Type Ia Supernova Remnants in Different Circumstellar Environments

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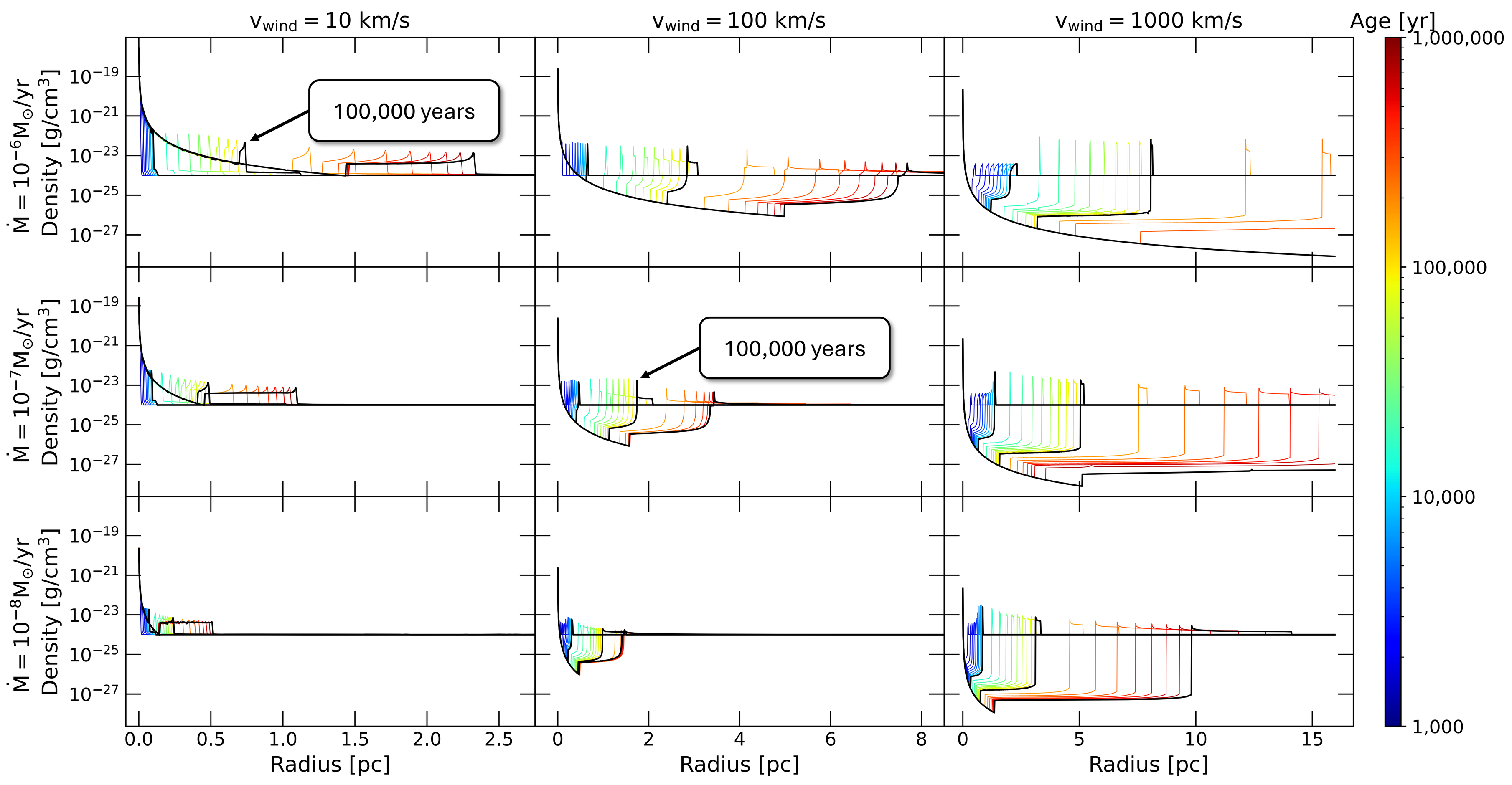
- Bulk dynamics of Type Ia (SN Ia) supernova remnants, such as radius and centroid energy of Fe Kα in the X-ray spectrum, are primarily determined by interaction between ejecta and ambient medium (Yamaguchi et al. 2014; Patnaude et al. 2015; Martínez-Rodríguez et al. 2018; Court et al. 2024).
- Several SN Ia remnants have been interpreted as expanding in a modified ambient medium, e.g., N103B, RCW 86, and 3C 397 (Vink et al. 1997, 2006; Badenes et al. 2007; Yamaguchi et al. 2015).
- Our goal is to constrain CSM interaction in Type Ia SNRs. In this work, we assume that SN Ia progenitors lose mass in a continuous, isotropic outflow, and we investigate the impact that the mass loss rate ($\dot{M}$), outflow velocity (v_{wind}), and outflow timescale (t_{wind}) have on the structure of the CSM and the properties of the SNRs interacting with this CSM.
- We use a standard hydrodynamics code to calculate the CSM structure, and an HD+NEI code to calculate the SNR evolution and generate synthetic X-ray spectra that can be directly compared to the bulk properties of real SNRs measured by *Suzaku* and *Chandra*.

Circumstellar Structure Models

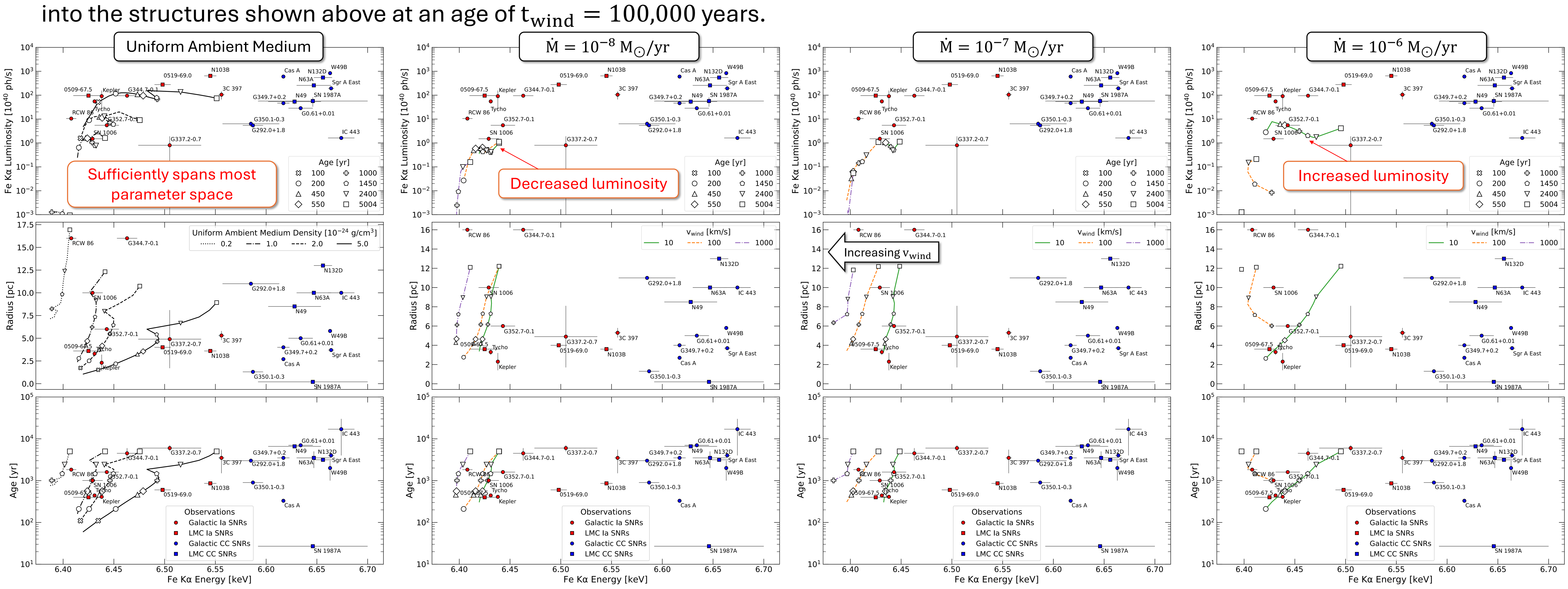


Parameter space for CSM structure

- We model our cavities using VH1 (Colella & Woodward 1984; Blondin & Ellison 2001) with gas expanding to a uniform ambient medium density of $\rho_{AM} = 1.0\times10^{-24}$ g/cm^3.
- We simulate the outflow models at a **constant mass loss rate and wind velocity** for 10^6 years. The results presented below are all taken at an age of $t_{wind} = 100{,}000$ years.
    - The mass loss rates are varied between $\dot{M} = 10^{-6}, 10^{-7}$, and 10^{-8} $M_\odot$/yr.
    - The wind velocity rates are varied between $v_{wind} = 10, 100$, and 1000 km/s
- This span of parameter space includes pressure and momentum driven cavities, as well as ones with sizes on the order of observed remnants (Koo & McKee 1992a,b).

Remnant Simulations

- To model the dynamics and non-equilibrium ionization (NEI) in the plasma, we simulate these models using ChN, a cosmic-ray-hydrodynamic-NEI simulation code (Patnaude et al. 2012, 2015, 2017; Lee et al. 2014, 2015).
- We created a fiducial set of simulations using a delayed detonation, M_{Ch} SN Ia model with $\rho_{DDT} = 2.4\times10^{7}$ g/cm^3. The parameter space explored includes a uniform ambient medium (AM) of densities consistent with the ISM (e.g. $\rho_{AM} = 0.2, 1.0, 2.0, 5.0\times10^{-24}$ g/cm^3, as well as into the structures shown above at an age of $t_{wind} = 100{,}000$ years.



- **Left:** SNR models expanding into **uniform ambient medium** provide a **reasonable match** for the Fe Kα luminosity, centroid energy, age, and radius of observed Type Ia SNRs (Badenes et al. 2007, Yamaguchi et al. 2014,Martínez-Rodrígues et al. 2018).
- **Left and Right center:** SNR models expanding into CSM structures with progenitor mass loss rates of **10^{-8}** and **10^{-7}** $M_\odot$/yr can match Type Ia observations in age, radius, and Fe Kα centroid, but fall short in Fe Kα luminosity. In general, lower values of v_{wind} lead to higher Fe Kα centroid energies due to higher densities in the CSM profiles (smaller dilution parameters).
- **Right:** SNR models expanding into CSM structures with progenitor mass loss rates of **10^{-6}** $M_\odot$/yr can match Type Ia observations in age, radius, and Fe Kα centroid. The Fe Kα luminosity can match for lower values of v_{wind}.
- Several SNRs believed to have significant CSM interaction (e.g., N103B, RCW 86, and 3C 397), are still not well modeled by our uniform AM or isotropic outflow SNR models. We will explore longer or shorter timescales for isotropic outflows, as well as non-constant outflows in future work.