Zooming in on proto-planetary disks

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We use the adaptive mesh refinement computer code RAMSES to model the formation of protoplanetary disks in realistic star formation environments, with resolution scaling over 29 powers of two (nearly 9 orders of magnitude), covering a range from outer scales of about 50 pc to inner scales of less than 0.015 AU.

The simulations are done in three steps, with the first step covering 16 powers of two, following individual star formation in a 40 pc GMC model. In the 2nd step, the neighborhoods of several stars with a final system mass of 1-2 solar masses are followed during the accretion process, with a smallest mesh size of 2 AU, sufficient to follow the development of the large scale structure of their accretion disks and the accretion history over about 200 kyr. Finally, a selection of these disks are studied over shorter time intervals, of the order 100-1000 yr, with cell sizes ranging down to 0.015 AU, sufficient to resolve the vertical structure of a significant radius fraction of the disks.

The purpose of this procedure is to characterize the typical properties of accretion disks around solar mass protostars, with as few free parameters as possible, and to gather a statistical sample of such conditions, to quantify the extent of statistical variation of properties. This is a vast improvement over models where initial and boundary conditions have to be chosen arbitrarily. Here, the initial and boundary conditions follow instead from the statistical properties of the interstellar medium, which are reasonably well established, as per for example the Larson relations and the B-n relation, which provide typical values for the velocity and magnetic field RMS values on different scales.

As a byproduct of this type of modeling, which starts out from a supernova driven interstellar medium (no artificial forcing), we can follow the transport of short-lived radioactive nuclides (SLRs), from the time of ejection from supernovae and until they become part of the proto-planetary disks. The transport time is on average short enough to be consistent with initial abundance of 26Al in the Solar System derived from cosmochemistry.

Subject :	:	oral
Topics	:	Astrophysics
Topics	:	Numerical simulations

Zooming in on Proto-Planetary Disks

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Accretion and Outflows Throughout the Scales, Lyon 2014

Accretion & Outflows

The title of this meeting makes exactly the right connection:

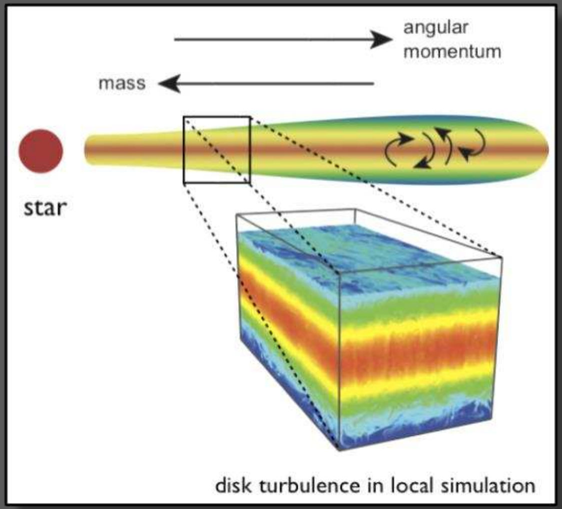
Accretion and outflows are intimately coupled !

Historically, and even today, this coupling is not universally recognized, and a huge amount of work has in fact gone into research that essentially ignores this coupling

This is a classic example of letting what's considered possible to handle (by theory and modeling) overly influence thinking

[*… searching for the keys under the street lamp …*]

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

Perceived advantages with the SAD model

Can reach high spatial resolution

- Resolving instabilities with intrinsically small scales

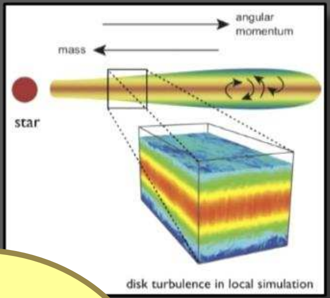
`Self-consistent'

- Does not require / assume specification of external parameters
- Allows determining 'alpha' from first principles

Additional physics may be added – affordably

- Ambi-polar diffusion
- Hall MHD

Key SAD historic events



1973: Shakura & Sunyaev (~7000 citations)

- In... the famous alp... para... ti...

1974: Lynd...

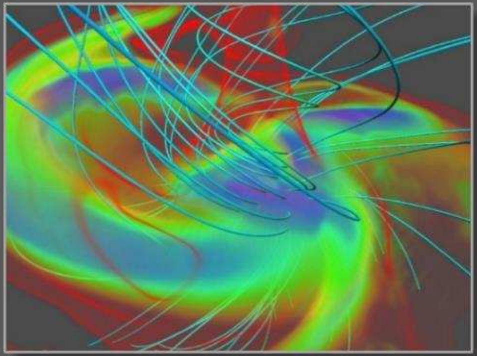
- Pointed...
  - Tr...
  - ...

1991: B...

- Re-...
  - Re-ig...

Remarkably, over essentially the same period of time, a completely different – and most likely much more realistic – concept, where angular momentum transport is mainly in the vertical direction, has lived an apparently nearly independent life (Blandford & Rees 1974, Blandford 1976, Blandford & Payne 1982, Lovelace et al 1986, Konigl 1989, Konigl & Pudritz 2000, …)

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

As evidenced by …

Observations

- Ubiquitous outflows
- Keplerian disks, with short replenishment times $M/\dot{M}$

Theory of outflows and winds

- Blandford $\rightarrow$ Königl
- Pudritz, Wardle, Krasnopolsky, Salmeron, …

Modeling

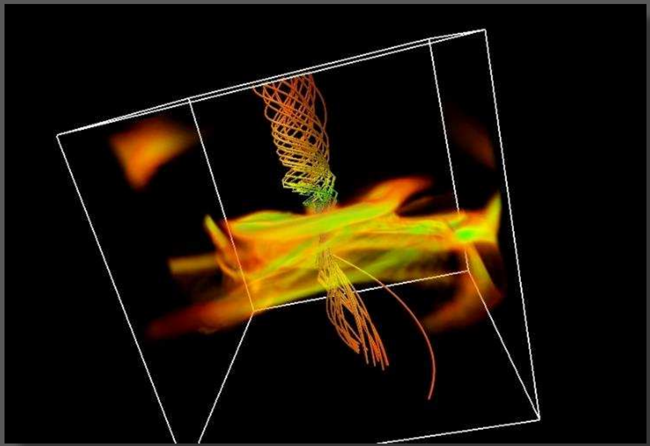
- Inutsuka, Machida et al, Zanni et al, Fendt et al, …
- Hennebelle, Commercon, …, Joos
- Königl, Pudritz, Banerjee, Oyed, Staff, …, Seifried
- Our group: Haugbølle, Padoan, ÅN, …, Küffmeier

Demonstrated that turbulence can prevent catastrophic magnetic braking

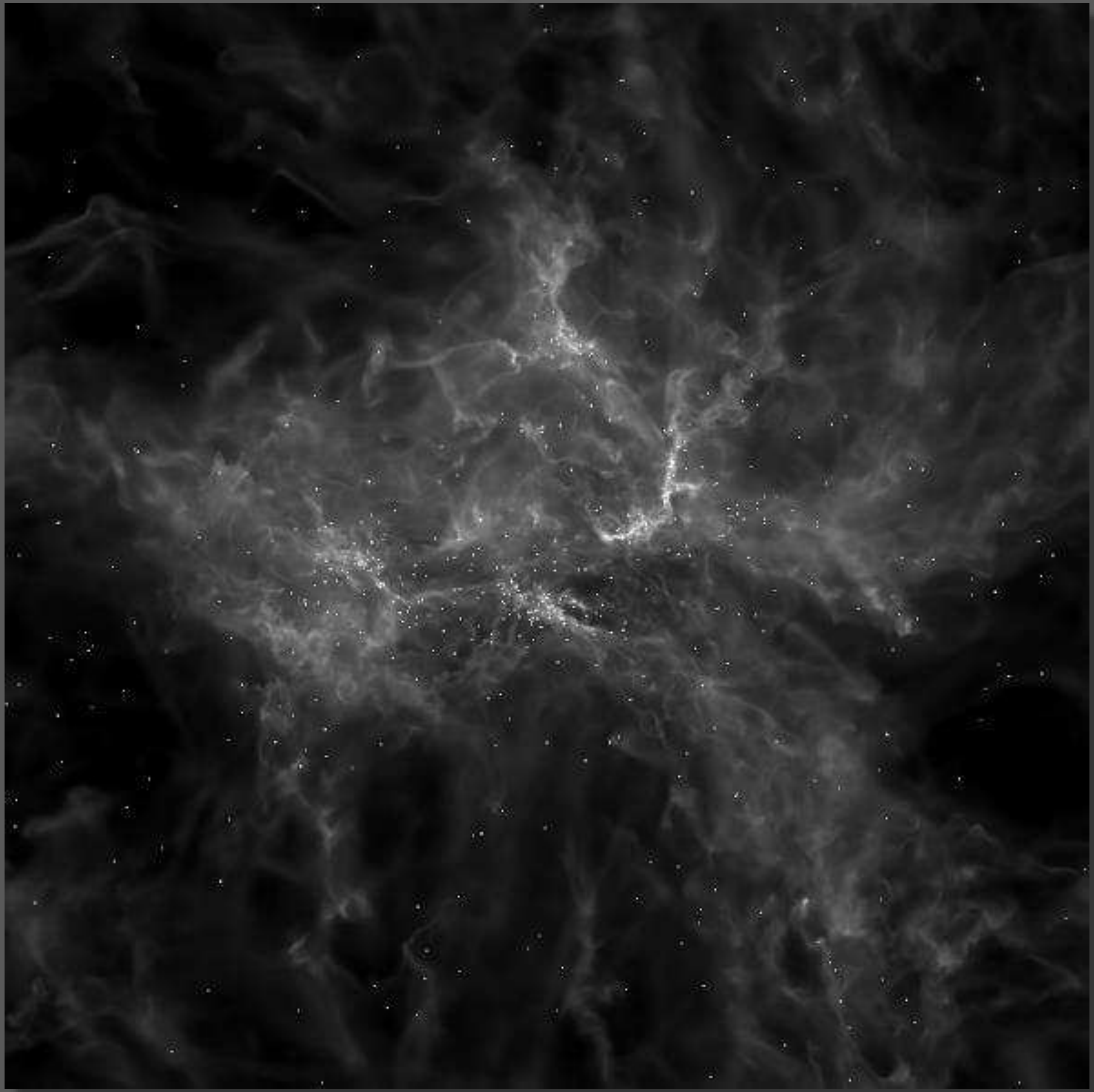
Non-ideal MHD and magnetic braking

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
- Ionization levels may in fact be larger than assumed
  - Dust settling !
  - Short-lived radionucleids (^{26}Al, ^{60}Fe) !



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

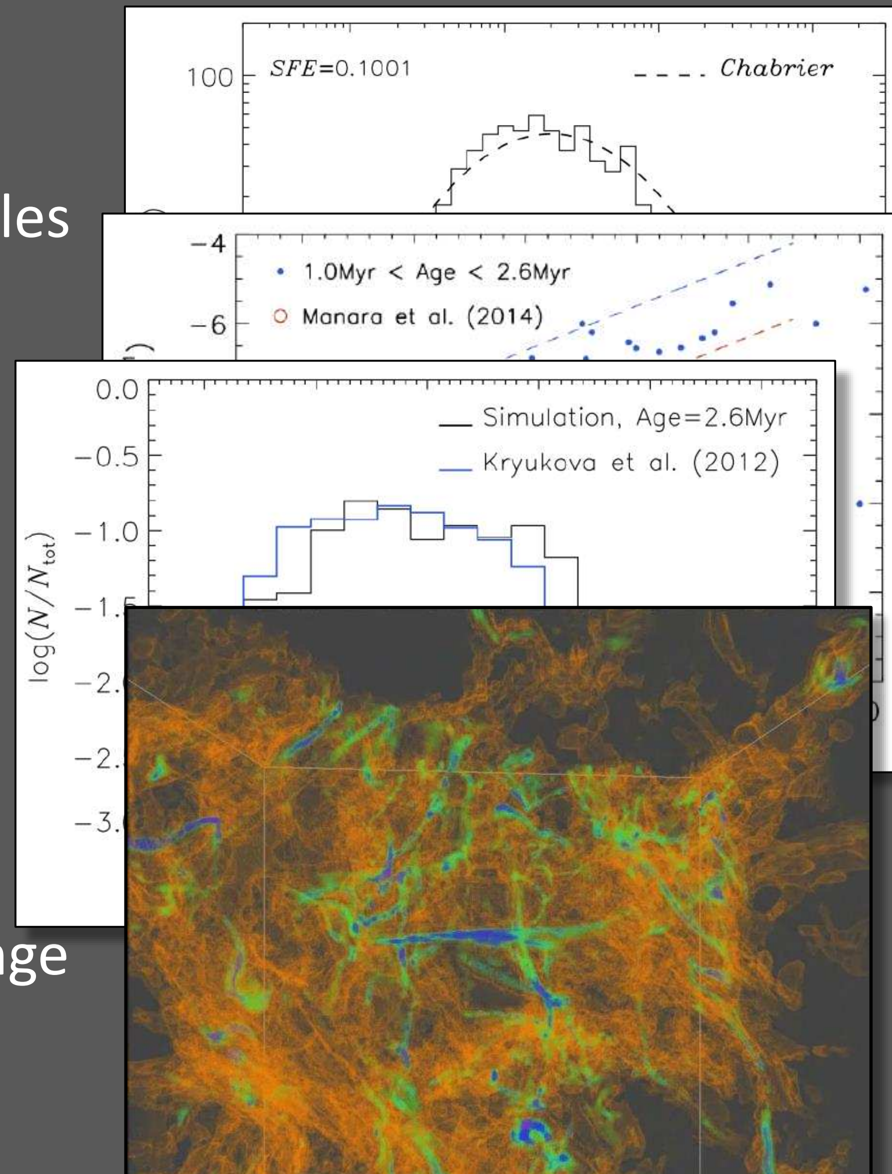
- Consistent IMF from 1st principles
- Numerically converged

Luminosity Problem Solved

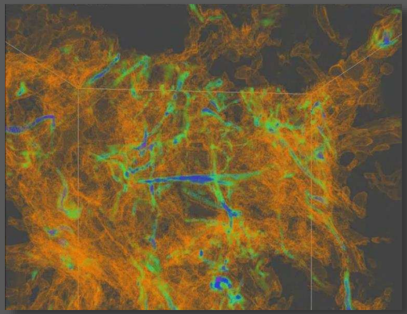
- Consistent ensemble values
- Reproduce observed spread

Zoom Simulations

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



Our Group: Zoom Idea

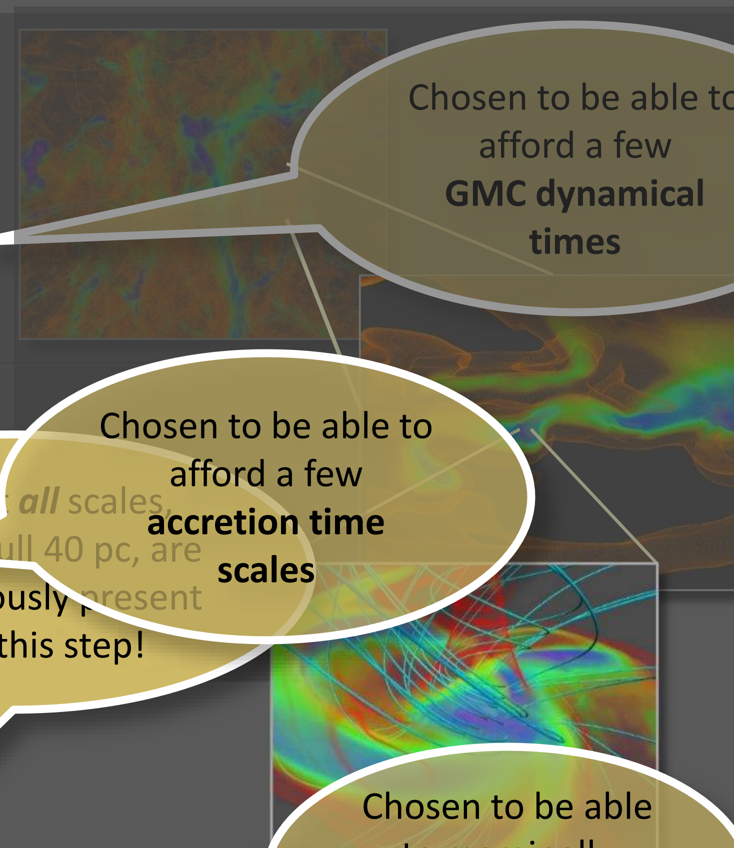


- ***"Anchor" dynamics*** in **well-observed spatial range**
  - Similar to using cosmological ICs for galaxy formation
  - Here: Giant Molecular Clouds (GMCs) and their fragments
    - "Larson relations" (Larson 1979, 1981; Solomon et al 1987, …)
    - B-n relation (Crutcher 2012, …)
- ***Advantage:*** 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!)

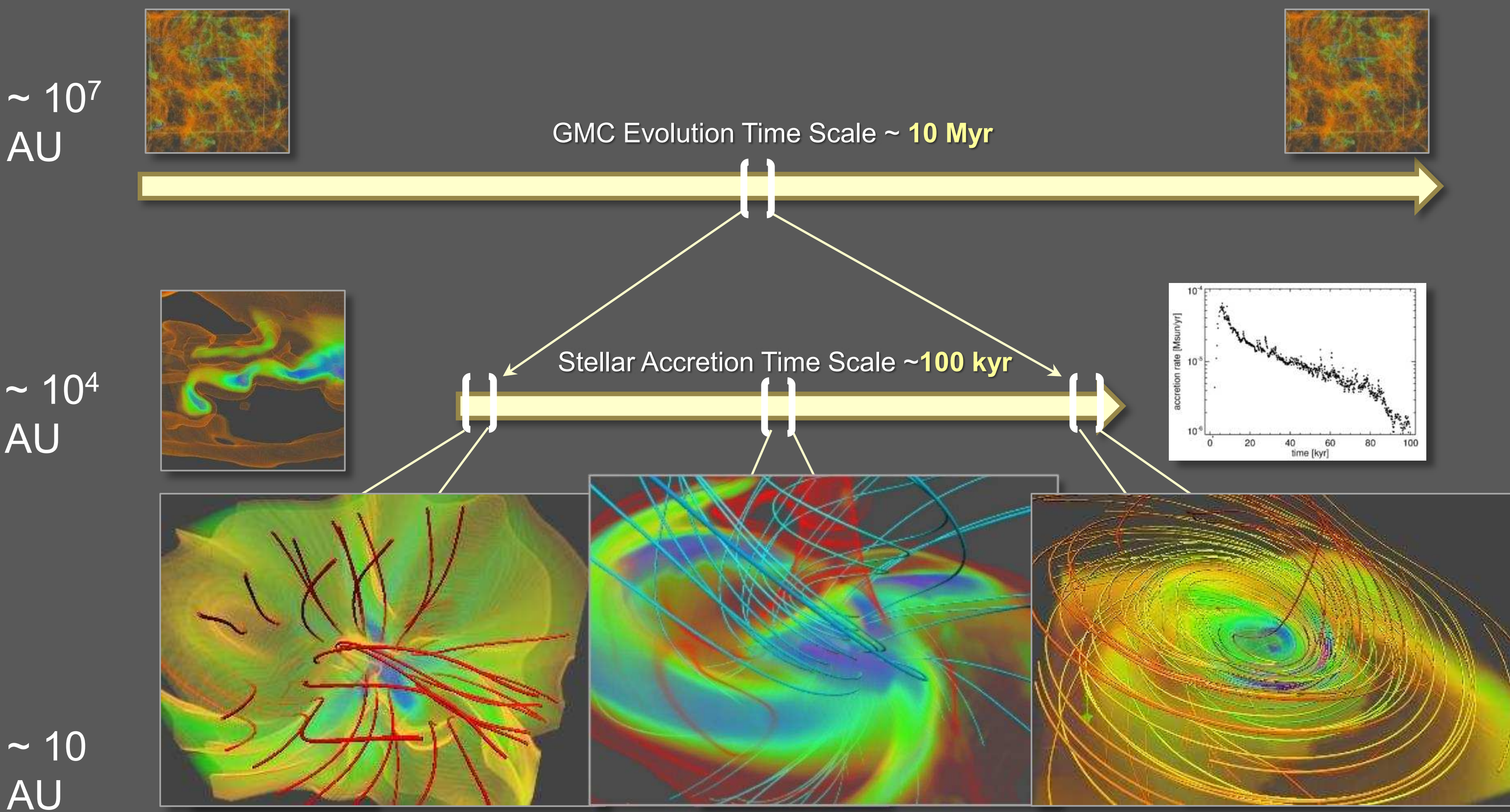
Three Simulation Zoom Levels

- *Giant Molecular Cloud scales*
  - Size: 40pc
  - Refinement: $2^{16} \Rightarrow$ cell size 120 AU
  - Time duration: $\approx$ 10 Myr
- *Stellar accretion scales*
  - Dynamic scale: ~ 0.5 pc
  - Refinement: $2^{22} \Rightarrow$ cell
  - Time duration: $\approx$ 100 kyr
- *Accretion disk scales*
  - Dynamic scale: ~ 5 AU
  - Refinement: 2^{29} => cell size 0.015 AU
  - Time duration: $\approx$ 100-1000 yr

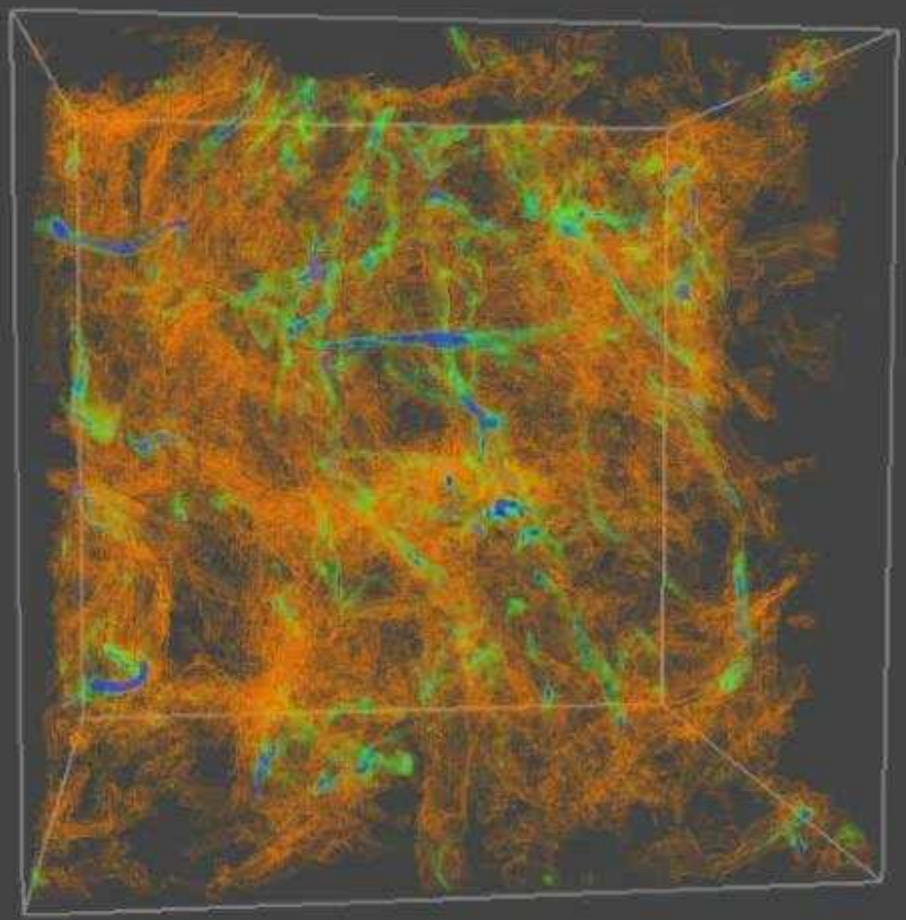


ÅN et al, IAU S299 (2013) = astro-ph/1309.2278

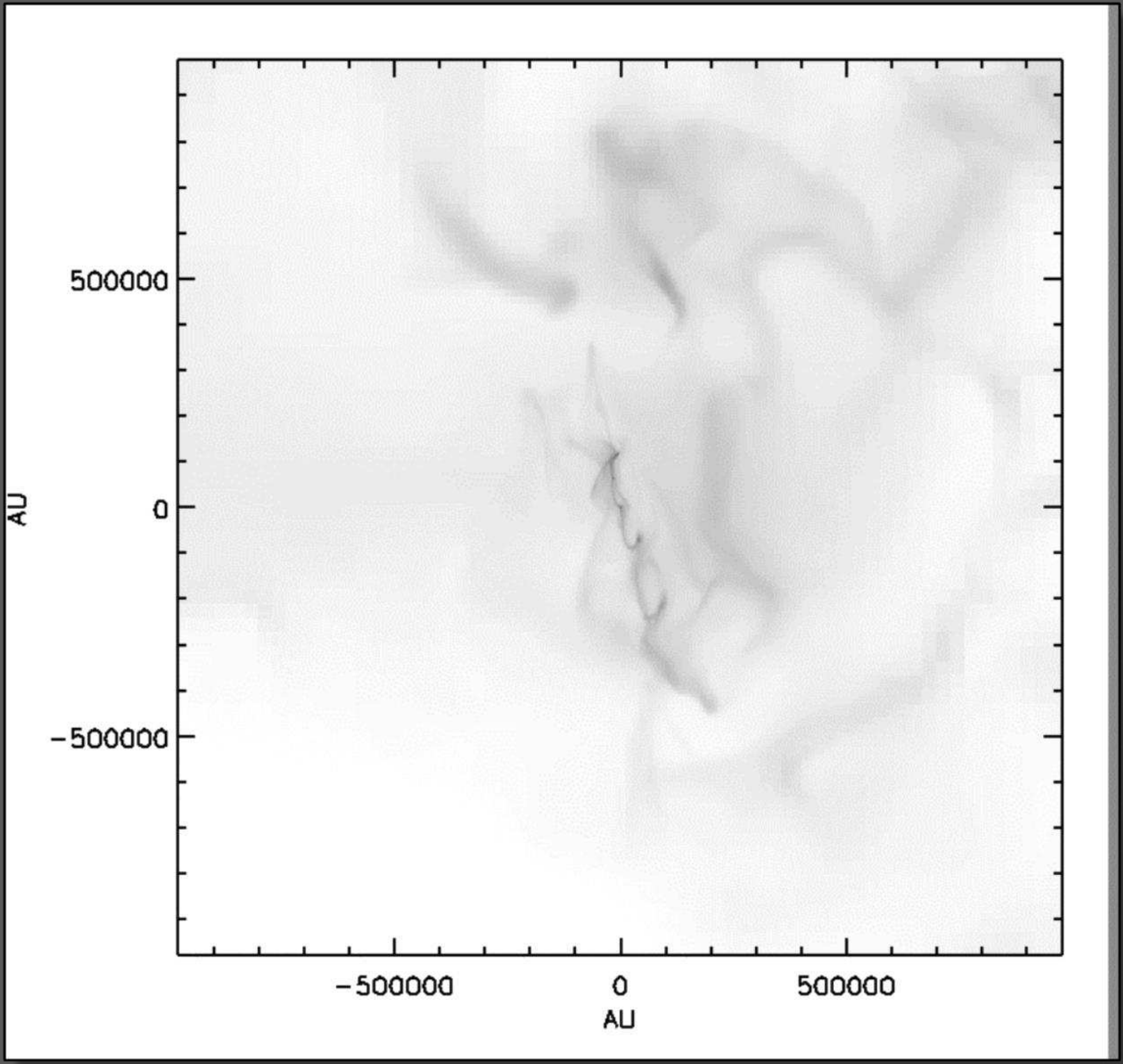
Zoom Overview



From GMC scales to disc, jet, and outflows



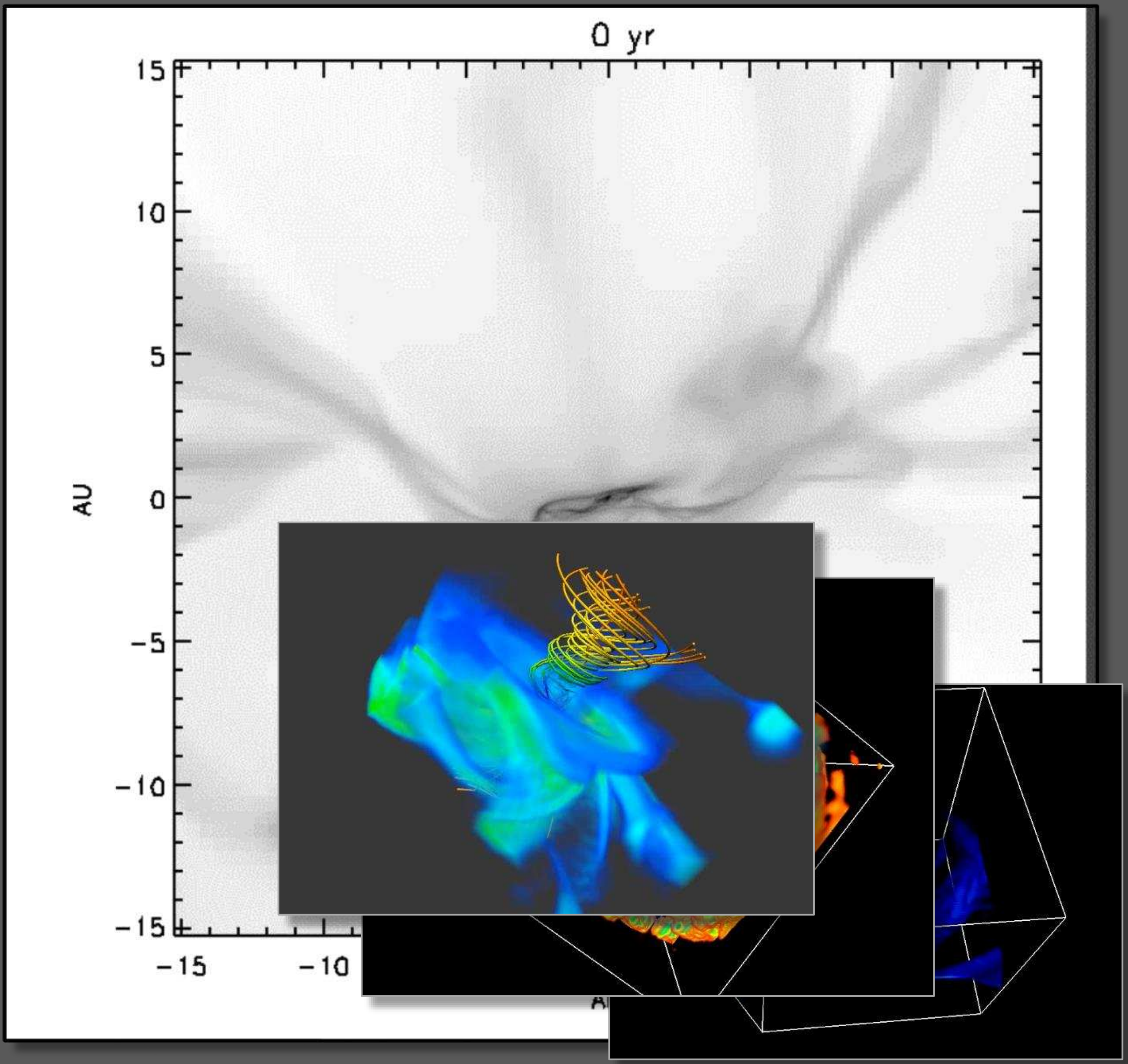
Hierarchy of scales, from ~8 pc to ~4 AU



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

Time evolution at inner scales

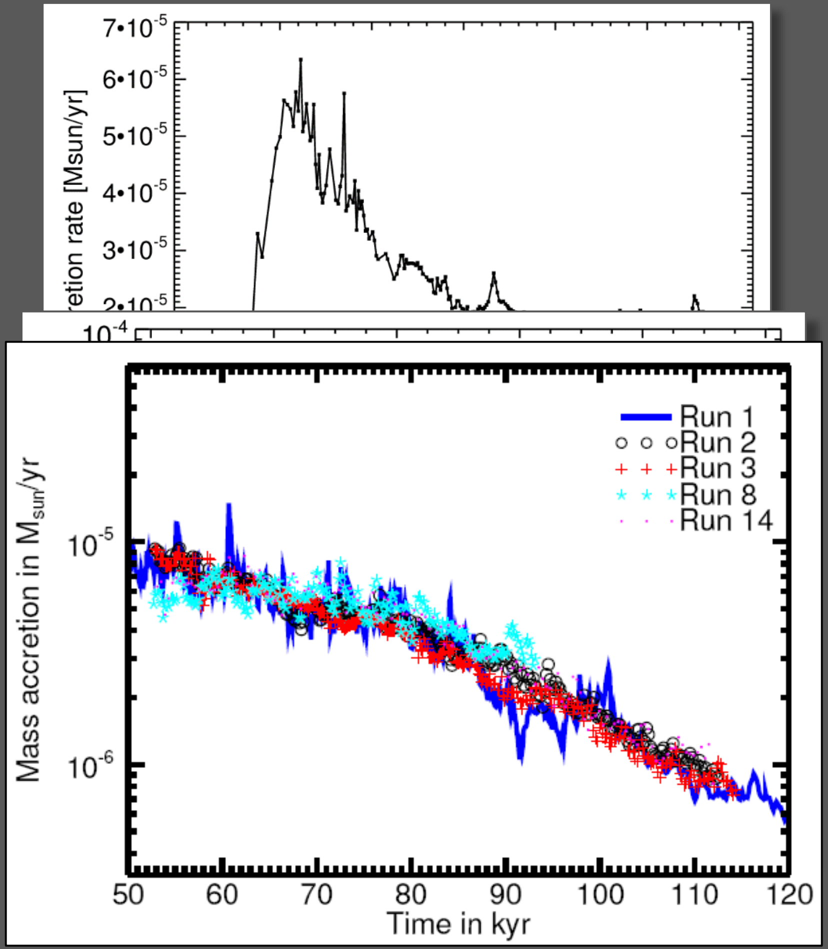


Even the "Keplerian" part (inside about +-10 AU) has a complex structure

- 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

Accretion Rate

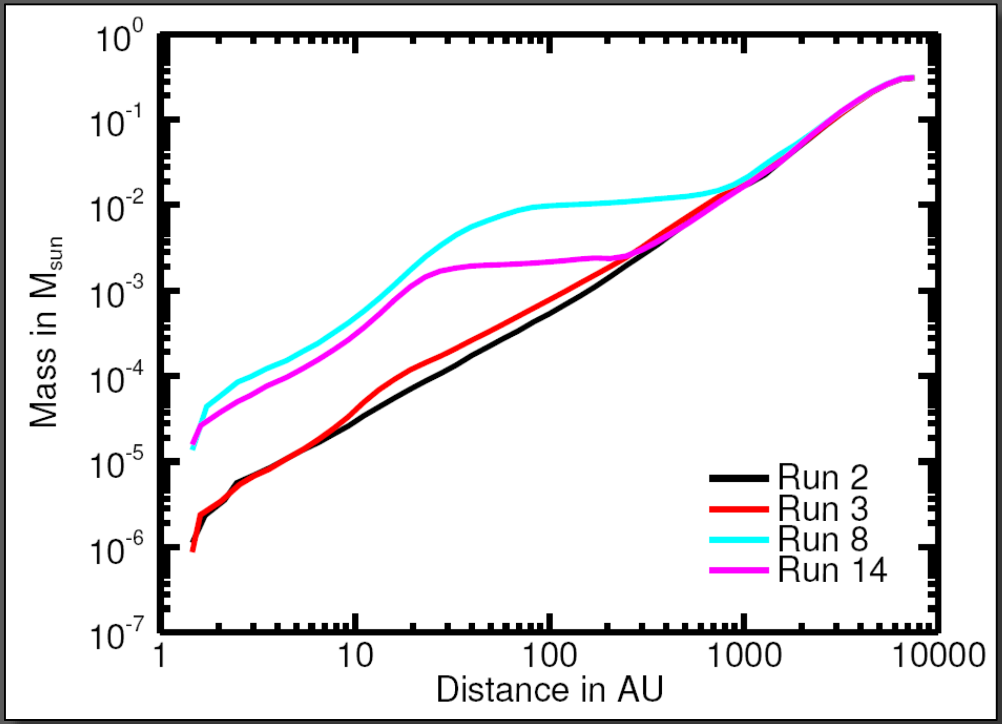
- Peaks after a few kyr, fluctuates due to magnetic field topology changes
- Decreases exponentially with time thereafter
  - Robust result, for these cases
  - Slow accretion cases tend to have a phase with ~constant accretion rate



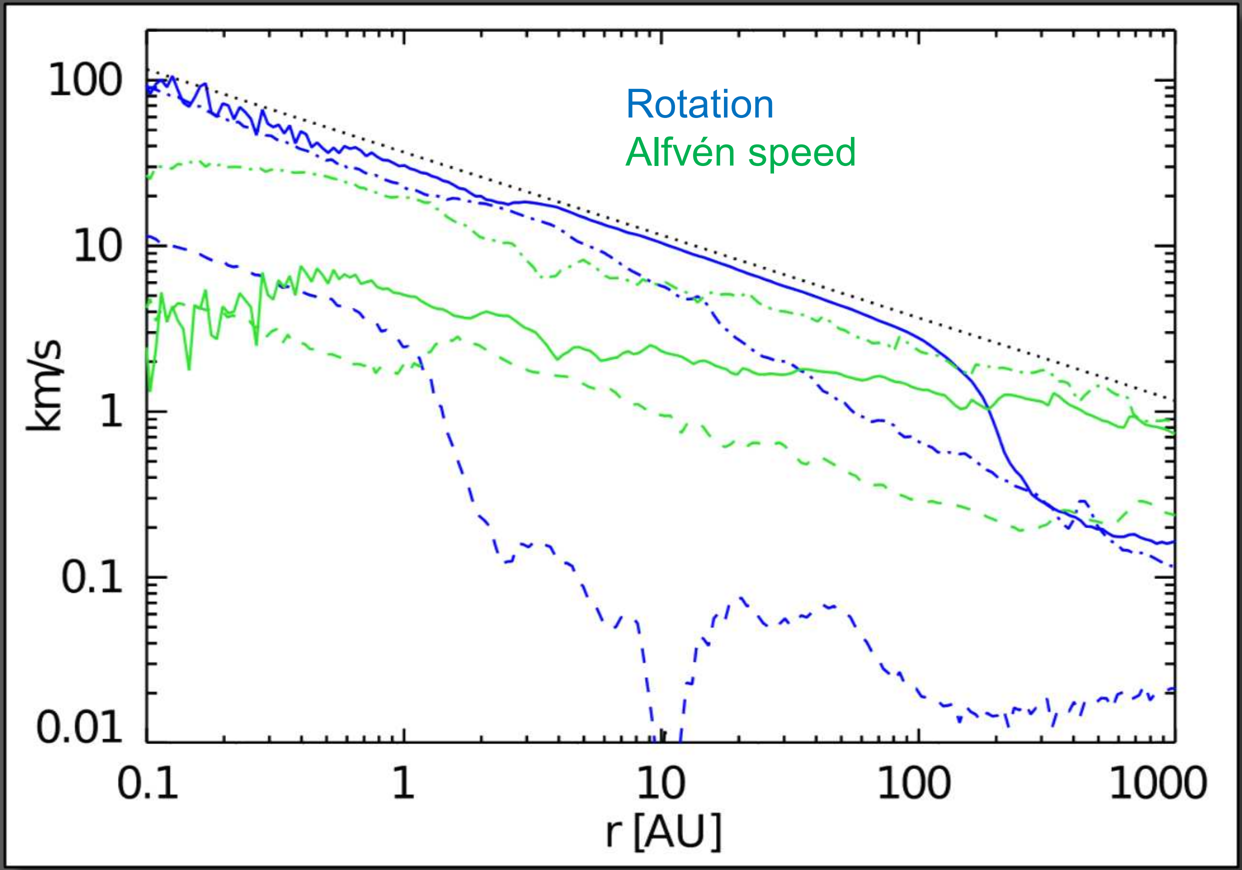
Mass Distribution with Radius

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, with of the order 10^5 cells per level



Disk rotation and size

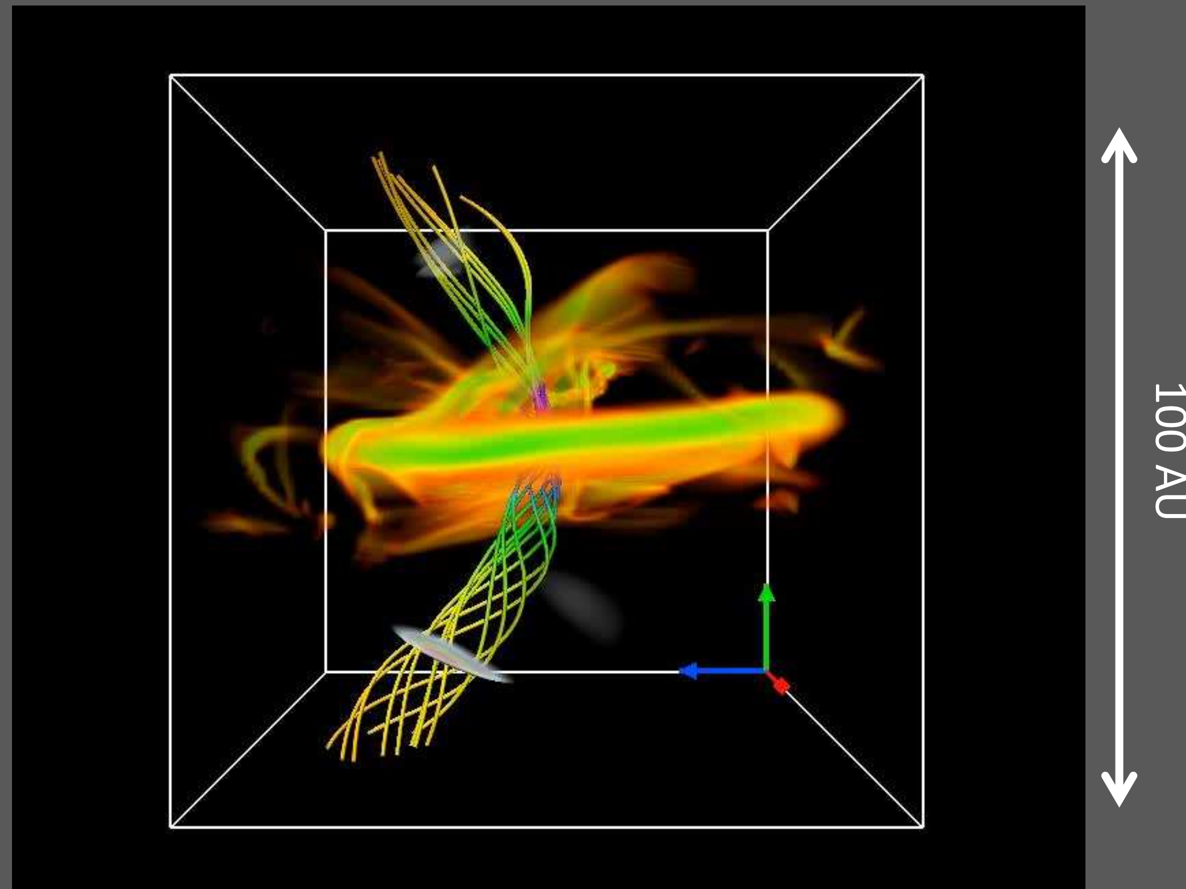


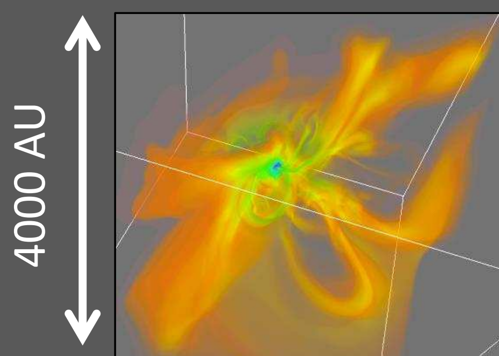
Early (dashed)
~50 kyr (dash-dot)
~100 kyr (full)

Accretion from molecular cloud-core

- Accretion happens from filaments onto the disc, not at “the edge”

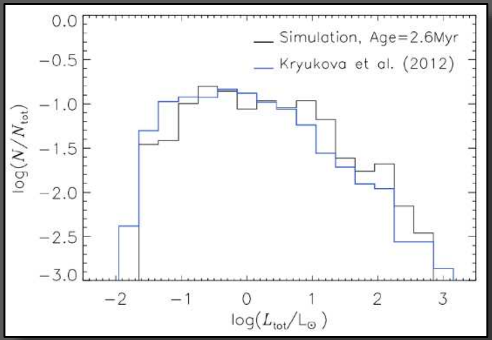
- Vertical transport is crucial !



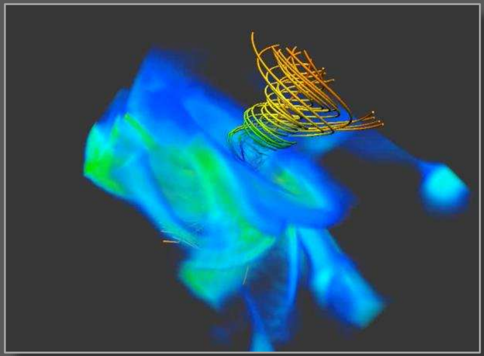


Conclusions: GMC-anchored models

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

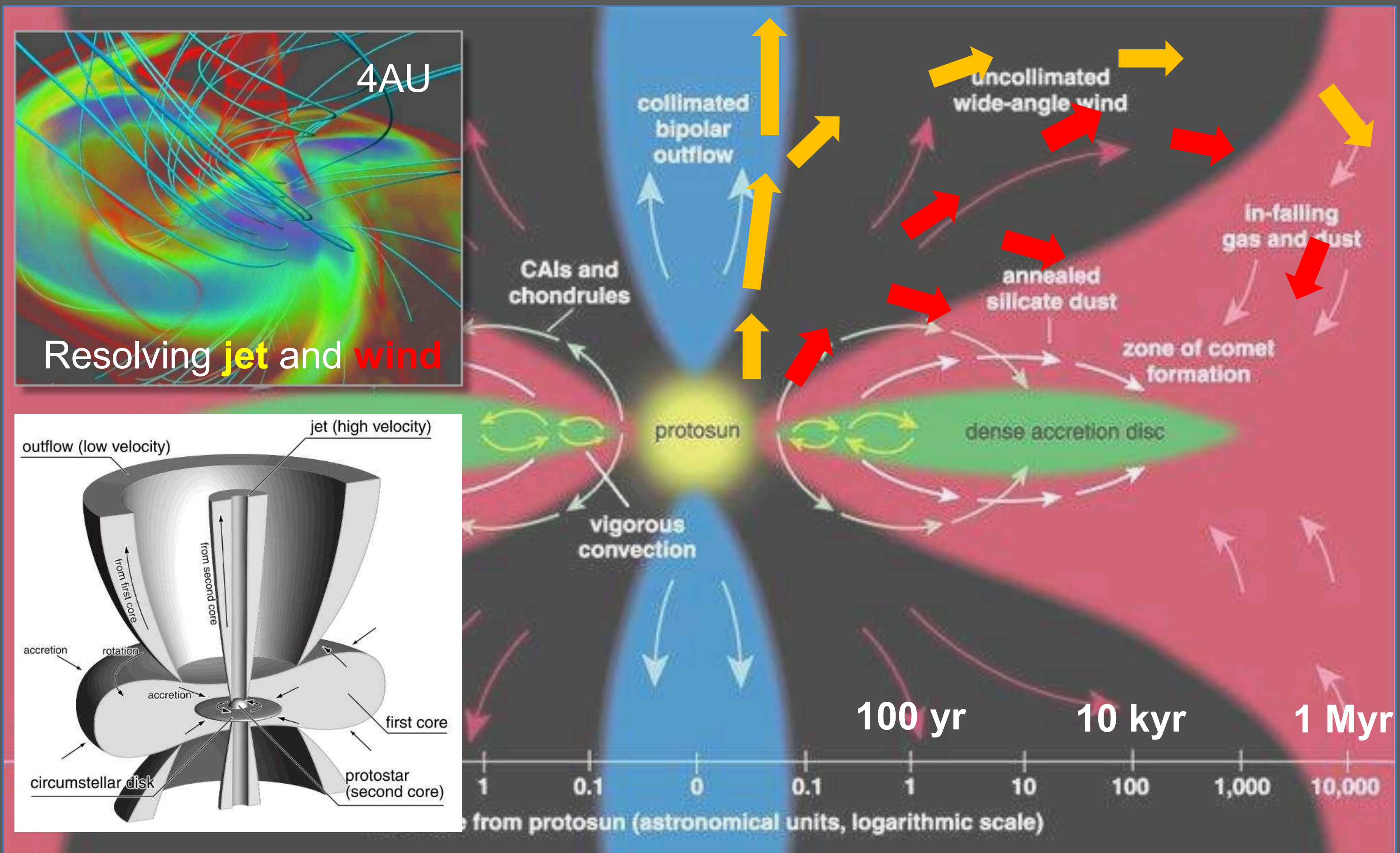


- Star formation $\Rightarrow$ **generic jets and wind outflows**
  - Any volunteers for arguing: “they shouldn’t be there” ;-?

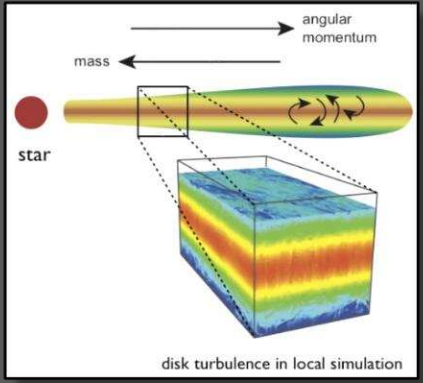


- Mutually **annihilates two problems**
  - The angular momentum problem
  - The magnetic braking catastrophe
- Produces **quantitative estimates of PPD conditions**
  - Environment $\Rightarrow$ variety of ICs and BCs
  - Open to further modeling (dust, RT, AD, Hall, AD, non-eq. chemistry, …)

Cosmochemistry application: The *Conveyor Belt Paradigm*



SAD Conclusions

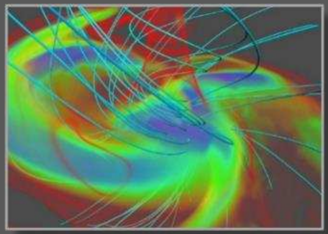


Main & hidden assumptions:

- 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 $\rightarrow$ equation of state, opacities
  - Radiative transfer
  - Non-ideal MHD
  - Dust+gas dynamics
  - ….

Thanks for your attention!