2015.06.02 3rd DTA Symposium
The Origins of Planetary Systems:
from the Current View to New Horizons

# Electron Heating and Suppression of Magnetorotational Turbulence in Protoplanetary Disks

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**Okuzumi & Inutsuka (2015) ApJ 800, 47**

**Mori & Okuzumi, submitted; arXiv# 1505.04896**

# INTRODUCTION

# MRI in Protoplanetary Disks

Disk turbulence affects

angular momentum transport and dust dynamics

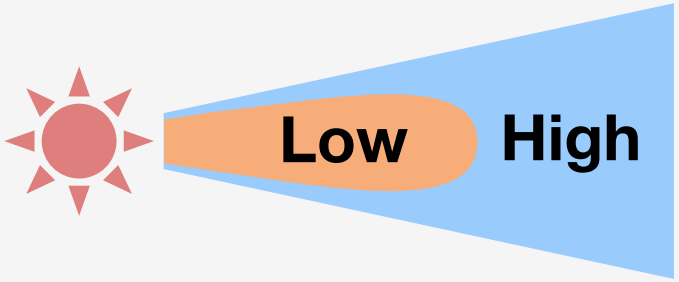
Magnetorotational instability (MRI) is

a possible source of the turbulence

- Interplay between ionized gas and magnetic fields

# Ionization Fraction

MRI growth requires
sufficient ionization fraction




High ionization fraction
→ MRI grows and generates turbulence

Low ionization fraction
→ MRI is stabilized by magnetic dissipation

MRI + Ionization → Turbulence

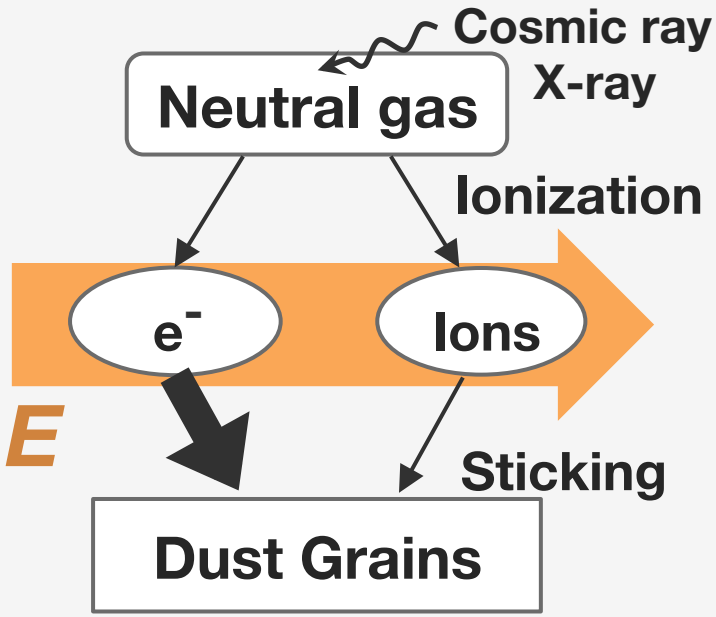
# New Concept: Electron Heating (EH) by MRI

MRI turbulence generates strong electric fields which can heat electrons (**Electron Heating**; Inutsuka & Sano 2005)

Heated electrons stick to grains.

→ Ionization fraction decreases

(Okuzumi & Inutsuka 2015)




→ **Electron heating can suppress MRI turbulence**

# Purpose

**The effect of electron heating on**

**MRI turbulence in PPDs is unknown**

**We investigate**

**WHERE the electron heating occurs and**

**HOW this effect suppresses MRI turbulence**

# MODEL & METHOD

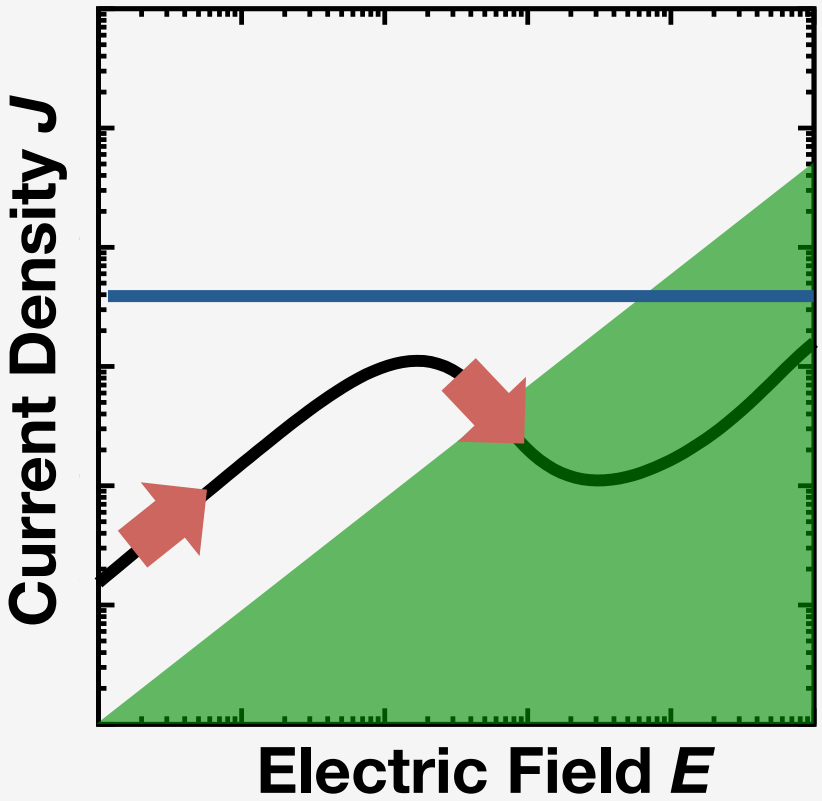
# How to know whether EH occurs and affects MRI turbulence

**Current—Field relation including electron heating**
**(Okuzumi & Inutsuka 2015)**

**MRI has an upper limit of current (Muranushi et al. 2012)**

**Ohmic dissipation stabilizes MRI**
**(Magnetic Reynolds # $R_m < 1$)**

**When MRI grows from E=0, current decreases and Ohmic dissipation occurs**




**→ EH will suppress MRI turbulence**

# Current Density Model & Disk Model

**We calculate the *J-E* relation in the following steps:**

**Given electric field *E***

↓

**Plasma heating**

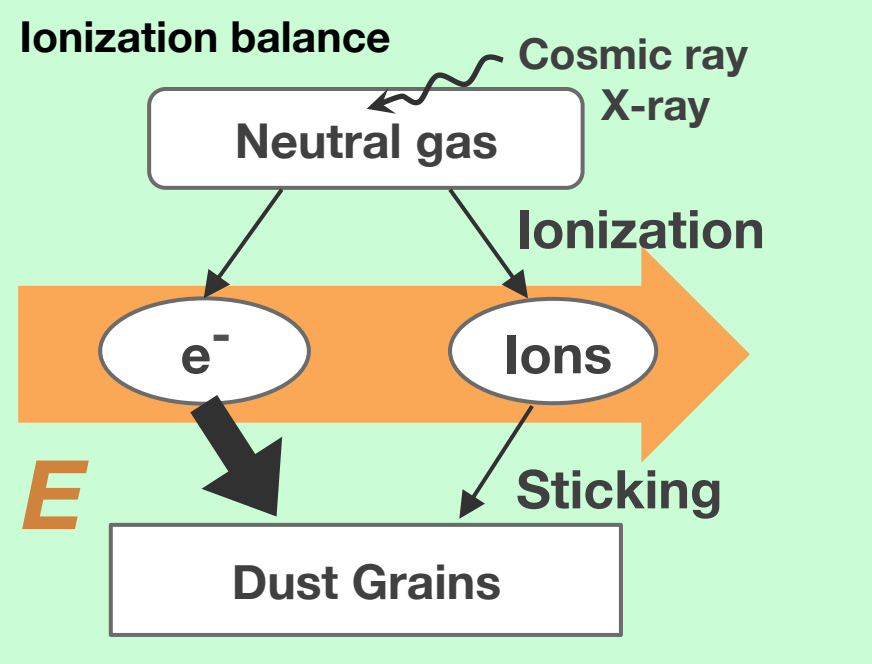
↓

**Number densities $n_e$ and $n_i$ from ionization balance**

↓

$$J = en_e \langle v_e \rangle + en_i \langle v_i \rangle$$

$\langle v_e \rangle$, $\langle v_i \rangle$ : mean drift velocity of e- , +ion

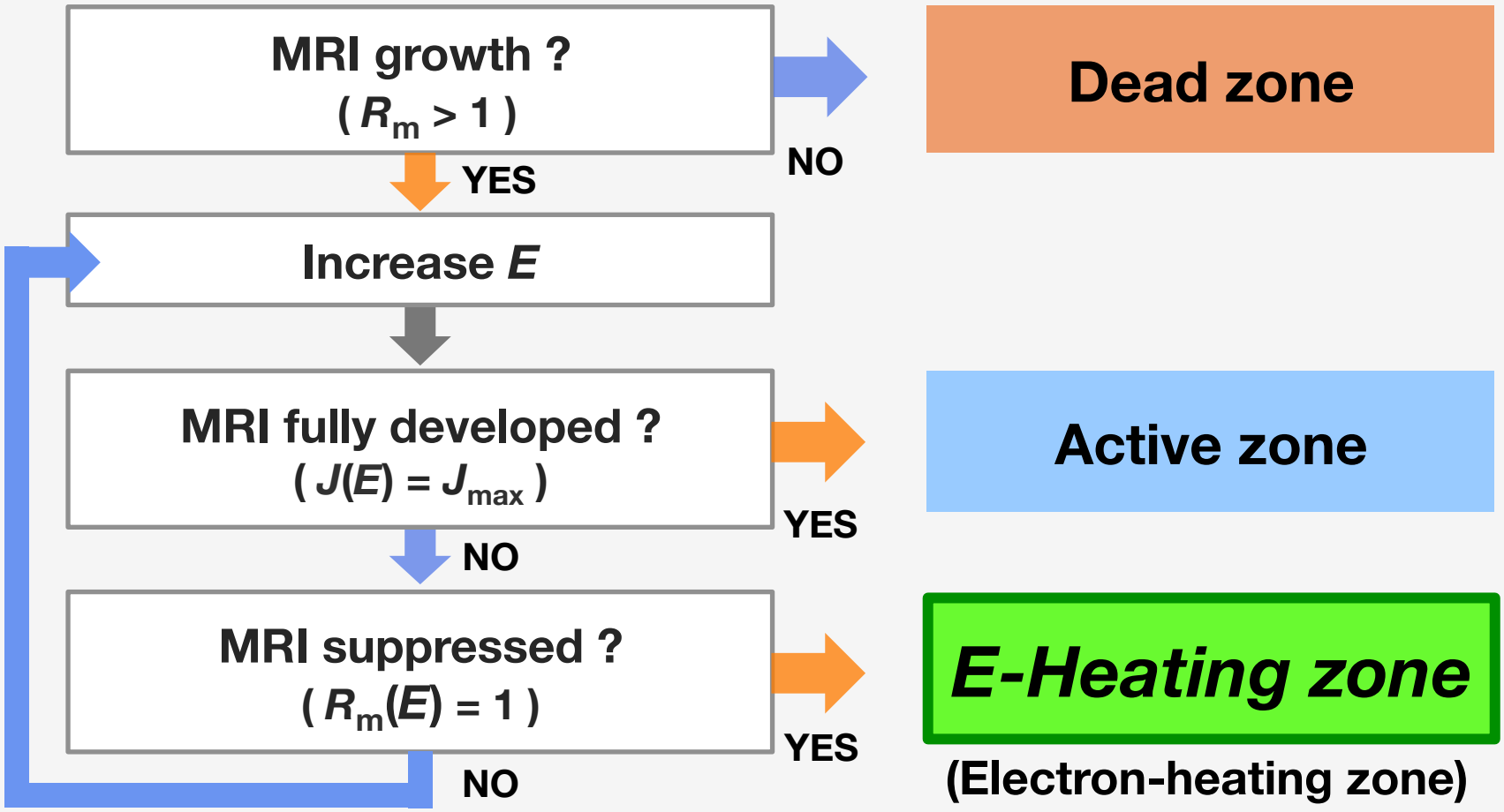



## Disk Model

- MMSN
- Temperature: optically thin
- Midplane $\beta$ (:= $P_{gas}/P_{mag}$) = 1000
- Dust grain : radius = 0.1μm, material density = 3g/cm$^3$
- Dust-to-gas ratio $f_{dg}$ = 0.01

# Determination of Turbulent State

**We determine the turbulent state as follows:**



# RESULTS

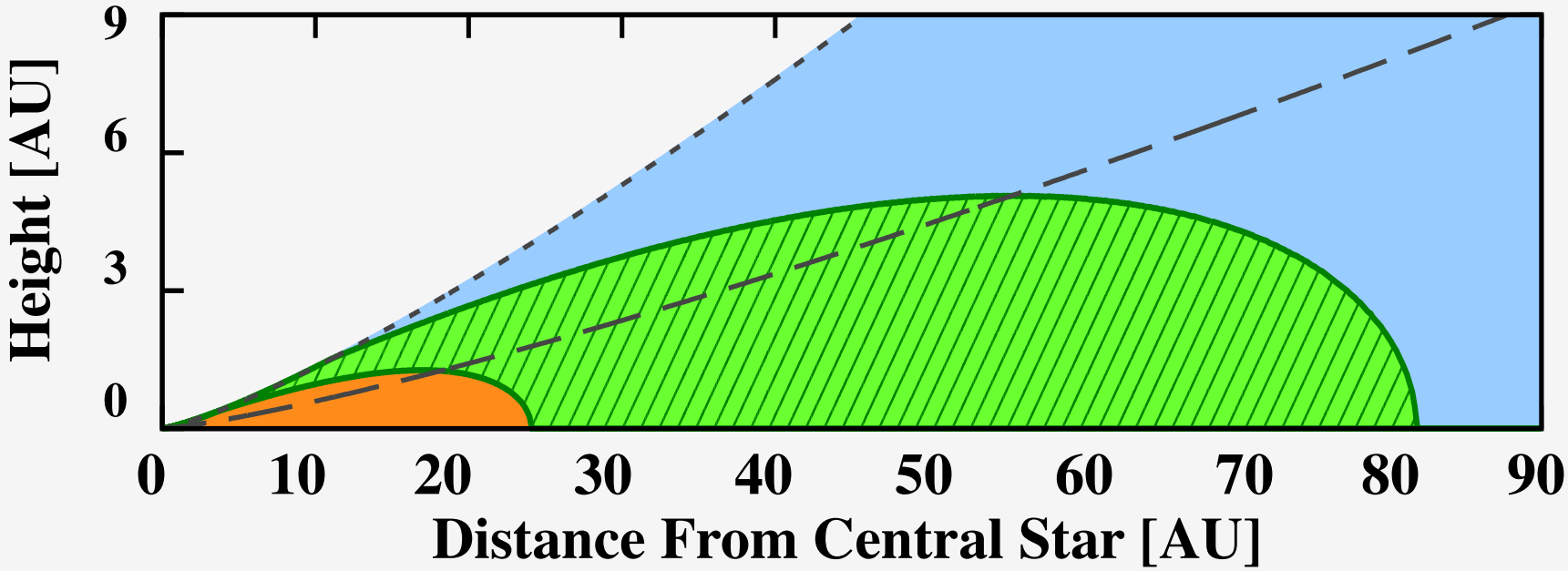
# E-Heating Zone

Mori & Okuzumi, submitted
arxiv# 1505.04896

Dead Zone : MRI is stabilized

E-Heating Zone : Electron heating amplifies Ohmic dissipation

Active Zone : Vigorous MRI turbulence




→ EH region extends out to 80 AU

# How to Estimate Turbulent Strength α

- **Shakura-Sunyaev *α* parameter** (Shakura & Sunyaev 1973)
- **Scaling relation between *α* and $J_{sat}/J_{max}$**

  from Ampere's law, Maxwell stress,

  and simulation results (Sano et al. 2004)

$$\alpha \approx 0.2\left(\frac{\beta_c}{10^3}\right)^{-1}\left(\frac{J_{\rm sat}}{J_{\rm max}}\right)^2 \exp\left(\frac{z^2}{2H^2}\right)$$

(Mori & Okuzumi, submitted)

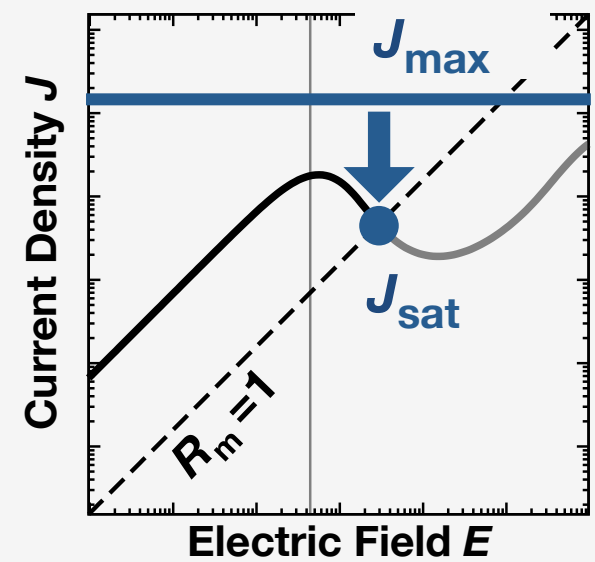
- α in dead zone = 0

**We plot $\alpha_{mid}$ (: midplane α)**

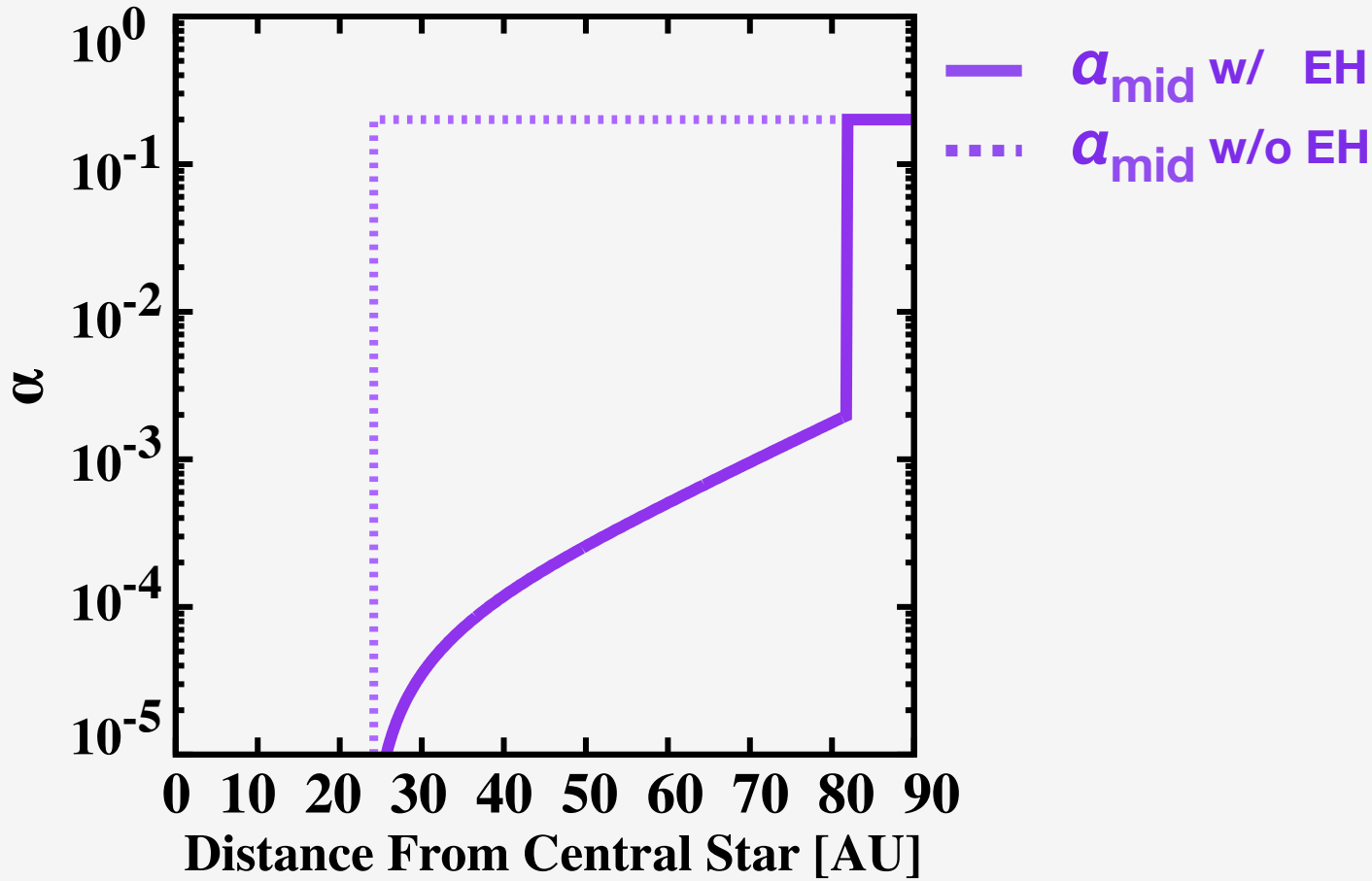
**in the same disk model**

**Assumption :**

***J* is saturated at $R_m = 1$**



# Suppression of MRI Turbulence




$\alpha_{mid}$ (: midplane α) is decreased

by more than two orders of magnitude

# DISCUSSION

# Discussion: Secular GI in HL Tau

## HL Tau observed by ALMA

- Multiple rings
- Widths are typically ~ 10 AU


## Secular Gravitational Instability (Youdin 2011)

- Dust concentration mediated by gas friction with GI

**Takahashi & Inutsuka 2014**

- did linear analysis that consistently treats gas and dust
- found most unstable wavelength is ~ 10 AU at ~ 100 AU

**➔ SGI may explain HL Tau's multiple ring structure**

# Effect of Electron Heating

**The SGI condition (Takahashi & Inutsuka 2014):**

$$\boxed{\left(\frac{\alpha}{4\times10^{-5}}\right)}\left(\frac{f_{dg}}{0.1}\right)^{-2}\left(\frac{Q}{10}\right)^{2}\left(\frac{\eta}{0.01}\right)\lesssim 1$$

$f_{dg}$ **: Dust-to-Gas ratio** $\eta$ **: Pressure/Gravity** $Q$ **: Toomre's Q value**

**➔ Weak turbulence is needed !**

**- Strong turbulence diffuses dust region**

**Electron heating can suppress MRI turbulence far from the star**

**➔ Electron Heating causes SGI ??**

# Test Calculation: Model

## Disk model

**Midplane plasma beta = 1000**

**Stellar Mass = 1.2 $M_\odot$** (White & Hillenbrand 2004)

**(Steady) accretion rate = $6\times10^{-6}$ $M_\odot$/yr** (Hayashi et al. 1993)

**Surface density:**

$$\Sigma(r) = \frac{\dot{M}}{3\pi\alpha_{\rm active} c_s H} = 4\times10^3 \left(\frac{r}{1\,{\rm AU}}\right)^{-1}\ {\rm g/cm^2}$$

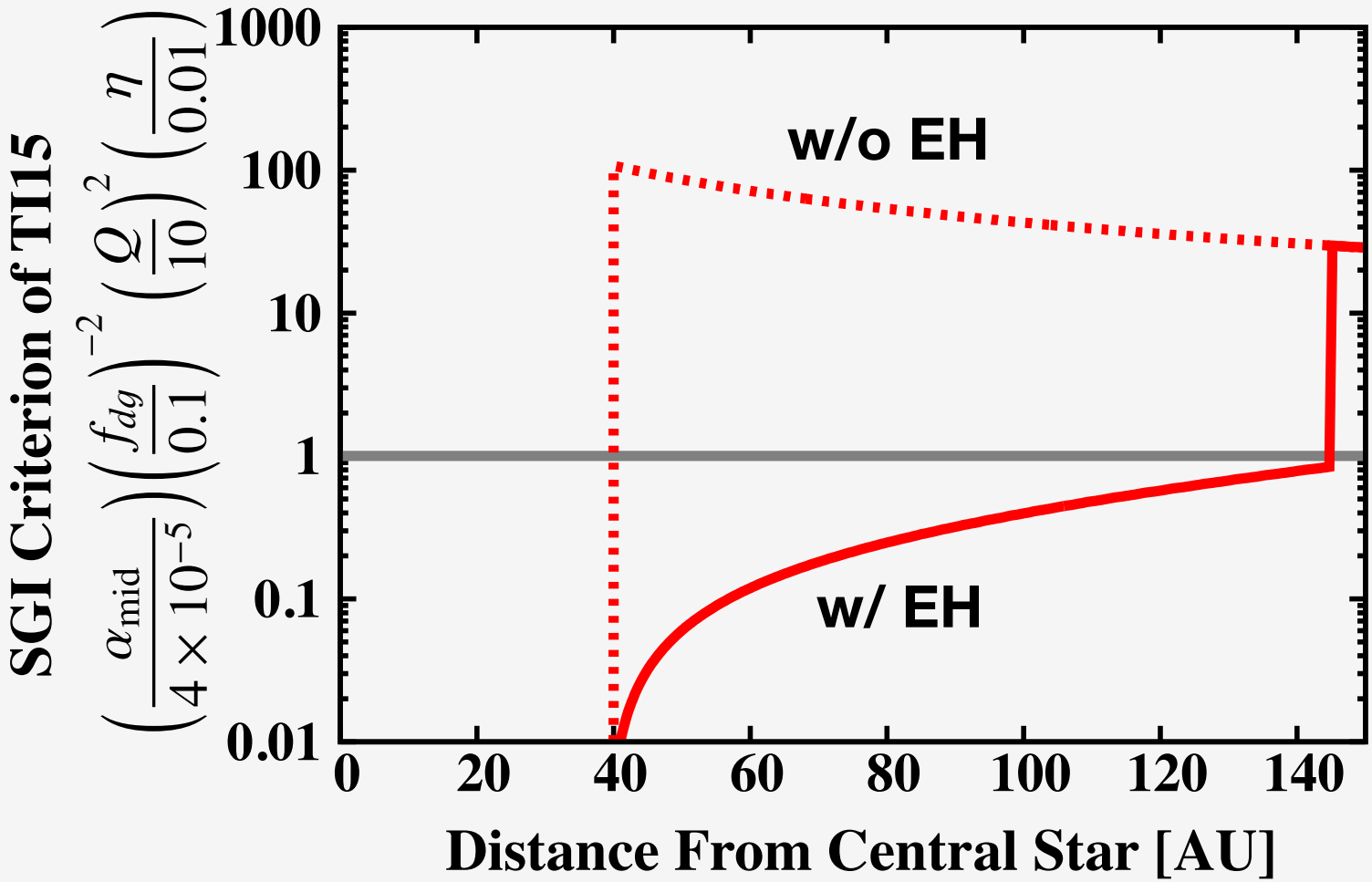
$$\alpha_{\rm active} = 0.2$$

**Dust grain : radius = 1μm**

**Dust-to-gas ratio $f_{\rm dg}$ = 0.1**

**Temperature: optically thin**

# Test Calculation: Result




➔ **Electron heating can cause SGI within ~ 140 AU for this model**

# Summary

We investigated where **electron heating** affects MRI turbulence. We found **e-heating zone** extends out to 80 AU in MMSN with abundant submicron grains.

We also estimated the MRI turbulent strength and found electron heating can **suppresses** the MRI turbulence.

Suppression of turbulence may cause **secular GI** which may explain HL Tau's multiple ring structure.