Applications of Magnetocentrifugal Disk Wind Models:

from Dust Growth to HL Tau

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Mario Flock (JPL/Caltech), Neal Turner (JPL/Caltech)

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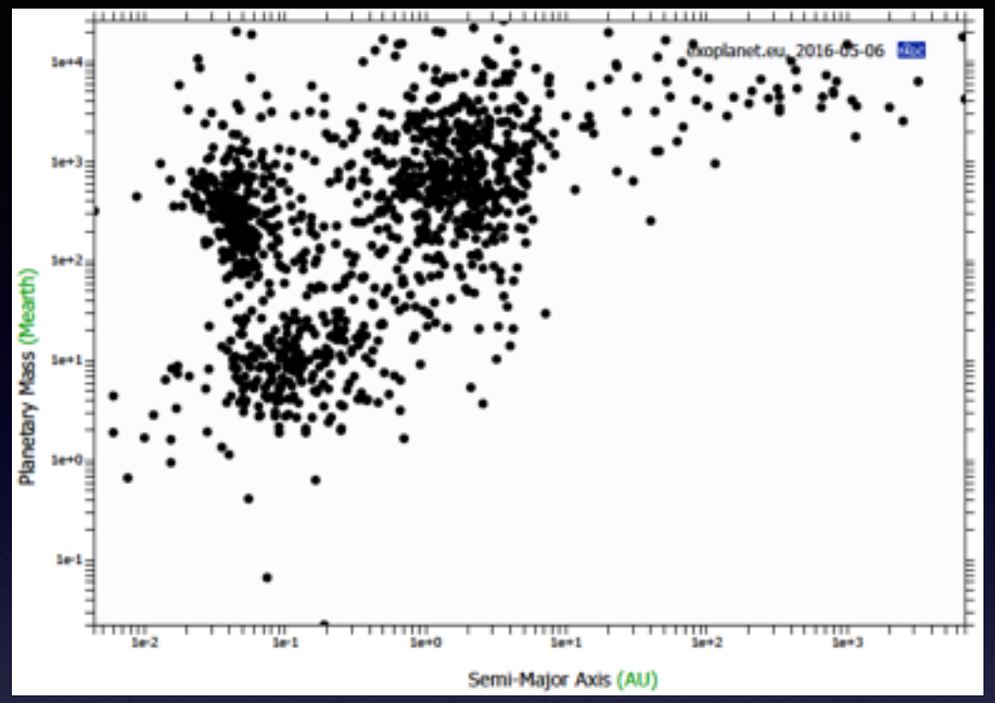
Recent Astonishing Discoveries



Surprising Exoplanet Populations!!

: Rare (~ 1 %) Hot Jupiters

: More Warm Jupiters

: the Most Dominant Super-Earths

=> migration of massive bodies??
or, radial drift of solid particles??

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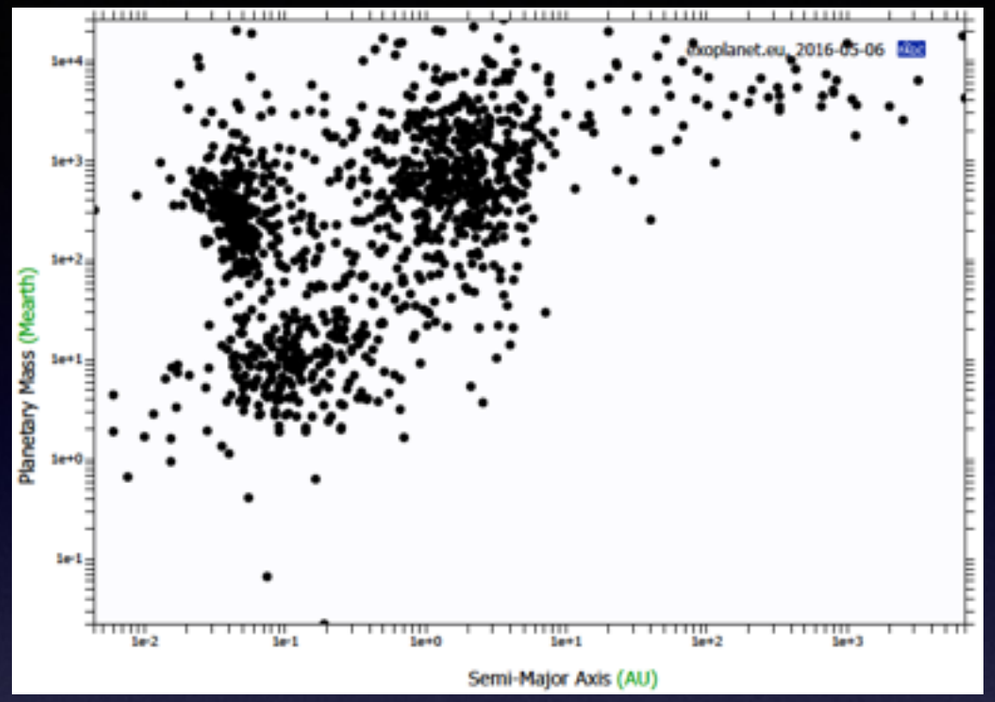

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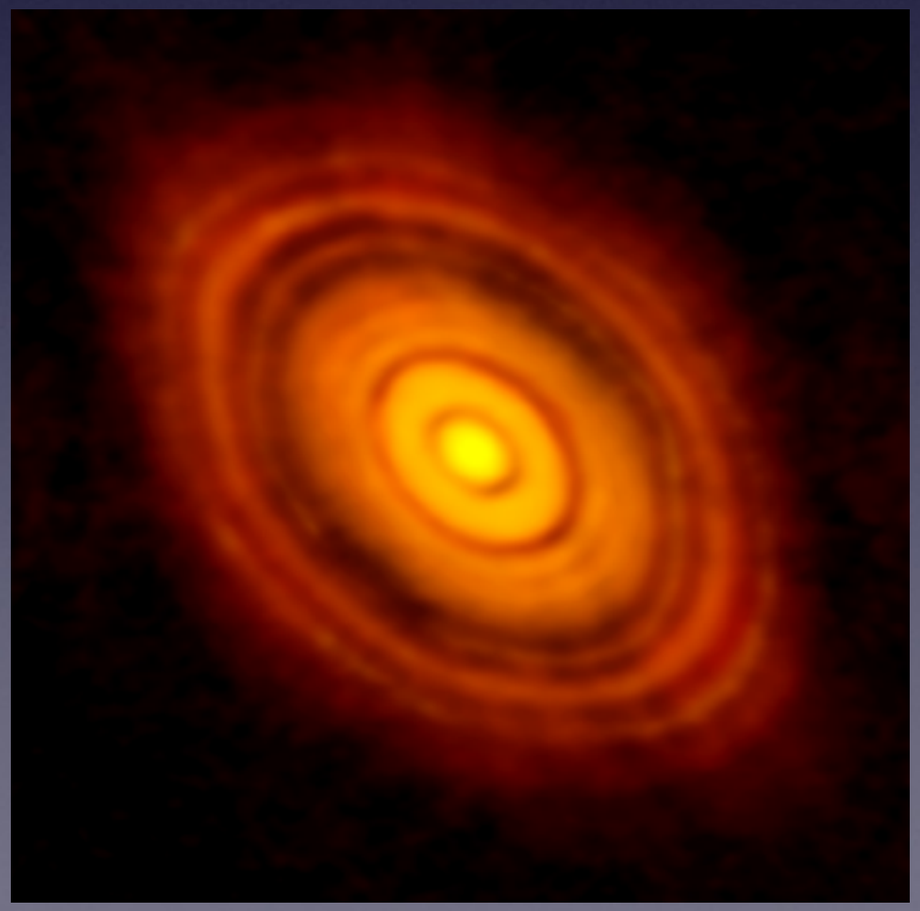

ALMA Images of HL Tau!!

Origins of nearly axisymmetric gaps

: massive objects formed by GIs??

: massive objects formed by Secular GIs??

: dust gaps formed by ice lines??

: dust gaps formed by sintering??

etc…

The Fundamental Information:

1) How Protoplanetary Disks evolve with time
2) How Planet-Forming Materials distribute in the disks

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Origin of
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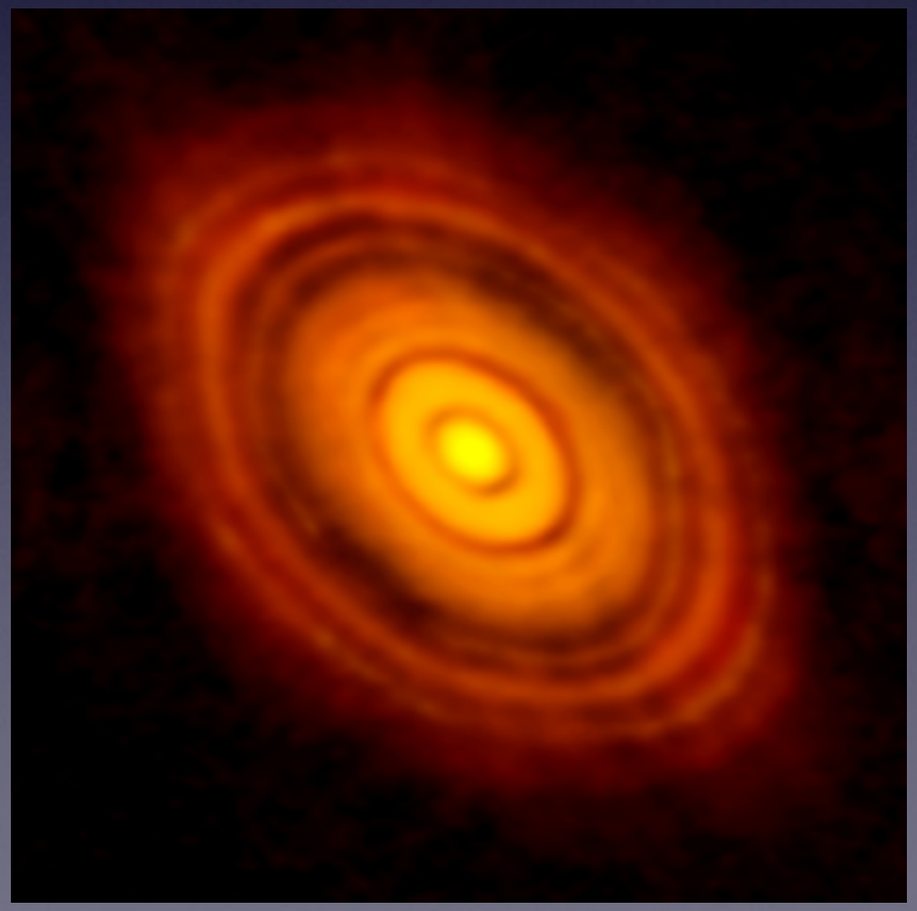

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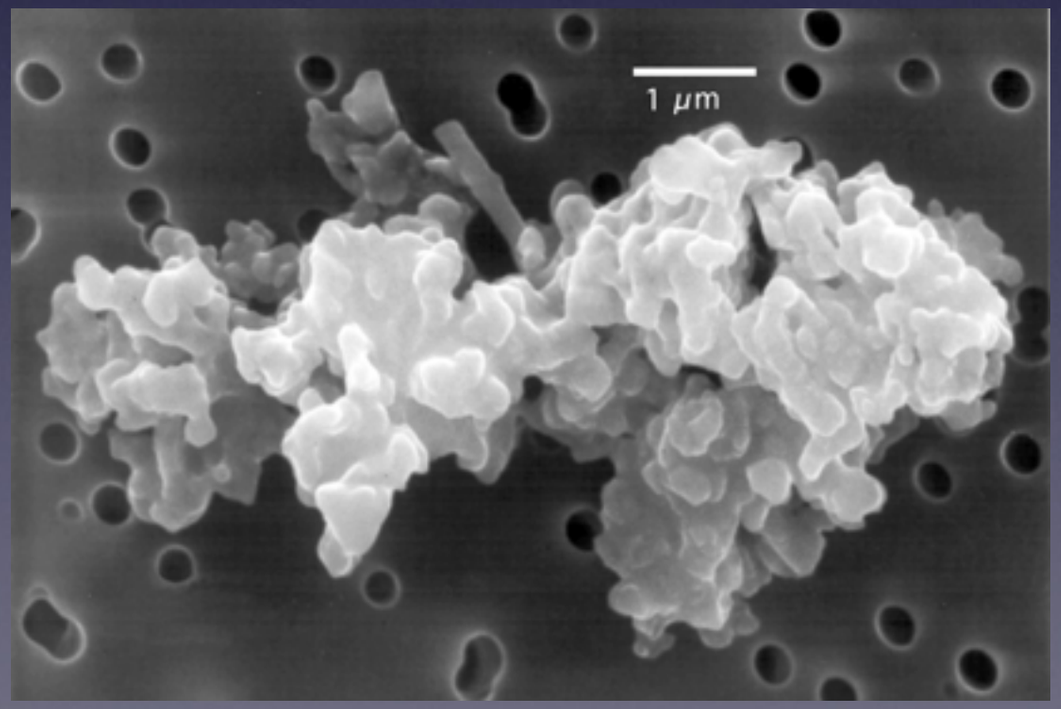

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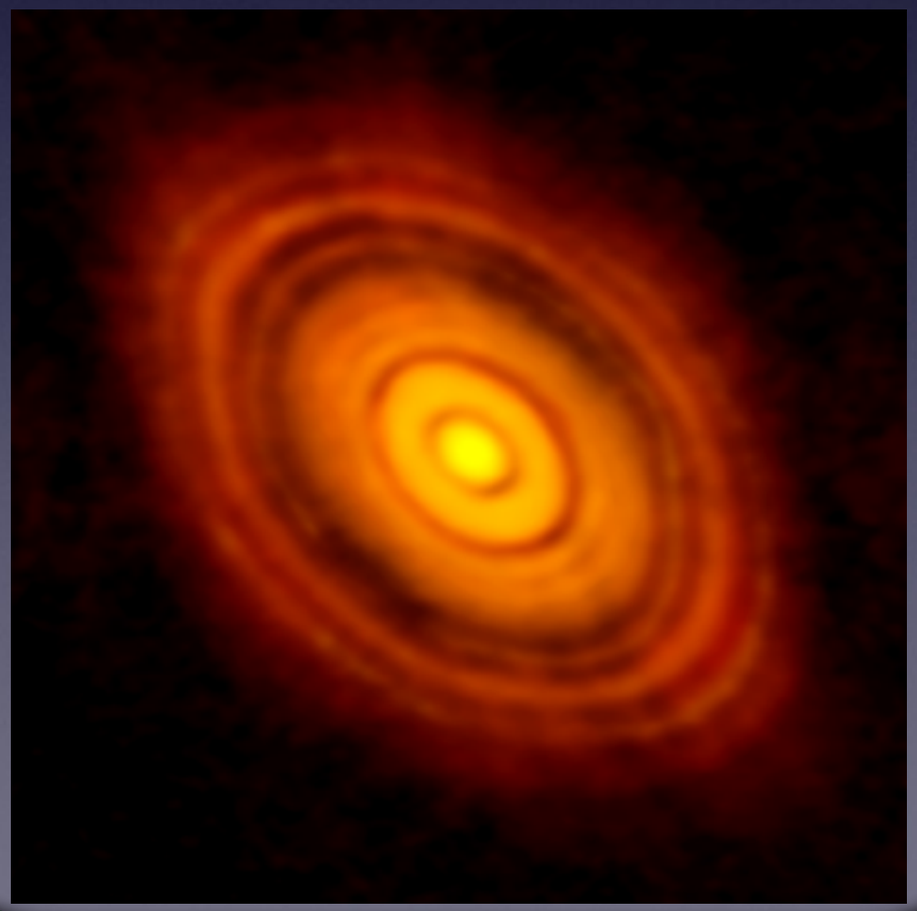

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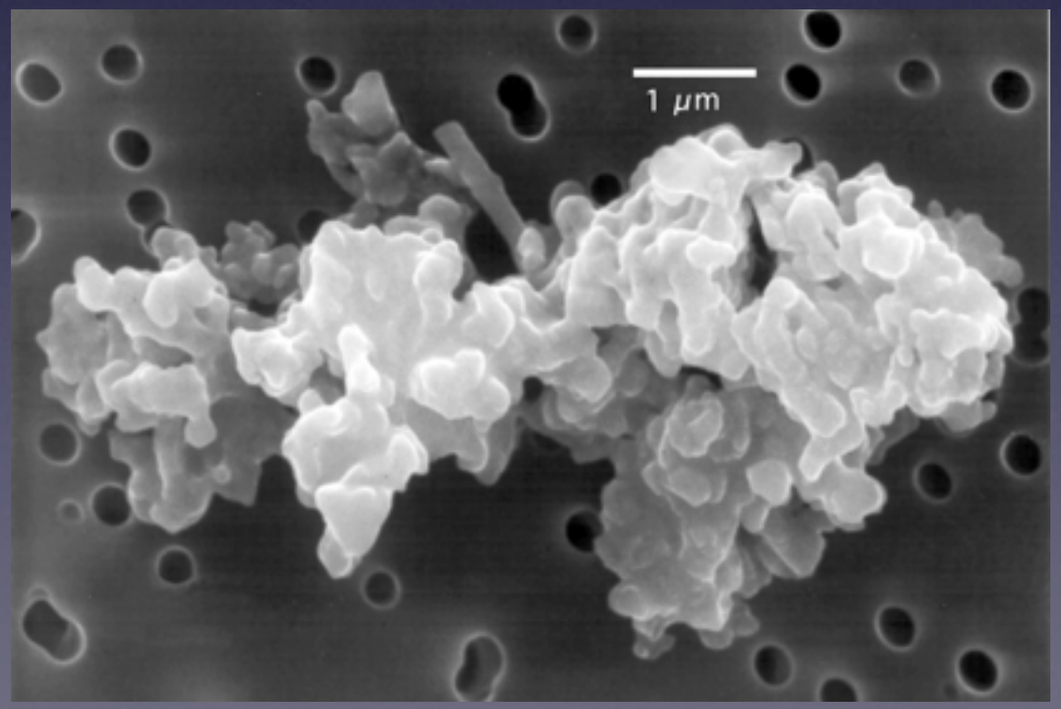
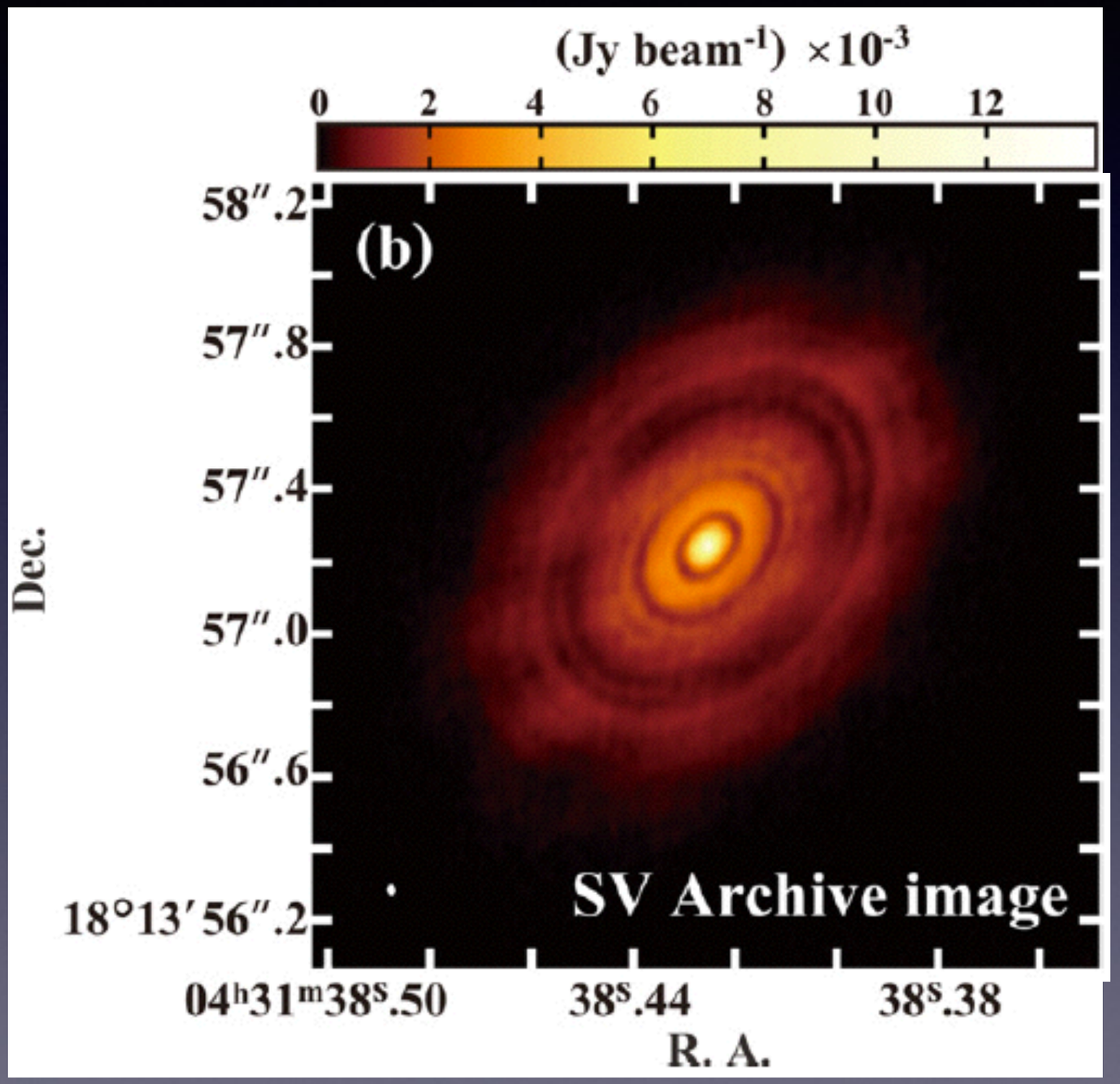


Astonishing ALMA Images of HL Tau

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

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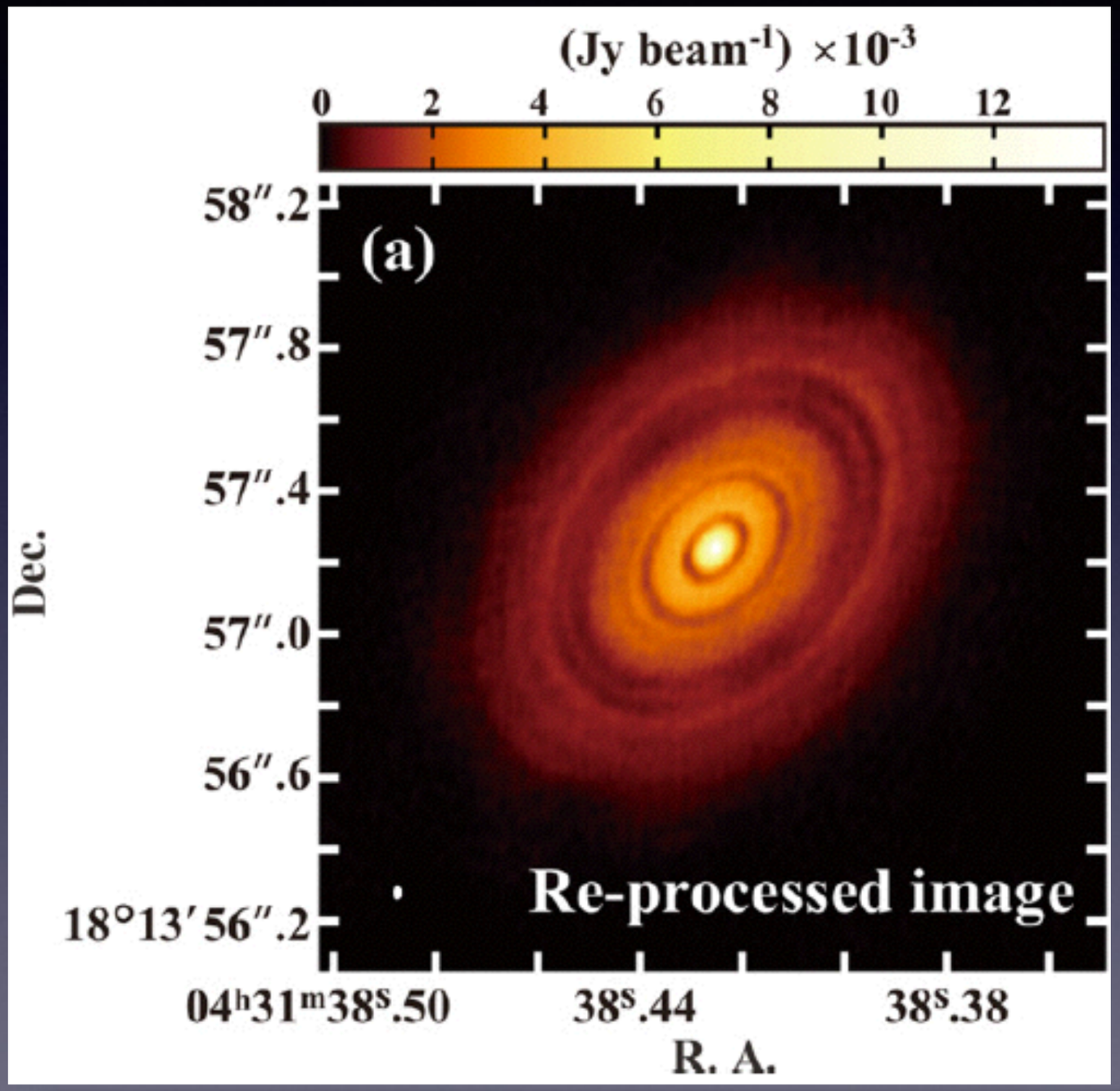

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Akiyama, **YH** et al 2016 obtain a better quality of images

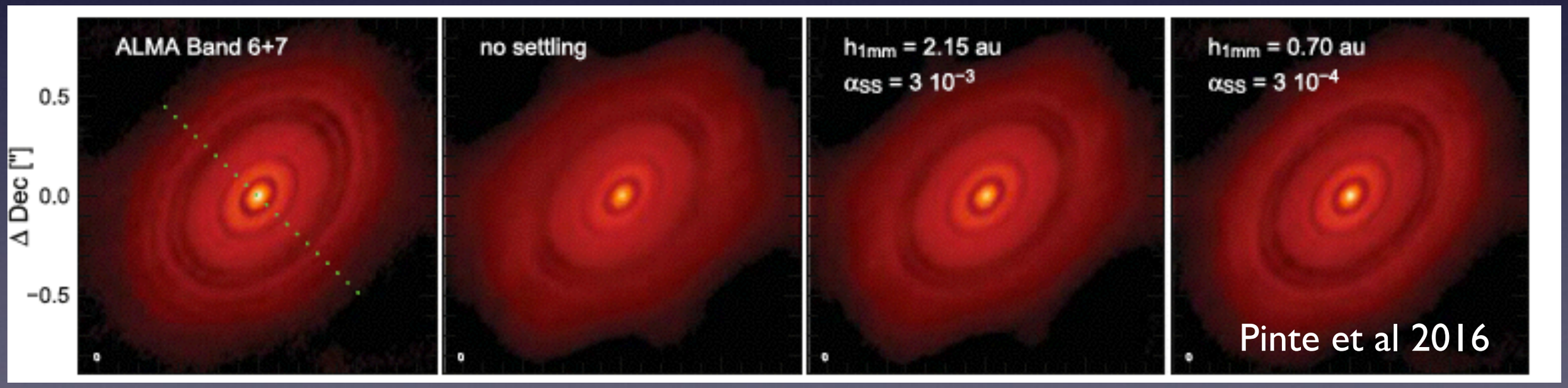
A "mystery" for the disk around HL Tau

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

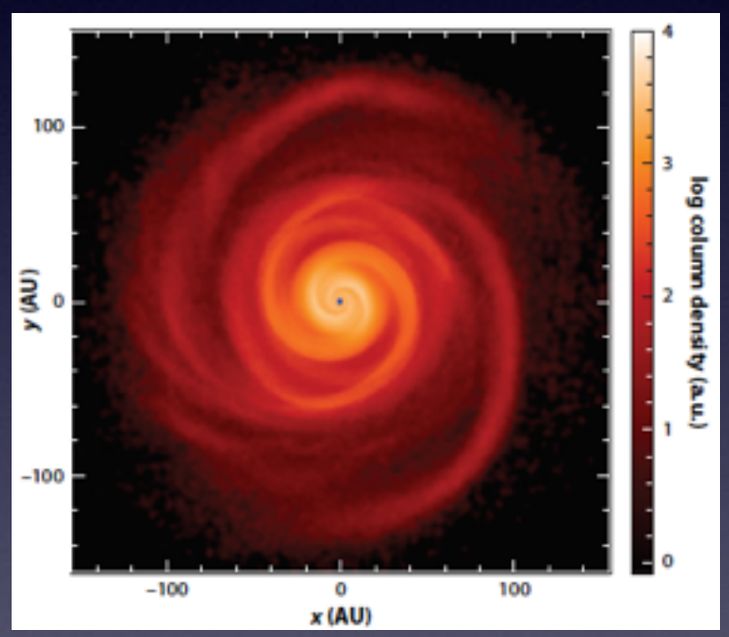


=> the strength of local turbulence should be low

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

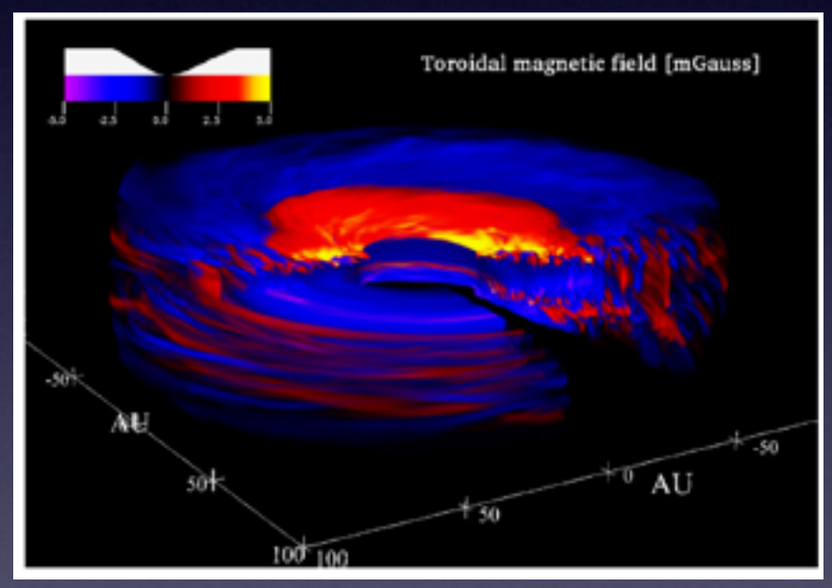
Explore 3 possible origins of disk accretion

Self-gravity (GIs)



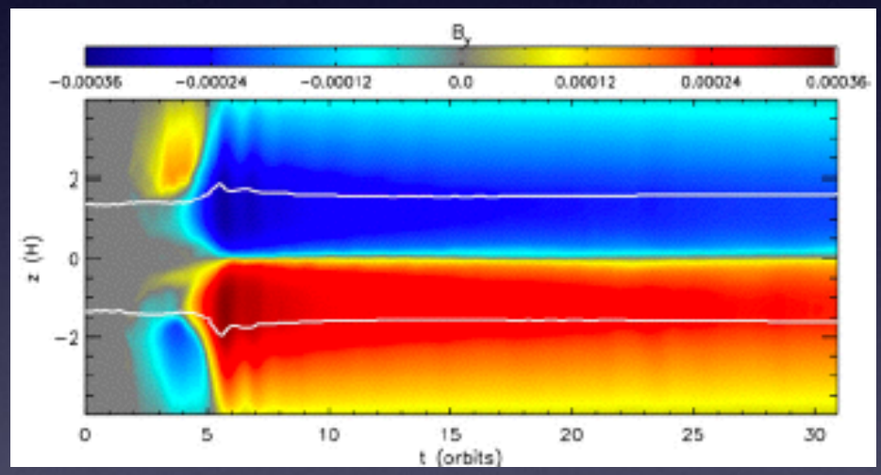
e.g., Forgan et al 2010

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

e.g., Wardle 2007, Armitage et al 2013, Suzuki et al 2016

$$\dot{M}_{\rm g} \equiv \dot{M}_{\rm Turb} + \dot{M}_{\rm Mean} + \dot{M}_{\rm Wind}$$

Turbulent Stress

Mean Stress

Wind Stress

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

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

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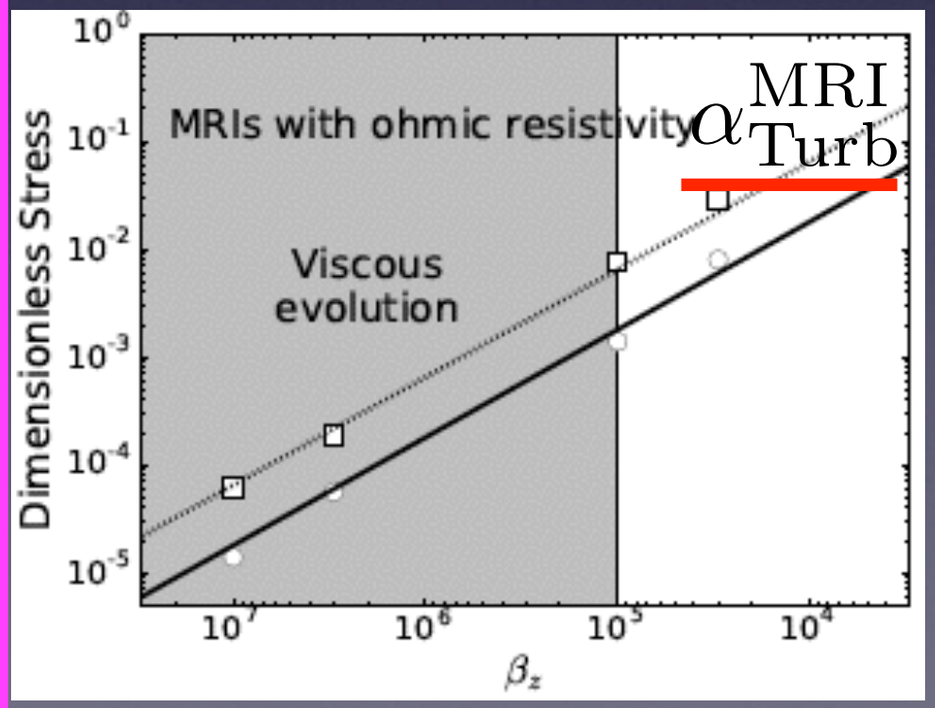
Vorobyov & Basu 2007

MRIs with Ohmic resistivity



Okuzumi & Hirose 2011

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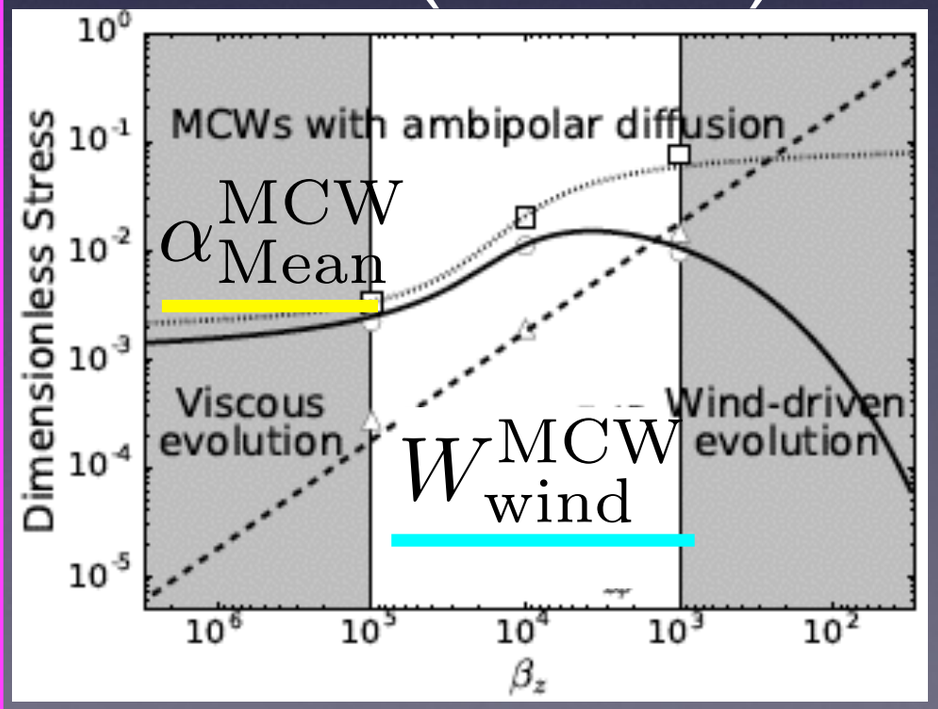

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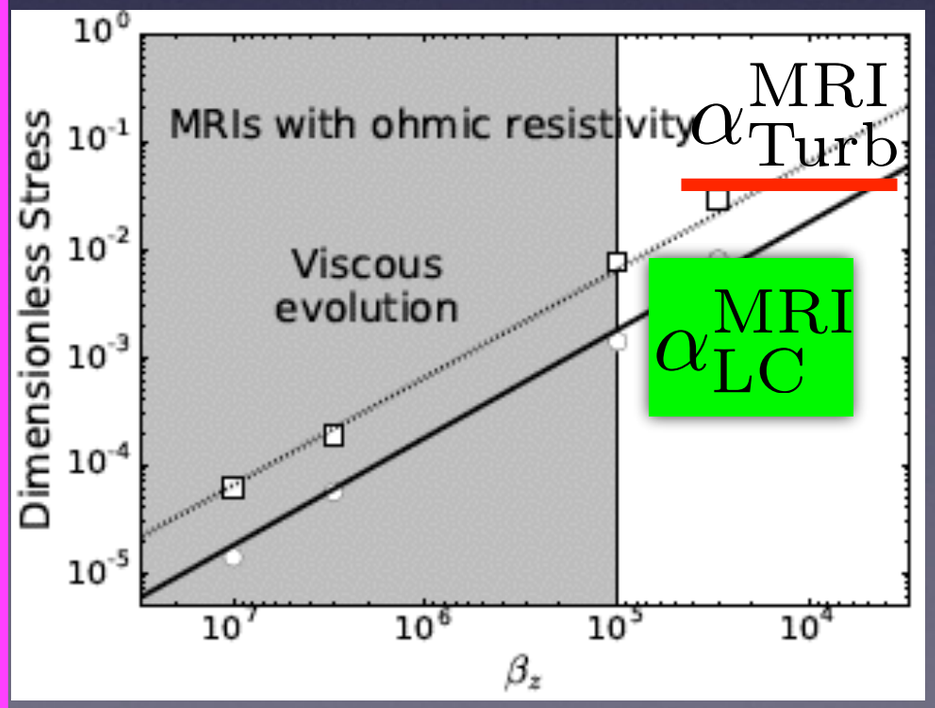

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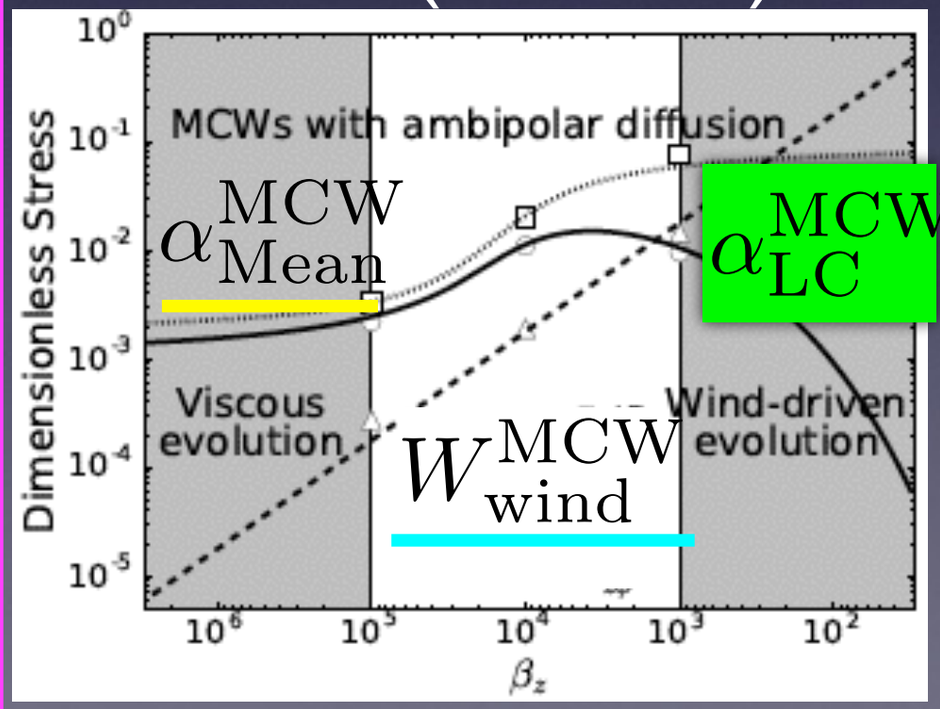

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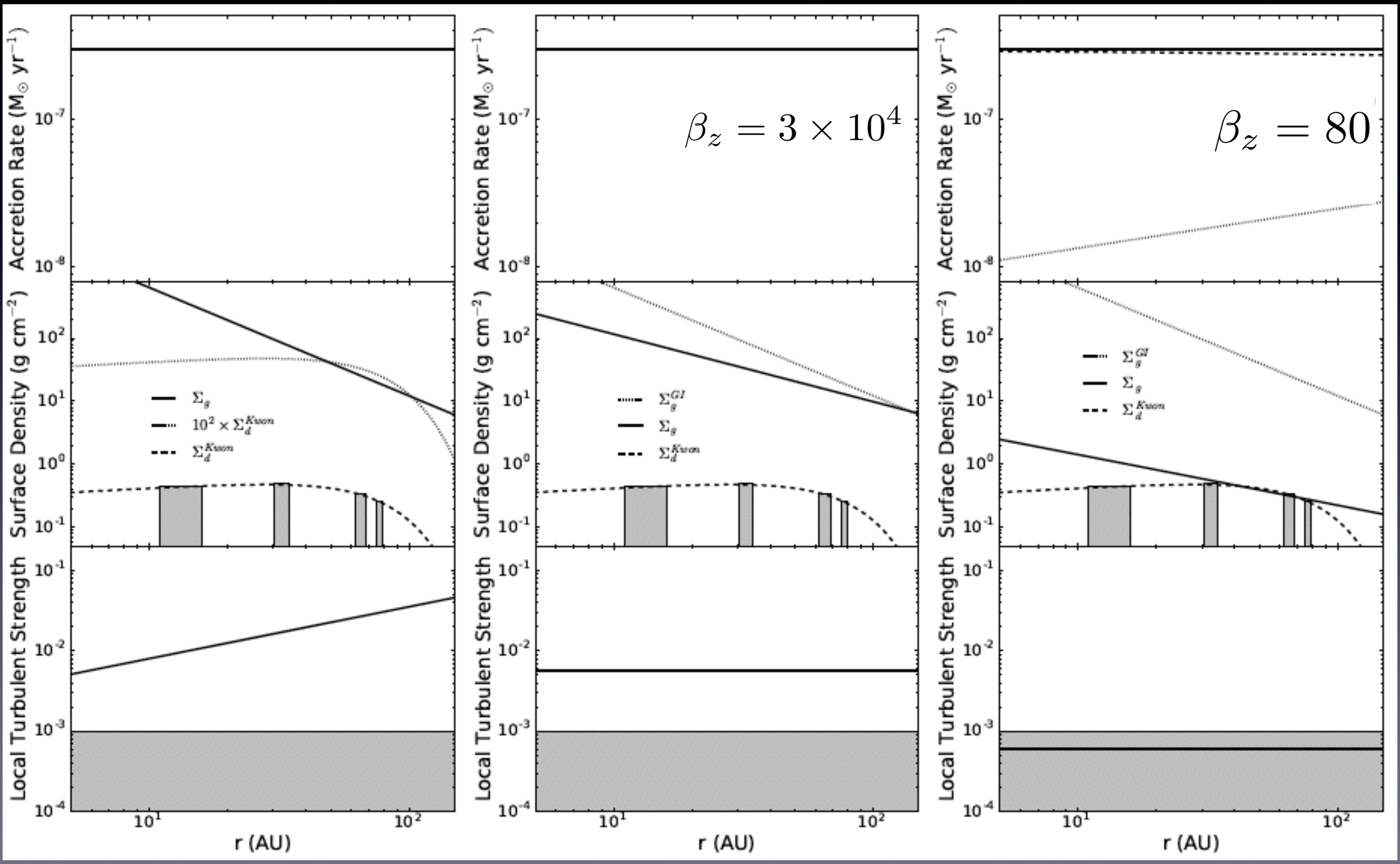

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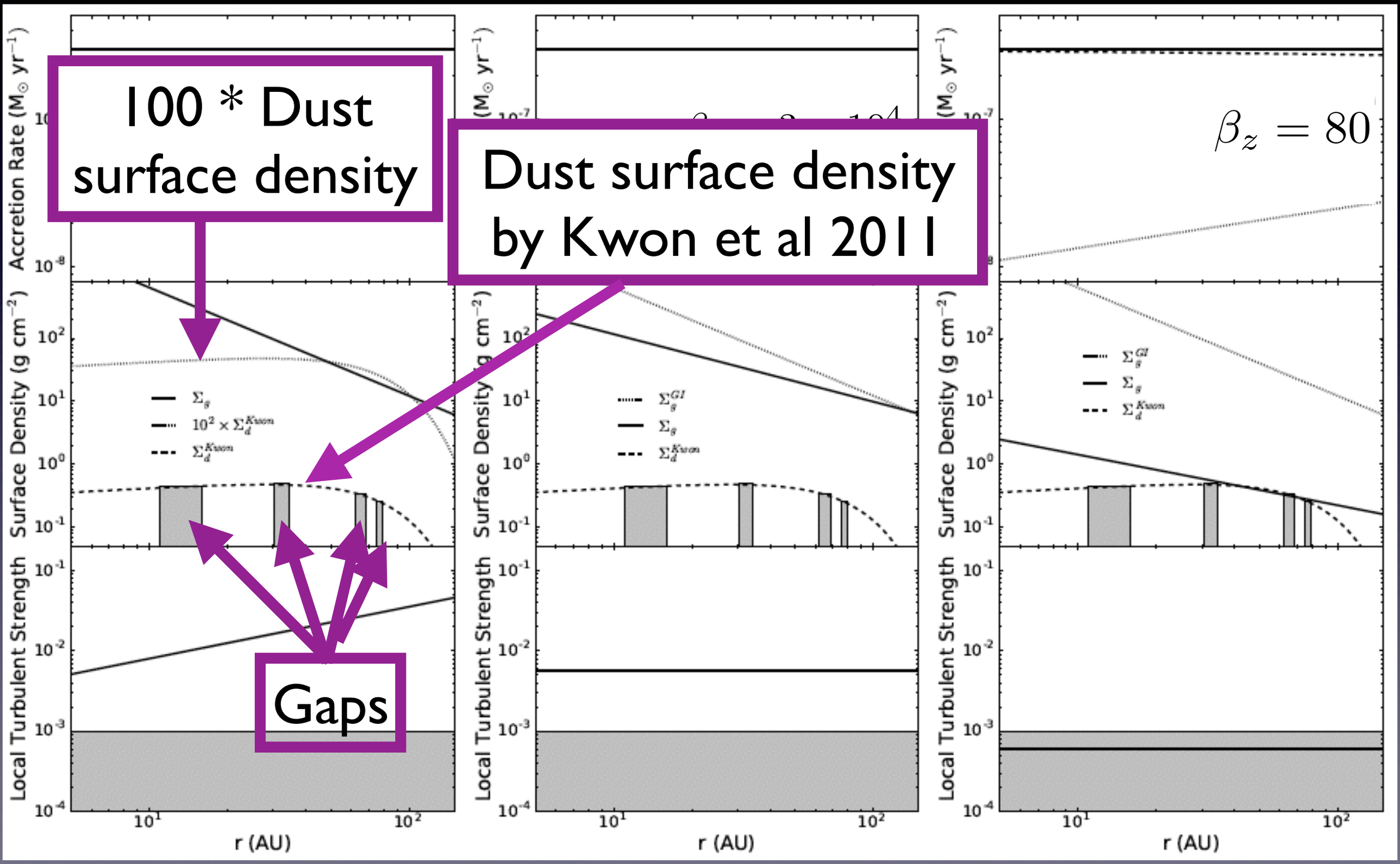

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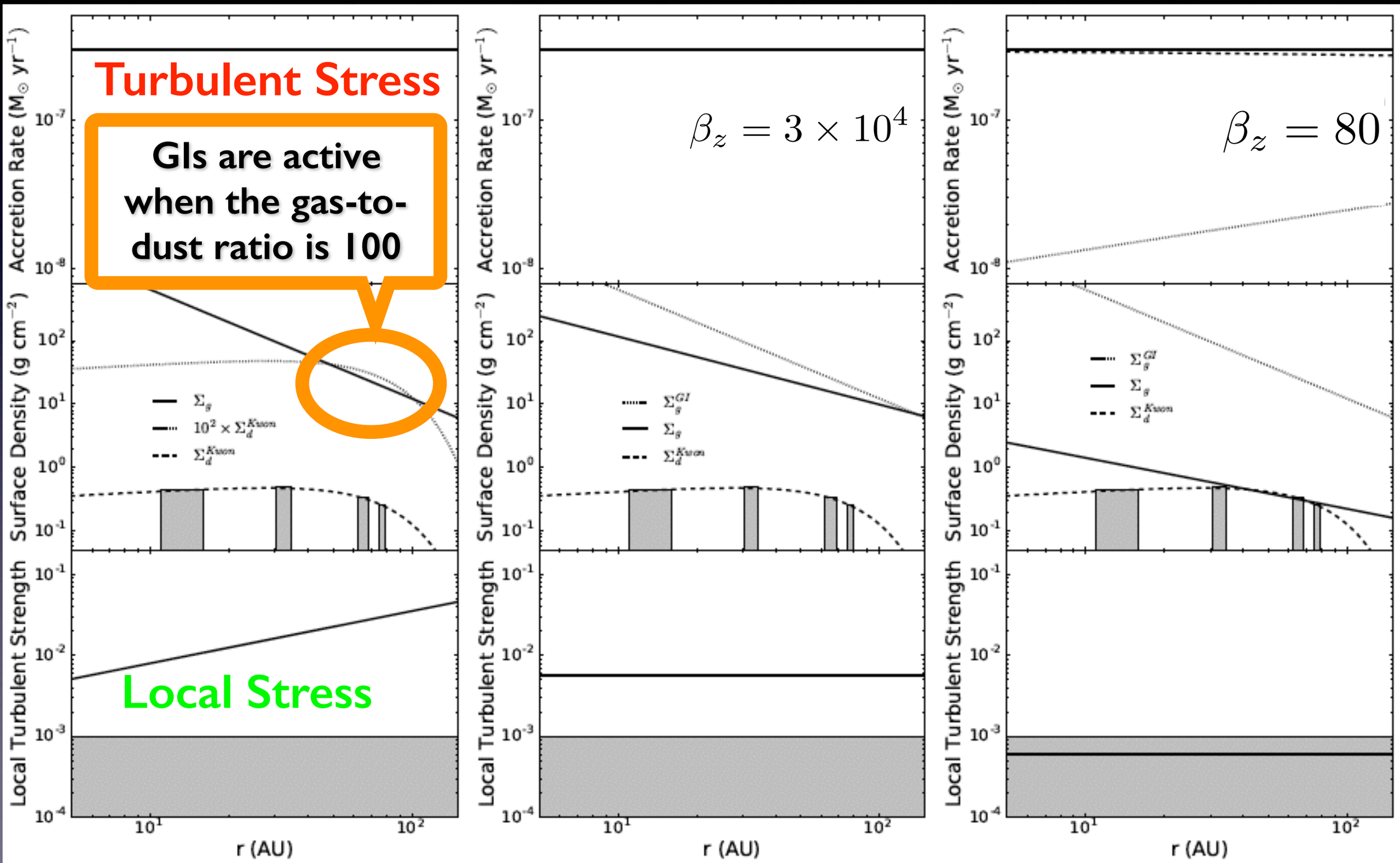

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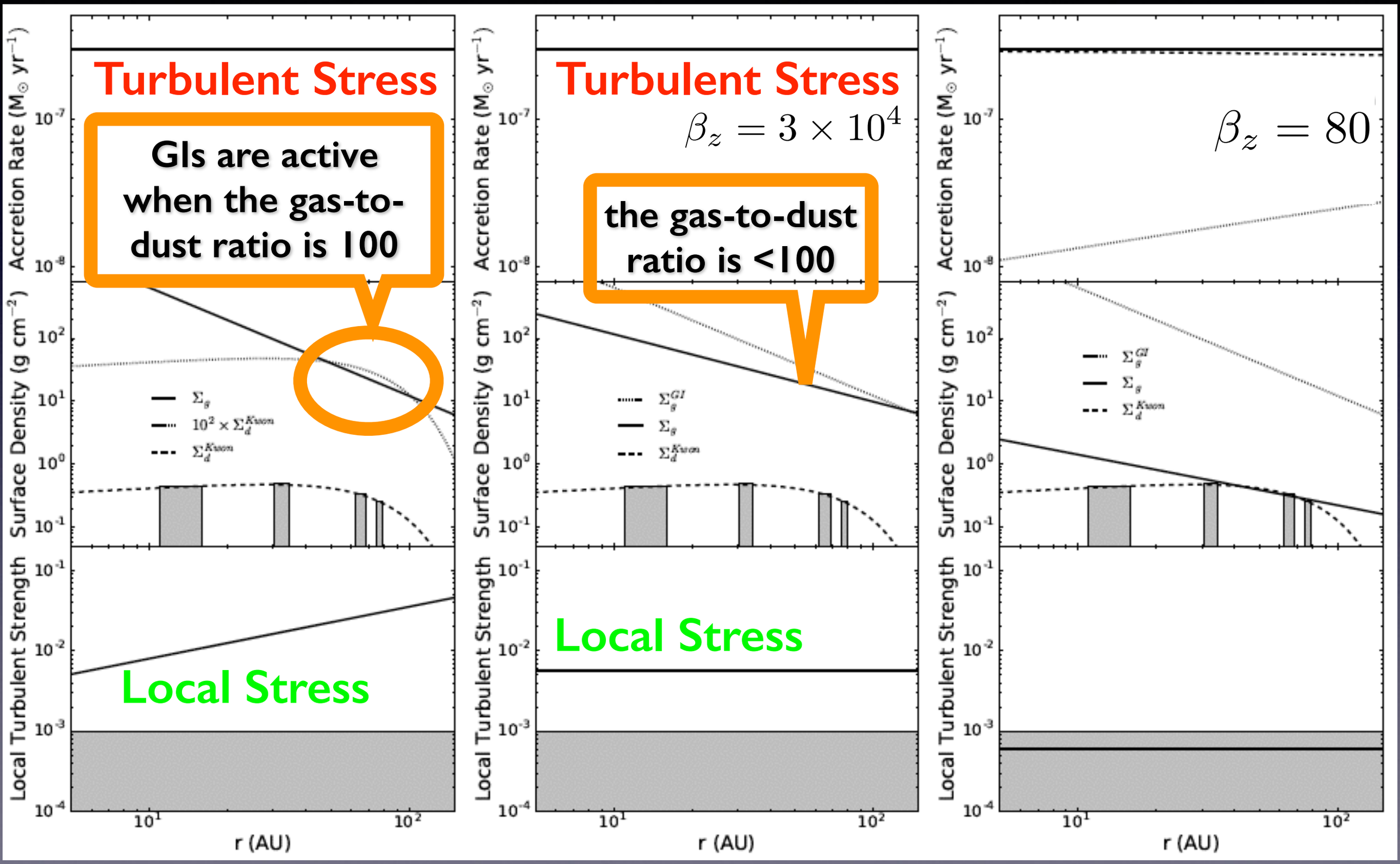

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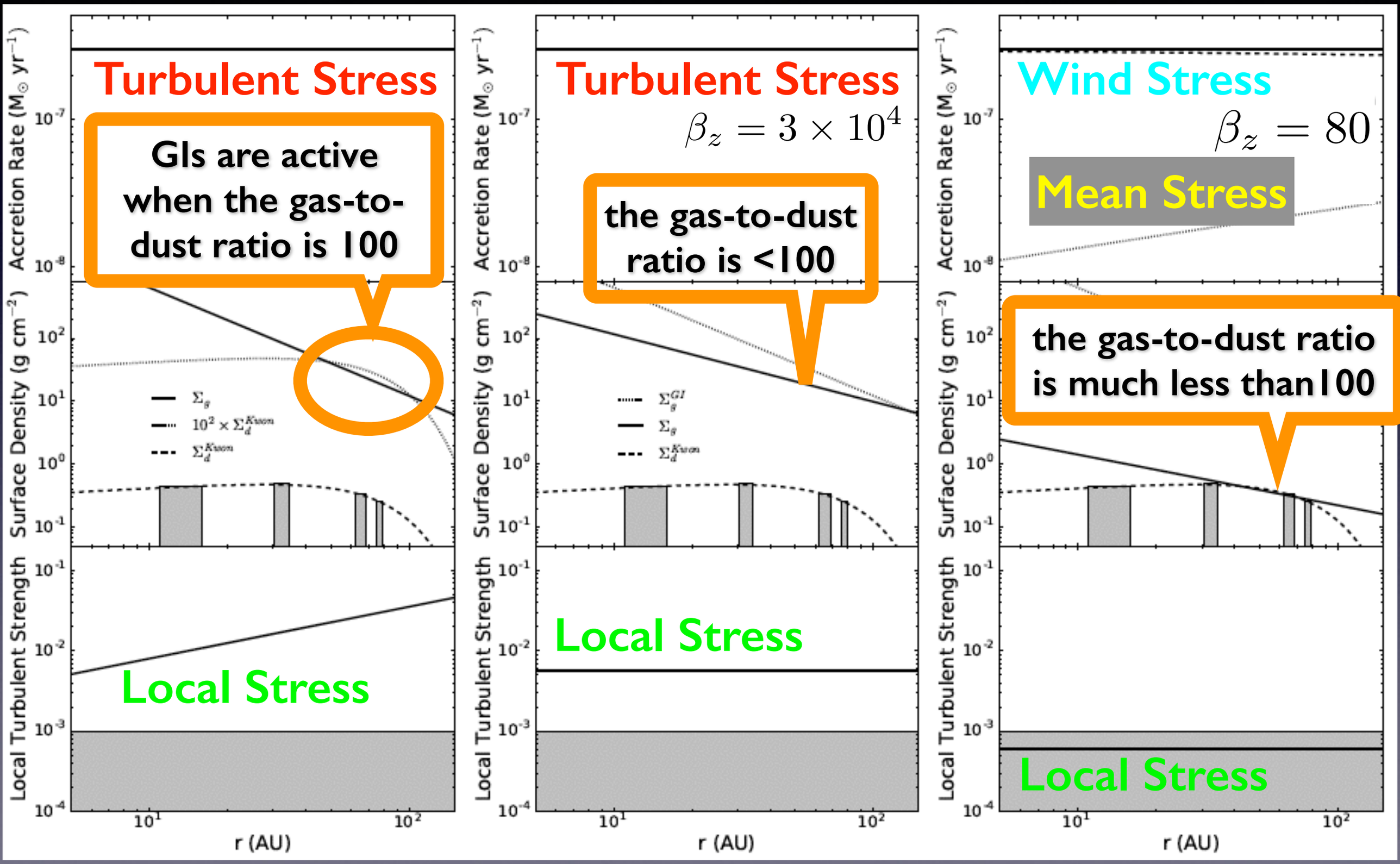

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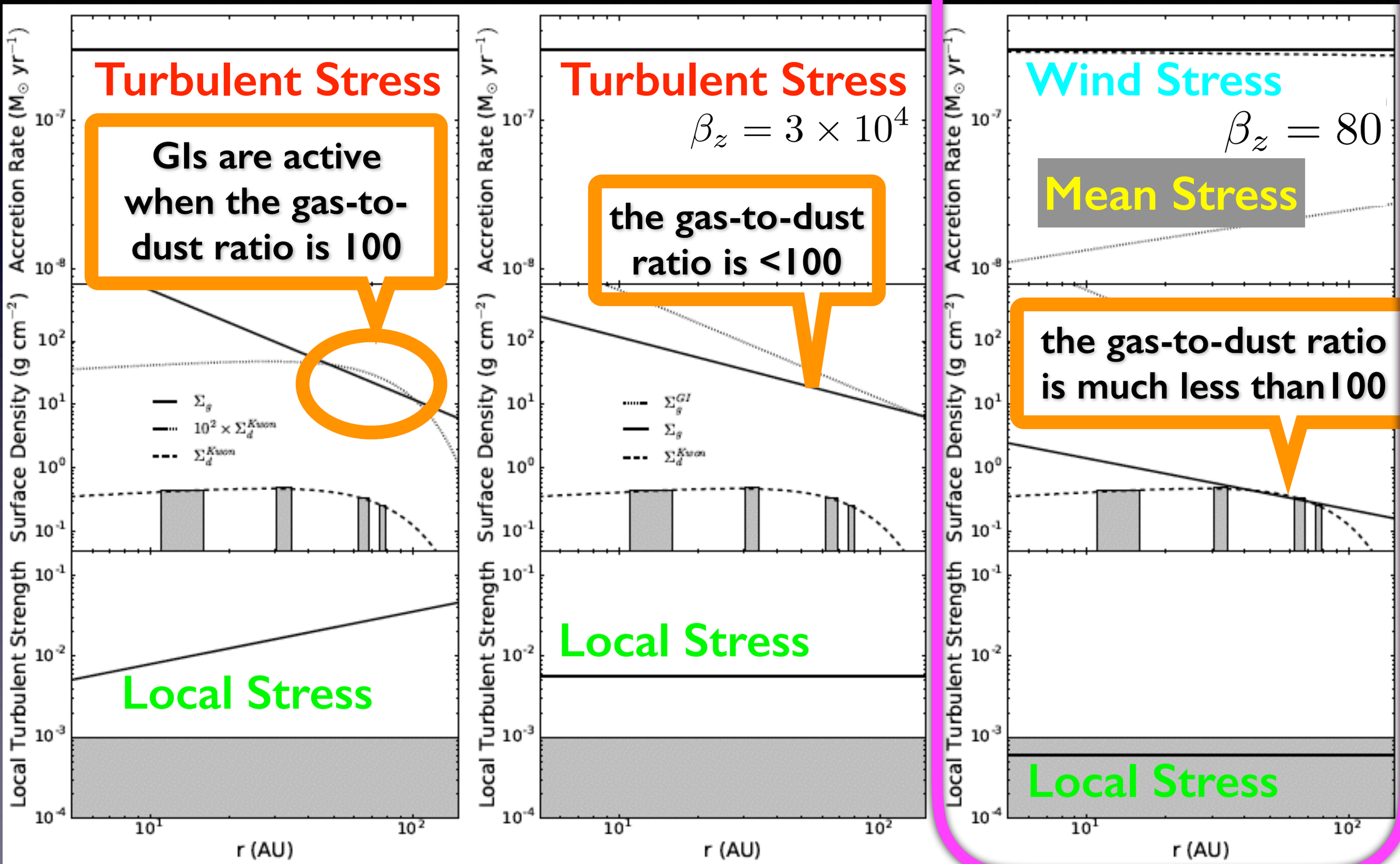

Next steps

Complete the analysis

Hasegawa et al in prep

Consider another possibilities
to explain origins of disk accretion in the HL Tau
e.g.) a quiescent phase of episodic accretion

Discuss possible observational tests
about our results;

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

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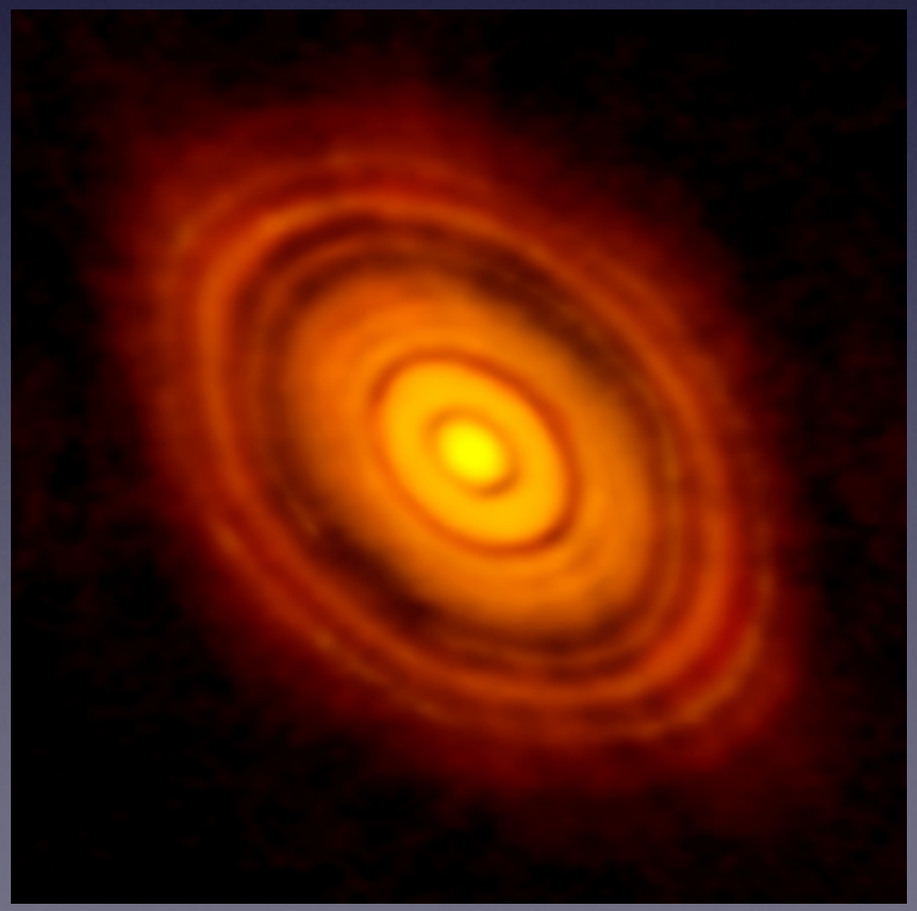

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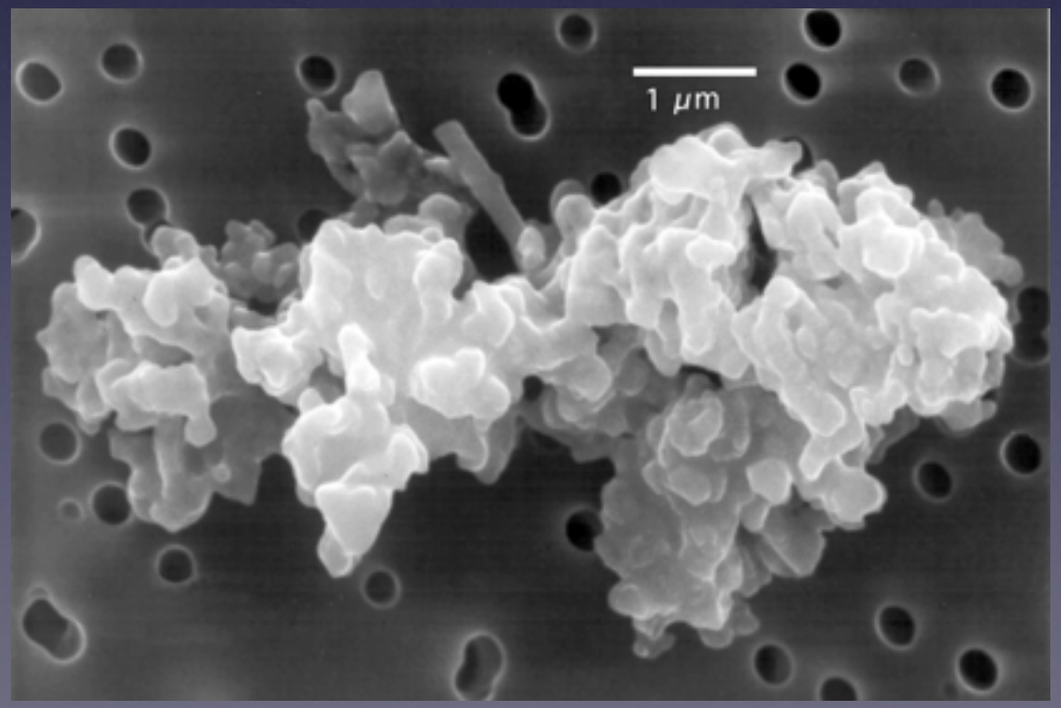
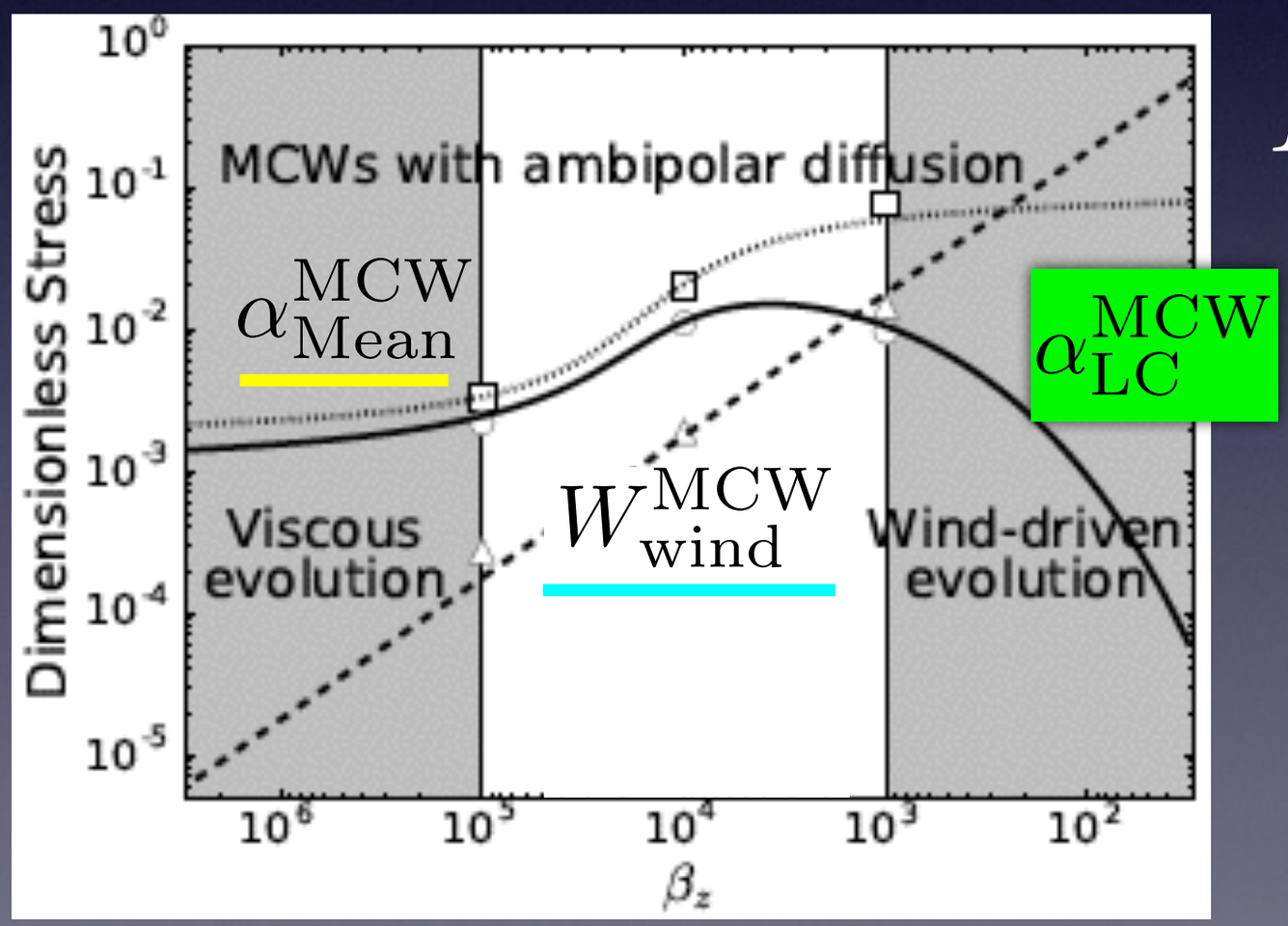


Two Additional Motivations

1) the HL Tau disk may be regulated by MCWs

2) the local turbulence tends to be damped out as the plasma beta decreases



Simon et al 2013

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Wind Stress

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Simplified Model for Dust Growth

e.g., Birnstiel 2012, Okuzumi et al 2016

Coagulation (collisions)

the dust size:

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

Draine 1985

Follow the evolution of the largest dusty aggregates

The radial drift regime:

$$\mathrm{St}_{\mathrm{drift}} \equiv \frac{\pi}{2} \frac{\rho_d a_*}{\Sigma_{\mathrm{g}}}$$

$$= f(c_{\mathrm{s}}, \Sigma_{\mathrm{g}}/\Sigma_{\mathrm{d}}, \alpha_{\mathrm{gg}})$$

The fragmentation regime:

$$\mathrm{St}_{\mathrm{frag}} = g(c_{\mathrm{s}}, v_{\mathrm{frag}}, \alpha_{\mathrm{gg}})$$

$$\Sigma_{\mathrm{g}}/\Sigma_{\mathrm{d}} = 100 \quad v_{\mathrm{frag}} = 30\mathrm{m/s}$$

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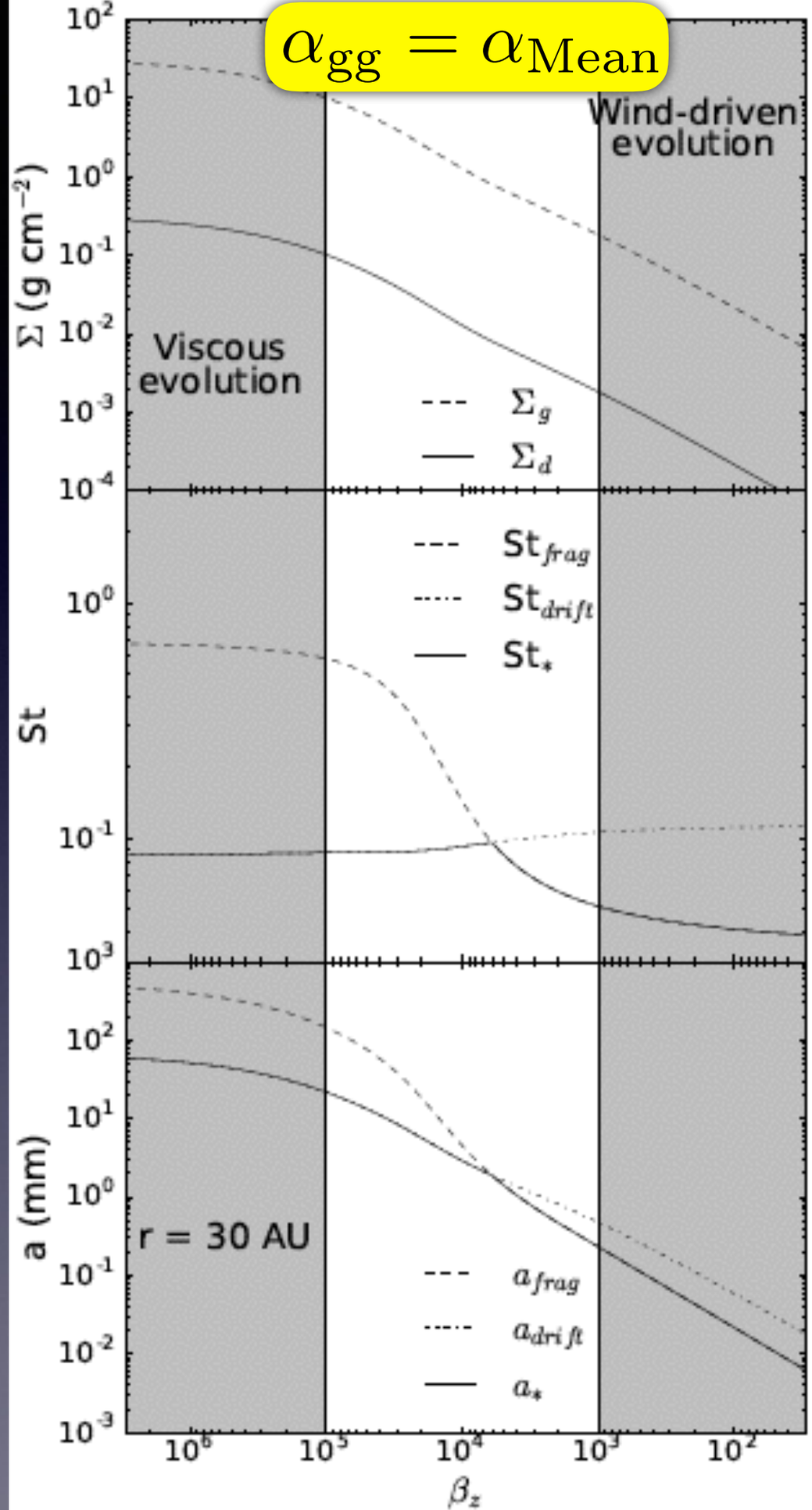
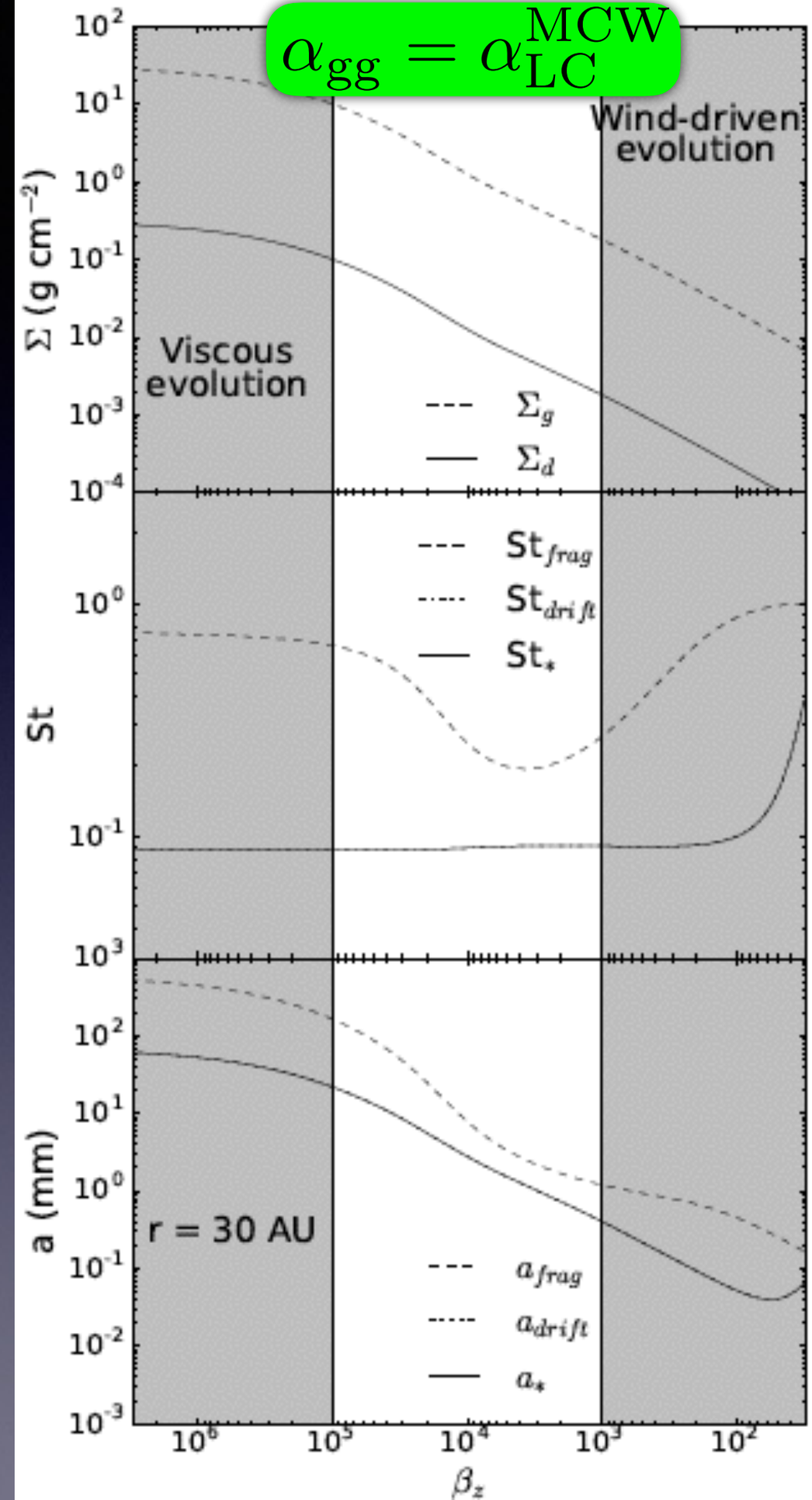

$\alpha_{gg} = \alpha_{Mean}$
Wind-driven evolution
Viscous evolution
Σ (g cm^{-2})
Σ_g
Σ_d
St
St_{frag}
St_{drift}
St_*
a (mm)
r = 30 AU
a_{frag}
a_{drift}
a_*
β_z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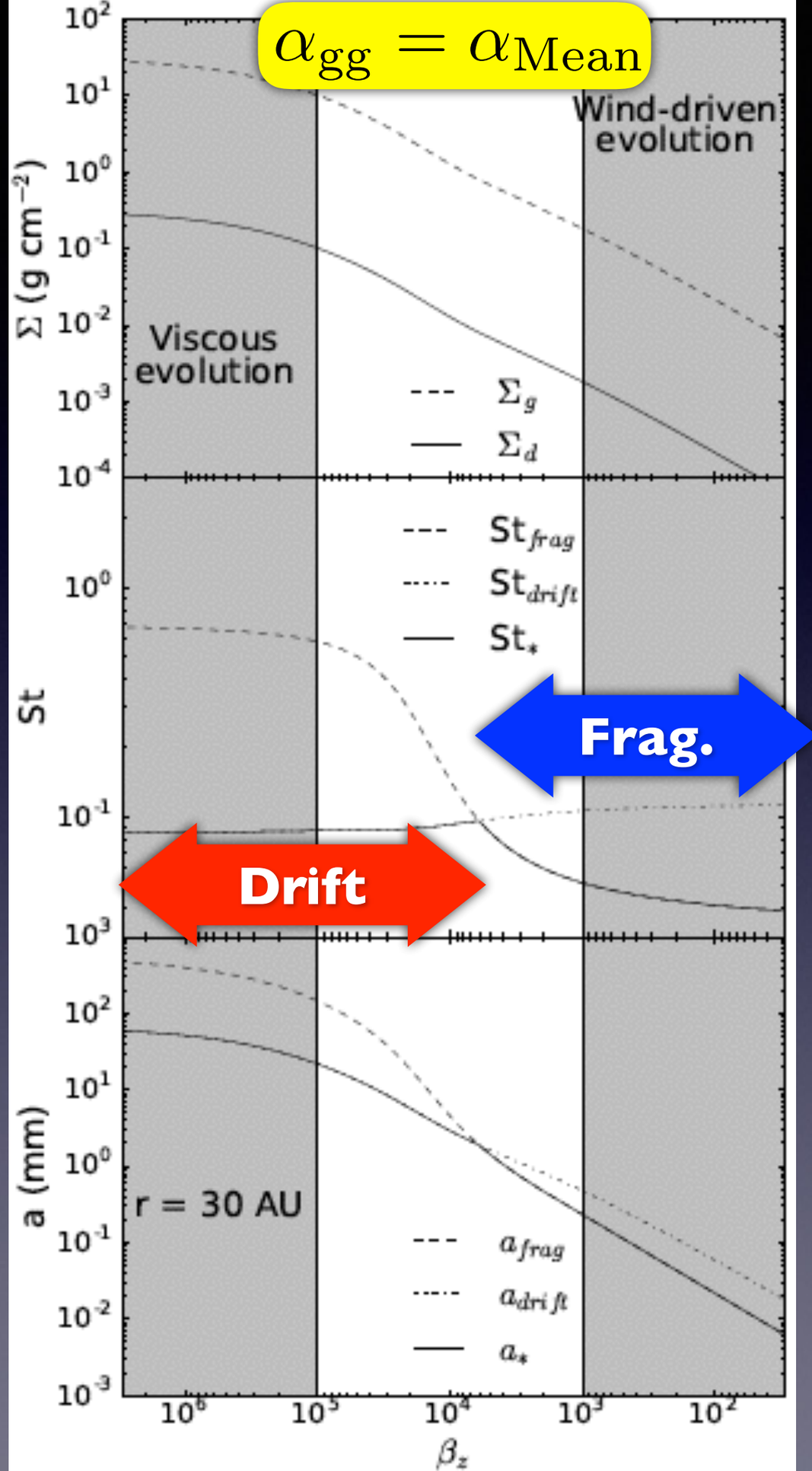
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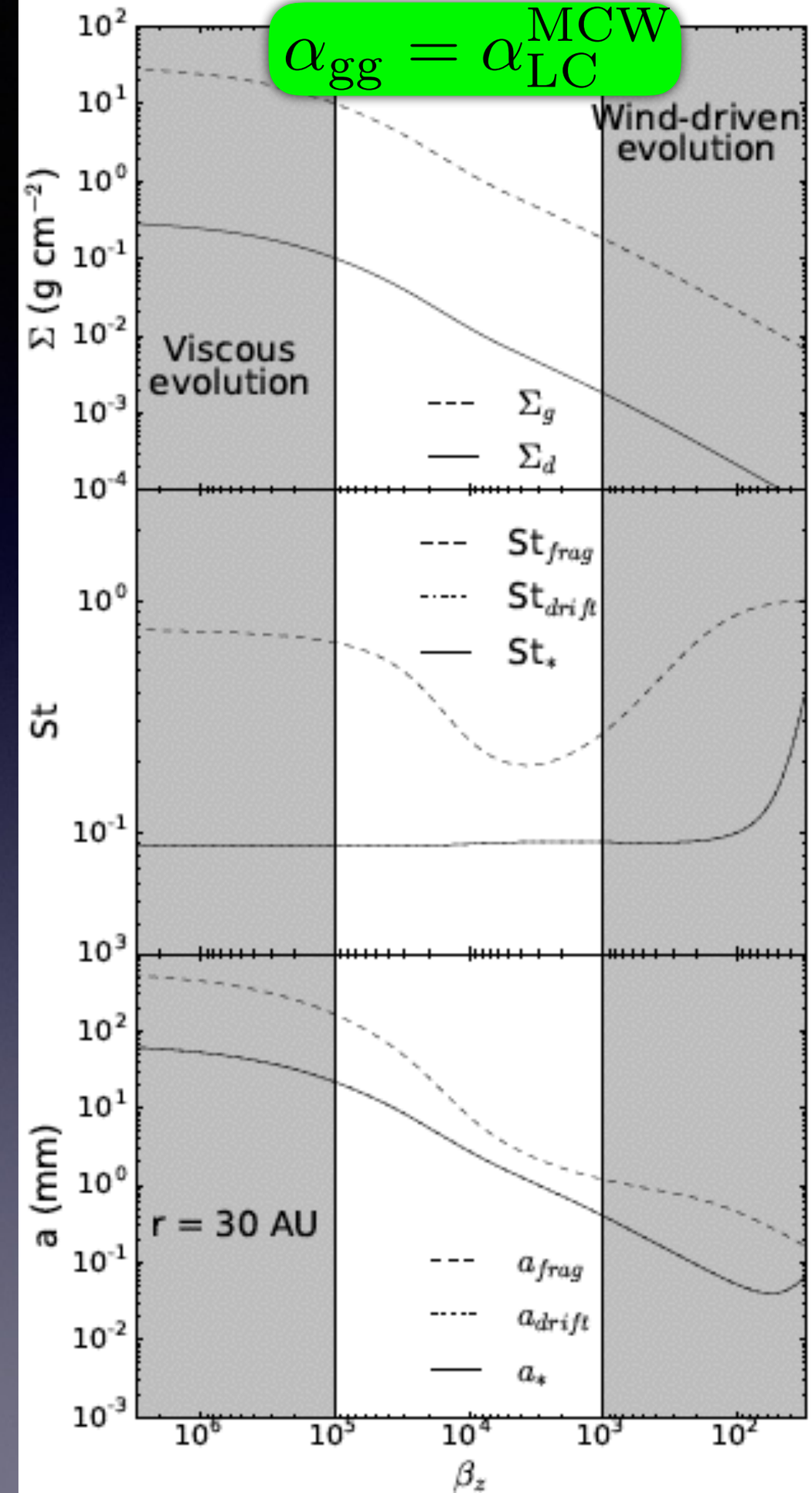
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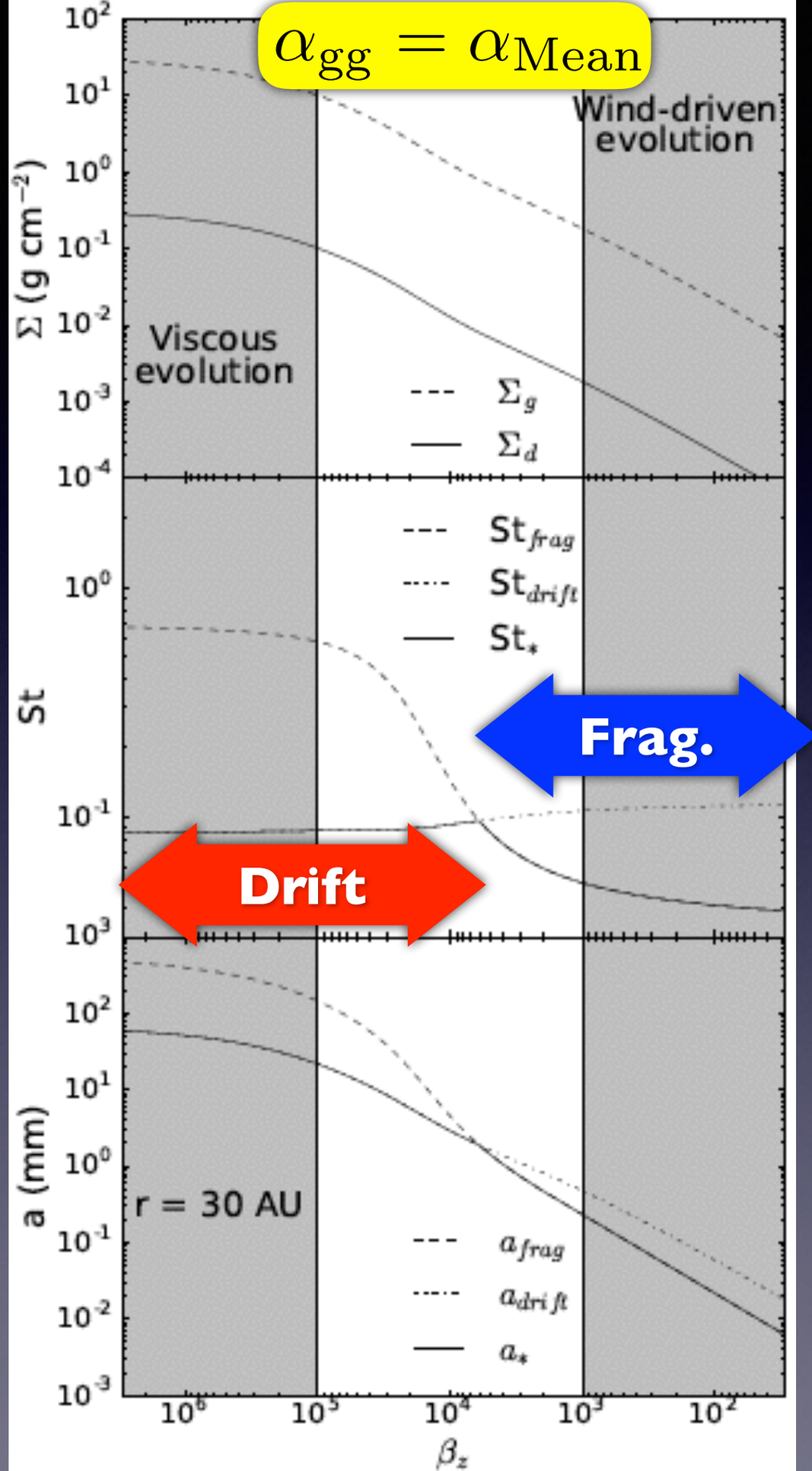
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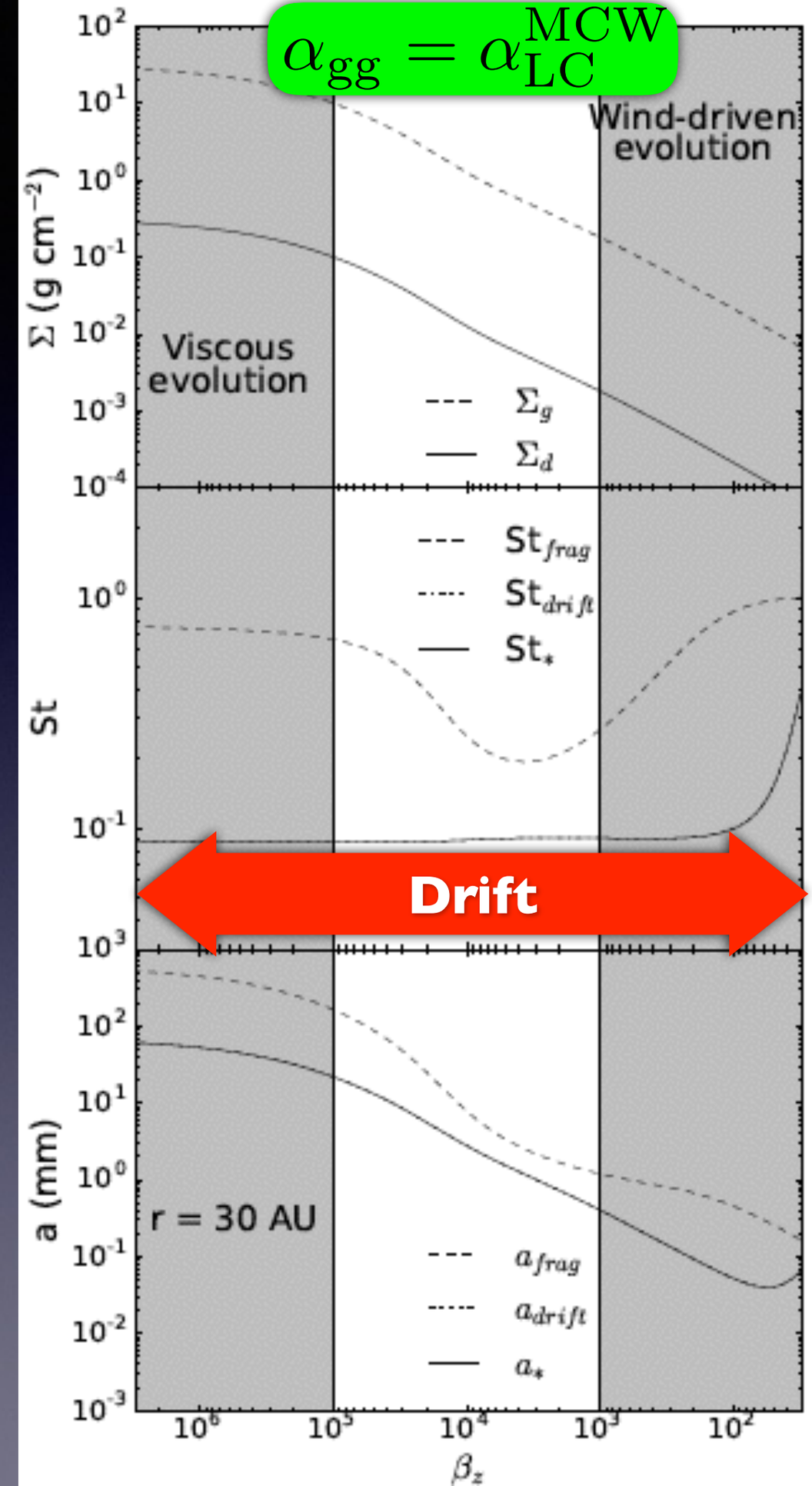
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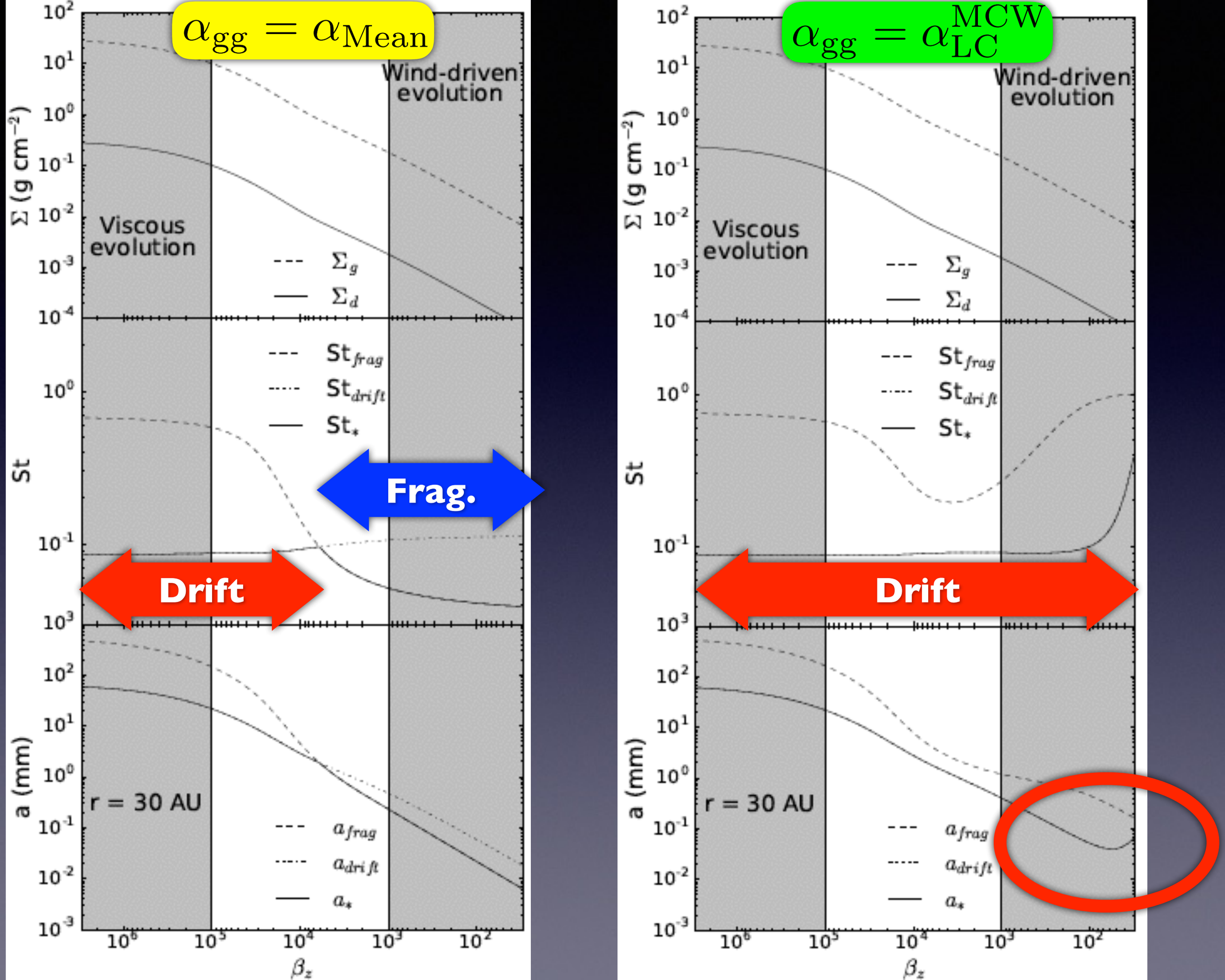
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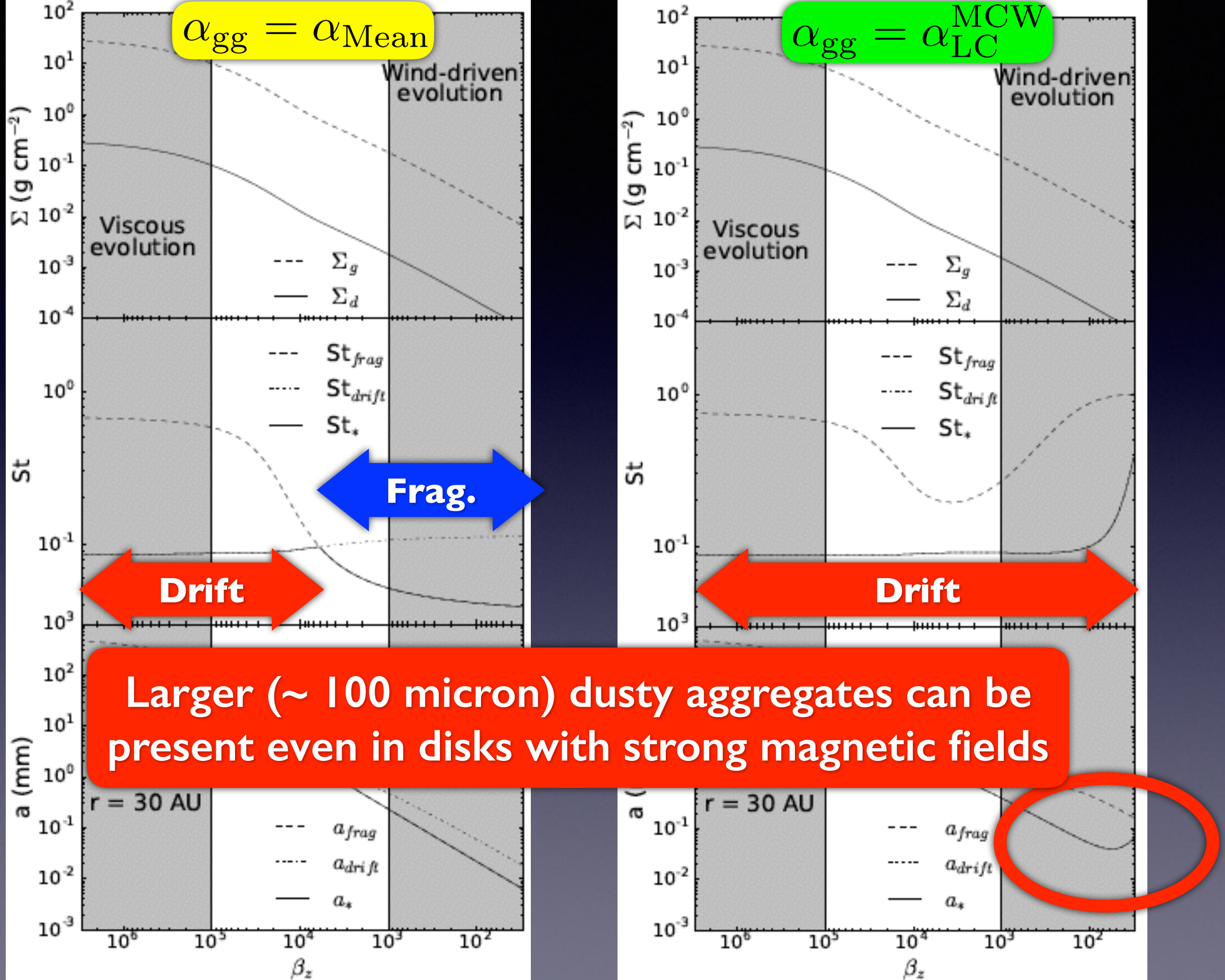
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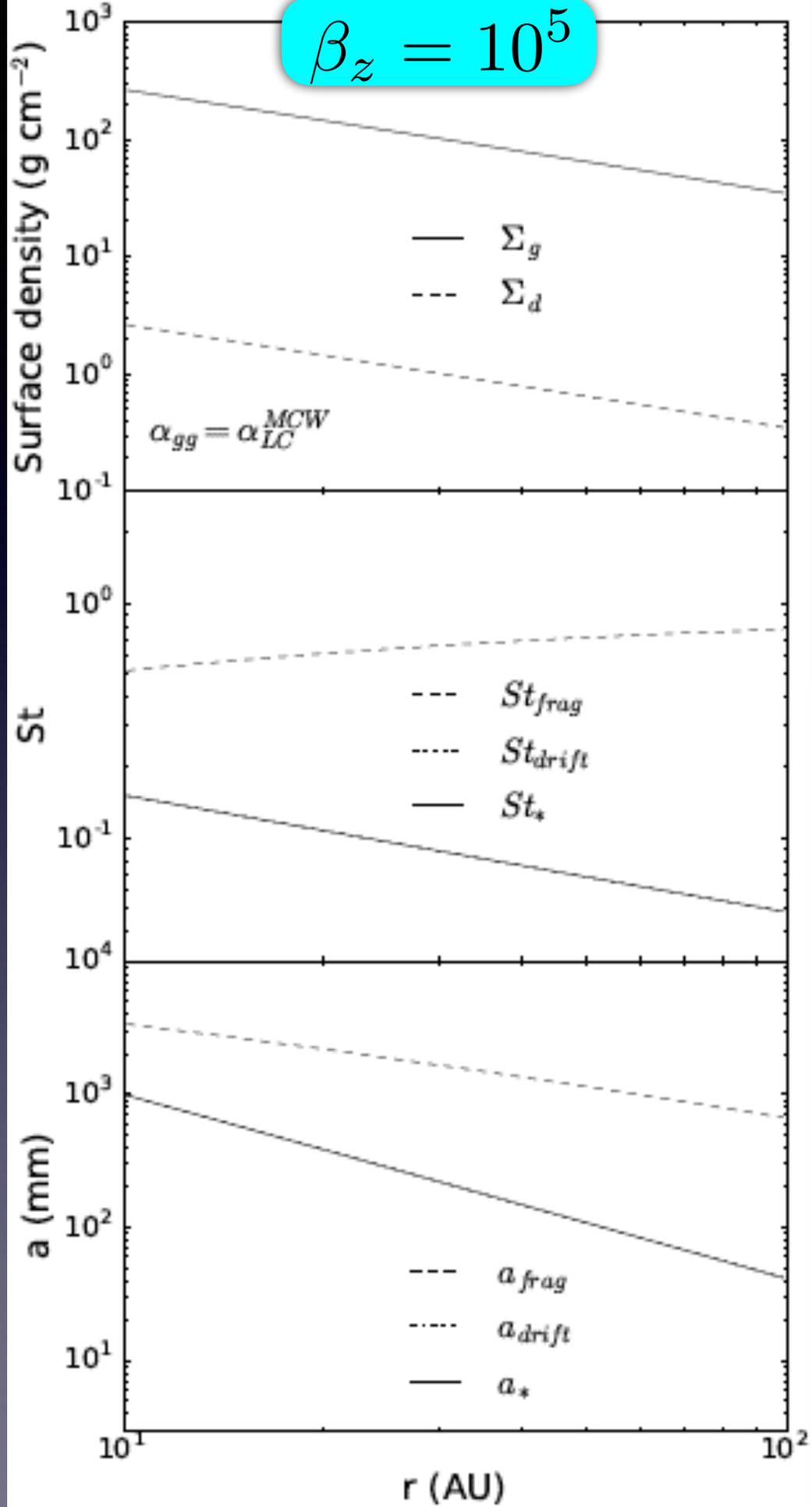
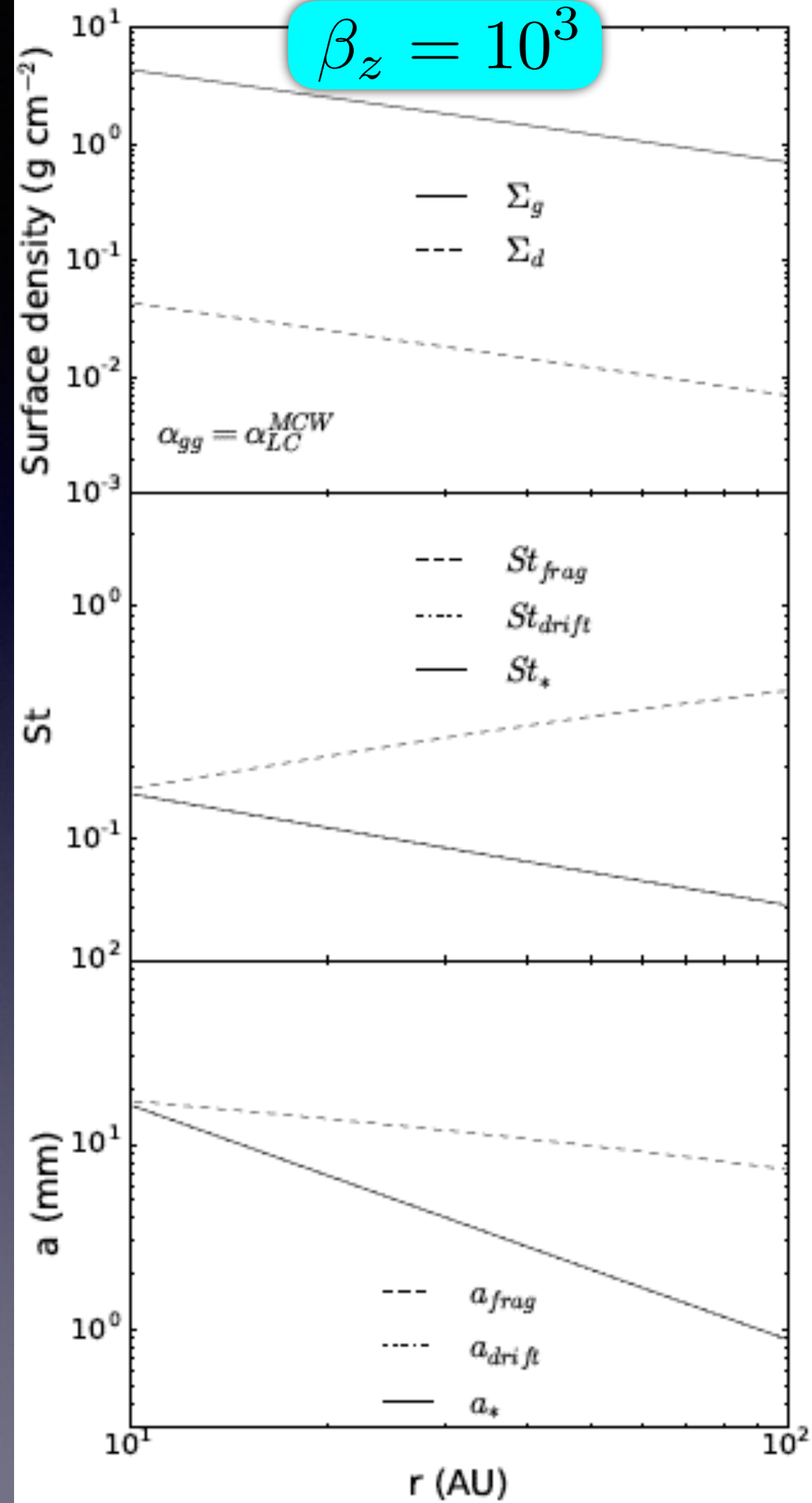
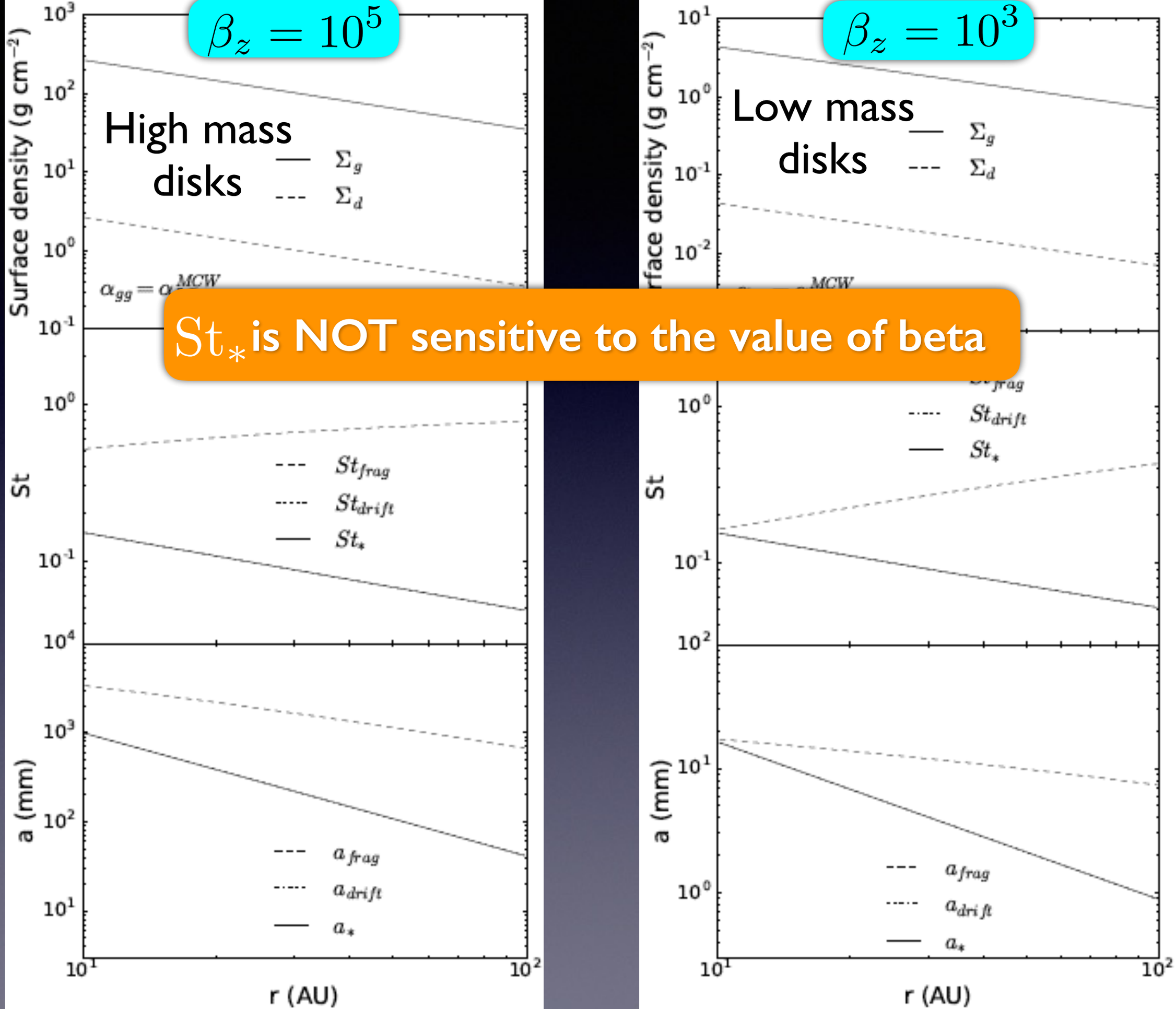
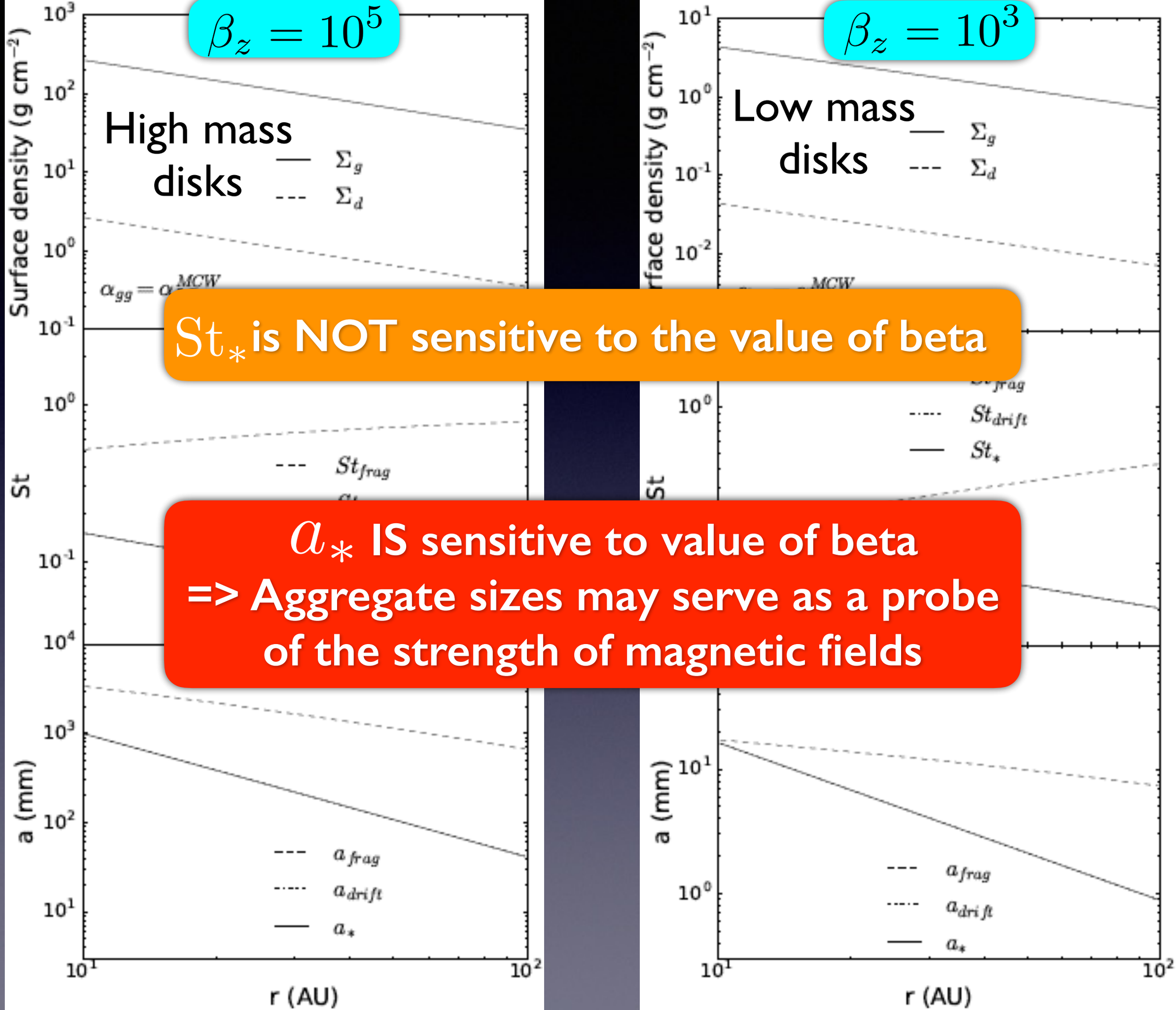
Larger (~ 100 micron) dusty aggregates can be present even in disks with strong magnetic fields


$\beta_z = 10^5$
Surface density (g cm^{-2})
Σ_g
Σ_d
$\alpha_{gg} = \alpha_{LC}^{MCW}$
St
St_{frag}
St_{drift}
St_*
a (mm)
a_{frag}
a_{drift}
a_*
r (AU)


$\beta_z = 10^3$
Surface density (g cm^{-2})
Σ_g
Σ_d
$\alpha_{gg} = \alpha_{LC}^{MCW}$
St
St_{frag}
St_{drift}
St_*
a (mm)
a_{frag}
a_{drift}
a_*
r (AU)



St_* is NOT sensitive to the value of beta



St_* is NOT sensitive to the value of beta

a_* IS sensitive to value of beta
=> Aggregate sizes may serve as a probe of the strength of magnetic fields

Next steps

Complete the analysis

Hasegawa et al in prep

Cover the larger parameter space
to verify our results

Develop a more sophisticated model
e.g.) improve the dust growth model
couple with non-ideal MHD simulations
perform long-term simulations

Summary

- A number of astonishing observational discoveries have recently been achieved in exoplanet sciences
- These discoveries are still not fully digested yet
- The key information is 1) origins of disk evolution and 2) the spatial distribution of planet-forming materials
- Performed a simplified, but comprehensive analysis of disk accretion; examined 3 disk models (GIs, MRIs with Ohmic resistivity, Magnetocentrifugal winds) for the HL Tau disks
- Found that MCWs would be the most likely for the HL Tau disk
- Investigated how dust growth would be affected in the MCW disk model, using a simplified dust growth model
- Found that the aggregate size may be used to infer the strength of magnetic fields threading the disks