Measurement of anisotropies in observed SNRs and their interpretation using hydrodynamical models

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ABSTRACT

Many Supernova remnants (SNRs) display a typical size of anisotropies, such as Tycho's SNR or SN 1006. Measuring this scale is not trivial, since the observations suffer from projection effects. We implement a technique to measure these anisotropies and test it using 3D hydrodynamical SNR models. We apply this technique to Tycho's SNR and pick out the size of its fleece-like structures. This provides an estimate for the CSM density (n~0.28/cm^3). We also observe additional power at large scales, which may provide clues about the explosion mechanism itself.

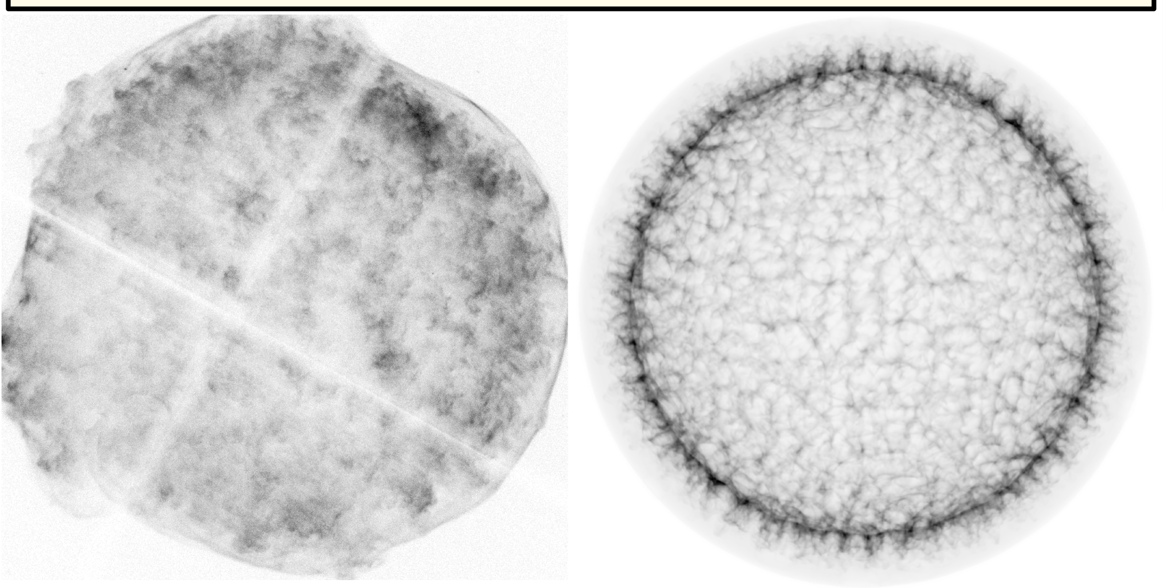


Fig 1. (*left*) Tycho's remnant in x-rays, and (*right*) synthetic image from 3D model at t/T=0.1.

NUMERICAL MODEL

- We model a typical Type-Ia SNR, starting from an exponential density profile for the ejecta (corresponding to deflagration).
- Calculations were performed using `Sprout`[1], an expanding mesh hydro code that tracks the growing SNR for many orders of magnitude in time.
- The radially integrated column density (and velocity) of the shocked plasma in the model reveals two interesting features:
  - their distribution is anisotropic, &
  - the typical size of anisotropies grows with time.

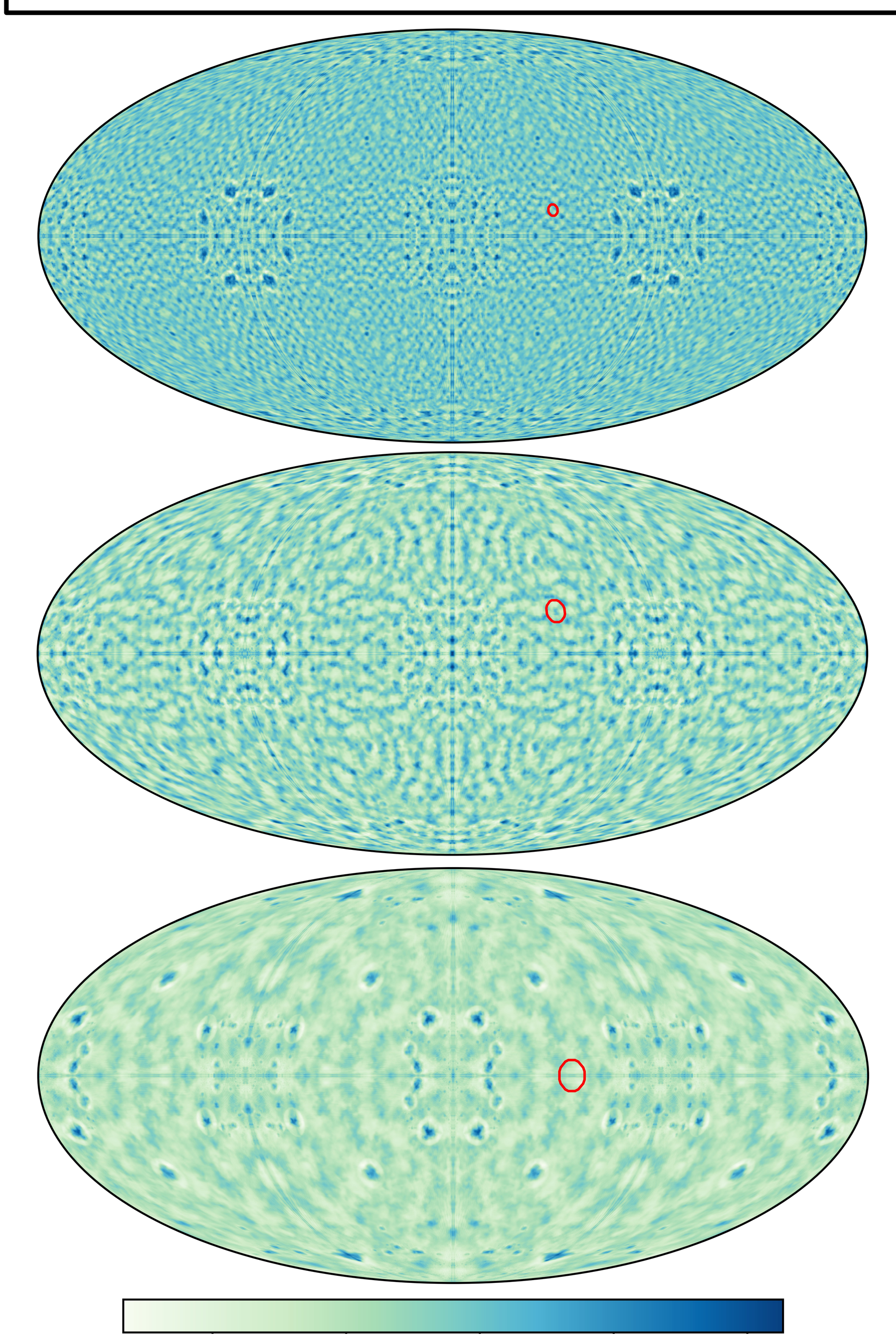


Fig 2. Radially integrated shocked plasma density at (*top*) t/T = 0.001, (*middle*) t/T = 0.01, and (*bottom*) t/T = 1. T is a characteristic time for the SNR, and is defined as the time it takes for the forward shock to sweep up mass comparable to that of the ejecta. Red circle marks the typical size of anisotropies for each instant.

POWER SPECTRAL ANALYSIS

- Typical or dominant angular scale of substructures is computed using **power spectral analysis**[2,3] :
  - Expand the density/velocity map in Fig 2 (which is a function of polar angles θ and ϕ) in terms of spherical harmonics.
  - Calculate a power C_l of these harmonics as a function of the angular wavenumber l (Fig 3).

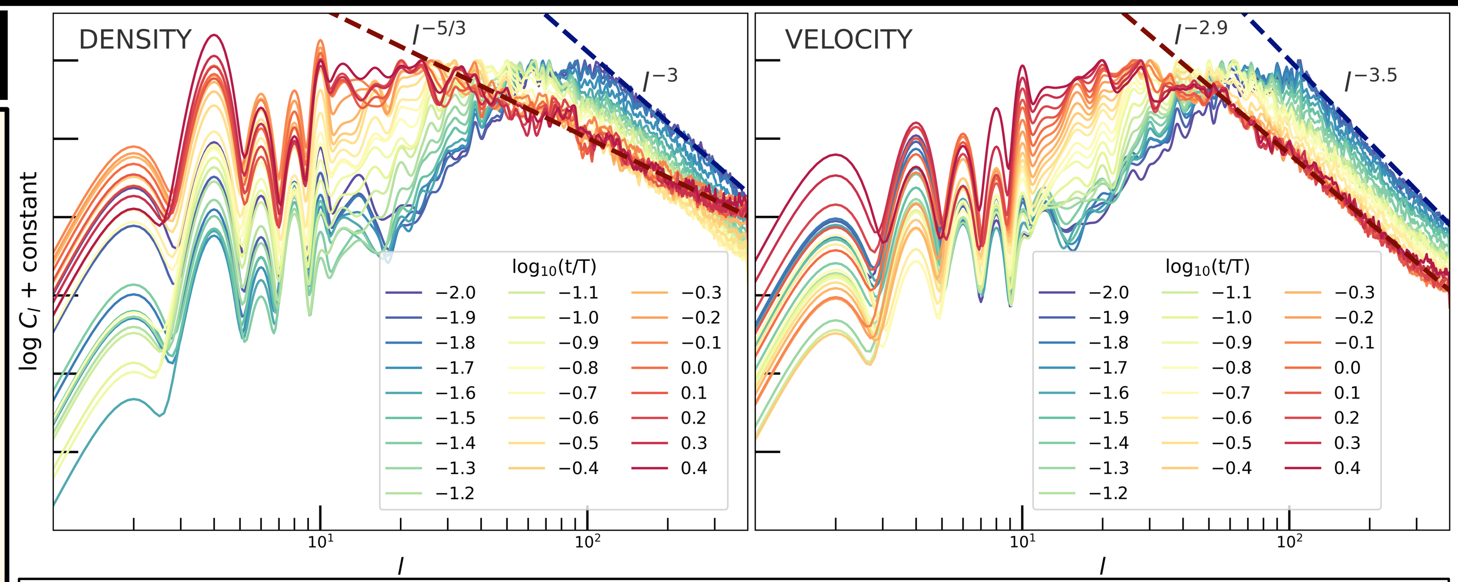


Fig 3. (*left*) Power spectrum of density, and(*right*) the same for velocity, as a function of the age of the remnant. Both spectra display a broken power-law shape with a peak (l_0) that corresponds to the typical size of substructures.

- The peak angular scale (l_0) grows with time, as expected.
- Similar results are obtained for another model (Fig 4) with a lower adiabatic index (γ), which is used to mimic the effects of shock slowdown due to cosmic ray acceleration.
- Now we ask: is this peak angular scale related to the typical size of substructures seen in SNRs such as Tycho or SN 1006? Is it possible to measure this size directly from images?

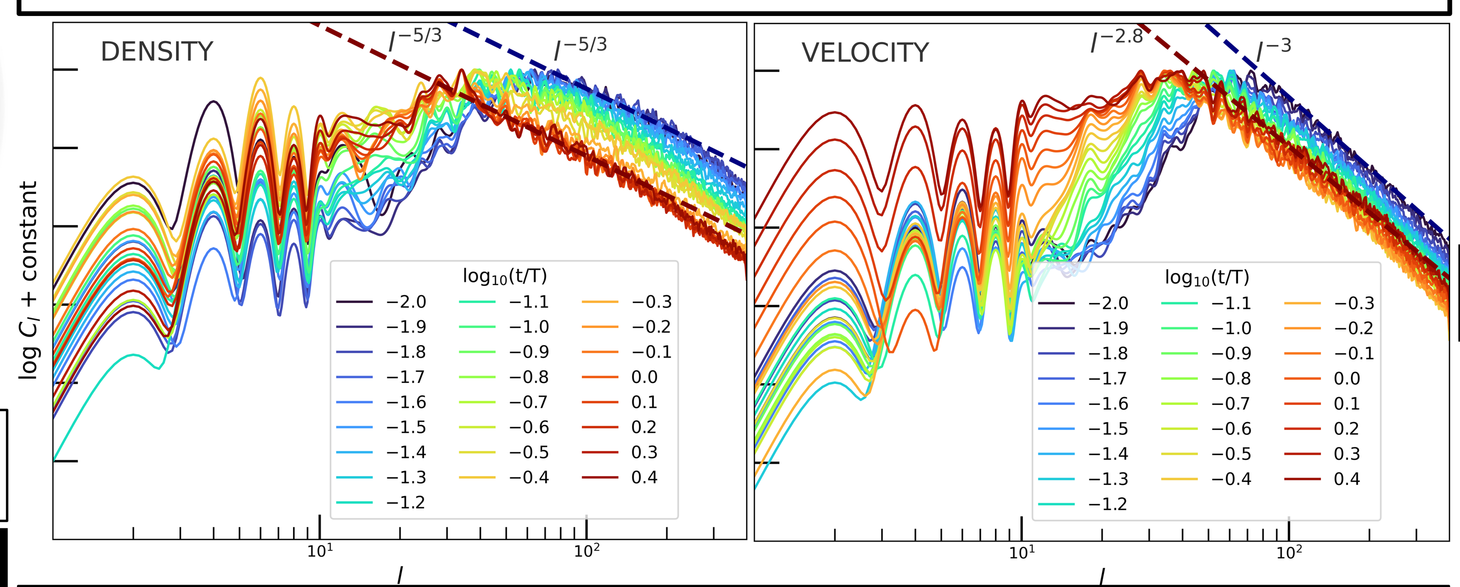


Fig 4. Same as Fig 3, but with a model that takes into account cooling of the forward shock due to cosmic ray acceleration. This is thought to happen in Tycho, and cause the fleece-like structures to catch up with the forward shock. This model employs a lower adiabatic index (γ=4/3). The basic structure of the power spectrum remains the same, but the peak angular scale is smaller for this model at every time instant.

IMAGE ANALYSIS

- The Δ-variance[4] method picks out power at different length scales in an image.
- The basic idea is to convolve given image separately with two Gaussians of std. dev. (σ+ϵ) and (σ-ϵ). The difference of the resulting images then only picks out structures of size σ.
- We apply Δ-variance to synthetic images produced from our models (see Fig 1).
- These images are intended as a proxy of x-ray images dominated by thermal emission, and are generated by integrating the square of density along parallel lines of sight.
- The power spectra thus obtained from the synthetic images are compared to those computed before directly from the corresponding 3D models, shown in Fig 5.

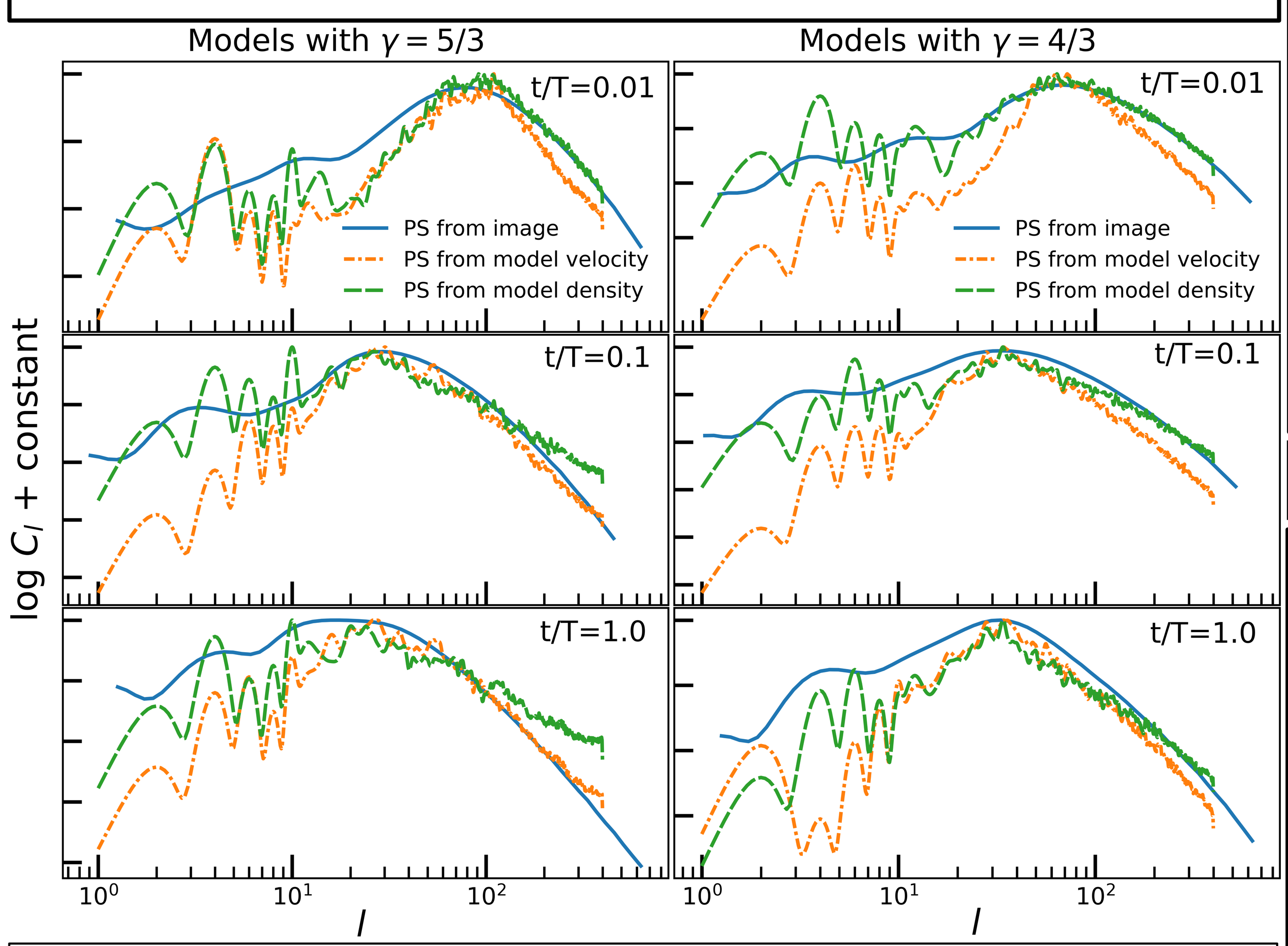
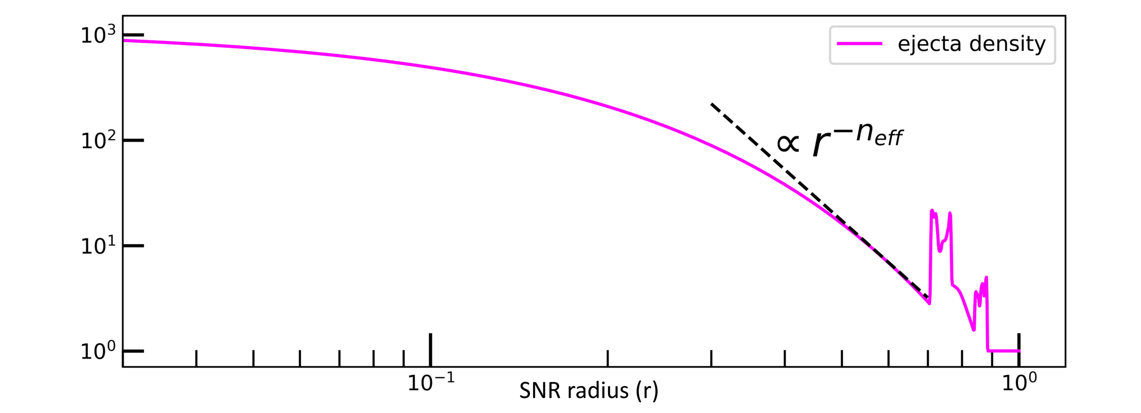


Fig 5. Power spectra obtained from 3D models, compared against the Δ-variance power spectrum, obtained from corresponding synthetic images. For either model, the power spectrum of images correctly picks out the peak angular scale, but the slope at small scales matches that of the density power spectrum at early times and that of the velocity power spectrum at late times.

TYPICAL SIZE OF ANISOTROPIC STRUCTURES

- The Δ-variance power spectrum thus picks out the correct peak angular scale from 2D images of remnants.
- This peak angular scale is found to be proportional to the power-law slope of the density profile of the outermost ejecta, which the reverse shock encounters, shown in Fig 6.
- Armed with the inferences so far, we probe Tycho's SNR.



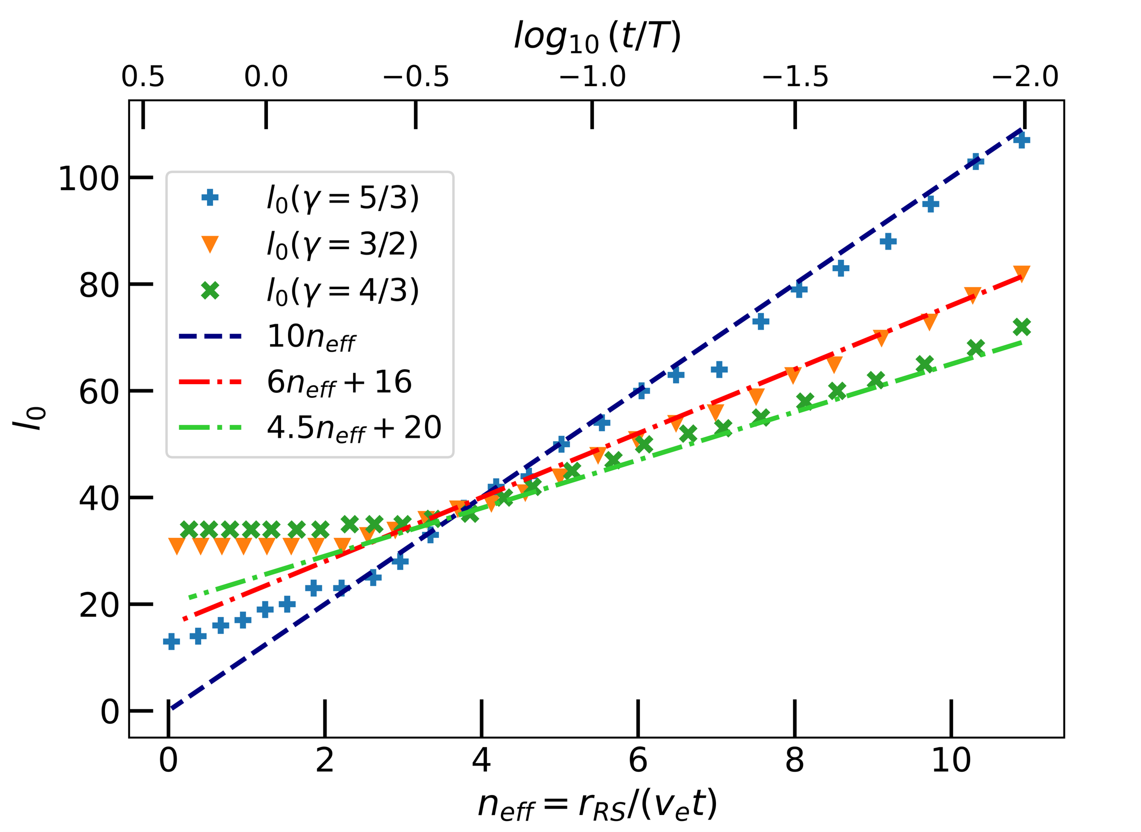


Fig 6. (*Top*) Density profile of the SNR ejecta, depicting the power-law slope n_{eff} of the outermost part. (*Bottom*) Relation between l_0 and n_{eff}. Also shows l_0 as a function of time.

APPLICATION TO TYCHO

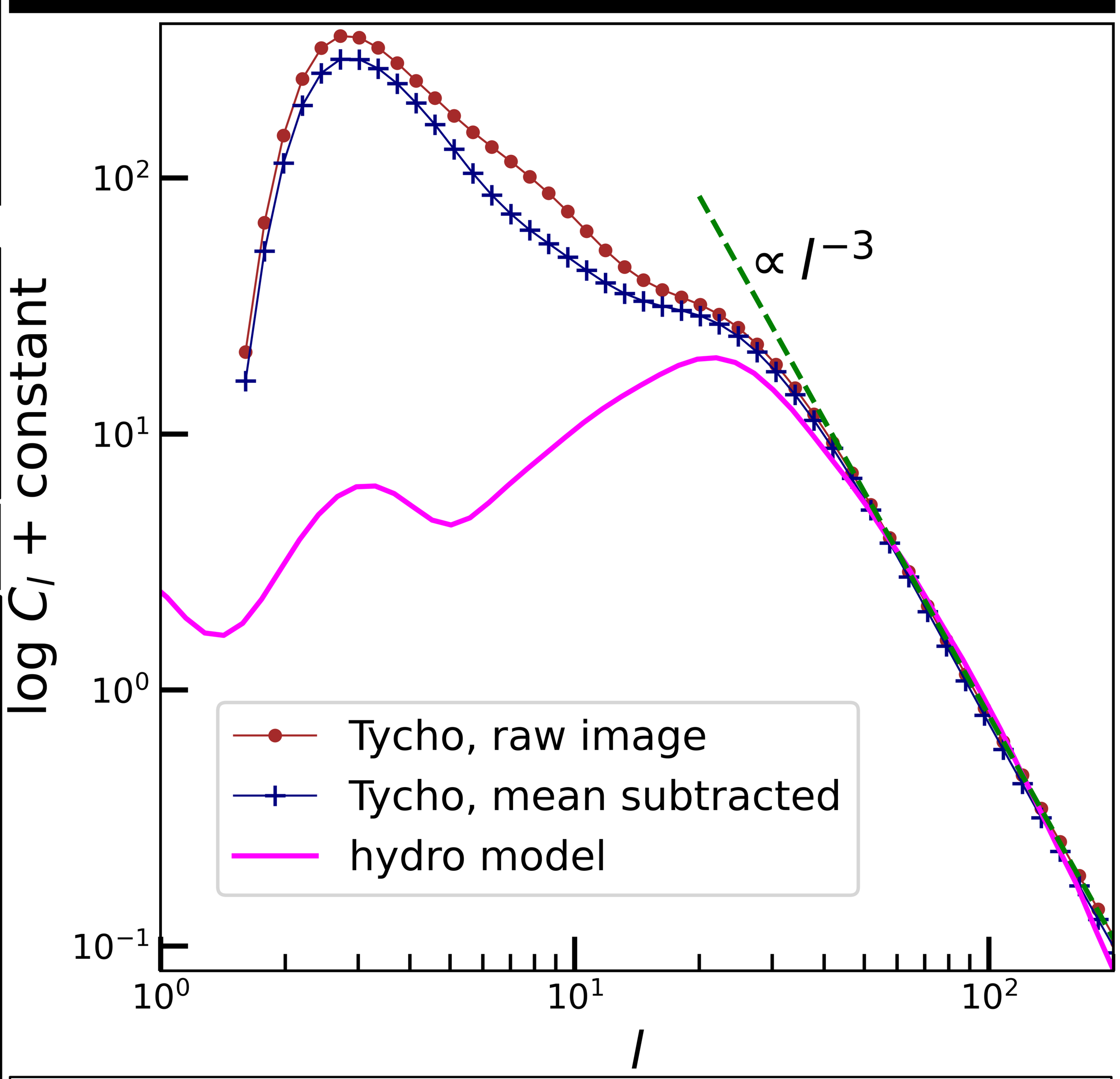


Fig 7. Power spectrum of Tycho's SNR, compared against that of a synthetic image from the hydro model.

- The power spectrum of Tycho's SNR shows a distinct bend at $l \approx 23$.
- Power spectrum of our hydro model also peaks at $l_0 \approx 23$ at the time t/T=0.5.
- Comparing the two, we find a near-exact match for the small scale behavior (large l).
- We infer that $l_0 \approx 23$ indeed corresponds to the fleece-like structures in Tycho (see Fig 1).
- Moreover, the power spectrum shows additional power at large scales (small l).

WHAT DOES THE FLEECE SIZE TELL US?

- Using Fig 5 and the typical angular scale of $l \approx 23$, we infer the **outermost ejecta** in Tycho has a density profile $\rho \propto r^{-2}$.
- **Scaled age** of Tycho is t/T=0.5, as mentioned.
- Assuming mass and energy of a typical Type-Ia SN, the scaled age gives an estimate of the **ambient (CSM) density:** n~0.28/cm^3.
- Large power at low- l modes indicates an **asymmetric explosion mechanism** (or asymmetries in the pre-explosion CSM).

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