Dust Growth and Magnetic Fields:
From Cores to Disks

Yasuhiro Hasegawa (JPL/Caltech)

I-Hsiu Li (UIUC), Hau-Yu Baobab Liu (ESO), Naomi Hirano (ASIAA)
Satoshi Okuzumi (TokyoTech), Neal Turner (JPL/Caltech)

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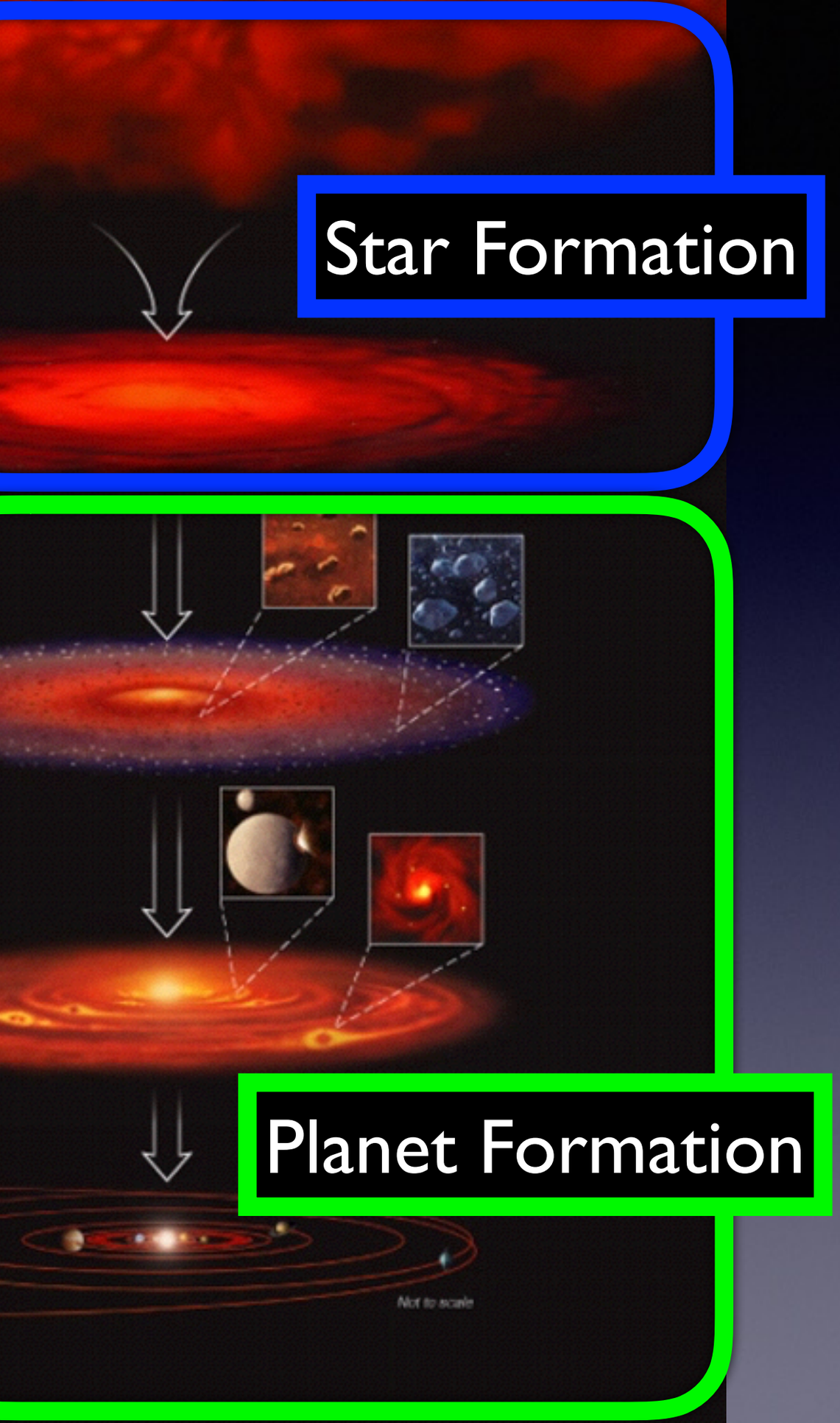
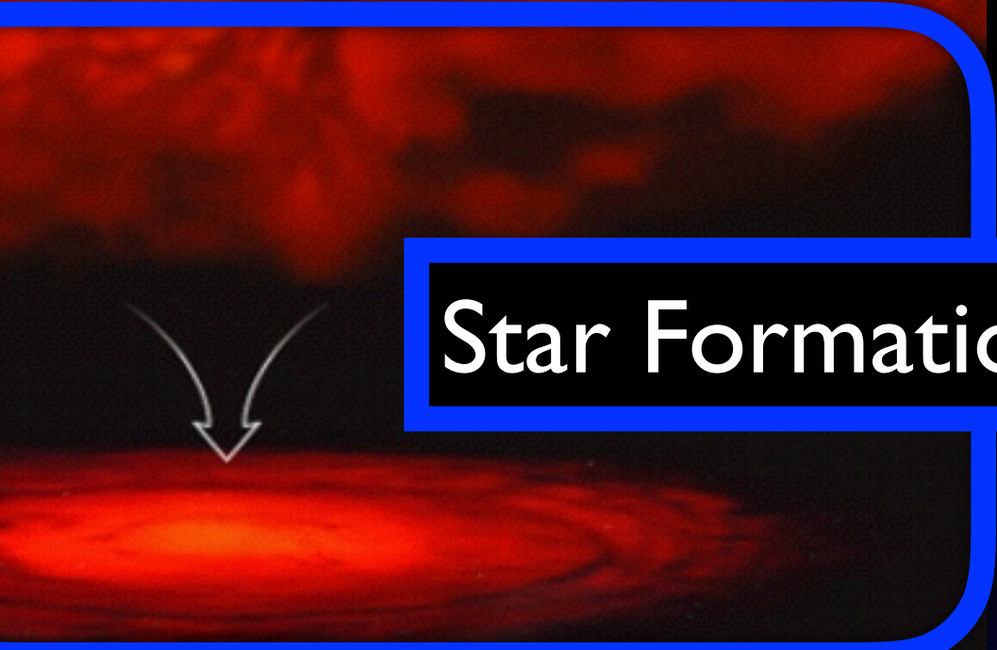
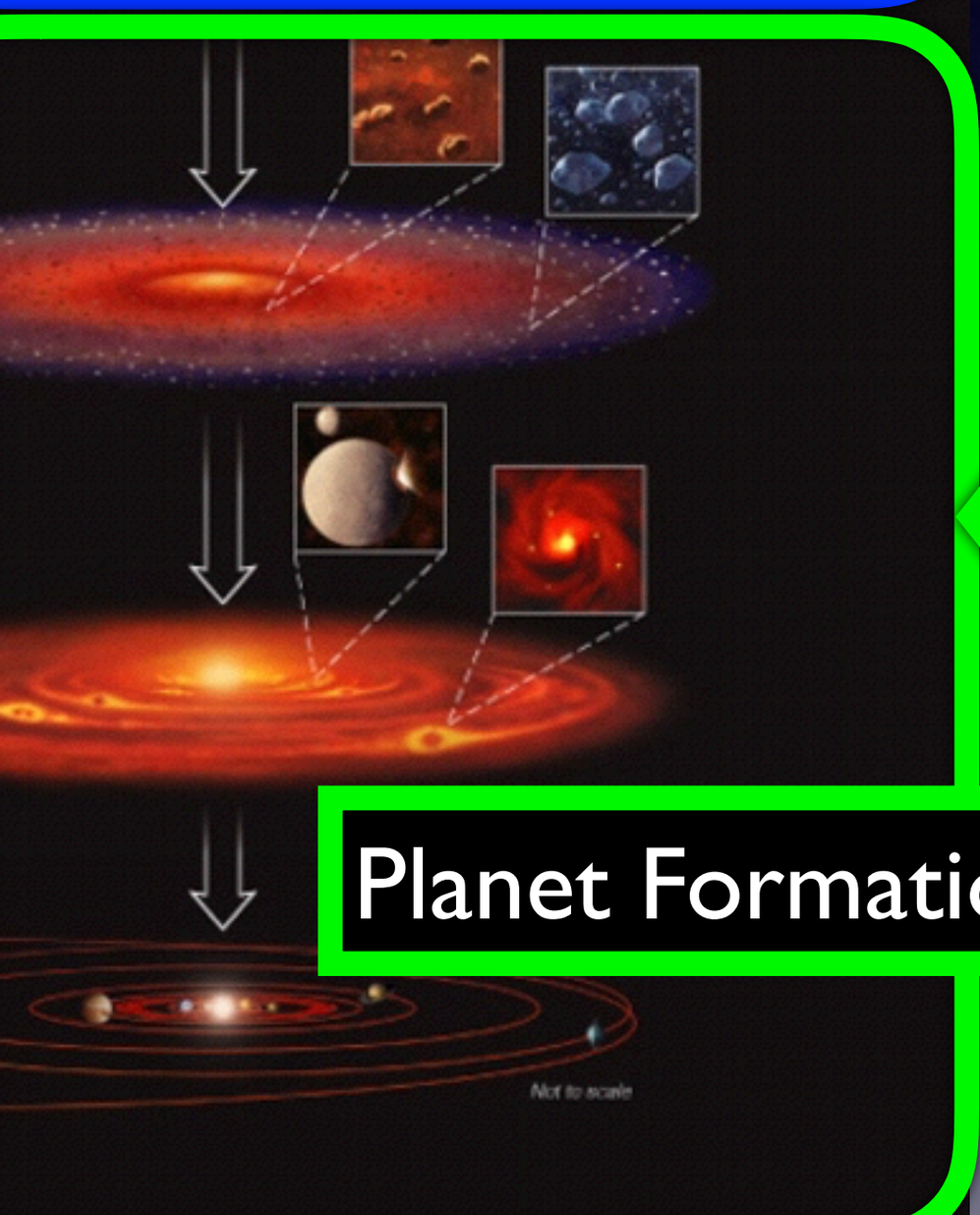

Star Formation
Planet Formation
Not to scale





Radiative Transfer & Planetary Migration

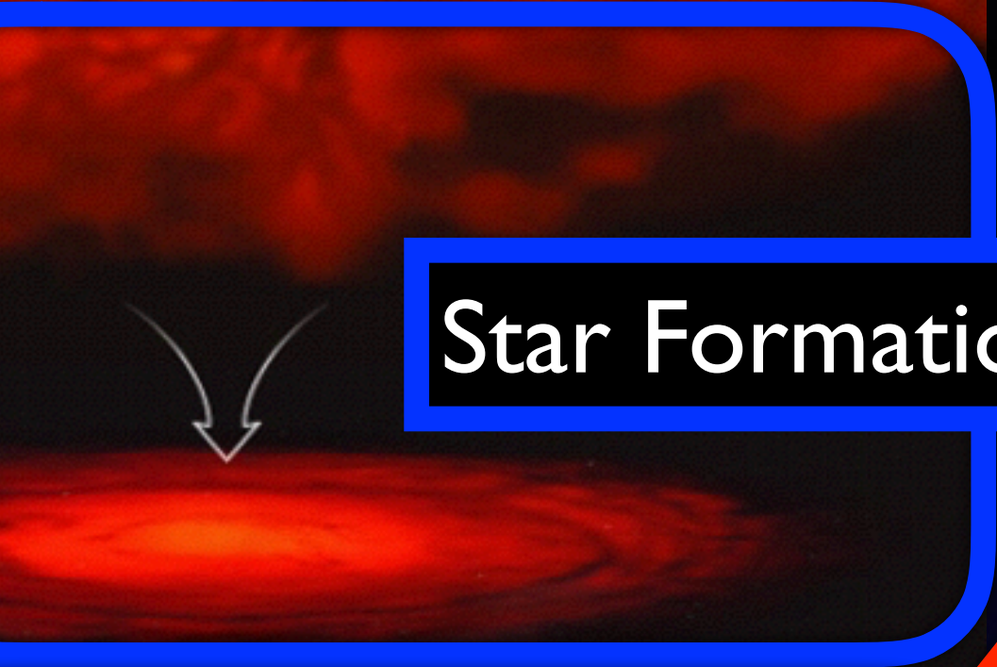
Hasegawa & Pudritz, 2010b, MNRAS, 401, 143
Hasegawa & Pudritz, 2011a, MNRAS, 413, 286

Disk Inhomogeneities & Planet Traps

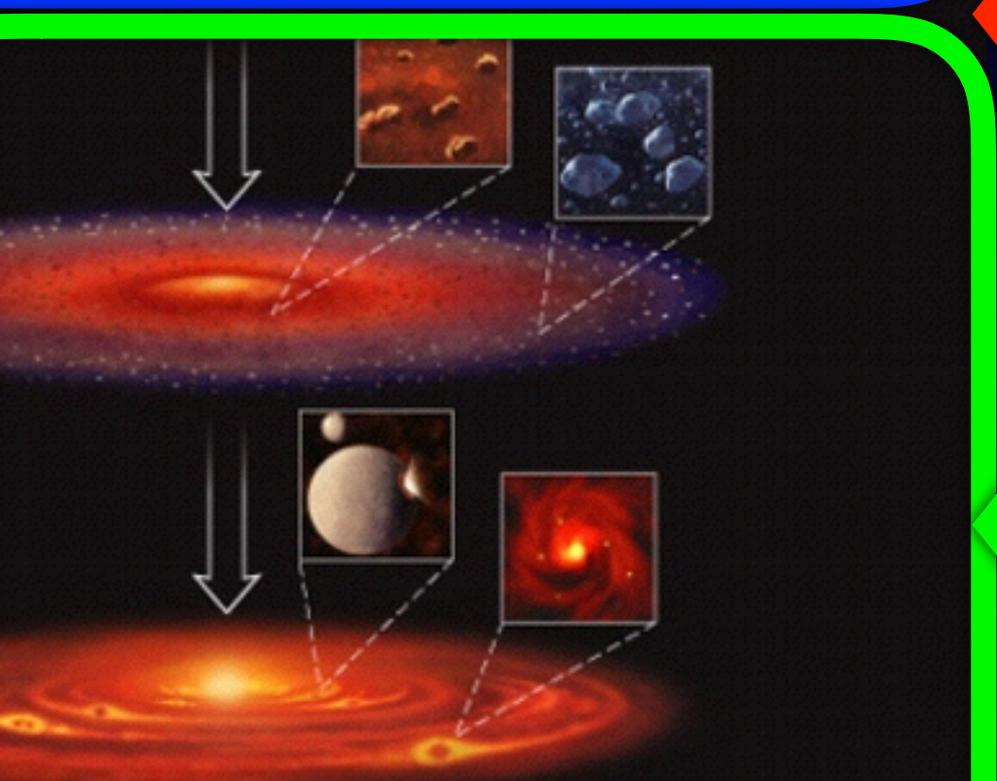
Hasegawa & Pudritz, 2010a, ApJ, 710, L167
Hasegawa & Pudritz, 2011b, MNRAS, 417, 1236

Planet Traps & Planetary Populations

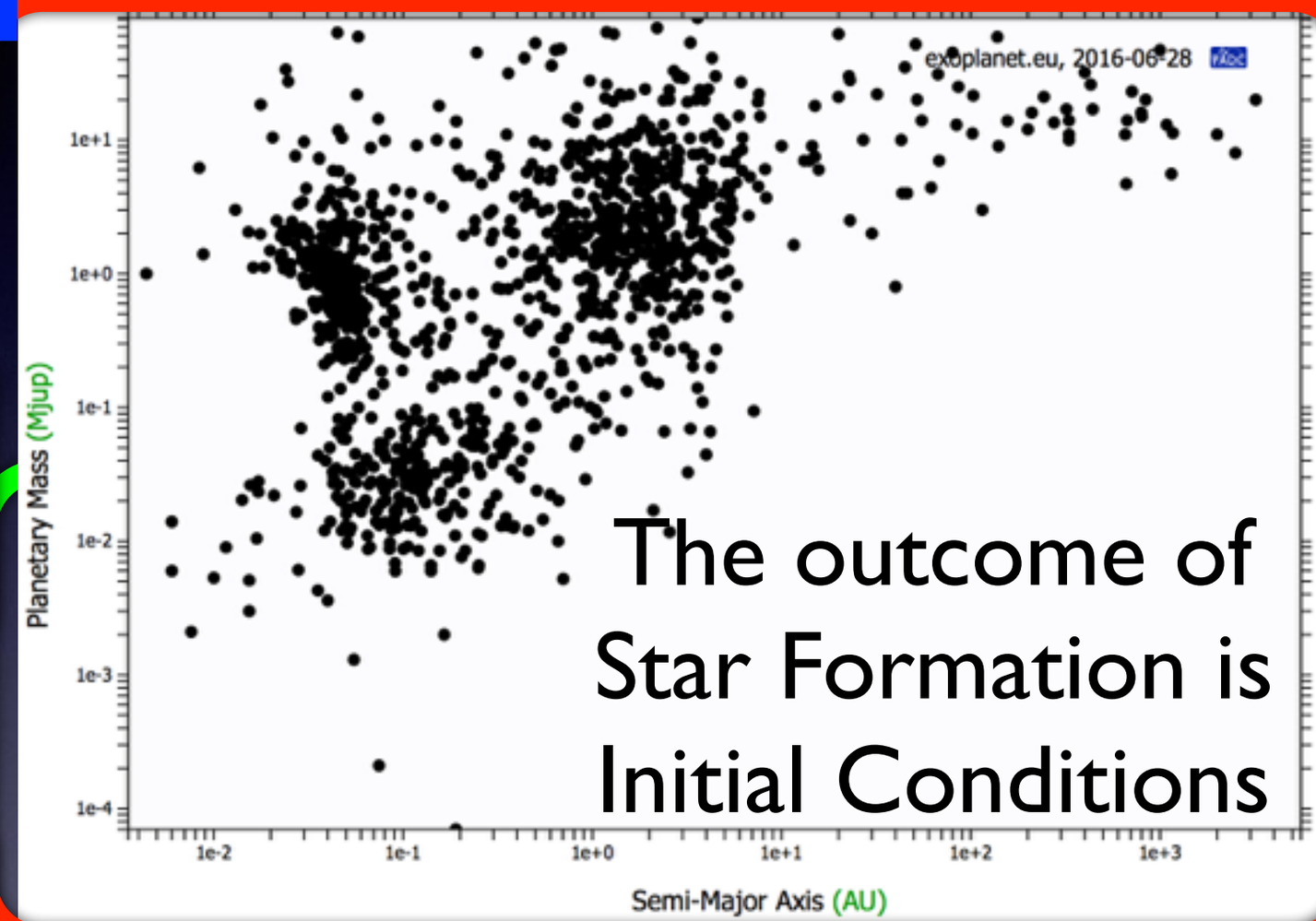
Hasegawa & Pudritz, 2012, ApJ, 760, 117
Hasegawa & Pudritz, 2013, ApJ, 778, 78
Hasegawa & Pudritz, 2014, ApJ, 794, 25
Hasegawa, 2016, ApJ, submitted



Star Formation



Planet Formation



The outcome of Star Formation is Initial Conditions

Hasegawa & Pudritz, 2011b, MNRAS, 417, 1236

Planet Traps & Planetary Populations

Hasegawa & Pudritz, 2012, ApJ, 760, 117
Hasegawa & Pudritz, 2013, ApJ, 778, 78
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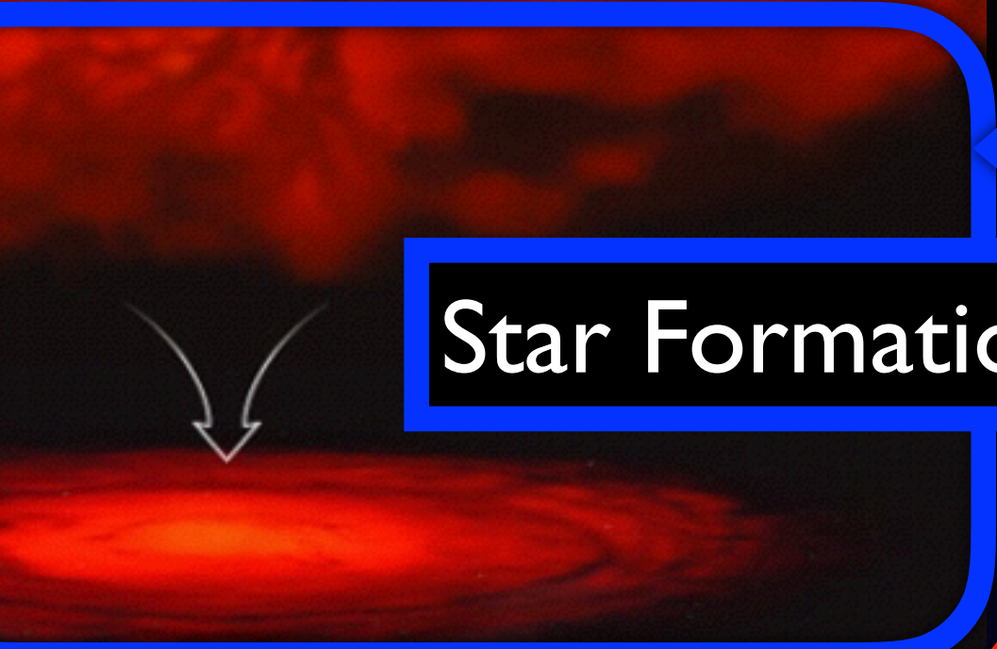
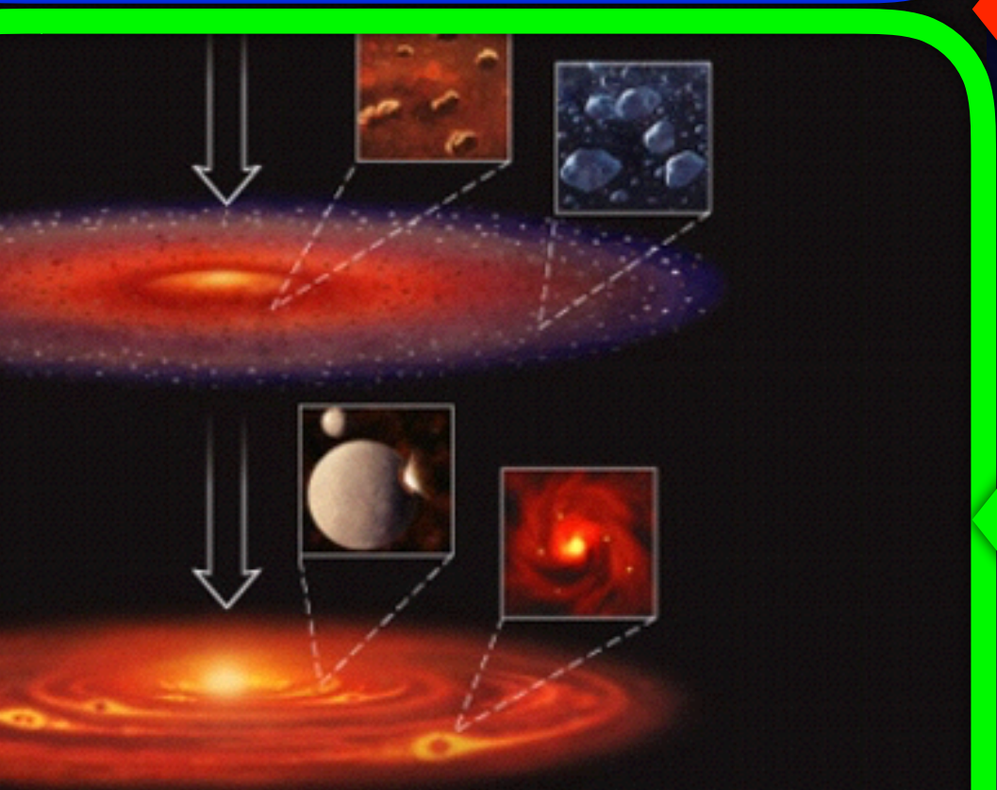
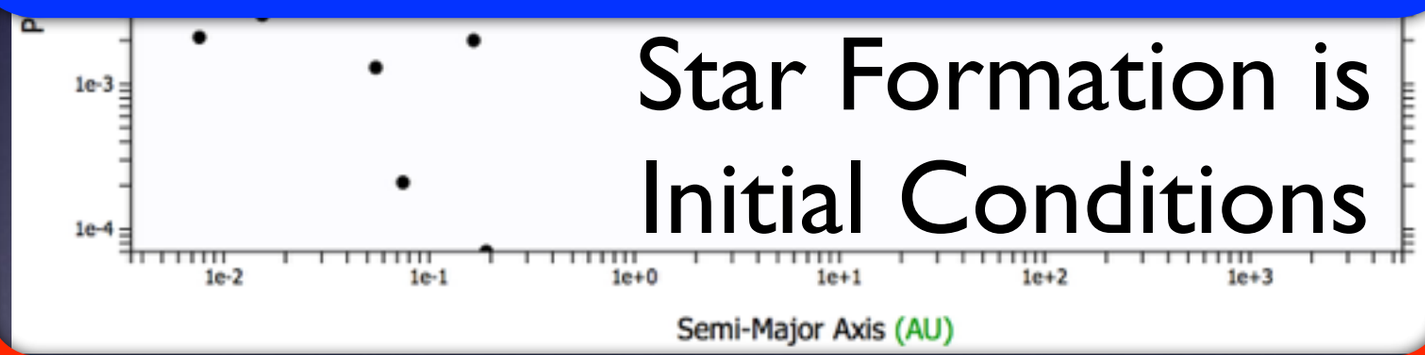


Star Formation



Planet Formation



Star Formation is Initial Conditions

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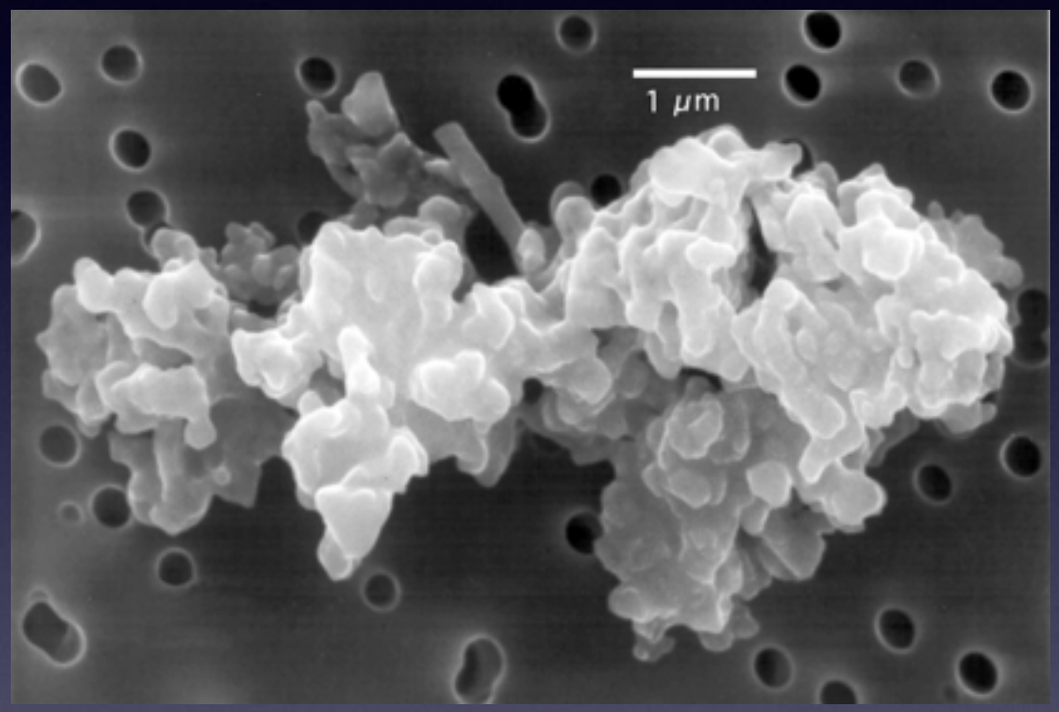
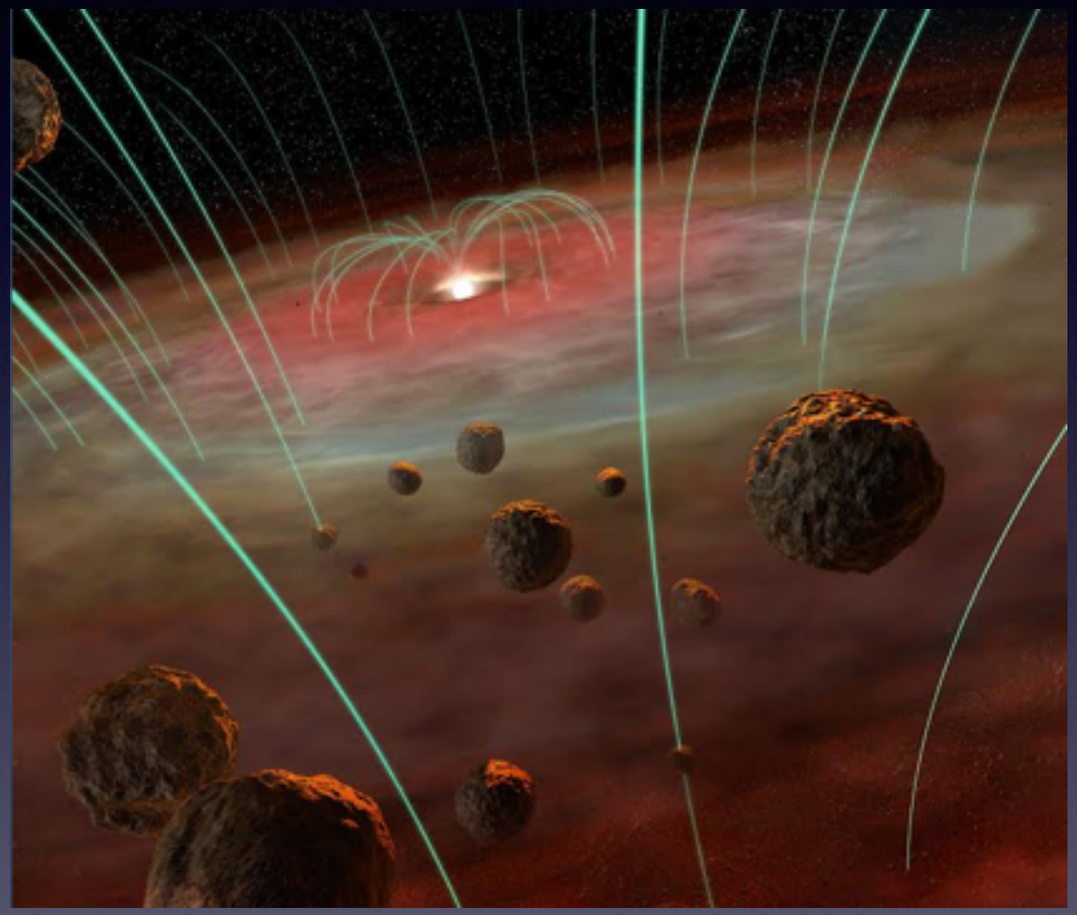
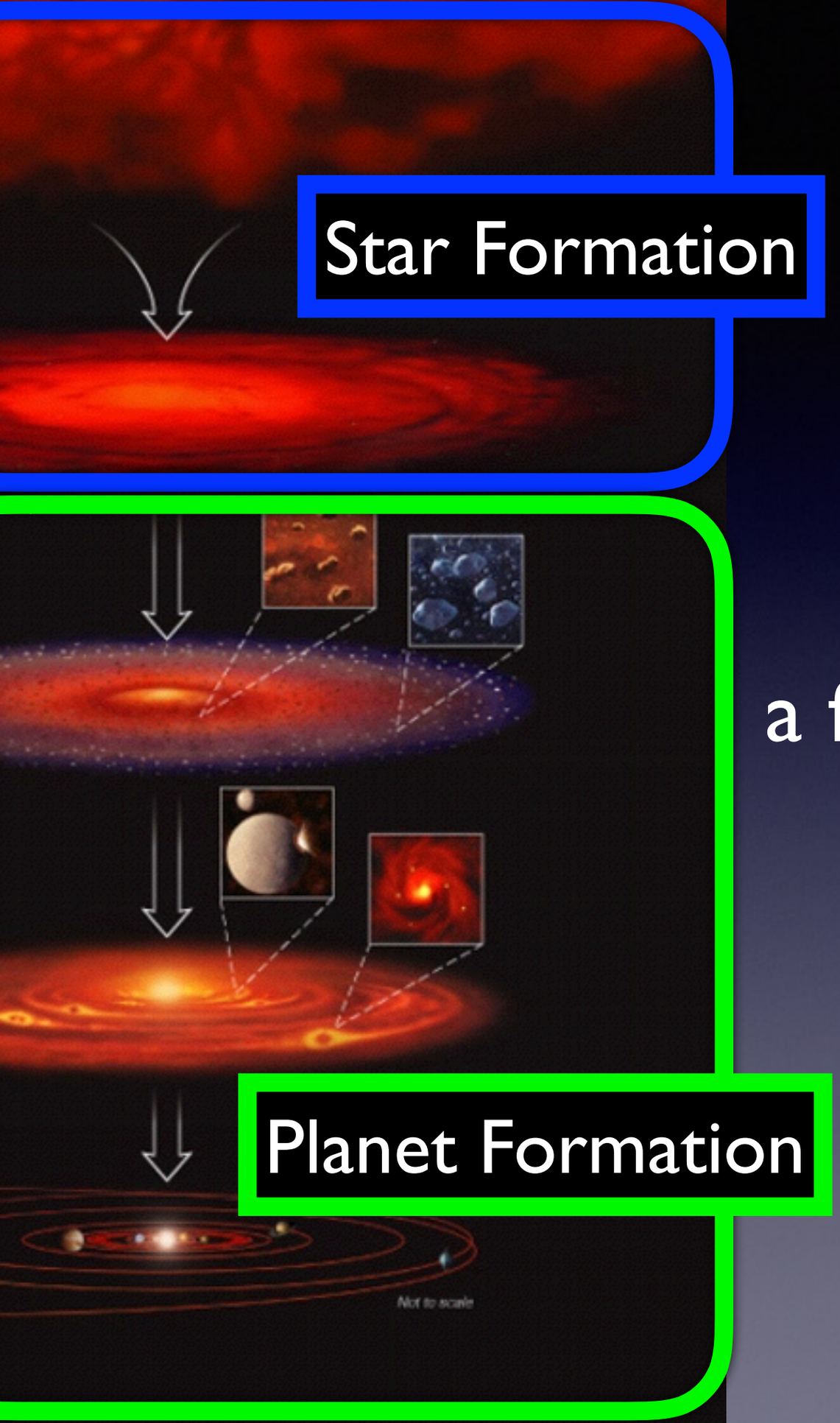
Dust Growth
in Class 0/I YSOs



Magnetic Fields
in Circumstellar Disks



They can make vital connections
between star and planet formation!!



Dust Growth in Class 0/I YSOs

When does dust growth,
a first step of planet formation,
occur??

I-Hsiu Li (UIUC),
Hau-Yu Baobab Liu (ESO),
Naomi Hirano (ASIAA)

Accretion (condensation)

the dust size:

$$< 2 \times 10^{-2} \mu m$$

Draine 1985

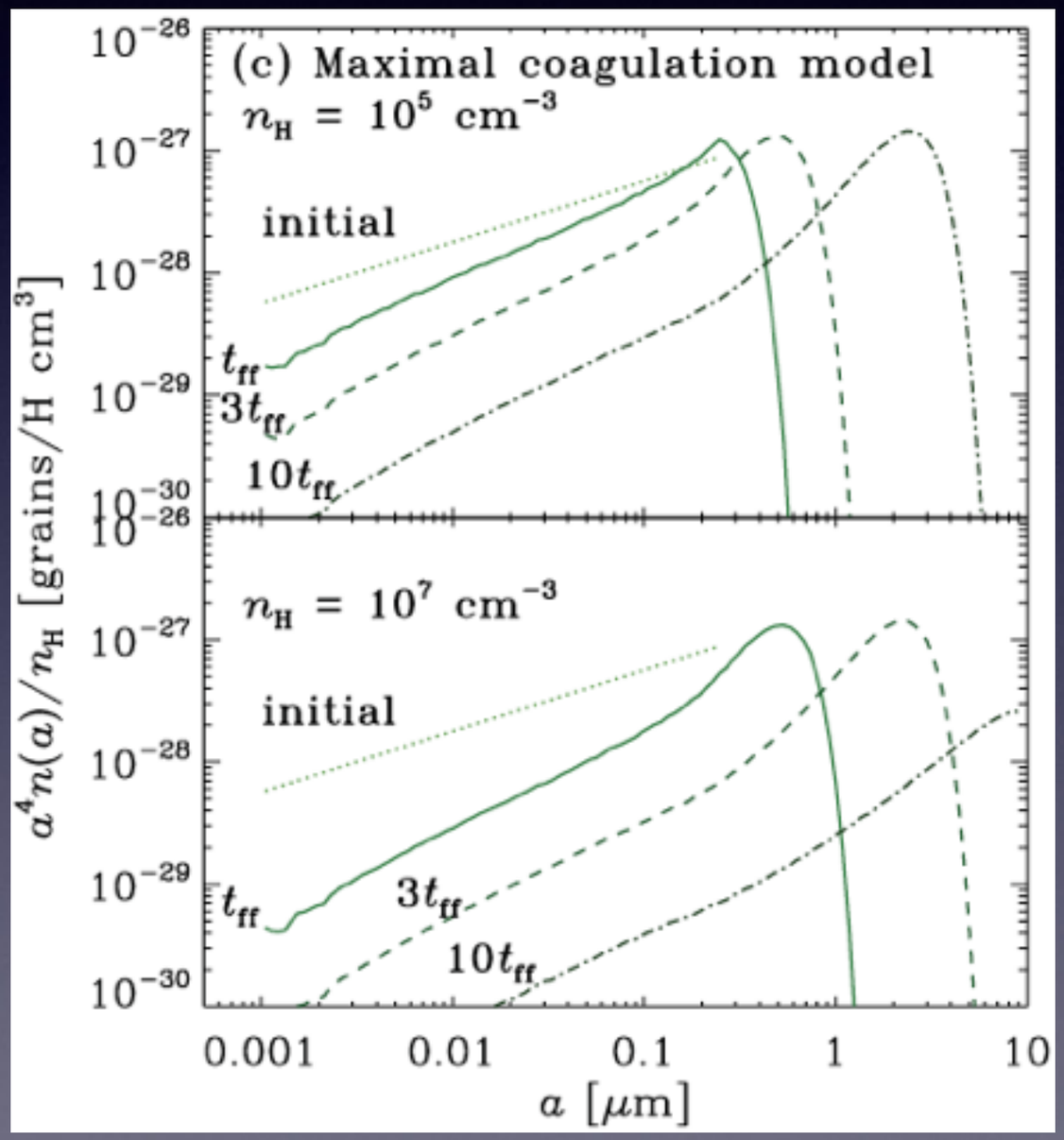
Coagulation (collisions)

the dust size:

$$> 1 \times 10^{-1} \mu m$$

Theoretical points of view…

it is extremely difficult to form larger (~ 1mm) grains in Class 0/I YSOs



Dust grains > 10 micron only when

grains are sticky

the density is high

the lifetime is vey long

Note that T ~ 10 K & $t_{ff} \simeq 10^5 \mathrm{yr}$

e.g., Ormel et al 2009, Hirashita & Li 2013

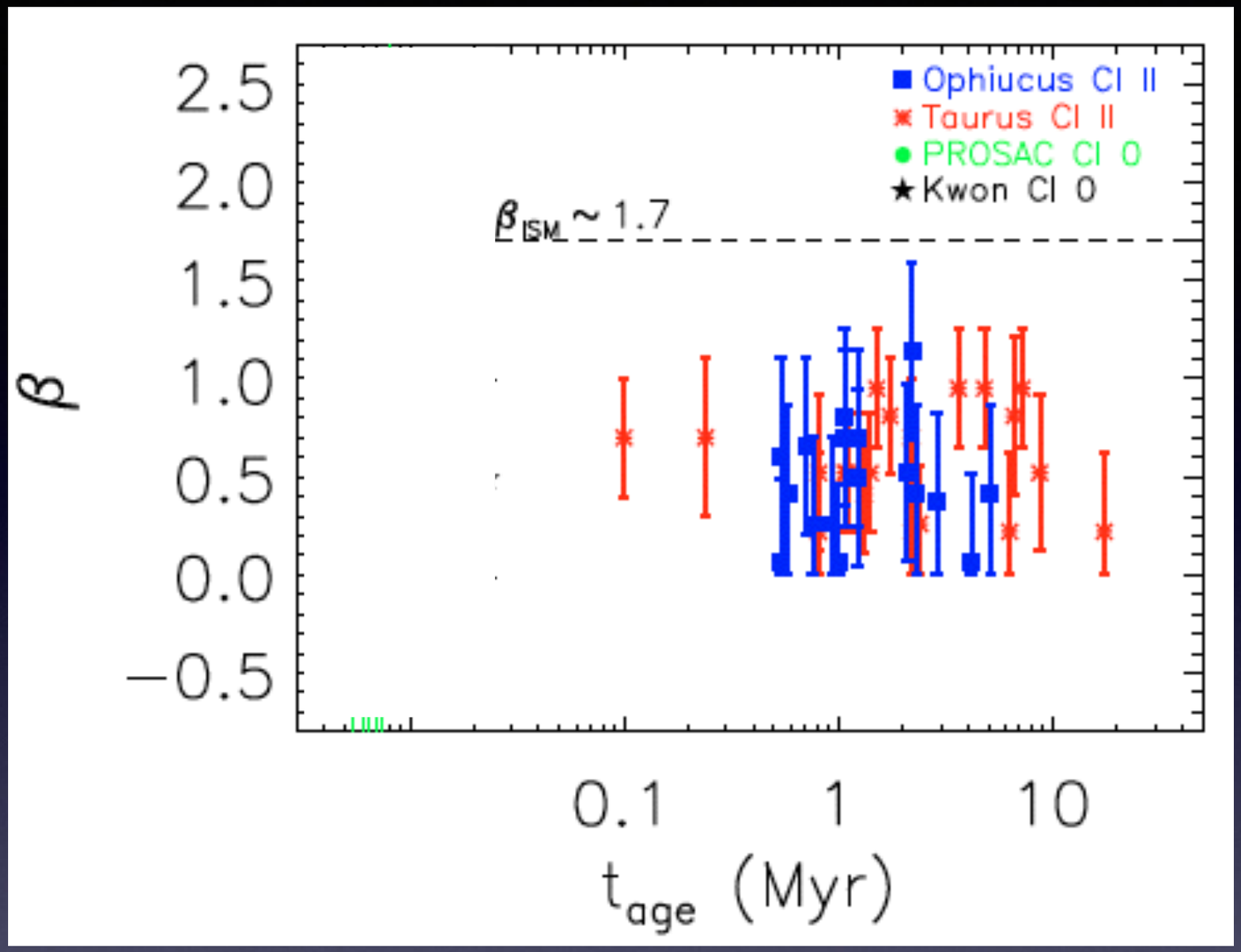
How about observations??

Spectral index (α)

$\alpha = 2$ for optically thick regimes

$\alpha = \beta + 2$ for optically thin regimes

$\beta < 2$: indication for grain growth



Class II YSOs (protoplanetary disks)

: beta < 1

: grain growth occurs

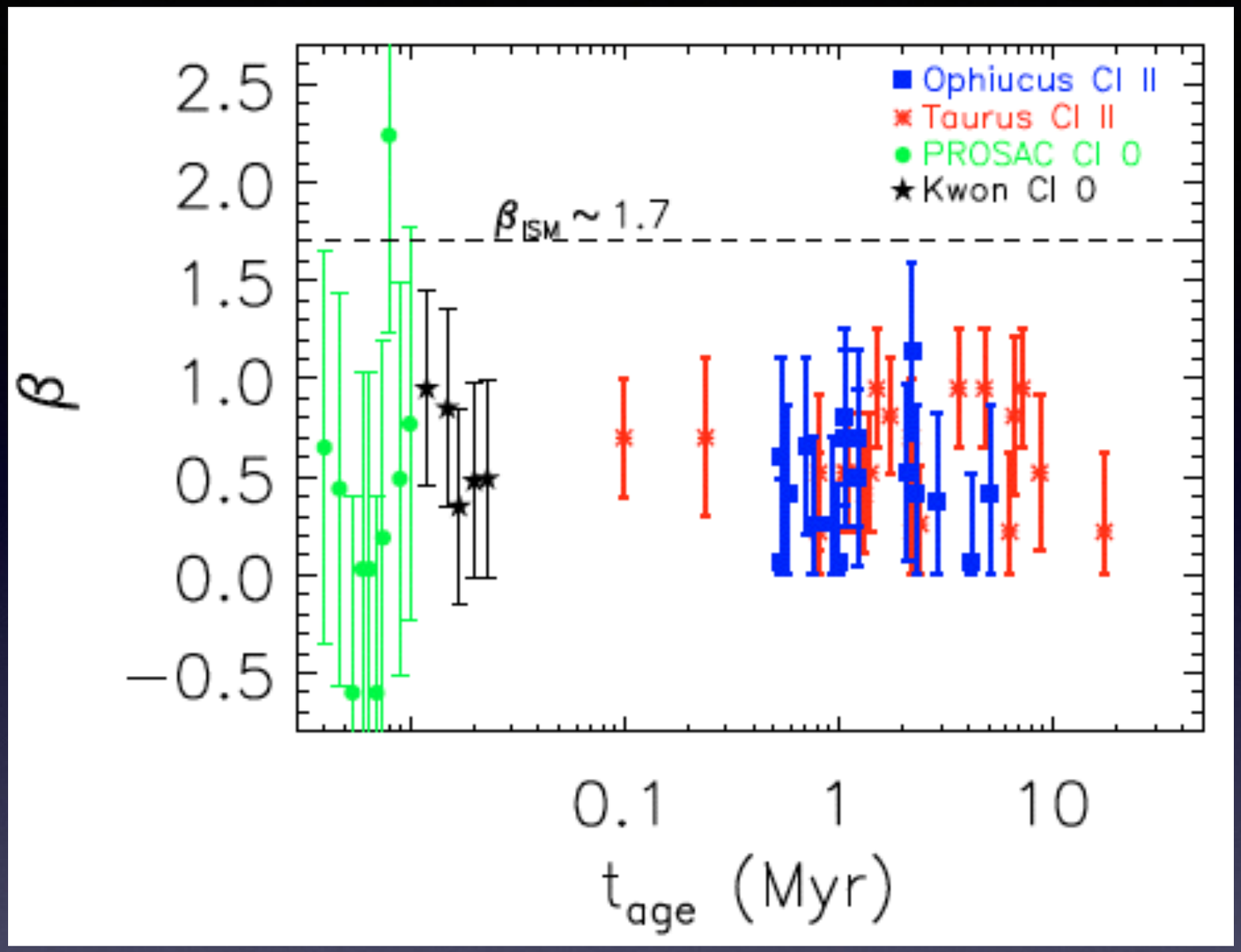
Spectral index (α)

$\alpha = 2$ for optically thick regimes

$\alpha = \beta + 2$ for optically thin regimes

$\beta < 2$: indication for grain growth

e.g., Joergensen et al 2007, Ricci et al 2010, Tobin et al 2013, Miotello et al 2014



Class II YSOs
(protoplanetary disks)
: beta < 1
: grain growth occurs

Class 0/I YSOs
: beta < 1
: grain growth occurs

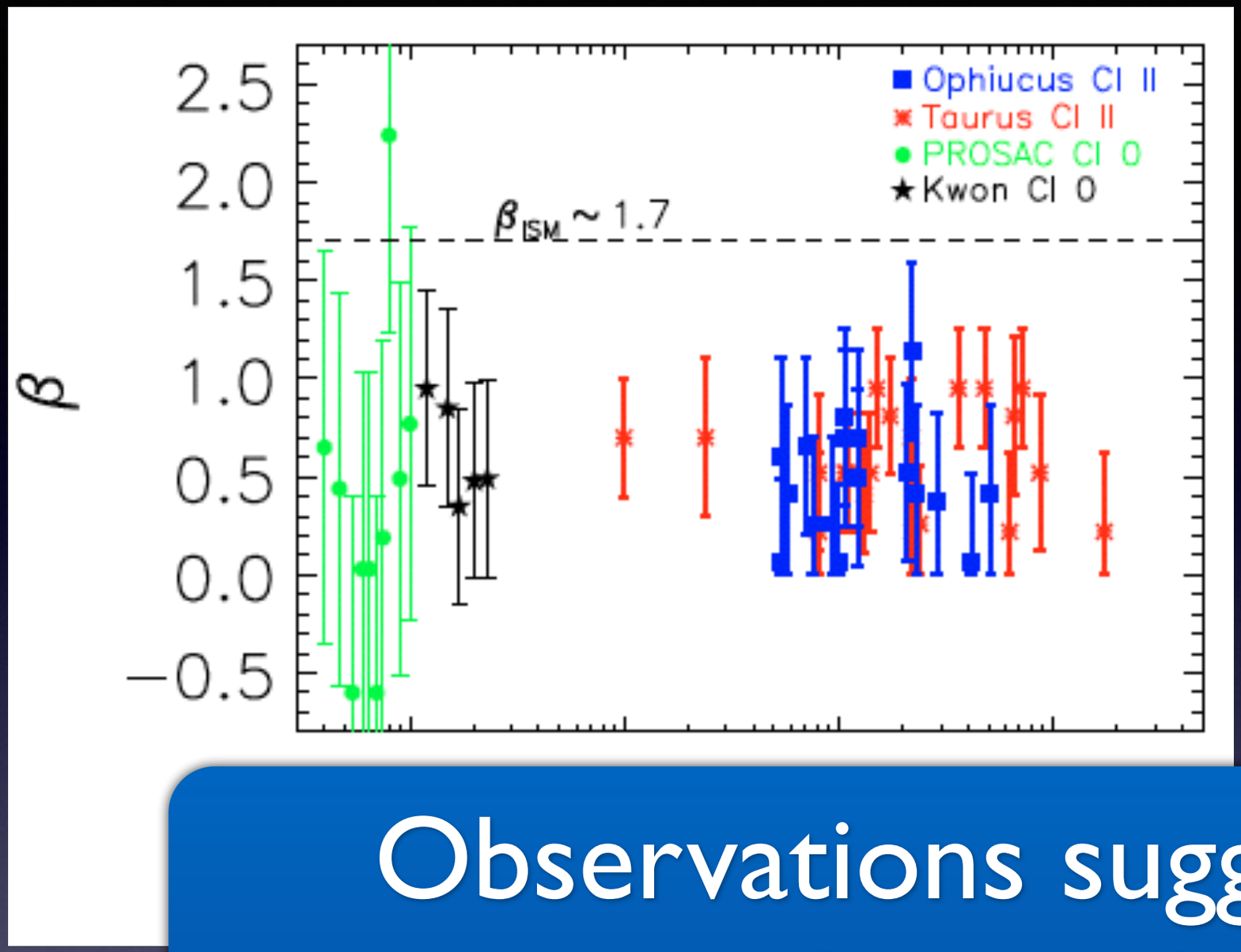
Spectral index (α)

$\alpha = 2$ for optically thick regimes

$\alpha = \beta + 2$ for optically thin regimes

$\beta < 2$: indication for grain growth

e.g., Joergensen et al 2007, Ricci et al 2010, Tobin et al 2013, Miotello et al 2014



Class II YSOs
(protoplanetary disks)
: beta < 1
: grain growth occurs

Class 0/I YSOs
: beta < 1
: grain growth occurs

Spe

nes

es

Observations suggest that larger (~ 1mm) grains do exist in Class 0/I YSOs!!

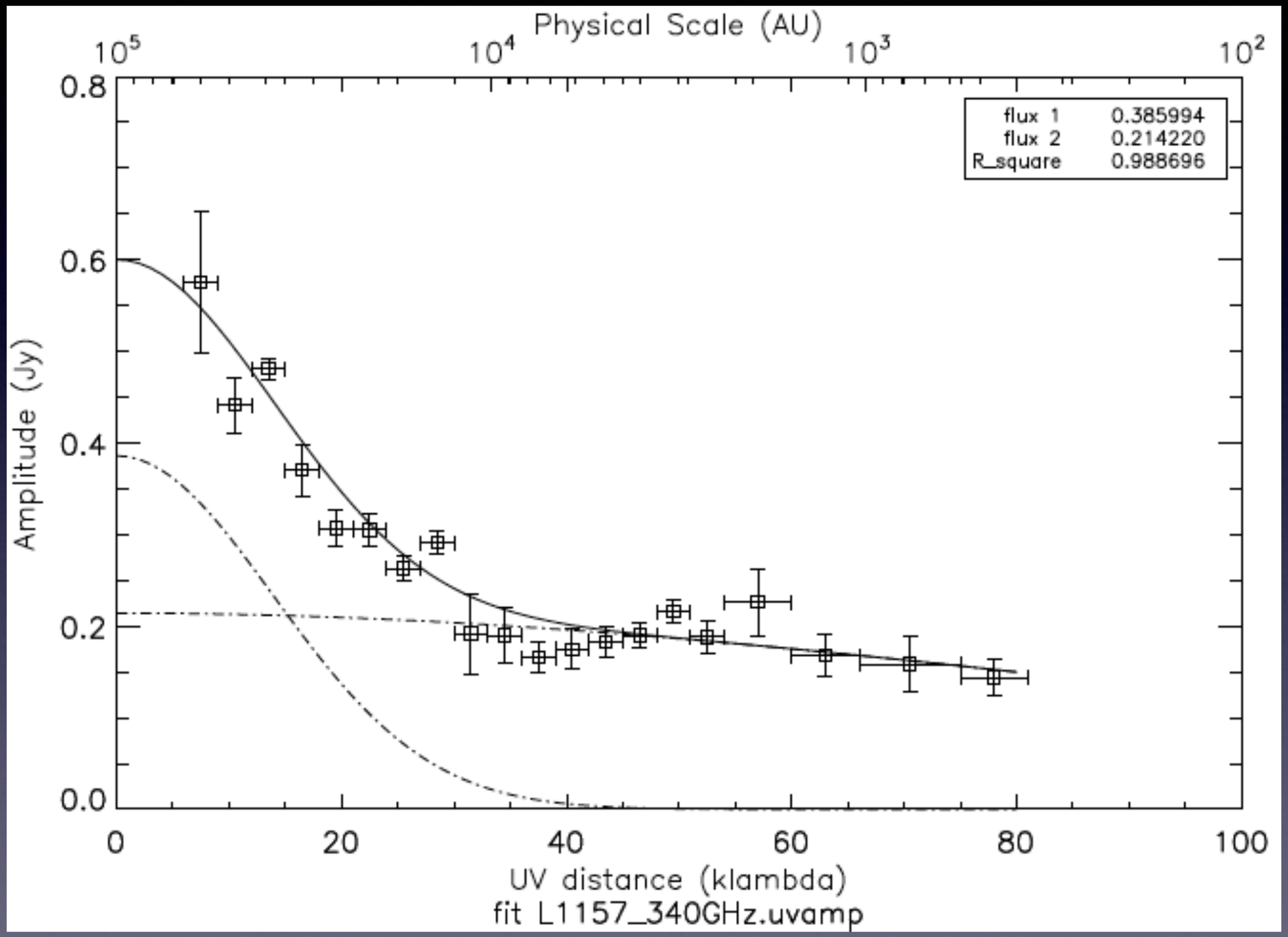
e.g., Joergensen et al 2007, Ricci et al 2010, Tobin et al 2013, Miotello et al 2014

List of our targets

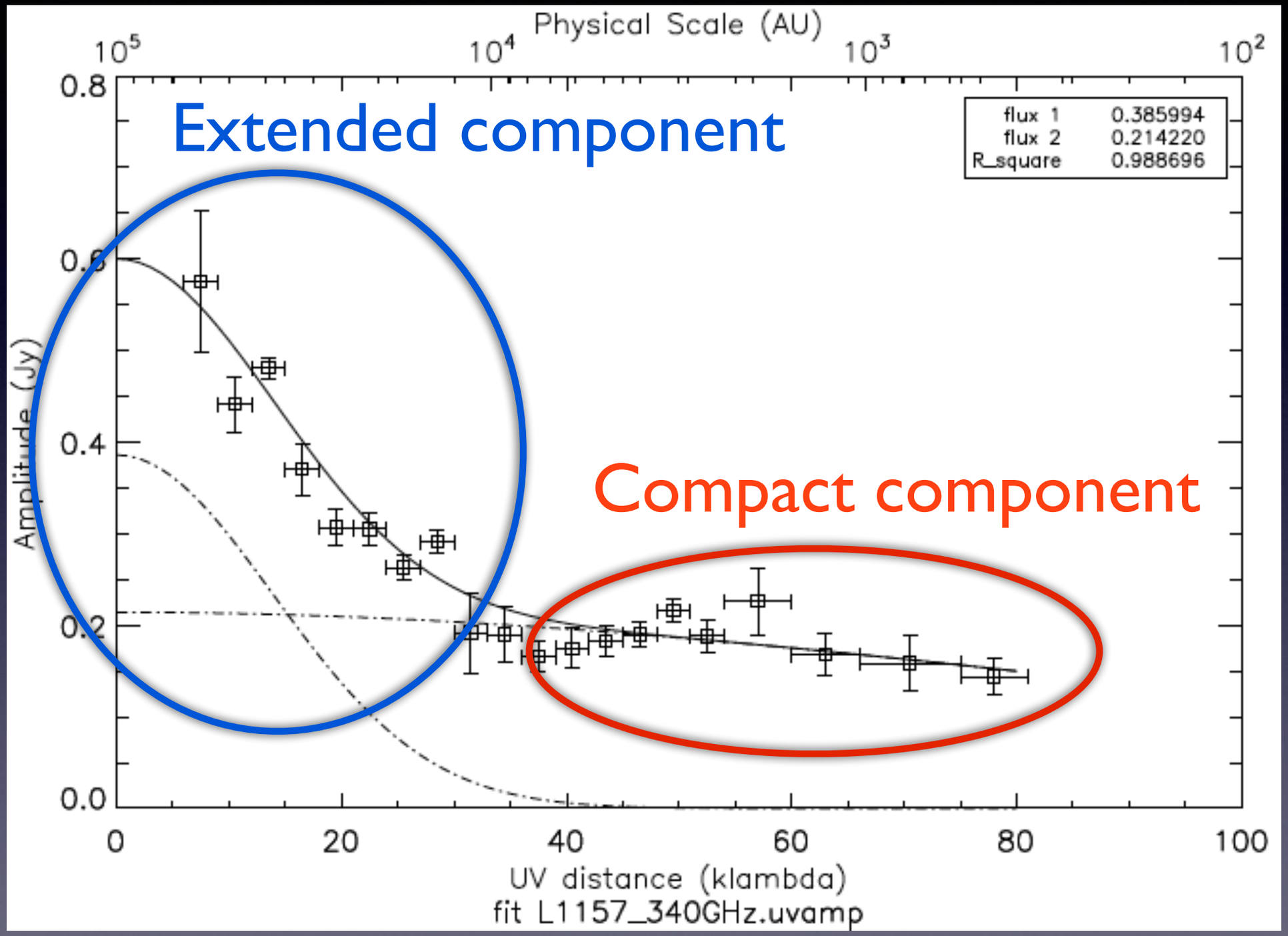
Source Name	R.A. and Dec.	Region	Distance (pc)	Class
L1448 IRS3	03:25:36.00, +30:45:20.0	Perseus	240	0/I
L1448C	03:25:38.80, +30:45:05.0	Perseus	240	0
NGC1333 IRAS2 (A, B)	03:28:55.70, +31:14:37.0	Perseus	240	0
NGC1333 IRAS4 (A1, A2)	03:29:10.50, +31:13:31.0	Perseus	240	0
Barnard 1b (N, S)	03:33:21.14, +31:07:35.3	Perseus	240	0
L1527	04:39:53.90, +26:03:10.0	Taurus	140	0/I
L483	18:17:29.86, −04:39:38.8	Isolated	200	0/I
Serpens FIRS 1	18:29:49.80, +01:15:20.6	Serpens	415	0/I
L1157mm	20:39:06.19, +68:02:15.9	Isolated	325	0

use the archive data of
SMA (0.88mm, 1.3mm, 1.6mm)
VLA (7mm, 1.36cm, 2cm, 3.7cm)
ALMA (0.88mm)
CARMA (3mm)
Spitzer MIPS (24 micron, 70 micron)

Example: visibility data



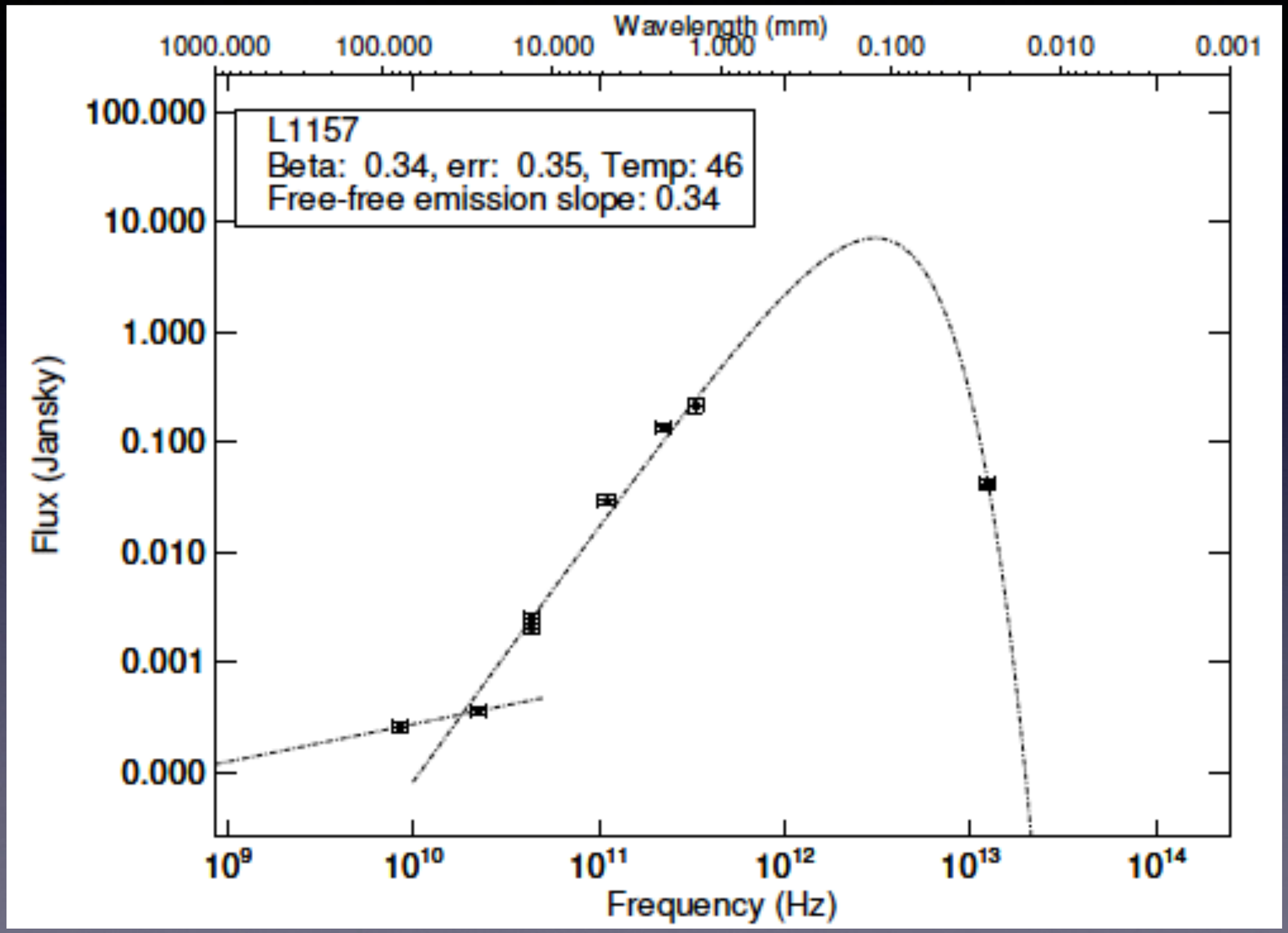
Example: visibility data



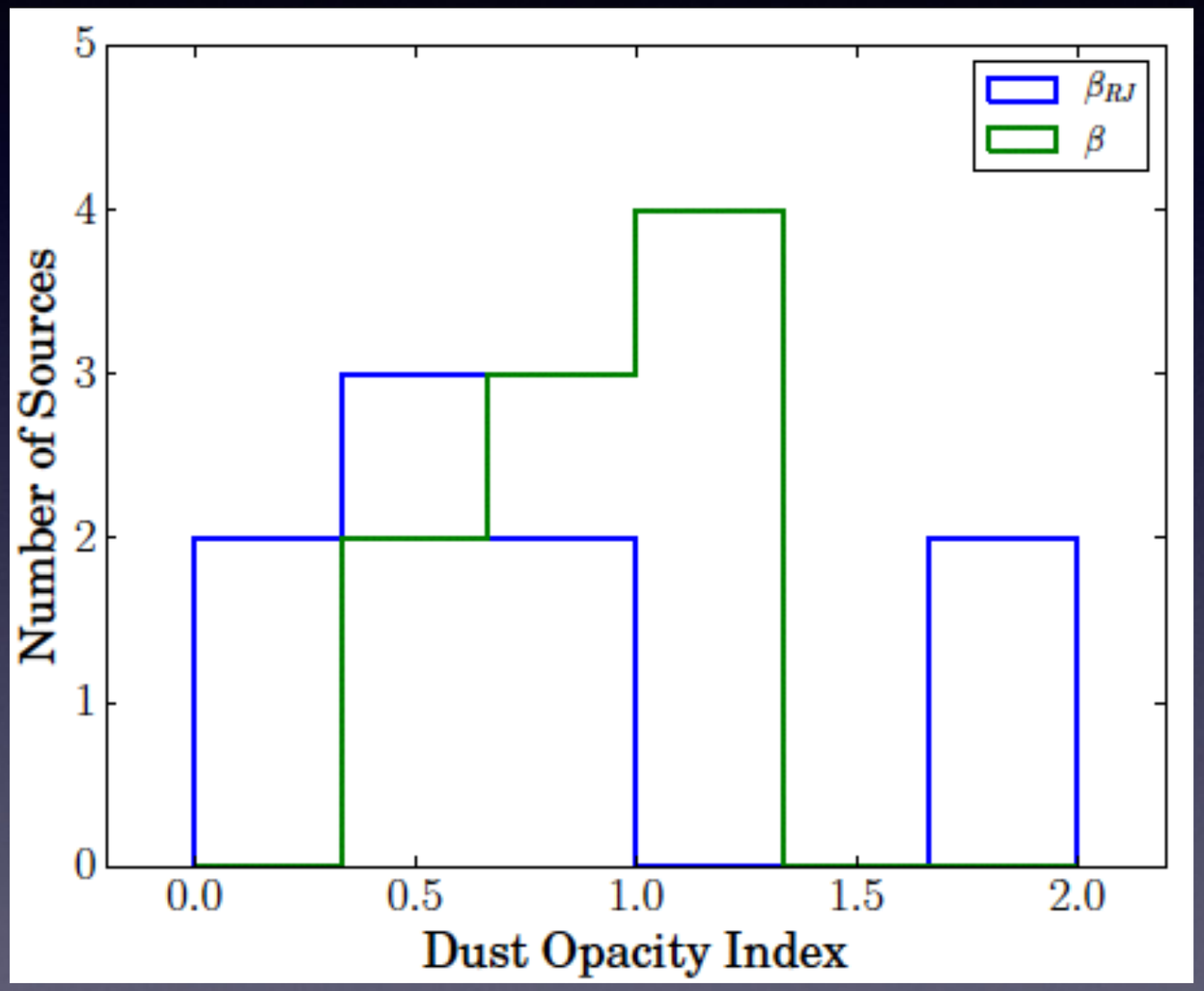
perform a Gaussian fit for two components

focus on the compact component

Example: SED fitting



Grain growth likely occurs in most Class 0/I YSOs!!



β_{RJ} : Rayleigh-Jean approx.+ optically thin assumption

β : no approximation

grain growth might have occurred in the prestellar phase

Note that the results are still preliminary

Next steps

Complete the analysis I-Hsiu Li et al in prep

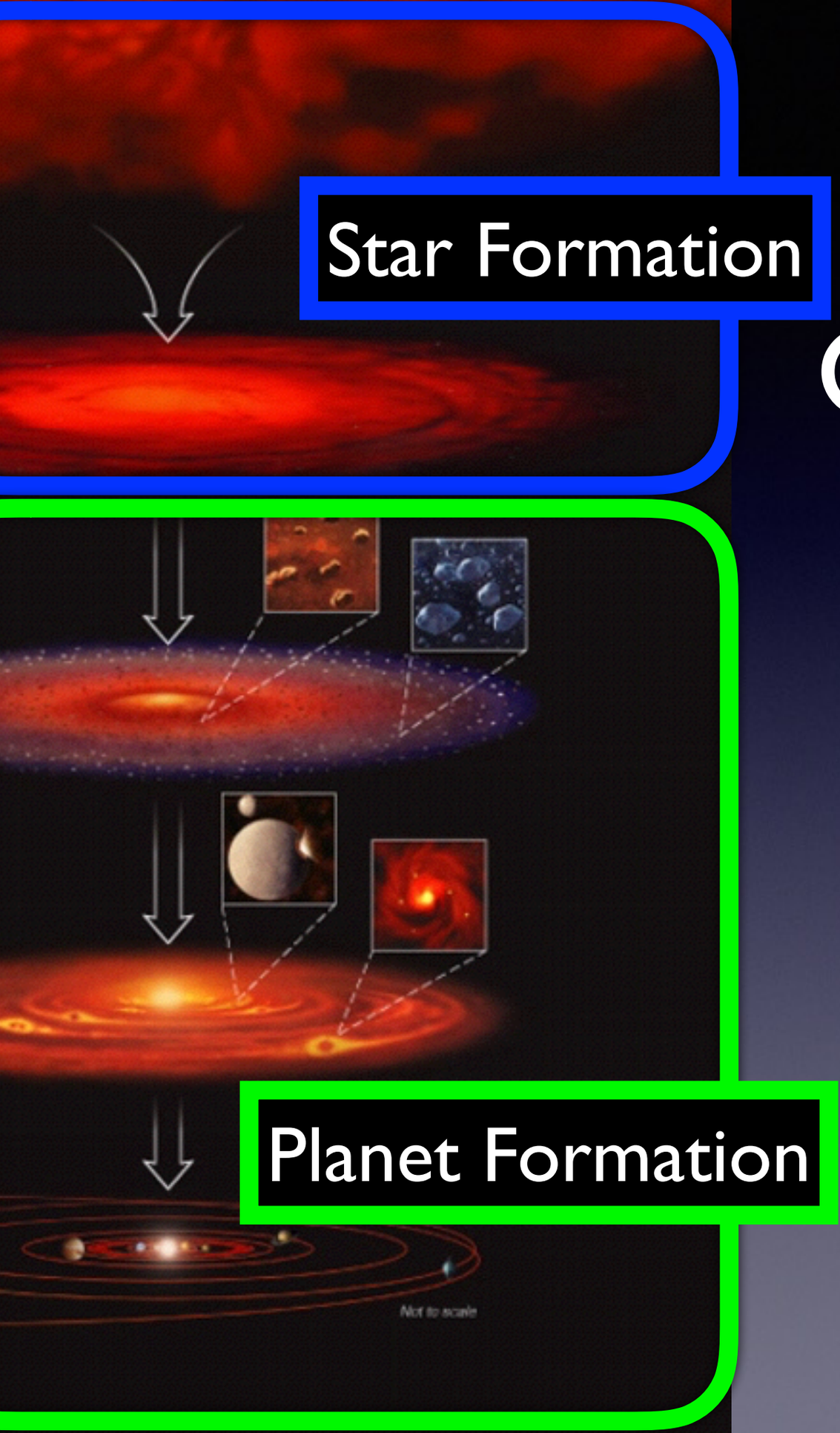
examine a number of (anti-)correlations

Follow-up observations to confirm the trend

ALMA proposed submitted (PI: I-Hsiu Li)

examine the effect of grain growth in chemistry

Harada et al in prep



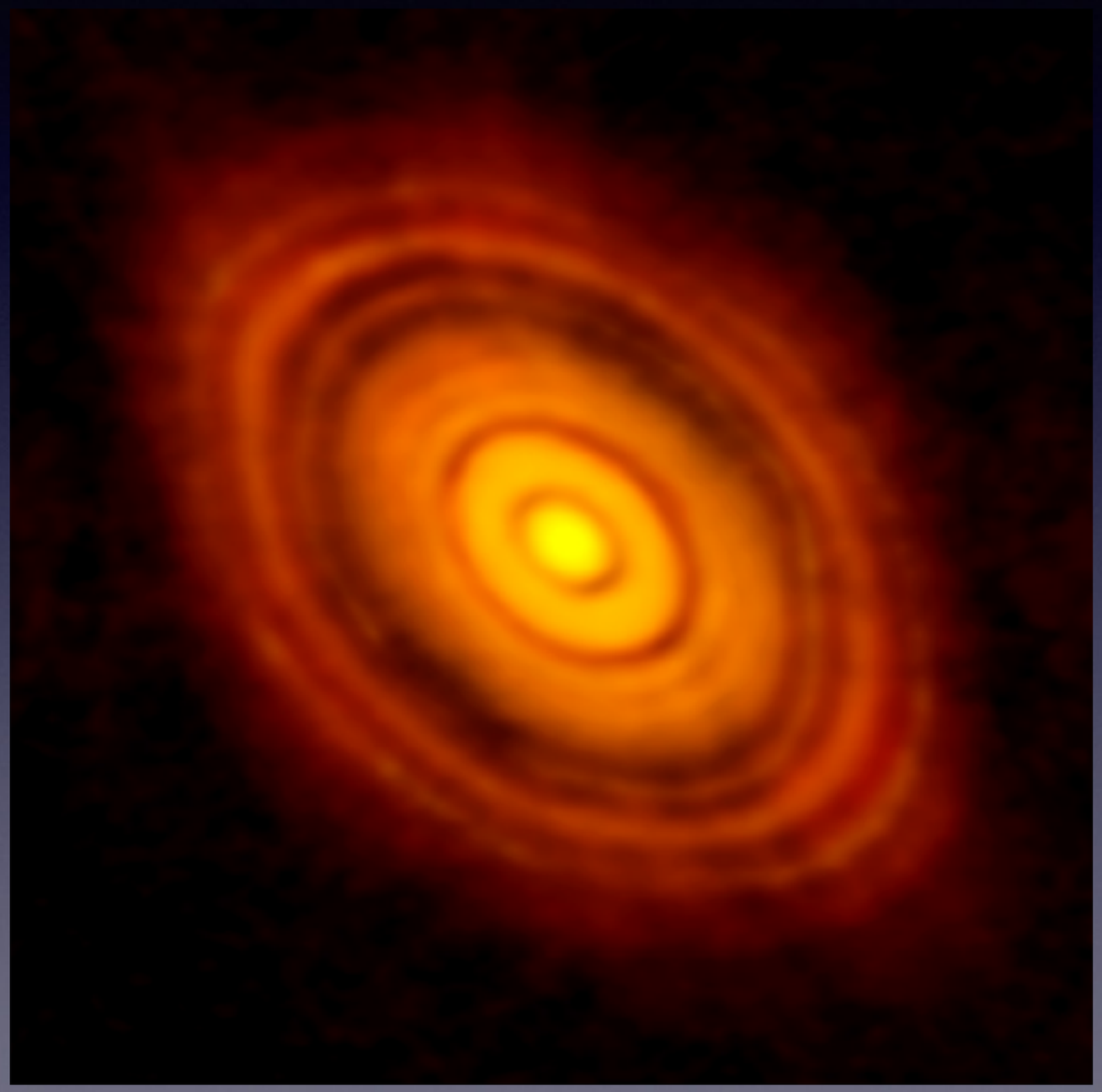
Magnetic Fields in Circumstellar Disks

Theoretical modeling of the HL Tau disk

Satoshi Okuzumi (TokyoTech)
Neal Turner (JPL/Caltech)

Astonishing ALMA Images of HL Tau

Partnership et al 2015



HL Tau : a Class I/II YSO
: ~140 pc

Observations
: done on Oct. 24, 2014
: 14.5 hr at band 3 (101.9 GHz)
: 9.5 hr at band 6 (233 GHz)
: 11.9 hr at band 7 (343.5 GHz)

Baselines
: ~15m - ~ 15km

# of antennas
: up to 37

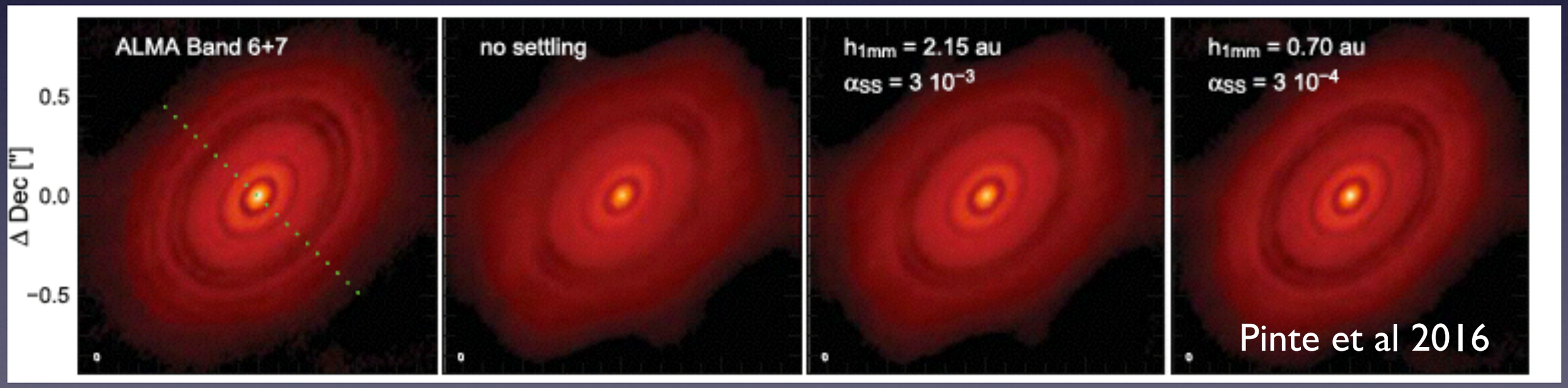
A "mystery" for the disk around HL Tau

Disk accretion rate $\simeq 10^{-7} - 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

=> the strength of accretion stress should be high

Global diffusion coefficient : $\alpha_{\mathrm{GL}} \simeq 10^{-2} - 10^{-1}$

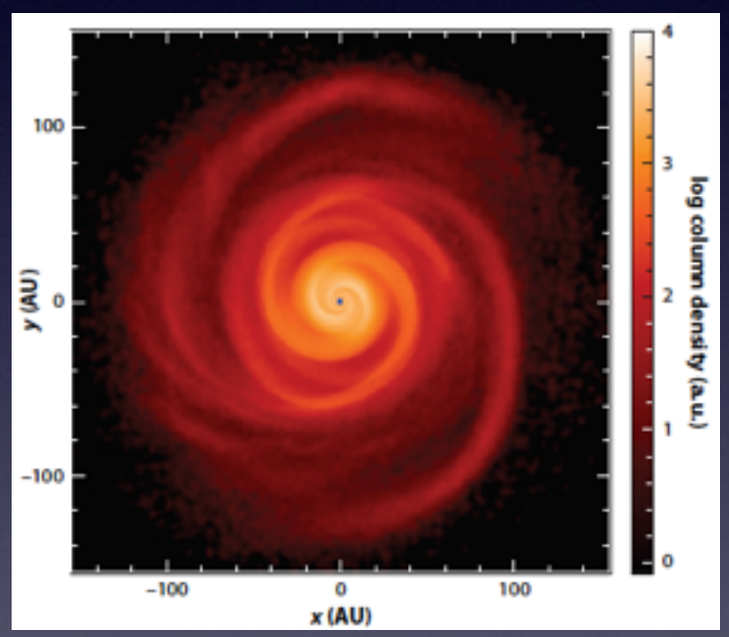


=> the strength of local turbulence should be low

Local diffusion coefficient : $\alpha_{\mathrm{LC}} \simeq \mathrm{a\ few} \times 10^{-4}$

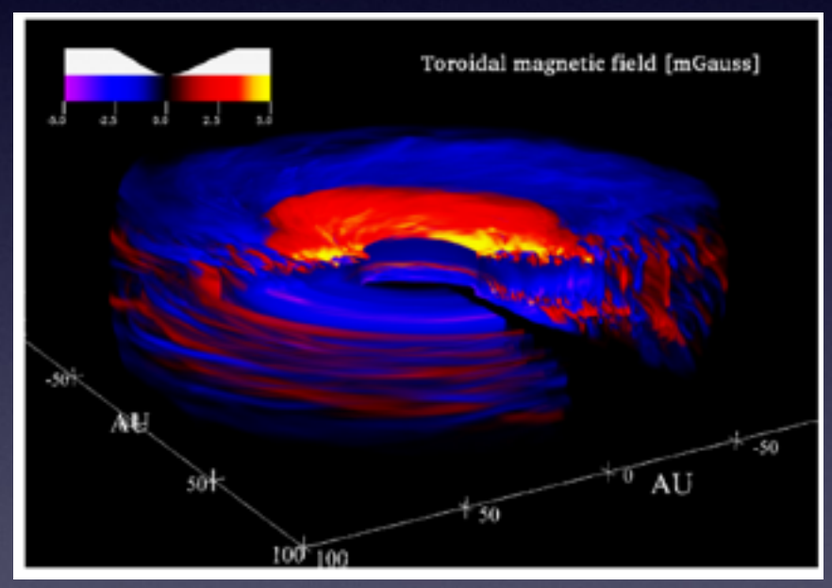
Explore 3 possible origins of disk accretion

Self-gravity (GIs)



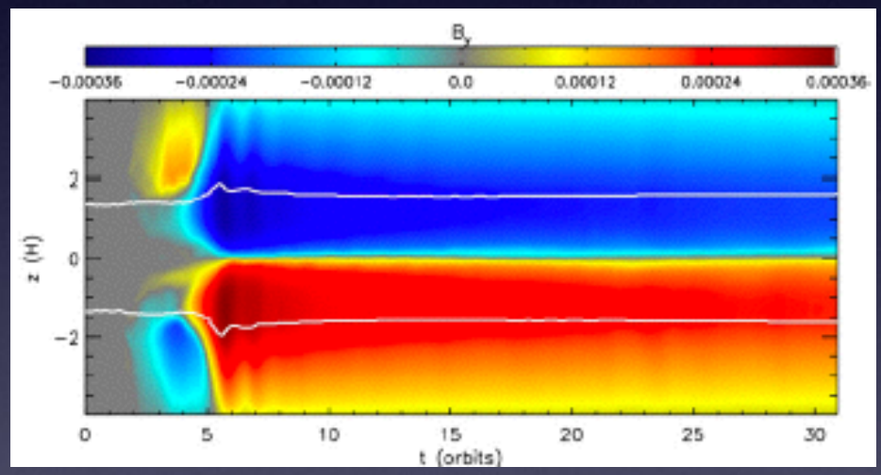
e.g., Forgan et al 2010

MRIs with Ohmic resistivity



e.g., Flock et al 2015

Magnetocentrifugal winds (MCWs)



e.g., Simon et al 2013

Develop a steady state disk model and examine the disk around HL Tau

Steady State Disk Models

$$\dot{M}_{\rm g} \equiv \dot{M}_{\rm GL} + \dot{M}_{\rm wind}$$

Global Stress

Wind Stress

e.g., Wardle 2007, Armitage et al 2013

$$\dot{M}_{\rm GL} \simeq 3\pi\alpha_{\rm GL} c_{\rm s} h_{\rm g} \Sigma_{\rm g}$$

$$\dot{M}_{\rm wind} \simeq 2\pi W_{\rm wind} c_{\rm s} r \Sigma_{\rm g}$$

Steady State Disk Models

e.g., Wardle 2007, Armitage et al 2013

$$\dot{M}_{\rm g} \equiv \dot{M}_{\rm GL} + \dot{M}_{\rm wind}$$

Global Stress

Wind Stress

$$\dot{M}_{\rm GL} \simeq 3\pi\alpha_{\rm GL} c_{\rm s} h_{\rm g} \Sigma_{\rm g}$$

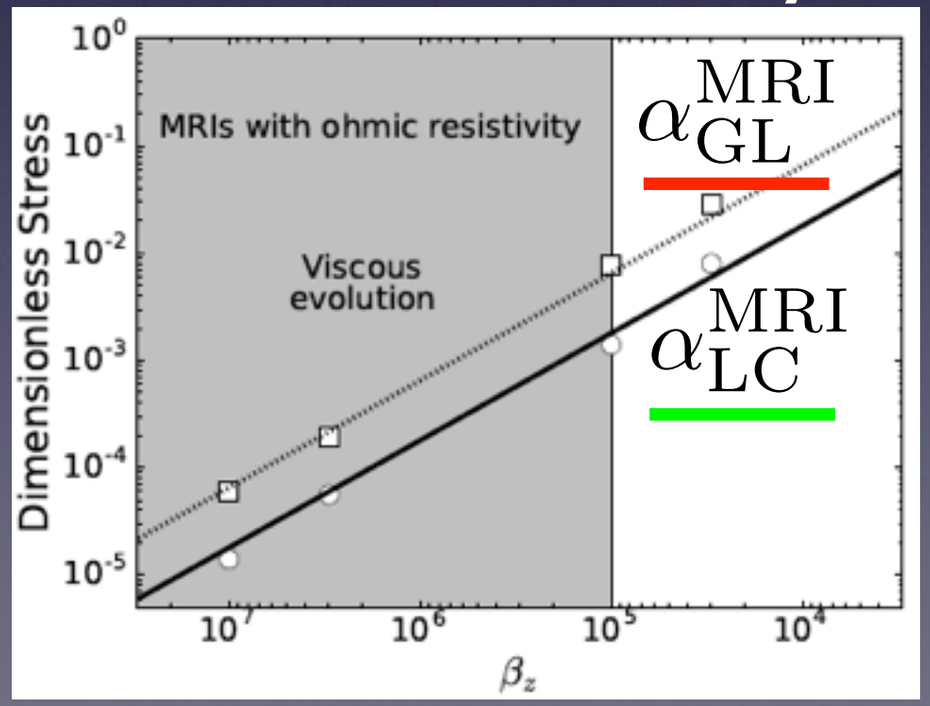
$$\dot{M}_{\rm wind} \simeq 2\pi W_{\rm wind} c_{\rm s} r \Sigma_{\rm g}$$

Self-gravity (GIs)

$$\alpha_{\rm GL}^{\rm GI} \simeq \frac{\dot{M}_{\rm g} G Q_0}{3 c_{\rm s}^3} = \alpha_{\rm LC}^{\rm GI}$$

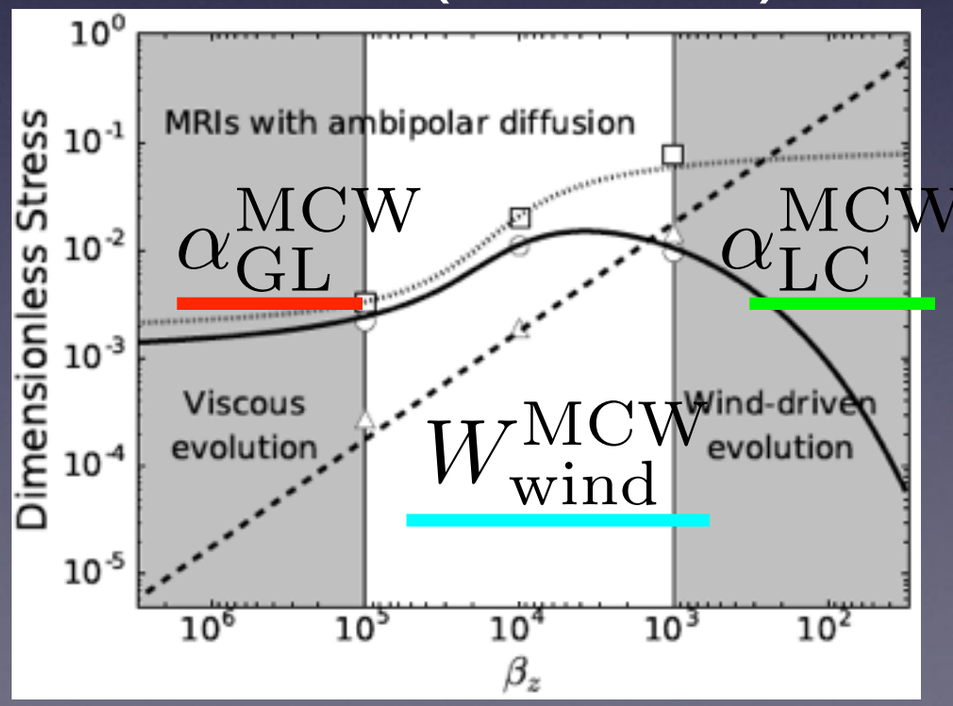
Vorobyov & Basu 2007

MRIs with Ohmic resistivity



Okuzumi & Hirose 2011

Magnetocentrifugal winds (MCWs)



Simon et al 2013

Self-gravity (GIs)

MRIs with Ohmic resistivity

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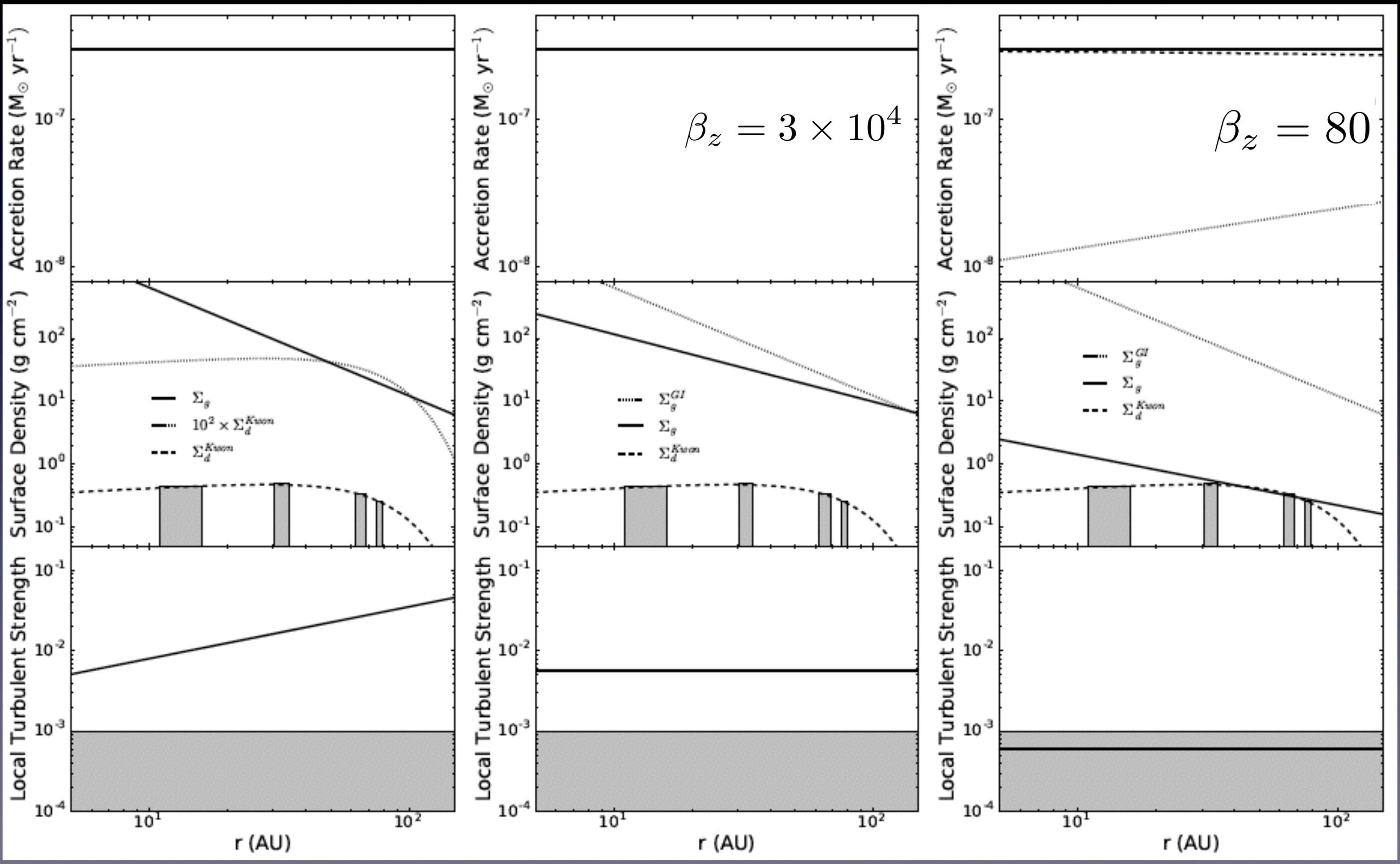
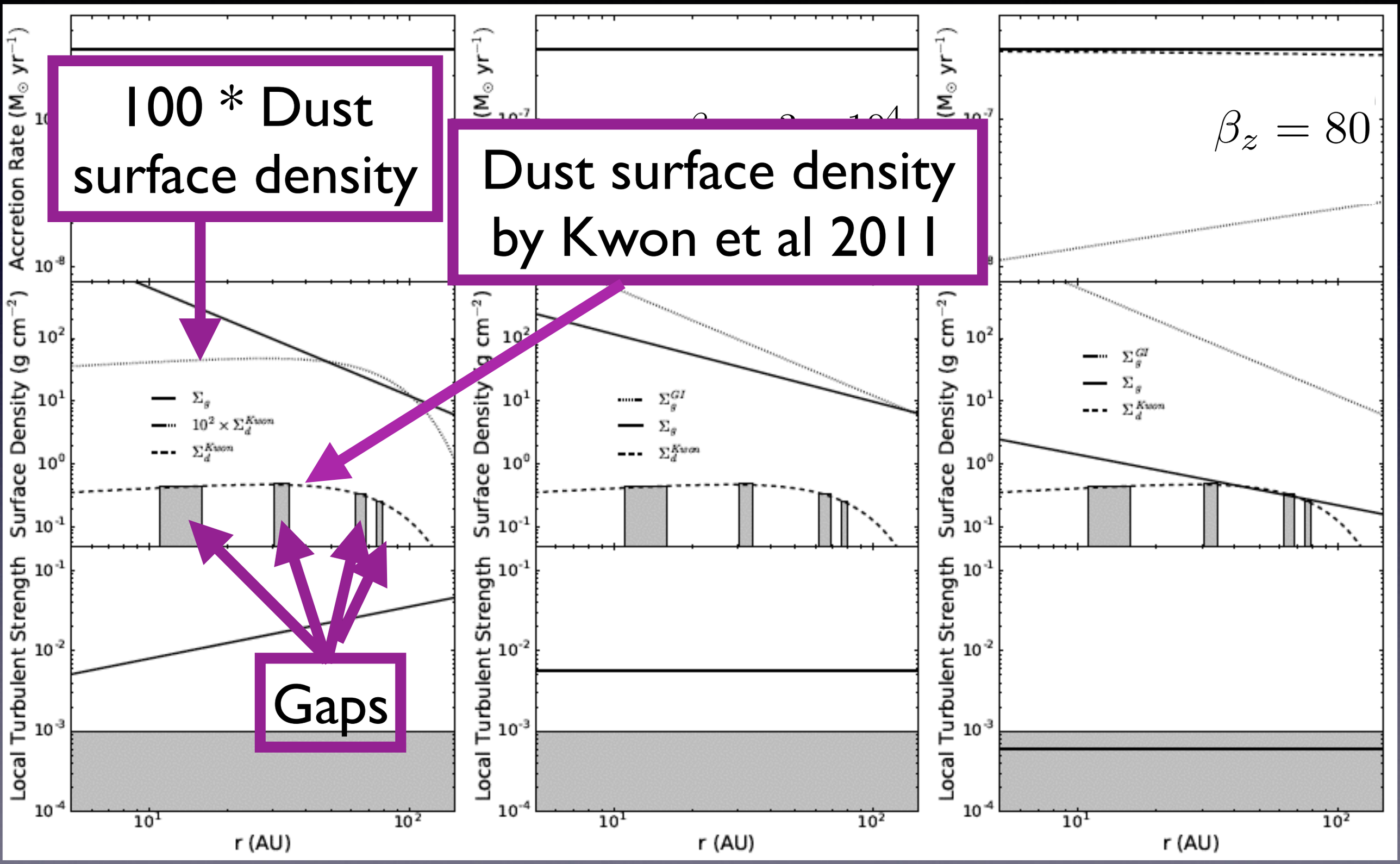


Self-gravity (GIs)

MRIs with Ohmic resistivity

Magnetocentrifugal winds (MCWs)



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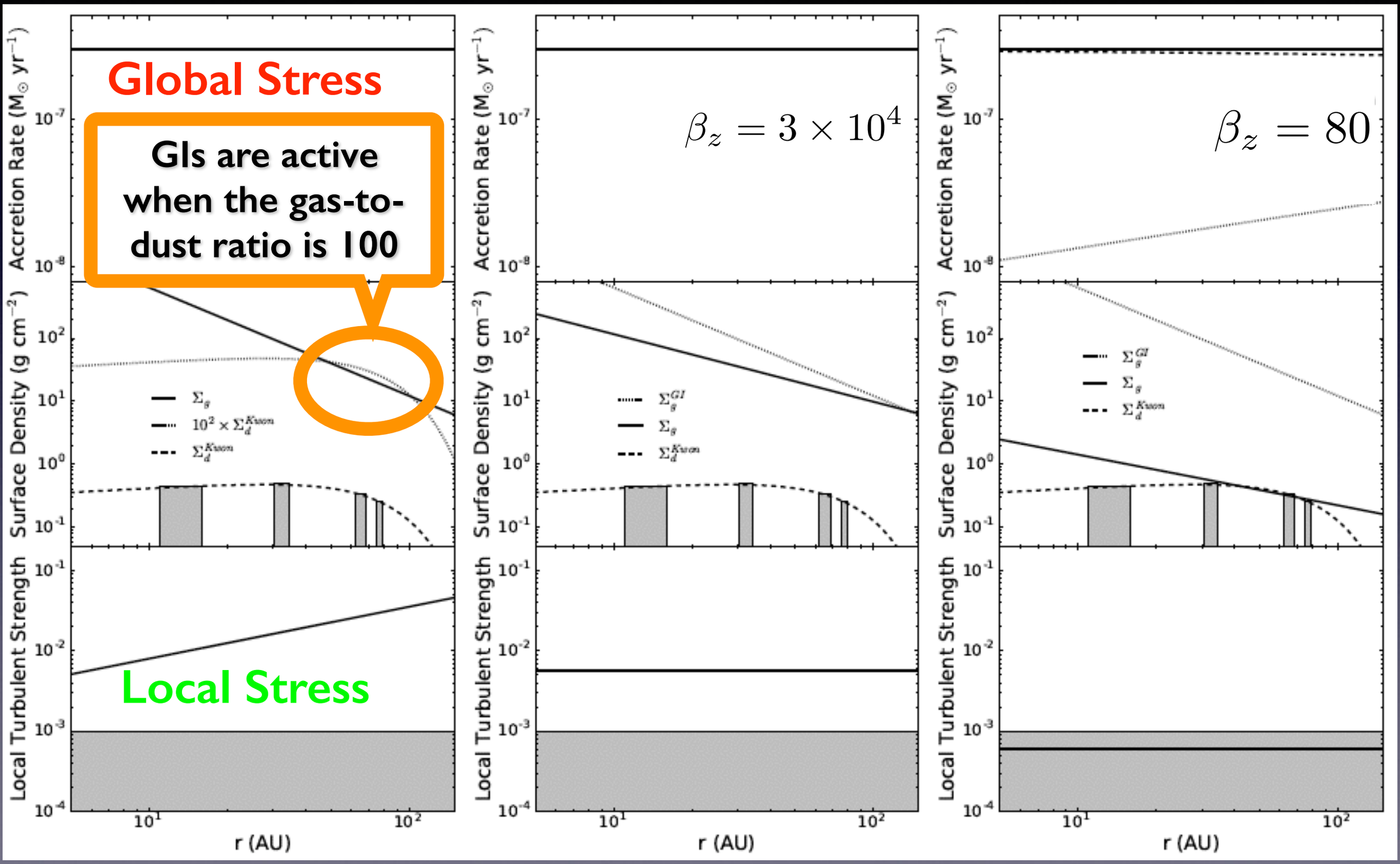
MRIs with Ohmic resistivity

Magnetocentrifugal winds (MCWs)



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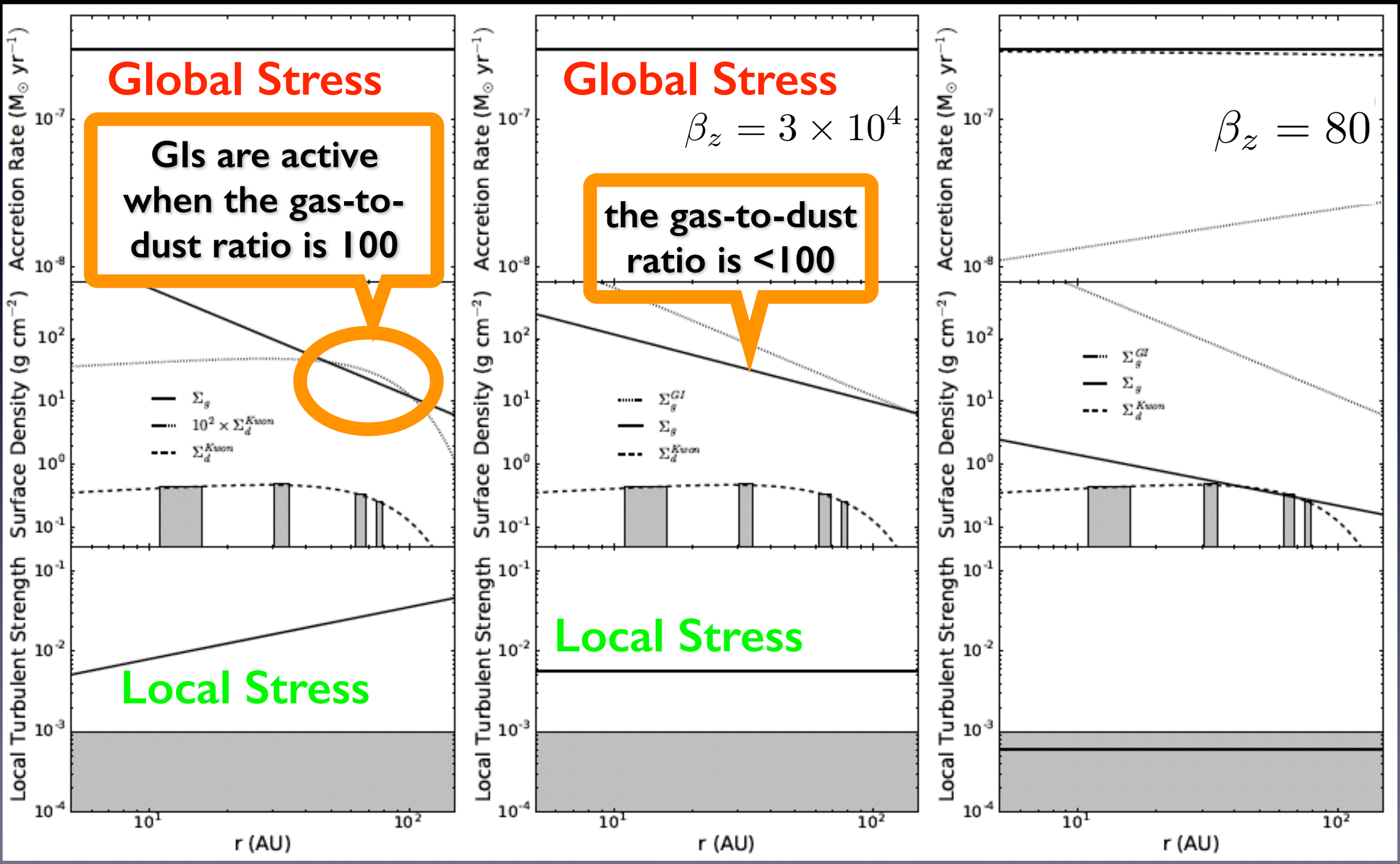

Self-gravity (GIs)

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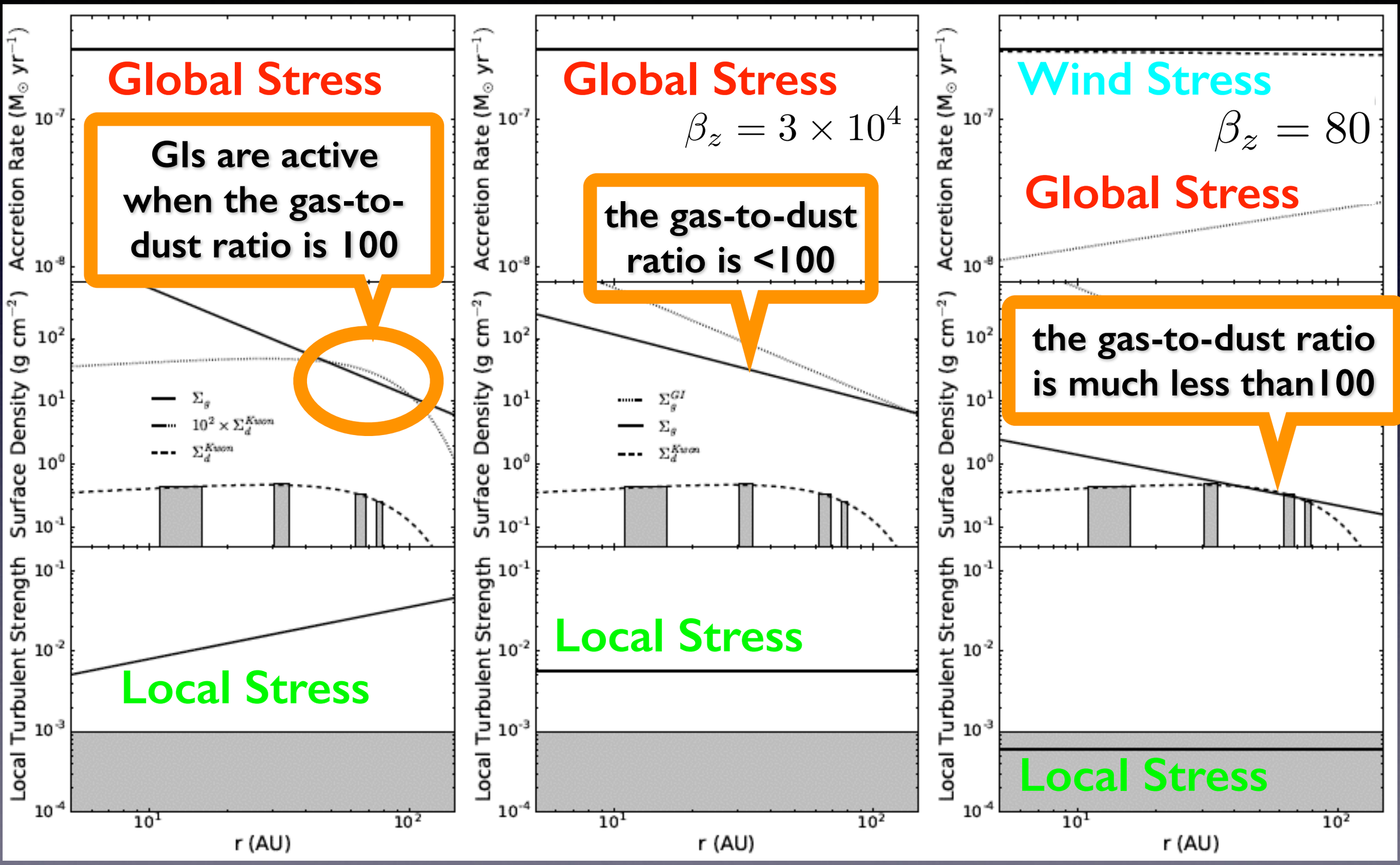
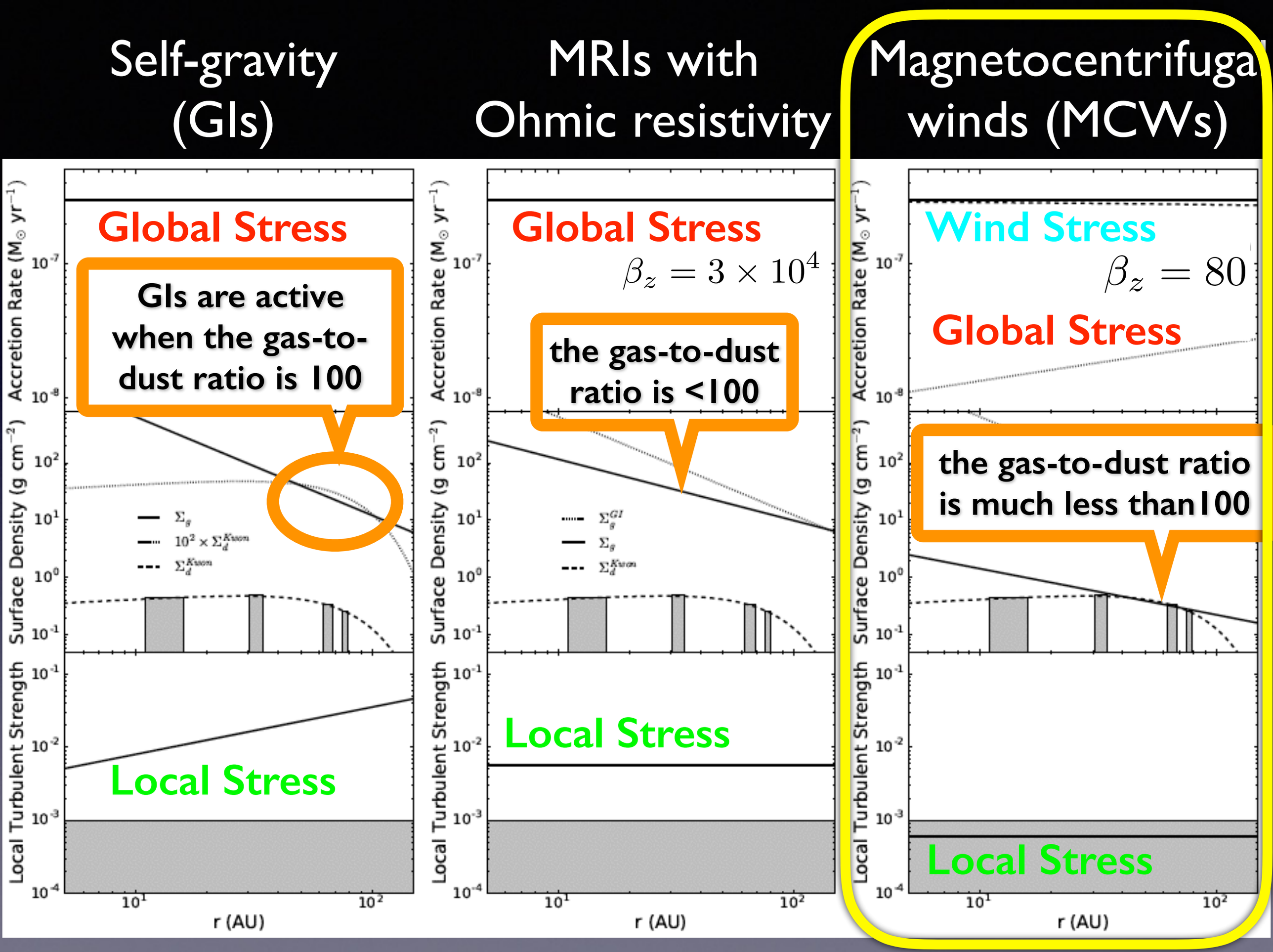
Magnetocentrifugal winds (MCWs)




Self-gravity (GIs)
MRIs with Ohmic resistivity
Magnetocentrifugal winds (MCWs)
Global Stress
GIs are active when the gas-to-dust ratio is 100
Accretion Rate ($M_\odot$ yr^{-1})
Surface Density (g cm^{-2})
Local Turbulent Strength
Σ_g
$10^2 \times \Sigma_d^{Kuan}$
Σ_d^{Kuan}
Local Stress
r (AU)
Global Stress
$\beta_z = 3 \times 10^4$
the gas-to-dust ratio is <100
Σ_g^{GI}
Σ_g
Σ_d^{Kuan}
Local Stress
r (AU)
Wind Stress
$\beta_z = 80$
Global Stress
the gas-to-dust ratio is much less than100
Local Stress
r (AU)

Next steps

Complete the analysis

Hasegawa et al in prep

Discuss a possibility that HL Tau disk is in a quiescent phase of episodic accretion

Discuss possible observational tests about our results;

1) infer the low gas-to-dust ratio
2) detect gas outflow from disk surfaces

Summary

- Planet formation should be coupled intimately with star formation
- Dust growth and magnetic fields would play important roles in exploring such coupling
- Dust growth, a first step of planet formation, may occur even in Class 0/I YSOs
- Performed a survey-type of an observational study using the archive data, and found that grain growth does occur in the very early stage of star formation
- Explored an origin of disk structures for the HL Tau, focusing on 3 disk models (GIs, MRIs with Ohmic resistivity, Magnetocentrifugal winds)
- MCW models are the most likely for explaining two kinds of α