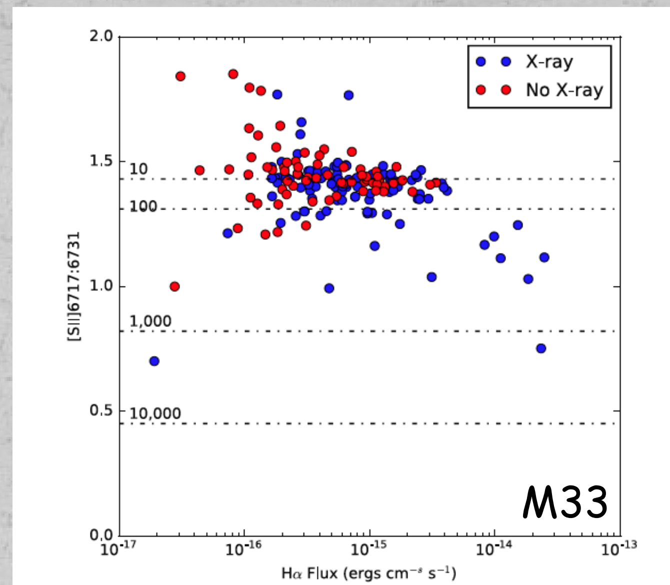
- SNRs in irregular galaxies present higher Ha/[NII] ratios (lower metallicities) than those in spirals.
- New locus of extragalactic SNRs
- Case of M33: high [NII]/Ha -> non-uniform/clumpy ISM ? Galaxy type?

SNRs in the optical: Emission line diagnostics

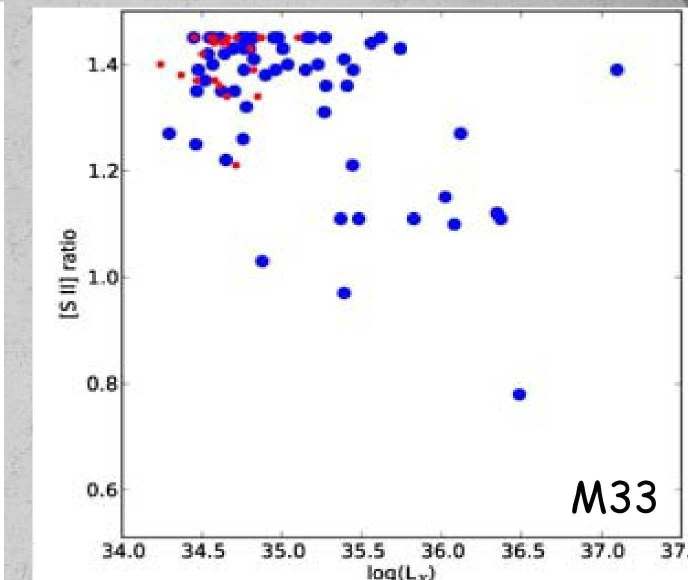
[SII] 6716/6731: electron density indicator



Winkler et al. (2017)



Long et al. (2018)



Long et al. (2010)

- Smaller (and likely younger) remnants generally lie at higher-density (circumstellar) material
- The X-ray detected (and probably younger?) remnants are generally smaller and have higher densities
- In most cases the higher the density in the [SII] zone the higher the Ha and X-ray emission.

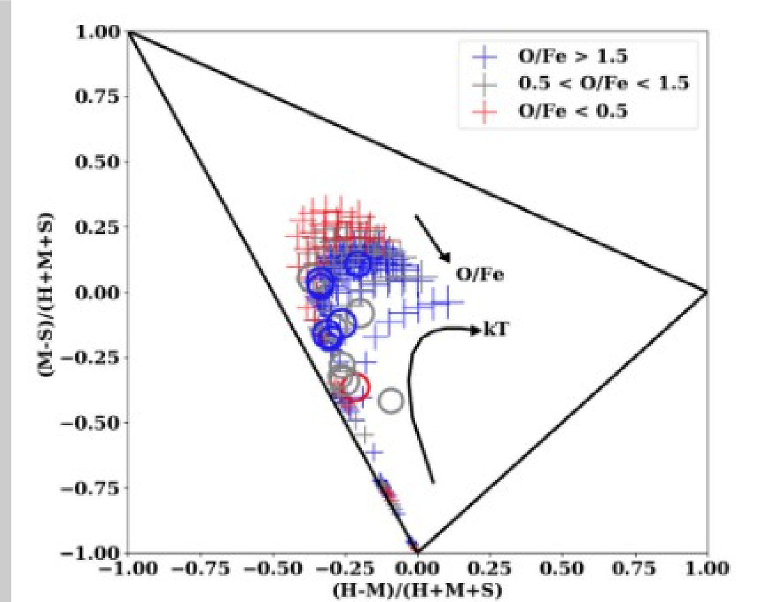
SNRs in the X-rays: Hardness Ratios

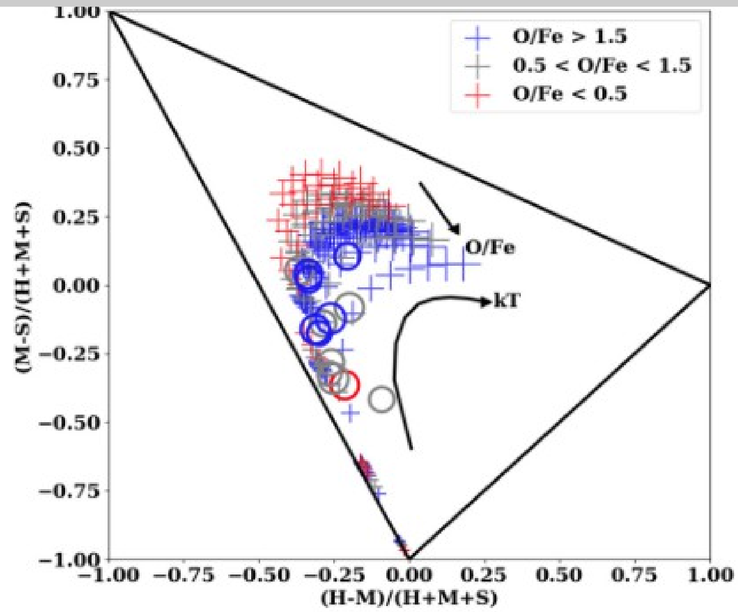
Characterizing SNR populations

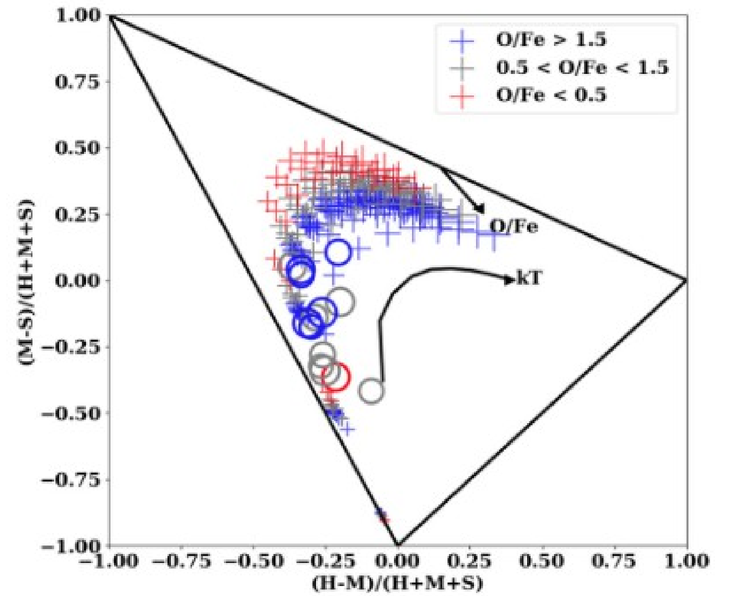
<u>Metal abundances</u>:

- Fe-rich -> Type Ia,
  O-rich -> Type II (Hughes et al. 1995, Maggi et al. 2016)

- Fe Ka line energy centroids: 6.4 keV -> Type Ia; 6.7 keV -> Type II (Yamaguchi et al. 2014)



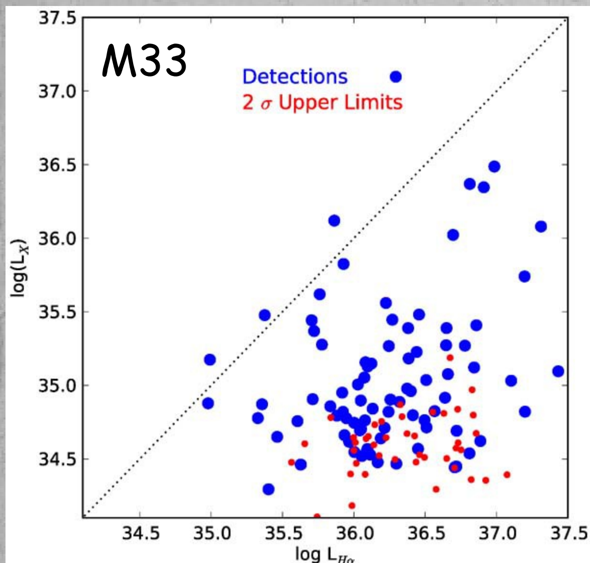




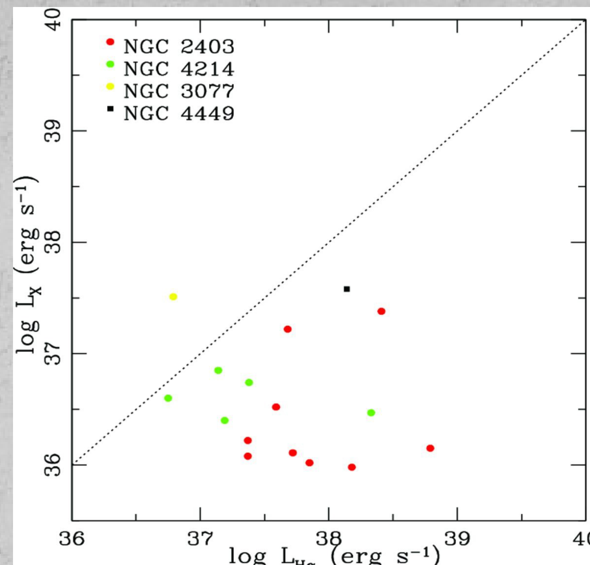
Garofali et al. (2017)

Multi-λ properties: Luminosity relations

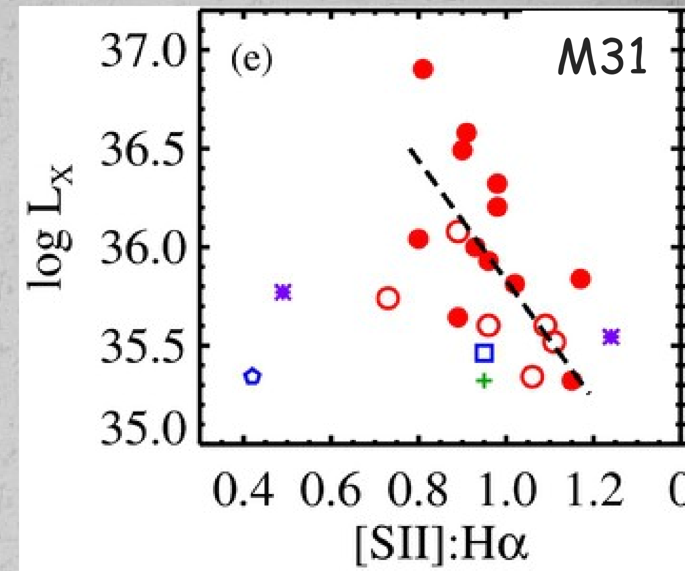
L_X – $L_{H\alpha}$ - [SII]/Hα



Long et al. (2010)



Leonidaki et al. (2013)



Lee & Lee (2014)

<u>No strong correlation</u>

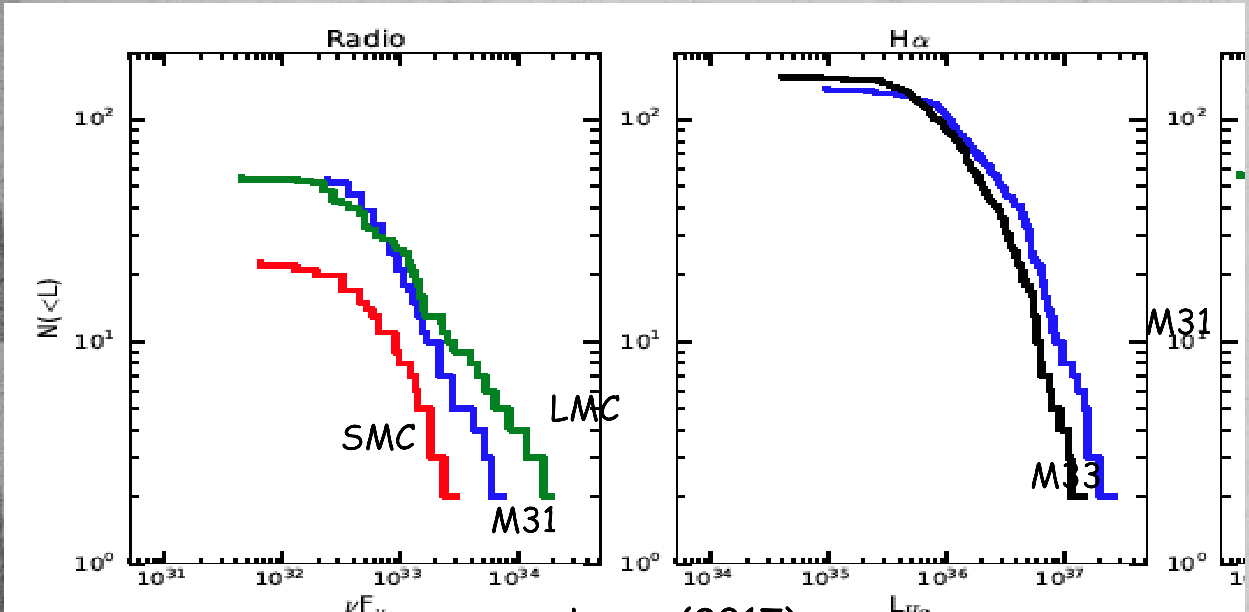
- Large scatter in ratio: Different materials in a wide range of temperatures (Long et al. 2010, Leonidaki et al. 2013)
- Inhomogeneous local ISM around SNRs (Pannuti, Schlegel & Lacey 2007)

<u>Higher Lx…less [S II]/Hα</u>

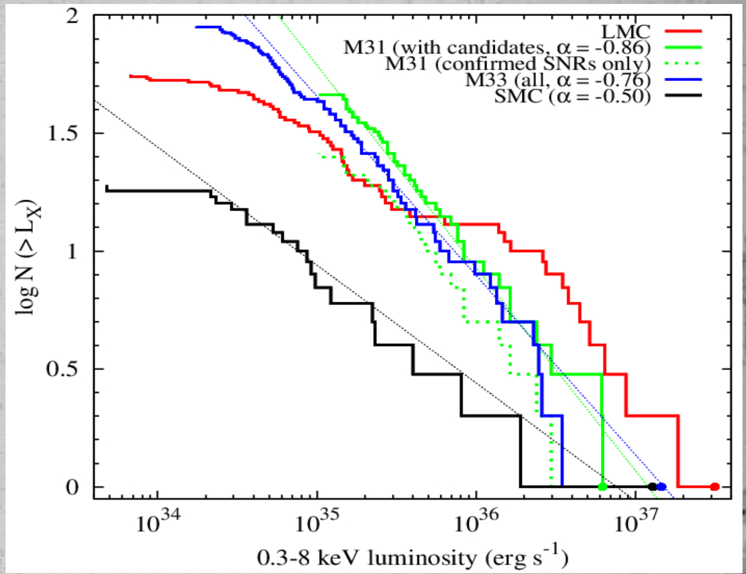
Long cooling time of the X-ray material → the shock velocity we are measuring does not necessarily correspond to the shock that generated the bulk of the X-ray emission material.

Multi-λ properties: Luminosity functions

Showing environmental effects...



Long (2017)



X-rays: Maggi et al. (2016)

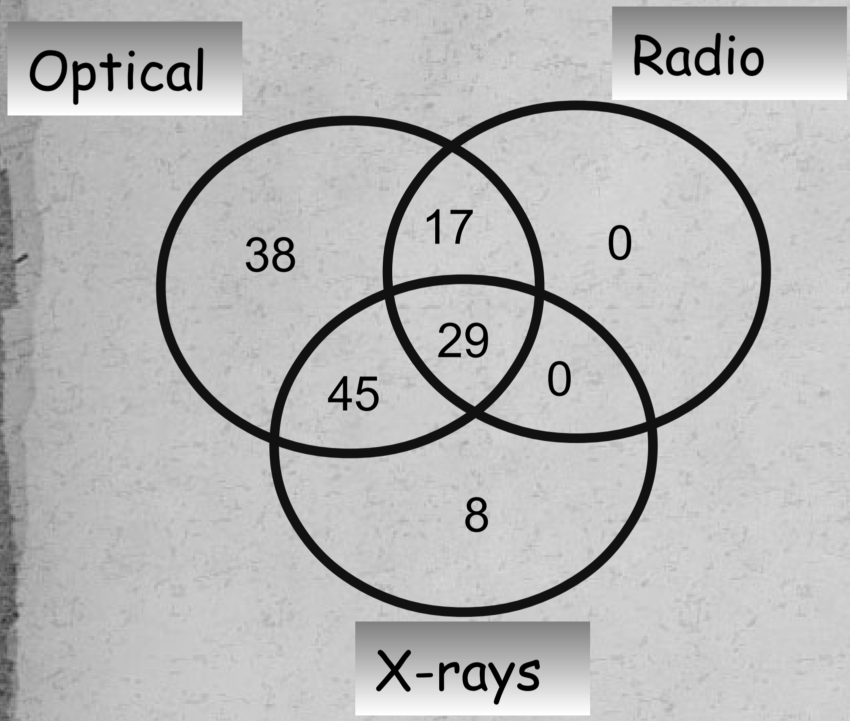
Shape: Sample completeness at low luminosities

Slope: different populations

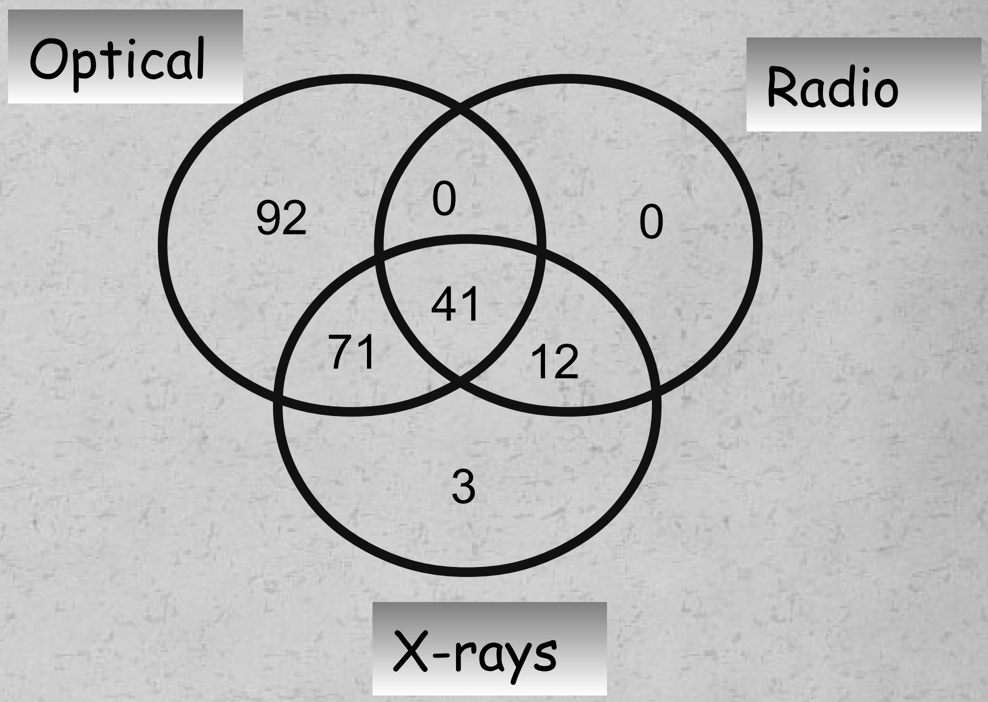
Wavelength: Radio LFs are much less dependent on local ISM density than optical/X-ray LFs

Multi-λ properties: Venn diagrams

M33



Long et al. (2010)

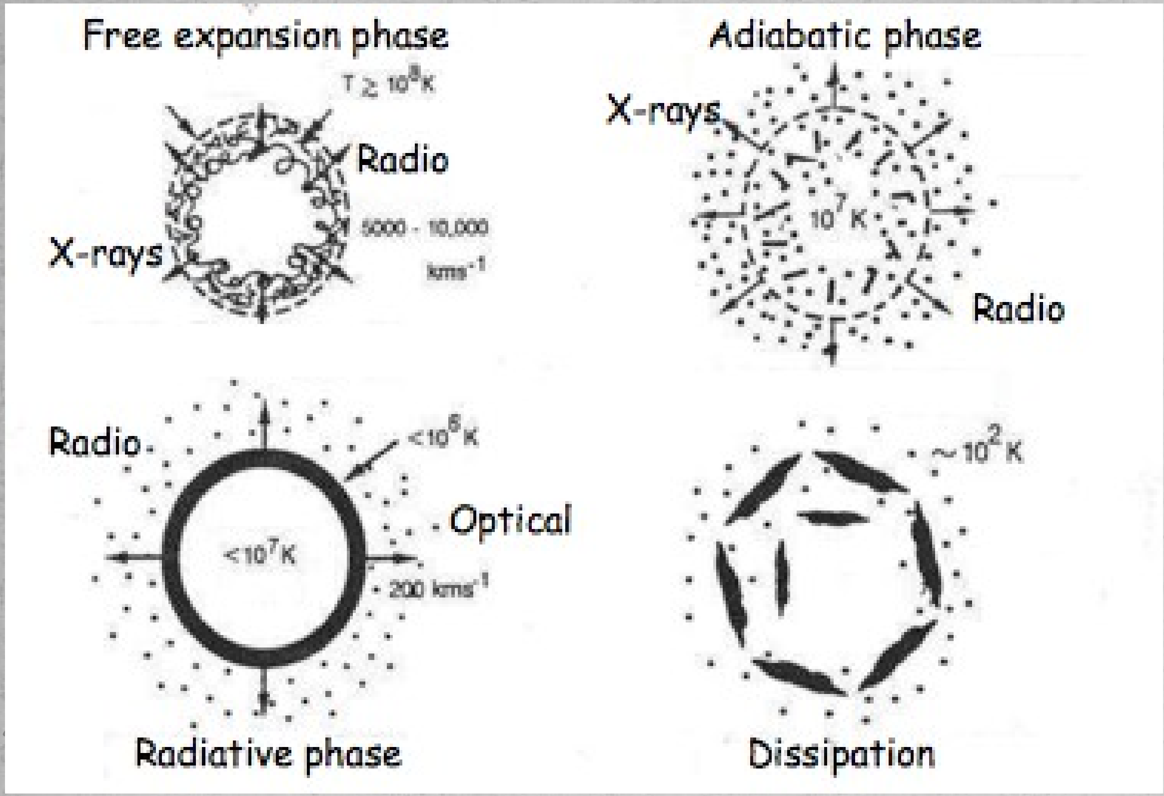


Garofali et al. (2017)

- Not individual multi-wavelength studies
  - Observational sensitivities
    - Environmental effects

Different evolutionary stages...????

TOY MODEL



<u>X-RAYS: newly formed SNRs</u>
Thermal emission from the material behind the shock front ($T>10^6$ K) or/and non-thermal emission from relativistic electrons
(e.g. review by Vink 2012)

<u>OPTICAL</u> **<u>: sign of older SNRs</u>**
Cooling region behind the shock front ($T \sim 10^5$ K)

<u>RADIO: throughout the life of a remnant</u>
Around the shock or behind it

Different wavelengths depict different evolutionary stages in the life of a remnant

Motivation

Multi-wavelength emission as a function of age and environment

Using a sample that allows the study of their morphology or physical properties in small scales

SNR studies: state-of-the-art

Extragalactic

- Numerous, multi-wavelength studies have been conducted the last decades

(e.g. Long et al. 2019, 2018; Leonidaki et al. 2019, 2013; Pannuti et al. 2007; Ghavamian et al. 2005).

Census: > 1000

Galactic

- A large number of Galactic SNRs has been studied in detail in various wavebands

(e.g. Fesen & Milisavljevic 2010; Boumis et al. 2009, 2005, 2002; Slane et al. 2002; Reach et al. 2006).

Census: 294 (Green 2014)

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Census: 294 (Green 2014)

- Structures can be observed in parsec scales

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- Structures can be observed in parsec scales

- Important information on the morphological characteristics, kinematics, and dynamics in various individual regions of the remnants.

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Census: > 1000

- SNRs in galaxies with different metallicities and different ISM properties.

- Has allowed the systematic, multi-wavelength investigation of extragalactic SNR populations.

BUT:

No information on the insights of shock structure and shock physics

Galactic

- A large number of Galactic SNRs has been studied in detail in various wavebands

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Census: 294 (Green 2014)

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- Important information on the morphological characteristics, kinematics, and dynamics in various individual regions of the remnants.

BUT:

No study of Galactic SNRs ***as a population***

The missing link...

Large samples of extragalactic SNR populations, which are hampered by limited sensitivity and low resolution not allowing the detailed study of their multi-wavelength emission, excitation and interplay with the ISM

Our spiral Milky Way has the largest census of SNRs known (294; Green 2014), with structures that can be observed in parsec scales, but this SNR population has embarrassingly incomplete optical coverage.

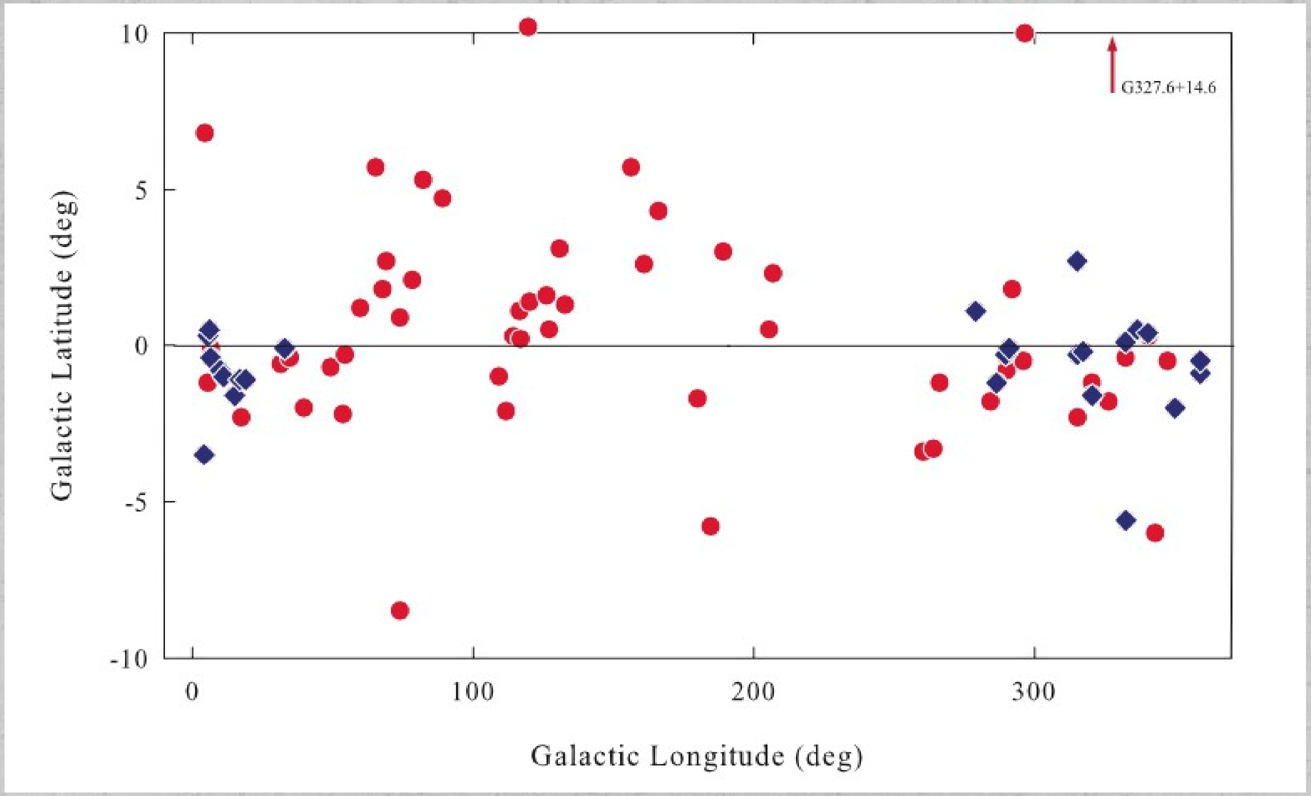
Investigating Galactic SNRs as a population

(and in a multi-wavelength context)

That will enable our comprehensive understanding of how they evolve and interact with the ISM.

Galactic SNRs: An unexploited treasure

Surprisingly, no study has been conducted so far to investigate the multi-wavelength properties of Galactic SNRs as a population...mostly due to the incomplete optical (~25%) and X-ray (~35%) coverage...



Distribution of all optically detected Galactic SNRs (Stupar & Parker 2011). Blue diamonds and red circles indicate objects observed in different surveys.

Project Overview

Systematic survey of all Galactic SNRs in the optical band which, together with existing multi-wavelength data,
will create the first complete multi-wavelength atlas.

We have embarked in a comprehensive campaign of observing the 294 Galactic SNRs in various narrow-band filters (Hα, [SII], [OIII], Hβ).

Team members:

Andreas Zezas (IA/FORTH - UoC)
Panos Boumis (IAASARS/NOA)
Makis Palaiologou (UoC)
Giannis Kypriotakis (UoC)

Observing Northern SNRs...(~165 out of 294)

ΑΣΤΕΡΟΣΚΟΠΕΙΟ ΣΚΙΝΑΚΑ
SKINAKAS STERNWARTE

45 sources (almost all observed)

120 sources

1.3 m (FOV: 10')

0.3 m (FOV: 3°)

Immediate Objectives

1. SNR evolution

2. Investigate how SNRs energize the ISM (ISM feedback)

3. Remedy the inherent biases of extragalactic SNR surveys

Immediate Objectives

1. SNR evolution

Correlate the multi-wavelength emission of SNRs with their ages

↓

Provide ***for the first time*** an observational framework for understanding the evolution of SNRs as a function of their age and environment.

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Immediate Objectives

2. Investigate how SNRs energize the ISM (ISM feedback)

<u>How the SNR kinetic energy is thermalized in its local medium?</u>

SNR properties ↔ impact of the local medium on the SNR parameters

(such as temperatures, total luminosities, shock-velocities)

e.g. higher SNR temperatures/luminosities/velocities denote more efficient heating of the ISM

e.g. more efficient heating in denser or more clumpy environments is expected (e.g. Chevalier & Fransson 2001).

Multi-wavelength approach: will allow us to disentangle the different gas phases (hot ~10^6 K, warm ~10^4 K, and cold, dense gas < 300 K; e.g. and dust that surrounds SNRs.

- X-ray emission is evidence of hot gas that has been shock-heated by the ejecta of SN.
- Optical emission is more sensitive to warm, ionized gas
- Denser, cooler ambient ISM is responsible for HI emission.

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Provide ***for the first time*** an observational framework for understanding the evolution of SNRs as a function of their age and environment.

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Construct excitation, shock-velocity and extinction maps (SNR parameters)

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The distribution and intensity of these components will provide significant information on the ISM energetics and thermalization.

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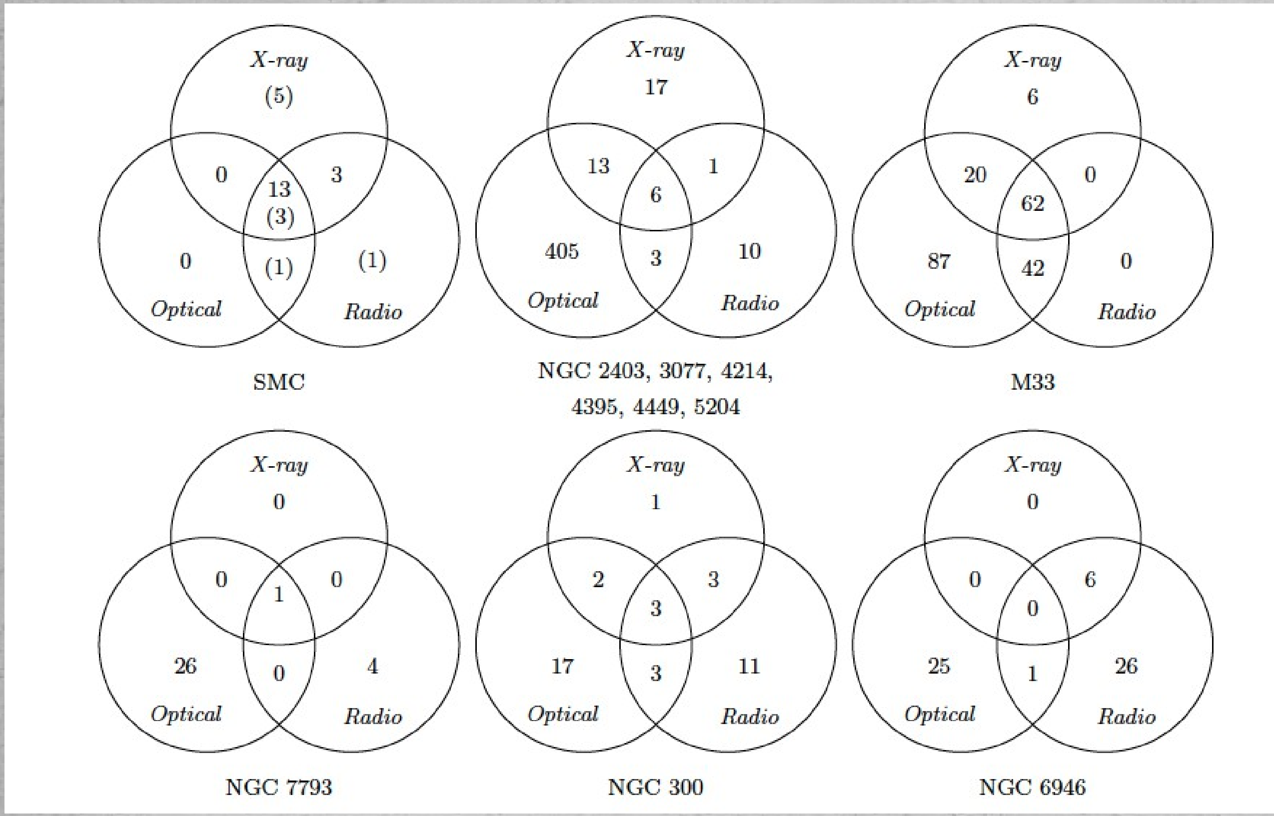

Bozzetto et al. 2017

Selection effects are present in extragalactic SNR surveys performed in individual wavebands.

(e.g. evolutionary stages, observational sensitivities, environmental effects)

Immediate Objectives

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The distribution and intensity of these components will provide significant information on the ISM energetics and thermalization.

3. Remedy the inherent biases of extragalactic SNR surveys

We will quantify them based on the age dependence of the multi-wavelength emission of Galactic SNRs and the morphology of the ISM.

⬇

We will alleviate a long-standing limitation of extragalactic SNR surveys and greatly increase their scientific value.

First Results

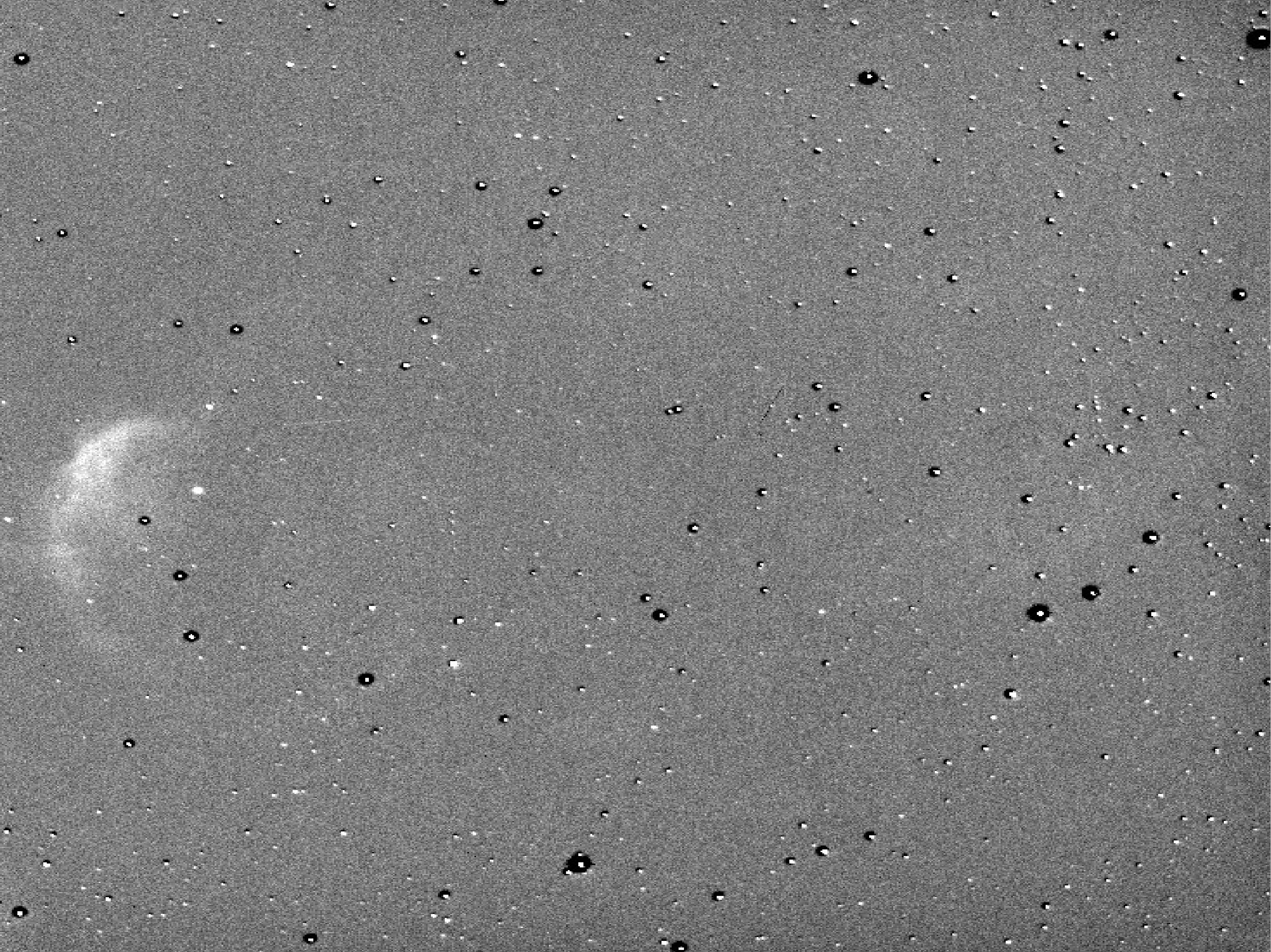
Data reduction is performed by using a newly developed pipeline (Kypriotakis et al., in preparation) which involves a novel approach for the removal of foreground and background stars, a significant problem in studies of Galactic SNRs.

Poster

S1.11 J.A.Kypriotakis: Mapping the physical properties of Supernova Remnants in our Galaxy

The efficiency of this pipeline has been tested in a handful of Galactic SNRs, leading to striking results

Case study: G65.8 - 0.5



Spatially variant PSF fitting

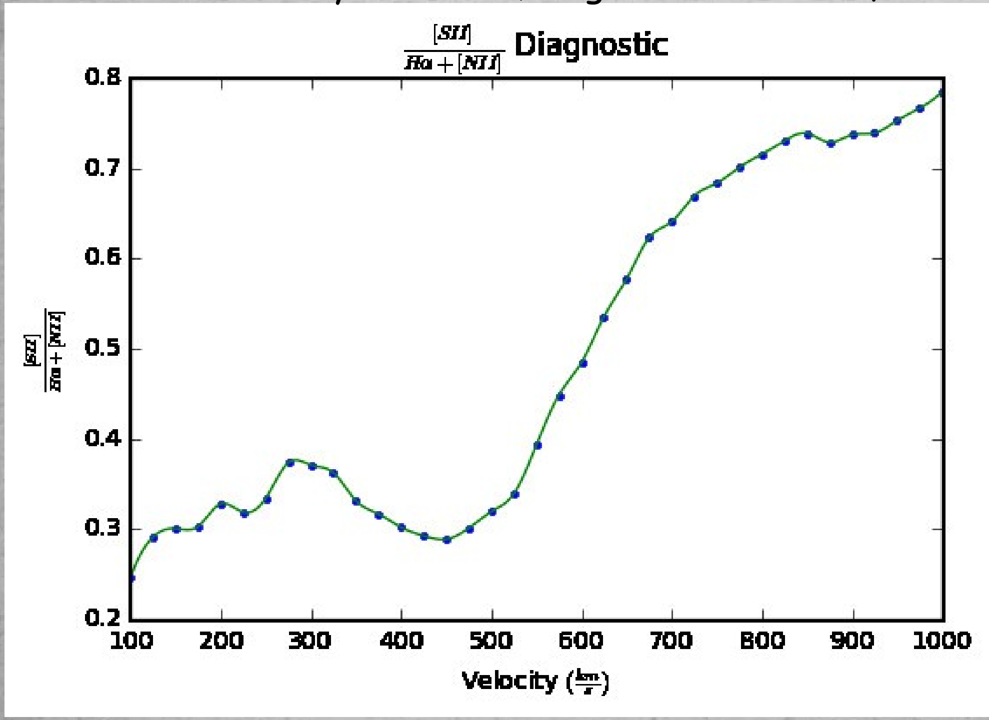
First Results

(See Poster S1.11)

Pioneering method: takes advantage of imaging instead of spectroscopy

(Kypriotakis et al. 2019, in preparation)

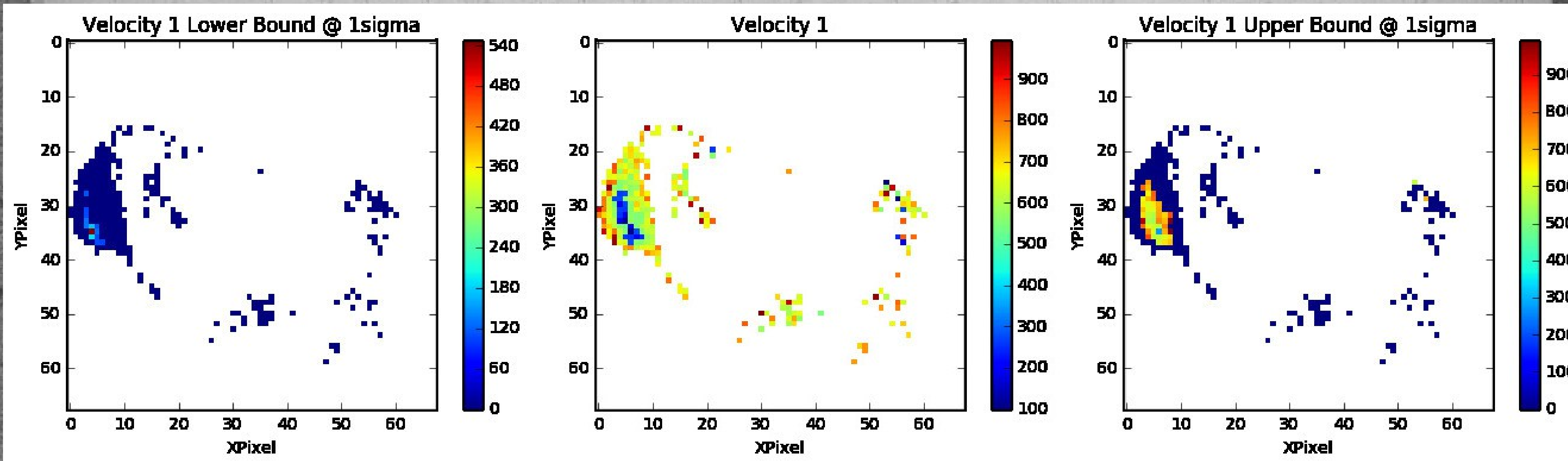
Electron density: 100cm^{-3}, magnetic field of 5μG .



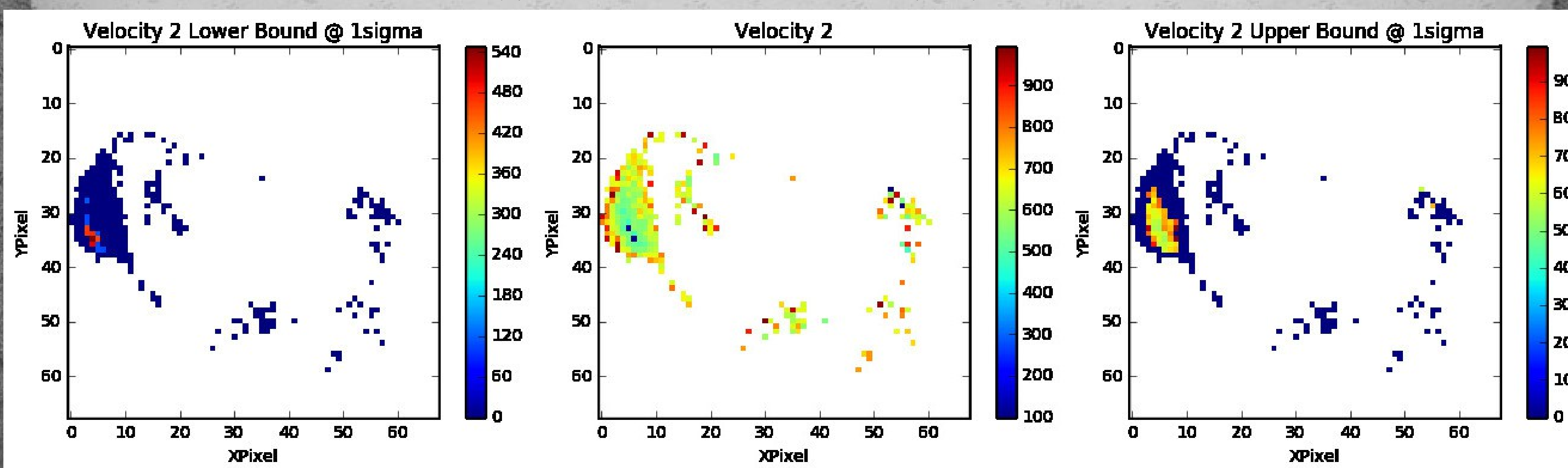
The 1D [SII]/(Hα+[NII]) vs. shock-wave velocity diagnostic. The blue points are the diagnostic data from MAPPINGS III (Allen et al. 2008), while the green line is the interpolated 1D diagnostic.

First Results

(See Poster S1.11)



Kypriotakis et al. 2019, in preparation



First Results

Observations of the first sub-sample of Galactic SNRs are almost completed

X-ray selected sample

(drawn from the compilation of Ferrand & Safi-Harb (2012) which also provides ages for > 80% of the sample)

Northern + Thermal, X-ray emitting + shell-like or composite + with sizes <10'

Theoretical models predict that (shell-like, thermal) X-ray emitting remnants allow us to look into the early stages in the life of the remnant.

WHAT HAPPENS OBSERVATIONALLY???

The vast majority of the X-ray selected sample doesn't show optical emission...
The first results are in general agreement with the toy model.
However, with this systematic campaign we can go one step further and test the theoretical models quantitatively.

Summing up...

We have initiated a systematic survey of <u>all</u> Galactic SNRs in the optical band which, together with other multi-wavelength data, **will create the first complete multi-wavelength atlas of Galactic SNRs.**

- First time to explore our nearest SNRs as a population
- Scientific breakthrough in understanding SNR evolution
- Disentangle how they energize and transform the ISM
- Reveal optical emission from individual remnants

Stay tuned... !