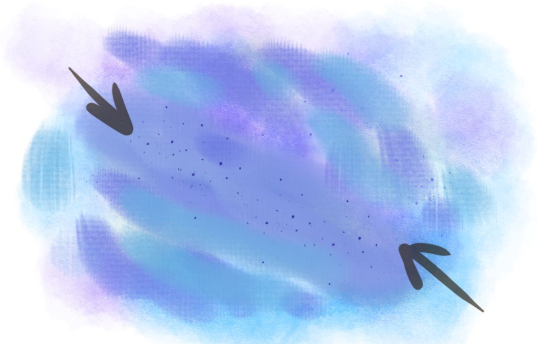
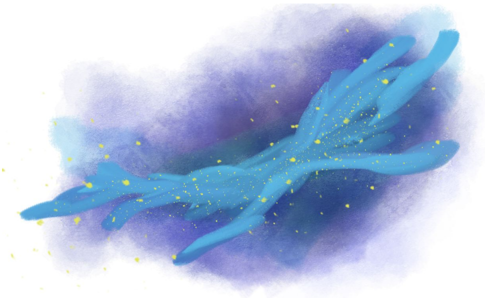
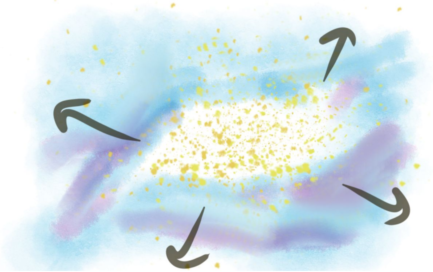
Numerical Experiments on (Proto) star Formation



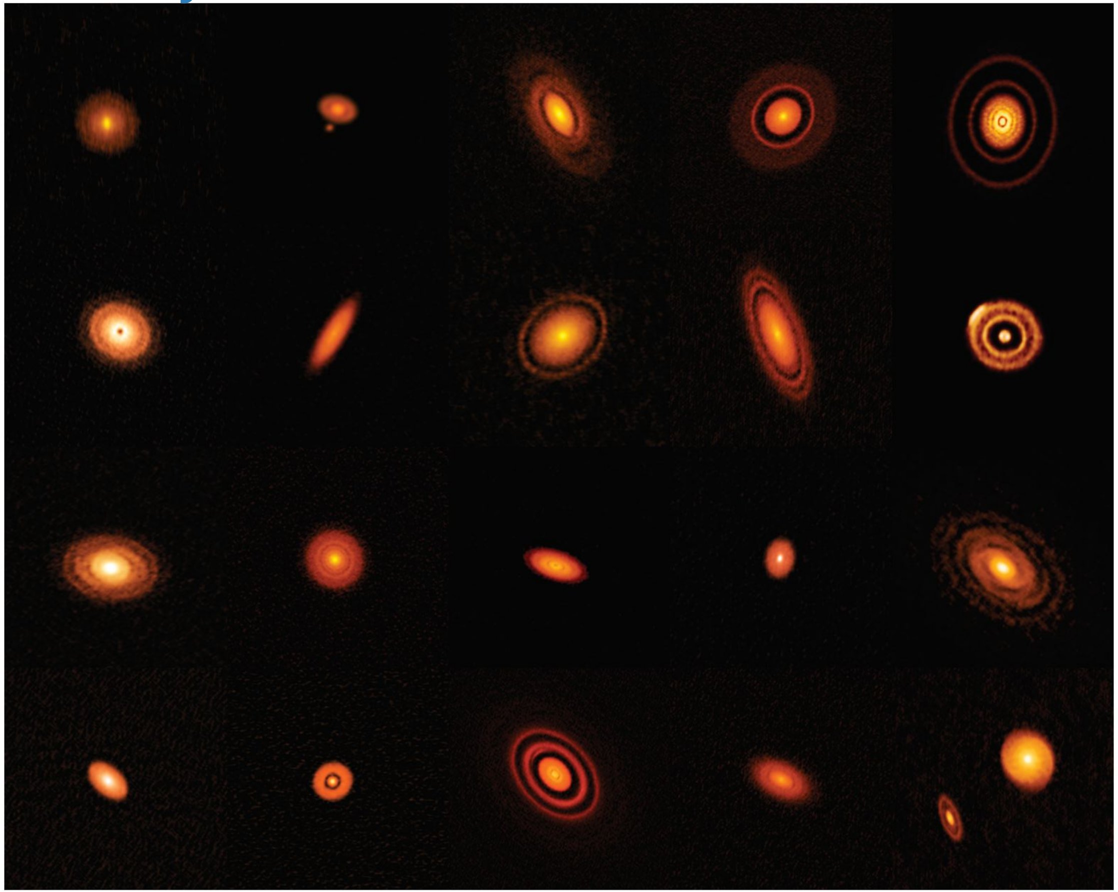




Aleksandra Kuznetsova
University of Michigan

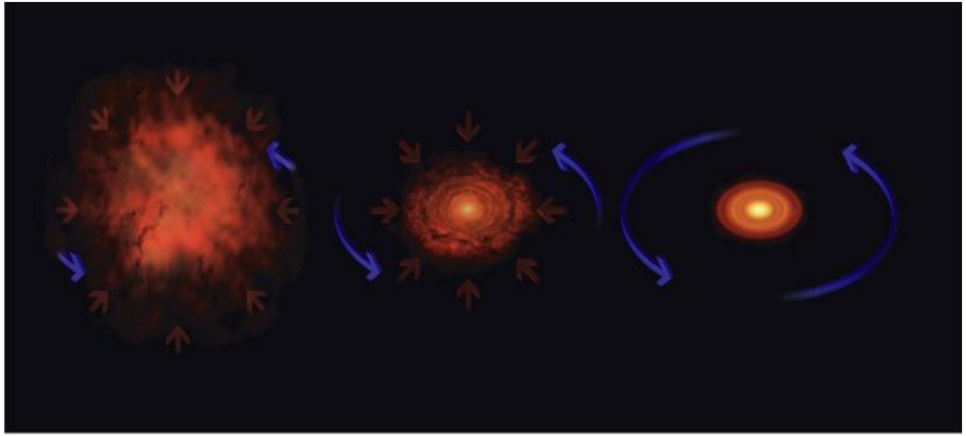
with: Lee Hartmann, Fabian Heitsch, Javier Ballesteros-Paredes

Protoplanetary Disks are diverse



ALMA DSHARP

What are the initial conditions for disks?



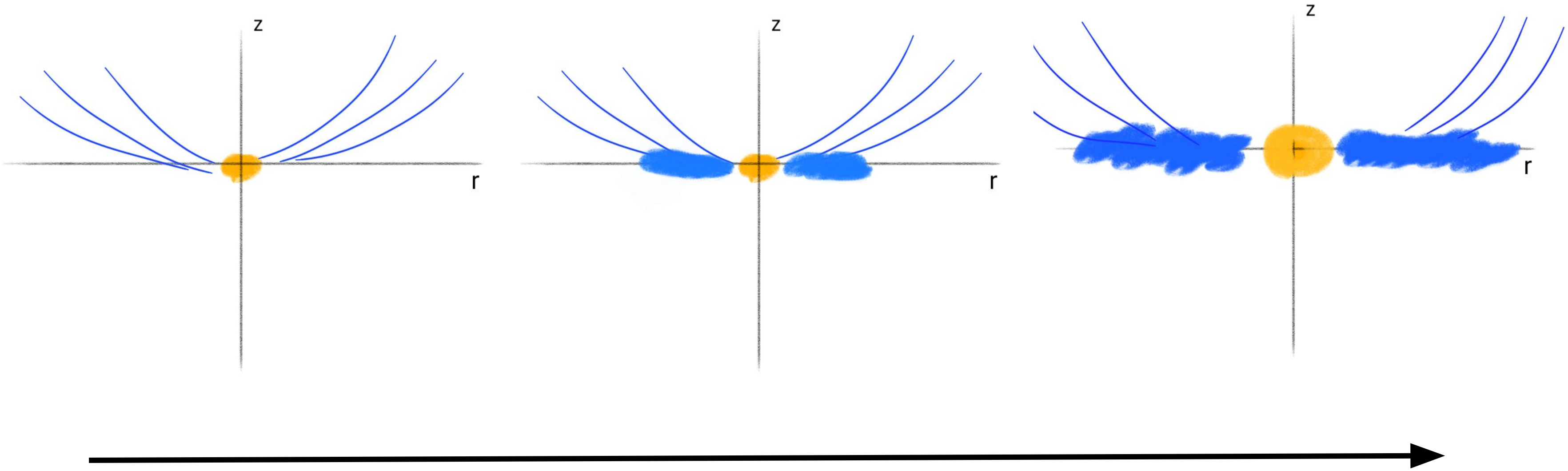
Disks are a natural consequence of angular momentum conservation

What sets the range and relative distribution of protoplanetary disk properties?

Self consistent modeling of disk/core formation from cluster to core scales can provide physically motivated initial conditions and disk properties

For pages of math see: Terebey, Shu, Cassen 1984
Cassen & Moosman 1981

Disk Formation Primer

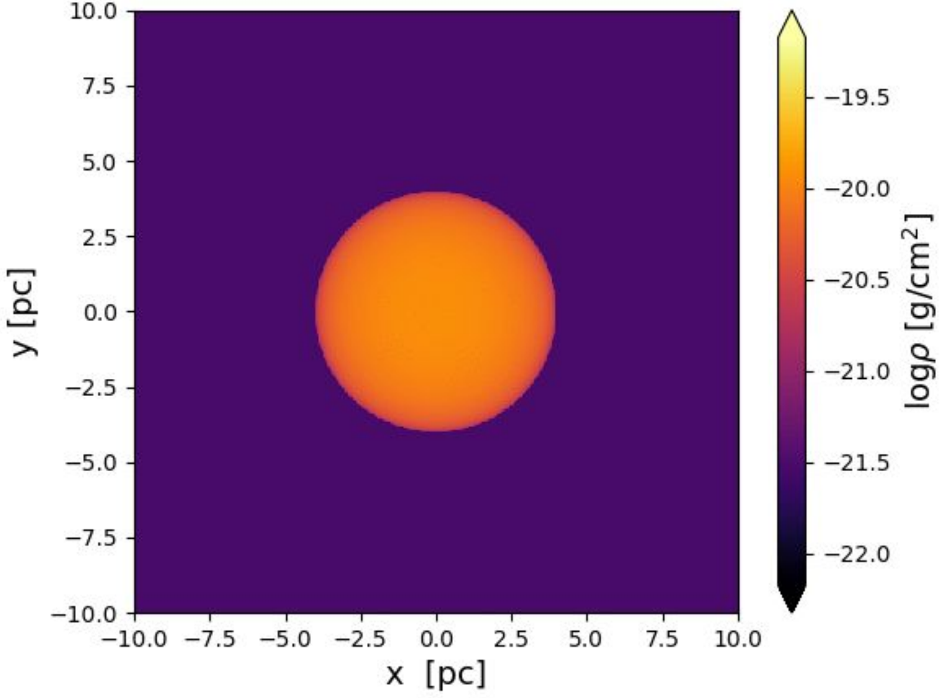


time
central mass
centrifugal radius

$$r_c \propto j^2/GM$$

$$j \propto t^2$$

Modeling Star Cluster Formation with Athena



Box size = 20 pc
Cloud radius = 8 pc

Self gravity (FFT)
Periodic boundaries

Seeded turbulence (no driving)
$P(k) \propto k^4\, dk$

Globally isothermal T = 14 K

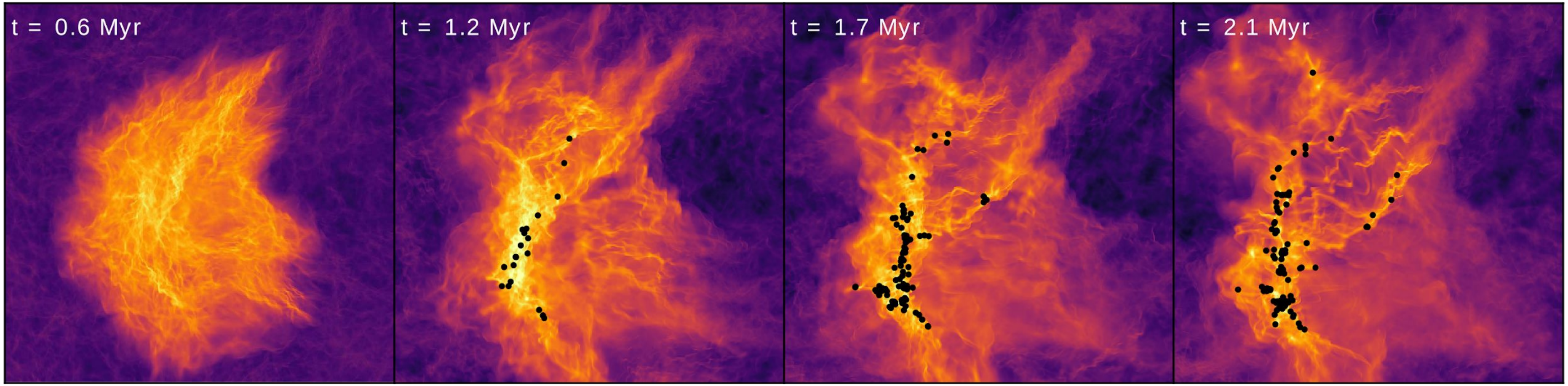
Freefall time ~ 1.7 Myr
Initial cloud mass ~ 2000 Msun

Modeling Star Cluster Formation with Athena

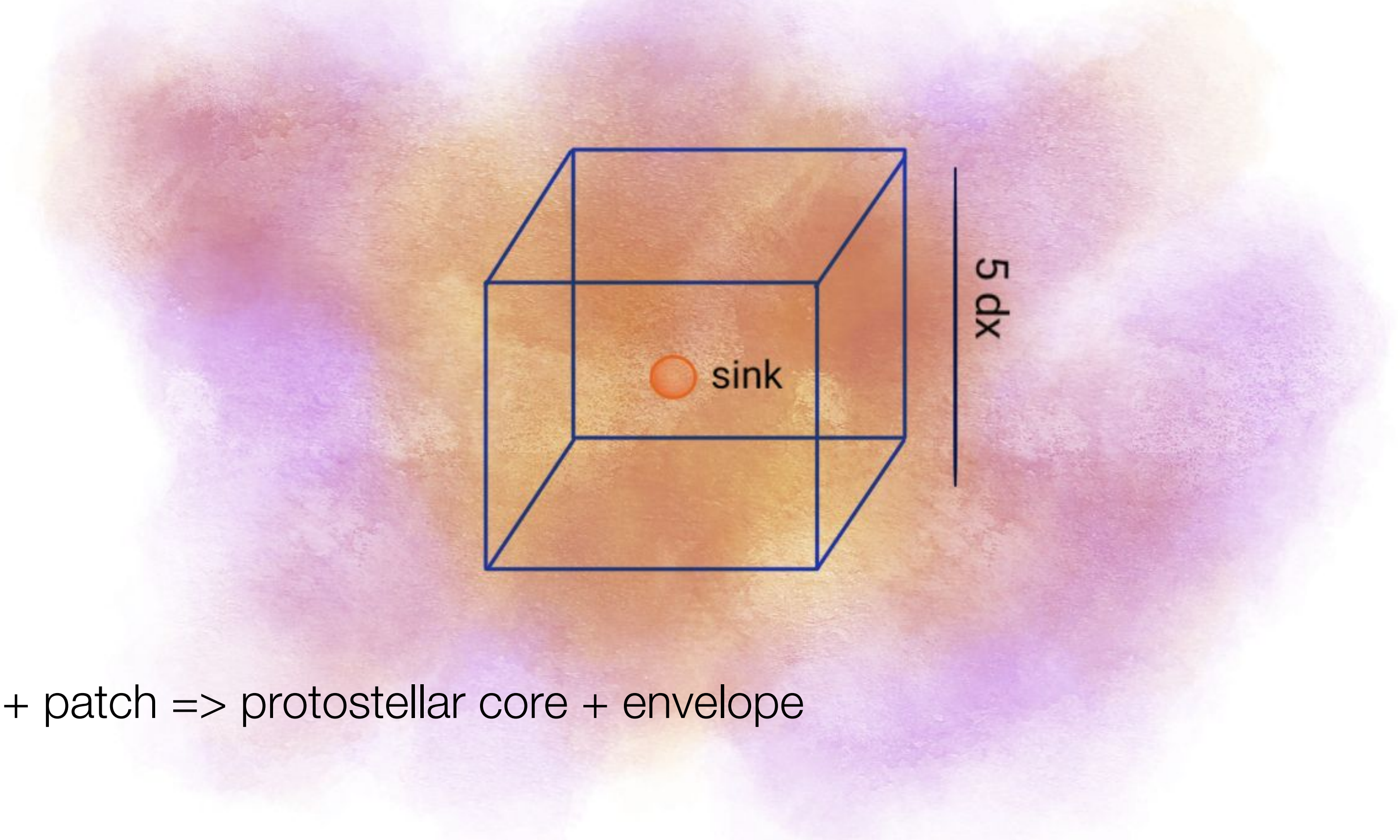
Table 1. A tabulated list of runs and their initial parameters used for this study. All runs have $r_{acc} = 2$ and $T = 14$ K.

Run	Seed	Ω_c^{-1} [Myr]	Ω_k^{-1} [Myr]	t_{end} [Myr]	N_{sink}	$\langle n_s \rangle$ [pc^{-3}]
$N_{cell} = 512^3$						
IR_s0	0	...	15	2.35	98	0.018
IR_r1_s0	0	6	15	2.35	66	0.012
IR_r2_s0	0	3	15	2.35	42	0.009
IR_r3_s0	0	1.5	15	2.35	19	0.002
$N_{cell} = 1024^3$						
HR_s2	2	...	10	2.1	115	0.028
HR_s0	0	...	15	1.9	110	0.024
HR_s1	1	...	8	2.4	70	0.011
HR_r1_s0	0	6	15	1.9	122	0.028
HR_r1_s1	1	6	8	2.5	88	0.014
HR_r2_s0	0	3	15	1.9	134	0.032
HR_r2_s1	1	3	8	2.5	54	0.009
HR_r3_s0	0	1.5	15	1.9	102	0.024
HR_r3_s1	1	1.5	8	2.5	10	0.001

Modeling Star Cluster Formation with Athena



Subgrid Models - The sink-patch environment



sink + patch => protostellar core + envelope

Subgrid Models - The sink-patch environment

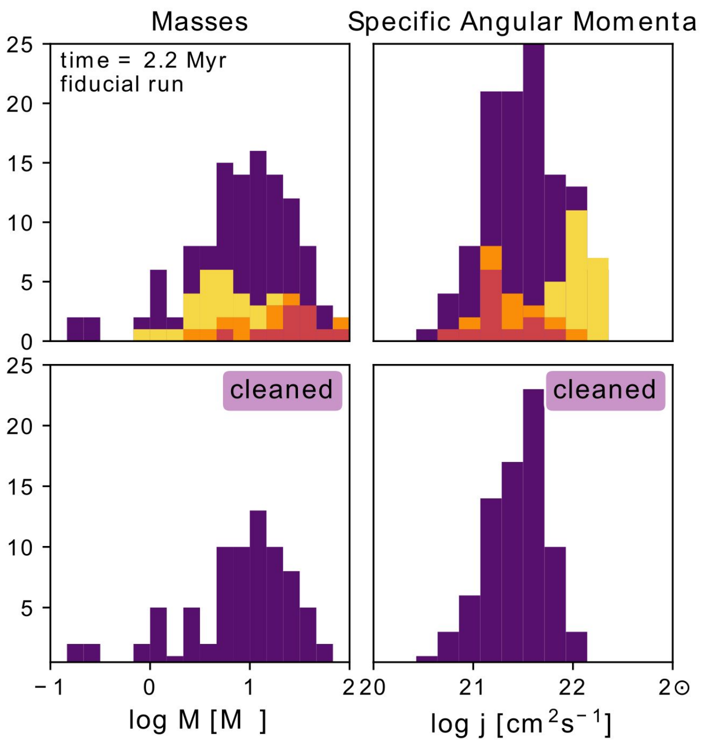
Sink-patch algorithm based on Bleuler & Teyssier 2014

Similar to Gong & Ostriker 2013 for Athena except for accretion, which goes like:

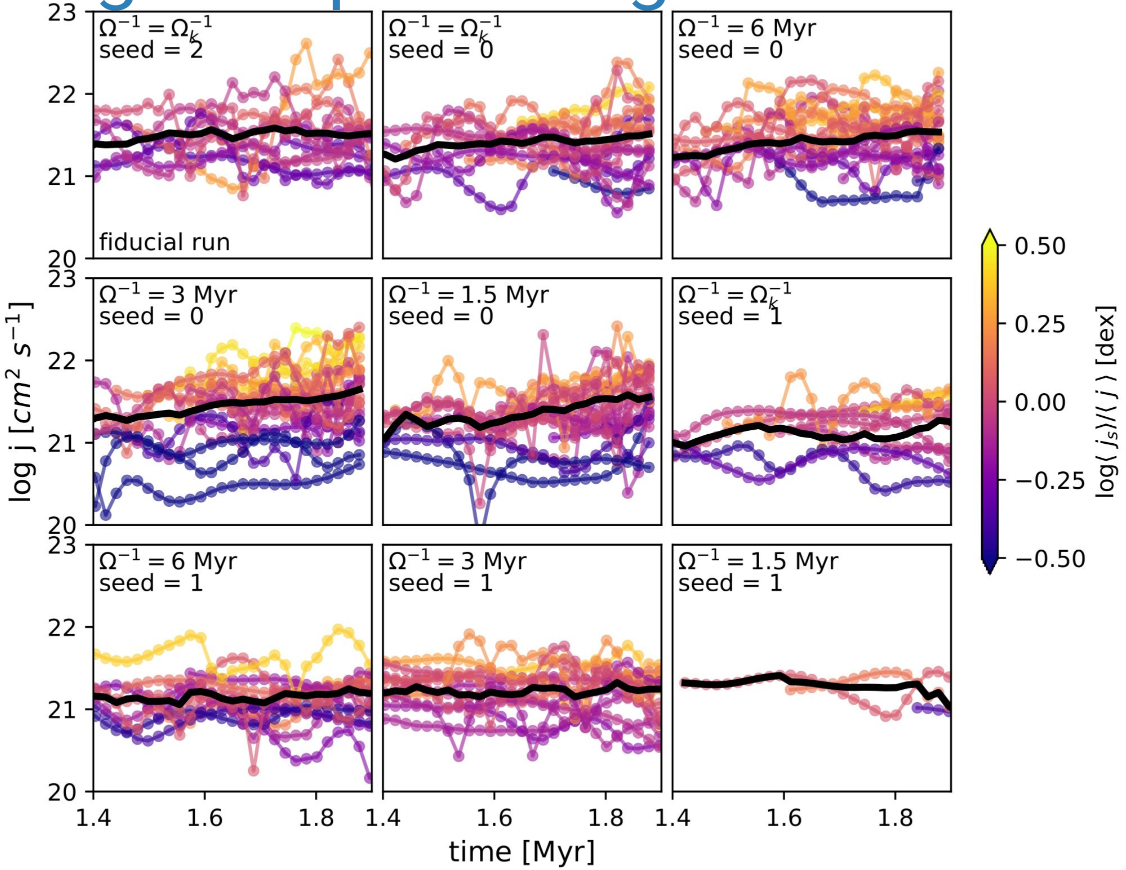
$$\dot{M}_s = \left(1 + \eta \log \frac{\bar{\rho}}{\rho_{\mathrm{thr}}}\right) \int \nabla \cdot (\rho(\mathbf{v} - \mathbf{v}_{\mathrm{sink}}))dV$$

see “The Role of Gravity in Producing Power-law Mass Functions” (Kuznetsova+2018b) for details

A Little Bookkeeping Is Necessary

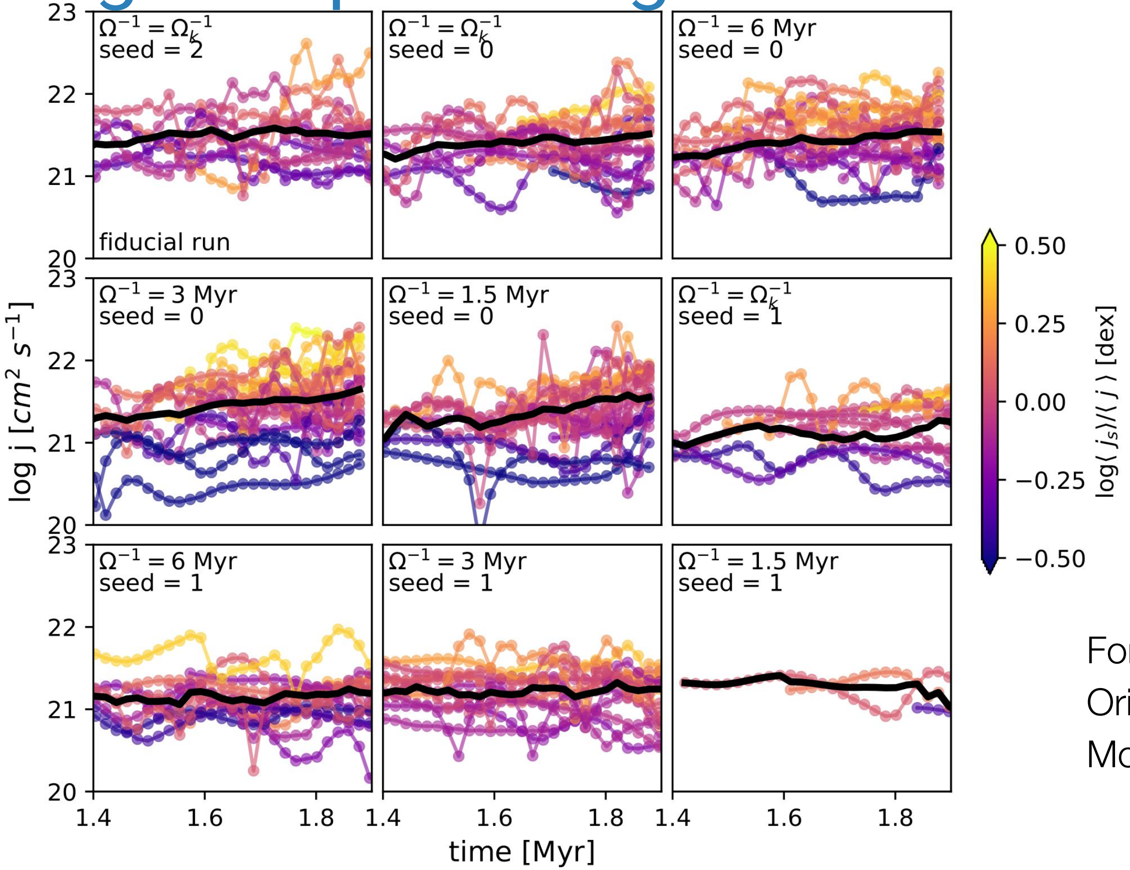


Insights - Specific Angular Momentum is Constant



For more keep an eye out for "The Origins of Protostellar Core Angular Momentum" (Kuznetsova+submitted)

Insights - Specific Angular Momentum is Constant



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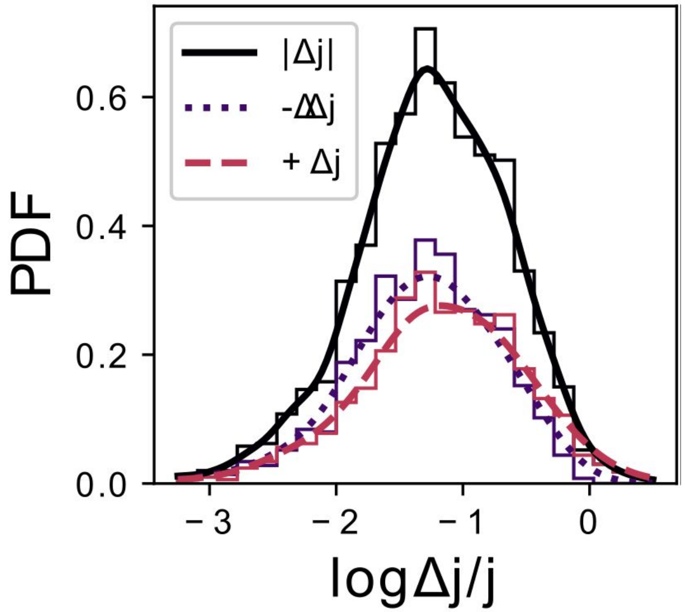
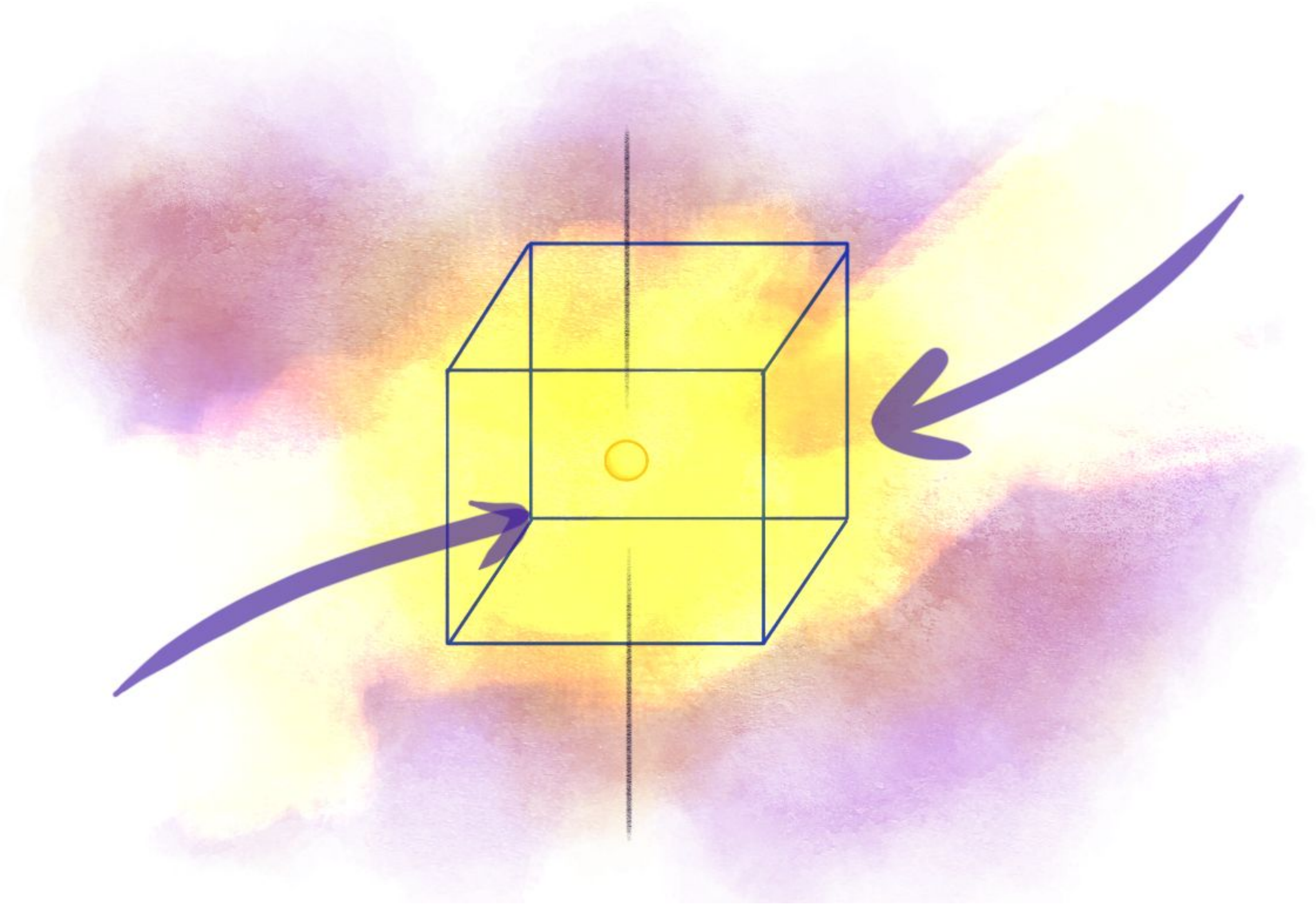
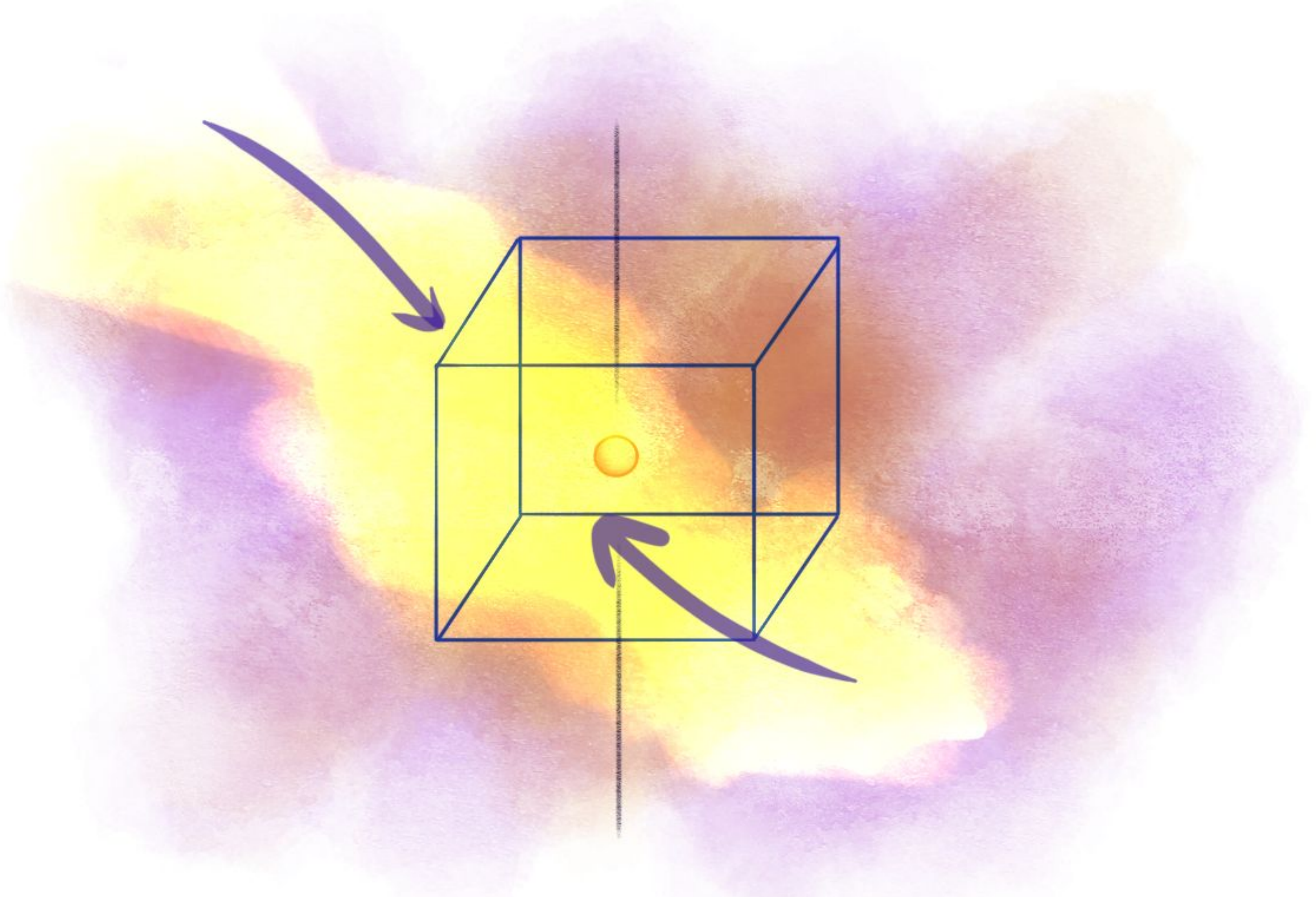
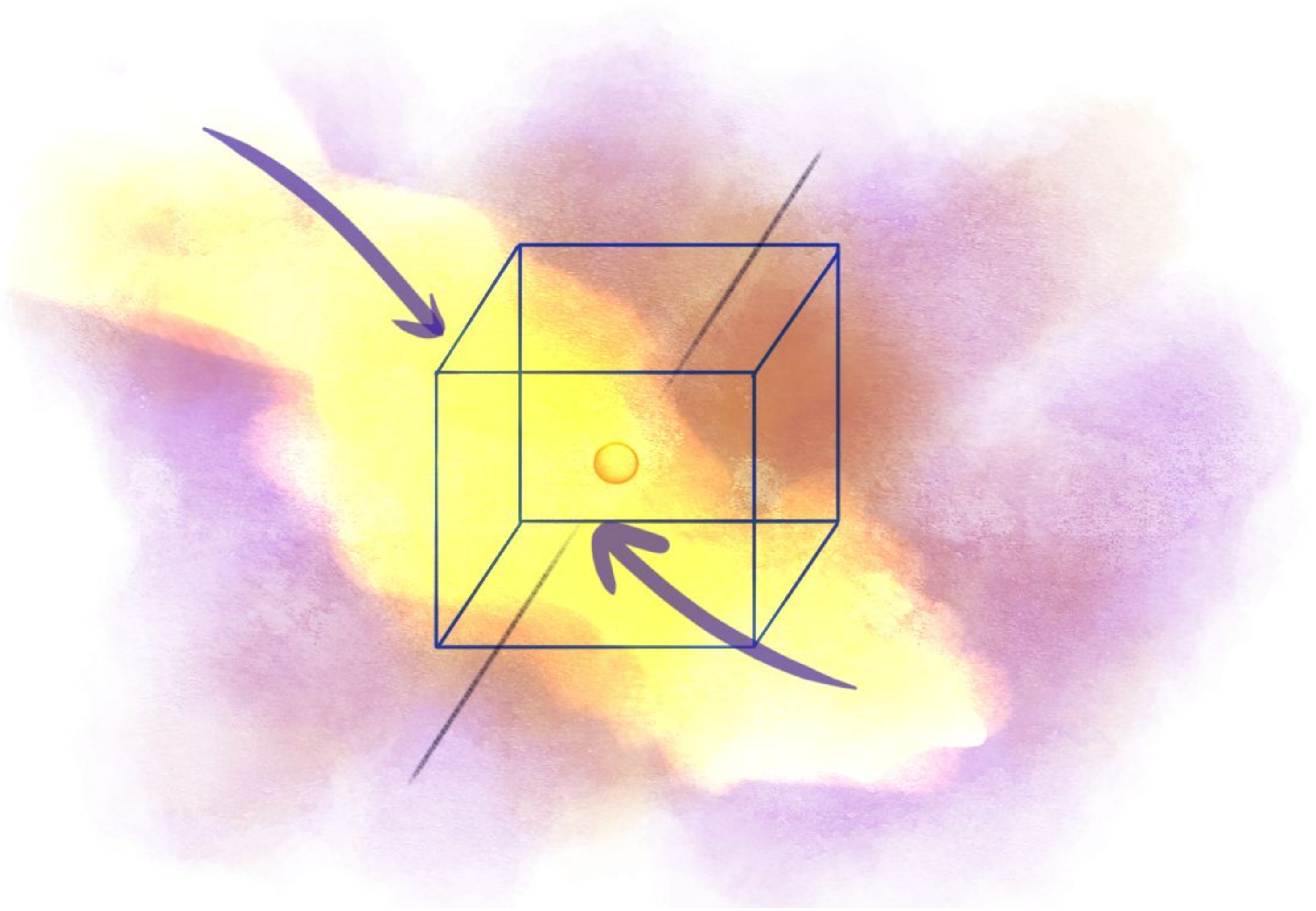
Just as likely to gain angular momentum as you are to lose it!

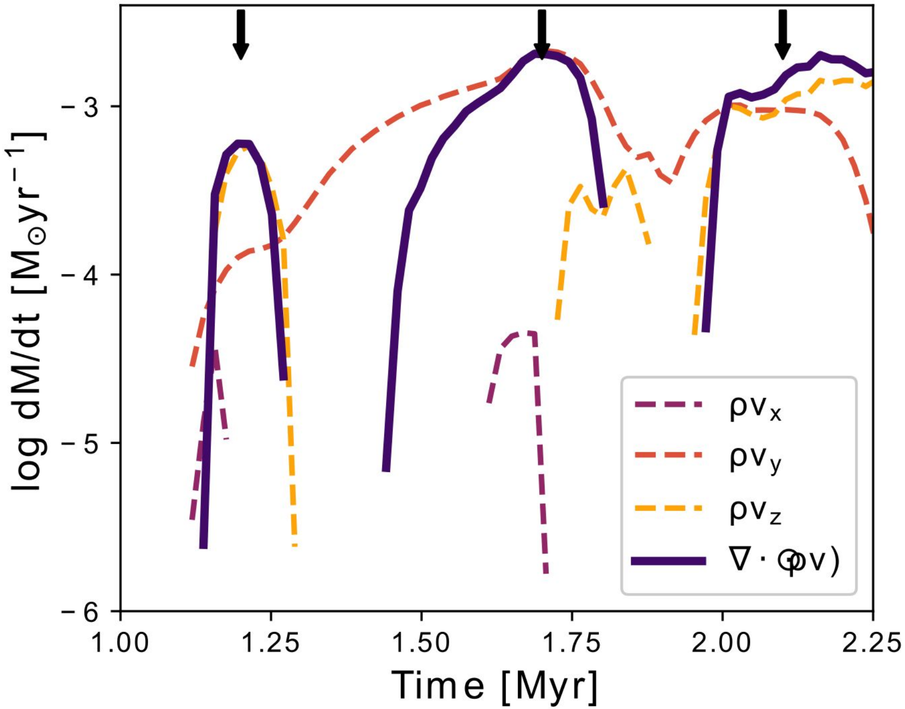








Insights - Accretion is 3D



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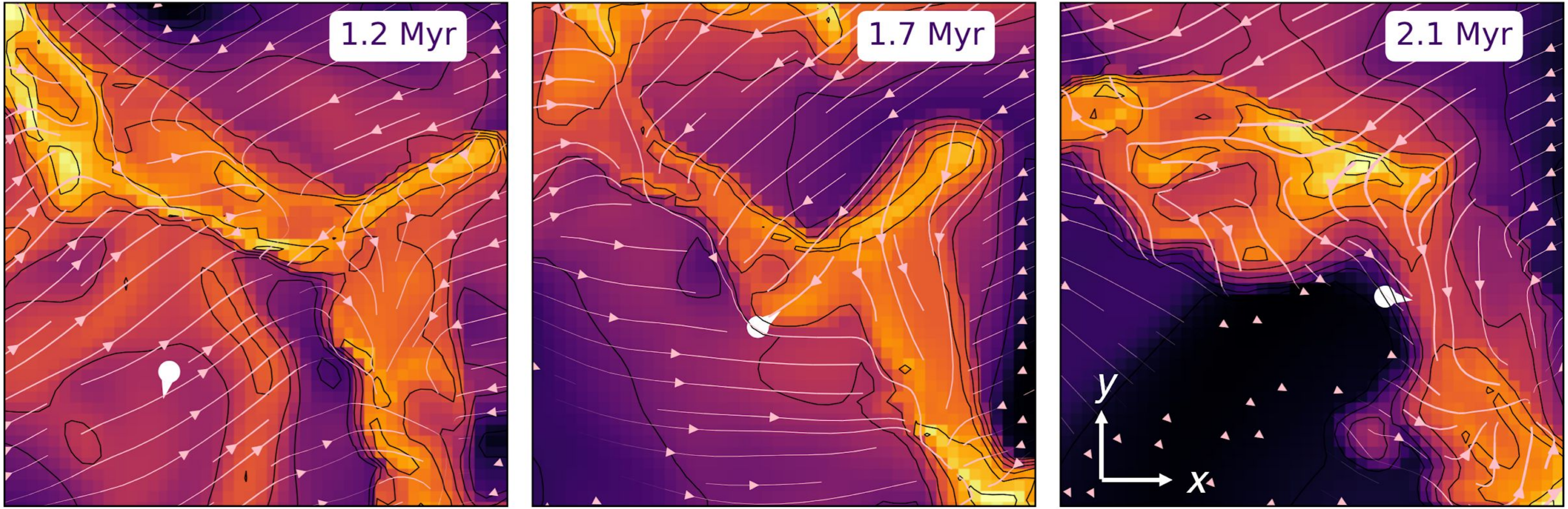
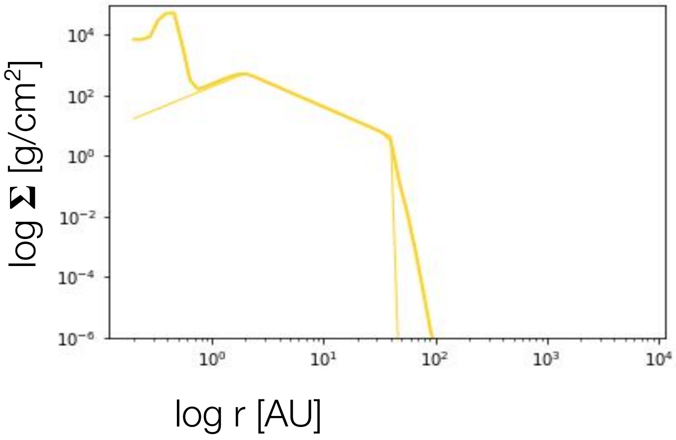
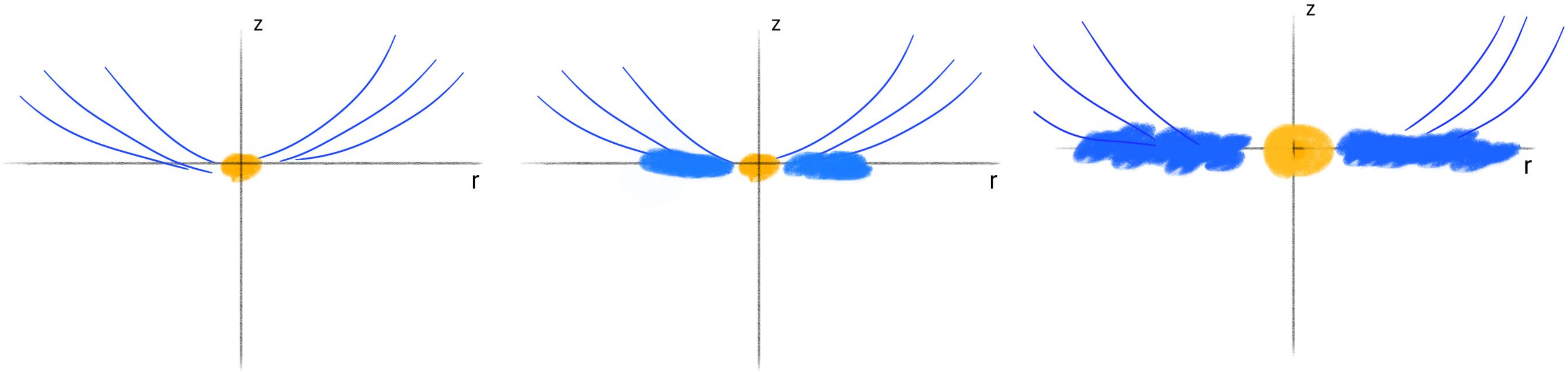


Implications for Disk Formation

Standard rotating collapse (TSC 1984)

Centrifugal radius grows outward as disk is built





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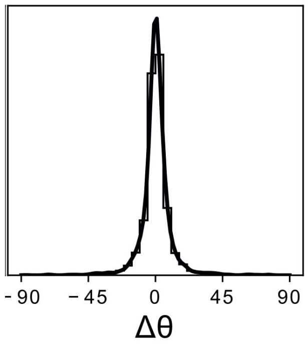


Variable multidirectional infall

Constant j (averaged over time)

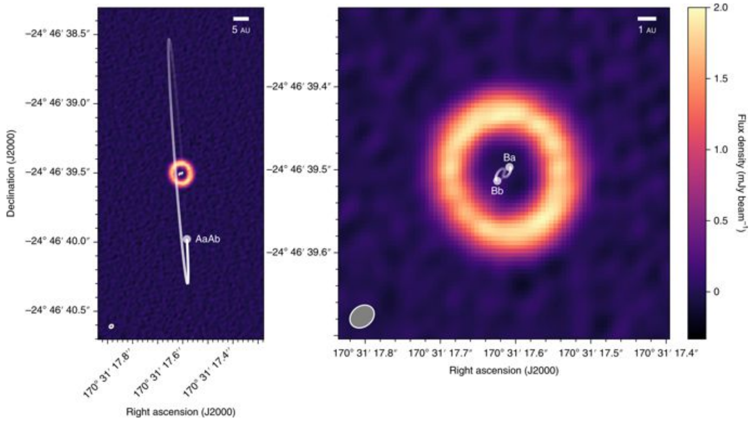
Centrifugal radius should be nearly constant over time

→ Disk forms outside in

→ Different disk surface densities

→ Trigger GI, shear instabilities?

→ How common are misaligned disks?



Kennedy+ 2019 *Nature*

Summary

Star formation is dynamic - collapse from cloud to core scales happens on a dynamical time

Self consistent modeling starts from the cluster scale

Infall onto cores is messy and three dimensional

Next steps will be to model disk formation with variable multidirectional accretion in mind

A job for Athena++ !