The Formation and Angular Momentum Evolution of Protoplanetary Disks

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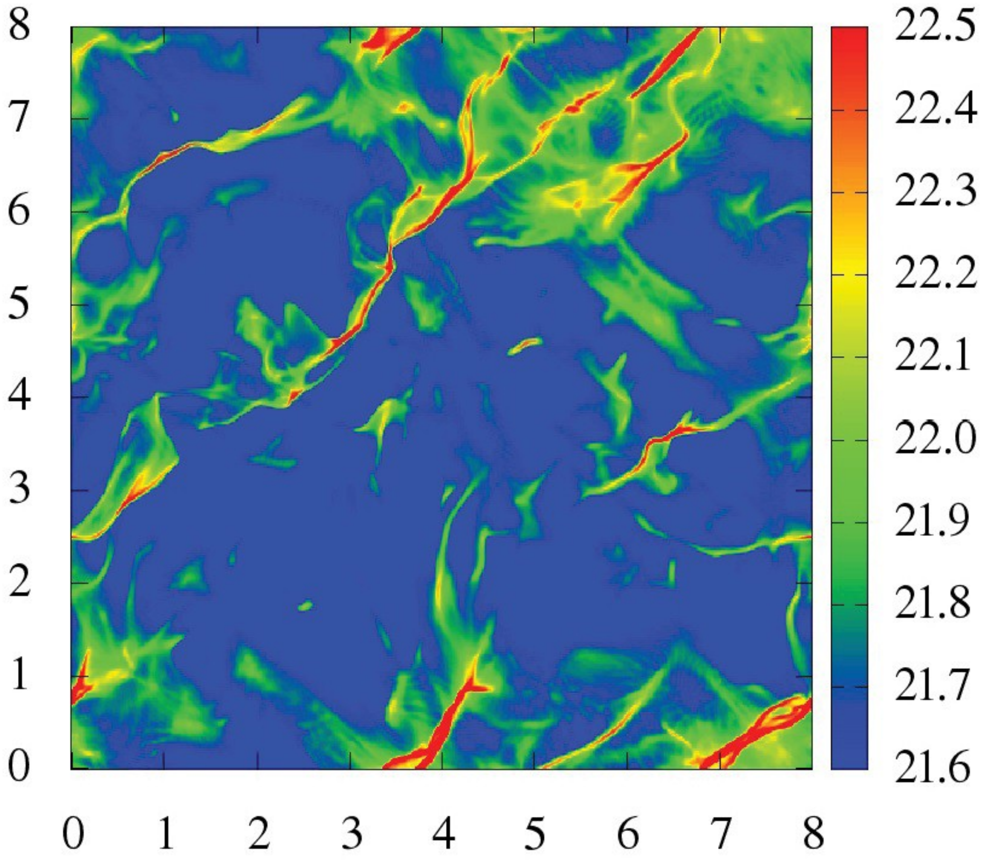
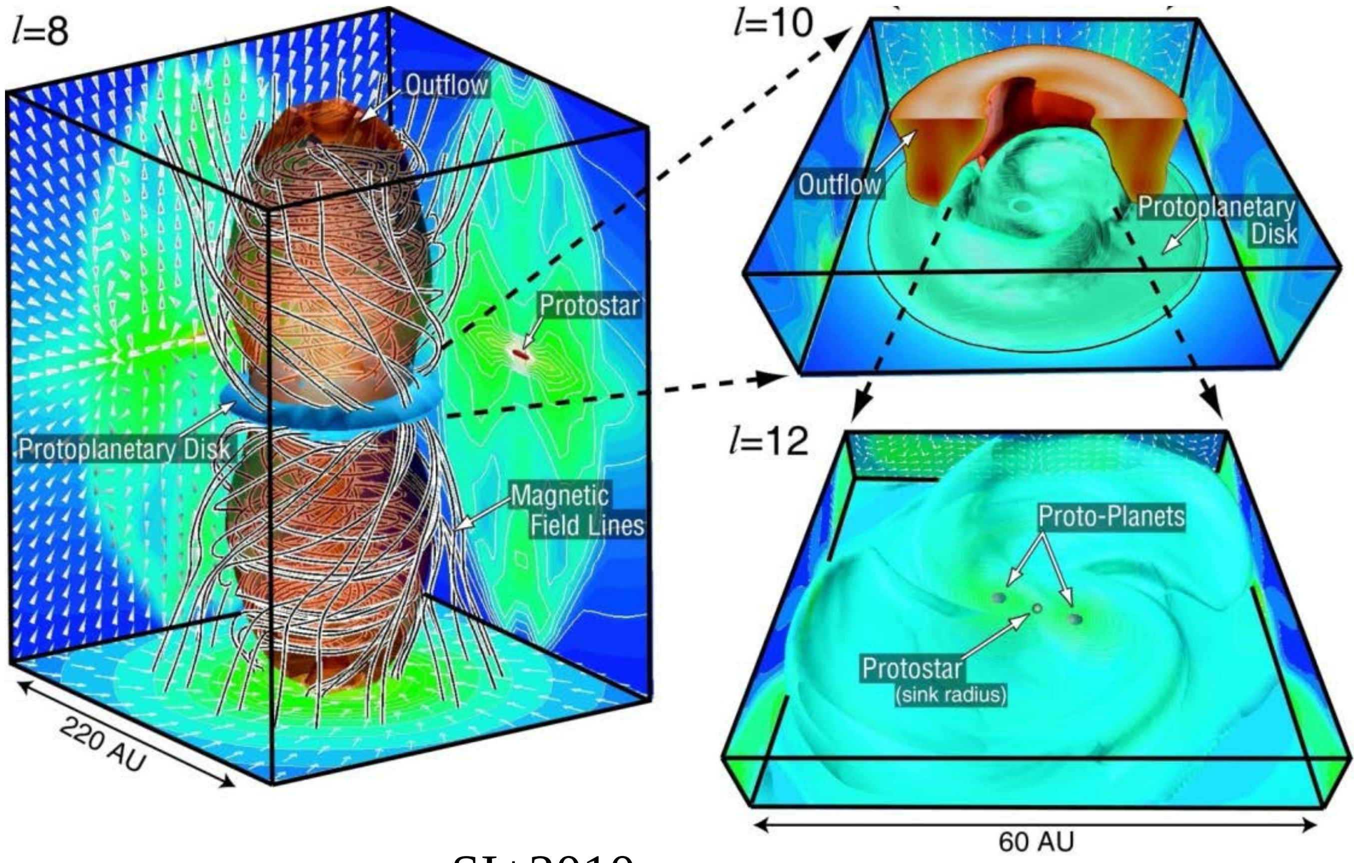


SI+2015

?



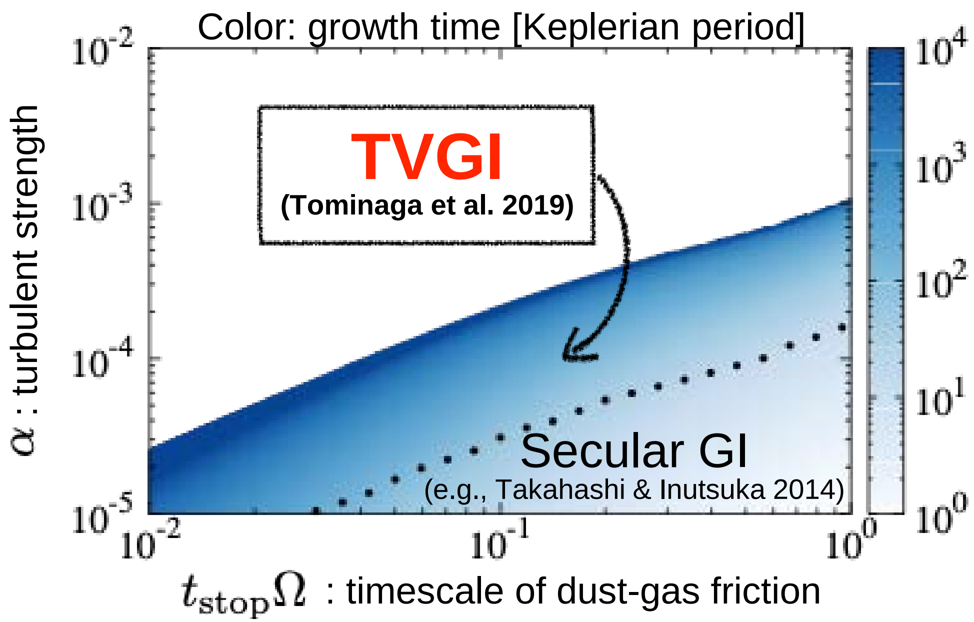
SI+2010

Revised description of dust diffusion and a new secular instability to create multiple rings in protoplanetary disks

Ryosuke T. Tominaga, Sanemichi Z. Takahashi, & Shu-ichiro Inutsuka

Reference: Tominaga et al. (2019), **arxiv# 1905.12899**

- ✓ Reformulation of equations describing the dust diffusion in PPDs based on the mean-field approximation (Reynolds-averaging)
- ✓ The formulated equations conserve the total angular momentum, which is contrary to the frequently used equations.
- ✓ **A new secular instability**: Two-component Viscous Gravitational Instability (**TVGI**)



- TVGI is triggered by dust-gas friction & turbulent viscosity.
- The growth of TVGI leads to **concentration of dust grains.**

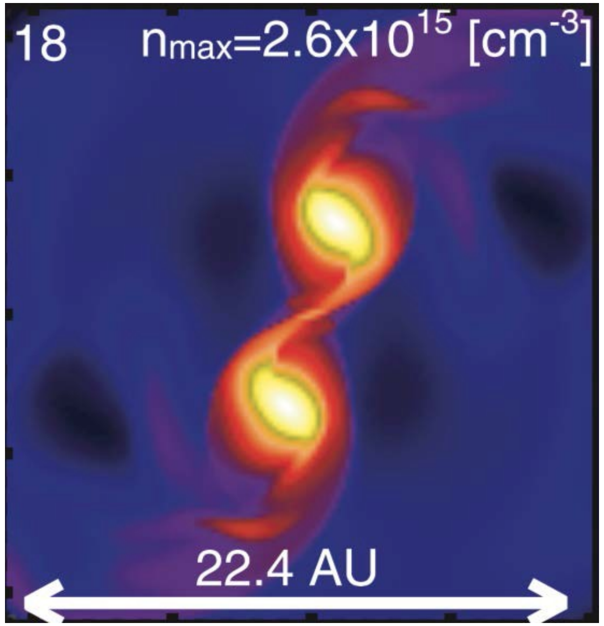
↓

A possible mechanism for the formation of observed multiple rings and planetesimals !

Role of Angular Momentum in Star Formation

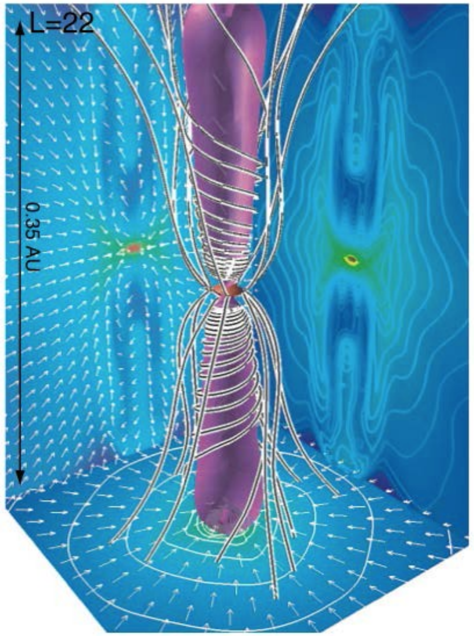
The angular momentum (AM) of a molecular cloud core is directly related to…

Multiple system



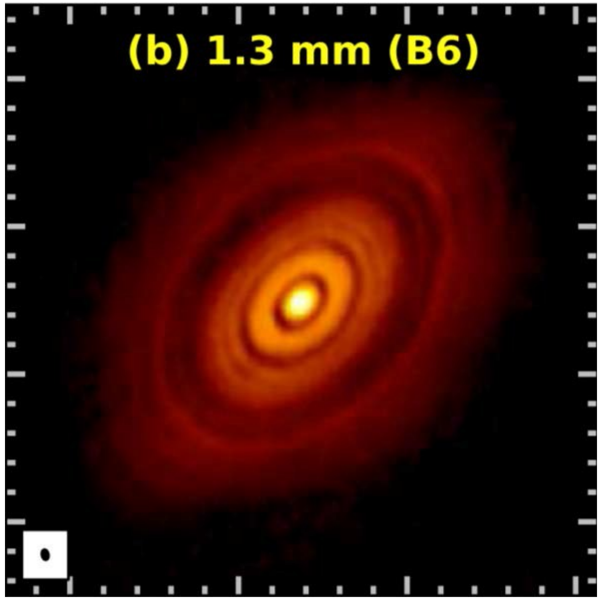
Machida et al. (2008)

Outflow



Machida et al. (2008)

Protoplanetary disk



ALMA Partnership et al. (2015)

The angular momentum of molecular cloud cores plays an essential role in the star formation process.

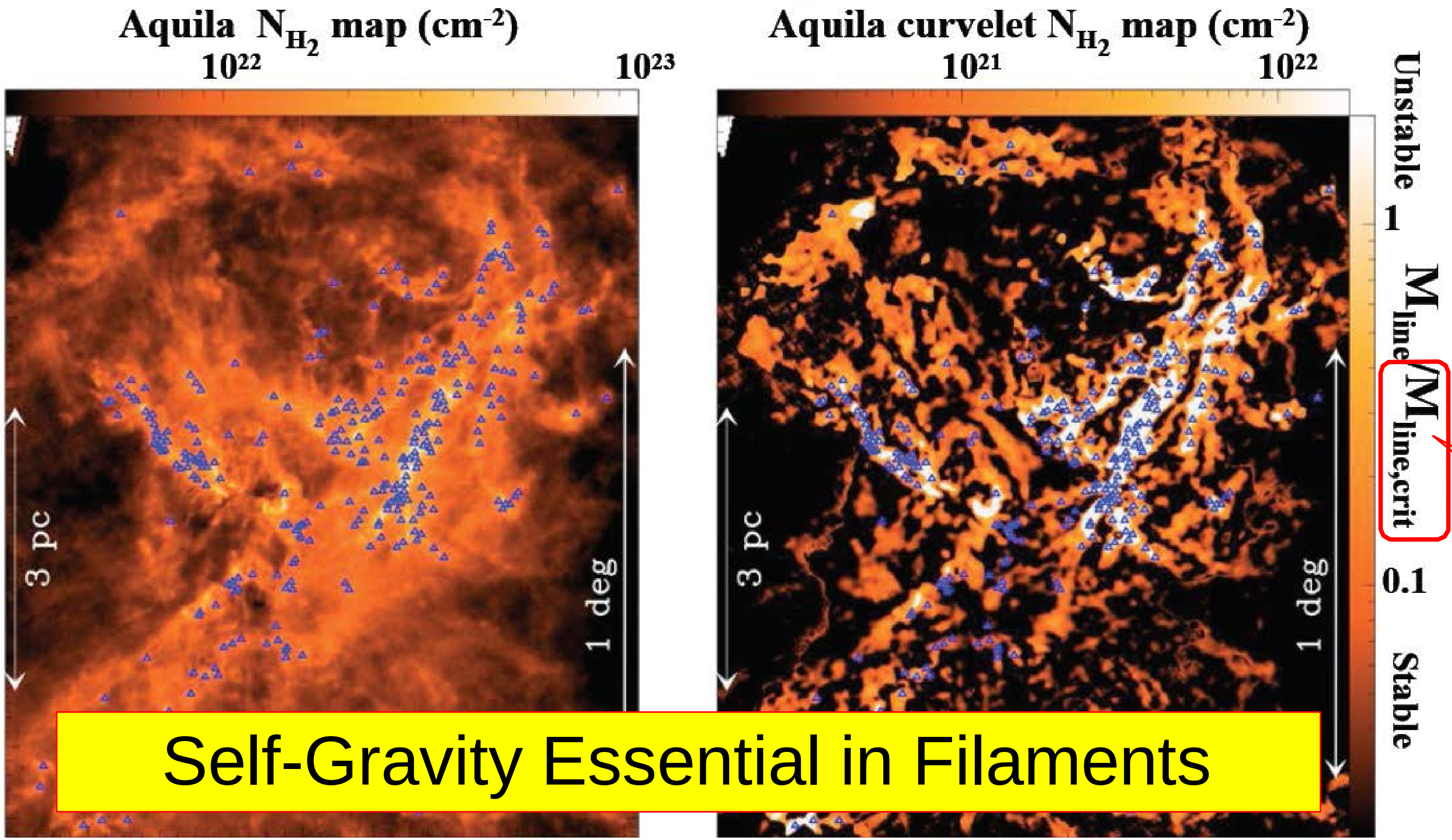
Outline

1. “Filament Paradigm” of Star Formation
2. Core Mass Function
3. Angular Momentum of Molecular Cloud Cores
4. Disk Misalignment
5. Summary

Filament Paradigm Highlighted by Herschel (e.g., André+2010)

Prestellar cores are preferentially found within the densest filaments

△: Prestellar cores - 90% found at $N_{H_2} > 7 \times 10^{21}\ cm^{-2}$ <=> A_v(back) > 8



$2C_s^2/G$

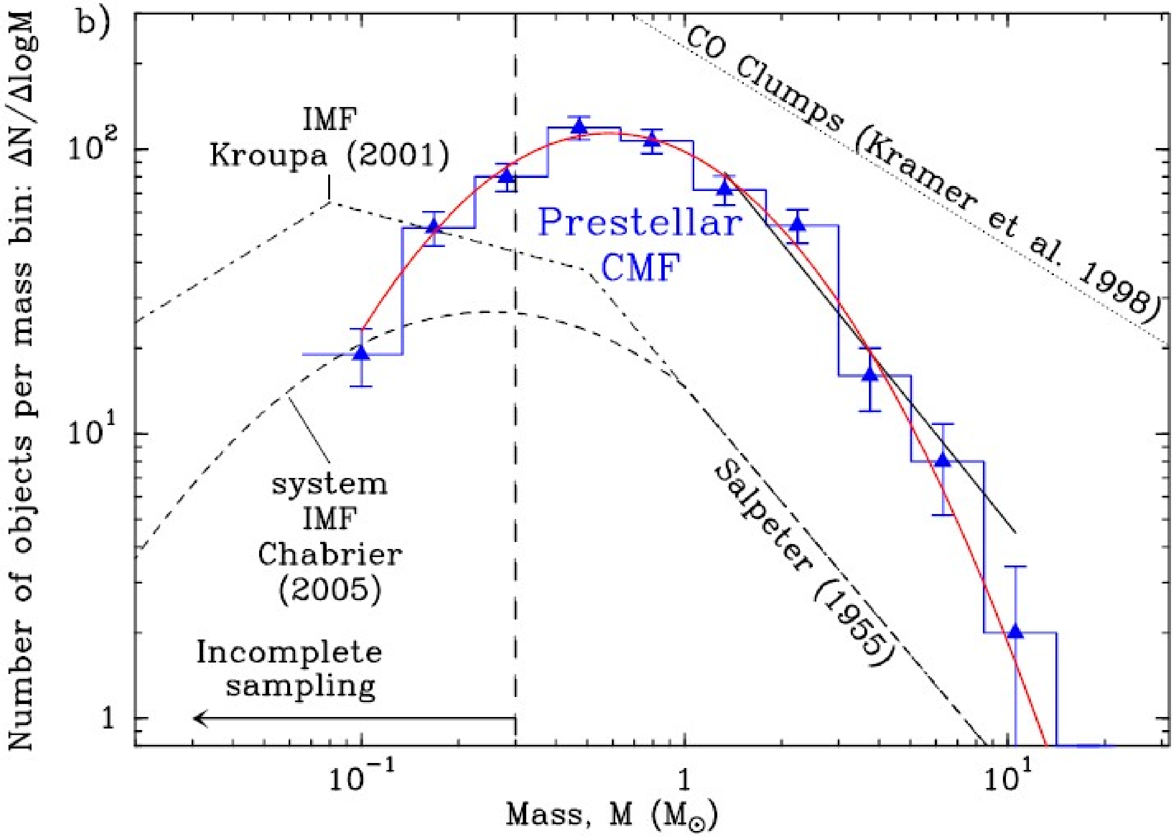
Self-Gravity Essential in Filaments

Toward Understanding IMF

An Origin of Core Mass Function

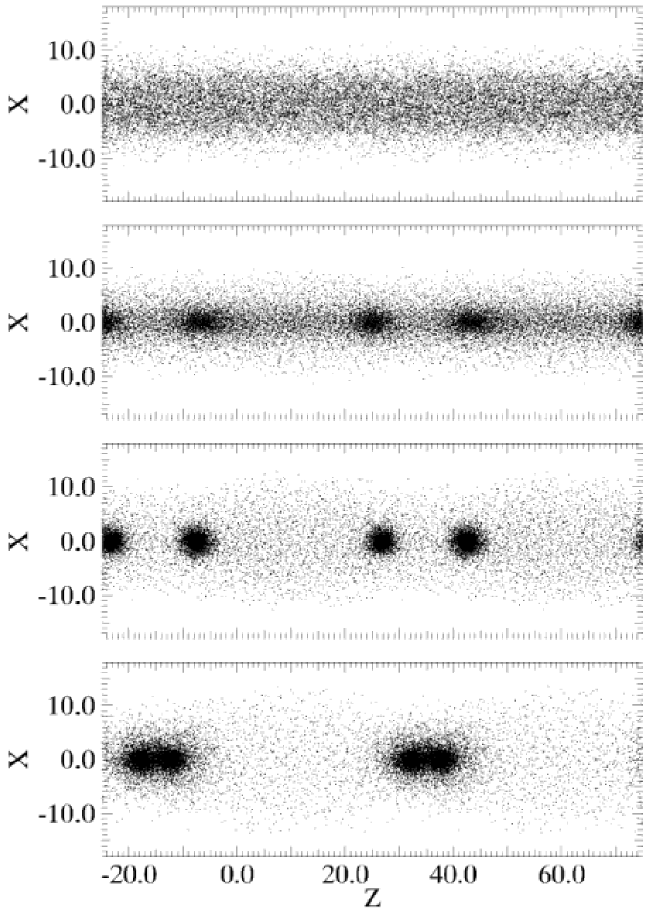
Mass Function of Dense Core?

Aquila CMF from Herschel



André+2010; Könyves+2010

See also Motte+1998, etc.



SI & Miyama 1997

Larger Wavelength

➔ Massive Core

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

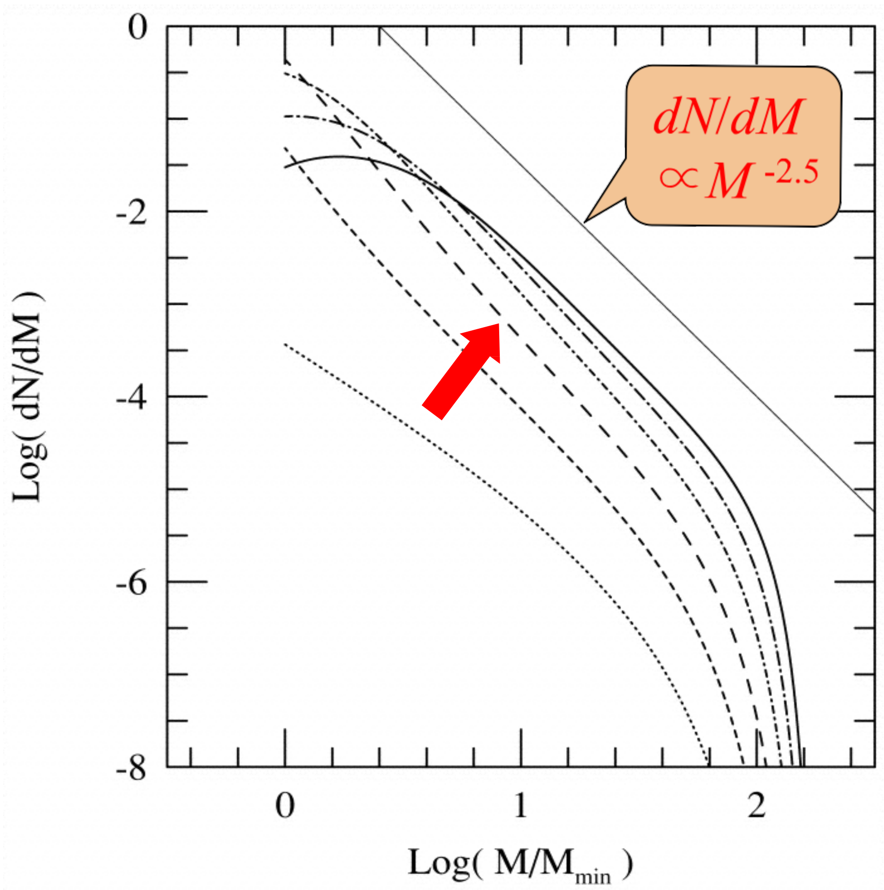
$$P(k) \propto k^{-1.5}$$

Mass Function

$$dN/dM \propto M^{-2.5}$$

Observation of Both Fluctuation Spectrum & Core Mass Function

➔ Clear and Direct Test!

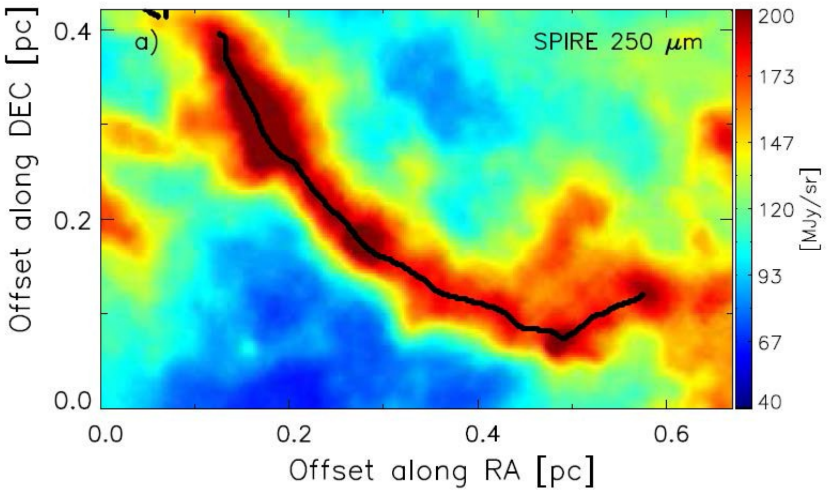


$$P(k) \propto k^{-1.5}$$

t/t_{ff} = 0 (dotted), 2, 4, 6, 8, 10 (solid)

"A possible link between the power spectrum of interstellar filaments and the origin of the prestellar core mass function"

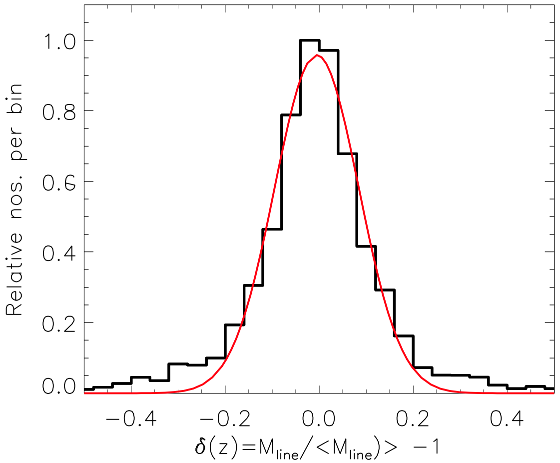
Roy, André, Arzoumanian et al. (2015) A&A **584**, A111

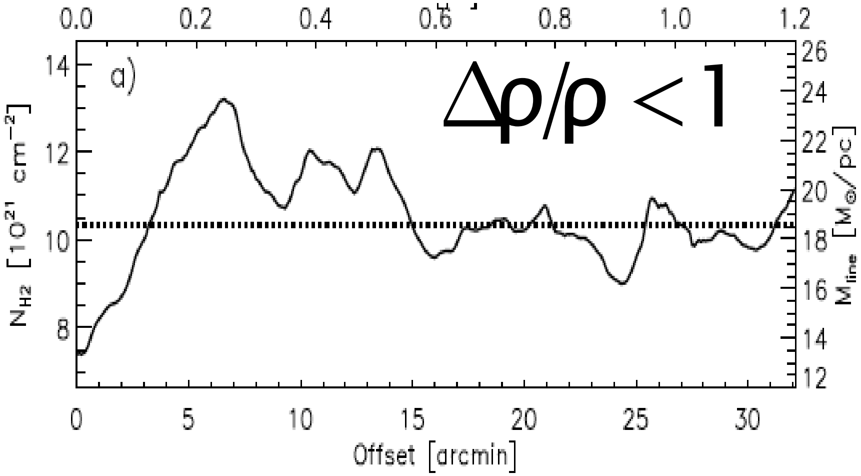


80 Young Filaments!

$\delta = \Delta\rho/\rho$ ...

Nearly Gaussian

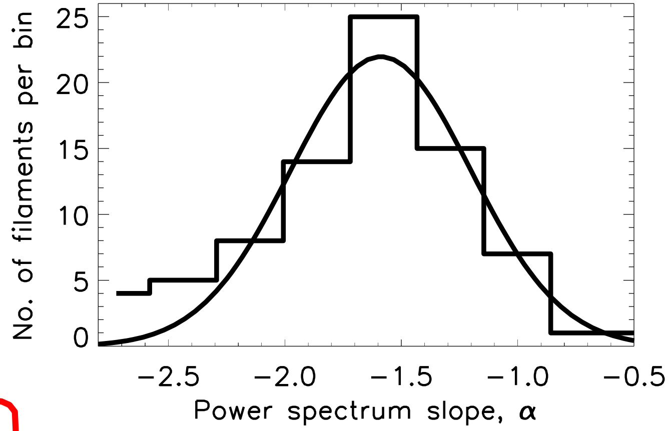




$P(k) \propto k^n$

$n = -1.6 \pm 0.3$

~5/3 Kolmogorov



Supporting *Inutsuka* 2001; See also *Lee, Hennebelle & Chabrier* 2017

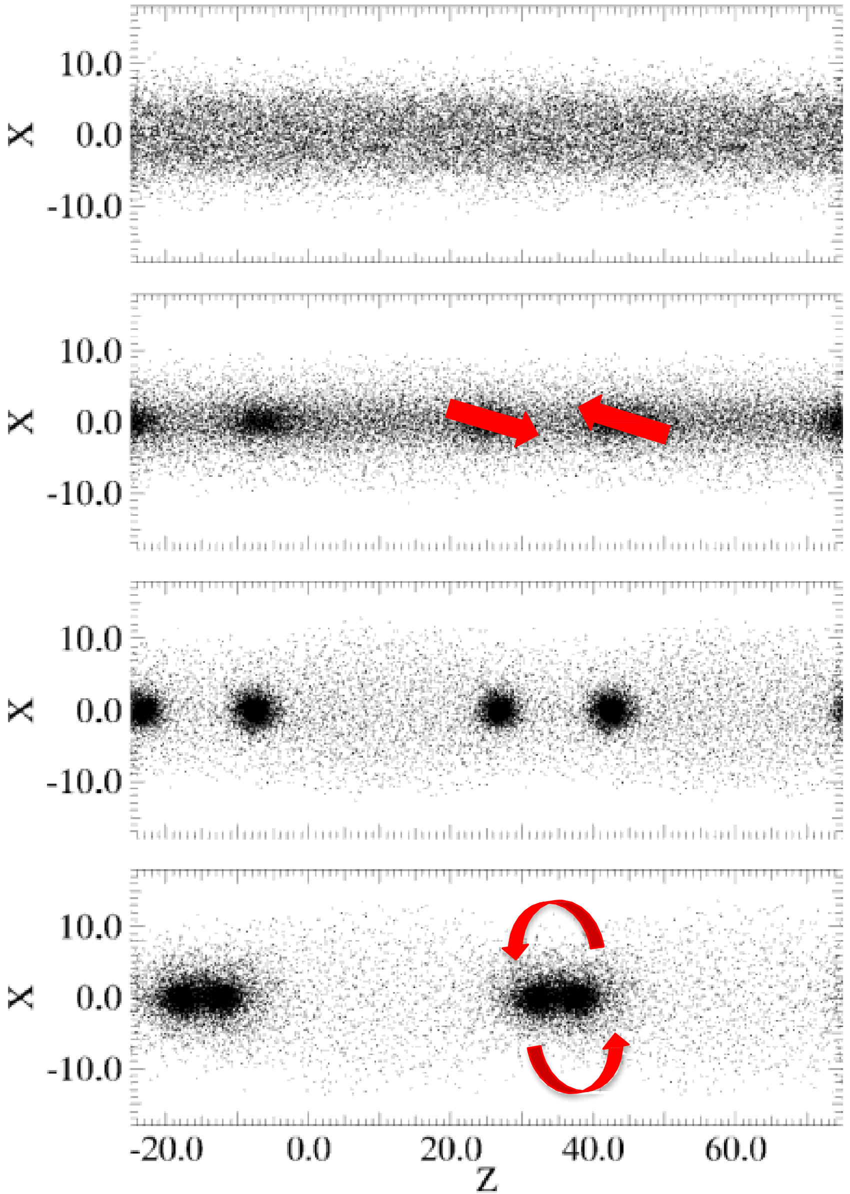
Toward Understanding the Origin of Rotation

The Angular Momenta of
Molecular Cloud Cores

An Origin of Core Angular Momentum

Misugi, SI, & Arzoumanian 2019, ApJ accepted (arXiv:1905.08071)

Episodic Merging
令 Random Accretion of
Angular Momentum



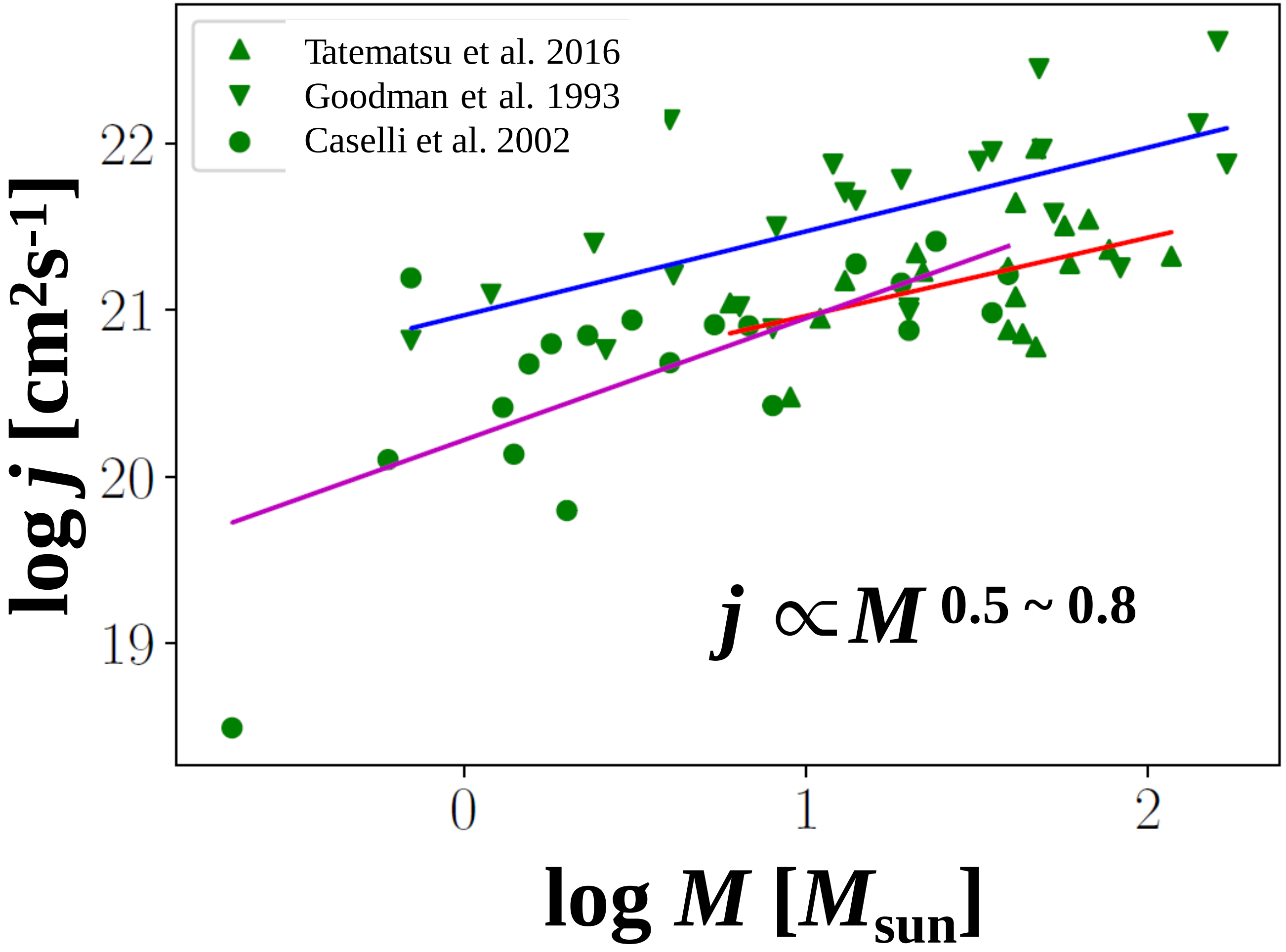
Mathematical Formulation

Subsonic Velocity
Fluctuation on Filament

⇕

Resultant Core Angular
Momenta

Observed Angular Momenta of Molecular Cloud Cores



Almost Consistent with Larson's law

—Goodman+1993, NH_3

—Caselli+2002, N_2H^+

—Tatematsu+2016, N_2H^+

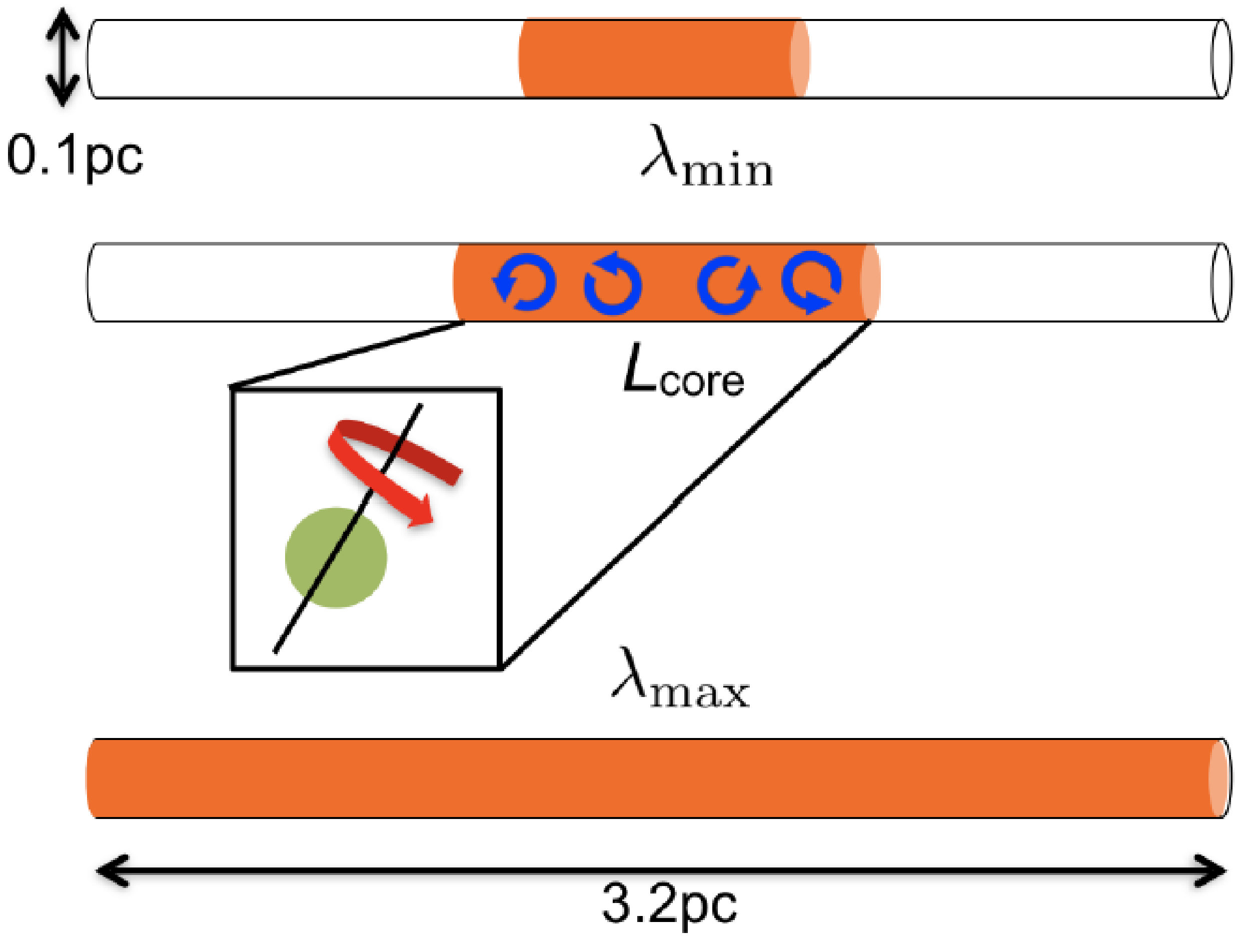
- Can we explain the angular momenta of observed cores by the velocity fluctuation of the filament?

Method of Calculations

Misugi, SI, & Arzoumanian 2019 ApJ accepted
(arXiv:1905.08071)

Line mass : $M_{\rm line}$ =16 $M_{\rm sun}$ pc^{-1}

Constant density for Simplicity



Solenoidal Velocity Field with power spectrum $P(k) \propto k^{-n}$

Subsonic Velocity Dispersion: $\sigma_{3D} = \sqrt{<\delta v^2>} = C_s$

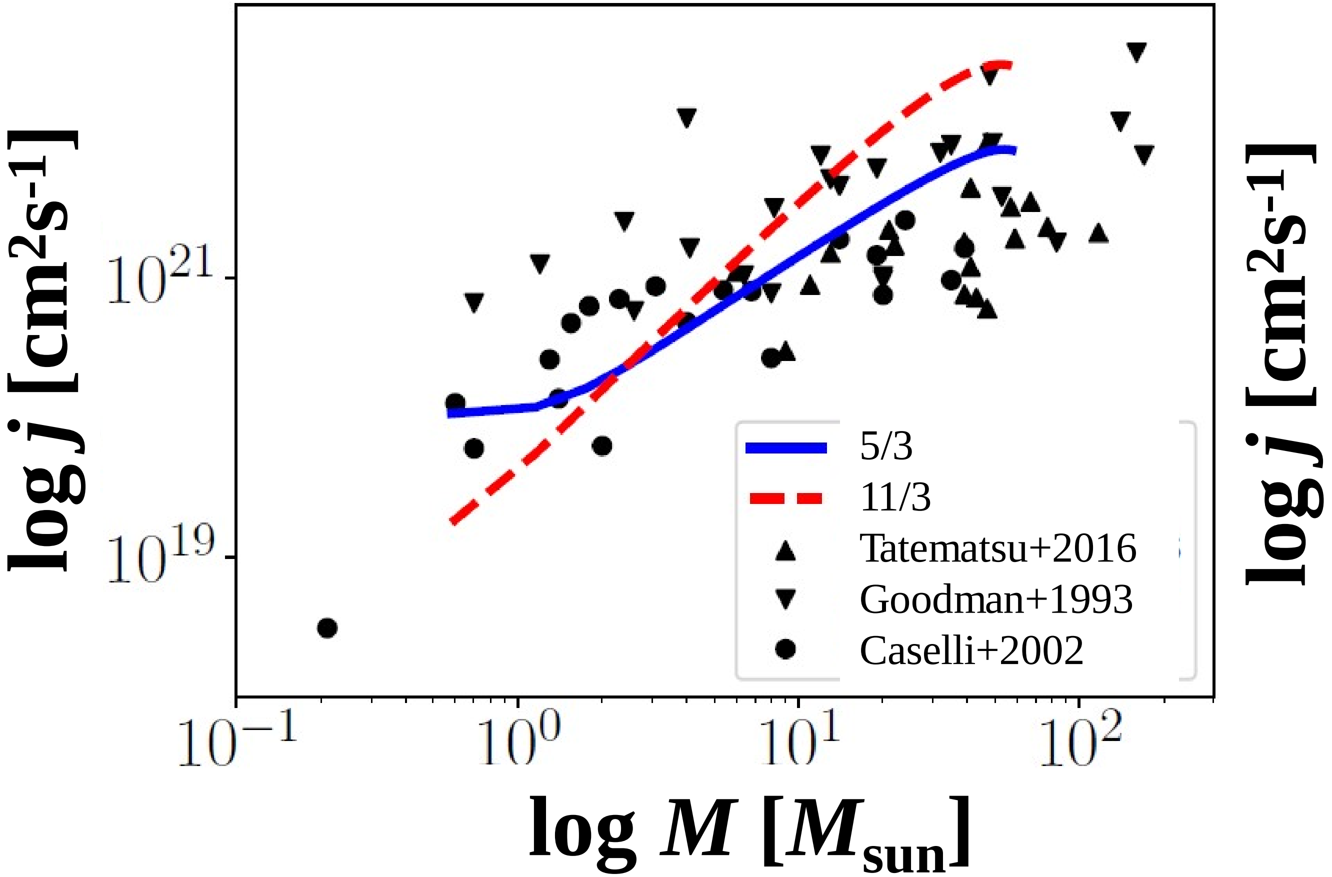
(e.g., Hacar & Tafalla 2011)

Angular Momenta of Cores from Filament Fragmentation

Misugi, SI, & Arzoumanian 2019 ApJ accepted (arXiv:1905.08071)

1D Kolmogorov: $P(k) \propto k^{-5/3}$

3D Kolmogorov: $P(k) \propto k^{-11/3}$



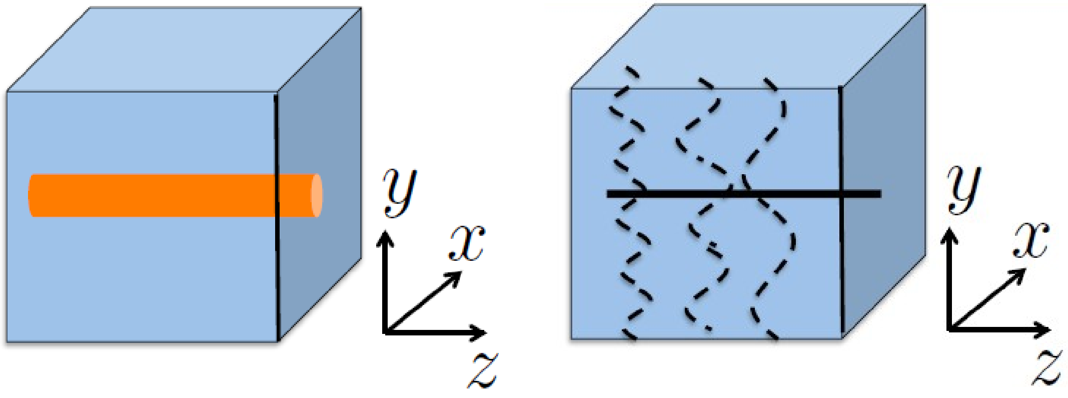
Surprisingly Good Result from 1D Kolmogorov-like Spectrum $P(k) \propto k^{-5/3}$

with $\sigma_{3D} = \sqrt{\langle \delta v^2 \rangle} = C_s$

Large power in the small length scale ⊥ filament required!

Why 1D Kolmogorov -5/3 in Filaments?

Fluctuation along the Axis



$$P_{\tilde{\boldsymbol{v}}}(k_z) = \sum_{k'_x} \sum_{k'_y} P(k'_x, k'_y, k_z)$$

$$\sim \frac{L_x L_y}{(2\pi)^2} A \int_0^{k_{\max}} \int_0^{k_{\max}} (k'^2_x + k'^2_y + k^2_z)^{-11/6} \, dk'_x dk'_y$$

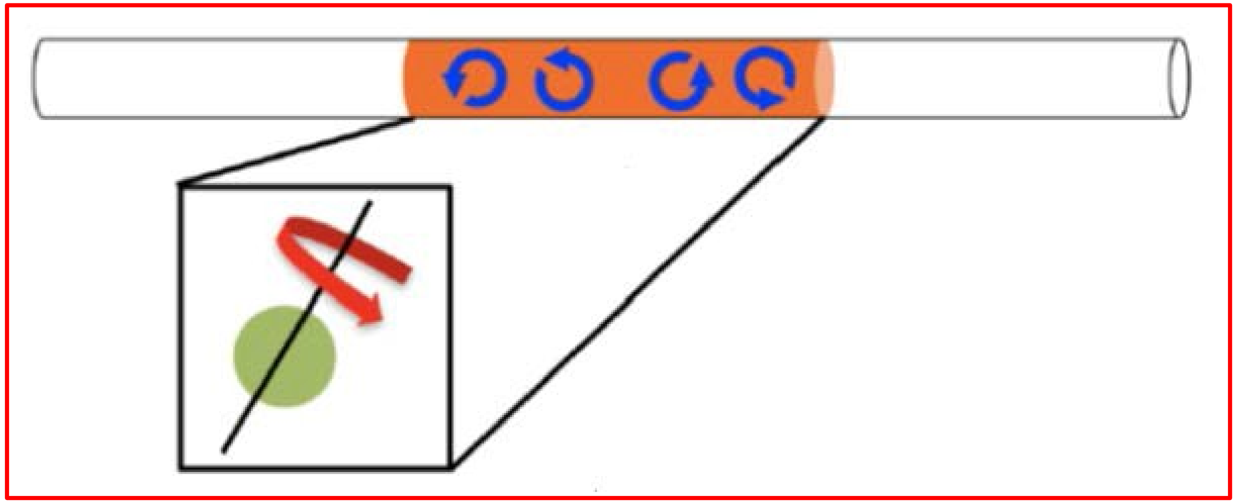
$$\sim \frac{L_x L_y}{(2\pi)^2} A \int_0^{\infty} \int_0^{\infty} (k'^2_x + k'^2_y + k^2_z)^{-11/6} \, dk'_x dk'_y$$

$$= \frac{L_x L_y}{(2\pi)^2} A \int_0^{\infty} (k'^2_r + k^2_z)^{-11/6} \, \frac{\pi}{2} k'_r dk'_r$$

$$\propto k_z^{-5/3},$$

Implication: Mass in a star forming filament should be small!

Internal Distribution of Ang. Momentum

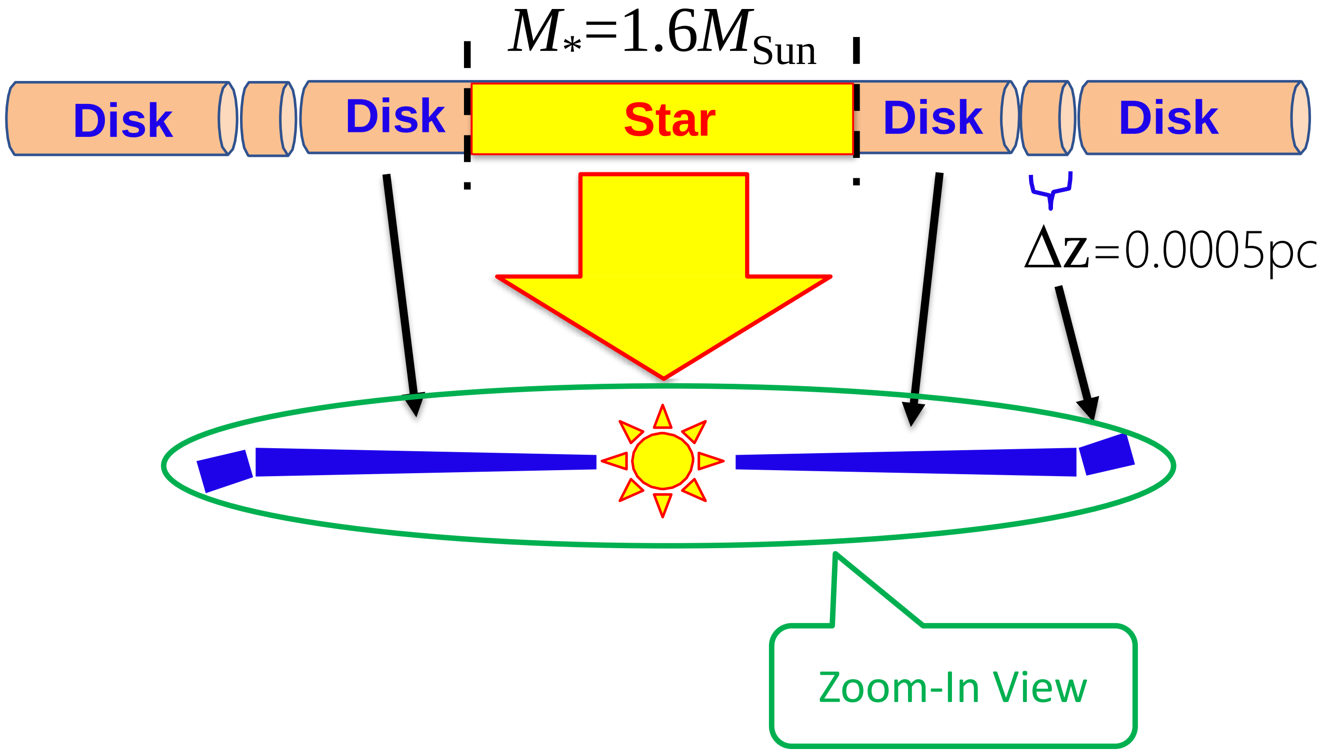


Line mass: $\boldsymbol{M}_{\mathbf{line}}$ **=16** $\boldsymbol{M}_{\mathbf{sun}}\mathrm{pc}^{-1}$

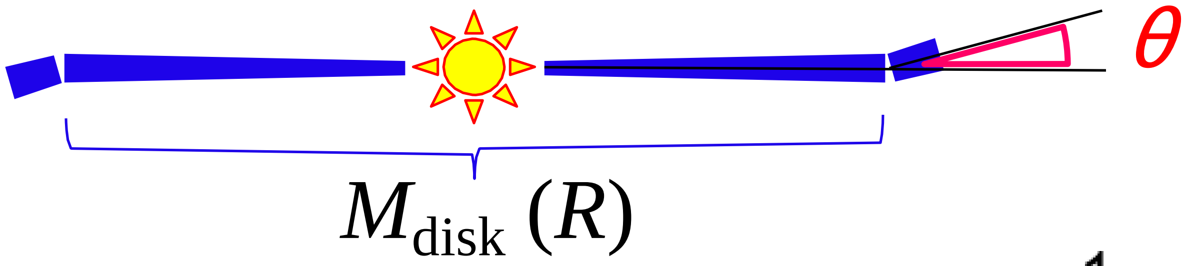
Constant density for Simplicity

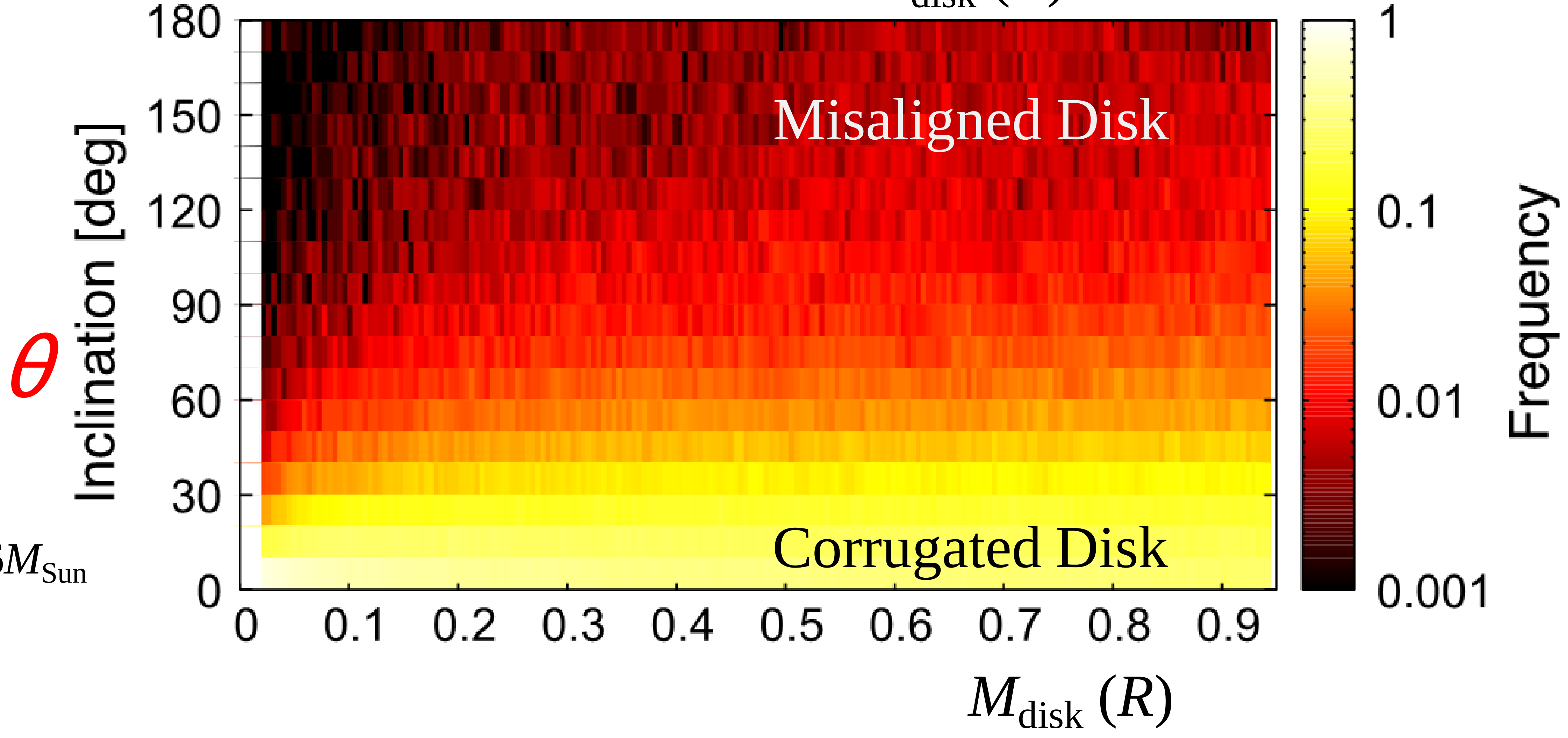
Solenoidal Velocity Field
with power spectrum: $P(k) \propto k^{-n}$

Subsonic Velocity Dispersion:
$\sigma_{3D} = \sqrt{\langle \delta v^2 \rangle} = C_s$
(e.g., Hacar & Tafalla 2011)



Disk Misalignment Frequency





$M_*=1.6M_{Sun}$

Implication

- Velocity Fluctuation along the Filament ➔ Core Angular Momentum
  ➔ Non-Coherent Angular Momentum Distribution inside the Core
  ➔ The Formation of Misaligned Disk
- Observation of Misaligned Disks???
  - HD142527
  - HD100546
  - HD100543
  - J1604-2130
  - DoAr44
  - IRAS04368+2557

(Reported so far)

So Many!

Summary

- Gravitational Fragmentation Self-Gravitating Filament with

Kolmogorov Fluctuation, $P(k) \propto k^{-5/3}$

➔ (Standard IMF-Like) Core Mass Function

➔ Angular Momenta of Molecular Cloud Cores

Misugi, SI, Arzoumanian 2019, ApJ accepted (arXiv:1905.08071)

- Prediction for Frequency of Misaligned Disks

Future Work

- Effect of Magnetic Braking in Core-Phase & Binary Formation
- Analysis of Angular Momentum Redistribution inside Disk