Dark Matter Halo Effects on the X-ray Pulsar Pulse Profiles

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Introduction

- The existence of dark matter (DM) has been well established
- The latest experimental results with Earth-based detectors are not conclusive
- Neutron stars (NSs) might capture DM particles due to their high density
- Different dark matter models have different effects on compact stars

→ Study dark matter admixed neutron stars (DANS)

Structure of DANS

- Tolman-Oppenheimer-Volkoff (TOV) equations

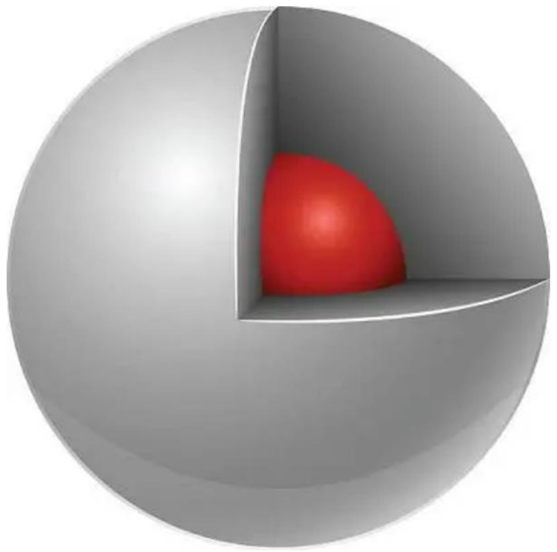
$$\frac{dm_i}{dr} = 4\pi r^2 \epsilon_i$$

$$\frac{dp_i}{dr} = \frac{4\pi r^3 p + m}{r^2(1 - 2m/r)}(\epsilon_i + p_i)$$

p_{BM} for baryonic matter and p_{DM} for dark matter

Two free parameters: $p_{\mathrm{DM}}^{\mathrm{c}}$ and $p_{\mathrm{BM}}^{\mathrm{c}}$

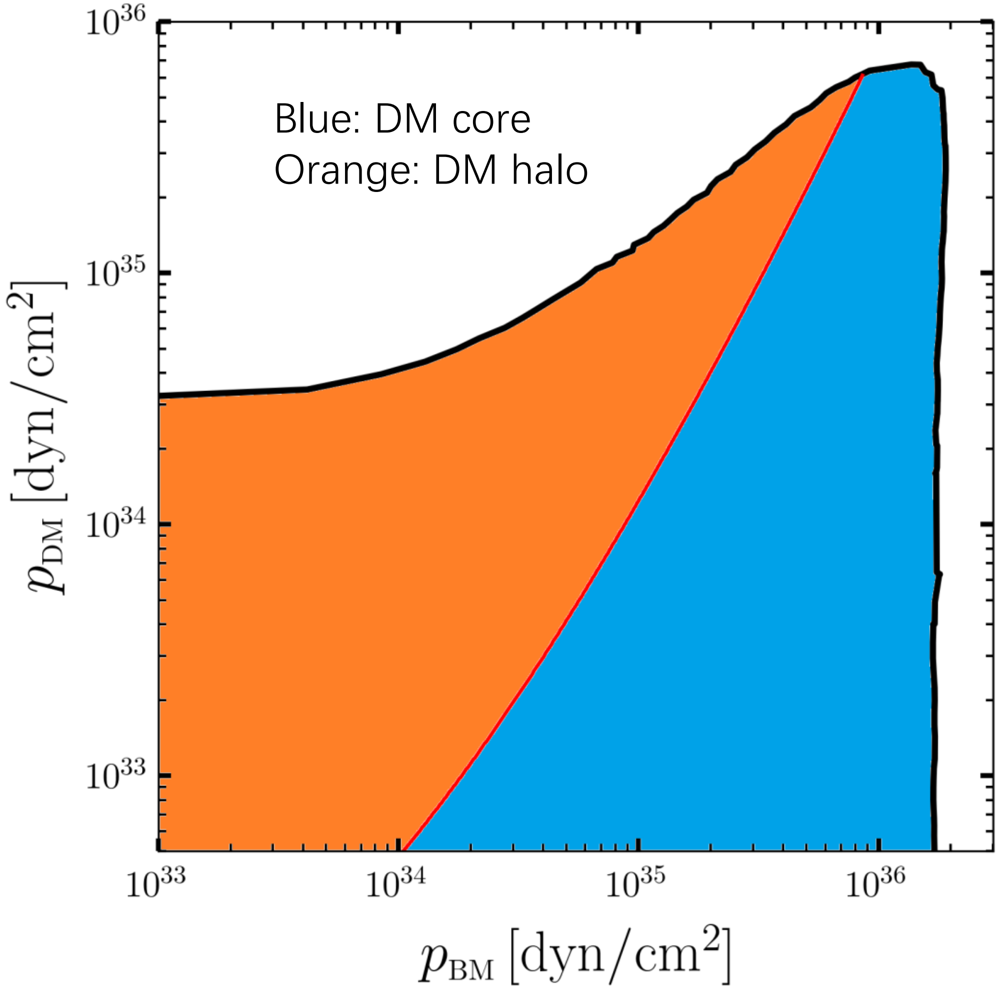
DM: Free Fermi gas model

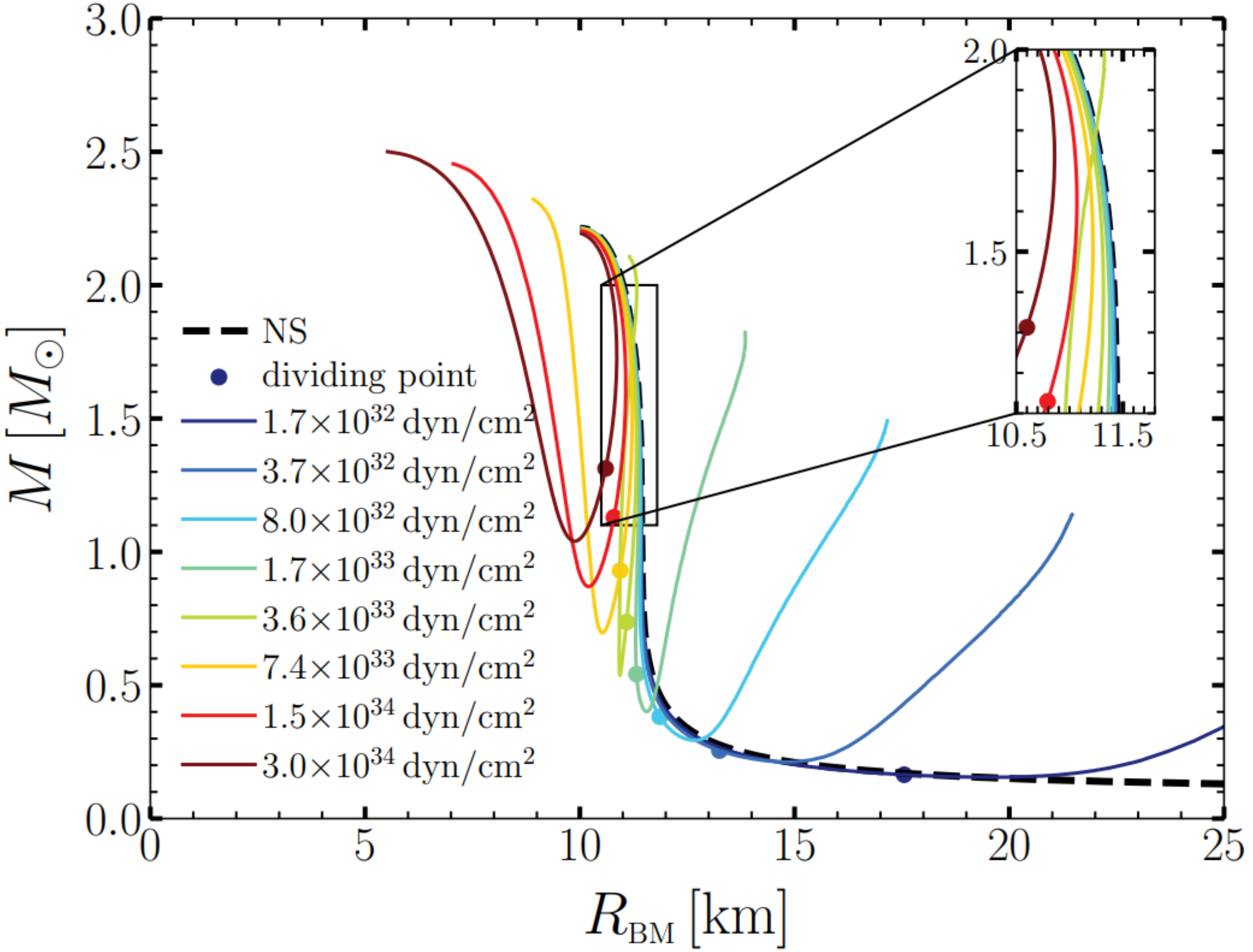


Credit: https://image.google.com

Mass-Radius Diagrams

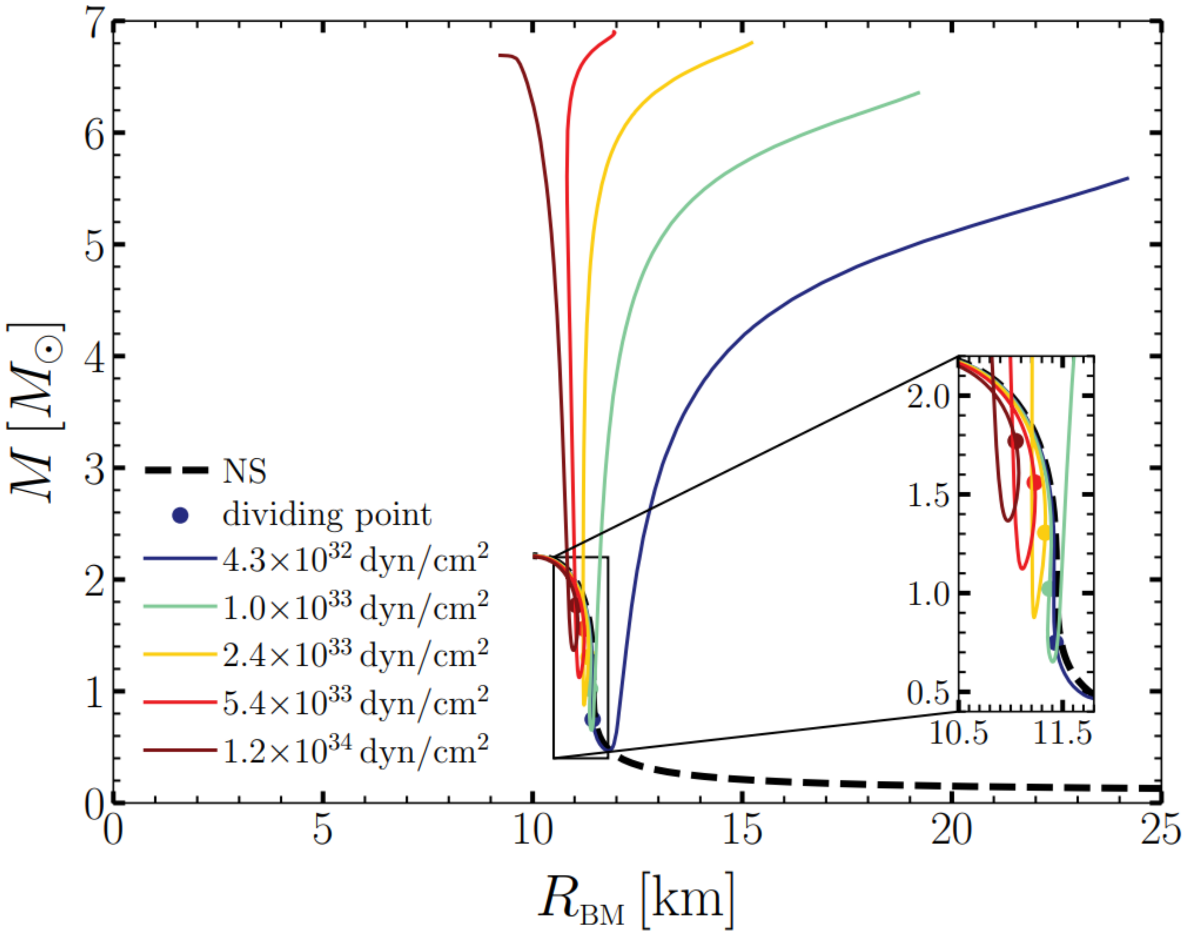
$m_f = 0.5$ GeV



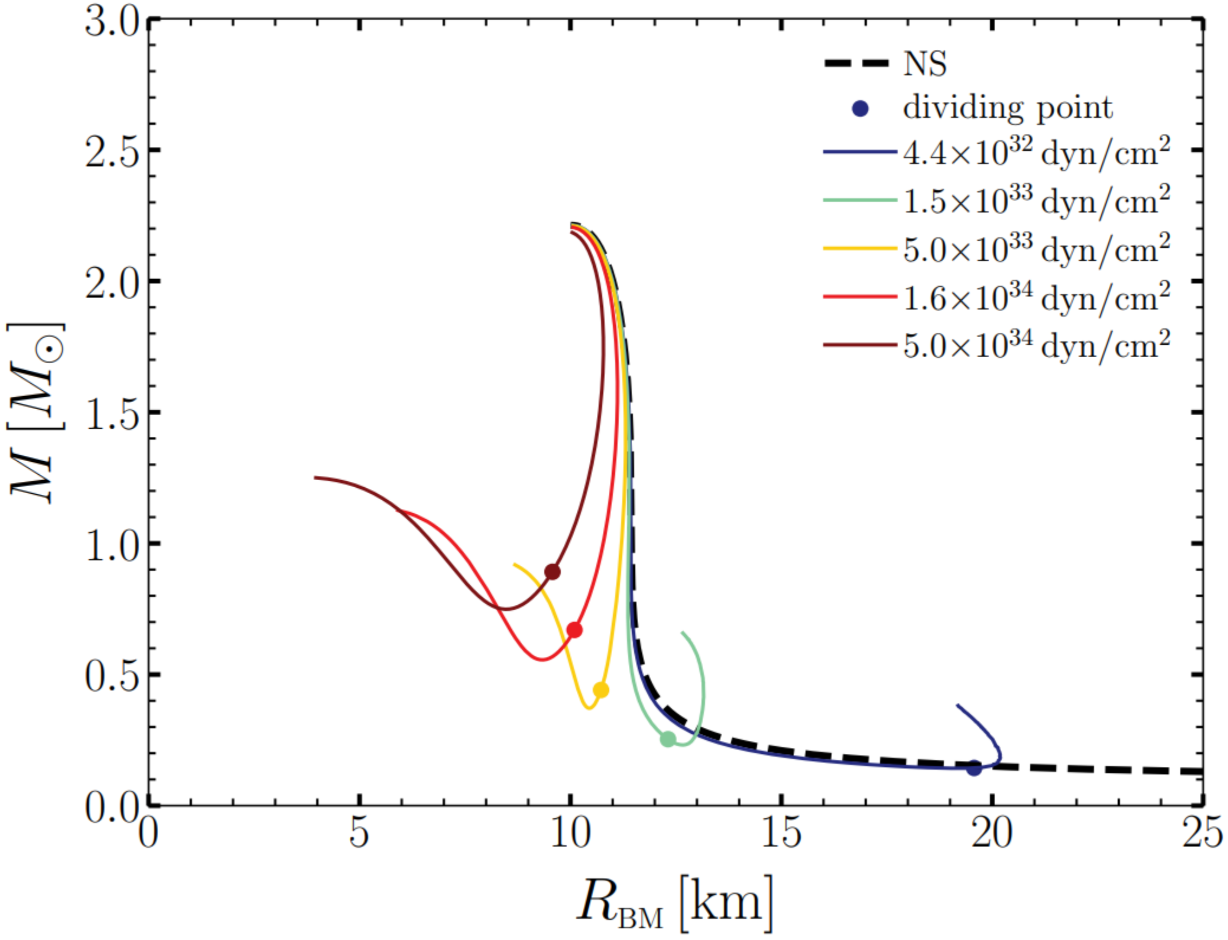


Mass-Radius Diagrams

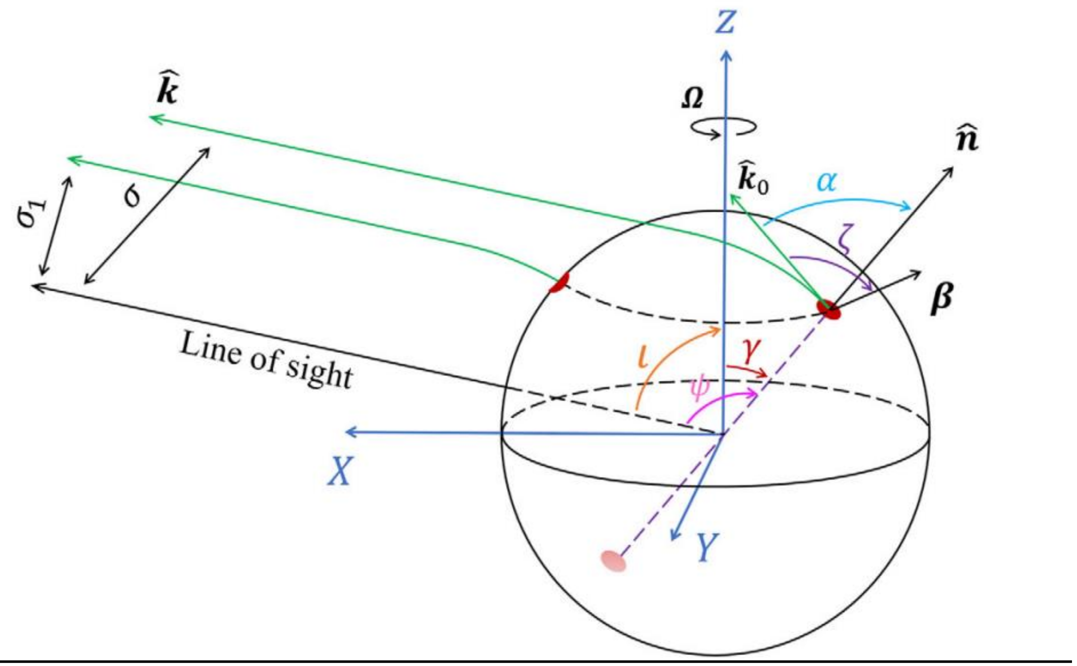
$m_f = 0.3$ GeV



$m_f = 0.7$ GeV



Pulsar Pulse Profile



Credit: Rui Xu, Yong Gao, and Lijing Shao (2020)

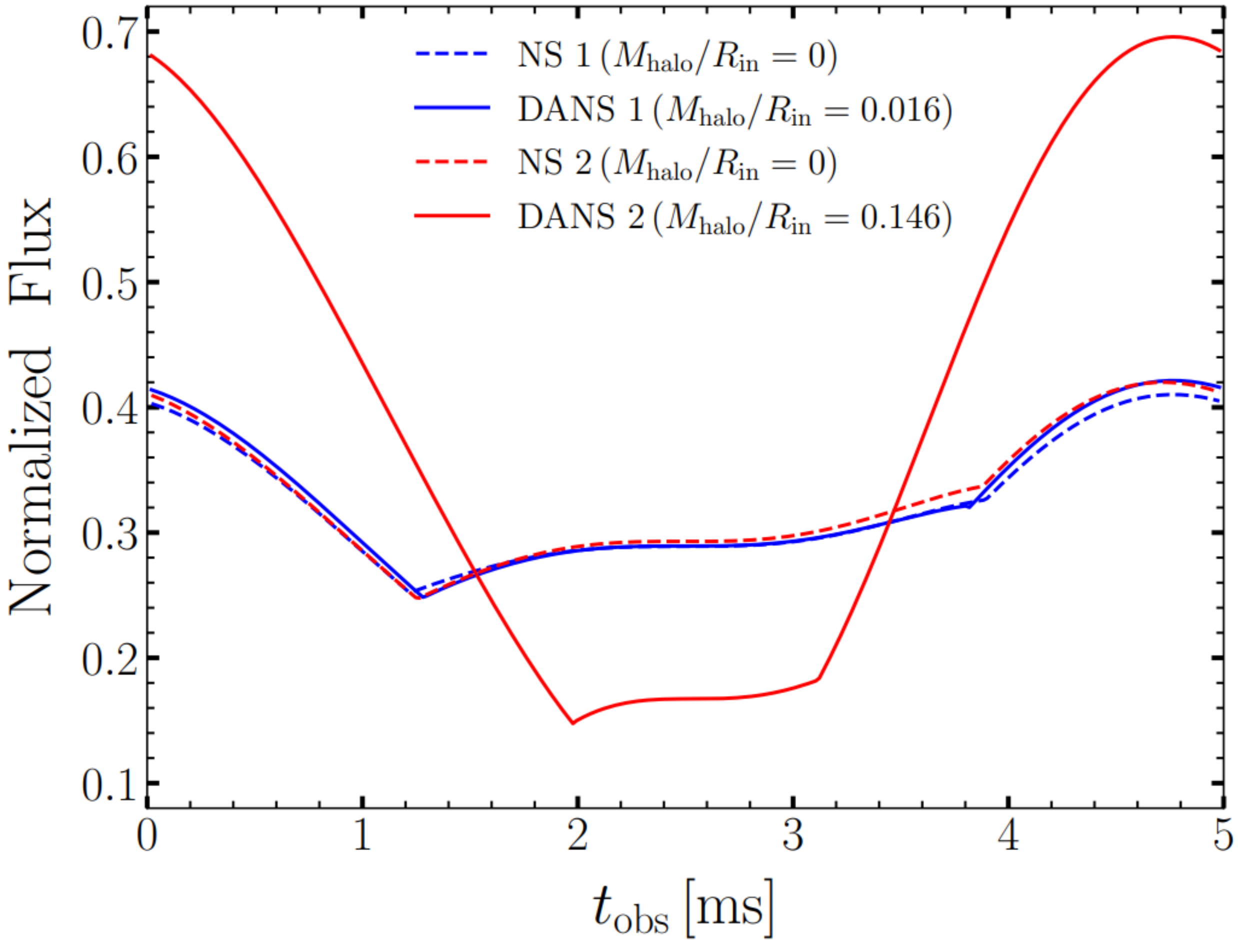
Schematic illustration for the X-rays emitted from a hot spot on a rotating NS and reaching the observer at infinity. We will summarize the derivation for the observed flux F at infinity with this picture.

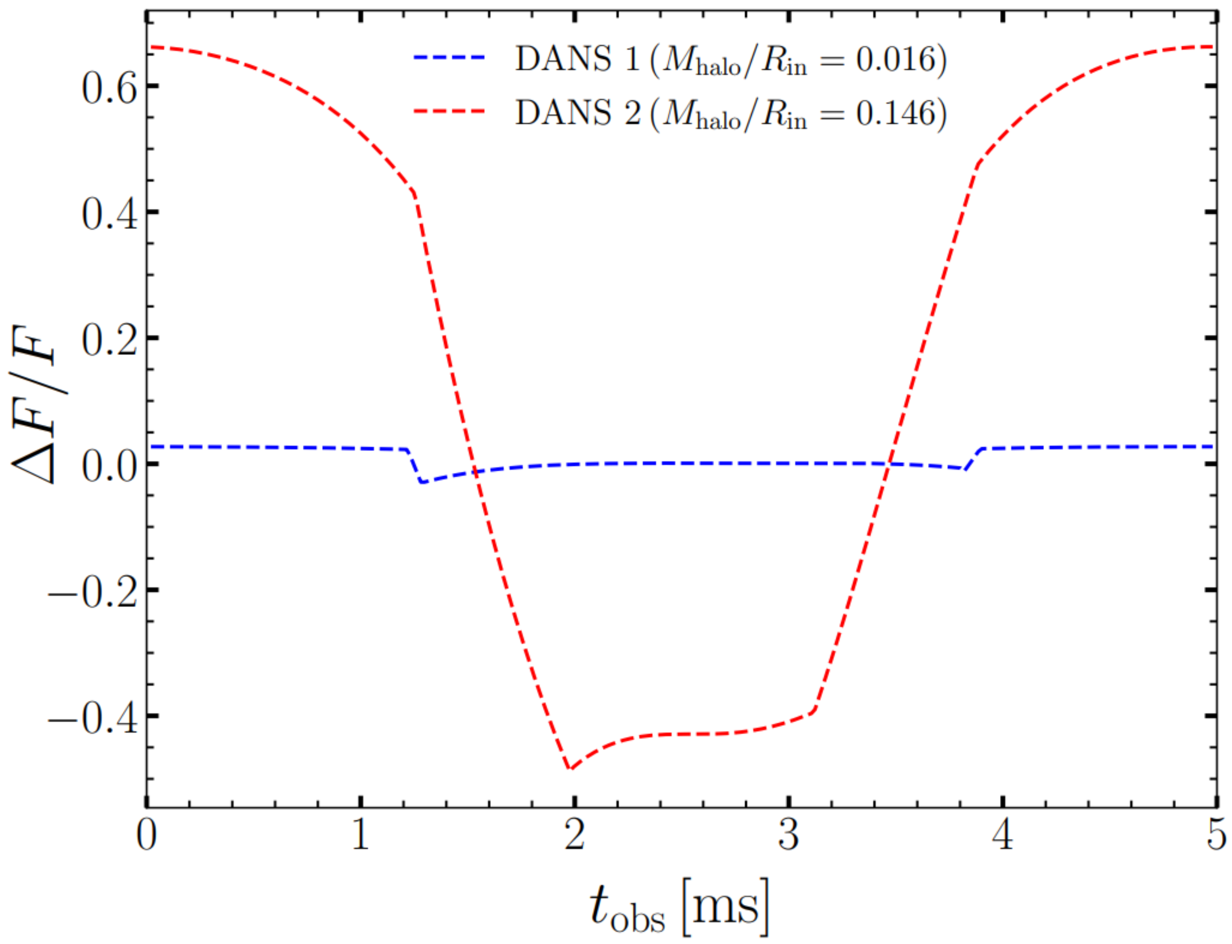
Fixing $\gamma = \pi/4$, $\iota = \pi/4$, $T = 5$ ms.

Model	$R_{\mathrm{in}}/\mathrm{km}$	$R_{\mathrm{out}}/\mathrm{km}$	$M/M_{\odot}$	$M_{\mathrm{dm}}/M_{\odot}$	$M_{\mathrm{halo}}/M_{\odot}$	$M_{\mathrm{halo}}/R_{\mathrm{in}}$
DANS1	9.5	16.9	1.2	0.44	0.11	0.016
NS1	9.5	9.5	1.2	0	0	0
DANS2	11.5	51.5	1.4	1.27	1.14	0.146
NS2	11.5	11.5	1.4	0	0	0

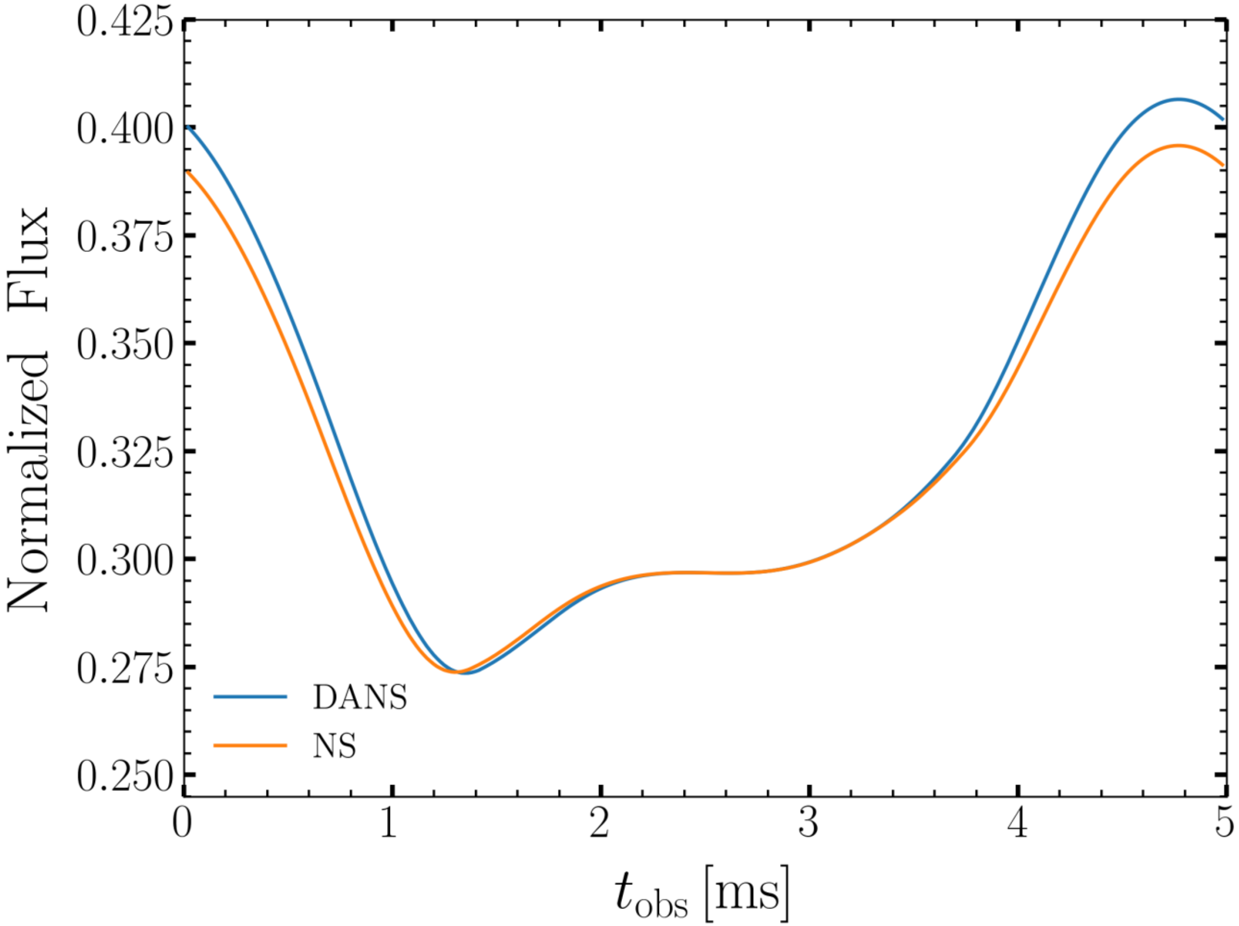
Numerical Results

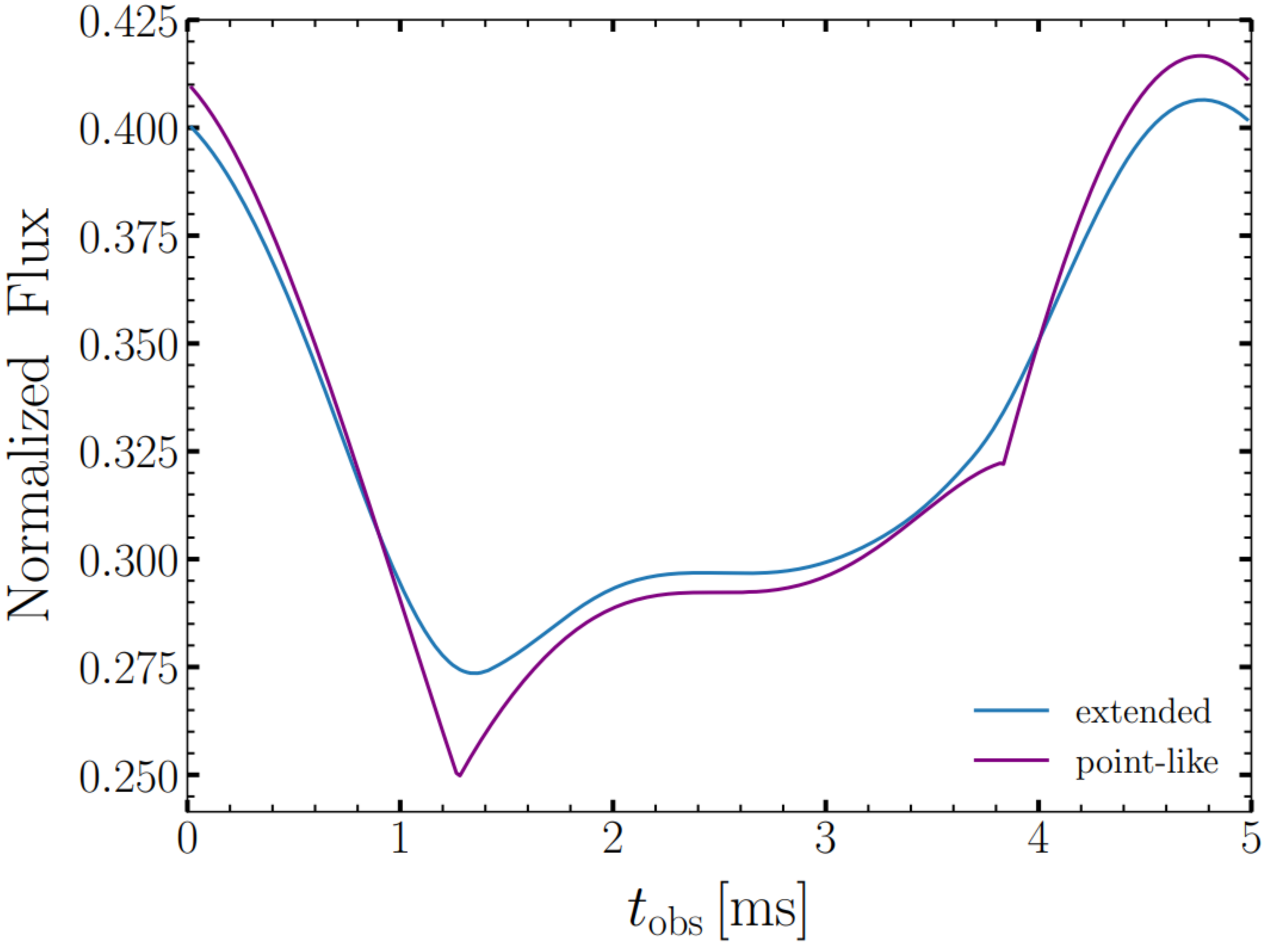
The normalized flux is as follows:



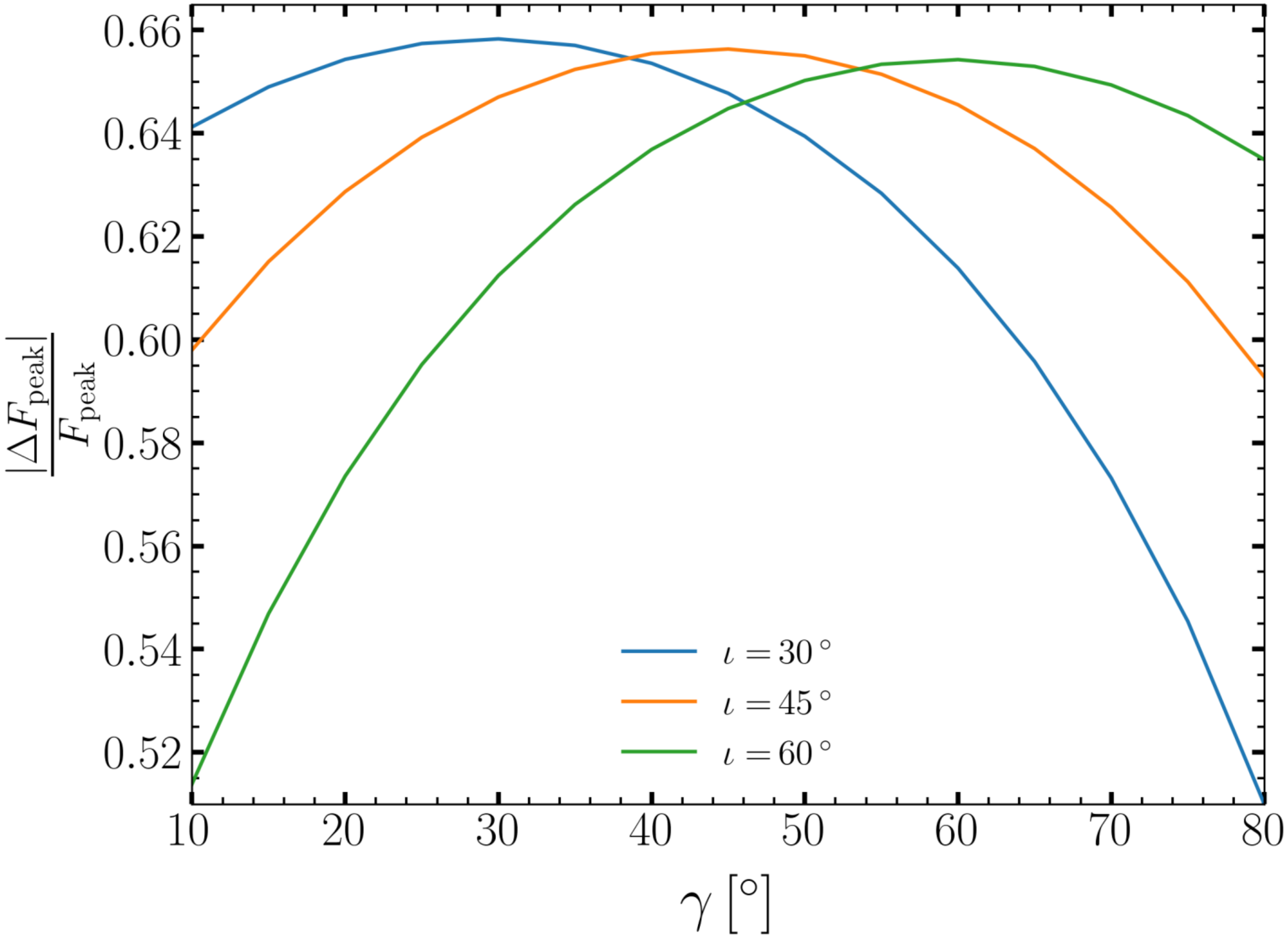


Here we also consider more realistic extended hot spots of radius 3 km. Take DANS1 and NS1 as an example.



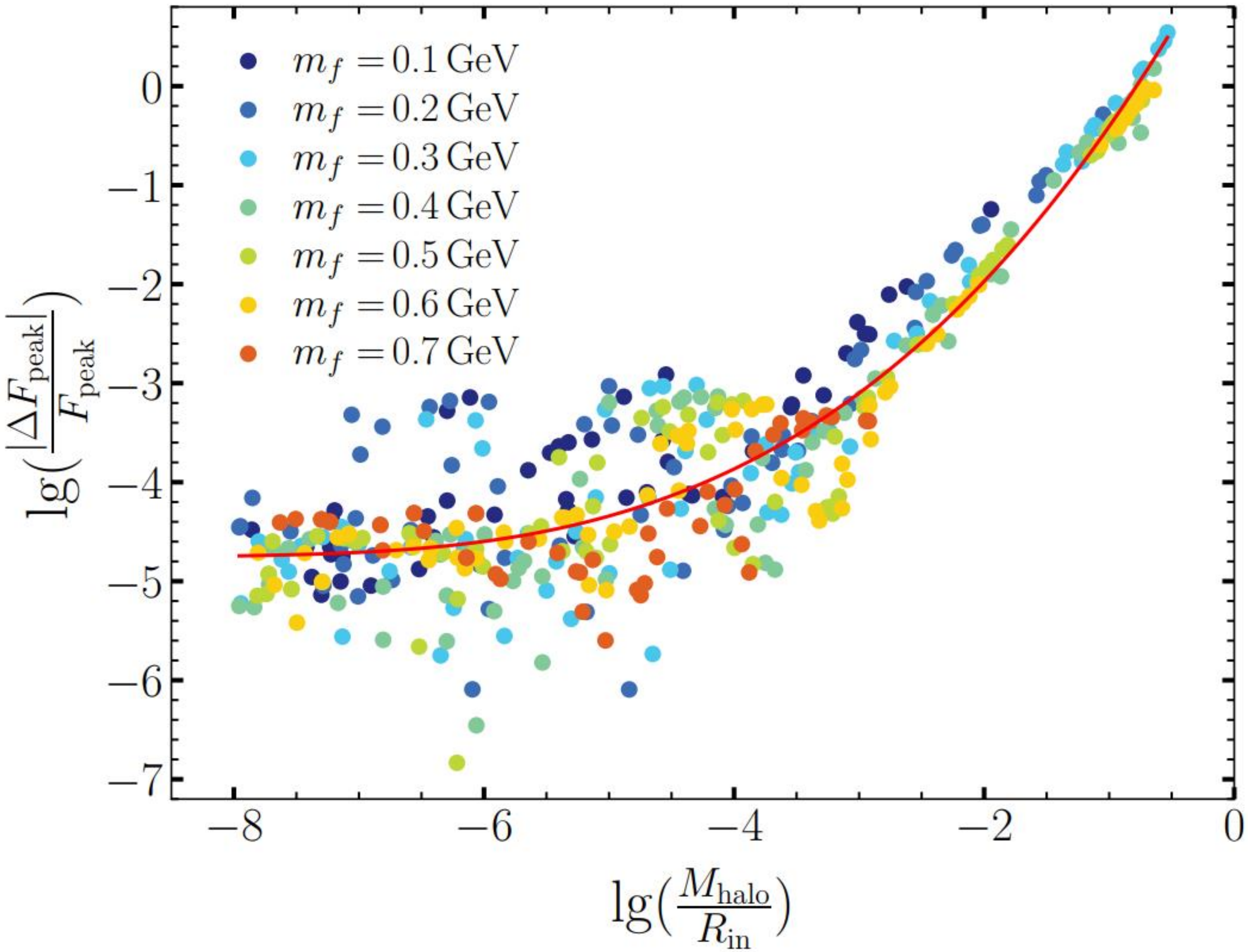


Numerical Results



Then we study the influence of colatitude of light source γ and the inclination angle of the line of sight ι to the peak flux deviation. The comparison is between DANS2 and NS2. The deviation is the biggest when $\gamma = \iota$.

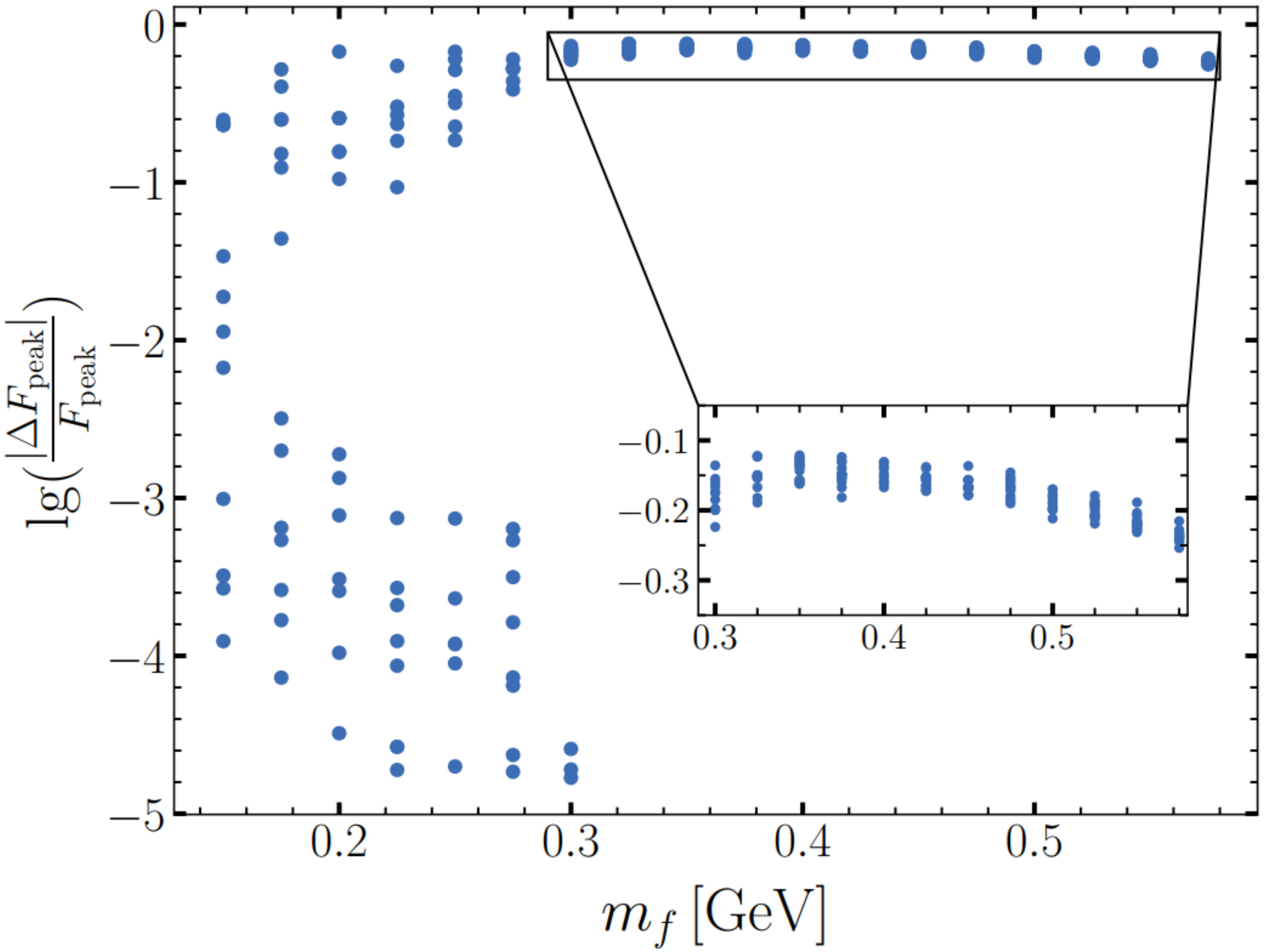
Numerical Results



We found that the modification of the peak flux is highly dependent on the quantity $M_{\mathbf{halo}}/R_{\mathbf{in}}$. All of the randomly chosen data points can be can be fitted with a cubic function.

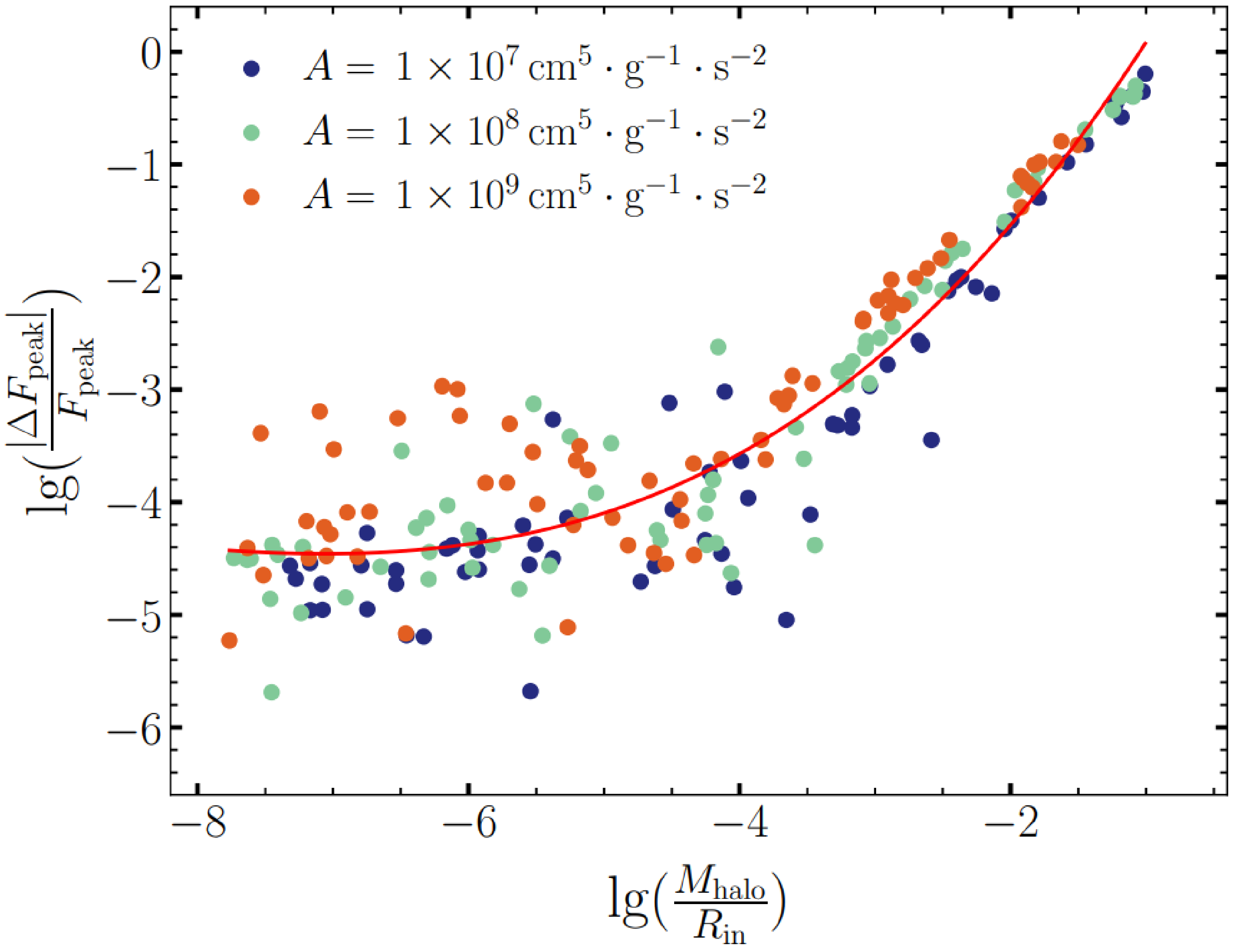
$$f_F(x) = 0.012x^3 + 0.290x^2 + 2.351x + 1.667$$

Numerical Results



Then we study how dark matter halos affect pulsar pulse profiles with typical NS mass and radius. Here we randomly choose DANSs with $M \in [1.37, 1.43]\ M_{\odot}$, $R_{\rm in} \in [11.2, 11.6]$ km.

Numerical Results



More generally, we extend our research to bosonic DM. By analyzing both the mathematical expressions and the corresponding figures, we observe striking similarities that underscore the generality of our results.

$$f_B(x) = 0.010x^3 + 0.270x^2 + 2.364x + 2.190$$

Conclusion

- we analyze the structure of DANSs in a two-fluid model and construct the mass-radius diagram
- we investigate the impact of DM halos on pulsar pulse profiles
- we establish a cubic functional relation between the variation of the X-ray flux and the dimensionless quantity $M_{\mathrm{halo}}/R_{\mathrm{in}}$, which validates for both fermionic and bosonic DM

Thanks for Listening

Ben Kain, Dark matter admixed neutron stars.

Zhiqiang Miao, Yaofeng Zhu, Ang Li, and Feng Huang, Dark matter admixed neutron star properties in the light of X-ray pulse profile observations.

Rui Xu, Yong Gao, and Lijing Shao, Strong-field effects in massive scalar-tensor gravity for slowly spinning neutron stars and application to x-ray pulsar pulse profiles.