# SNRs in the Magellanic Clouds

## Are there ANY surprises?

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Parker, Q. A., Reid, W. A., Dickel, J., Williams, R., Ehle, M., Gruendl, R., Chu, Y.-H., Points, S., Brantseg, T.,
McEntaffer, R. L., Pietsch, W. Payne, J. L., Smith, R. C., Ballet, R., Buckley, D., Cajko, K., Lakicevic, M. , Warth, G.

*Background image uses data from the MCELS (Smith et al. 2005)

SNRs, Beograd 2016

# ABSTRACT

SNe, their remnants (SNRs), together with progenitors and local environment in which they evolve are still one of the most puzzling questions in modern astrophysics.

What kind of particles we can detect right now and what is the future of SNR Physics with the next generation of telescopes (read CTA, eRosita & SKA)?

Our preliminary results shows an extraordinary discovery that some young (Type Ia) SNRs are expanding twice faster then the theoretical predictions. This could directly confronts and challenge our understanding about the accelerated expansion of Universe?

From high energies to long radio waves ? SNRs are continue to surprise us!

# The CRAB Nebula and the first "cover-up" in the history of science

24th June 1054 and the East-West Schism

For many days Venus and SN 1054 occupied symmetric positions with respect to the Sun

**The coinage of Costantino Monomaco**

(Solidus Aureus) Minted from 1042 to 1055 for 4596 days.

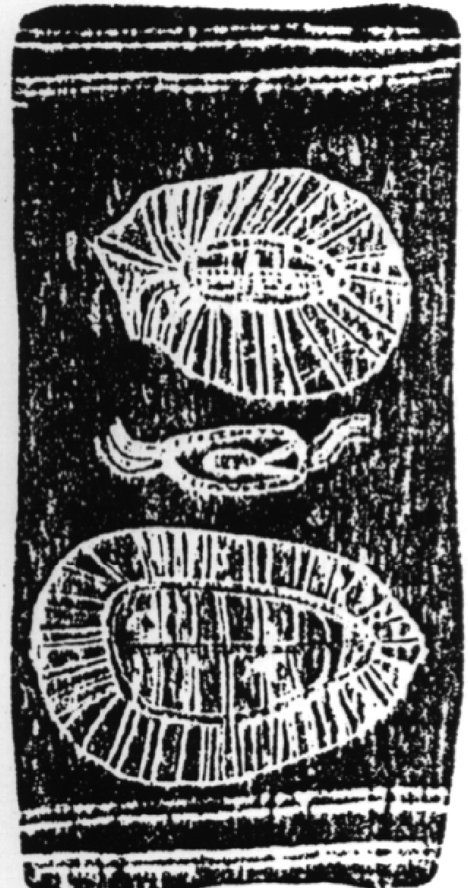
Two varieties:

Out of the 4000 known coins, in 20 the emperor's face is sided by two symmetric stars

$4000:4596 = 20:x \rightarrow x = 23$ days!!!

*Fig. 1.*

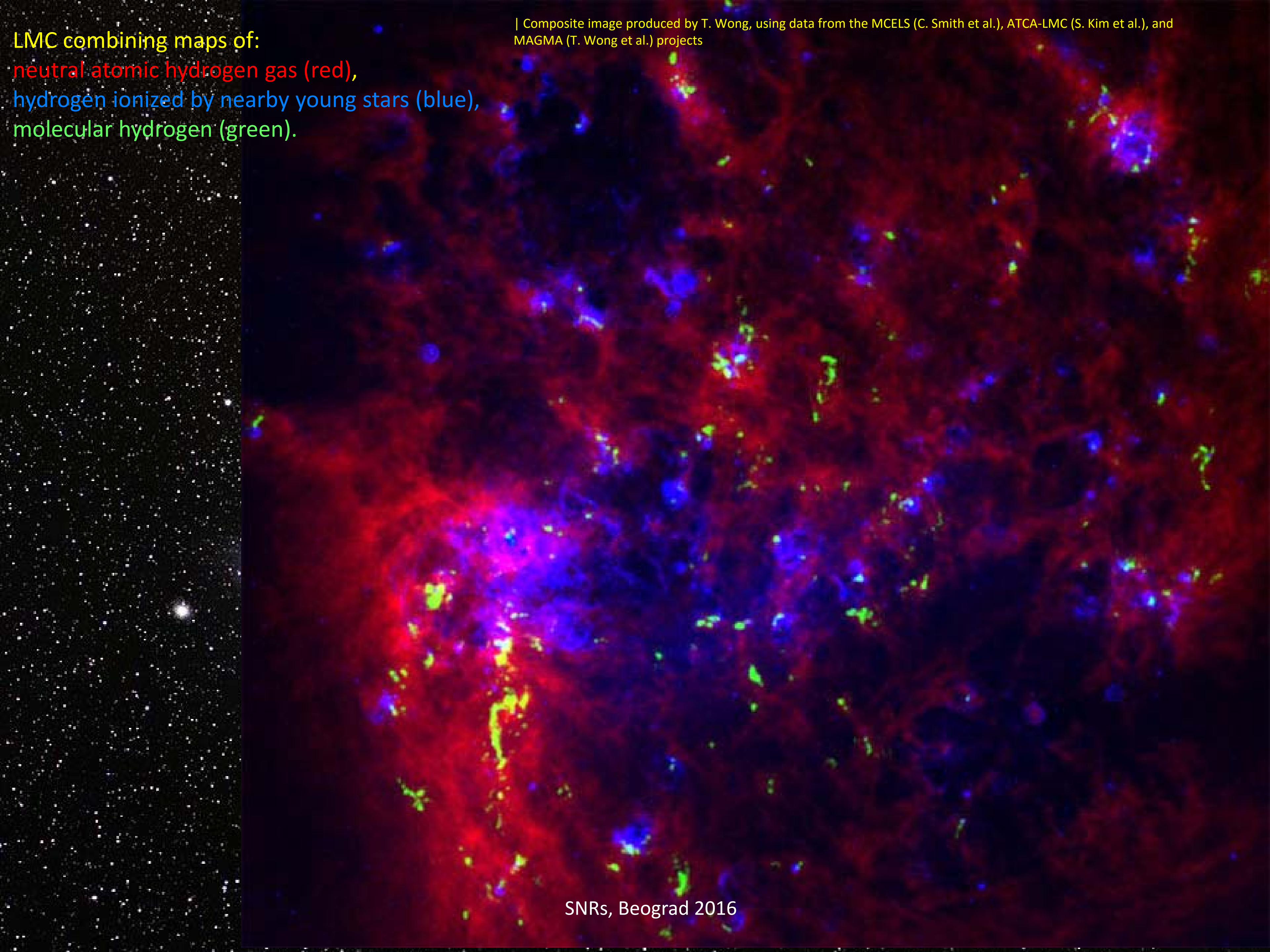
Haynes+1992



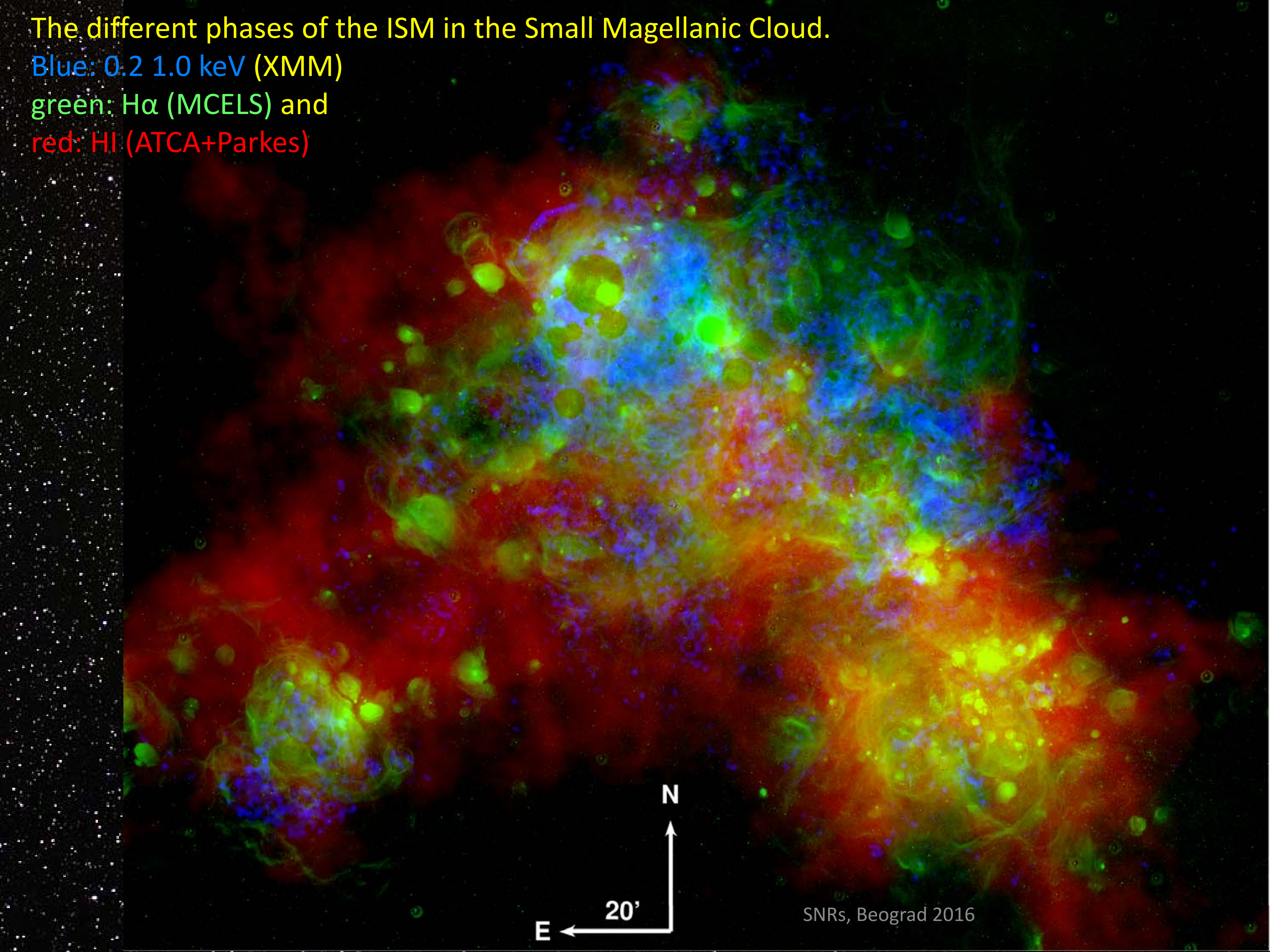
*In this bark painting, the lower oval represents the Large Magellanic Cloud, the camp of the Jukara man, while the upper is the Small Magellanic Cloud, the camp of the Jukara woman. Between the two camps lies the cooking fire (probably the star Achernar with a ring of surrounding stars) with burning logs and the emblems of smoke leaving the fire.*

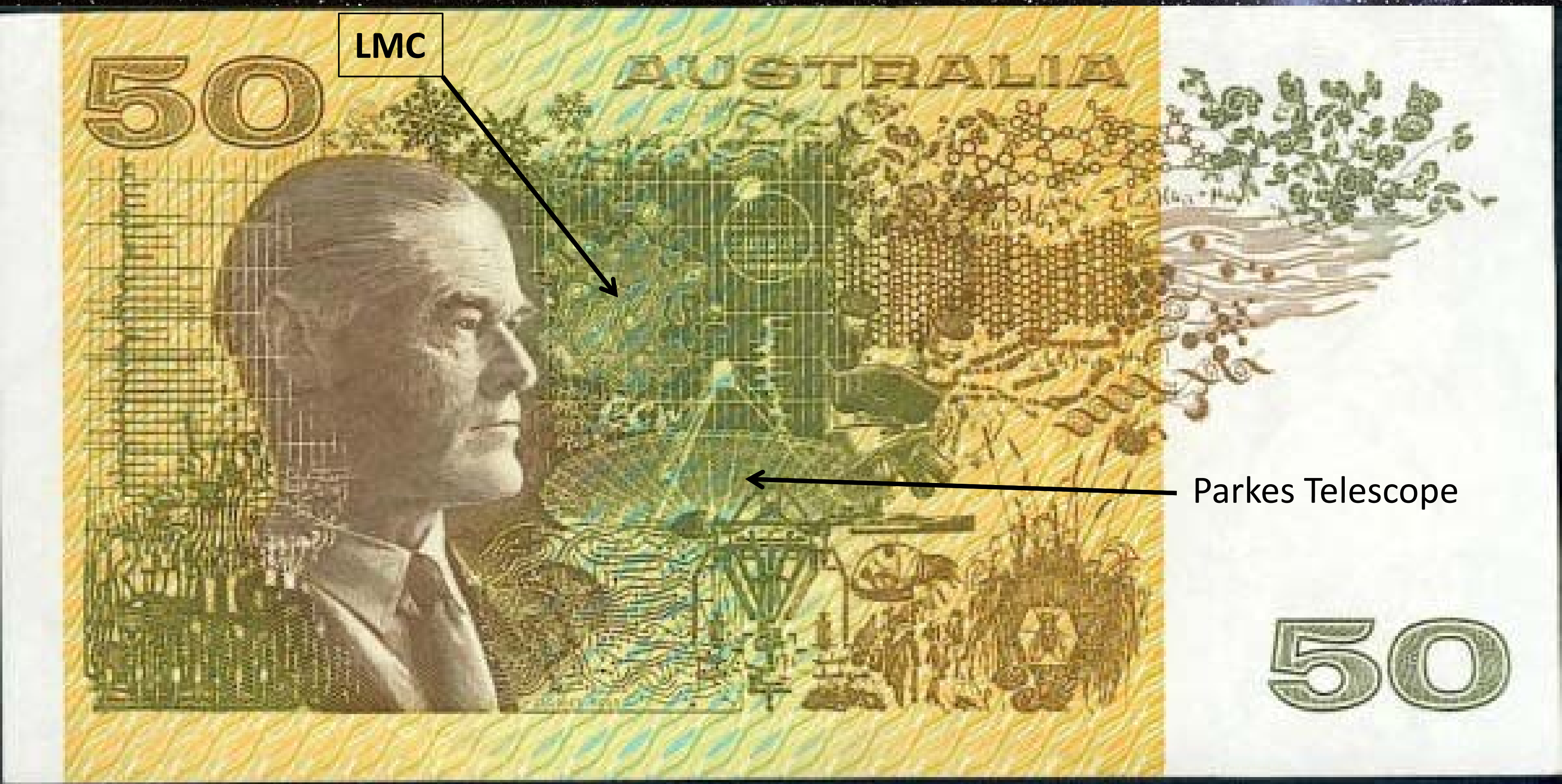
LMC combining maps of:
neutral atomic hydrogen gas (red),
hydrogen ionized by nearby young stars (blue),
molecular hydrogen (green).

| Composite image produced by T. Wong, using data from the MCELS (C. Smith et al.), ATCA-LMC (S. Kim et al.), and MAGMA (T. Wong et al.) projects



The different phases of the ISM in the Small Magellanic Cloud.
Blue: 0.2 1.0 keV (XMM)
green: Hα (MCELS) and
red: HI (ATCA+Parkes)




LMC
50
AUSTRALIA
Parkes Telescope
50


AL 08519999
50
Australia
AL 08519999

# Our business started in 1964





telescope at Mt. Stromlo. There is no central exciting star and it has a looped filamentary appearance characteristic of some remnants of galactic supernovae. It is therefore suggested that N49 is a supernova remnant and it is the first extragalactic "radio" supernova to be discovered. Cassiopeia A, the well-known galactic supernova, which has a similar spectral index to N49, would be five times more intense if placed at the same distance as N49 (55 kpc).

# My Brief Extragalactic SNRs history

- 60-ties … Fesen+ Dopita+ optical work…
- M31 Dickel 1968 and 70-ties
- LHG 1981 (soft X-rays from the LMC)
- 1987A
- Chu&Kennicutt 1988 – MCs SNR environments
- Dickel+ 1993+ Mag Fields of MCs SNRs
- Prompt type Ia (Borkowski+ 2006)
- Chomiuk&Wilcots 2009 – 43 SNRs in “distant” galaxies
- Long+ 2010 on M33
- Other nearby Galaxies SNRs - Leonidaki+ 2013
- Expansion of MCSNR 0509-675 (Hovey+15, Roper+16)

# TYPE CLASSIFICATION OF MAGELLANIC CLOUD SNRS

## CORE COLLAPSE:

- PRESENCE OF A PULSAR OR OTHER COMPACT REMAINS IN A REGION OF YOUNG STARS
- OXYGEN RICH

## TYPE Ia:

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- BALMER DOMINATED IN OPTICAL

# SNR IDENTIFICATION

- EXTENDED GENERALLY SHELL -LIKE OBJECT - ~0.3 PC FOR 1987A TO 158 PC FOR DEM L203

  (1 PC IS 4 ARCSEC AT THE LMC AND 3.4 ARCSEC AT THE SMC)
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  WHERE $S_f$ = const $f^{⟨}$
- THERMAL X-RAYS - TYPICAL TEMP ~ 1 keV WITH A LARGE SPREAD
- CAVEAT - PULSAR WIND NEBULAE HAVE FLATTER RADIO SPECTRA AND NON-THERMAL HIGH ENERGY X-RAY TAILS
- [S II]/ H⟨ > 0.4

# Magellanic Clouds

- Why MCs?
- Key Science questions
- What kind of objects we can observe?

HESS.CTA.CHANDRA.X

MMNewton.eRosita.

Herschel.FUSE.OPTICAL.

IRAS.Spitzer.Nanten2.

MOPRA.ATCA.Parkes.

ASKAP.MWA.SKA…

# Why LMC is so “sexy”?

- 30 Doradus -- The largest star-forming region of the LG
- SN 1987A – Closest naked-eye supernova since Kepler in 1604
- About 60 well-established and 20 good SNR candidates
- R 136 -- One of the densest stellar clusters ever known
- The most massive stars ever observed
- Hundreds of HII regions
- More than a dozen superbubbles
- ~20 supershells and a hundred giant shells
- Two most powerful pulsars known, with PWN (N157B and 0540)

# Some Key Science questions!

- What are the processes and sites in which the bulk of CRs are accelerated ?
- How do CRs propagate away from their sources and interact with the interstellar medium ?
- What is the nature of dark matter ?
- **Type Ia…**

# LMC & SMC in HE

- Cosmic Ray origin: SNRs & Superbubbles
- Cosmic Ray propagation
- Nature of dark matter
- Other Benefits

# MCs in (v)HE: Nature of Dark Matter

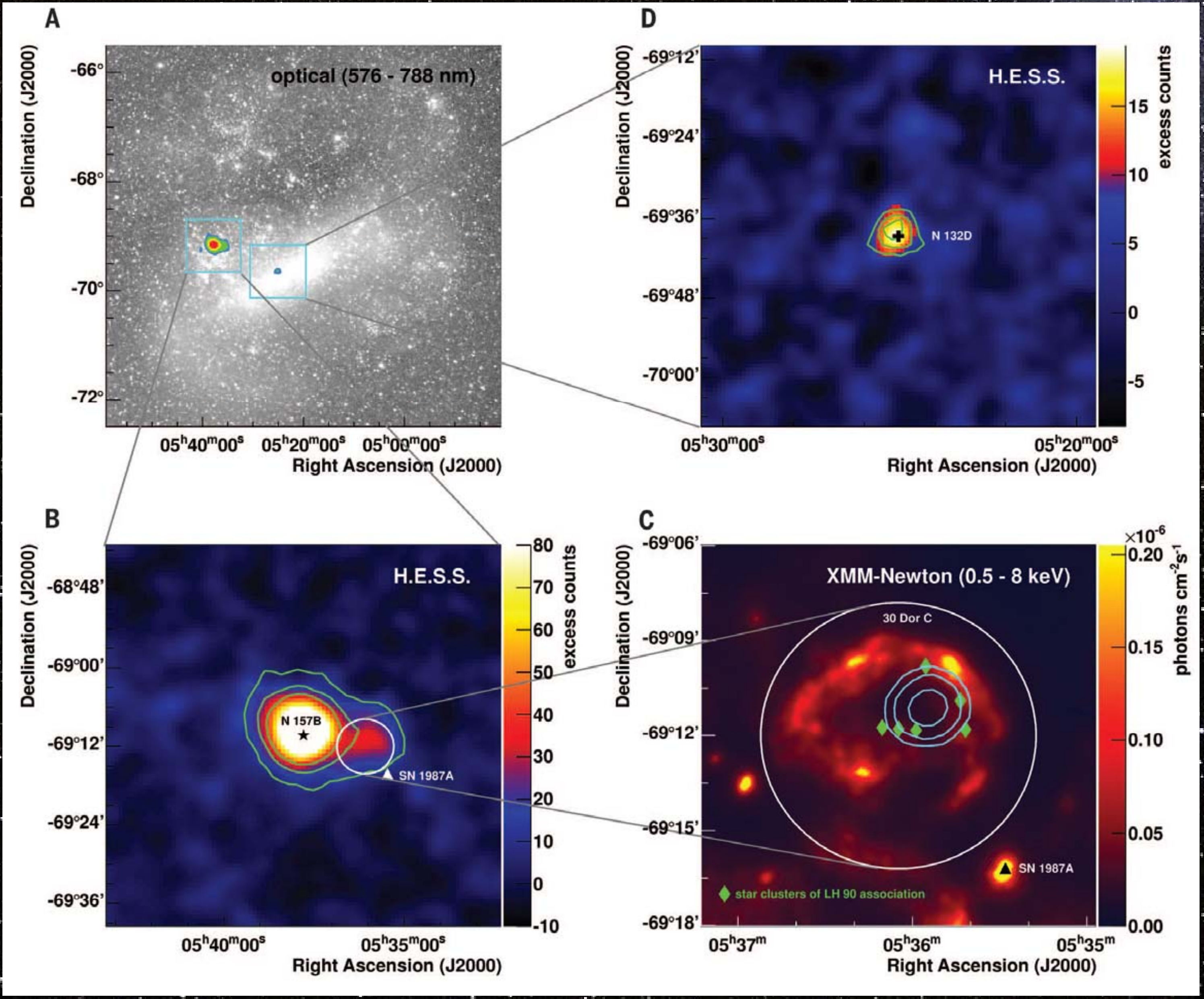
- The MCs is an extremely promising target for a search for gamma rays from DM annihilation.
- The expected DM flux depends on the particle properties of DM and the DM distribution.
- The most favorable targets of DM searches are nearby and have large concentrations of dark matter (“J-factor”).
- Targets with larger J-factors produce larger DM signals.
- The J-factor of the Galactic Center can be as large as $\log_{10}(\mathbf{J}) \sim 23$.
- The J-factor of the LMC may be as high as $\log_{10}(\mathbf{J}) \sim 20.7$.
- Dwarf galaxies of the Milky Way, which have been considered extensively in dark matter searches because of their known locations, high dark matter densities, and low backgrounds, typically have much smaller J-factors of $\log_{10}(\mathbf{J}) \sim 18 - 19$.
- This simple comparison suggests that the LMC could yield strong sensitivity to DM signals from the LMC, and also complements the dark matter search that will be performed in the Galactic Center and in dark matter clumps by providing a different target with different uncertainties and systematics in the analysis.

# MCs in (v)HE: Other Benefits

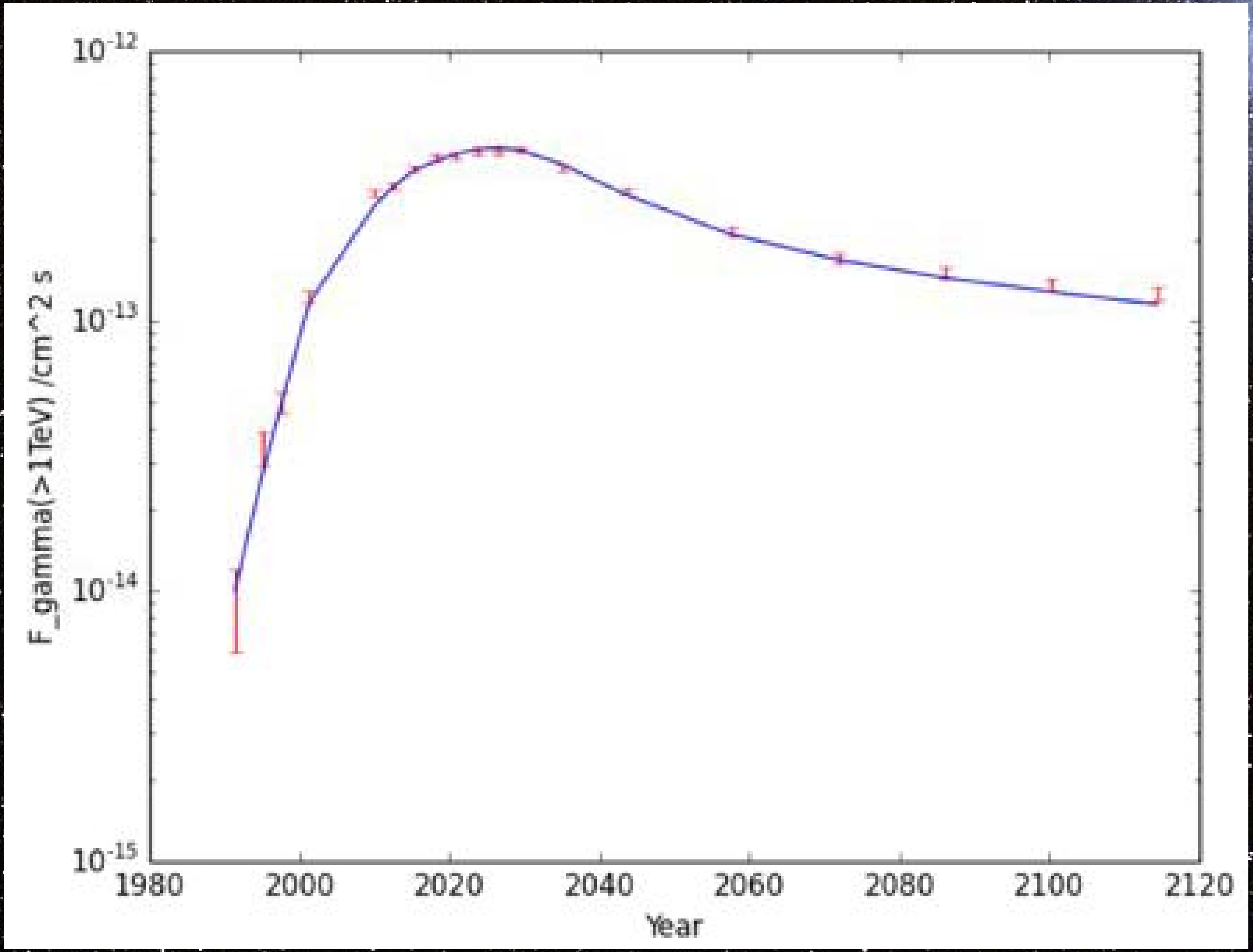
- 1-2 Gamma-Ray Binaries
- AGNs (PKS 0601-70)…
- ?

# H.E.S.S. LMC

Abramowski et al 15

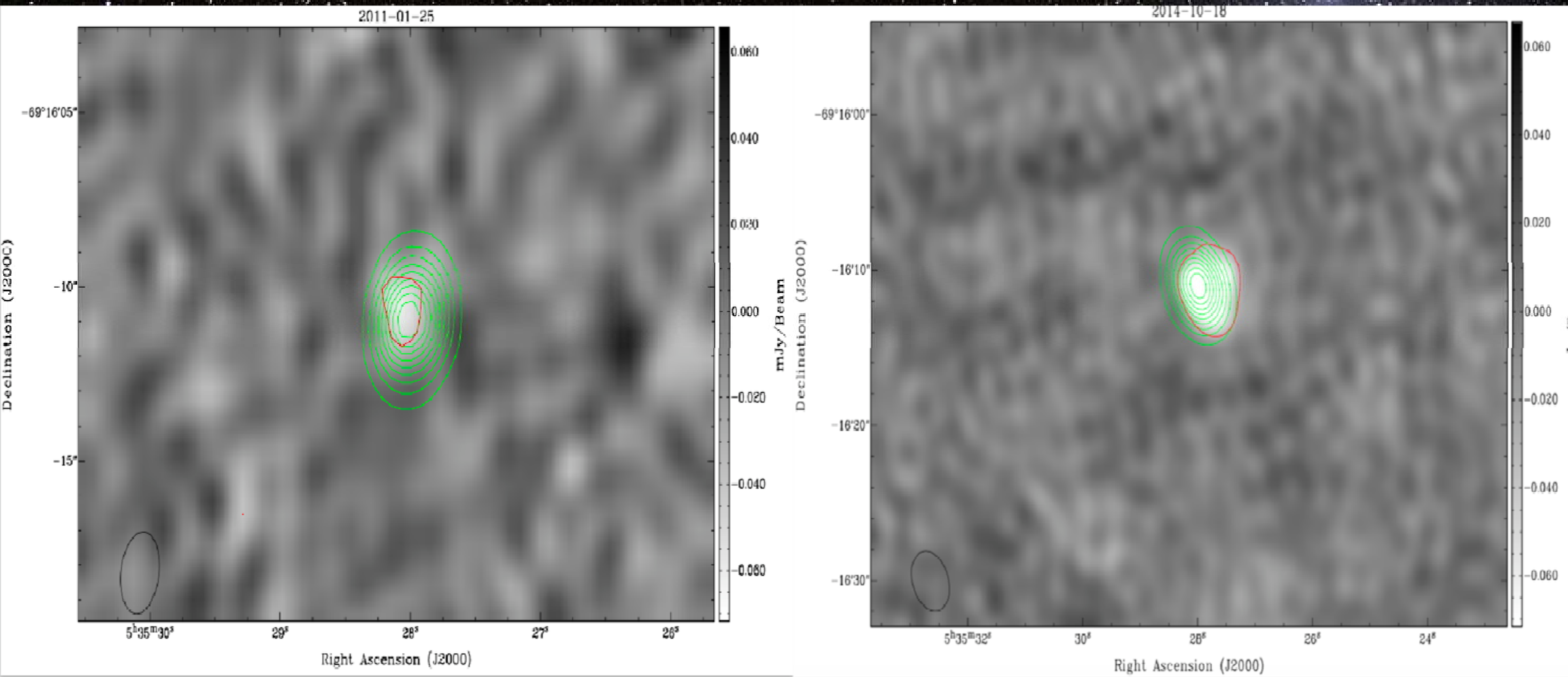


# CTA LMC SN 1987A



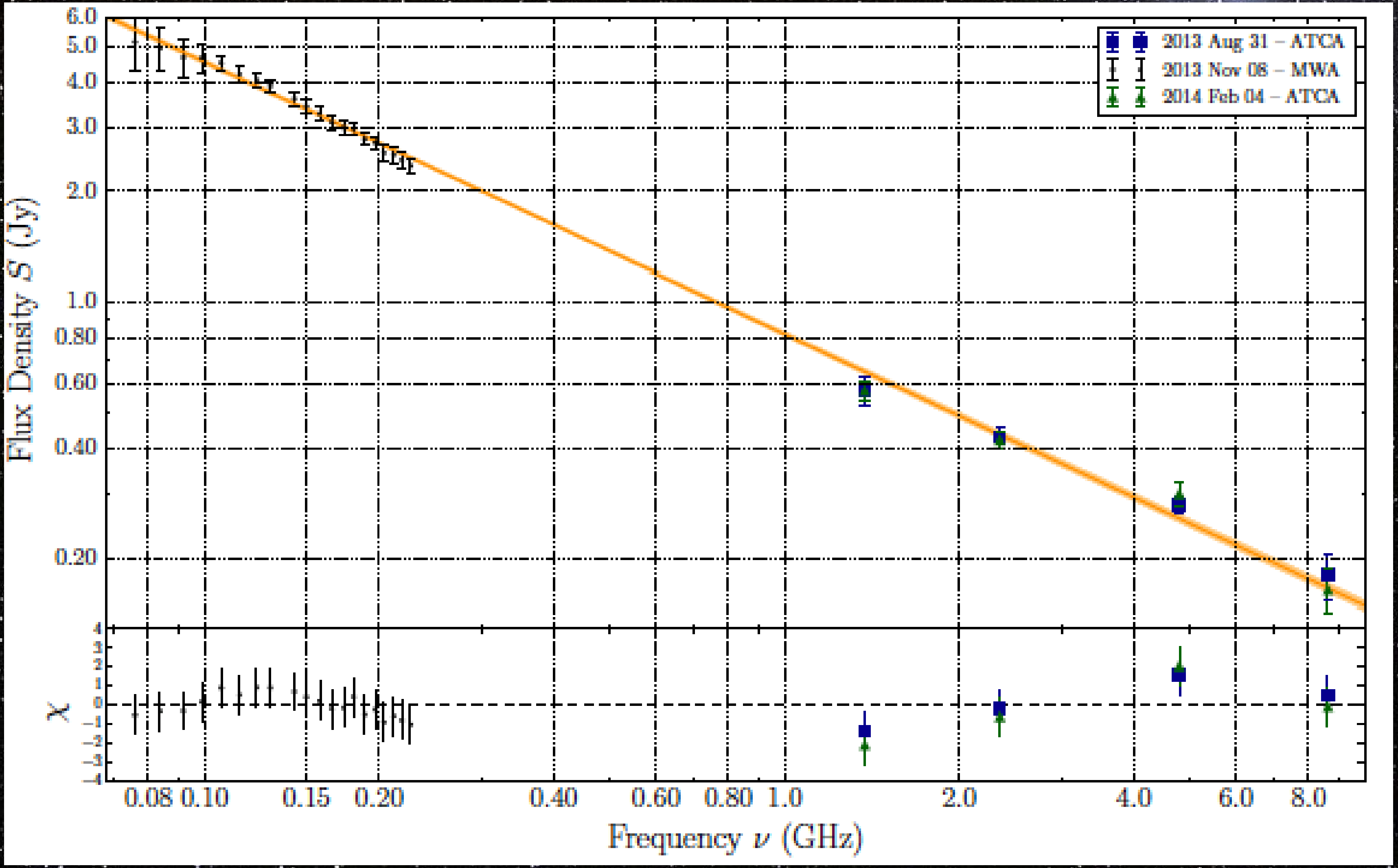

Predicted gamma-ray light curve for SN1987A (blue, from E.G. Berezhko, priv. com.) and anticipated detections with CTA for several 50h observations distributed over decades (red points).

# SN1987A Circular Polarisation Detection



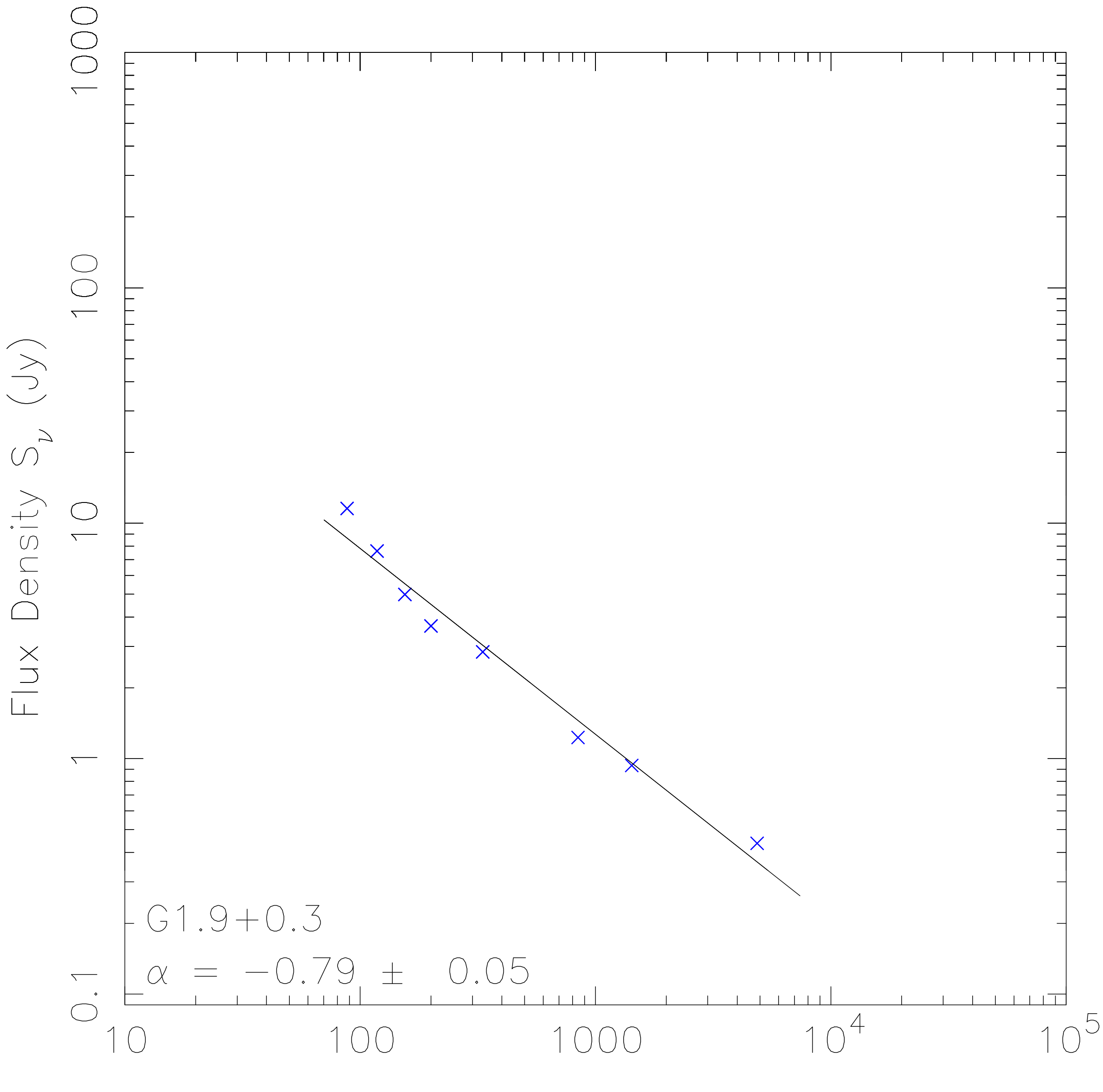

Two separate observations imaged (Stokes-V vs. Stokes-I).
Contours: Stokes-I SN1987A (*Green*), Stokes-V 3σ *r.m.s.* (*Red*)

# 1987A radio spectral index α=-0.74



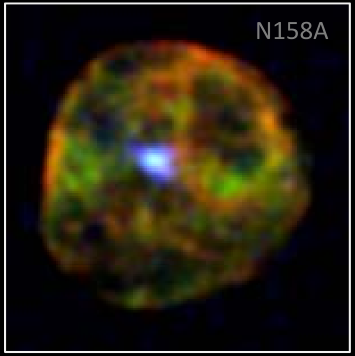



Callingham+ 16

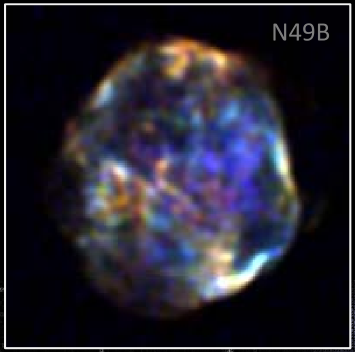


1000
100
10
1
0.1
Flux Density $S_\nu$ (Jy)
G1.9+0.3
$\alpha$ = −0.79 ± 0.05
10
100
1000
$10^4$
$10^5$
Frequency $\nu$ (MHz)


# G1.9+0.3




- Result of supernova explosion
  - Core Collapse
  - Thermonuclear (type Ia – SD, DD (prompt) or Iax)




- Important source of nucleosynthesis products and energy in the ISM
- Trigger star formation
- Provide details of explosion mechanism
- Used as standard candles in cosmology


*Data from *Chandra* SNR catalog

- Magellanic Clouds
  - Ideal Laboratory
  - Nearby ~50-60 kpc

# Supernova

- Massive explosion at the end of a stars lifetime that releases ~$10^{51}$ ergs of energy
- Can outshine entire galaxies (which may contain $10^{11}$ stars) for a brief period of time
- Important part of the chemical enrichment of the universe and one of the most important sources of energy in the ISM
- Occurs 1-2 times a century in a galaxy like the Milky Way

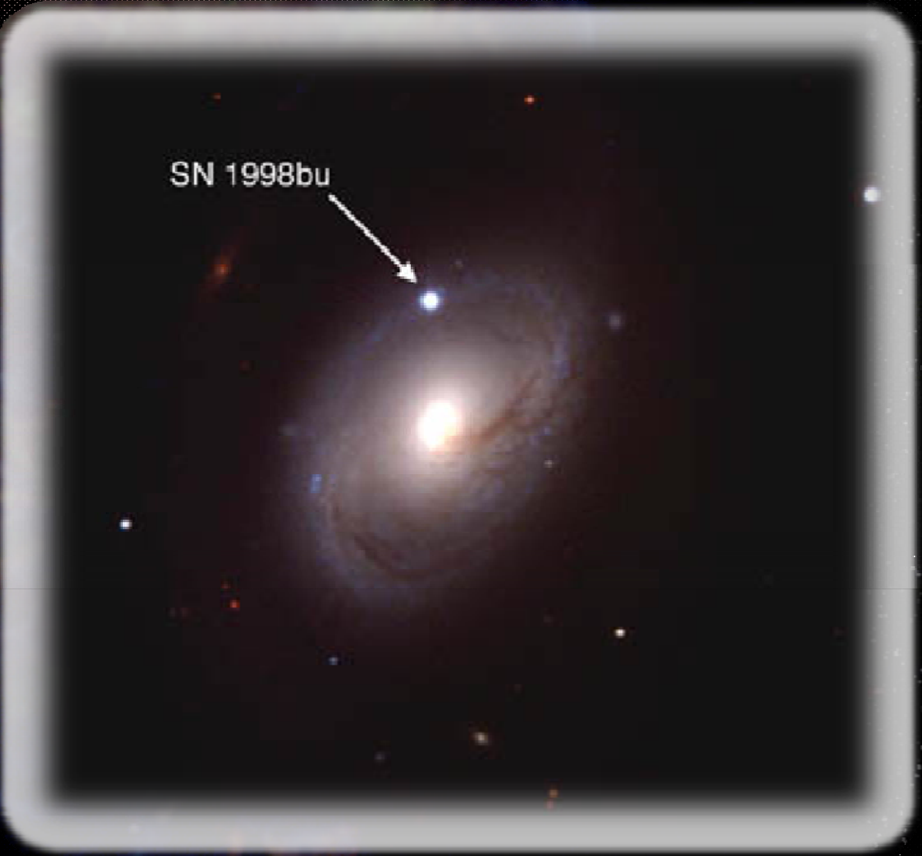



Image credit: N. Suntzeff

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# Supernova

## Thermonuclear detonation

- Thought to occur in small C/O white dwarfs in a binary system
- Detonate when they reach their critical mass known as the Chandrasekhar limit (~1.38 $M_{\odot}$)
- Single degenerate or double degenerate

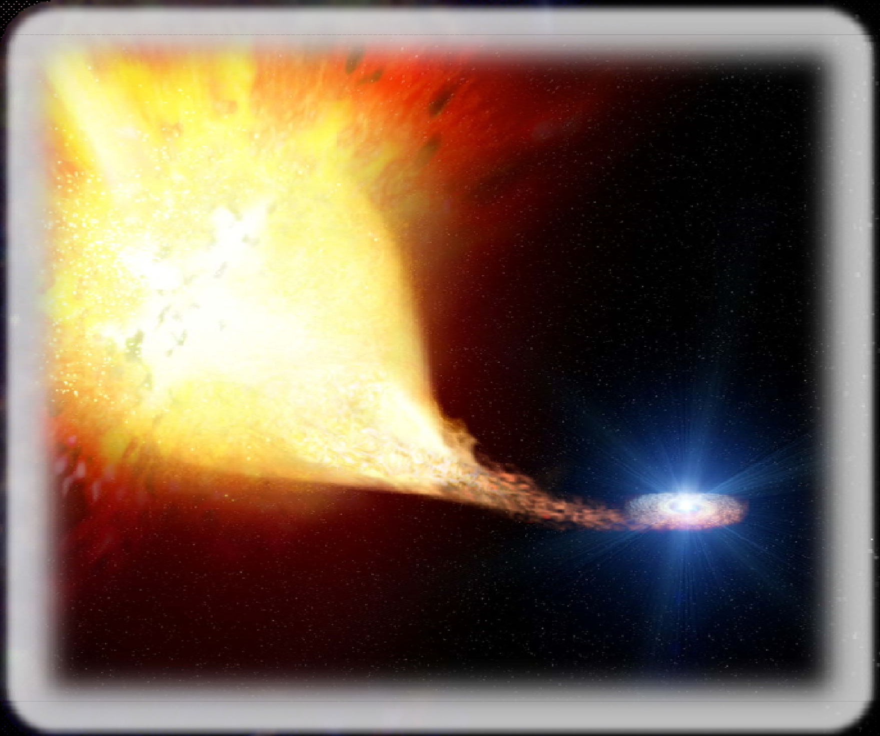

Image credit: NASA

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Credit: NASA/CXC/A.Hobart

# Type Ia SN progenitor have many questions

Type Ia SN

many questions

What is the nature of the progenitor?

-- Double Degenerate or Single Degenerate?

-- prompt or delay channel?

What are nucleosynthesis?

**What is progenitor metallicity?**

etc…

metallicity depends of luminosity

to know the environment when the progenitor was born

Chu+14, Badenes08 proposed a new method to measure progenitor metallicity from the Cr and Mn lines from SNR in X-ray spectra.

# So, how to find progenitor of Type Ia SN from its SNRs??

Search for the REMNANT STAR (RS)!!!

- If SD than Red (or some massive star) Giant should be there…
- If DD than no massive star?!

# Supernova

## Core collapse detonation

- Found in regions containing young, bright stars (e.g spiral arms) and therefore, from larger stars with a mass $M \geq 8\ M_{\odot}$
- Once the star exhausts its nuclear fuel and move from exothermic reactions to endothermic (iron) e.g they remove kinetic energy and therefore, fluid pressure
- With no gain of energy from the fusion of iron, gravity wins and the star collapses

Credit: NASA/CXC/A.Hobart

# Core objects

## Neutron stars and black holes

- A core that is ~1.4$M_\odot$ - 3$M_\odot$ will collapse to give a neutron star
- If earth is in the neutron stars axis, the neutron star will be observable as a pulsar
- Stars who go supernova with a core > 3$M_\odot$ will collapse even further to form a black hole

Image credit: Dana Berry/NASA

# X-ray

- Diffuse thermal emission

- *XMM-Newton*
- *Chandra*
- *ROSAT*

# Optical

- Optical line; enhanced [SII]/Hα
- High-velocity gas (> 100 $kms^{-1}$)

- *NOAO (MCELS)*
- *HST*
- *SALT*
- *MSSSO (WiFES)*

# Radio

- Non-thermal (synchrotron) radio emission

- *ATCA*
- *Parkes 64-m dish*
- *MOPRA*
- *Nanten2*

## IR (Spitzer, Herschel)

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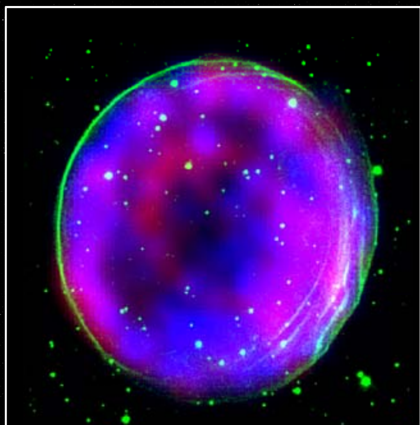
## LMC SNR 0509-67.5

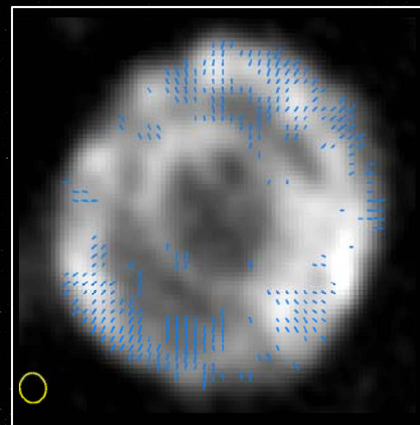
## Type Ia, ~400 yr

Bozzetto+ 2014, MNRAS

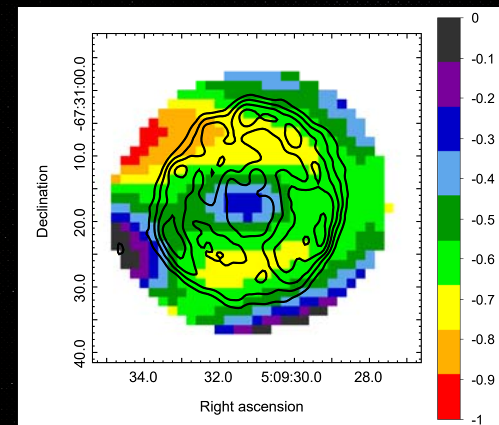
### Morphology



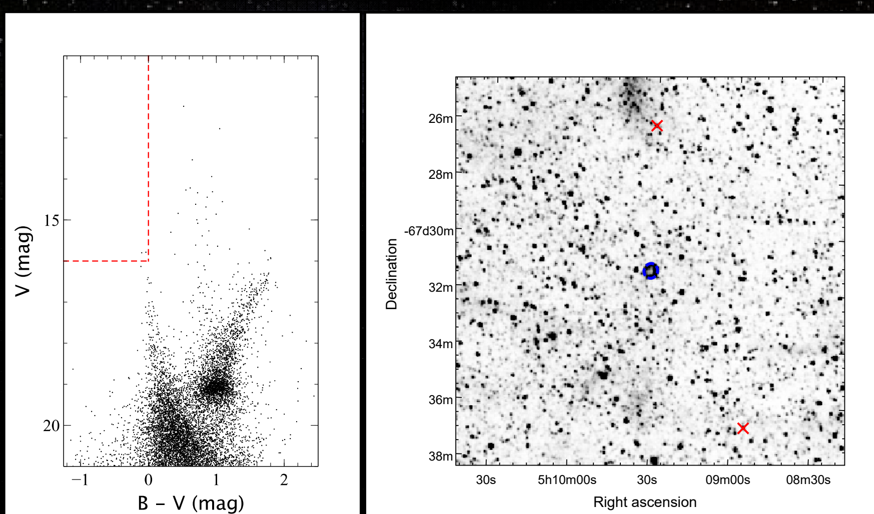
### Polarisation



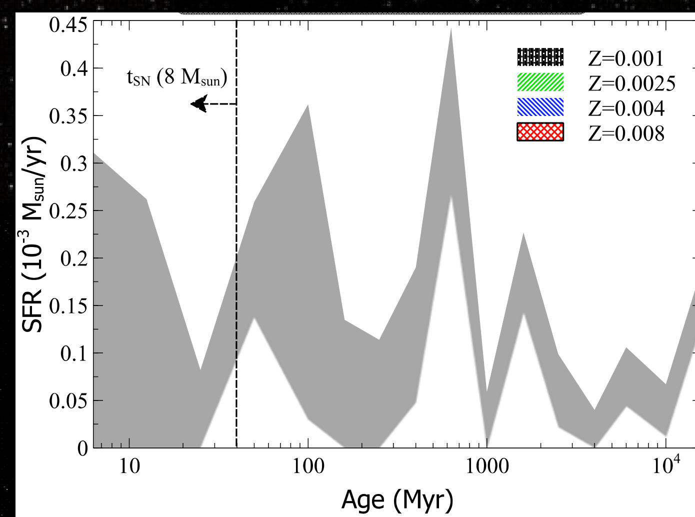
### Spatial spectral variations




### Stellar Environment




### Star Formation History



# LMC SNR J0509-6731

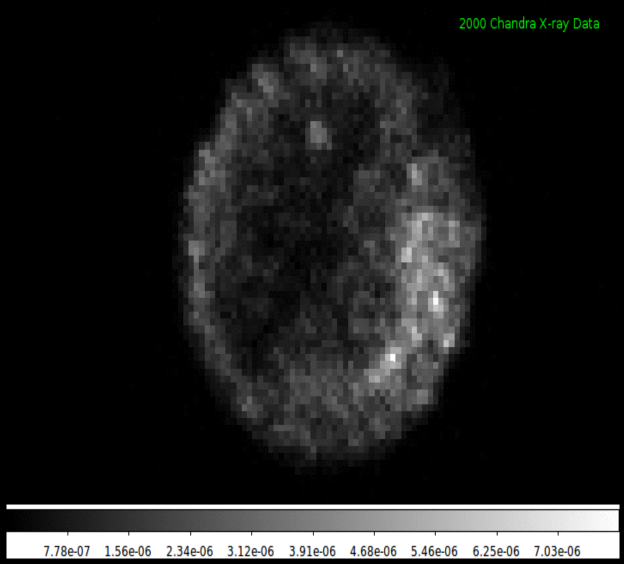
Hovey+15 → HST expansion ~6500km/s

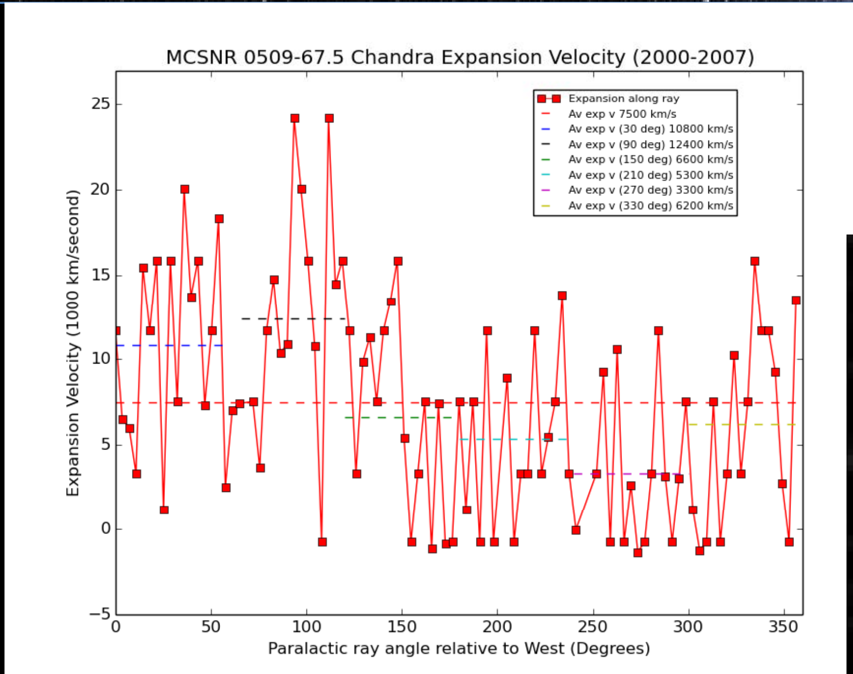
$D$ = 8 pc x 7 pc

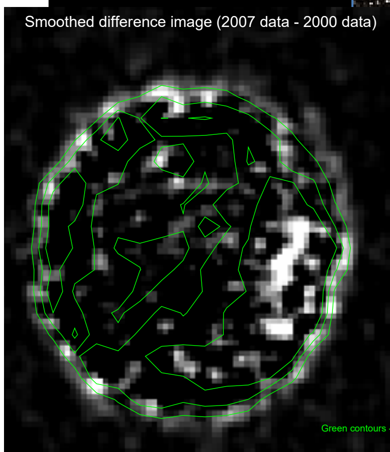
Cassiopeia A 325 yr -0.77

SNR J0509-6731 ~310 yr -0.73

Kepler's SNR 409 yr -0.64



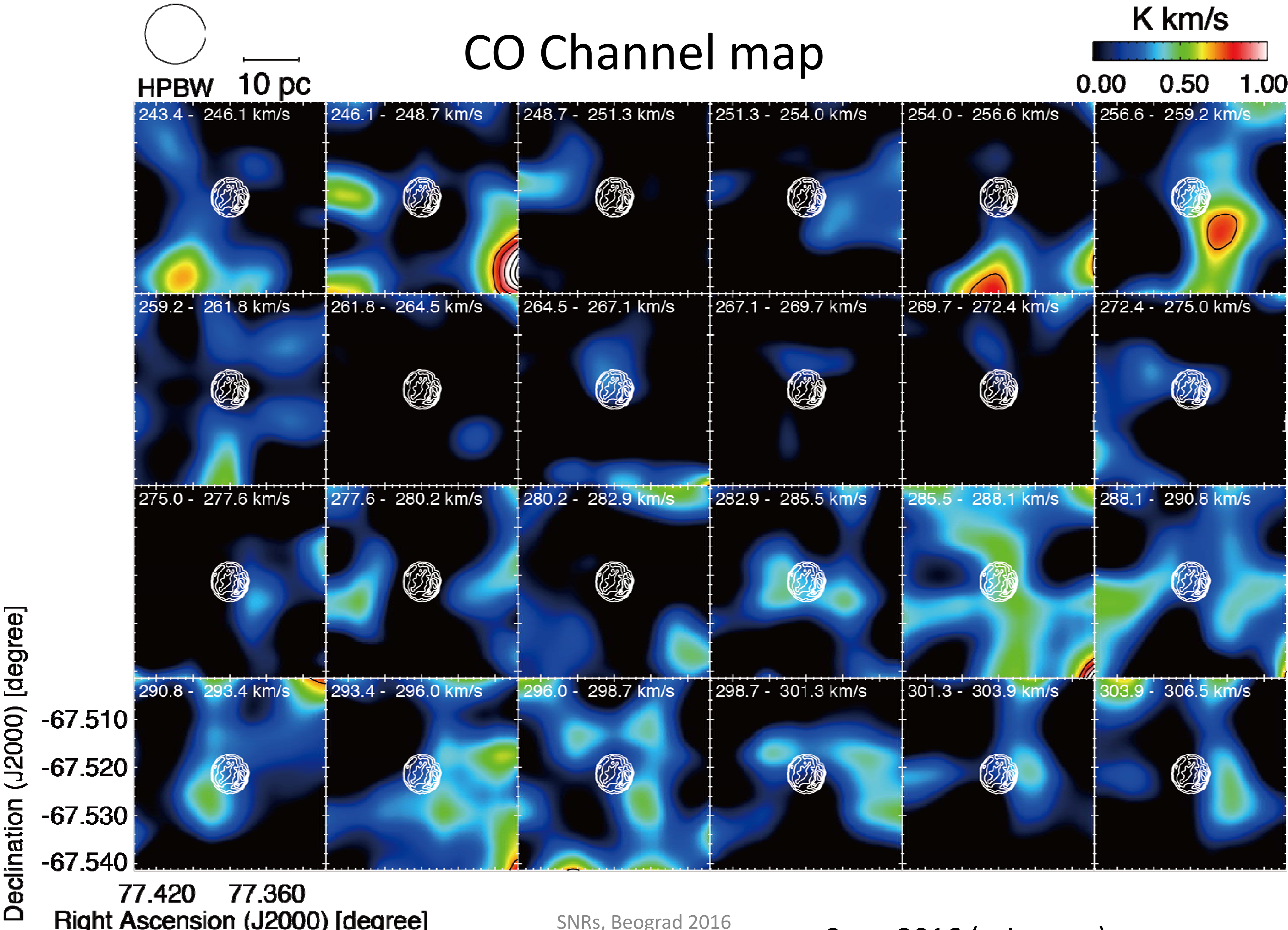




# 12,000±1,800 km/s

# Between 2000 and

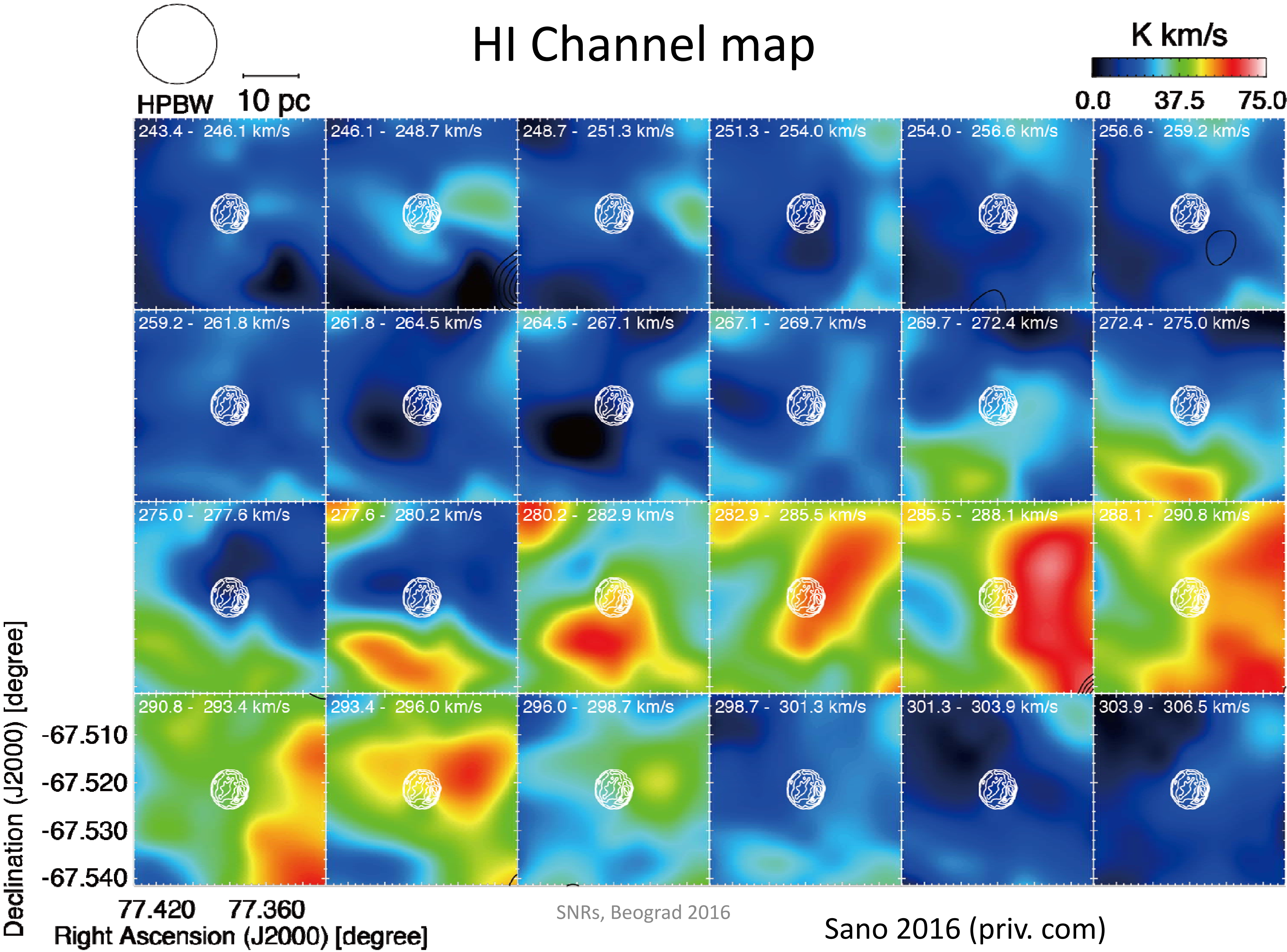
# CO Channel map






Sano 2016 (priv. com)

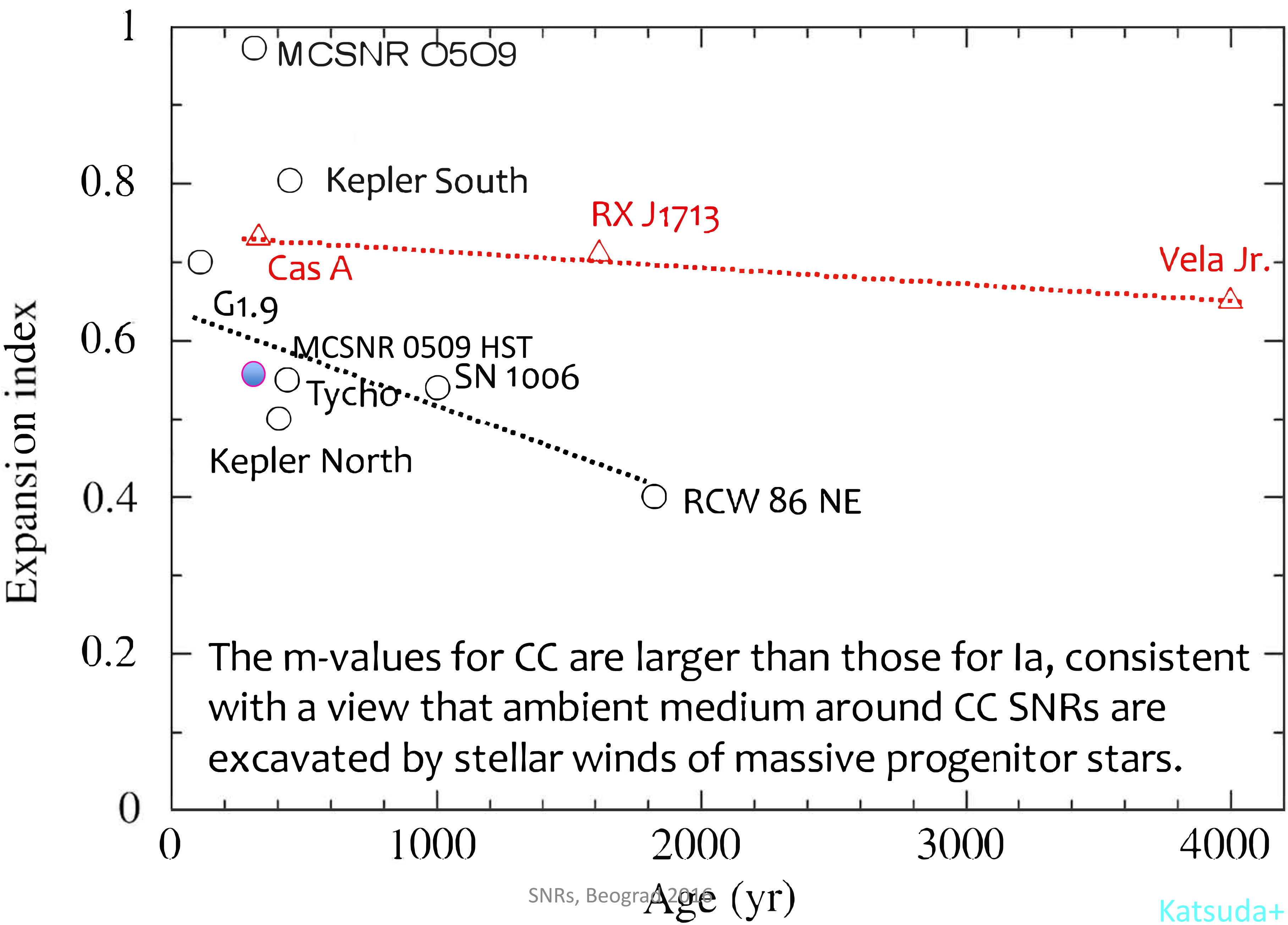
# HI Channel map






Sano 2016 (priv. com)

# What Can We Learn from Expansion Index?






Katsuda+

## LMC SNR 0536-7038

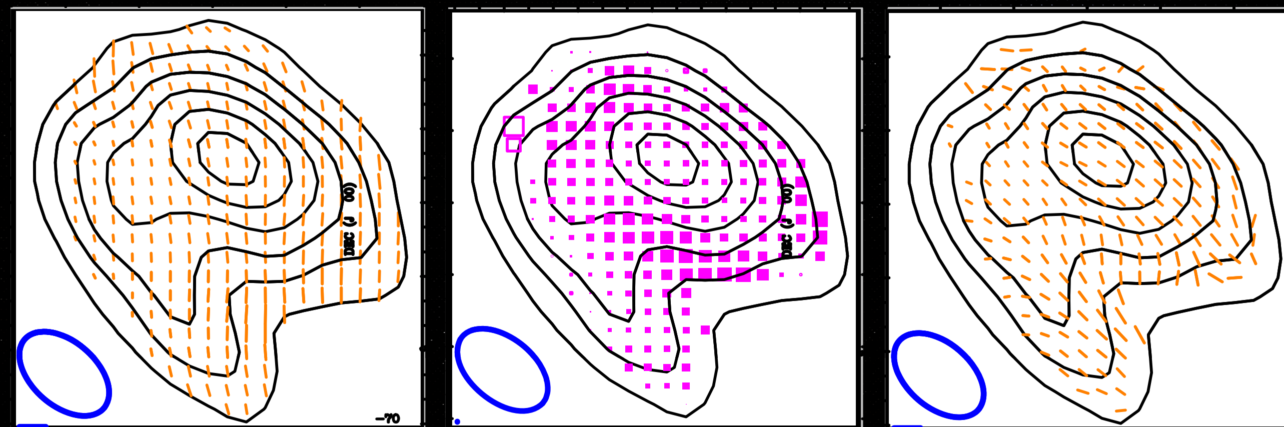
Bozzetto et al. 2014, ApSS

**Type Ia, ~13,500yr**

Morphology

ATCA 6cm Magnetic Field

α = -0.52±0.07



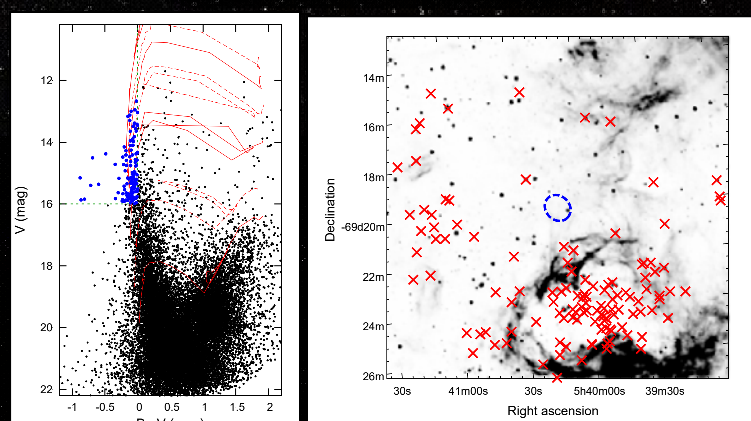
## LMC SNR 0540-6919

**CC-PWN, ~760yr**

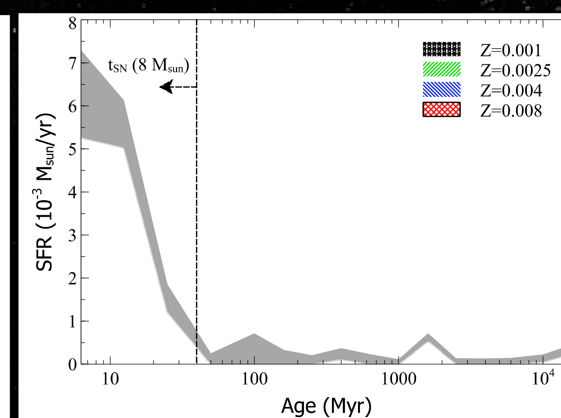
Brantseg et al. 2014, ApJ

Morphology

Stellar Environment



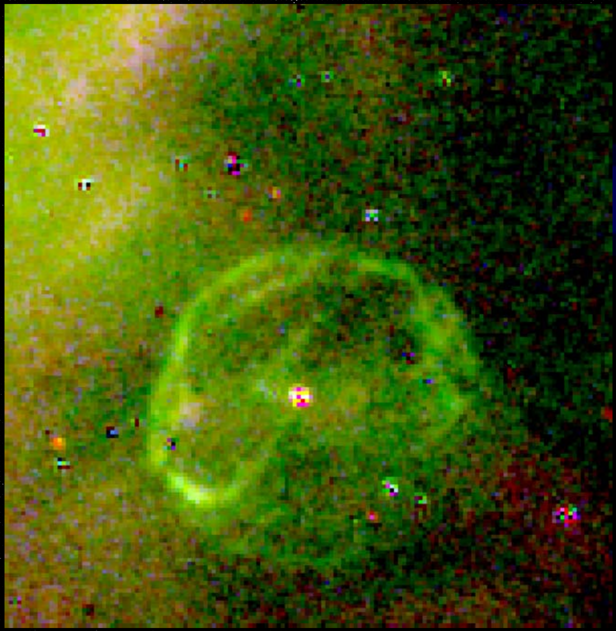

Star Formation History



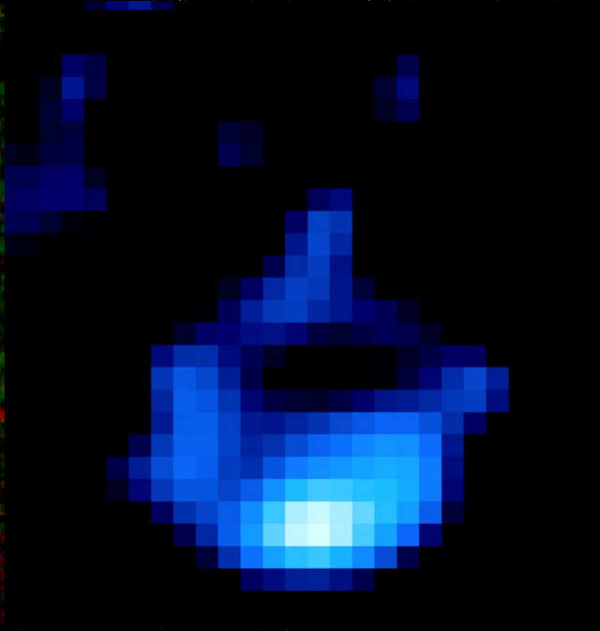
## SMC SNR 0127-7332 (SXP 1062)

Haberl et al. 2012, A&A

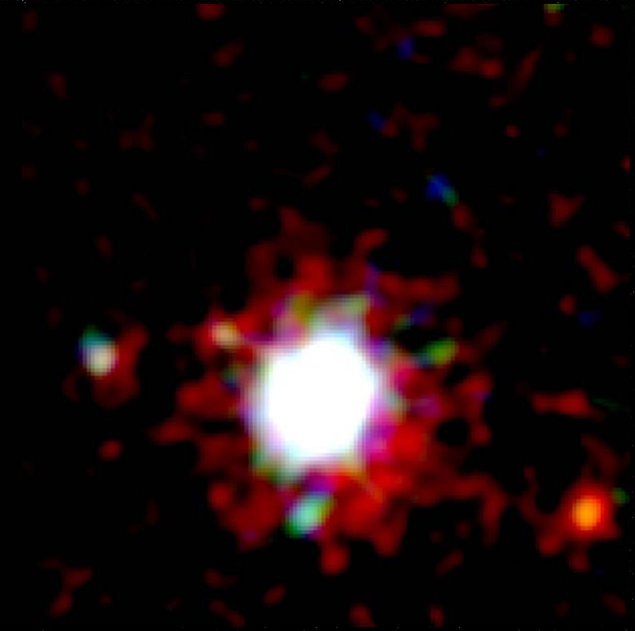
- SNR around Be/X-ray binary,
- Oxygen-rich -> Type Ib?
- Neutron start with a spin of 1062sec
- <25,000yr



MCELS



ATCA



XMM

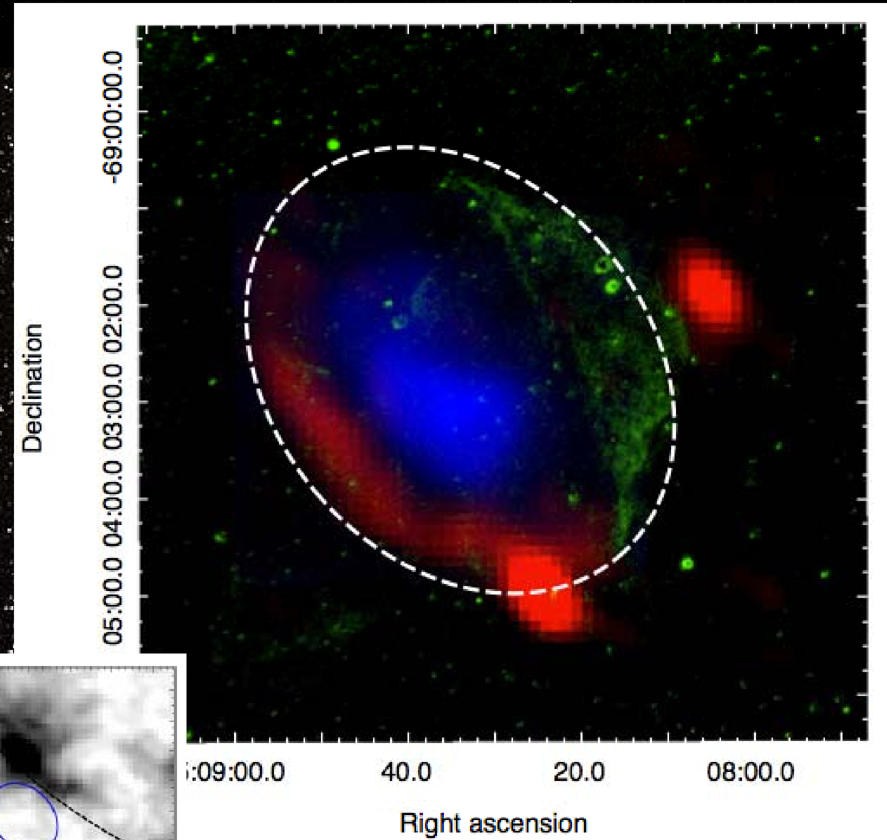
MC SNR 0508-6902

~74 pc **x** 57 pc

Fe mass of 0.5–1.8 Msol

TYPE Ia

B ~ 29 μGa




GREEN – MCELS

BLUE – XMM-Newton

RED -- ATCA

Bozzetto et al. 14

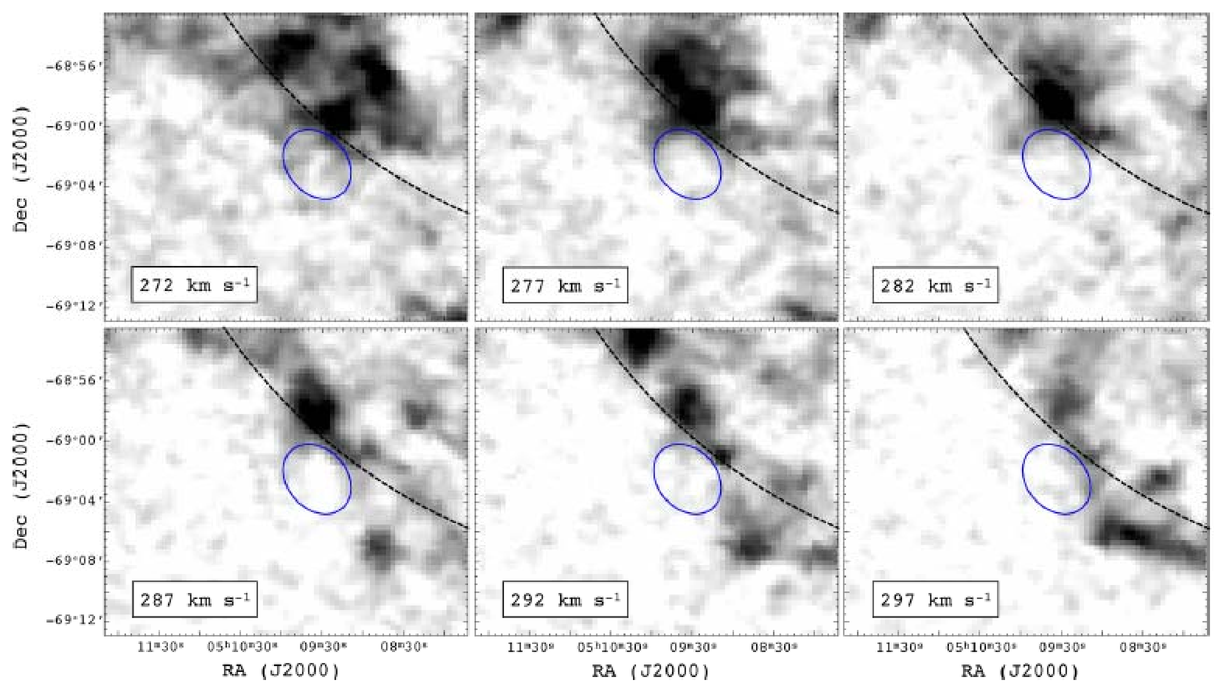
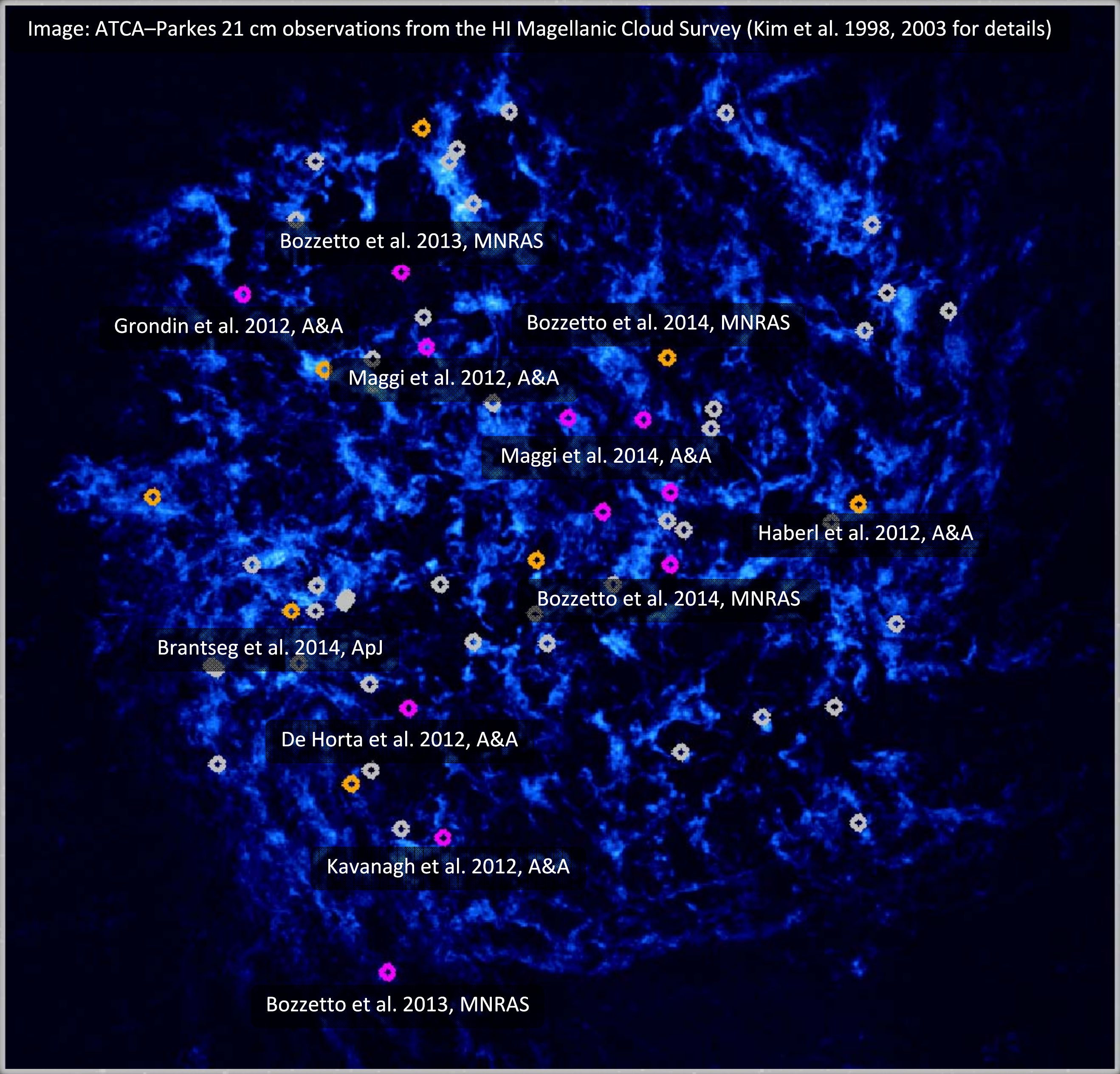



**Figure 9.** H I channel maps of SGS 5 in the region of MCSNR J0508−6902. The dimensions of the SNR are shown by the blue ellipses. The black dashed lines mark the approximate SGS 5 dimensions as determined by Kim et al. (1999). The heliocentric velocities are also indicated. A density gradient across MCSNR J0508−6902 due to SGS 5 is evident in each channel.

# Results | LMC Population

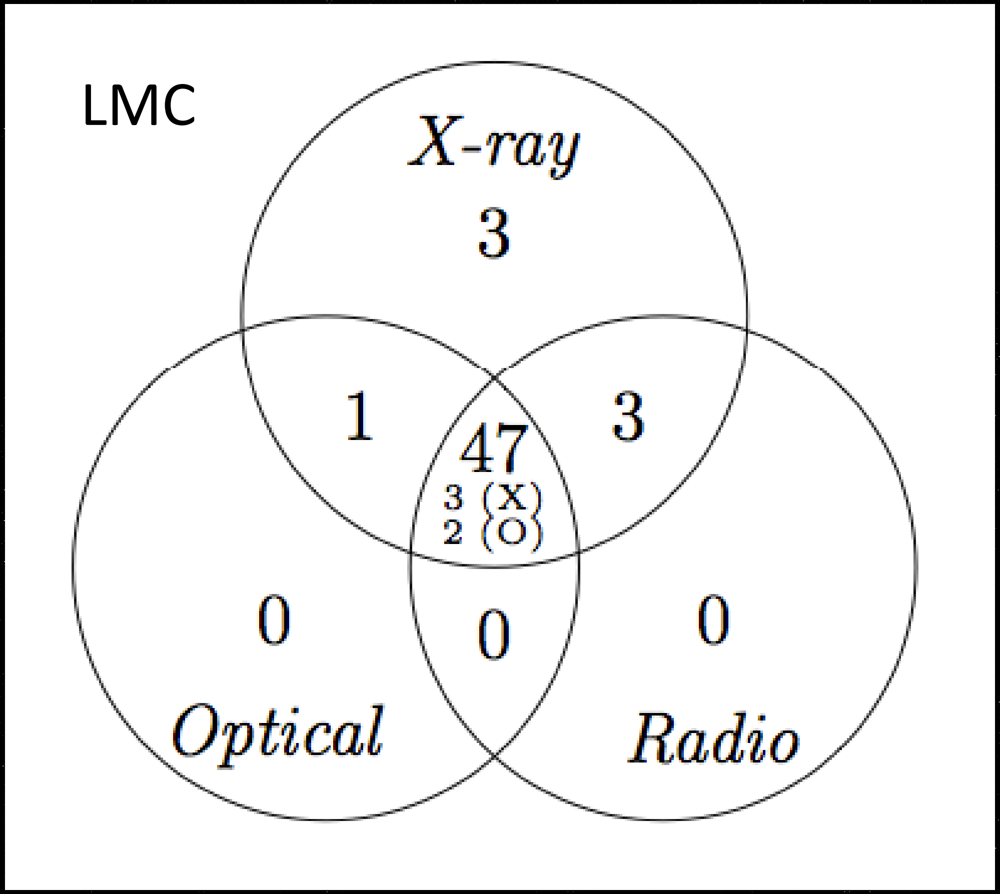


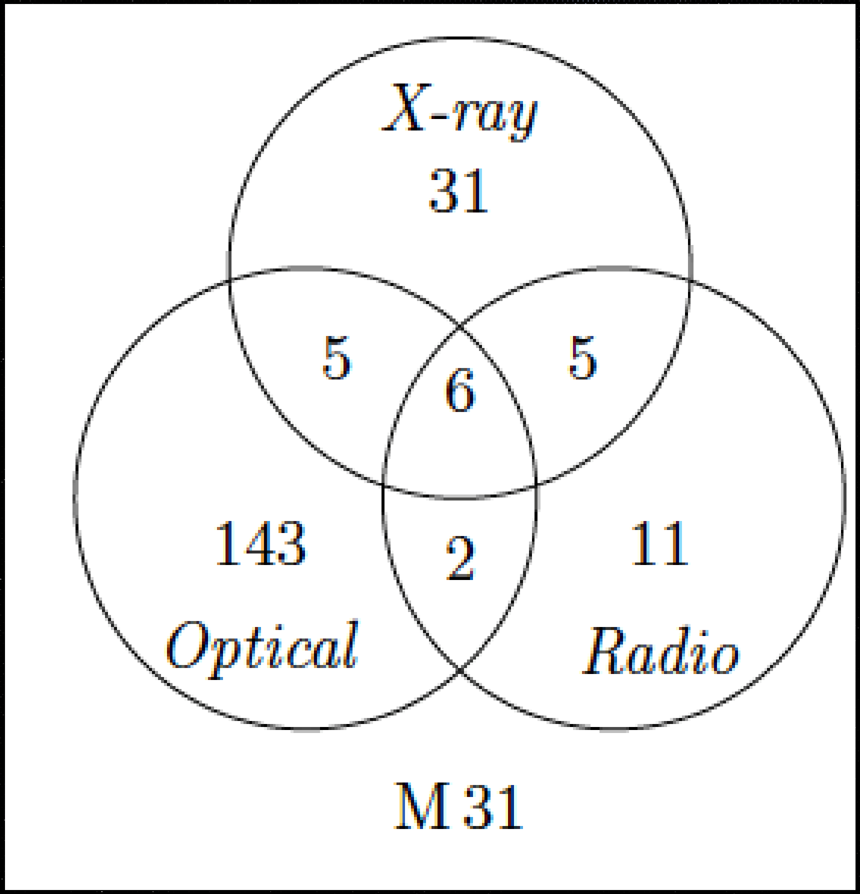

- 59 SNRs now classified
- 19 candidates
- 5 PWN (5-10%)
- 15 Type Ia (~20%)
- Detecting the very old and diffuse remnants
- Re-measure fluxes and extents

Published new SNR

Published additional data

Unpublished


LMC
X-ray
3
1
47
3 (X)
2 (O)
3
0
0
0
Optical
Radio


X-ray
31
5
6
5
143
2
11
Optical
Radio
M 31

## Multi-wavelength Detection

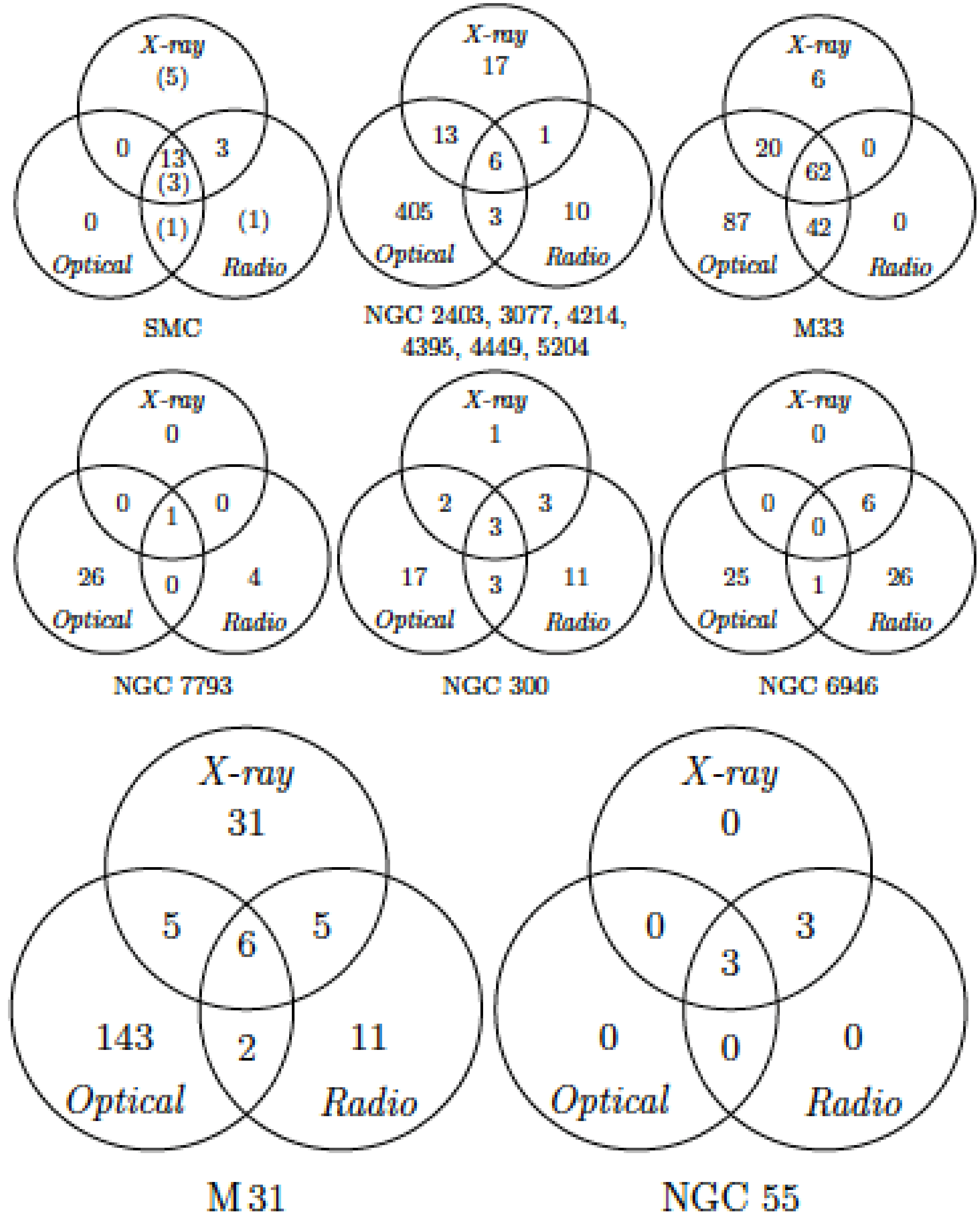
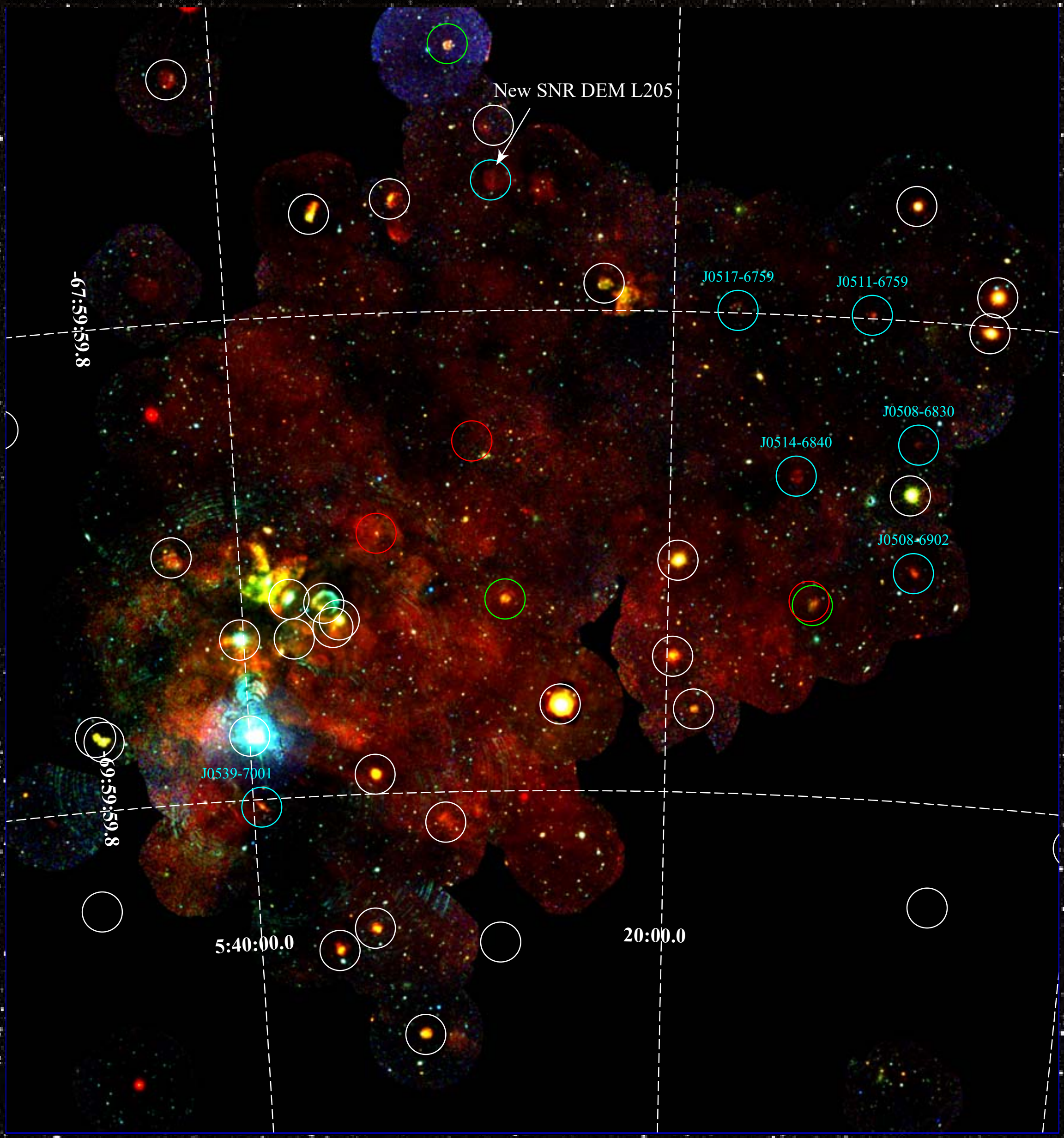
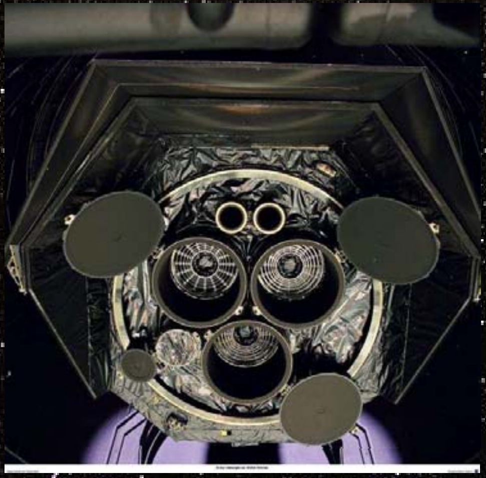


Image: XMM-Newton (Maggi et al. in prep.)



- 0.2 – 1 keV (red)
- 1 – 2 keV (green)
- 2 – 4.5 keV (blue)

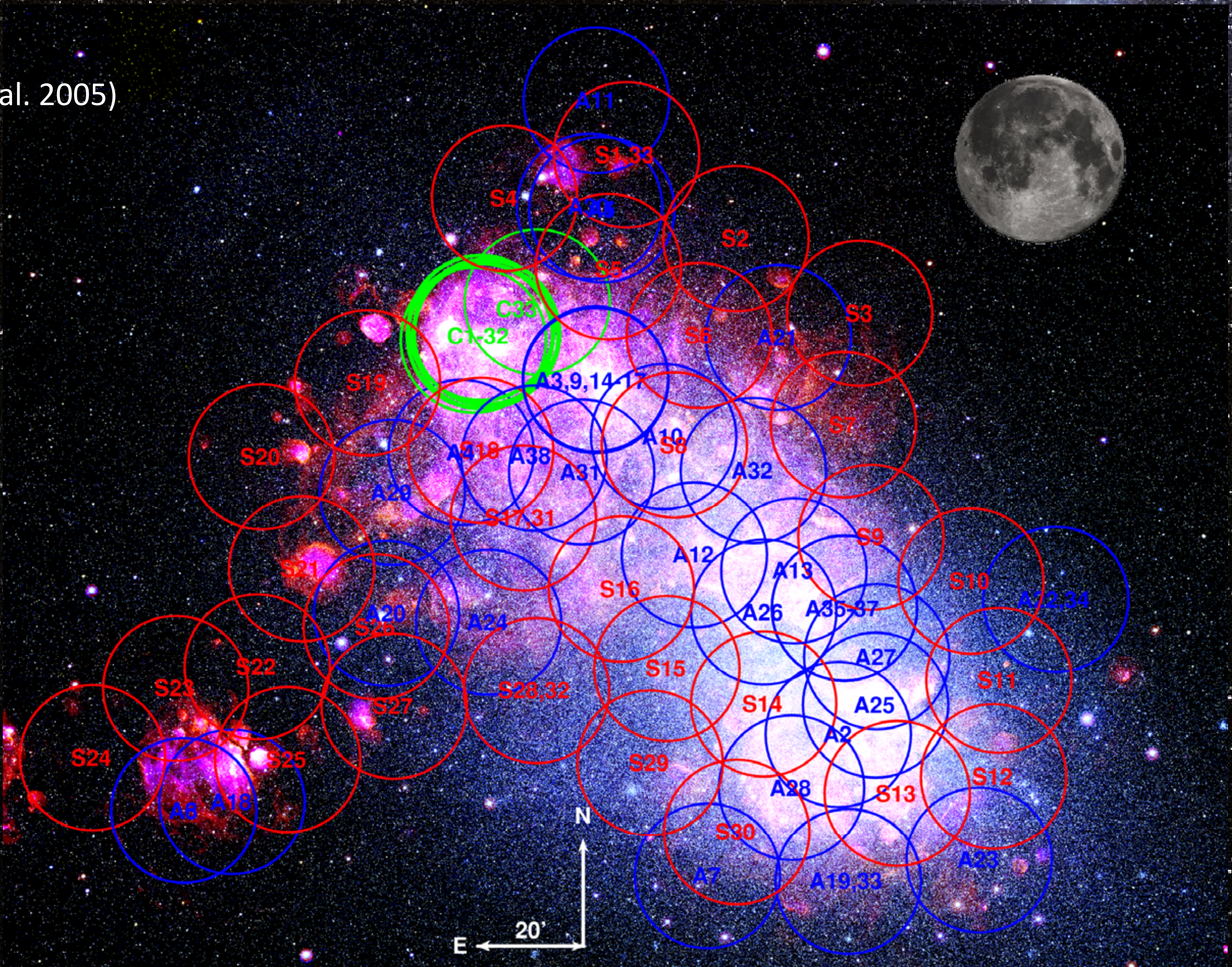
MCELS

(Winkler et al. 2005)

Hα

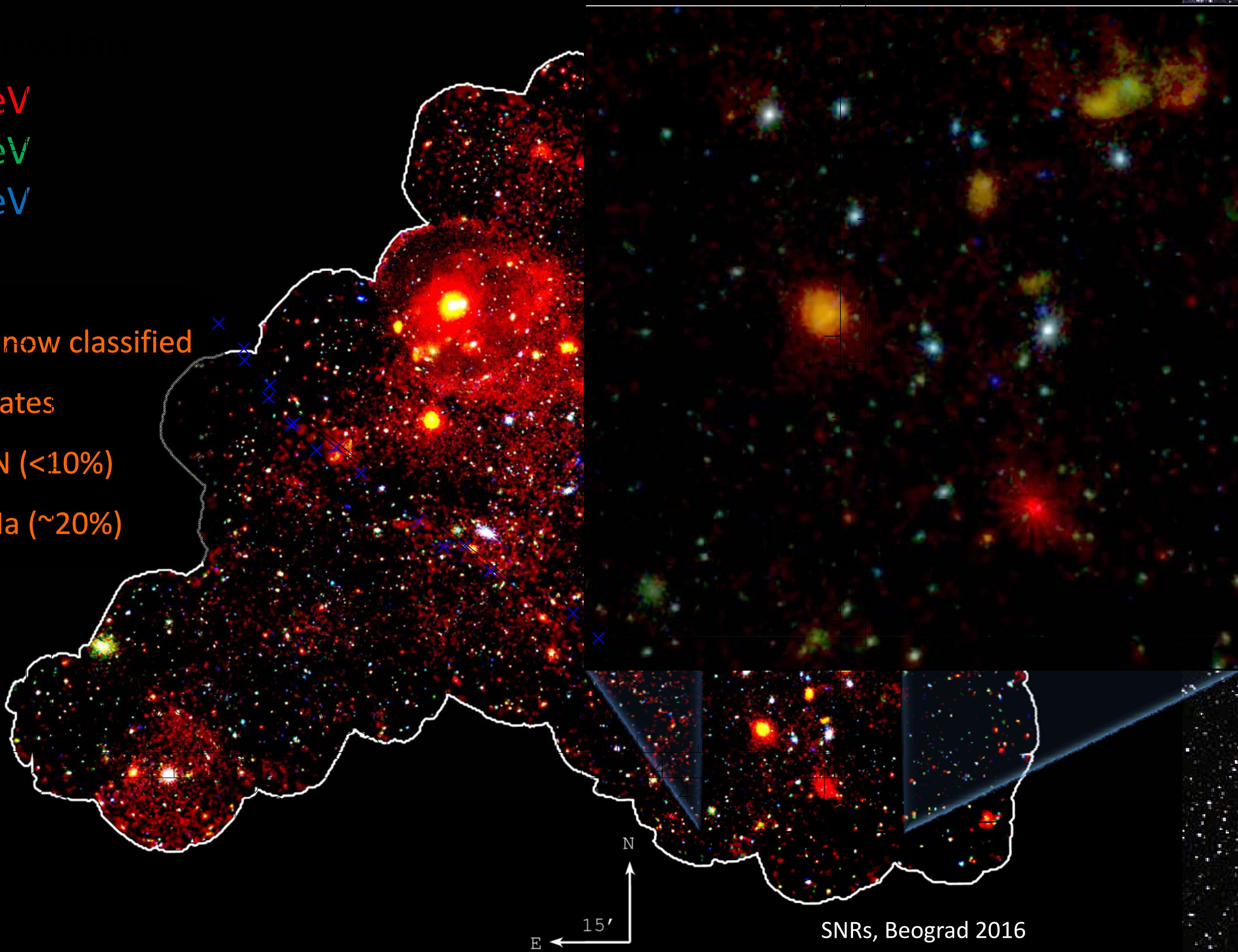
[SII]

[OIII]

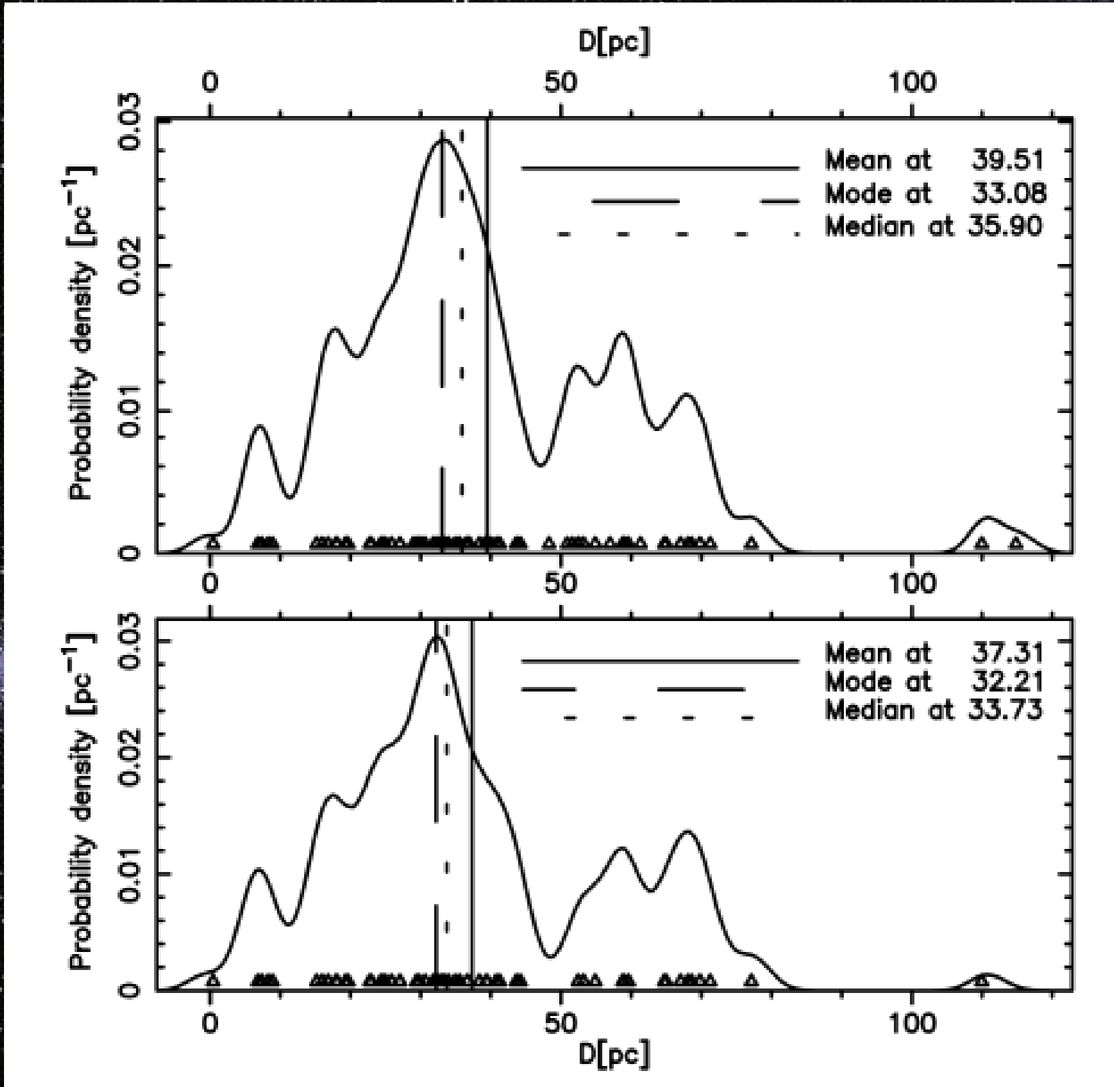


0.2-1.0 keV
1.0-2.0 keV
2.0-4.5 keV

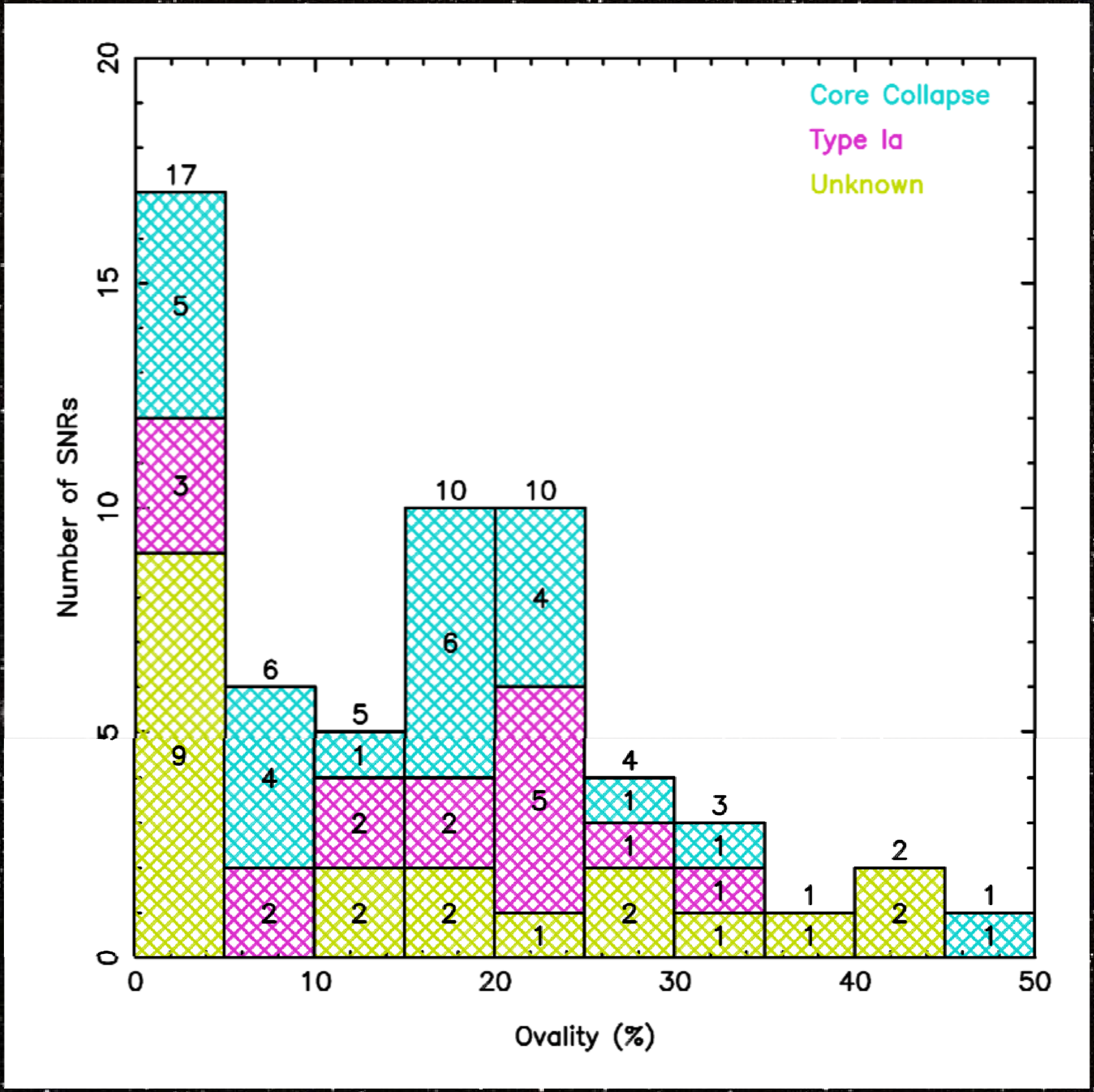
- 19 SNRs now classified
- 6 candidates
- 1+1 PWN (<10%)
- 4? Type Ia (~20%)



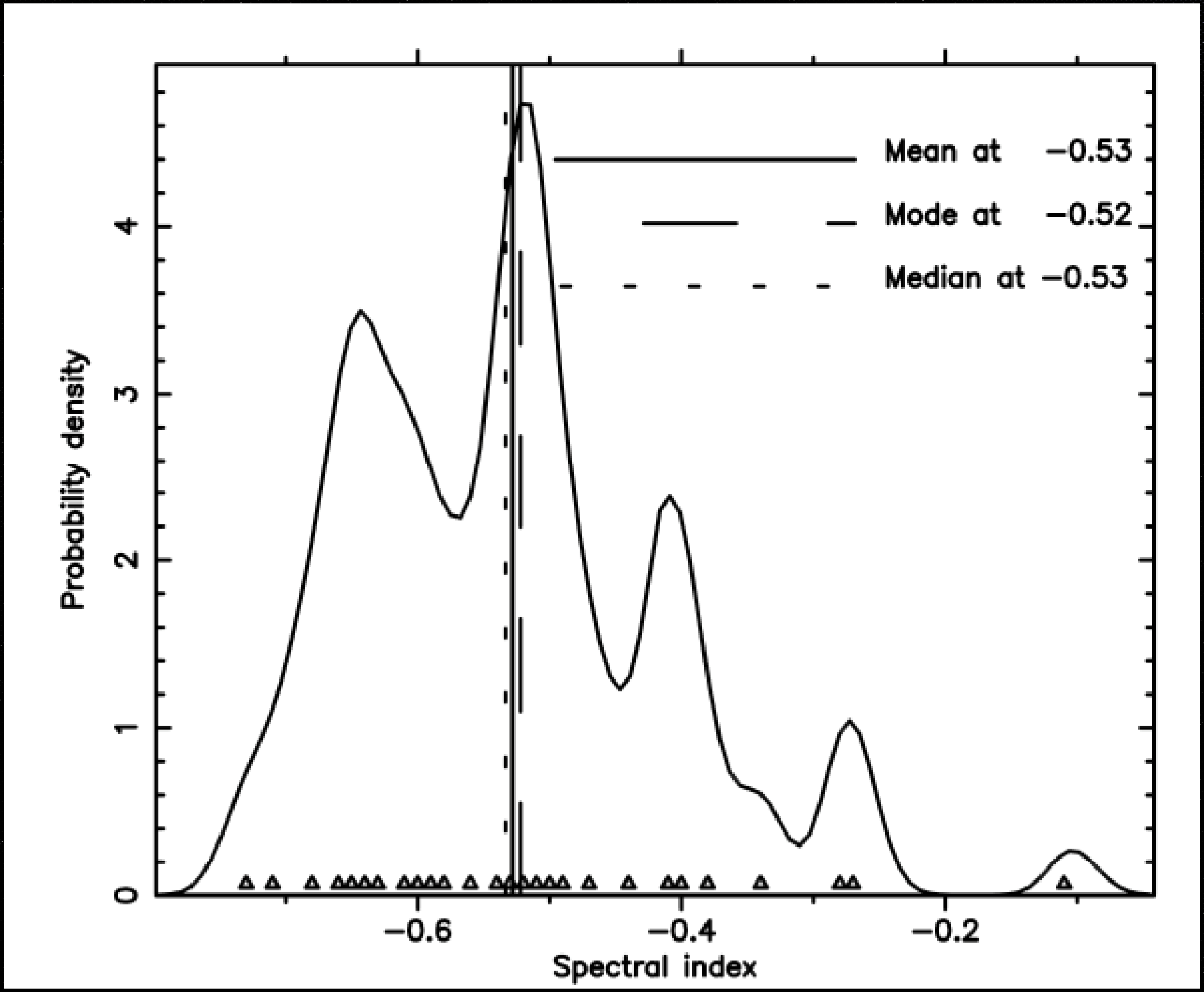
## Diameter Distribution LMC SNRs



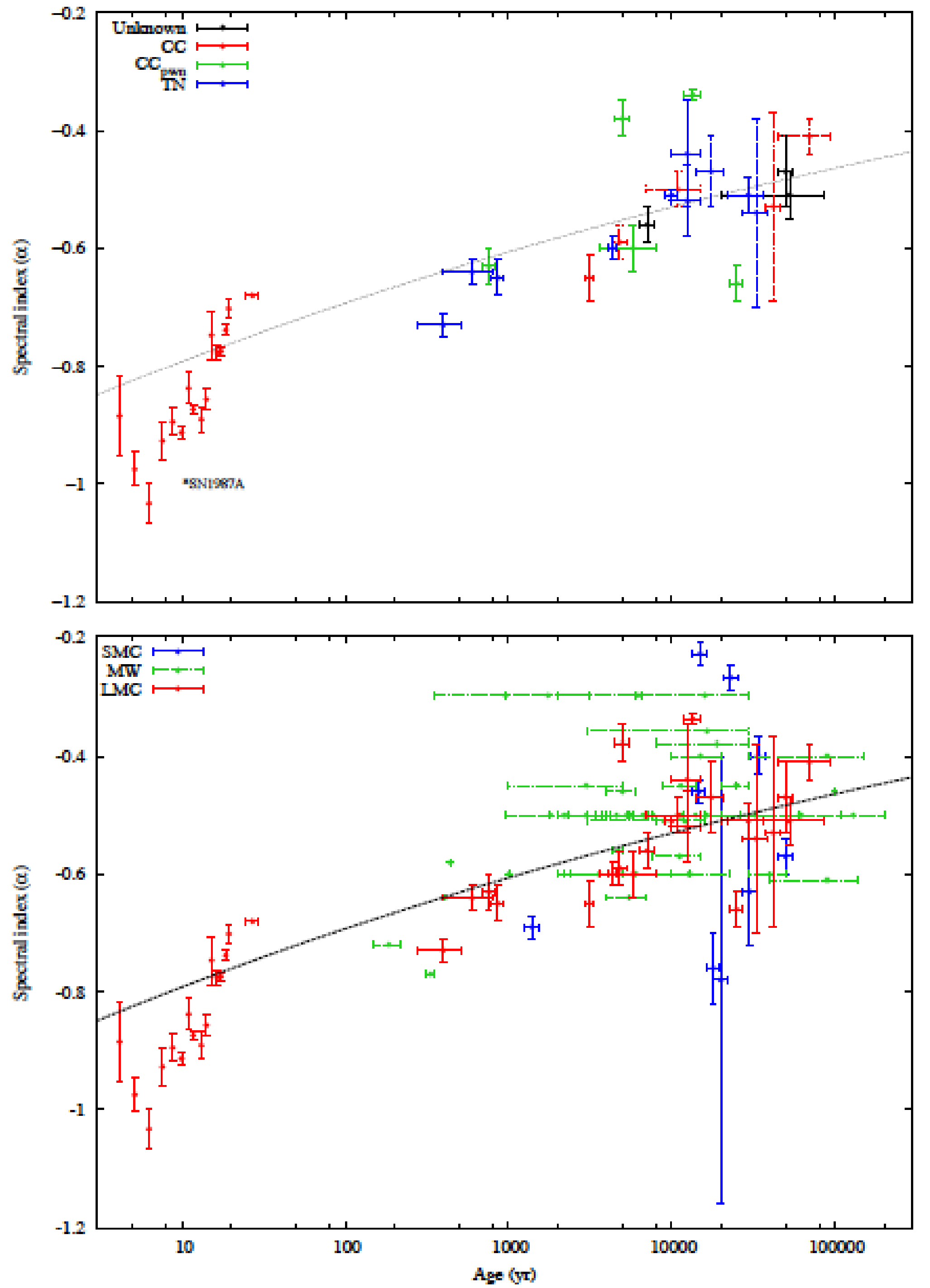
## Ovality Distribution LMC SNRs



**LMC (59 SNRs)** **SMC (19 SNRs)**

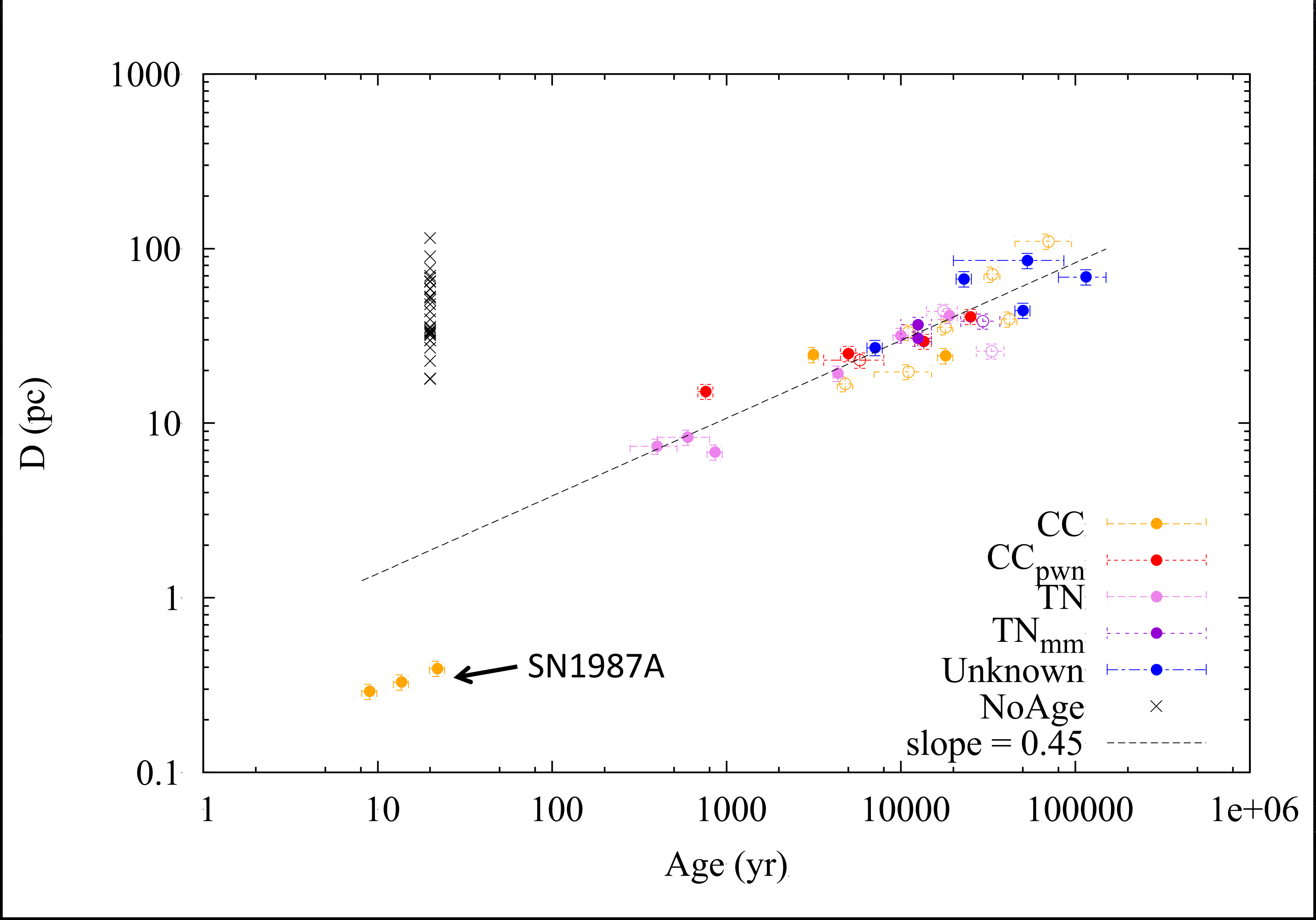


# Spectral Index Distribution

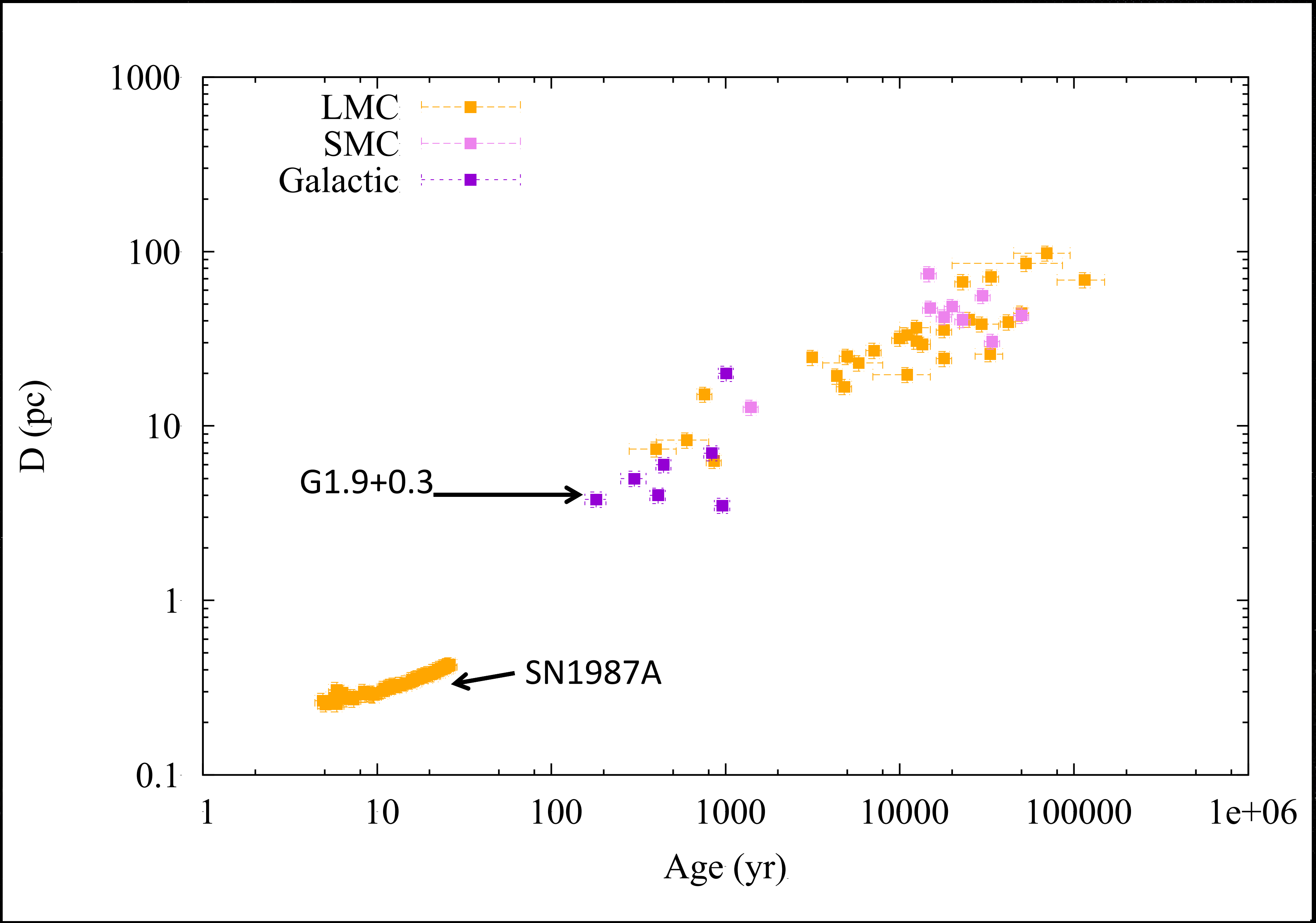



* SN1987A values from Gaensler et al. 1997

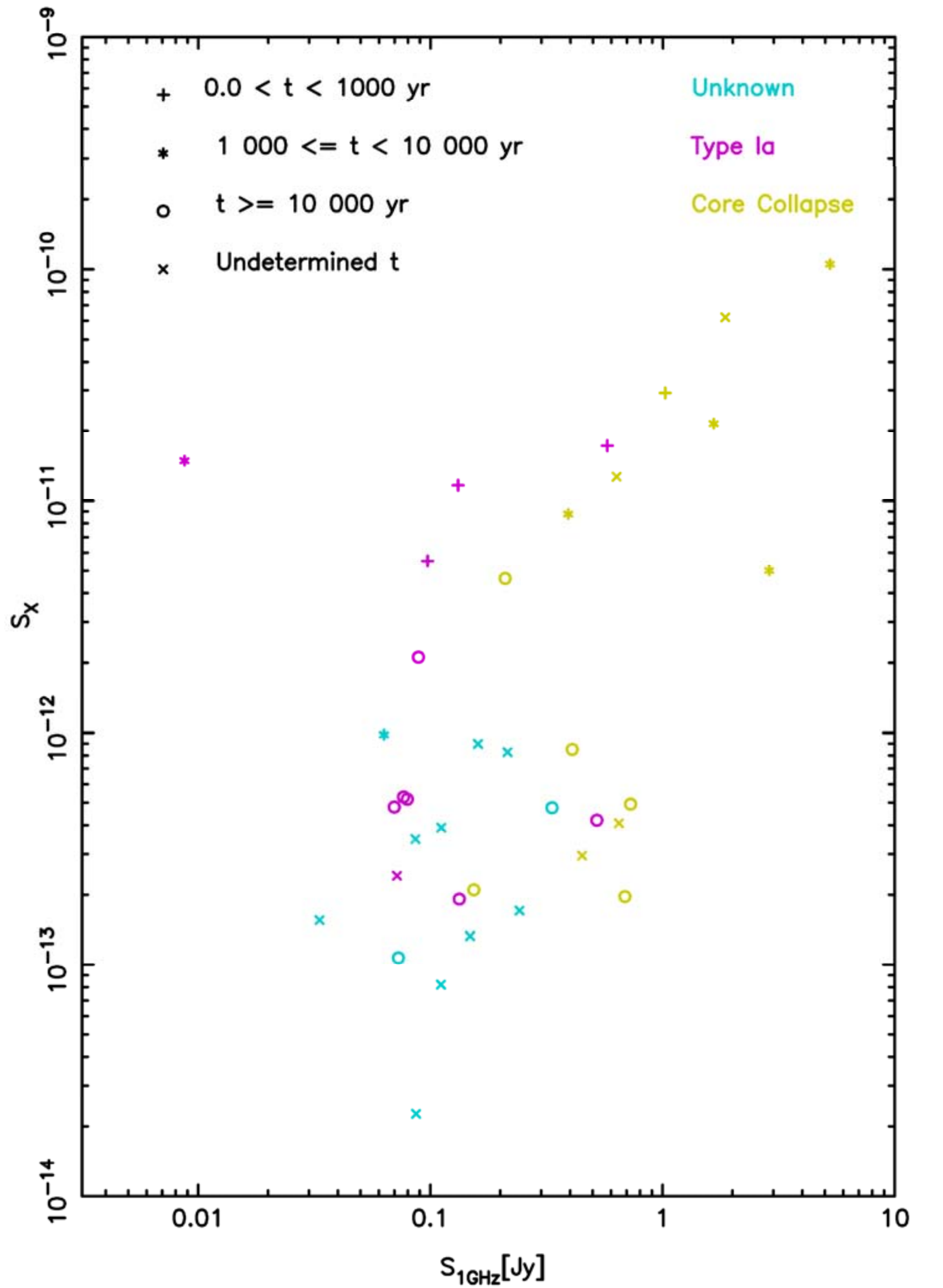
## SNR Diameter Evolution -- LMC



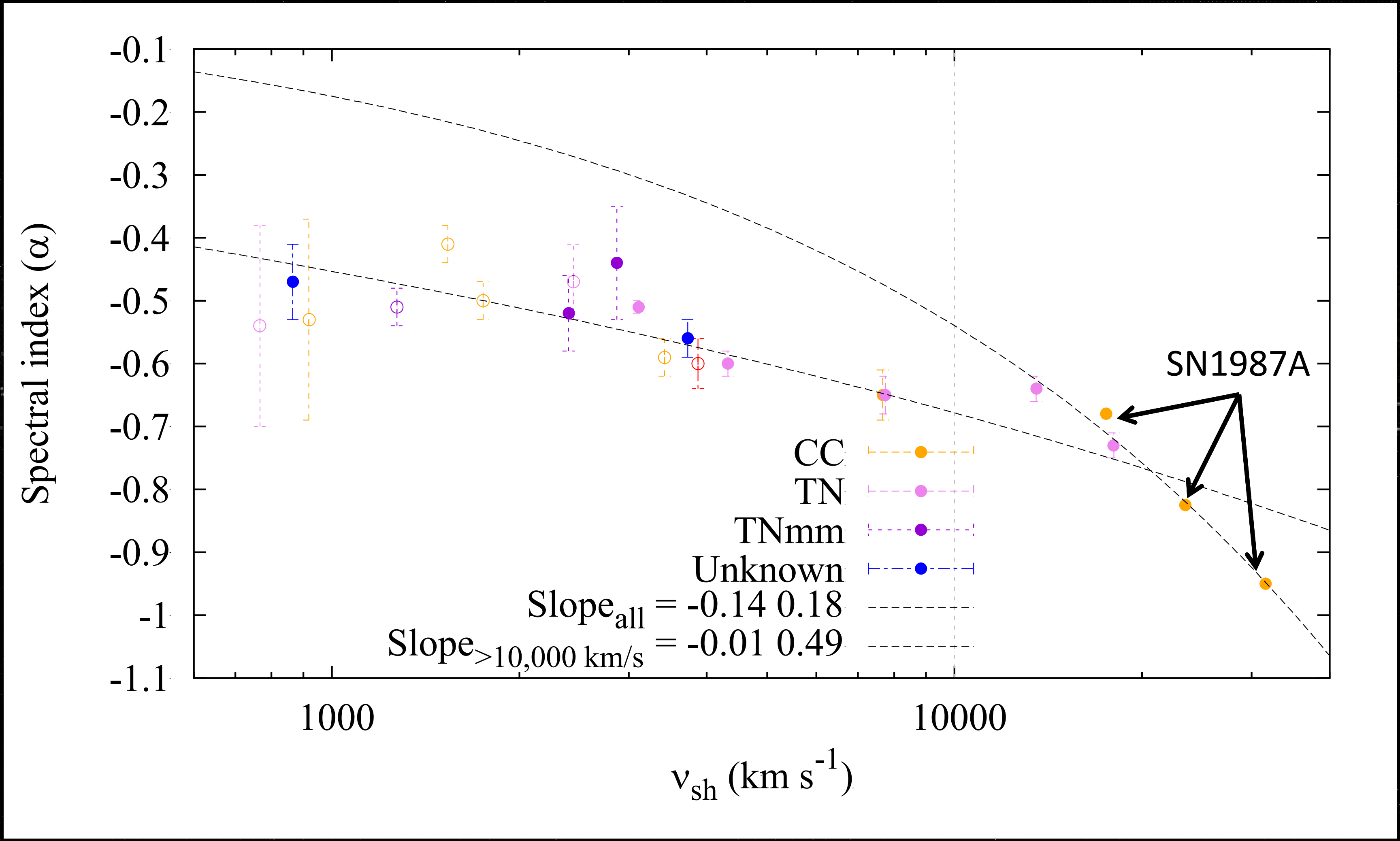
## SNR Diameter Evolution MCs+MW



# Radio vs X-ray

## Average Expansion Velocity vs. Radio Spectral Index (LMC)



## LMC SNR RC Luminosity function

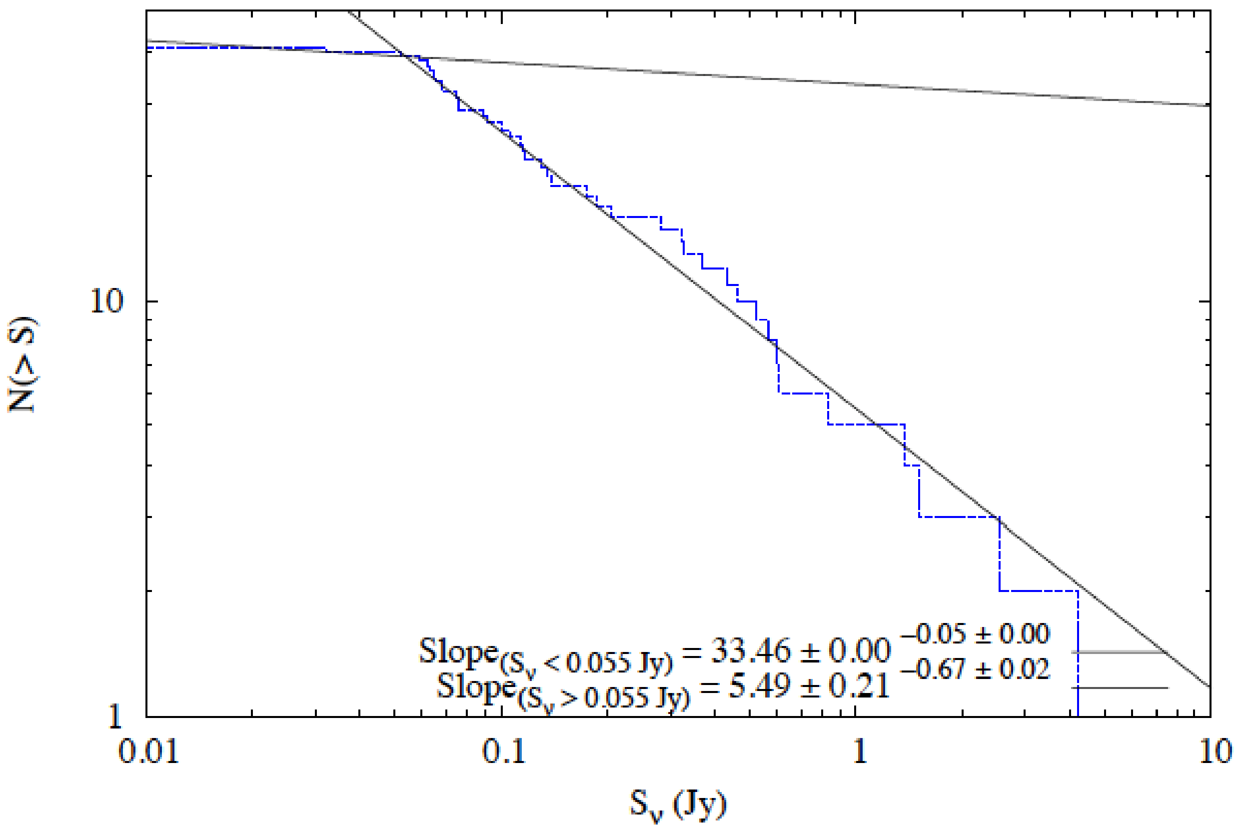
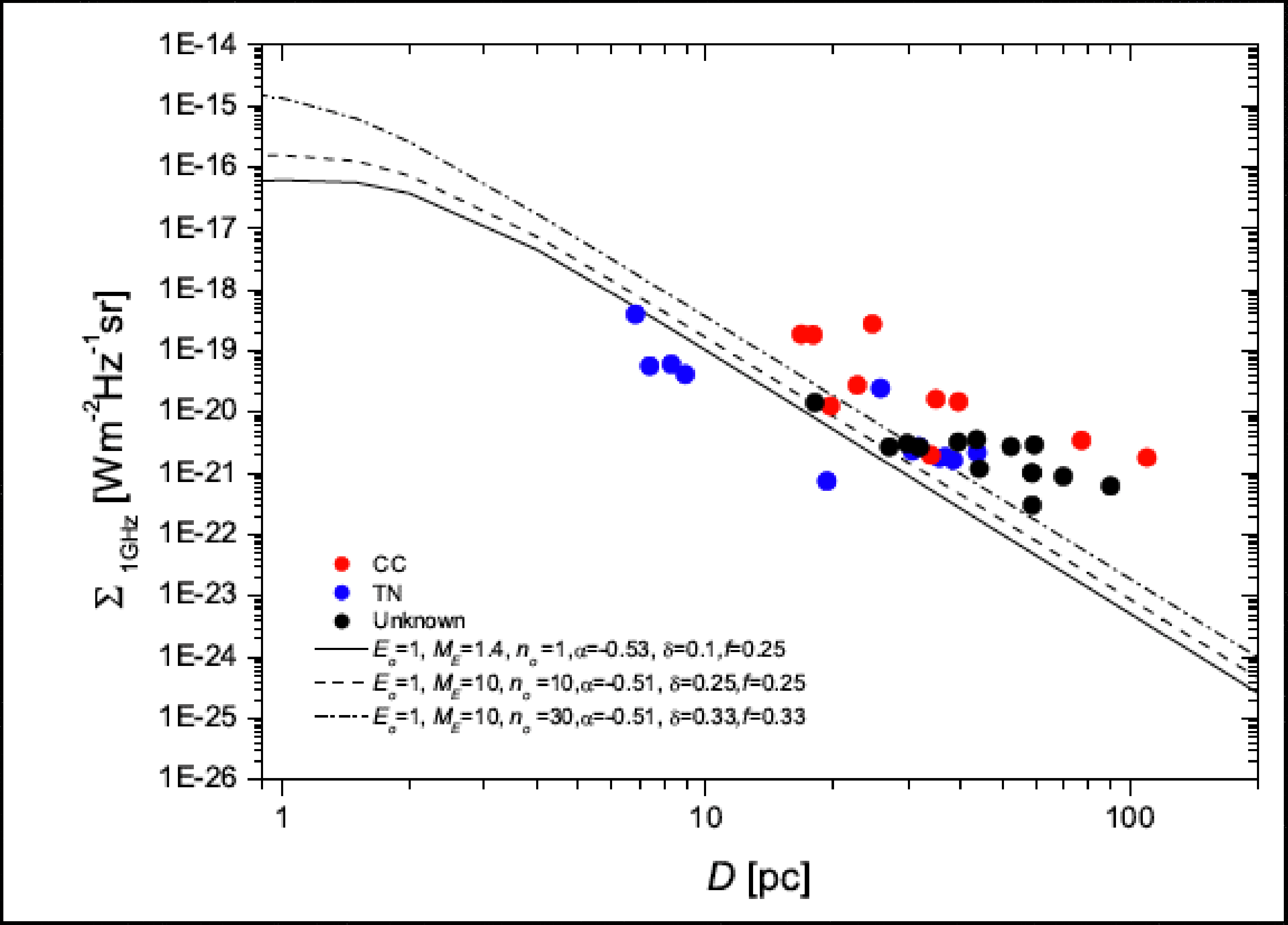
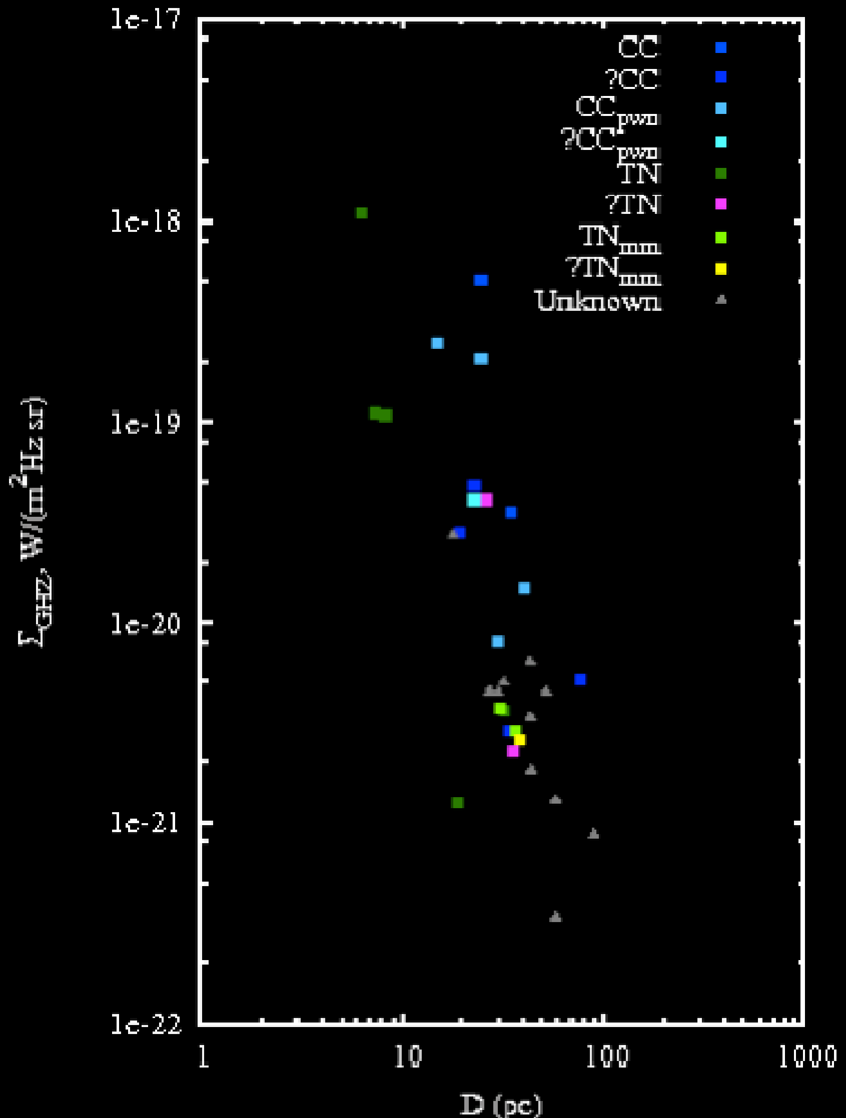



Fig. 18.— Luminosity function for a sample of 40 LMC SNRs at $\lambda = 20$ cm, represented by a blue dashed line. The two solid black lines represent the power law fits to the two components above and below the break at 55 mJy.

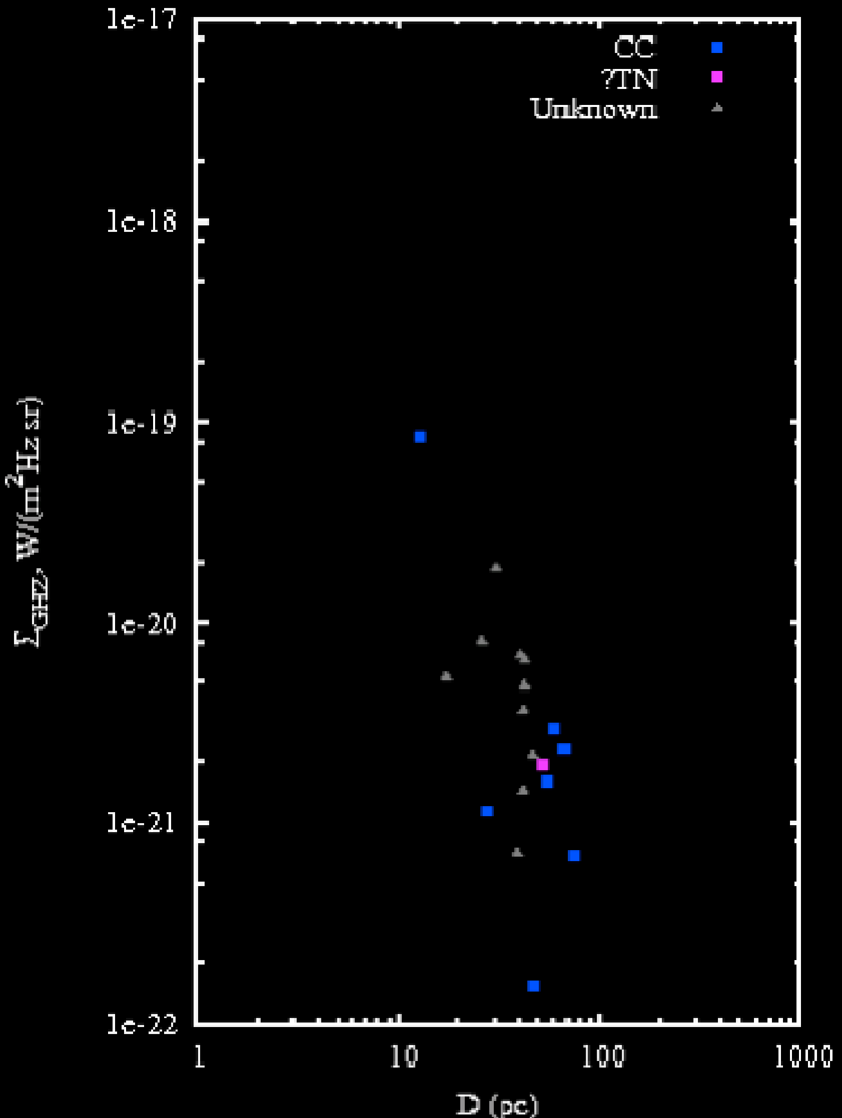
## LMC SNR equipartition evolution models



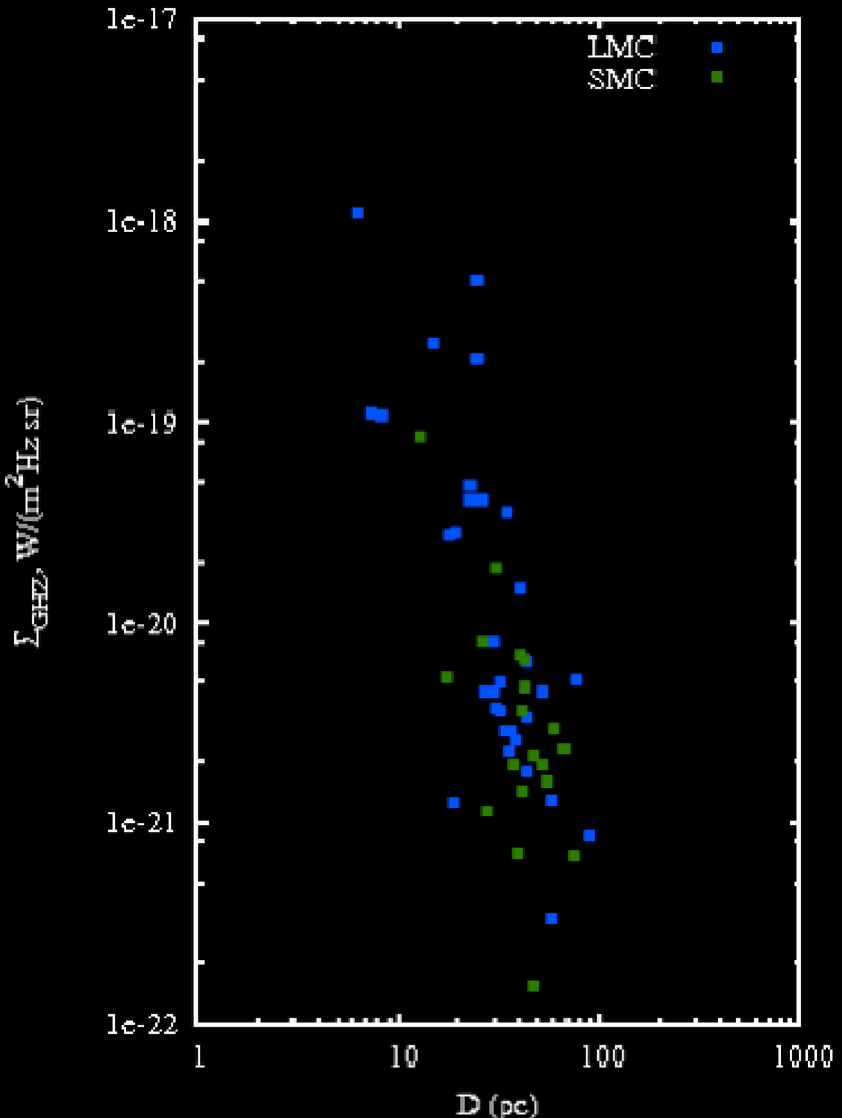
## $\Sigma - D$ Distribution LMC SNRs



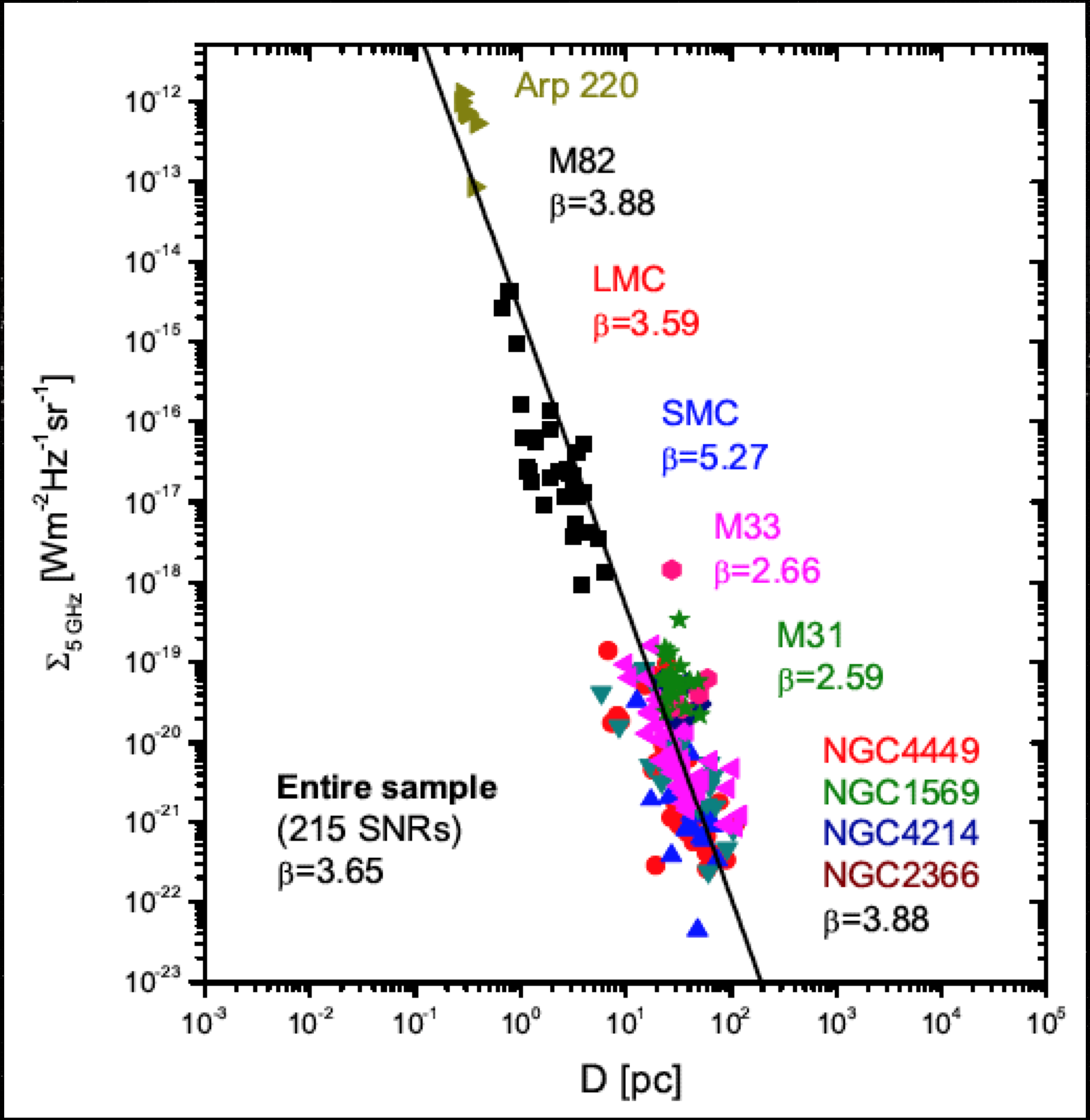
## $\Sigma - D$ Distribution SMC SNRs



## $\Sigma - D$ Distribution MCs SNRs



## $\Sigma - D$ Distribution ALL extraGal SNRs



## Results | Evolution and statistics –LMC Type Ia SNRs

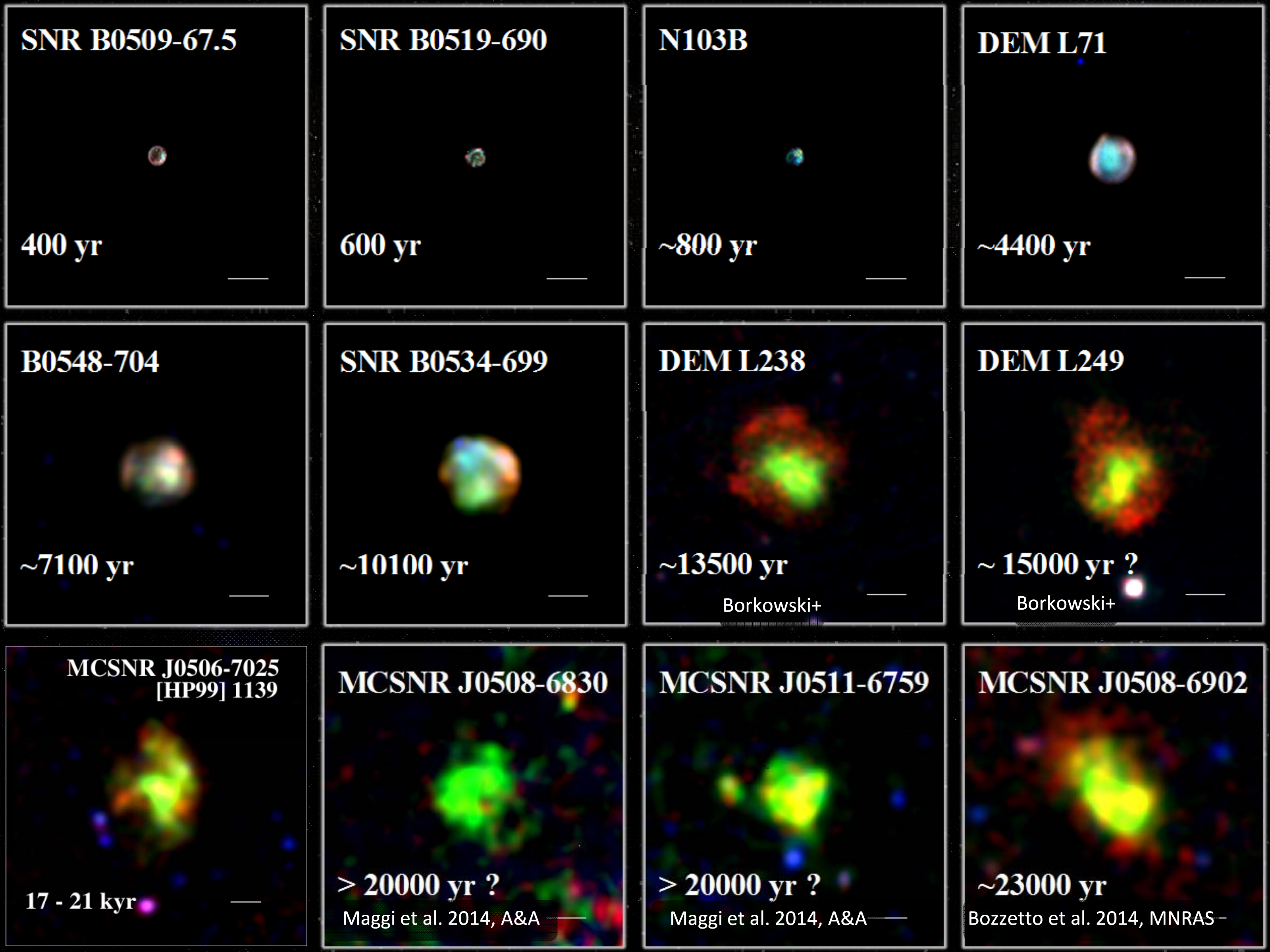
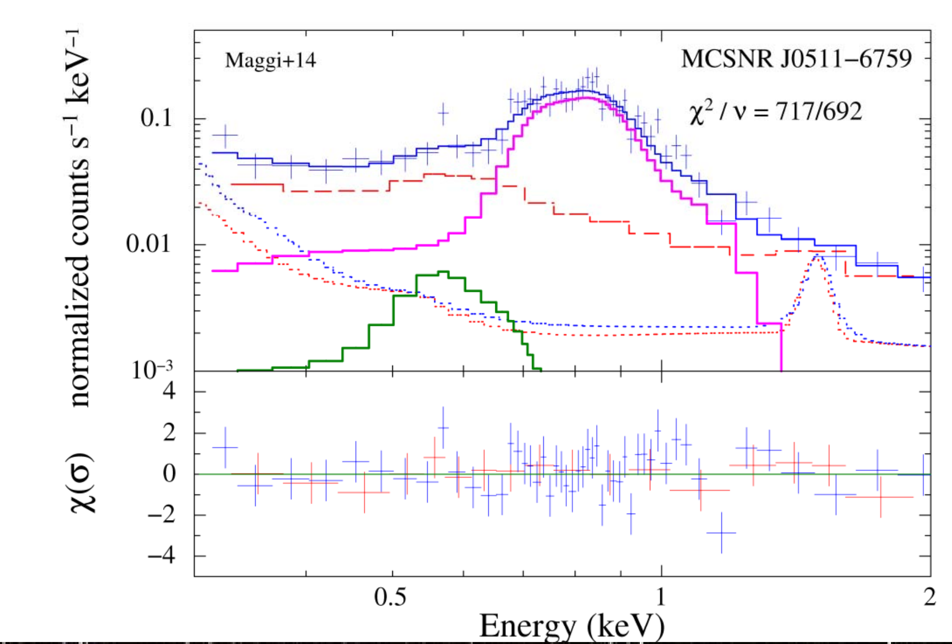
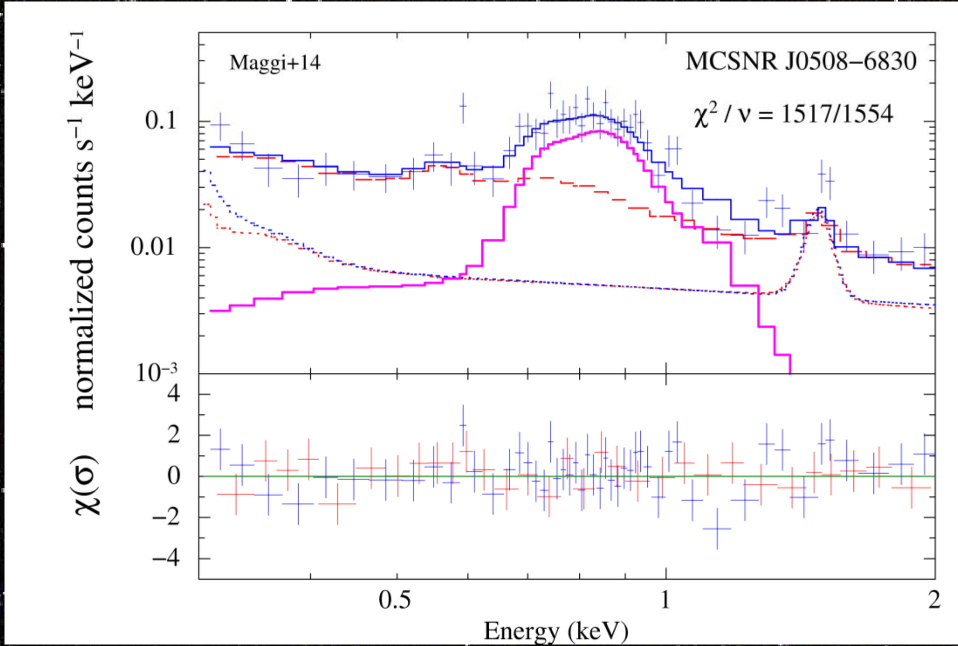



Image from Maggi et al. (2016)

X-ray spectra dominated by Fe-L emission lines

Thermonuclear SN (Ia)



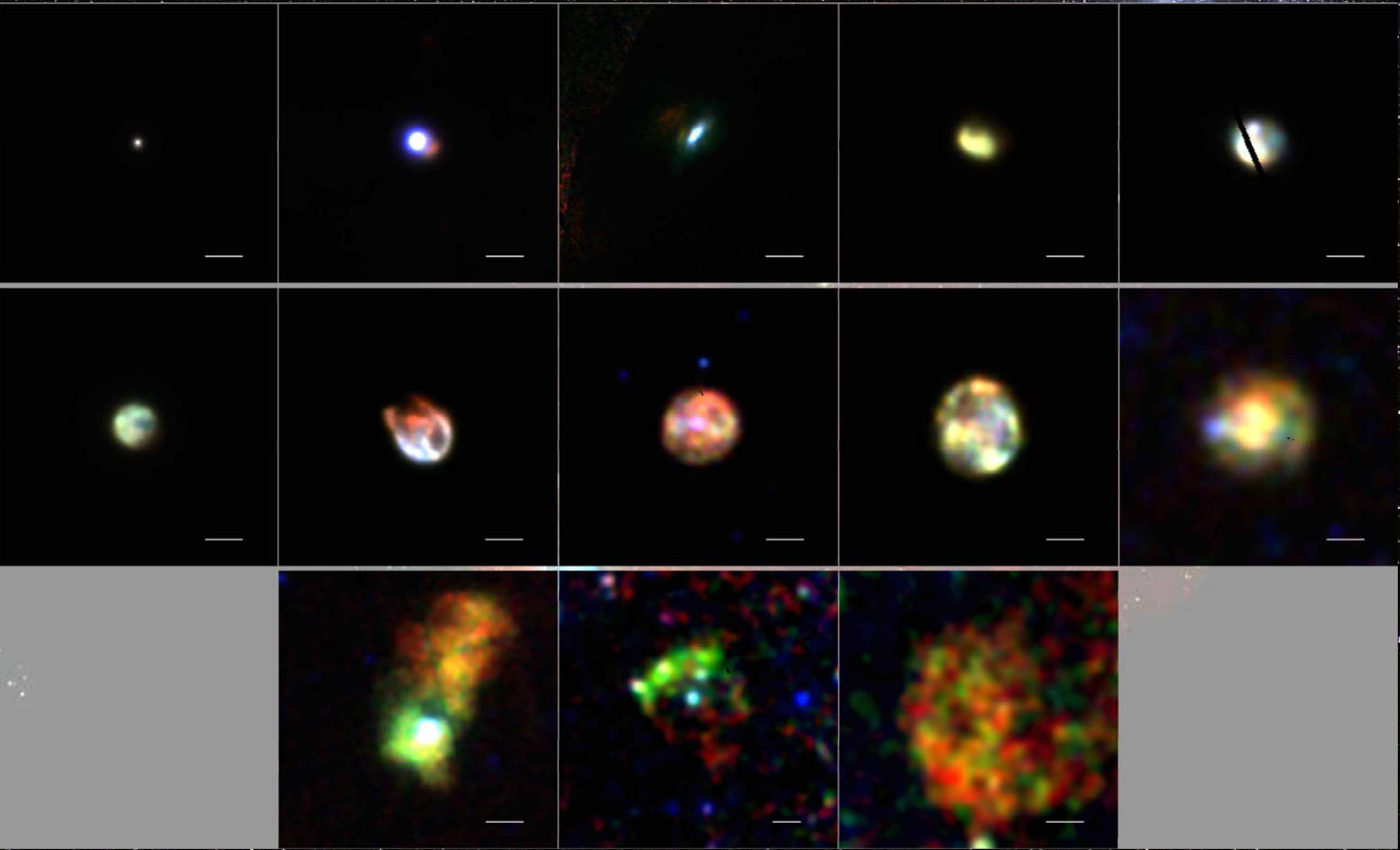




vapec model:

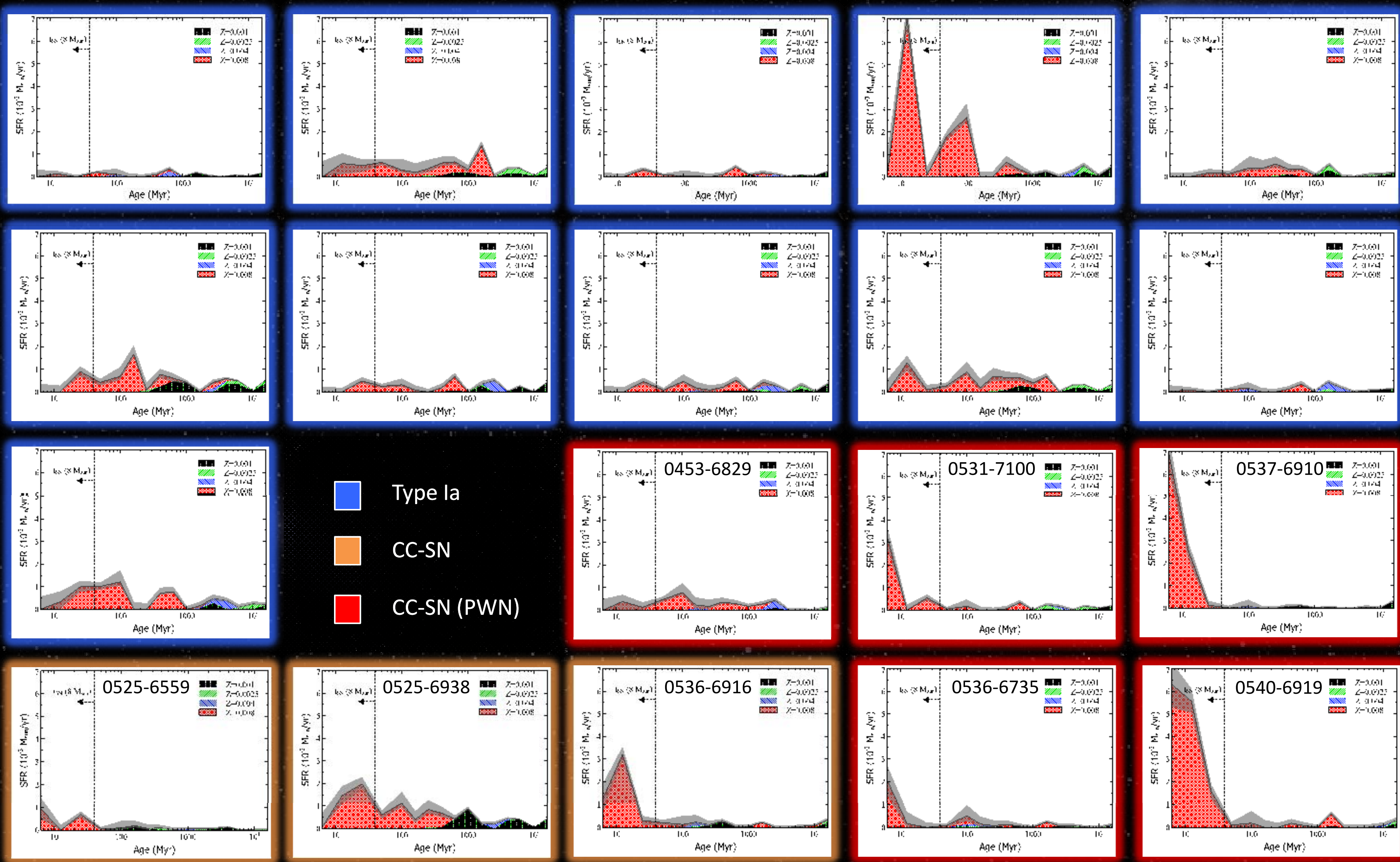
kT ≈ 0.7 keV

Large Fe abundance

Credit: P. Maggi 2014

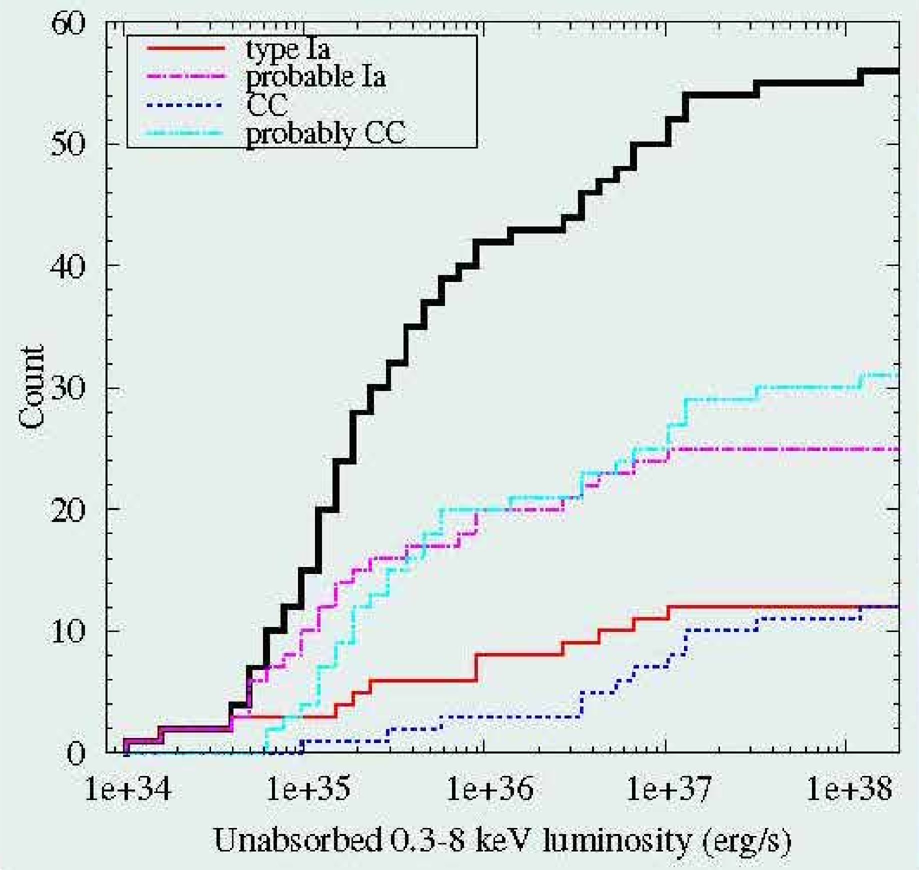


Star formation rate vs. cosmic time (from the LMC SFH maps of Harris & Zaritsky 2009)

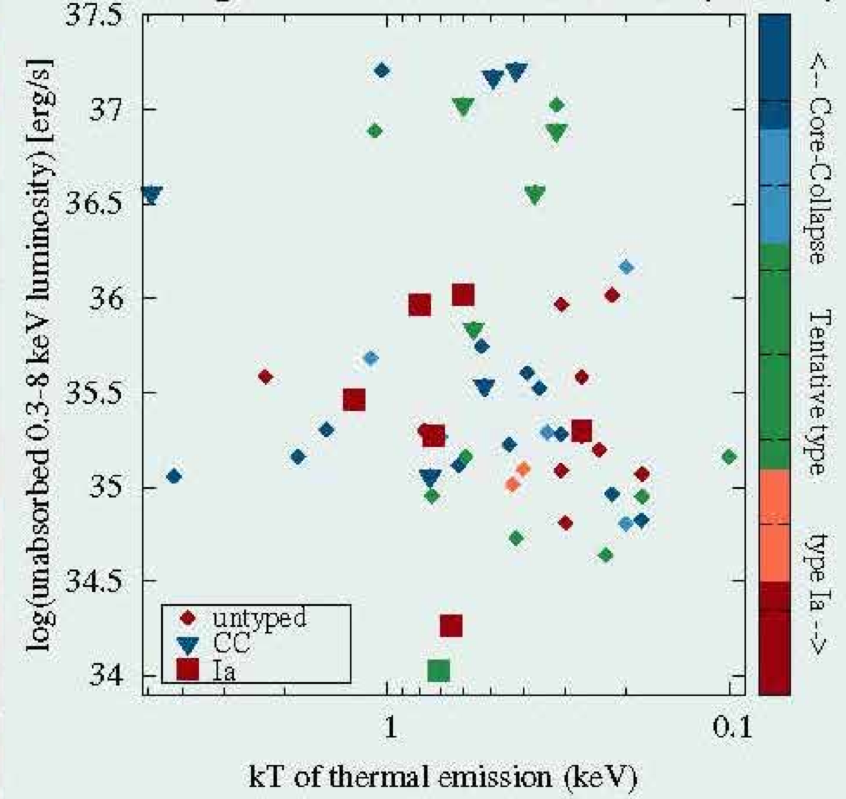


Credit: P. Maggi 2014

## Cumulative X-ray luminosity function




## Luminosity vs. X-ray temperature



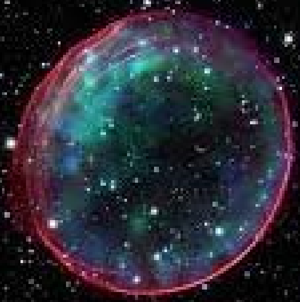

- The population of definitive and likely type Ia SNRs dominates the faint end.
- At same temperature, type Ia SNRs tend to have lower luminosities.

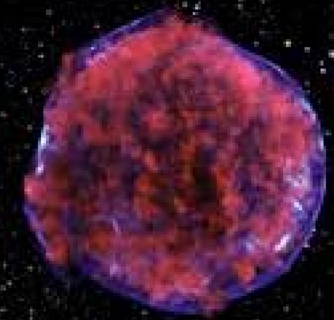
⇒ Likely an effect of the low density media where type Ia SD explode, compared to the denser star-forming region hosting core-collapse SNRs.

# Future Work

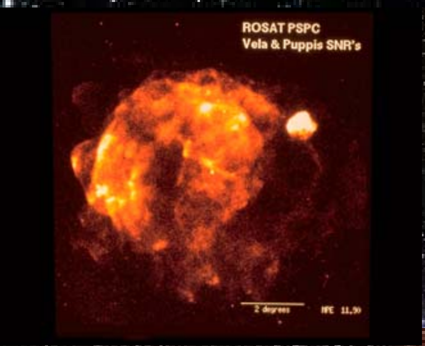

- Have an in-depth look into this new class of Type Ia SNRs proposed by Borkowski+ and see if we find any deviations form normal Type Ia remnants in the radio-continuum
- A better study of magnetic fields of SNRs, tracking evolution and observing the difference (if any) between the SNR types.
- Try to better constrain statistics by taking into account the local ISM density
- CTA + ASKAP/ATCA/MOPRA/MWA + eRosita + …

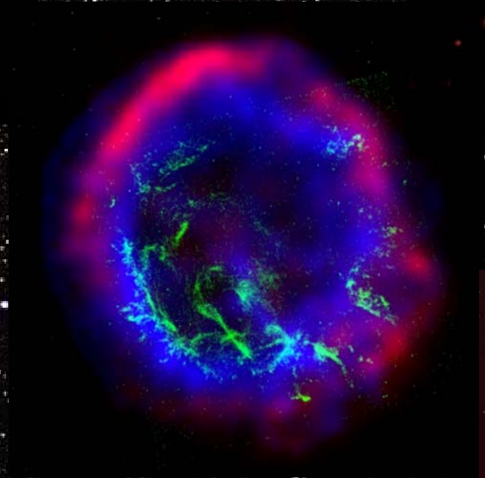

We're All Different!
Just Accept It.



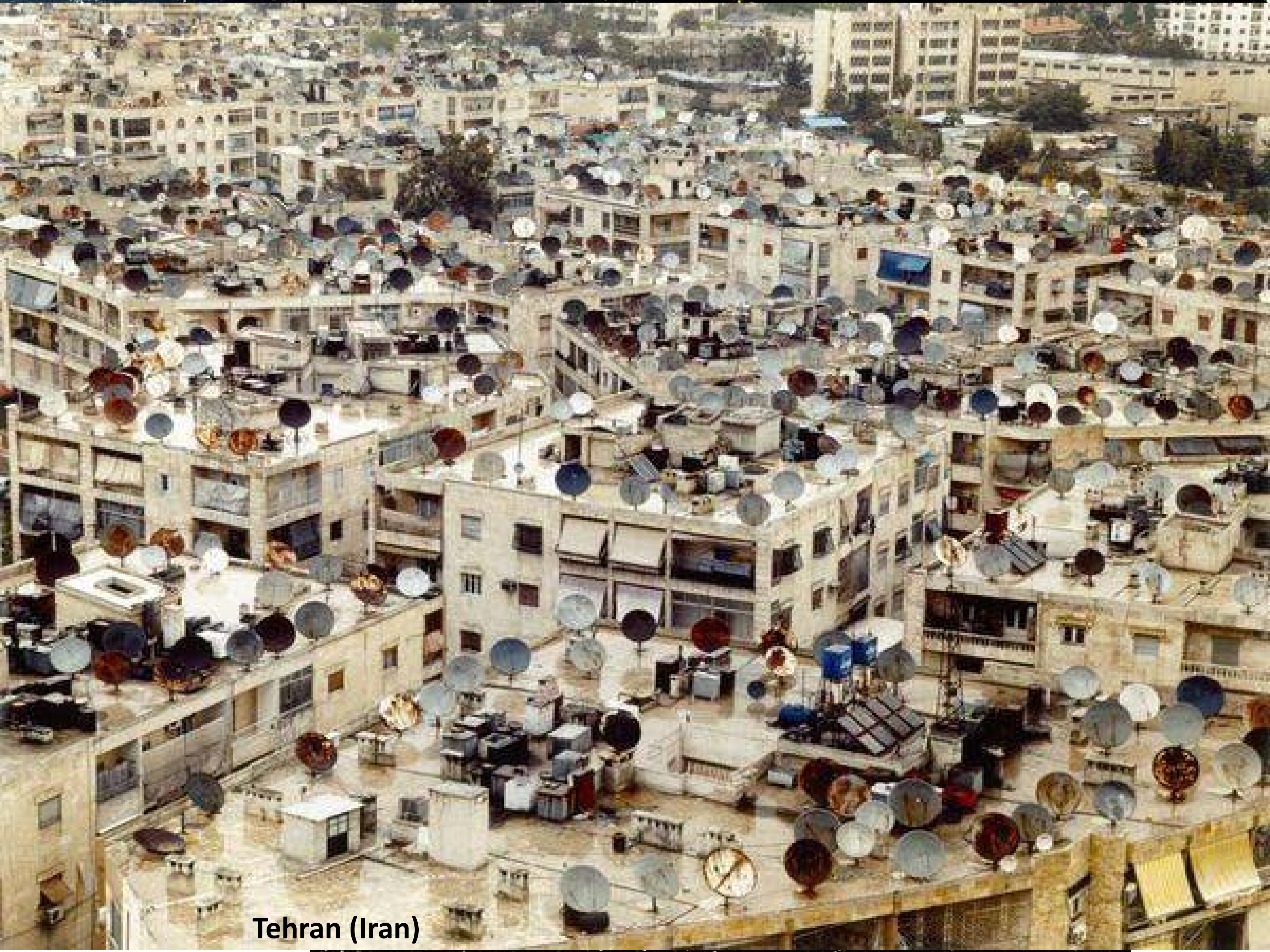


# We are all different!



# Just accept it!


Tehran (Iran)

# Thank You

**A universe made for life?**