# Effect of Plasma Turbulence on the Evolution of Specular Meteor Echoes

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## Introduction

Specular meteor echoes are signals back-scattered from expanding meteor trails, when a radar **k**-vector points perpendicular to this trail. These radar echoes are currently used to derive atmospheric parameters such as temperature, pressure, and drifts; under the assumption of non-turbulent diffusion rates. In this poster, we present a numerical model of underdense specular meteor echoes that includes for the first time the effect of plasma turbulence on its evolution. Our numerical method simulates both the trail at different stages and its corresponding received power. Understanding the role of turbulence on the growth of underdense specular echoes is particularly important because the inference of mesospheric temperatures from trail diffusion rates and their usage for meteor scatter communication systems.

## Meteoric Plasma Instabilities

Meteor plasma studies demonstrates that plasma instabilities can develop in the meteor trail. These plasma instabilities generated from field-aligned irregularities (FAI) [1,2] are able to lead to an anomalous cross-field diffusion [3]. This anomalous diffusion can exceed the ambipolar cross-field rate by an order of magnitude and therefore modify the evolution of meteor trails.

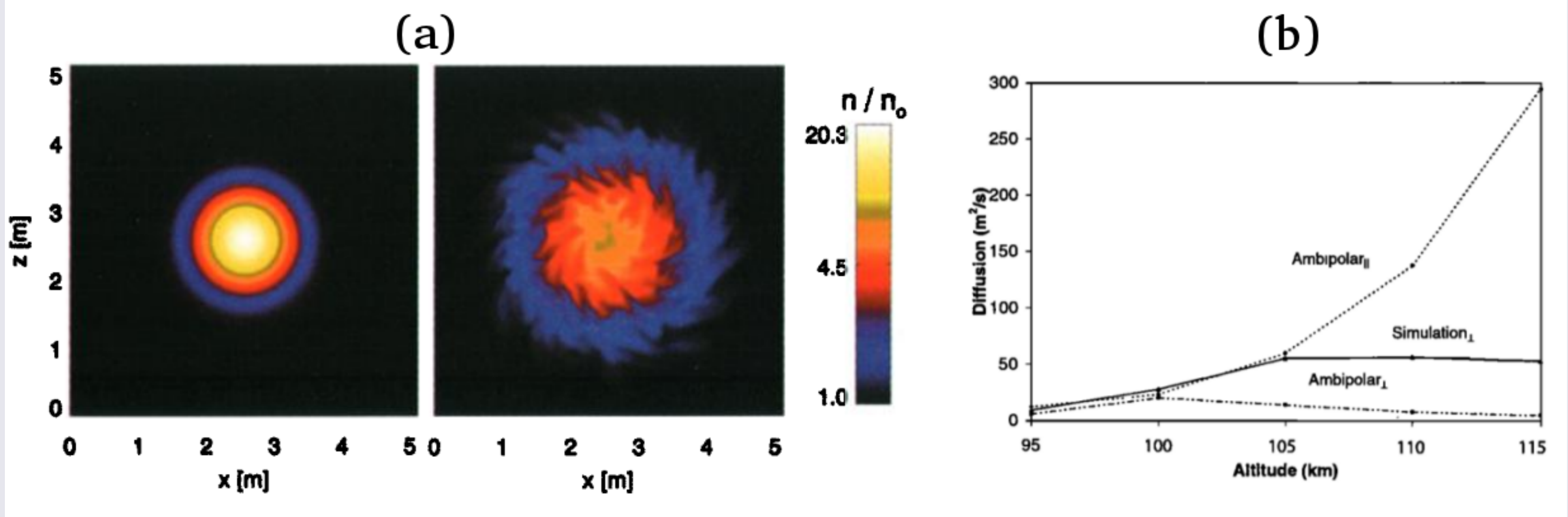


Figure 1. a) Density ratio of trail plasma to background density, n/n$_o$, in a log scale at two different times. The density is indicated by the color bar. All panels show cross sections perpendicular to both the trail axis and **B** which points into the page. b) Ambipolar diffusion parallel and perpendicular to the Earth's magnetic field, and turbulent diffusion.

## Experimental Evidence of Plasma Instabilities

Below we present two specular meteor events. Panel (a) depicts a specular meteor trail echo that seems to follow the classical ambipolar diffusion, i.e. exponential decay; while panel (b) shows a specular meteor that exhibits a sudden change in the diffusion rate. The comparison between these two panels demonstrates that the meteors seem to decay at the same rate (blue slanted line). We hypothesize that turbulent diffusion affects the meteor trail showed in panel (a) from the start of the event; while the meteor trail in panel (b) is first affected by ambipolar diffusion and later by turbulent diffusion.

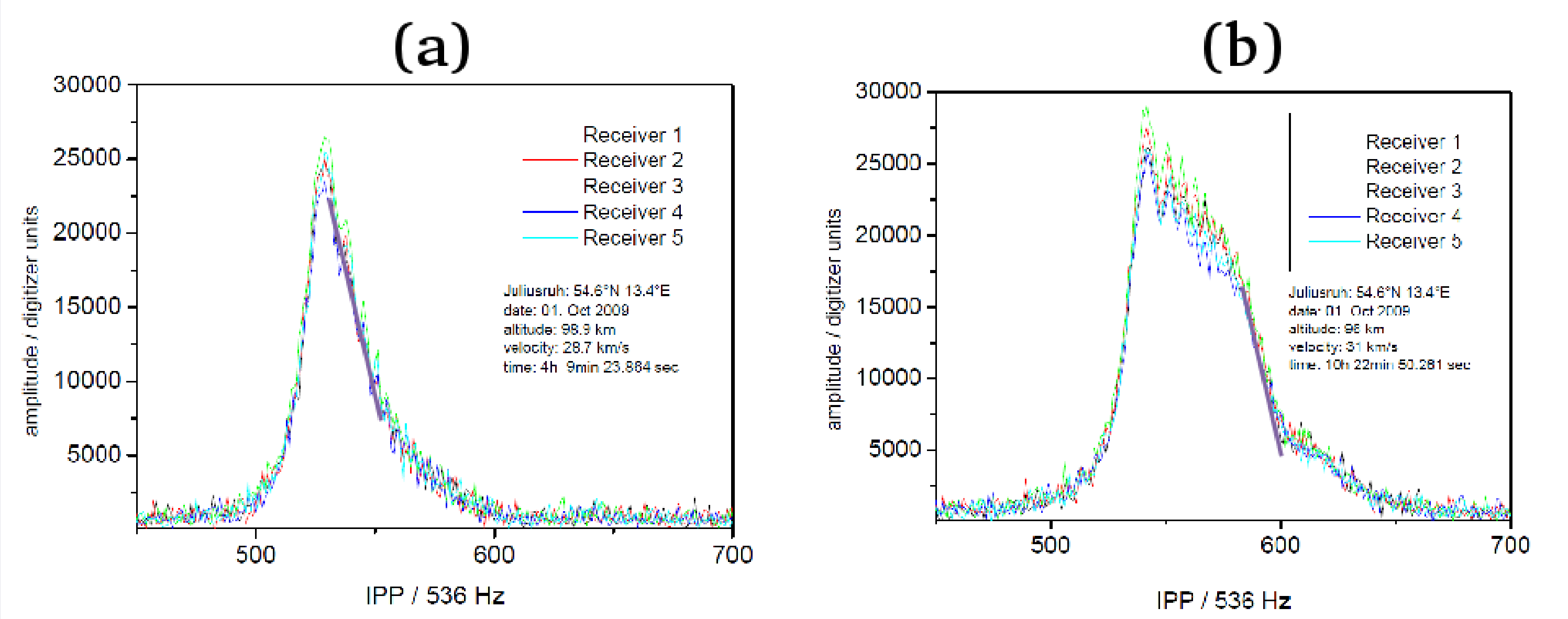


Figure 2. Specular meteor trail echoes showing the effect of plasma turbulence on their decays. Panel (a) shows a trail where plasma turbulence dominates the evolution from the beginning. Panel (b) shows a trail where ambipolar diffusion is first present and later by turbulent diffusion.

## The Underdense Specular Simulator

- The simulator tracks the evolution of an individual meteoroid from its passage through the atmosphere to the analysis of the meteor plasma column in order to find altitudes where the trail is unstable.
- We determine if the trail is unstable by solving the Farley-Buneman Gradient-Drift dispersion relation for meteor trails:

$$0 = \omega^2\left[-\frac{j\Psi}{\nu_i} - \frac{1}{\Omega_i kL}\right] + \omega\left[1 + \Psi - \frac{j\nu_i}{\Omega_i kL}\right] + \left[-kV_{e\perp} + \frac{jk^2C_s^2\Psi}{\nu_i} + \frac{kC_s^2}{\Omega_i L}\right]$$

- It was demonstrated by [3] that the diffusion rate perpendicular to the magnetic field will match the parallel diffusion rate due to the instabilities:

$$D_{eff} = \begin{cases} D_{\parallel}\sin^2\mu\sin^2\theta + D_{\perp}(1-\sin^2\mu\sin^2\theta), & \text{if } \gamma \le 0 \\ D_{\parallel}\sin^2\mu\sin^2\theta + D_{\parallel}(1-\sin^2\mu\sin^2\theta), & \text{if } \gamma > 0 \end{cases}$$

- In the standard model, diffusion is only a function of altitude, while in our model diffusion depends on both altitude and time. In other words, diffusion rate would switch from turbulent to non-turbulent diffusion, or vice-verse, depending on the presence of meteor plasma instabilities.

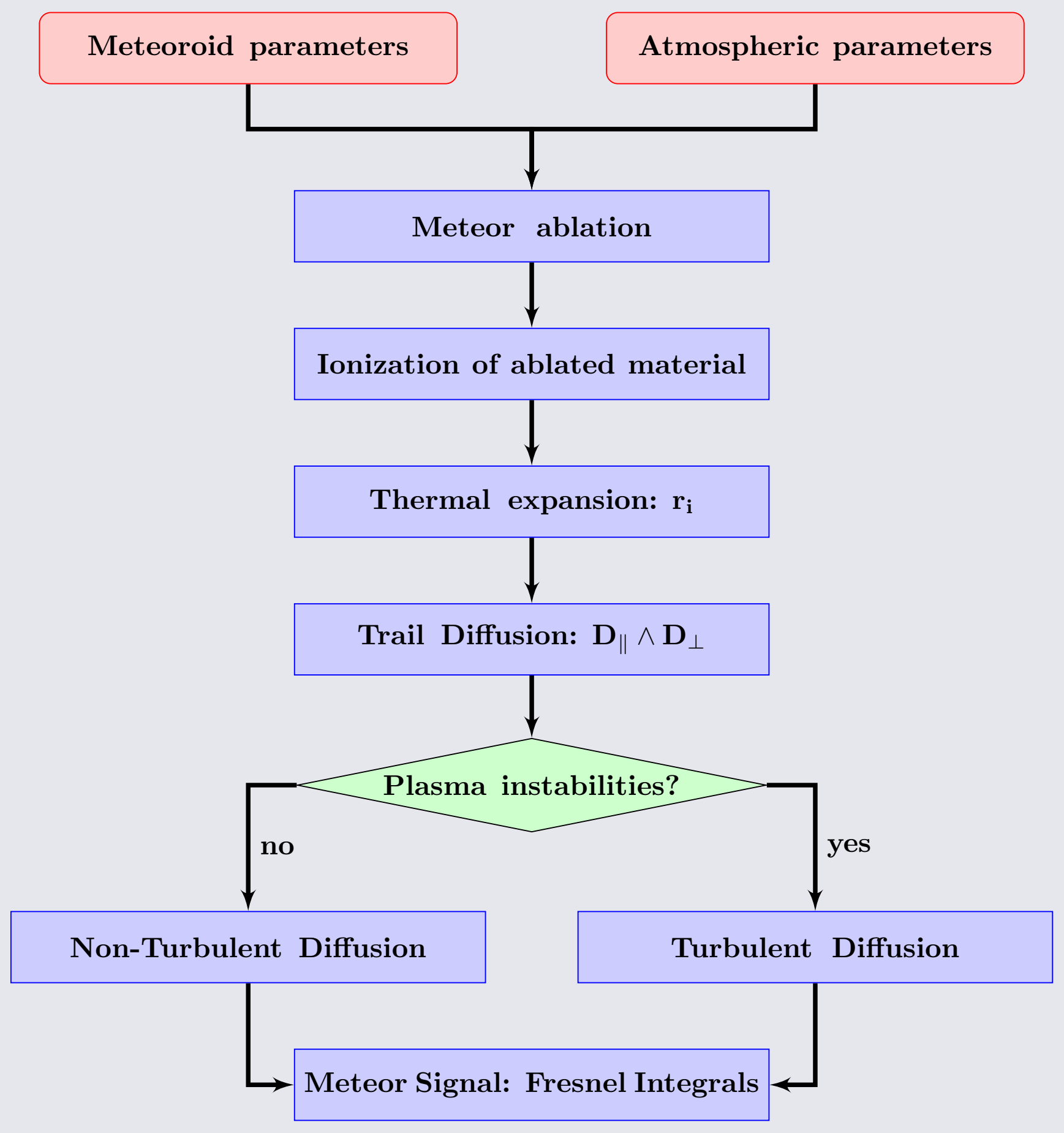


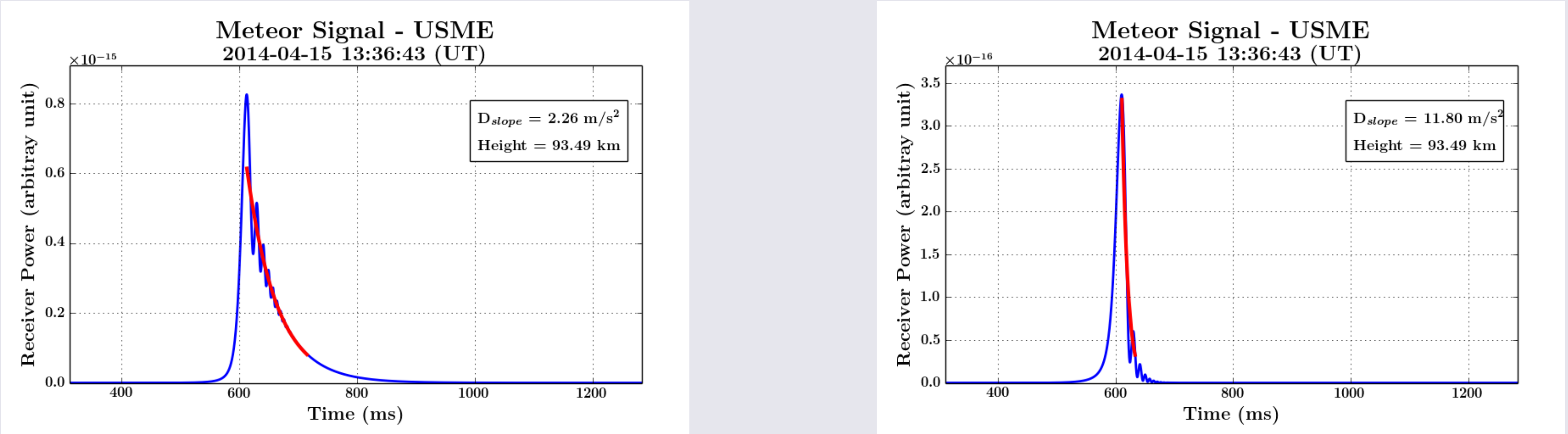
Figure 2. Simplified diagram of the algorithm that is employed to simulate underdense specular meteor trail echoes.

## The Underdense Specular Simulator

- Modified Fresnel Integrals were derived in order to include: a non-constant line density along the meteoroid trajectory, the effect of the initial radius, and the effect of diffusion inside the integrals:

$$D_{eff} = \begin{cases} D_{\parallel}\sin^2\mu\sin^2\theta + D_{\perp}(1-\sin^2\mu\sin^2\theta), & \text{if } \gamma \le 0 \\ D_{\parallel}\sin^2\mu\sin^2\theta + D_{\parallel}(1-\sin^2\mu\sin^2\theta), & \text{if } \gamma > 0 \end{cases}$$

- Our outcome is the in-phase and quadrature time series of the theoretical meteor trail echo:


**(a) Non-turbulent diffusion**

**(b) Turbulent diffusion**

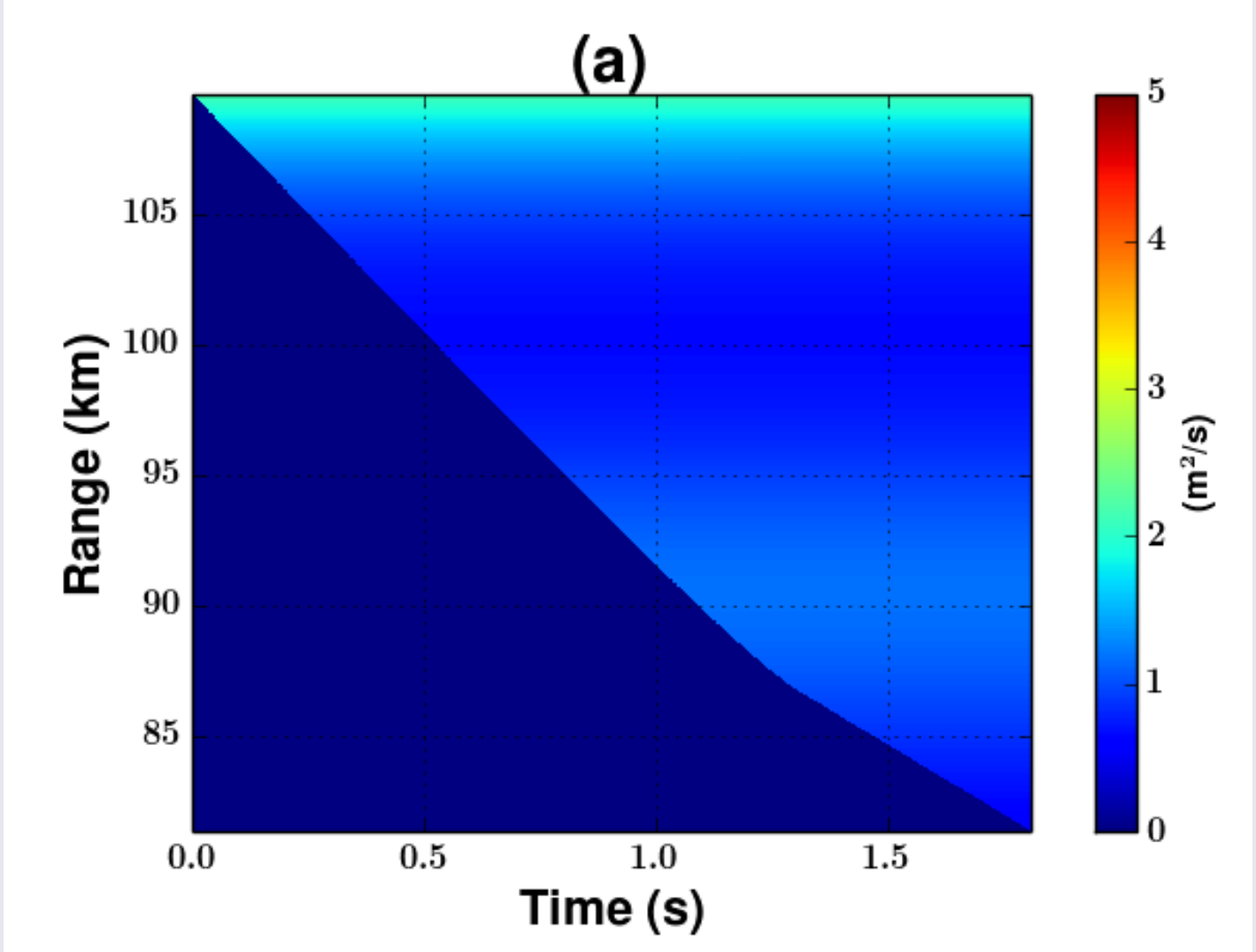
Figure 3. Simulated meteor trail echoes: a) The simulation in the left panel considers that the meteor trail expands only due to ambipolar diffusion, i.e. non-turbulent diffusion. b) Meteor trail in the right panel includes the effect of plasma instabilities, i.e. turbulent diffusion.

## Preliminary Results

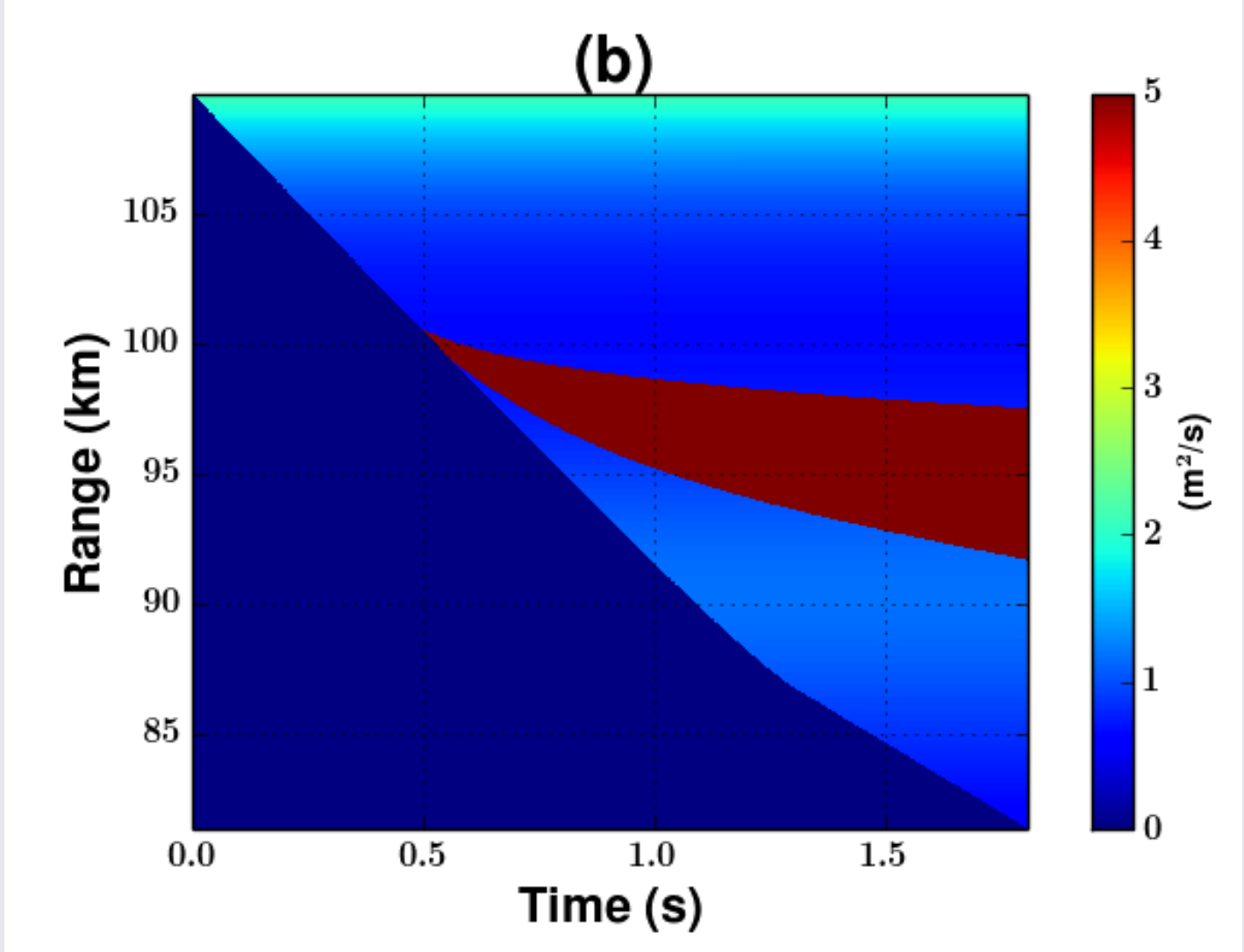
**Turbulent/Non-turbulent Diffusion:**

Panels (a) and (b) present the effective diffusion affecting a meteor trail. Panel (a) was found not considering plasma instabilities, while panel (b) included the effect of plasma instabilities. Panel (c) shows the meteor trail echoes that result from applying turbulent and non-turbulent diffusion in the evolution of the trail. We have simulate 500 events (see panel (d)) to compare diffusion rates. Our simulation shows that around 65% of our simulating meteors exhibit diffusion values that differ in less than 10 %.

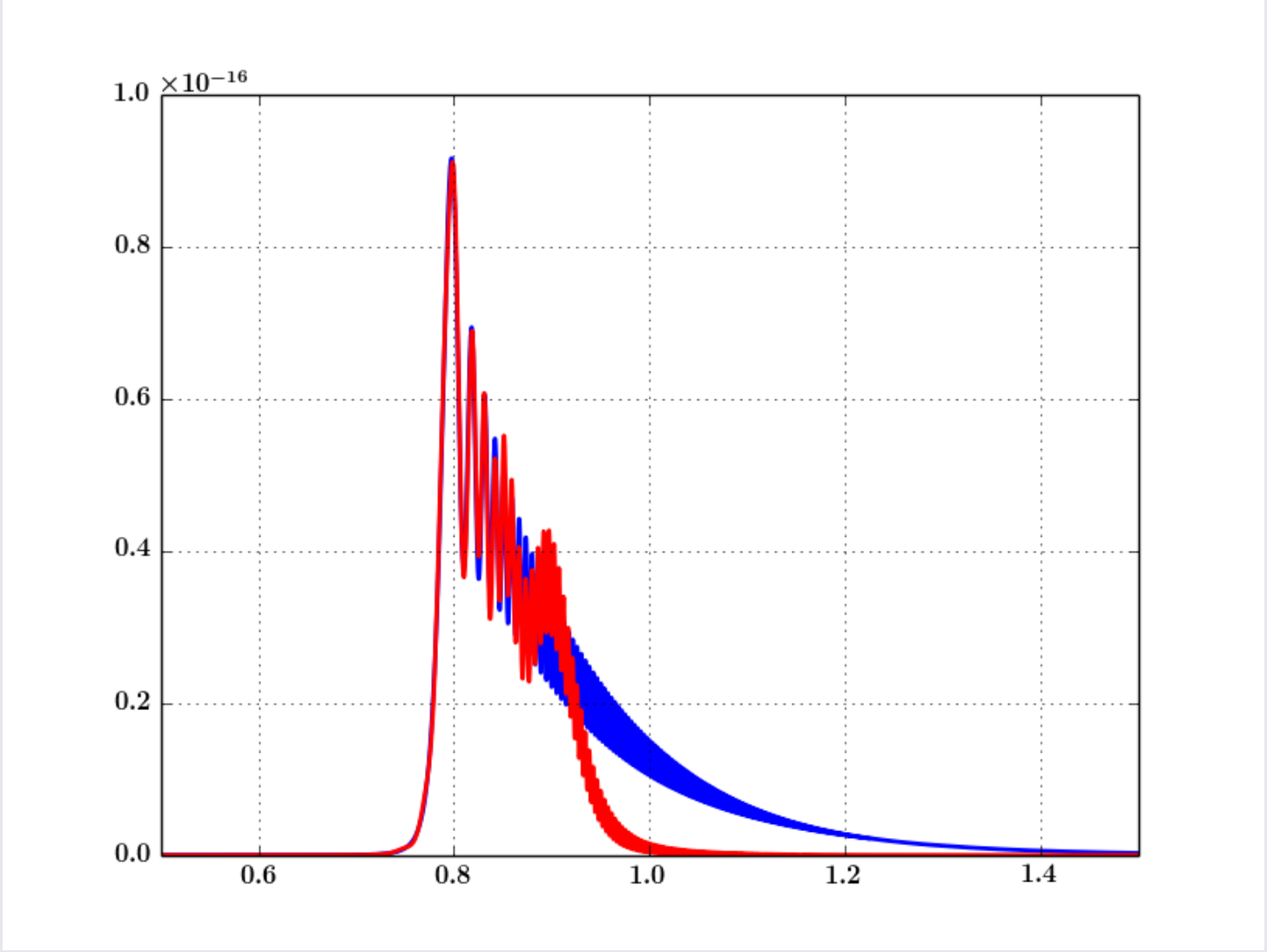
**(a) Non-turbulent diffusion**



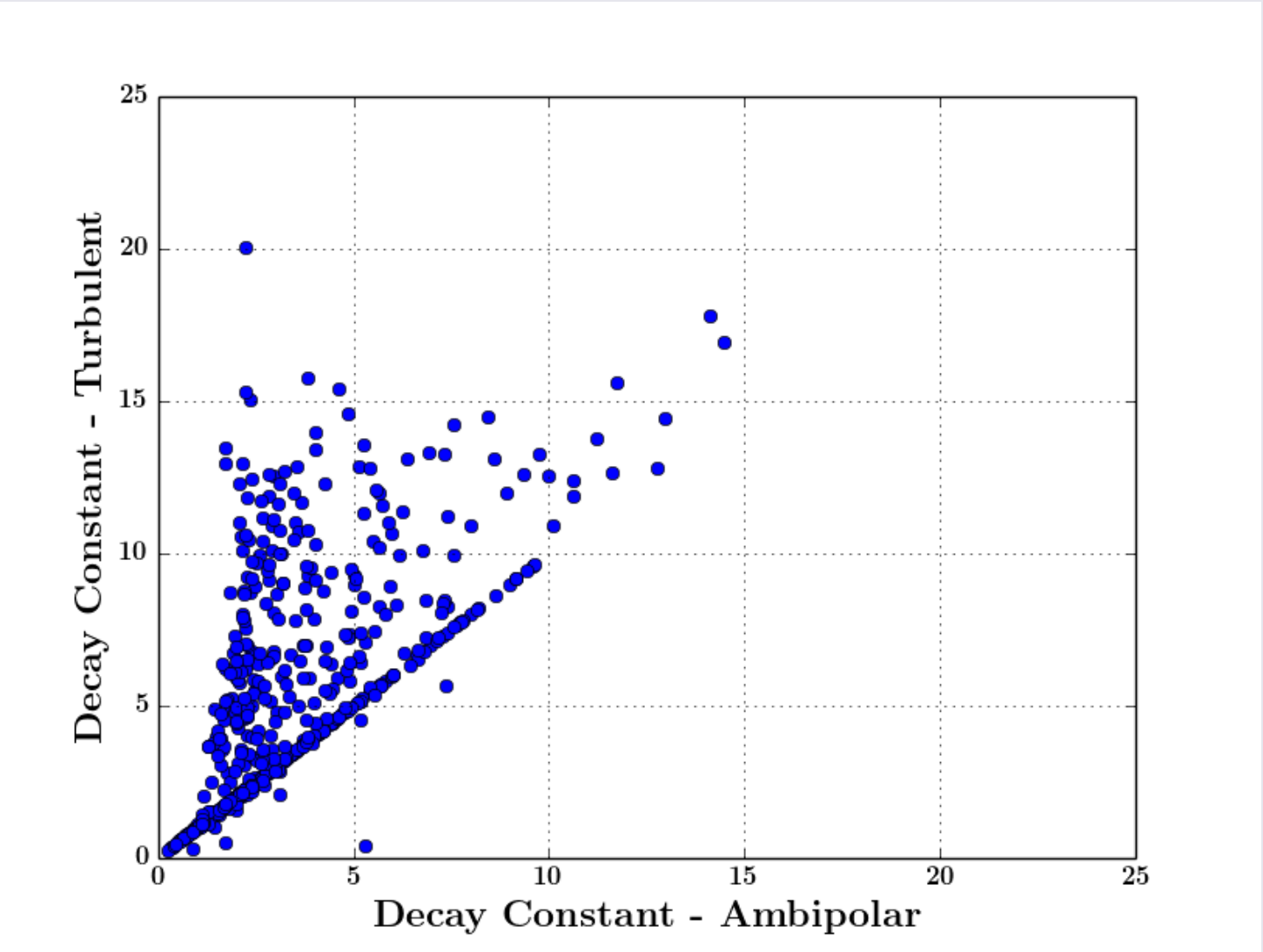
**(b) Turbulent diffusion**



**(c) Turbulent/Non-turbulent Evolution**



**(d) Statistical Analysis**



## Conclusions

We have included for first time the effect of meteor plasma instabilities on the evolution of underdense specular meteor echoes. Our results shows that in the worst case, classical underdense meteor echoes would be distorted and therefore they would not be recognized as a underdense trails. In the best scenario, meteor trail echoes will exhibit the characteristic exponential; however, time decay will not match the ambipolar value. We know from non-specular simulations that these echoes can exhibit complex patterns due to wind shears, i.e. plasma instabilities are not sustained in the trail when winds are too small. We expect to study specular meteor echoes embedded in wind shears in a future work.

## Acknowledgments

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## References

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