The Origin of the X-ray Clumpy Structures in a Type Ia Supernova Remnant

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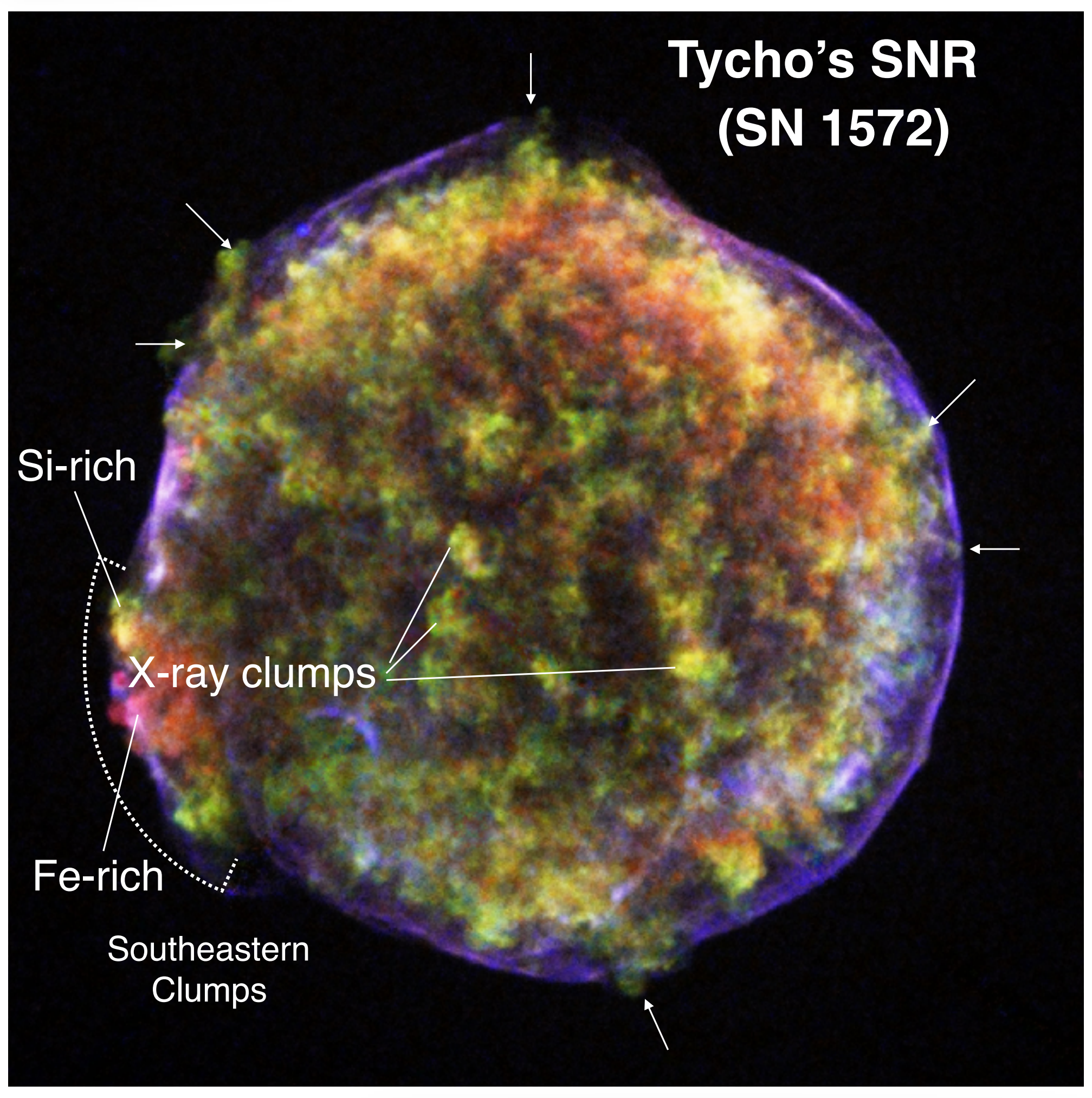
ABSTRACT: Clumpy structures are a common feature in X-ray images of young Type Ia supernova remnants (SNRs). Although the precise origin of such clumps remains unclear there are three generic possibilities: clumpiness imposed during the explosion, hydrodynamic instabilities that act during the remnant's evolution, and pre-existing structures in the ambient medium. In this article we focus on discriminating between clumping distributions that arise from the explosion and those from the remnant's evolution using existing 3D hydrodynamical simulations. We utilize the genus statistic for this discrimination, applying it to the simulations and Chandra X-ray observations of the well-known SN Ia remnant of SN 1572 (Tycho's SNR). The genus curve of Tycho's SNR strongly indicates a skewed non-Gaussian distribution of the ejecta clumps and is similar to the genus curve for the simulation with initially clumped ejecta. In contrast, the simulation of perfectly smooth ejecta where clumping arises from the action of hydrodynamic instabilities produced a genus curve that is similar to a random Gaussian field, but disagrees strongly with the genus curve of the observed image. Our results support a scenario in which the observed structure of SN Ia remnants arises from initial clumpiness in the explosion.

Type Ia SNR & X-ray Clumps



Clumpy structures are a common feature in X-ray images of young Type Ia SNRs (left figure). There are Si- and Fe-rich clumps, however the origin of the clumps have not been clear yet. Mainly, there are two candies for the origin of the ejecta clumps (see below).

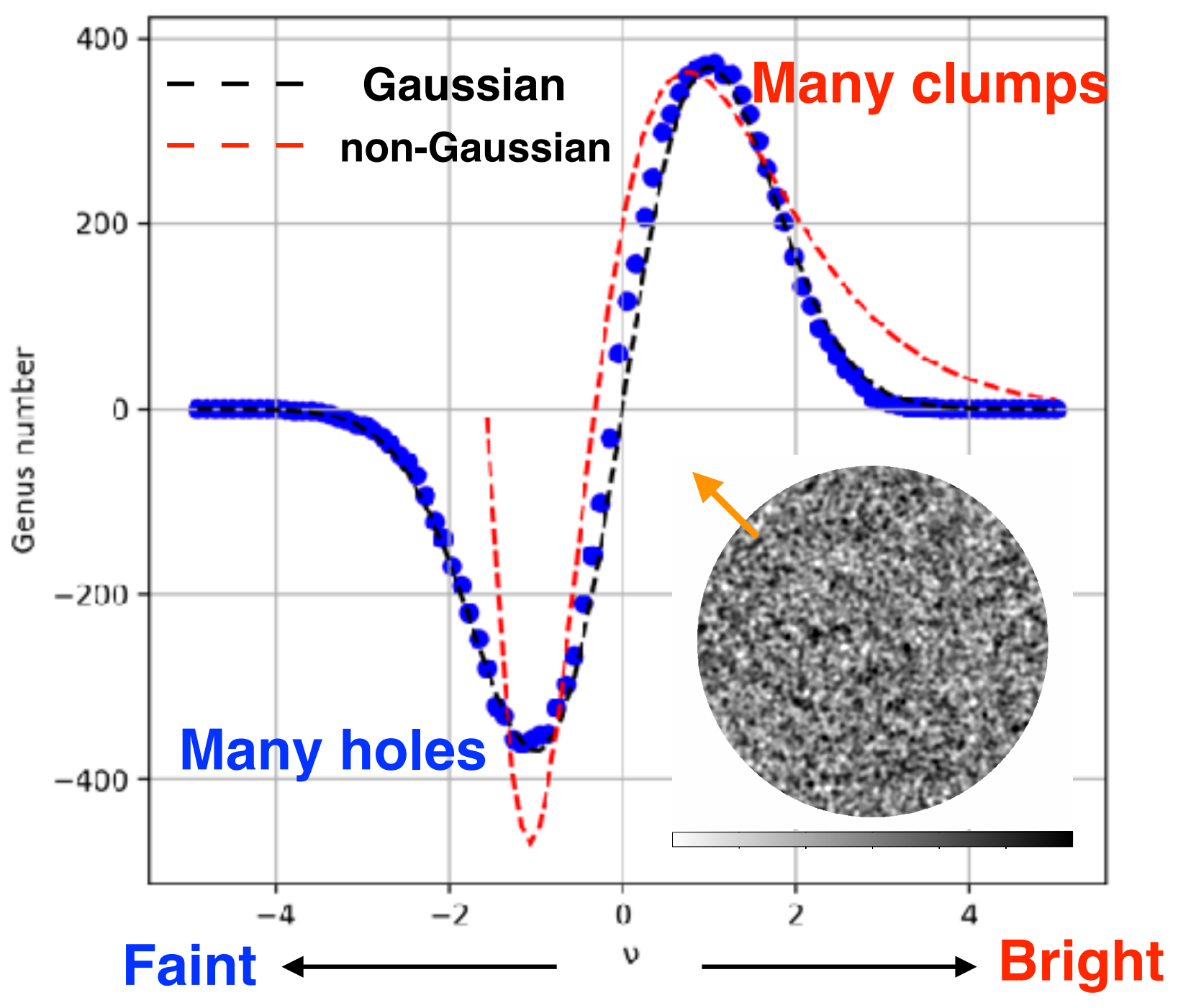
① Clumpiness imposed during the SN
→ Clumpy ejecta model

② Hydrodynamic instabilities
→Smooth ejecta model

Especially, in the case of 1, the clumpy structures are important information for understanding the explosion mechanism.

Genus Statistics

Example: Random filed & Genus curves



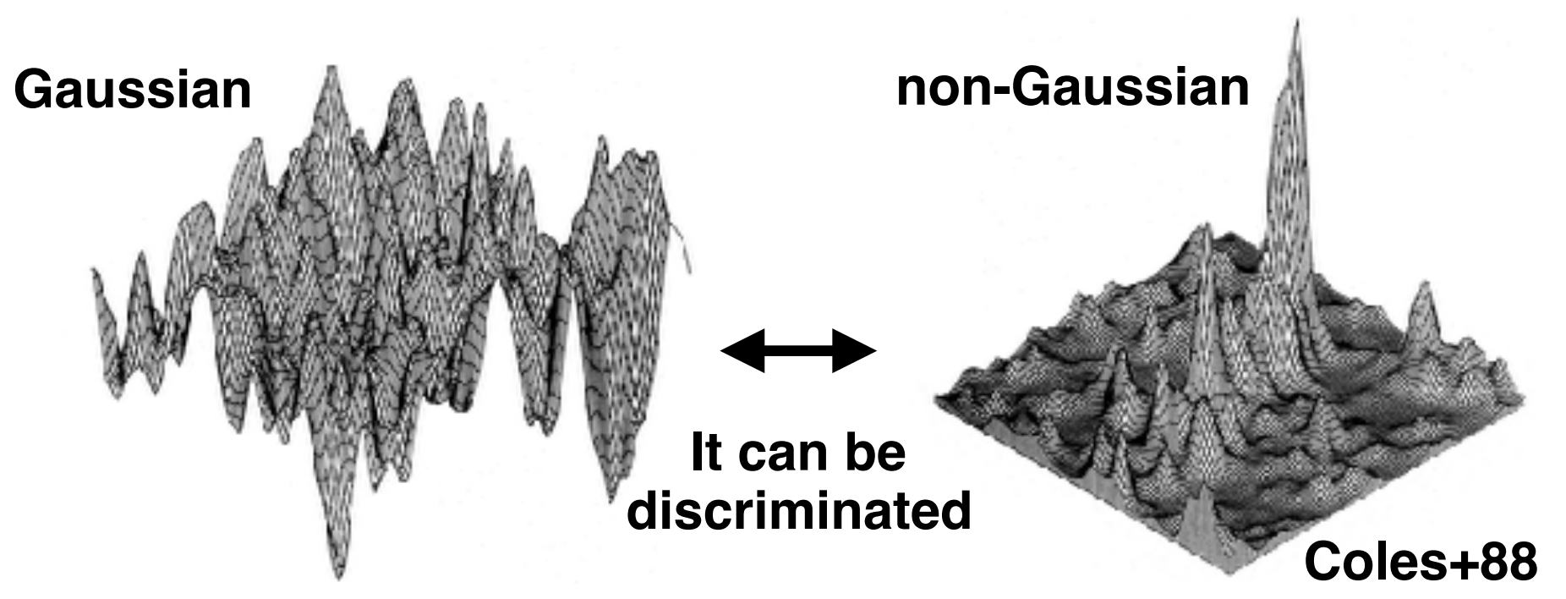
Counts clumps and holes at each threshold

Important characteristic

Analytic solution for a random Gaussian field

$$G(\nu) = \frac{A}{(2\pi)^{3/2}\ \theta_c^2}\ \nu \exp\left(-\frac{\nu^2}{2}\right)$$

A : area, θ_c : coherence angle, ν : intensity

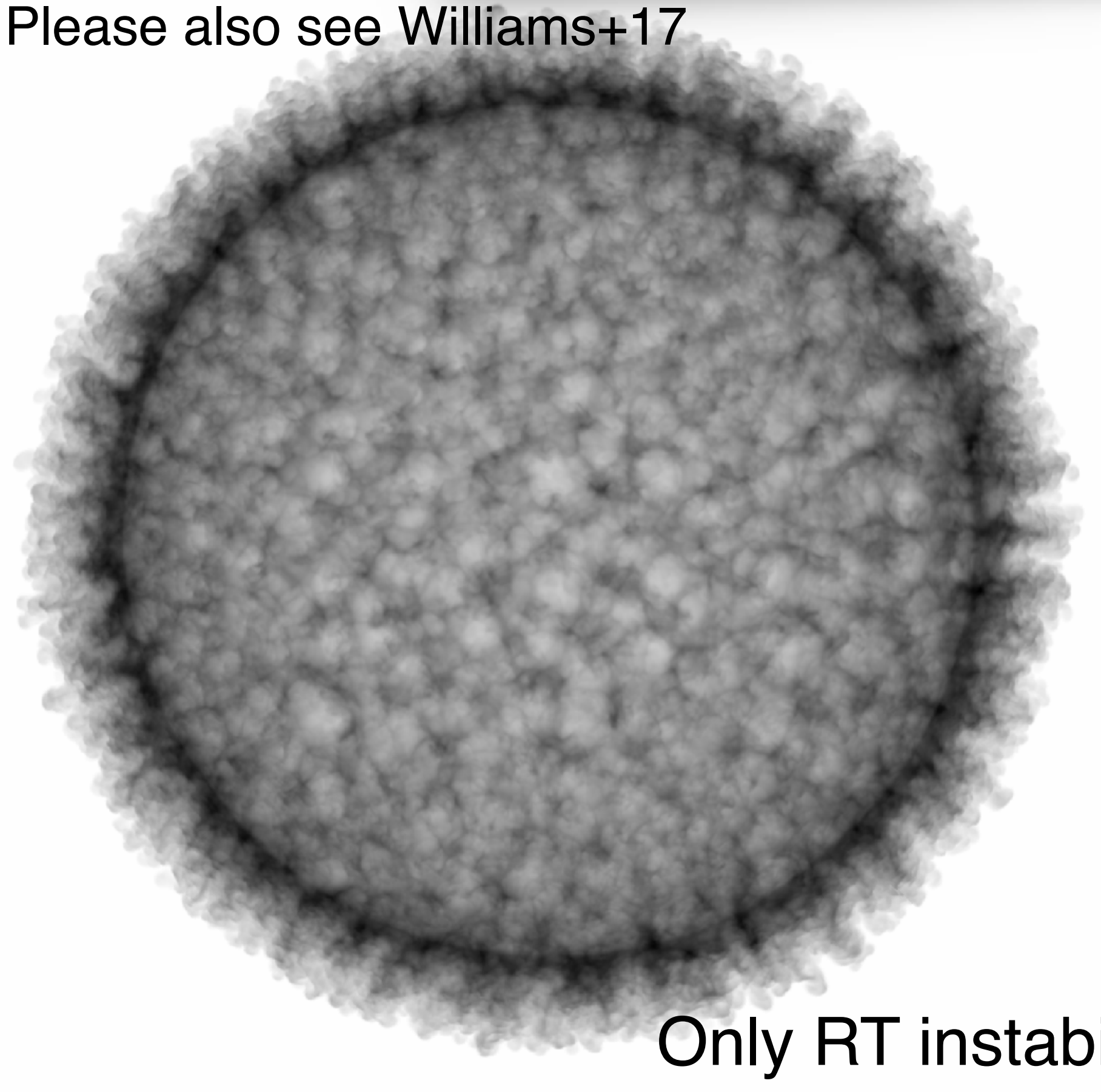


Differences of small structures appear in differences of genus curves

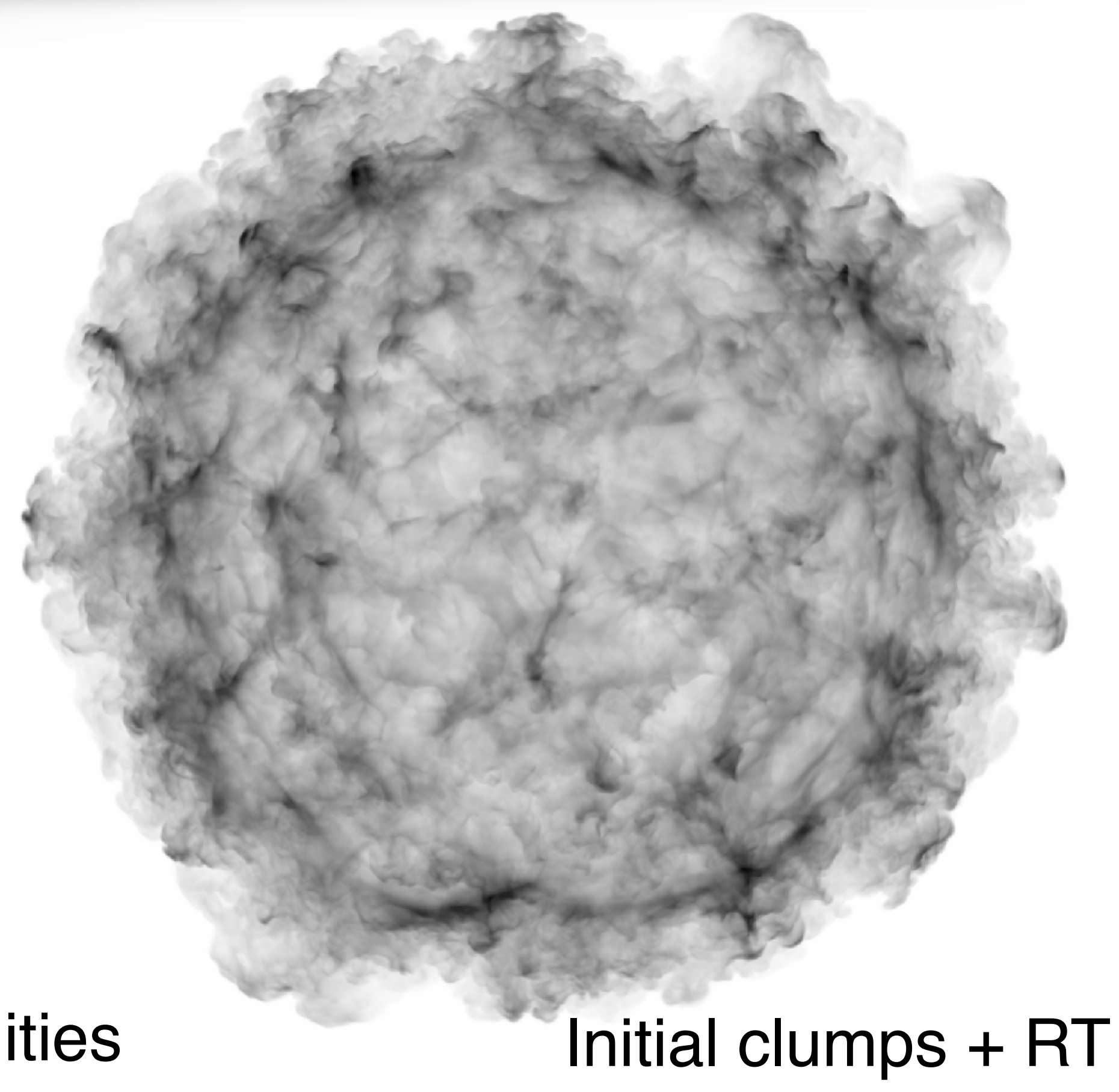
It is effective for investigation whether to follow a random Gaussian field and comparison between models and observations

SNR Hydro models : Smooth vs Clumpy model

Please also see Williams+17



Only RT instabilities
Smooth model



Initial clumps + RT
Clumpy model

Comparison with 3D hydro models for Type Ia SNRs

Initial condition for the hydro models

- E = 10^{51} erg, M = 1.4 M_{sun} for both Smooth & Clumpy models
- condition for clumpiness: 1. Uniform Perlin noise 2. a maximum angular scale ~20° 3. A max-to-min density contrast = 6

Similar kinematics, but **quite different sizes and shapes** (left figs, Williams+17)

Smooth model

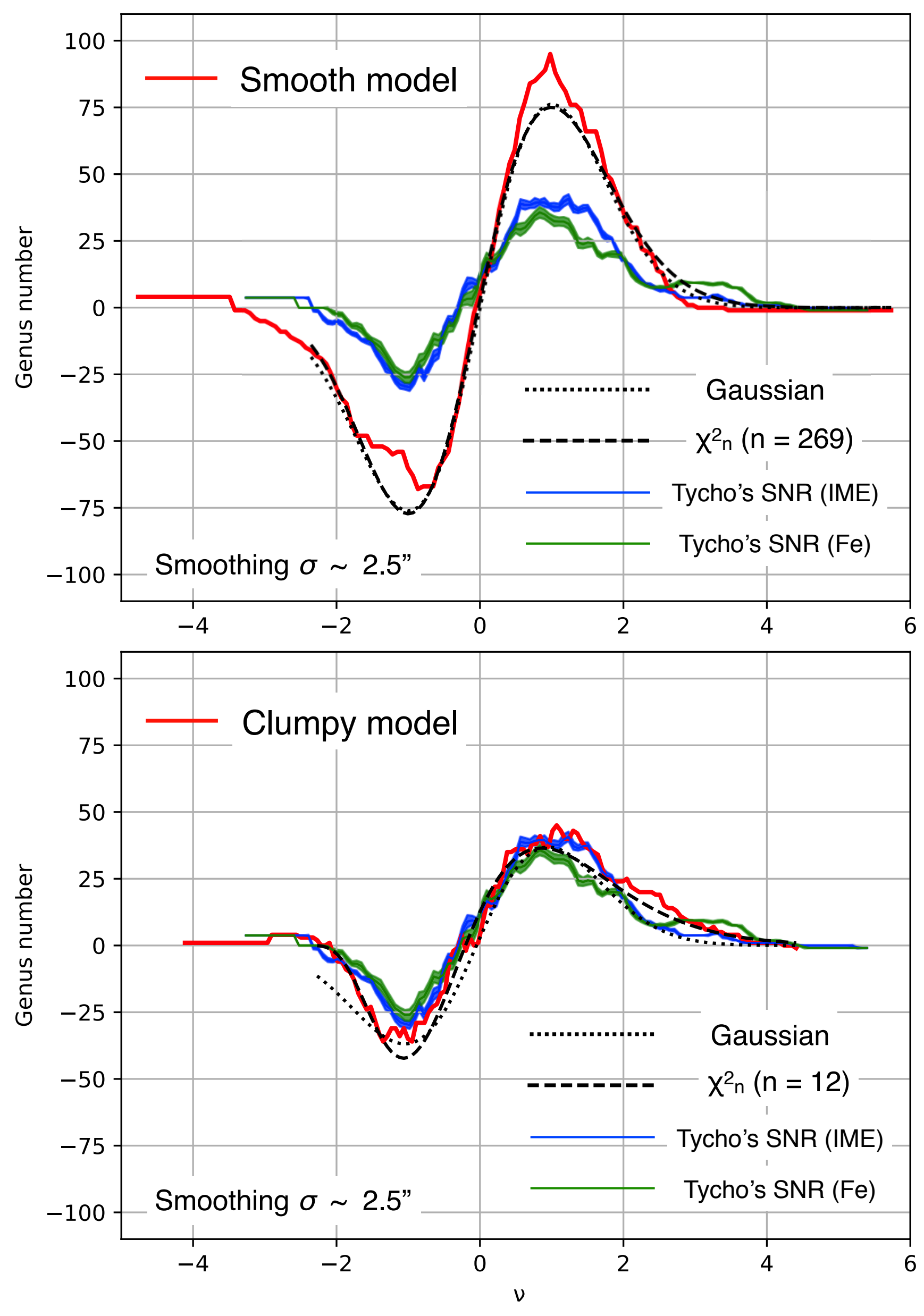
The clumpy structures are small compared to the observation (Tycho), and the clumps with a similar size are uniformly distributed.

Clumpy model

The structures are larger and more skewed than those of the Smooth model, and the distribution is sparse.

Which is more similar to the observation?

Comparison of Genus Curves



Tycho's SNR (blue+green)

- skewed genus curve (does not pass through zero + falls slowly at higher intensities)
- similar to that of the χ^2 distribution

Smooth model (top: red)

- small structures, which makes larger genus values → not consistent with that of Tycho's SNR
- more similar to the genus curves for the random Gaussian distribution

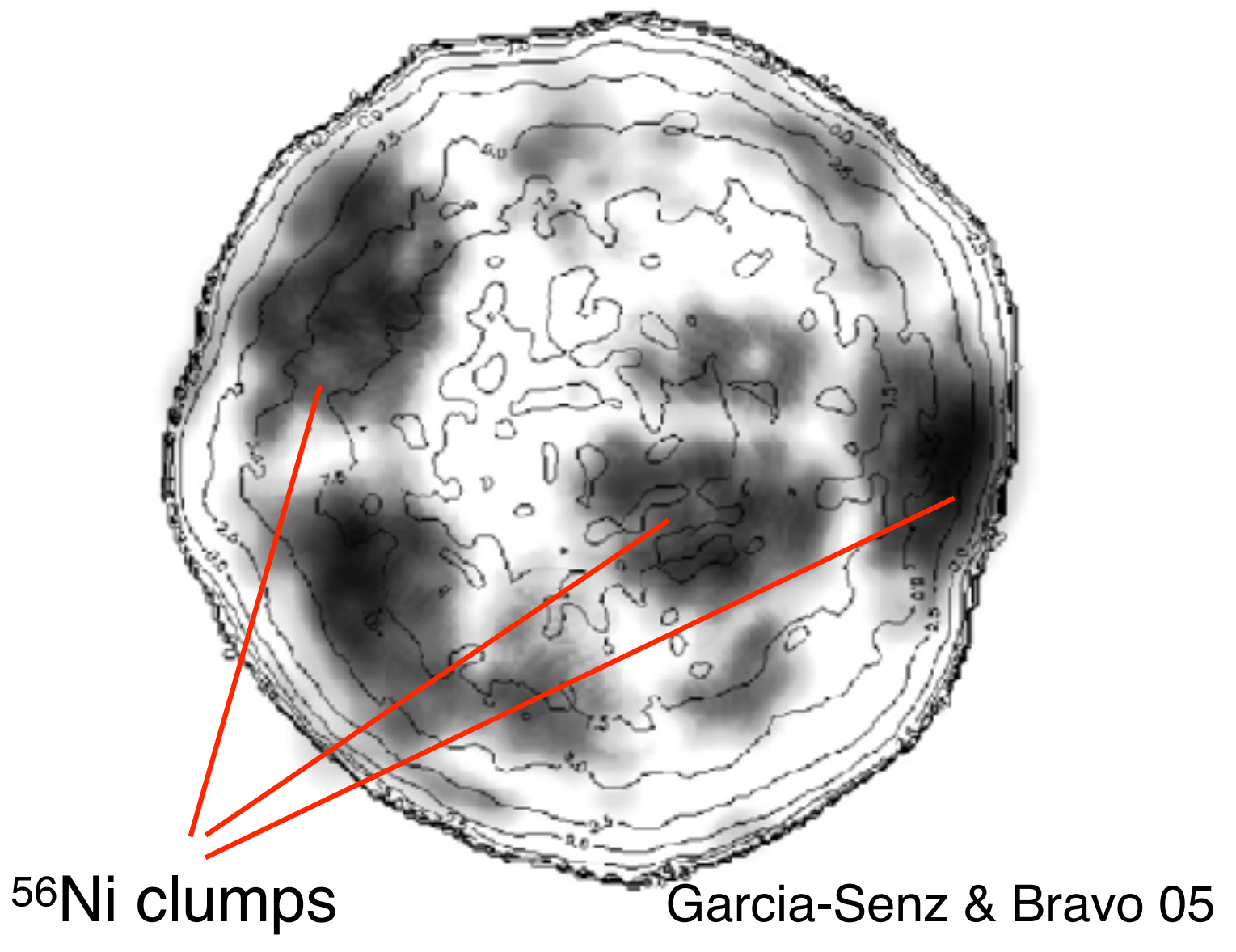
Clumpy model (bottom: red)

- Genus curve shape and maximum/minimum values are similar to Tycho
- More similar to that of Tycho.

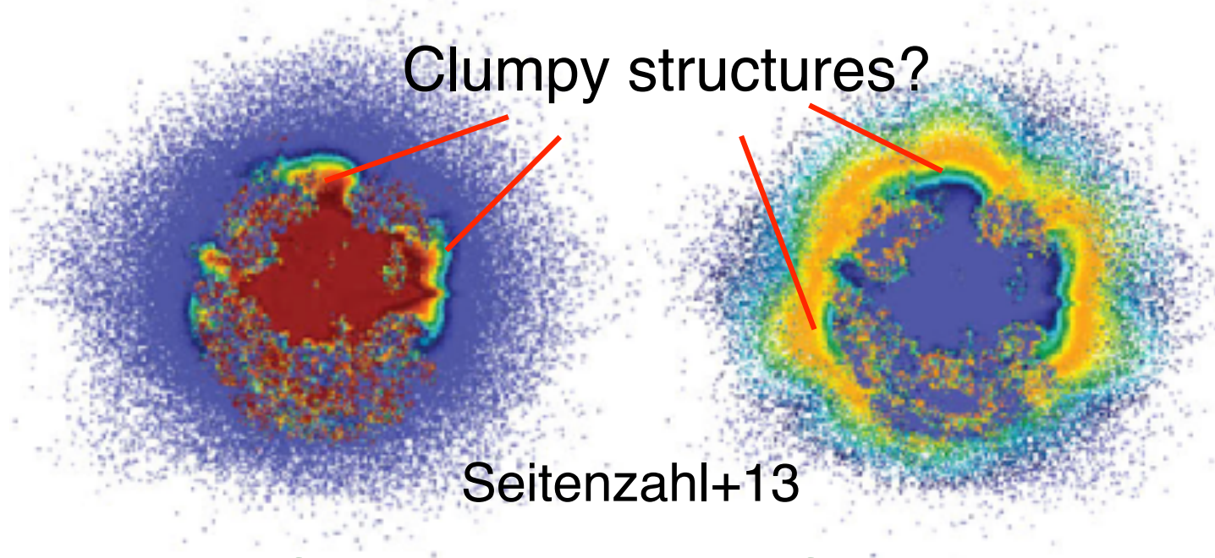
The genus statistic strongly supports an initial clumped ejecta distribution as the origin of the clumps in Tycho's SNR.

What is the origin of clumps?

3D Pure Deflagration model



3D Delayed Detonation model



Few Predictions of Ejecta Clumps

① 3D pure deflagration models

- 3D pure deflagration models indicate 4–5 large ^{56}Ni clumps (left fig.).
- The large ^{56}Ni clumps seem to be a common feature in all 3D pure deflagration models. But, the observed clumps in the SNRs are much smaller than those in the simulations.

② Deflagration → Detonation

- Large ^{56}Ni clumps do not appear, and there seems to be small structures.
- However, we do not know whether those structures could be the clumpy structures in Type Ia SNRs or not for now.

The future study for the structure in SNe Ia might reveal the relation between the origin of clumps and the burning process
→ Then, genus statistic will be an useful tool!!

For more details "Genus Statistic Applied to the X-ray Remnant of SN 1572: Clues to the Clumpy Ejecta Structure of Type Ia Supernovae", Submitted to ApJ, arXiv: 1903.00764