Hyper-Global Zoom-in Simulations of Protostellar Disc Formation

Sapere Aude

Niels Bohr Institute, August 2014

PRACE

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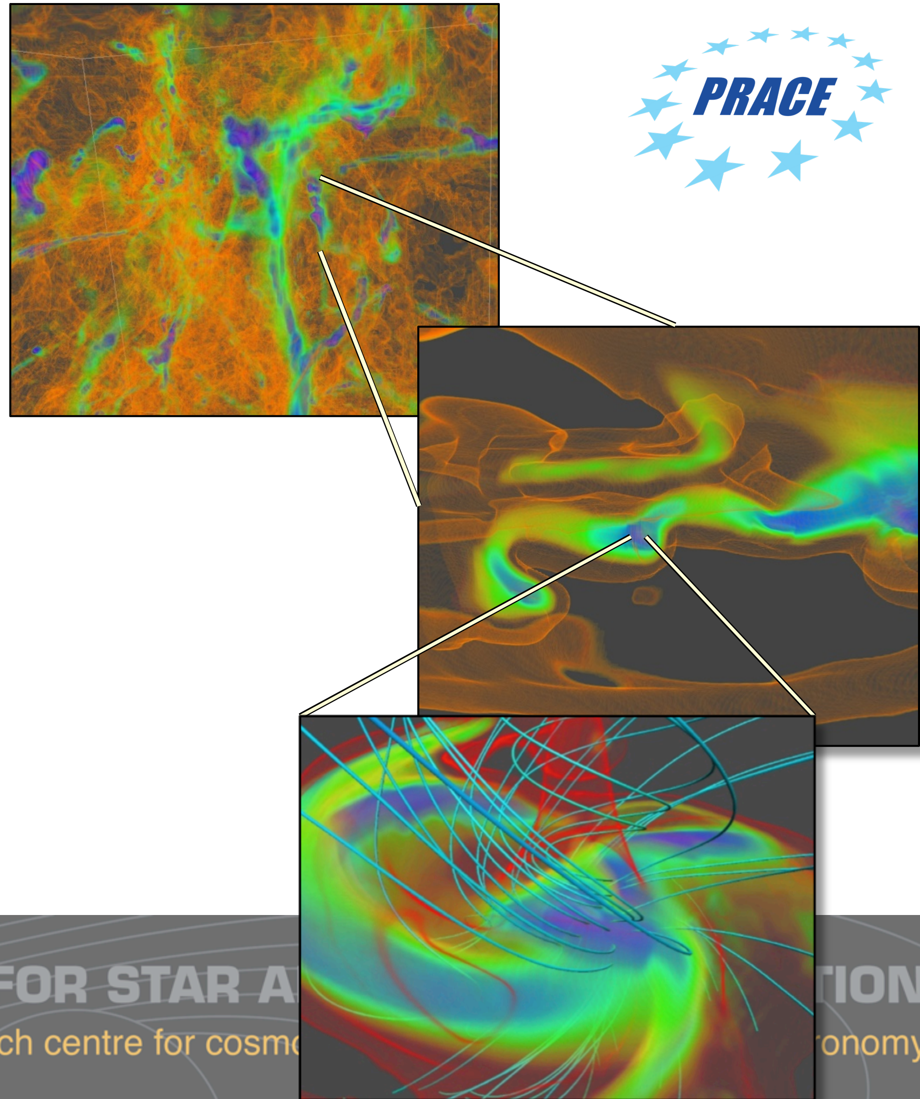

In collaboration with

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STARPLAN

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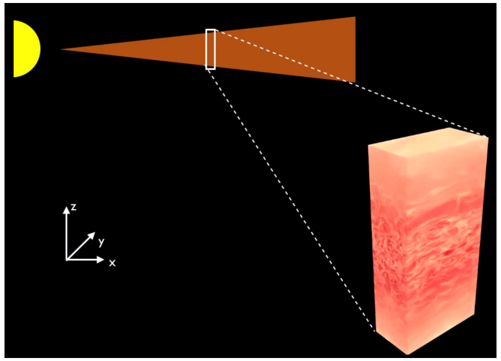
A research centre for cosm… onomy

Why "Hyper-Global" ?

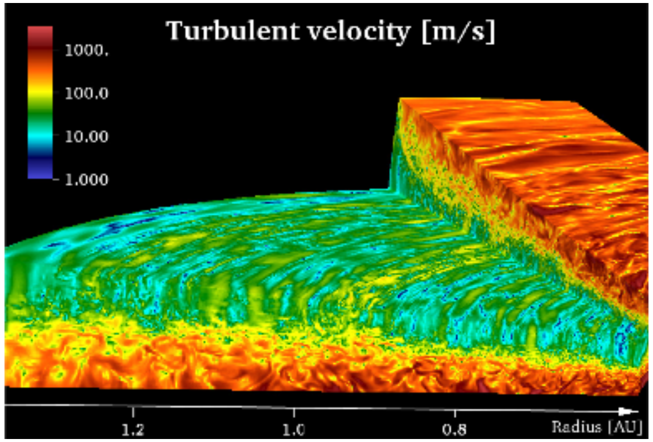
Many different approaches exist to model proto-planetary discs:

- Local models



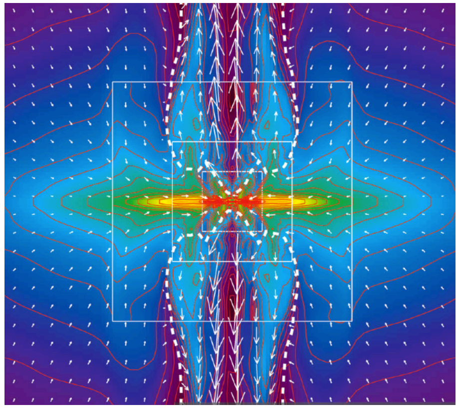
[J. B. Simon]

- Global models



[Flock et al 2013]

- Cloud-core collapse models



[Machida et al 2014]

Hyper-Global: Zoom-In over one billion in scale

- ***Anchor dynamics*** in well established observational relations at large scales (e.g. the Larson relations).

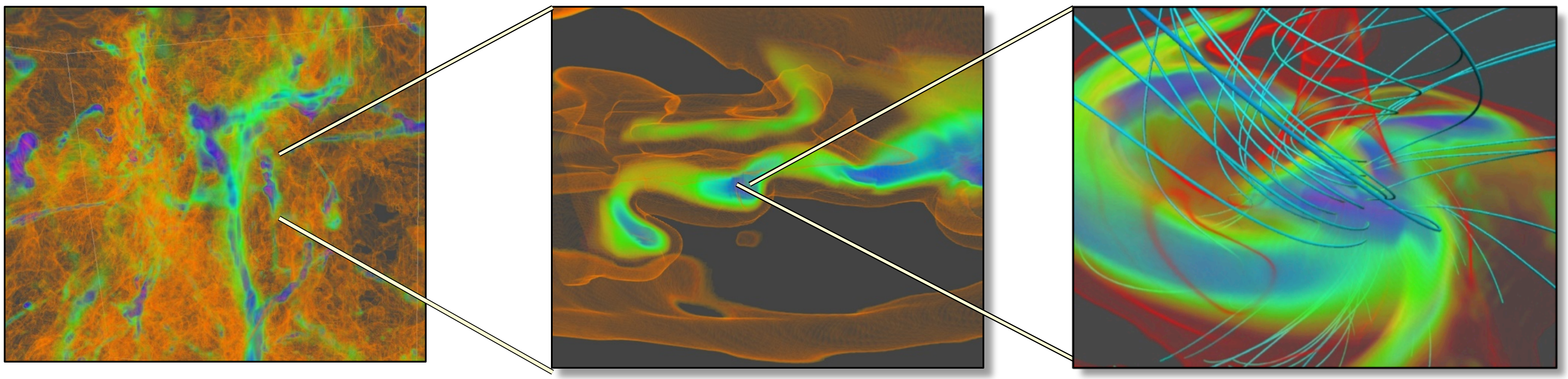
  -> Start at the GMC scale (40 parsec)

- ***Advantage:*** Avoid unknown initial and boundary conditions at the cloud-collapse scale

  -> Similar to what is done in cosmology

- ***Drawback:*** Have to cover 9 orders of magnitude in size

  -> From GMC to a vertical scale height



Disclaimers

- We do not pretend to have the ***final recipe*** for how a one solar mass star is formed…
  - …but it is clear there is great variation in the initial conditions

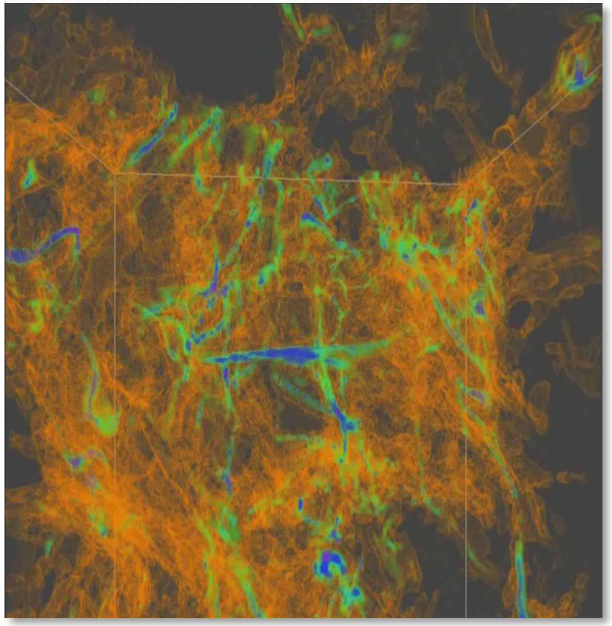
- We are only covering the early protostellar phase with zoom-in…
  - …but are working on pushing it deep in to the Class II phase

- We do not so far include ***non-ideal MHD***…
  - …but even without there is no magnetic braking catastrophe
  - …and like others we find that the turbulent cascade is the enabling mechanism, irrespective of non-ideal MHD

- We do not have ***radiative transfer*** and ***detailed chemistry***
  - …but both are coming very soon

Zooming in on the formation of a solar mass star

- First of a kind ab initio models of the formation of protostellar systems, using the AMR code *RAMSES*



- Outer scale 40 parsec, inner scale 0.015 AU

- So far:
    - Zoom-ins on four solar mass stars
    - Explored impact of many different refinement strategies

- Currently: Working on getting a statistically significant sample of solar mass stars to probe episodic accretion events, impact of magnetic field geometries, and impact of environment.

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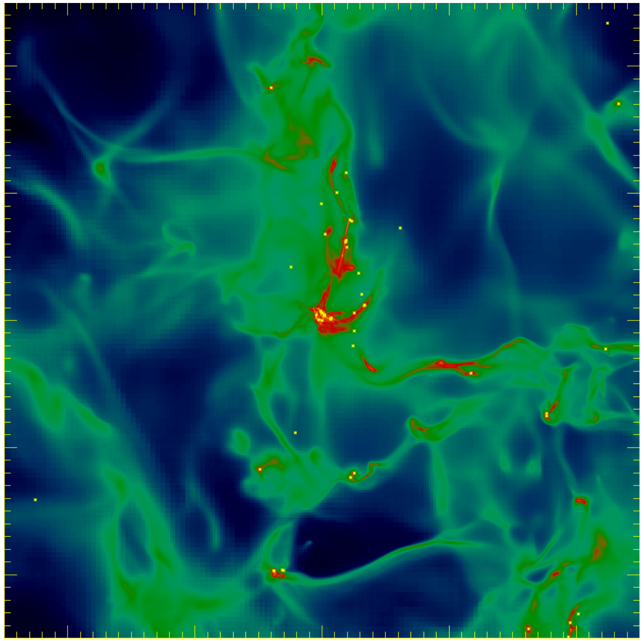
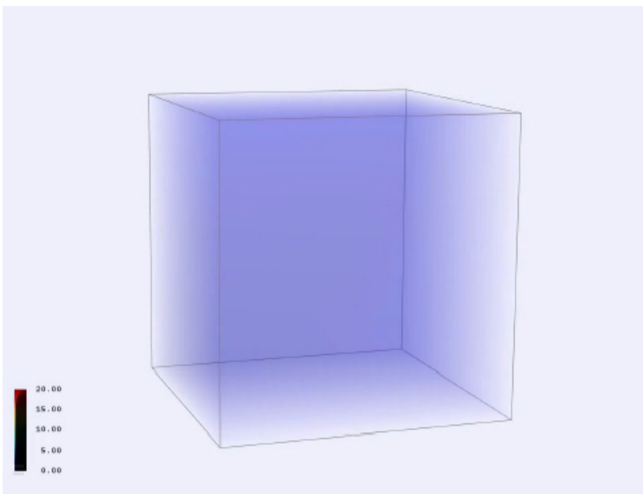
On arXiv: 1309.2278 [astro-ph]

A Model of Star Formation



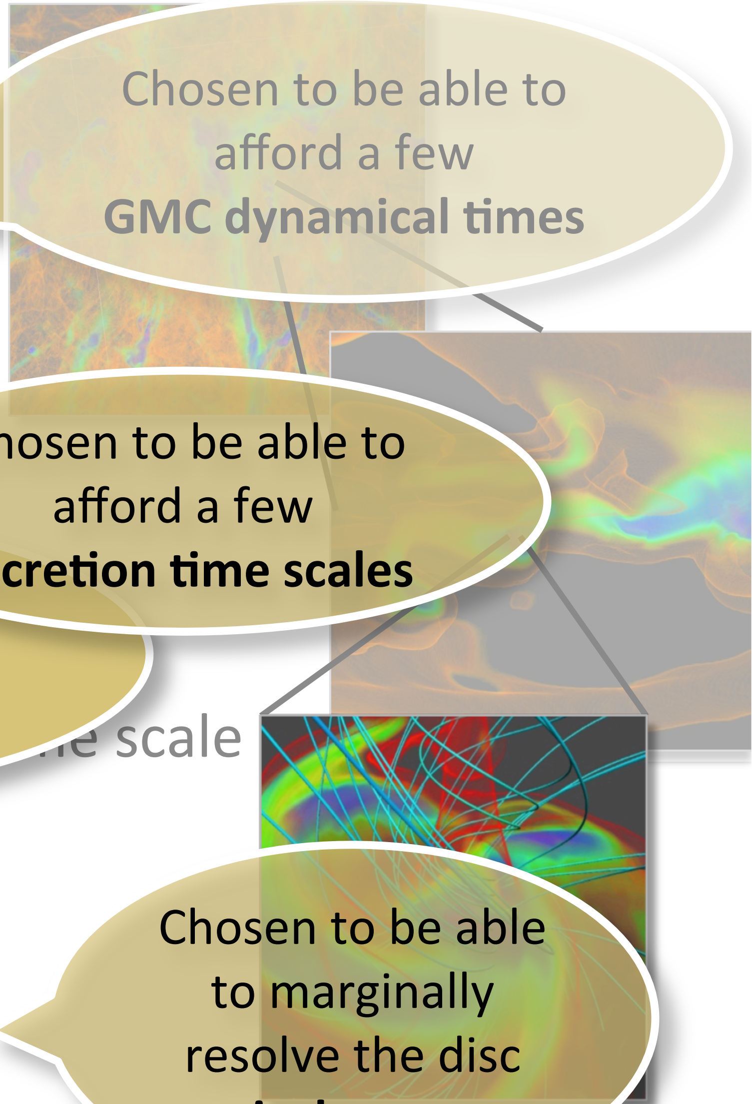


- We use *Ramses* to simultaneously resolve parsec scales, and have high resolution around stars

- The setup includes
  - MHD with HLLD that is stable at high Mach
  - Self-gravity
  - Tabulated cooling and heating
  - Sink star particles with accretion
  - Supernovae feedback from massive stars
  - Initially driven turbulence, then at low resolution massive stars sampled through "star-cluster particles"
  - Total evolution is longer than 15 Myr
  - Individual star formation model lasts >3 Myr
  - Zoom-in during up to 200 kyr

Three Simulation Zoom Levels

- ***Giant Molecular Cloud scales***
  - Size: 40pc
  - Refinement: $2^{16} \Rightarrow$ cell size 120 AU
  - Time duration: $\approx$ 20 Myr
- ***Stellar accretion scales***
  - Dynamic scale:
  - Refineme
  - Time duratio ... e scale
- ***Accretion disc scales***
  - Dynamic scale: $\approx$ 5 AU
  - Refinement: 2^{29} => cell size 0.015 AU
  - Time duration: $\approx$ 100-1000 yr



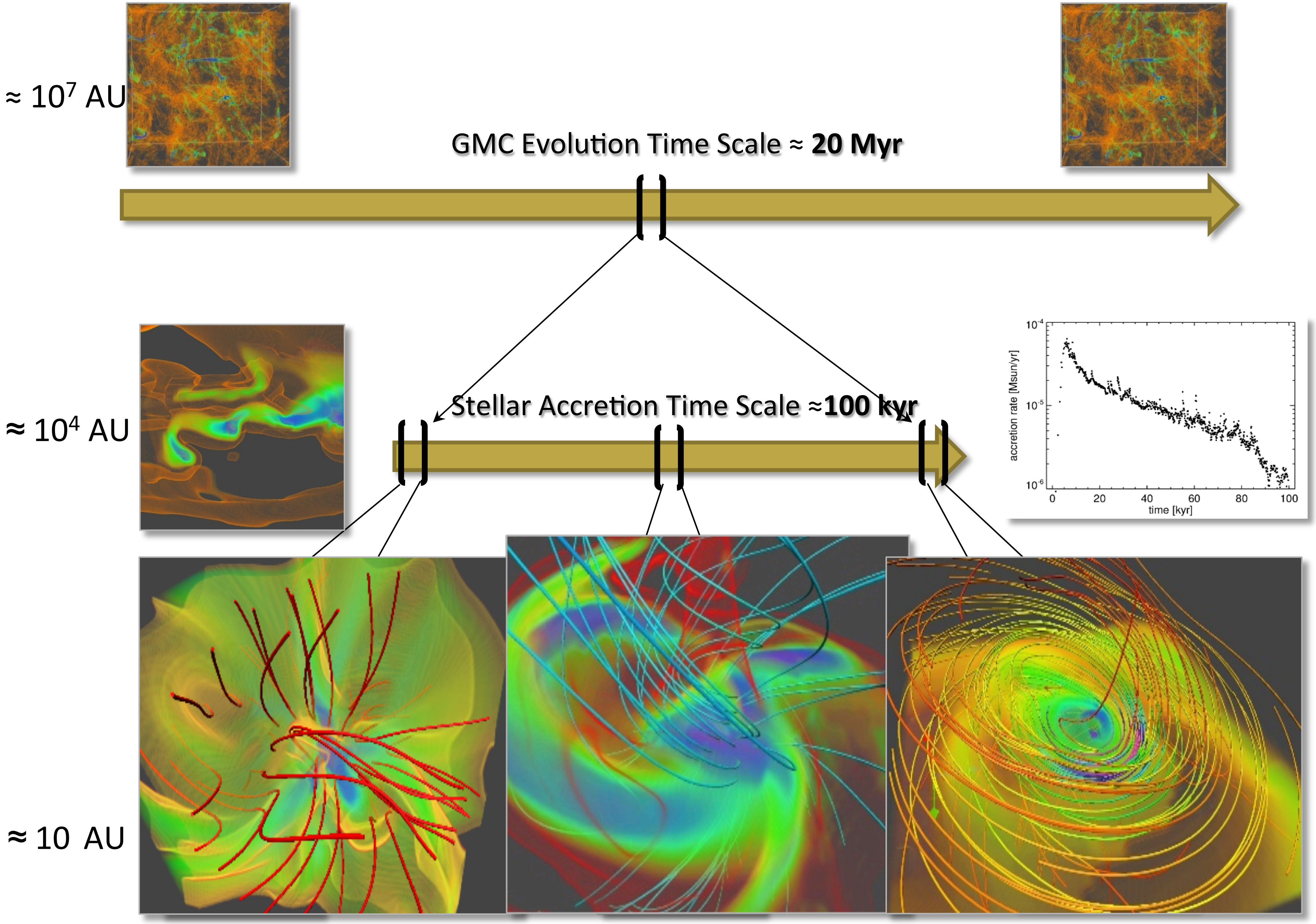
Chosen to be able to afford a few **GMC dynamical times**

Chosen to be able to afford a few **accretion time scales**

Note that ***all*** scales, up to the full 40 pc, are simultaneously present also in this step!

Chosen to be able to marginally resolve the disc **vertical structure**

Time Scale Zoom



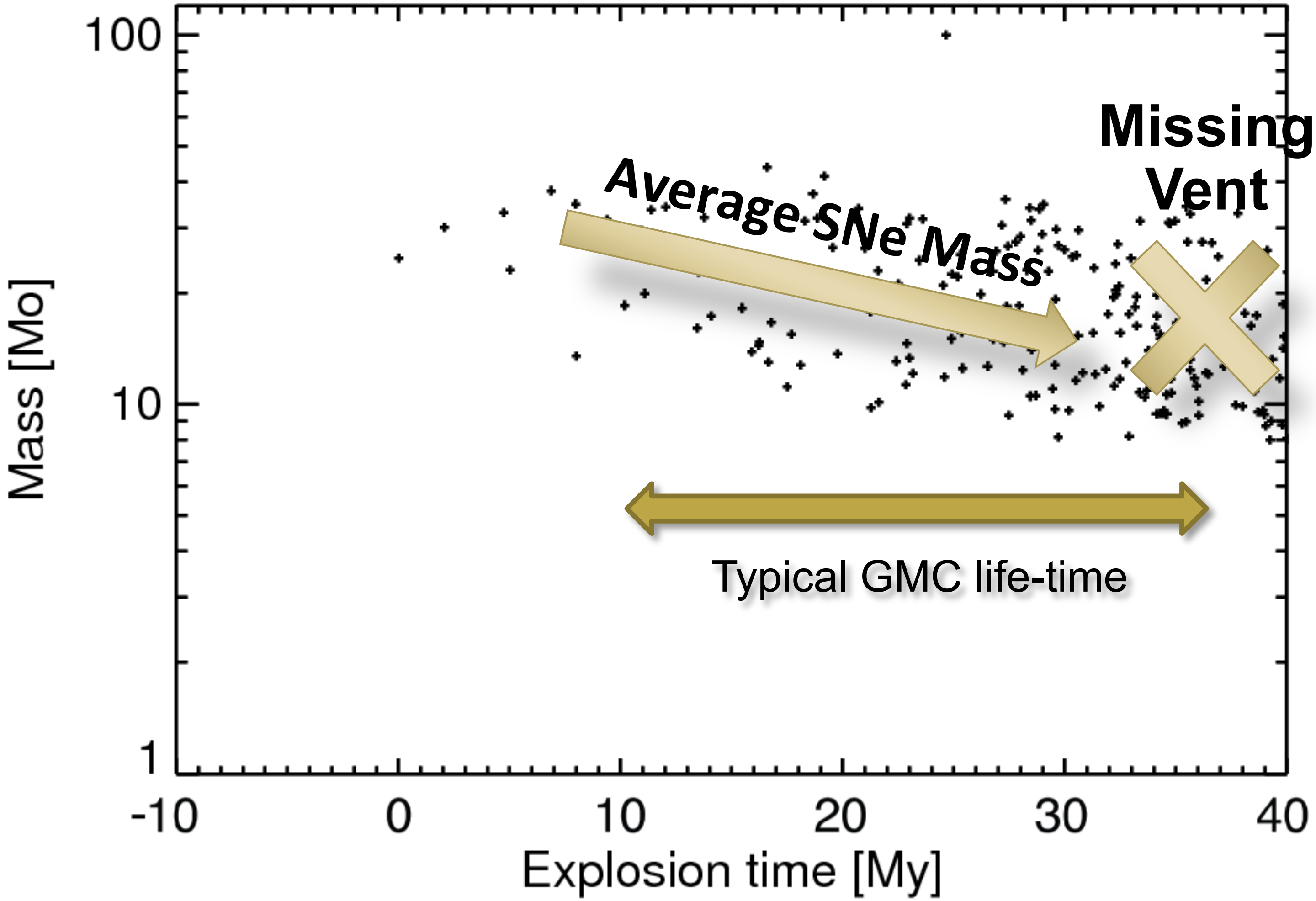
Giant Molecular Cloud Evolution Step

- ***Drive turbulence*** at typical warm ISM velocities, ≈15 km/s
  - With realistic optically thin cooling ➔ supersonic cold phase

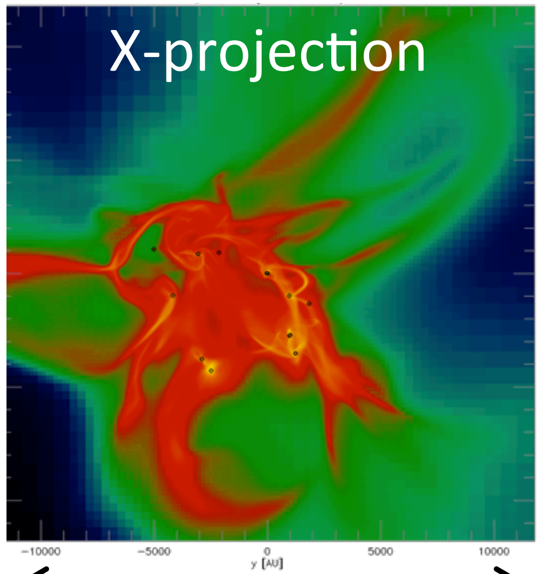
- ***Seed the cold phase*** with stars from theoretical IMF
  - Using a few % of the mass for this ***artificial star formation***
  - Keep track of their age ➔ ***explode as SNe*** when appropriate
  - Keep track of ***Short-Lived Radionucleids***

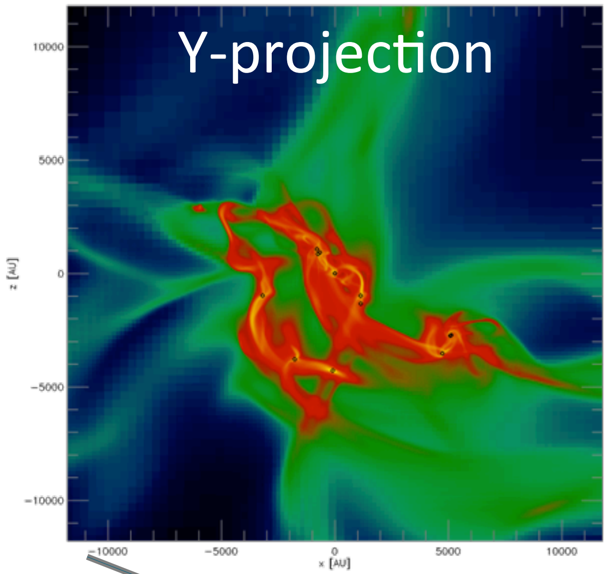
- Turn on selfgravity, ***turn off artificial driving***
  - Sink particles ➔ ***realistic star formation***
  - Keep track also of their age, ***exploding SNe do the driving***
  - This phase has now been running for almost 4 Myr

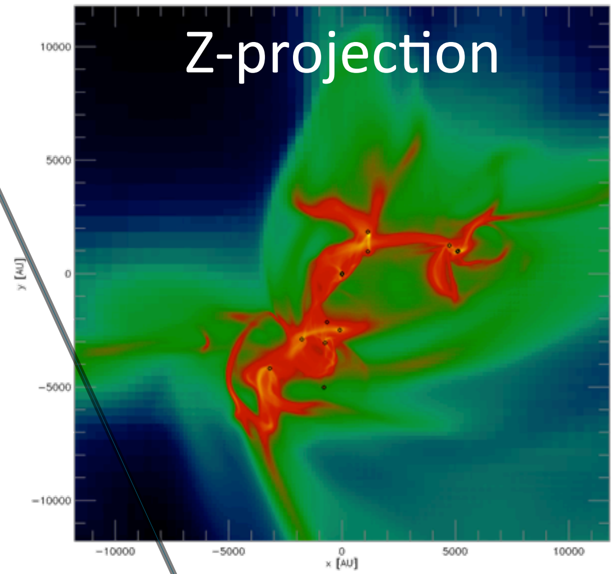
Supernovae Explosion History



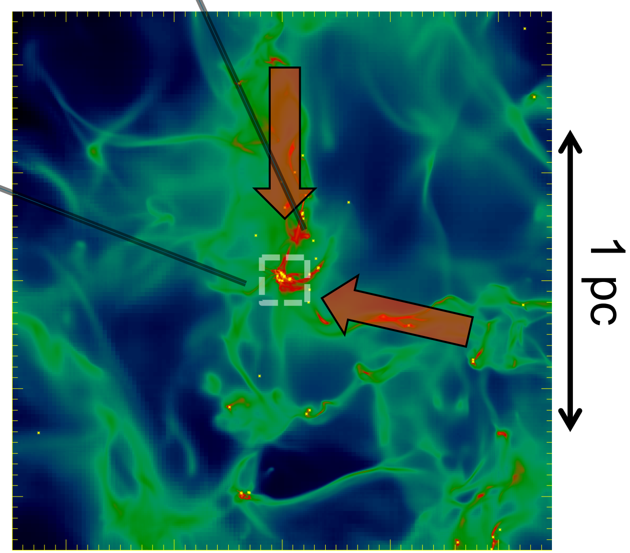
How is material distributed in a molecular cloud?







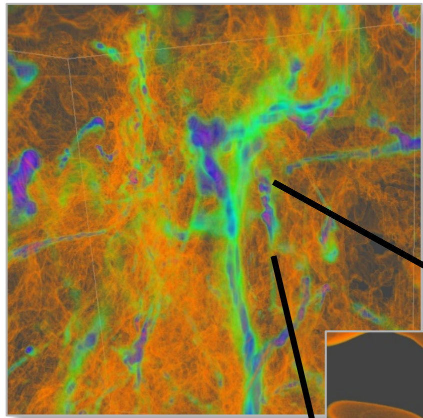
25000 AU = 0.12 pc

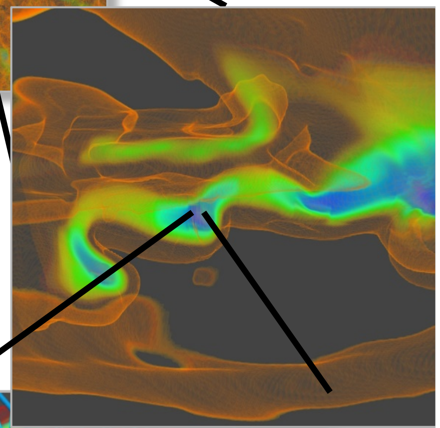


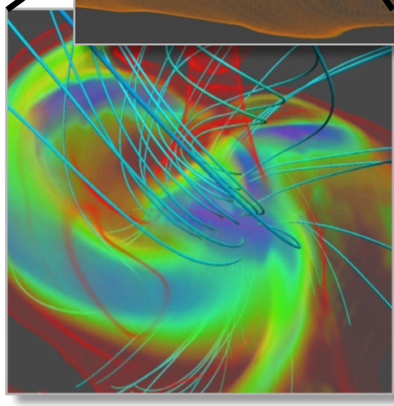
- Clusters are formed where large scale modes in the turbulence make the flow converge.
- The small scales are connected to the large scales.
- Most stars are formed in binary systems(!)
- Assuming an ***isolated cloud-core is biased***

Intermediate Zoom Levels

- ***Giant Molecular Cloud scales***
  - Size: 40pc
  - Refinement: $2^{16} \Rightarrow$ cell size 120 AU
  - Time duration: $\approx$ 20 Myr
- ***Stellar accretion scales***
  - Dynamic scale: $\approx$ 0.5 pc
  - Refinement: $2^{22} \Rightarrow$ cell size 2 AU
  - Time duration: $\approx$ 100 kyr $\approx$ accretion time scale
- ***Accretion disc scales***
  - Dynamic scale: $\approx$ 5 AU
  - Refinement: 2^{29} => cell size 0.015 AU
  - Time duration: $\approx$ 100-1000 yr





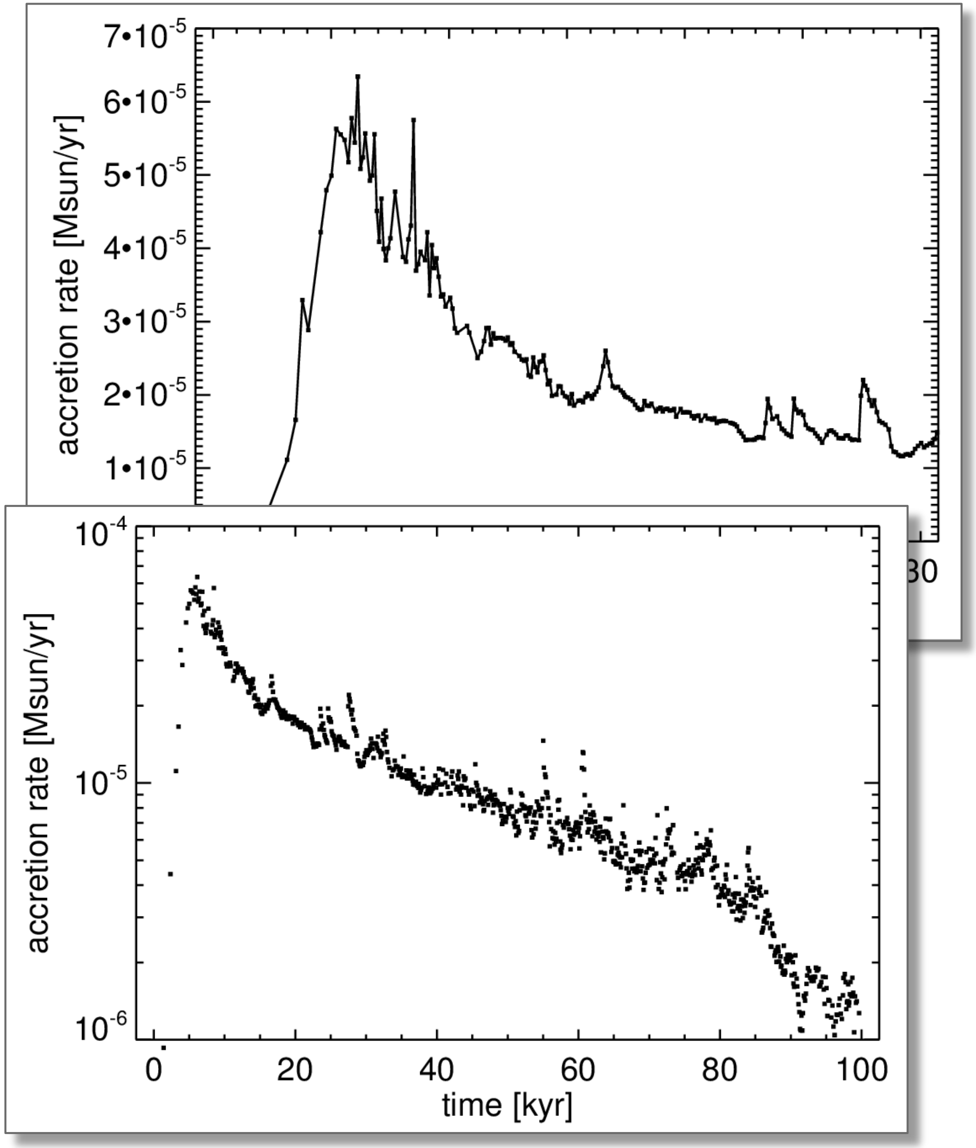


Accretion Rates

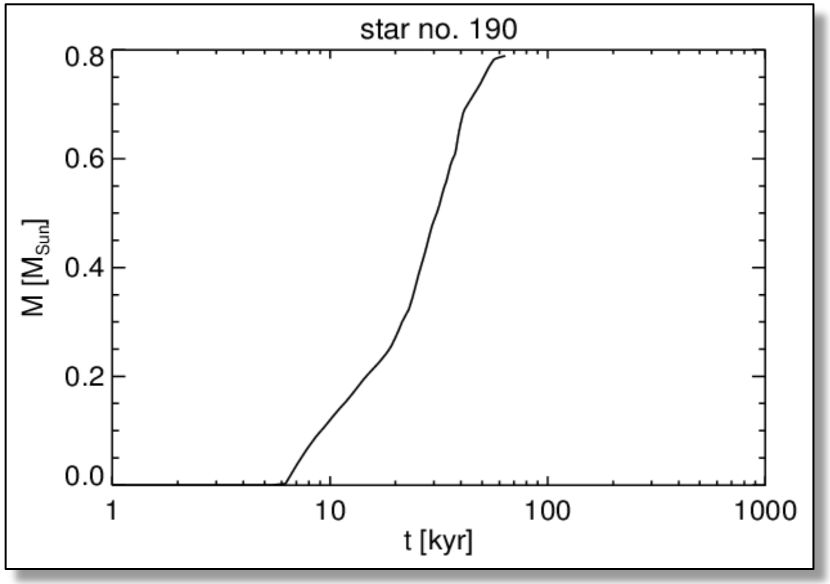
Instantaneous accretion rate to the central sink particle:

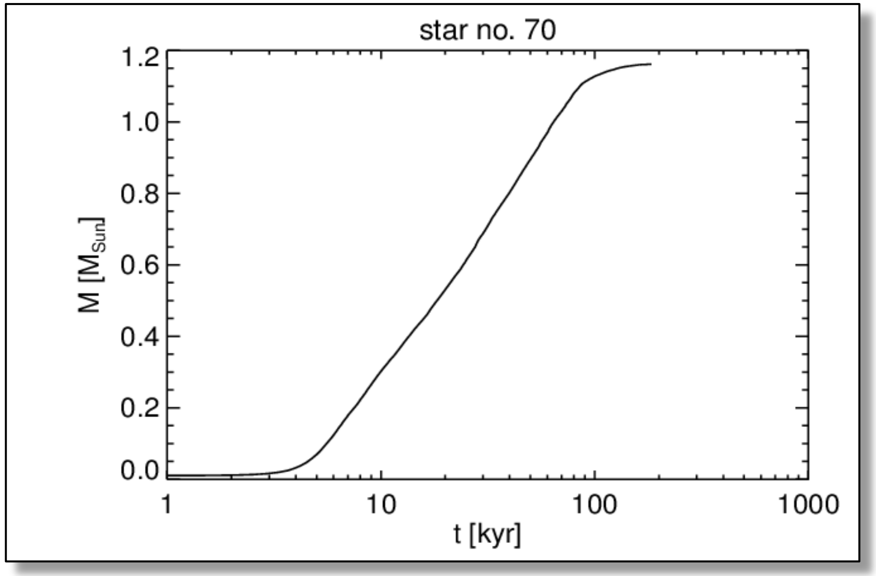
- Peaks after about 5 kyr, fluctuates due to magnetic field topology changes and accretion events

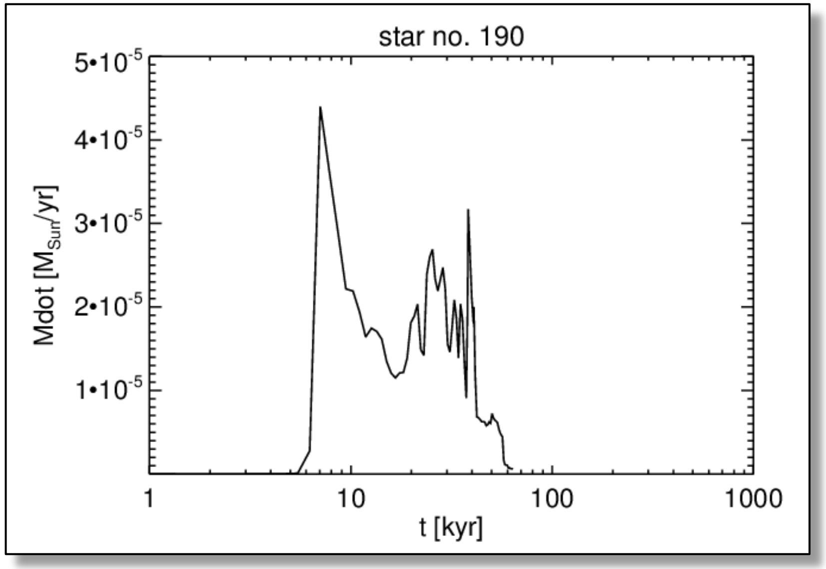
- Decreases exponentially with time thereafter

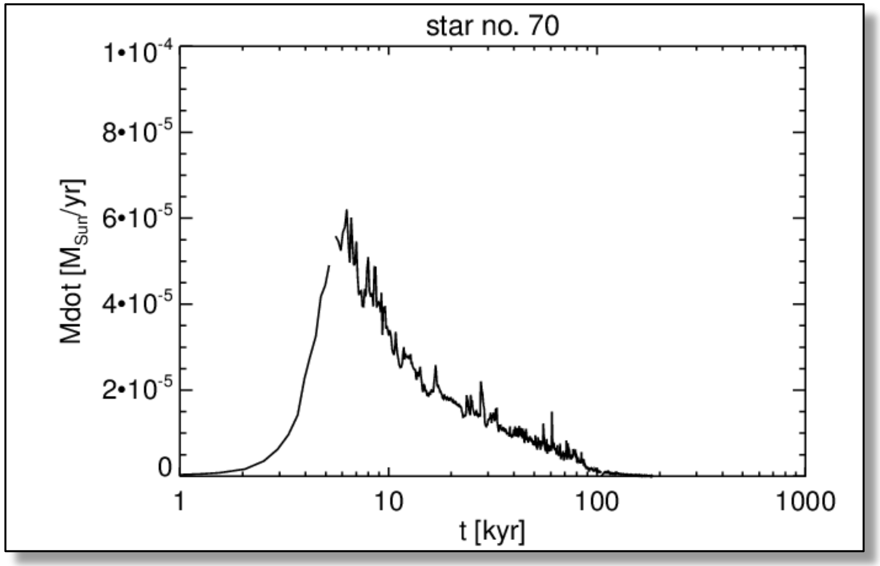


Accretion History Examples





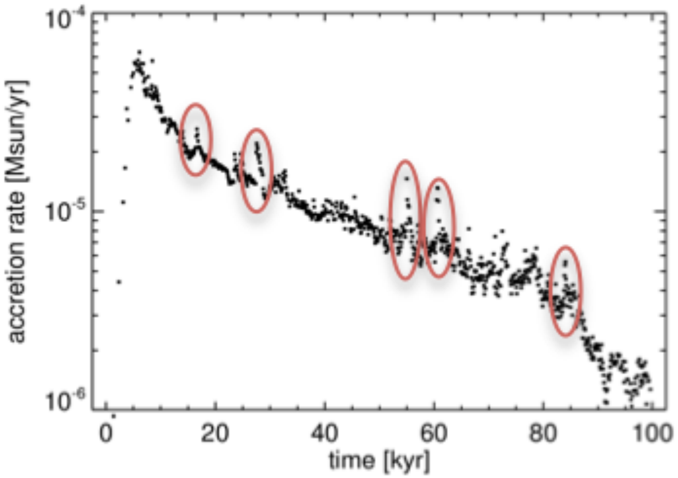


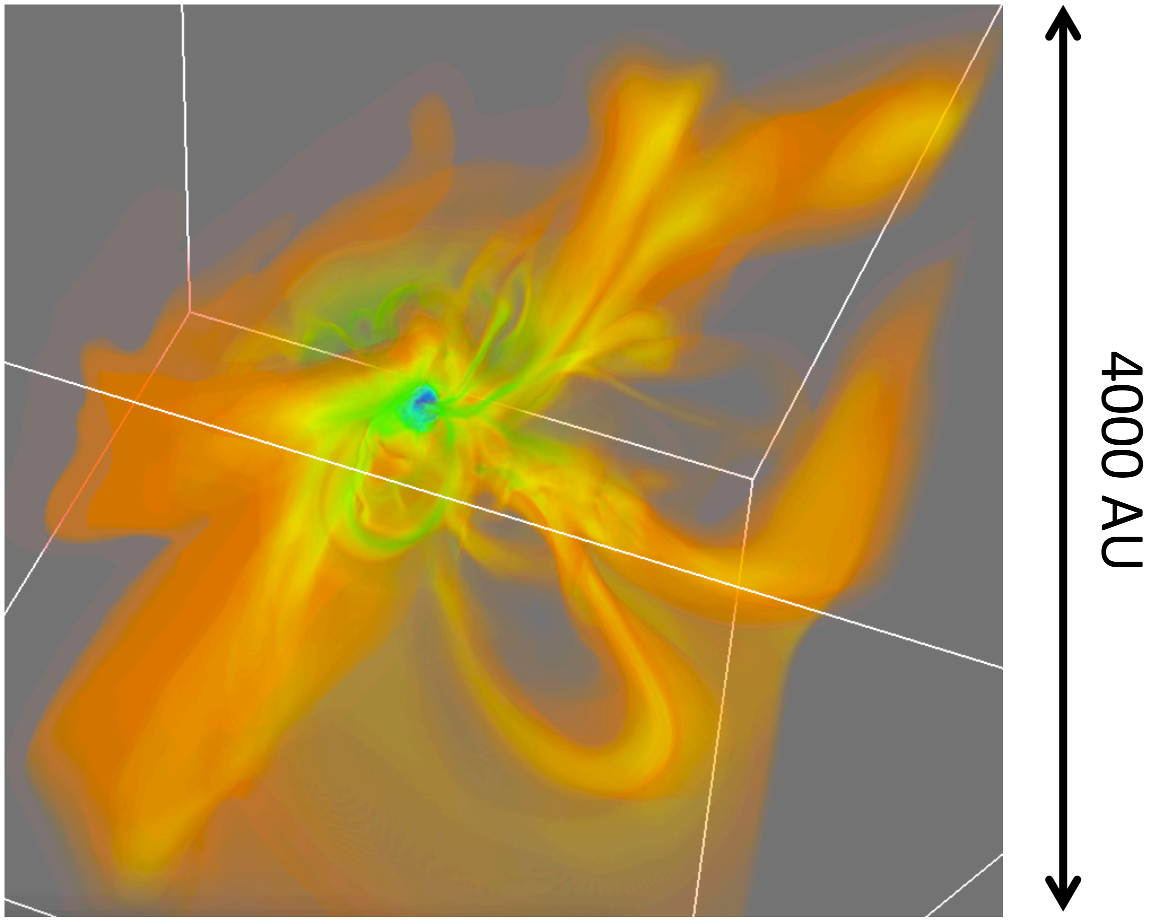


See also arxiv:1407.1445 [astro-ph]

Accretion from molecular cloud-core

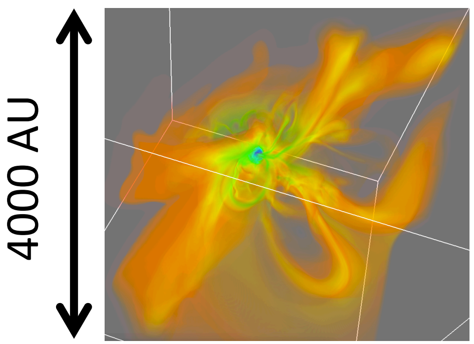
- *Isolated low Mass star* – accretion is filamentary from the cloud core to the disc. The star is essentially fed from the local molecular filament / cloud core

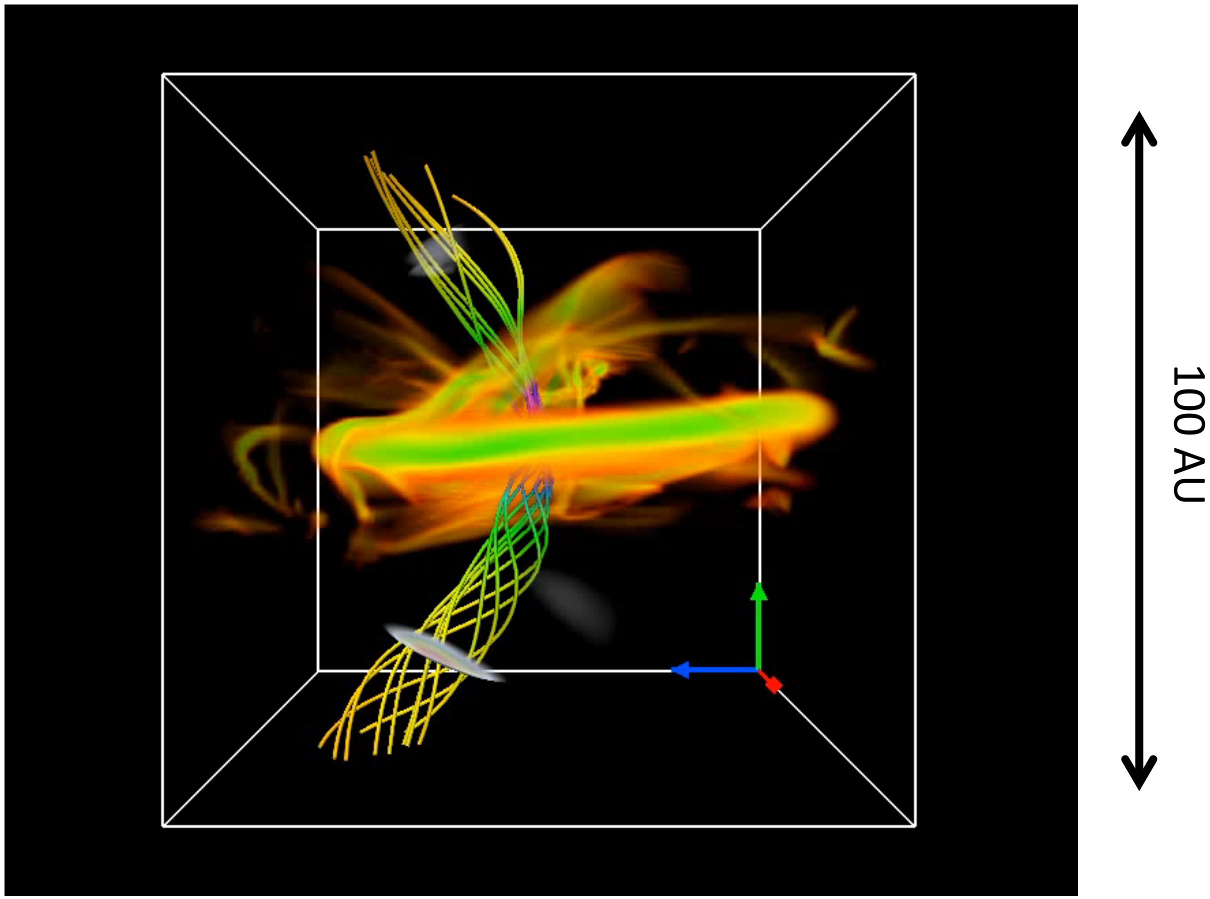




Accretion from molecular cloud-core

- *Isolated low Mass star* – accretion is filamentary from the cloud core to the disc. The star is essentially fed from the local molecular filament / cloud core
- Accretion happens from filaments on to the disc, not at "the edge"
- Vertical transport is crucial





Highest Zoom Level

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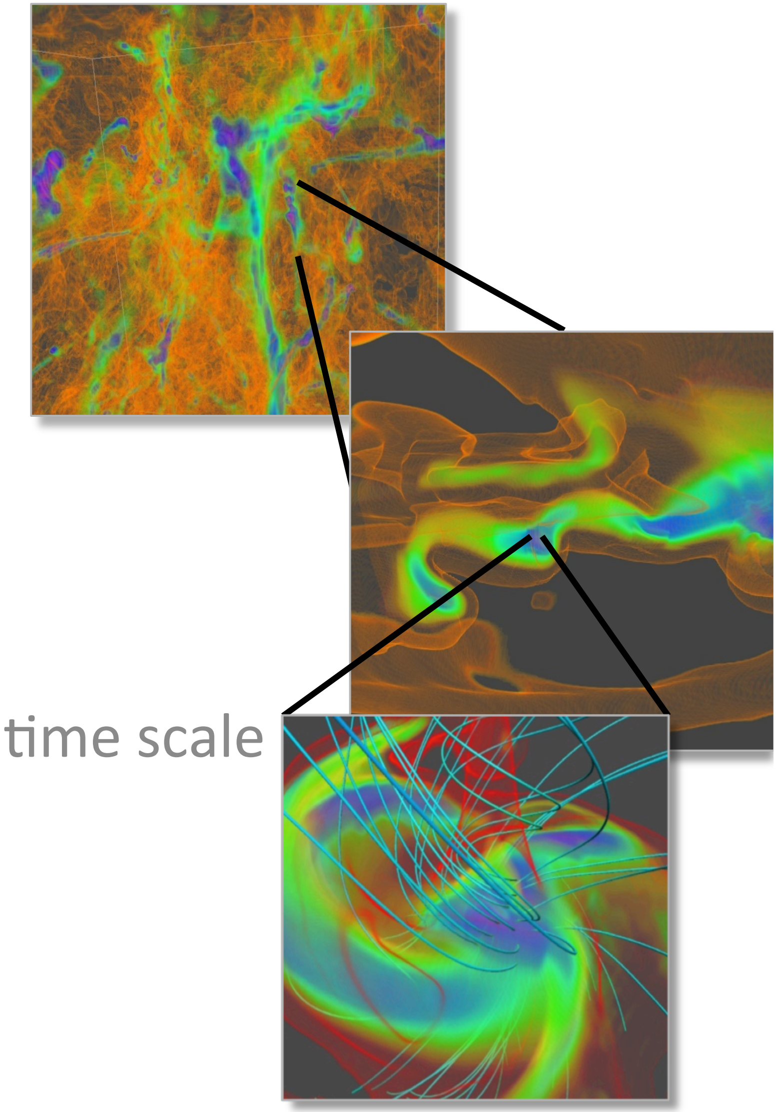
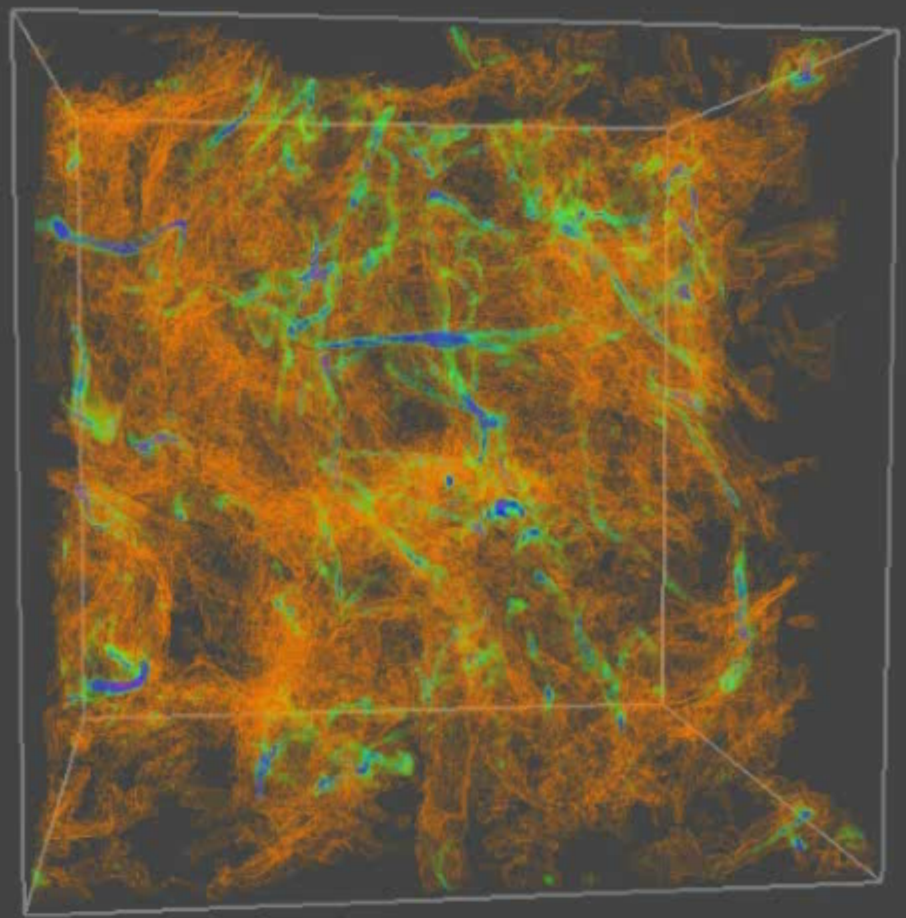
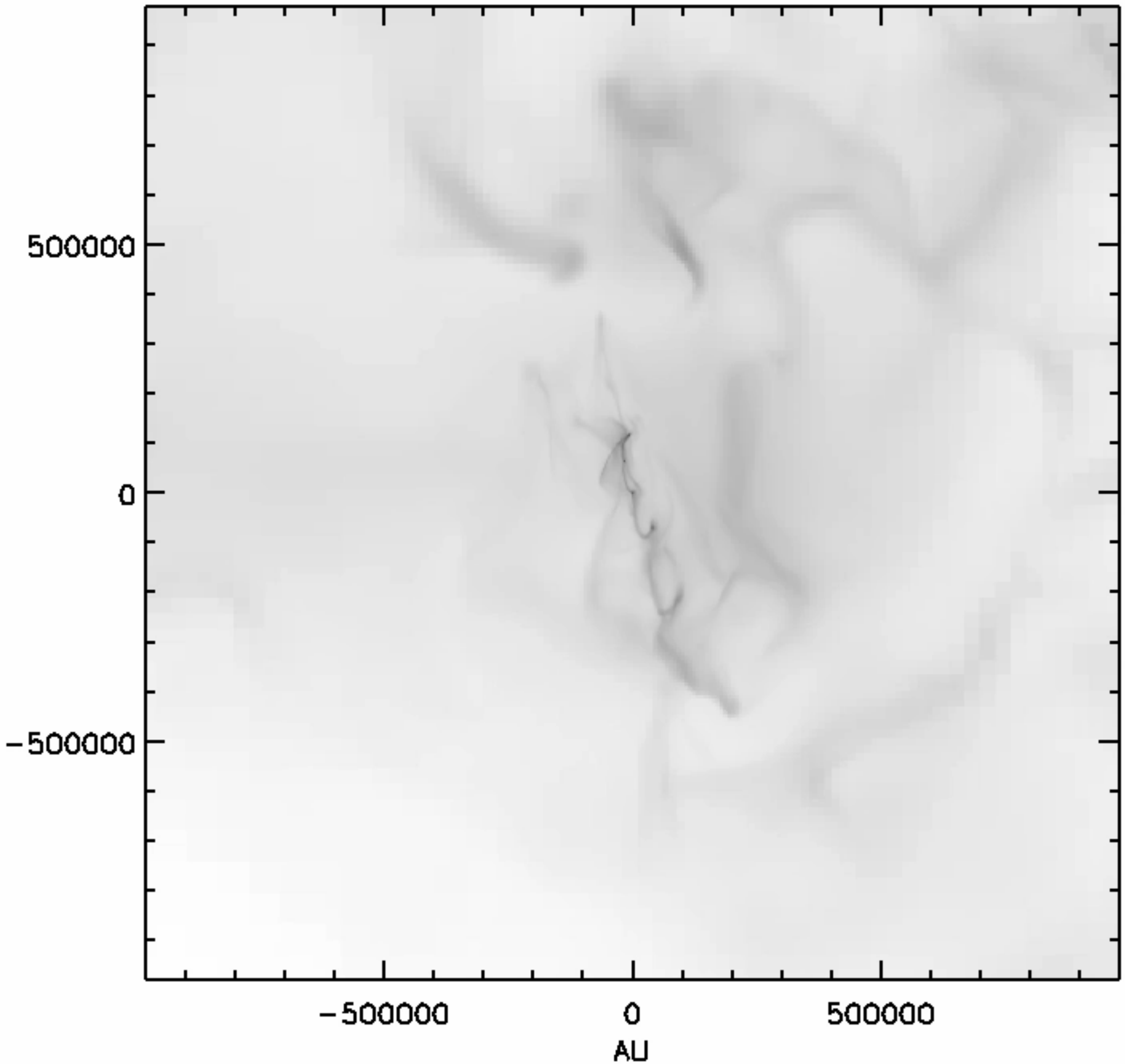


From GMC scales to disc, jet, and outflows





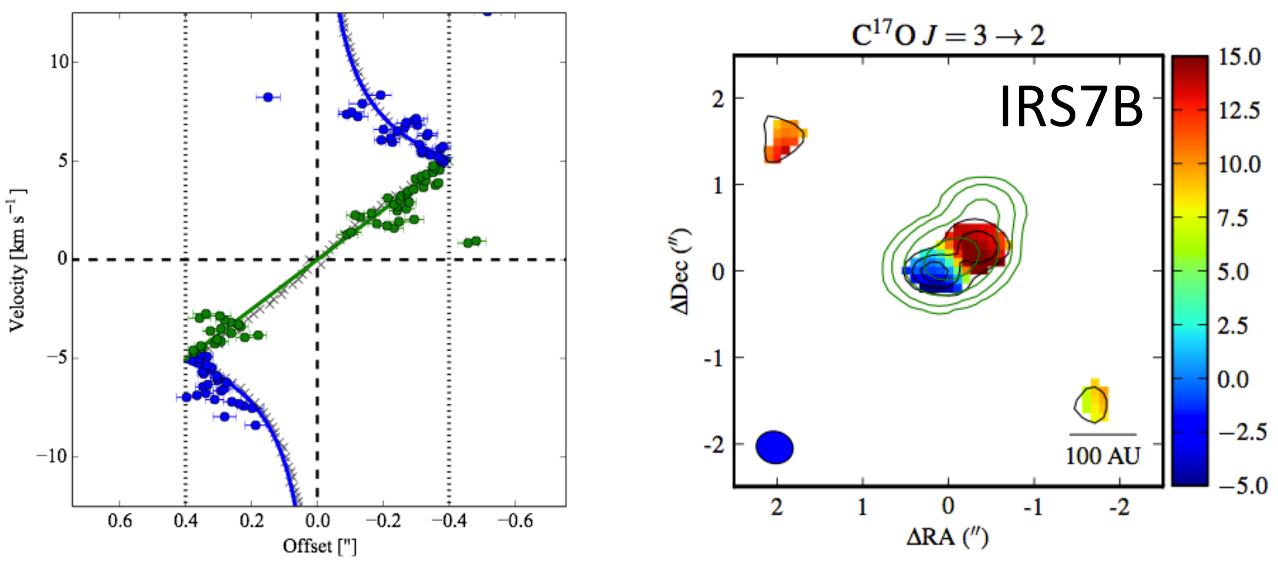
Zoom of projections of mass density at t≈50kyr, illustrating the hierarchical filamentary structure, both outside and inside the collapsing core at the center.

Inner scale: 4 AU
Outer scale: 10 pc

Column density in a 20% slice

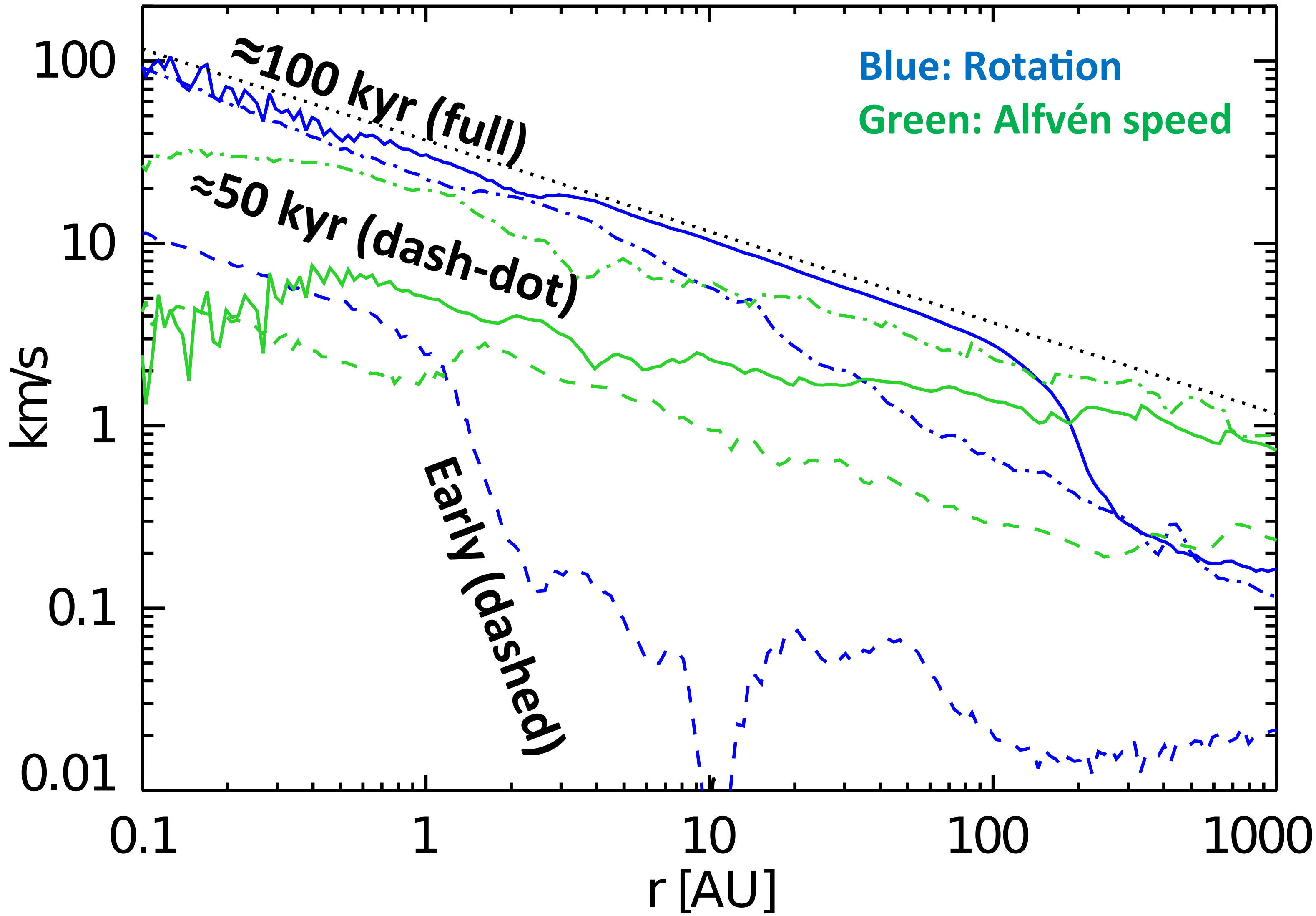
Timing of Disc Formation

- Observations:
  - It is well established that most Class I and II stars have Keplerian discs
  - In the past the evidence for early stage discs was less clear
  - From the newest ALMA observations we see growing evidence that ≈50 AU discs can form already before 100 kyr



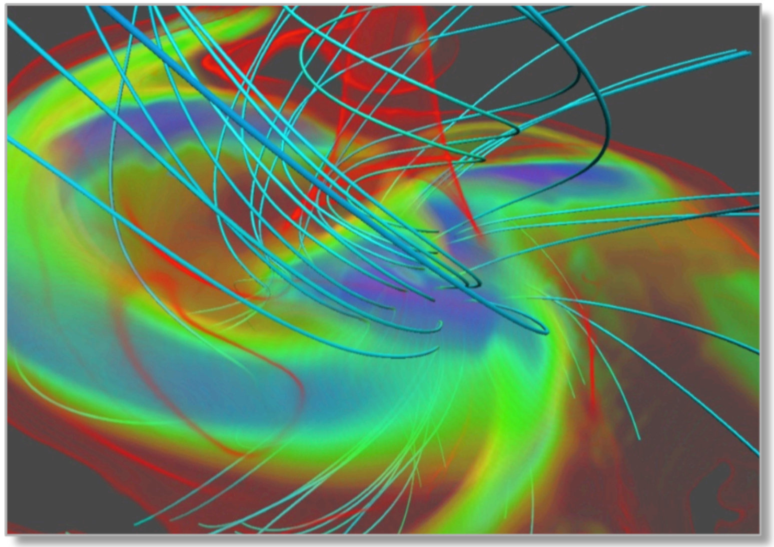
[Lindberg et al 2014]

Disc rotation and size

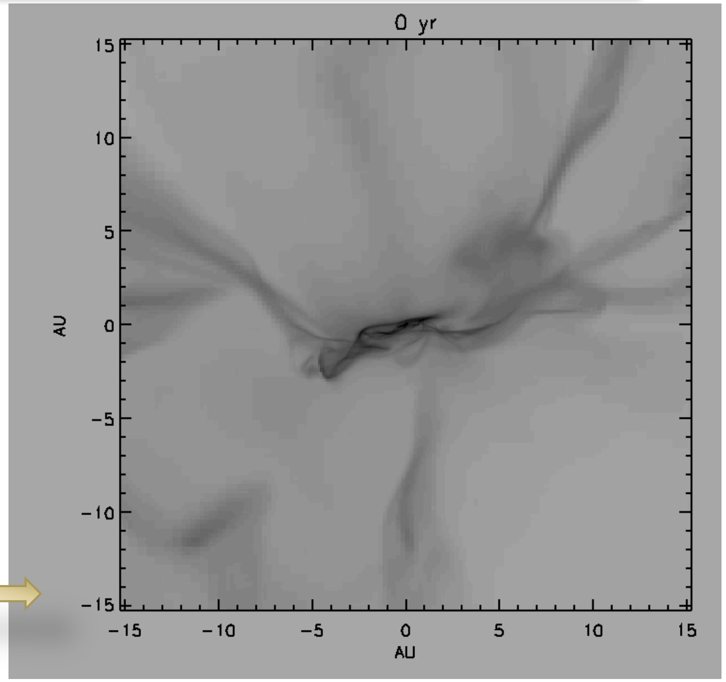


Jets and Disc Wind Outflows

The simulations produce, spontaneously, inner ***jets*** and larger scale ***disc wind outflows***

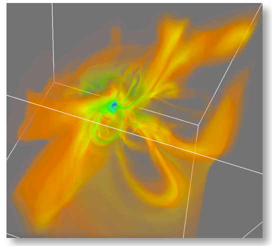


- Outer parts:
  - Disc wind with speeds ≈10 km/s
  - driven by inclined magnetic fields
- Inner parts:
  - Highly collimated jet with outflow speeds ≈100 km/s
  - Resolving the near-star environment is ***not*** necessary for jet formation!

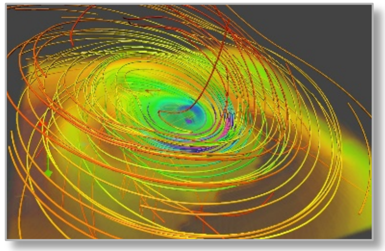


Time evolution of the inner scales at t≈50kyr

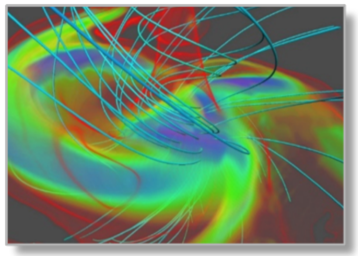
Summary



- ***Ab-Initio Hyper-Global*** models correctly
  - Couple the dynamics of the gas-reservoir and the new-born stars
  - Anchor the large scale magnetic fields at “infinity”



- Resolves the ***issue of angular momentum transport***
  - Rapid accretion does NOT require MRI, relies on ***large scale fields***
  - Magnetic braking is NOT catastrophic, ***chaotic behavior*** is the savior
  - ***Vertical transport*** is at least as important as radial transport
- Demonstrates that star formation ***depends crucially on <B>***
  - A ***pseudo-random ‘parameter’*** among star forming envelopes!
  - Surviving angular momentum may be a ***remnant dep. on B***



- Illustrates the ***central importance of bi-polar outflows***
  - Disc winds and jets carry away ***≈50% of the mass***
  - Much MORE of the angular momentum ***and energy***