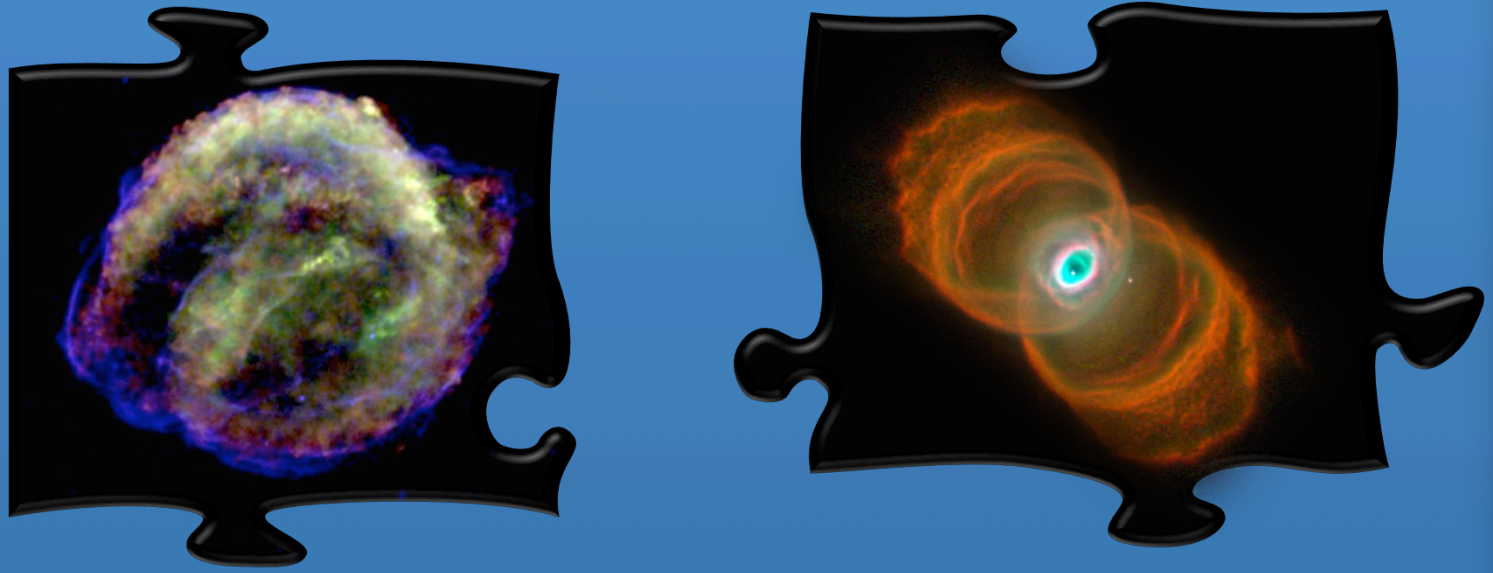
On the interaction of Type Ia SNRs with Planetary Nebulae

Alexandros Chiotellis

Panos Boumis



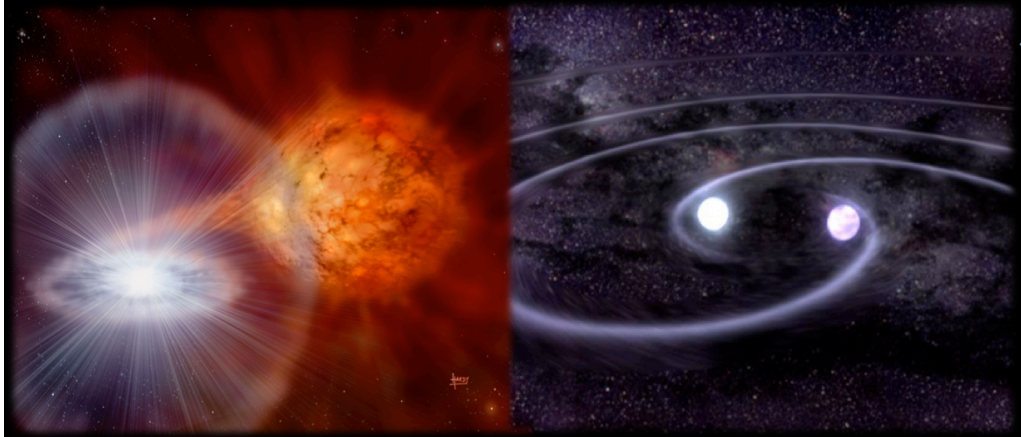
National Observatory of Athens

Chania, June 2019

Type Ia Supernovae (SNe Ia)

"Explosions of CO white dwarfs in binary systems, which get destabilized through mass accretion from the companion star"

Accretors Vs Mergers



SNe Ia ZOO

Accretors:

- Cataclysmic Variables
- Symbiotic stars
- Recurrent Novae

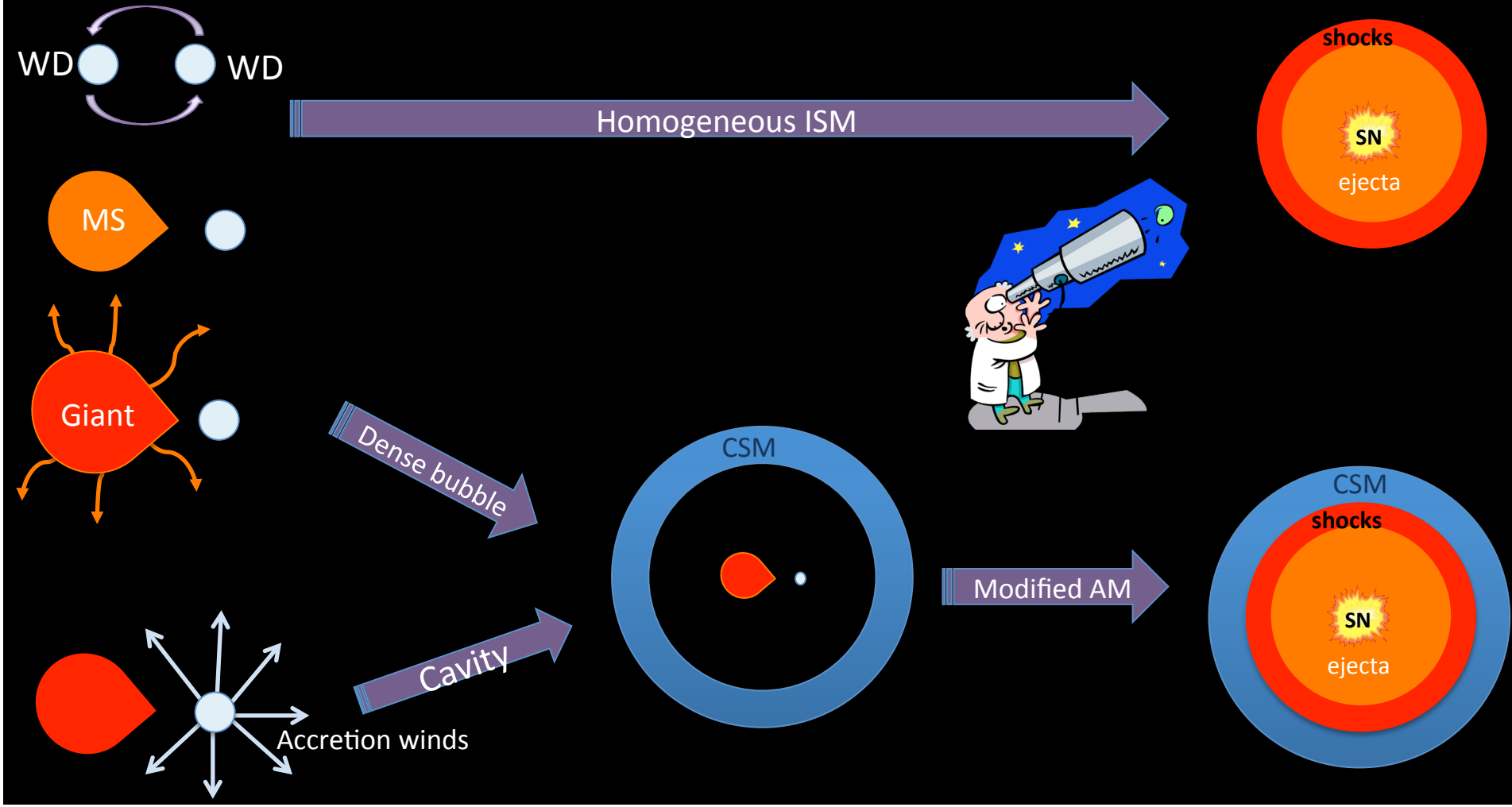
Mergers:

- Double degenerate
- Core degenerate
- Violent mergers

etc…

The importance of CSM in the quest of SNe Ia origin

Different paths of binary evolution which lead to Type Ia → **Different (or no) mass outflows from the progenitors** → **Different properties of SNe Ia/SNRs**



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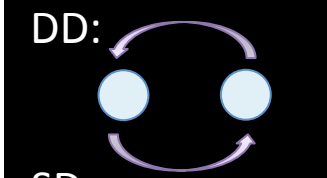
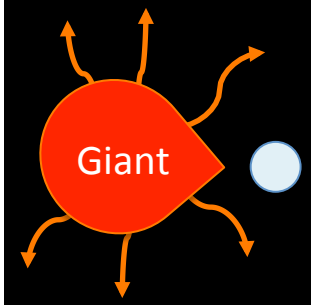
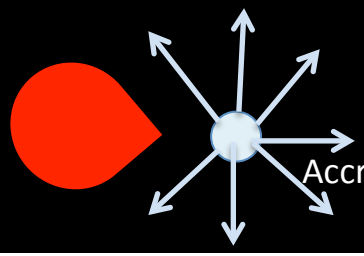


SD:

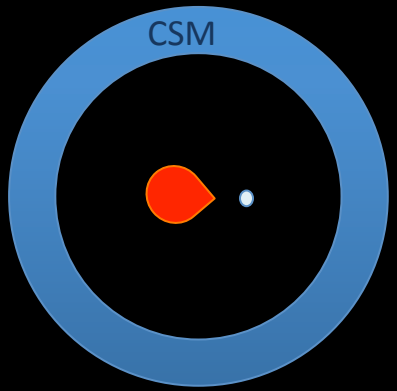




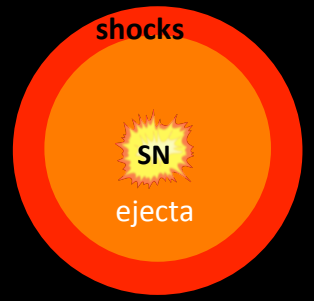
Homogeneous ISM

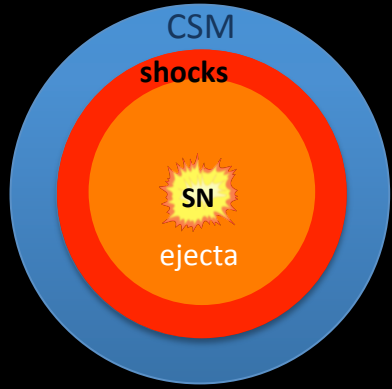
Dense bubble

Cavity



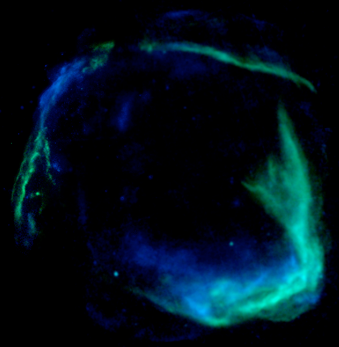
Modified AM



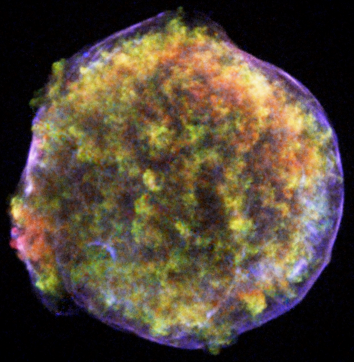


The (controversial) observational evidence for SNRs Ia + CSM interaction

Kepler's SNR: Interaction with a dense AGB wind bubble (Chiotellis+ 2012; Patnaude +2012; Burkey+2013, Toledo-Roy+ 2014)

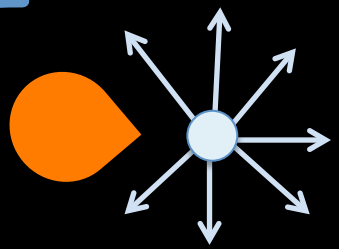


RCW 86 : Interaction with an extended cavity (Vink et al. 1997, Williams et al. 2011; Broersen et al. 2014)



Tycho's SNR : The SNR is surrounded by an expanding molecular bubble (Zhou+ 2016; Chen+ 2017)

Accretion winds (Hachisu+ 1996)



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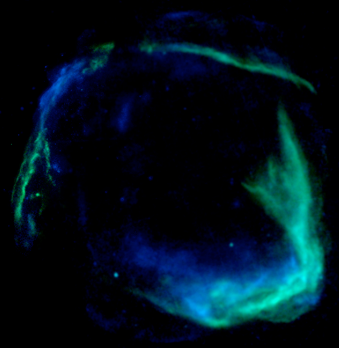
Observations: there is no such an AGB star in the center of Kepler's SNR (Kerzendorf et al. 2014; Ruiz-Lapuente (2017)



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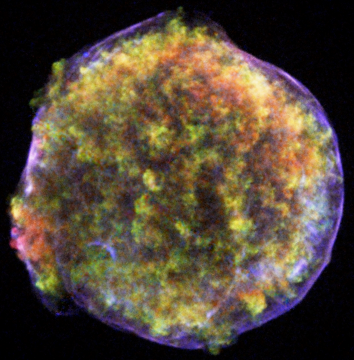

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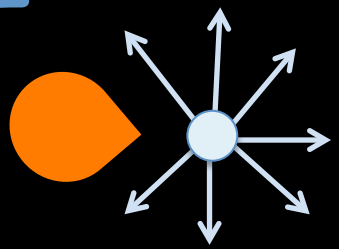

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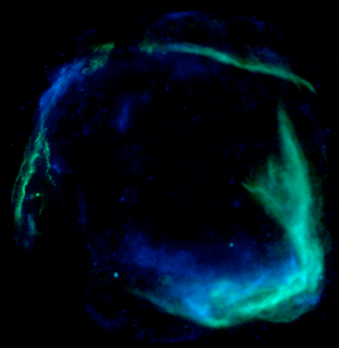

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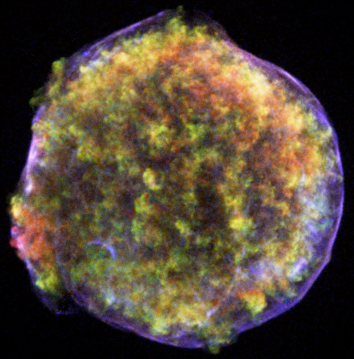

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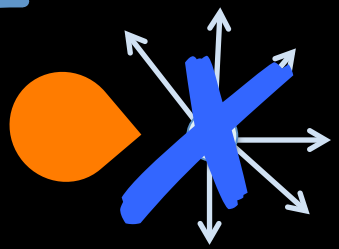


Tycho: - donor star? Debatable **(Ruiz-Lapuente talk)**
- Not a steadily accreting WD (Woods+ 2017)

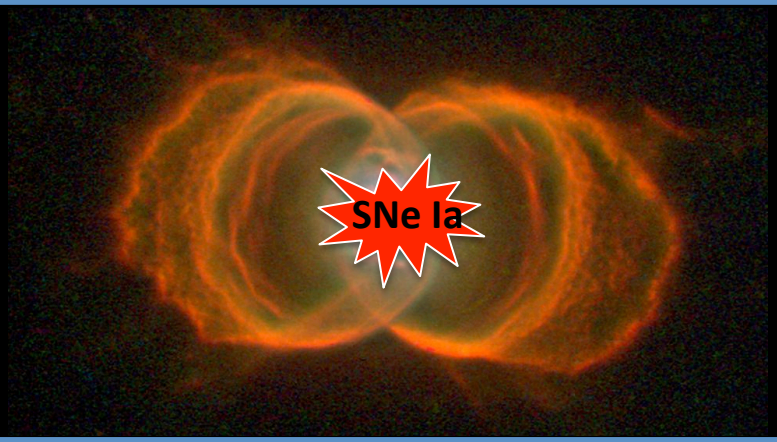
now the question is…

- *Is a circumstellar medium where:*

a) Its formation can naturally be explained by the binary evolution towards a SN Ia?

b) it can explain (at least some of) the properties observed in SNRs Ia?

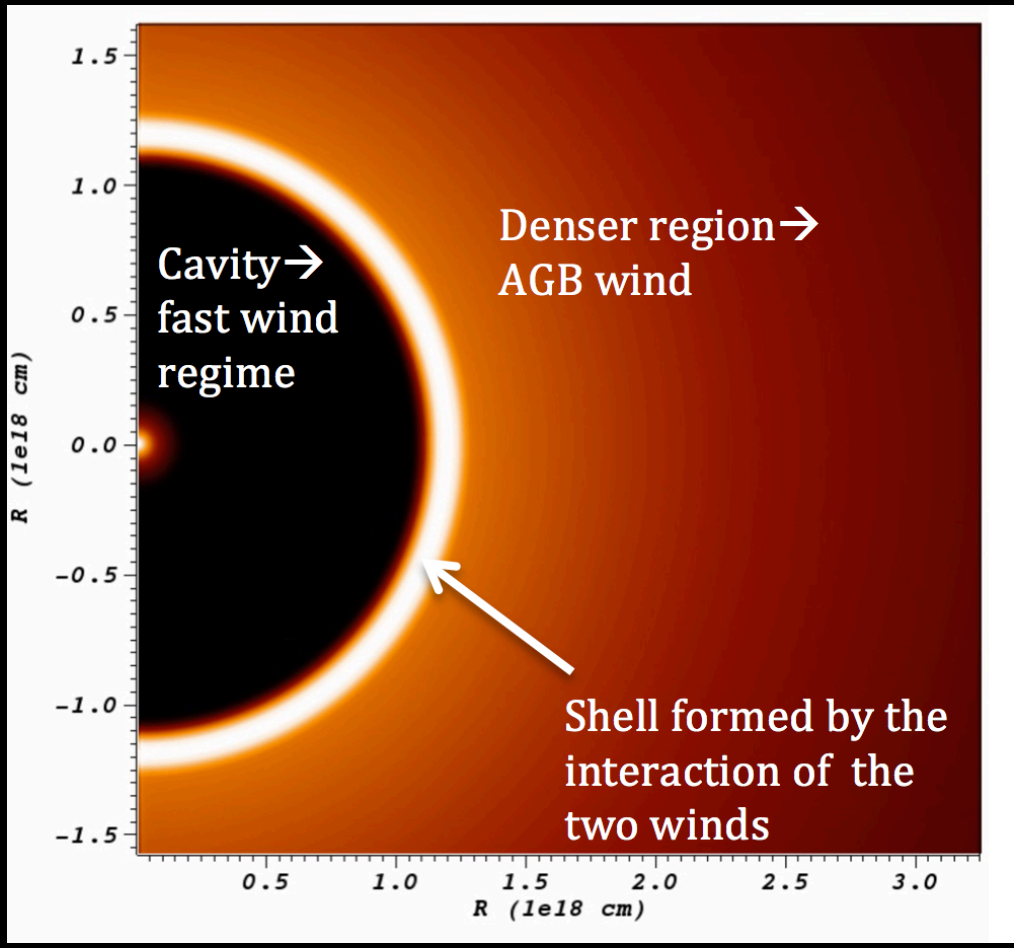
We suggest that such a CSM could potentially be represented by **Planetary Nebulae (PNe)**



Planetary Nebulae (PNe)

Interactive Stellar Wind theory (Kwok et al. 1978)

- AGB: slow, dense stellar wind
- Contraction of AGB core: Fast, tenuous wind



Planetary Nebulae (PNe)

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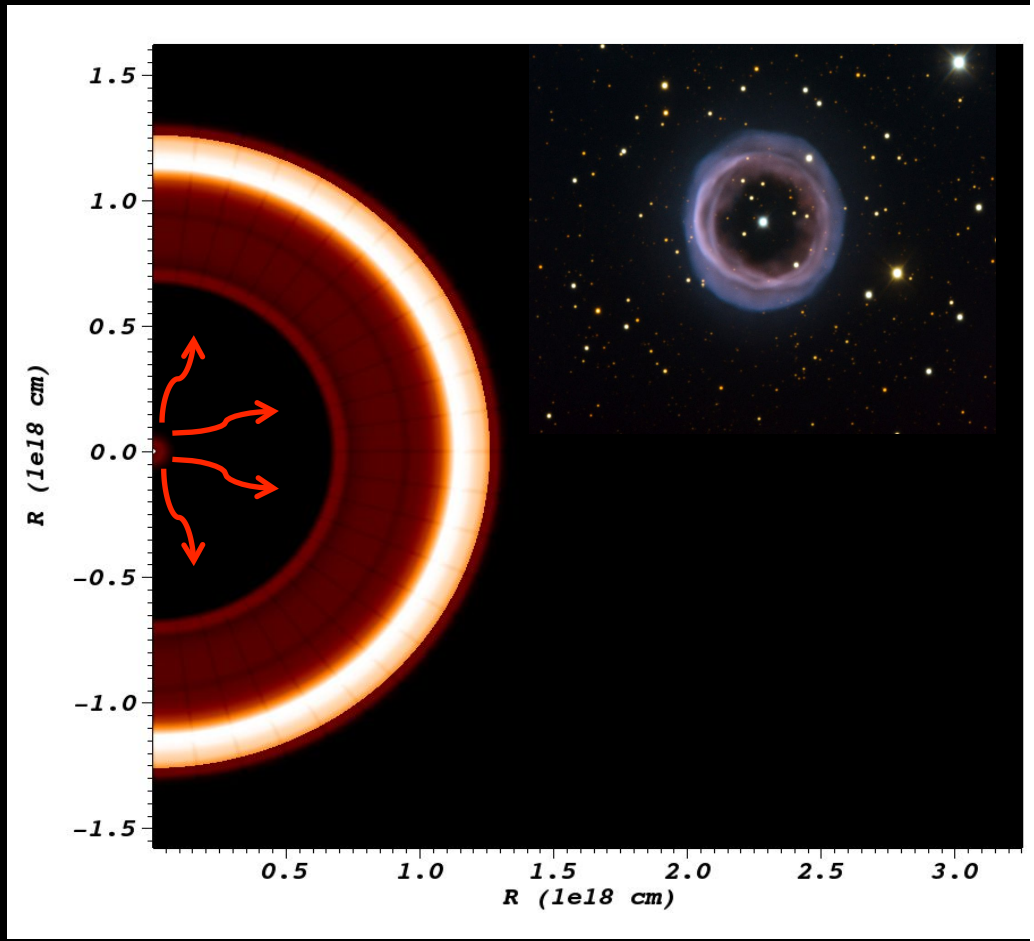
- Photoionization from the hot central star



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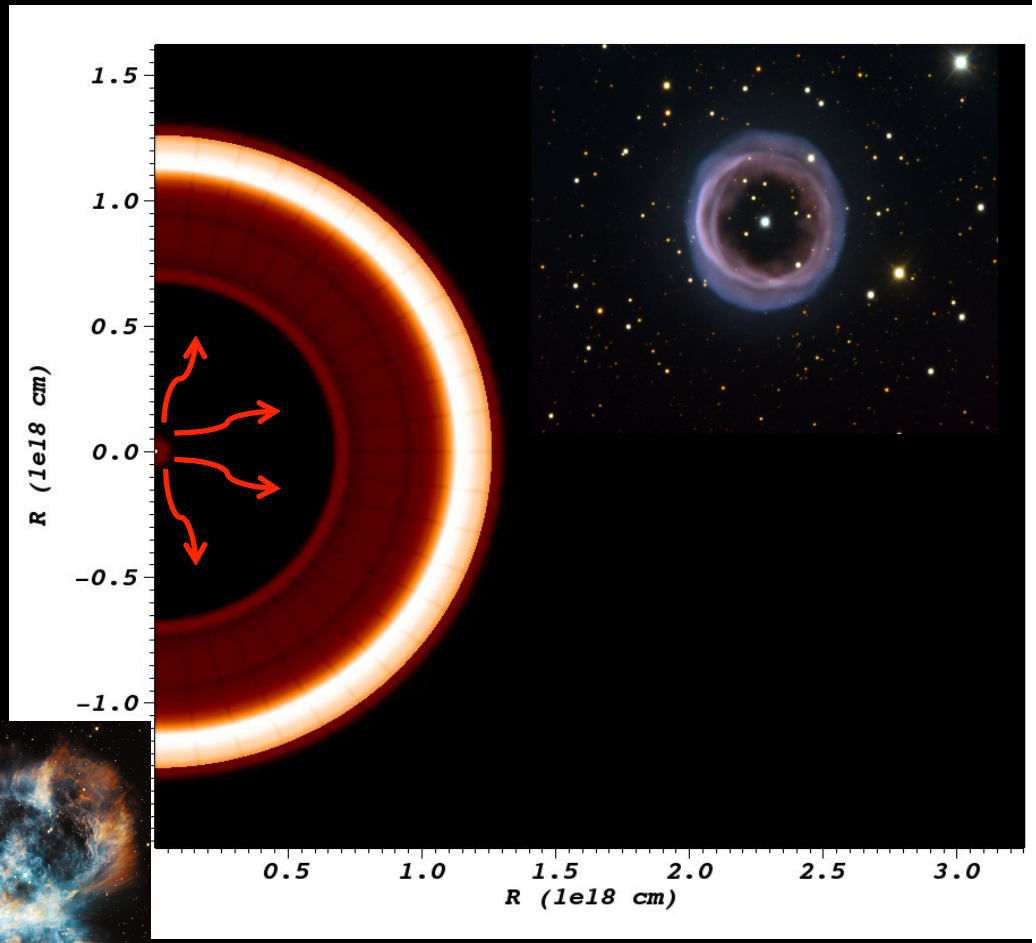
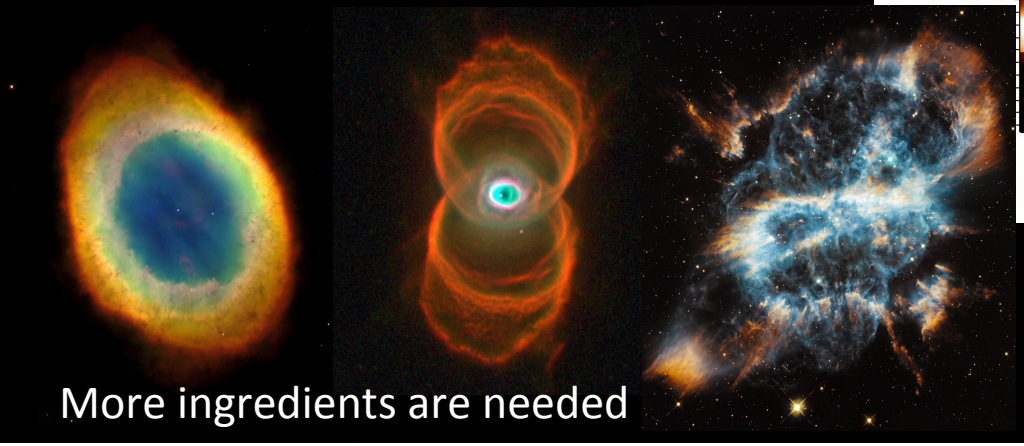
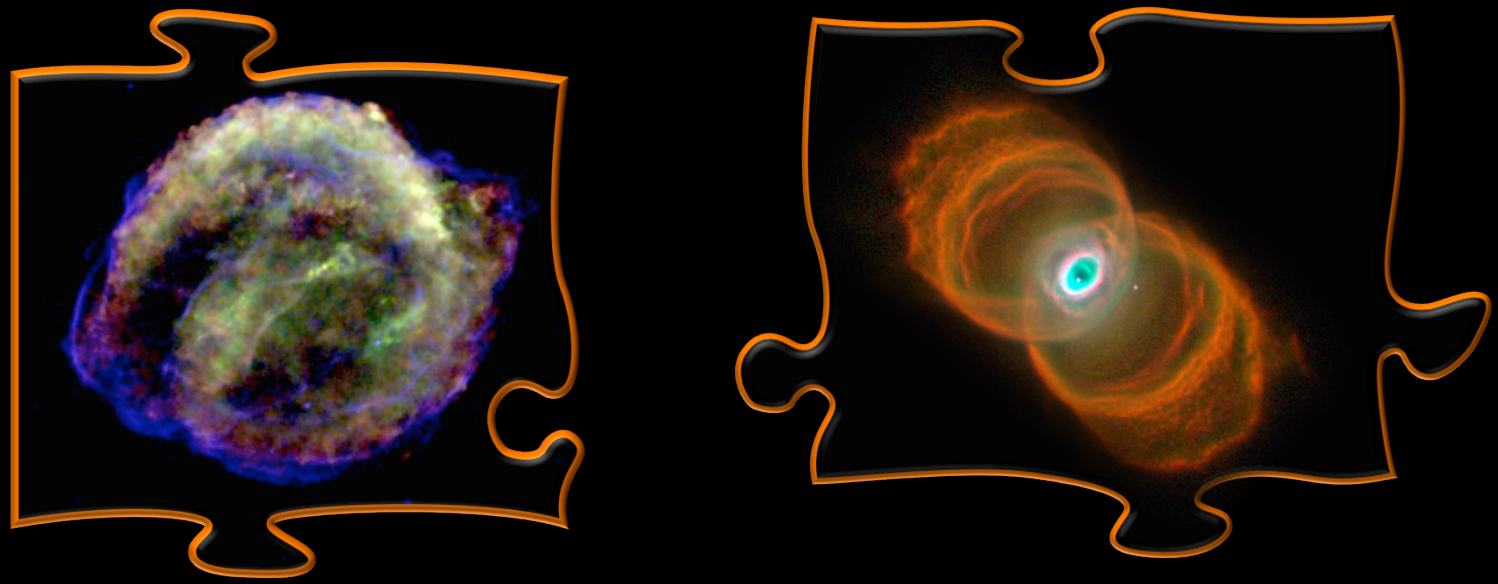




More ingredients are needed

Why Planetary Nebula?



Motivation (I): PNe nature

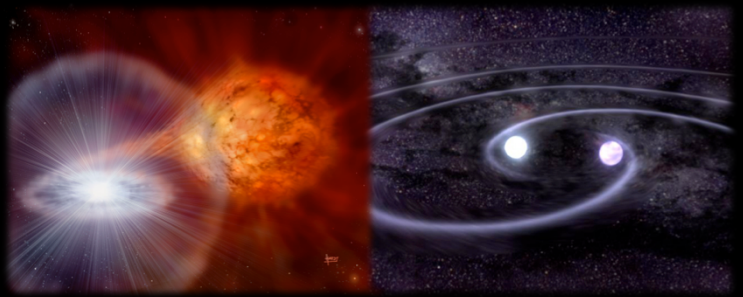
1) *PNe central stars*: low-mass binary systems involving one or two WDs.
(De Marco et al. 2013)

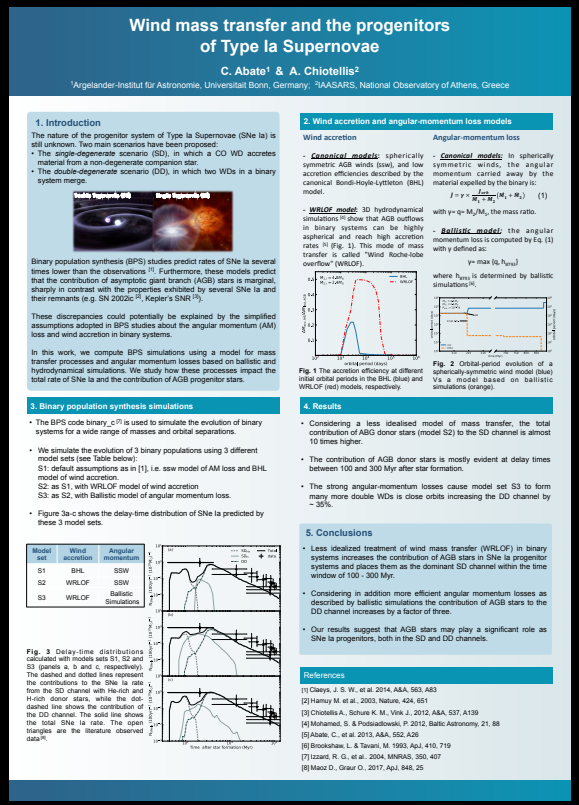
→ *As the expected progenitors of SNe Ia*

2) *Binary population synthesis models:* Several SNe Ia progenitors pass through the AGB/PNe phase.

➔ **A.J Ruiter talk**

➔ The SN Ia + PNe scenario host both the SD and DD paths





Wind mass transfer and the progenitors of Type Ia Supernovae

C. Abate[1] & A. Chiotellis[2]

[1]Argelander-Institut für Astronomie, Universitait Bonn, Germany; [2]IAASARS, National Observatory of Athens, Greece

1. Introduction

The nature of the progenitor system of Type Ia Supernovae (SNe Ia) is still unknown. Two main scenarios have been proposed:

- The *single-degenerate* scenario (SD), in which a CO WD accretes material from a non-degenerate companion star.
- The *double-degenerate* scenario (DD), in which two WDs in a binary system merge.

Binary population synthesis (BPS) studies predict rates of SNe Ia several times lower than the observations [1]. Furthermore, these models predict that the contribution of asymptotic giant branch (AGB) stars is marginal, sharply in contrast with the properties exhibited by several SNe Ia and their remnants (e.g. SN 2002ic [2], Kepler's SNR [3]).

These discrepancies could potentially be explained by the simplified assumptions adopted in BPS studies about the angular momentum (AM) loss and wind accretion in binary systems.

In this work, we compute BPS simulations using a model for mass transfer processes and angular momentum losses based on ballistic and hydrodynamical simulations. We study how these processes impact the total rate of SNe Ia and the contribution of AGB progenitor stars.

2. Wind accretion and angular-momentum loss models

Wind accretion

- ***Canonical models:*** spherically symmetric AGB winds (ssw), and low accretion efficiencies described by the canonical Bondi-Hoyle-Lyttleton (BHL) model.

- ***WRLOF model:*** 3D hydrodynamical simulations [4] show that AGB outflows in binary systems can be highly aspherical and reach high accretion rates [5] (Fig. 1). This mode of mass transfer is called "Wind Roche-lobe overflow" (WRLOF).

Angular-momentum loss

- ***Canonical models:*** In spherically symmetric winds, the angular momentum carried away by the material expelled by the binary is:

$$J = \gamma \times \frac{J_{orb}}{M_1 + M_2} (M_1 + M_2) \quad (1)$$

with $\gamma = q + M_2/M_1$, the mass ratio.

- ***Ballistic model:*** the angular momentum loss is computed by Eq. (1) with γ defined as:

$$\gamma = \max(q, h_{min})$$

where h_{min} is determined by ballistic simulations [6].

Fig. 1 The accretion efficiency at different initial orbital periods in the BHL (blue) and WRLOF (red) models, respectively

Fig. 2 Orbital-period evolution of a spherically-symmetric wind model (blue) Vs a model based on ballistic simulations (orange).

3. Binary population synthesis simulations

- The BPS code binary_c [7] is used to simulate the evolution of binary systems for a wide range of masses and orbital separations.
- We simulate the evolution of 3 binary populations using 3 different model sets (see Table below):
  S1: default assumptions as in [1], i.e. ssw model of AM loss and BHL model of wind accretion.
  S2: as S1, with WRLOF model of wind accretion
  S3: as S2, with Ballistic model of angular momentum loss.
- Figure 3a-c shows the delay-time distribution of SNe Ia predicted by these 3 model sets.

Model set	Wind accretion	Angular momentum
S1	BHL	SSW
S2	WRLOF	SSW
S3	WRLOF	Ballistic Simulations

Fig. 3 Delay-time distributions calculated with models sets S1, S2 and S3 (panels a, b and c, respectively). The dashed and dotted lines represent the contributions to the SNe Ia rate from the SD channel with He-rich and H-rich donor stars, while the dot-dashed line shows the contribution of the DD channel. The solid line shows the total SNe Ia rate. The open triangles are the literature observed data [8].

4. Results

- Considering a less idealised model of mass transfer, the total contribution of AGB donor stars (model S2) to the SD channel is almost 10 times higher.
- The contribution of AGB donor stars is mostly evident at delay times between 100 and 300 Myr after star formation.
- The strong angular-momentum losses cause model set S3 to form many more double WDs is close orbits increasing the DD channel by ~ 35%.

5. Conclusions

- Less idealized treatment of wind mass transfer (WRLOF) in binary systems increases the contribution of AGB stars in SNe Ia progenitor systems and places them as the dominant SD channel within the time window of 100 - 300 Myr.
- Considering in addition more efficient angular momentum losses as described by ballistic simulations the contribution of AGB stars to the DD channel increases by a factor of three.
- Our results suggest that AGB stars may play a significant role as SNe Ia progenitors, both in the SD and DD channels.

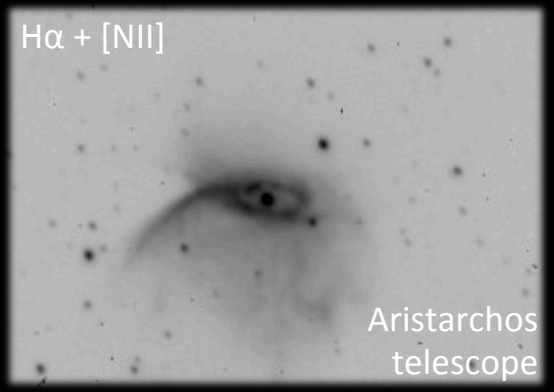
References

[1] Claeys, J. S. W., et al. 2014, A&A, 563, A83
[2] Hamuy M. et al., 2003, Nature, 424, 651
[3] Chiotellis A., Schure K. M., Vink J., 2012, A&A, 537, A139
[4] Mohamed, S. & Podsiadlowski, P. 2012, Baltic Astronomy, 21, 88
[5] Abate, C., et al. 2013, A&A, 552, A26
[6] Brookshaw, L. & Tavani, M. 1993, ApJ, 410, 719
[7] Izzard, R. G., et al., 2004, MNRAS, 350, 407
[8] Maoz D., Graur O., 2017, ApJ, 848, 25

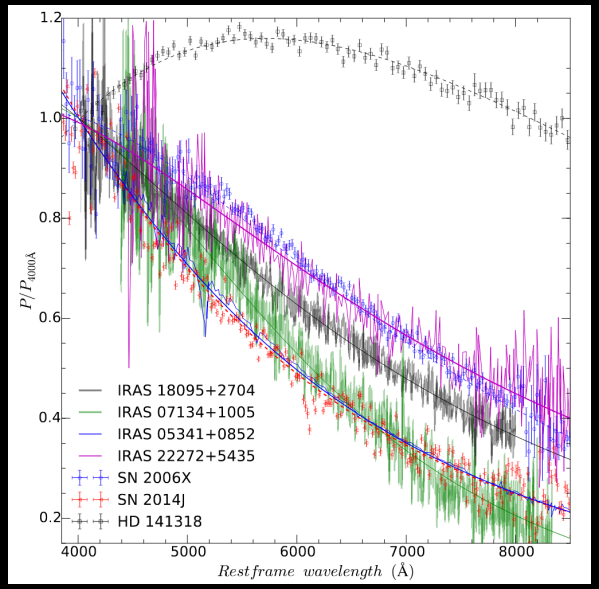
(See Poster: S10.1)

Motivation (II): Observational evidence

1) Henize 2–428:
DD super-Chandra central binary
→ will merge triggering a SNe Ia.
(Santander- Garcia et al. 2015)

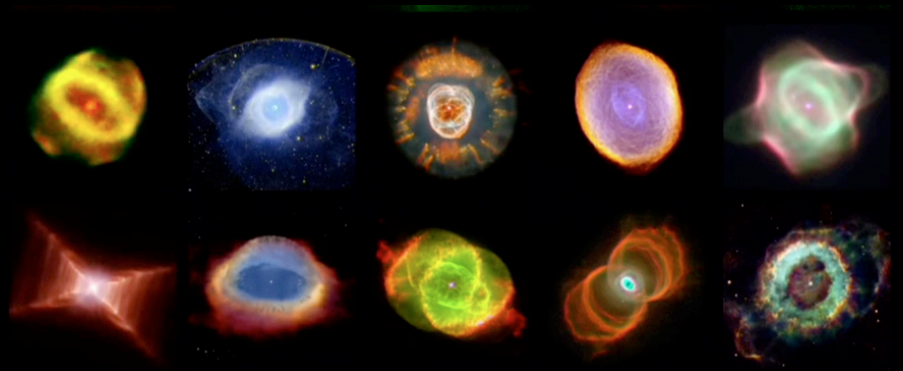


2) Polarization measured of pre-PNe
→ very similar to polarization curves of several SNe Ia (Cikota et al. 2017)



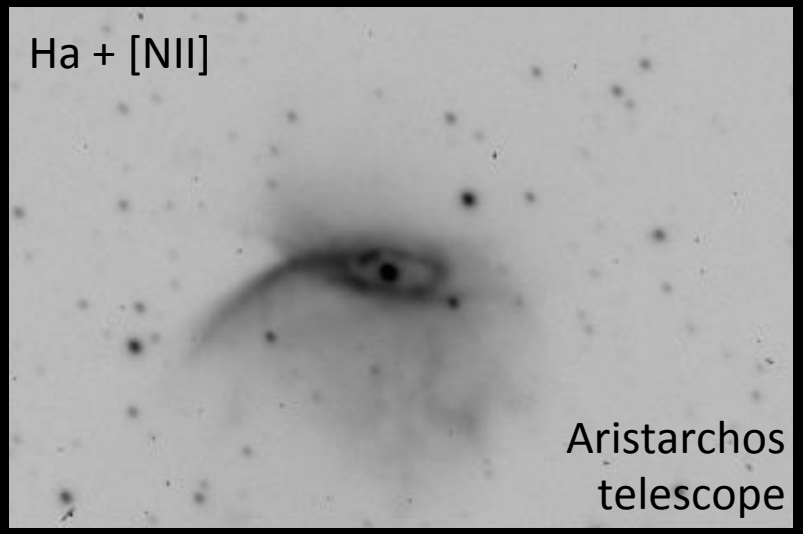
Simulating the SNR Ia – PN interaction model

- The result depends on:
  1) the properties of the PN
  2) the time delay between the PN formation and the SN Ia explosion



First attempt:

- PN structure: bipolar
- Time delay: - t_{delay} = 0 Myr
  - t_{delay} = 1.0 Myr
  - t_{delay} = 8.0 Myr



Formation of a bipolar PN

- 2D hydrosimulations
- Code AMRVAC (Keppens + '04)

Wind Formalism

- Asymmetric wind is imposed as an inflow at the inner boundary
- Asymmetry described by trigonometrical function

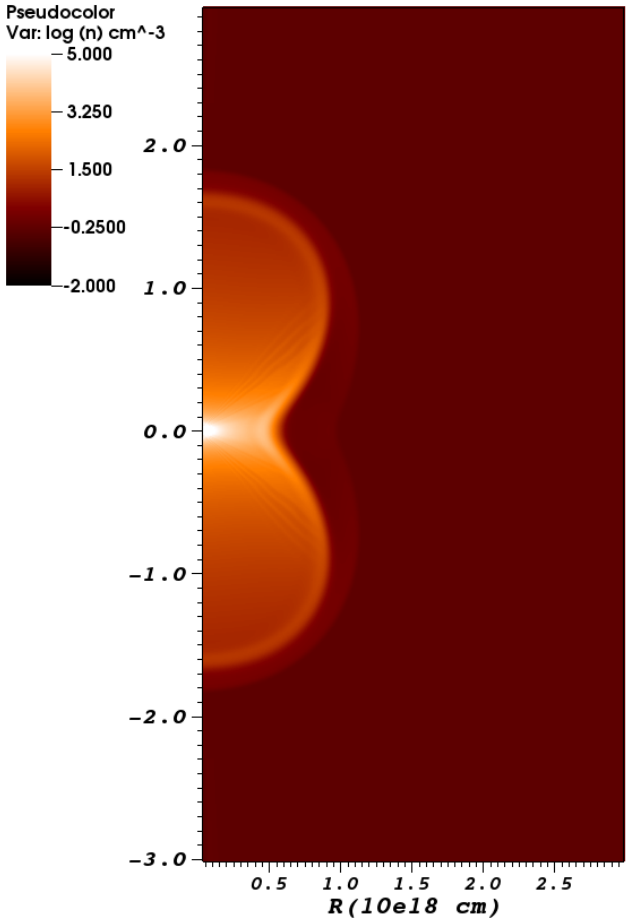
$$\rho(\theta) = (1 - a \sin(\theta)^{\kappa})^{-1} \times (\dot{M}_p / 4\pi\ u(\theta)\ r^2)$$

$$u(\theta) = (1 - b \sin(\theta)^{\kappa}) \times u_p$$

a,b,κ = constants

→ Determine the density/velocity contrast from poles to equator and their angular gradient

1rst step AGB wind



$n_{ISM} = 0.5\ cm^{-3}$

$\dot{M}_p = 10^{-5} M_{\oplus} yr^{-2}$

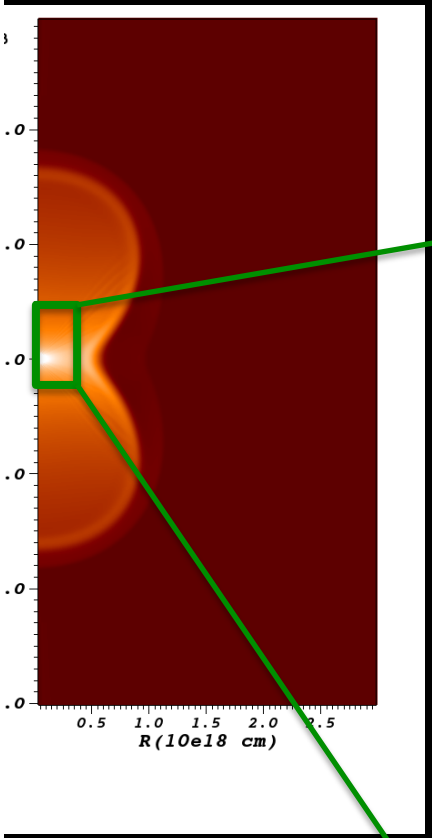
$u_p = 10\ km/s$

$a = 0.8, \quad b = 0.75,$

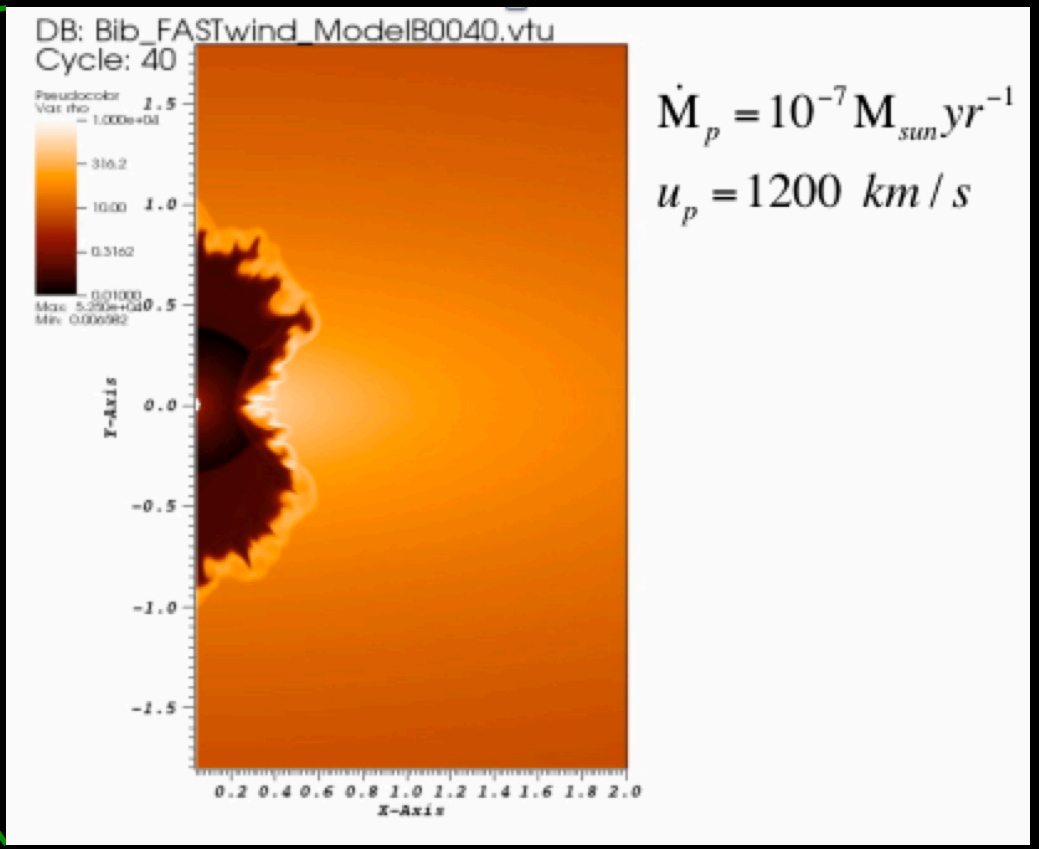
$\kappa = 3$

$\frac{\rho_{eq}}{\rho_p} = 10\ ; \frac{u_{eq}}{u_p} = 0.25$

Formation of a bipolar PN



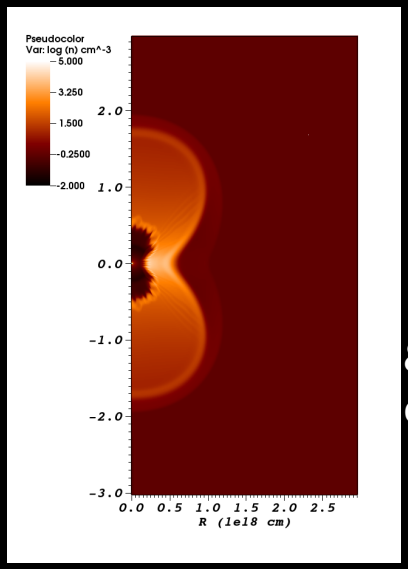
2nd step fast wind



$$\dot{M}_p = 10^{-7} M_{sun} yr^{-1}$$

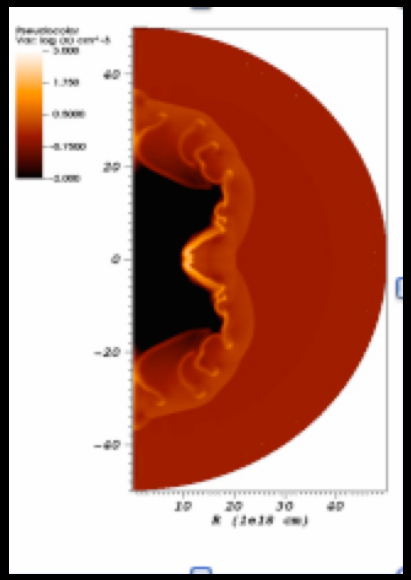
$$u_p = 1200 \ km/s$$

The resulting CSM…

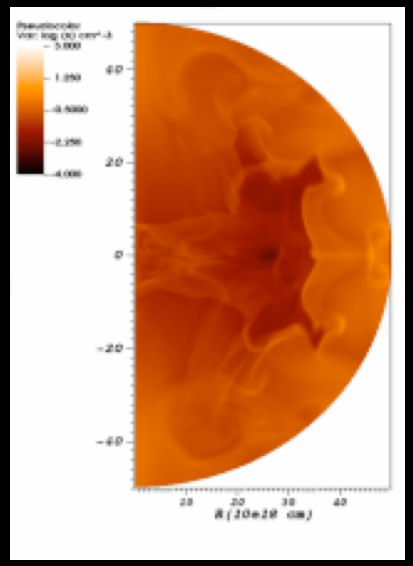


Stop the wind

& let the CSM to evolve for 1 Myr



… and for other 7 Myr



Dense CSM + small cavity

Extended Cavity

Cavity collapses

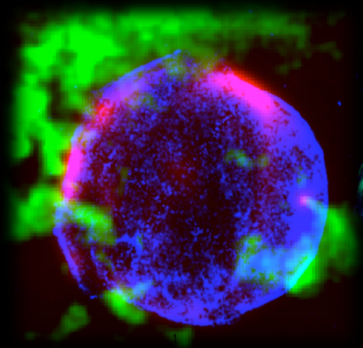
0 Myr

1 Myr

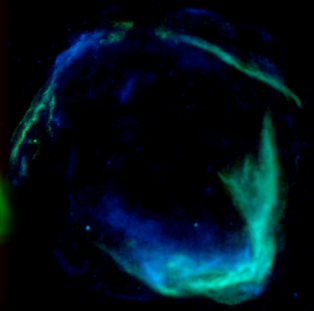
8 Myr

t_{delay}

Kepler's SNR



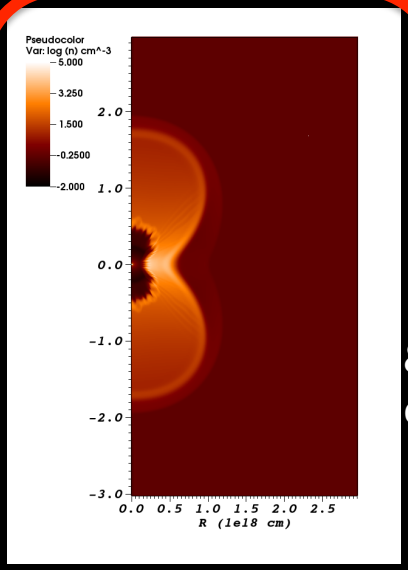
Tycho's SNR



RCW 86

SNR 0509

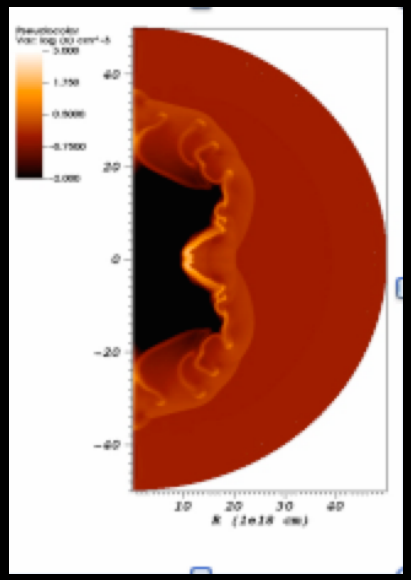
The resulting CSM…



Dense CSM + small cavity

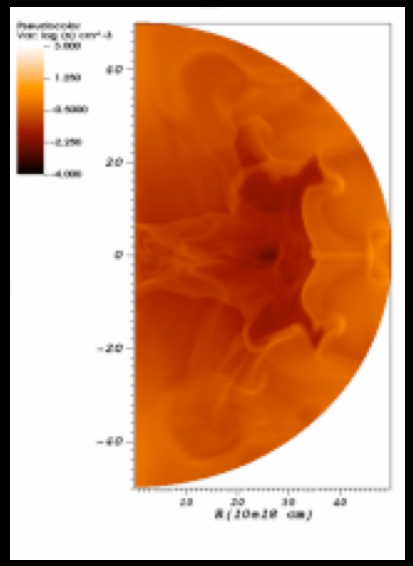
Stop the wind

& let the CSM to evolve for 1 Myr



Extended Cavity

… and for other 7 Myr



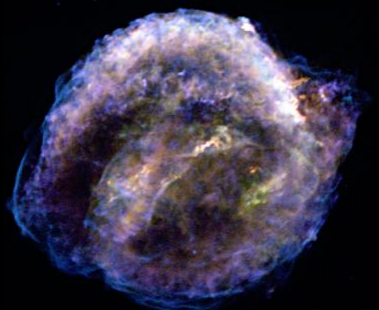
Cavity collapses

0 Myr

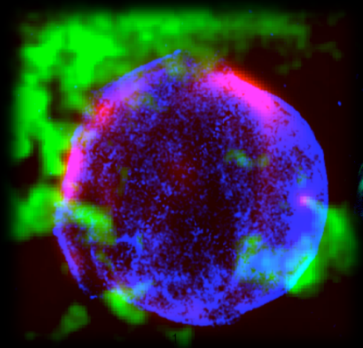
1 Myr

8 Myr

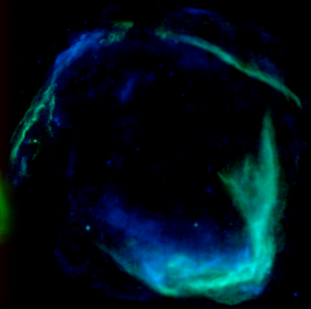
t_{delay}



Kepler's SNR



Tycho's SNR



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Kepler's SN: A SNe Ia Interacting with a bipolar PN

- Dynamics: $r \propto t^{0.6}$ => m =0.6 (overall)
  $r \propto t^{0.35}$ => m =0.35 (northern)
  (Vink 2008; Katsuda et al. 2008)

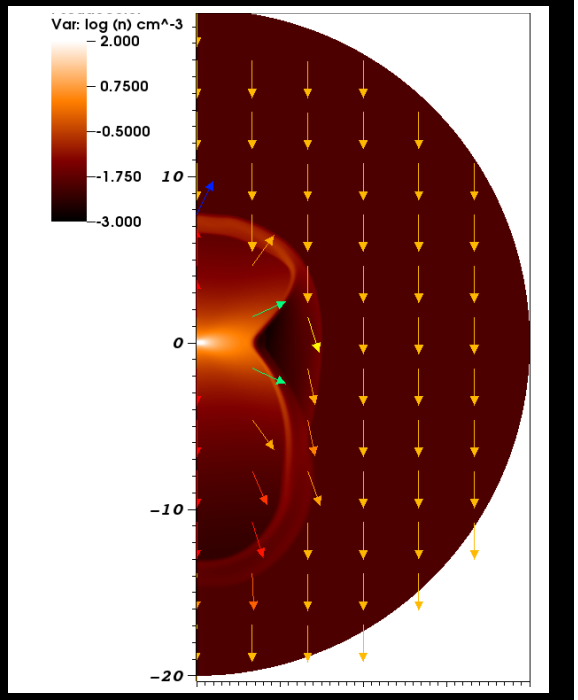
=> $M_{shell} > 1\ M_{\odot}$; **Nitrogen rich** (Blair et al. 2007)

Hα narrow component: Blueshifted → $u_* \approx 250$ km s^{-1}

(Bandiera & van der Berg 1991; Sollerman et al. 2004)

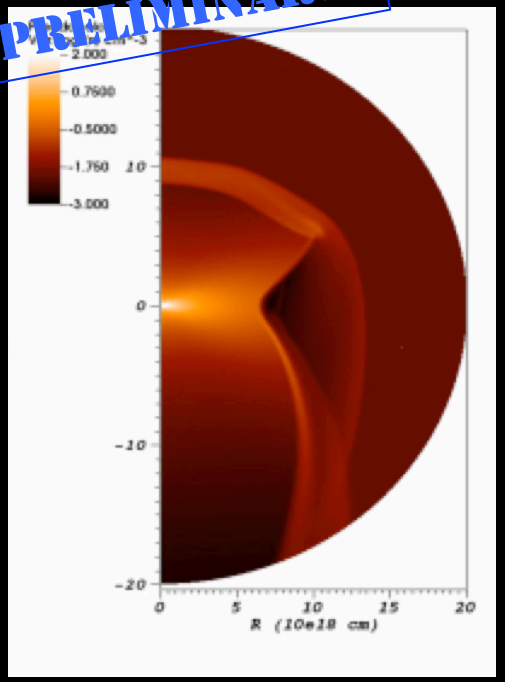
Model main Ingredients:

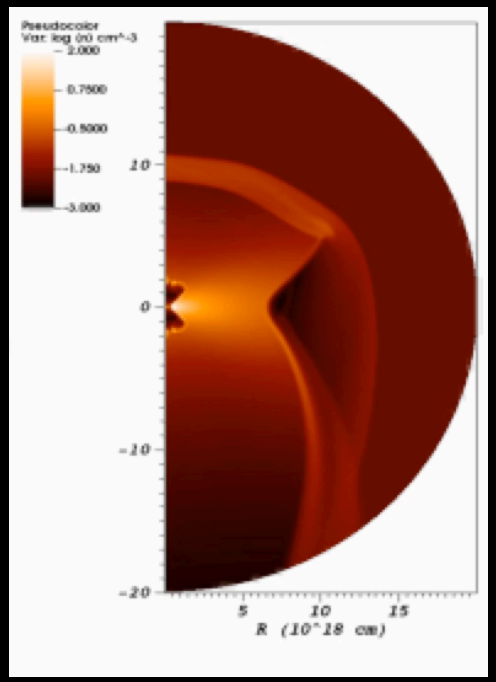
CSM= Bipolar PNe **+ high systemic motion**

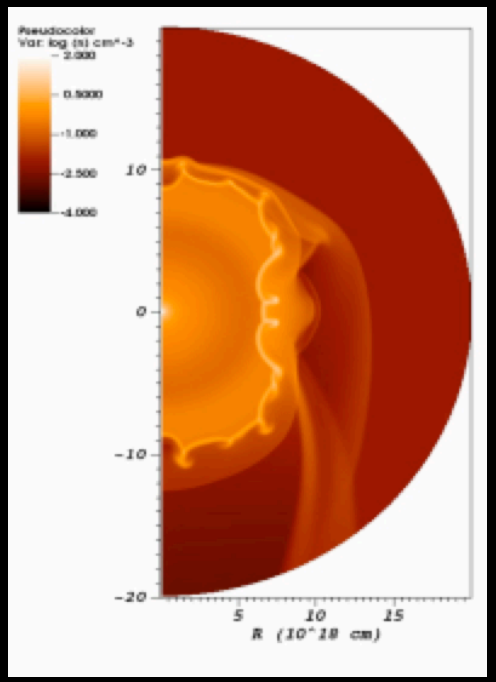


Kepler's SN: A SNe Ia Interacting with a bipolar PN

PRELIMINARY







AGB wind:

$$\frac{\rho_{eq}}{\rho_p} = 30 \quad ; \quad \frac{u_{eq}}{u_p} = \frac{1}{5}$$

Δt= 0.02 Myr → t_{final} = 0.12 Myr

Fast wind:

$$\frac{\rho_{eq}}{\rho_p} = 3.7 \quad ; \quad \frac{u_{eq}}{u_p} = 0.6$$

Δt= 1000 yr → t_{final} = 5000 yr

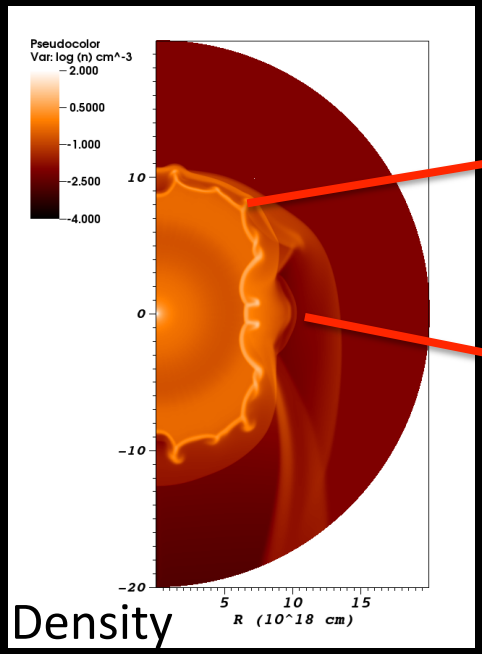
SNR:

$E_{ej.}$ = 1.2 x 10^{51} erg
M_{ej} = 1.38 $M_\odot$

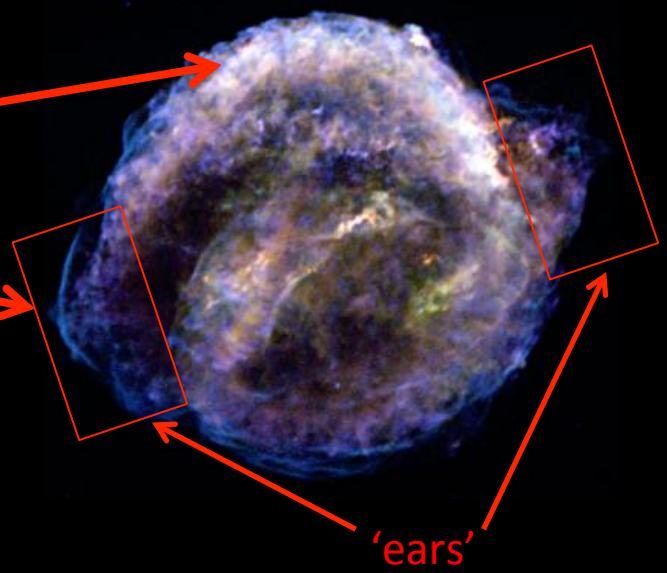
ejecta profile: power law n=7

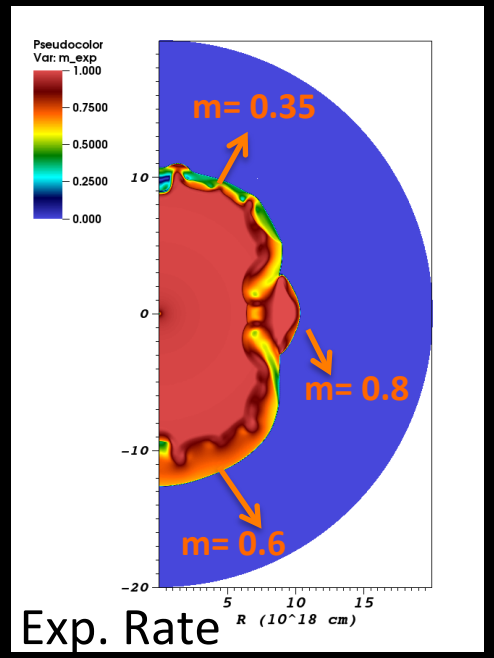
Δt= 30 yr → t_{final} = 420 yr

Kepler's SN: A SNe Ia Interacting with a bipolar PN



Density





Exp. Rate

The SNR + bipolar PN interaction model can explain:

- ✓ Asymmetry and the chemical abundances of the shell
- ✓ The formation of two antisymmetric lobes (ears) in Kepler's morphology
- ✓ The Expansion rates of the remnant and its northern part

➡ *Condition: The SNe Ia occurred right after the PN formation*

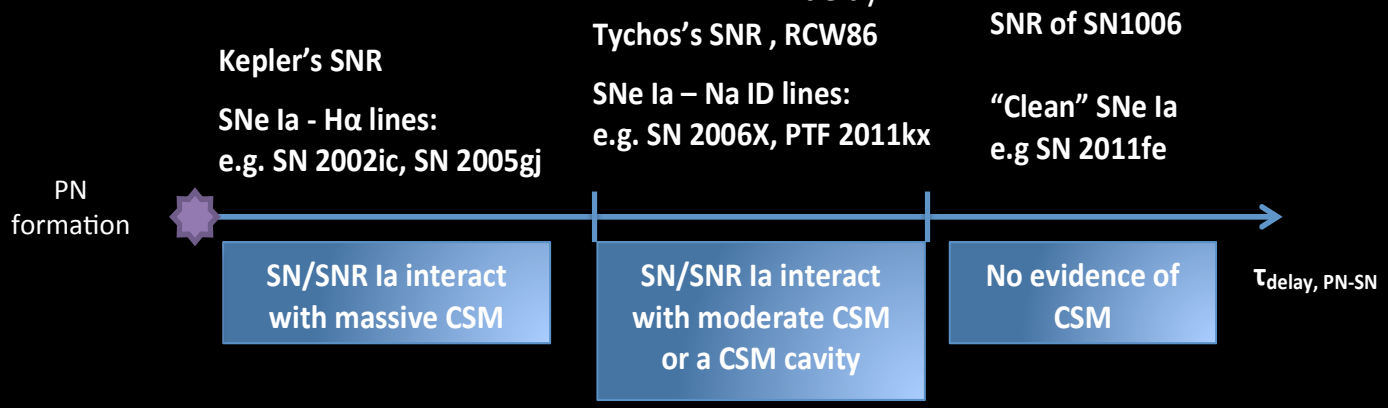
Conclusions

- Model of SNe Ia + PNe:

PNe seem promising candidates for the CSM observed around SNRs Ia as:

✧ Can naturally be explained by the SN Ia binary evolution theory

✧Explain SNe/SNRs Ia diversity: $f(t_{delay})$



- A Henize 2-428 – like PN the progenitor of Kepler's SNR?

✧ Overall morphology and dynamics of SNR + CSM composition and distribution

✧The formation of two antisymmetric lobes (ears)

- Ears formation in SNR's morphology: Interaction history with a bipolar CSM