3D Radiation-Hydrodynamical Simulations of Shadows on Transition Disks

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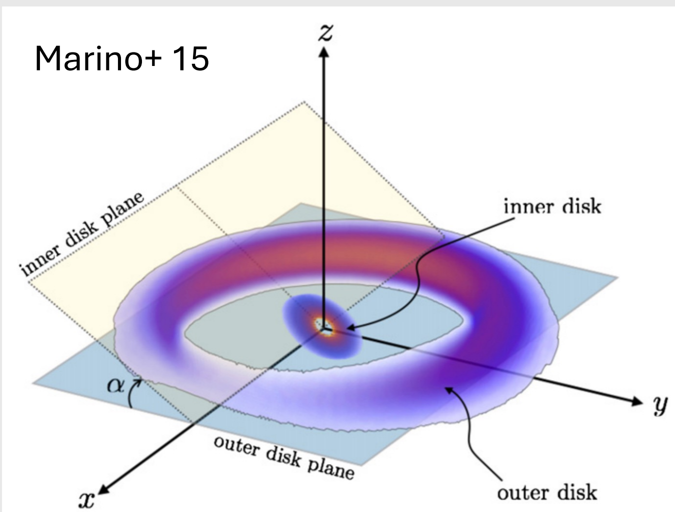
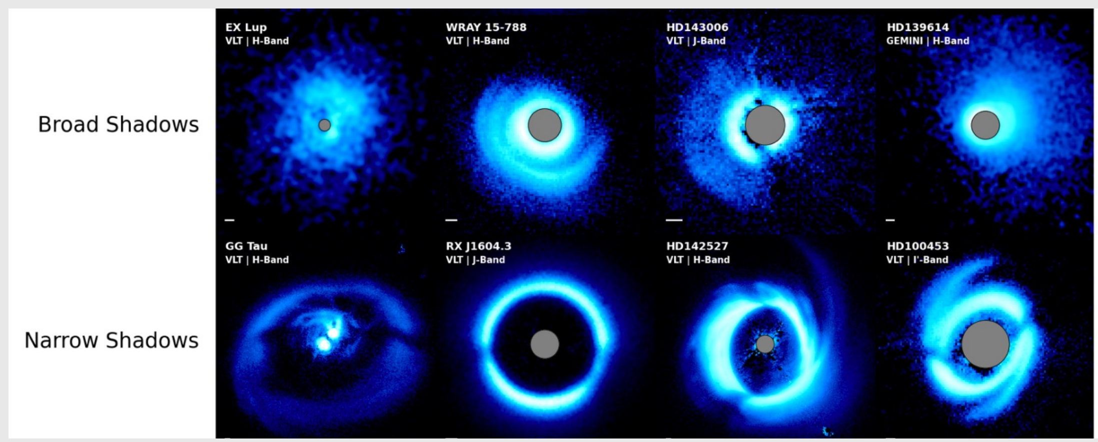
Zhang & Zhu, submitted
arxiv:2409.08373

Motivation: Near-IR

- Misaligned inner and outer disks

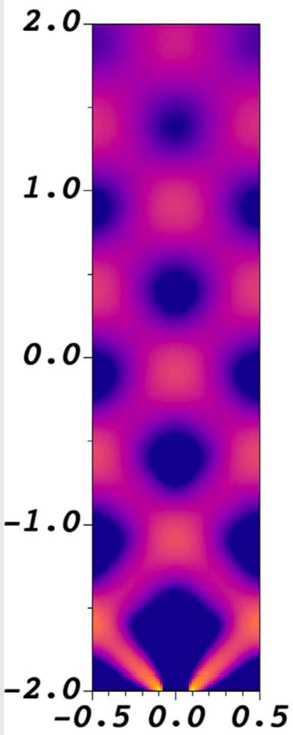




Benisty+ 23, PPVII

Tool: Radiation-Hydrodynamics

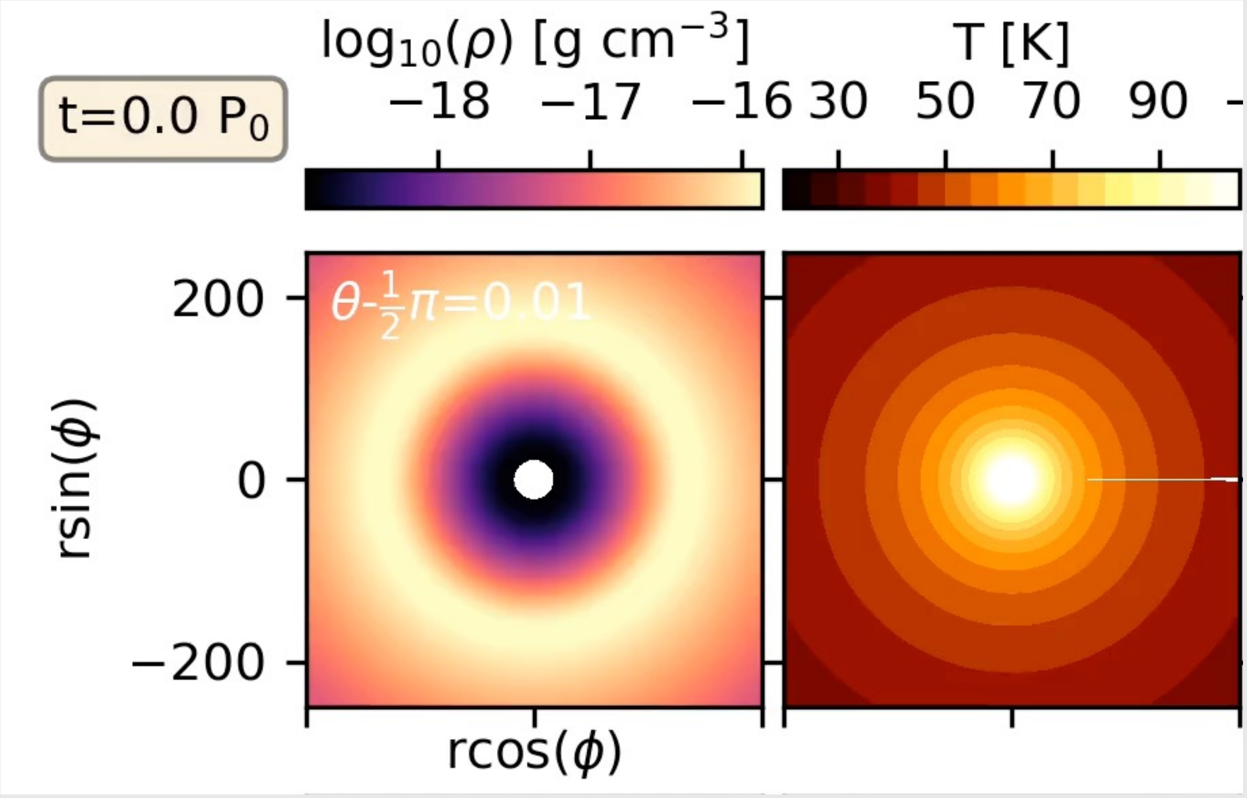
- How can we update temperature self-consistently? – Radiation Hydrodynamics
- Athena++ (Stone+ 20) and implicit radiation scheme (Jiang 2
  - Solves the time-dependent radiative transfer equation for the specific intensity (Jiang+ 14)
  - Works at both optically thin and thick regimes
  - Treats shadow and beam crossing properly, not possible for FLD method (Stoll&Kley 14,16,17, Flock+ 17,20; Szulágyi+ 16,22; Binkert+ 21,23; Cilibrasi+ 23) or M1 (Melon Fuksman+ 21,22).



Jiang 21

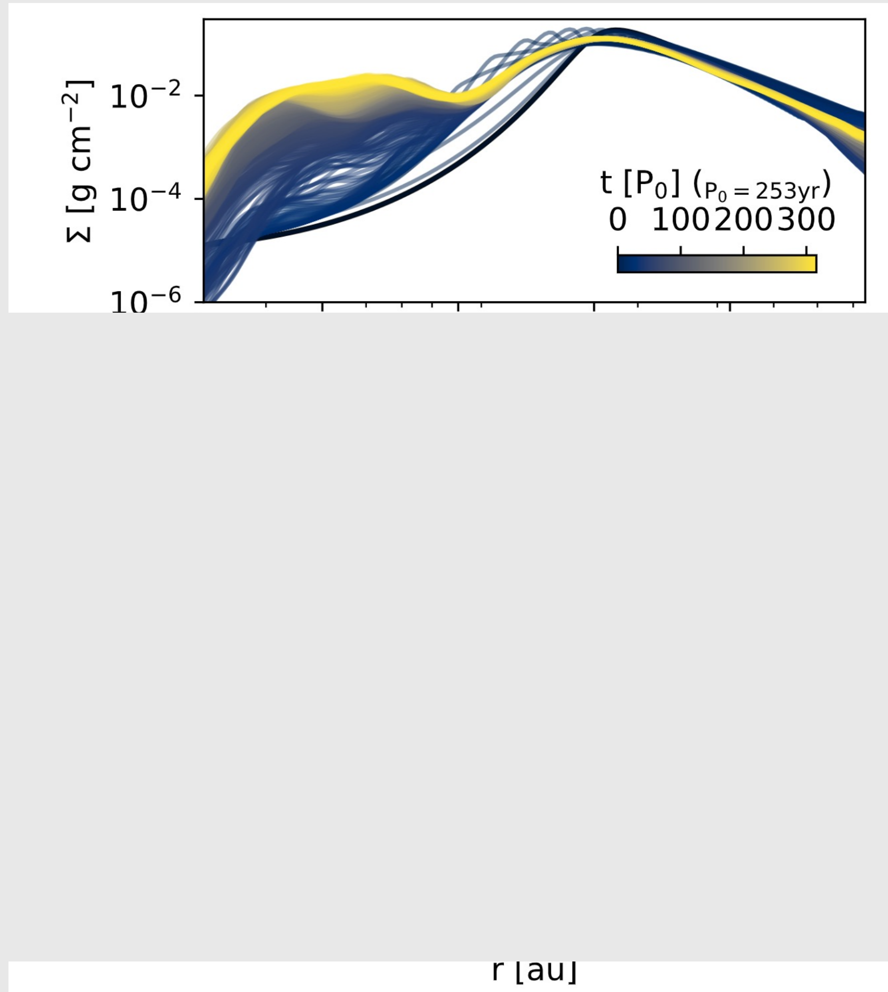
Shadow as a driving force

- 3D radiation-hydro simulations
- Inner disk is perpendicular to the outer disk
- Non-precessing



Also Montesinos+16, 18 ;Cuello+ 19; Su&Bai 24, Qian&Wu 24

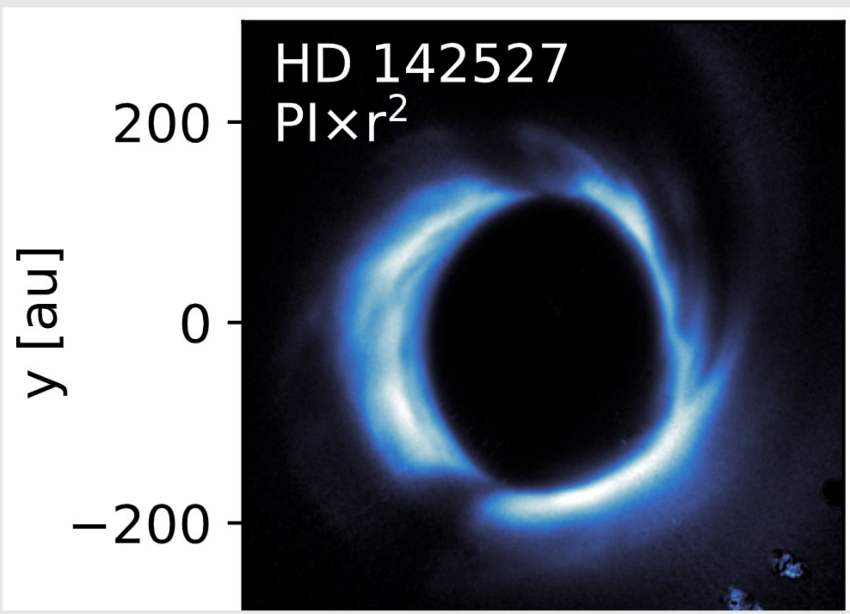
Accretion



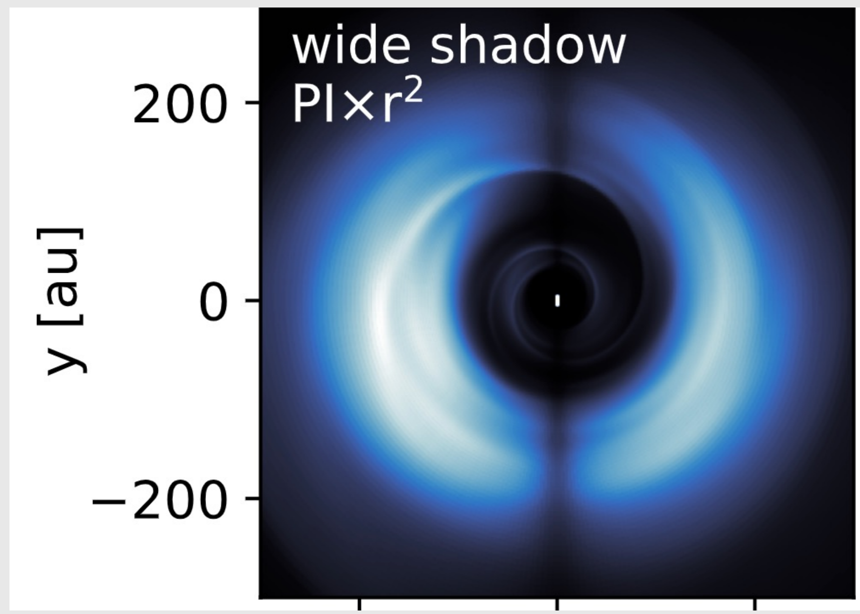
- Lead to accretion in the cavity
- α~10^{-2} in the cavity
- α~10^{-3} at the ring

Comparison to observation

- Spirals can be launched by shadows



VLT/SPHERE (Hunziker+ 21)

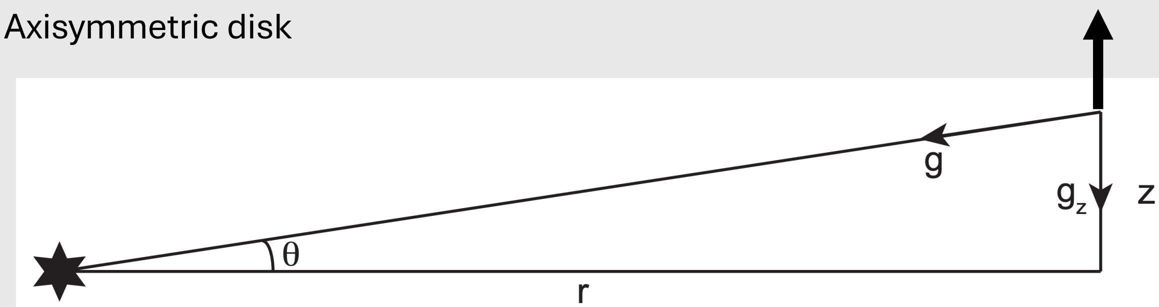


Rad-Hydro + RADMC-3D (Zhang & Zhu, submitted)

Disk vertical structure

$$\frac{1}{\rho}\frac{dP}{dZ}$$

Axisymmetric disk

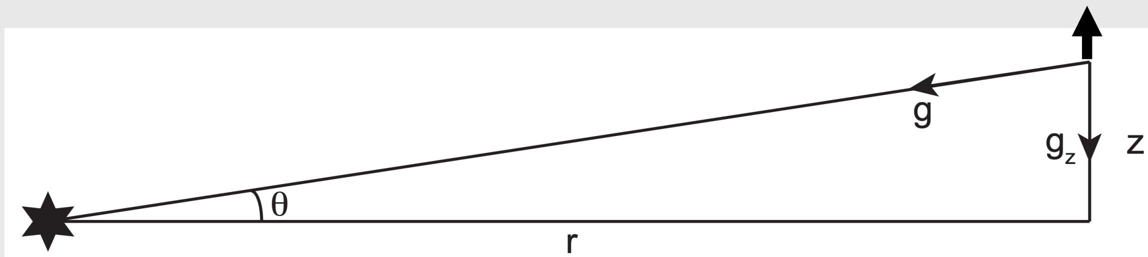


From Phil Armitage's Planet Formation Book

Disk vertical structure

$$\frac{1}{\rho}\frac{dP}{dZ}$$

In the shadow

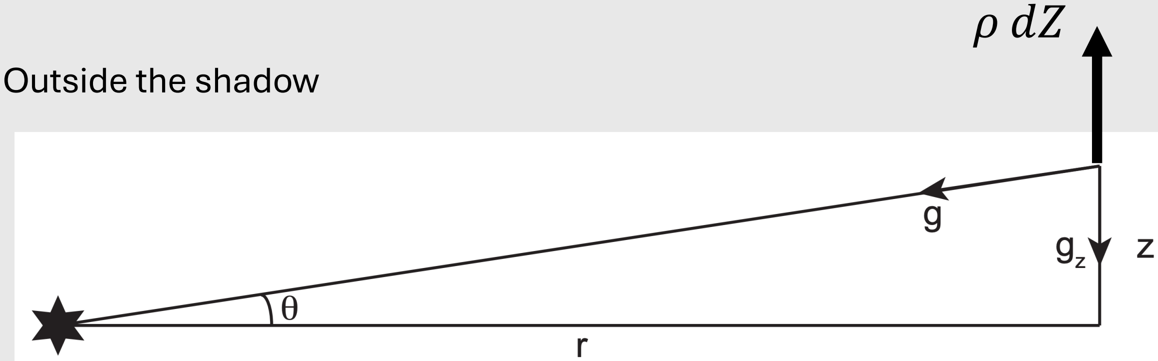


From Phil Armitage's Planet Formation Book

Disk vertical structure

$$\frac{1}{\rho}\frac{dP}{dZ}$$

Outside the shadow

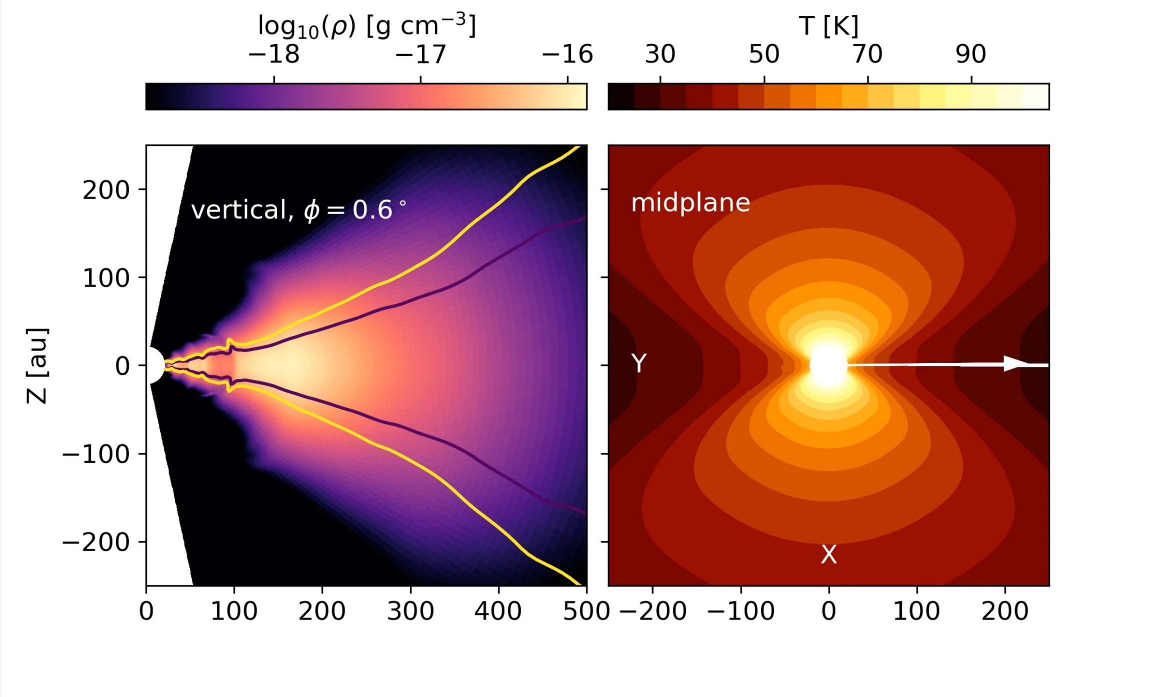


From Phil Armitage's Planet Formation Book

$$\frac{\partial P}{\partial Z} - \rho g_z + \frac{1}{R}\frac{\partial(\rho v_\phi v_Z)}{\partial \phi} = 0.$$

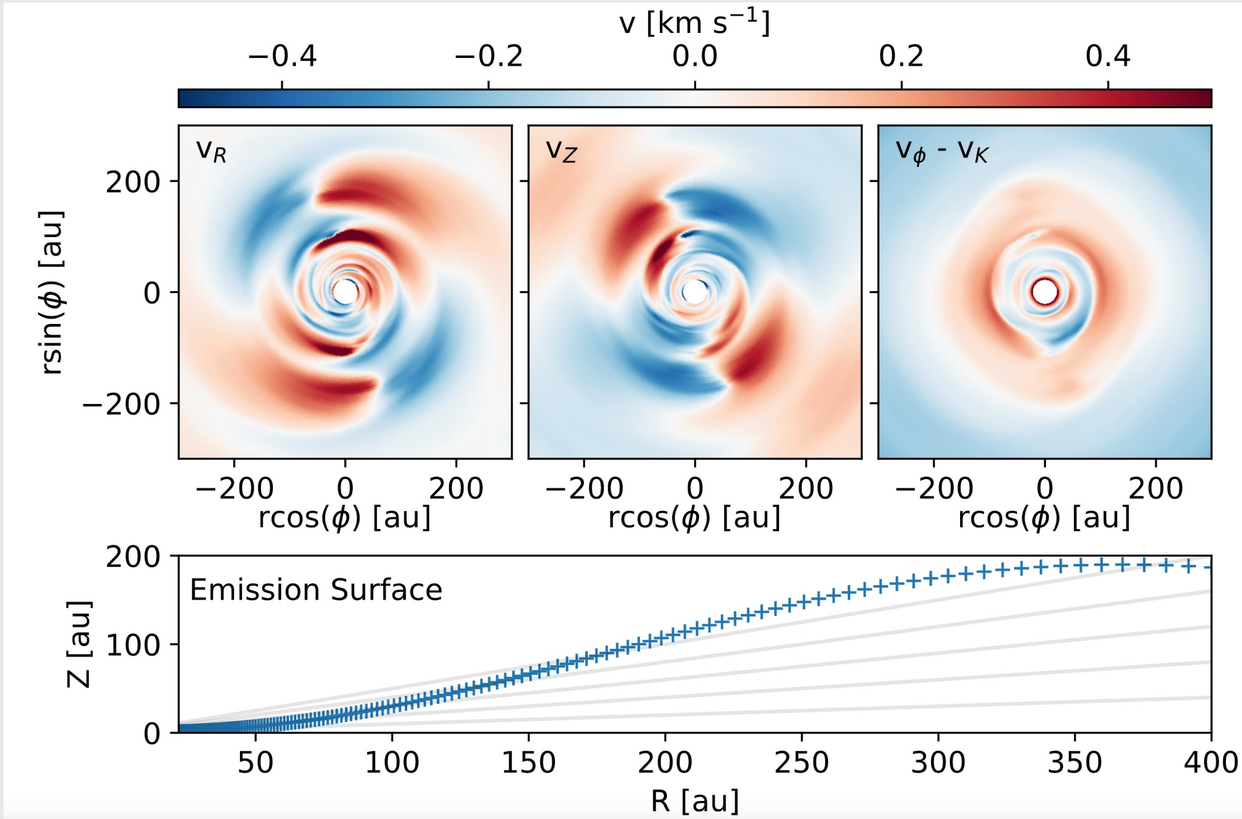
Disk vertical structure

- Gas vertical motion due to shadows
- Vertical gravity is no longer balanced by the pressure gradient
- An azimuthal convective acceleration term is needed



Disk vertical structure

- The vertical motion of the gas can reach ~0.1 km/s
- Can be observed by ALMA.



Summary

- Shadows act as a driving force to launch spirals.
- The spirals lead to accretion with $\alpha \sim 10^{-2}$ in the cavity.
- The spirals launched by shadows can explain the coexistence of shadows and spirals in Near-IR scattered light images.

- The imbalance of vertical gravity and pressure gradient leads to an additional term to compensate in the vertical force equation.
- This additional stress term leads to azimuthal modulation of the vertical velocity, which can be observed in ALMA kinematics.

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