The Demise of the SAD Model

Åke Nordlund

Niels Bohr Institute & Centre for Star and Planet Formation

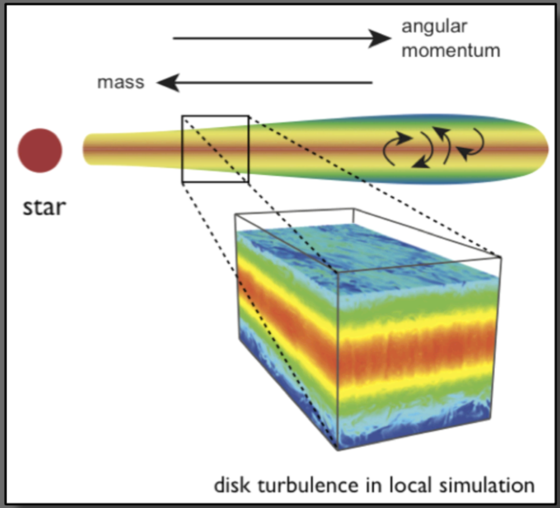
University of Copenhagen

with

- Troels Haugbølle, Michael Küffmeier, Troels Frostholm Mogensen, Aris Vasileiades (STARPLAN, Copenhagen)
- Paolo Padoan (ICREA, Barcelona)

NBIA, Copenhagen 2014

The Standard Accretion Disk (SAD) Model



Main assumptions:

- Angular momentum transport is in the radial direction
- No (explicit) 'external' accretion

Other common assumptions:

- Local shearing box, isothermal, …
- No mean vertical field, or only a weak seed field
- No vertical exchange (no BC-influence, no out-flows, …)

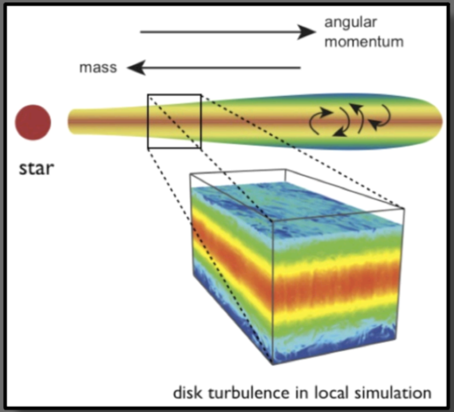
Even worse:

- No stratification / vertically periodic

The Standard Accretion Disk (SAD) Model

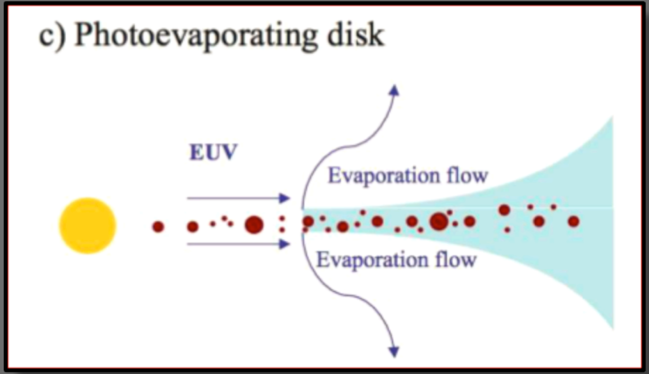
Hidden (implicit) assumptions:

- Disk are “nice”
  - well defined plane of rotation
  - well defined mean structure
  - ‘turbulence’ = small scale fluctuations

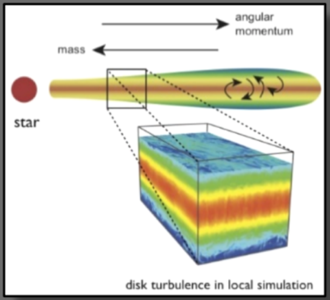


- PP-disks are (very) thin:
  - $H/r \sim c/v_{Kepler} \sim$ a few percent or less

- Long-lived – end-of-life needs a ‘cause’
  - Must be ‘dispersed’ (by EUV or similar means)



Key SAD historic events



1973: Shakura & Sunyaev (~7000 citations)

- Introduced the famous alpha-parameterization

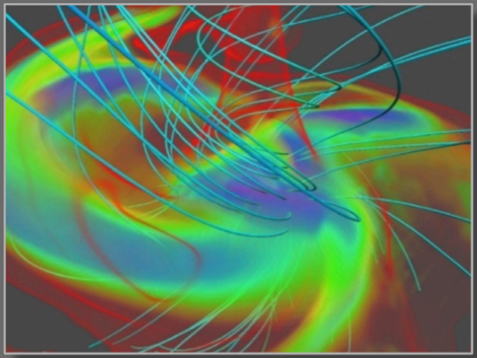
1974: Lynden-Bell & Pringle (~1500 citations)

- Pointed out that viscous transport ⇒ outward energy flux
  - Triples (unavoidably) the local energy divergence!

1991: Balbus & Hawley (~2300 citations)

- Re-discovery of the magneto-rotational instability (MRI)

What’s wrong with the SAD model?



Essentially everything!

- Transport is mainly in the vertical direction
  - Mass loss: observed outflows, CMF/IMF discrepancy
  - Angular momentum loss: unavoidable and significant
  - Energy loss: unavoidable and significant
- Disk are “buffers”, with relatively short time constants
  - Approximate balance btw “external” and “internal” accretion
- Disk are crucially dependent on (external) boundary conditions
  - Significant pseudo-random scatter of properties / extra parameters
    - initial core / filament relation
    - initial mass-to-flux ratio
    - binarity / multiplicity

What do I base this on?

Observations

- Ubiquitous outflows
- Keplerian disks, with short replenishment times M/M

Theory of outflows and winds

- Blandford → Königl
- Pudritz, Wardle, Krasnopolsky, Salmeron, …

Modeling

- Inutsuka, Machida et al, Zanni et al, Fendt et al, …
- Hennebelle, Commercon, …, Joos
- Königl, Pudritz, Banerjee, Oyed, Staff, …, Seifried
- Our group: Haugbølle, Padoan, ÅN, …, Küffmeier

Modeling: Seifried et al

'Turbulence circumvents the magnetic breaking catastrophe'

(MNRAS 423, 2012; MNRAS 423, 2013)

PhD thesis 2013 (on ADS):

> Recently, Krasnopolsky et al. (2011) have proposed that including the Hall effect can result in the formation of large-scale Keplerian discs. They claim, however, that a Hall coefficient about one order of magnitude larger than expected under realistic conditions would be required. Furthermore, in this case the spin-up of the disc is not due to a reduced magnetic braking efficiency but due to the Hall-induced magnetic torque, which depends on the direction of the magnetic field. This is demonstrated by the fact that Krasnopolsky et al. (2011) find counterrotating discs, i.e. discs which rotate in the opposite direction as the surrounding core when the field direction is flipped. Recently it was also shown that Ohmic dissipation fails to produce Keplerian discs larger than roughly 10 solar radii in the earliest evolutionary stage (Dapp & Basu, 2010; Dapp et al., 2012), unless a strongly enhanced resistivity is used (Krasnopolsky et al., 2010). Furthermore, also the inclusion of ambipolar diffusion does not help to form Keplerian discs (Mellon & Li, 2009; Duffin & Pudritz, 2009). Hence, it seems that all three non-ideal MHD effects cannot account for the formation of Keplerian discs. However, as we have shown, already for the ideal MHD limit Keplerian discs can form in strongly magnetised cores when turbulent motions are included. Therefore, it seems that non-ideal MHD effects or turbulent reconnection are not necessarily required to avoid the "magnetic braking catastrophe".

Hall

Ohm

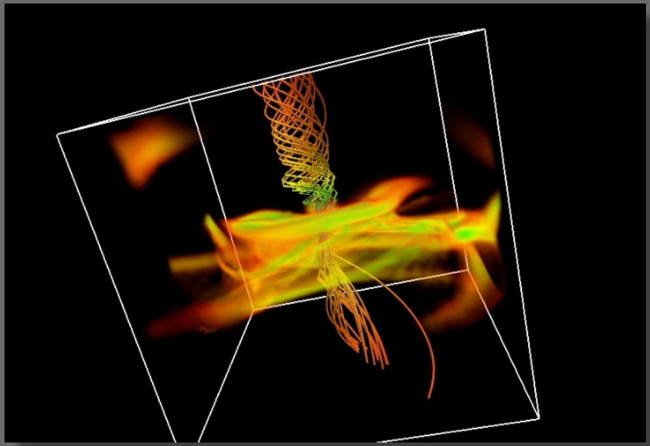
AD

!!!

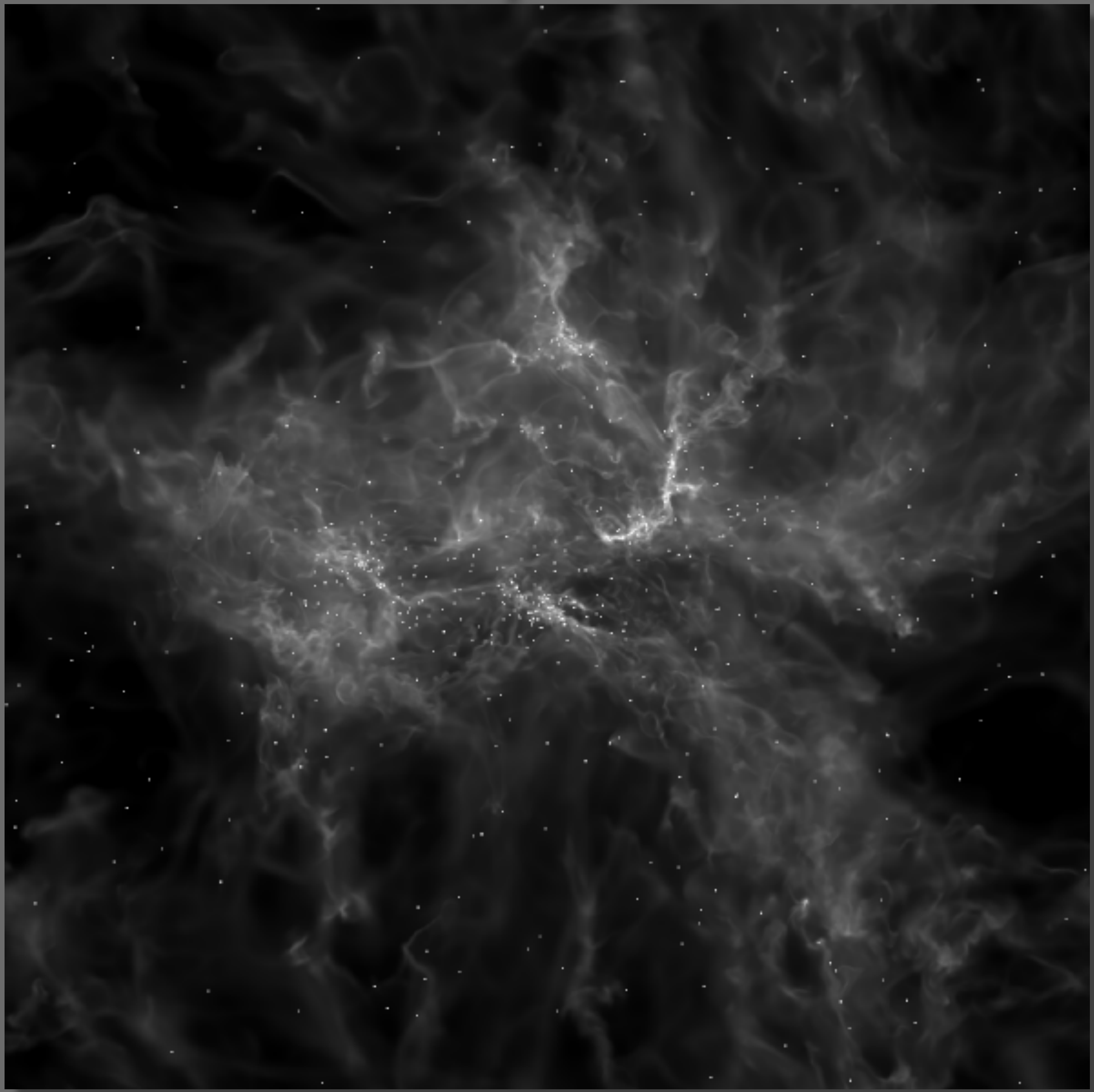
Non-ideal MHD and magnetic braking

Why non-ideal MHD is less important than in MRI:

- Scales are larger and velocities are higher
  - Most of the angular momentum loss happens at large radii
  - At small radii velocities are large
- Disks are dynamic structures, thicker than SADs
  - Hence volume densities are lower – and decreasing with time



Our Group: Star Formation Results



Padoan, Haugbølle, ÅN
astro-ph/1407.1445

- 4 pc GMC fragment
- > 1000 stars formed
- accretion histories
- luminosity distrib.

Our Group: Star Formation Results

Initial Mass Function

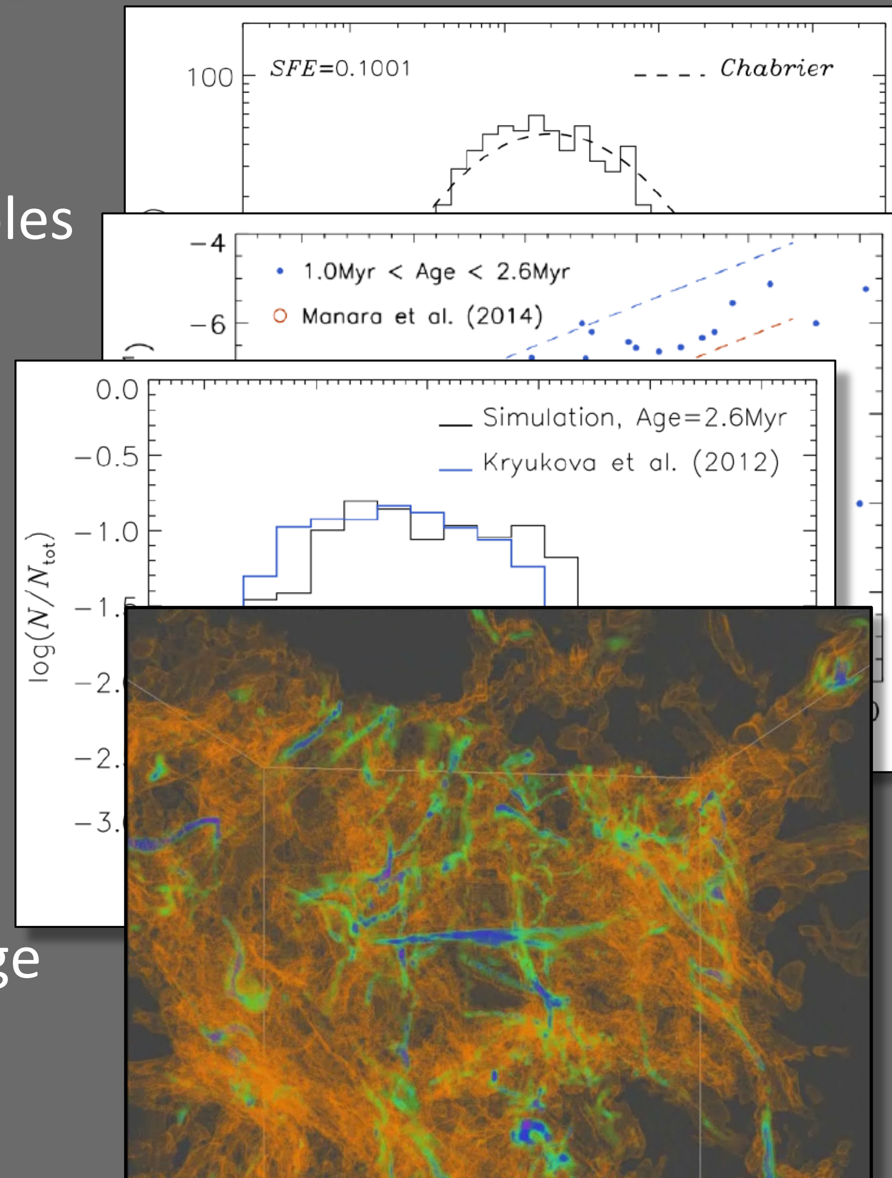
- Consistent IMF from 1st principles
- Numerically converged

Luminosity Problem Solved

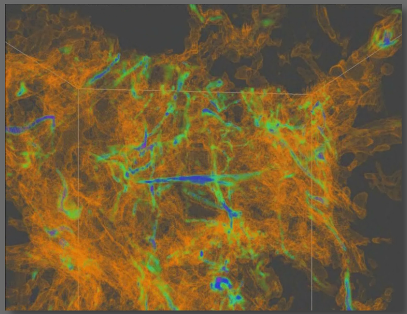
- Consistent ensemble values
- Reproduce observed spread

Zoom Simulations

- First-of-a-kind: 10^9:1 scale range
- PPDs in realistic context



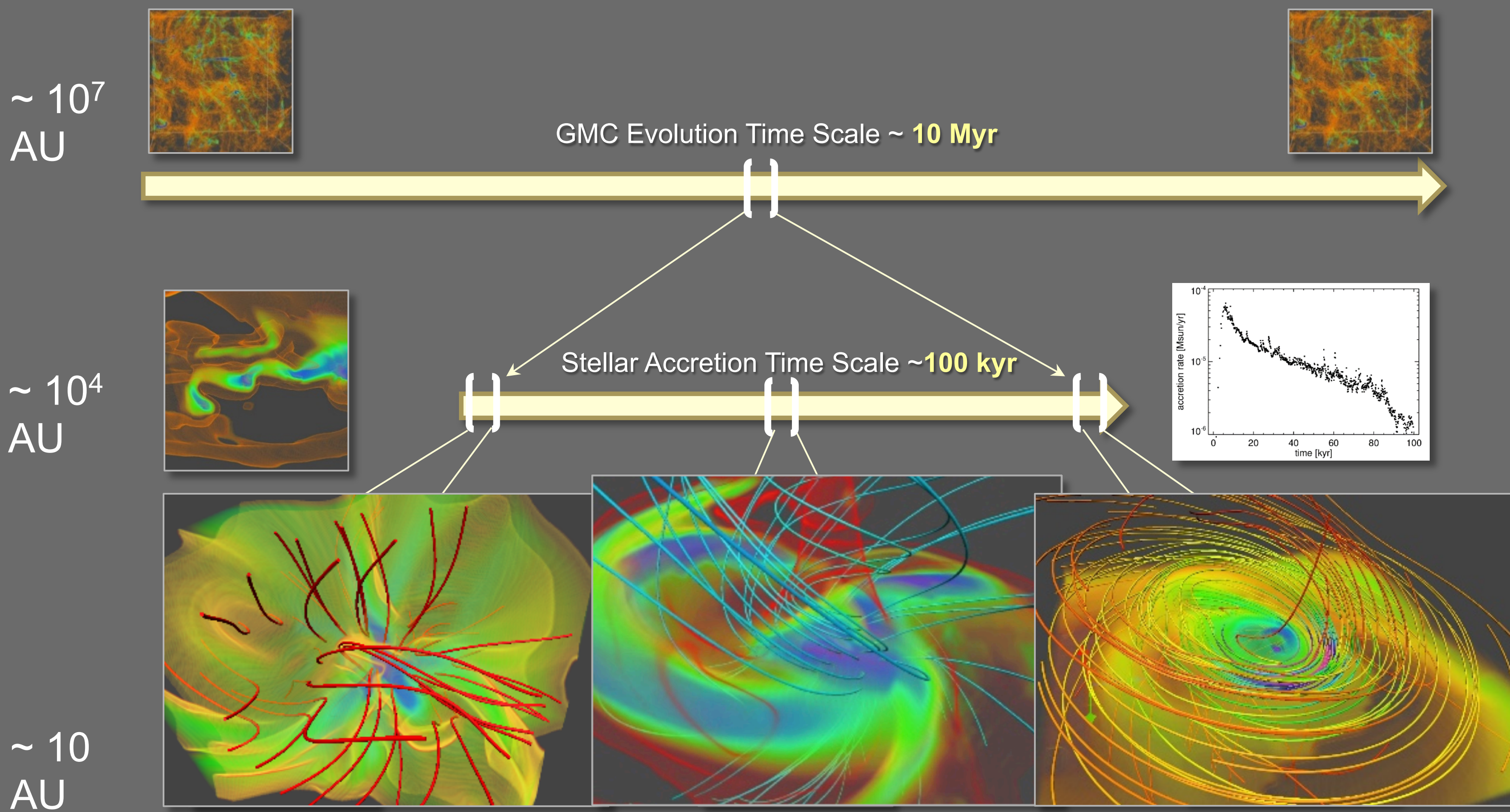
Our Group: Zoom Idea



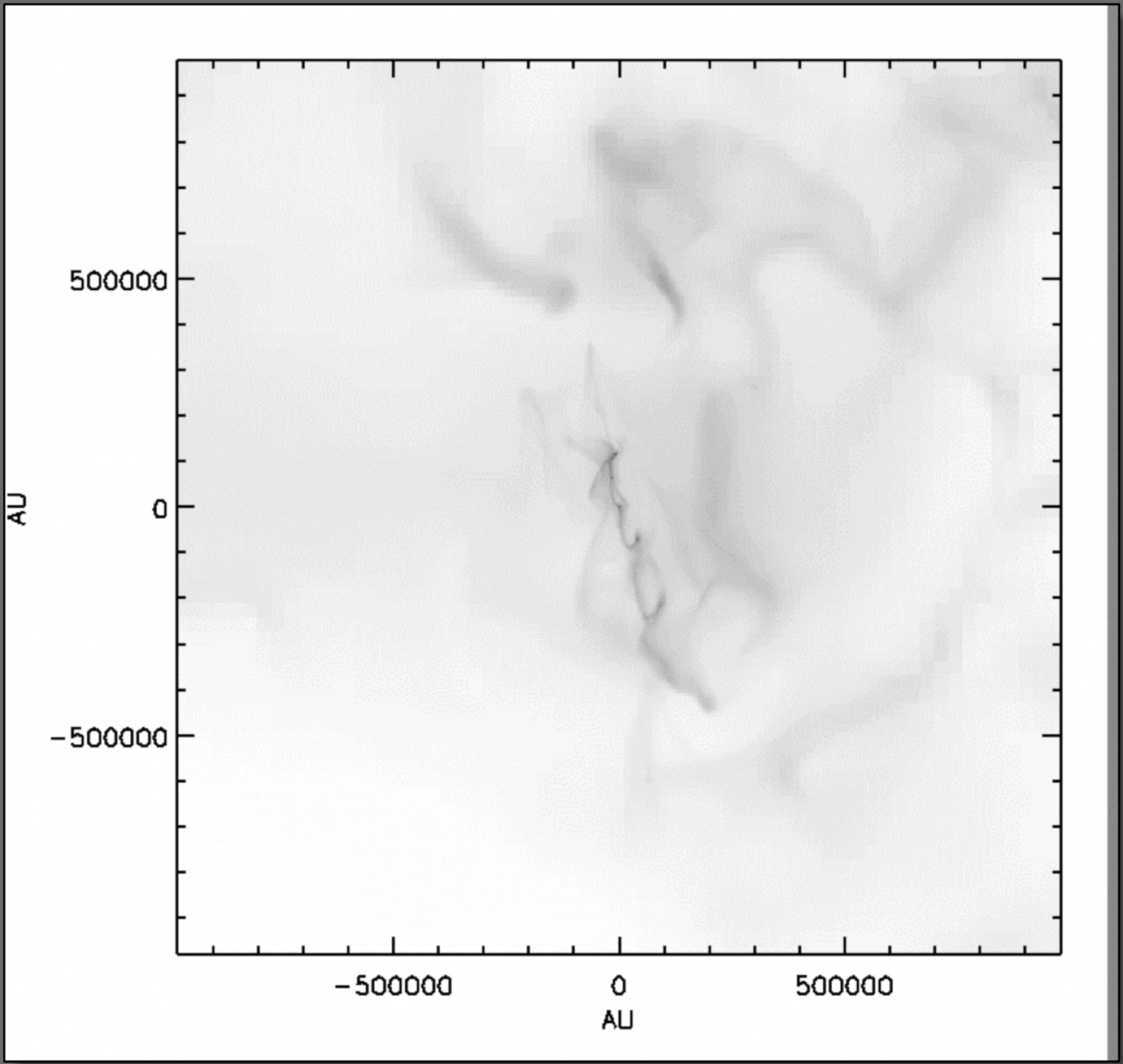
- ***"Anchor" dynamics*** in **well-observed spatial range**
  - Similar to using cosmological ICs for galaxy formation
  - Here: Giant Molecular Clouds (GMCs) and their fragments
    - "Larson relations" (Larson 1979, 1981; Solomon et al 1987, …)
    - B-n relation (Crutcher 2012, …)
- ***Advantage:*** Avoids having to pose unknown initial & boundary conditions
  - Similar to techniques used in simulations of galaxy formation
- ***Drawback:*** Must cover about 9 orders of magnitude in size
  - From GMC scales to resolving vertical structure of PP disks

However, even simulating only the PP-disk part would require a scale range from at least ~300 AU to ~0.01 AU – the full range is "only about twice as expensive" (with AMR!)

Zoom Overview



Hierarchy of scales, from ~8 pc to ~4 AU

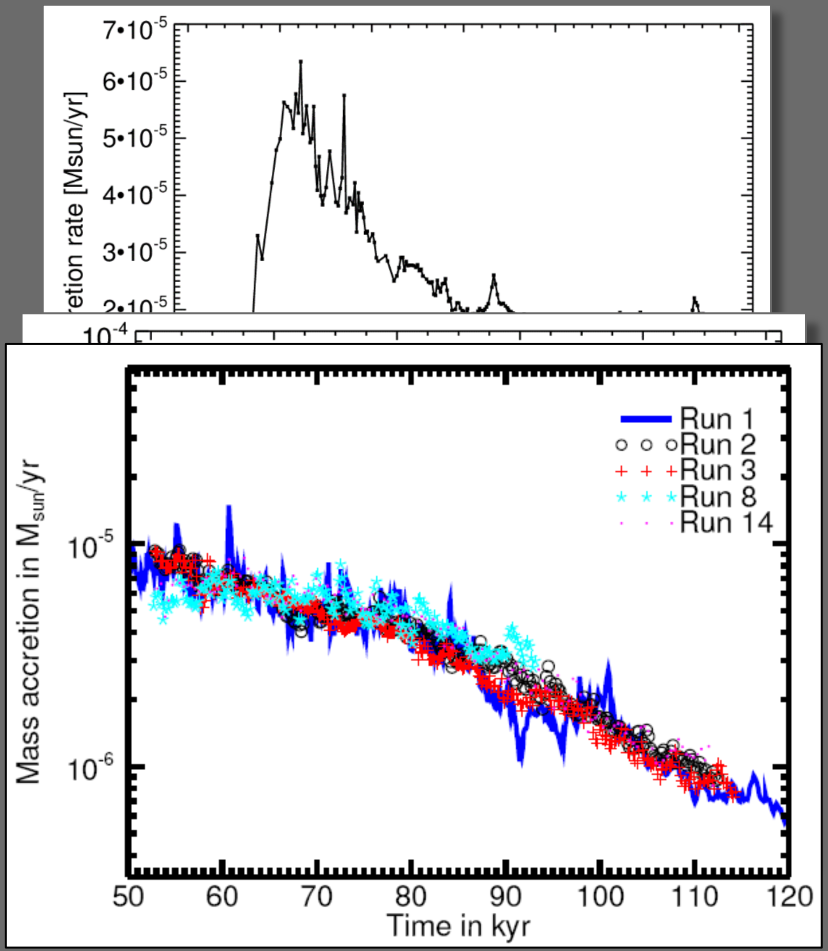


One of the ***least interacting*** among all ~solar mass star forming events in this GMC

- Filament with a few stars at relatively large distances
- Final mass about 1.5 solar in level 16 (GMC) run, 1.1 solar in level 22 (single star) run, less in level 29

Accretion Rate

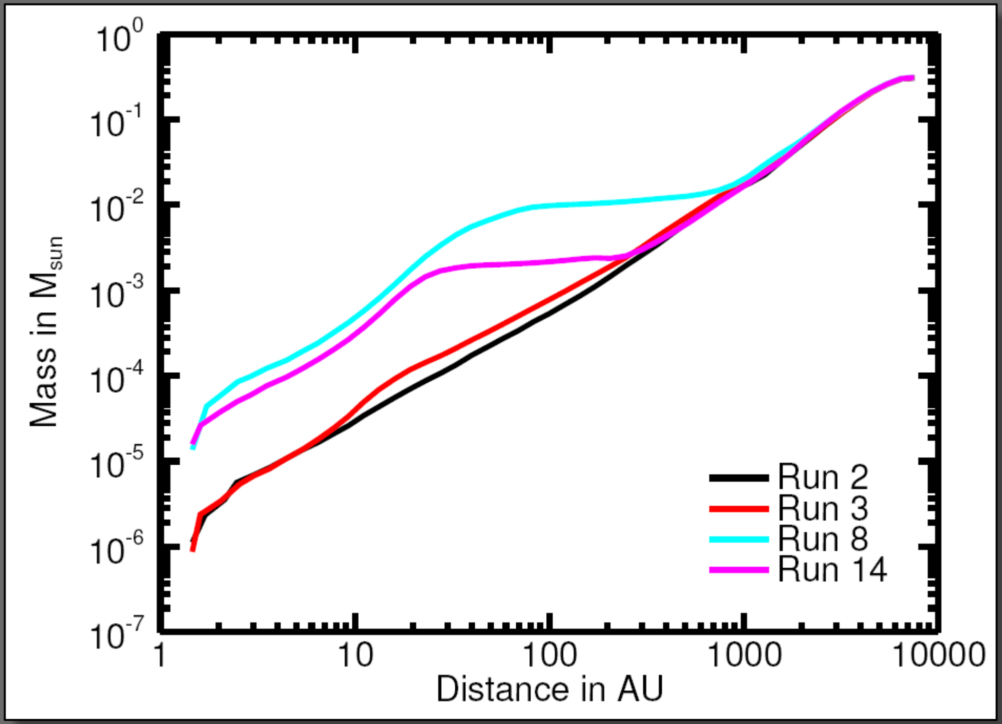
- Peaks after a few kyr, fluctuates due to magnetic field topology changes
- Decreases exponentially with time thereafter
  - Robust result



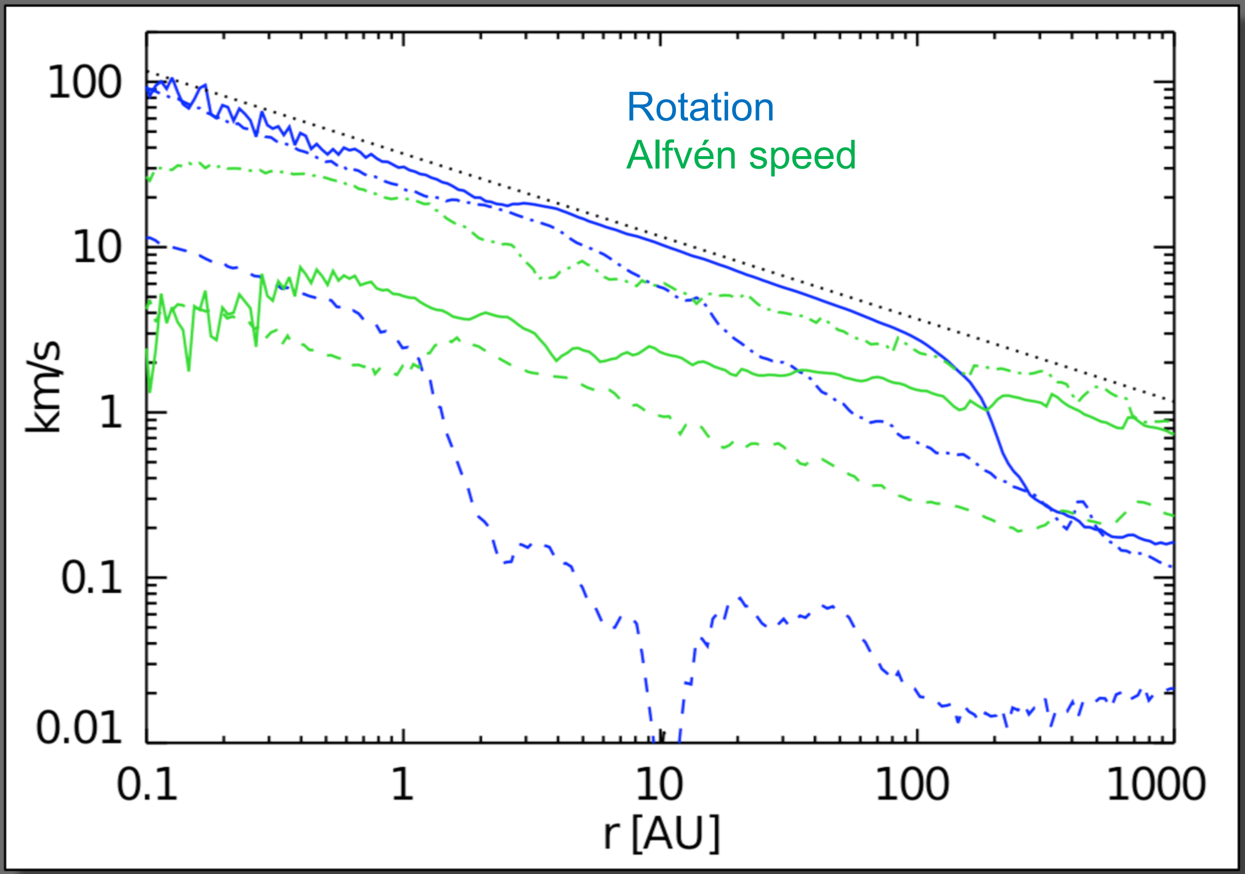
Mass Distribution with Radius

Integrated mass as a function of distance from the star

- Initially (dashed) ~ r^3 , because of initial approx Bonnor-Ebert structure
- Quickly develops power law dependence $m \sim r^{3/2}$, ***characteristic of "free fall"***
  - Consequence of ~self-similarity
  - Good resolution required at all levels

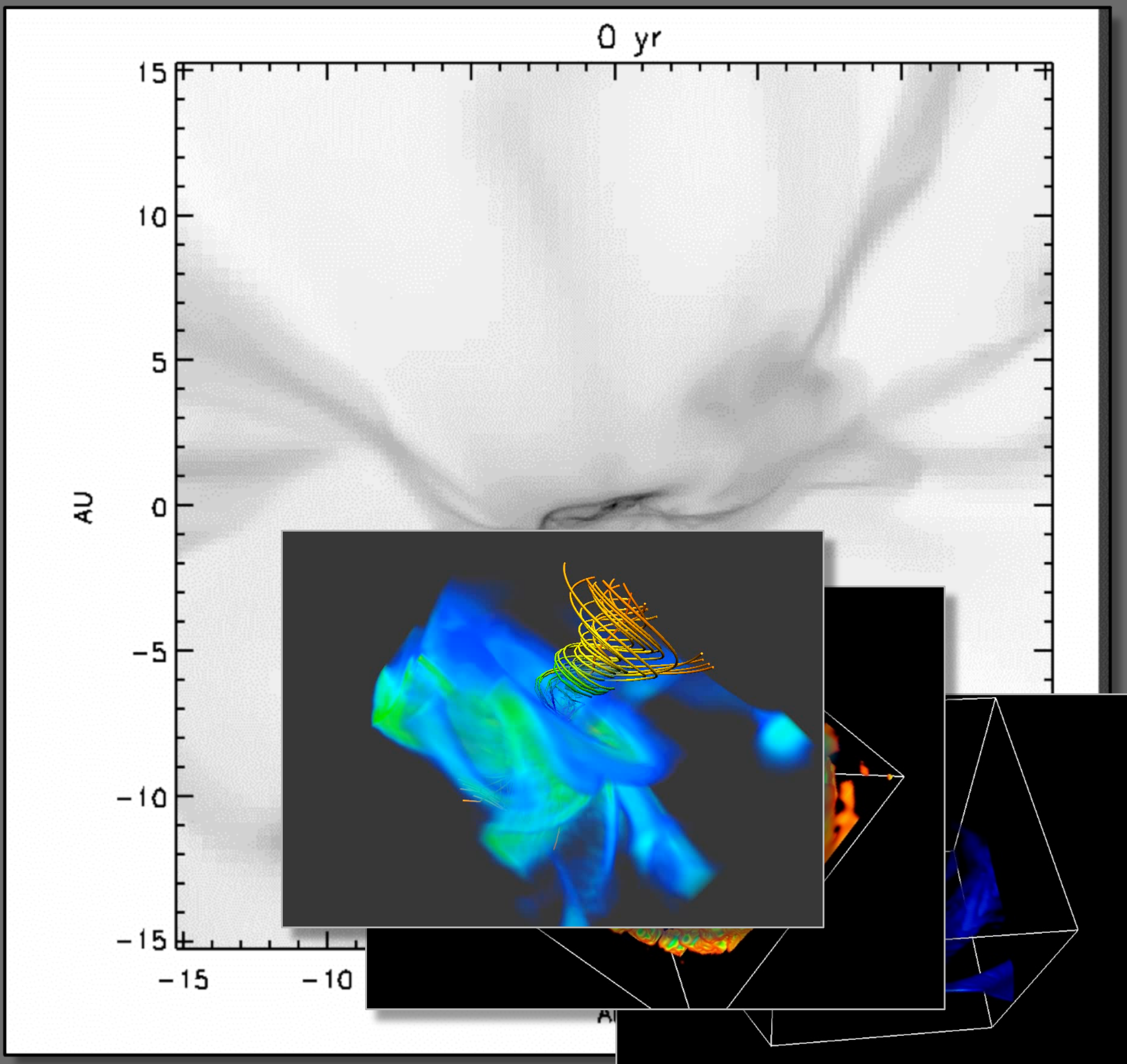


Disk rotation and size



Early (dashed)
~50 kyr (dash-dot)
~100 kyr (full)

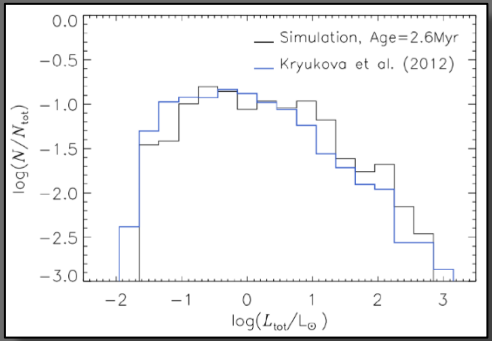
Time evolution at inner scales



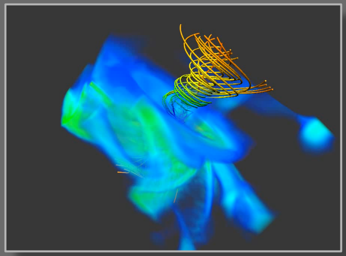
Even the "Keplerian" part (inside about +-10 AU) has a complex structure

- Note the differences in dynamical time scales as a function of distance from the center
  - Applies recursively outwards …
- Accretion filaments reaching well into the Keplerian part

Conclusions: GMC-anchored models

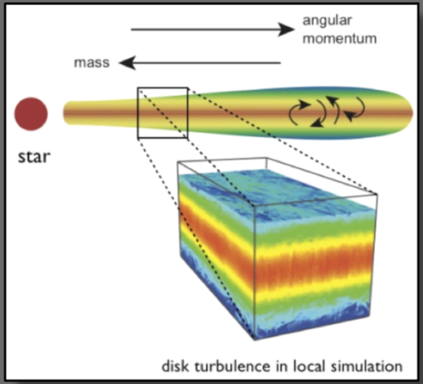


- Reproduce global GMC properties
  - Initial Mass Function (IMF)
  - Protostellar Luminosity Function (PLF)



- Star formation ⇒ generic jets and wind outflows
  - Any volunteers for arguing: "they shouldn't be there" ;-?
- Mutually annihilates two problems
  - The angular momentum problem
  - The magnetic braking catastrophe
- Produces quantitative estimates of PPD conditions
  - Environment ⇒ variety of ICs and BCs
  - Open to further modeling (dust, RT, AD, Hall, AD, non-eq. chemistry, …)

SAD Conclusions

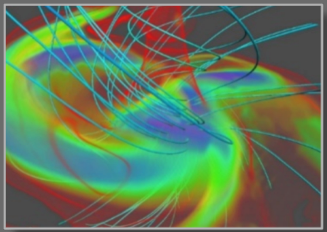


Main & hidden assumptions:

- Angular momentum transport only in the radial direction
- No 'external' accretion
- Thin, nice disks
- Long-lived, need to be 'dispersed'

False

Other common assumptions:



- Local shearing box, isothermal, ...
- No mean vertical field, or only a weak seed field
- No vertical exchange (no BC-influence, no out-flows, ...)

Unrealistic

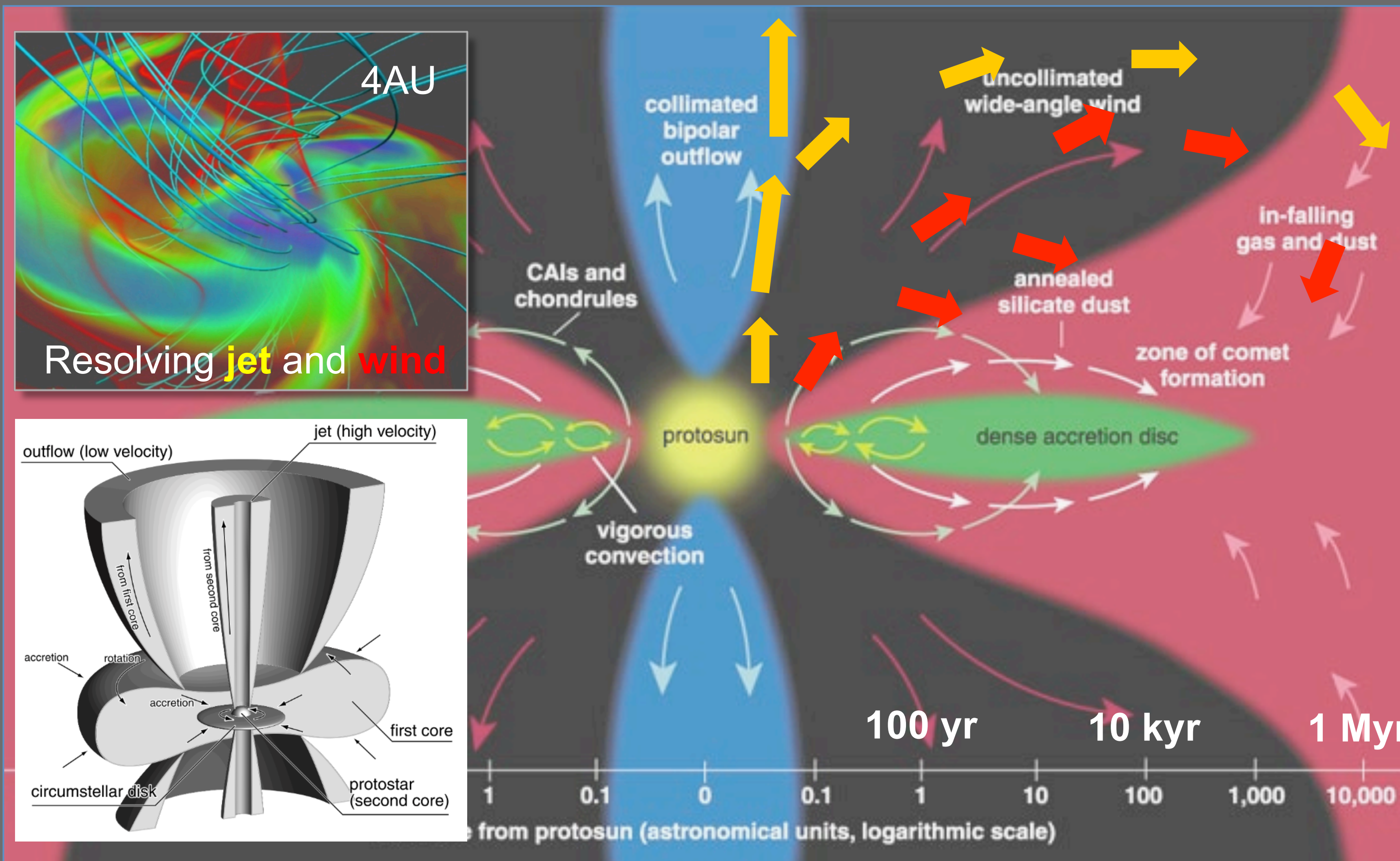
Overall Conclusions

- The SAD model, where transport is ***assumed*** to be exclusively or mainly radial is no longer sustainable

- Computational power and methods are now sufficiently developed to investigate proto-planetary disks in a realistic context

- Lots of future opportunities for improvements:
  - KROME chemical network → equation of state, opacities
  - Radiative transfer
  - Non-ideal MHD
  - Dust+gas dynamics
  - ….

Reminder: The conveyor belt paradigm



Thanks for your attention!

non-ideal MHD