SUPERNOVA REMNANTS

AN ODYSSEY IN SPACE AFTER STELLAR DEATH

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Probing the properties of extragalactic SNRs

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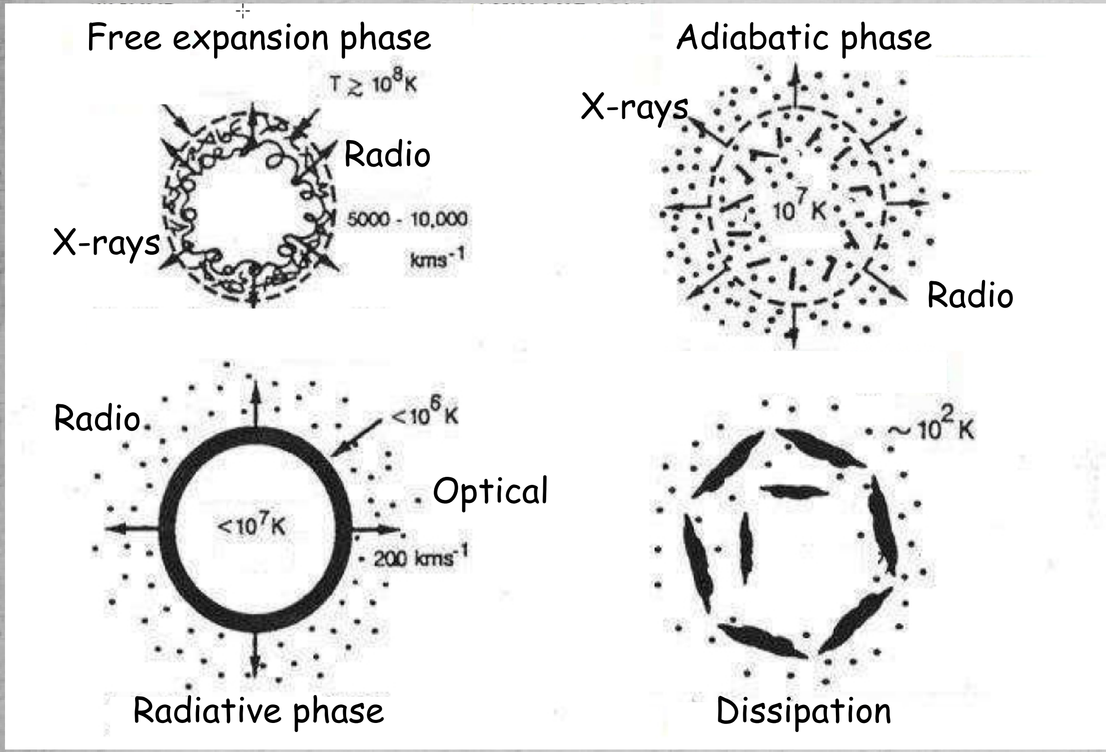
TOY MODEL

Origin and emission mechanisms



<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*: sign of older SNRs</u>
Cooling region behind the shock front ($T\sim10^5$ 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

Importance of multi-wavelength studies on SNRs

The (derived) properties of SNRs depend on:

Environment/ISM (density, temperature)

Progenitor properties (stellar wind density, mass loss rate, composition)

The details of this connection are poorly understood

Age / Evolutionary stage of the SNR

Selection effects

Importance of multi-wavelength studies on SNRs

The (derived) properties of SNRs depend on:

Environment/ISM (density, temperature)

(multi-wavelength properties)

Progenitor properties

(e.g. X-ray spectra from the ejecta of young SNRs)

A multi-λ study is essential

Age / Evolutionary stage of the SNR

(Toy model)

(e.g. easier to detect optical SNRs in low density/diffuse emission regions)

Selection effects

MW SNRs: Pros and Cons

Census of Galactic SNRs: 294 (Green 2014)

Physics from individual remnants - interaction with ISM

However, they are severely hampered by

Galactic absorption
(SNRs are almost exclusively in the galactic plane-most can only be studied at radio)

distance uncertainties
(crucial properties cannot be estimated; e.g. size, luminosities)

Difficulties in probing their evolution and performing systematic studies

Extragalactic SNRs: Pros and Cons

- At the same distance

- Internal Galactic absorption effects are minimized (especially on face-on galaxies)

- Observing SNRs in different environments

- Larger samples

Limited sensitivity and spatial resolution

However:

Sampling more galaxies helps us understand the global properties and the systematics of SNR populations as a function of their environment.

Historically...

- First record of extragalactic SNRs: LMC (radio)
  (Mathewson & Healey 1964)
- Pioneering work of Mathewson & Clarke (1973) on the MCs
  (based on the [SII]/Hα criterion and radio data)
- The SNR census continued primarily by exploiting ground-based telescopes
  (largest number of extragalactic SNRs in the optical band)
- Advent of multi-λ sensitive observations:
  X-rays: Einstein, ROSAT, XMM, Chandra
  Optical: HST
  Radio: VLA

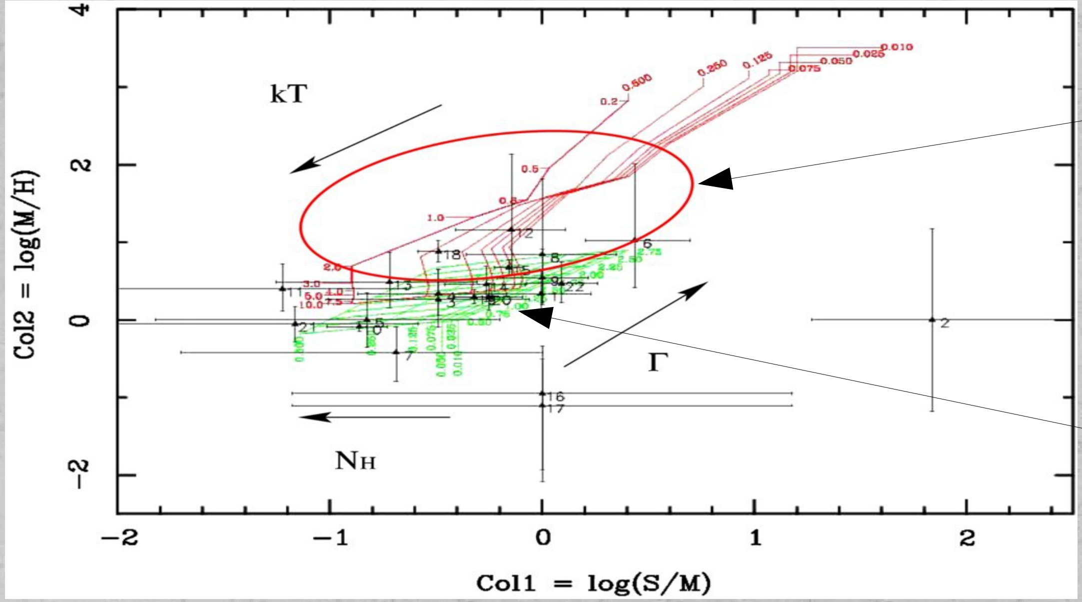
Last decade: more systematic studies of extragalactic SNR populations

Selection Criteria for detecting SNRs

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

2. *Radio: Non-thermal emission*

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



SNRs

XRBs

Leonidaki et al. (2010)

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

SNRs in the optical: Emission line diagnostics

Various physical parameters can be estimated:

[SII]/Hα: main shock-heating gas indicator

[NII]/Hα: metallicity indicator, secondary shock-heating gas indicator

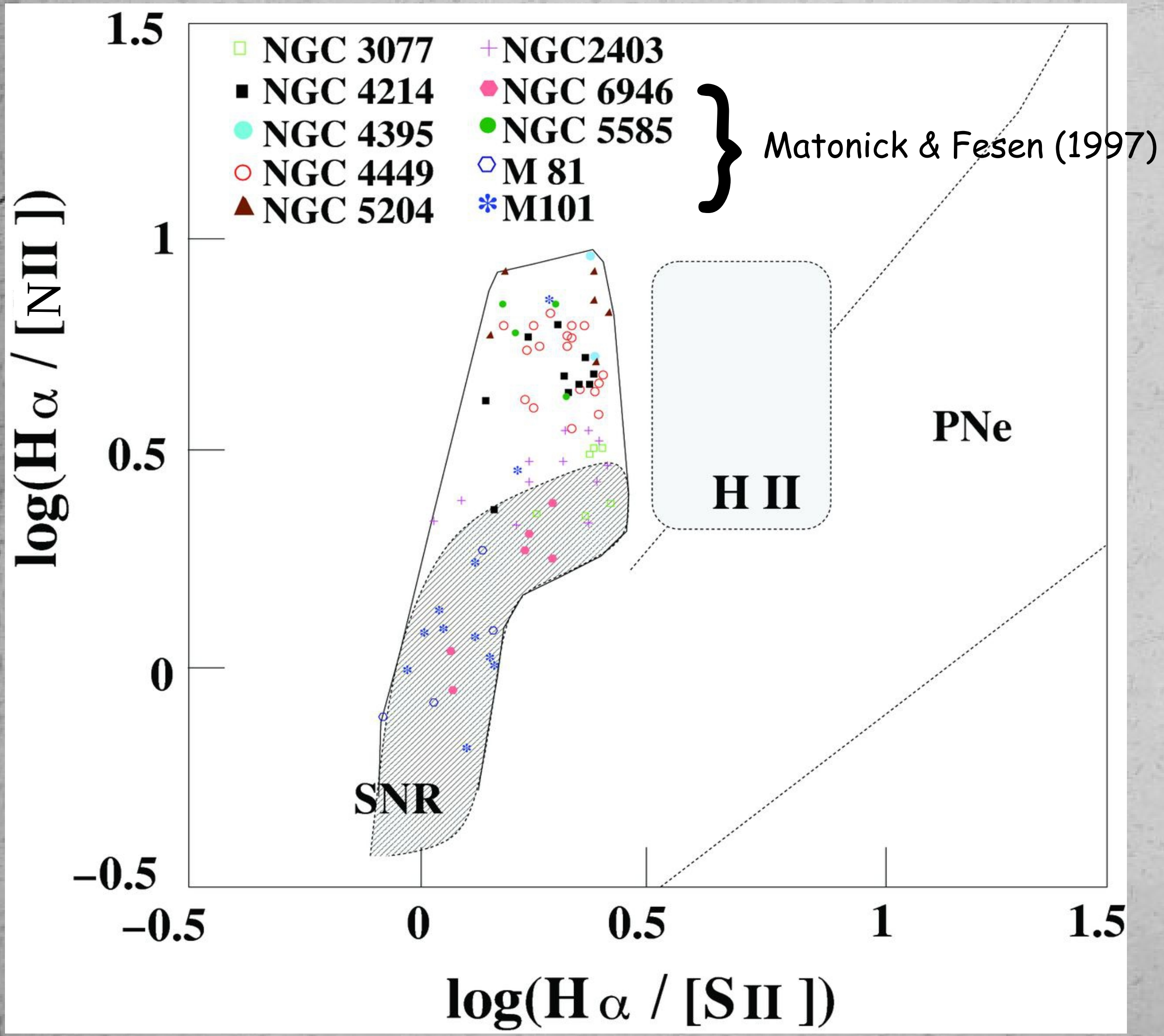
[OIII]/Hβ: shock velocity indicator

[SII]6716/6731: electron density indicator

Elemental abundances and shock velocities can be calculated using sophisticated shock models
(e.g. Raymond 1979, Dopita 1984, Allen 2008)

SNRs in the optical: Emission line diagnostics

[NII]/Hα: metallicity and shock-heating gas indicator



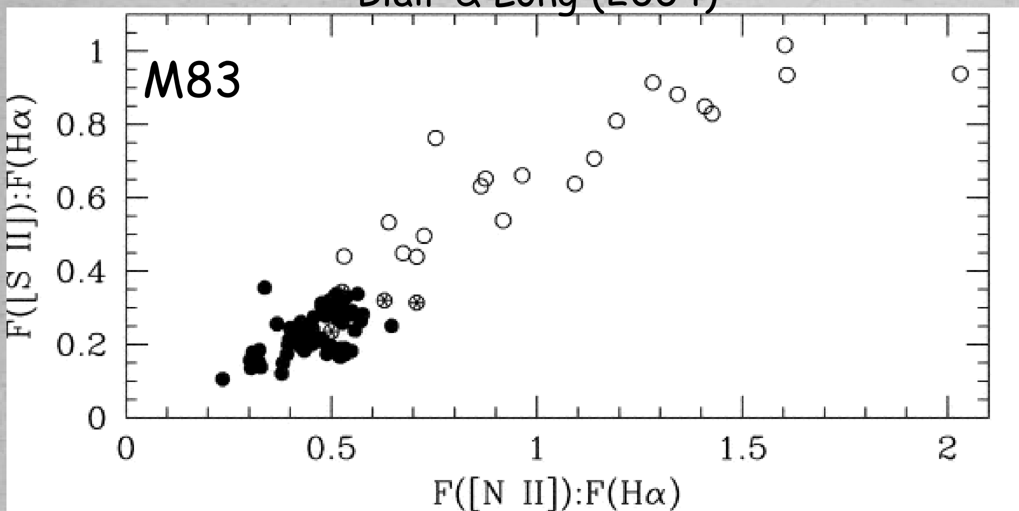
Leonidaki et al. (2013)

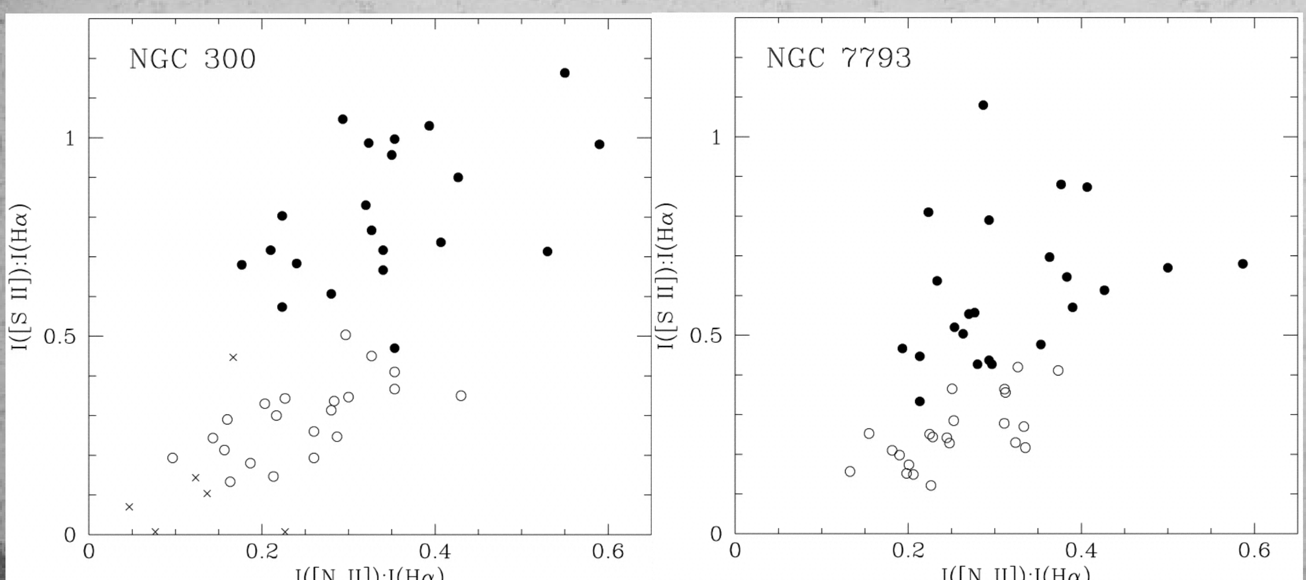
SNRs in irregular galaxies present higher Hα/[NII] ratios (lower metallicities) than those in spirals.

SNRs in the optical: Emission line diagnostics

[NII]/Hα: metallicity and shock-heating gas indicator

Blair & Long (2004)



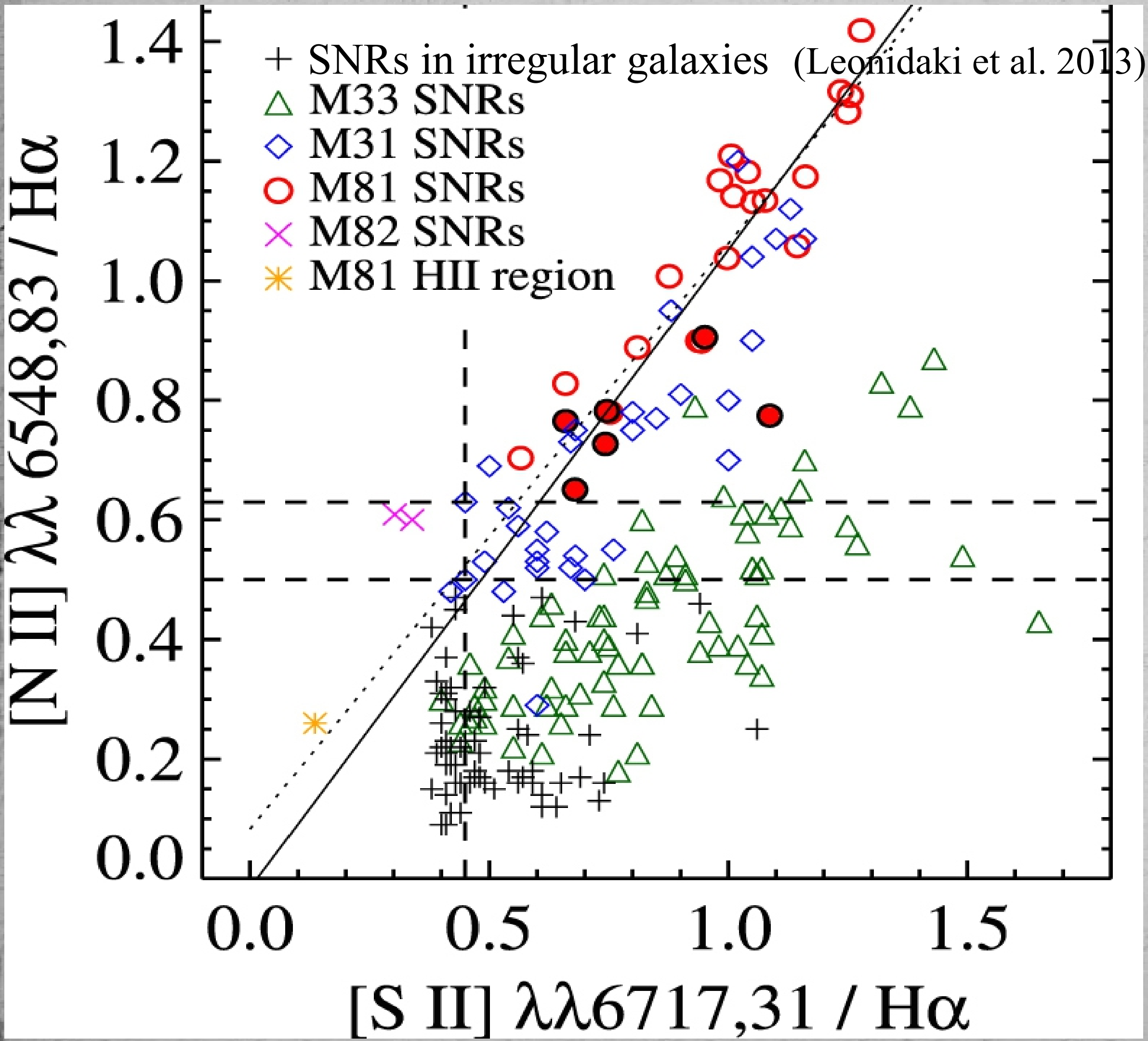


- SNRs present higher [NII]/Hα than HII regions
- Higher [SII]/Hα ratios present higher [NII]/Hα ratio values

Blair & Long (1997)

SNRs in the optical: Emission line diagnostics

[NII]/Hα: metallicity and shock-heating gas indicator



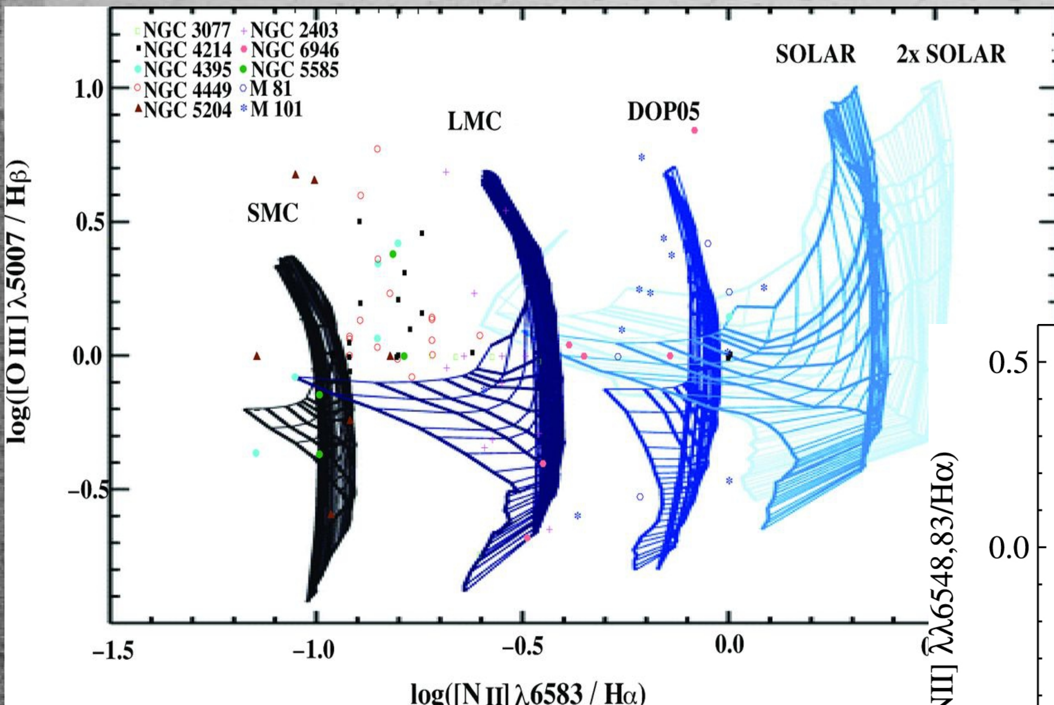
Lee & Lee (2015)

Secondary shock-heating gas indicator

Flatter slope -> higher [SII]/Hα -> non-uniform ISM ?

SNRs in the optical: Emission line diagnostics

Shock models for measuring abundances and shock velocities

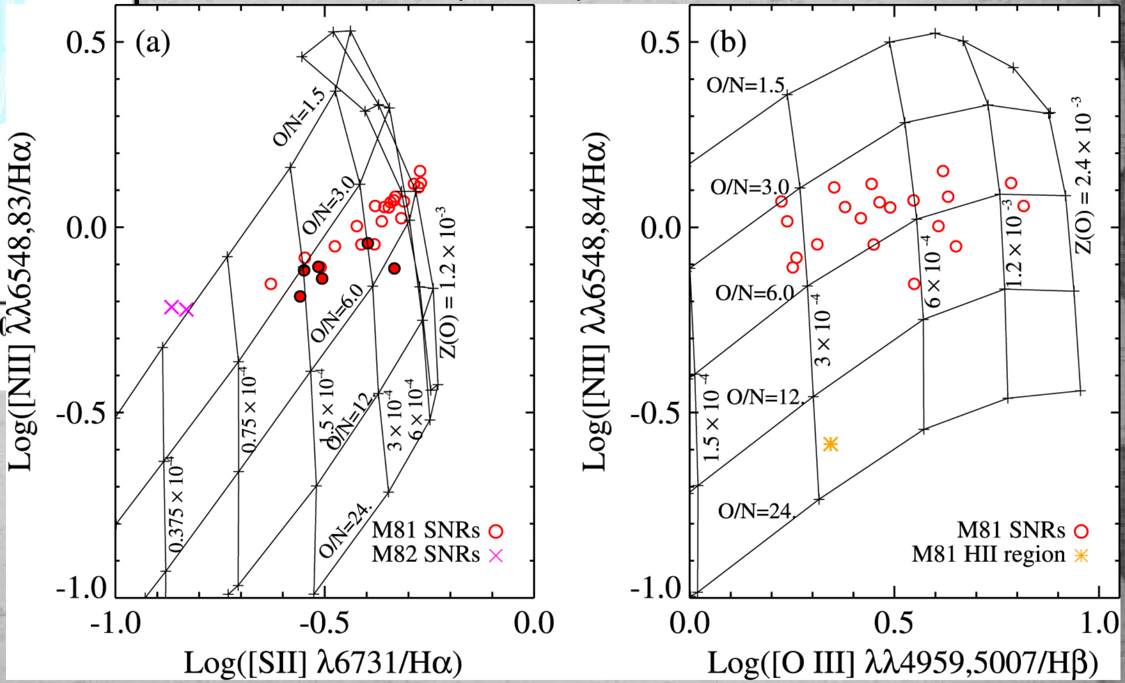


Leonidaki et al. (2013)

Using theoretical shock model grids (of Allen et al. 2008) for different values of shock velocity, magnetic field parameters and chemical abundances.

Using shock ionization models (of Dopita et al. 1984) for various values of oxygen abundance and the ratio of oxygen to nitrogen abundance.

Lee & Lee (2015)

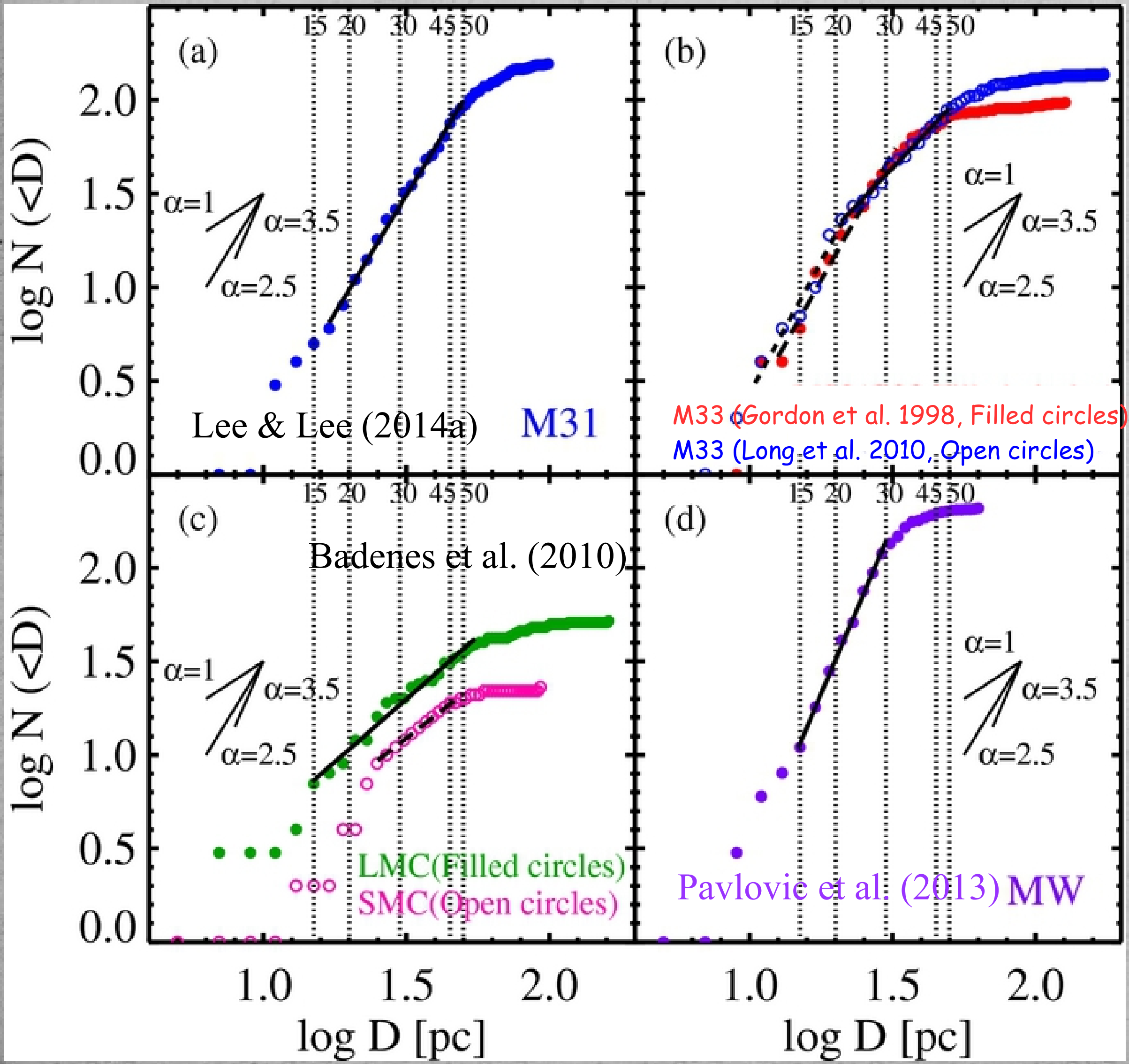


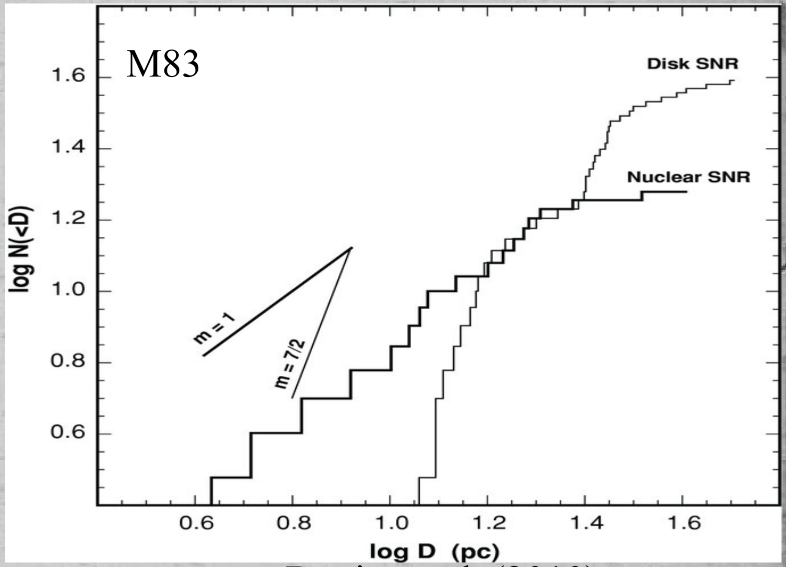
Alternative method for calculating abundances: X-ray spectra (Maggi et al. 2016)

SNRs in the optical: Age / Evolutionary stage

Cumulative Size Distributions

(Hughes & Helfand 1984 ; Long et al. 1990 ; Gordon et al. 1998 ; Dopita et al. 2010 ; Badenes et al. 2010)





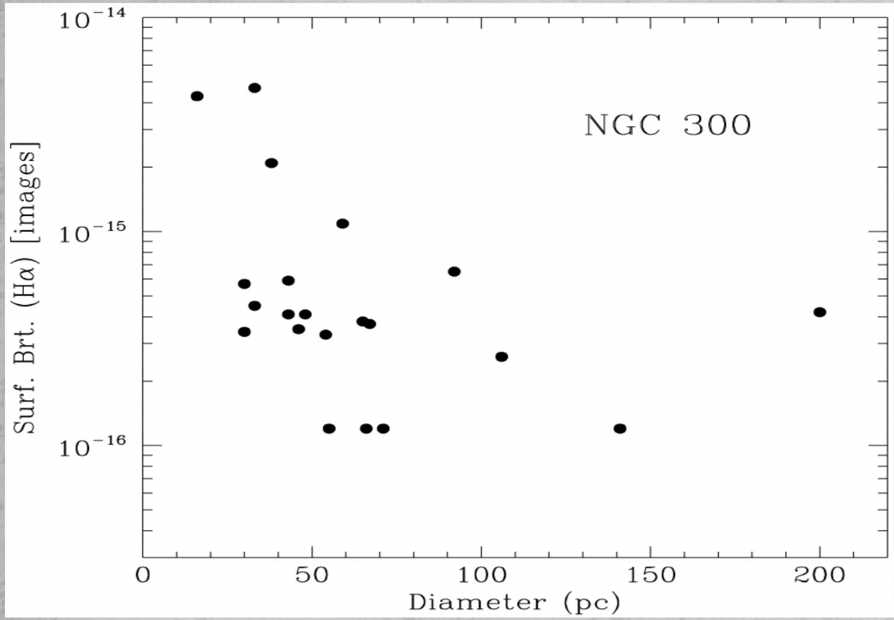
Dopita et al. (2010)

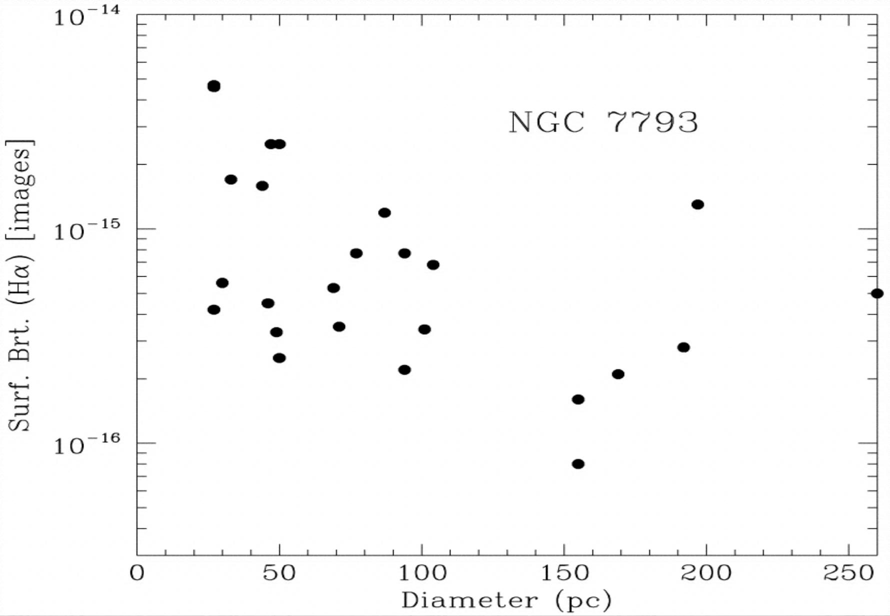
SNRs in the optical: Age / Evolutionary stage

Surface Brightness – Diameter (Σ-D relation)

(The Σ-D relation has also been used to estimate the distances to the MW SNRs; Pavlović et al. 2013)

Blair & Long (1997)





Slight trend for the relatively small diameter objects to have higher surface brightnesses.

Discrimination from superbubbles

- Moderate [S II]/Hα values (0.45 < [S II]/Hα < 0.6)
  (e.g. Lasker 1977; Walterbos & Braun 1994; Chen et al. 2000)
- Large sizes (>100 pc) which are rare among known SNRs
  (e.g. Williams et al. 1999)
- Slower Hα expansion velocities than those of SNRs (<100 km s^{-1})
  (e.g. Franchetti et al. 2012)
- OB associations
- Their low-density environment is responsible for their rather faint X-ray emission (below that of SNRs: 10^{34}–10^{36} erg/s)
  (e.g. Chu & Mac Low 1990)
- Mainly thermal radio emission

Discriminating progenitors

Criteria for Type II/Type Ia:

(1) Distinct type of objects (plerions, oxygen-rich, Balmer-dominated)

(2) Presence/absence of OB stars (Maggi et al. 2016, Franchetti et al 2012)

(3) Symmetric/non-symmetric morphology (Lopez et al. 2009, 2011)

(4) Type Ia SNRs present relatively low Hα flux compared to Type II SNRs (e.g. Franchetti et al. 2012)

(5) Metal abundances:

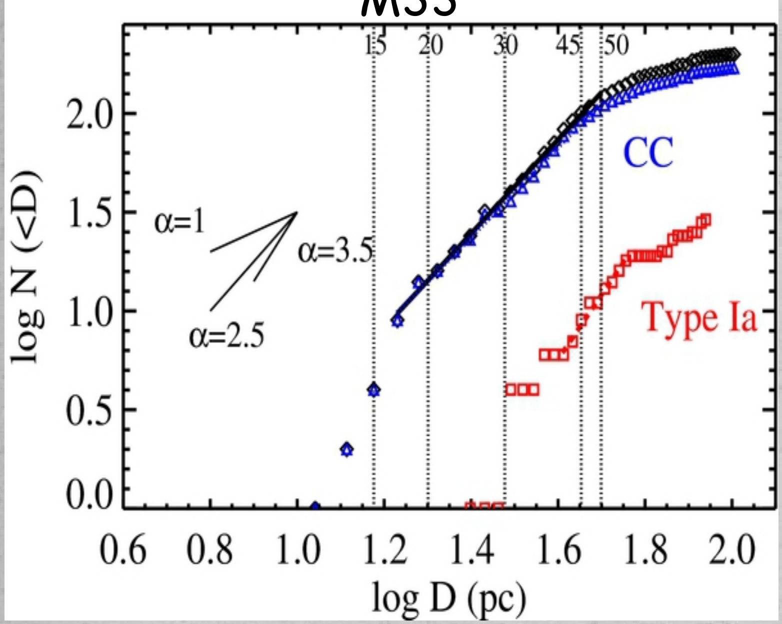
- Fe-rich –> Type Ia, O-rich –> Type II (Hughes et al. 1995, Maggi et al. 2016)
- Fe Kα line energy centroids: 6.4 keV –> Type Ia; 6.7 keV –> Type II (Yamaguchi et al. 2014)

(6) Light echoes (Rest et al. 2005, 2008)

SNRs in the optical: Age / Evolutionary stage

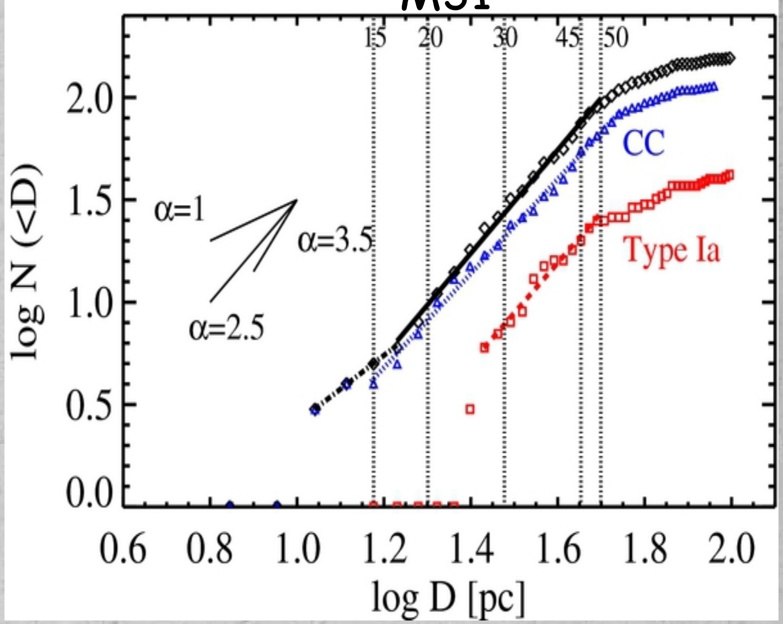
Cumulative Size Distributions: Based on progenitors

M33



Lee & Lee (2014b)

M31



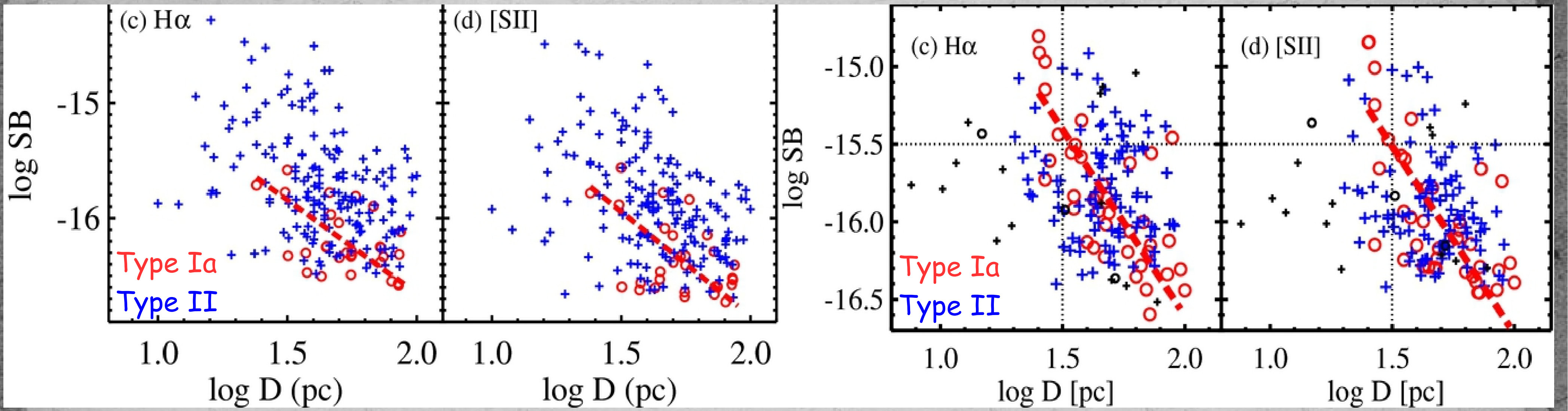
Lee & Lee (2014a)

The mean diameter of Type Ia remnants is larger than that of the CC remnants. This means that a majority of the CC remnants may lie on dense ambient ISM than the Type Ia remnants

SNRs in the optical: Age / Evolutionary stage

Surface Brightness – Diameter (Σ-D relation): Based on the progenitors

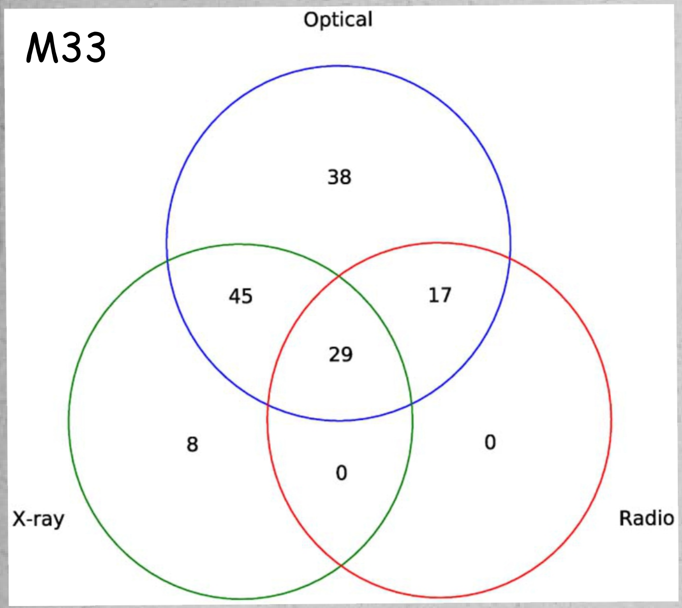
M31 M33



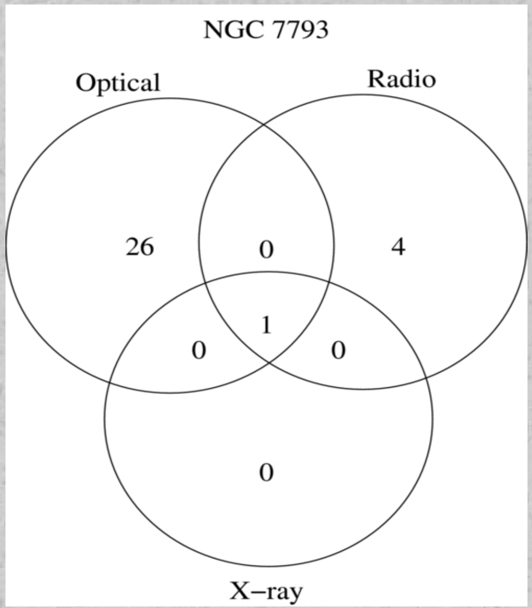
Lee & Lee (2014a) Lee & Lee (2014b)

The Ha and [S II] surface brightnesses of the Type Ia SNR candidates show stronger linear correlations with their sizes than the CC SNR candidates.

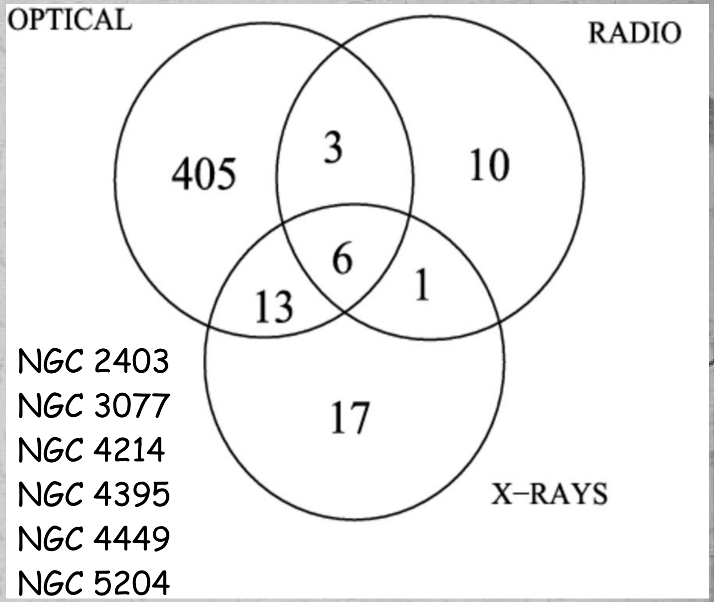
Multi-λ properties: Venn diagrams



Long et al. (2010)



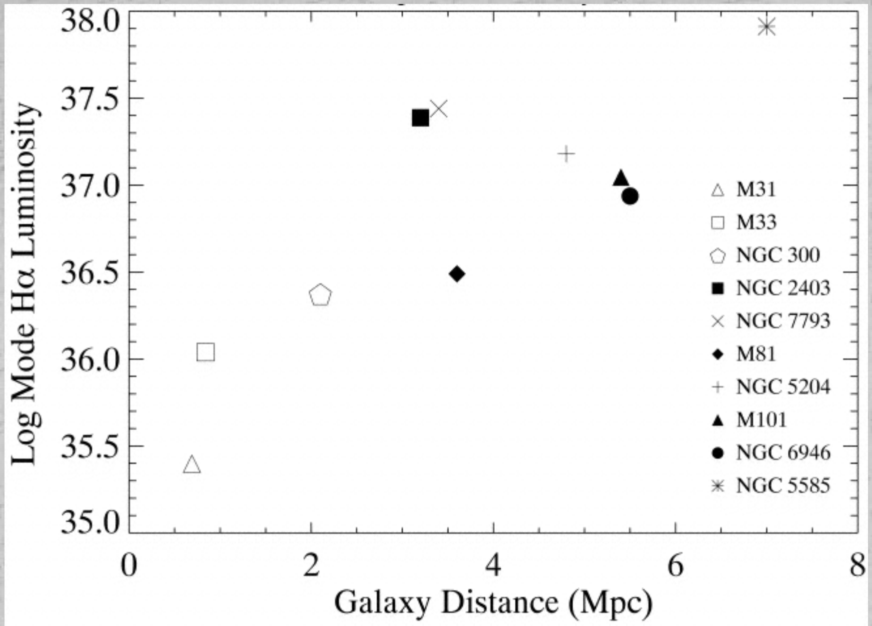
Pannuti et al. (2011)



Leonidaki et al. (2013)

Multi-λ properties: Venn diagrams

- Limited sensitivity



Matonick & Fesen (1997)

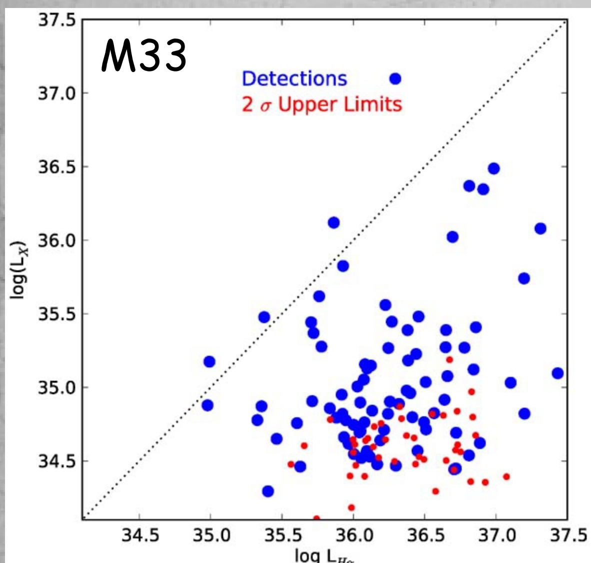
- Easier to detect optical SNRs in regions with low density/diffuse emission (Long et al. 2010, Pannuti, Schlegel & Lacey 2007,2002)

- Missing specific-types of SNRs (Balmer-dominated/oxygen-rich/wind-blown bubbles (optical), plerions(X-rays/radio)

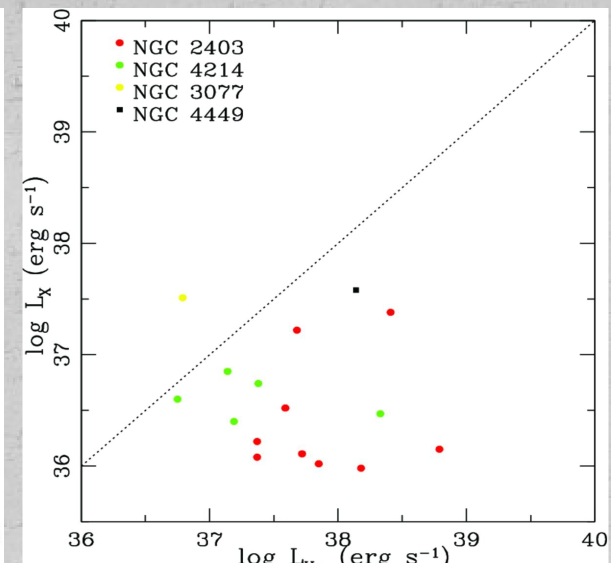
- Evolutionary stage (easier to detect evolved/older SNRs in the optical)

Multi-λ properties: Luminosity relations

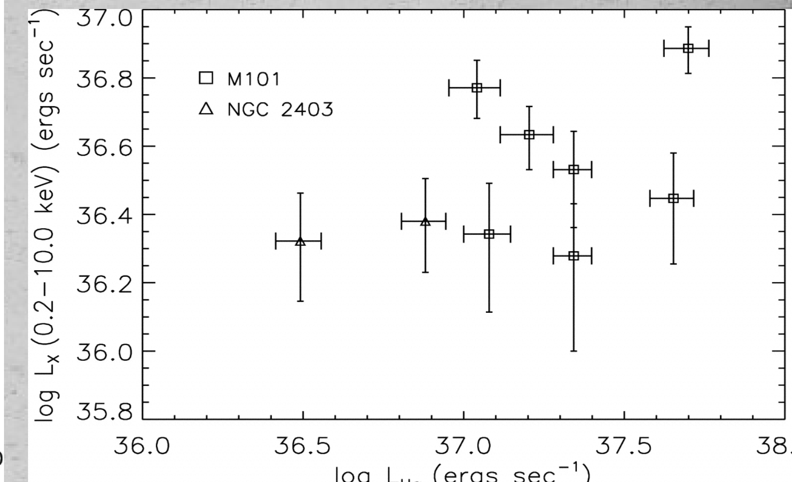
L_X - $L_{H\alpha}$



Long et al. (2010)



Leonidaki et al. (2013)



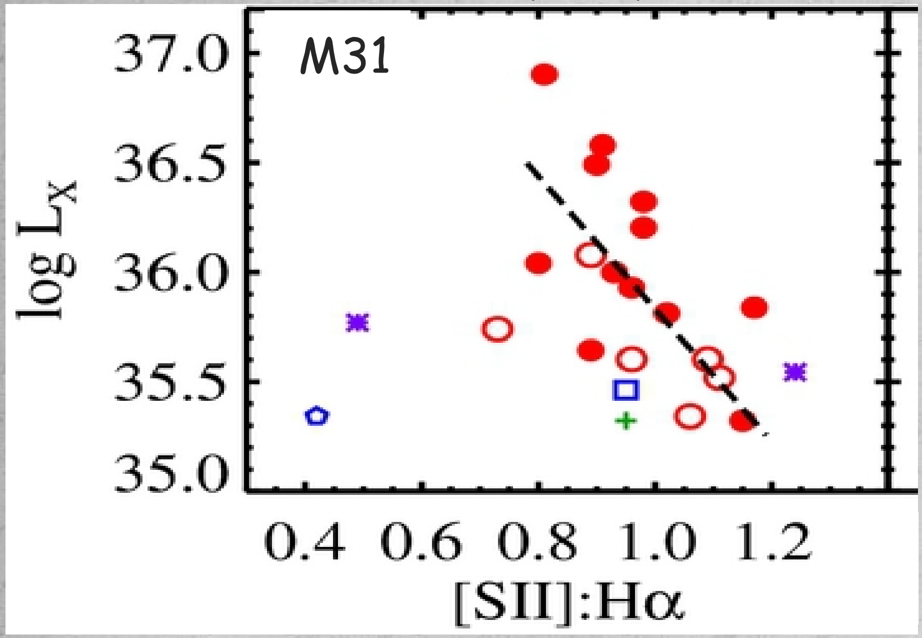
Pannuti, Schlegel & Lacey (2007)

- The most luminous X-ray SNRs tend to be the SNRs with the higher Hα luminosities
- The X-ray luminosities are lower than the Hα luminosities
- No strong correlation
- 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)

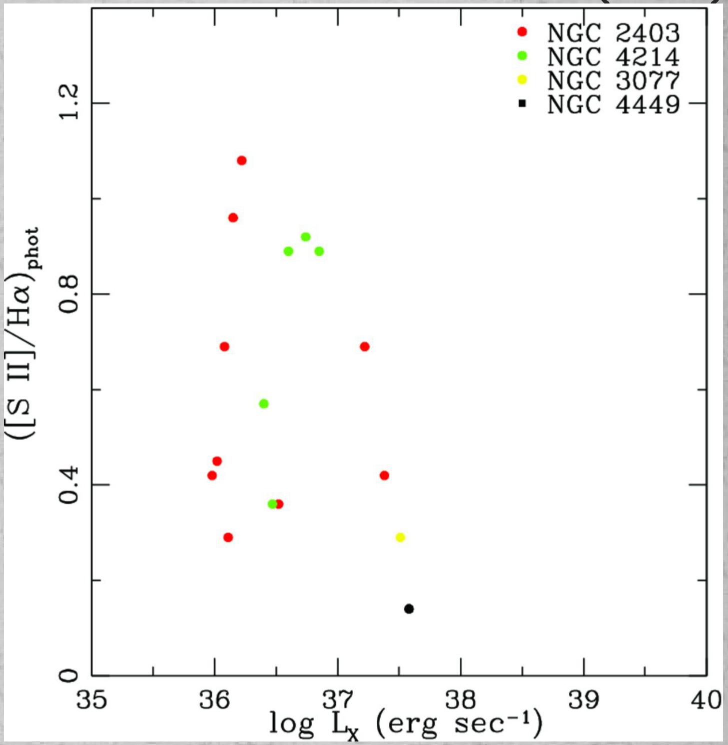
Multi-λ properties: Luminosity-shock heated indicator

L_X - [SII]/Hα

Lee & Lee (2014)



Leonidaki et al. (2013)

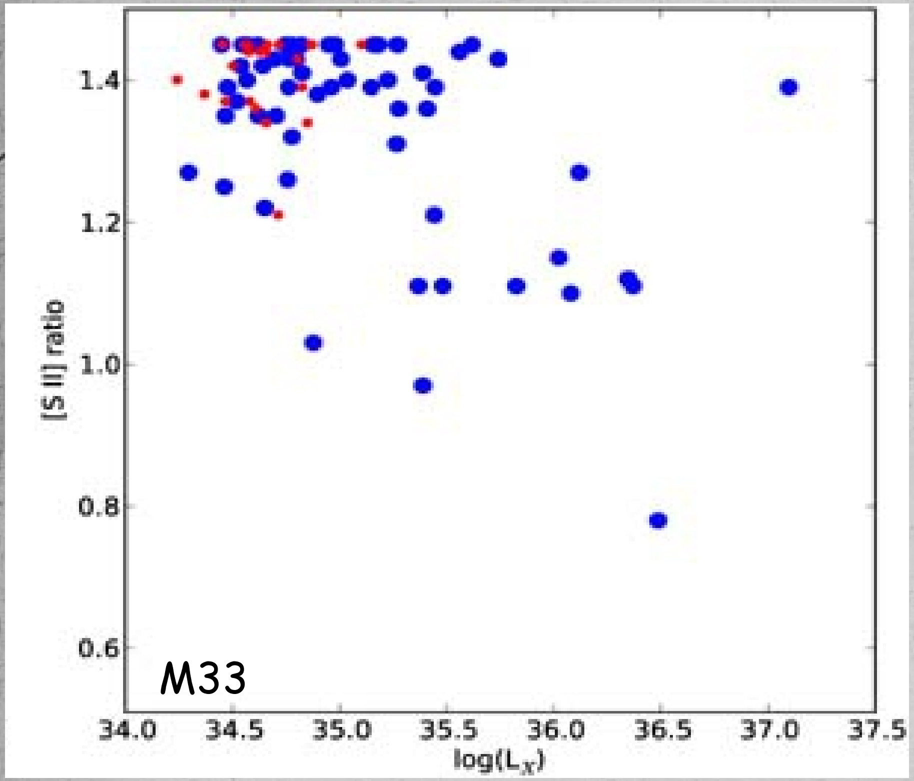


Trend for SNRs with higher L_X to have less [S II]/Hα ratios

Because of the 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-density

L_x – [SII] 6716/6731

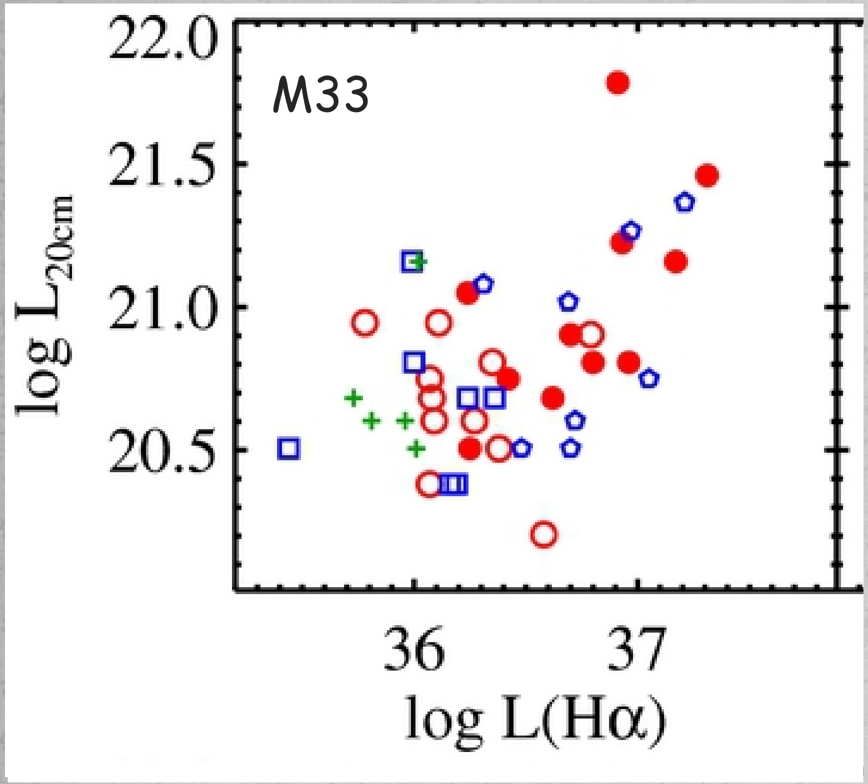


Long et al. (2010)

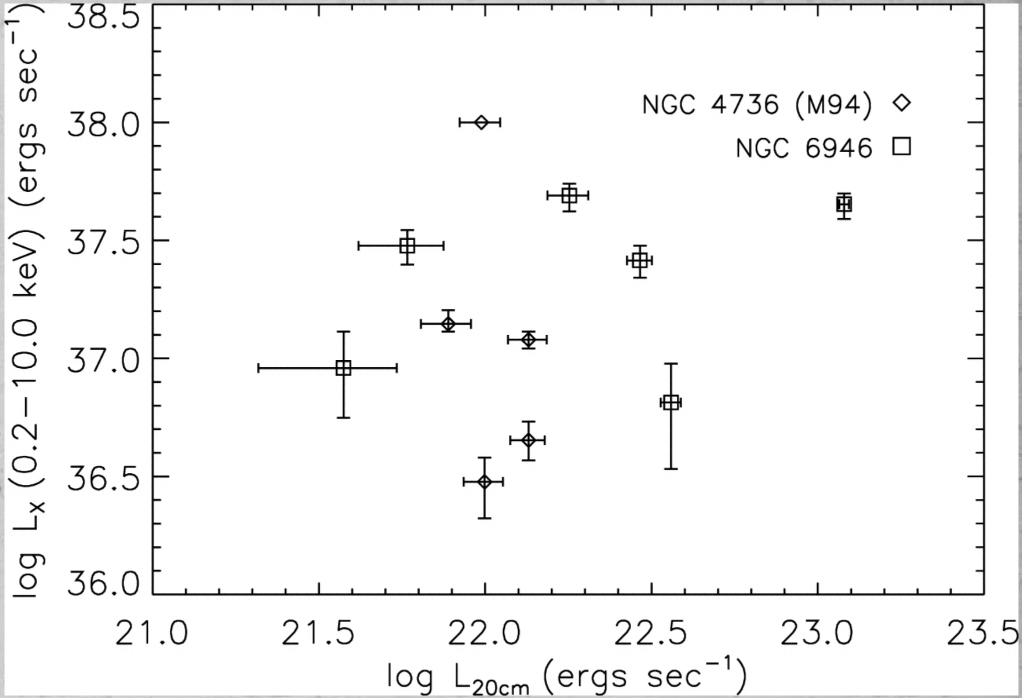
In most cases the higher the density in the [S II] zone the higher the X-ray luminosity.

Multi-λ properties: Luminosity relations

LHα – Lradio, LX – Lradio



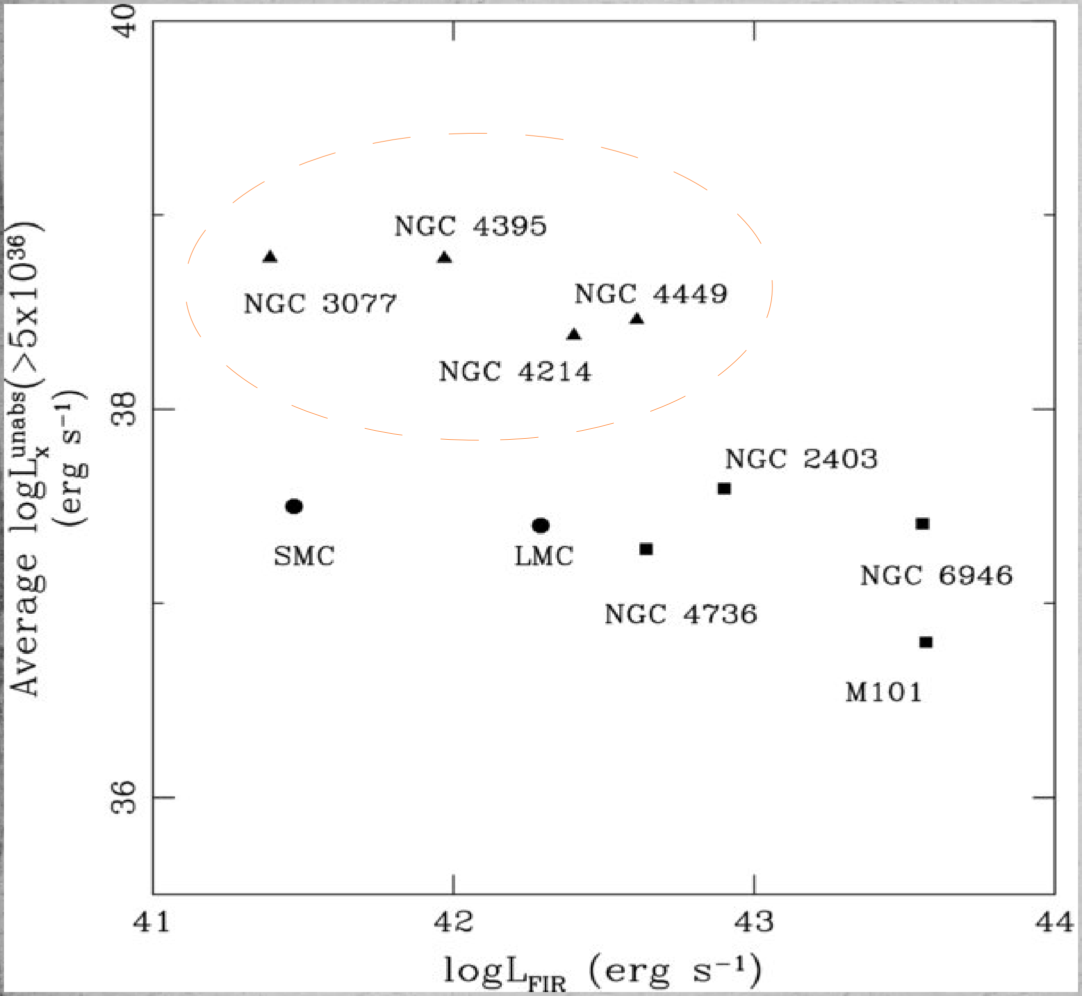
Lee & Lee (2014b)



Pannuti, Schlegel & Lacey (2007)

No correlation – inhomogeneous local ISM around SNRs

SNRs in the X-rays: Environmental effects



Leonidaki et al. (2010)

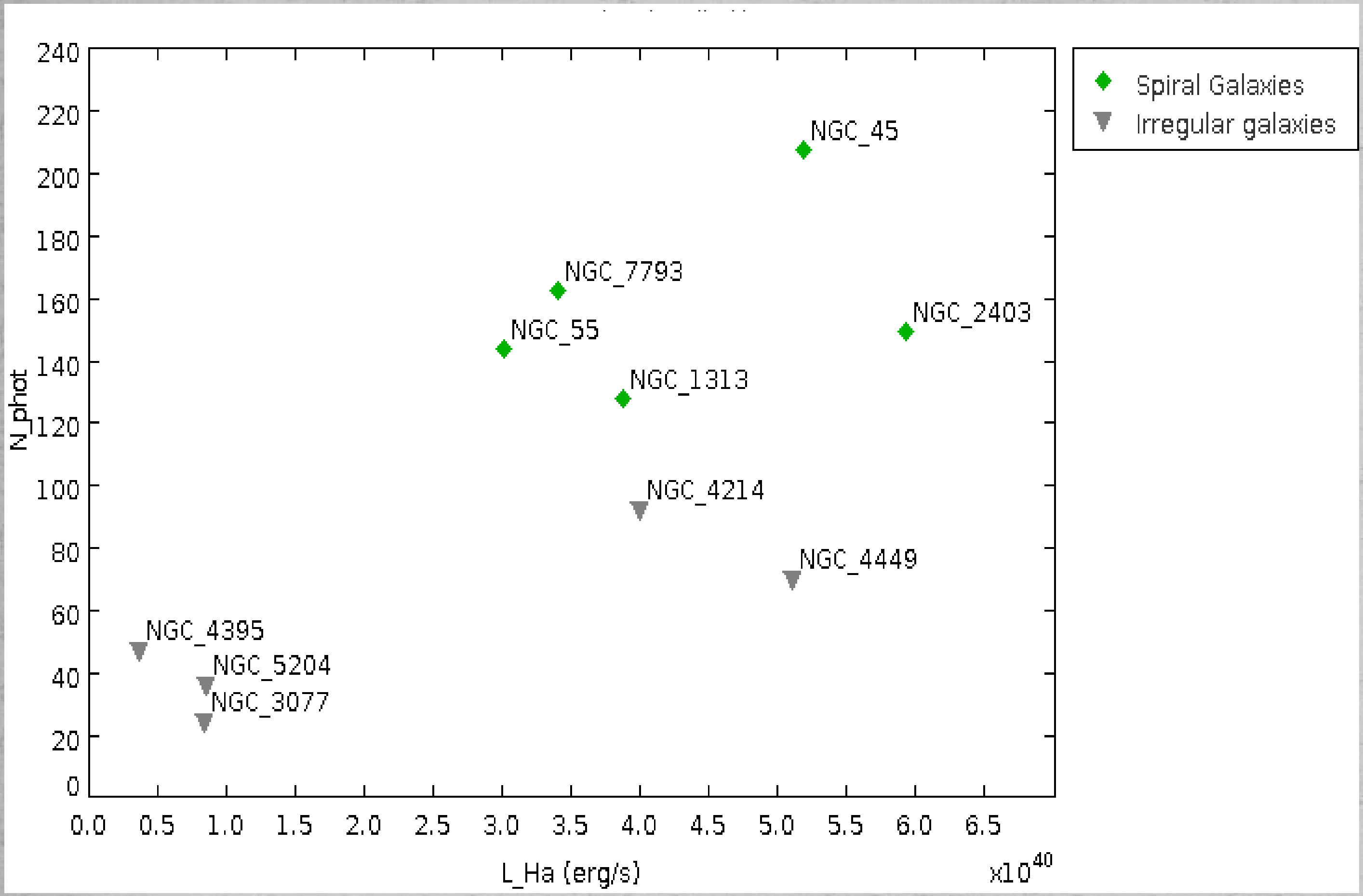
Systematic trend for more luminous SNRs to be associated with irregular galaxies:

- Either due to the typically lower metallicity of irregular galaxies than in typical spiral galaxies

(e.g. Pagel & Edmunds 1981; Garnett 2002)

- The non-uniform ISM which is often the case in irregular galaxies

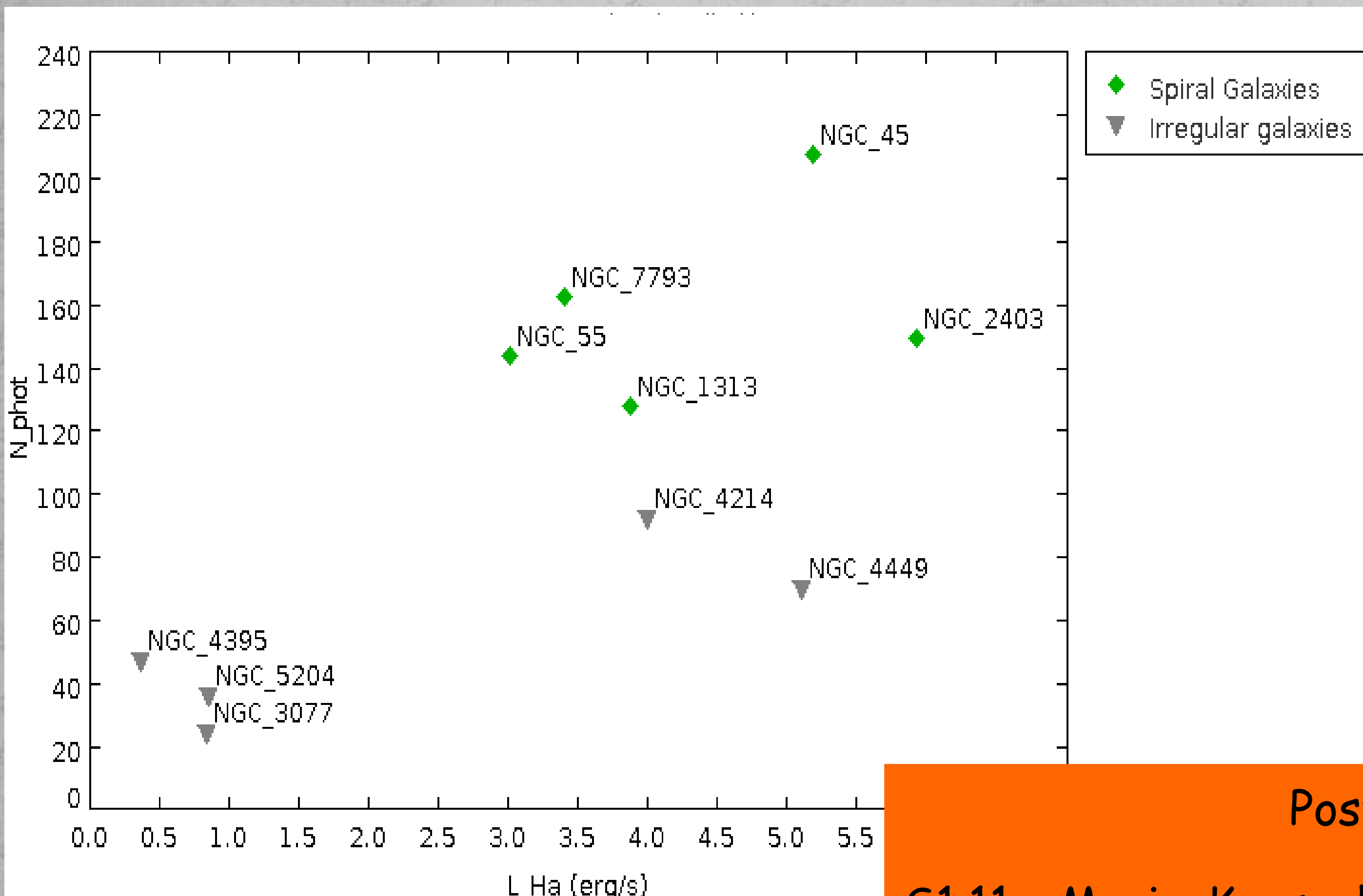
SNRs and SFR



Since core-collapse SNe are the endpoints of the evolution of the most massive stars, their SNRs are good indicators of the current SFR.

Kopsacheili et al. (in preparation)

SNRs and SFR



Kopsacheili et al. (in preparation)

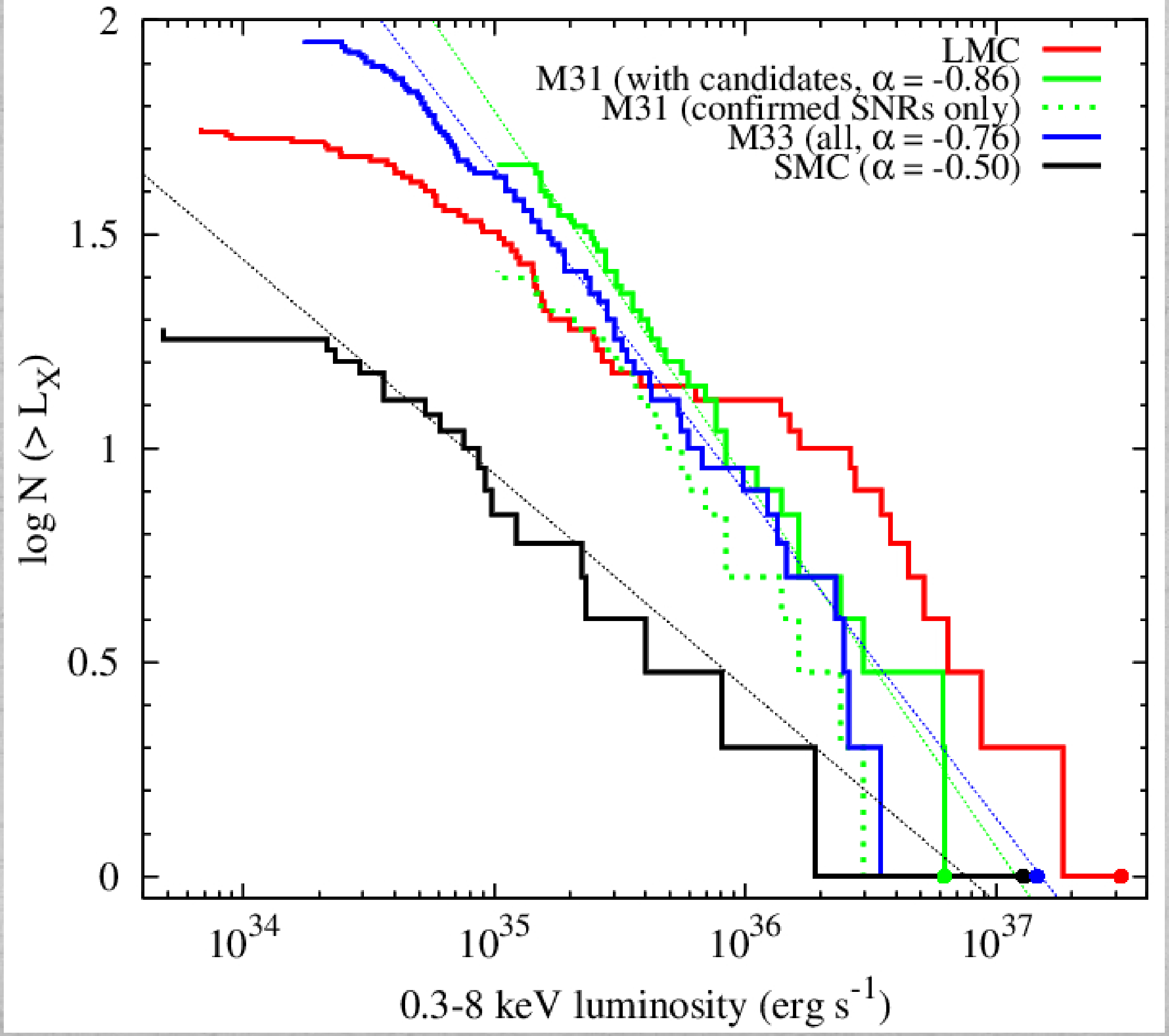
Since core-collapse SNe are the endpoints of the evolution of the most massive stars, their SNRs are good indicators of the current SFR.

Poster

S1.11 Maria Kopsacheili: New candidate supernova remnants in nearby galaxies

X-ray properties: Environmental effects

Luminosity functions: X-rays



Maggi et al. (2016)

Summing up...

- Revolution on extragalactic SNRs

- Enabled the study of the physical properties of SNRs in different environments (evolutionary stage, progenitors)

But this is just the beginning..

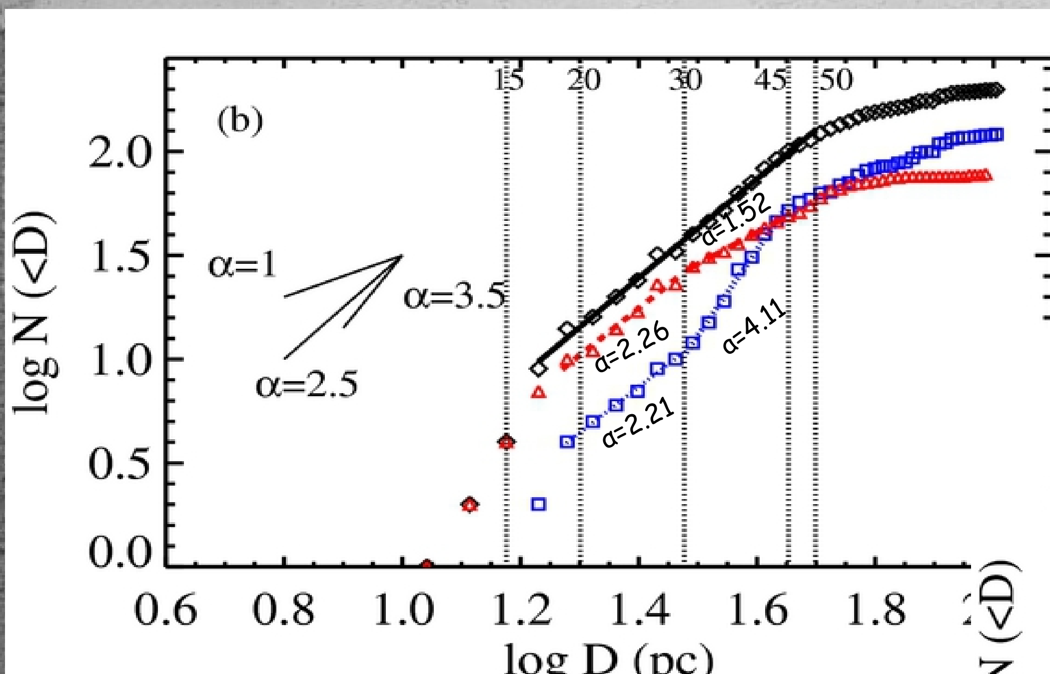
Need to observe more galaxies to larger depths and in a multi-λ context in order to:

- alleviate the selection effects that hamper the current studies of SNRs

- obtain a more complete picture of the SNR populations

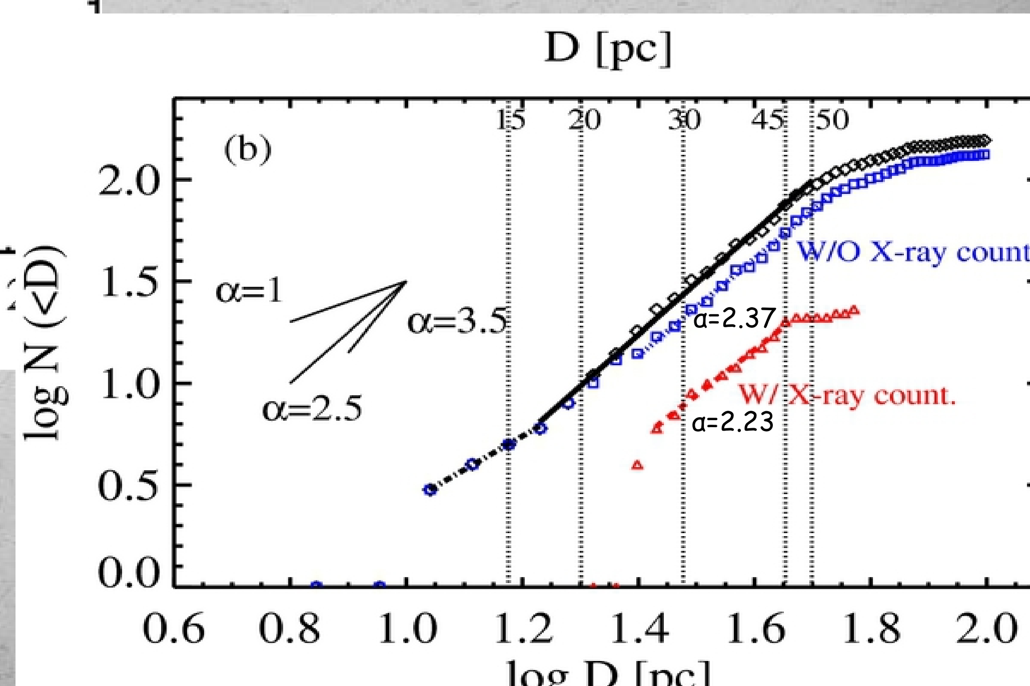
SNRs in the optical: Evolution

Cumulative Size Distributions: What happens if X-rays are present?



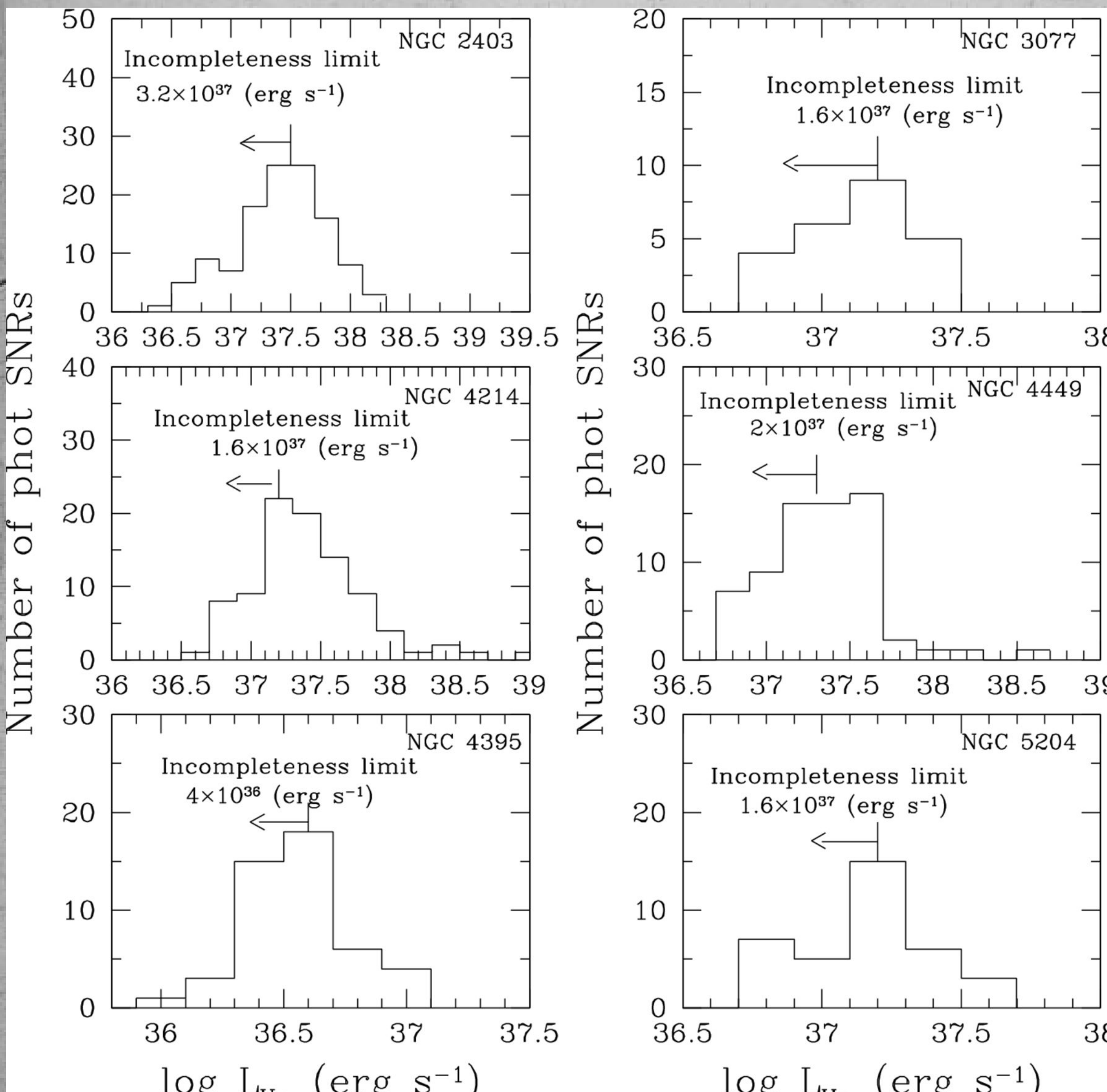
M33 - Lee & Lee (2014b)

M31 - Lee & Lee (2014a)

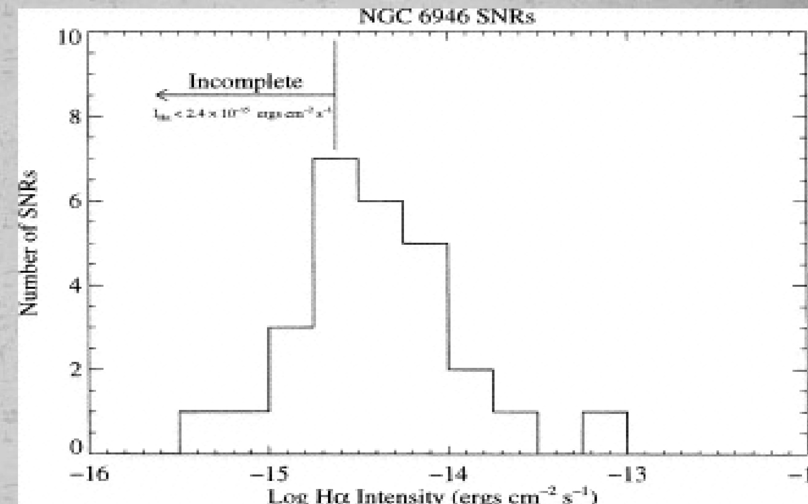


Multi-λ properties: Complete picture

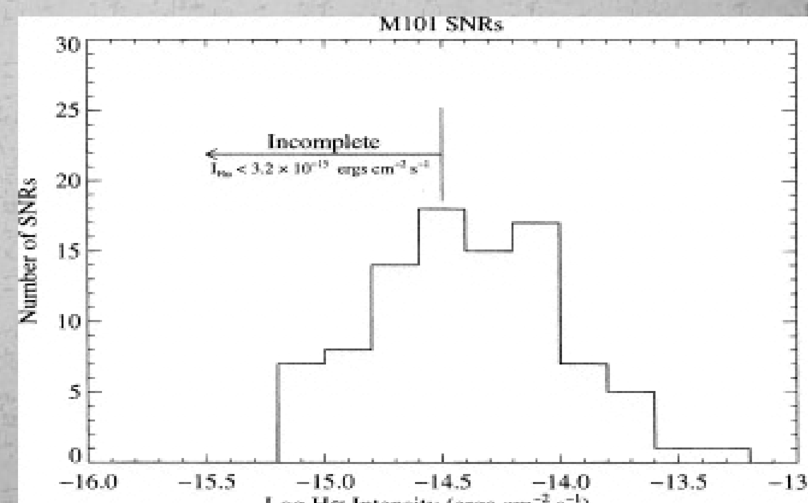
Luminosity functions: Optical



Leonidaki et al. (2013)

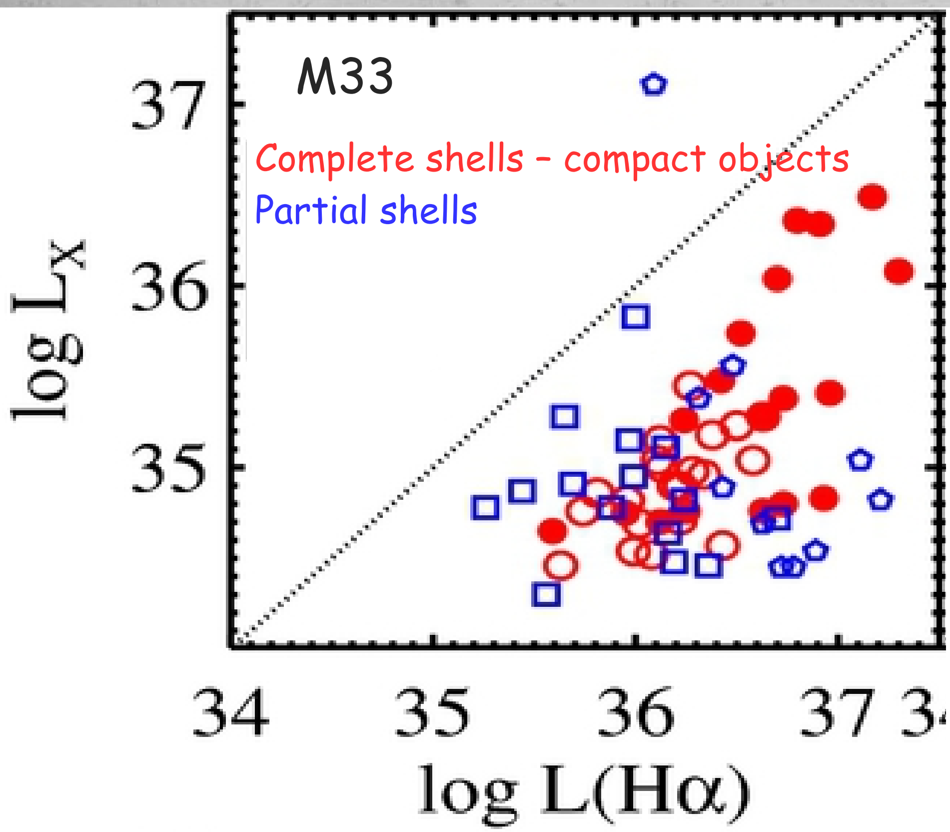


Matonick & Fesen (1997)

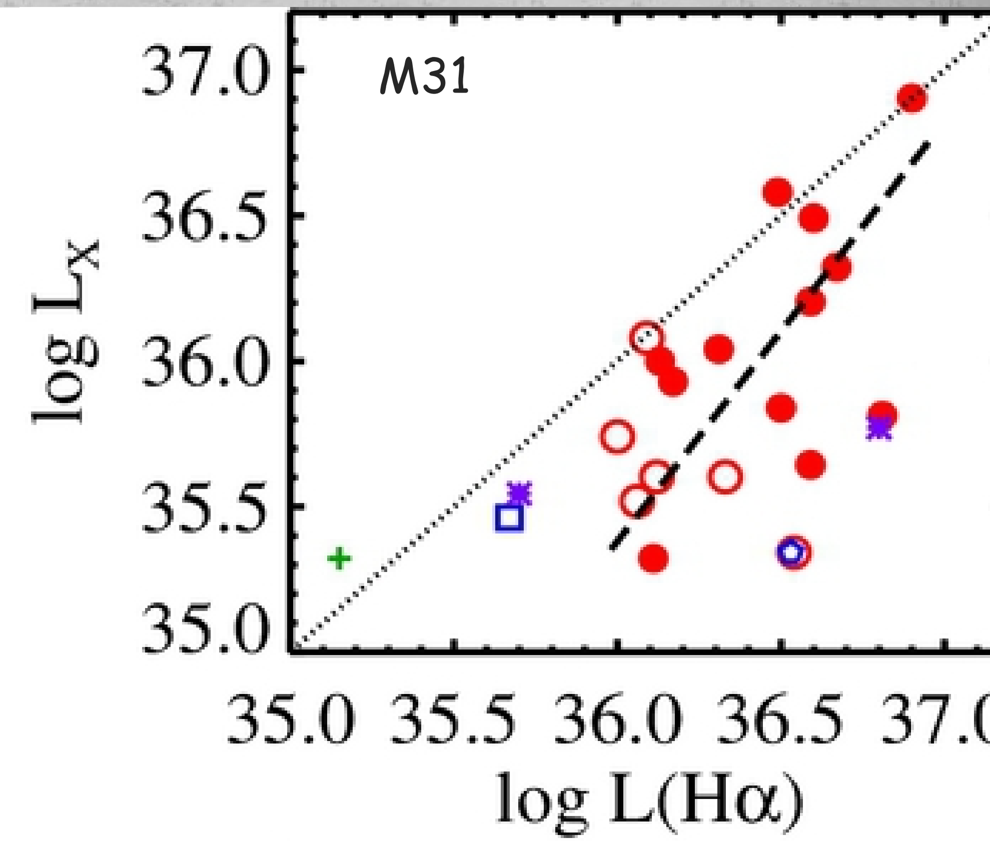


Multi-λ properties: Luminosity relations

$L_X - L_{H\alpha}$



Lee & Lee (2014b)

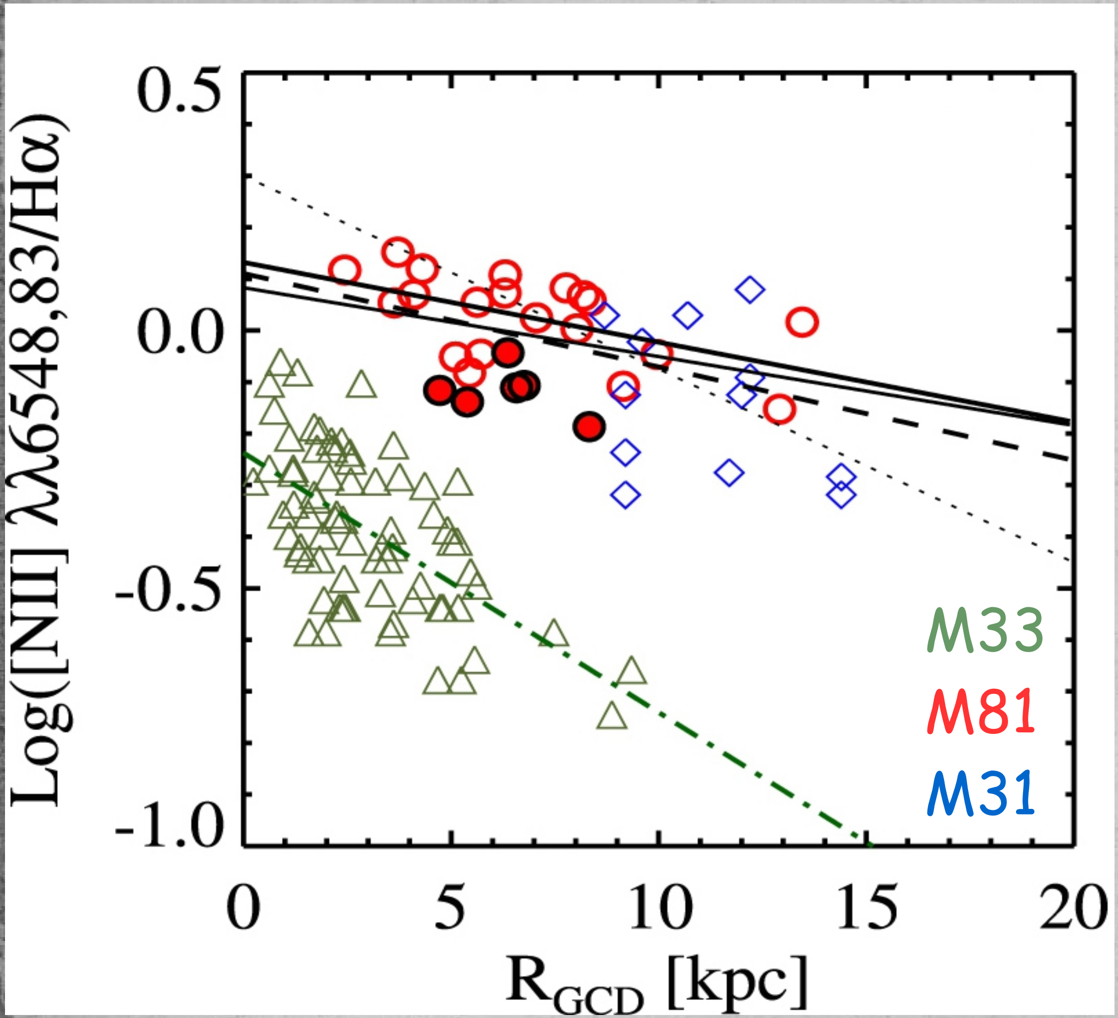


Lee & Lee (2014a)

ISM around the A-class remnants (complete shells, compact-center bright objects) seems more uniform than that around the B-class (partial shells) remnants

SNRs in the optical: Emission line diagnostics

[NII]/Hα: abundance gradient



Lee & Lee (2015)

Dependence on:

- Clumpy ISM?
- Progenitors (Type Ia/Type II)?

Galaxy type?