What are We Learning from Supernova Remnant Samples in Nearby Galaxies?

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and

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Galactic vs. Extragalactic Samples

Galactic

- 295 SNRs in the Galaxy (Green 14)
- Where are they detected?
  - Radio – nearly all
  - Optical – 30%
  - X-ray – 40%
- Advantages
  - Spatially resolved
  - Detailed studies of individual objects possible
- Disadvantages
  - Distances are poorly known
  - Variable absorption

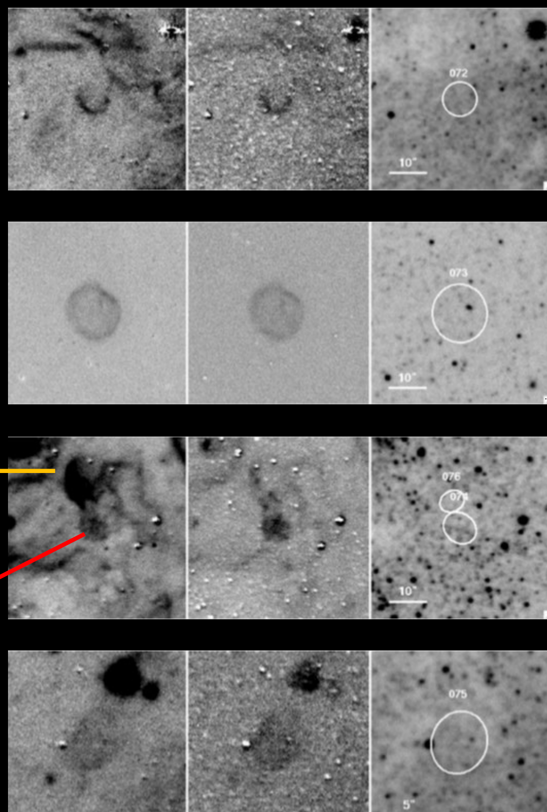
Extragalactic

- 1500 SNRs and SNR candidates (beyond MC)
- Where are they detected
  - Radio 10%
  - Optical 95%
  - X-ray 15%
- Advantages
  - Distance is known
  - Absorption is less of a problem
  - Snapshot of the locations where SN are occurring in a galaxy
- Disadvantages
  - Not spatially resolved in all bands
  - Photons are few

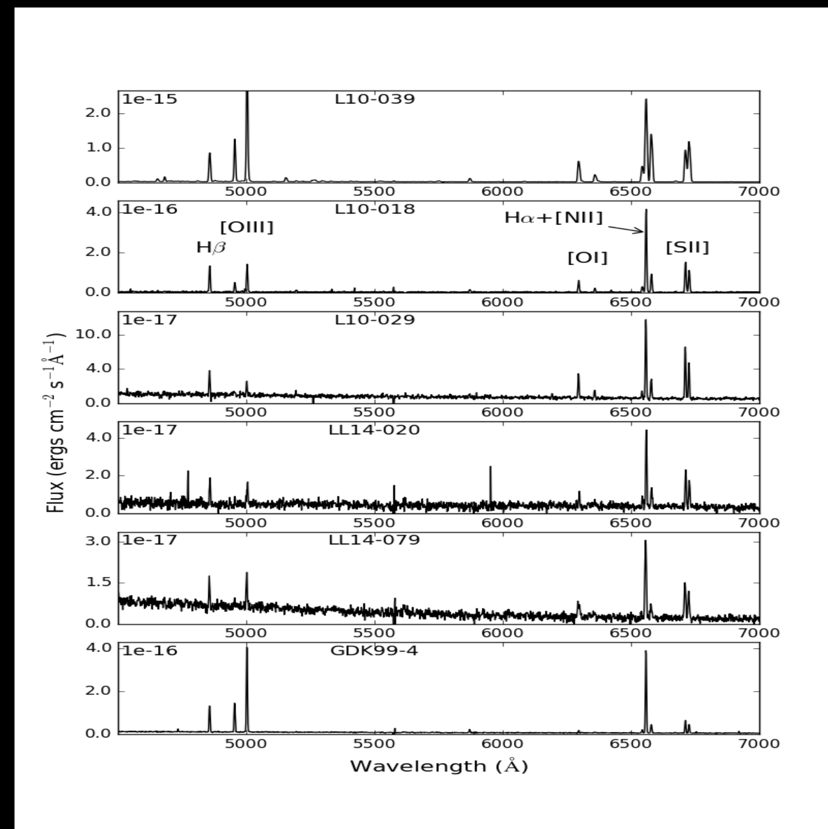
The technique for identifying SNRs optically

HII region

SNR

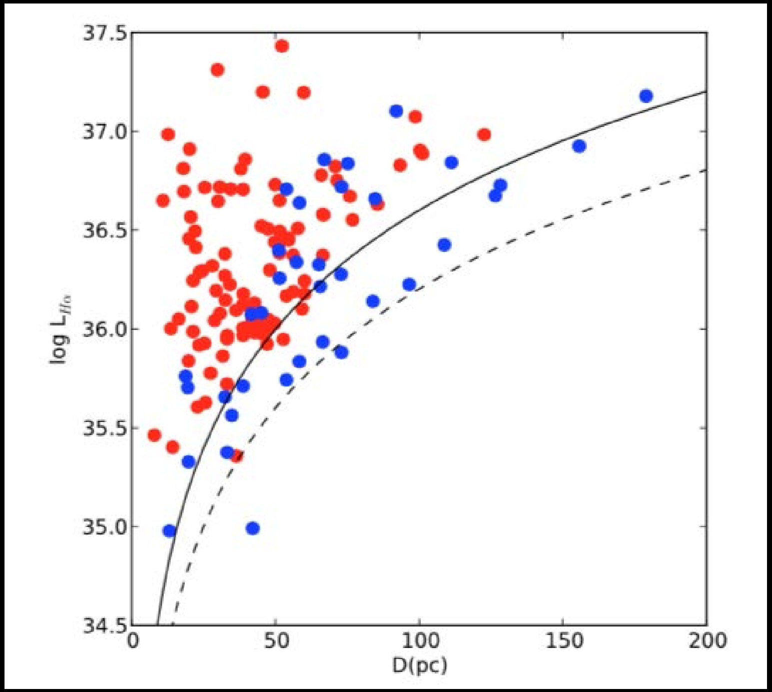


Hα [S II] V



Optical Identification of SNRs

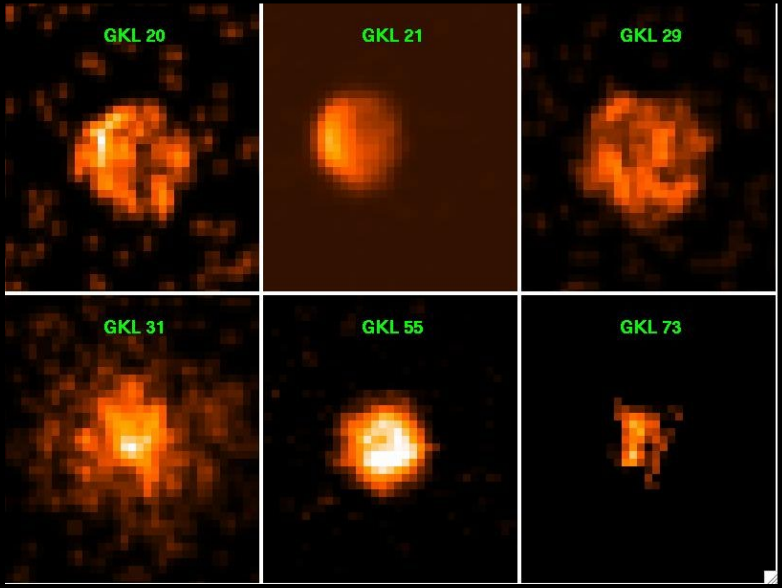
- Surface Brightness limited (if objects are resolved)
- Objects that are missed
  - Very small diameter objects
  - Balmer-dominated SNRs
  - Most pulsar dominated SNRs
  - The remnant of a 2nd SN (unless the progenitor has produced its own circumstellar cloud)



M33: Red – Gordon+98 Blue – added by Long+10

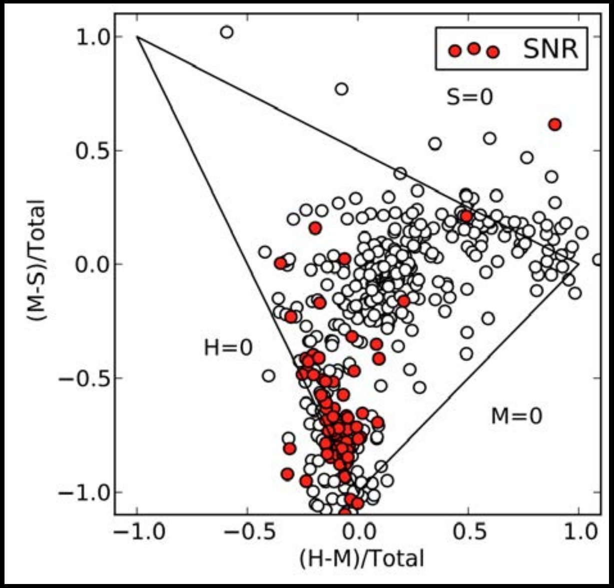
X-ray identification of SNRs

In the nearest galaxies, SNRs are extended plasma dominated sources



M33 – Long+10

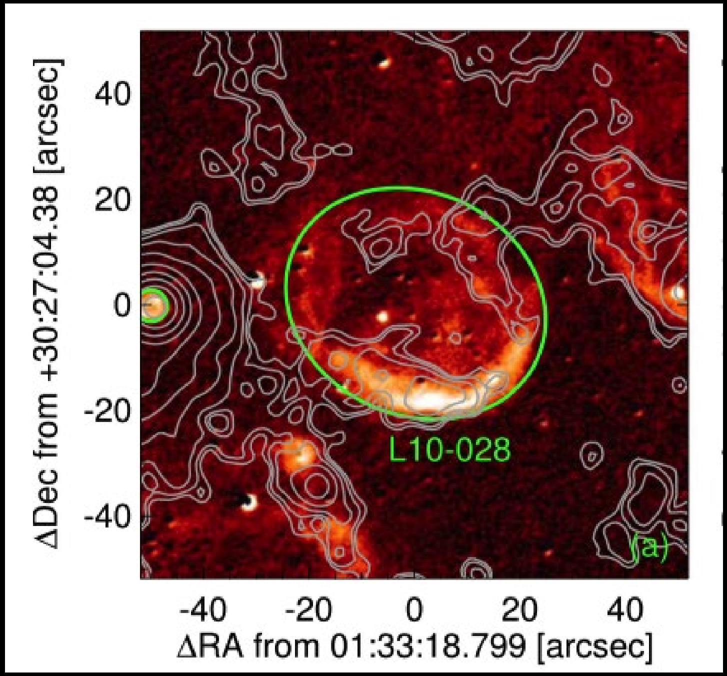
In more distant galaxies, SNRs are soft sources, but softness is insufficient



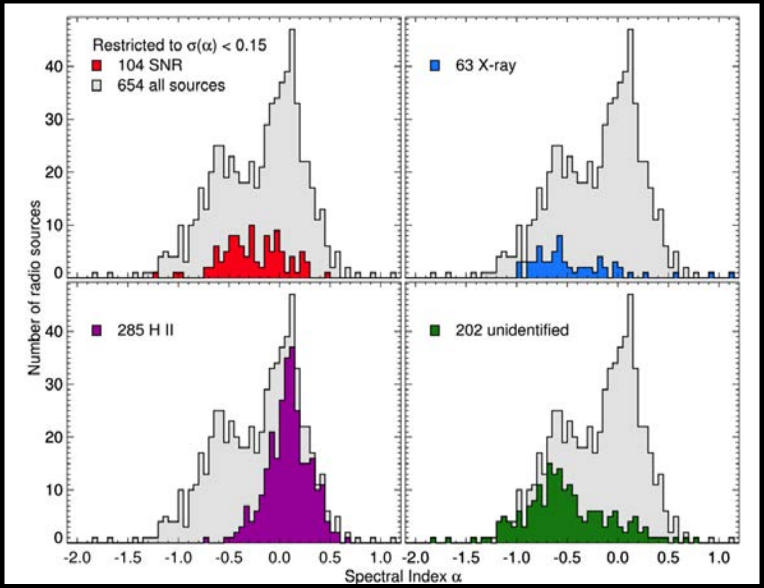
M83 – Long+14

Radio Identification of SNRs

In the MC and M33, SNRs are extended, non-thermal sources



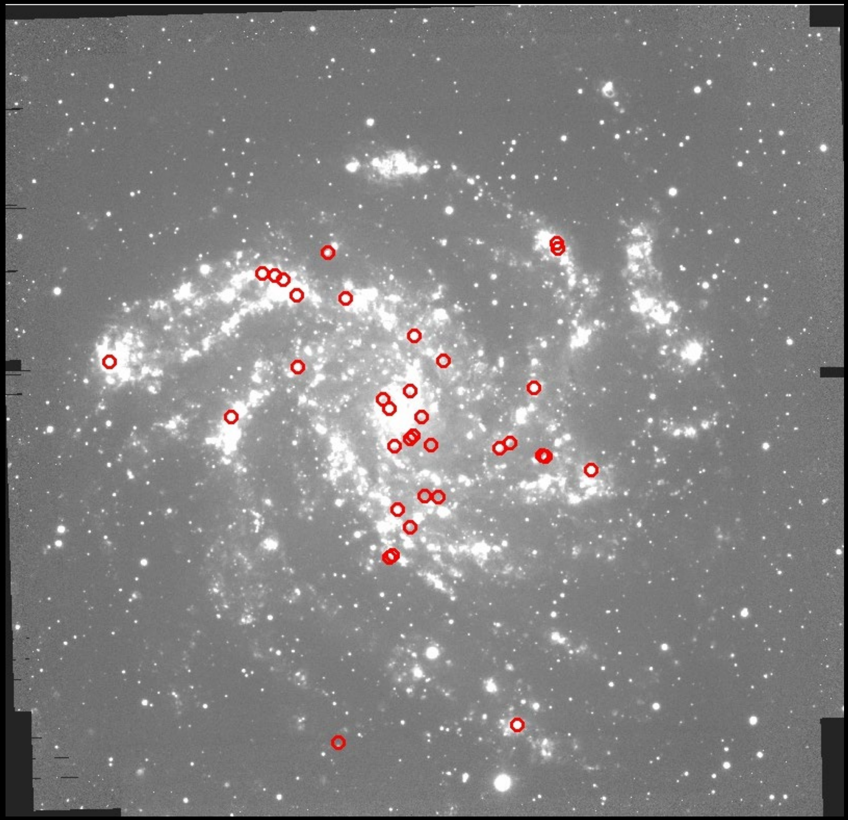
In more distant galaxies, SNRs can in principle, be separated from HII regions on the basis of spectral index (but background AGN are a problem)



Spectral indices of known SNRs (in red) in M33 - White+19

Radio Identification of SNRs

- 3 years ago , at this conference , I suggested we might be able to identify SNRs in M33 based on the radio data alone. Ultimately we (White+19) decided that at least in M33 it was not possible to separate these source from background galaxies
- Lacey and others have argued that non-thermal sources associated with Hα emission are credible candidate SNRs
- 35 radio SNR candidates in NGC6946
- Of the 35, only a couple had been detected as optical SNR candidates by Matonick and Fesen
- To explain this, Lacey & Duric suggested the radio SNRs (partly by the selection criteria) are located in regions that make them hard to detect optically
- Deeper radio surveys are now possible/underway to try to resolve this problem
- Caveat – Measuring spectral indices is hard
    - Scaled array observations are needed if the source is resolved
    - If one measures a source at 1.4 and 5 GHz to an accuracy of 10%, the error in the spectral index will be about 40%
- Luminosity limited beyond the local group

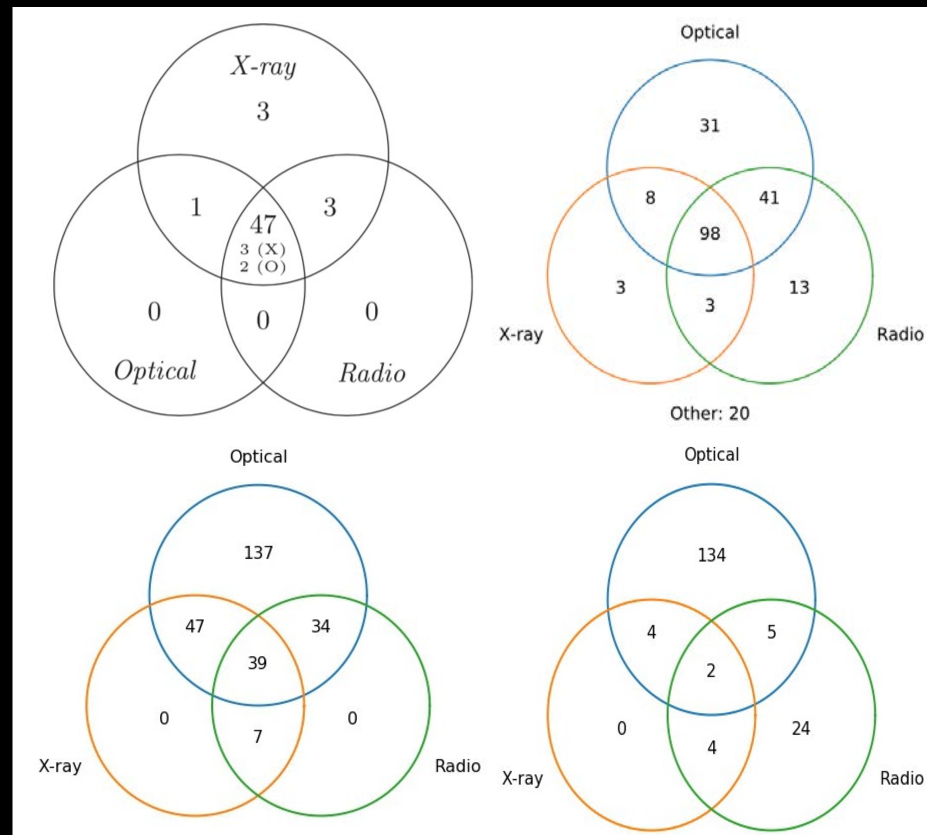


Radio SNR Candidates in NGC6946 – Lacey & Duric 1990

A Tale of 4 Galaxies

LMC – 59 SNRs – Bozzeto+18 M33 – 221 SNRs – White+19

- LMC @ 50kpc
  - 0.3 $M_o yr^{-1}$ → 1 SNe
- M33 @ 815 kpc
  - 0.3 $M_o yr^{-1}$ → 0 SNe
- M83 @ 4.6 Mpc
  - 3-4 $M_o yr^{-1}$ → 6 SNe
- NGC6946 @ 6.7 Mpc
  - 3.2 $M_o yr^{-1}$ → 10 SNe

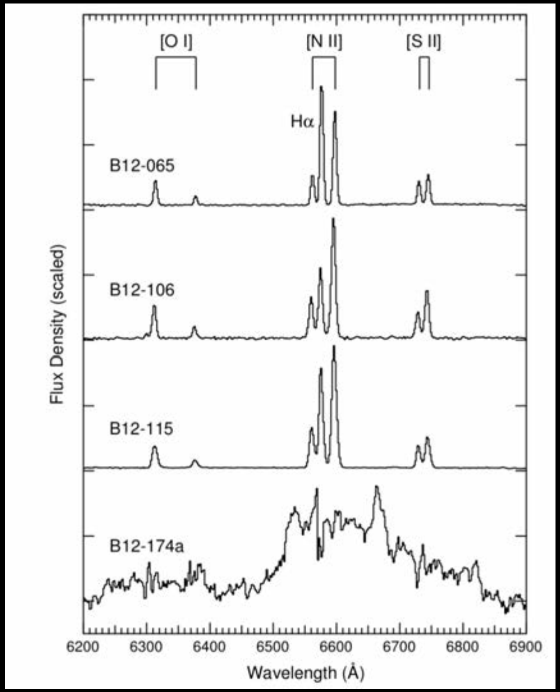


M83 – 257+7 SNRs -- Long+14 → Williams+19 NGC6946 – 147 + 35 SNRs – Long+17

What have we learned (or not) from the large samples?

Ejecta dominated objects are rare

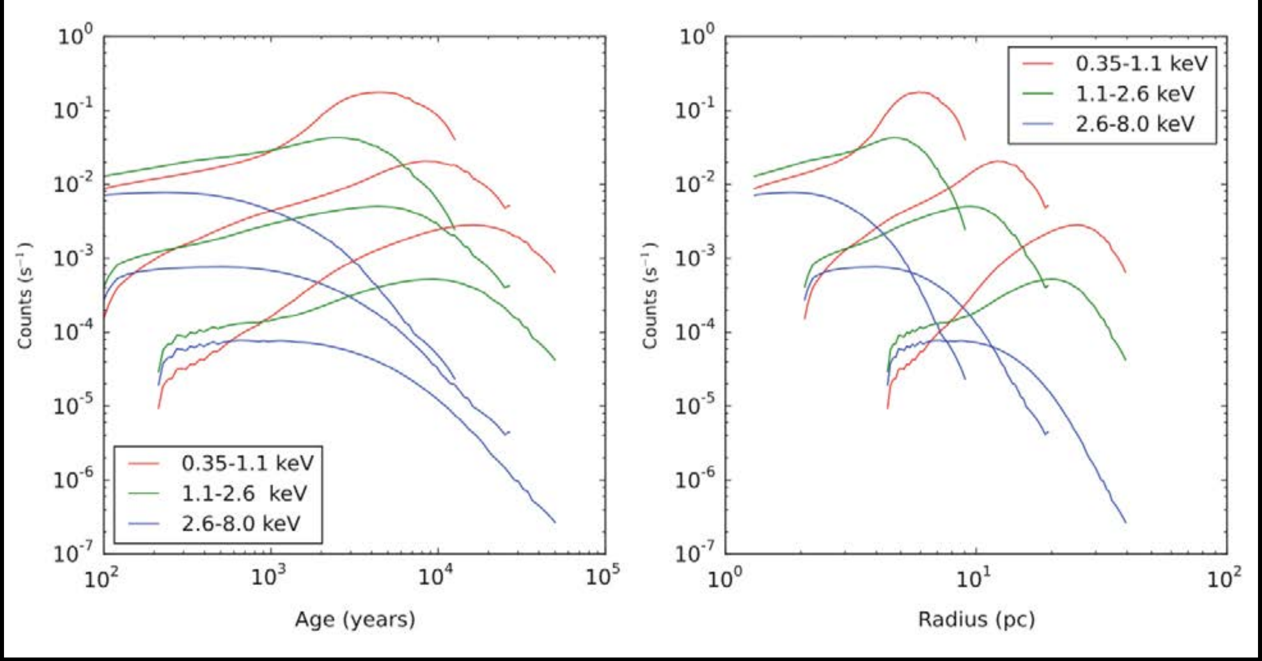
- Despite having identified more than 1400 SNRs optically, exceedingly few remnants with broad optical emission lines have been found
- LMC (and SMC)
  - N132d (and EO102)
- M33
  - None
- M83
  - SN1957d and B12-174a
- NGC6946
  - None, except SN1980k and SN2004et
- Why
  - Optically SNRs evolve quickly
  - Small diameter SNRs are faint and hard to find



4 (of many) small diameter SNRs in M83 – Winkler+17

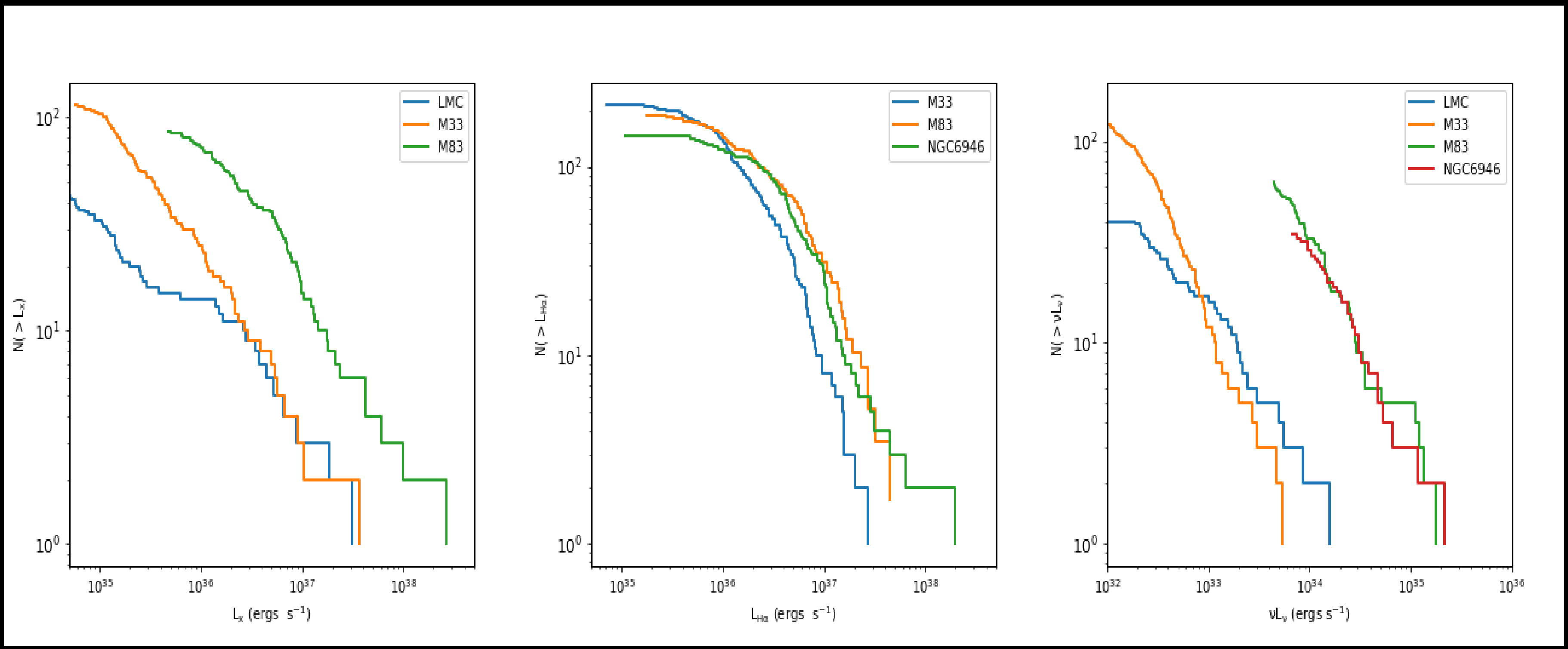
Old SNRs tend to be brighter

- Optically the shocks we detect are dense phases of ISM and large SNRs have more surface area
- Nearly all SNe fade to nothing



X-ray L_X prediction for Sedov SNRs @ 1 Mpc observed with Chandra

Luminosity function



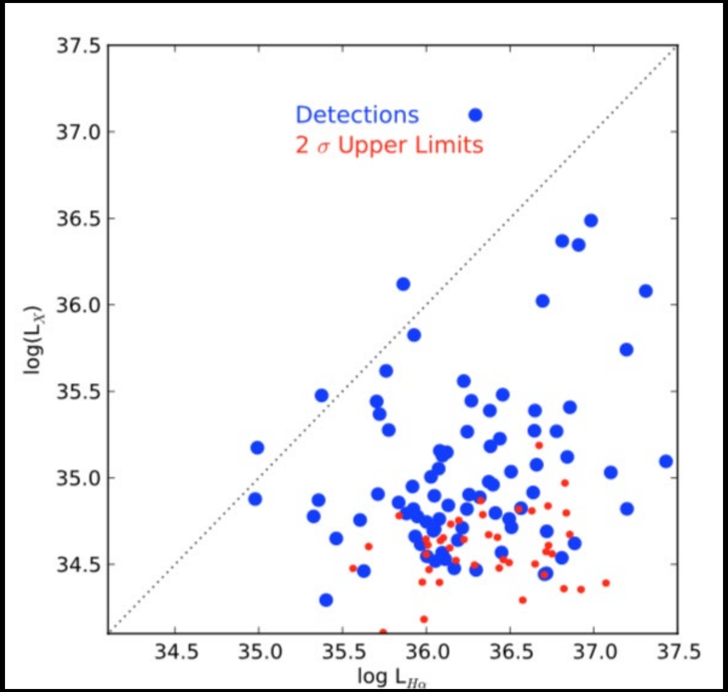
X-ray

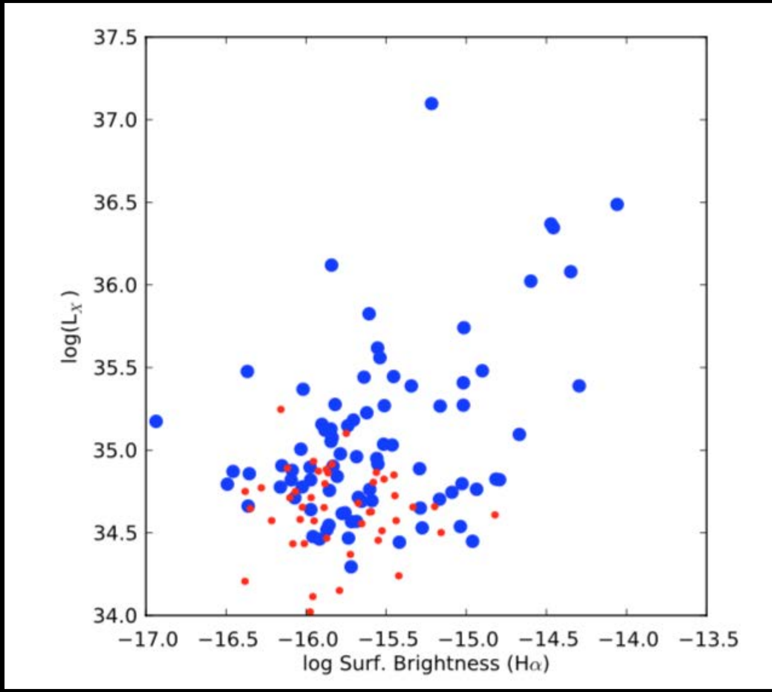
Hα

Radio

Colors inconsistent

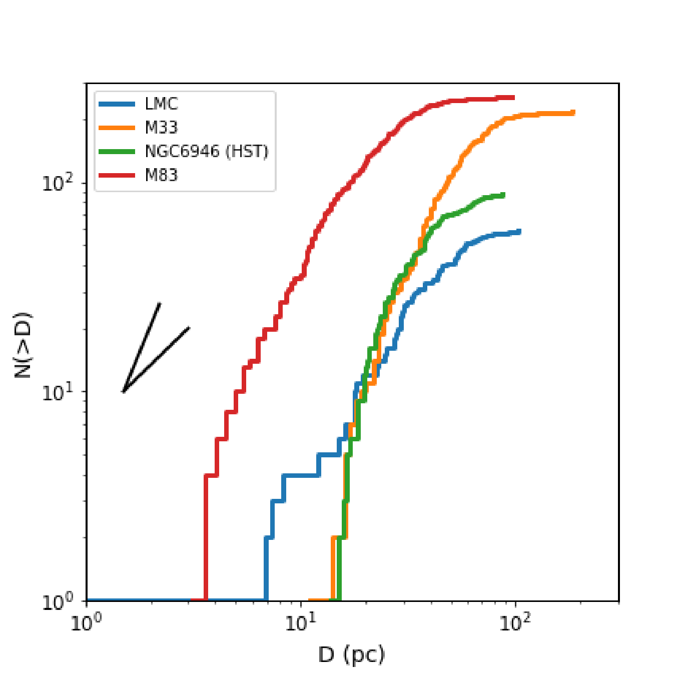
X-ray – Hα correlations or lack thereof

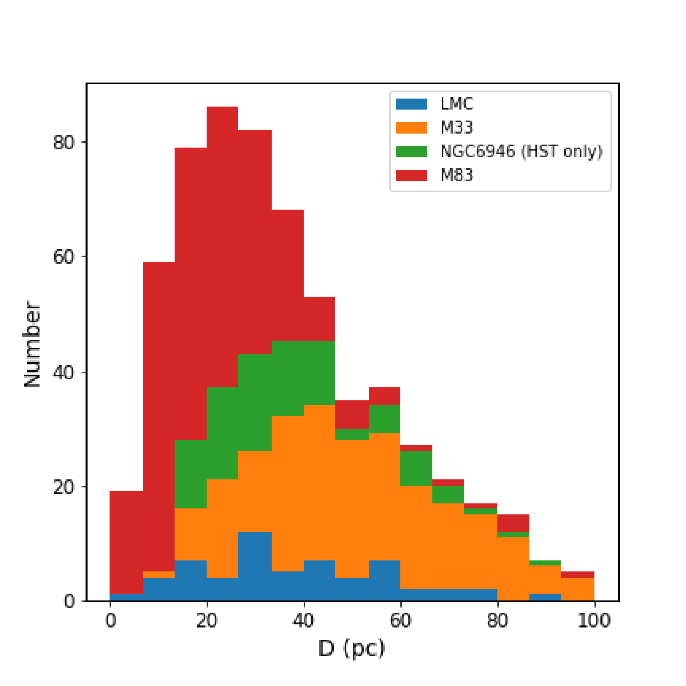




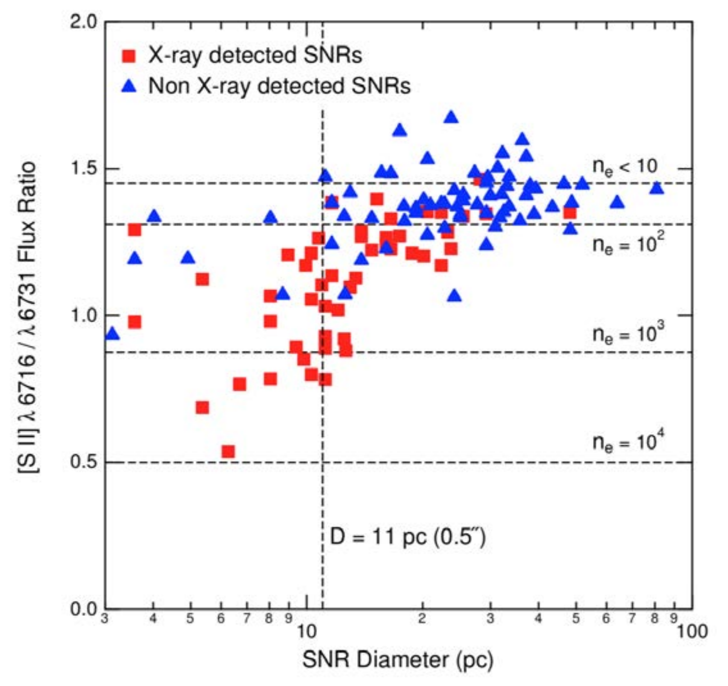
M33 – Long+10

Diameter distributions – LMC, M33, M83, NGC6946

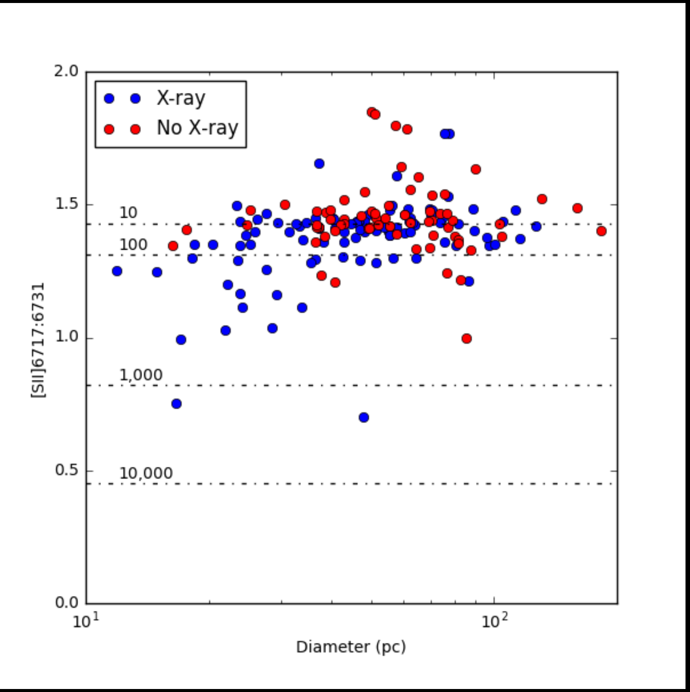




Densities vs diameter

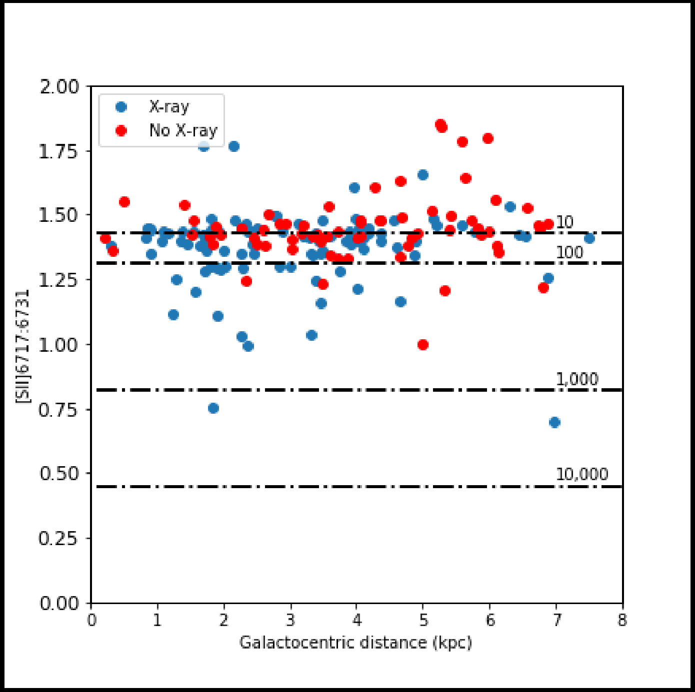


M83 – Winkler+17

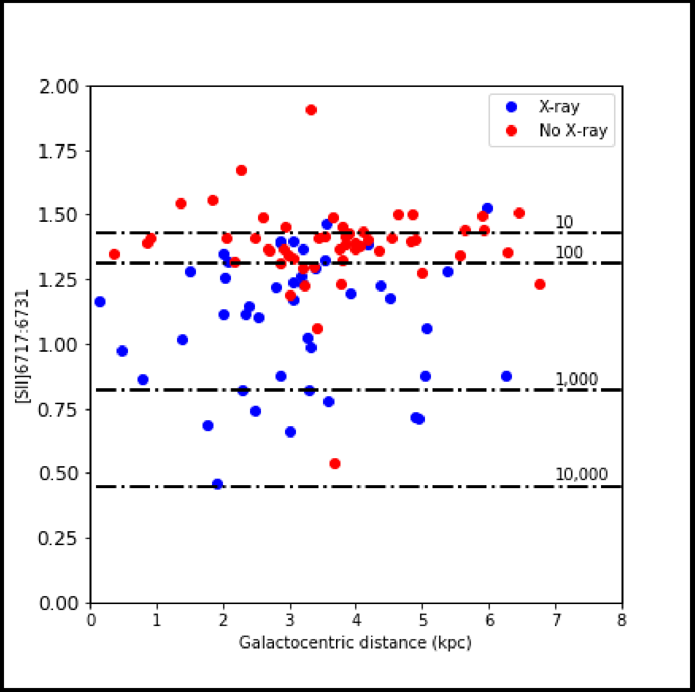


M33 – Long+18

Density vs GC distance

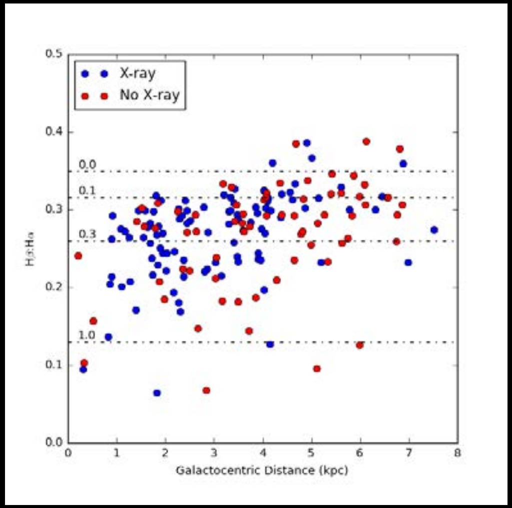


M33 – Long+18

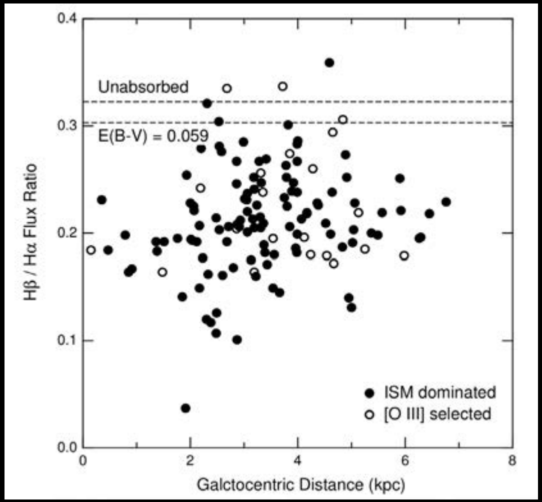


M83 – Winkler+17

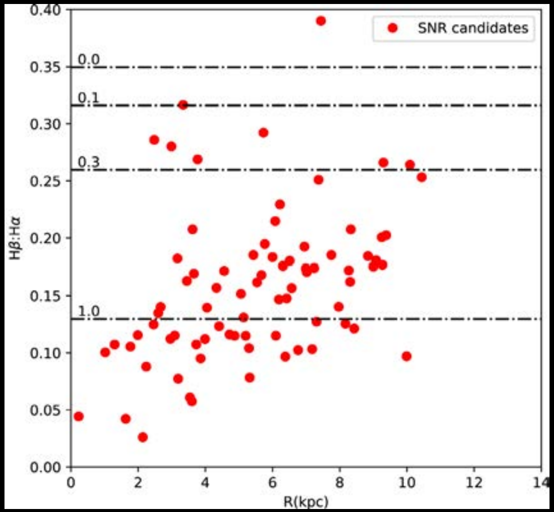
Reddening



M33 – Long+18

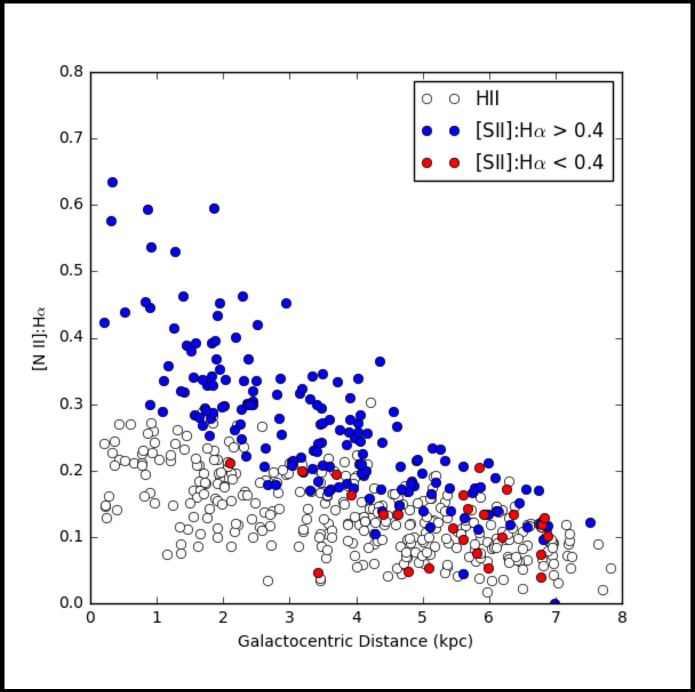


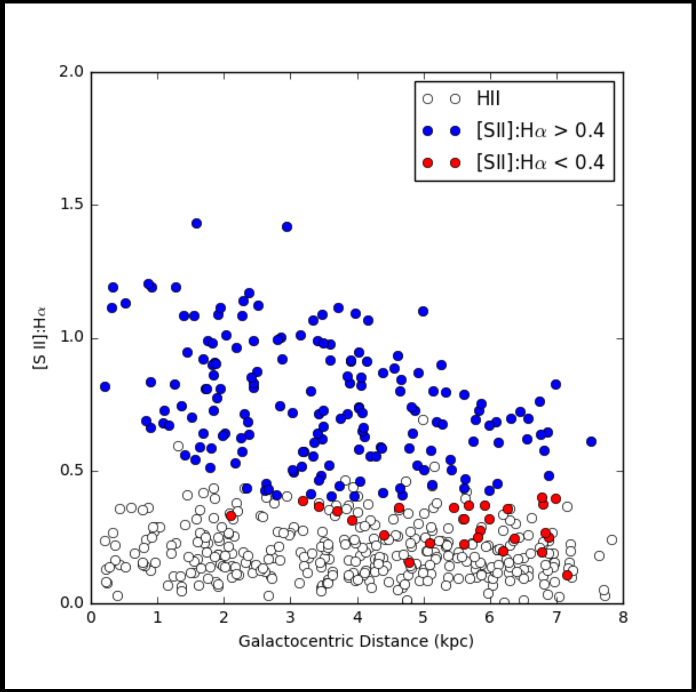
M83 – Winkler+17



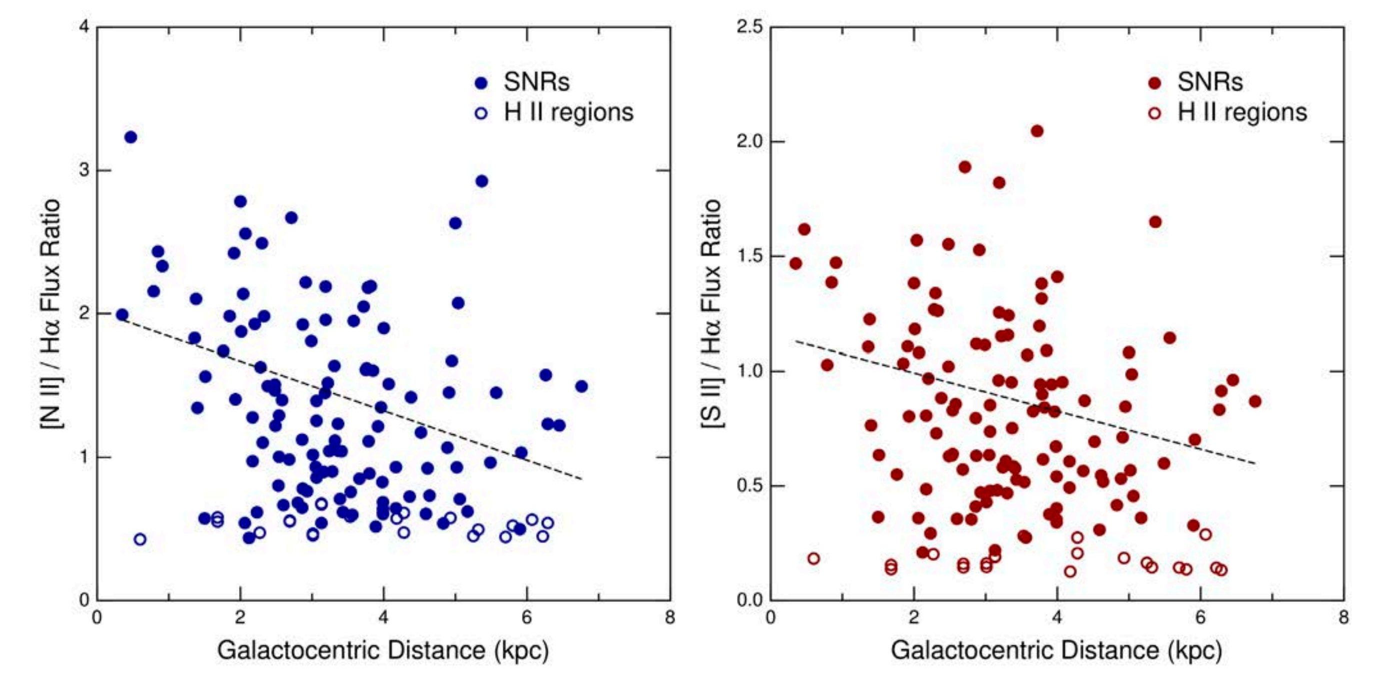
NGC6946 – Long+19

M33 – [N II]:Hα and [S II]:Hα vs. GC

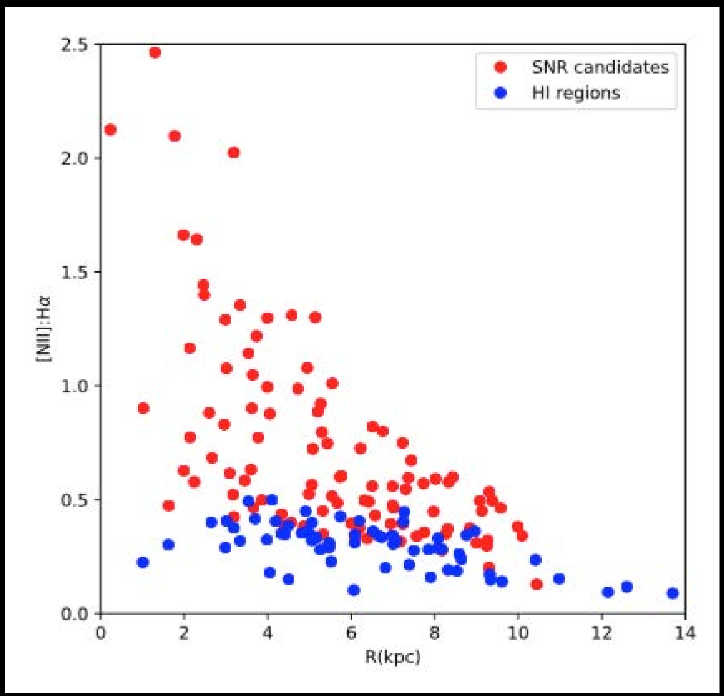


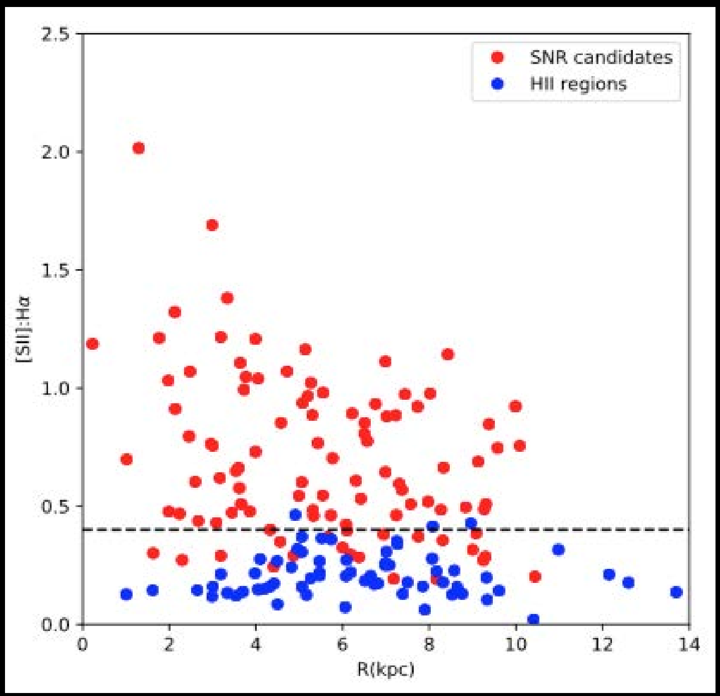


M83 – [N II]:Hα and [S II]:Hα vs. GC



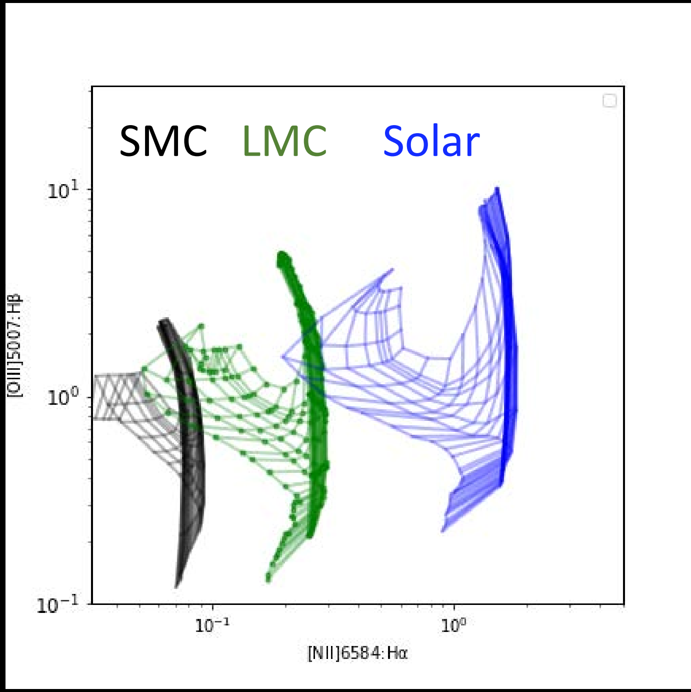
NGC6946 – [N II]:Hα and [S II]:Hα vs. GC

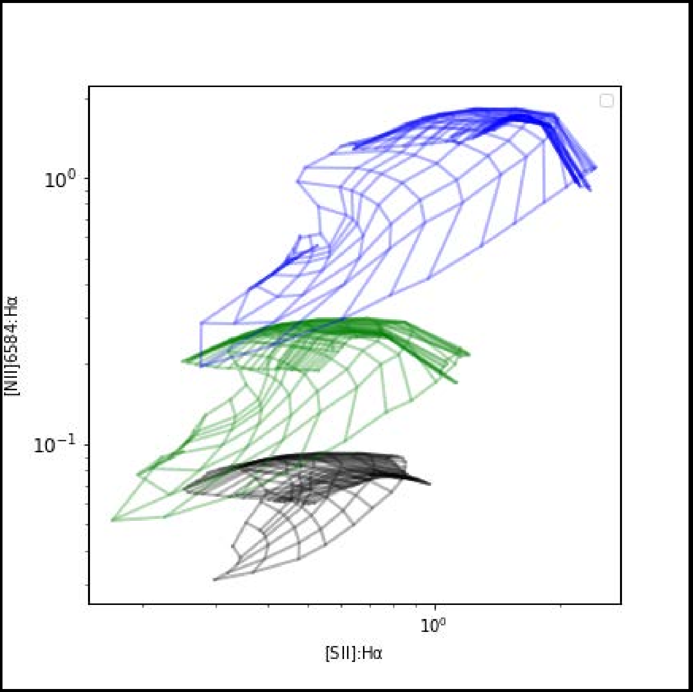




Long+19

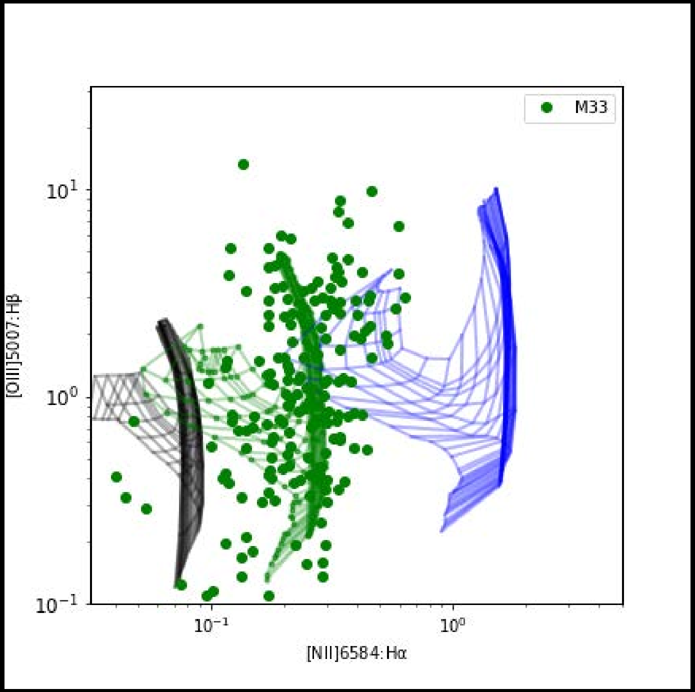
Shock models

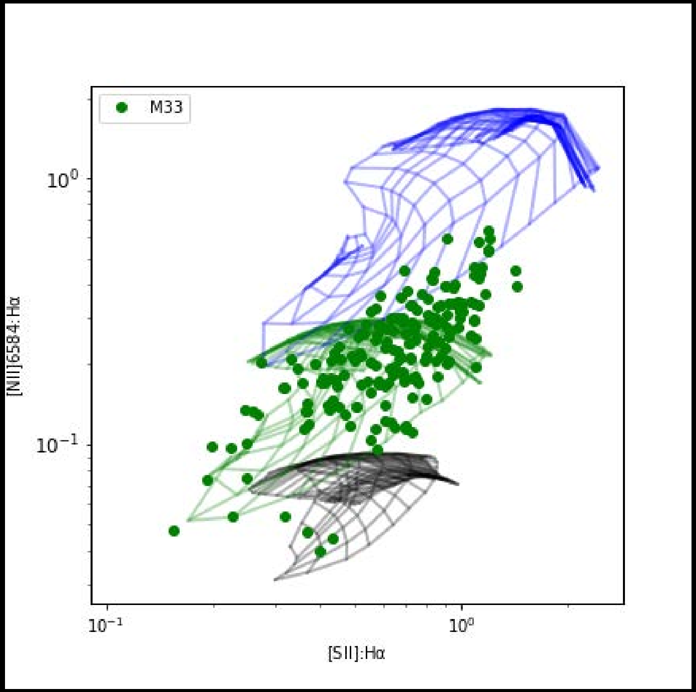




Mappings grid (no precursor) 100-1000 km s, various values of n for fixed B- Allen+08

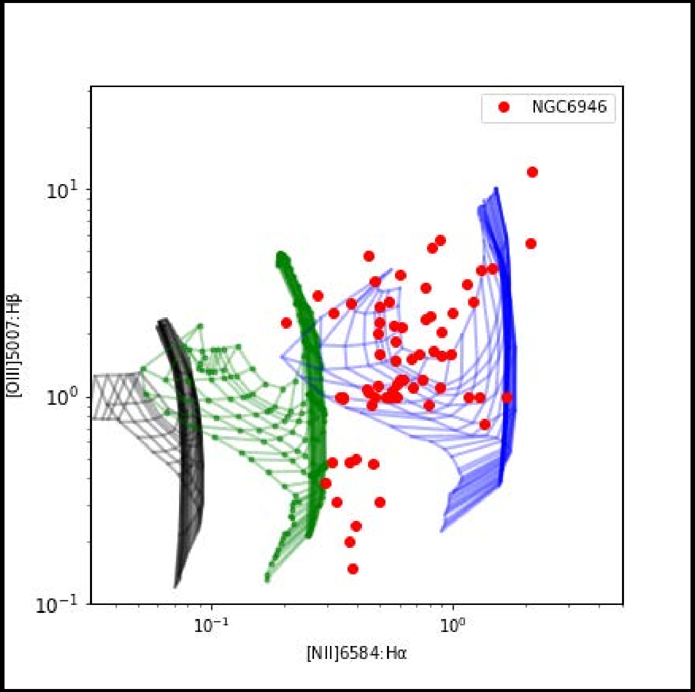
Model Comparisons – M33

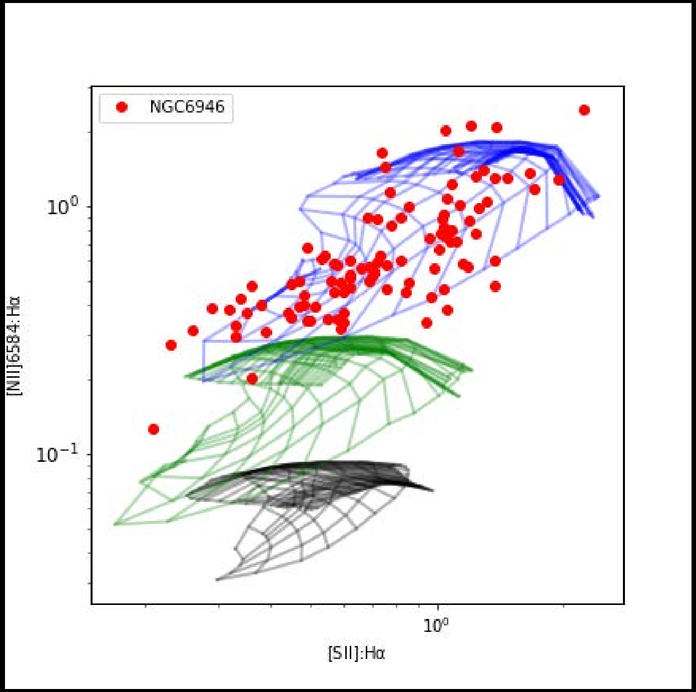




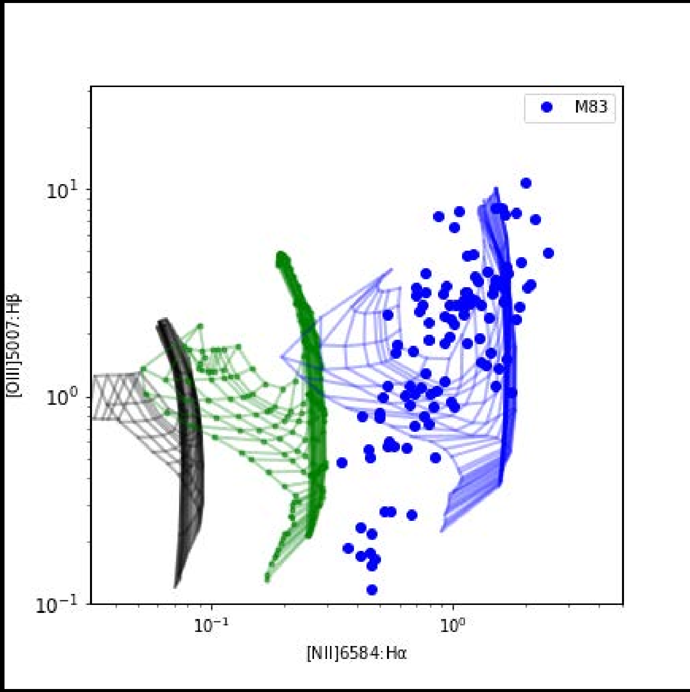
Long+18

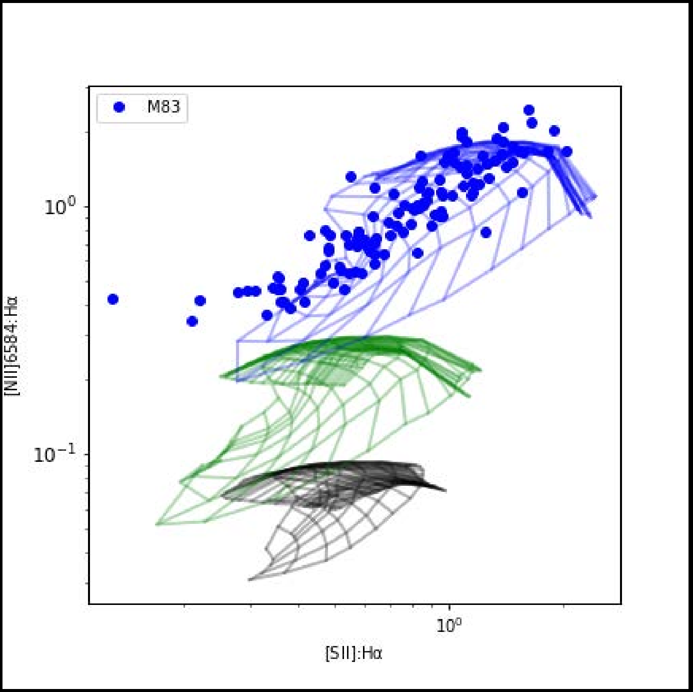
Model Comparisons – NGC6946





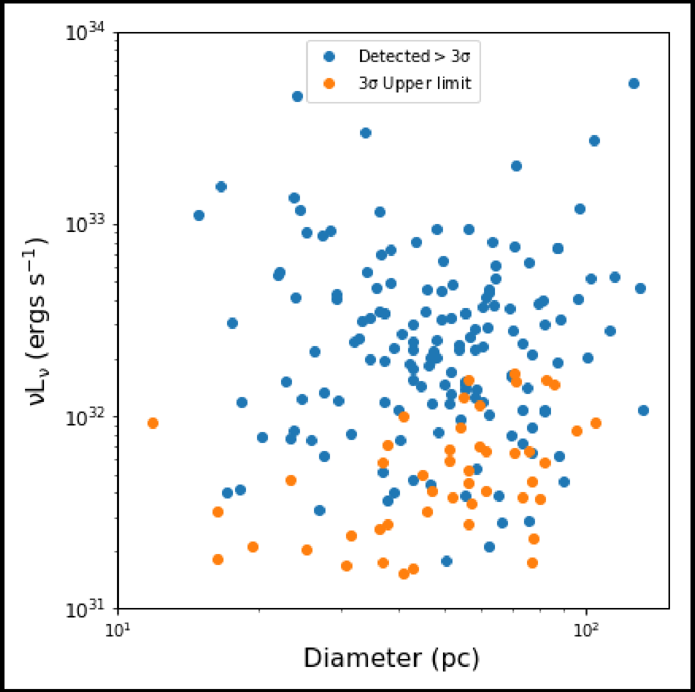
Model Comparisons – M83

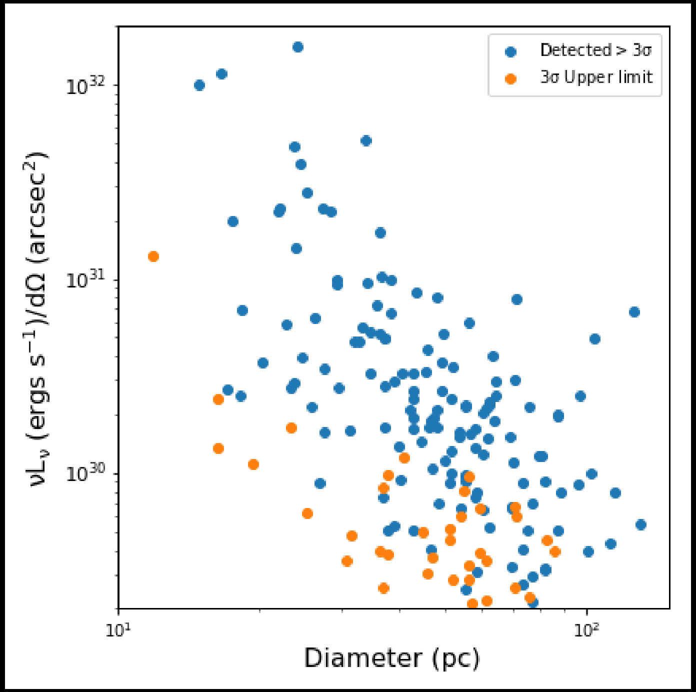




What do the radio detections indicate?

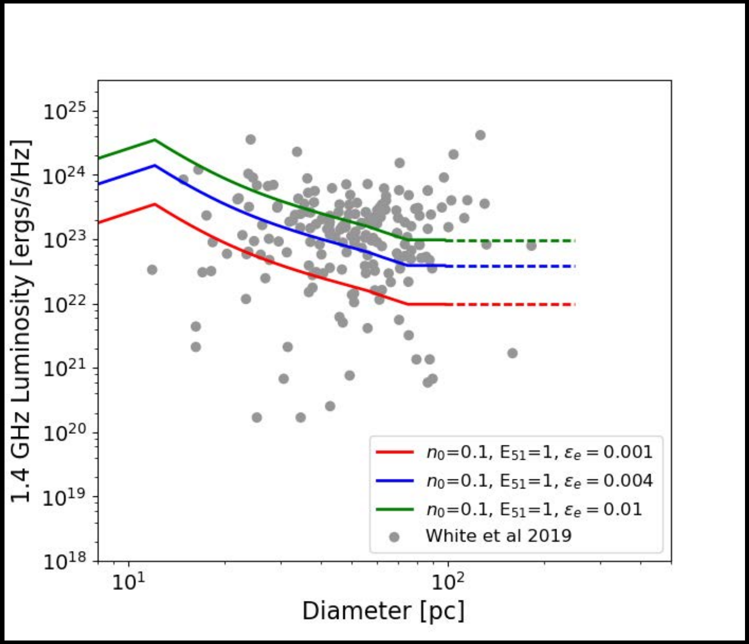
M33 radio – Luminosity and Σ – D

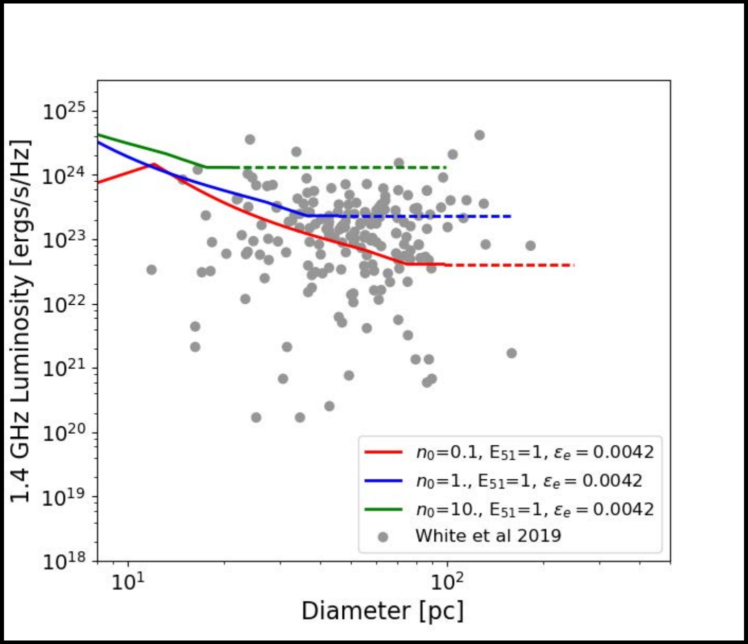




LMC and M83 similar, but ask me later

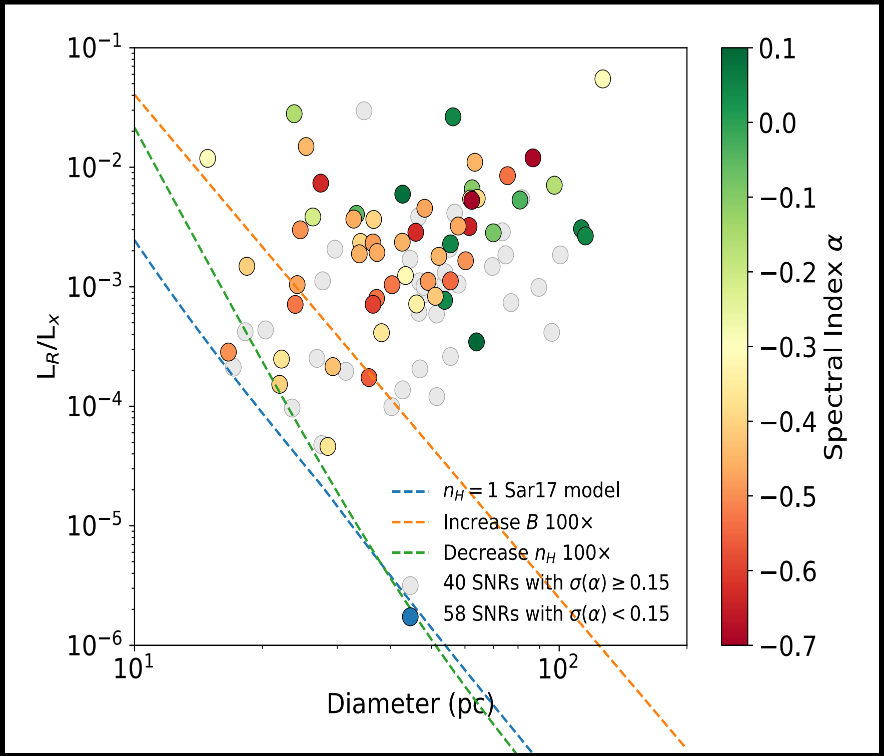
M33 radio - luminosity





M33 with L_R models of Sarbardhicary+17 (updated)

M33 radio – L_r:L_x



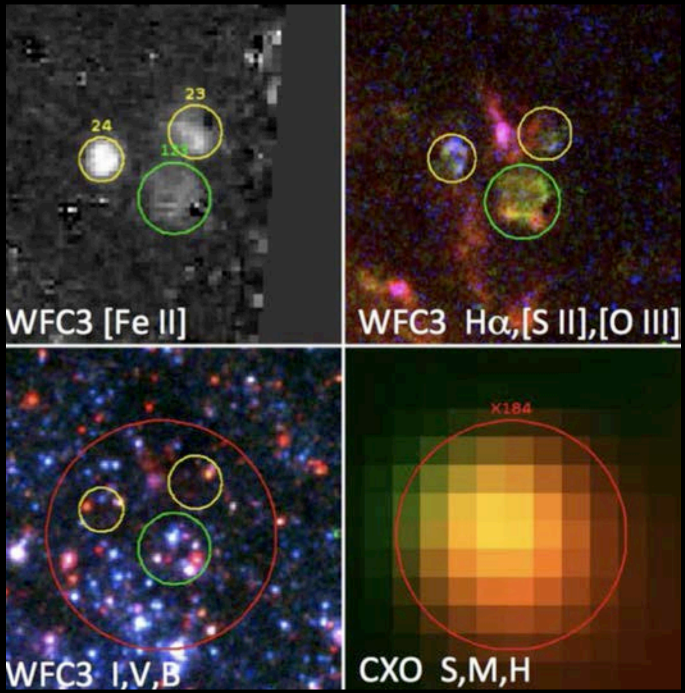
- With X-ray emission, ne can be estimated crudely but directly for a SNR in the Sedov phase, given the E_o and D.
- In the context of the S17 models, one predicts a steep decline in L_r:L_x

This needs to be sorted out, but demonstrates importance of a multiwavelength comparison

Expanding the Sample

New techniques/Additional tests – [Fe II]

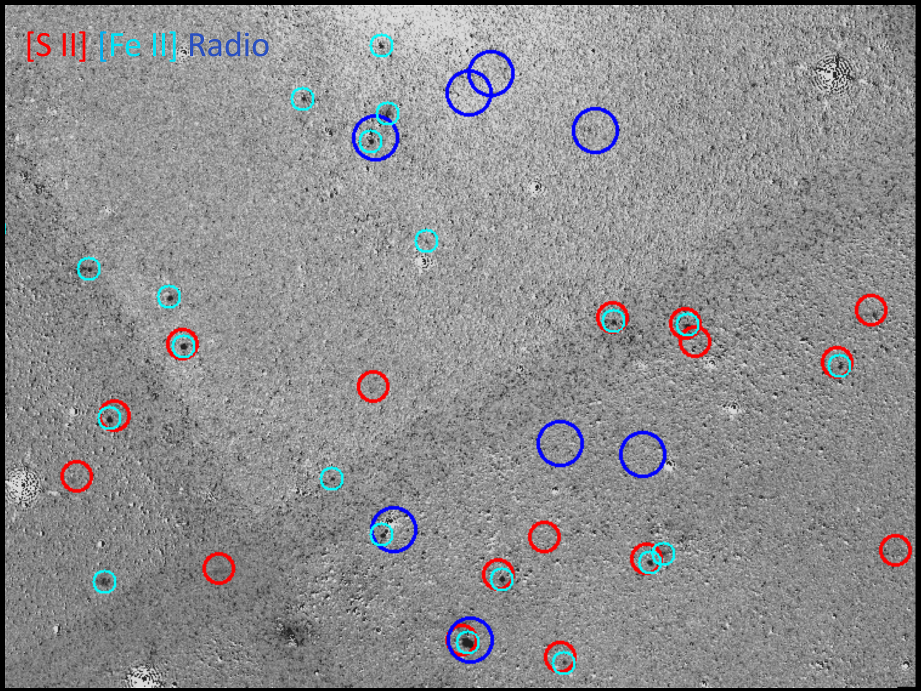
- With improvements in IR detectors it is also possible to observe lines from SNRs in the IR, which makes absorption less of a problem
- Shock models predict [Fe II]:Paβ ratios greater than 1 whereas HII regions have very low ratios
- Fe II is less affected by dust than [S II]
- [Fe II] lines at 1.28 and 1.65μ which allow measurements of the reddening
- Considerable work is being done on Galactic SNRs from the ground, e.g Lee+19, who detected 25% of the known SNRs in the first quadrant of the Galaxy with UKIRT
- With HST, with a far lower thermal background, we have found that many of the SNRs in M83 have [Fe II] emission
    - 88 known SNRs detected along with 26 [Fe II] only objects



M83 – Blair+14

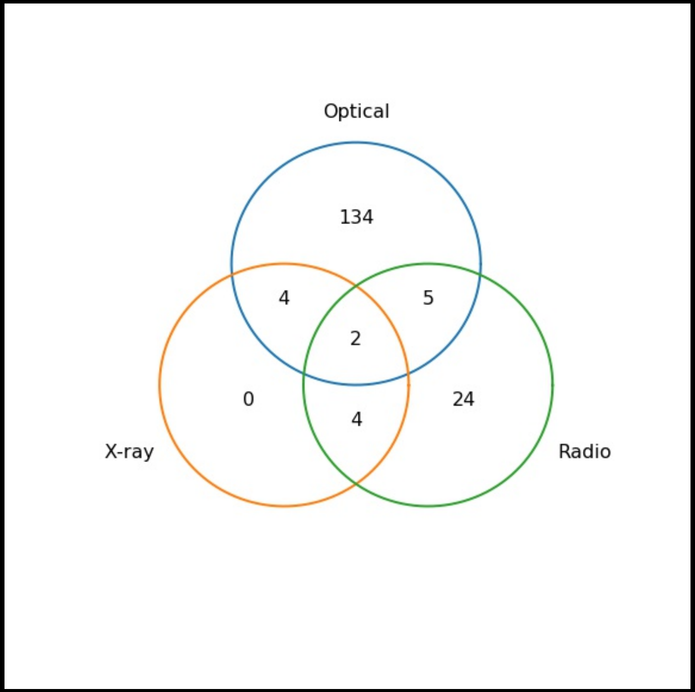
[Fe II] – NGC6946

- HST [Fe II] imagery of NGC6946
- Goal
  - Explore the relationship between [Fe II] and [S II] SNRs
  - Attempt to see whether Lacey & Duric's suggestion that radio SNRs were hidden in Hα was correct
- Results:
  - 106 [Fe II] nebulae in blind search

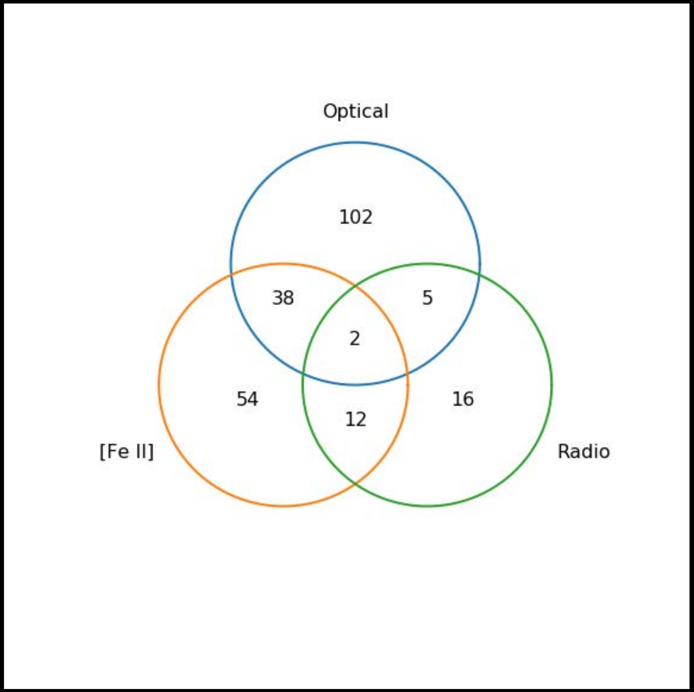


Continuum-subtracted [Fe II] image

With [Fe II], # of radio SNRs seen in two bands from 11/35 → 19/35)



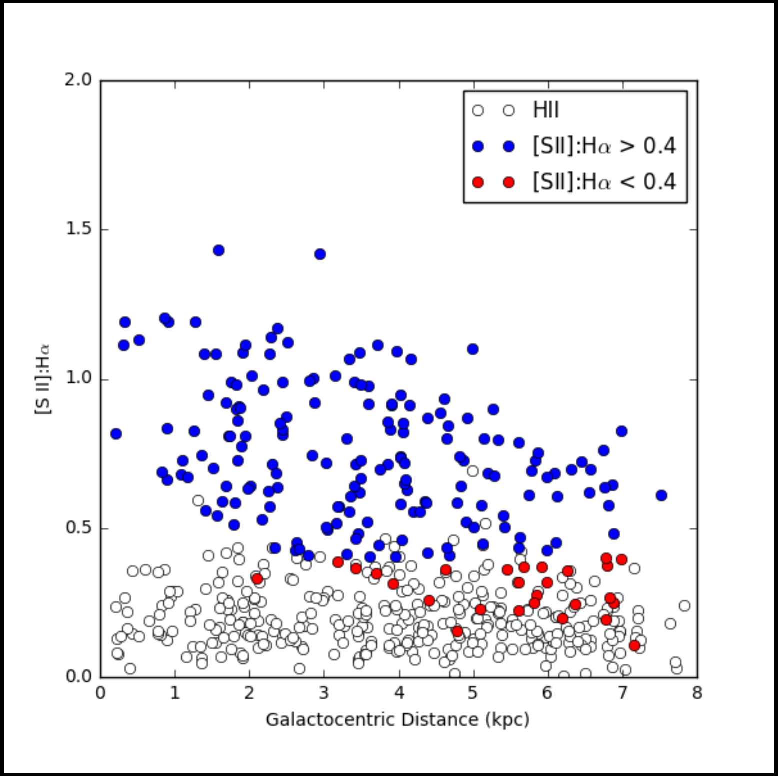
Before [Fe II]



After [Fe II]

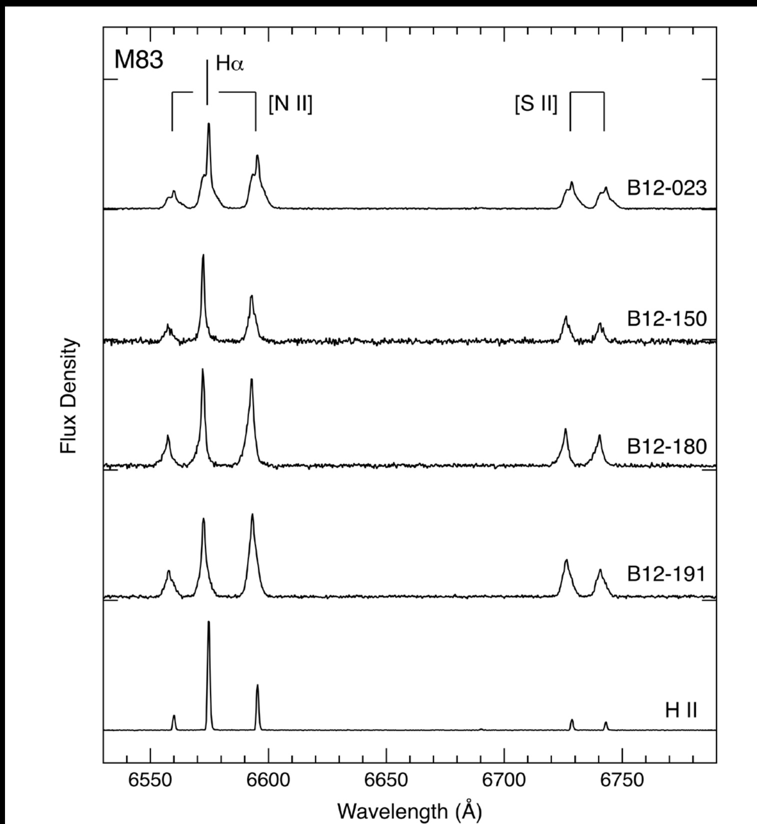
Purifying the Sample

- Radio issues (already discussed)
    - Spectral indices are hard to measure
    - Background galaxies are difficult to eliminate (unless SNRs are resolved)
- X-ray issues (already discussed)
    - Need a bigger telescope
    - Loss of soft sensitivity for Chandra hurts
- Optical issues
    - In early work, there was a clear separation of [S II]:Ha ratios between SNRs and HII regions because only the brightest objects were observed
    - Boundary far less clear now that much fainter objects can be observed
    - Long slit spectroscopy is used to subtract background, but is tricky, especially for Hα
- One way to "purify" a sample is to require detection in multiple wavelength bands, but ….



M33

Higher resolution spectroscopy



SOAR spectra of M83 – Points+I n prep

- Bulk motions
  - HII regions ~10 km s^{-1}
  - SNR >100 km s^{-1}
- To test this idea
  - In LMC, scanned spectra of about 10 SNRs and several HII regions
  - In M83, long-slit spectra of 4 SNRs and several HII regions

Completeness is an illusion

- “SNRs provide an instantaneous snapshot of where SNe explode in a galaxy”
- If that statement were true, or even it were mostly true in some limited diameter/age range ,then we could use the SNR to estimate the SN rate in individual galaxies
  - NGC6946 has had 10 SNe in 100 years, so there should be 1000 SNRs younger than 10,000 years old. We currently have 153
  - Of those 10 SNe in NGC6946, we have two
- Of the 5 SNe, we know about in the Galaxy, SN1006, the Crab Nebulae Tycho, Kepler and Cas A, we should have detected Cas A and possibly the Crab, but are unlikely to have found Kepler any of the others
- There are many problems
  - Detecting SNRs optically in the presence of Hα emission is problematic
  - Not a single Balmer dominated SNR outside the LMC has been detected Ia SNRs are likely underrepresented, however see the poster by C D.J. Lin (S1.12)
  - Small diameter objects have to be picked out from stellar vermin
  - The 2nd SNR in a cluster is expected to be faint.
- Much more systematic studies of missed SNRs are really needed

Conclusions

- Since the first extragalactic SNRs were discovered in the Magellanic Cloud, we have identified more than 1500 SNRs in nearby galaxies, many more than in the galaxy
- The SNR sample are not complete (or likely even nearly) complete to a certain diameter or age in any galaxy (possibly excluding the LMC).
  - Deeper/different types of observations are needed
- Ejecta dominated objects are rare
- The SNRs that we find are heavily weighted towards middle-aged ISM – dominated SNRs because the [S II]:Ha method favors their discovery
- Various trends in line ratios from galaxy to galaxy and within galaxies are apparent.
  - Density – diameter
  - Reddening – Galactocentric Radius
  - Abundance – Galactocentric Radius
- However the properties of SNRs are very heterogenous for reasons that are associated with environment (which we are not been able to disentangle quantitatively)

Suggestions

- Rather than finding samples in new galaxies, a better course of action is to hammer on the galaxies where we already have good samples
  - Examples of the types of observations that are needed include [Fe II] and higher spectral resolution in the optical
  - Repeating some of the previous studies would be sensible
- LMC (and SMC) has good coverage in X-rays, but would benefit from a very systematic/uniform determination of optical fluxes and line-ratios and new radio data taken in a highly systematic manner
- Deep radio observations with the JVLA and ATCA of SNRs are needed (as are radio astronomers who can turn observations into results)
  - Careful attention needs to be paid to getting accurate spectral indices and separating SNR emission from HII region emission
  - Higher angular resolution observations are required to separate background galaxies from Crab like SNRs in M33, M31 and elsewhere, e.g. work on M31 described by Sarbadhicary (S7.9)