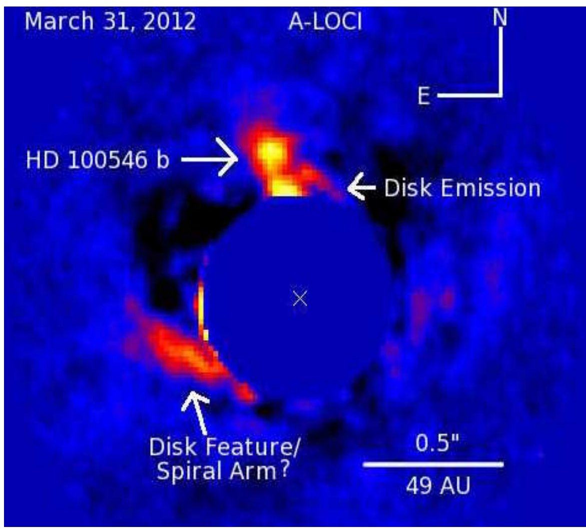
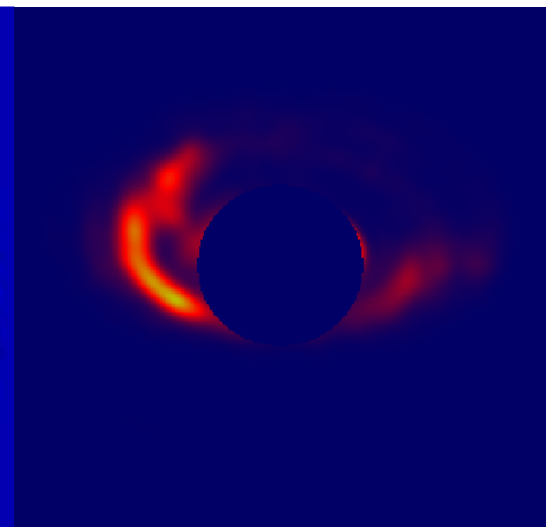
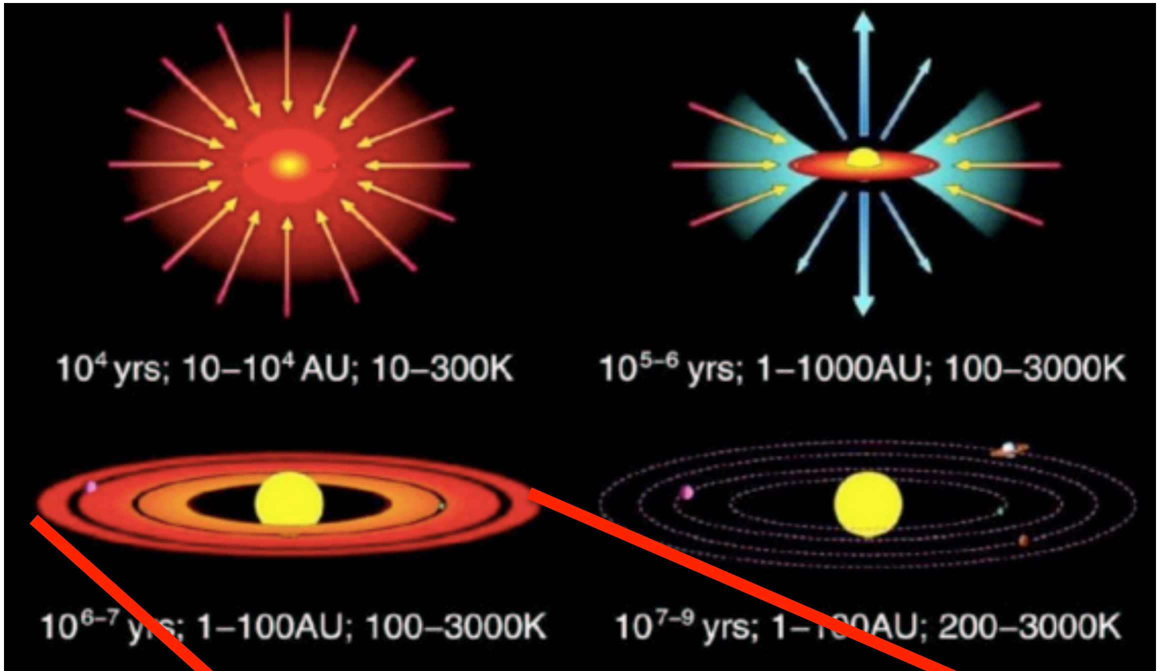
High Mass Planet Spiral Shocks as a Source of Infrared Emission in Protoplanetary Disks



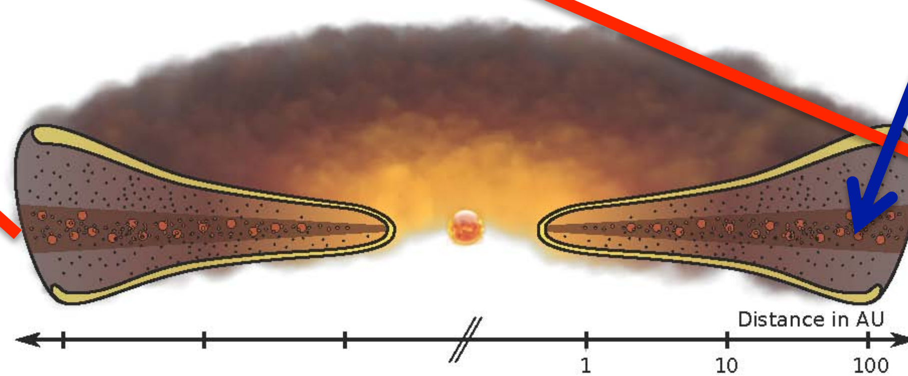


Blake Hord

Background – Planet Formation



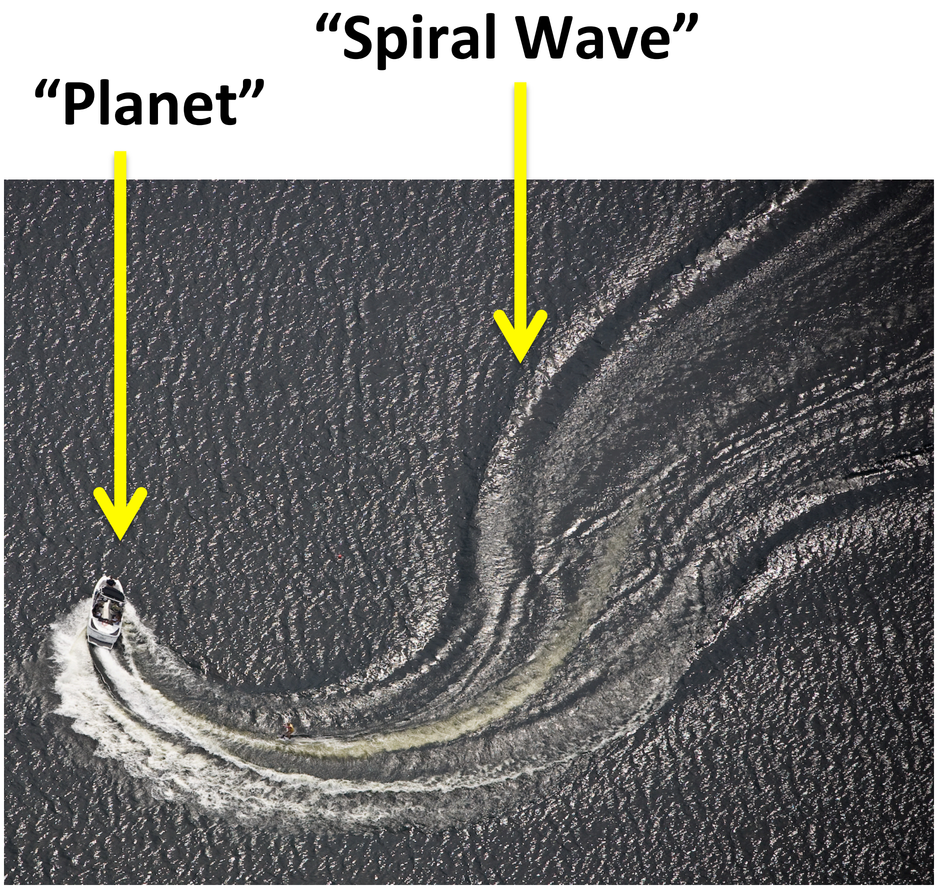
Midplane –
Area of planet formation

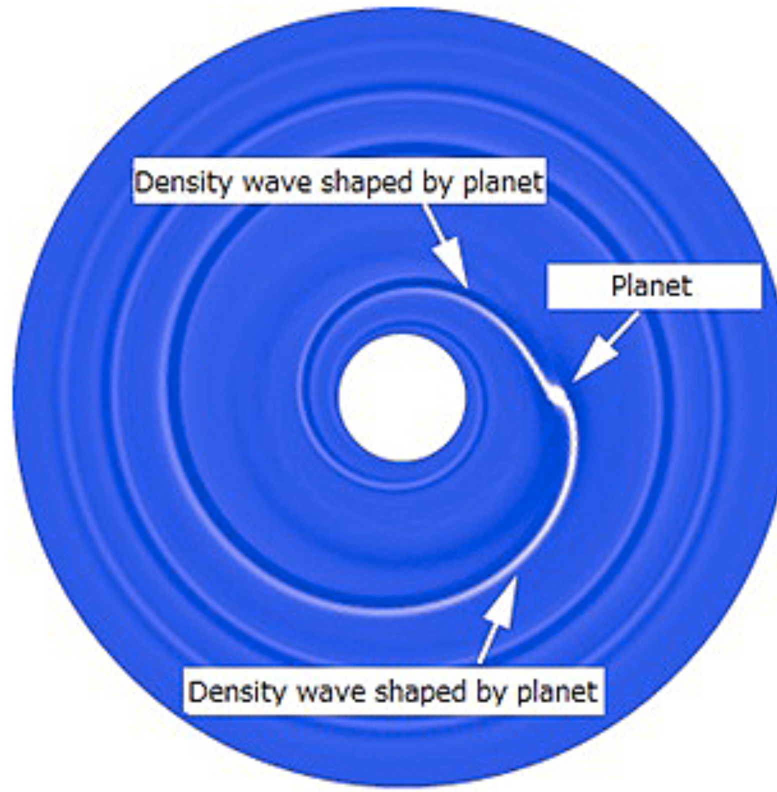


Shu, F. H., Adams, F. C., & Lizano, S. (1987). Star formation in molecular clouds-Observation and theory. *Annual review of astronomy and astrophysics*, *25*, 23-81.

Birnstiel, Til. Sketch of a Disk with Length Scale. Digital image. Til Birnstiel. N.p., n.d. Web. 15 Sept. 2016.

Background – Planet Spirals



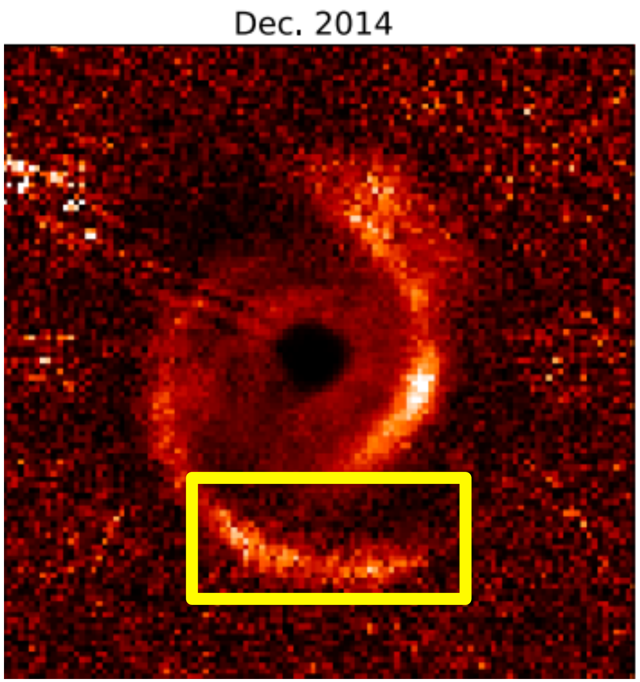


Boat Wake Aerial Zig. (n.d.). Retrieved October 23, 2016, from https://www.pinterest.com/pin/50876670765983672/

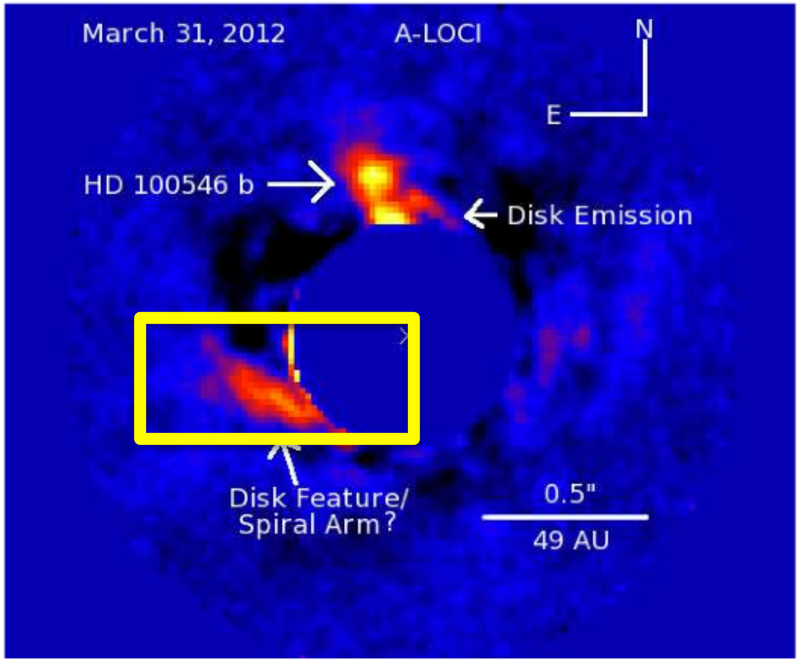
NAOJ. (2012, December 19). Spiral Structure of Disk May Reveal Planets. Retrieved October 23, 2016, from http://subarutelescope.org/Pressrelease/2012/04/11/fig3e.jpg

Background – Observable Wide Spirals

MWC 758



HD 100546



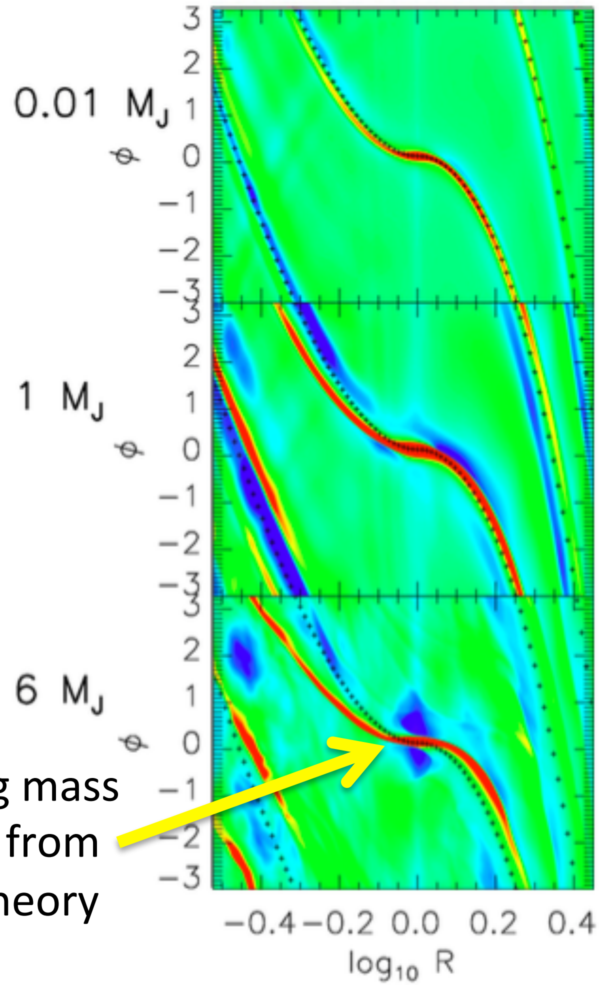
Spirals **hotter (300K)** than ambient gas (50K)

Disk feature not polarized **thermal emission**

Benisty, M., Juhasz, A., Boccaletti, A., Avenhaus, H., Milli, J., Thalmann, C., ... & Beuzit, J. L. (2015). Asymmetric features in the protoplanetary disk MWC 758. *Astronomy & Astrophysics*, *578*, L6.

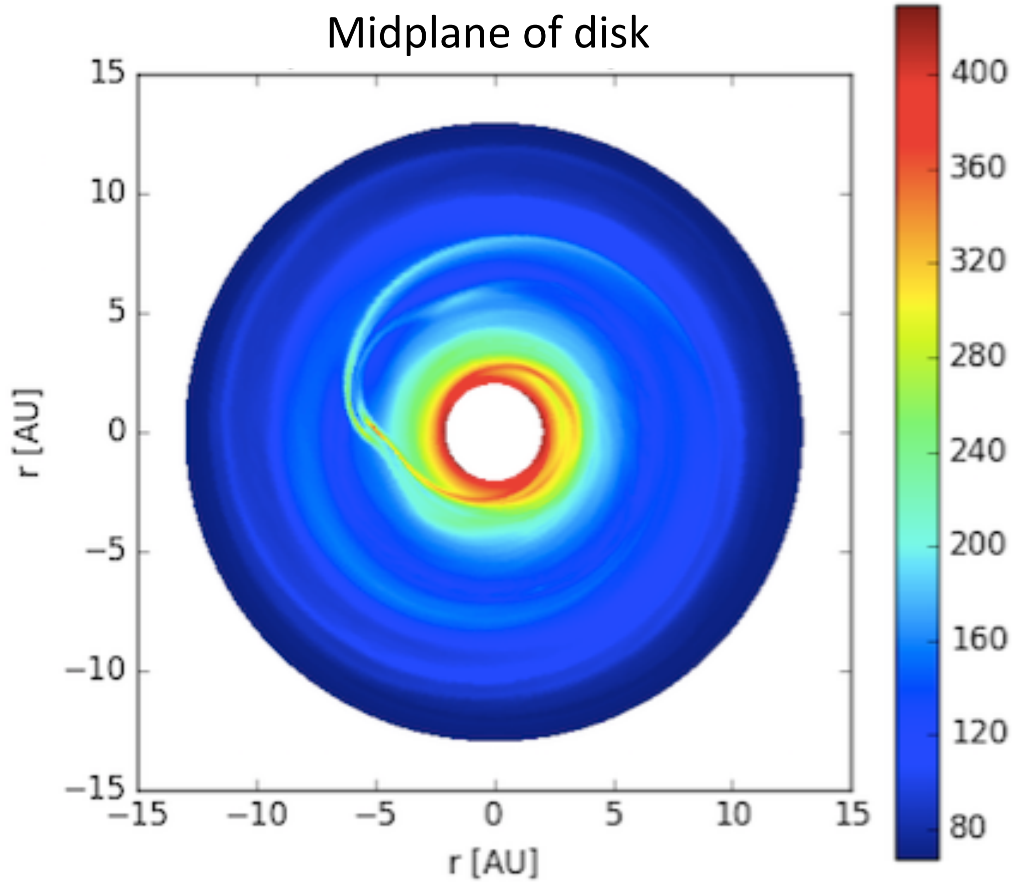
Currie, T., Muto, T., Kudo, T., Honda, M., Brandt, T. D., Grady, C., ... & McElwain, M. W. (2014). Recovery of the candidate protoplanet HD 100546 b with Gemini/NICI and detection of additional (planet-induced?) disk structure at small separations. *The Astrophysical Journal Letters*, *796*(2), L30.

Background – Supersonic Wakes



Increasing mass deviates from Linear Theory

Density



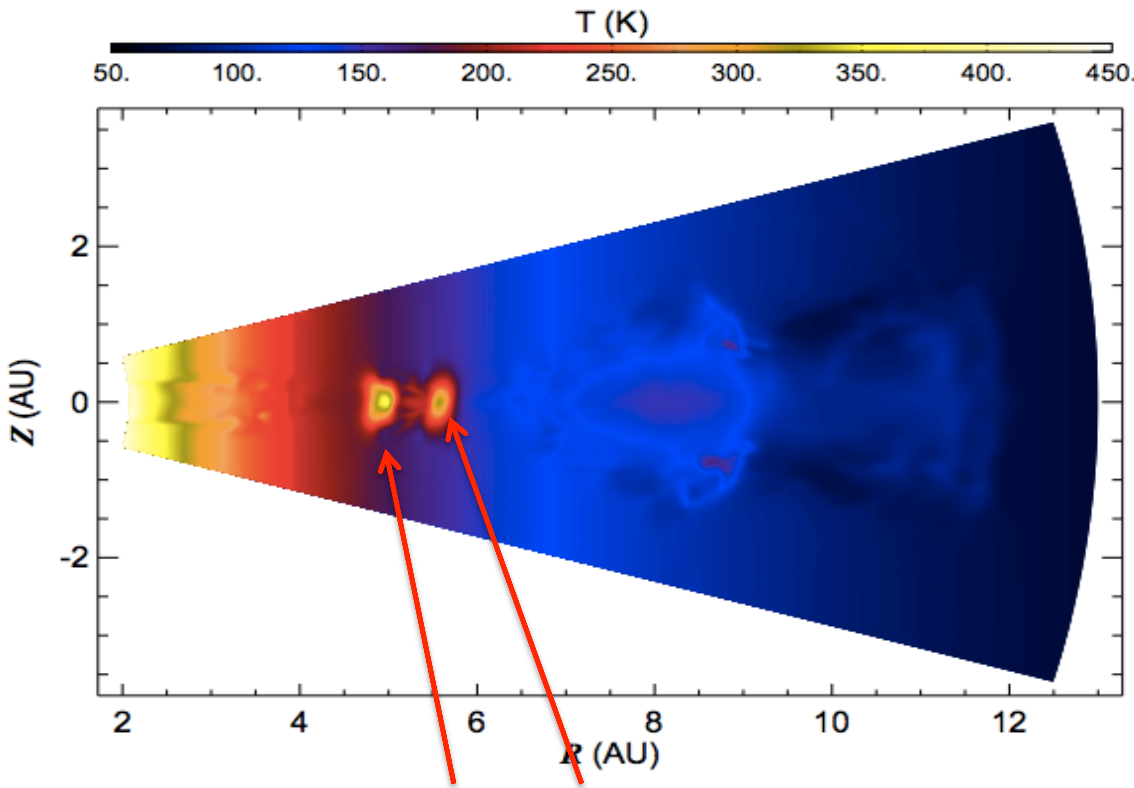
Temperature - **5M_J**

Zhu, Z., Dong, R., Stone, J. M., & Rafikov, R. R. (2015). The Structure of Spiral Shocks Excited by Planetary-mass Companions. The Astrophysical Journal, 813(2), 88.

Lyra, W., Richert, A. J., Boley, A., Turner, N., Mac Low, M. M., Okuzumi, S., & Flock, M. (2016). On shocks driven by high-mass planets in radiatively inefficient disks. II. Threedimensional global disk simulations. *The Astrophysical Journal*, *817*(2), 102.

Lyra et al. (2016)

Cross-section of Disk



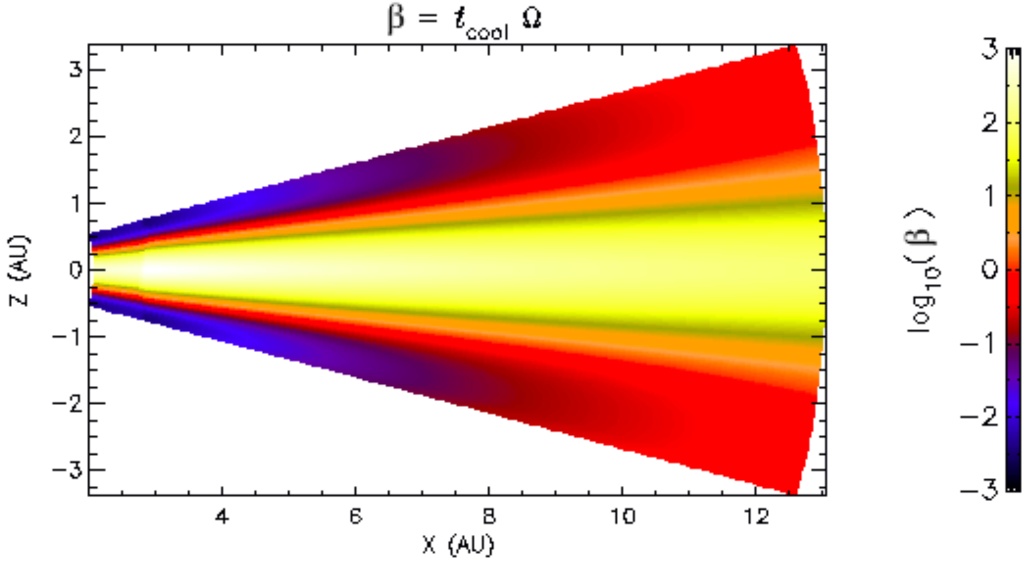
~450 K

High Temperature regions inwards and outwards from planet at 5.2 AU

Lyra, W., Richert, A. J., Boley, A., Turner, N., Mac Low, M. M., Okuzumi, S., & Flock, M. (2016). On shocks driven by high-mass planets in radiatively inefficient disks. II. Threedimensional global disk simulations. *The Astrophysical Journal*, *817*(2), 102.

Lyra et al. (2016)

Cross-section of Disk

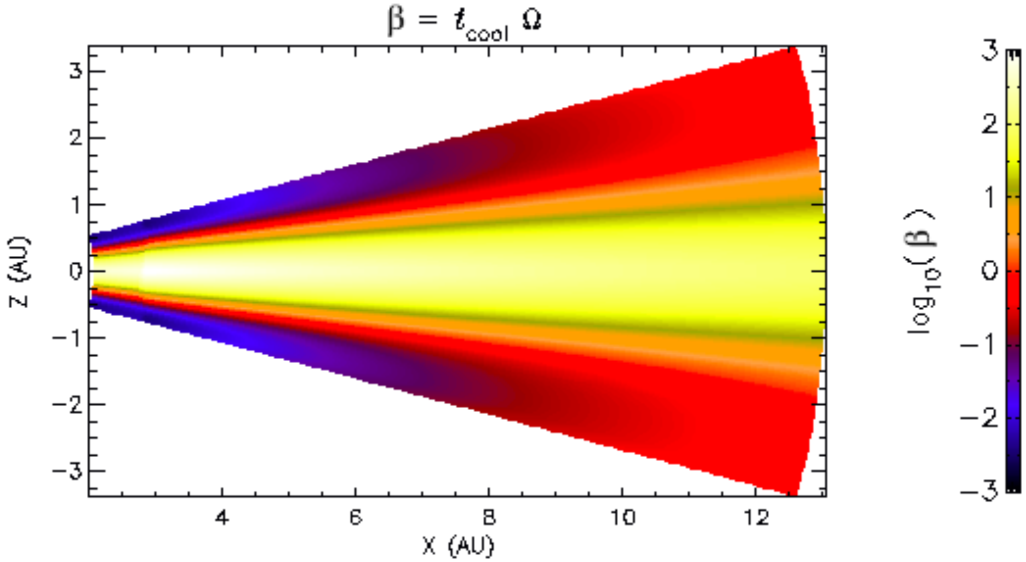


Adiabatic in the midplane
Isothermal in the atmosphere

Lyra, W., Richert, A. J., Boley, A., Turner, N., Mac Low, M. M., Okuzumi, S., & Flock, M. (2016). On shocks driven by high-mass planets in radiatively inefficient disks. II. Threedimensional global disk simulations. *The Astrophysical Journal*, *817*(2), 102.

Lyra et al. (2016)

Cross-section of Disk



Adiabatic in the midplane

Isothermal in the atmosphere

Uses on-the-fly Newton cooling function dependent on optical depth (for speed)

Lyra, W., Richert, A. J., Boley, A., Turner, N., Mac Low, M. M., Okuzumi, S., & Flock, M. (2016). On shocks driven by high-mass planets in radiatively inefficient disks. II. Threedimensional global disk simulations. *The Astrophysical Journal*, *817*(2), 102.

Problem Statement

Model of Lyra et al. (2016) has an **inaccurate cooling** function that prohibits a comparison of their model to observations of protoplanetary disks.

Goals

1. Run **Radiative Transfer** calculations on the Pencil Code output of Lyra et al. (2016)

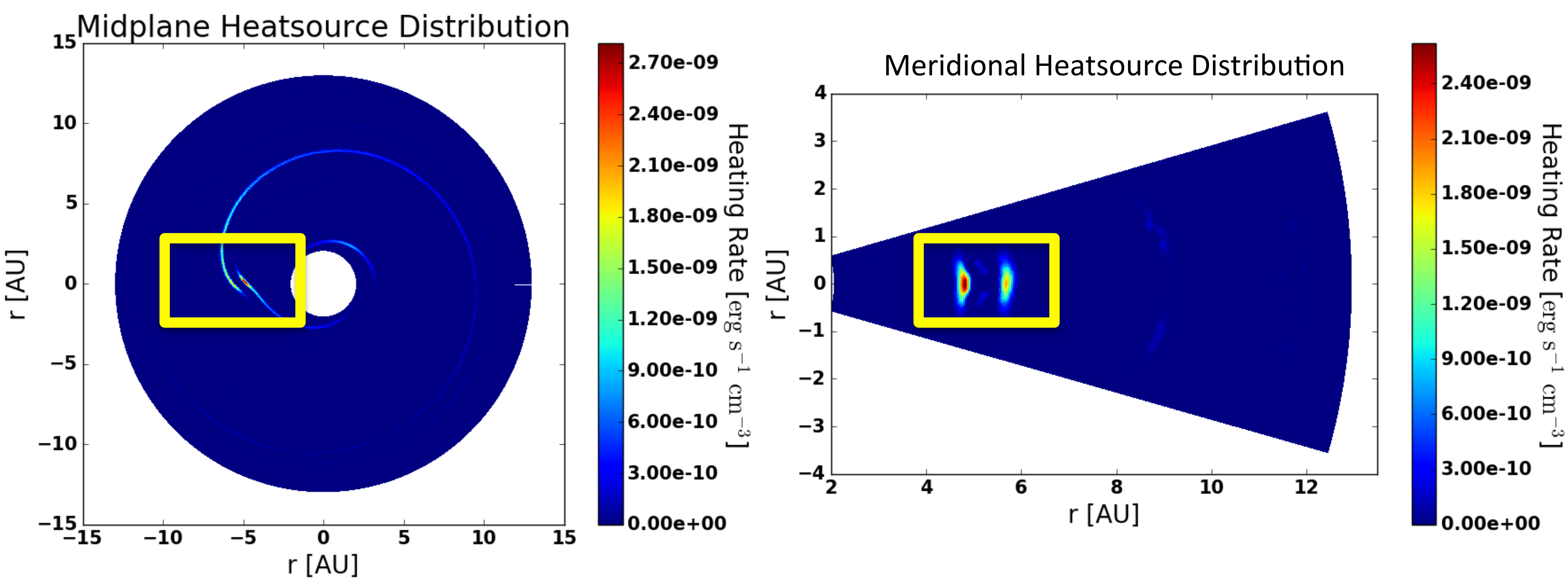
Determine **temperature spread** around high temperature regions in the midplane

2. Generate artificial **images** of resulting disk through ray-tracing

Determine whether simulation matches **observations**.

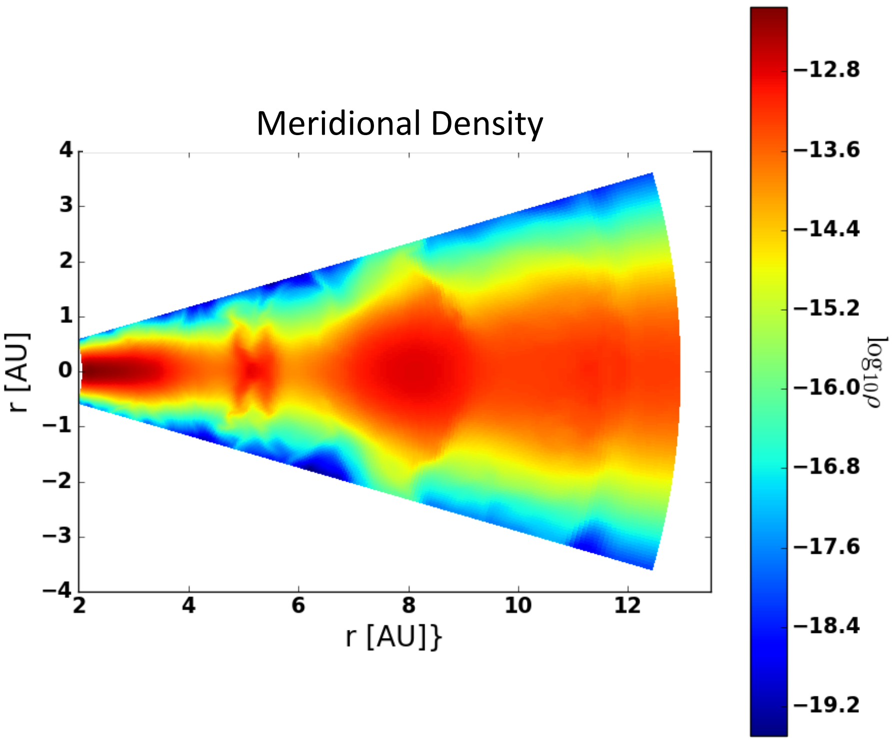
<u>**Methods** – RADMC-3D</u>

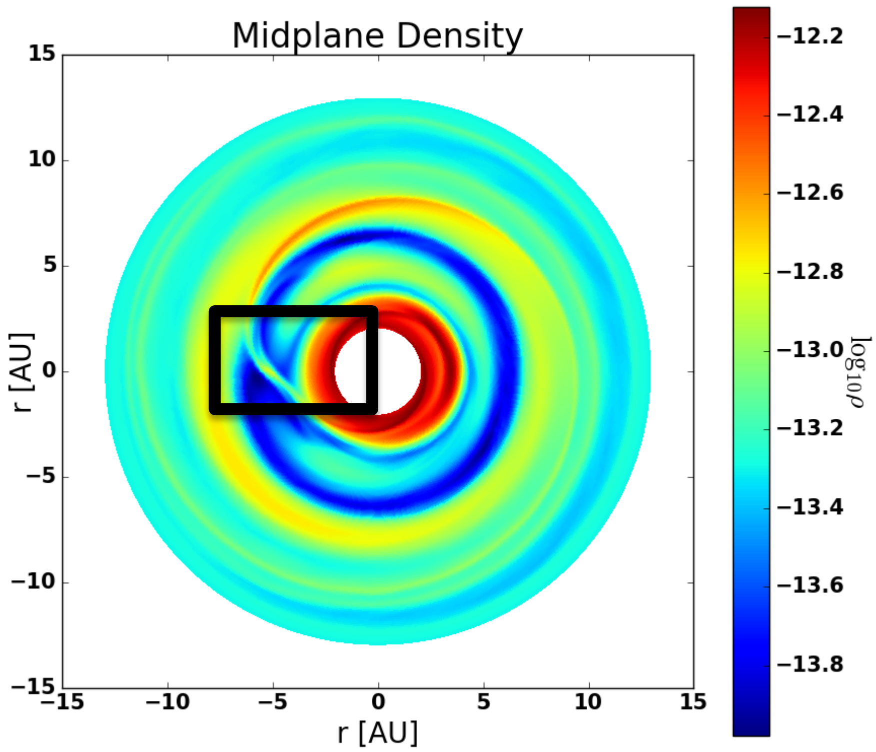
Radiative Transfer - **Shock heating**



Dullemond, C. P. (2012). RADMC-3D: A multi-purpose radiative transfer tool. *Astrophysics Source Code Library*, *1*, 02015.
Images generated by competition entrant

Methods – Pipeline Between Codes

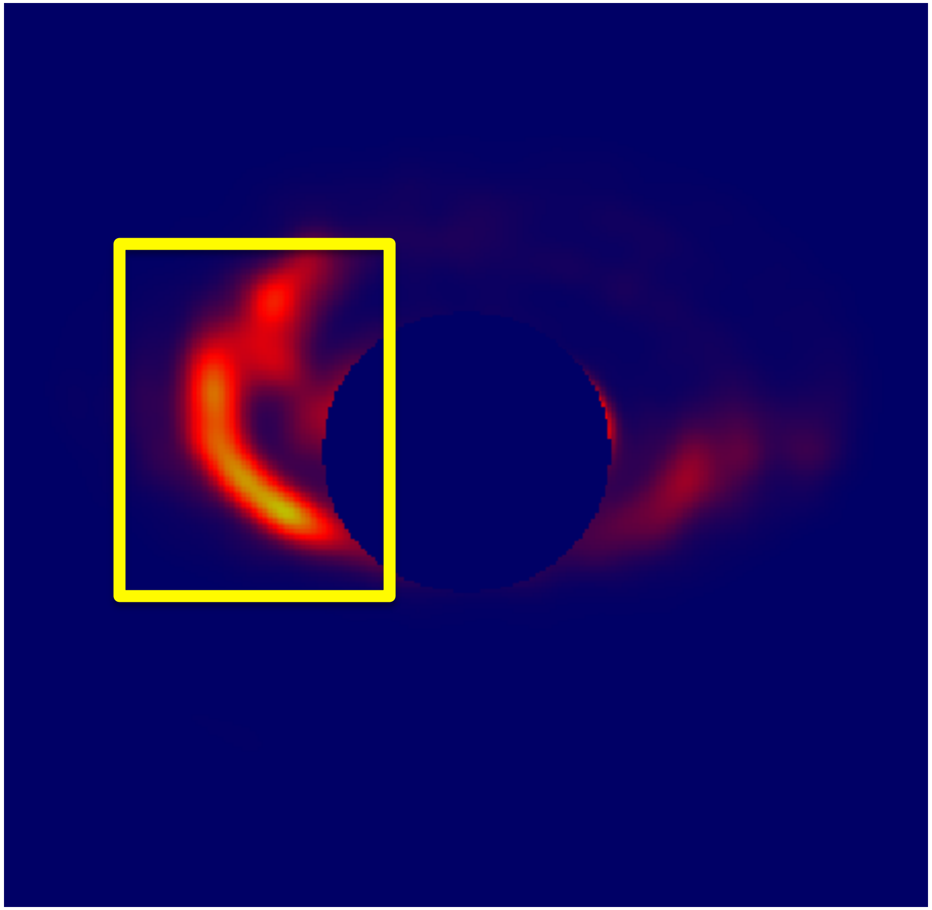




Input directly from the Pencil Code – new **pipeline** created

Images generated by competition entrant

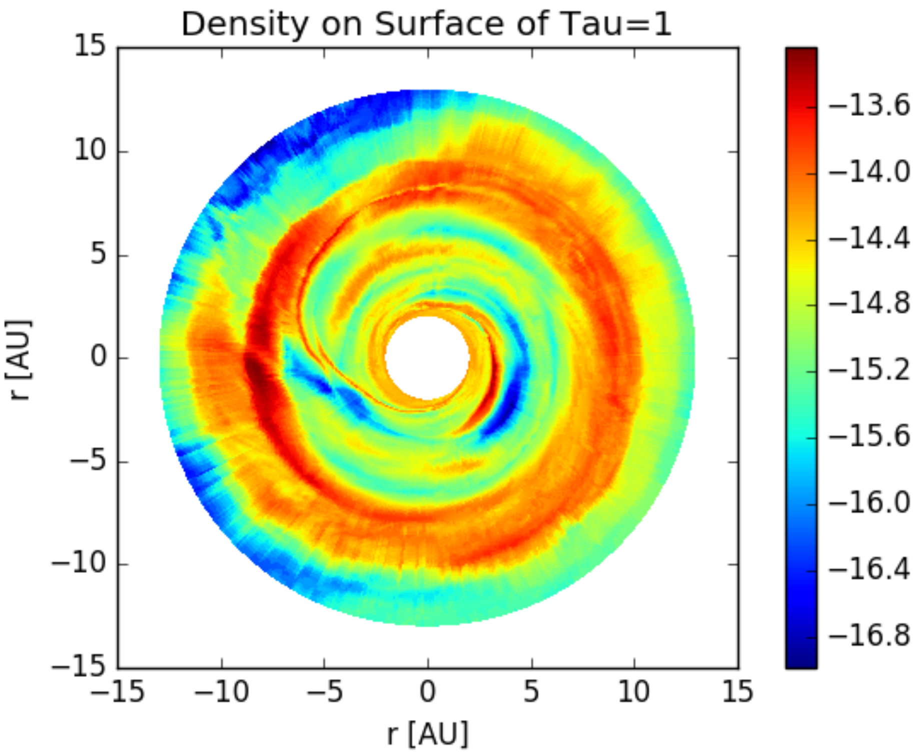
Results – Synthetic Image

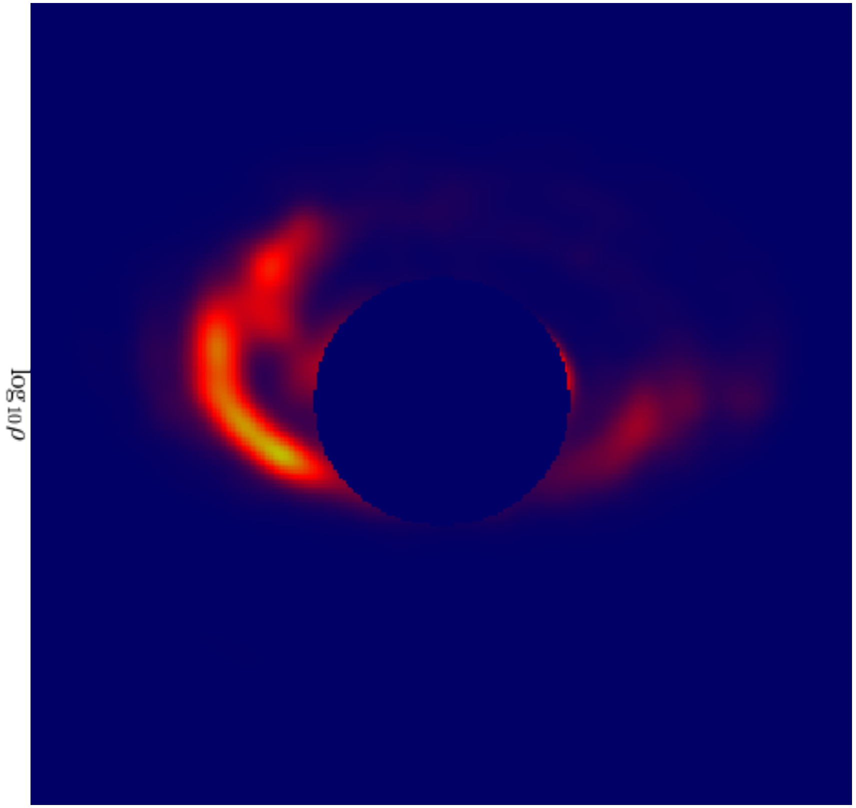


Made with position and inclination angles of HD 100546
50 degree inclination, 138 degree position

Images generated by competition entrant

Results – Scattering from High Density

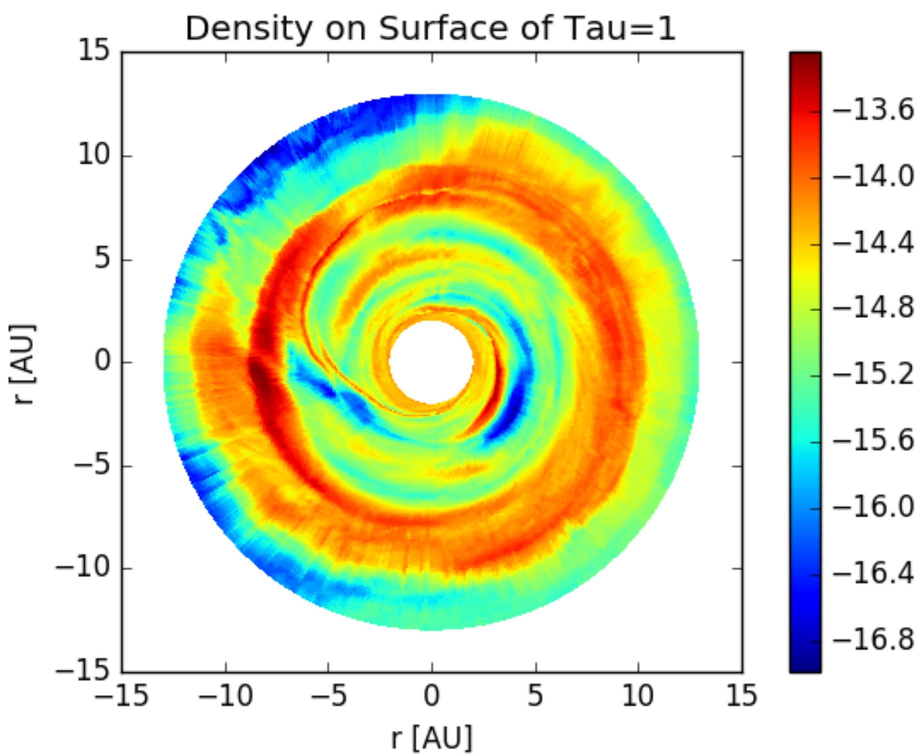


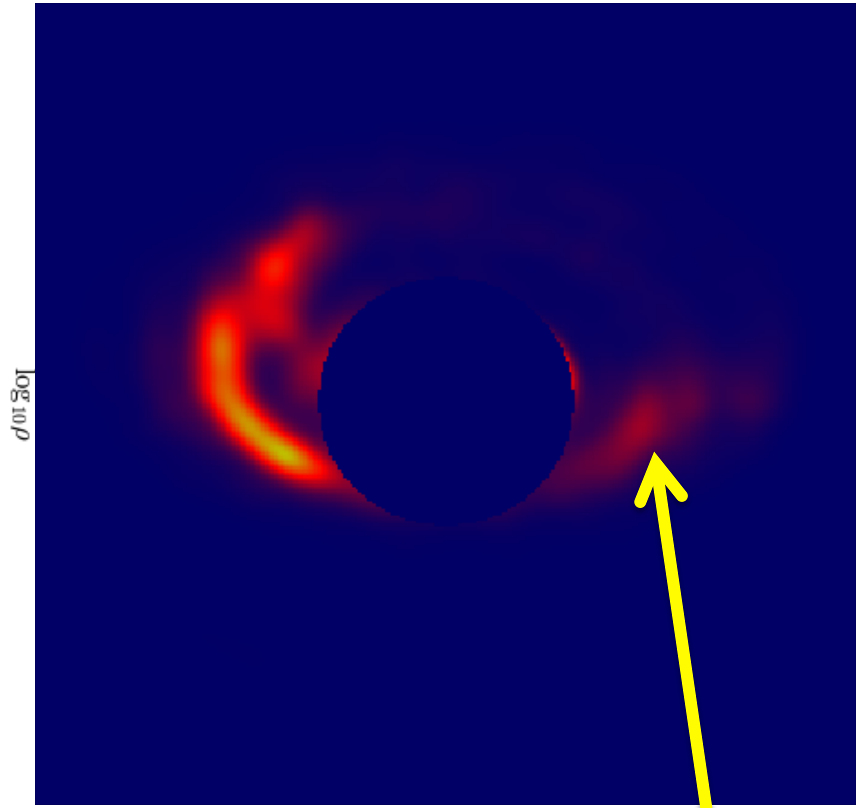


Scattering caused by high density dust

Images generated by competition entrant

Results – Scattering from High Density



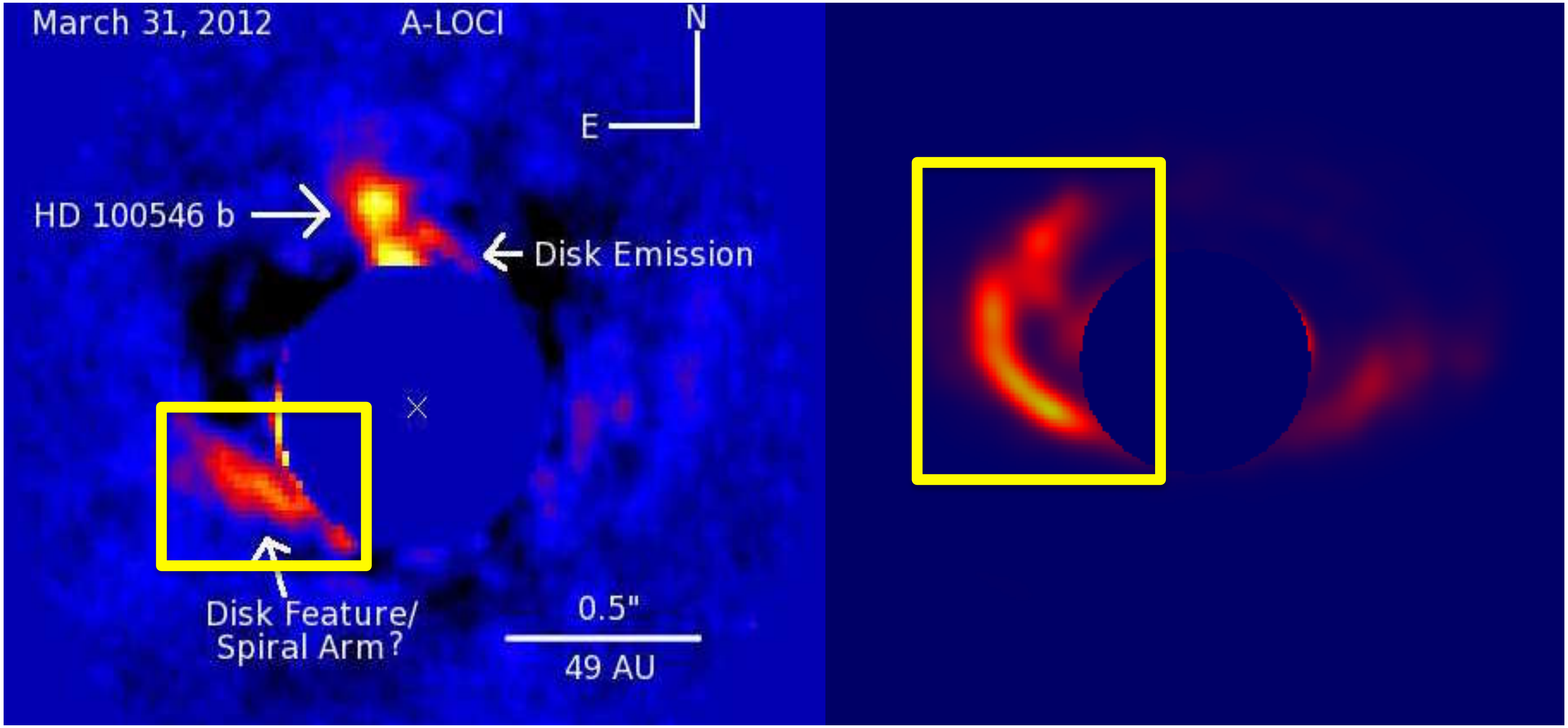


Scattering caused by high density dust

May be affected by increased mass (shock heating rate)

Images generated by competition entrant

Analysis – Comparison to HD 100546

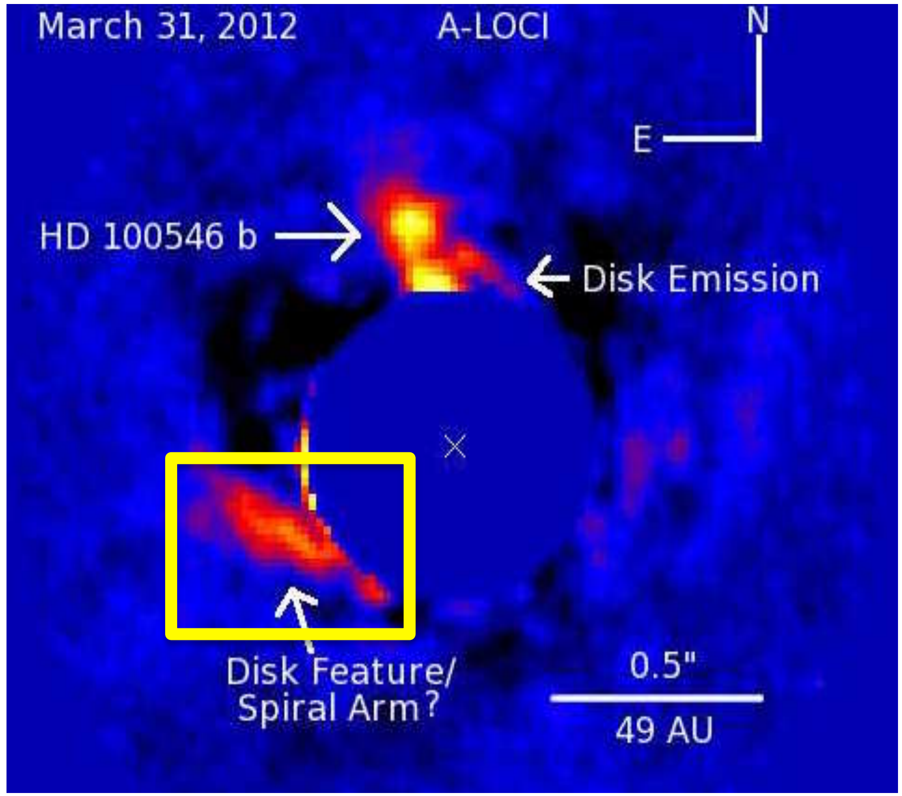


Loose match – obscured by **scattering**

Currie, T., Muto, T., Kudo, T., Honda, M., Brandt, T. D., Grady, C., ... & McElwain, M. W. (2014). Recovery of the candidate protoplanet HD 100546 b with Gemini/NICI and detection of additional (planet-induced?) disk structure at small separations. *The Astrophysical Journal Letters*, *796*(2), L30.

Right image generated by competition entrant

Analysis – Observation of HD 100546

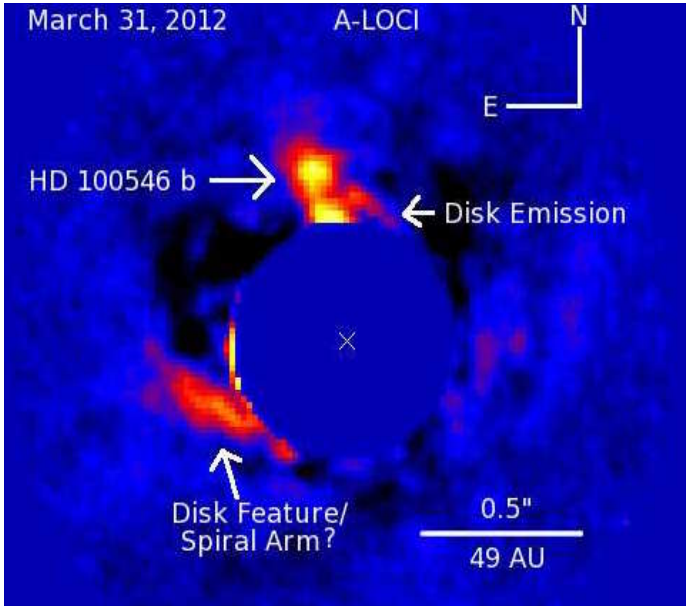


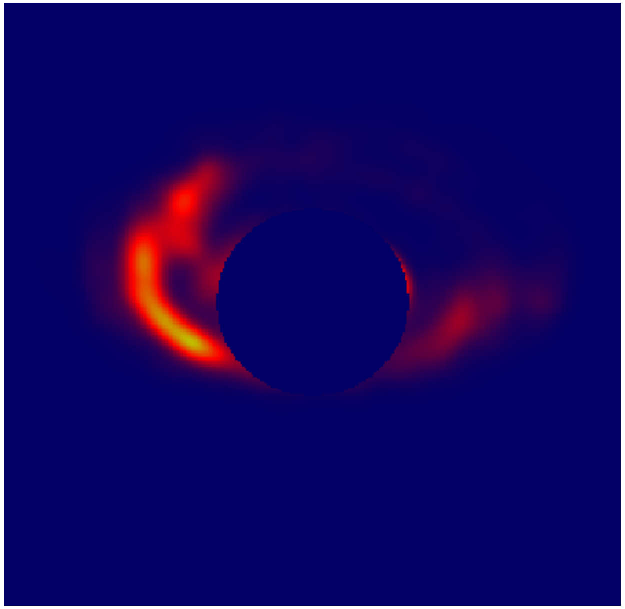
Disk Feature/Spiral Arm **not polarized** (little scattering)

Currie, T., Muto, T., Kudo, T., Honda, M., Brandt, T. D., Grady, C., ... & McElwain, M. W. (2014). Recovery of the candidate protoplanet HD 100546 b with Gemini/NICI and detection of additional (planet-induced?) disk structure at small separations. *The Astrophysical Journal Letters*, *796*(2), L30.

Conclusions

- Evidence for **second planet**
  - Requires more evidence, because emission could also be from residual waves of another source
- High mass planet spiral **shocks** may be **observable**
  - Synthetic Image matches observed image





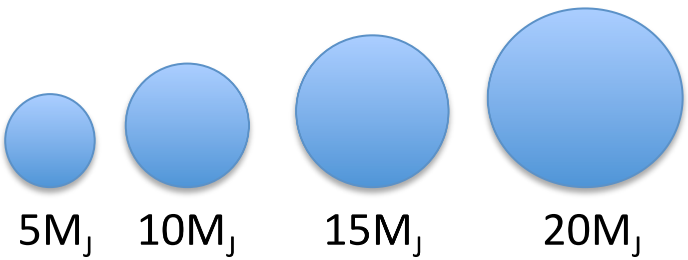
Currie, T., Muto, T., Kudo, T., Honda, M., Brandt, T. D., Grady, C., ... & McElwain, M. W. (2014). Recovery of the candidate protoplanet HD 100546 b with Gemini/NICI and detection of additional (planet-induced?) disk structure at small separations. *The Astrophysical Journal Letters*, *796*(2), L30.

Right Image generated by competition entrant

<u>**Future Research** – *Ad-hoc* Factor</u>

Increase Factor

Variation in Mass

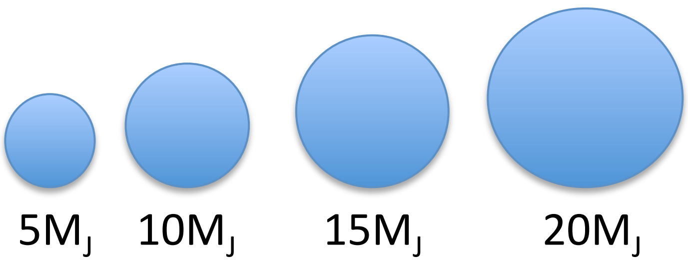


Images generated by competition entrant

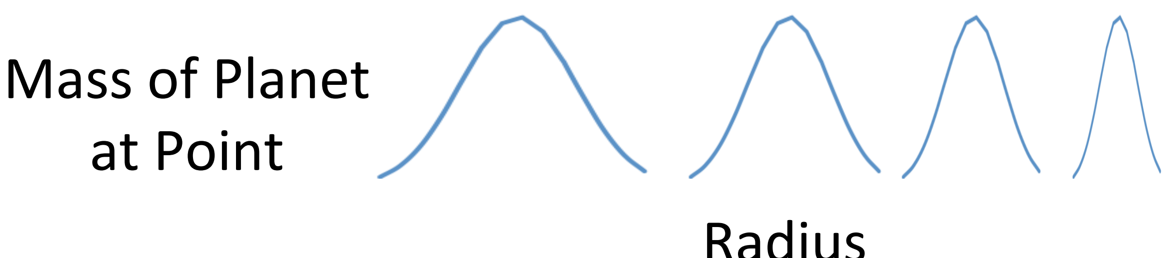
Future Research – *Ad-hoc* Factor

Increase Factor

Variation in Mass



Smoothing Radius of Lyra et al. (2016)

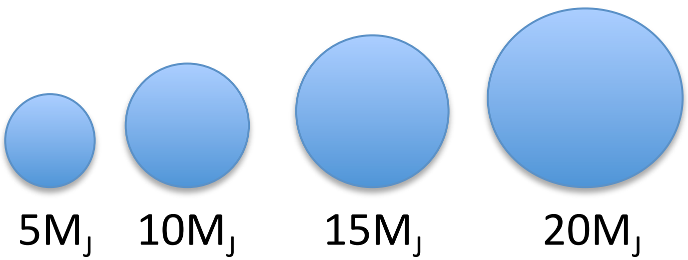


Images generated by competition entrant

Future Research – *Ad-hoc* Factor

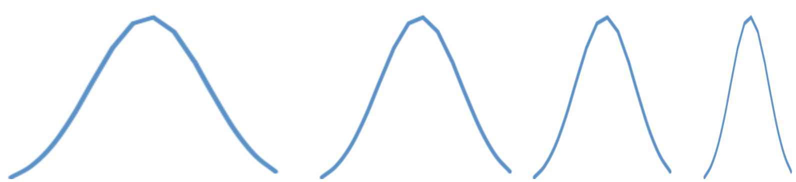
Increase Factor

Variation in Mass

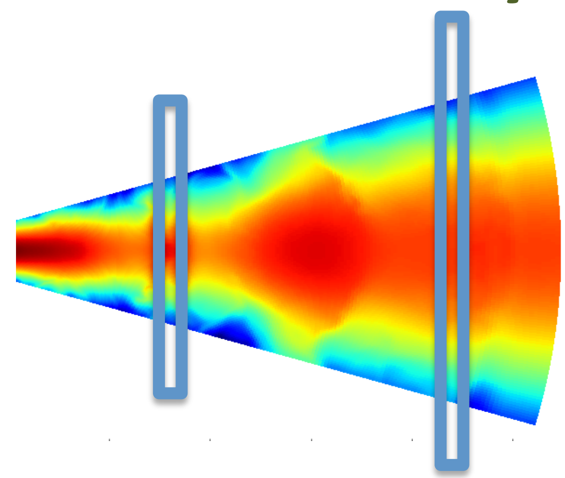


Smoothing Radius of Lyra et al. (2016)

Mass of Planet at Point



Difference in Column Density



Vertical integral of density not matched with observation

Images generated by competition entrant

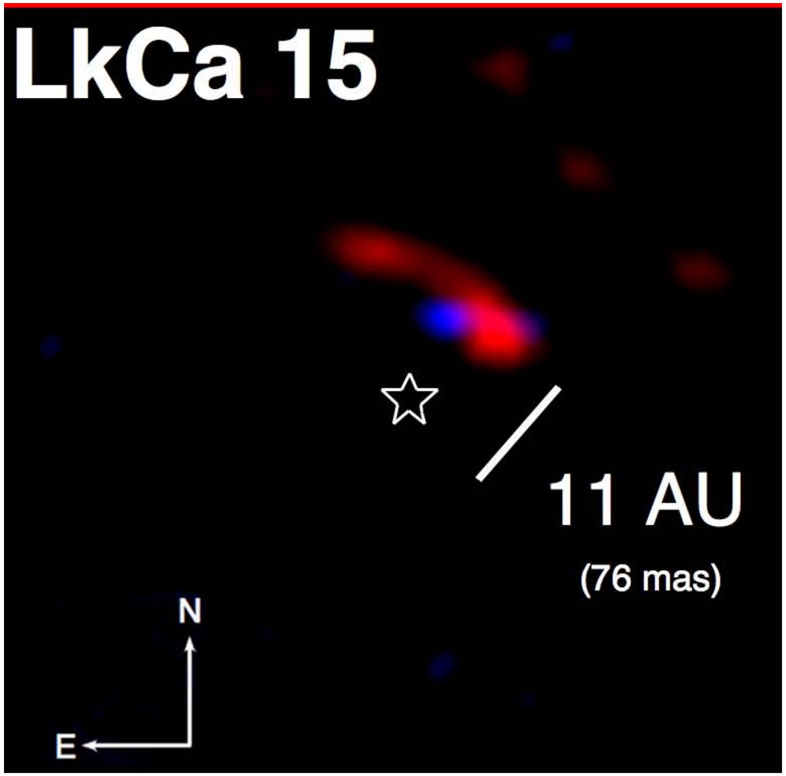
Future Research

- Other disks– LkCa 15
- Pipeline between Pencil Code and RADMC-3D can be used to determine observations of other models
- **Remove Scattering in Image**

Pencil Code

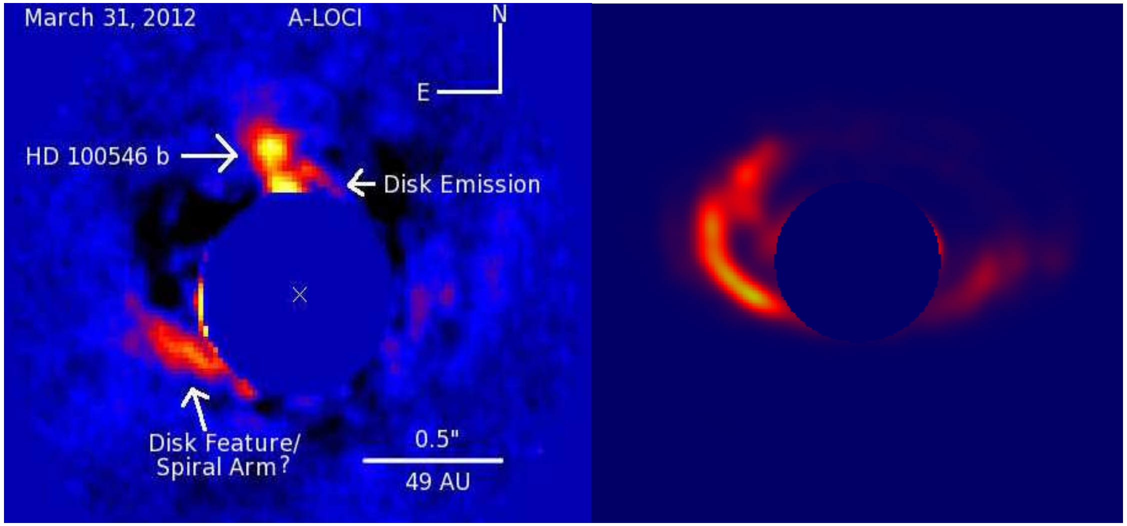
↓

RADMC-3D



Kraus, A. L., & Ireland, M. J. (2011). LkCa 15: A young exoplanet caught at formation?. The Astrophysical Journal, 745(1), 5.

High Mass Planet Spiral Shocks as a Source of Infrared Emission in Protoplanetary Disks



Blake Hord