On the Nova Super-Remnant Phenomenon

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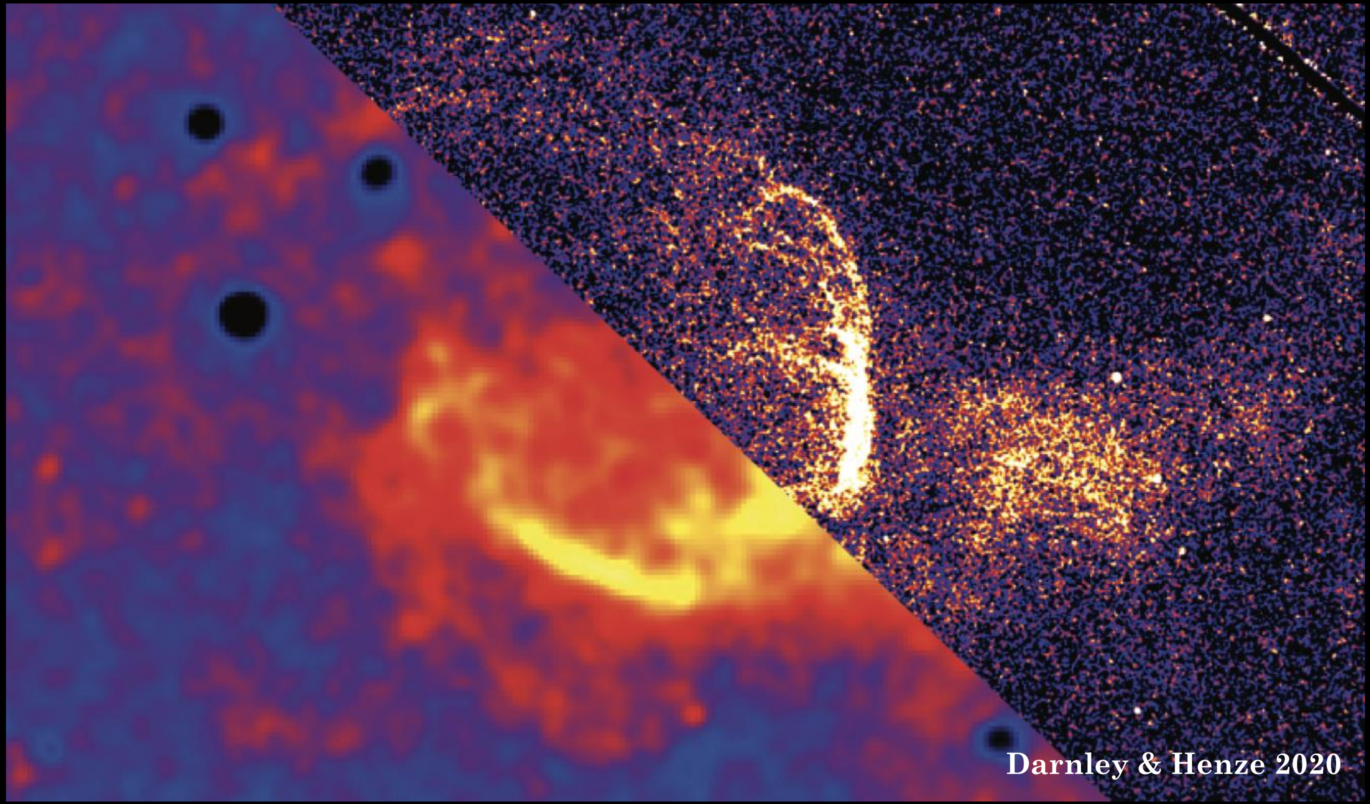


Symbiotic stars, weird novae, and related embarrassing binaries, Prague – 6th June 2024

What are recurrent novae?

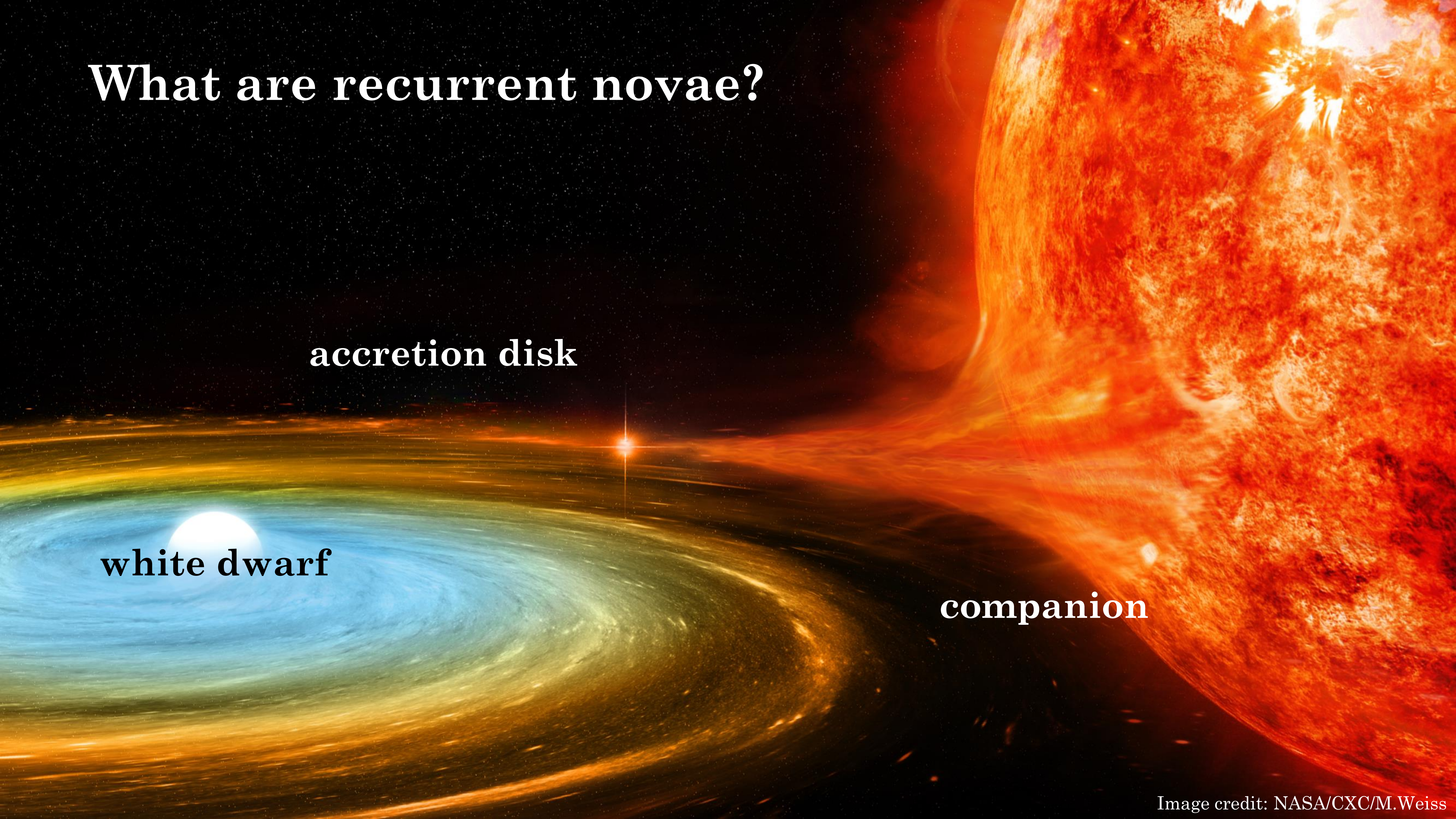


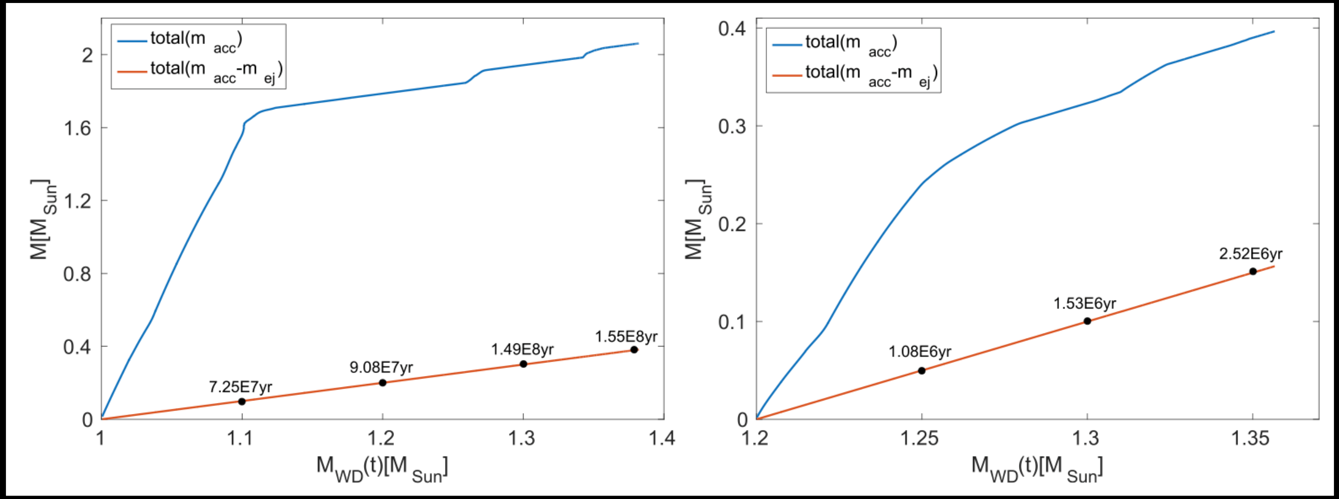
Image credit: NASA/CXC/M.Weiss

Progenitors of type Ia supernovae

Novae with a carbon-oxygen white dwarf provide a single degenerate evolutionary pathway towards **type Ia supernovae** (Whelan & Iben 1973)

Novae are the **brightest** of all SNe Ia progenitors

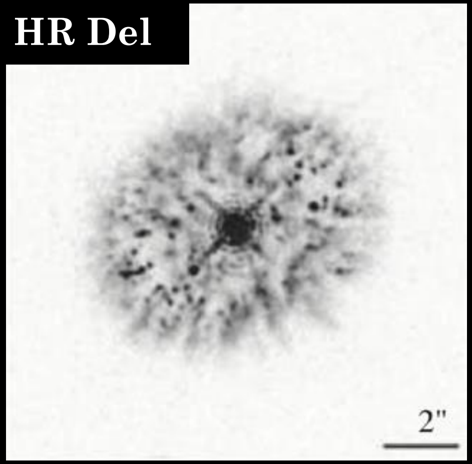
Many recent studies with multi-cycle nova eruption models have shown that white dwarfs **can grow in mass** towards the Chandrasekhar limit (Yaron et al. 2005, Hachisu et al. 2007, Kato et al. 2015, Hillman et al. 2015, Hillman et al. 2016, Starrfield et al. 2021)



Hillman et al. 2016

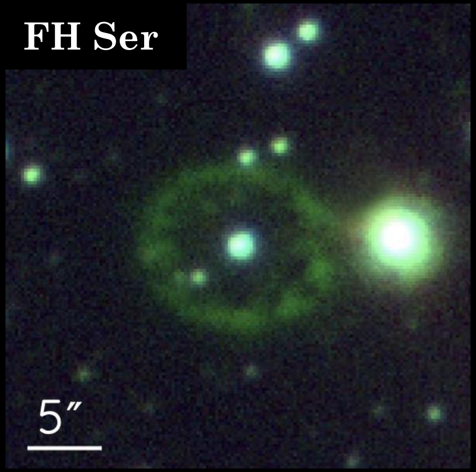
Nova shells

HR Del



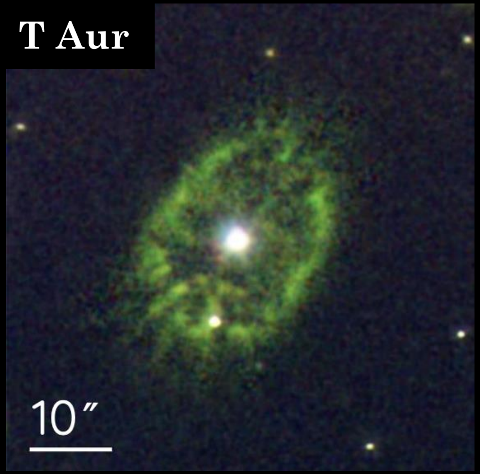
Bode & Evans 2008

FH Ser



Santamaría et al. 2020

T Aur



Santamaría et al. 2020

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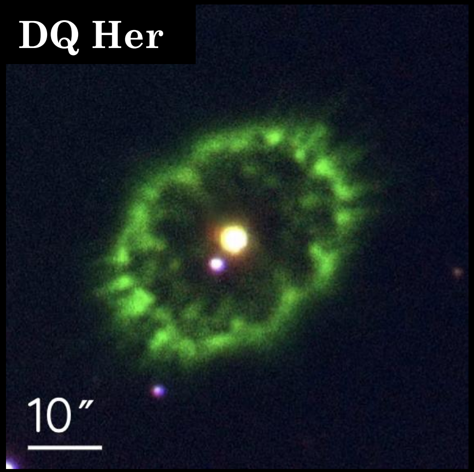

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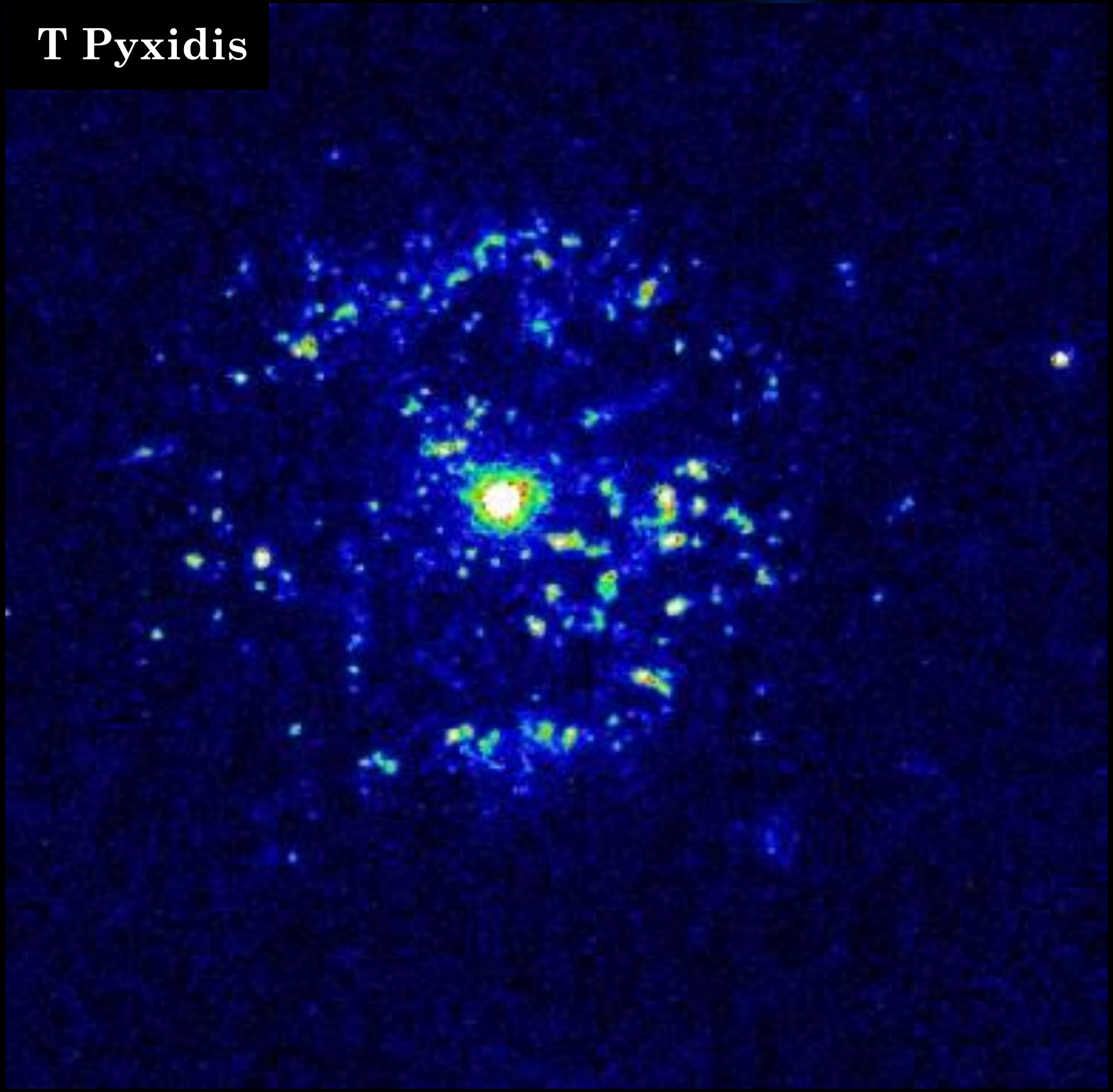


Shara et al. 1997, 2015

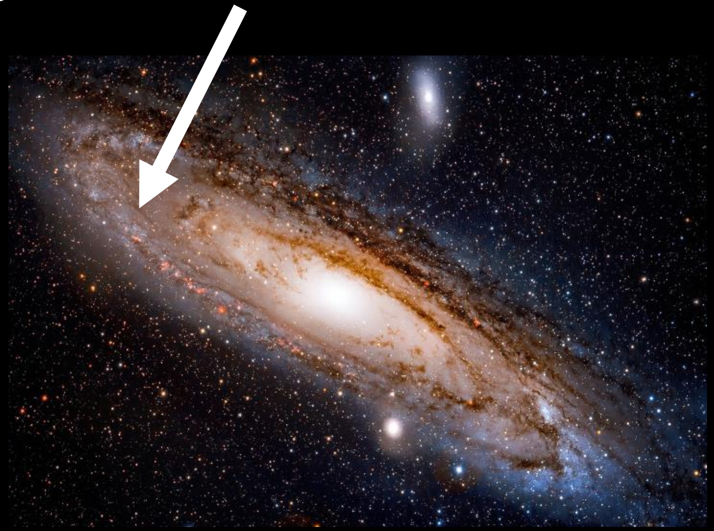
Nova Scorpii AD 1437 image credit: K. Ilkiewicz & J. Mikolajewska; GK Per image credit: X-ray: NASA/CXC/RIKEN/D.Takei et al; Optical: NASA/STScI; Radio: NRAO/VLA

Collection of recurrent novae

Galaxy	Number of RNe	Shortest Period	Recurrence Period
Milky Way	10 **(11)**	U Scorpii	~ 10 years
LMC	4	LMCN 1968-12a	~ 6 years
M31	20	M31N 2008-12a	~ 1 year

Pietsch 2010; Schaefer 2010; Hornoch & Shafter 2015; Shafter et al. 2015; Darnley et al. 2016a; Darnley et al. 2016b; Mroz & Udalski 2016; Sin et al. 2017; Kuin et al. 2018; Henze et al. 2018; Page, Kuin & Darnley 2020; Shafter et al. 2023 ; Schaefer et al. 2022; Shara et al. 2024

M31N 2008-12a Nova Super-Remnant



M31N 2008-12a is the fastest recurring nova: erupting annually

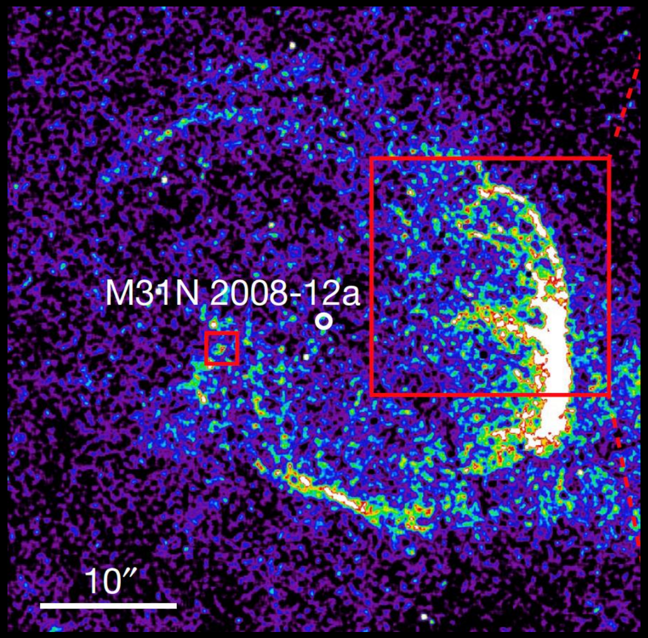
It is the **leading single degenerate progenitor** of a SN Ia:

- ▶ its WD accretes more mass than it ejects
- ▶ as such, its WD is growing towards the Chandrasekhar limit

Hα observations with the Liverpool Telescope to be used for photometry revealed a **vast nebulosity** coincident with the central nova

More observations over the next few years (including with *Hubble Space Telescope)* unveiled a structure **134 parsecs across** (Darnley et al. 2019)

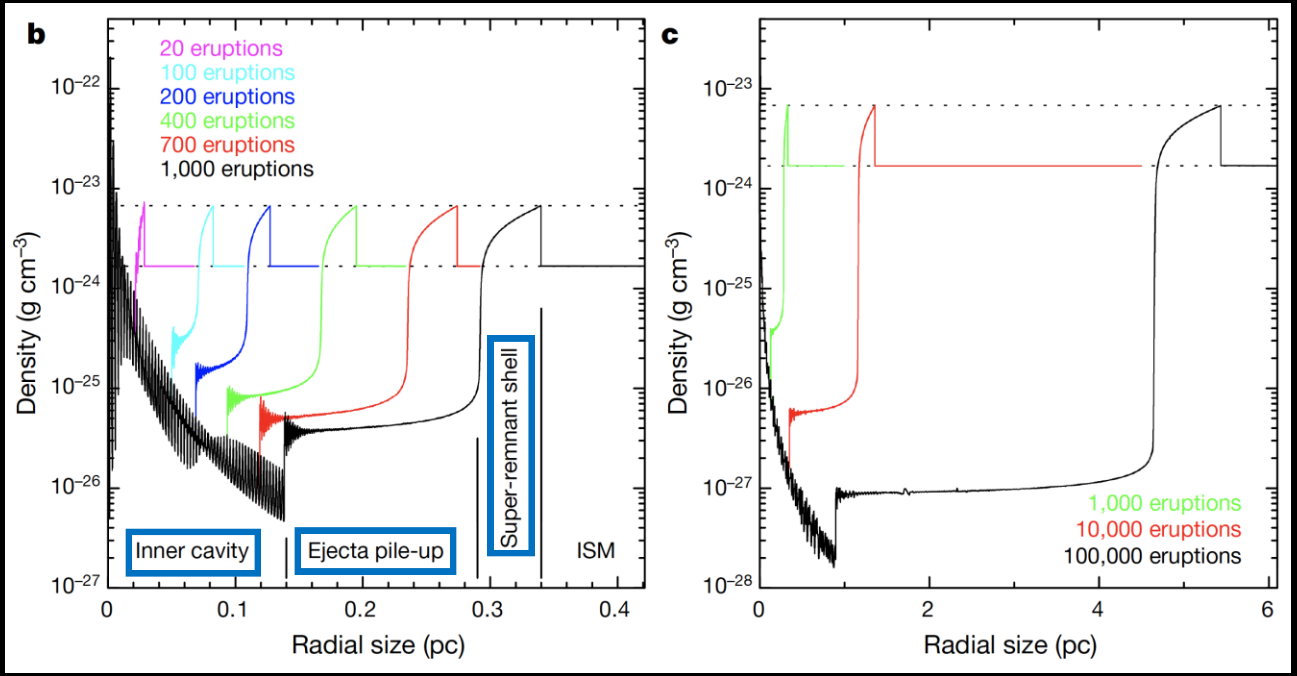
the first discovered **nova super-remnant**



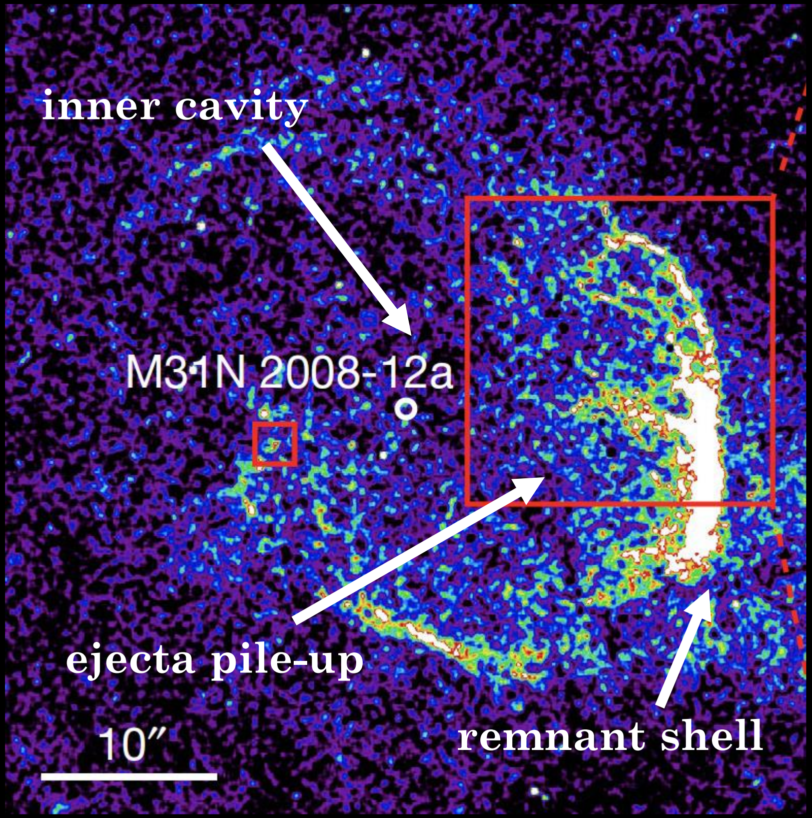
Darnley et al. 2019

Simulation of M31N 2008-12a NSR

A series of 1D hydrodynamical simulations of nova ejecta demonstrated that **repeated nova eruptions can sweep up the surrounding ISM into a shell** at the edge of the growing super-remnant (Darnley et al. 2019)

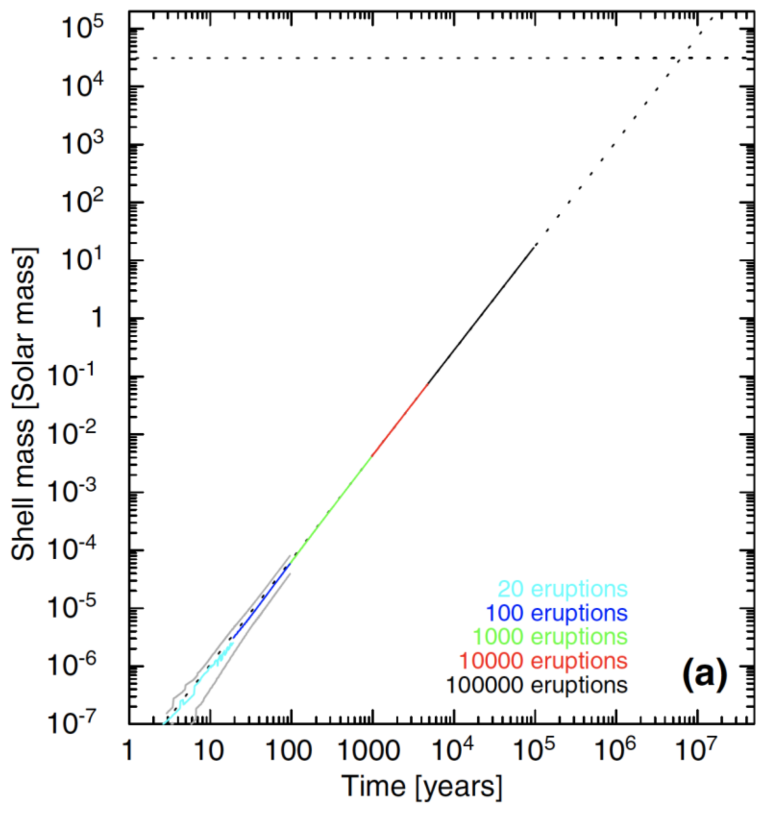


Darnley et al. 2019



Darnley et al. 2019

Simulation of M31N 2008-12a NSR



Darnley et al. 2019

NSR this size (67 pc) grown by annual nova eruptions sweeping up the surrounding ISM over **6×10^6 years**

Total mass swept up is about **$3 \times 10^4\, M_\odot$**

"the size and mass of this super-remnant demonstrate that 12a has not just been erupting frequently for a decade as observed, **but for millions of years**" (Darnley et al. 2019)

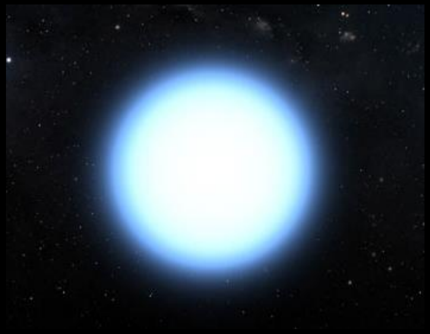
① Simulating more NSRs

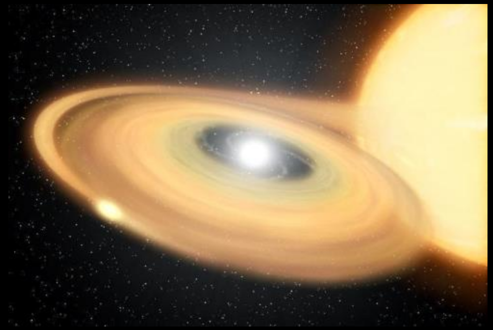
As the NSR surrounding 12a has grown as a result of frequent eruptions from 12a, we **should expect to see NSRs around other RNe** (Darnley & Henze 2020, Darnley 2021)

NSRs can also indicate a growing white dwarf close to the Chandrasekhar limit and therefore can inform us of **past or upcoming SN Ia**

To test whether other RNe should host NSRs, we **modelled the growth of NSRs** with simulated nova ejecta from growing (and eroding) WDs with differing system parameters including:

- ▶ interstellar medium density
- ▶ white dwarf temperature
- ▶ initial white dwarf mass
- ▶ mass accretion rate



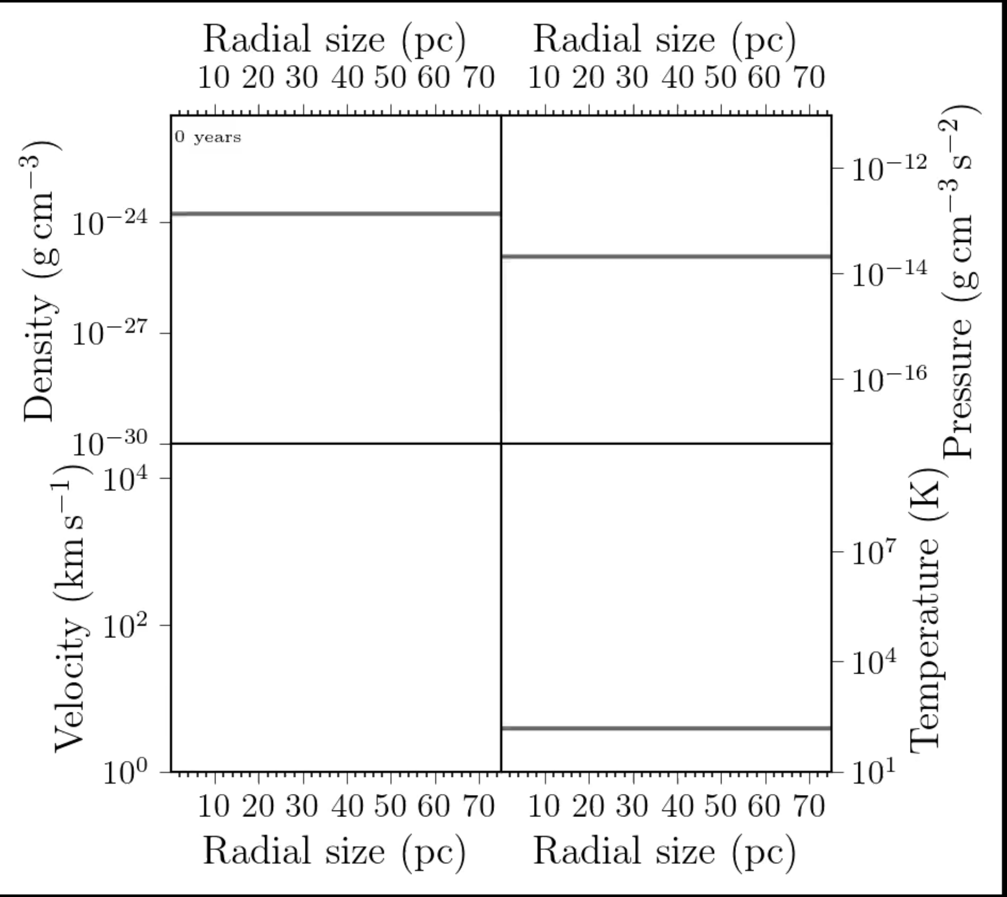


① Suite of NSR simulations

In Healy-Kalesh et al. 2023, we present a total of **26 simulations** with varying ISM, WD temperature, initial WD mass and accretion rate

Reference simulation with:

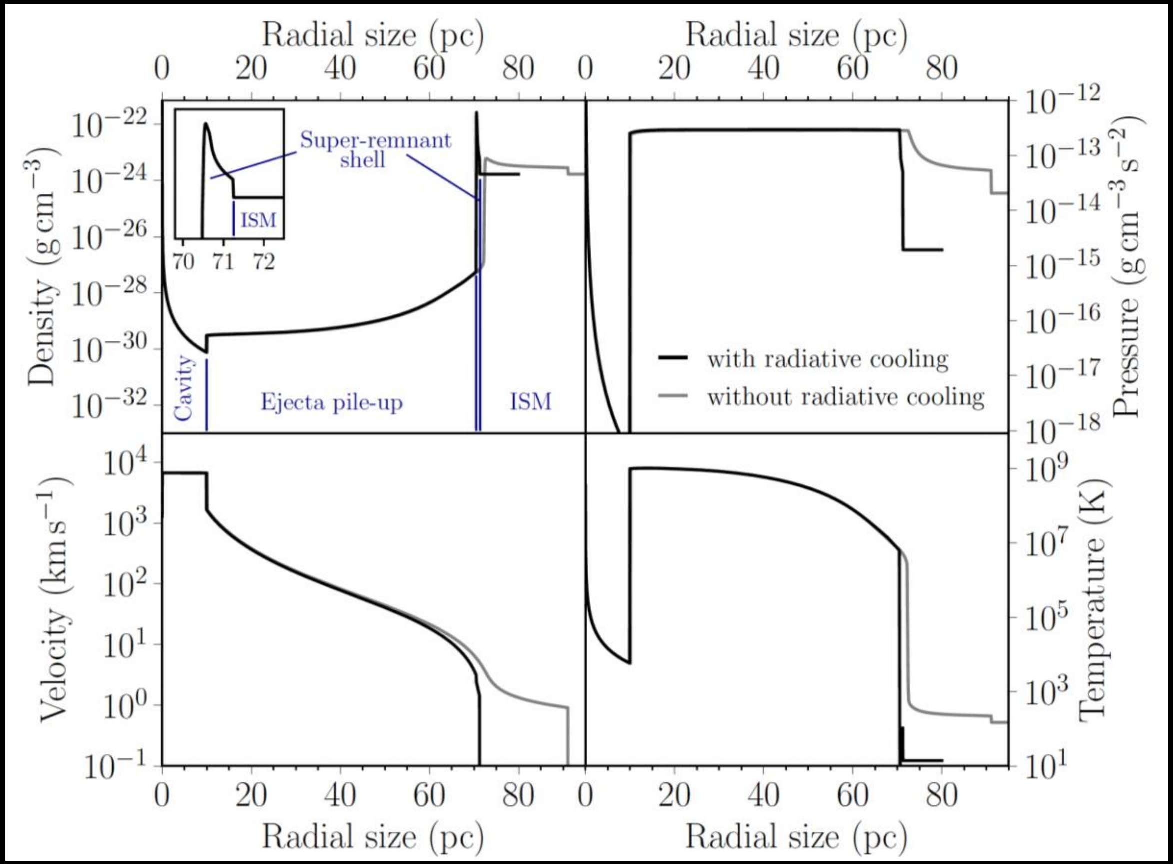
- ▶ ISM density – 1 hydrogen atom per cubic cm
- ▶ WD temperature – 10 million Kelvin
- ▶ initial WD mass – 1 solar mass
- ▶ accretion rate – 1/10000000 solar mass per year
- ▶ number of eruptions – 1,900,750
- ▶ evolutionary time – 31 million years
- ▶ resolution – 200 AU/cell



Healy-Kalesh et al. 2023

① Role of radiative cooling

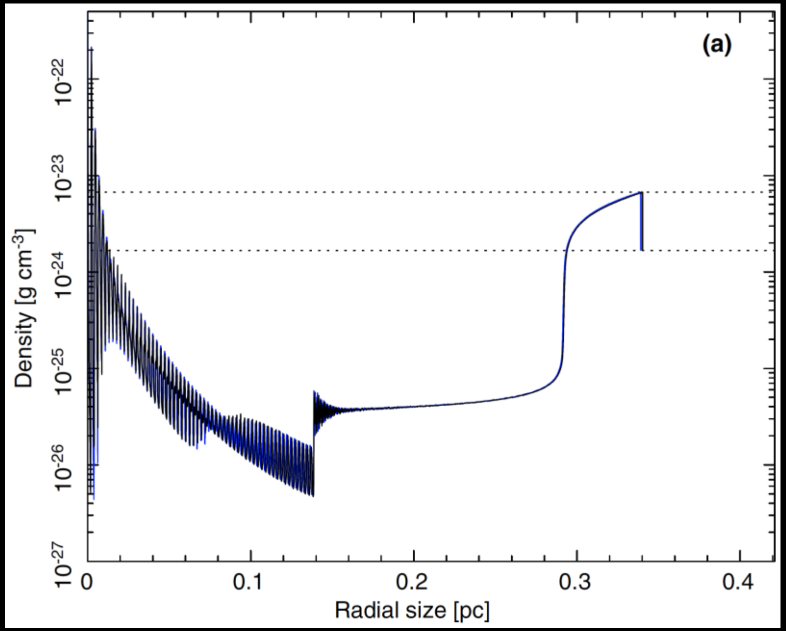
Radiative cooling **plays a key part** in the formation of dynamic NSRs



Healy-Kalesh et al. 2023

NSRs shells with incorporation of cooling are:

- ▶ significantly **thinner**
- ▶ significantly **denser**



Darnley et al. 2019

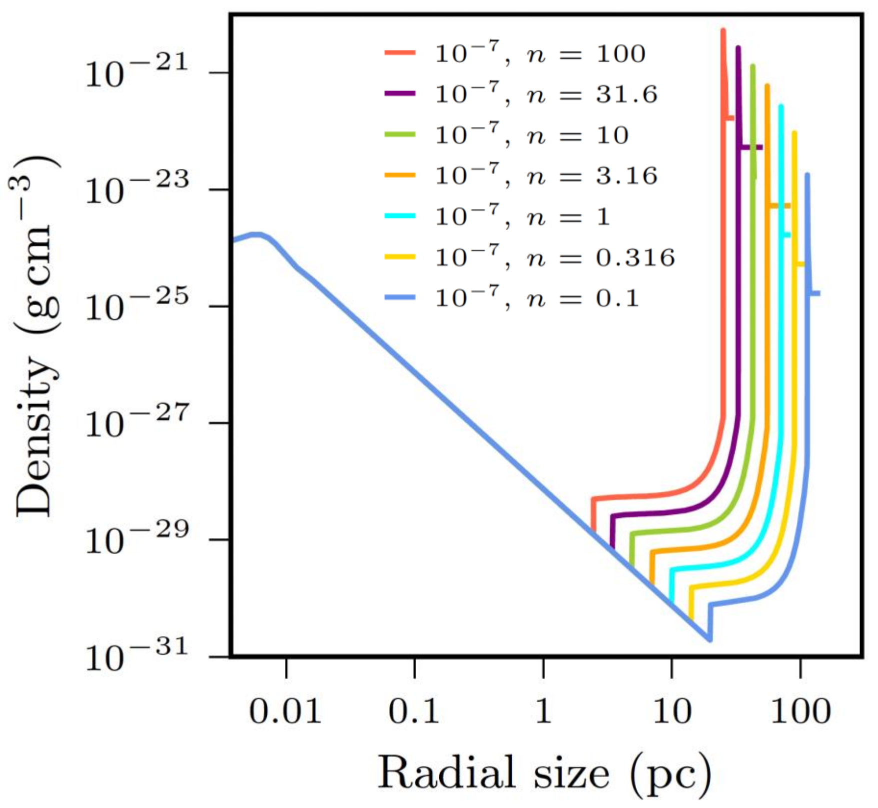
① System parameter influences on NSR growth

Large impact on NSR growth

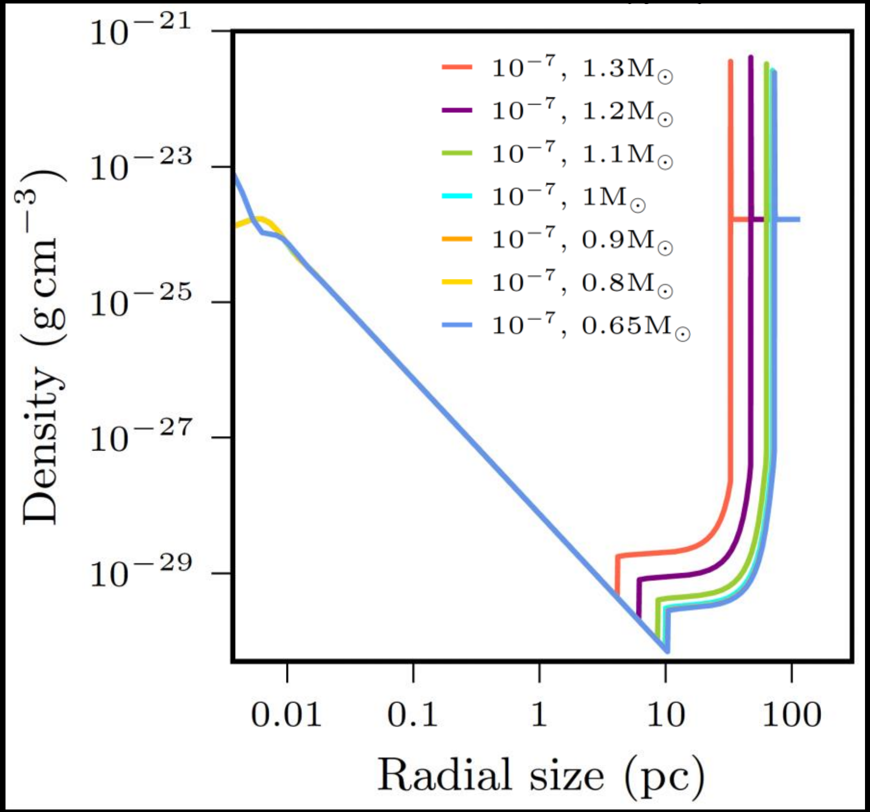
ISM density
mass accretion rate

Little impact on NSR growth

white dwarf temperature
initial white dwarf mass



Healy-Kalesh et al. 2023

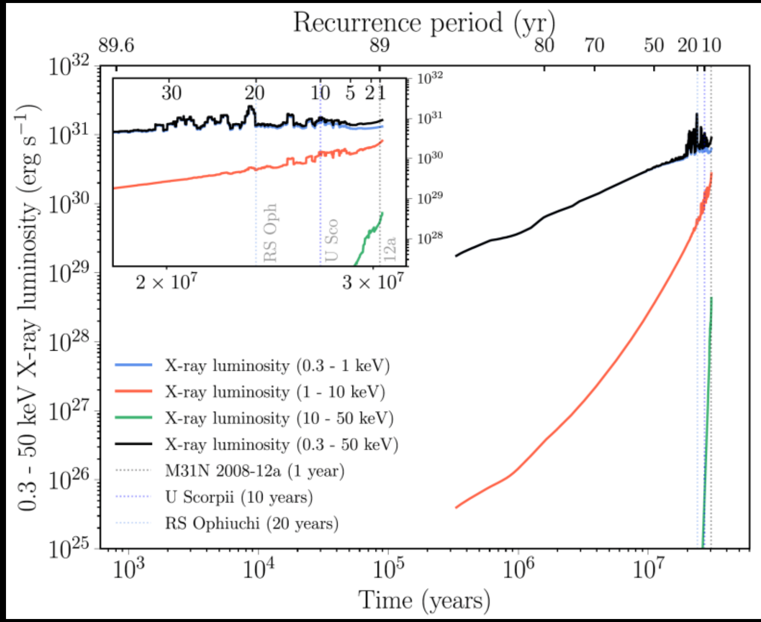


Healy-Kalesh et al. 2023

① Modelling NSR emission

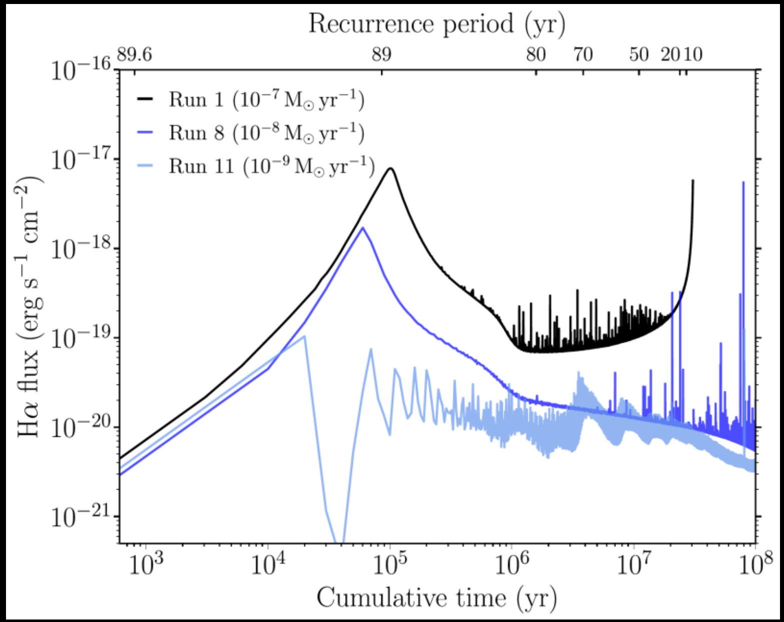
For the **X-ray emission** from NSRs:

- ▶ initially emission is negligible
- ▶ X-ray luminosity increases as recurrence period falls and the ejecta becomes more energetic
- ▶ harder emission from shock-heating as eruptions become more frequent and more energetic



For the **Hα emission** from NSRs:

- ▶ initially the emission increases as the early NSR shell sweeps the local ISM
- ▶ the shell temperature then decreases allowing for recombination and a drop in Hα flux
- ▶ Hα emission then increases as highly energetic eruptions impact the inner edge of the high density NSR shell

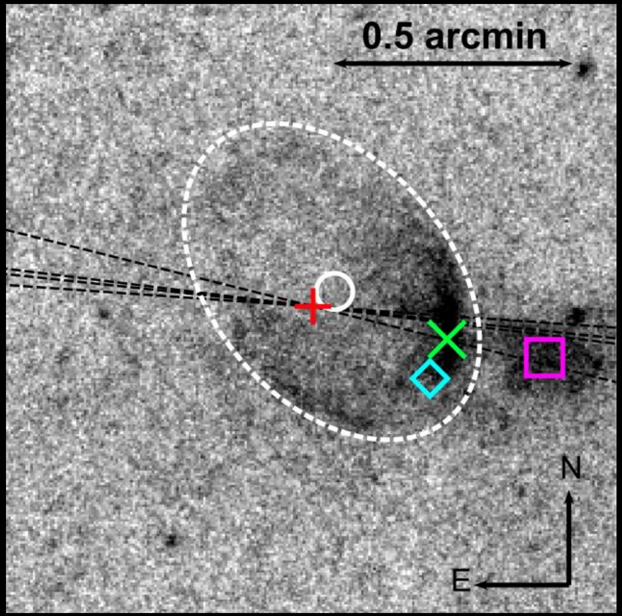


Healy-Kalesh et al. 2023

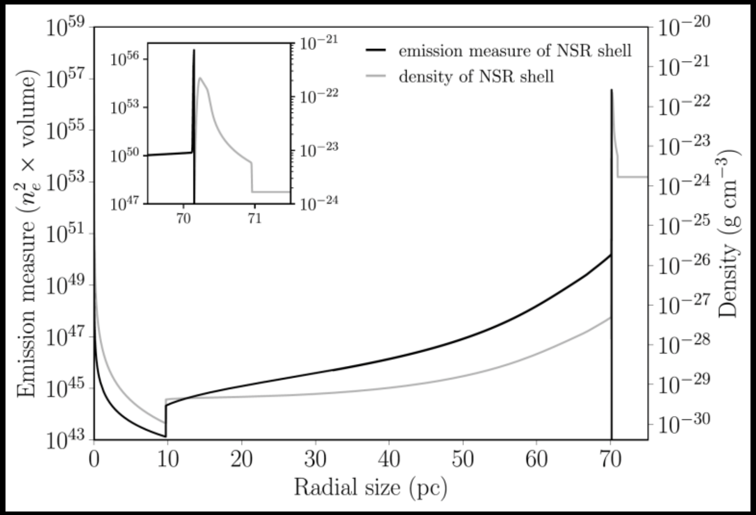
① Comparing the reference simulation to 12a NSR

Simulations that **most resemble 2008-12a** (ISM density and accretion rate) **can replicate the radial size** of the NSR but not the shell thickness
▶ other contributing factors in evolution and shaping not considered

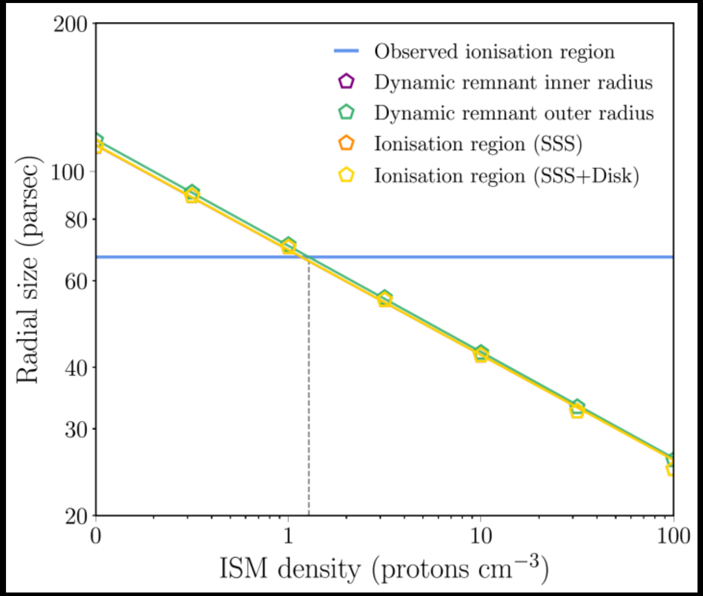
NSR around 2008-12a **not likely to be photoionisation structure**
▶ Hα emission should be from the inner edge of the NSR shell



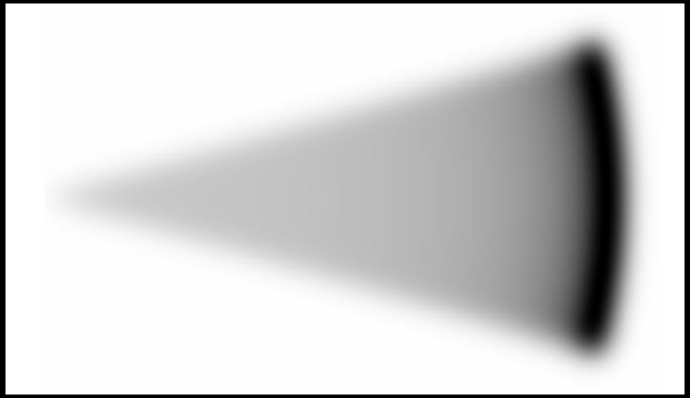
Darnley et al. 2015



Healy-Kalesh et al. 2023



Healy-Kalesh et al. 2023

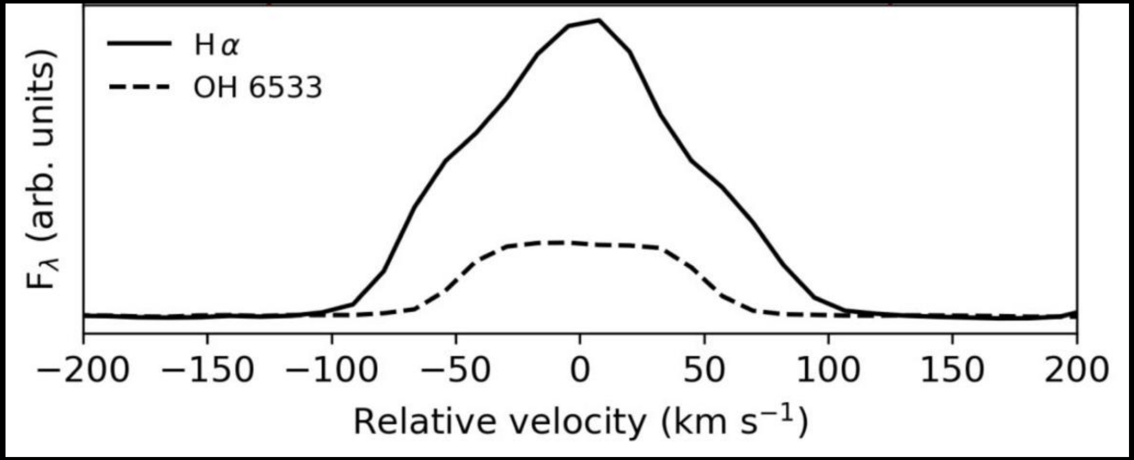

Healy-Kalesh et al. 2023

NSR around KT Eridani

The Condor Array Telescope was used to image the surroundings of **KT Eridani**, unveiling **another nova super-remnant** (Shara et al. 2024)

This shell has a **diameter of ~50 parsecs** and is most prominent through its **Hα emission** (Shara et al. 2024)

SALT spectra show **Hα emission lines** with velocities of up to 125 km/s, **consistent with the range of velocities in the 12a NSR** (Shara et al. 2024)



Shara et al. 2024

Shara et al. 2024

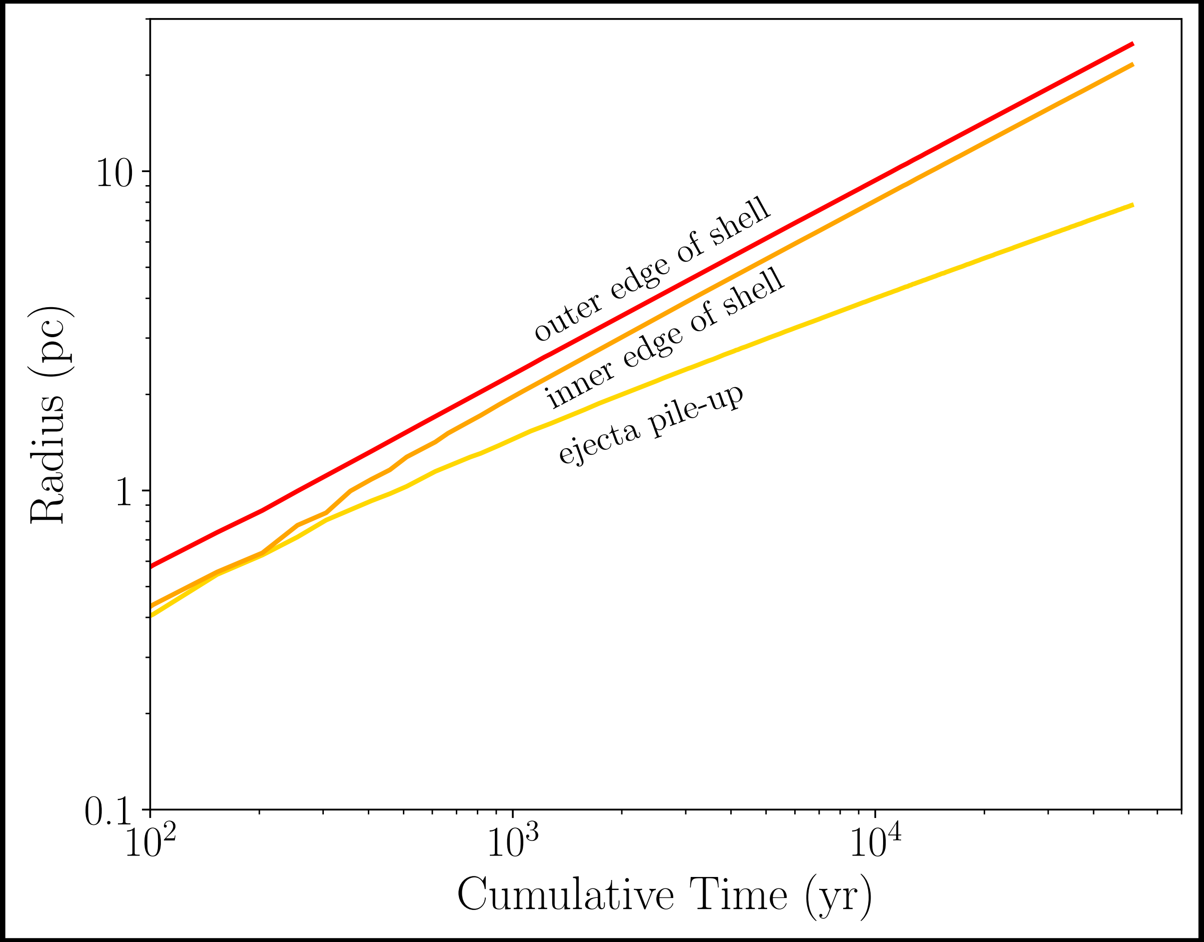
② Modelling KT Eridani NSR

Ran 20 simulations to grow a NSR to a radius of **25 parsecs to match the observed shell**

Vary recurrence period: 5, 10, 20, 50, 100 years
Vary ejecta velocity: 4000, 5000, 6000 km/s

Reference simulation with:

- ▶ recurrence period – 50 years
- ▶ ejecta velocity – 6000 km/s
- ▶ ISM density – 0.002 H atom per cubic cm
- ▶ ejected mass – 0.00001785 solar masses
- ▶ resolution – 1000 AU/cell
- ▶ number of eruptions – 1,019
- ▶ evolutionary time – ~50 thousand years



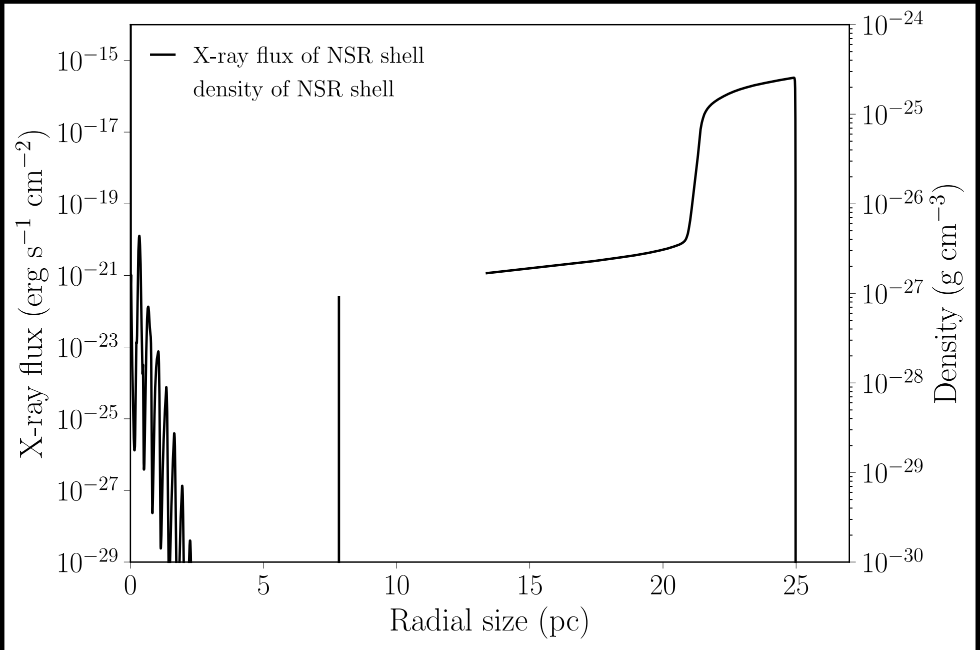
Healy-Kalesh et al. 2024c

Consistent with **KT Eri remaining within its shell** (Shara et al. 2024)

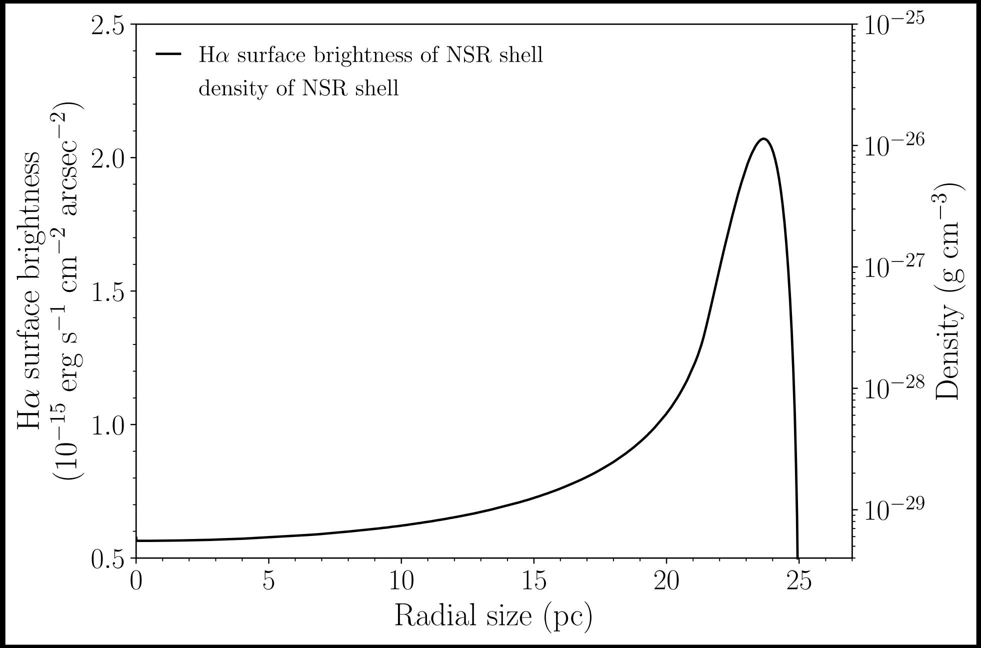
② Modelling KT Eridani NSR emission

Predicted X-ray luminosity of whole NSR suggests that the **structure may be accessible** to wide-field X-ray facilities

Predicted Hα surface brightness of the shell **is ~20–50 times** larger than measured for the observed shell



Healy-Kalesh et al. 2024c



Healy-Kalesh et al. 2024c

Factors affecting this estimate could be the ISM density chosen, assuming ISM is purely hydrogen, the assumed eruption history or the cooling package

Most significant factor is **assumption of spherical symmetry** of the ejecta and ISM

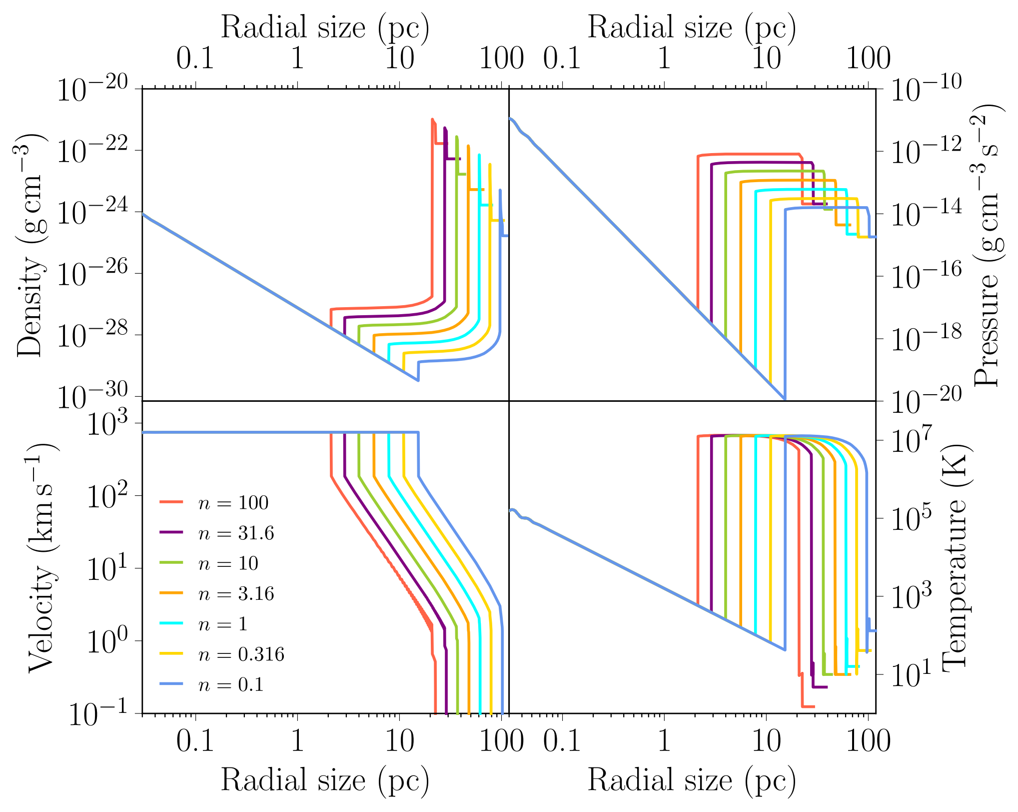
③ NSR cavity around RS Ophiuchi

We utilised the grid of simulations from Healy-Kalesh et al. 2023 to find the **dynamics of a NSR surrounding RS Ophiuchi** (with a recurrence period of 15 years)

ISM density in the region around RS Oph estimated to be closest to 0.1 hydrogen atom per cubic cm

NSR grown in surrounding ISM with density of 0.1 hydrogen atom per cubic cm has a shell ~100 parsec and **a cavity ~16 parsec**

This equates to angular size of 280 arcmin for the shell and **40 arcmin for the cavity**



Healy-Kalesh et al. 2024b

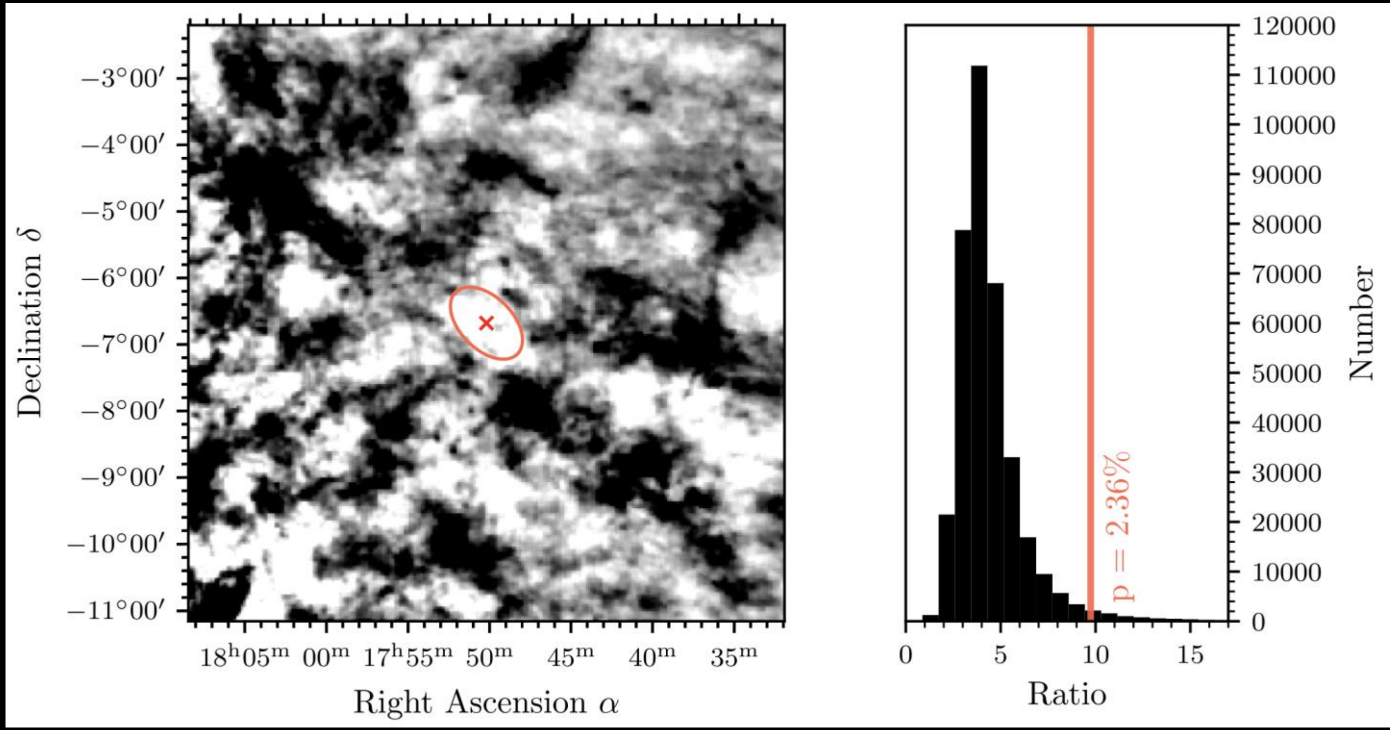
③ Possible NSR cavity around RS Ophiuchi

Discovered a cavity around RS Oph in IRIS (Improved Reprocessing of the IRAS Survey) data with semi-major and –minor axes of approximately **40 arcmin and 12 arcmin**

This equates to a **physical size of 16 x 5 parsecs**

We find that the probability of finding a cavity-like structure such as this in the same vicinity of the sky is **< 2.36%** so the **location of this cavity is significant**

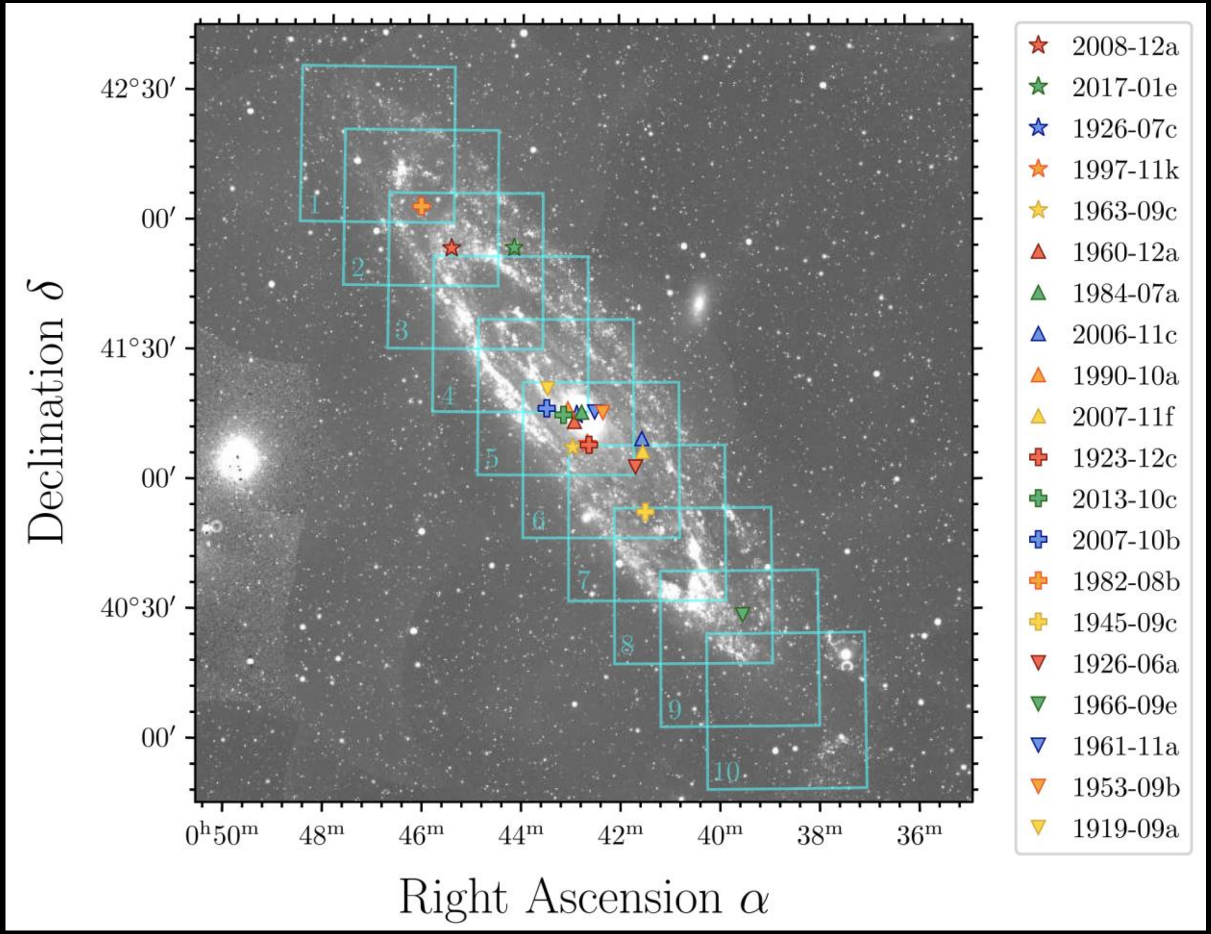
If a Hα shell were to be found surrounding RS Oph then this would confirm that the cavity is a part of **another nova super-remnant…**



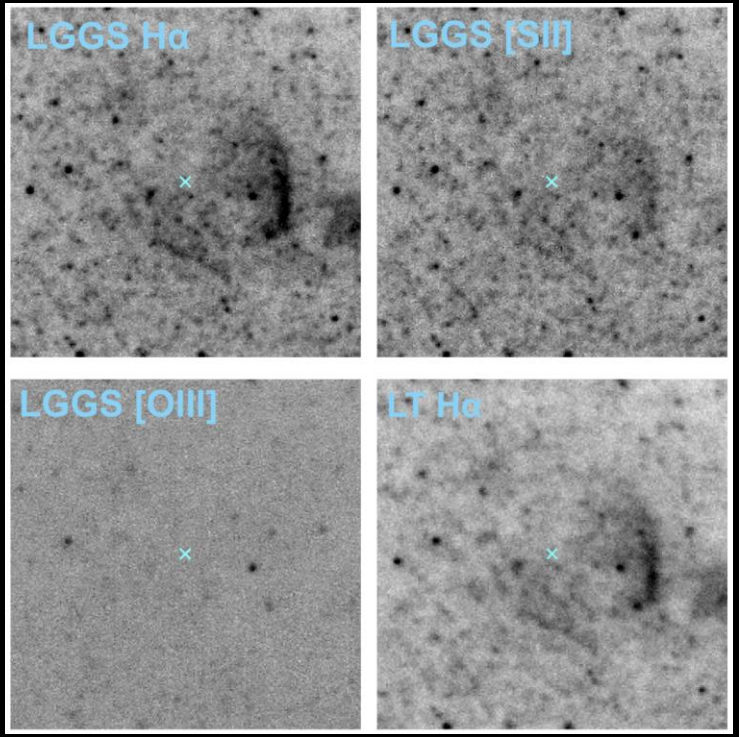
Healy-Kalesh et al. 2024b

④ NSR survey of M31 and targeted search in LMC

LGGS images covering the whole of M31 in Hα, [SII] and [OIII]



Healy-Kalesh et al. 2024a



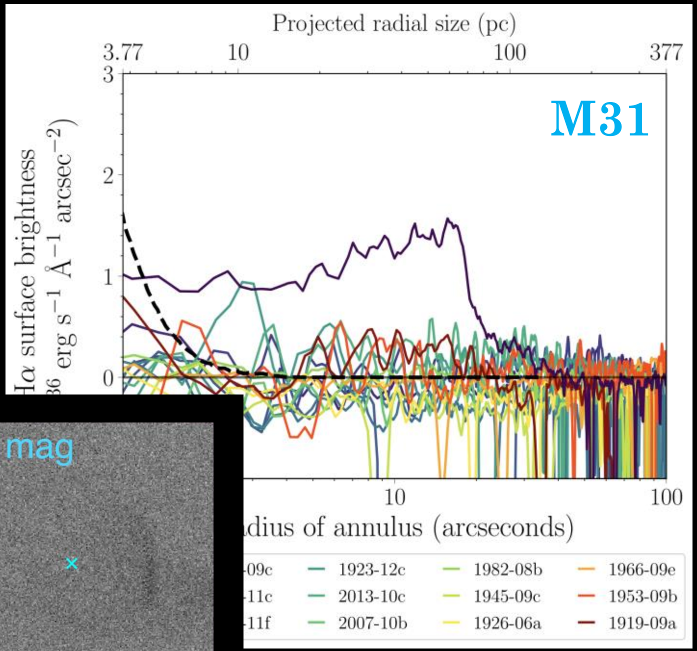
Healy-Kalesh et al. 2024a

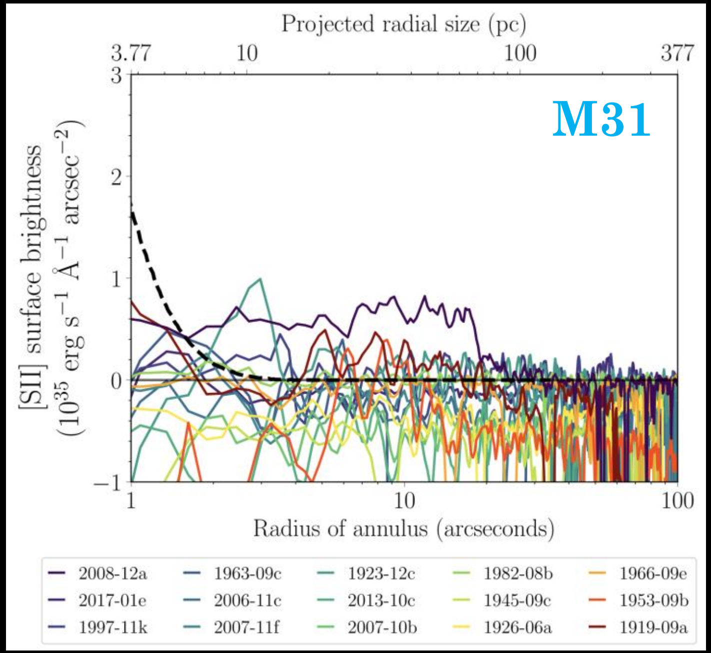
NSR around 2008-12a **visible in Hα and [SII],** but not [OIII]

Search around other 19 RNe in M31 and 4 RNe in the LMC for signs of NSRs

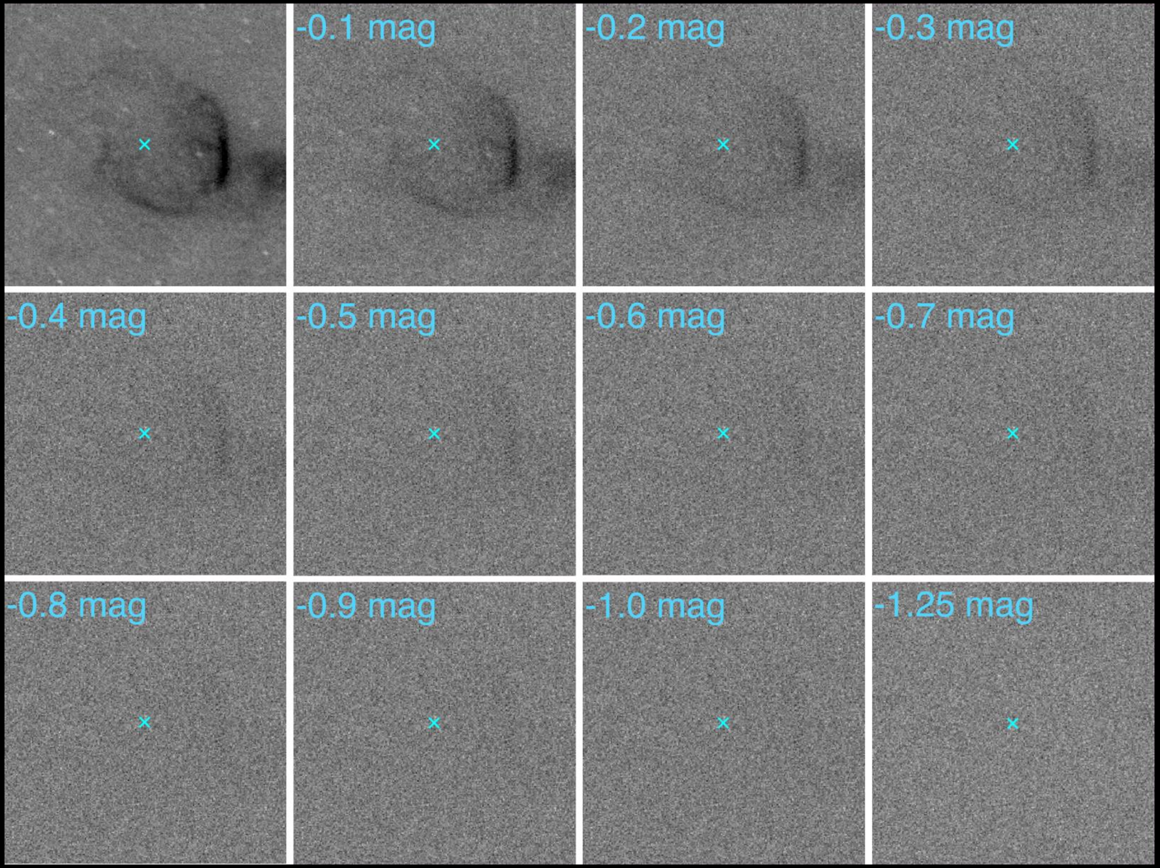
④ ~~A~~ Apparent dearth of NSRs

Surroundings of 14 recurrent novae in M31 and 4 recurrent novae in the LMC **show no evidence for NSRs**





Healy-Kalesh et al. 2024a

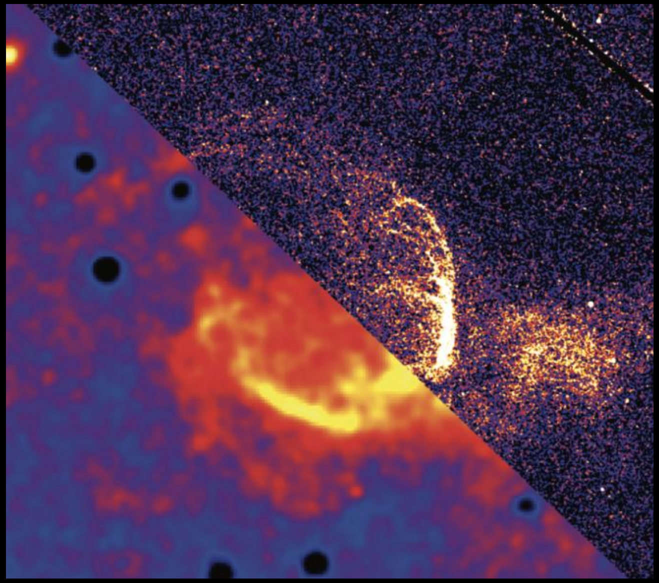


Intrinsic faintness of NSRs surrounding 'younger' systems (Healy-Kalesh et al. 2023) may explain absence of NSRs around other systems in these observations

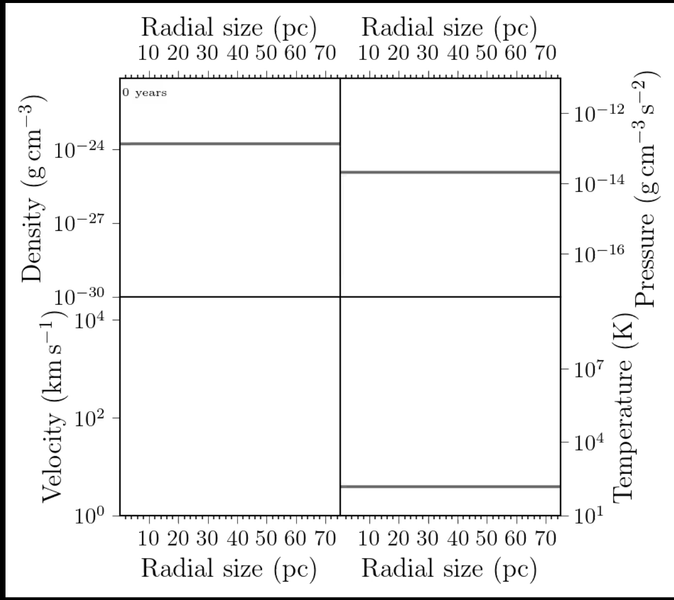
Though the NSR surrounding 12a **would likely have been missed if it were ~1 mag fainter** (Healy-Kalesh et al. 2024a)

Summary

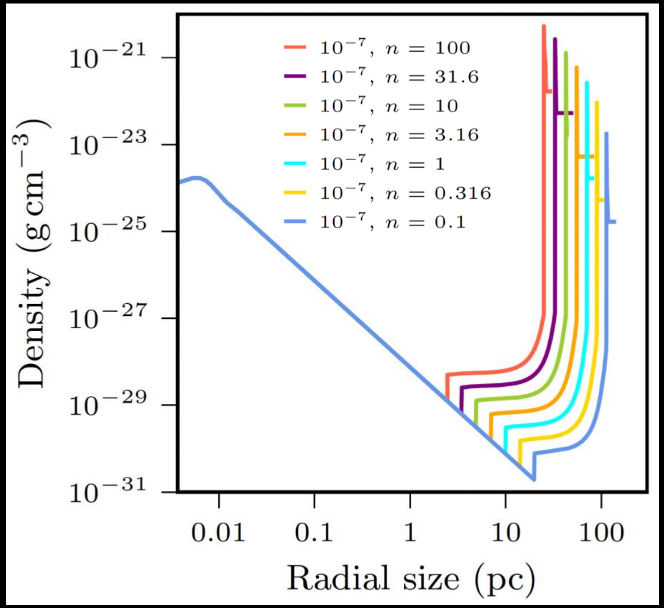
- Prototypical **nova super-remnant** grown through frequent eruptions from the most rapidly recurring nova, M31N 2008-12a (Darnley et al. 2019)
- Extensive hydrodynamical simulations indicate that **all RNe should host a nova super-remnant** (Healy-Kalesh et al. 2023)
- **Another nova super-remnant** discovered around putative RN, **KT Eridani** (Shara et al. 2024) … modelling reveals NSR can be grown to current size in **~50,000 years** (Healy-Kalesh et al. 2024c)



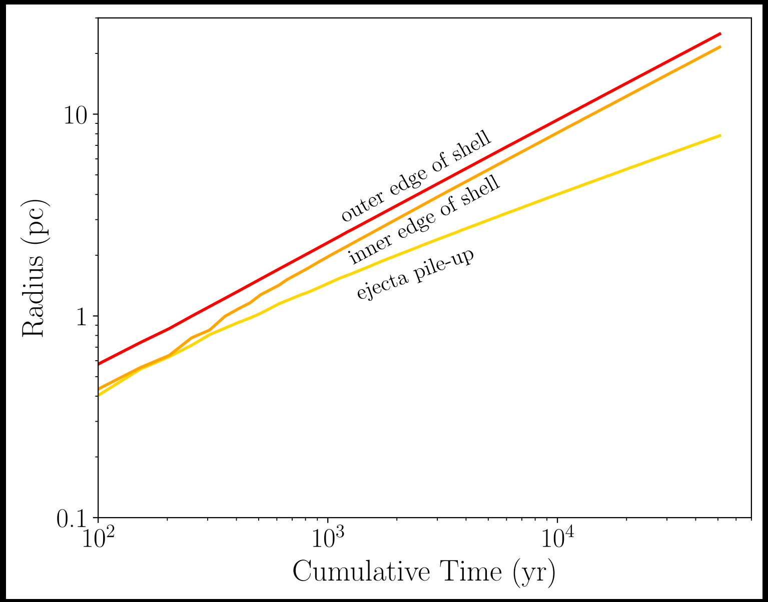
Darnley & Henze 2020



Healy-Kalesh et al. 2023



Healy-Kalesh et al. 2023

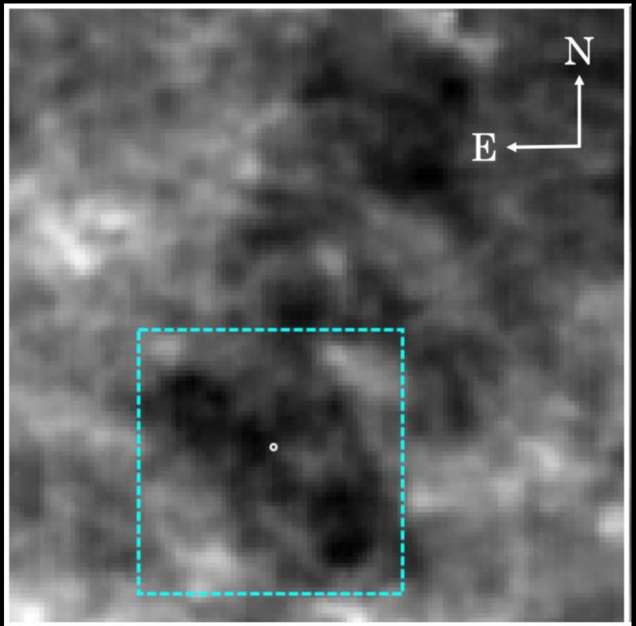


Healy-Kalesh et al. 2024c

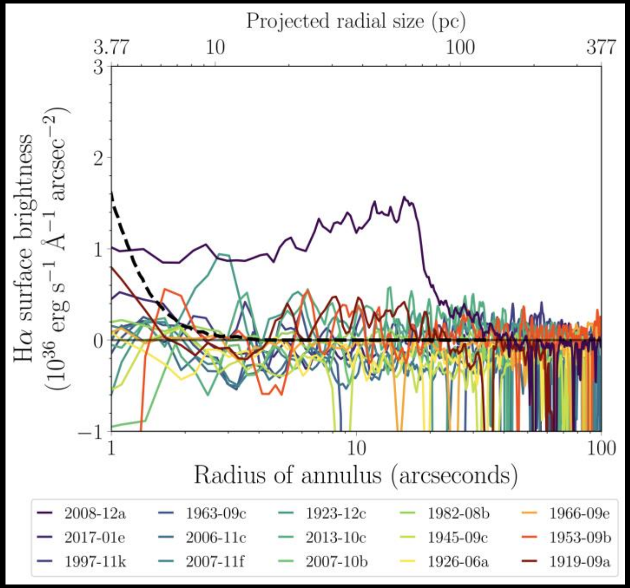
Summary

- Cavity of **another nova super-remnant** surrounding RN, RS Oph, discovered within far-infrared archival data (Healy-Kalesh et al. 2024b)

- To date we have **not found evidence for any other nova super-remnant in M31 or the LMC**, likely due to their intrinsic faintness and the **12a NSR would have been missed if ~1 mag fainter** (Healy-Kalesh et al. 2024a)



Healy-Kalesh et al. 2024b



Healy-Kalesh et al. 2024a

Moving forward

- **Deeper imaging** of surroundings of M31 and LMC novae
- Search for **more nova super-remnants** around other nova systems in **Hα, X-ray** and **IR regimes**
- **Develop modelling** of currently identified nova super-remnants
- **Conduct surveys of other Local Group galaxies** to look for nova super-remnants

Thank you for listening!