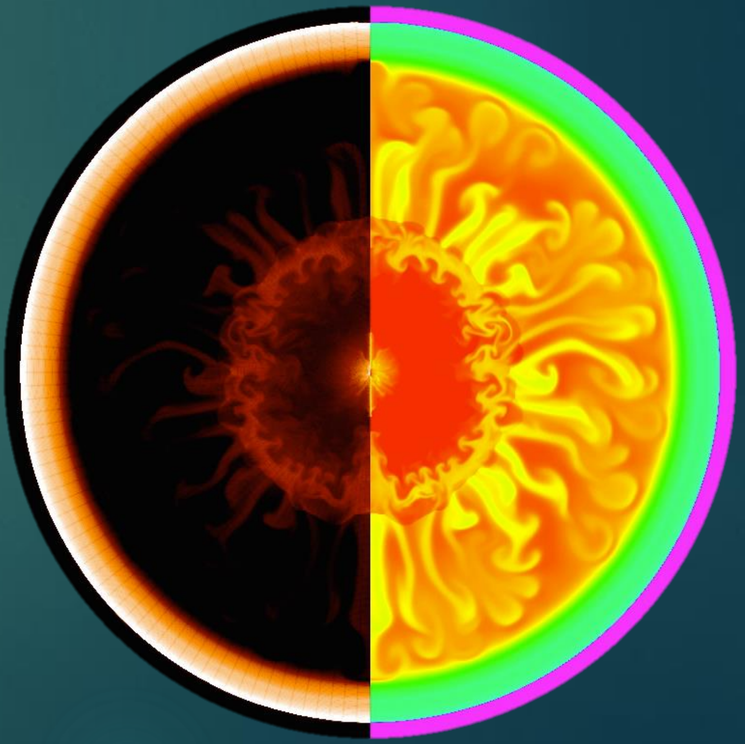
SUPERNOVA REMNANTS III
AN ODYSSEY IN SPACE AFTER STELLAR DEATH
9-15 June 2024, Chania, Crete, Greece

On the interaction of supernova remnants with their circumstellar medium

review talk

Alexandros Chiotellis

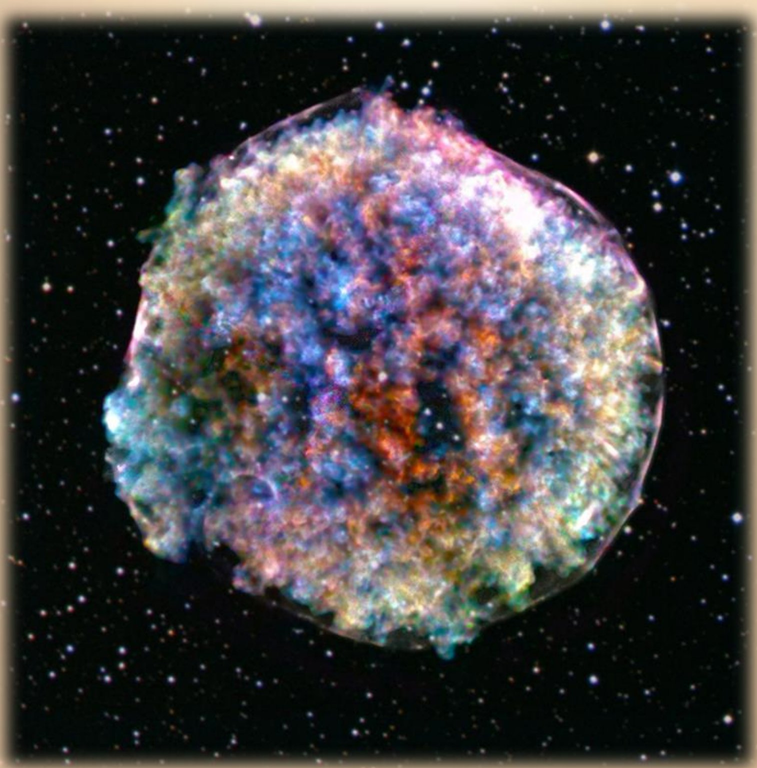
National Observatory of Athens



The physics of Supernova Remnants

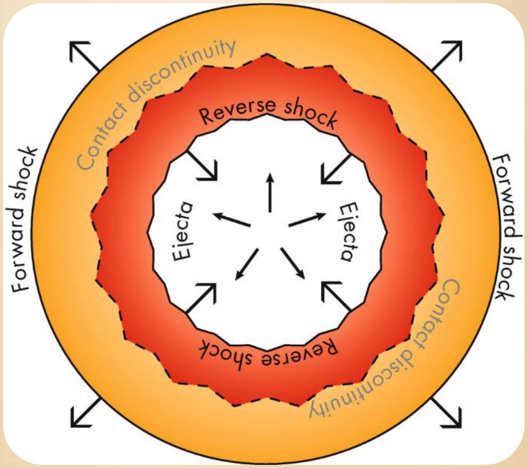
Students Handbook

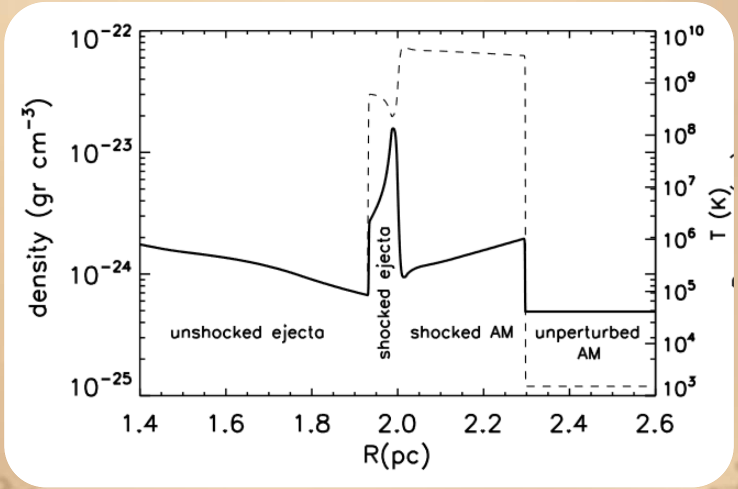
SNRs result by the interaction of the supersonically moving ejecta with their ambient medium



Structure:

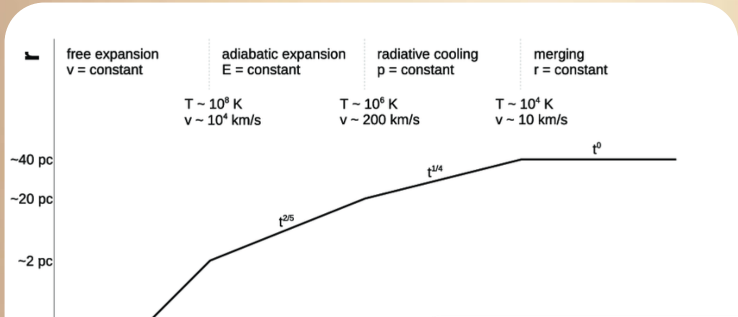
- Forward shock (or blast wave)
- Reverse shock
- Contact discontinuity

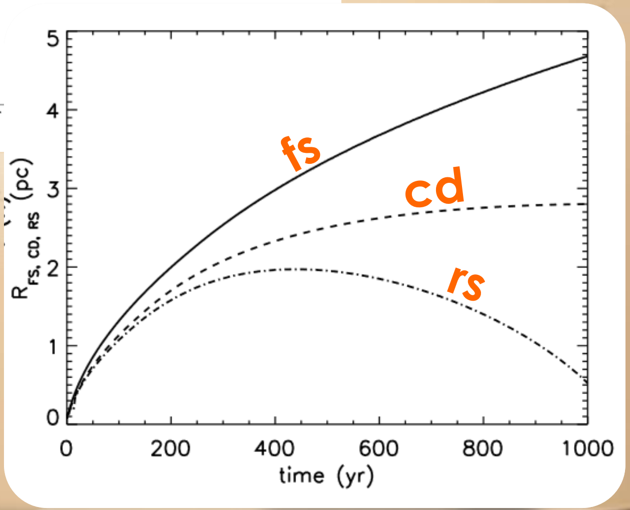




Evolution:

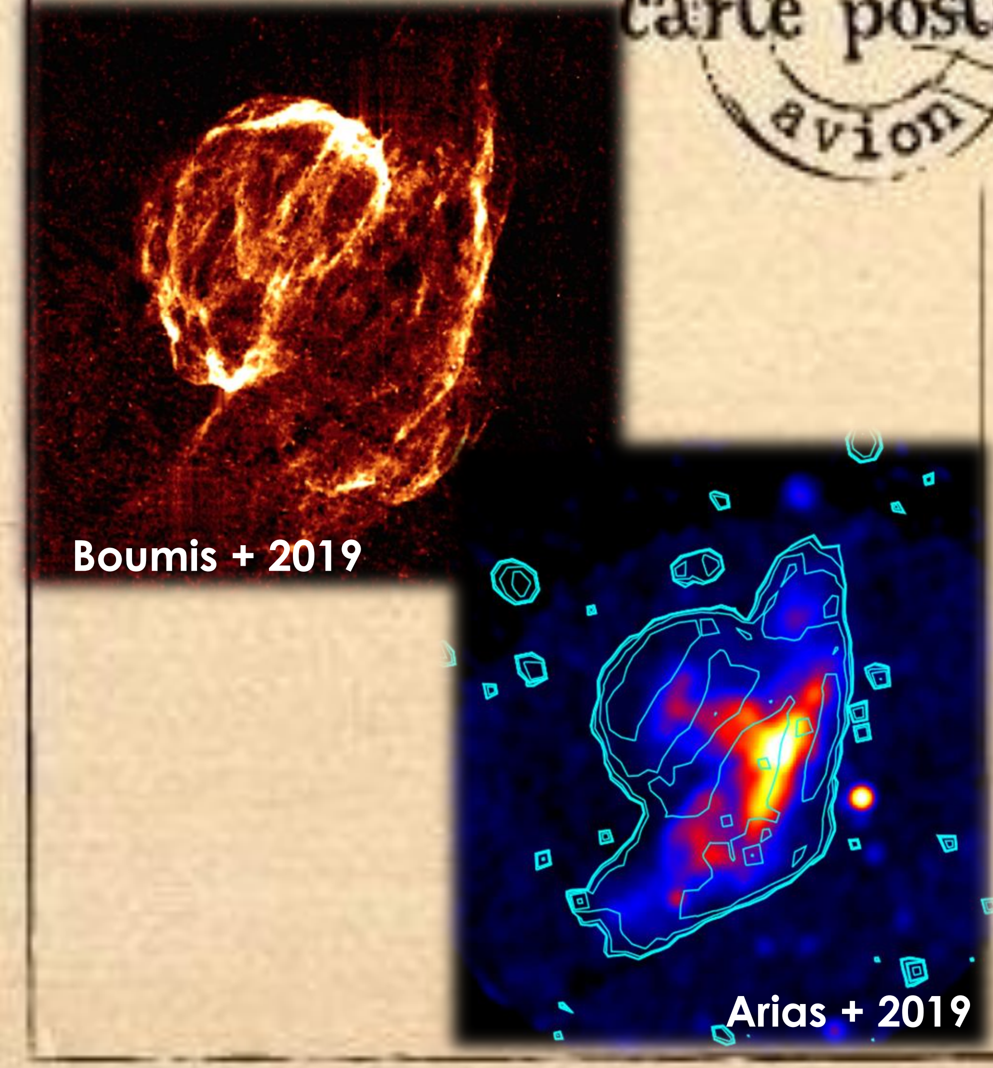
- Free expansion phase (m= 1)
- Sedov-Taylor phase (m = 0.4)
- Snowplow-phase (m=0.3)
- Momentum driven phase (m=0.25)
- Merge with the ambient medium





par
carte postale
avion

33USA
RING NEBULA
2000


Boumis + 2019

Arias + 2019

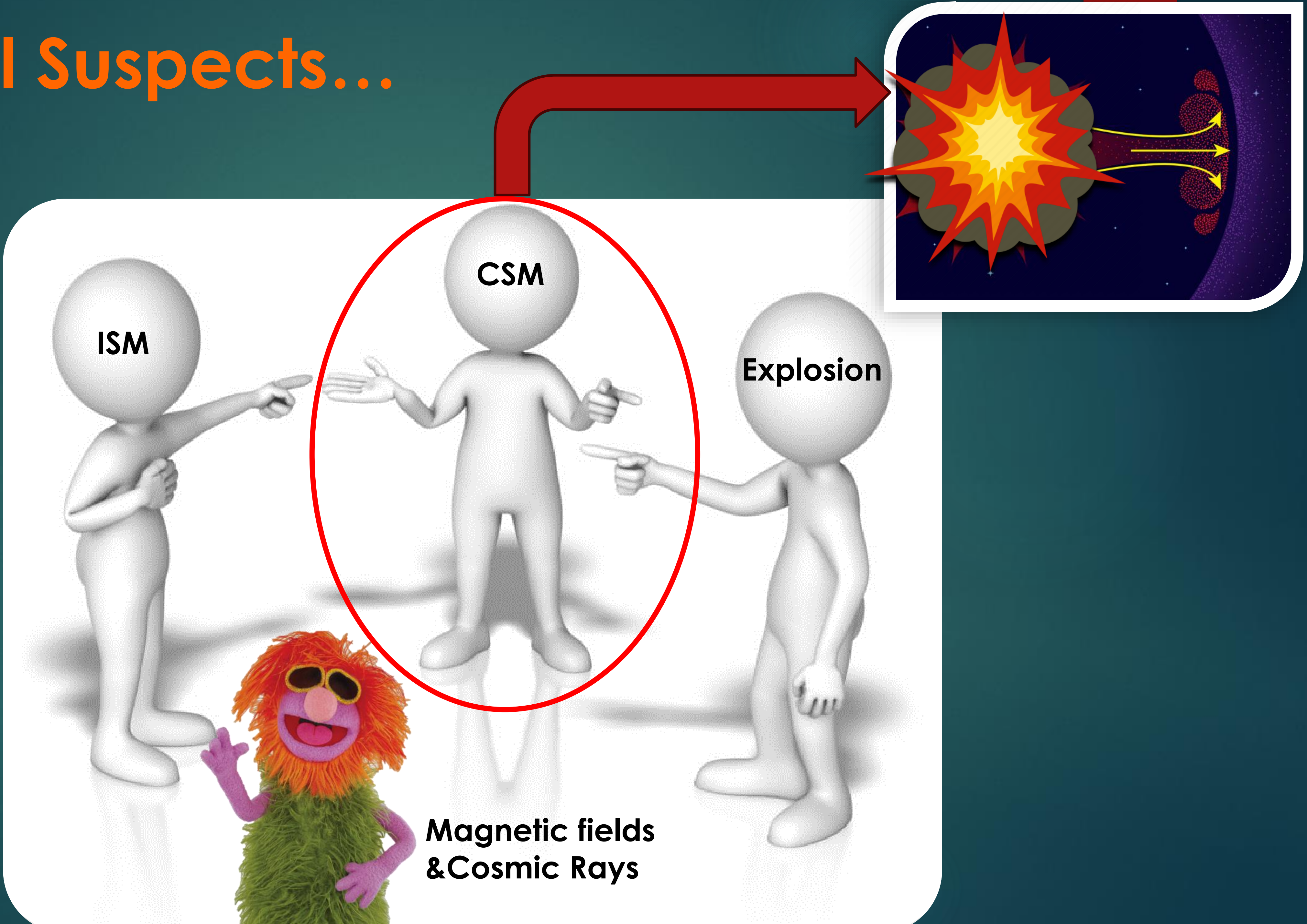
From nature

to humanity

with love...

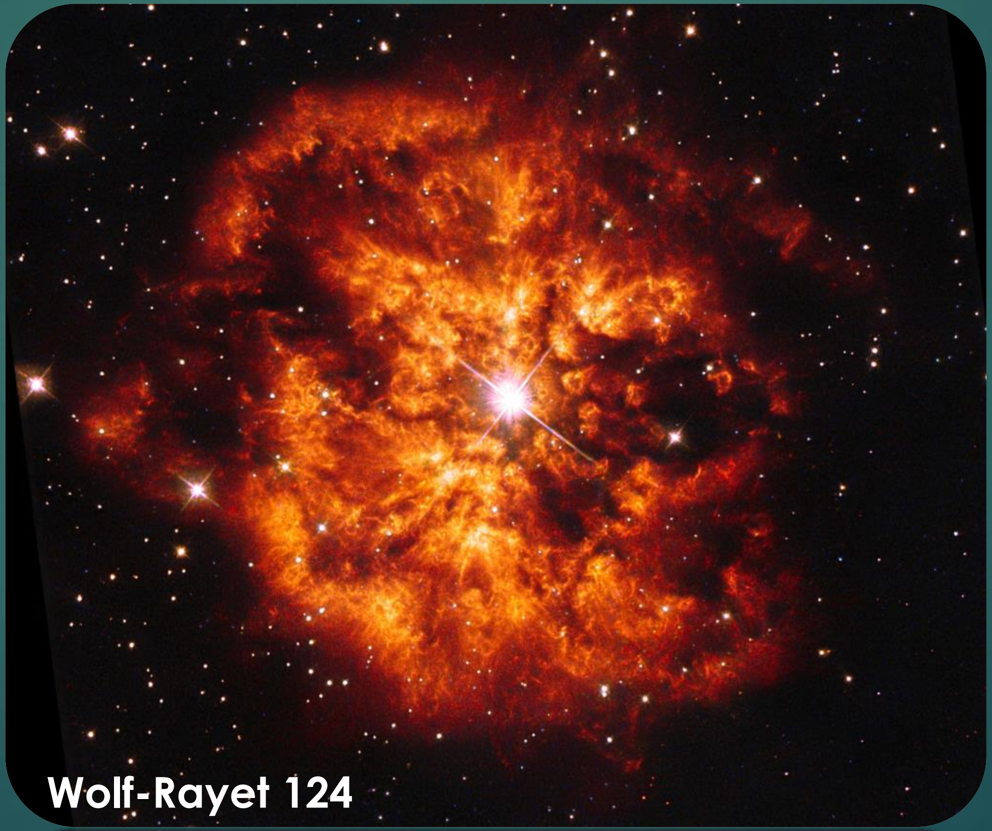
xxx

The Usual Suspects…



Circumstellar structures

Mass loss is a key phenomenon of SN progenitor stars



Core Collapse Supernovae

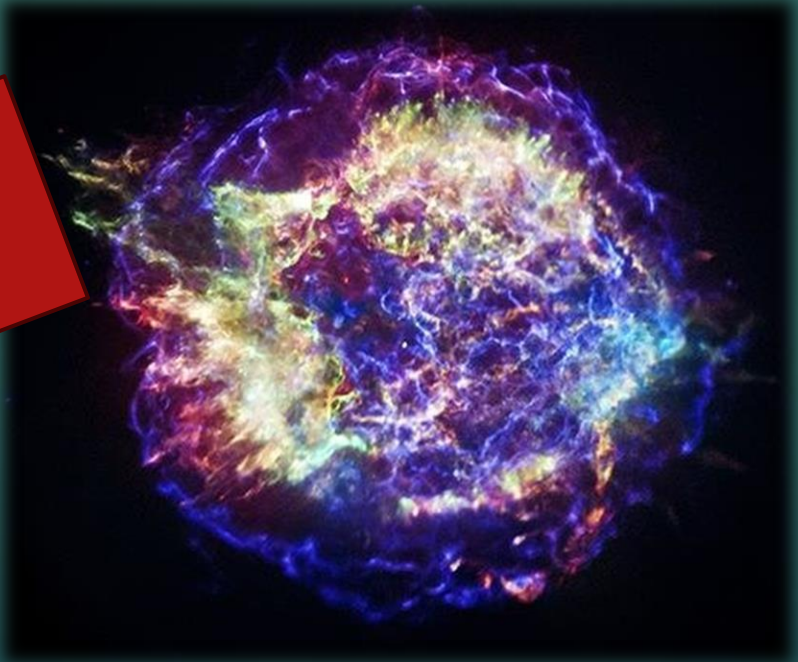
Progenitors:	SN Type:
- RSGs/YSGs	→ II P&L / IIb
- BSGs	→ II-pec
- He stars	→ Ib
- WR Stars	→ Ic
- LBVs	→ IIn / Ibn

(Smith 2014)

All of there progenitors are characterized by substantial mass outflows

For CC SNRs: SN + CSM interaction is inevitable

SNe: observational evidence (flash ionization, Xrays, Radio)
P. Chandra Talk

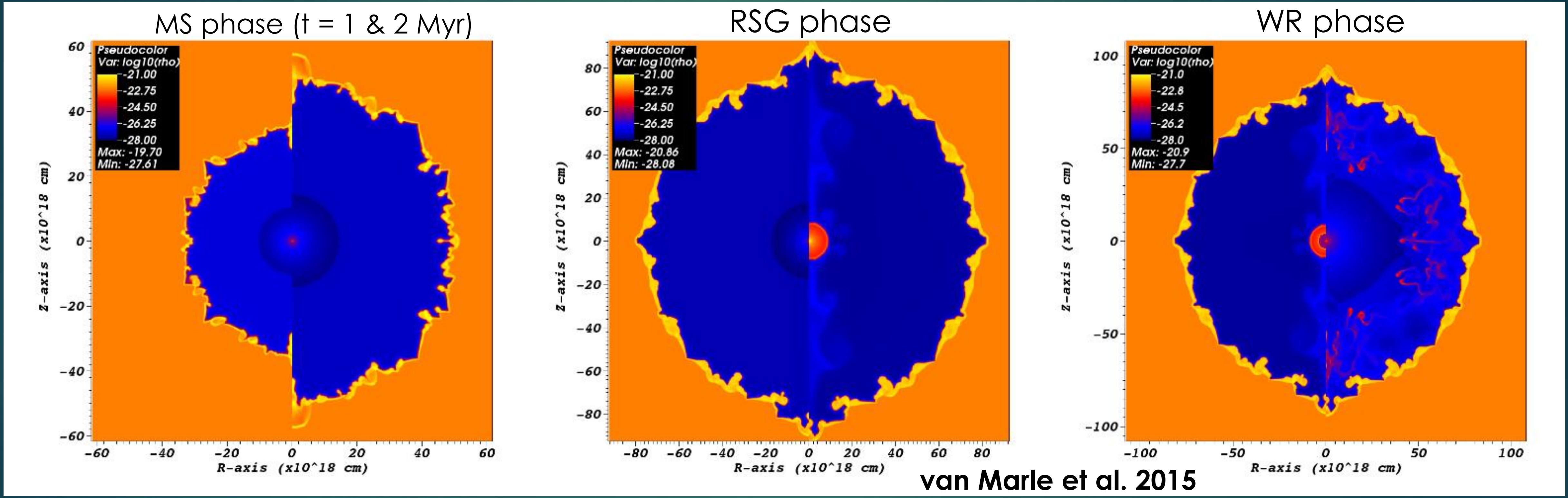


Cas A: Type IIb → Evolution within the wind bubble

SN 1987A: Type II-pec (BSG) → collision with a CSM shell

Core Collapse Supernovae

- ➢ **Multiple phases of mass loss → Complex CSM**



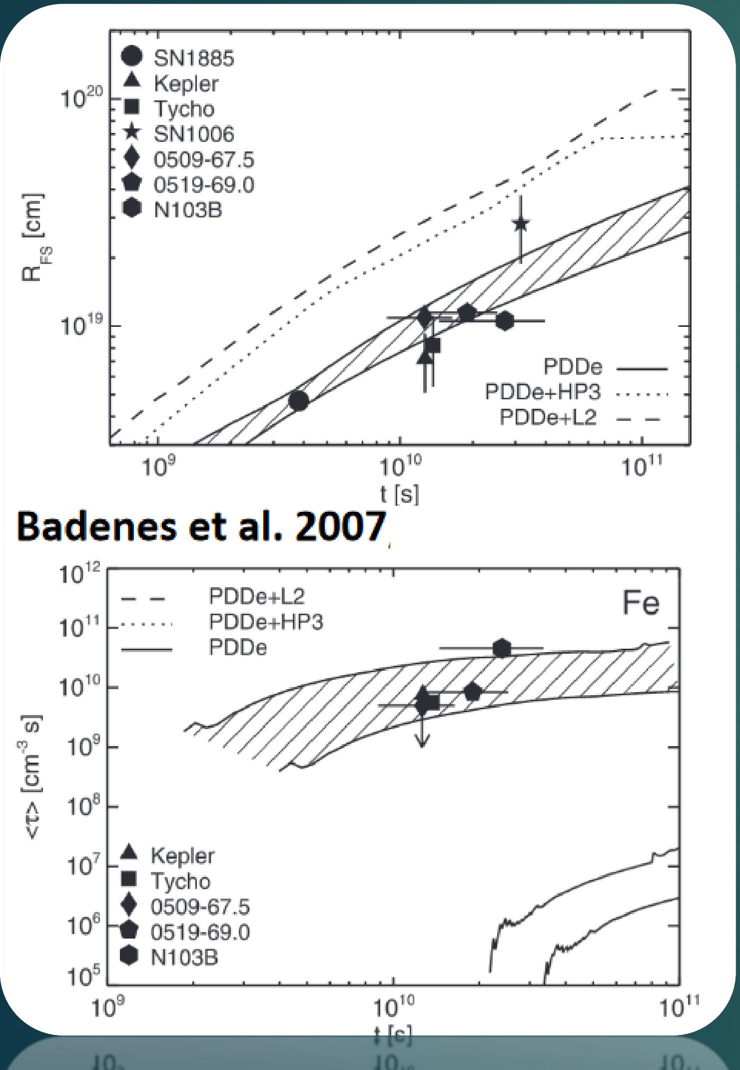
van Marle et al. 2015

See also: Garcia-Segura et al. (1996a), Freyer et al. (2006), Dwarkadas (2005) ,Toalá & Arthur (2011)

Type Ia Supernovae

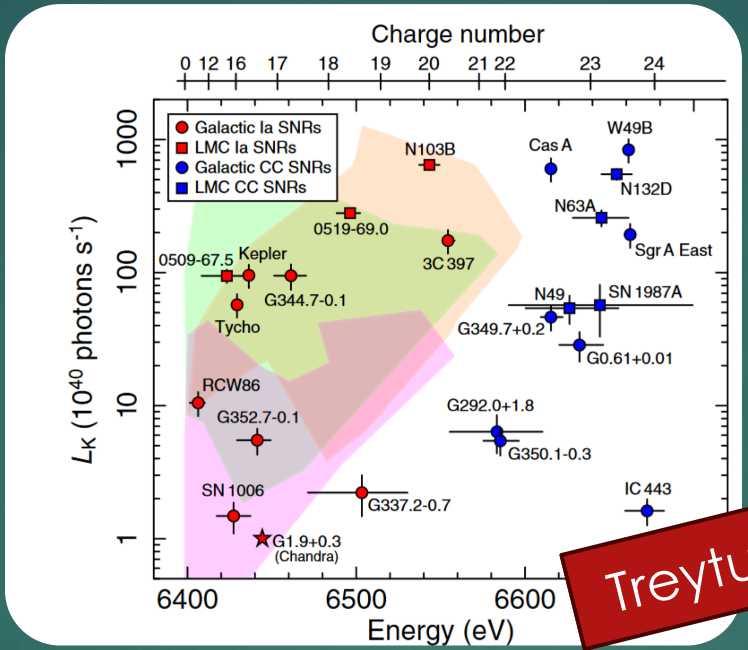
All evidence indicate…

Dynamics/ X-ray spectra:



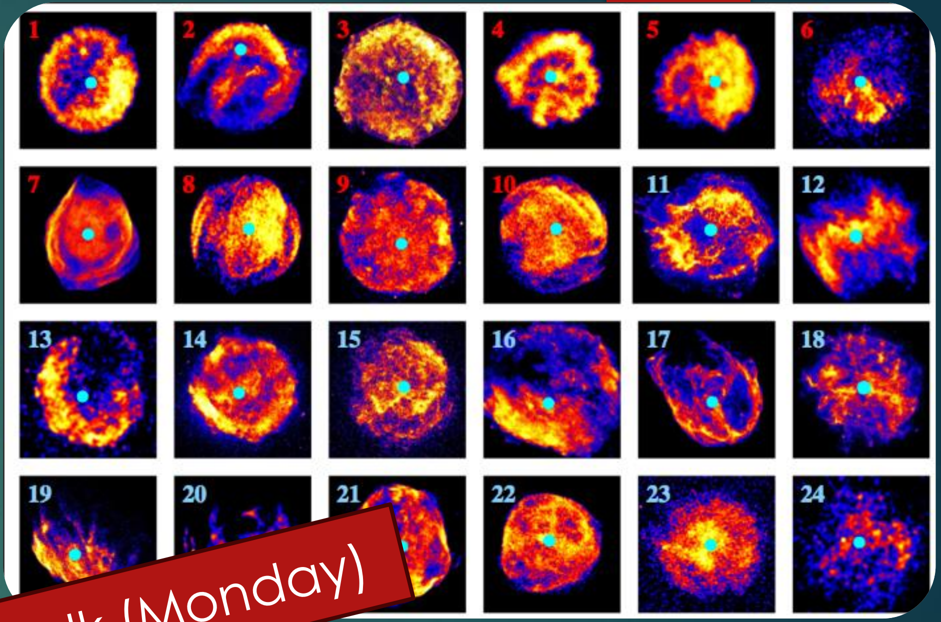
Badenes et al. 2007

Fe K luminosity:



Yamaguchi + 2014

Morphology:



Lopez + 2009

Treyturik talk (Monday)

… evolution to a rather homogeneous ambient medium

Makes sense…

- ➢ **Low mass progenitor stars (M < 8 Msun)**

  → No essential mass outflows are expected

However…

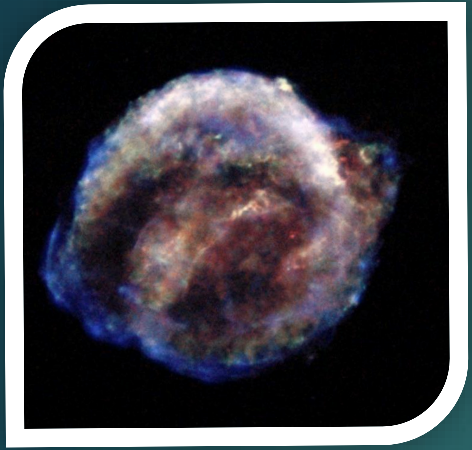
Type Ia Supernovae

" *A peculiar SNR is a well-observed SNR* "

P. Podsiadlowsky

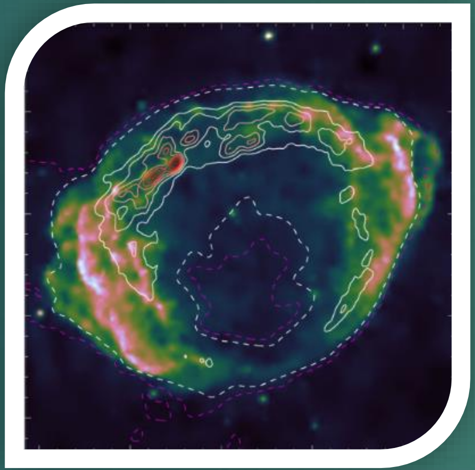
- ***Almost <u>none</u> of well observed SNRs Ia can be explained by considering a SNR + homogeneous ambient medium scenario***

Characteristic examples:



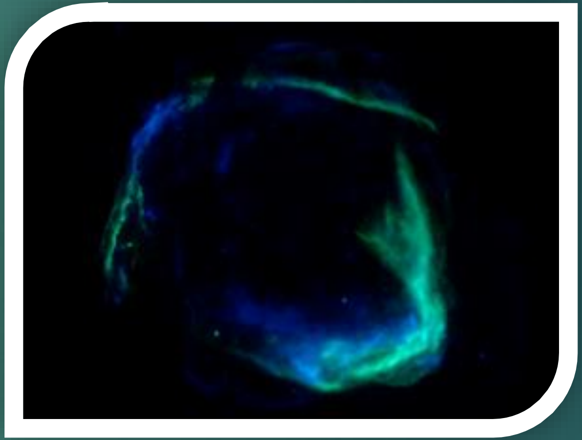
Kepler's SNR
interaction with a dense CSM

(e.g. Chiotellis + 2012, Patnaude + 2012, Kasuga + 2021)



G1.9 + 0.3
interaction with a dense circumstellar shell

(e.g. Borkowski et al. 2014, 2017; Villagran 2024)



RCW 86
Evolution in a low density cavity excavated by the progenitor

(e.g. Vink + 1997; Williams +2011; Broersen + 2014)

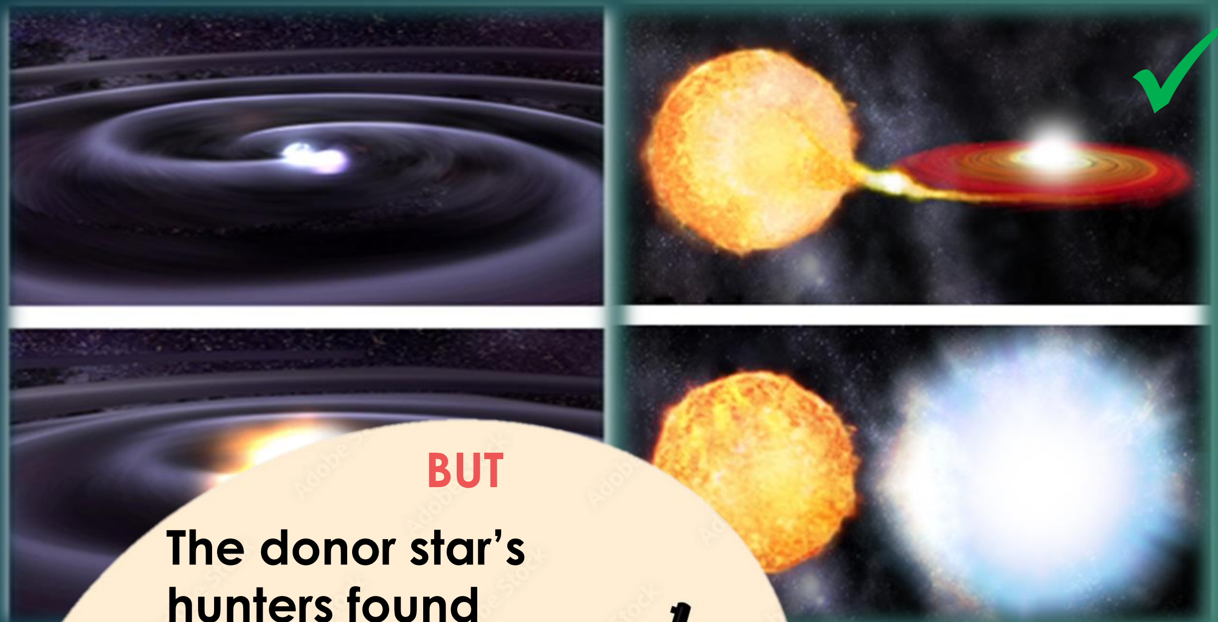
And… many others:

- ✓ Tycho
- ✓ DEM L 71
- ✓ N103B
- ✓ 190-69.0

Y.H. Chu talk

Type Ia Supernovae

- **The existence of CSM favors for the single degenerate scenario**



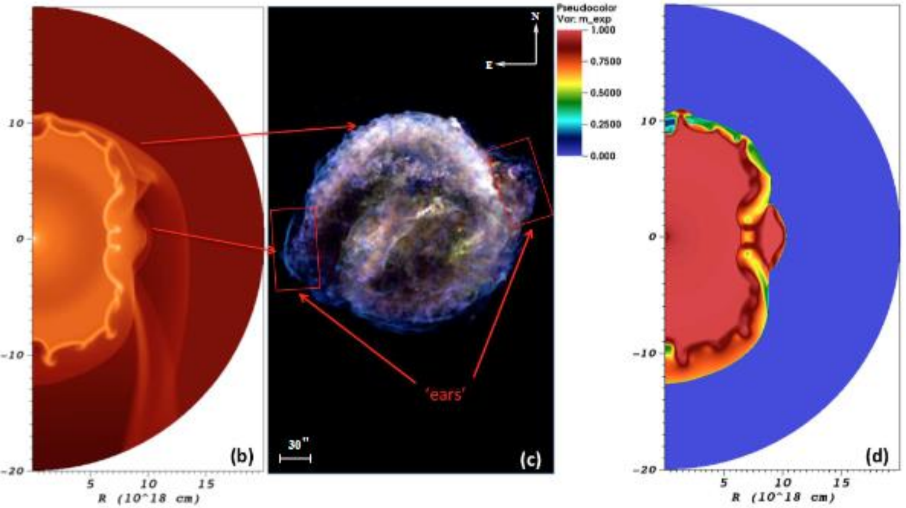
BUT

The donor star's hunters found nothing

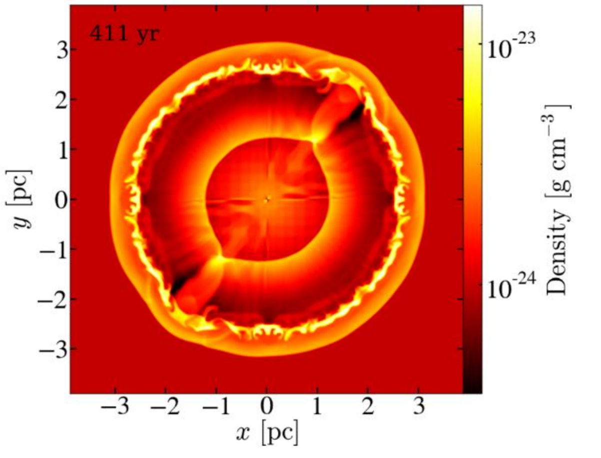
e.g. Kerzendorf +2014
Ruiz-Lapuente + 2017

"Alternative" Scenario:
interaction of SNR Ia with PNe

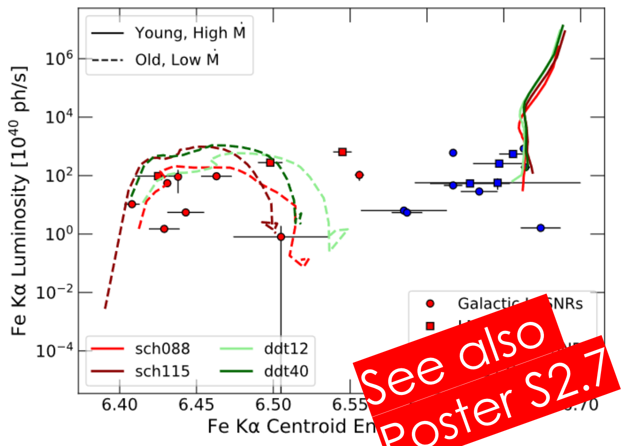
Bipolar PN (Chiotellis + 20)



PN +jet (Tsebrenko & Soker 13)



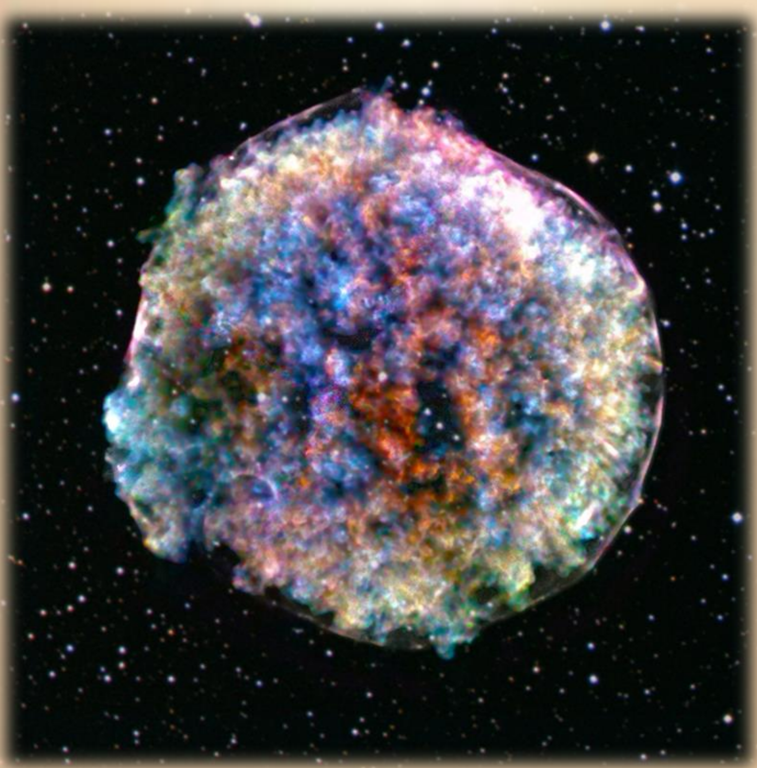
It works if $\Delta t > 10^4$yr (Court + 2024)



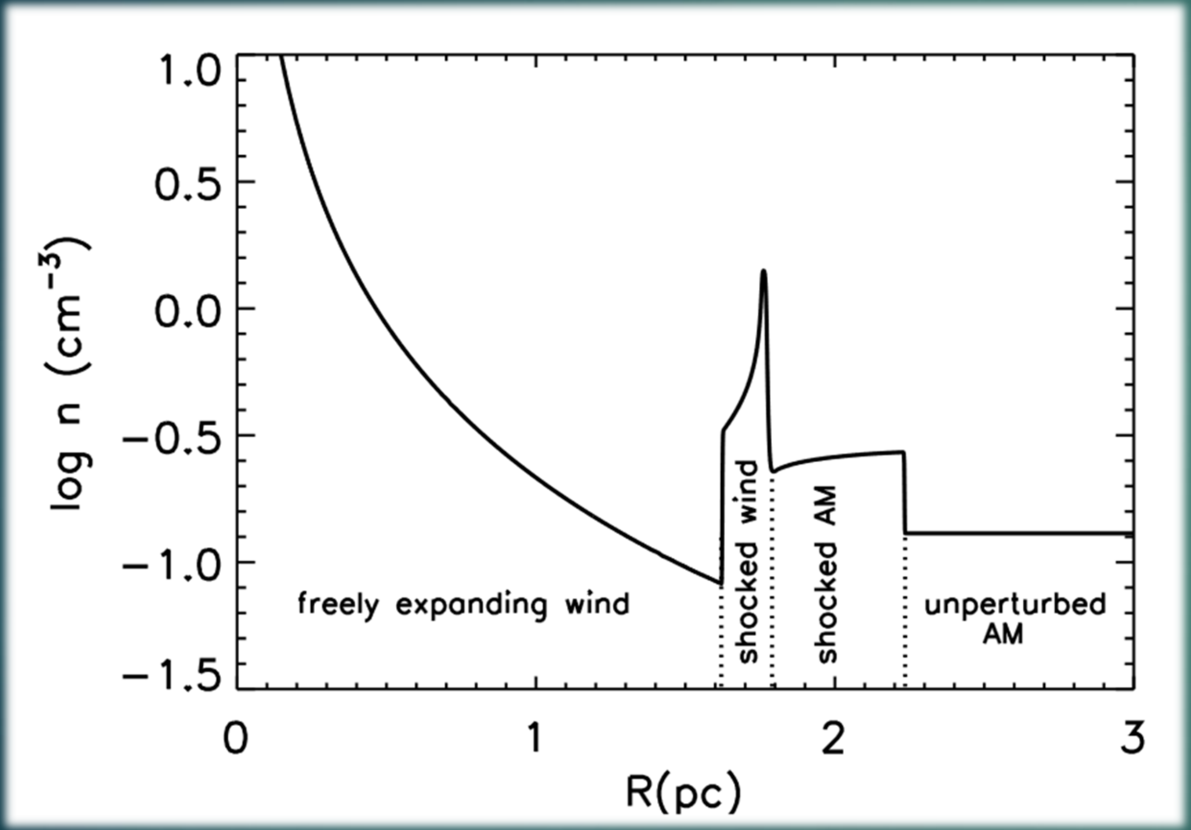
See also Poster S2.7

Chapter II

The effects of stellar winds on Supernova Remnants



Stellar winds ⇨ Mass losses in the form a continuum outflow



Density profile (mass conservation law):

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 u_w}$$

Wind bubble evolution:
Weaver et al. (1977); *Koo & McKee (1992)*

Stellar wind's CSM (overall density)

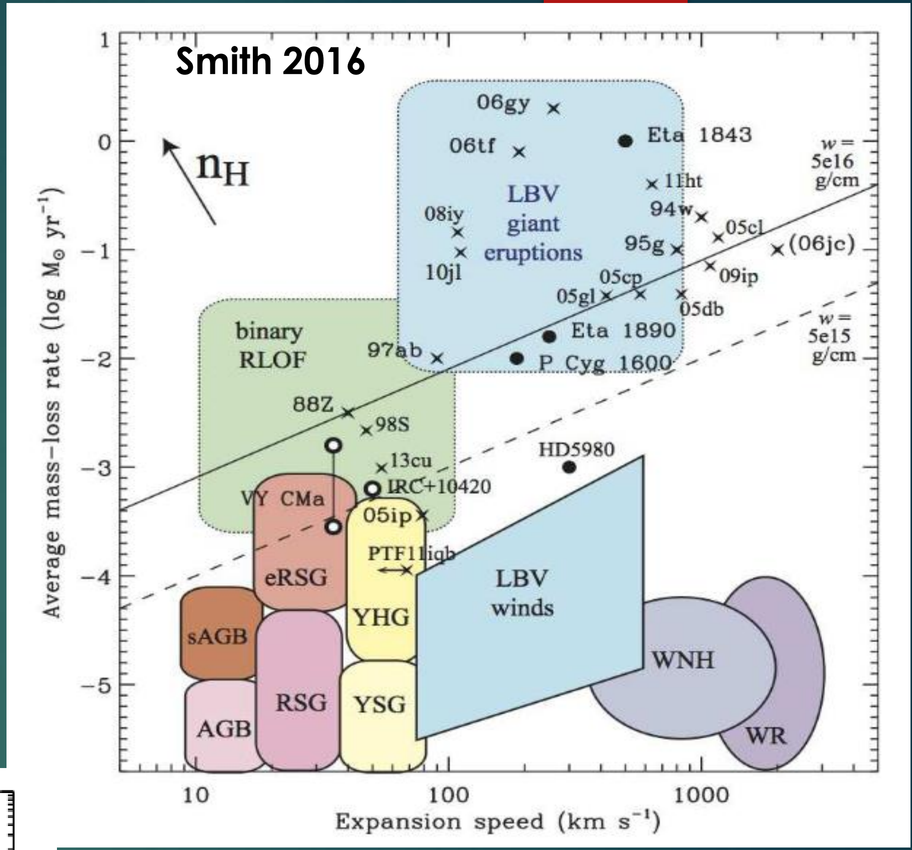
- Final result depends on the wind properties:

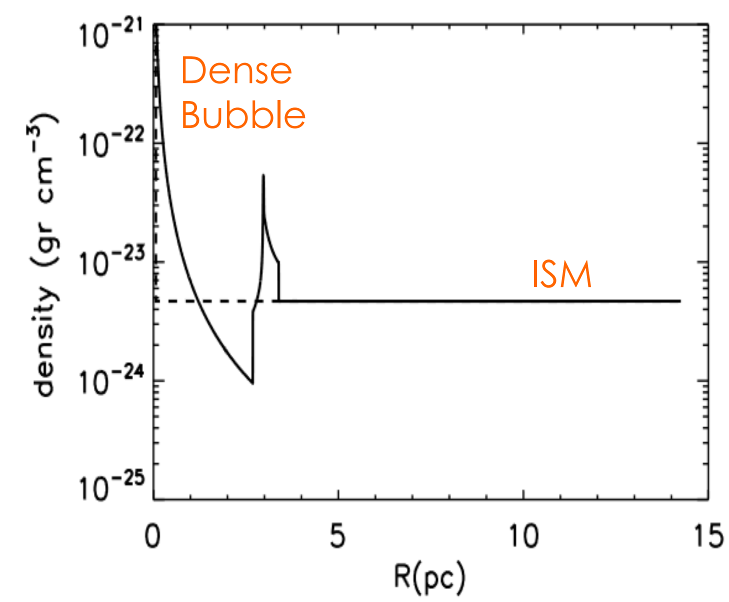
- Slow, intense winds ($\dot{M}\uparrow, u\downarrow$):

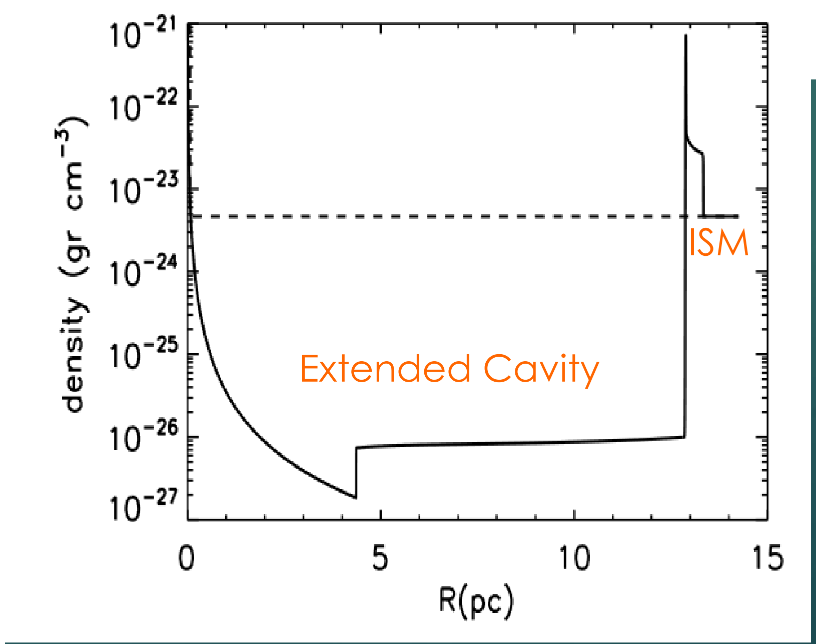
→ **Dense, small bubbles** → **(AGB, RSG, LBV)**

- Fast, tenuous winds($\dot{M}\downarrow, u\uparrow$):

→ **Extended cavities** → **(OB MS, WR, WDs)**

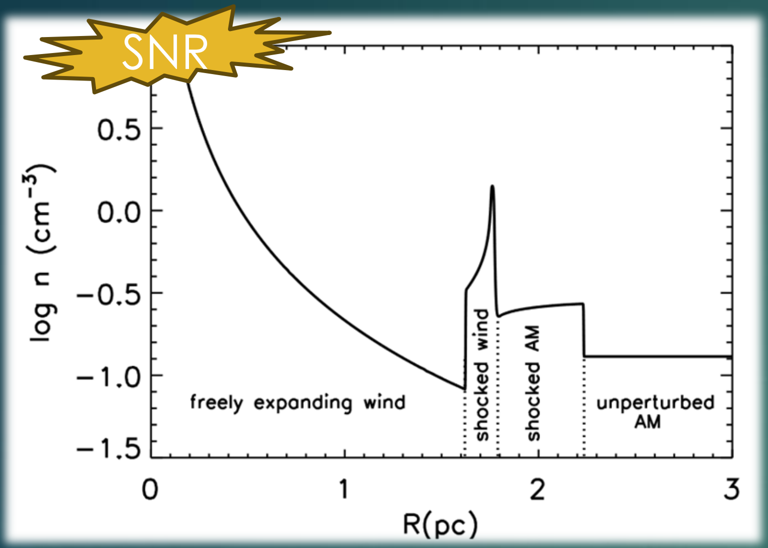






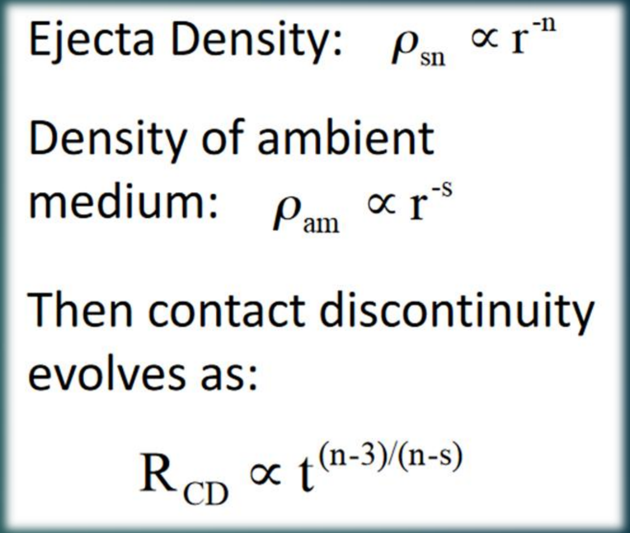
$$\rho(r) = \frac{\dot{M}}{4\pi r^2 u_w}$$

Evolution of a SNR within the wind bubble: I. Dynamics



- Evolution within the $\rho(r) \propto r^{-2}$ wind profile

- **Self-similar solution (Chevalier 1982):**
    - ISM: s= 0
    - Wind bubble: s= 2


Ejecta Density: $\rho_{sn} \propto r^{-n}$

Density of ambient medium: $\rho_{am} \propto r^{-s}$

Then contact discontinuity evolves as:

$$R_{CD} \propto t^{(n-3)/(n-s)}$$

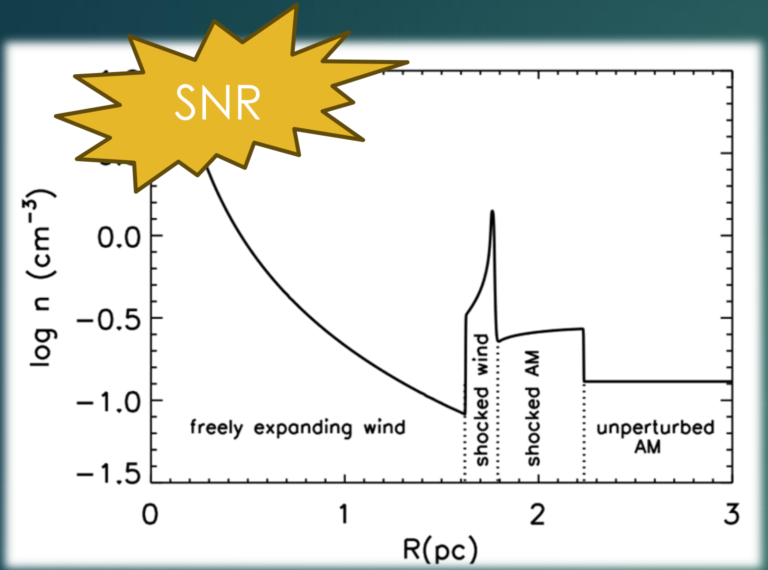
$$R_{CD} \propto t^{m}$$

expansion parameter: $m_{bubble} > m_{ism}$

e.g. for Type I SNe (n=7):

Bubble m= 0.8 ; ISM m= 0.57

Collision of SNR with the outer walls of the CSM



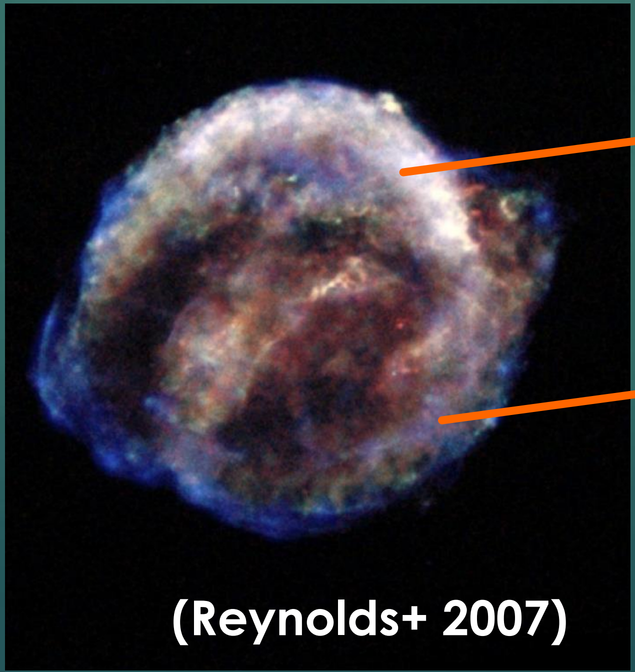
- **Effect I:** A substantial deceleration of the forward shock

→ The velocity decreases and the shocked density increases

Tdyn > Tcool (possible) -> **The shock becomes radiative**

e.g. Kepler's SNR

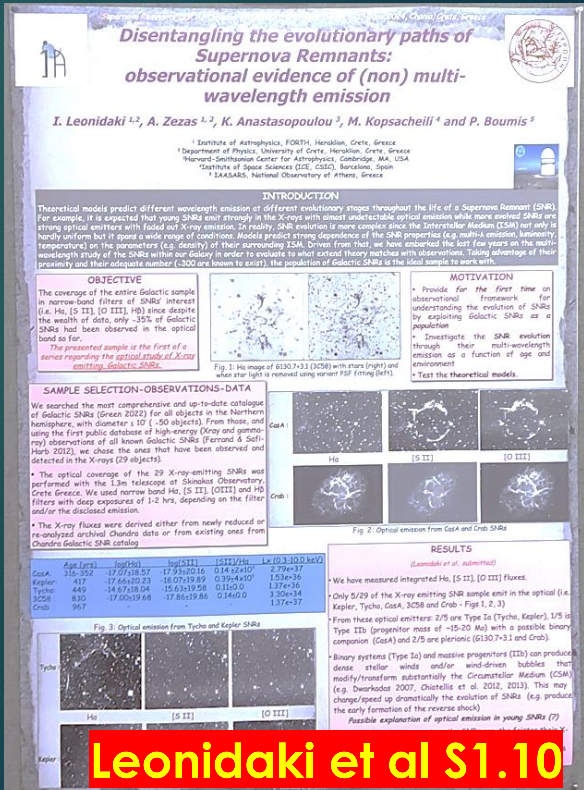

Ha (Blair + 1991)


(Reynolds+ 2007)

$R \propto t^{0.3}$

$R \propto t^{0.6}$

(Vink 2008)



Disentangling the evolutionary paths of Supernova Remnants: observational evidence of (non) multi-wavelength emission

I. Leonidaki [1,2], A. Zezas [1,2], K. Anastasopoulou [3], M. Kopsacheili [4] and P. Boumis [5]

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[2] Department of Physics, University of Crete, Heraklion, Crete, Greece
[3] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
[4] Institute of Space Sciences (ICE, CSIC), Barcelona, Spain
[5] IAASARS, National Observatory of Athens, Greece

INTRODUCTION

Theoretical models predict different wavelength emission at different evolutionary stages throughout the life of a Supernova Remnant (SNR). For example, it is expected that young SNRs emit strongly in the X-rays with almost undetectable optical emission while more evolved SNRs are strong optical emitters with faded out X-ray emission. In reality, SNR evolution is more complex since the Interstellar Medium (ISM) not only is hardly uniform but it spans a wide range of conditions. Models predict strong dependence of the SNR properties (e.g. multi-λ emission, luminosity, temperature) on the parameters (e.g. density) of their surrounding ISM. Driven from that, we have embarked the last few years on the multi-wavelength study of the SNRs within our Galaxy in order to evaluate to what extend theory matches with observations. Taking advantage of their proximity and their adequate number (~300 are known to exist), the population of Galactic SNRs is the ideal sample to work with.

OBJECTIVE

The coverage of the entire Galactic sample in narrow-band filters of SNRs' interest (i.e. Hα, [S II], [O III], Hβ) since despite the wealth of data, only ~35% of Galactic SNRs had been observed in the optical band so far.

The presented sample is the first of a series regarding the optical study of X-ray emitting Galactic SNRs.

Fig. 1: Hα image of G130.7+3.1 (3C58) with stars (right) and when star light is removed using variant PSF fitting (left).

MOTIVATION

- Provide *for the first time* an observational framework for understanding the evolution of SNRs by exploiting Galactic SNRs as a *population*
- Investigate the SNR evolution through their multi-wavelength emission as a function of age and environment
- Test the theoretical models.

SAMPLE SELECTION-OBSERVATIONS-DATA

We searched the most comprehensive and up-to-date catalogue of Galactic SNRs (Green 2022) for all objects in the Northern hemisphere, with diameter ≤ 10′ (~50 objects). From those, and using the first public database of high-energy (Xray and gamma-ray) observations of all known Galactic SNRs (Ferrand & Safi-Harb 2012), we chose the ones that have been observed and detected in the X-rays (29 objects).

- The optical coverage of the 29 X-ray-emitting SNRs was performed with the 1.3m telescope at Skinakas Observatory, Crete Greece. We used narrow band Hα, [S II], [OIII] and Hβ filters with deep exposures of 1-2 hrs, depending on the filter and/or the disclosed emission.
- The X-ray fluxes were derived either from newly reduced or re-analyzed archival Chandra data or from existing ones from Chandra Galactic SNR catalog

Fig. 2: Optical emission from CasA and Crab SNRs

	Age (yrs)	log(Hα)	log[SII]	[SII]/Hα	Lx (0.3-10.0 keV)
CasA	316-352	-17.07±18.57	-17.93±20.16	0.14 ±2×10 [illegible]	2.79e+37
Kepler	417	-17.66±20.23	-18.07±19.89	0.39±4×10 [illegible]	1.53e+36
Tycho	449	-14.67±18.04	-15.63±19.58	0.11±0.0	1.37e+36
3C58	830	-17.00±19.68	-17.86±19.86	0.14±0.0	3.30e+34
Crab	967	-	-	-	1.37e+37

Fig. 3: Optical emission from Tycho and Kepler SNRs

RESULTS

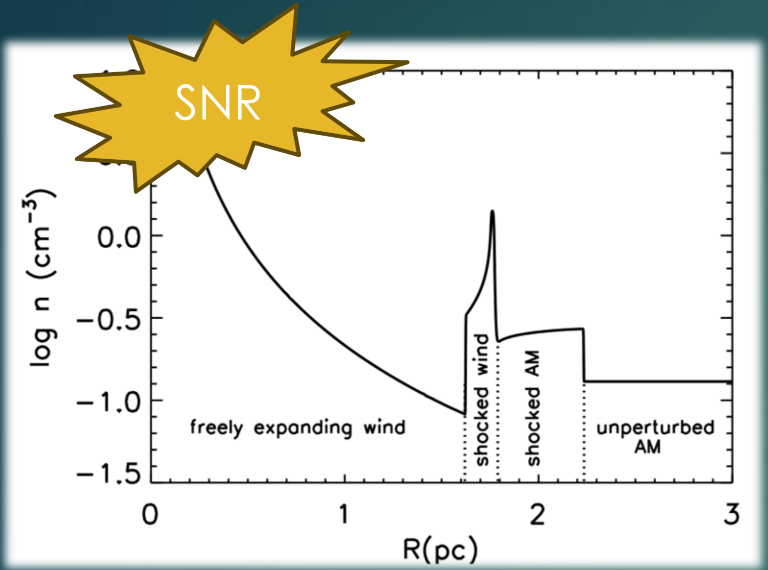
(Leonidaki et al., submitted)

- We have measured integrated Hα, [S II], [O III] fluxes.
- Only 5/29 of the X-ray emitting SNR sample emit in the optical (i.e. Kepler, Tycho, CasA, 3C58 and Crab - Figs 1, 2, 3)
- From these optical emitters: 2/5 are Type Ia (Tycho, Kepler), 1/5 is Type IIb (progenitor mass of ~15-20 M☉) with a possible binary companion (CasA) and 2/5 are plerionic (G130.7+3.1 and Crab).
- Binary systems (Type Ia) and massive progenitors (IIb) can produce dense stellar winds and/or wind-driven bubbles that modify/transform substantially the Circumstellar Medium (CSM) (e.g. Dwarkadas 2007, Chiotellis et al. 2012, 2013). This may change/speed up dramatically the evolution of SNRs (e.g. produce the early formation of the reverse shock)

Possible explanation of optical emission in young SNRs (?)

Leonidaki et al S1.10

Collision of SNR with the outer walls of the CSM



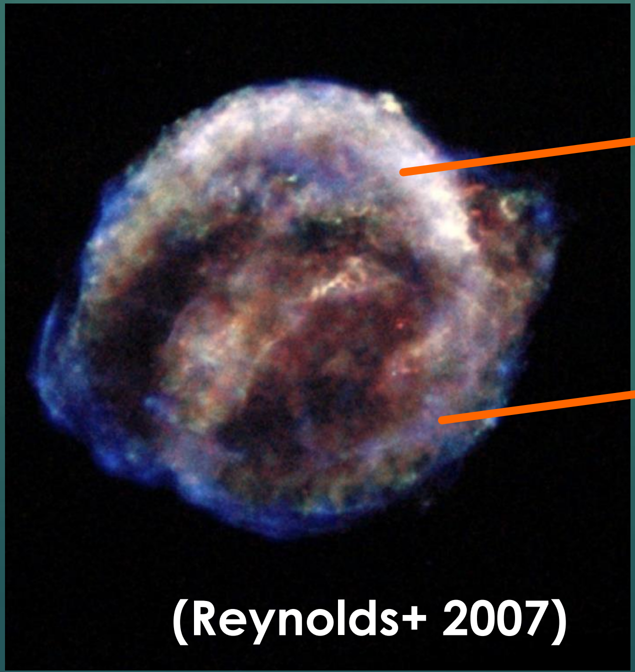
- **Effect I:** A substantial deceleration of the forward shock

→ The velocity decreases and the shocked density increases

Tdyn > Tcool (possible) -> **The shock becomes radiative**

e.g. Kepler's SNR

Ha (Blair + 1991)



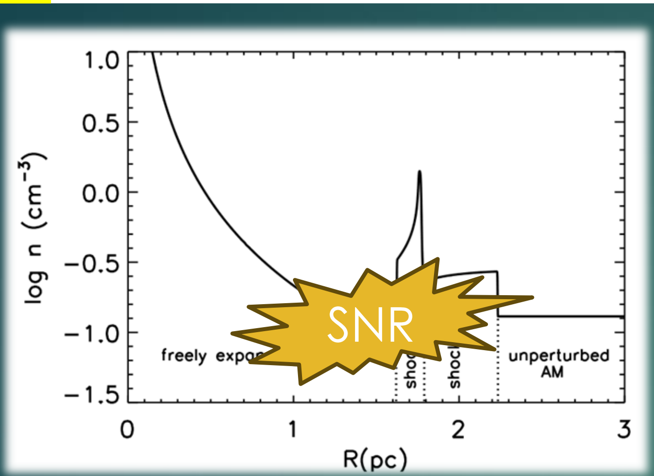
(Reynolds+ 2007)

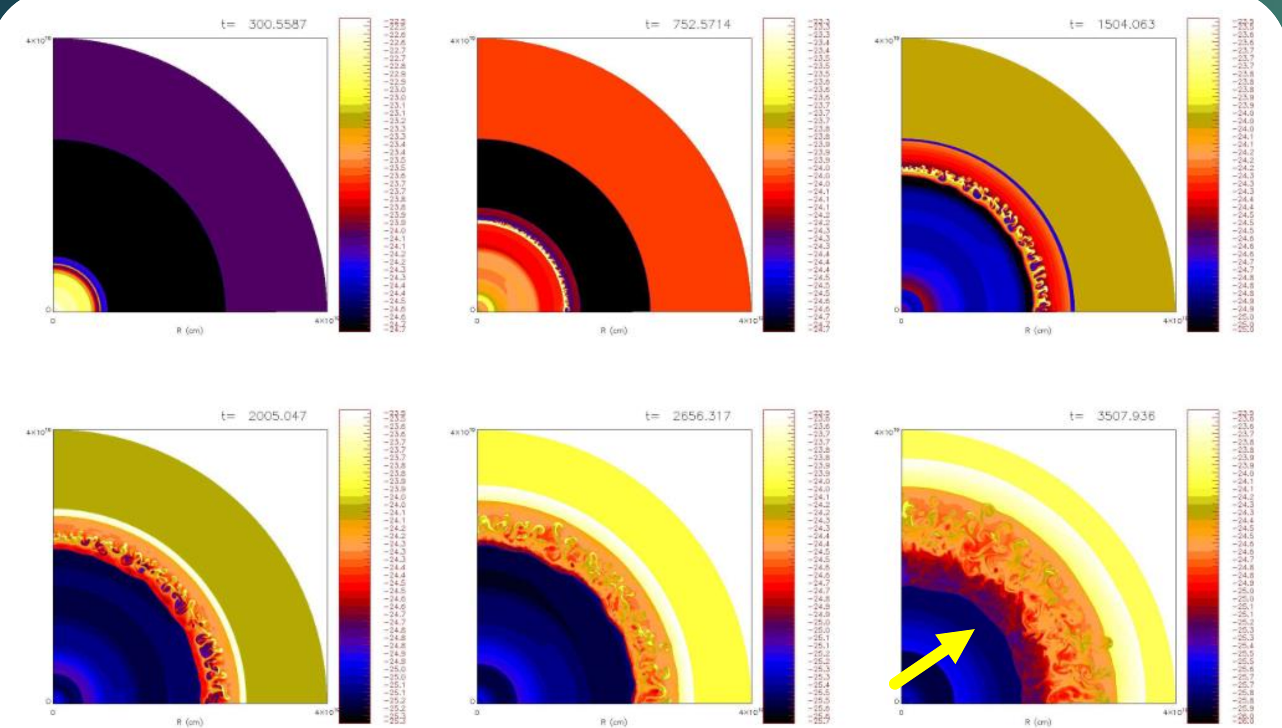
$R \propto t^{0.3}$

$R \propto t^{0.6}$

(Vink 2008)

➢ Effect II: Formation of a reflected shock





Dwarkadas & Dewey 2013

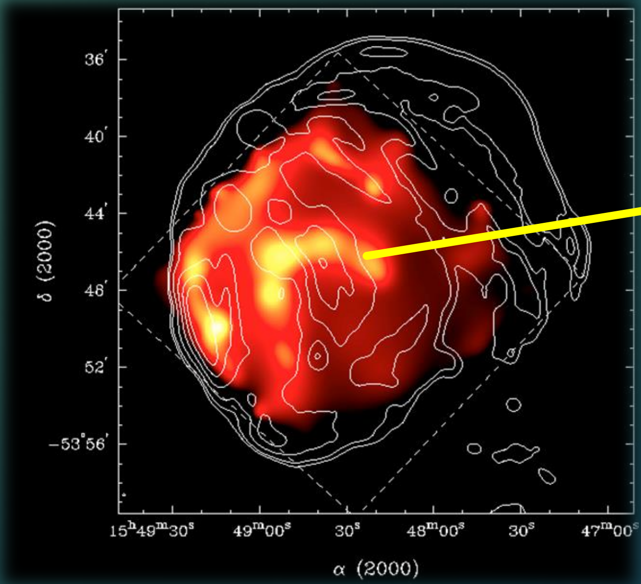
Reflected shock Velocity:

Sgro (1975):

$$V_r = \frac{1}{4}\left[3 - \left(\frac{15A_r}{4 - A_r}\right)^{\frac{1}{2}}\right] V_s,$$

Ar: related to the wall to cavity density contrast

- **For high contrast → Vr ≈ few x 10^3km/s**



Reflected shock

KESTEVEN 27

Chen et al. 2008

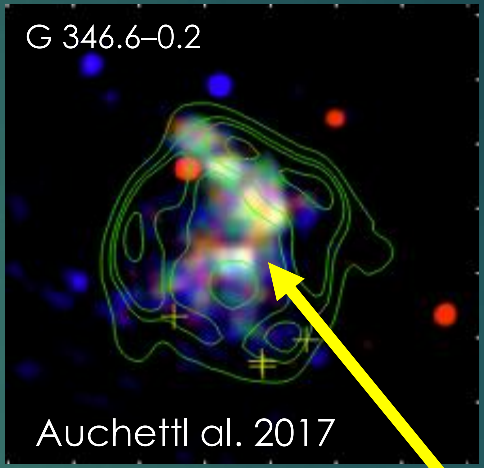
The role of reflected shocks in **MMSNRS**

MMSNRS:

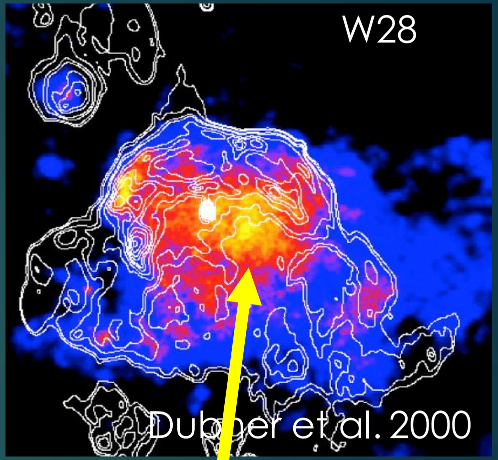
Peculiar SNRs (Rho & Petre 1998; Jones et al. 1998)**:**

- **Shell type in Radio (synchrotron)**
- **X-ray bright in their center (thermal)**

→ No active pulsar (as in Plerions or Composite SNRs)



Auchettl al. 2017

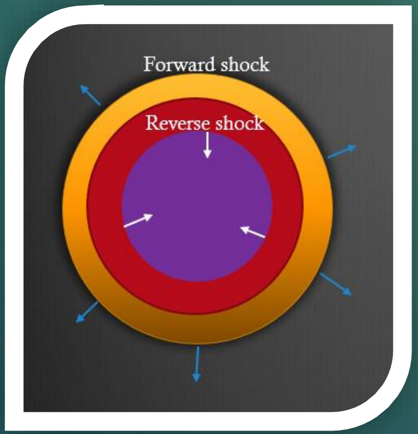


Dubner et al. 2000

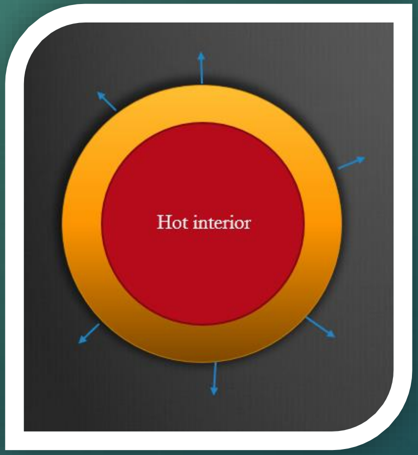
???

≠

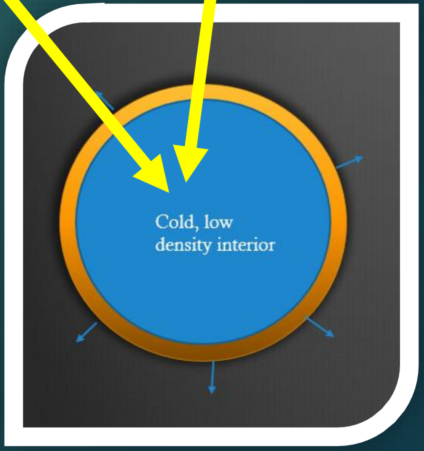
Standard SNR Evolution



Ejecta dominated phase



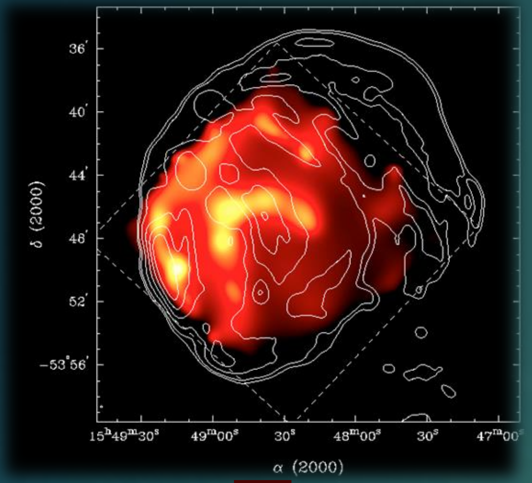
Sedov-Taylor phase

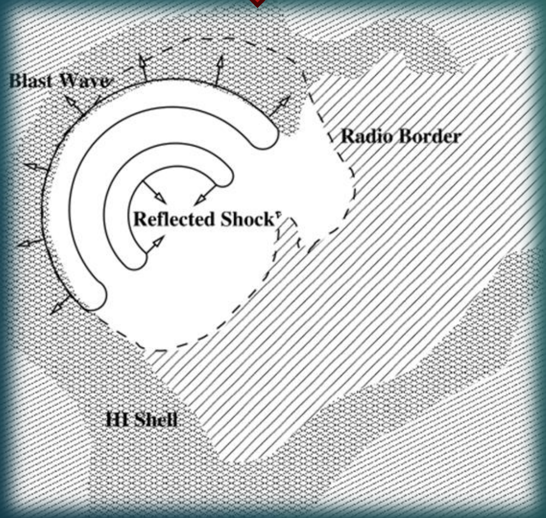


Radiative phase

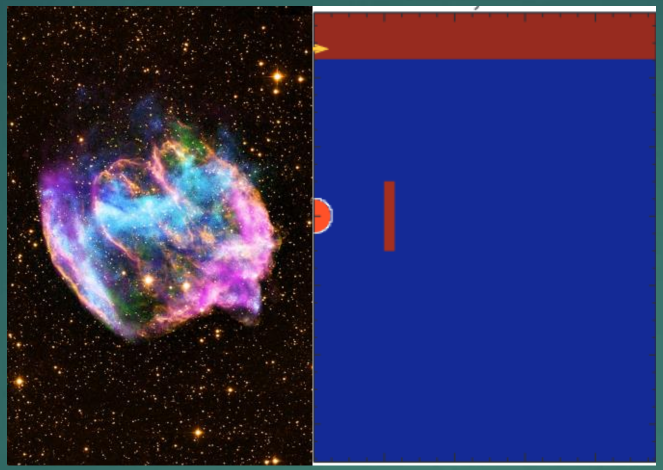
The role of reflected shocks in **MMSNRS**

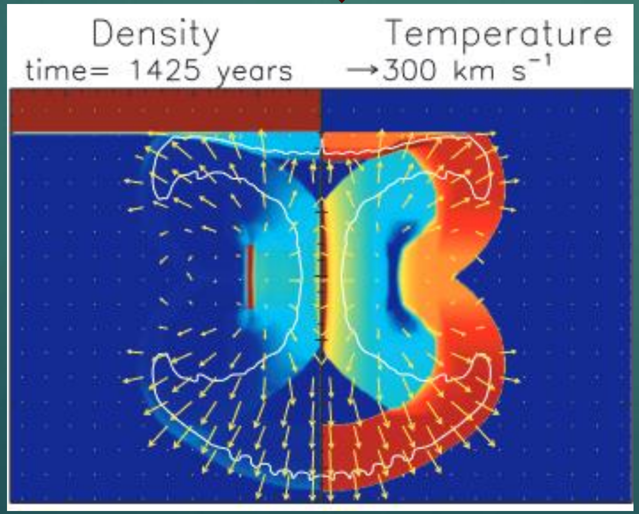
KESTEVEN 27 (Chen et al. 2008)



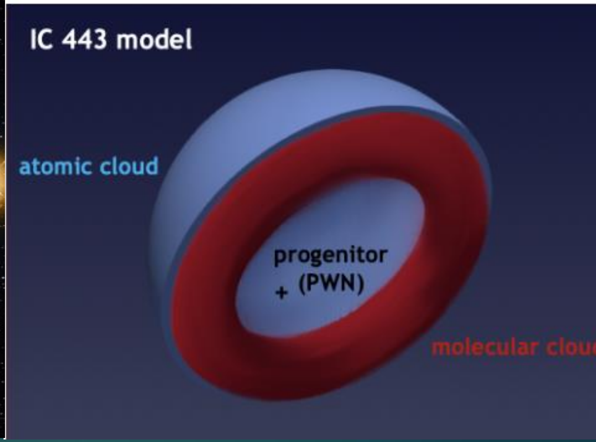


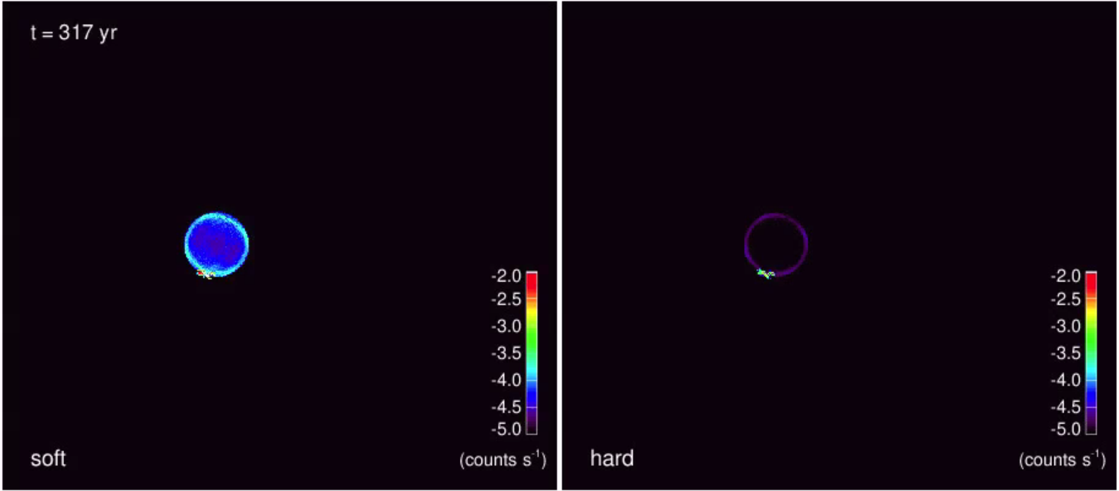
W49B (Zhou et al 2011)





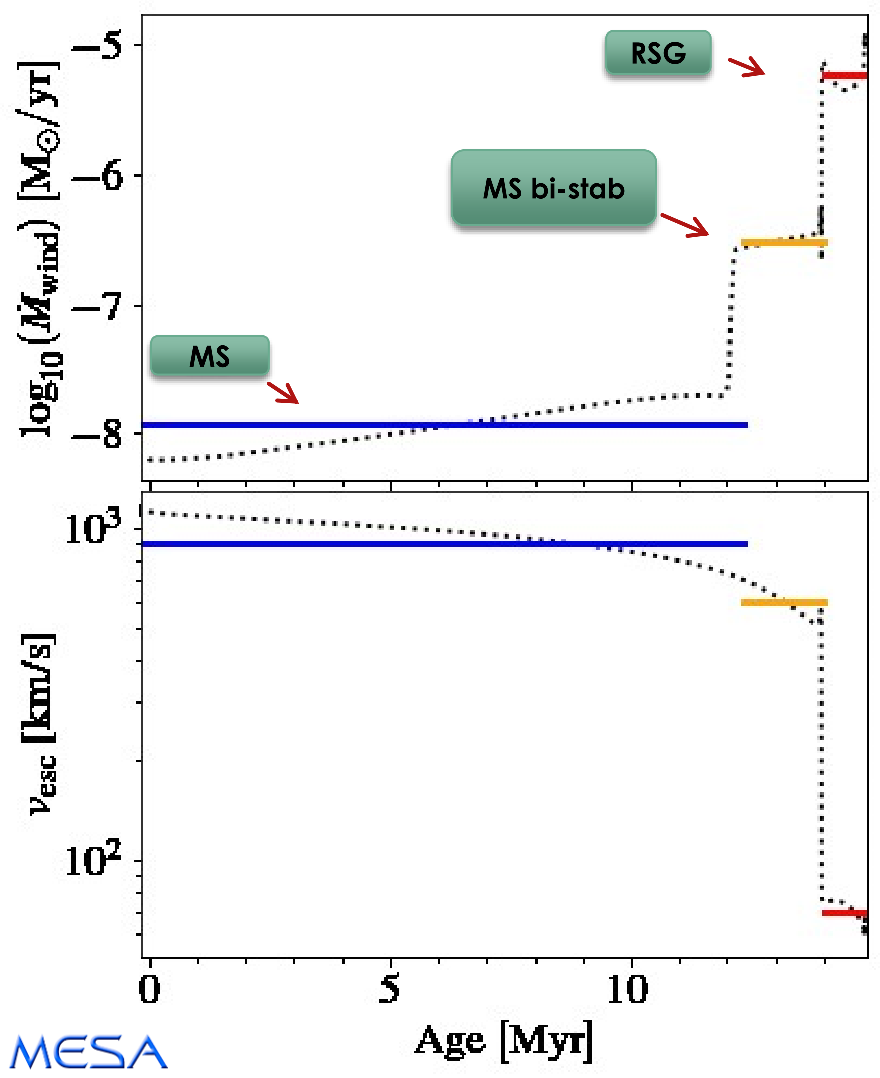
IC443 (Ustamujic et al 2021)

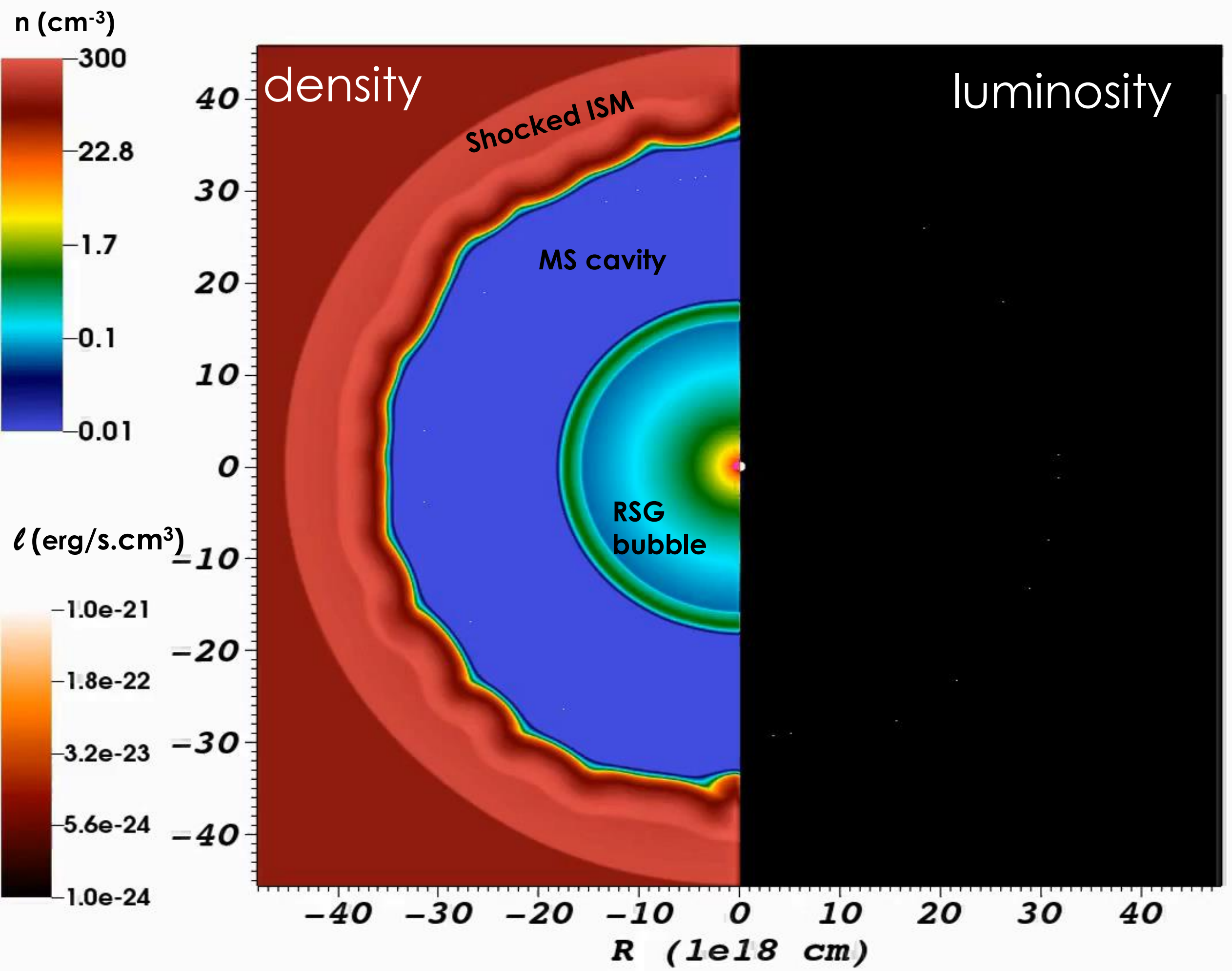




Linking the CSM of RSGs with **MMSNRS**

$M_{*} = 15\ M_{\odot}$ + $n_{ism} = 100\ \mathrm{cm}^{-3}$





Chiotellis, Zapartas & Meyer 2024

Linking the CSM of RSGs with **MMSNRS**

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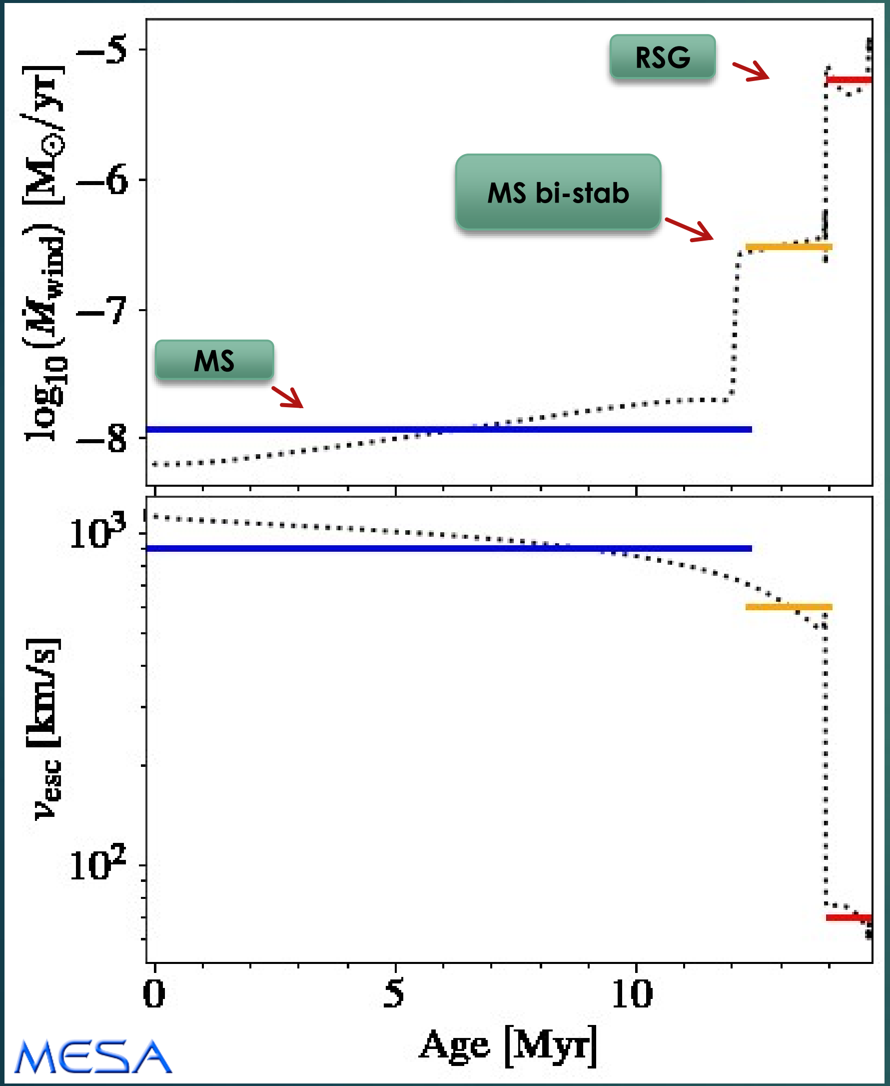
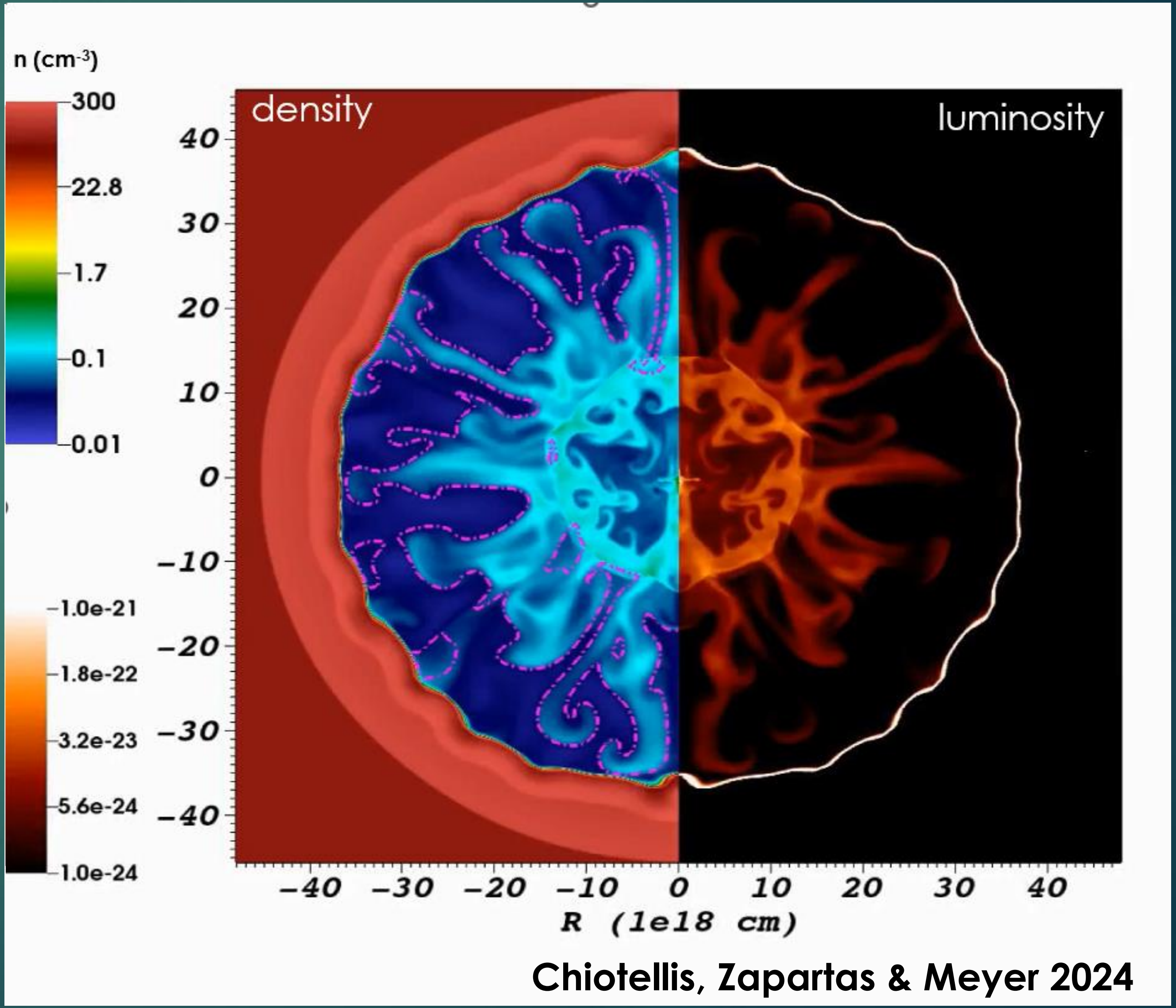
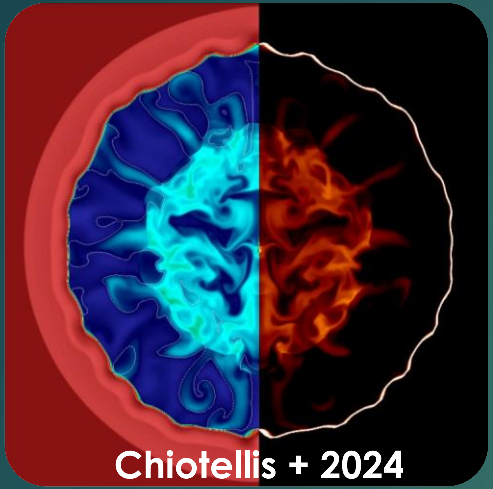




Chiotellis, Zapartas & Meyer 2024

Reflected shock → only solution?

Reflected shocks

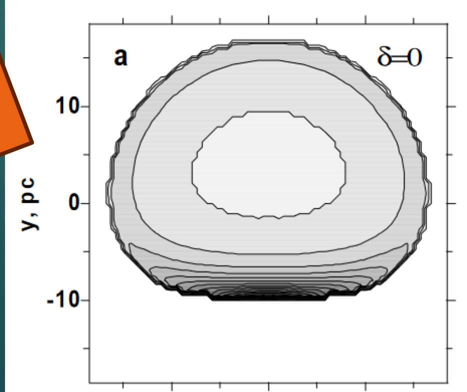

Chiotellis + 2024

“Dirty job”: ISM/CSM

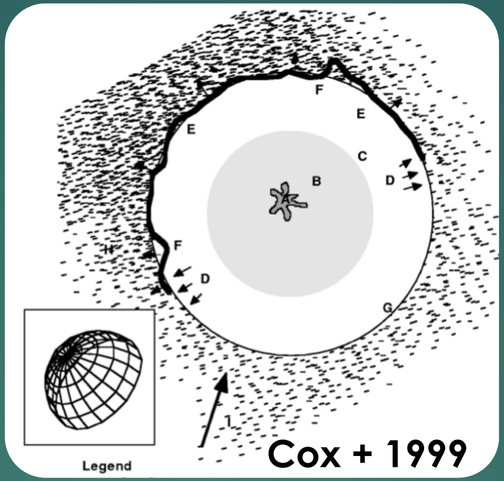
Require: density walls

(Chen+ 2008; Zhou + 2011;
Ustamujic +2021; Chiotellis+ 2024)

+ Projection effect
(Petruk 2001)



Thermal conduction



Cox + 1999

Physical process

No $\overrightarrow{B}$, no mixing

(Cox + 1999; Shelton+ 1999;
Velazquez+2004; Zhong + 2019)

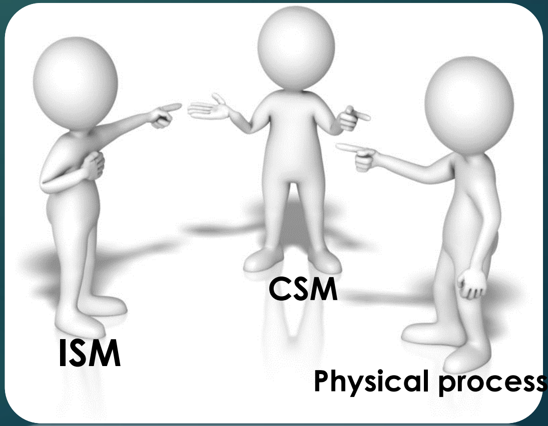
Evaporation of shock-engulfed cloudlets


Slavin + 2017

ISM

C> 10

(White and Lond 1991;
Slavin +2017, Zhang +2019)



Chapter III

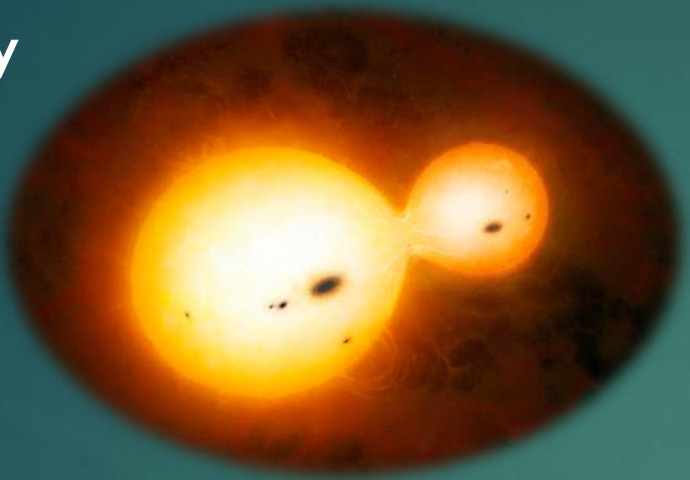
Deviations from spherical symmetry

Nature would have been strange if everything were spherical...

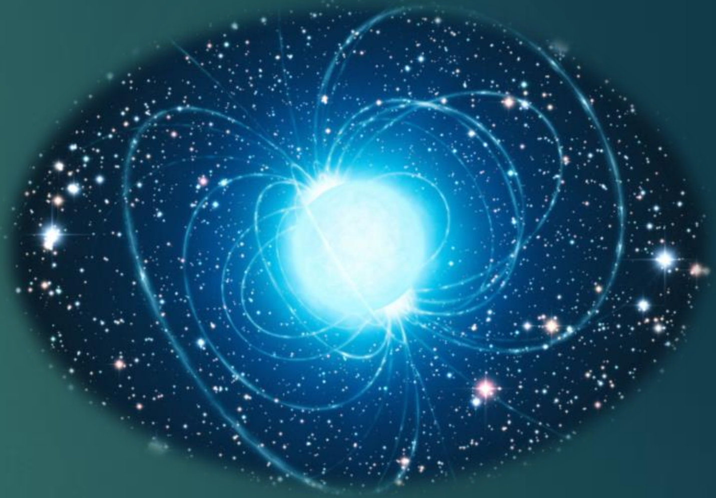
... same applies for Stellar winds & Supernova Remnants

Non-spherical symmetric stellar winds

- Stellar duplicity

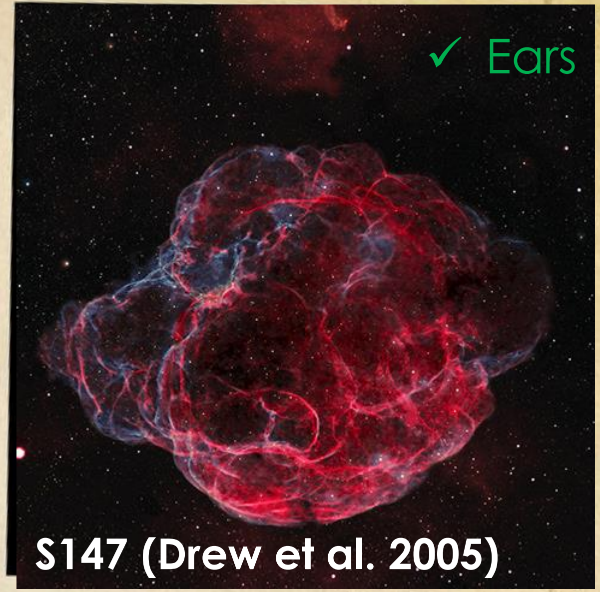


- Stellar magnetic fields

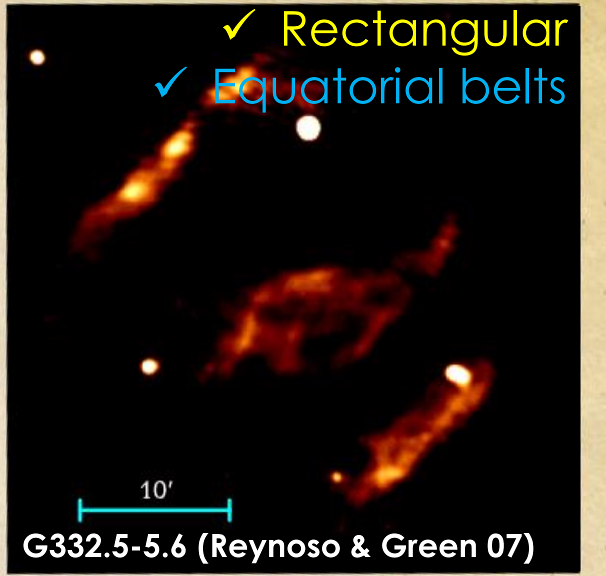


- Stellar rotation

- Stellar systemic motion

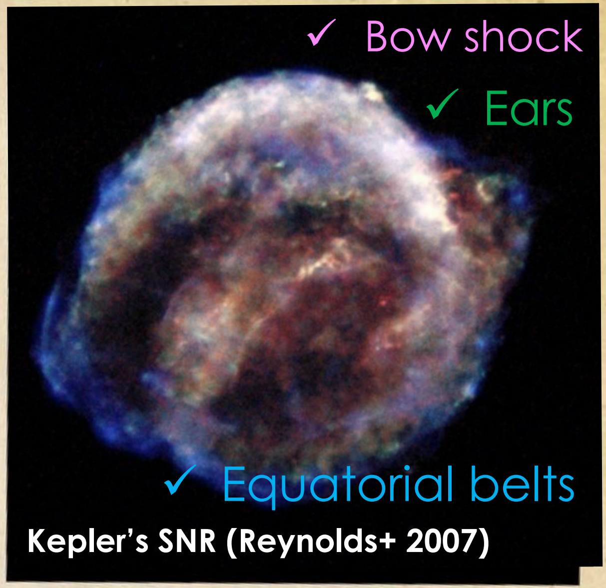

✓ Ears

S147 (Drew et al. 2005)


✓ Rectangular

✓ Equatorial belts

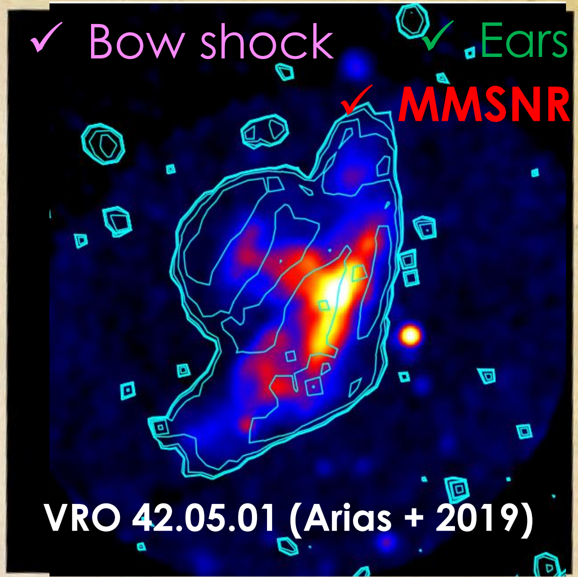
G332.5-5.6 (Reynoso & Green 07)


✓ Bow shock

✓ Ears

✓ Equatorial belts

Kepler's SNR (Reynolds+ 2007)

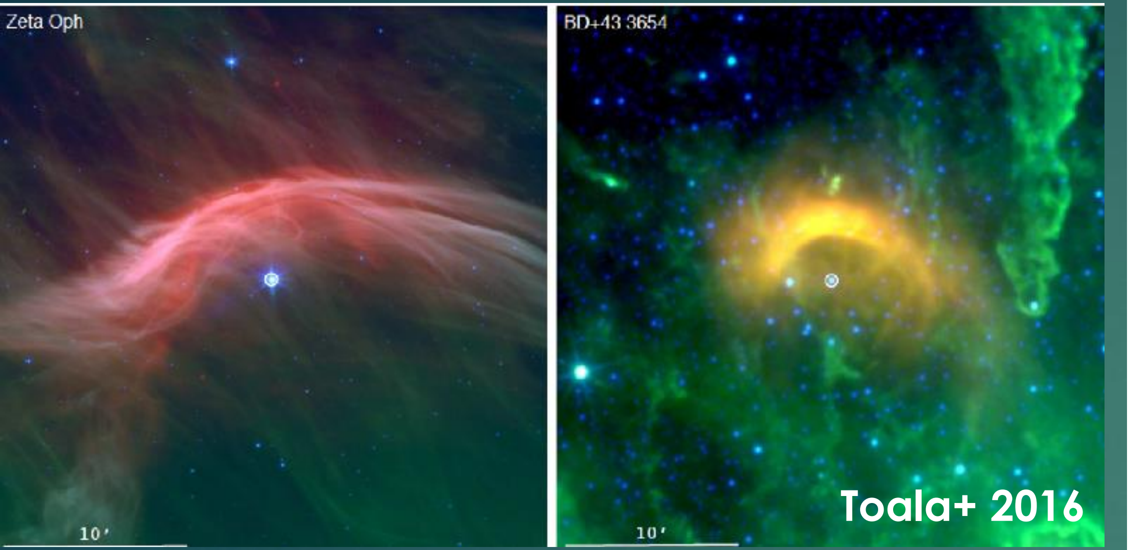

✓ Bow shock

✓ Ears

✓ MMSNR

VRO 42.05.01 (Arias + 2019)

I. Bow shocks

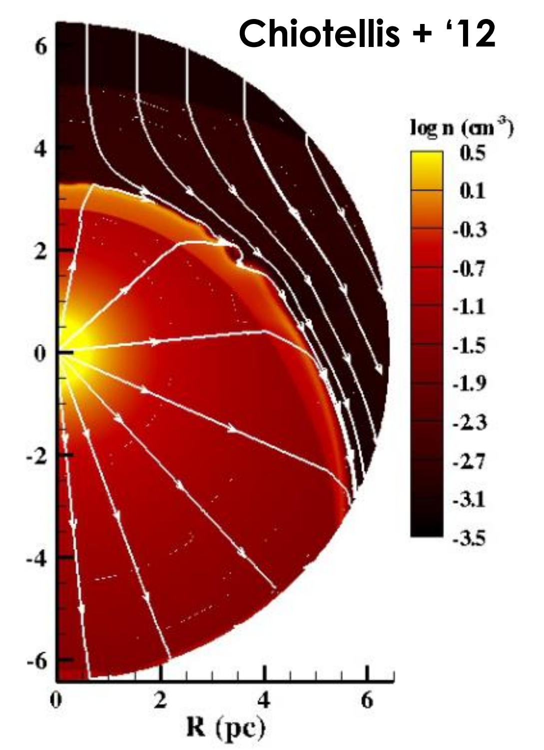


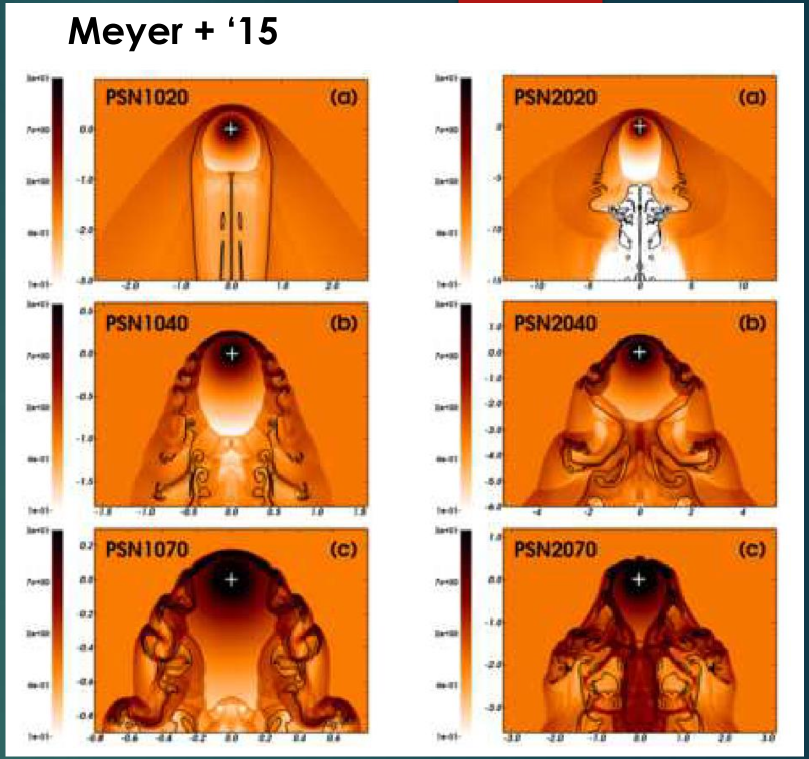
Toala+ 2016

Runways (progenitor) stars:

- ✓ Dynamical interactions of single/binary stars
  (Poveda+ 1967; Spitzer & Varshalovich 1980; Gvaramadze & Gualandris 2011)
- ✓ Supernova explosion in binary systems
  (Zwicky 1957; Blaauw 1961)

Ram pressure balance:


Chiotellis + '12

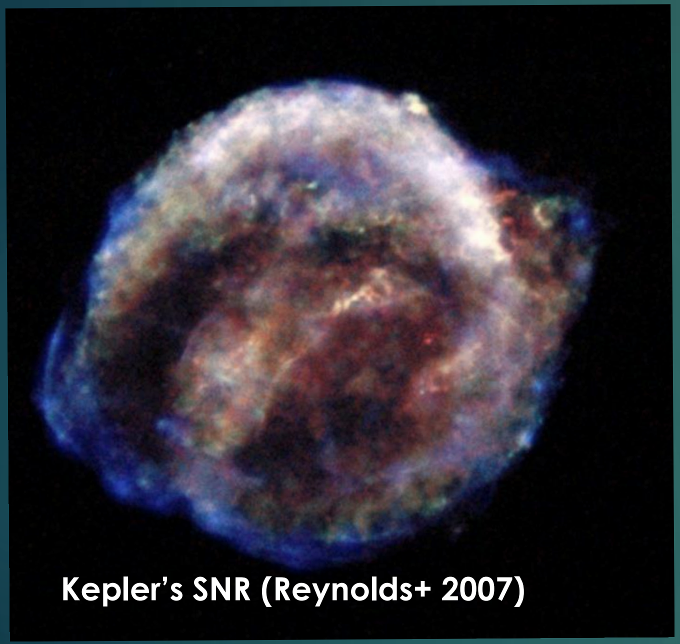

Meyer + '15

Stagnation point:

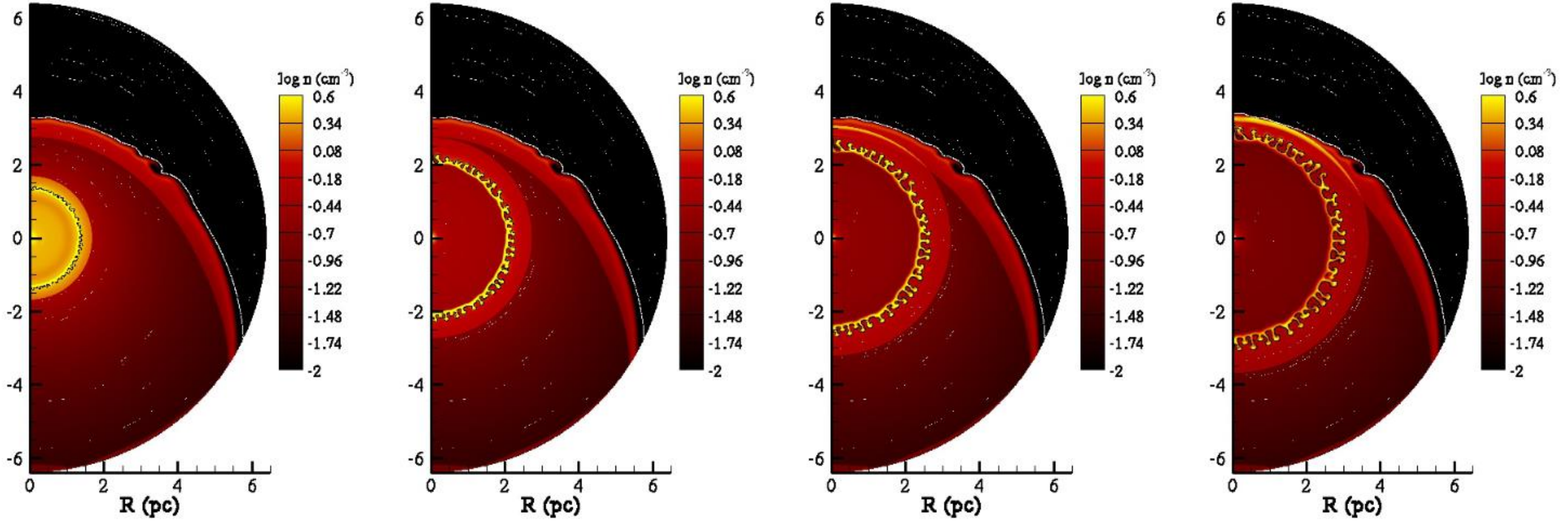
$$r_0 = 1.48 \left(\frac{\dot{M}}{5 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}} \right)^{1/2} \left(\frac{v_w}{15\ \mathrm{km\ s}^{-1}} \right)^{1/2} \times \left(\frac{v_*}{280\ \mathrm{km\ s}^{-1}} \right)^{-1} \left(\frac{n_0}{0.001\ \mathrm{cm}^{-3}} \right)^{-1/2} \mathrm{pc}$$

Borkowski + 1992; Houpis & Mendis (1980); Rozyczka +1993

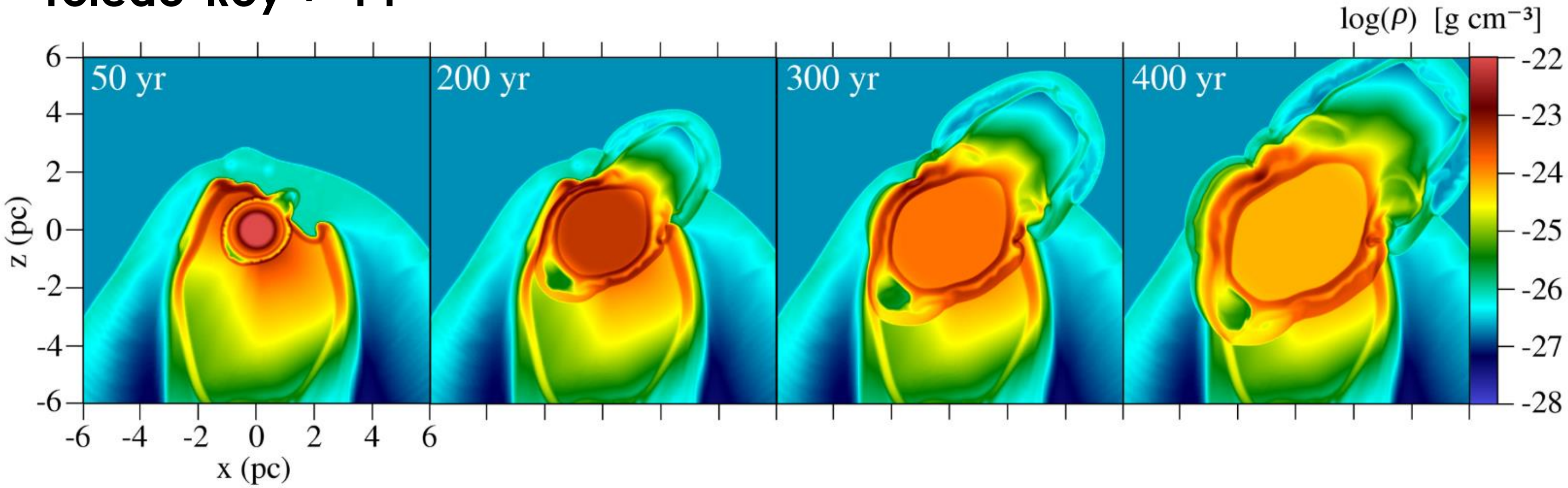
Bow shocks on SNRs


Kepler's SNR (Reynolds+ 2007)

Chiotellis + '12

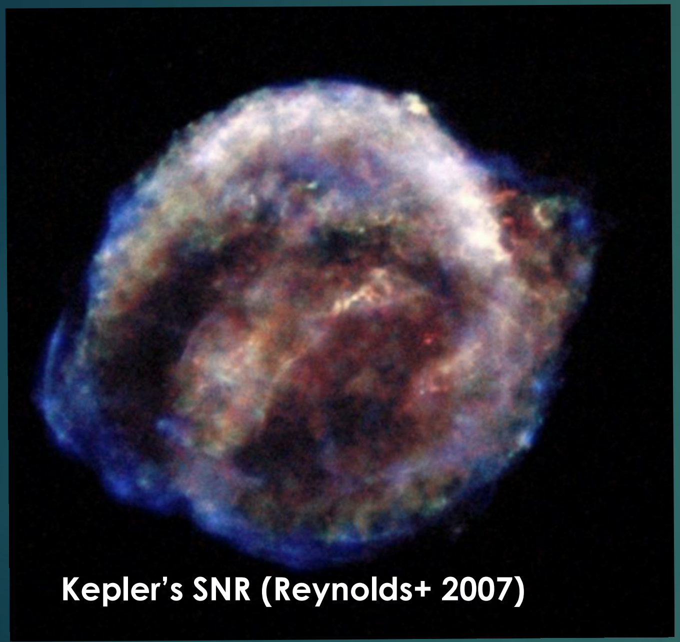


Toledo-Roy + '14



First idea by:
R. Bandiera 1987

Bow shocks on SNRs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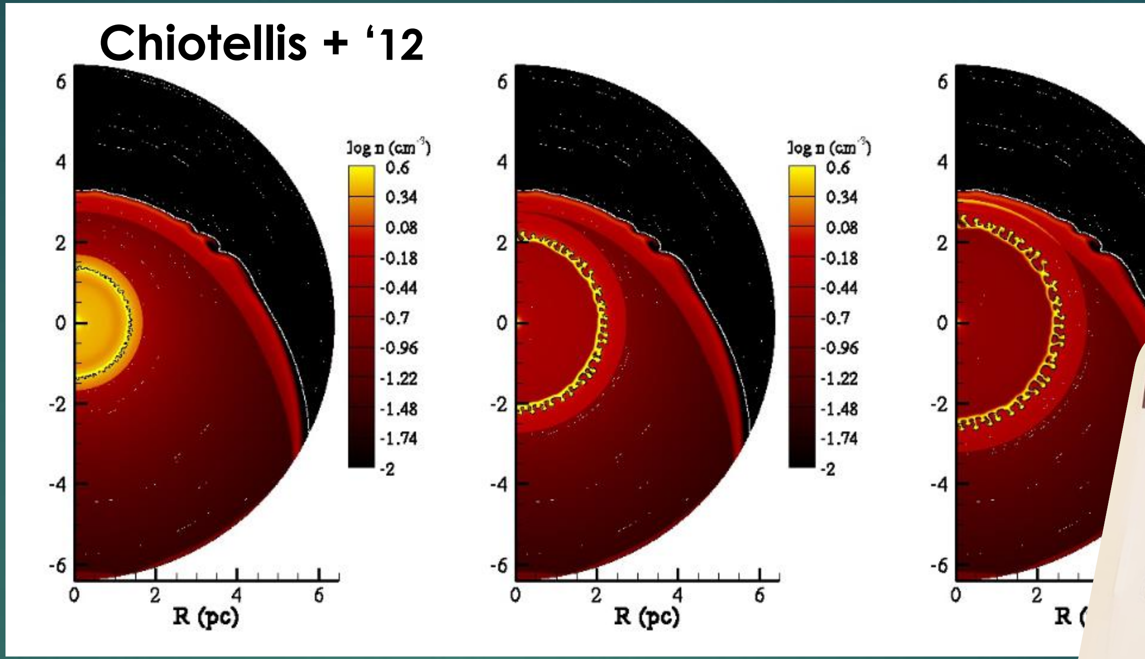
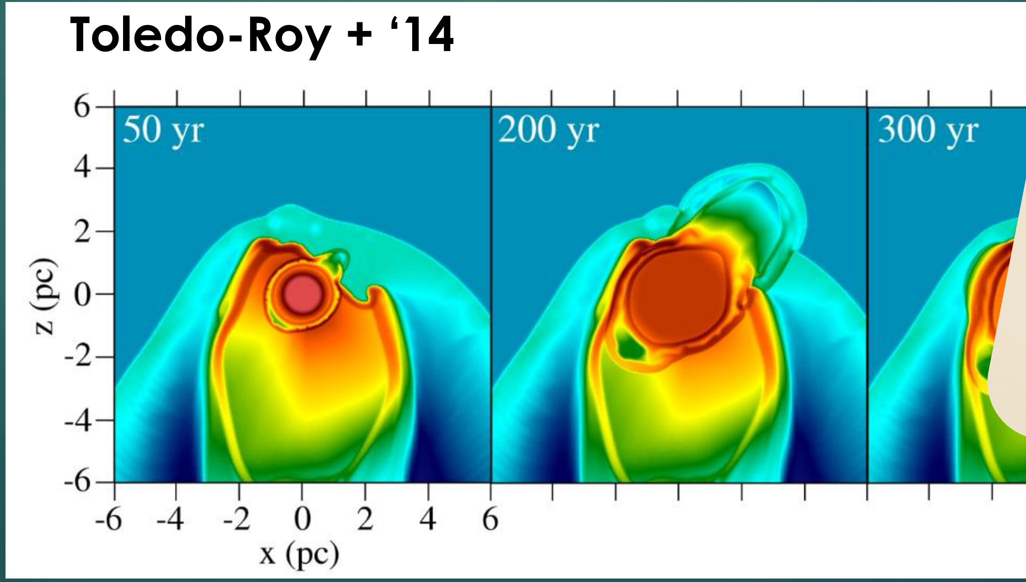


Toledo-Roy + '14




Study of non-thermal emission of Kepler's SNR with MHD numerical simulations

K.M. Vargas-Rojas [1] P.F. Velazquez [1] J. C. Toledo-Roy [1]

[1] Instituto de Ciencias Nucleares, UNAM, Mexico

Instituto de Ciencias Nucleares

Abstract

Our simulations: "ears" formation

The code: The initial setup

Why do we propose the Inverse Compton process?

Results: Comparing with the observations

Runaway star AGB wind + Asymmetric SN with jets = EARS!

Conclusions

References

Vargas et al.
Poster S4.28

II. Bipolar circumstellar structures

Possible Mechanisms:

✓ Stellar rotation
(e.g. Bjorkman & Cassinelli 1993; Heger + 2000)

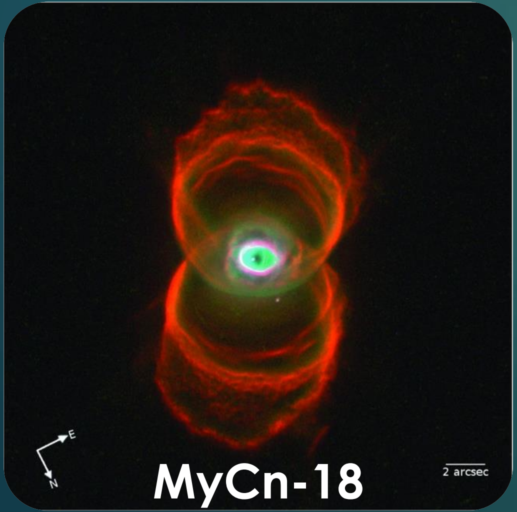
✓ Close binary interactions
(e.g. Mastrodemos & Morris 1999; Politano & Taam 2011)

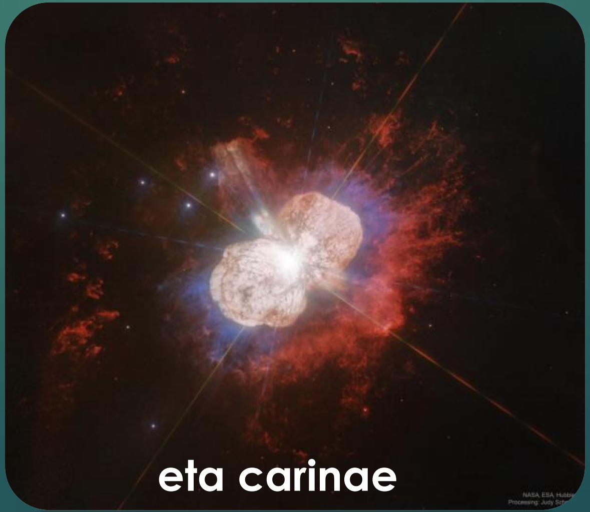
✓ Eruptive mass loss (e.g. Smith & Arnett 2014)

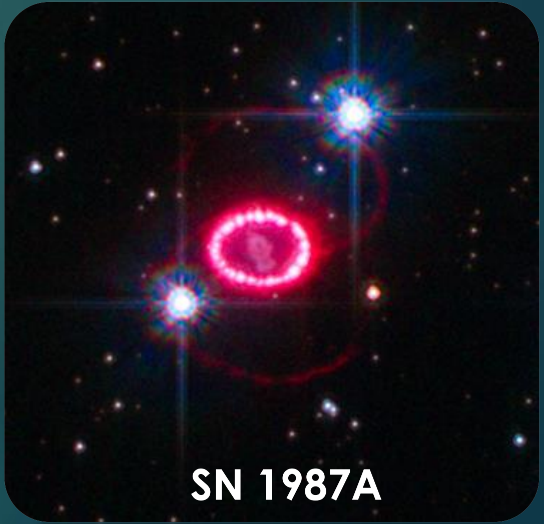
✓ Magnetic fields
(e.g. Garcıa- Segura et al. 1999; Townsend & Owocki 2005)

Most frequent met:

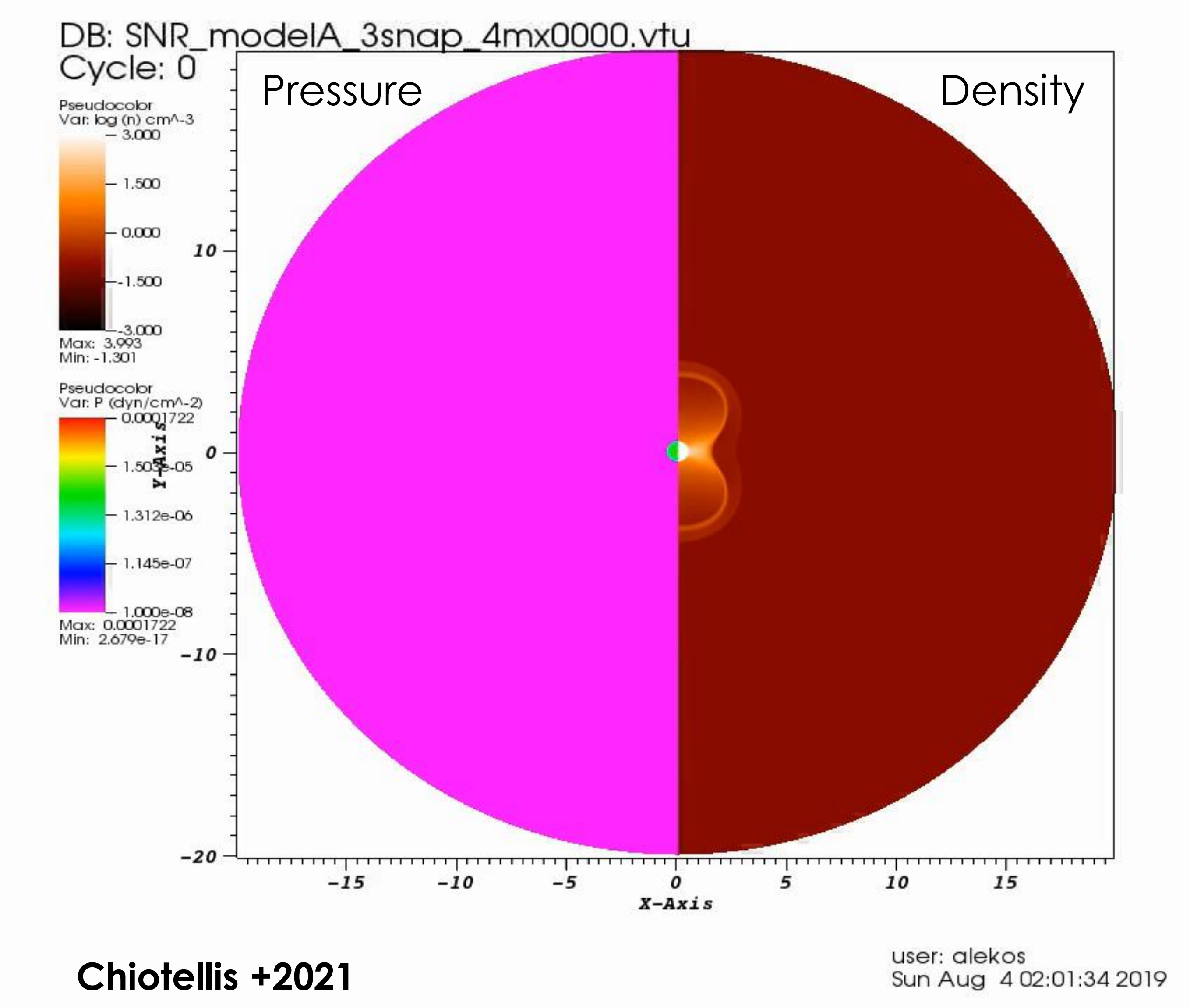
- LBVs (e.g. η Carinae; Smith 2002)
- Blue supergiants (e.g. SBW1, SBW2; Smith + 2007)
- Supernovae: Type II and Type IIn
  (e.g. SN 2010jl Katsuda et al. 2016)
- Low mas regime (SNe Ia):
  - PNe (e.g. Mz 3, Clyne et al. 2015)
  - AGB (Decin et al. 2020)


MyCn-18


eta carinae

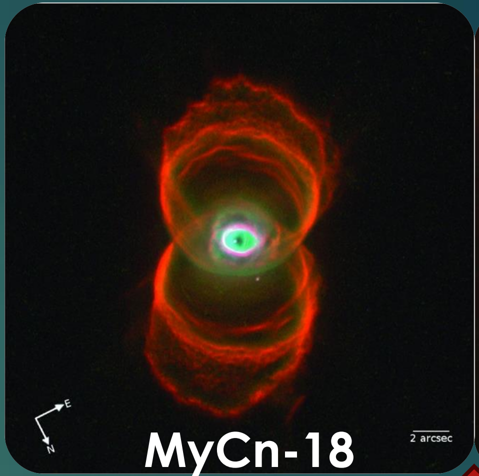

SN 1987A

SNR + Bipolar CSM interaction



Chiotellis +2021

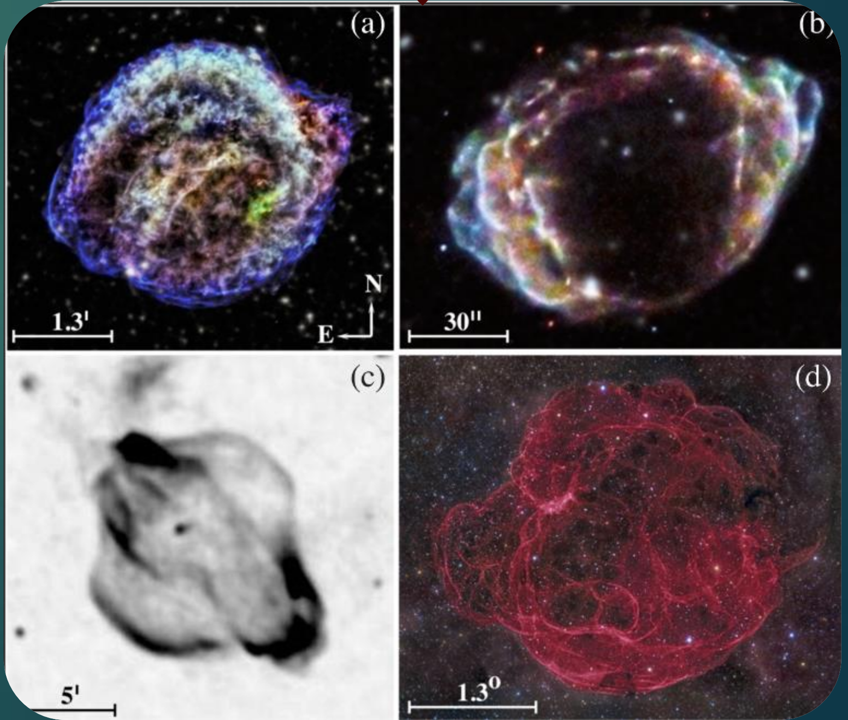
Bipolar CSM



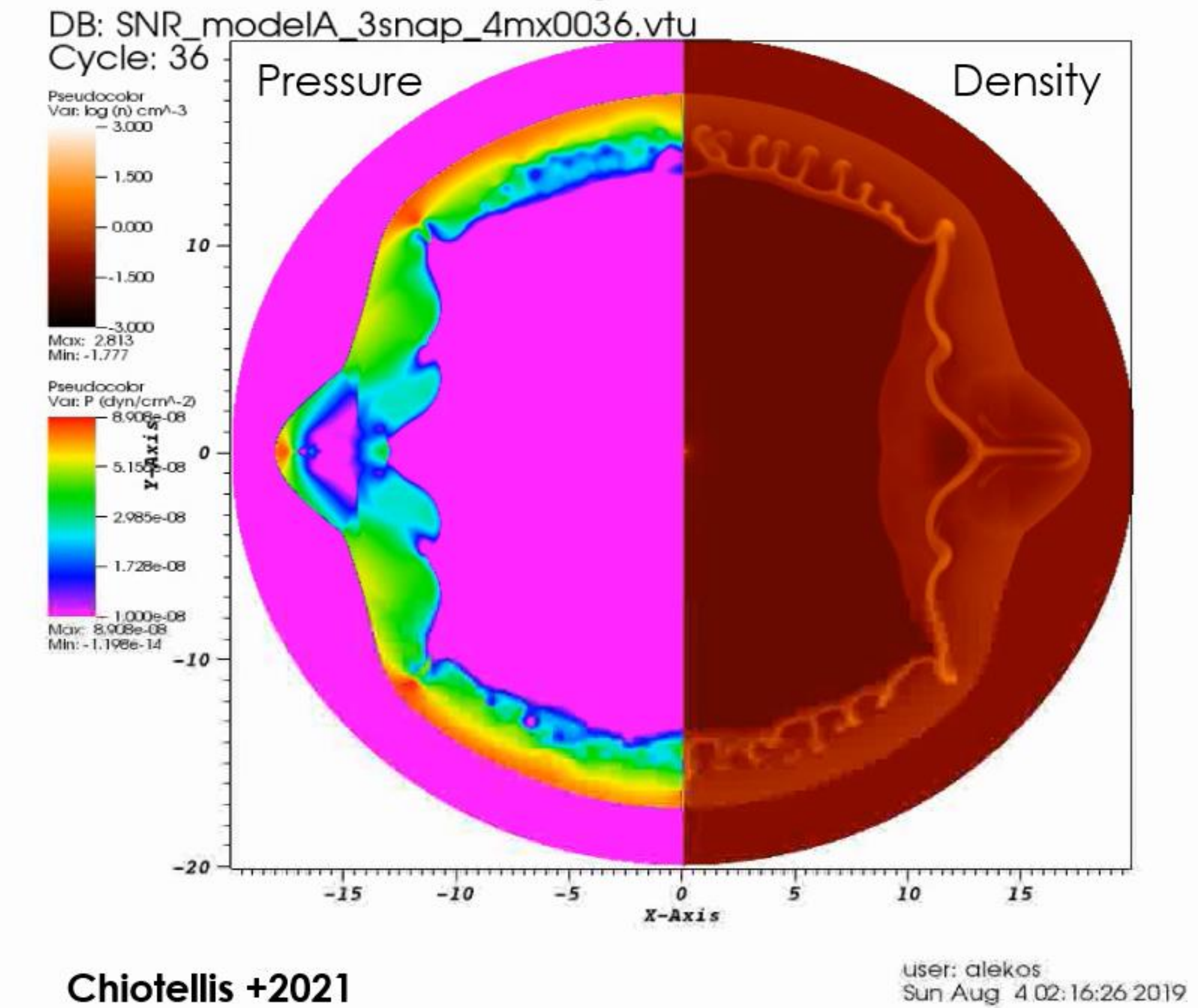
MyCn-18

eta carinae

SNR with ears

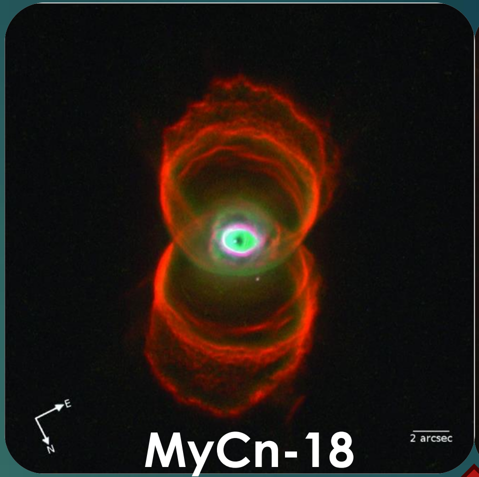


SNR + Bipolar CSM interaction



Chiotellis +2021

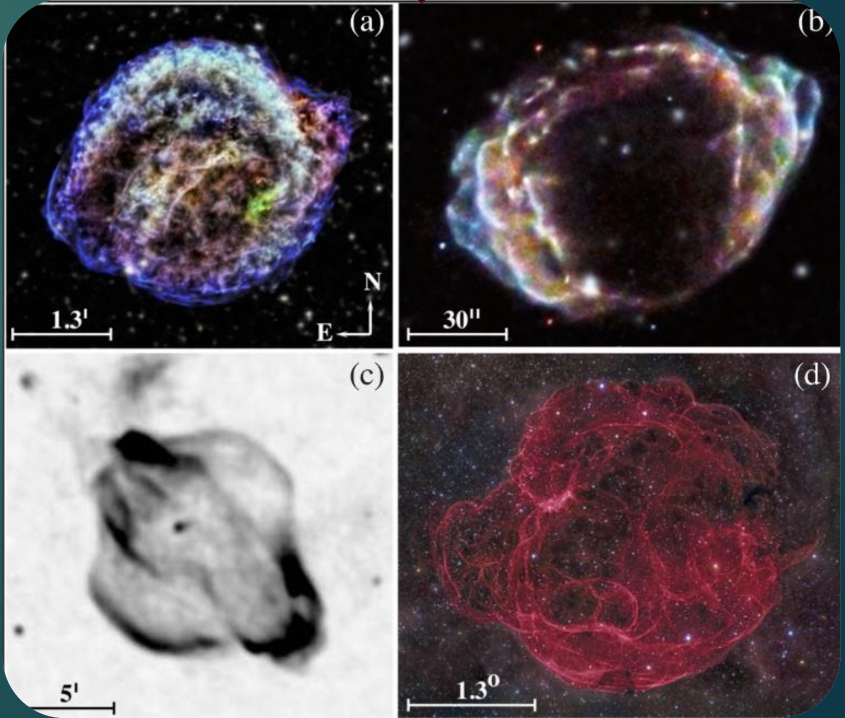
Bipolar CSM



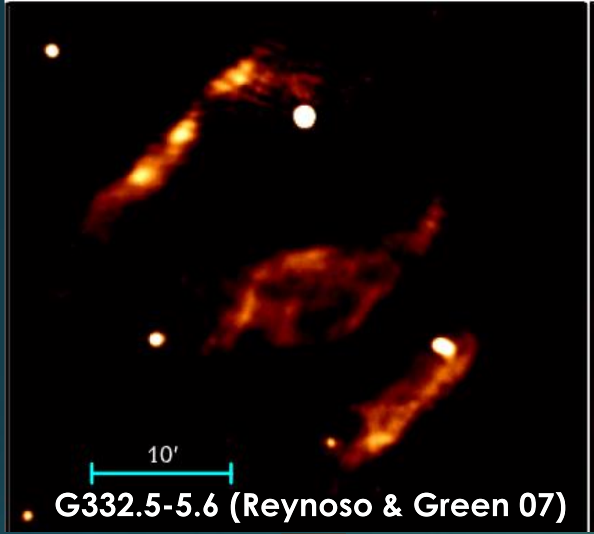
MyCn-18

eta carinae

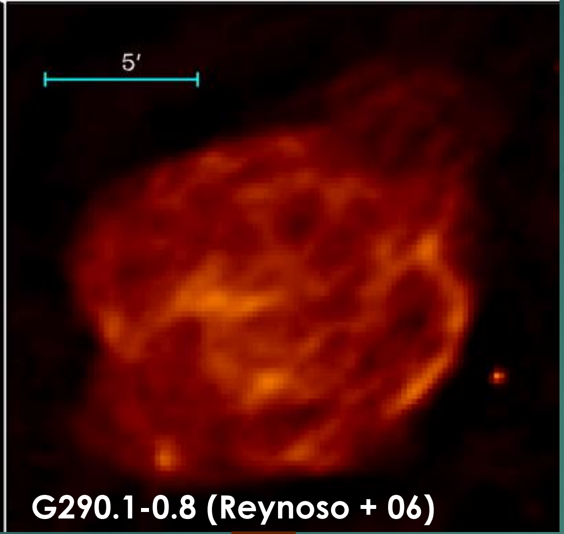
SNR with ears



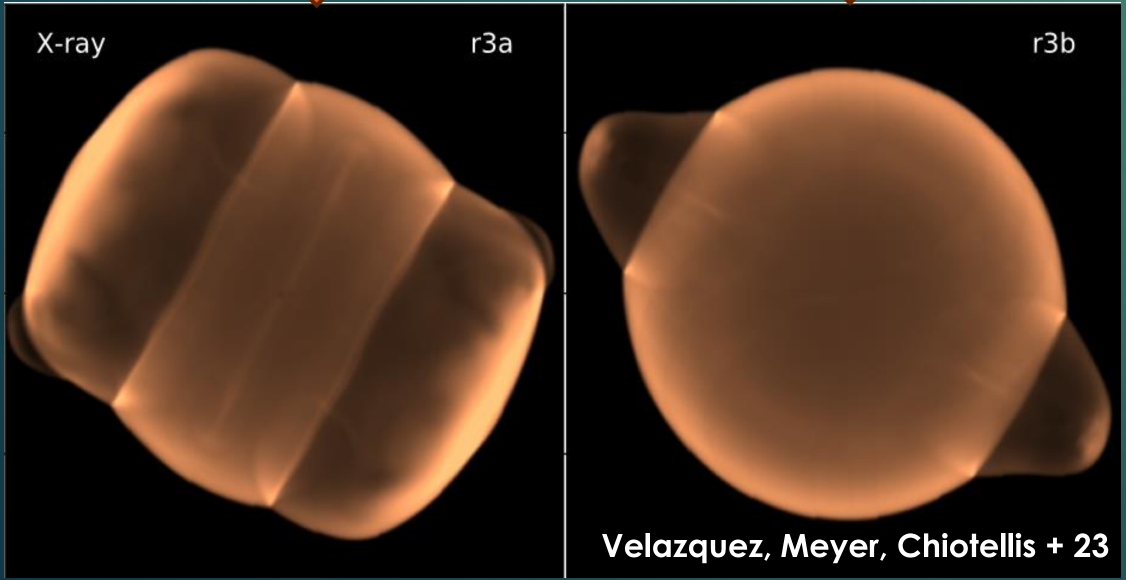
SNR + Bipolar CSM interaction



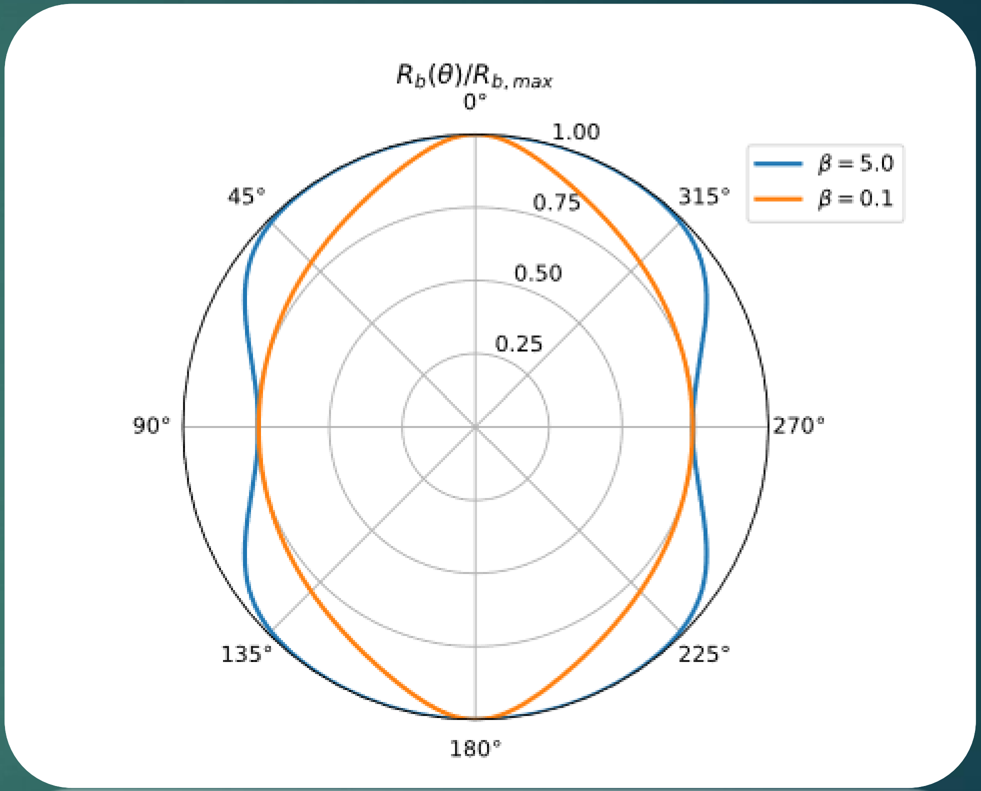
G332.5-5.6 (Reynoso & Green 07)



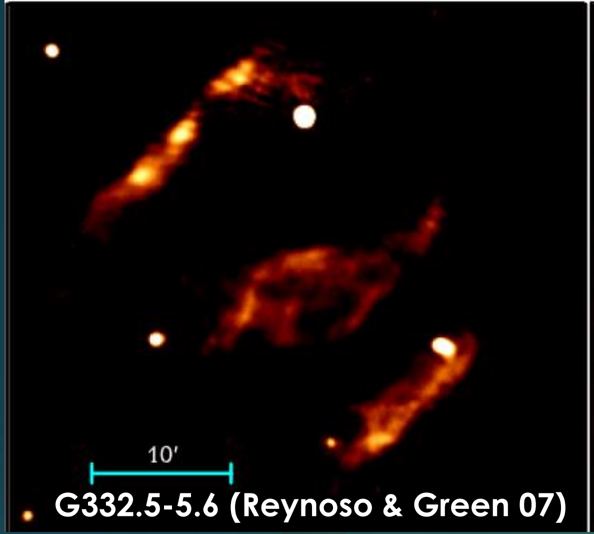
G290.1-0.8 (Reynoso + 06)



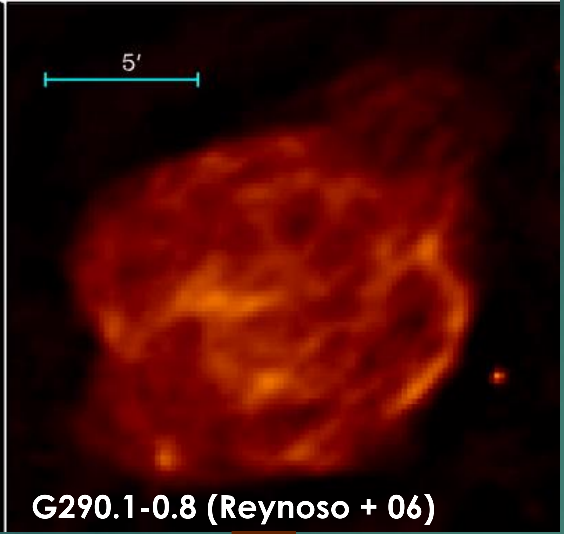
Velazquez, Meyer, Chiotellis + 23



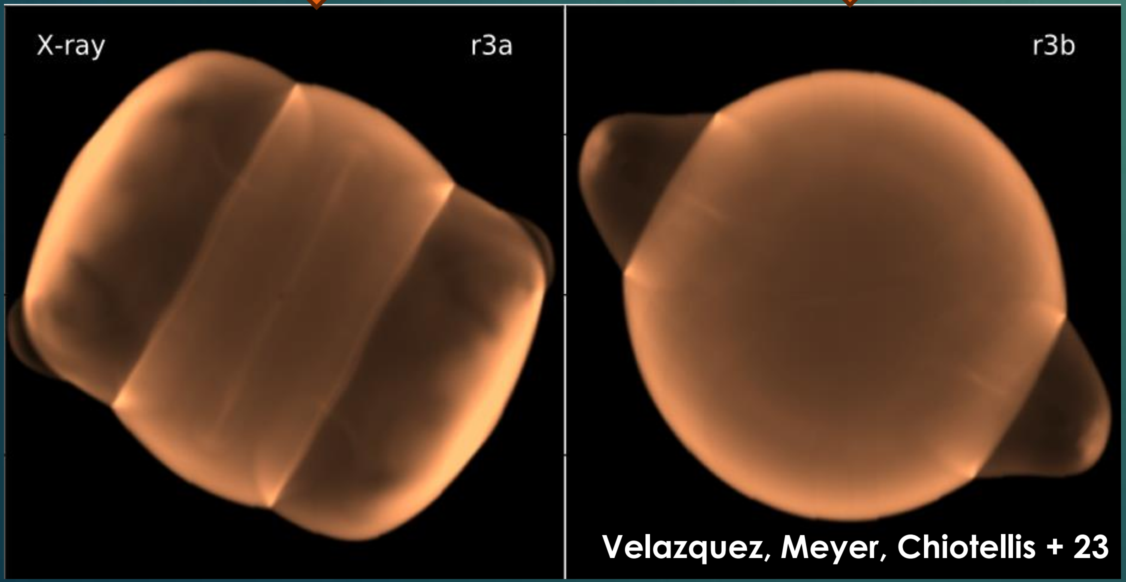
SNR + Bipolar CSM interaction



G332.5-5.6 (Reynoso & Green 07)



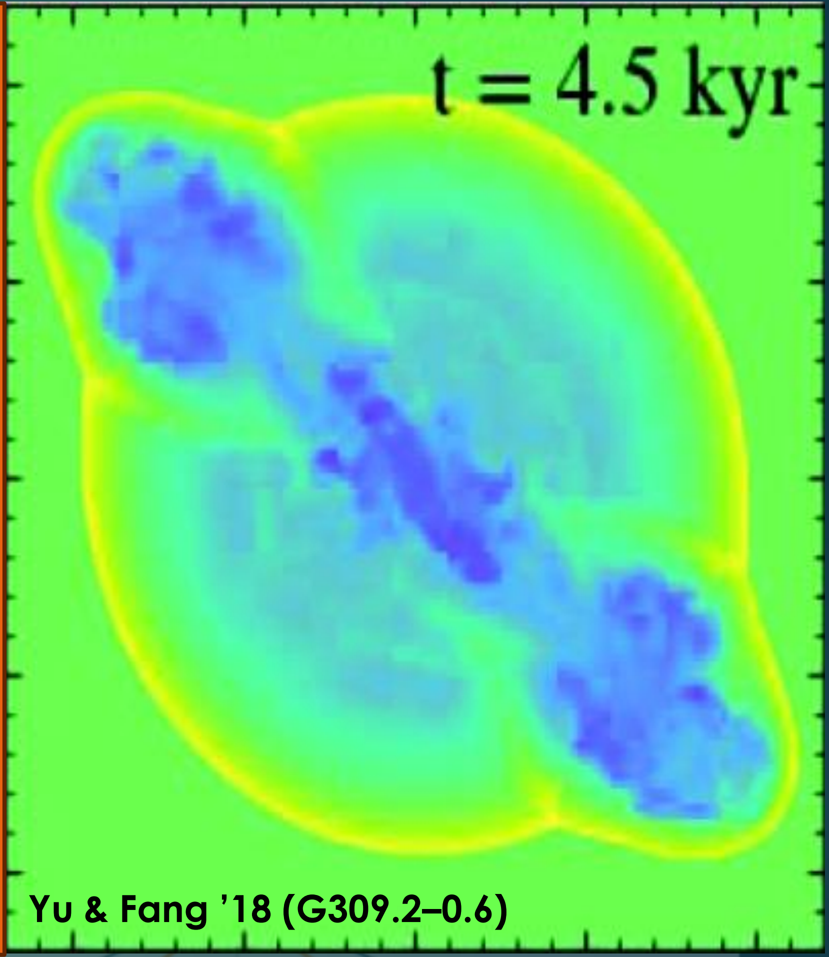
G290.1-0.8 (Reynoso + 06)



Velazquez, Meyer, Chiotellis + 23

Alternative for ear: Jets

Soker 2024, Yu & Fang '18, Ohmura + '21



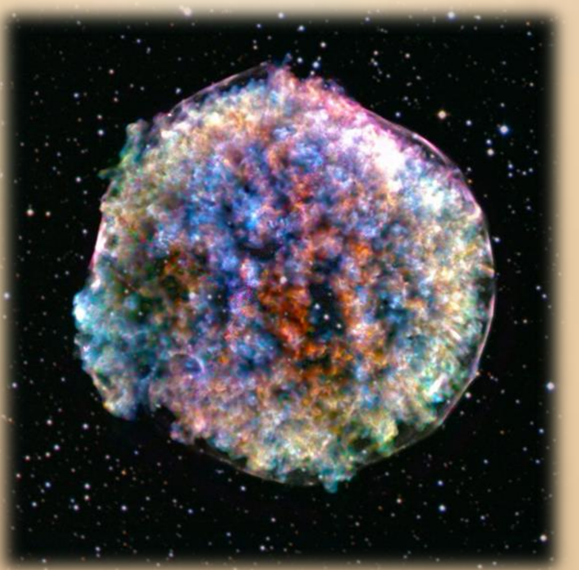
Yu & Fang '18 (G309.2–0.6)

Conclusions

- SNR properties deviate from the SN+ISM interaction model
  -> Reason: **CSM**
- SN progenitors shape the ambient medium properties through mass outflows
  - CC SNR -> Substantially
  - Type Ia SNR -> not much, but still…
- Wind bubbles alter the evolution of the SNR
- Important effect reflected shocks -> MMSNRs (?)
- Wind bubbles deviate from spherical symmetry
- Bow shock → Runaways progenitors
- Ears → Bipolar CSM (or jets)
- Endless debate:
  ISM Vs CSM Vs explosion

Main Conclusion

Talking about
violent stellar deaths
is a very
interesting and
intriguing topic



...but it's the opposite
when we talk about
violent human deaths

Thank you