Specular meteor observations and full wave scattering modelling: observing faint meteors (solicited)

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Motivation

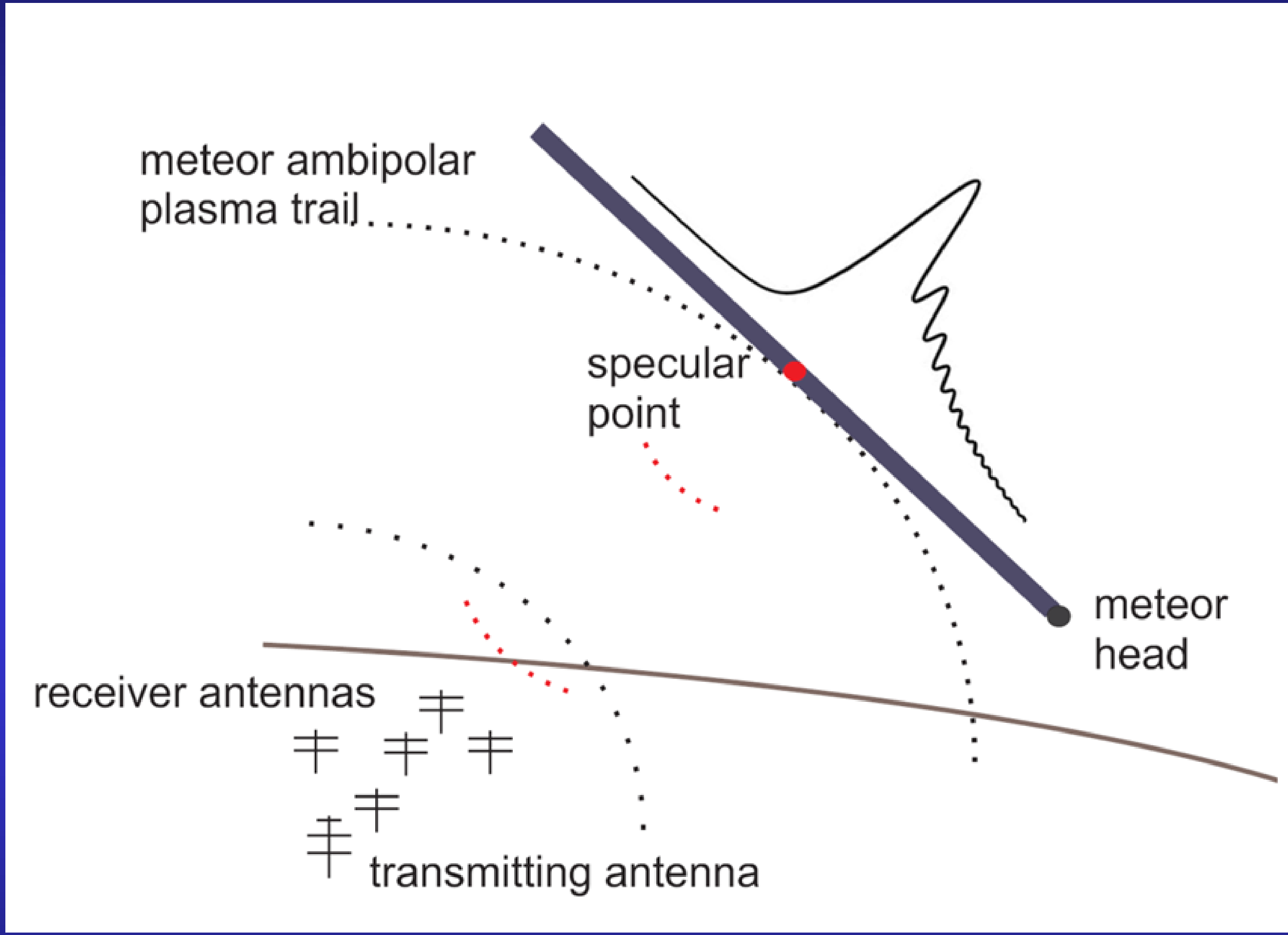
Atmospheric measurements:

- specular meteor radar observations are widely used to monitor atmospheric dynamics (winds and temperatures)

Meteor Earth environment:

- radiant mapping and orbit computation (multi-static)
- mass estimation and meteor velocity as well as mass deposition due to ablation
- neutral air density variability

Specular meteor radar geometry

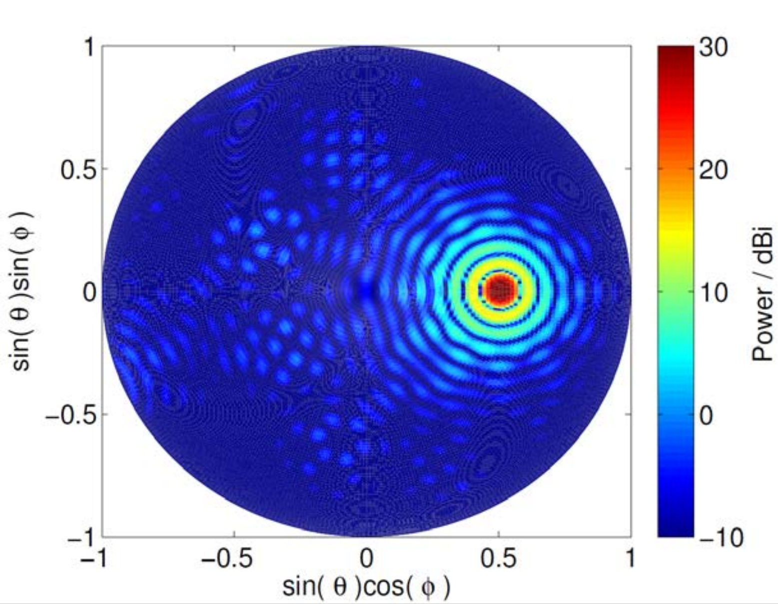


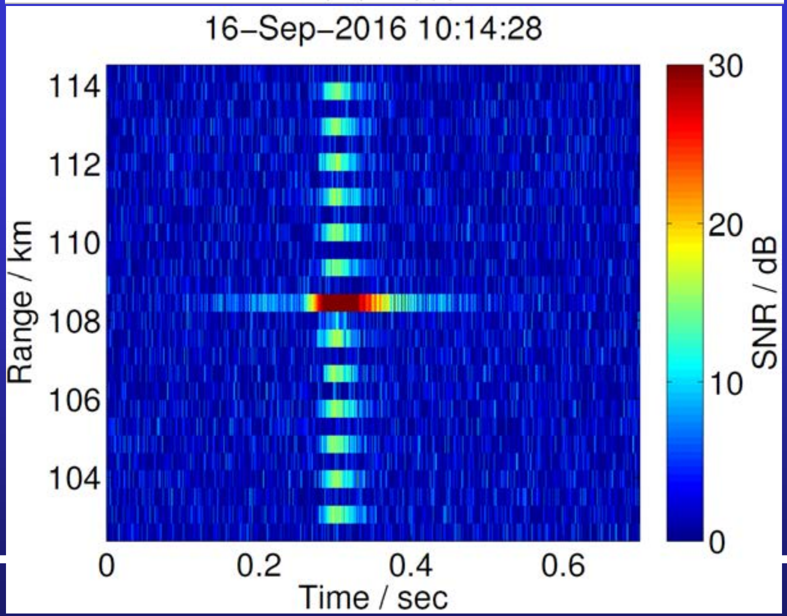
- the ambipolar diffusing plasma trail reflects a transmitted radio wave, if the specular condition is satisfied (trajectory perpendicular to radio wave propagation direction)
- trail echo has much larger RCS (radar cross section) compared to meteor head echo

MAARSY specular experiment

HPLA radar for specular trail observation
→combination of high power with large scattering target
→ observation of smallest meteoroids

PRF	1000 Hz
Code	13bit-Barker
Pulse-length	13x450 m
Start range	69.75 km
End range	139.95 km
Gates	157
Resolution	450 m
Beam	30° off-zenith east





Schult et al., 2020 (ICARUS)

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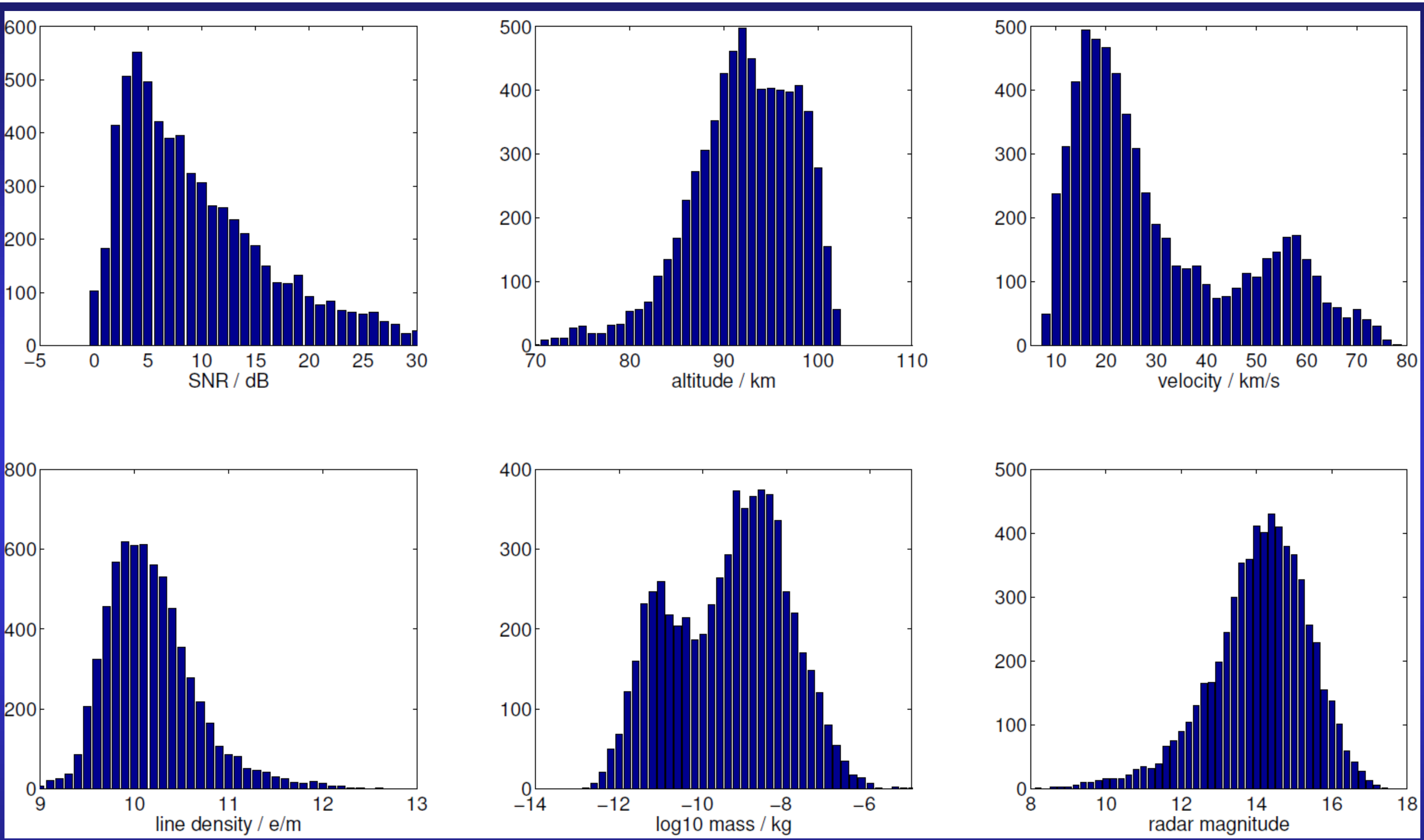
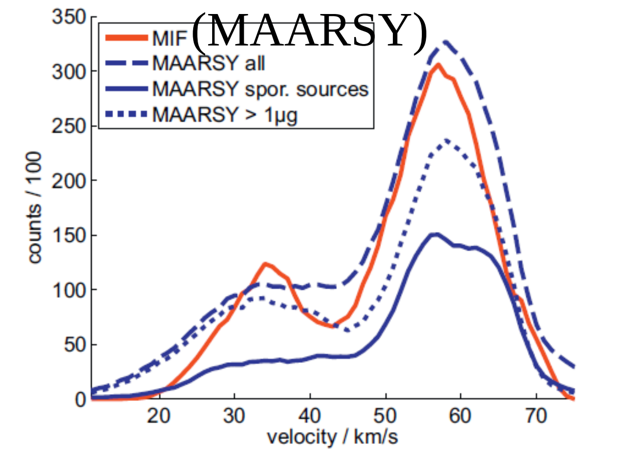
Statistical overview



head echo velocity (MAARSY)



Specular experiment shows peak in the velocity distribution at 16-18 km/s indicating a much higher sensitivity compared to head echoes.

Schult et al., 2020 (ICARUS)

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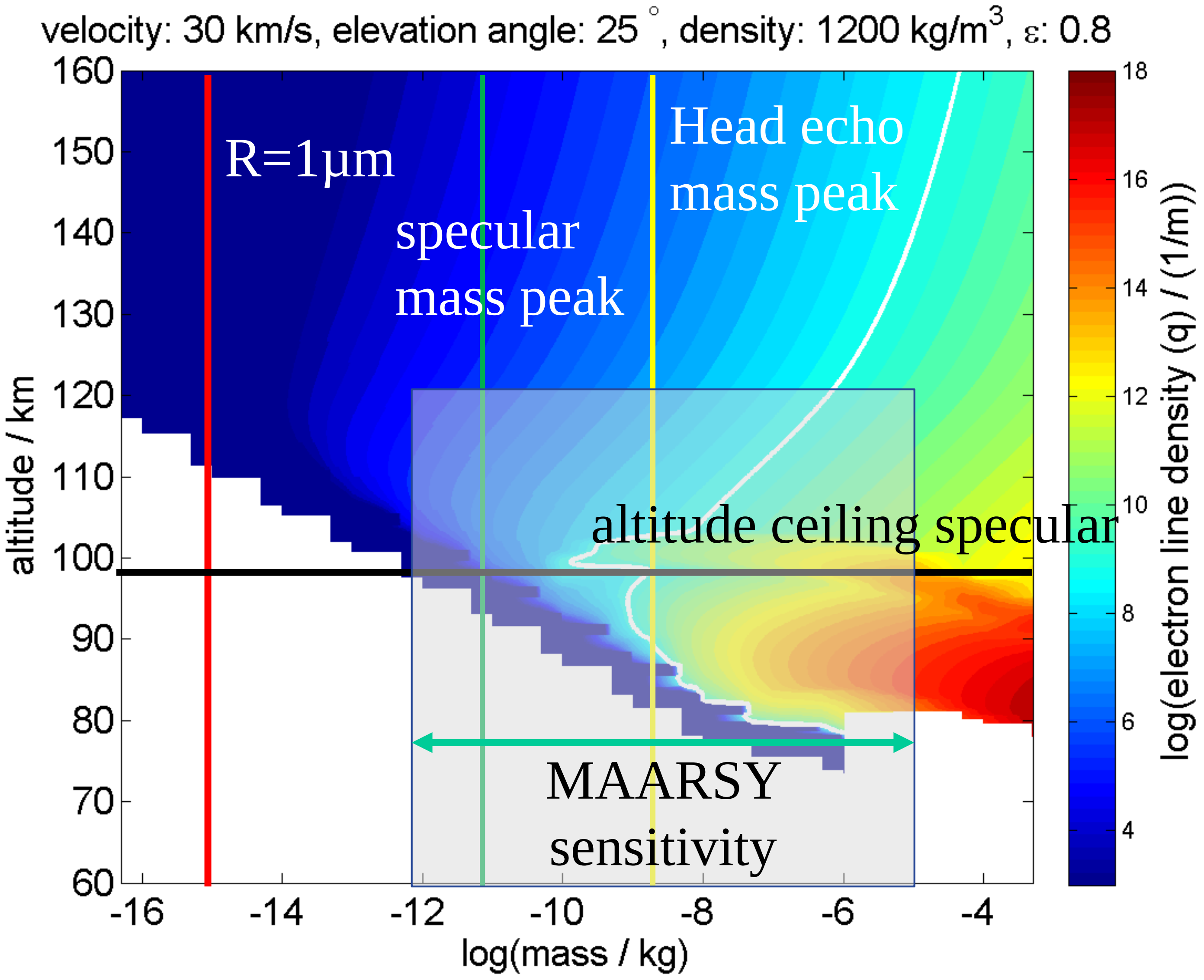
MARS – Meteor Ablation Model for Radio Optical Surveys



- constraining model parameter space with observations
- including scattering of transverse and head echo (RCS) in one model
- fragmentation (tensile strength measurements of meteoric material is needed)

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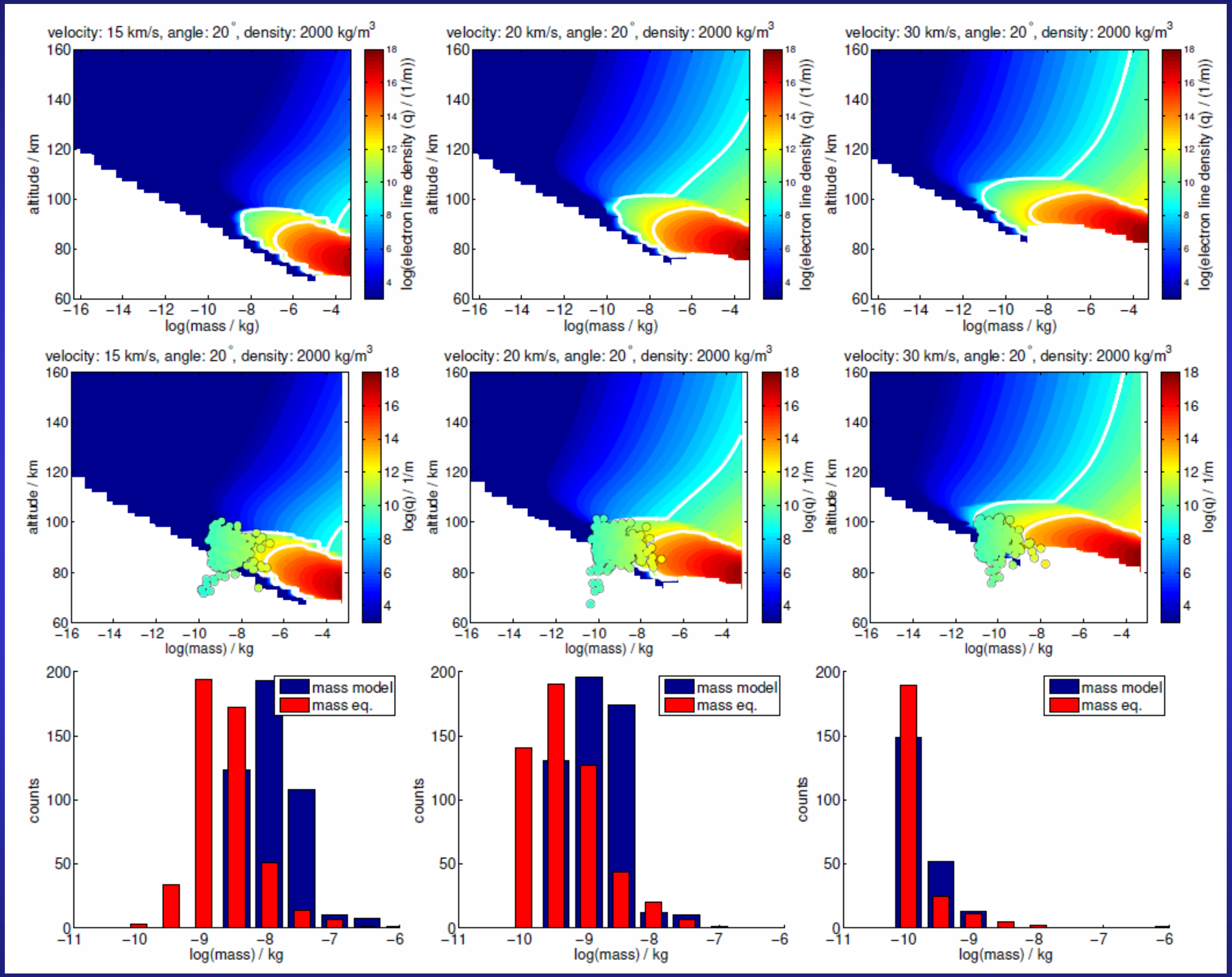
MARS – Meteor Ablation Model for Radio Optical Surveys



- Specular observations are sensitive to meteoroid mass at $10^{(-8..-10)}$ kg at slow velocities (<20 km/s)
- MARS reproduces mass estimates in altitude, density and electron line density
- **Can we verify the results from scattering theory?**

Schult et al., 2020 (ICARUS)

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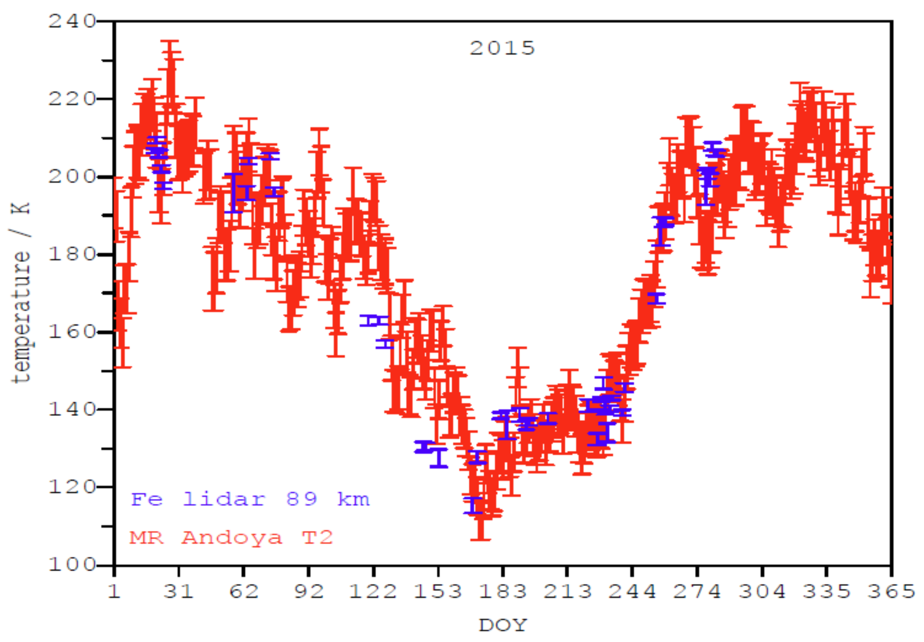
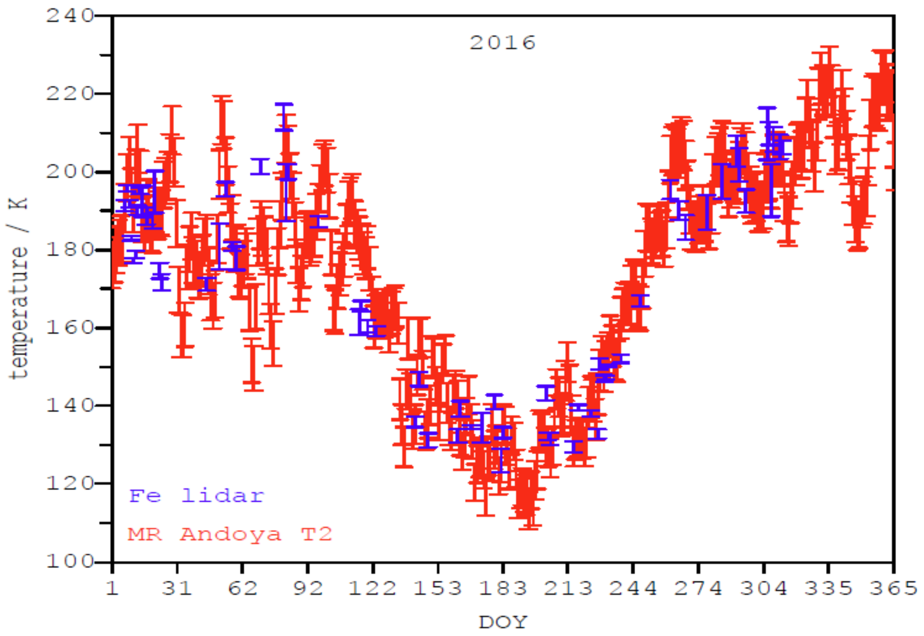
Temperature estimation from decay time of trail

- classical theory predicts a Gaussian plasma distribution in the trail and ambipolar diffusion
- decay time proportional to pressure and temperature
- Hocking et al., 1999, Holdsworth et al., 2004 algorithms to estimate mesospheric temperatures assuming either an empirical pressure model or temperature gradient model

Comparison Fe-Lidar vs. Meteor Radar temperatures



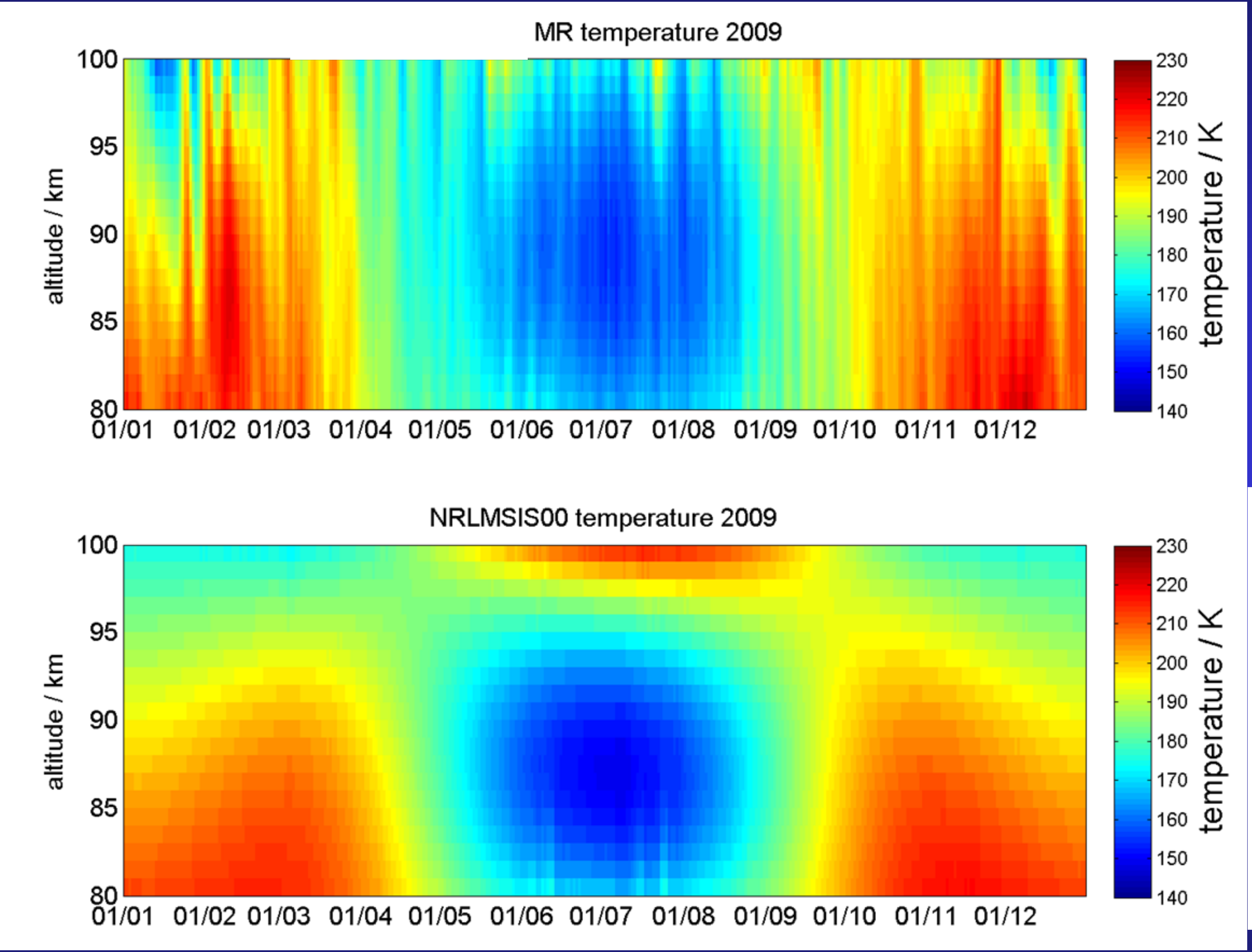
Meteor radar temperatures: Stober et al., 2017 (AG)



Comparison by Raimund Wörl

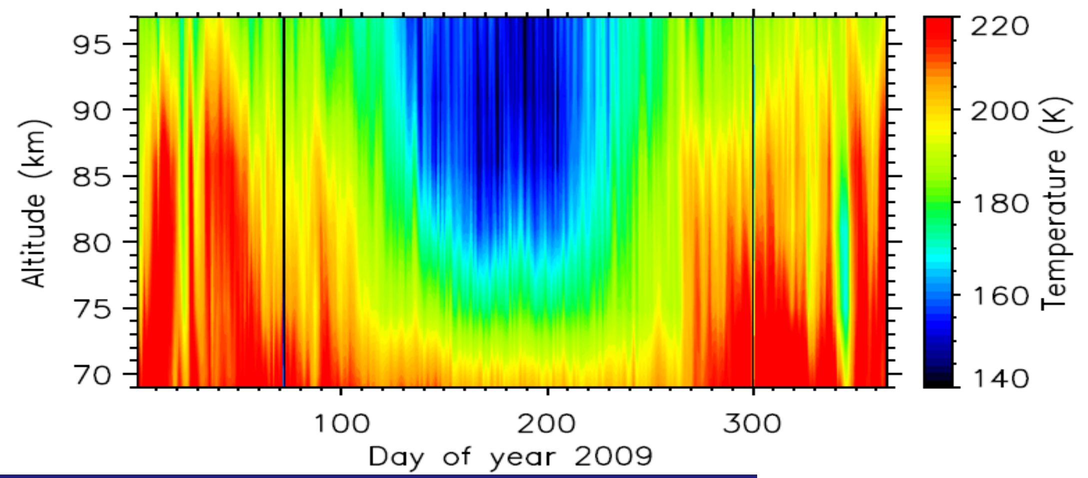
Courtesy of IAP Kühlungsborn

What is our understanding of the meteor trail?



- vertically resolved temperature profiles could be obtained if meteor trail physics is governed by ambipolar diffusion
- **but there is a frequency dependence and absolute offset that point towards some missing physics**

MLS temperature



MLS temperature analyzed by Vivien Matthias, DLR Neustrelitz

Full wave scattering theory

Maxwell-equations

$$\begin{aligned} \nabla \times \mathbf{H} &= -i\omega\kappa\epsilon_0 \mathbf{E} \\ \nabla \times \mathbf{E} &= -i\omega\mu_0 \mathbf{H} \end{aligned}$$

- scattering described by Maxwell equations
- incident plane wave aligned to trails axis
- infinit long trail
- trail physics governed by ambipolar diffusion

Herlofson, 1947 (thesis)

cylindrical coordinates

$$\frac{\partial^2 \mathbf{E_z}}{\partial r^2} + \frac{1}{r}\frac{\partial \mathbf{E_z}}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \mathbf{E_z}}{\partial \phi^2} + k^2\kappa \mathbf{E_z} = 0$$

$$\frac{\partial^2 \mathbf{H_z}}{\partial r^2} + \left[\frac{1}{r} - \frac{1}{\kappa}\frac{\partial \kappa}{\partial \kappa}\right]\frac{\partial \mathbf{H_z}}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \mathbf{H_z}}{\partial \phi^2} + k^2\kappa \mathbf{H_z} = 0$$

ambipolar Diffusion

$$\begin{aligned} \nabla \cdot \mathbf{H} &= 0 \\ \nabla \cdot \mathbf{E} &= 0 \end{aligned}$$

dielectric function

$$\kappa = 1 - \frac{ne^2}{\epsilon_0 m\omega^2(1 + i \cdot \nu/\omega)}$$

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Which plasma distribution best describes trail?

$$a^2 = r_0^2 + 4Dt$$

Gauss-distribution

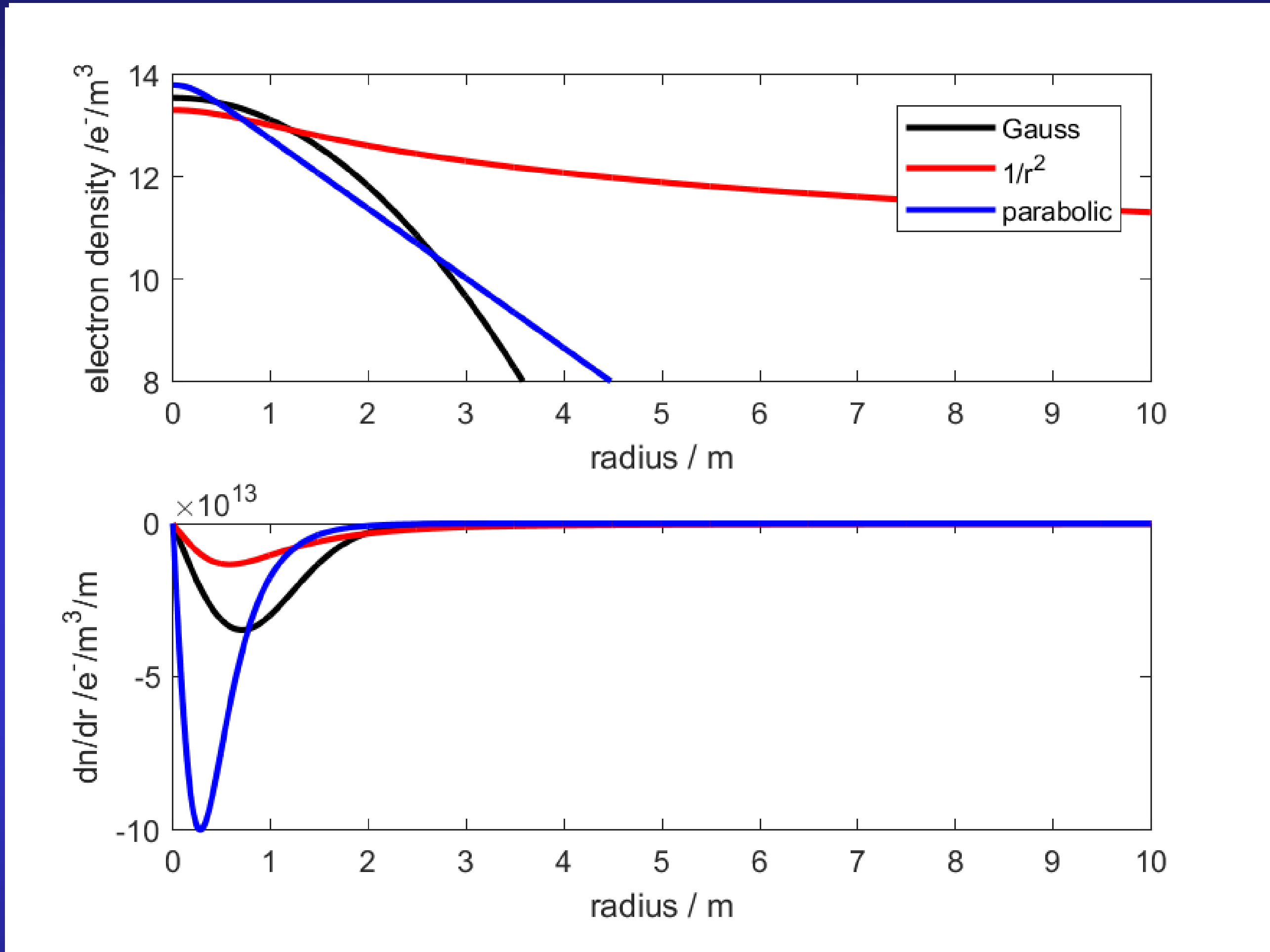
$$n(r,t) = \frac{q}{\pi a^2} e^{\frac{-r^2}{a^2}}$$

Parabolic-Exponential distribution

$$n(r,t) = \frac{q}{\pi a^2} \frac{2e^{\frac{\pi r}{a}}}{e^{\frac{2\pi r}{a}} + 1}$$

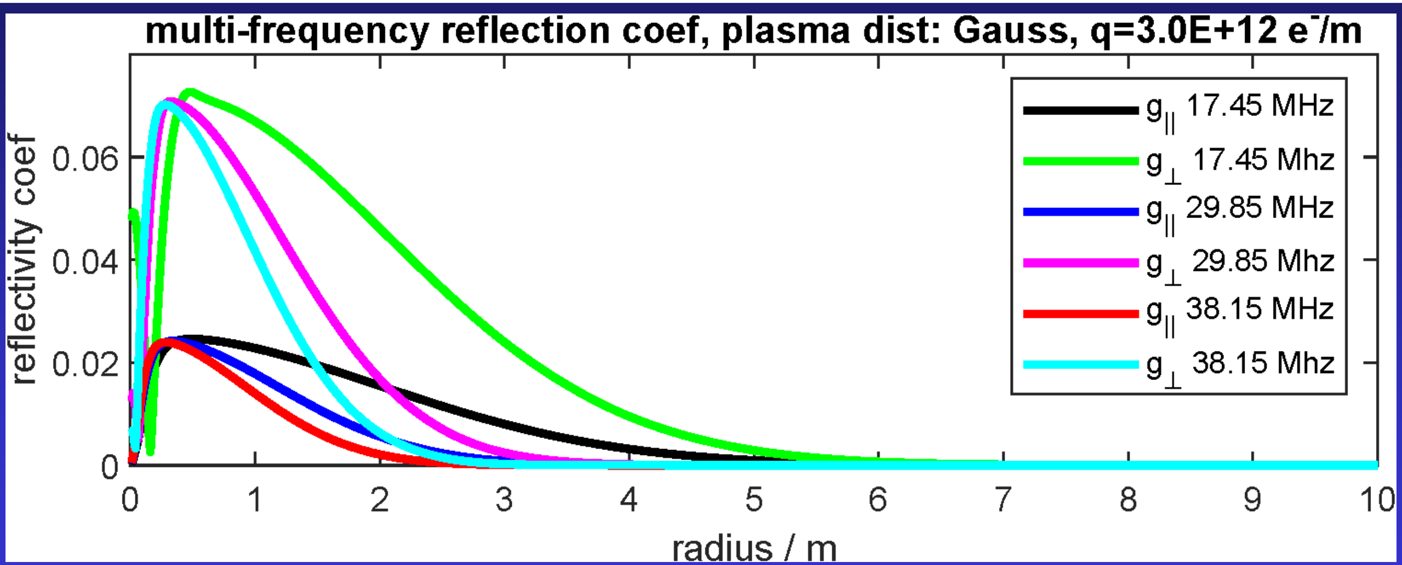
$1/r^2$-distribution

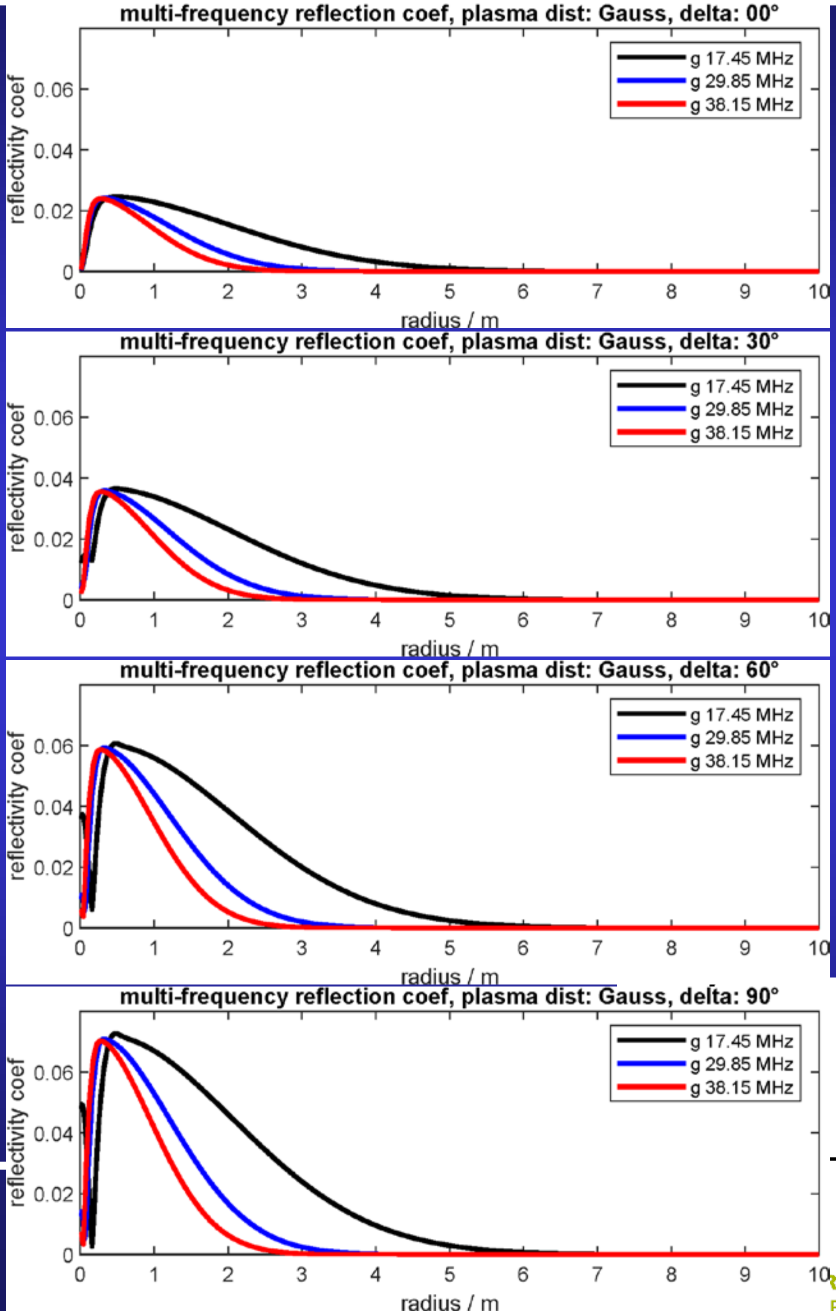
$$n(r,t) = \frac{q}{\pi a^2} \frac{1}{1 + r^2/a^2}$$



Gaussian plasma distribution is analytical solution of diffusion equation

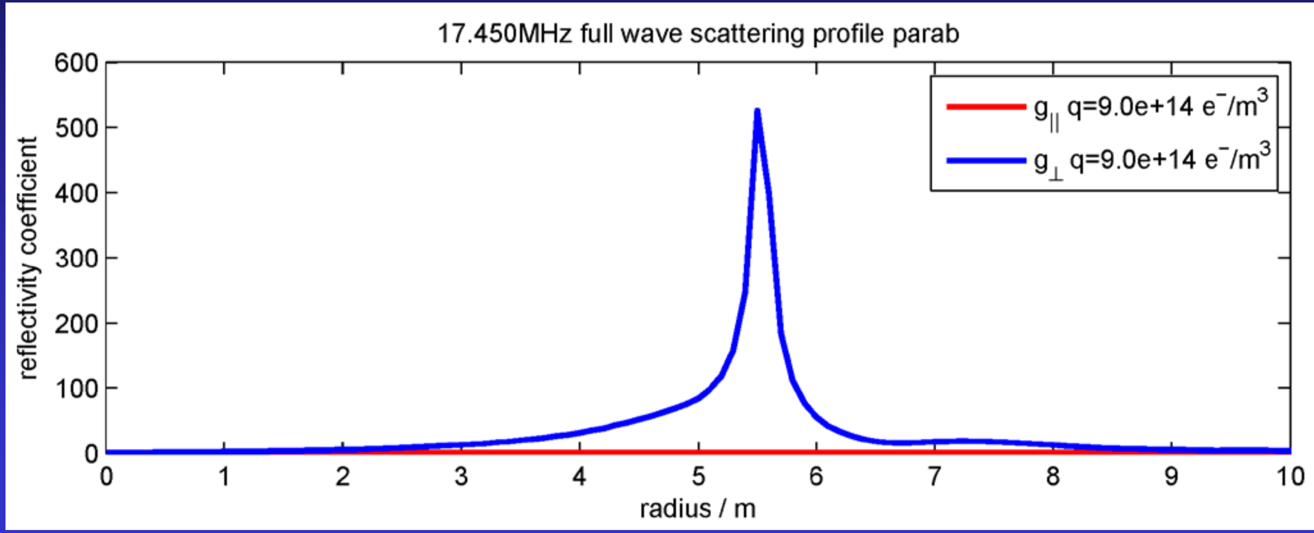
Full wave scattering reflection coefficients (Gauss model)

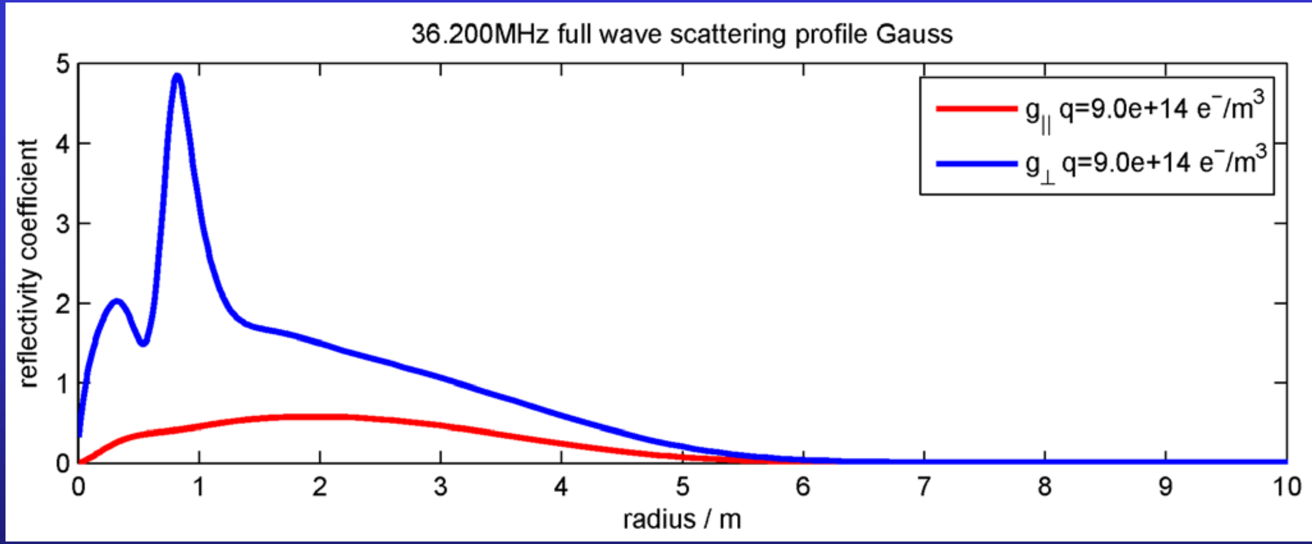




- reflection coefficients show dependence on scattering angle between trail alignment and polarization of transmitted electro-magnetic wave
- amplitude of signal and morphology depend on trajectory in the atmosphere

Full wave scattering -resonance effects





- full wave scattering represents solution for cw-radar signals or long radar pulses
- collisional coupling in the plasma essential for the generation of resonances
- pulsed radar systems might be less affected compared to cw-radars due to thermal motion and relaxation between successive radar pulses

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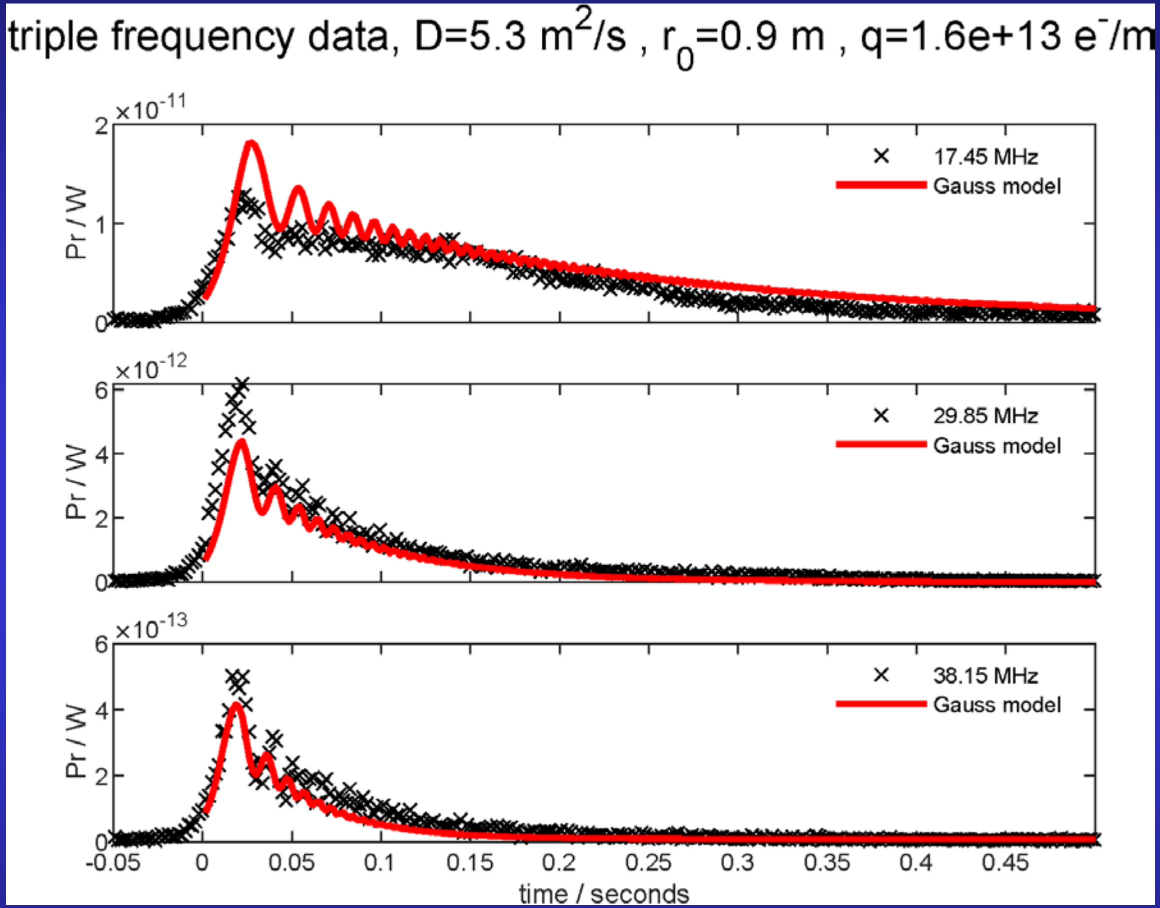
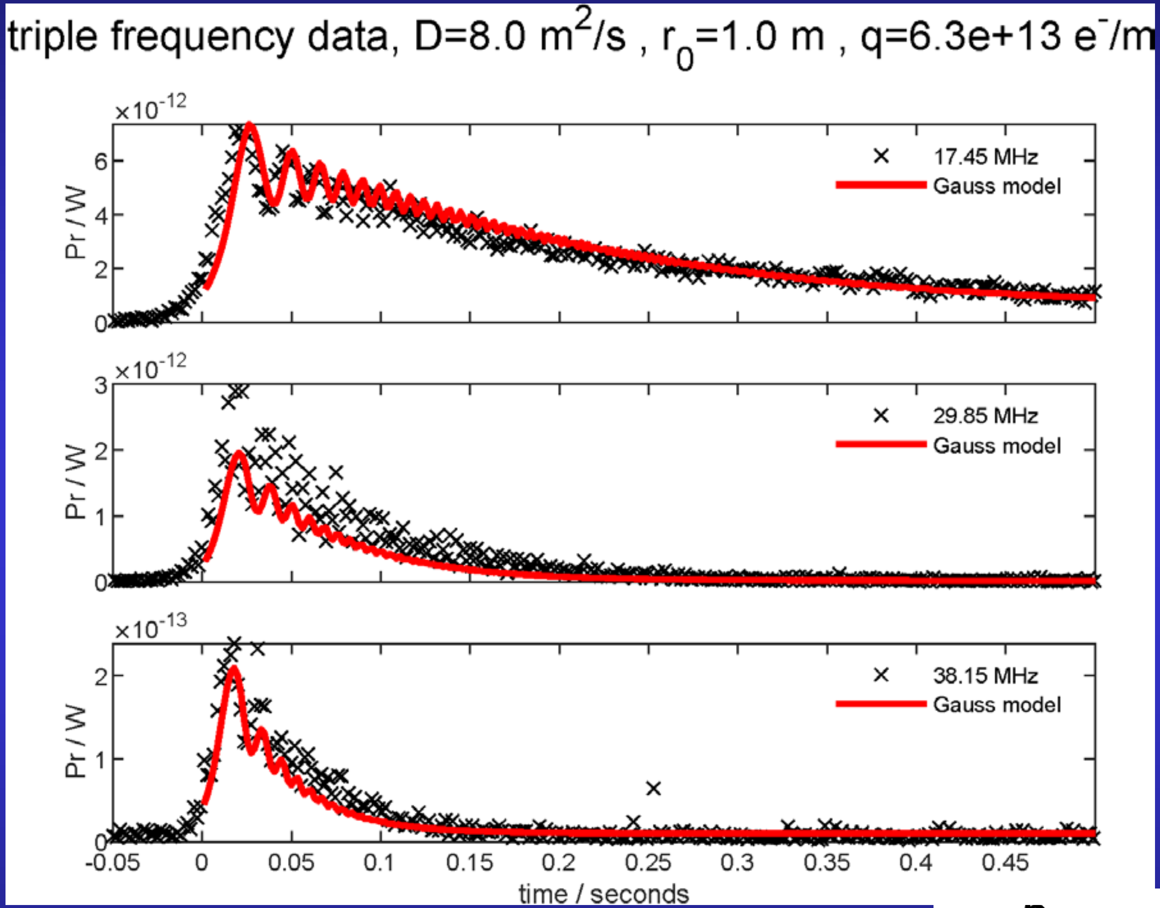
Comparison to CMOR triple frequency data





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Conclusion

- knowledge of ambipolar diffusion of scattering process could improve atmospheric observations
- MAARSY specular meteor experiment gets close to micrometeor limit for slow meteoroids (<20 km/s)
- full wave scattering model of trails for different plasma distribution
- dependence of signal morphology on scattering angle (angle between trajectory and incident electro-magnetic wave) – very essential to estimate diffusion and decay time
- resonance effects exists
- successful fitting of reflection coefficients obtained from full wave scattering model with triple frequency data from CMOR

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