Background

How Planets Form

- Planets form around **newborn stars**
- Collapsing gas and dust forms disk
- Dust settles into ***midplane*** in center of disk
- Grains of dust grow into **planetesimals**, about the size of an asteroid
- Planetesimals collide to form larger planets and attract an atmosphere from the gas around them
- Planets can be much larger than the planets in our solar system

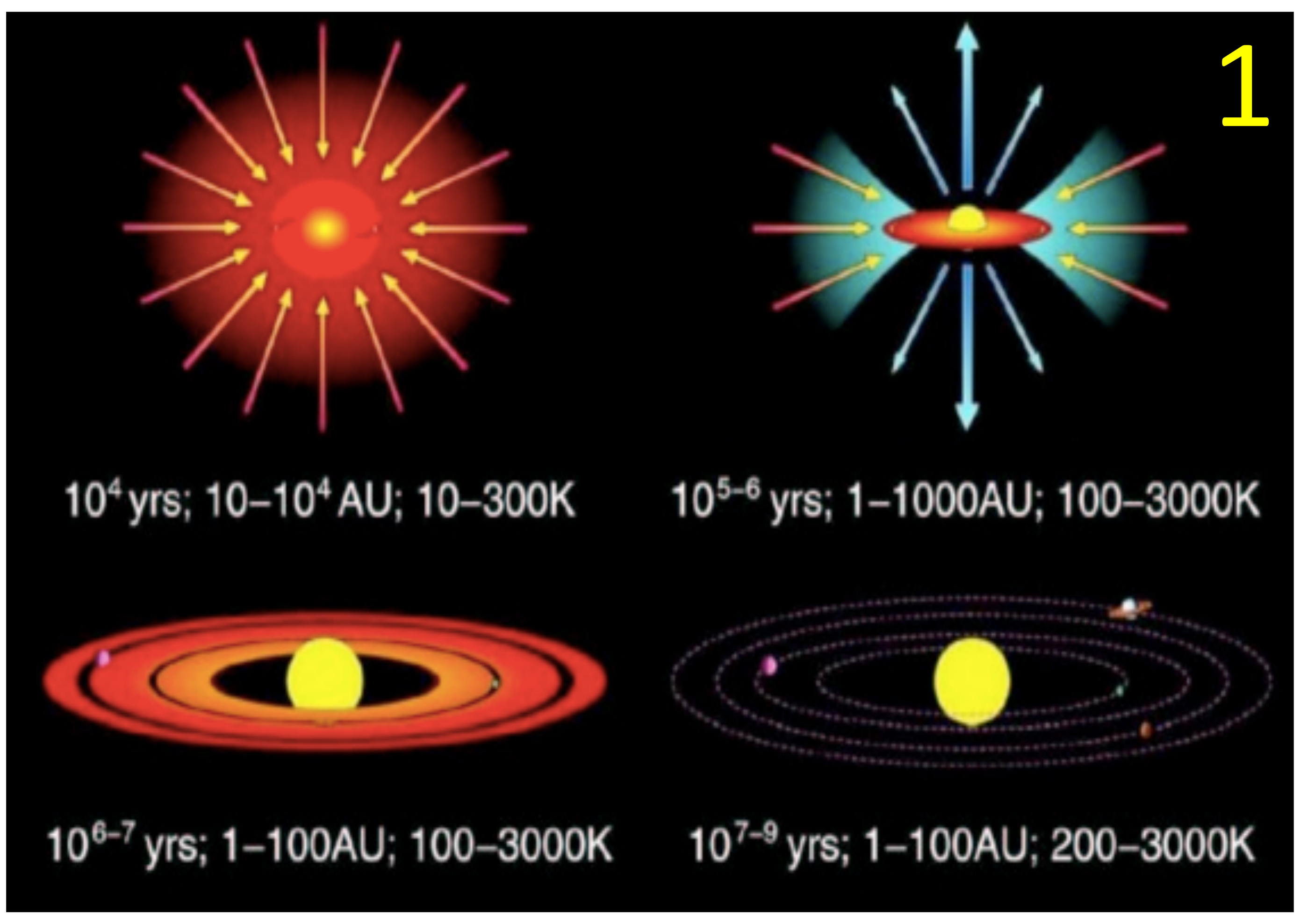


Figure 1: Main stages of planet formation. Era studied in this experiment is the bottom left, with planet carved gap formed (Shu et al. 1987)

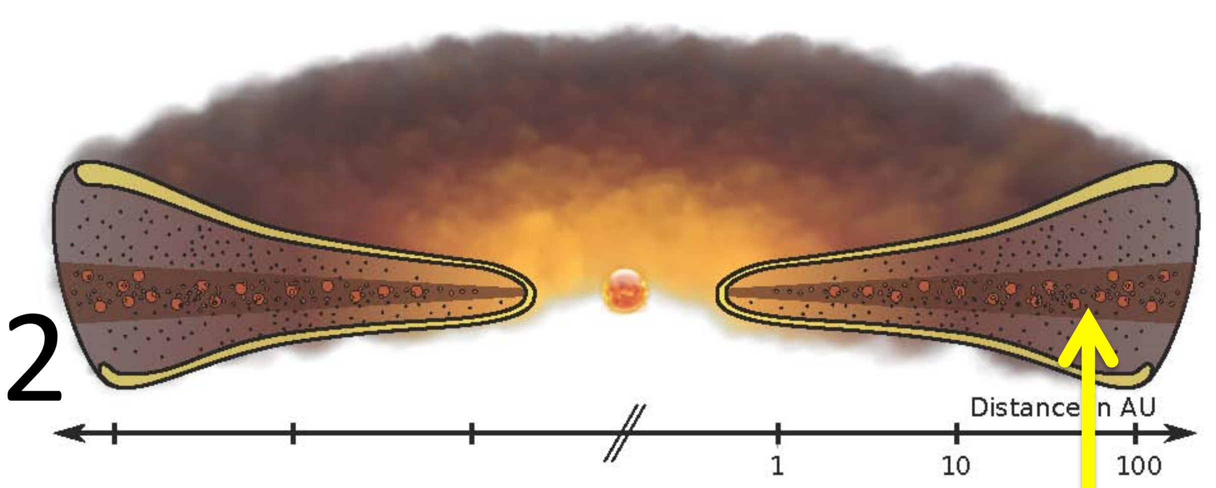


Figure 2: Schematic of protoplanetary disk, with midplane in center with larger planetesimals (large circles) forming (Birnstiel, n.d.)

Planet-Induced Spirals

- Numerical simulations indicated planets cause spiral density waves in disks
- ***Linear mathematical theory*** developed to predict pitch angle of spiral based on mass
- Theory works for low-mass planets

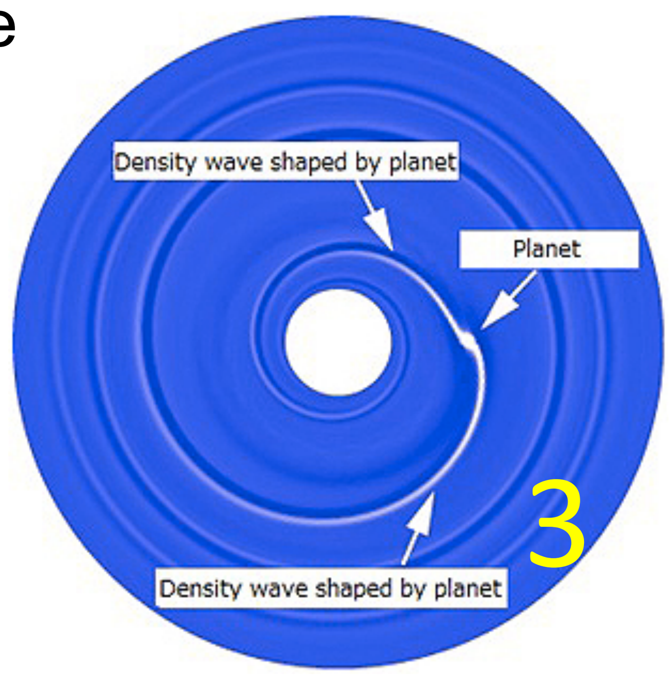
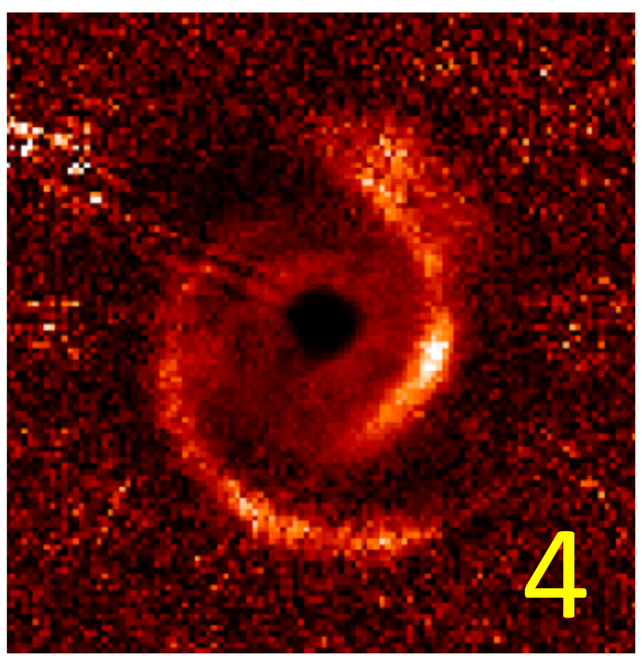
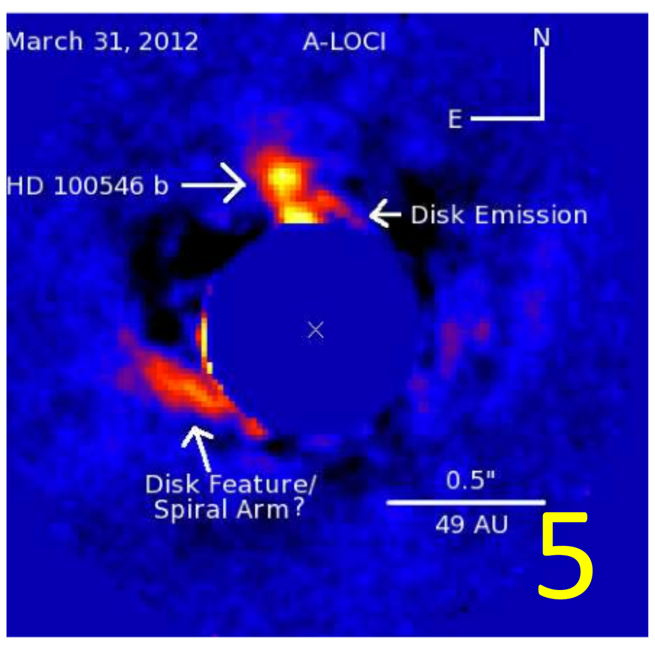
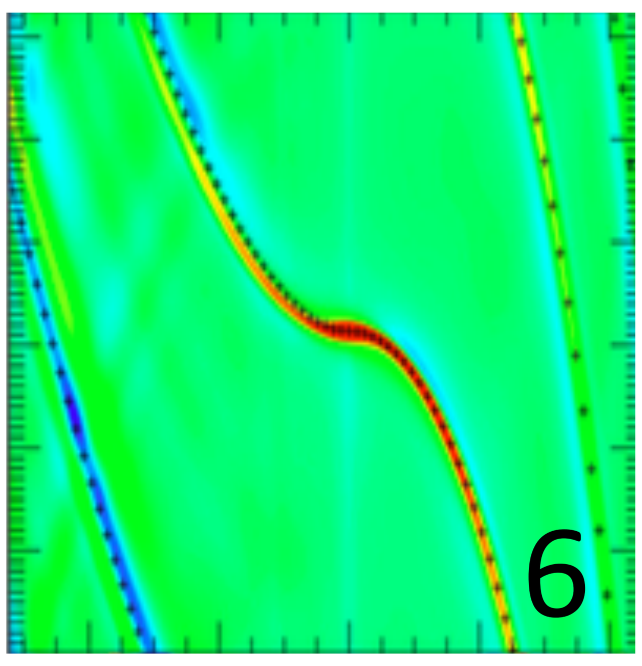
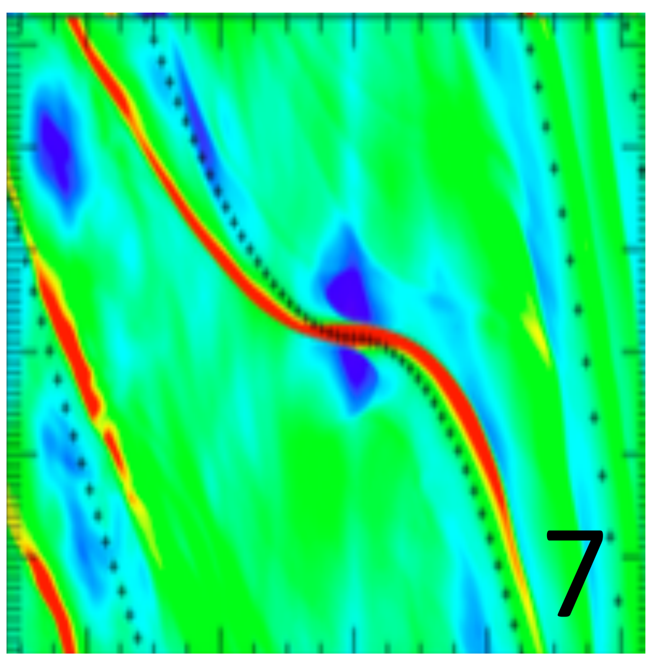


Figure 3: Spiral density wave numerical simulation result. Planet-caused wave located inwards and outwards radially from the planet (NAOJ. 2012)









Figures 4-7: (4) Observation of disk around MWC 758. 300K temperature required for spiral shape (Benisty et al. 2015); **(5)** Observation of disk around HD 100546, spiral arm in lower left corner unexplained thermal emission (Currie et al. 2014); **(6)** Simulation output of 0.01M_J density perturbations (Zhu et al. 2015); **(7)** Simulation output of 6M_J density perturbations (Zhu et al. 2015)

Wide Planet Spirals

Observations

- Many wide-angled spirals have been seen (Figures 4 and 5)
- Their large pitch angles cannot be explained by the linear theory
- Higher-massed planets may be the source
- Massive planets would disrupt gas to make it supersonic
- May alter morphology of spiral

Numerical Simulations

- High Mass planets - supersonic wakes
- Alter the gas following a nonlinear theory
- Density spirals with wider pitch angles (Figures 6 and 7)

Lyra et al. (2016)

- Simulated 5MJ planet around star to determine effects on disk
- Should be compared to observations
- But unrealistic cooling function prohibits accurate temperature of atmosphere

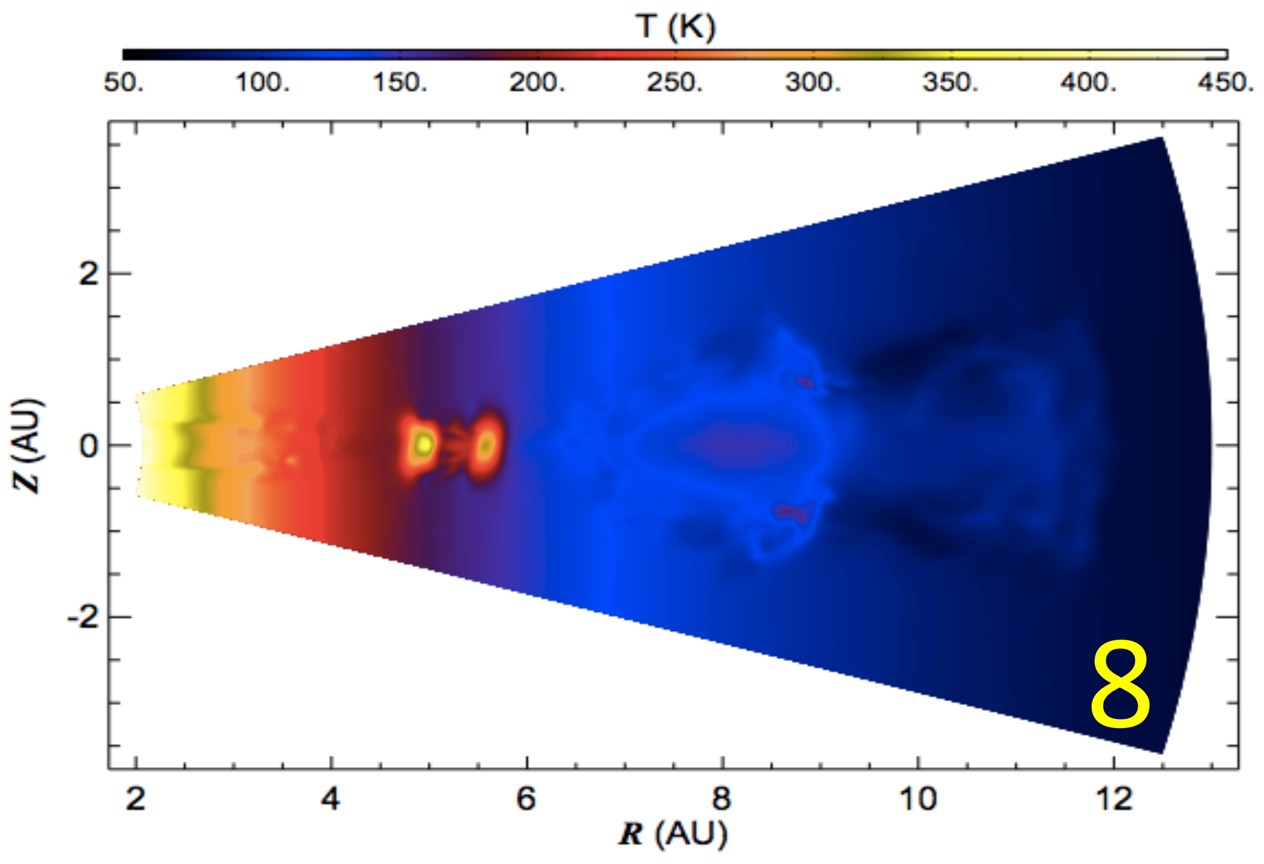


Figure 8: Temperature distribution in simulation of Lyra et al. (2016), showing two regions of high temperature on either side of the planet located at 5AU.

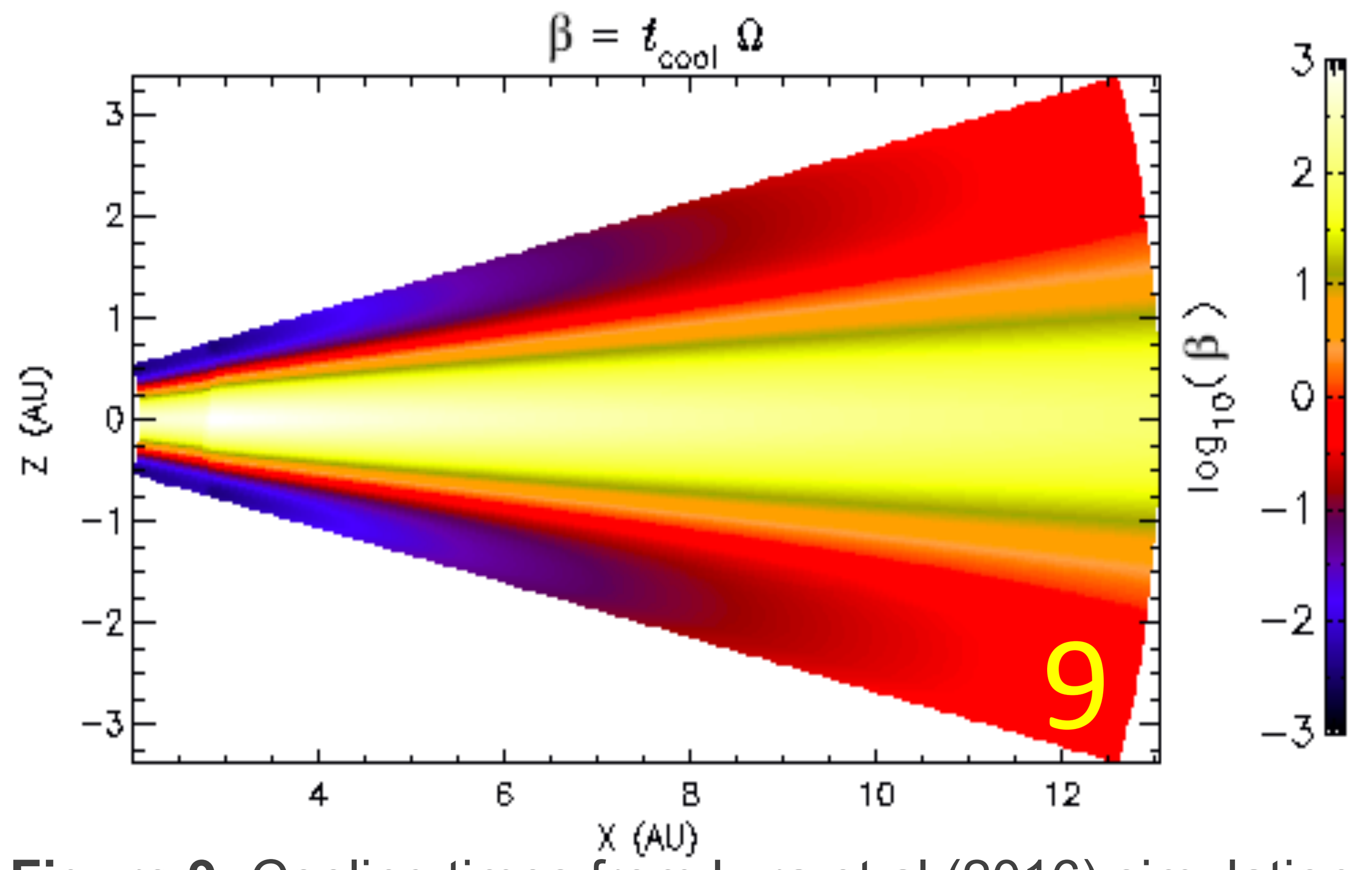


Figure 9: Cooling times from Lyra et al (2016) simulation. This simple function disregards most heating given off by high temperature regions through radiation

Problem Statement

Model of Lyra et al. (2016) has **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**.

Hypotheses

1. High **temperature will spread** to intersect line of optical depth of one for 3.5 microns

2. Synthetic Images of disk from Lyra et al. (2016) **will match** observations of disk around HD 100546

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

Blake Hord - Dobbs Ferry High School, Dobbs Ferry, New York

Methods

Pipeline Between Codes

- Lyra et al (2016) used hydrodynamic **Pencil Code**
- More realistic method of cooling is used in the radiative transfer **RADMC-3D** code (Dullemond 2012)
- RADMC-3D tracks all **individual photons** emitted from high temperature areas of the disk until they leave the simulation
- Pipeline developed in Python to translate output of Pencil Code to input of RADMC-3D
- Can be reused for any other spherical grid of Pencil Code

Parameters Input

- Input **shock heating rate** (Figure 10) as source of photons in disk, along with starlight
- Disk dust density (Figure 11) transferred
- Dust wavelength dependent opacity taken from Preibisch et al. (1993) (Figure 12)
- Used mix of silicate grains and carbonaceous components tested previously against observations
- Grid coordinates from Pencil Code

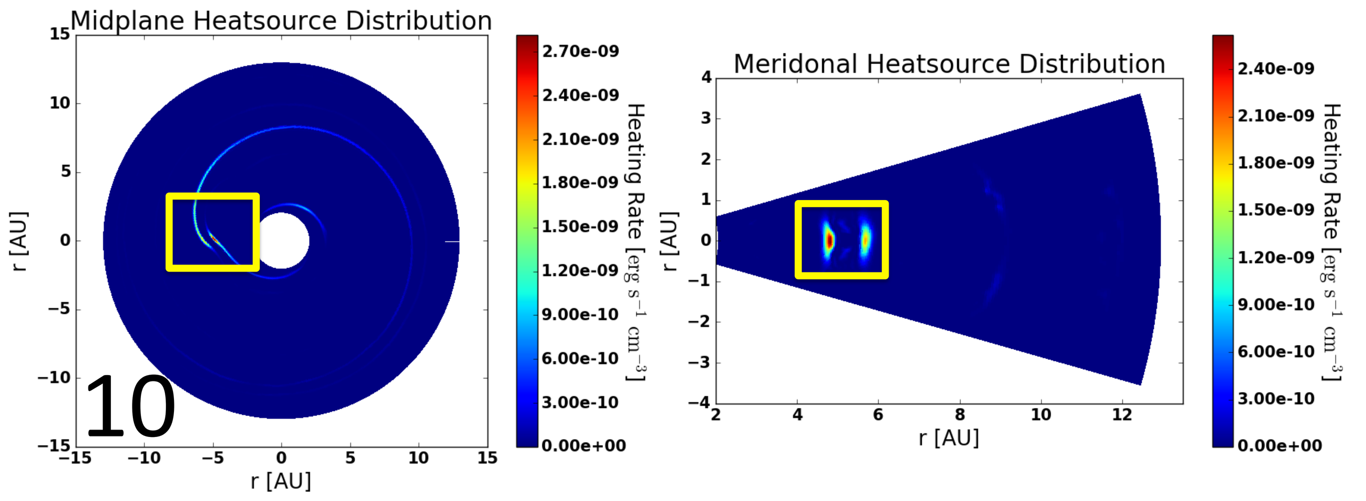
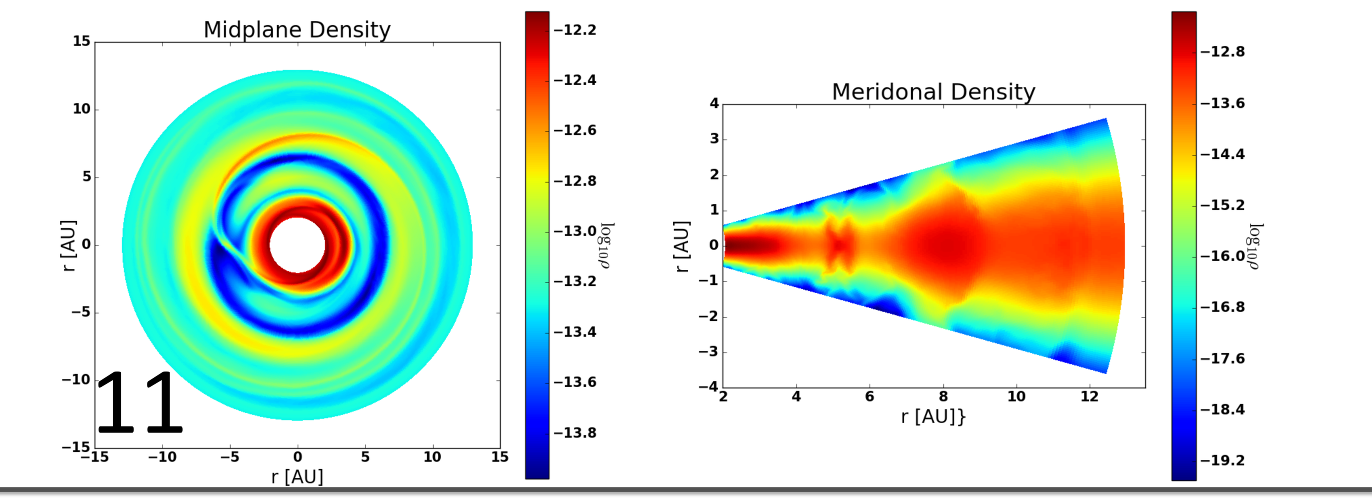


Figure 10: Shock heating rate in midplane and meridional plane of planet. Spiral shape in midplane, and same location as the two high temperature regions on either side of the planet at 5AU (generated by competition entrant)

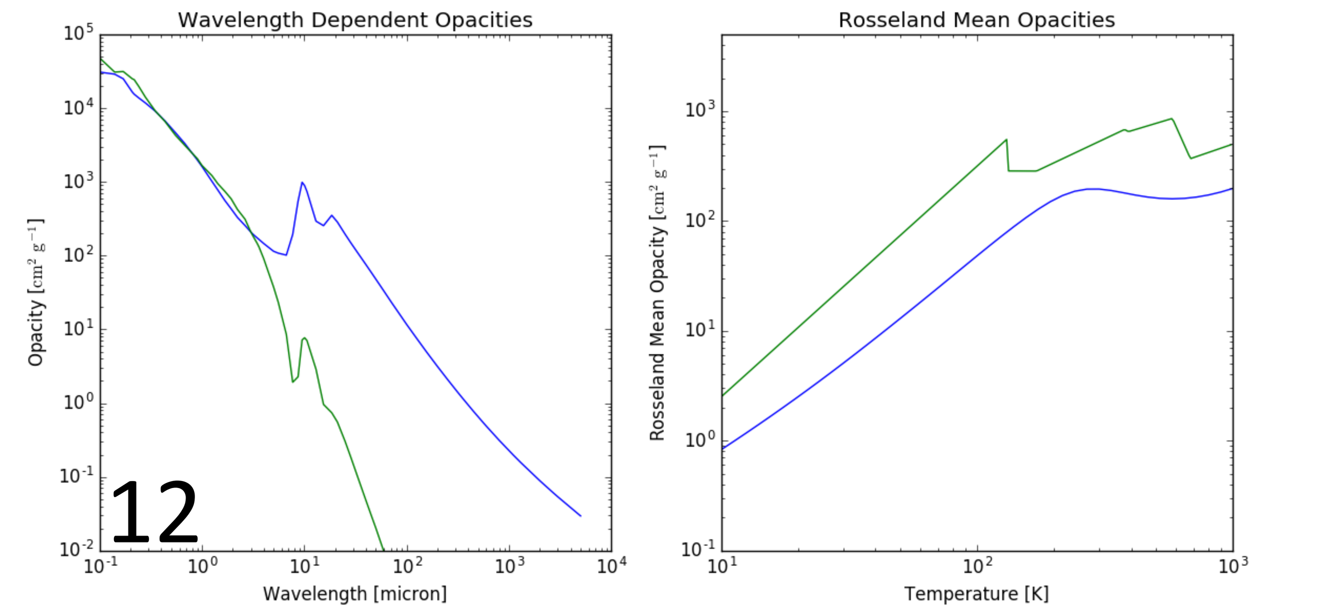
Figure 11: Density transferred from Pencil code to RADMC-3D. Spiral density wave seen in midplane view (generated by competition entrant)



Simulations Run

- RADMC-3D run with 10^7 photons being emitted in total by star and shock heating combined
- Output new temperature grid for disk
- Allowed **synthetic images** to be made with new, more accurate temperature of atmosphere

Figure 12: (left) Wavelength-dependent opacities from Preibisch et al. (1993), with scattering in green and absorption in blue. (right) Rosseland Mean opacities, controlling the transport of radiation, were calculated (blue). They match with only a factor of 2 difference with the expected values from Bell et al. (1997), accountable by a small change in dust composition (generated by competition entrant)



Results - Synthetic Images

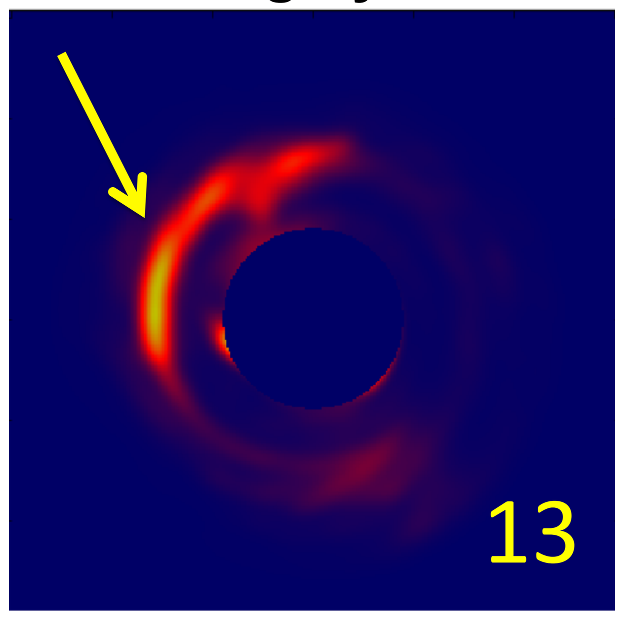
Creation

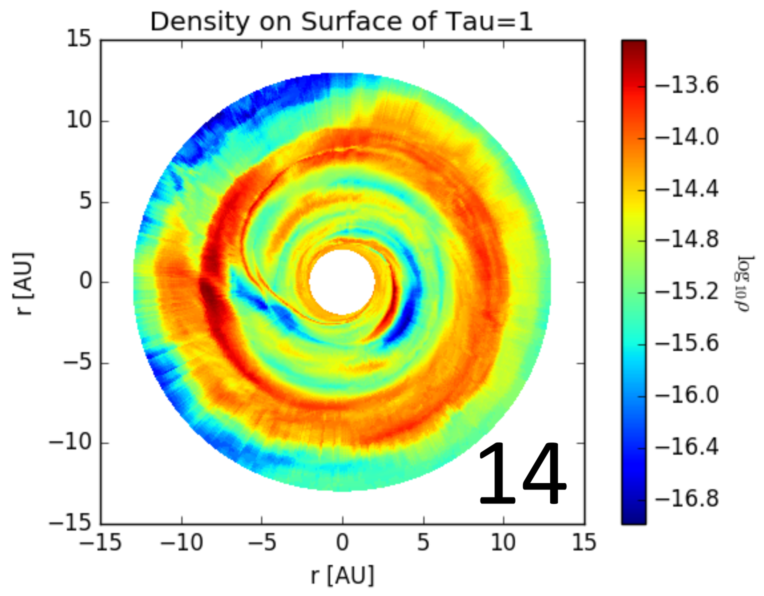
- Made with RADMC-3D ray-tracing module
- Traces effect of temperature through density of disk to determine what luminosity permeates at what wavelength
- Synthetic Images made at 3.5 microns to match observation of HD 100546 from Currie et al. (2014)
- Coronographic mask of diameter 0.80" applied

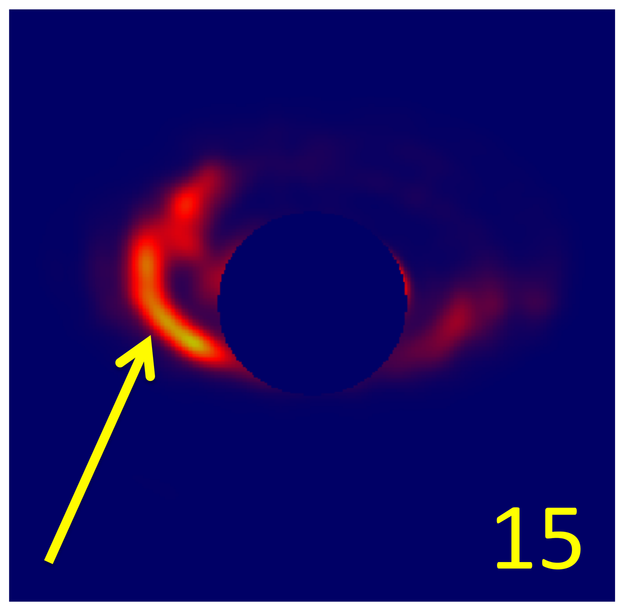
Scattering

- Included in images
- Dominates radiation observed
- Caused by high density gap outer edge (Figure 14)
- **Not present** in observation of HD 100546

Scattering Synthetic Images





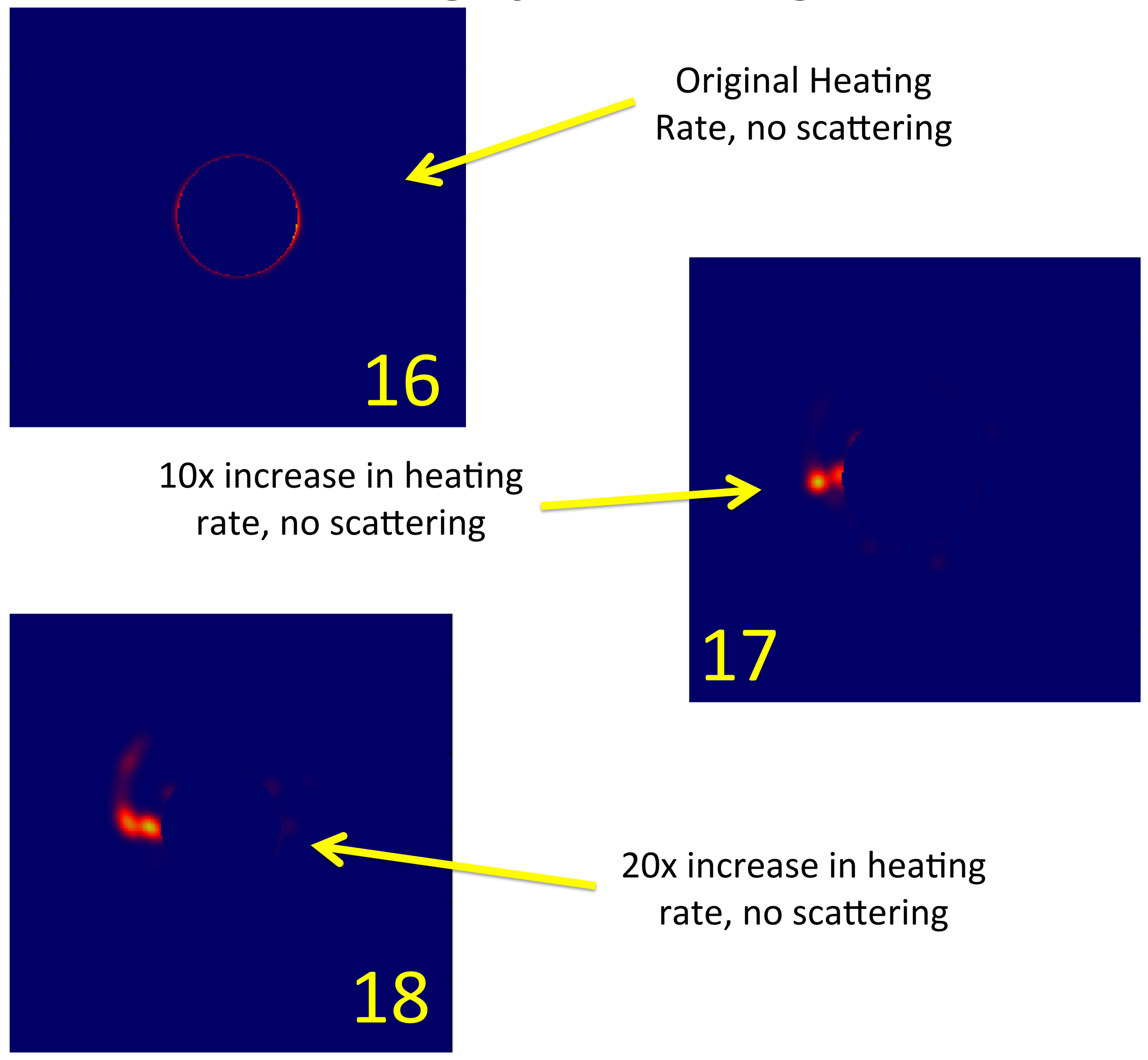


Figures 13-15: (13) Birdseye image of disk with scattering. Has spiral feature, but also ring of other radiation; **(14)** This other radiation is caused by scattering from the high-density gap outer edge at 8AU; **(15)** Given the position and inclination angles of HD 100546, the image appears to have more of a spiral, but still contains the ring of radiation not seen in HD 10046 (generated by competition entrant)

Influence of Reduced Scattering and Increased Mass

- HD 100546 image is thermal and may have different disk structure than Lyra et al. (2016) model
- Thus scattering may not be as important as just the planet's spiral shock's emission
- The effect of scattering illustrated in Figures 16-18
- **Increased mass of planet** would increase shock heating rate
- Iterations of increased shock heating rate (Figures 16-18)
- Spiral clearly shown when shock heating rate (mass) is increased and scattering from high density gap edge ignored

Removed Scattering Synthetic Images



Figures 16-18: (16) Image without scattering, showing the effect of the disk gap outer edge on the synthetic image created; **(17)** Image without scattering and the mass (shock heating rate) increased by a factor of 10. Spiral is not visible; **(18)** Image without scattering and the mass increased by a factor of 20. Spiral is visible. (generated by competition entrant)

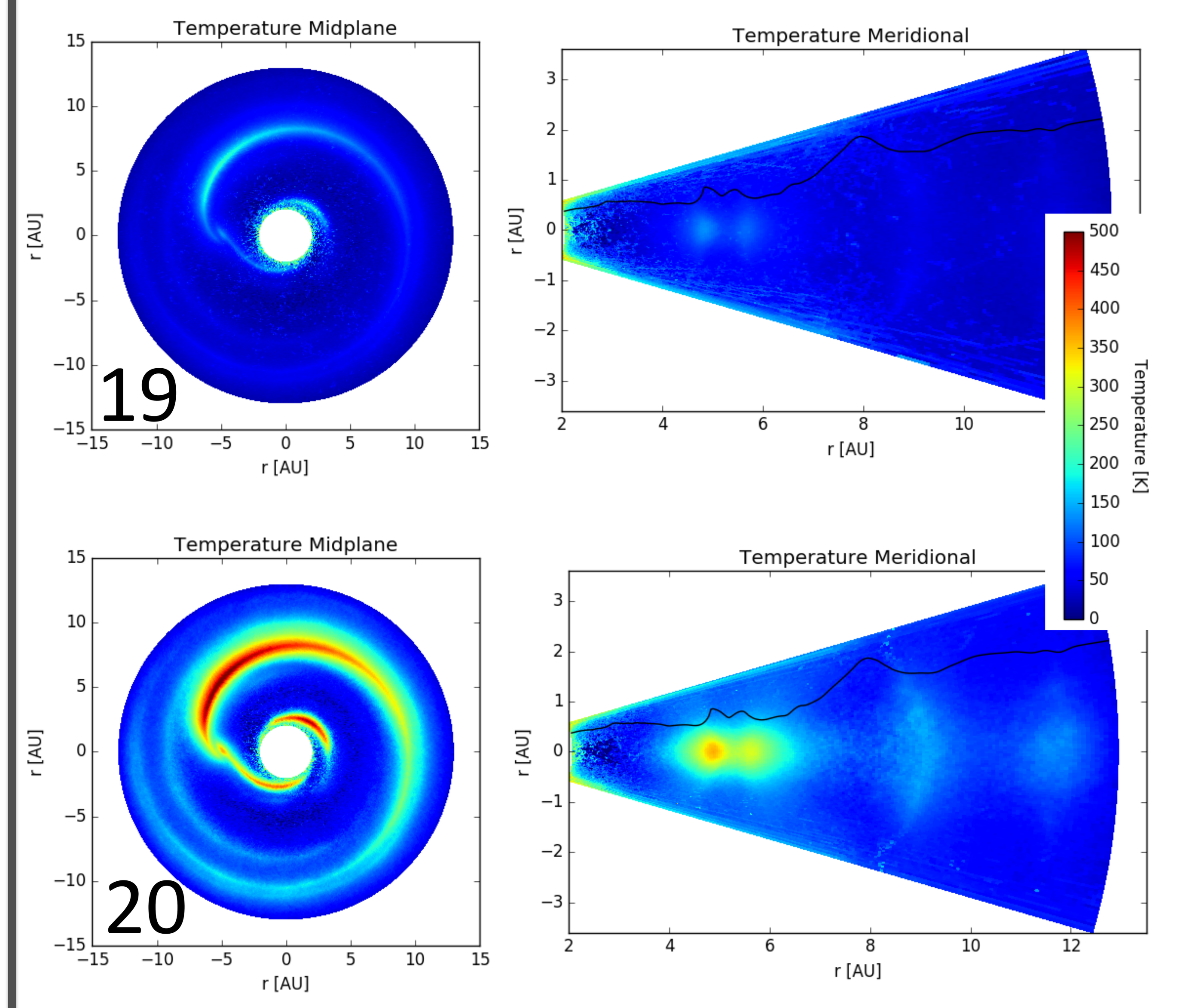
Results - Temperature Spread

Without Increase in Mass

- Spiral feature is at a temperature of ~200K
- In plane of planet, temperature does not spread far above the high temperature regions seen in Lyra et al. (2016)
- Illustrates why image without scattering showed no spiral features in disk

With Increase in Mass

- Spiral feature is at a temperature of ~450K
- Temperature spread well above planet, intersecting with line of optical depth of one
- Temperature at optical depth of one is ~200K around spiral



Figures 19 and 20: (19) Temperature of midplane and meridional cross-section containing planet; **(20)** Temperature with increase in planet mass by a factor of 20. Black line is the contour of optical depth of one for 3.5 microns, where most emitted photons come from in observations at that wavelength (generated by competition entrant)

Comparison

HD 100546 – Synthetic Image

- Observation and image with scattering are **loose match**
- Without scattering, the mass (shock heating rate) must be increased considerably to **match morphology**

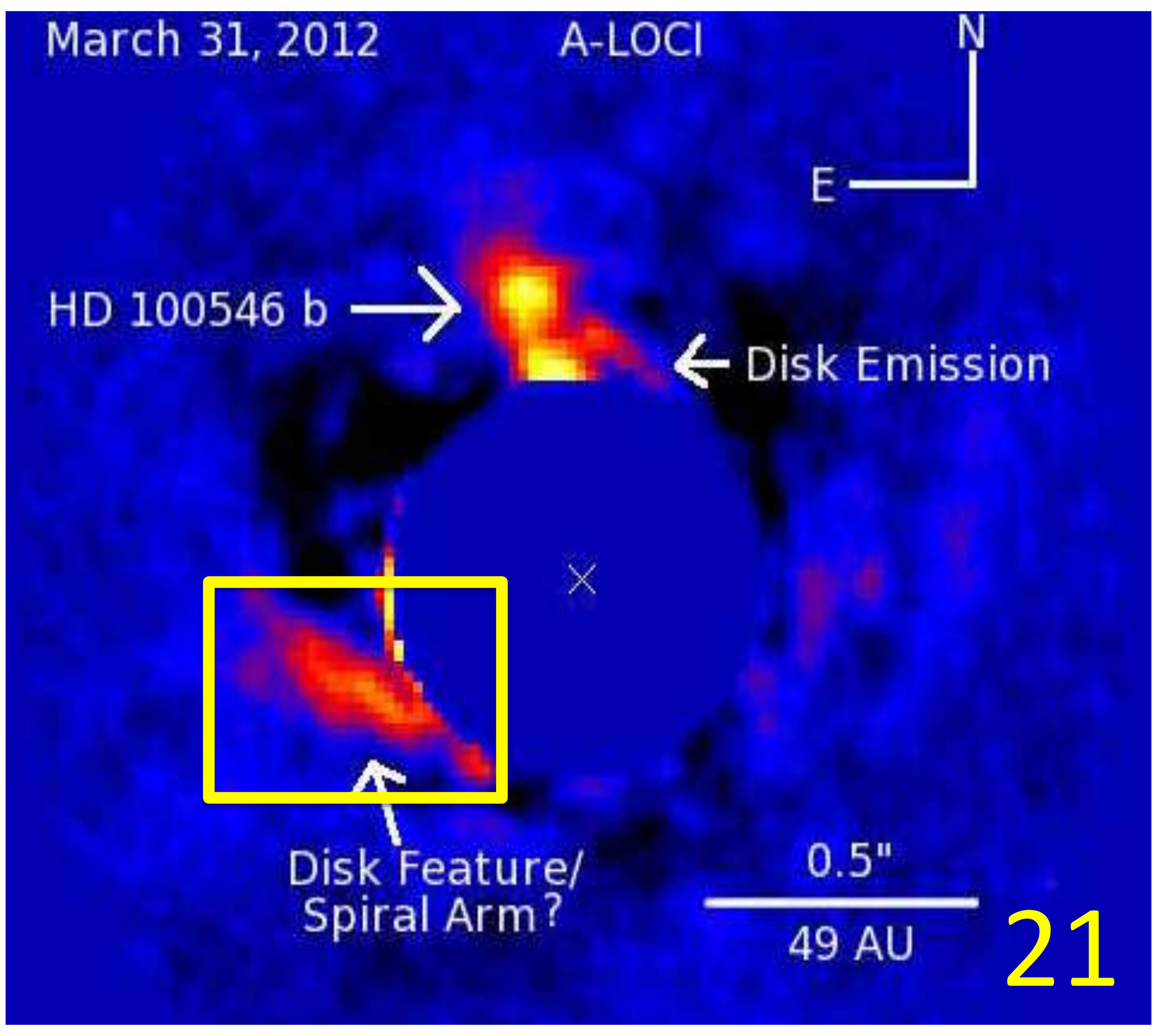


Figure 21: Observation of HD 100546 at a wavelength of 3.5 microns. Emission of interest is the lower left disk feature, which matches the synthetic image in morphology (Currie et al. 2014)

Other Emission in Disk

- May be from heat trapped in areas of high density
- Density profiles of disk are different
- Despite this, general morphologies of **two spirals match**

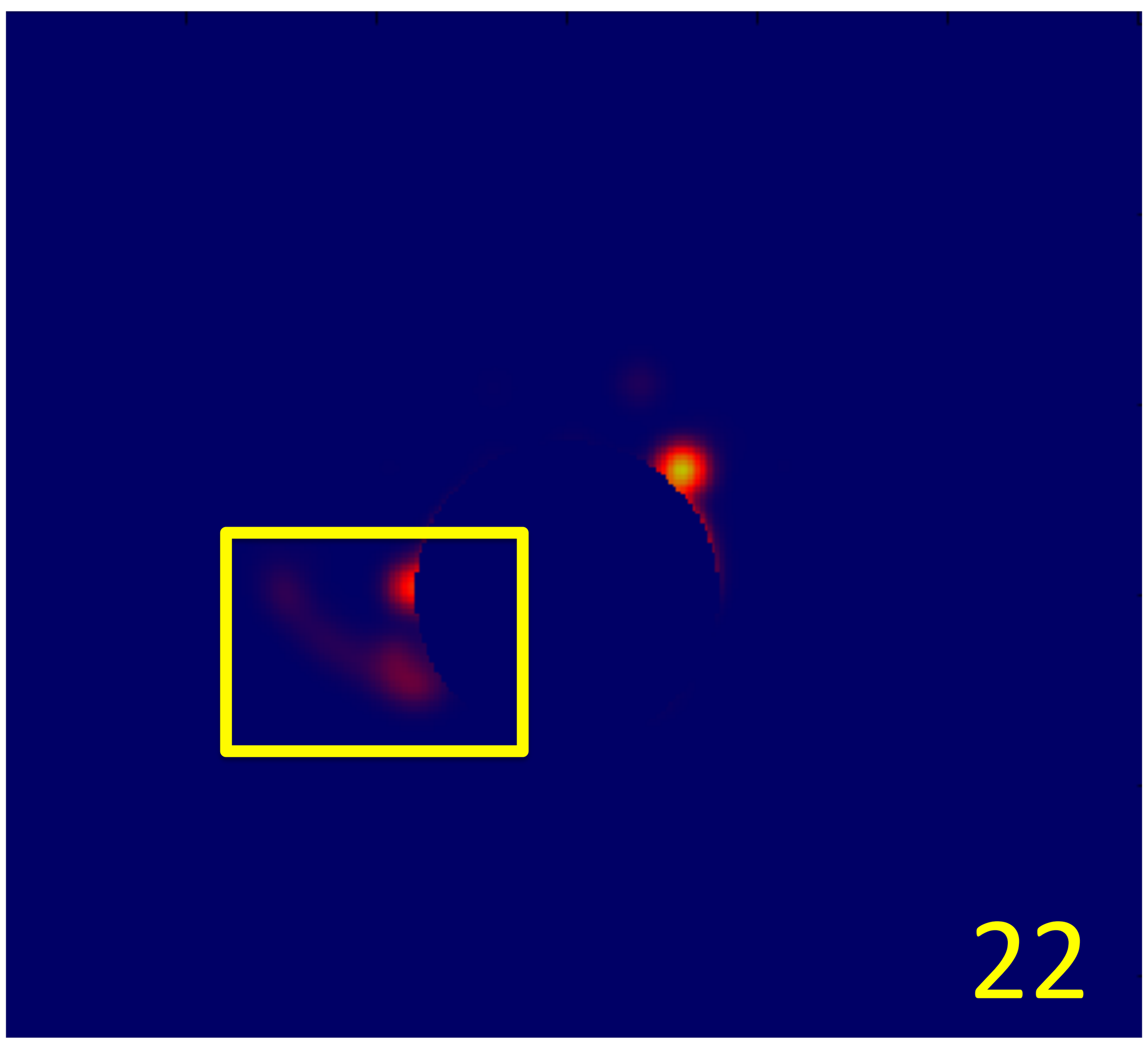


Figure 22: Synthetic Image of Lyra et al. (2016) simulation, without scattering, and with a mass (shock heating rate) increased by 20. It was given the same position and inclination angles as the observation (generated by competition entrant)

Conclusions

Disk Spirals

- Numerical simulations predicted visible spirals from planet-disk interaction
- Lyra et al. (2016) modeled a $5M_J$ planet, but had an unrealistic cooling function
- Cooling improved by post-processing **radiative transfer** technique

Future Research

Further Studies

- Confirm results with other systems, such as LkCa 15 (Figure 23; Kraus & Ireland, 2011)
- Determine source of increase in shock heating rate needed to create matching morphologies (Figures 24-26)
- Pipeline between Pencil Code and RADMC-3D can be used to determine observations of other models

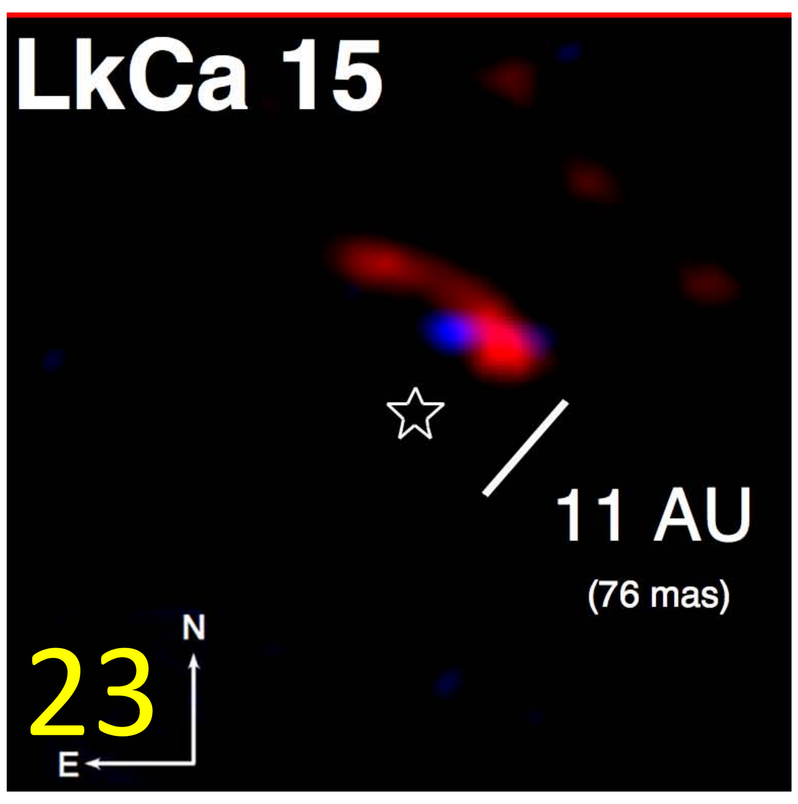
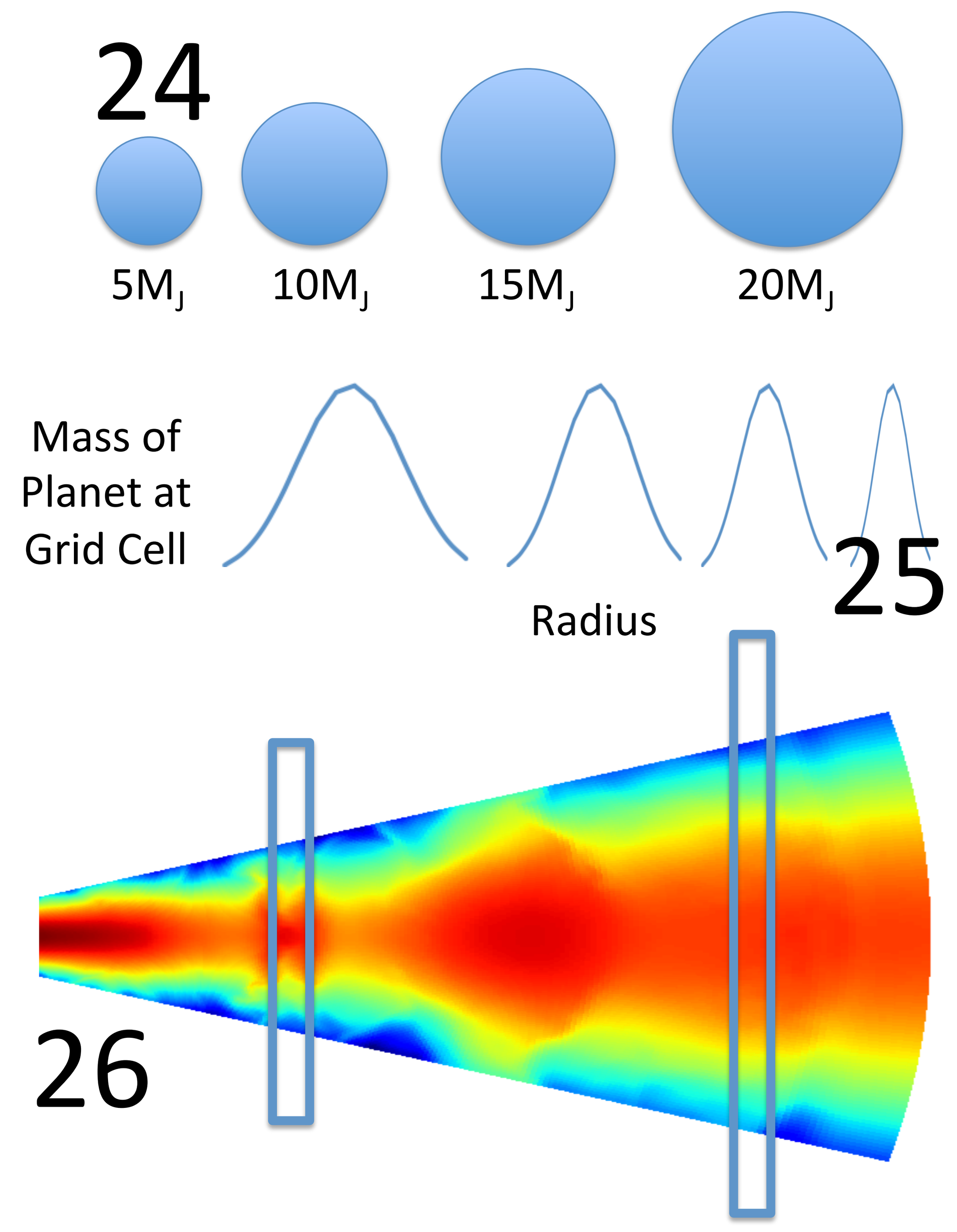


Figure 23: Observation of LkCa system with spiral arm seen at a distance of only 11 AU from the star (Kraus & Ireland, 2011)

Completion of Goals:

1. New temperature grid created from RADMC-3D simulation
2. Artificial image created, more similar with increased shock heating rate (factor 20 increase required)

Thus, **spirals formed by high mass planets may be observable**



Figures 24-26: (24) Increase in mass may contribute to increase factor; **(25)** Decreased smoothing radius in hydrodynamic simulation is related to the increase in mass and may contribute to the increase factor; **(26)** The column density of the disk simulated and the disk observed are different, and may make the spirals more visible (generated by competition entrant)

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