# Complex structure within and around circumstellar disk:
## Ring & Gap, Interchange instability, Streamer and pseudo disk

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2024/11/11-13 初代星･初代銀河研究会2024

# 内容

- 円盤形成と惑星形成 (観測)
- 低金属量環境下でのアウトフロー (観測)
- 磁気交換型不安定 (観測・理論)
- 非球対称(or 非軸対称)降着(streamer) (観測・理論)
- 星周円盤と原始惑星系円盤 (理論)

# 低金属量環境下でのアウトフロー

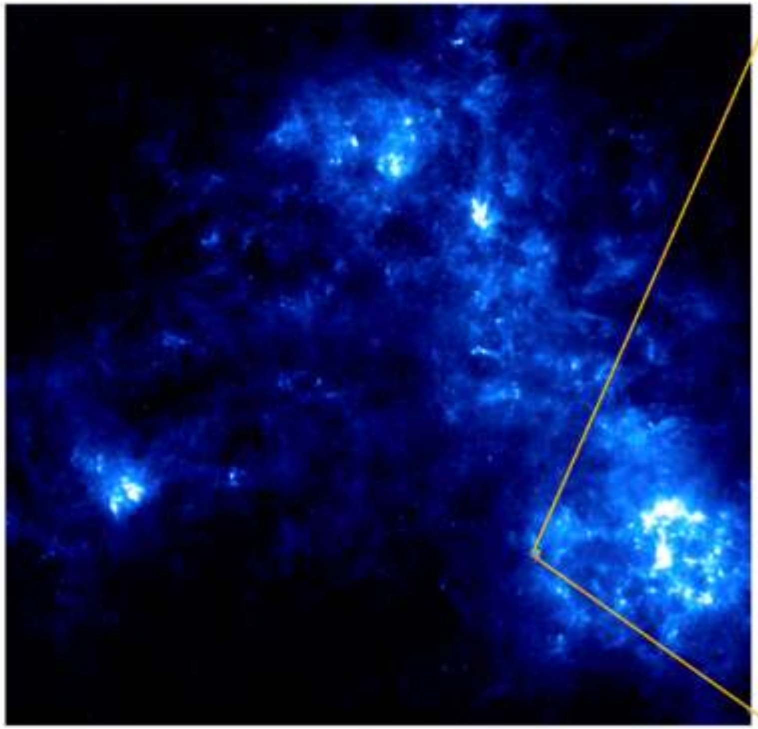
初期宇宙と現在の星形成の違い？

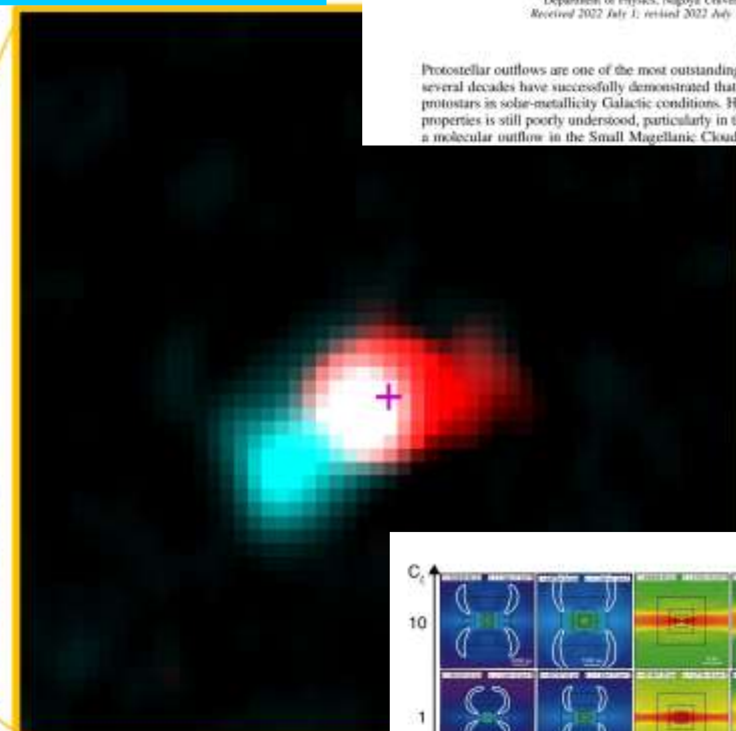
# プレスリリース: 小マゼラン雲での原始星アウトフローの検出

Tokuda et al. (2022)

2022.08.29

Z=0.2 $Z_{sun}$環境下での原始星アウトフロー





**The First Detection of a Protostellar CO Outflow in the Small Magellanic Cloud with ALMA**

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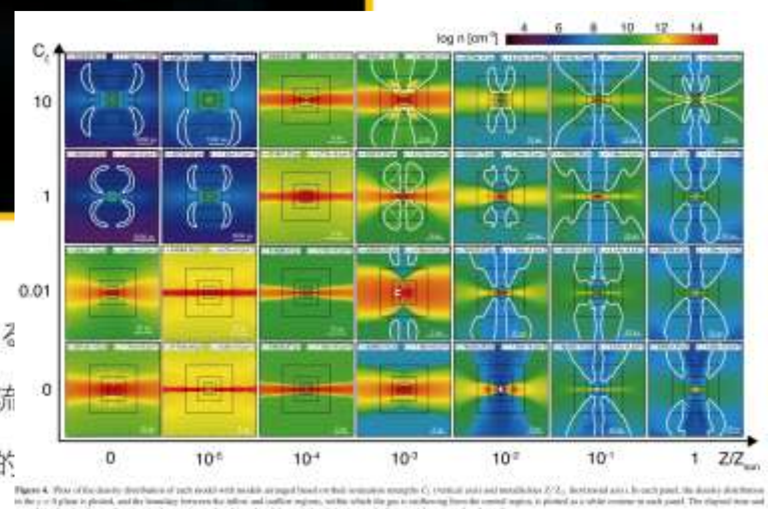
**Abstract**

Protostellar outflows are one of the most outstanding features of star formation. Observational studies over the last several decades have successfully demonstrated that outflows are ubiquitously associated with low- and high-mass protostars in solar-metallicity Galactic conditions. However, the environmental dependence of protostellar outflow properties is still poorly understood, particularly in the low-metallicity regime. Here we report the first detection of a molecular outflow in the Small Magellanic Cloud with 0.2 $Z_{\odot}$, using Atacama Large Millimeter/submillimeter



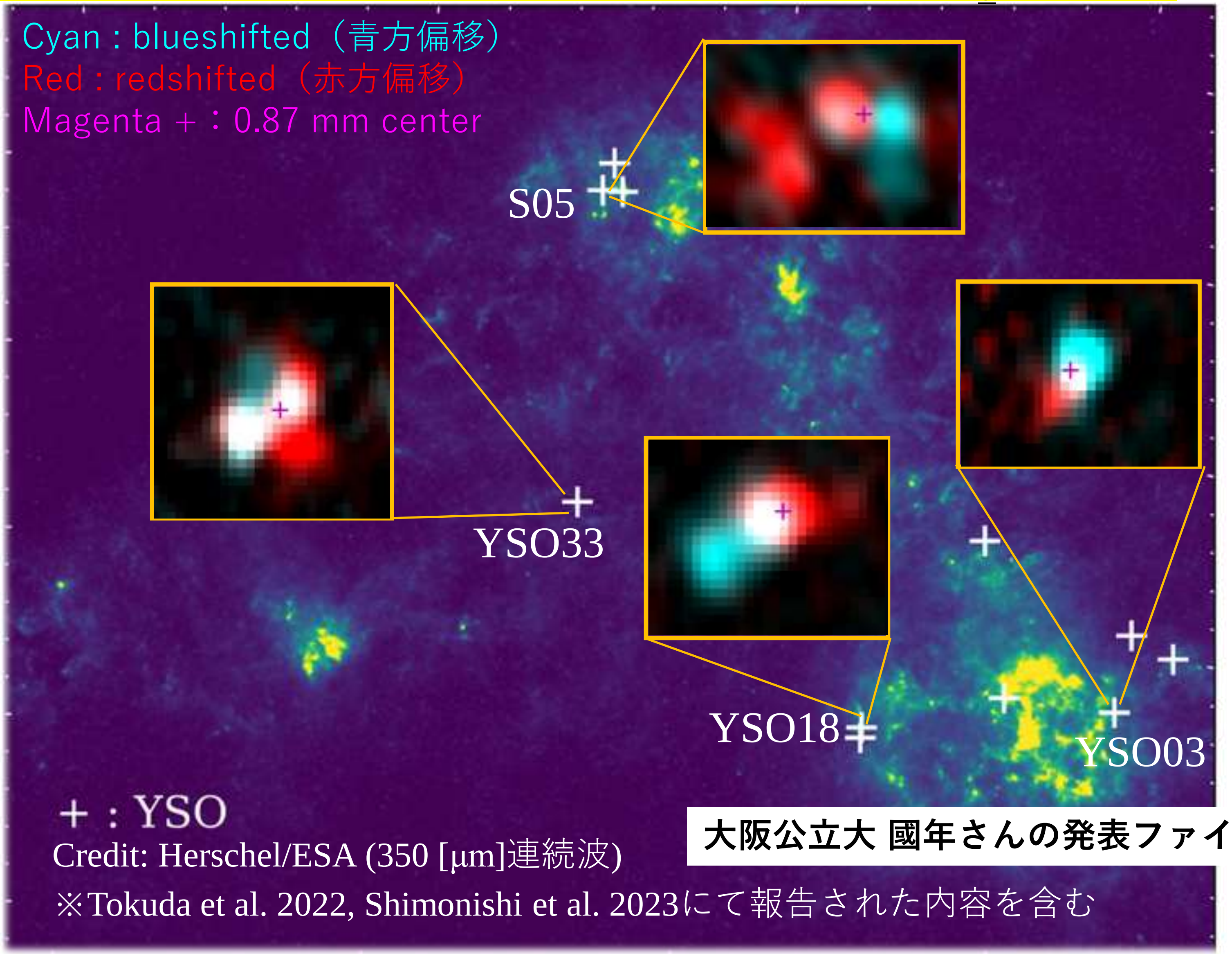

Higuchi et al. (2019)

徳田(公募研究21H00049 及びB01班)、大西(B01班)らは小マゼラン雲に存在する
遠鏡で観測しました。その結果、同銀河内にて始めて原始星からの双極分子流
しました。このことは、低重元素量環境においても星形成過程が現在と定性的
を示唆しています。

# SMC(Z=0.2 $Z_{sun}$)でのアウトフロー検出

Tokuda et al. (2024)

## アウトフローと思われる高速度成分を4天体で検出（$t_d$ ~$10^4$ yr）




大阪公立大 國年さんの発表ファイルから

# 磁気交換型不安定

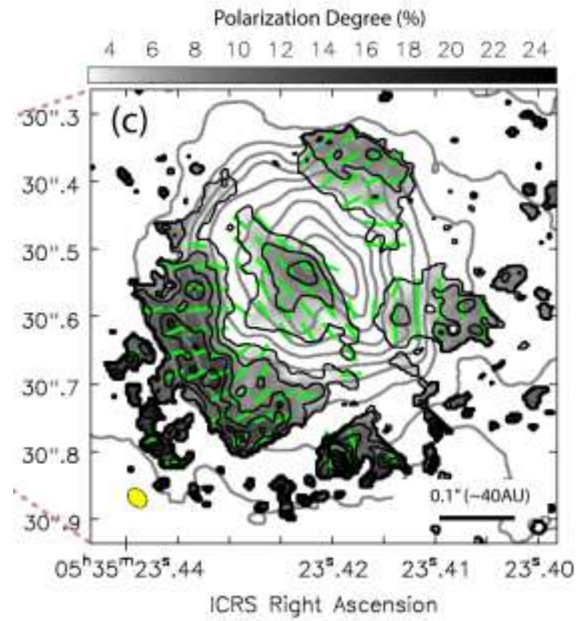
ALMAで検出される複雑な
星周構造の起源は？

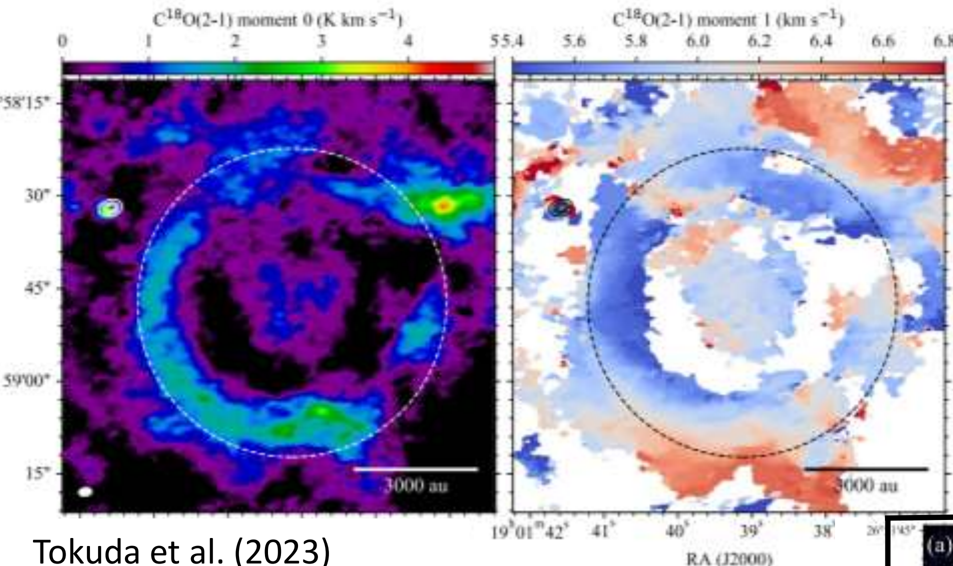
# Observations: magnetic interchange instability

星周円盤外側の複雑な構造：~1000 au

- Ring, spur, wavy structure
- Q>>1 → 重力不安定× v<1 kms-1→アウトフロー×

Takahashi, MNN et al. (2019)
Liu, MNM, et al. (2023)



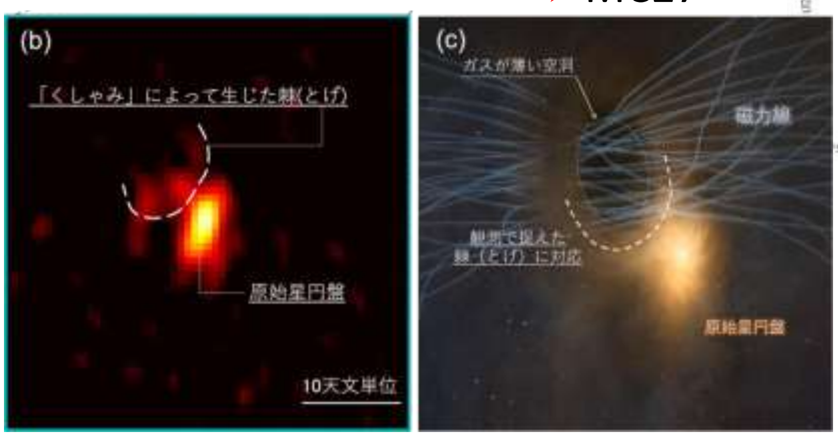



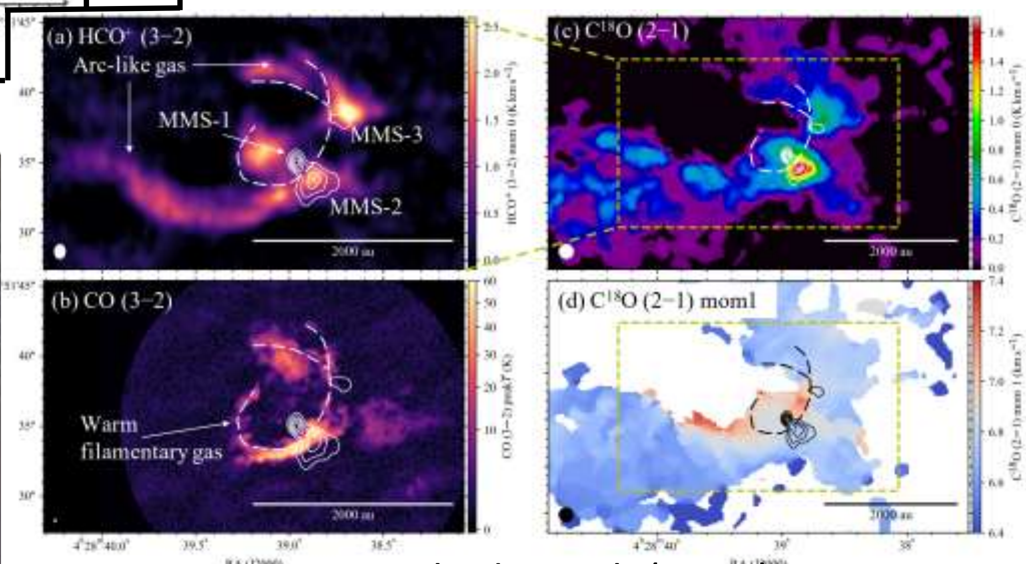

Tokuda et al. (2023)

- 円盤は比較的コンパクト
- 若い段階(Class 0/I)でよくにみられる

プレスリリース資料から

- MC27

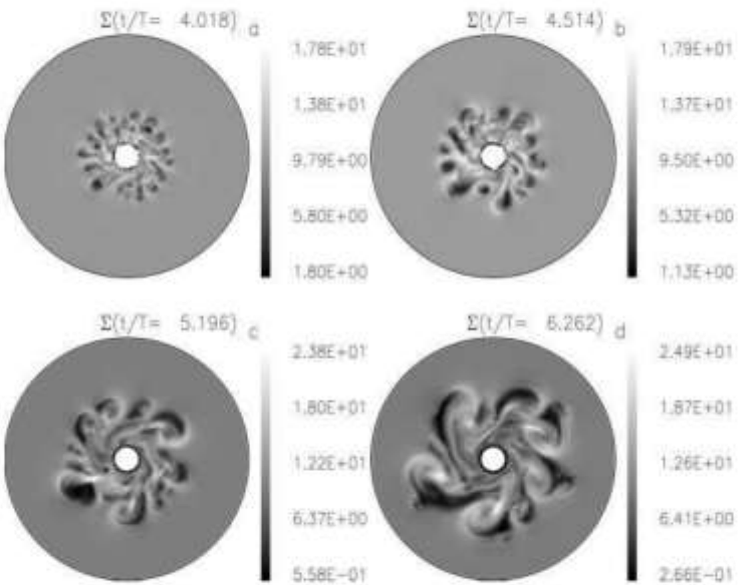


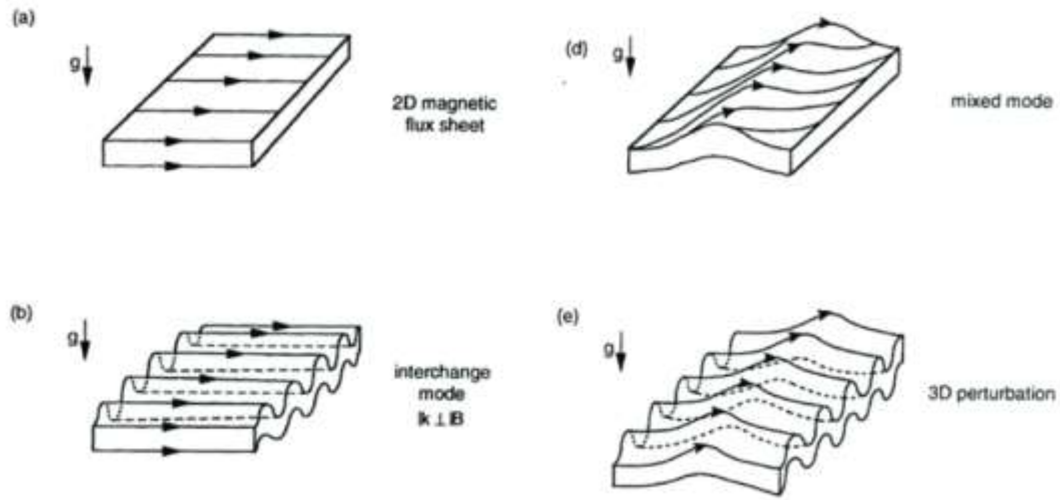




Tokuda et al. (2024)

# Magnetic interchange instability

Stehle & Spruit (2001)




Lubow & Spruit (1995)

$$\Omega_A^2/\Omega^2 \gtrsim L/H\ ,\ \Omega_A^2 = \frac{B_{z0}^2}{2\pi\Sigma_0 H}\ .$$

Magnetic pressure gradient increases as the distance from gravitational source increases

Li & Mckee (1996)

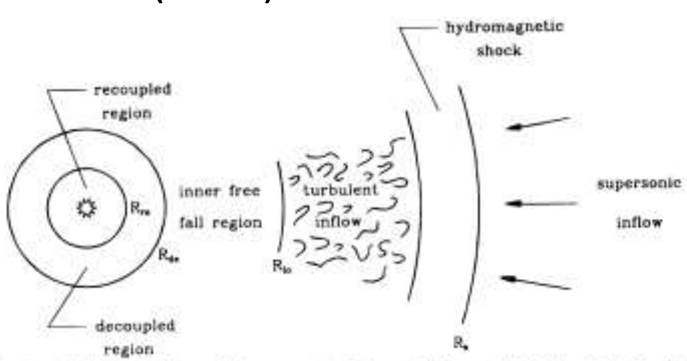
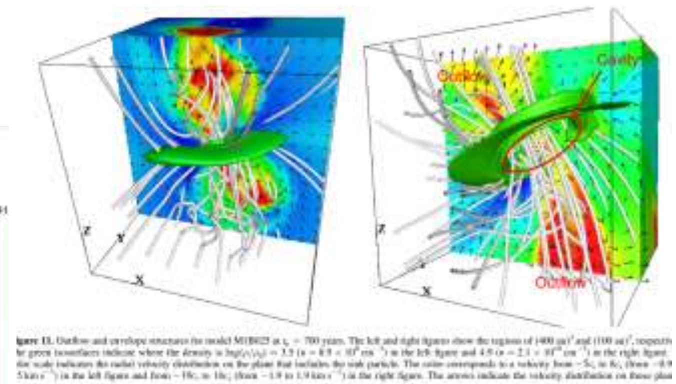



FIG. 1.—Schematic view of the accretion flow around low-mass protostars. The accretion hydromagnetic shock has a finite width, and is driv the supersonic inflow by the magnetic field accumulated behind the shock. The various postshock regions are discussed in the text.

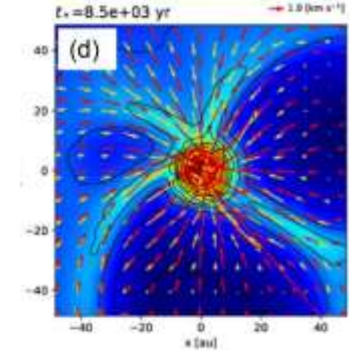
- 重力の方向に強い磁場(磁束)が存在すると、磁束内は磁気圧＋ガス圧で磁束外の圧力と釣り合う
- 磁束内のガス圧力は低いため密度も低い
- 浮力が働く、または、レイリーテイラー不安定(密度差のため)が起こる

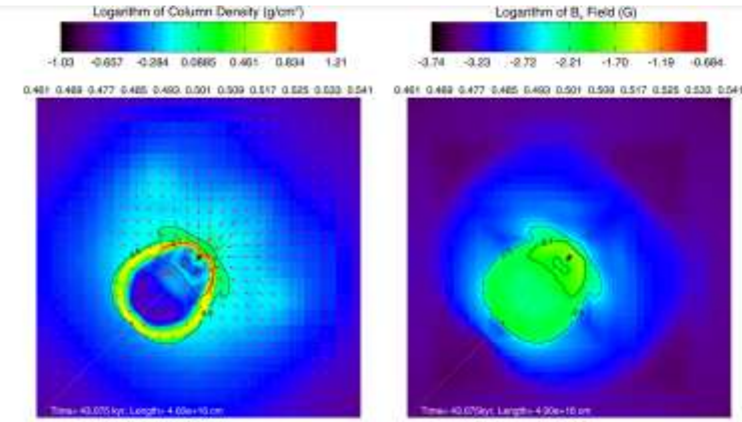
# Simulations: magnetic interchange instability

Matsumoto et al. (2017)

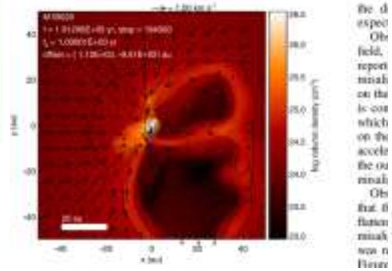


Tsukamoto et al. (2023)

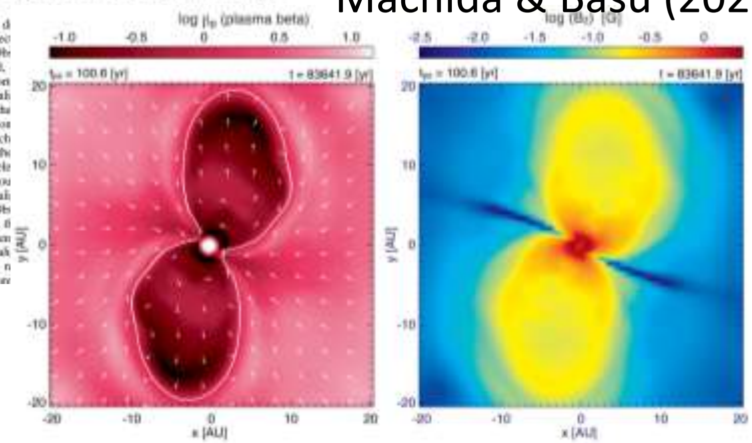


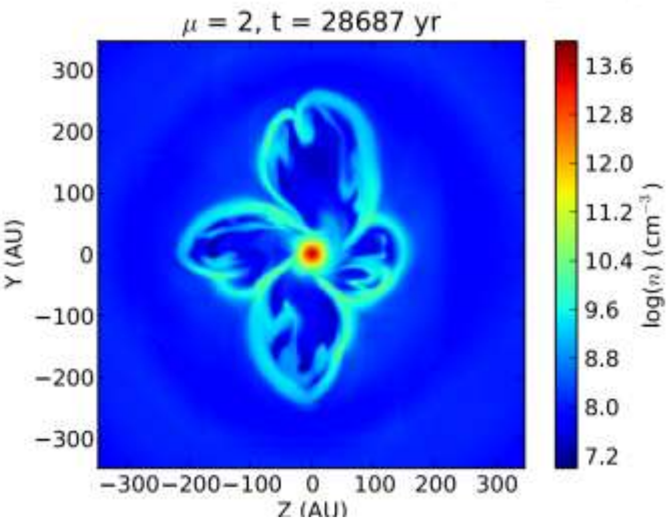

Zhao et al. (2011)

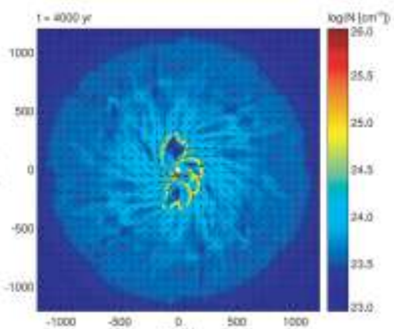


Machida & Basu (2020)

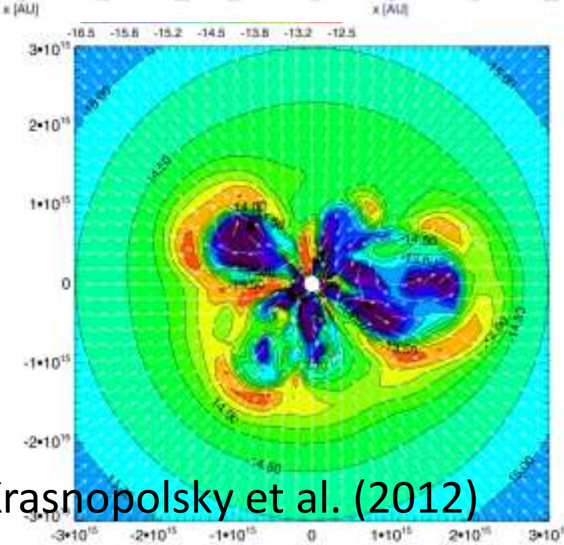


Joos et al. (2012)



Seifried et al. (2012)



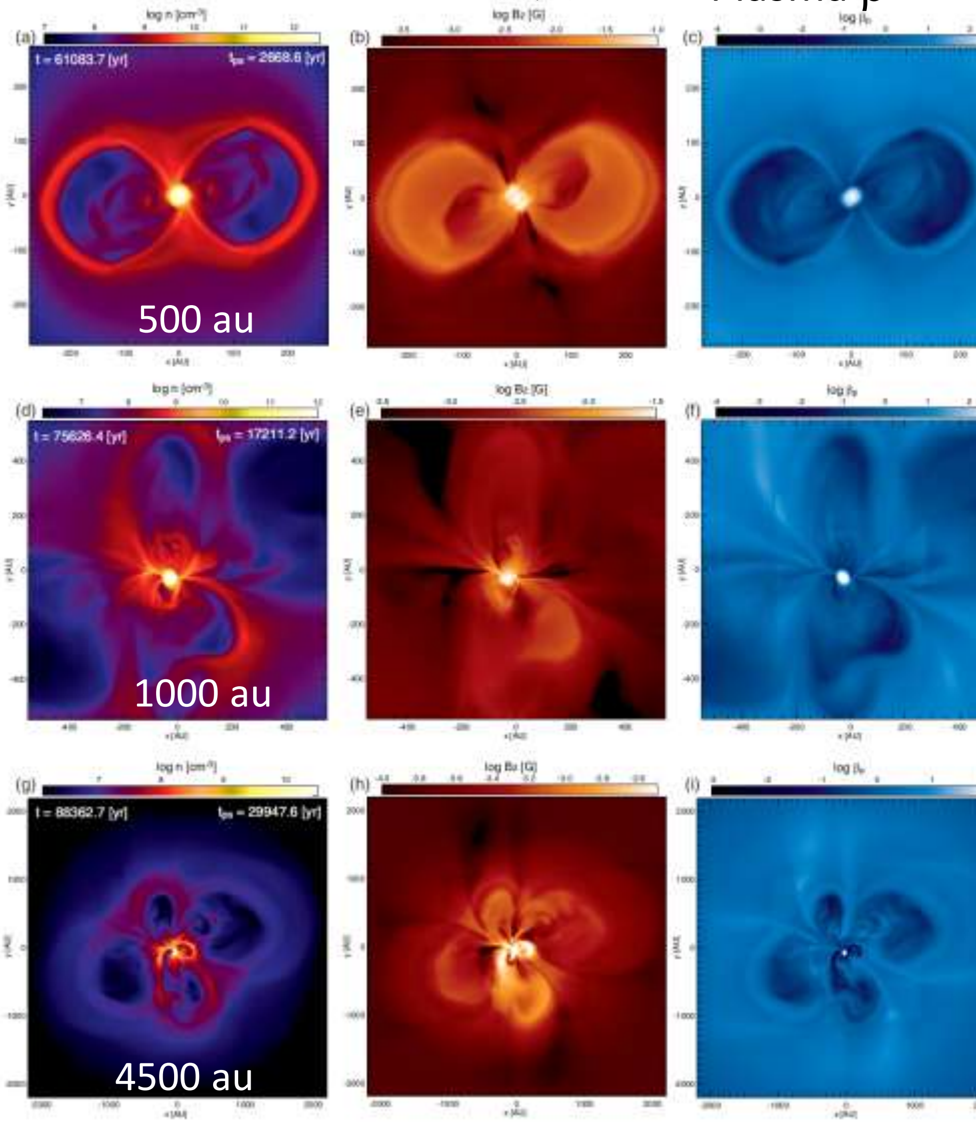
Krasnopolsky et al. (2012)

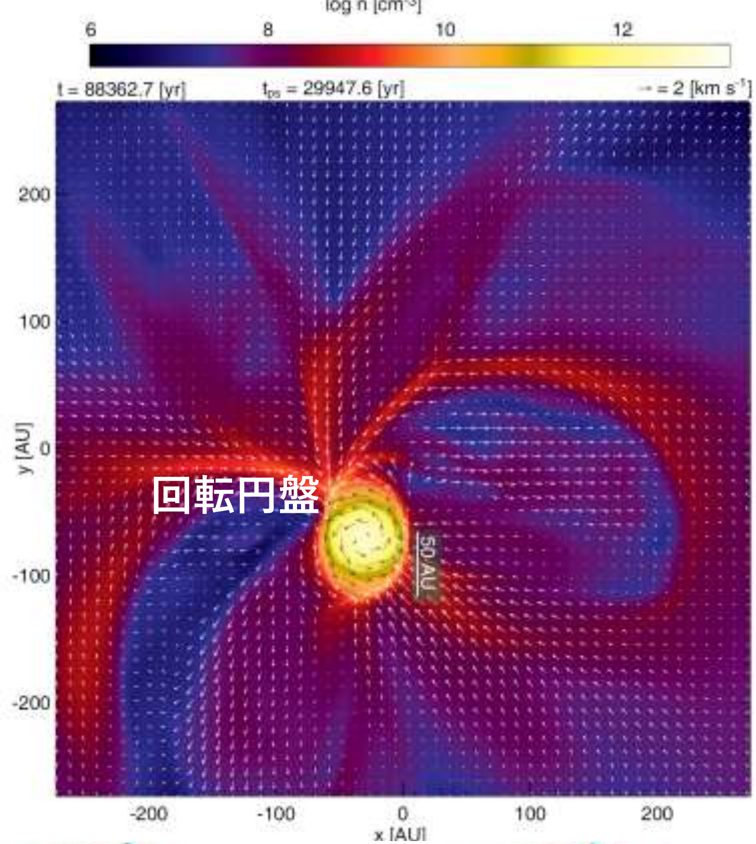
# 最近の研究:磁気交換型不安定

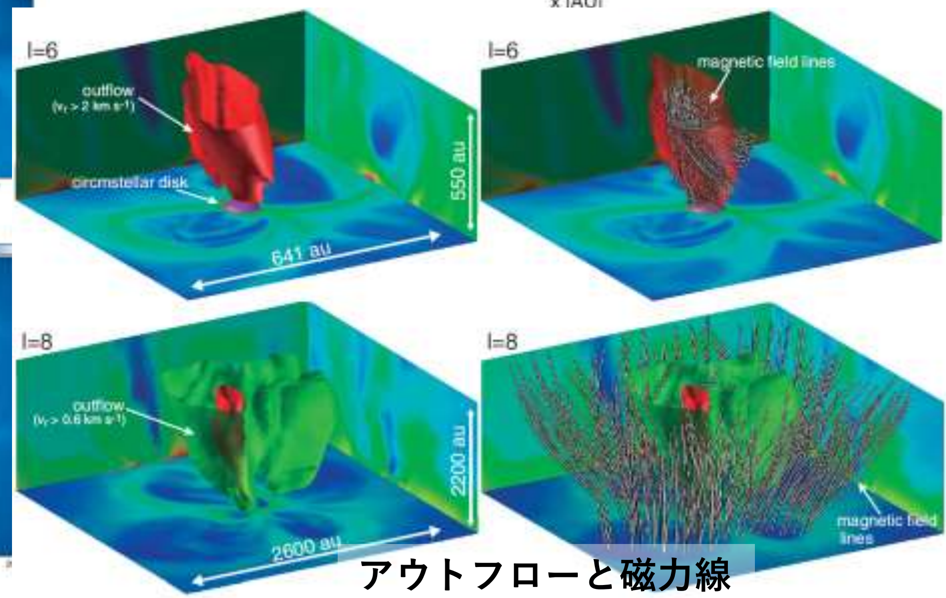
赤道面の物理量の時間進化

Machida & Basu

密度　　磁場強度Bz　　Plasma β



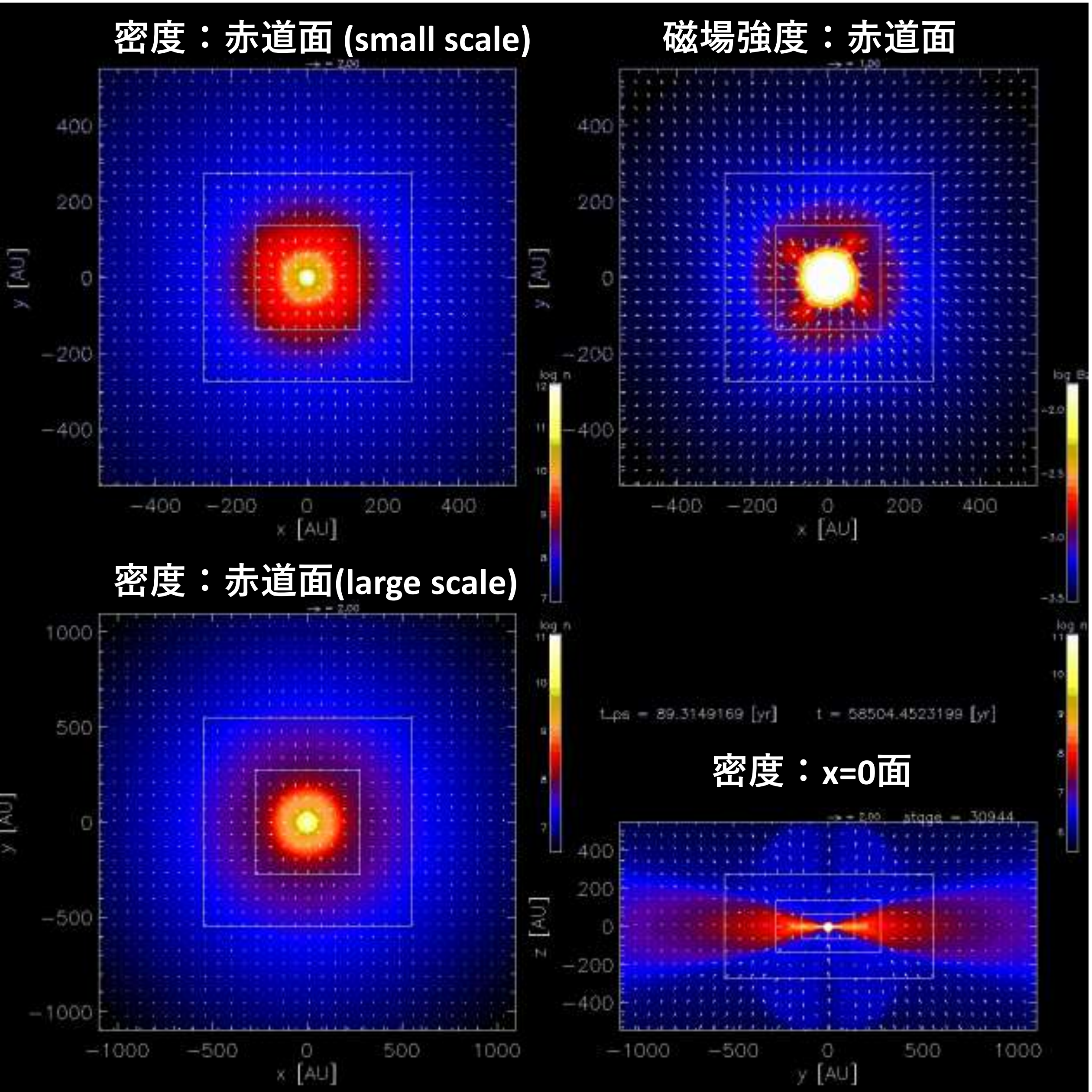



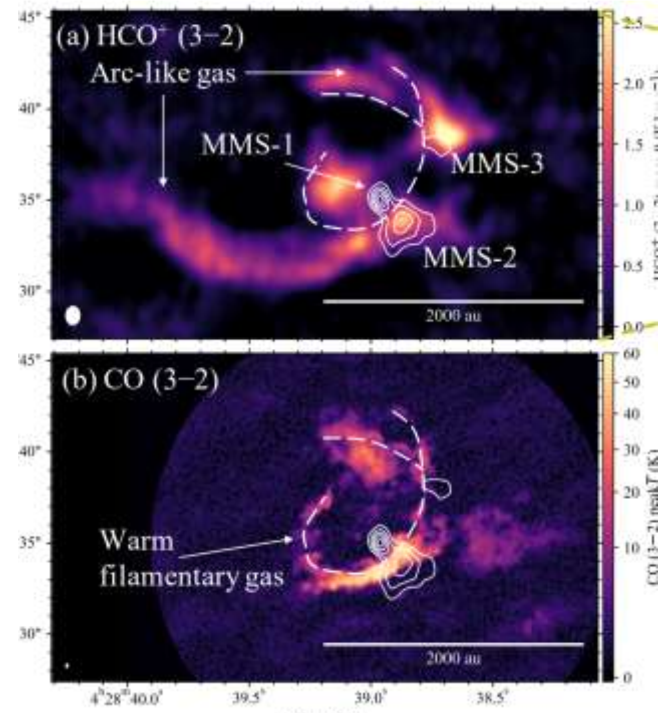



# Interchange instability:アニメーション

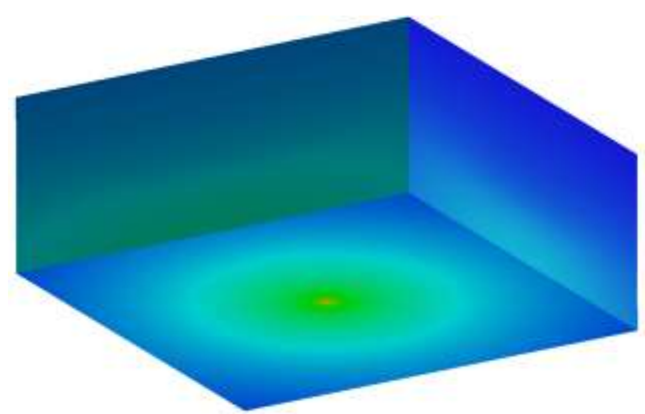
Machida & Basu

Interchange instabilityは、降着段階で再帰的に起こる




高速アウトフロー



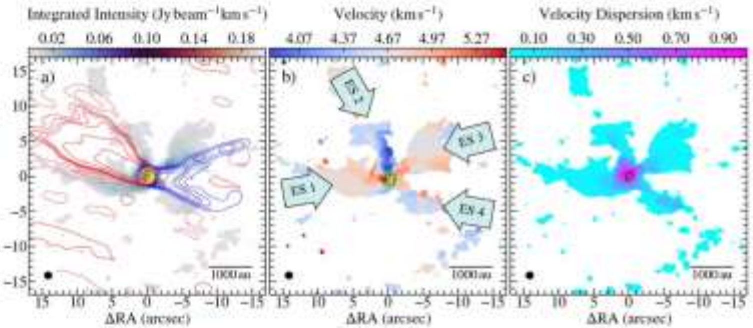
非球対称(or 非軸対称)降着
(streamer)

インフォーリングエンベロープで観測される非対称構造の起源は？

# 進化段階とStreamer

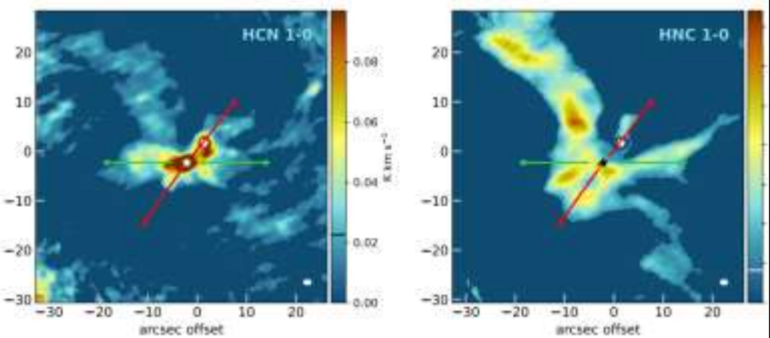
- 非球対称、非軸対称の降着
- 緩やかな速度勾配

## Class 0

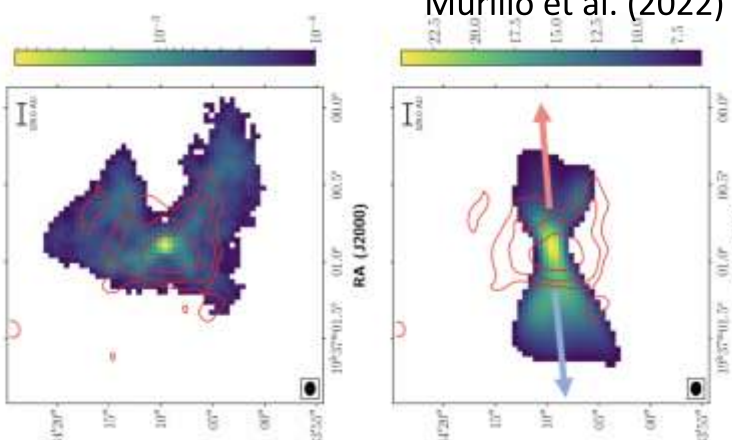



Thime et al. (2022)

Cabedo et al. (2021)

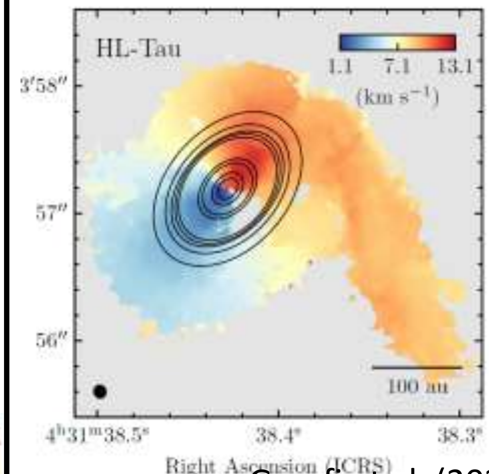



Murillo et al. (2022)

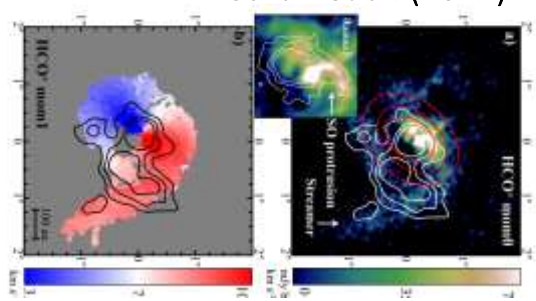


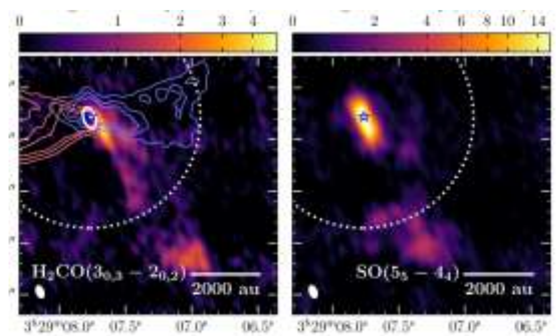

## Class I

Yen et al. (2019)




Garufi et al. (2022)

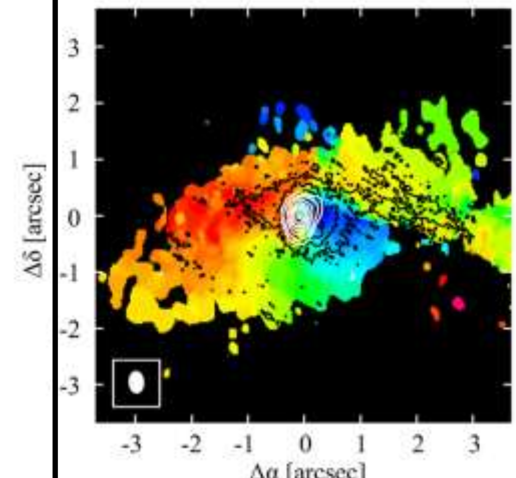


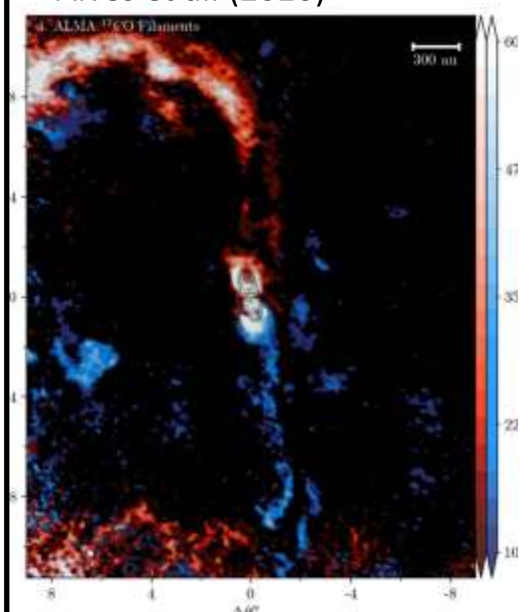

Valdivia-Mena et al. (2022)

## Class II

Akiyama et al. (2019)



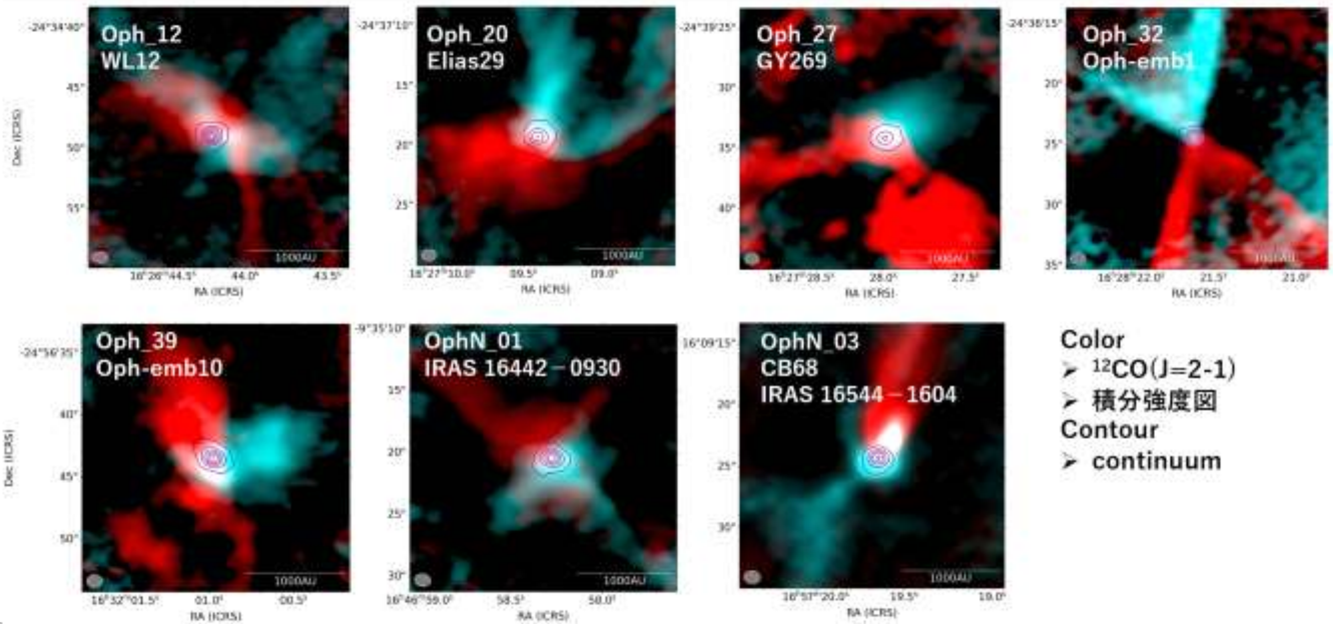

Alves et al. (2020)



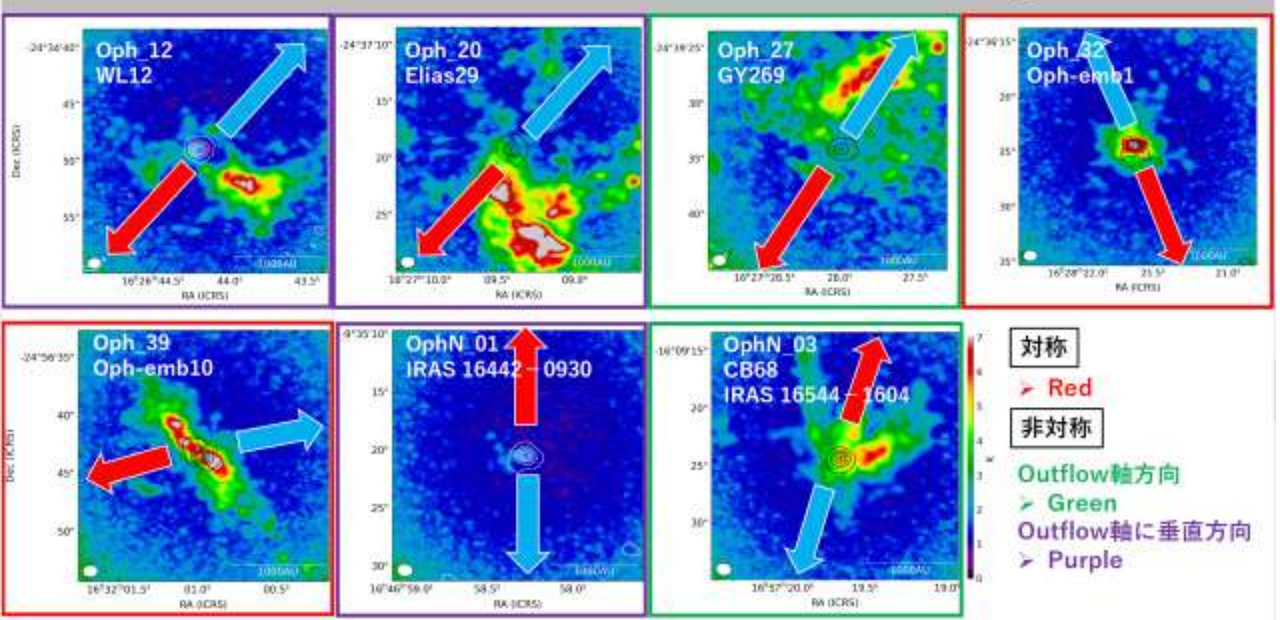
Yamazaki et al.
in preparation

# Result：$^{12}$CO(J=2-1) | Bipolar Outflow





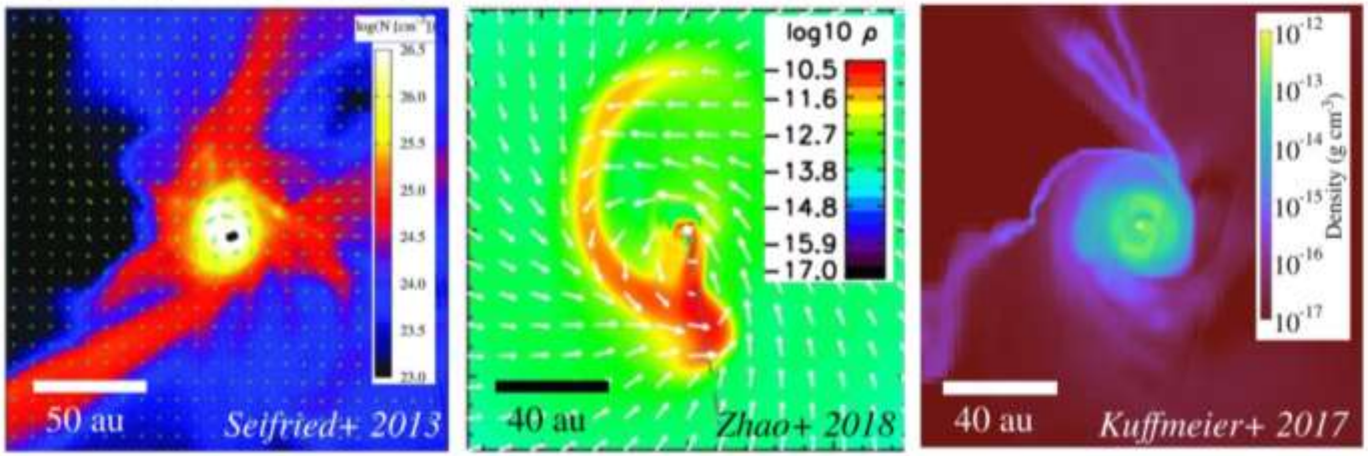

# Result：C$^{18}$O(J=2-1) | Envelope



# PP7での発表ファイル (Doris Arzoumanian)

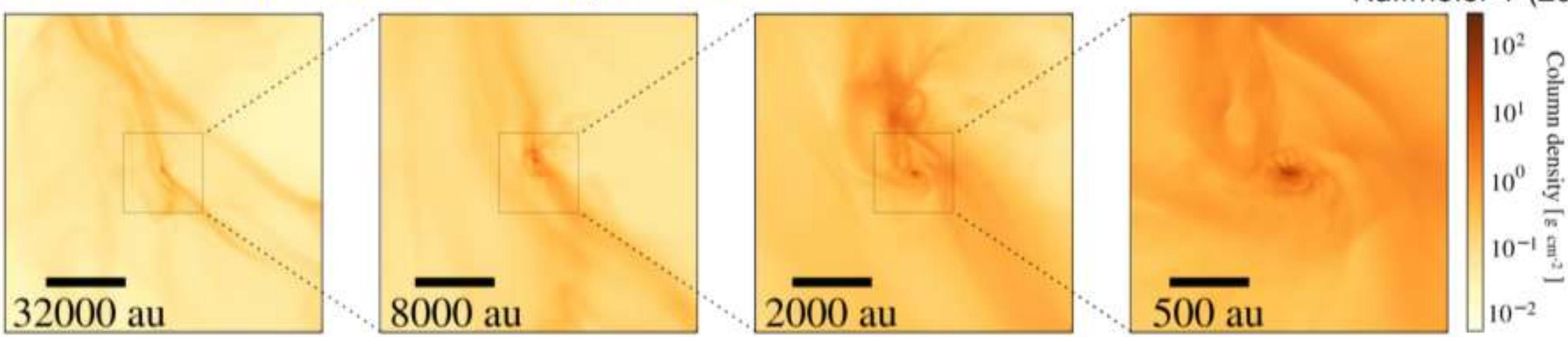
## Simulations: streamers connect core+ to disk scales

### Asymmetric infall leads to streamers in varying MHD setups




### Can streamers connect interstellar to protostellar scales?

Kuffmeier + (2019)

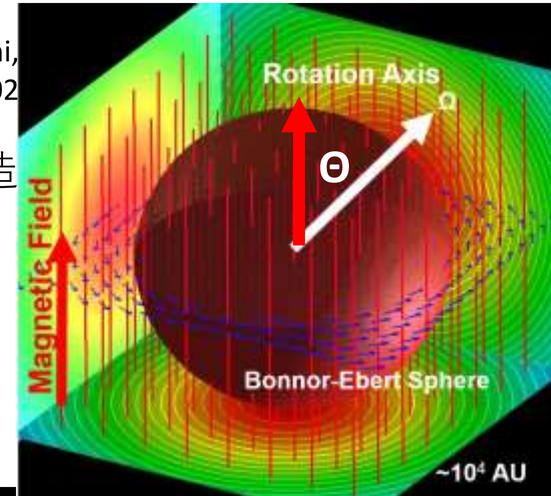


# Rotation disk and Pseudo disk

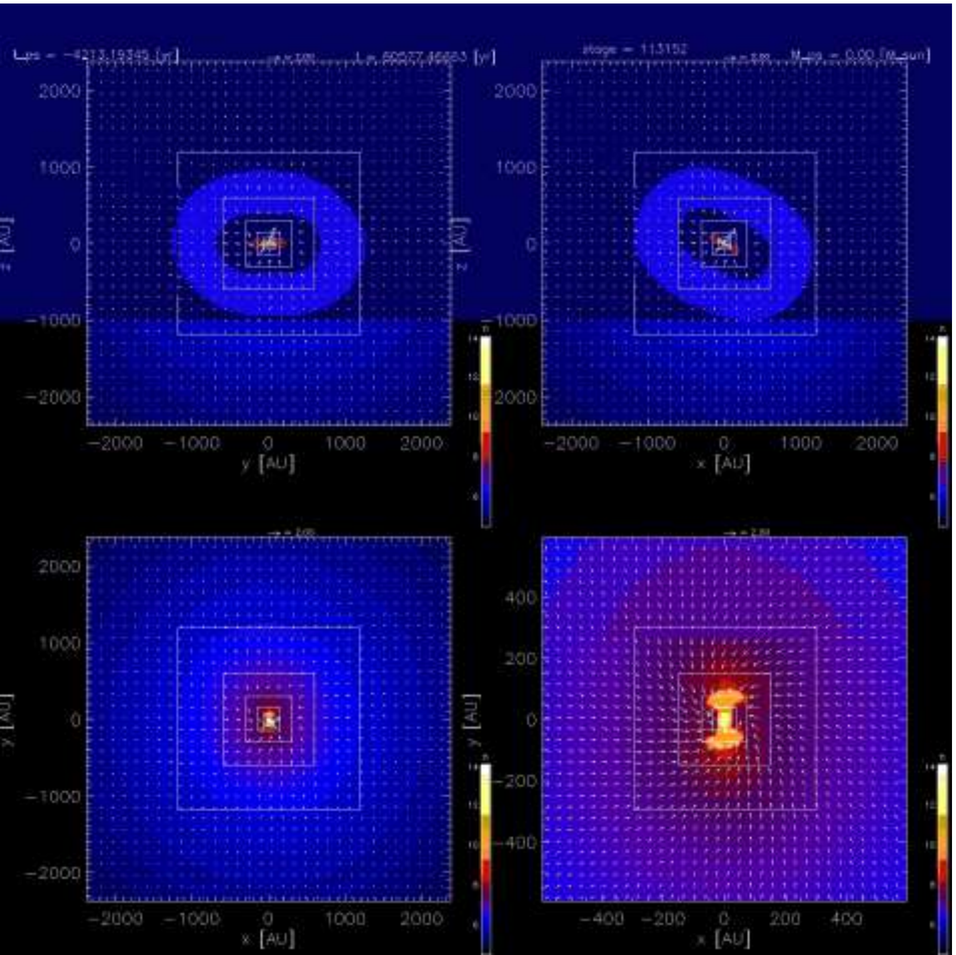
Shinnaga, Takahashi,
MNM+2019, Tu+202

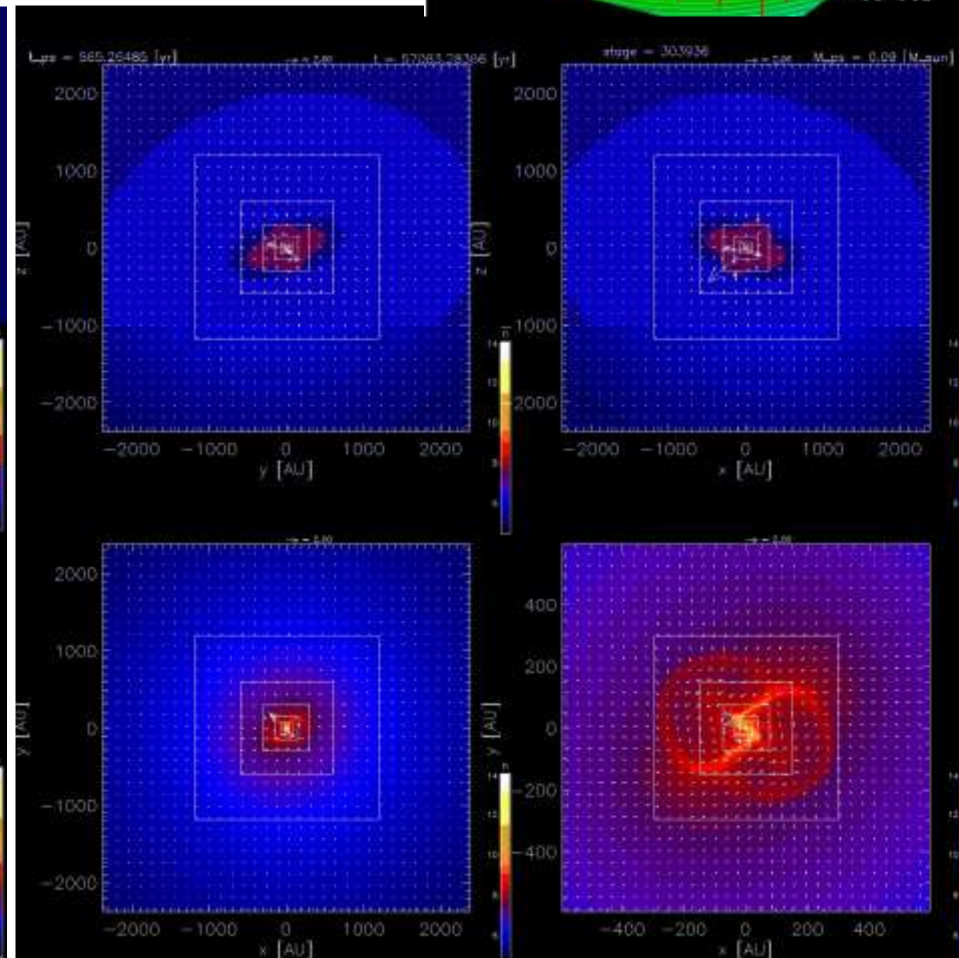
- 複雑な設定を考えなくても自然に非対称降着になる
  - Global scaleからの星形成を考える
  - 異常に強い乱流
  - ガスClumpの落下
  - コア動詞の衝突

- 磁場を考慮すると複雑な構造
- アウトフロー、ねじれた Pseudo disk
- μ =3,  β=0.02



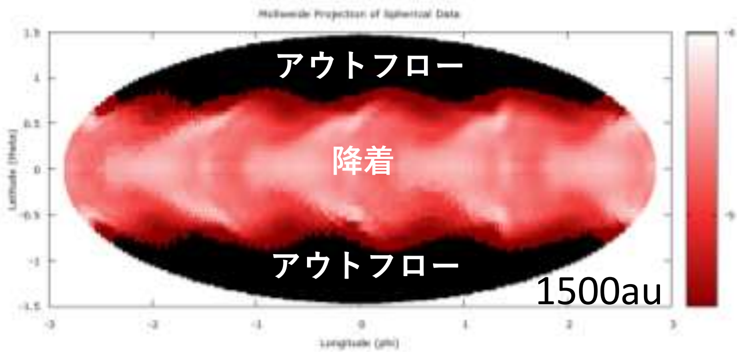

磁場なし　磁場あり　Θ=30°



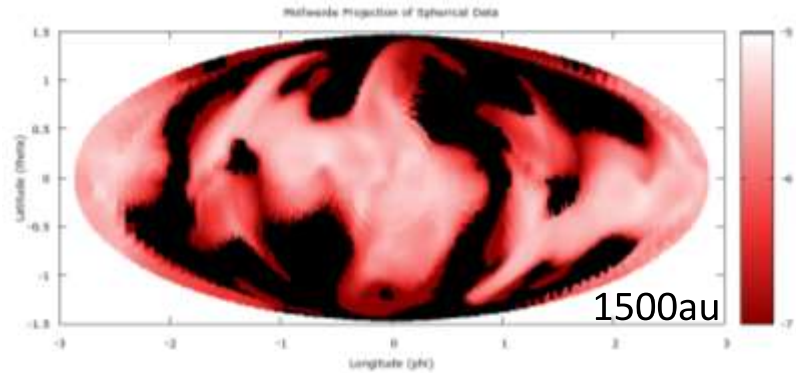


# Column density

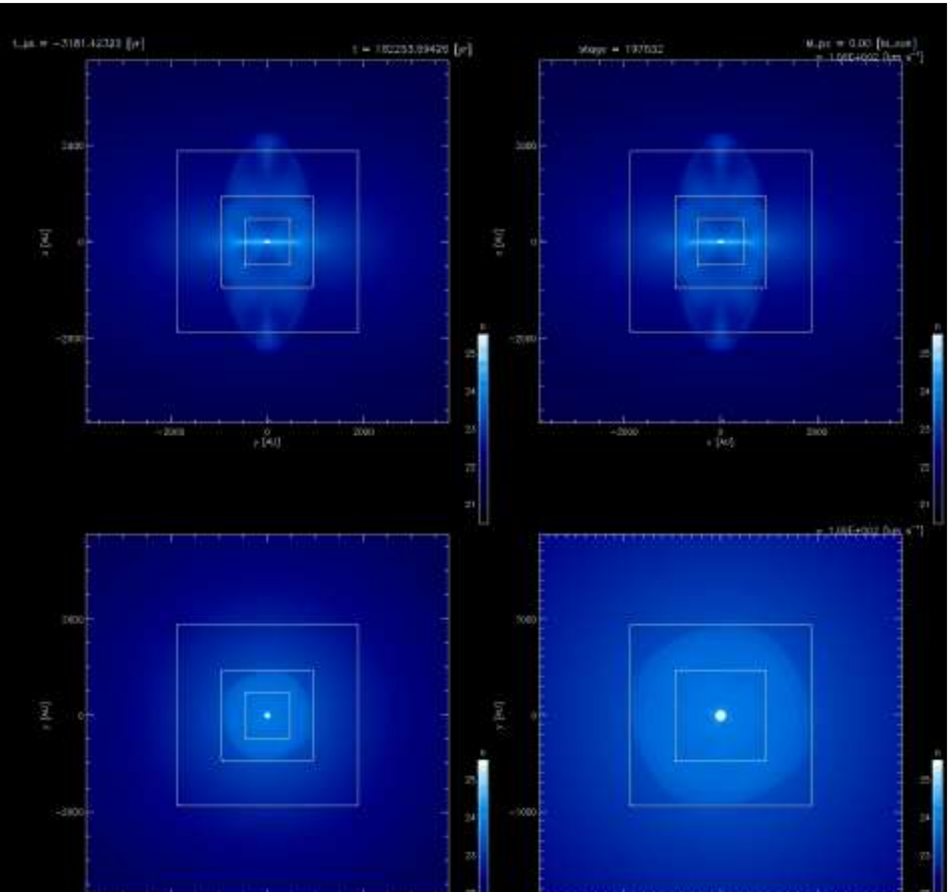
赤・ピンク：inflow 黒：アウトフロー

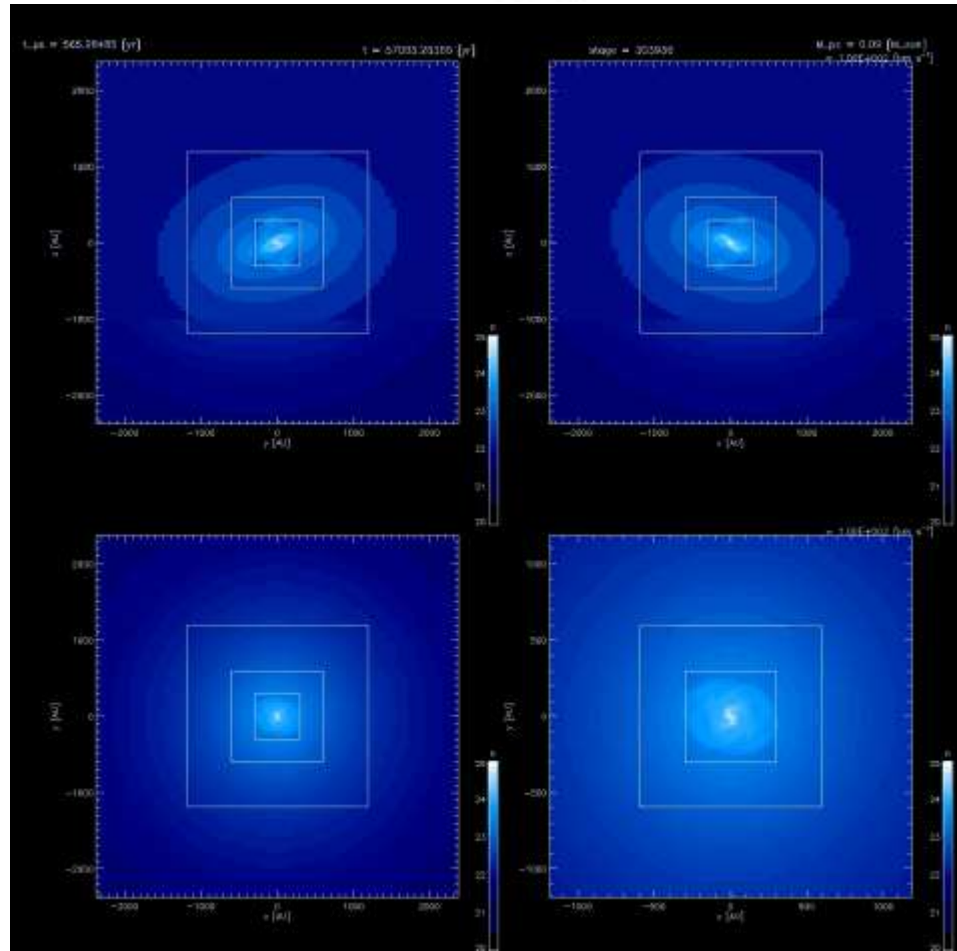



Θ=0°




Θ=30°



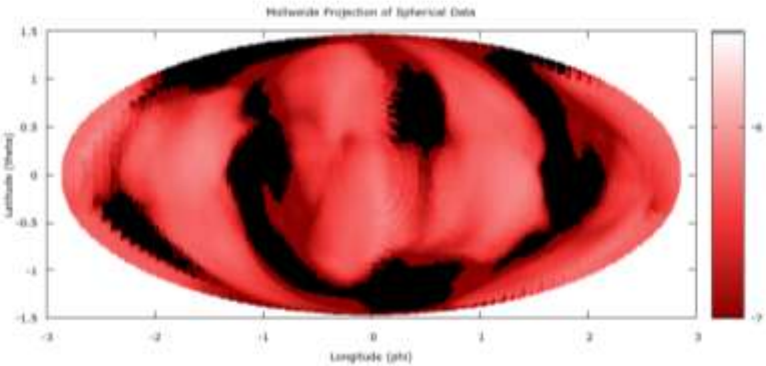


Machida & Basu (2026?)

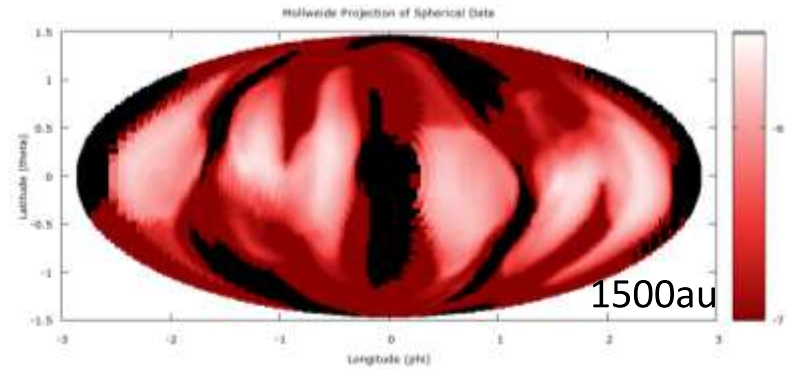
# Column density

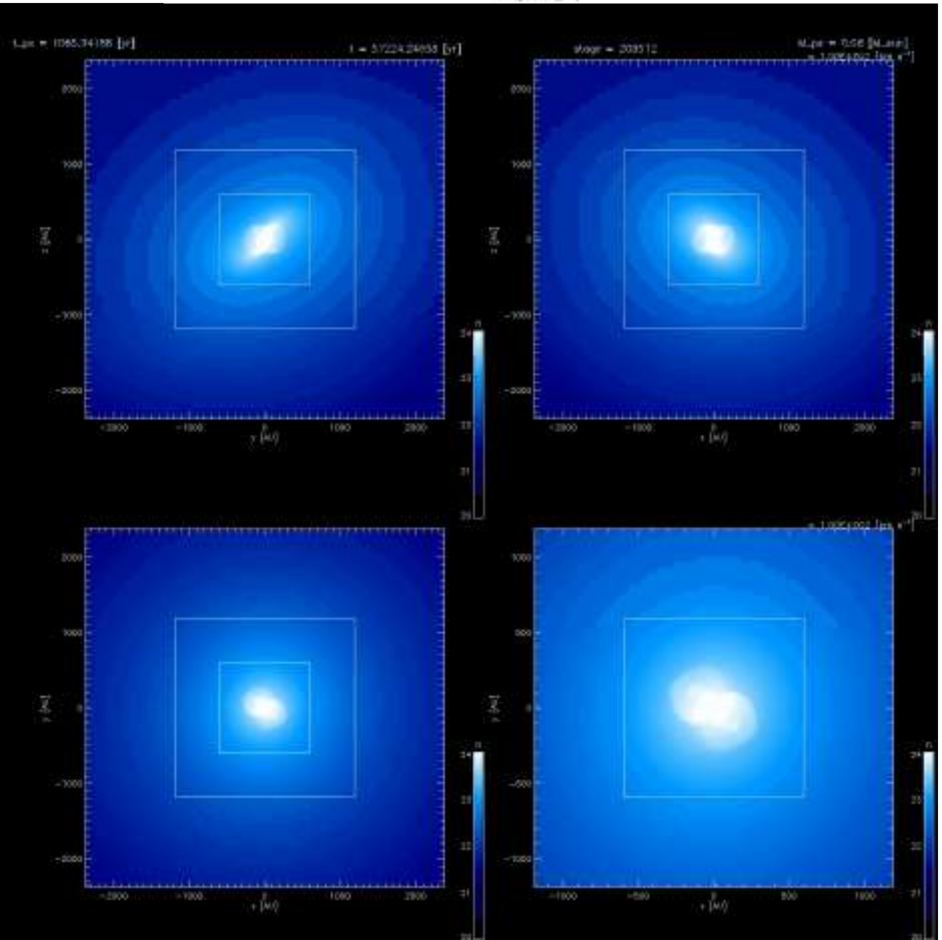
赤・ピンク：inflow  黒：アウトフロー

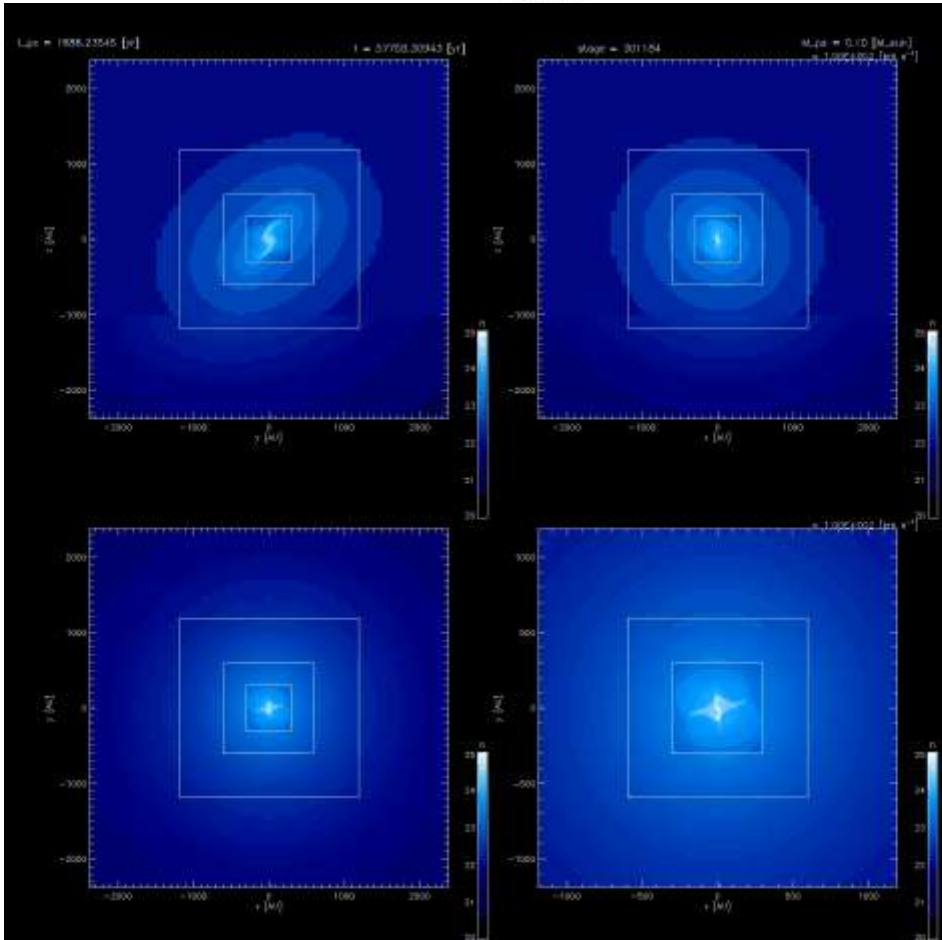
Θ=60°



Θ=80°

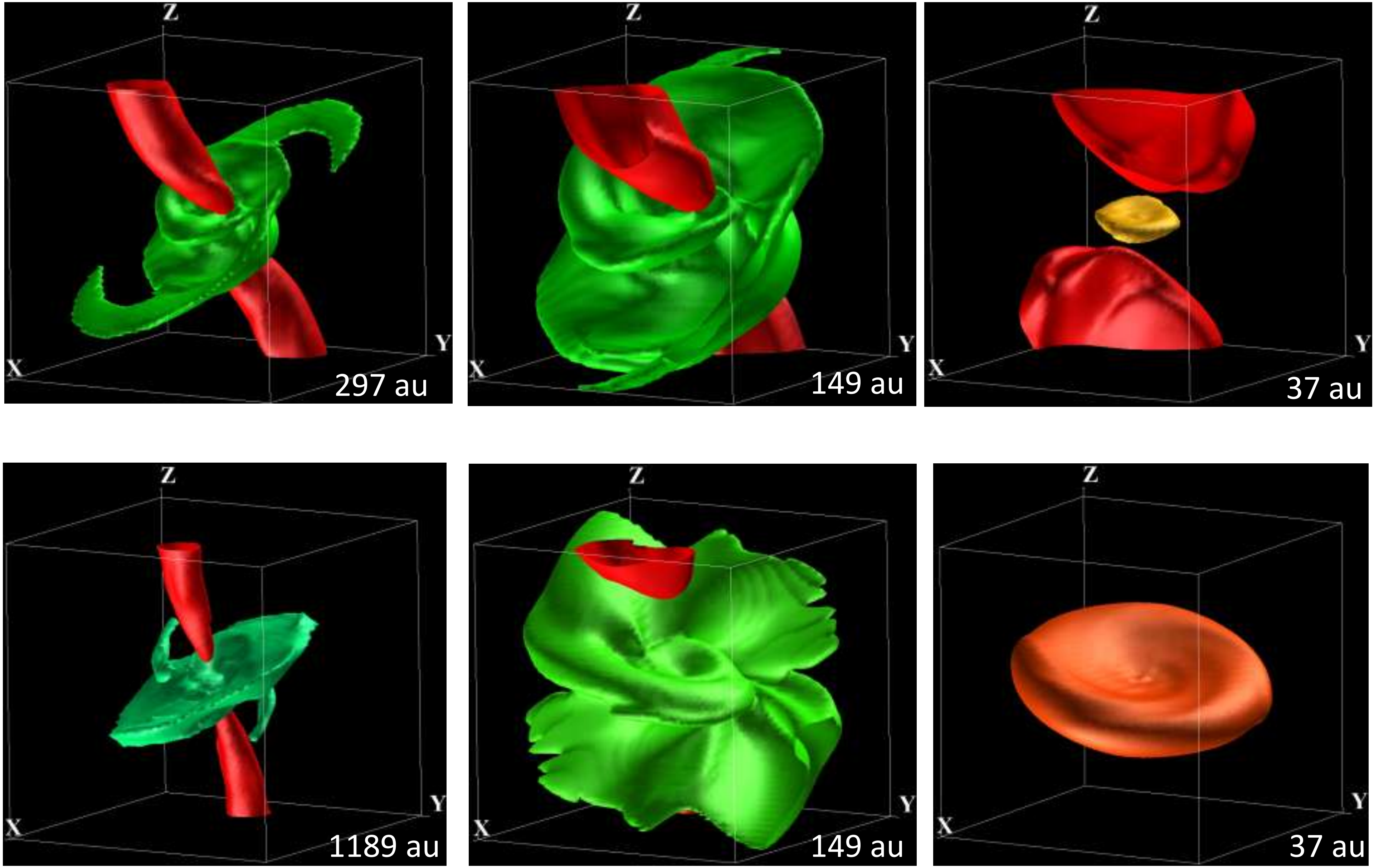




3D view

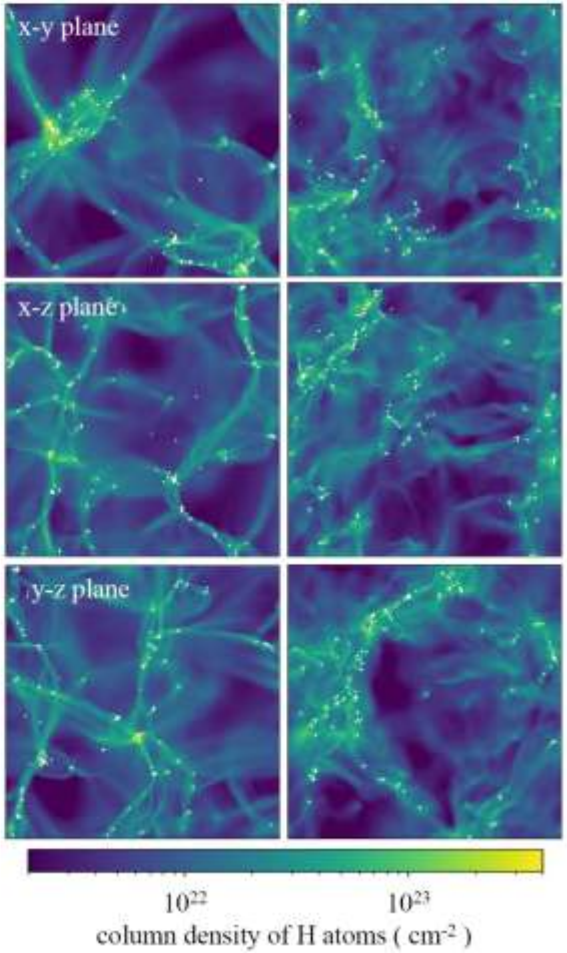
$\Theta=30^{\circ}$

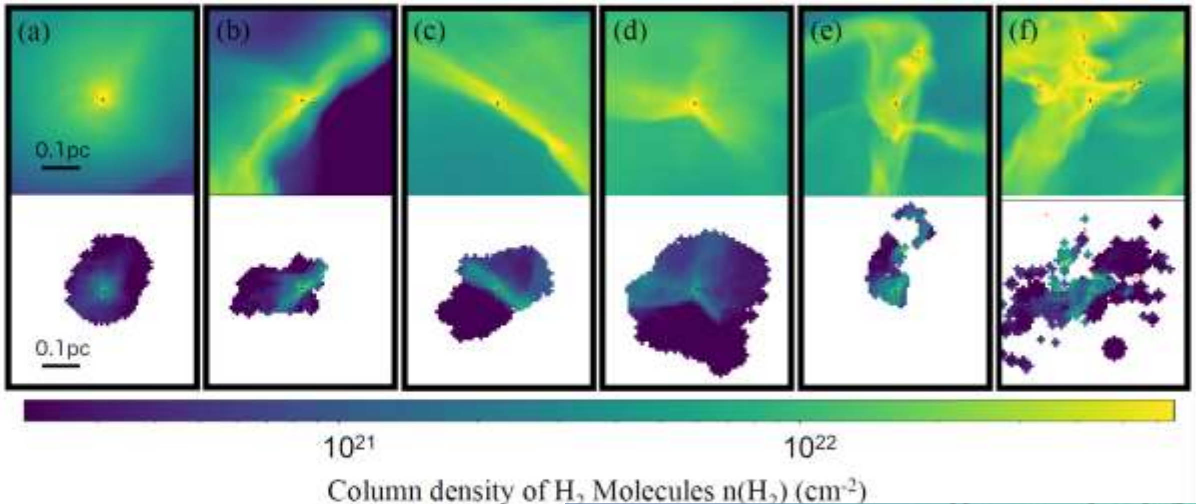


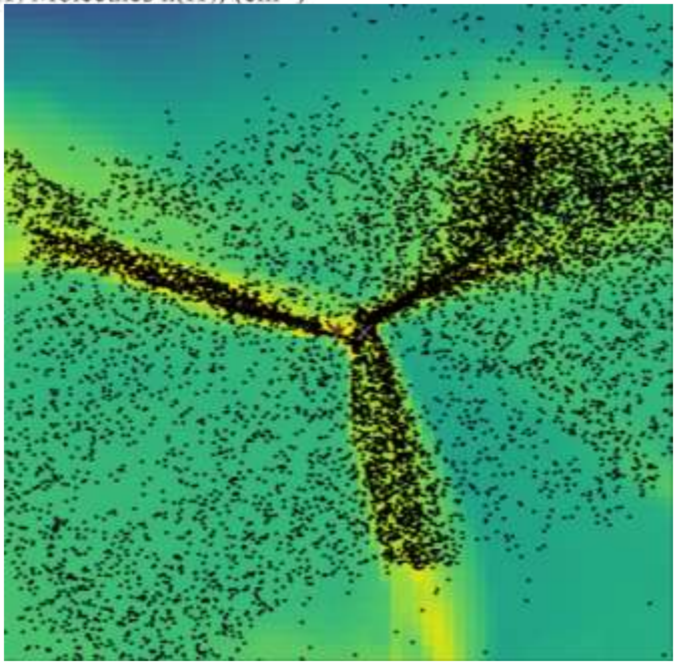
# 星形成コア

- 実際のprestellar coreは複雑な形状
- 理想的な設定(球対称)は、現実的ではないかも

Nozaki, Fukushima, Machida submitted



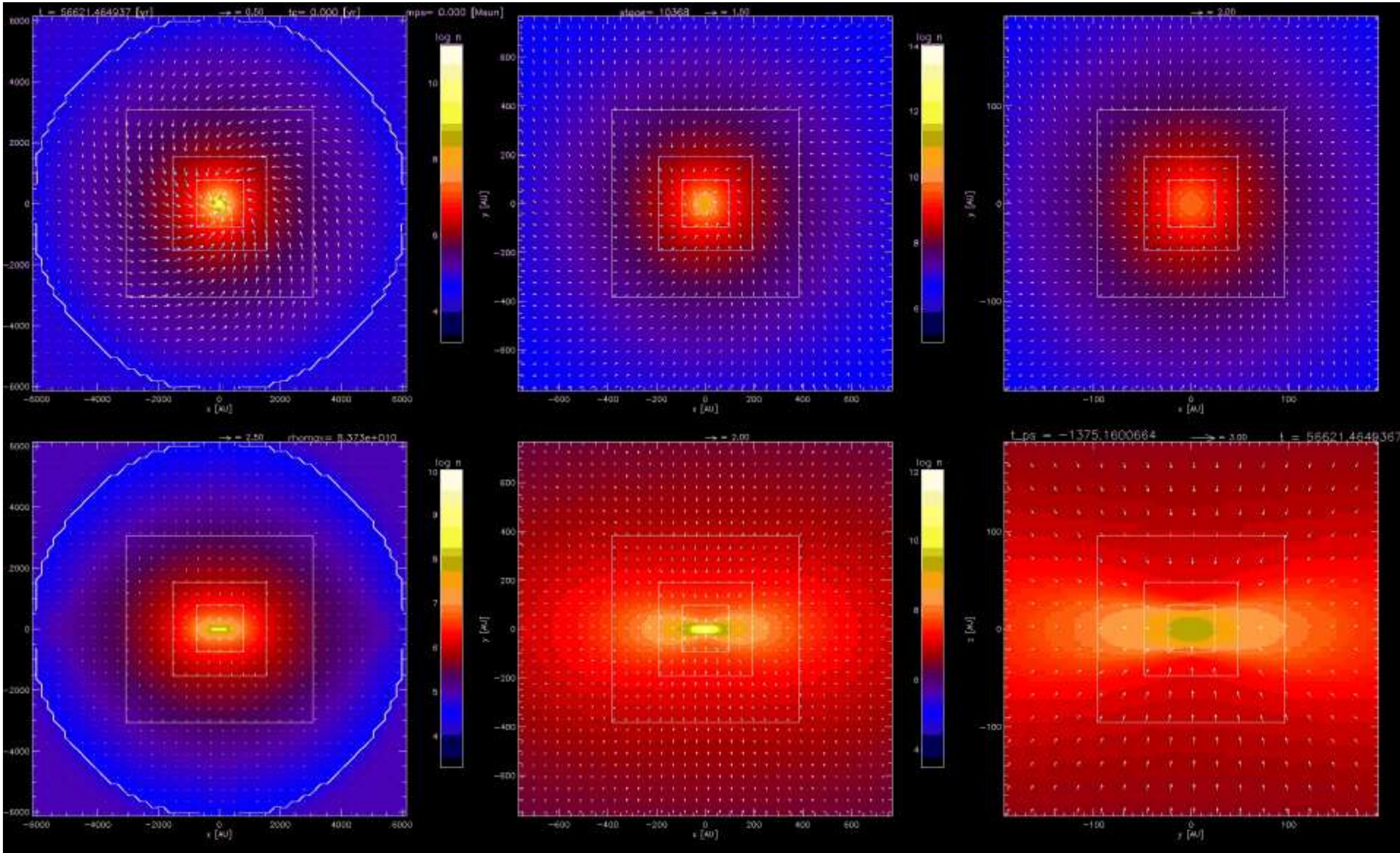



# 星周円盤と原始惑星系円盤

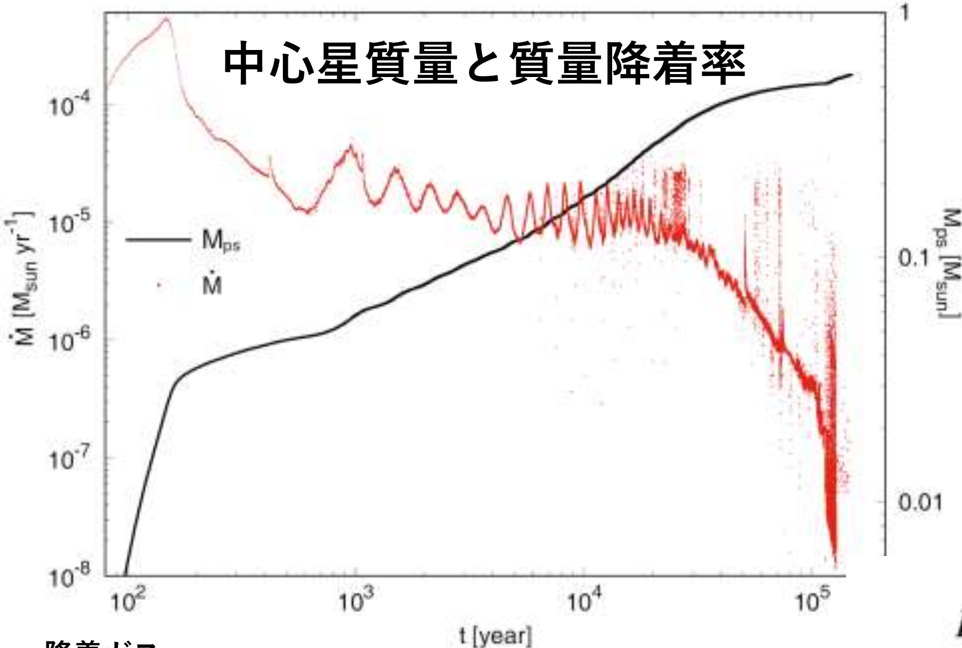
降着段階(Class 0/I)の星周円盤から降着終了後(Class II)の原始惑星系円盤の関係は？

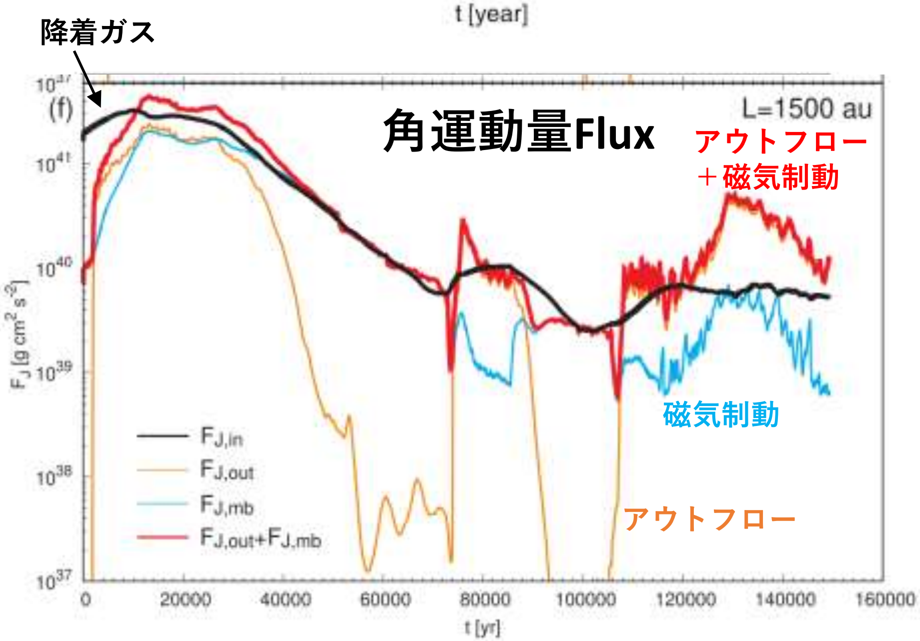
# 長時間進化

- 円盤形成、円盤進化の長時間計算
- 初期の1Msunのprestellar core → エンベロープ質量が$0.02M_{sun}$になるまで計算
- アウトフロー (disk wind)の再活性化 → Class IIではwind torqueによって円盤進化



# 円盤進化




- インフォーリングエンベロープが散逸
  → ラム圧低下 → disk wind
  → 磁気制動効率低下 → windで角運動量輸送
- アウトフロー (disk wind)の再活性化 → Class II ではwind torqueによって円盤進化
- 計算最後の角運動量輸送flux, 円盤の角運動量から円盤の角運動量は～$10^6$年で消失

$$F_{J,\mathrm{out}} = \left| \int_{v_r>0} \rho r_c v_\phi \boldsymbol{v} \cdot d\boldsymbol{S} \right|,$$

$$F_{J,\mathrm{in}} = \left| \int_{v_r<0} \rho r_c v_\phi \boldsymbol{v} \cdot d\boldsymbol{S} \right|,$$

$$F_{J,\mathrm{mb}} = \left| \int r \frac{B_\phi}{4\pi} \boldsymbol{B} \cdot d\boldsymbol{S} \right|,$$

$$t_{\mathrm{diss},J} = \frac{J_{\mathrm{disk}}}{F_{J,\mathrm{out}}} = \frac{J_{\mathrm{disk}}}{dJ_{\mathrm{out}}/dt} \simeq \frac{3\times10^{53}}{10^{40}}$$
$$\simeq 3\times10^{13}\ \mathrm{s} = 9.5\times10^{5}\ \mathrm{yr}.$$

# まとめ

- ダスト成長、惑星形成は降着段階(Class I)から開始(?)
  - 単にダストの分布なのか？惑星が出来ているのか？その後の進化？
- 複雑な星周構造は磁気交換型不安定性によって出来た構造(?)
  - 磁束の輸送は２つのモード？磁場の強さに依存？
- 低金属量でもアウトフロー駆動(?)
  - どの金属量までアウトフロー出現するのか？観測は困難？
- 非対称降着の起源は捩じられたPseudo disk(?)
  - 理想化しすぎた初期条件、現実的な星形成コア
- 原始惑星系円盤はdisk windによって持ちされれる角運動量によって進化(?)
  - 他の角運動量輸送機構？　より長時間の進化？