Zooming in on Star and Protoplanetary Disk Formation

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with

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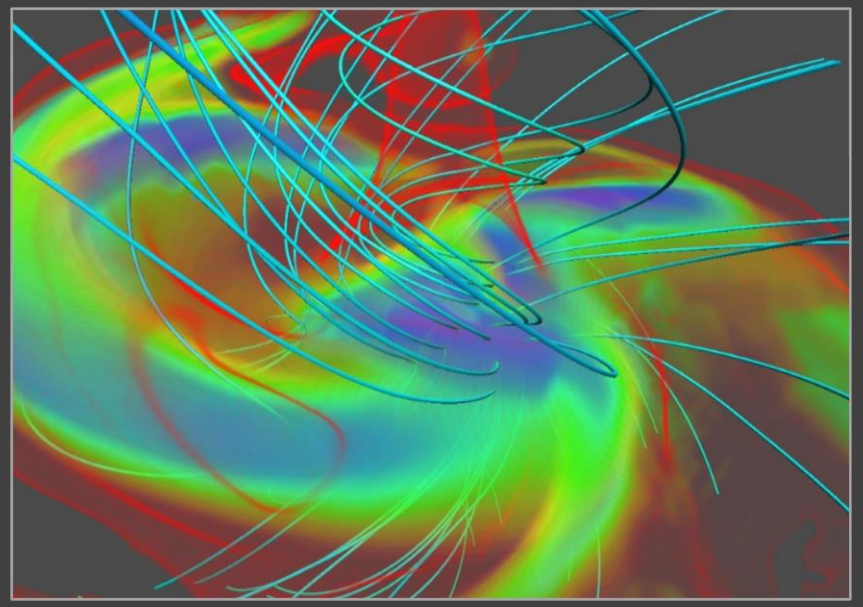
- Martin Pessah, Colin McNally, Gareth Murphy (Niels Bohr International Academy / Copenhagen)
- Paolo Padoan (Institute for Advanced Studies / Barcelona)

IAU Symposium 299, Victoria, June 2013

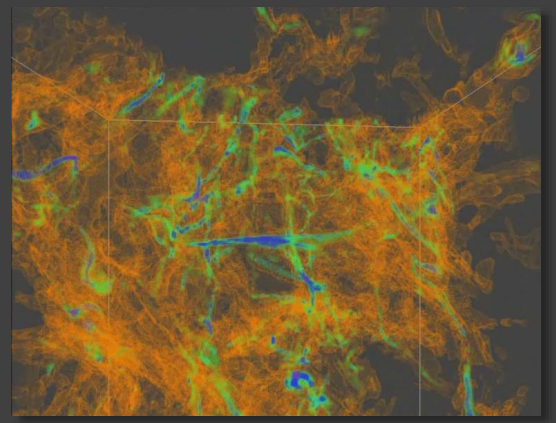
Overview

- First of a kind; ***ab initio* simulations** of formation of circumstellar disks
  - Using Adaptive Mesh Refinement (RAMSES)



- Outer scale 40 pc, inner scale 0.015 AU
  - **Ratio 1 : 2^{29} ≈ 1 : 540 million**
  - Animations zoom over 7 orders of magnitude
- So far: Proof of concept
  - One ≈ 1 solar-mass star
  - **Plan: Get a statistically significant sample of solar mass stars**

Basic Idea

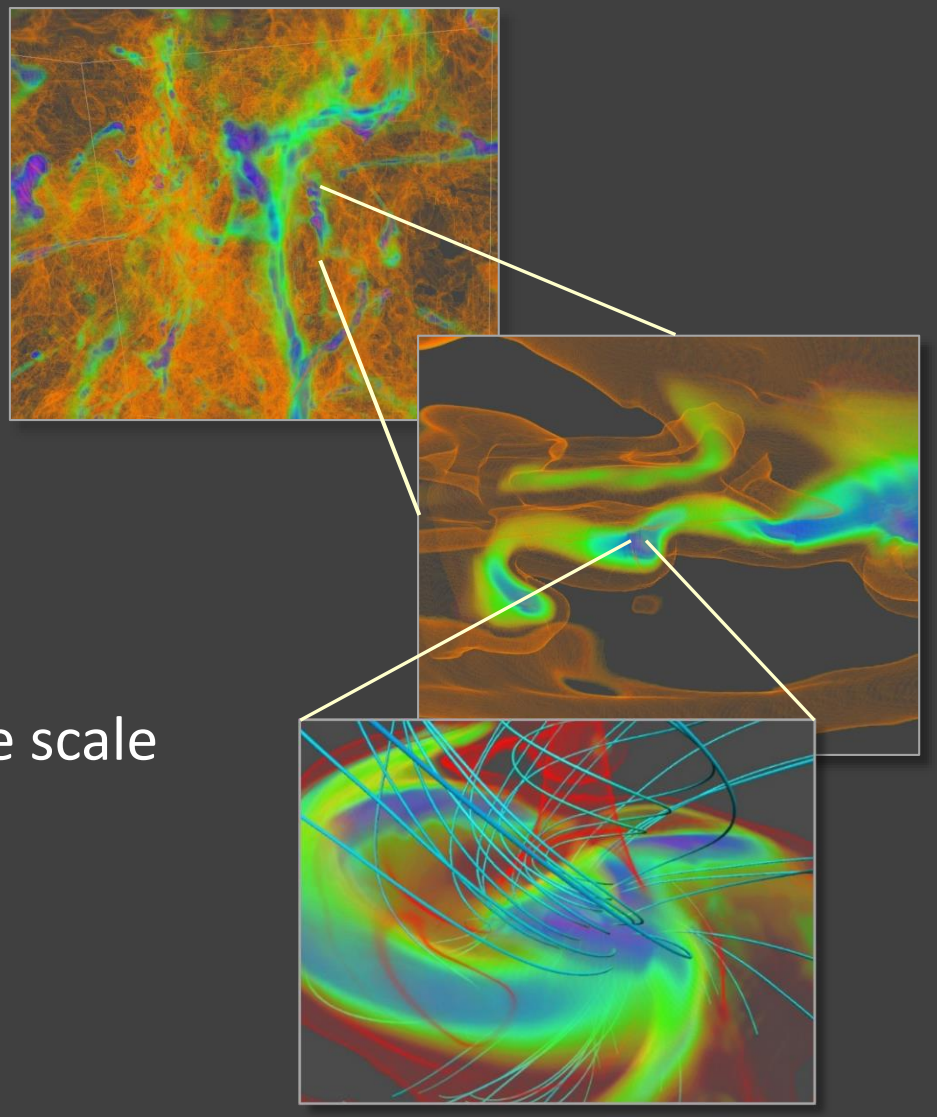


- ***"Anchor dynamics"*** in **well-observed spatial range**
  - Giant Molecular Clouds (GMCs) and their fragments
    - "Larson relations" (Larson 1979, 1981; Solomon et al 1987, …)
- ***Advantage:*** Avoids having to pose unknown initial & boundary conditions
  - Similar to techniques used in simulations of galaxy formation, "anchored" in Cosmic Microwave Background fluctuations
- ***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 ~1000 AU to ~0.01 AU – the full range is "only about twice as expensive" (AMR!)

Three Simulation Zoom Levels

- ***Giant Molecular Cloud scales***
  - Size: 40pc
  - Refinement: $2^{16} \Rightarrow$ cell size 250 AU
  - Time duration: $\approx$ 10 Myr
- ***Stellar accretion scales***
  - Dynamic scale: ~ 0.5 pc
  - Refinement: $2^{22} \Rightarrow$ cell size 2 AU
  - Time duration: $\approx$ 100 kyr $\approx$ accretion time scale
- ***Accretion disk scales***
  - Dynamic scale: ~ 5 AU
  - Refinement: 2^{29} => cell size 0.015 AU (!)
  - Time duration: $\approx$ 100-1000 yr



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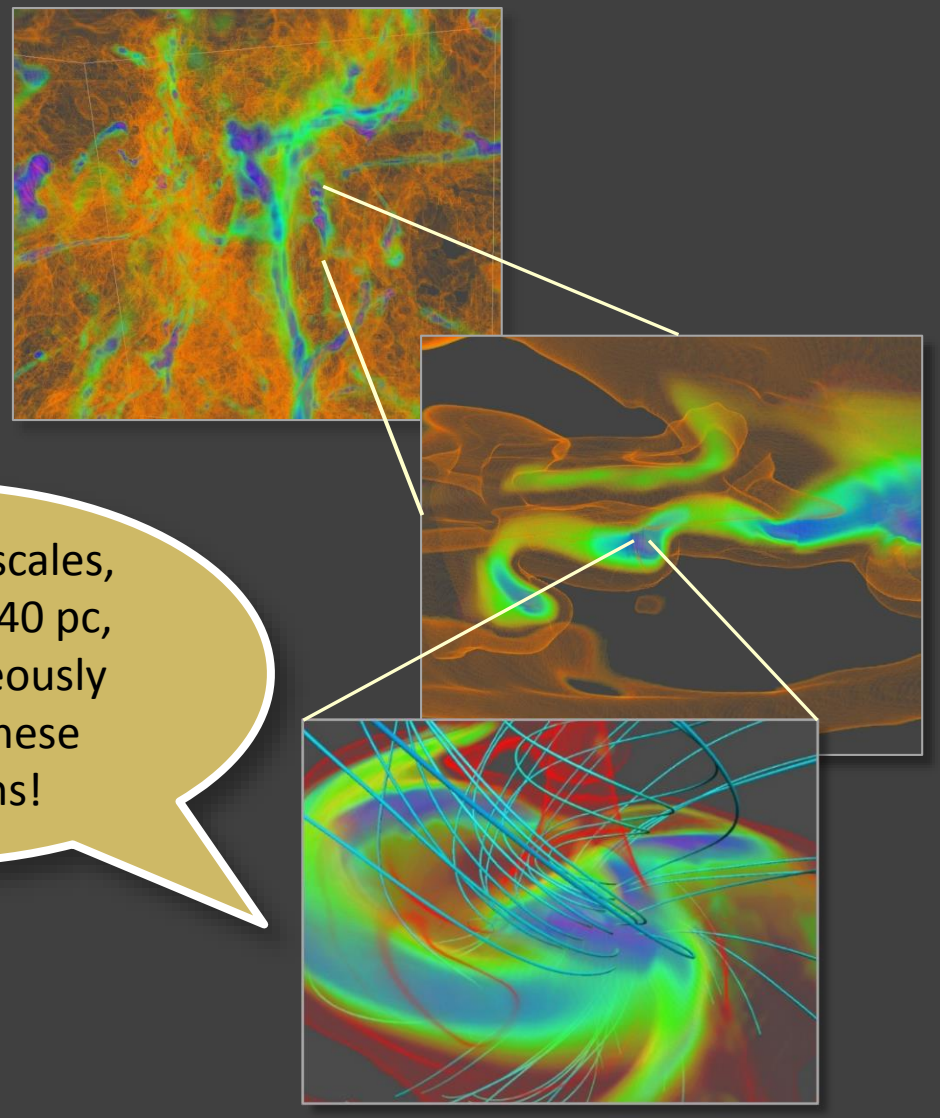
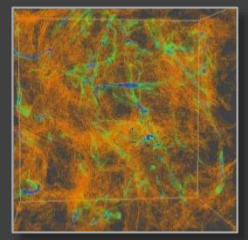
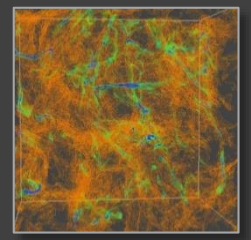


Note that ***all*** scales, up to the full 40 pc, are simultaneously present in these simulations!

Time Scale Zoom

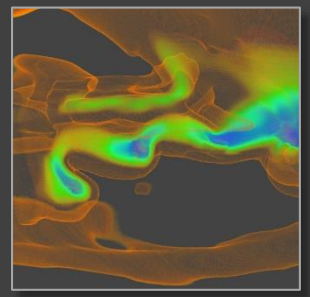
~ 10^8 AU



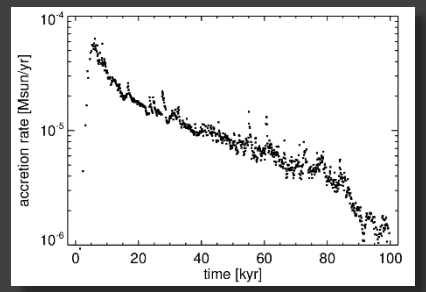


GMC Evolution Time Scale ~ **10 Myr**

~ 10^4 AU



Stellar Accretion Time Scale ~**100 kyr**



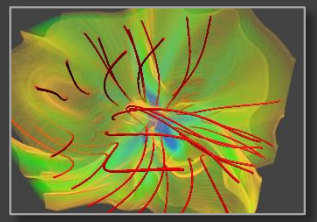
Disk Dynamics Time Scale ~ **1 kyr**

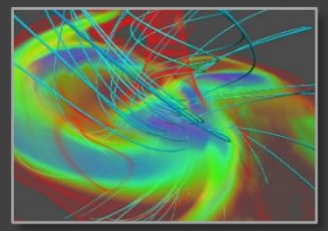
EARLY

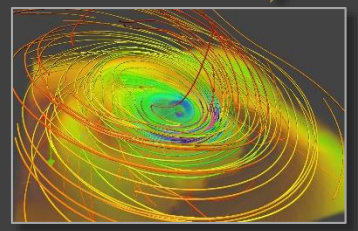
MID

LATE

~ 10 AU

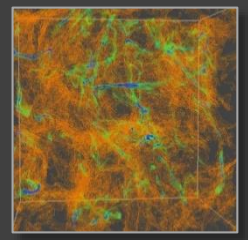


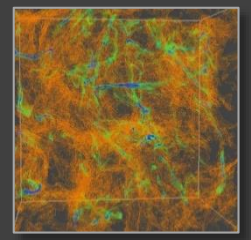




Time Scale Zoom

~ 10^8 AU





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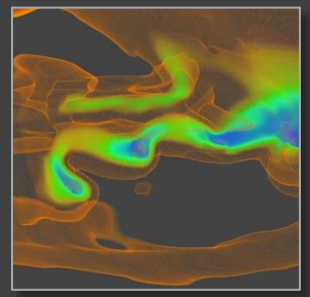

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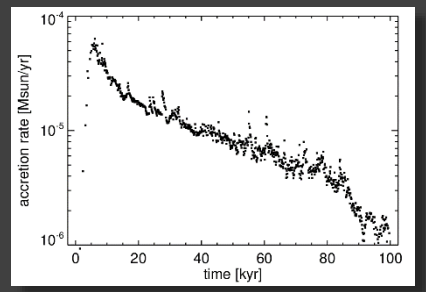
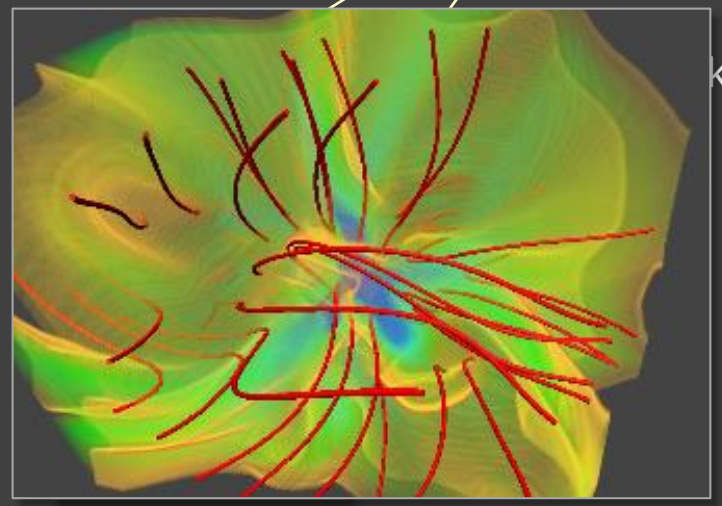
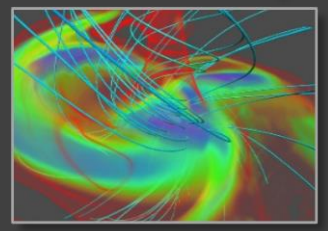


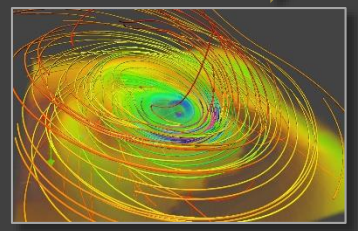


k Dynamics Time Scale ~ **1 kyr**

MID

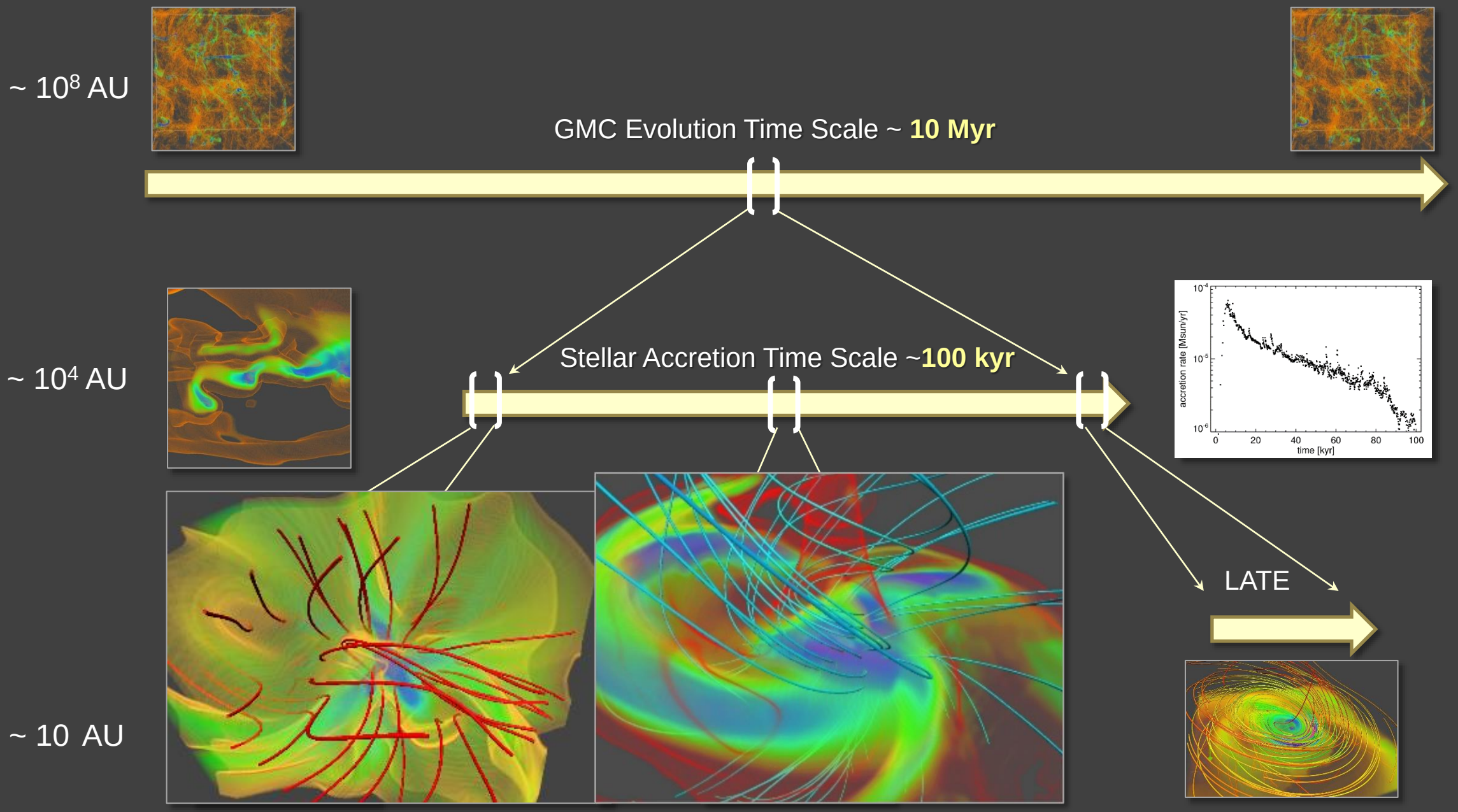


LATE



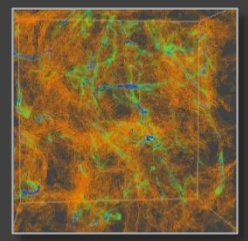
~ 10 AU

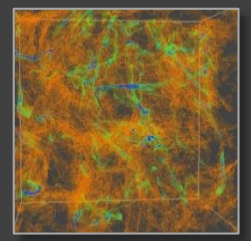
Time Scale Zoom



Time Scale Zoom

~ 10^8 AU





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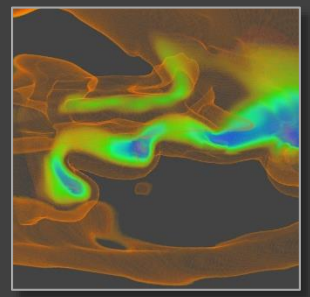

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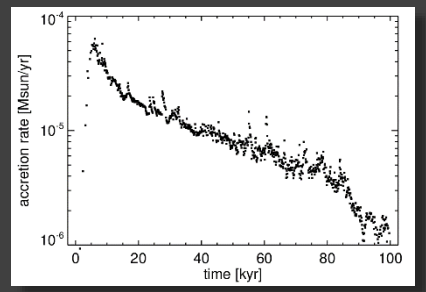

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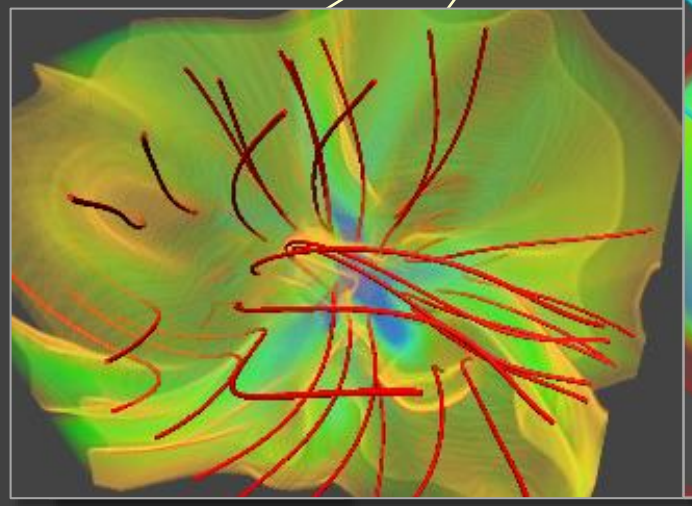
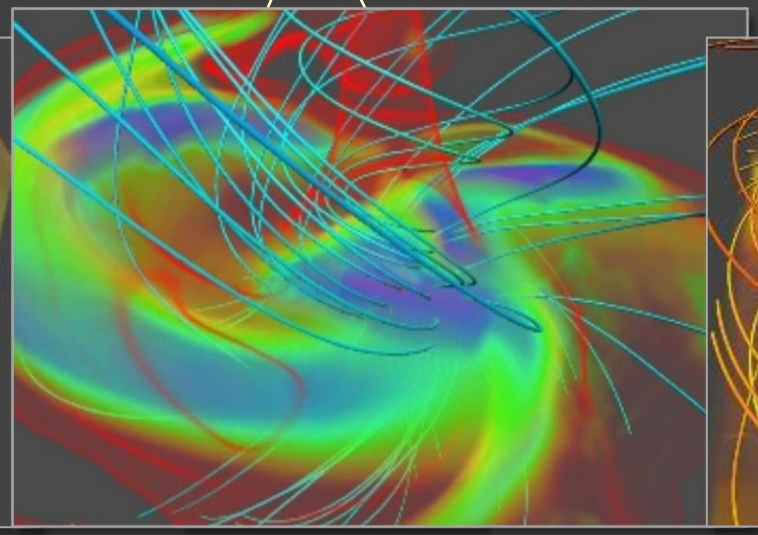
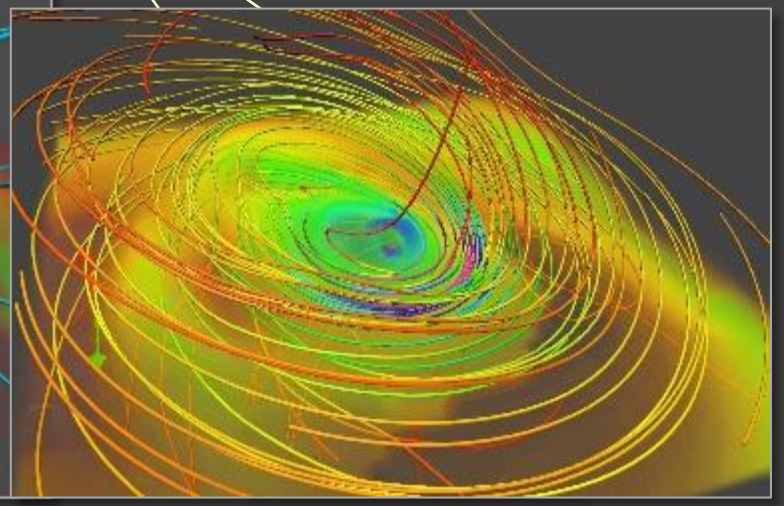
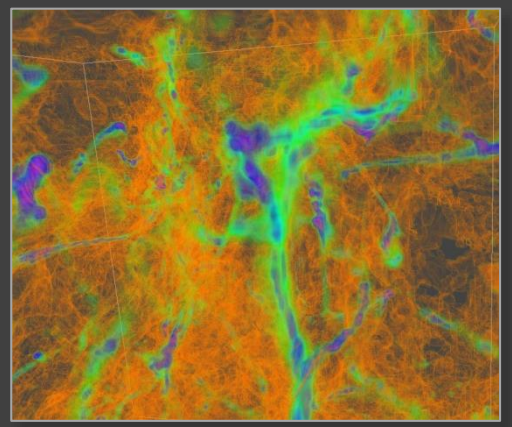






Why not do the whole box at uniform resolution – much simpler ;-!?

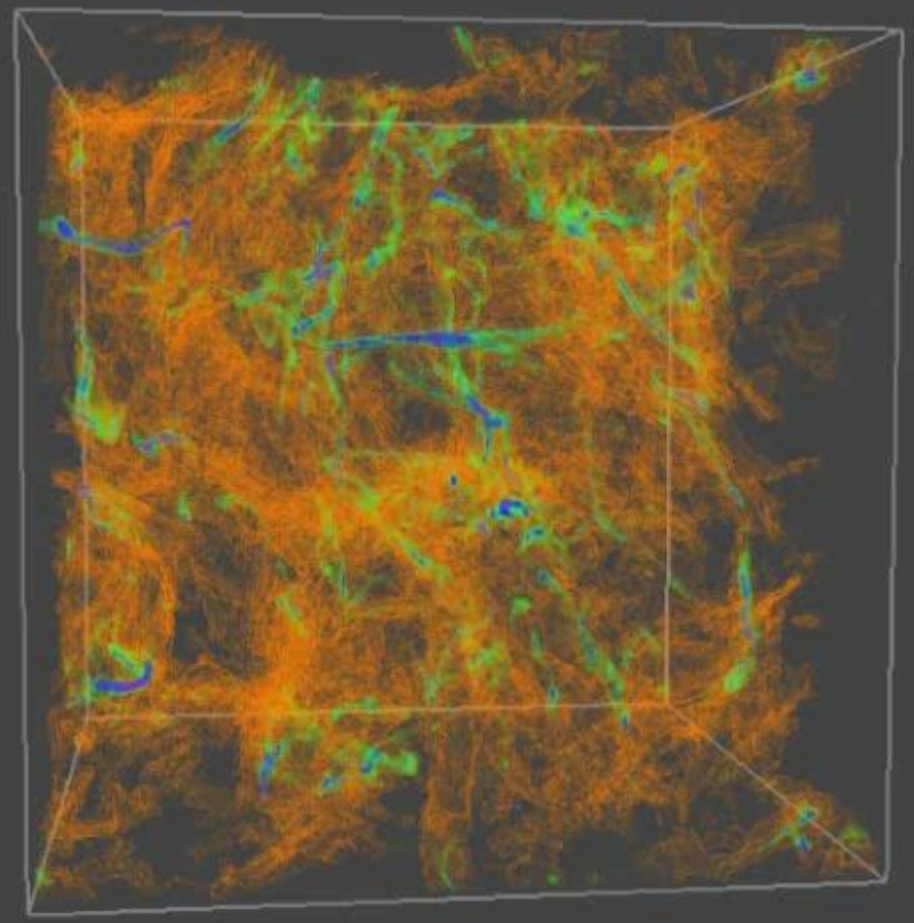


- At current speed a full 3-D $(2^{30})^4$ simulation would take ~10^5 ages of the Universe!
  - 1 PetaFlop for 10^{15} yr = 2^{50} times the largest supercomputer grants

But, if Moore's law continues, such an increase with 50 powers of two will take less than 80 years (!)

From GMC scales to disk with jet and outflow

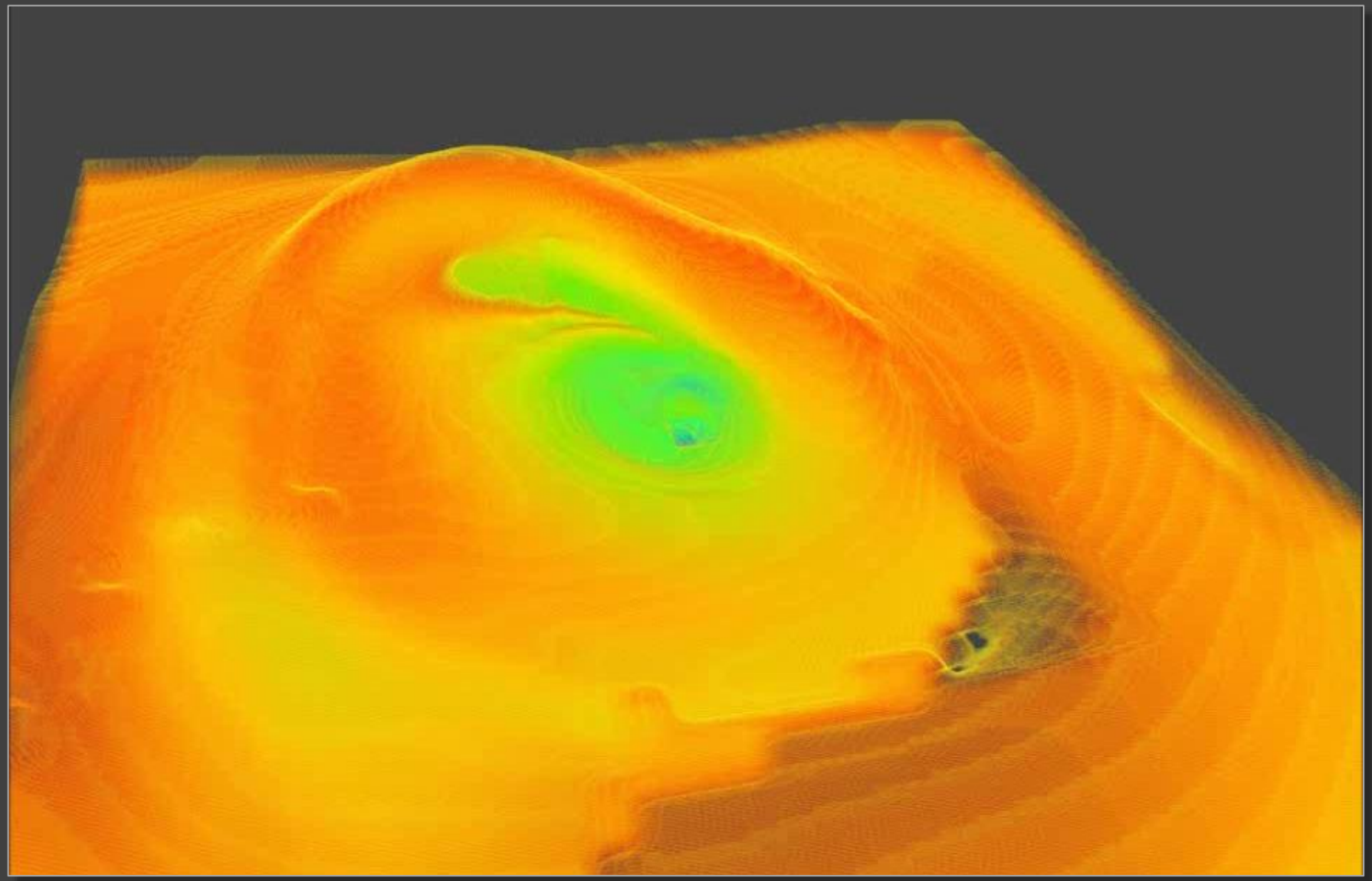
[see separate animation 1]



Late stage,
larger Keplerian
disk

Zoom from
about 15 AU
to about 2 AU

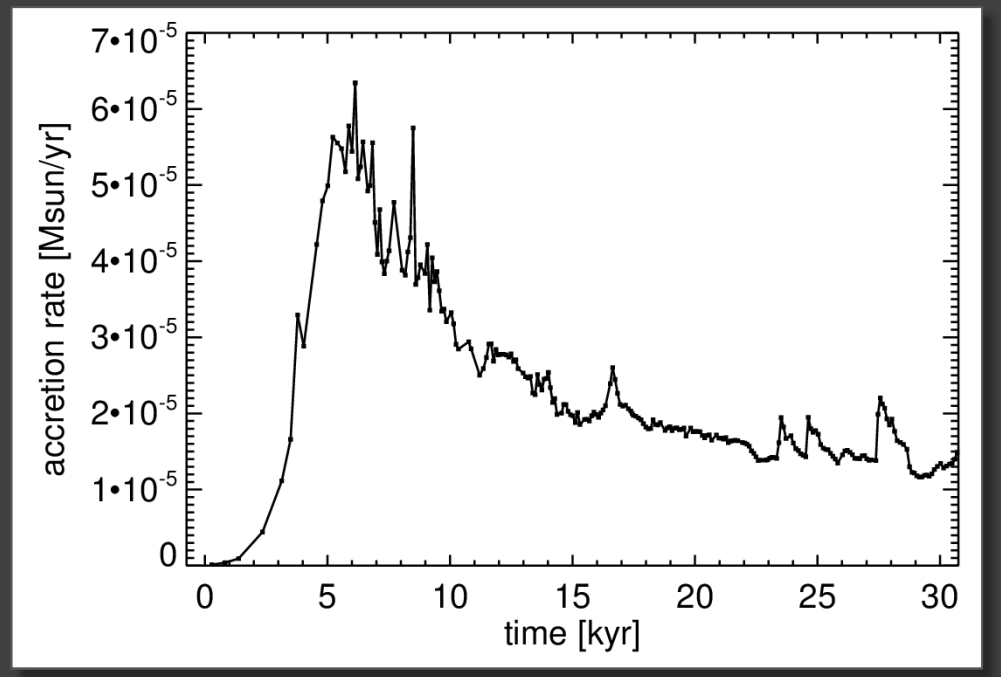
[see separate
animation 2]



Accretion Rates

We measure the instantaneous accretion rate to the central sink particle

- Peaks after about 5 kyr, fluctuates due to magnetic field topology changes
- Decreases exponentially with time thereafter



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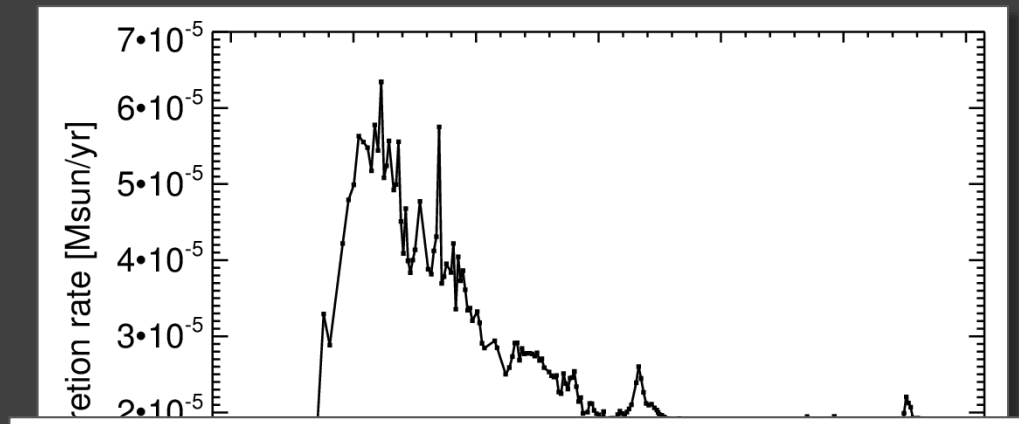
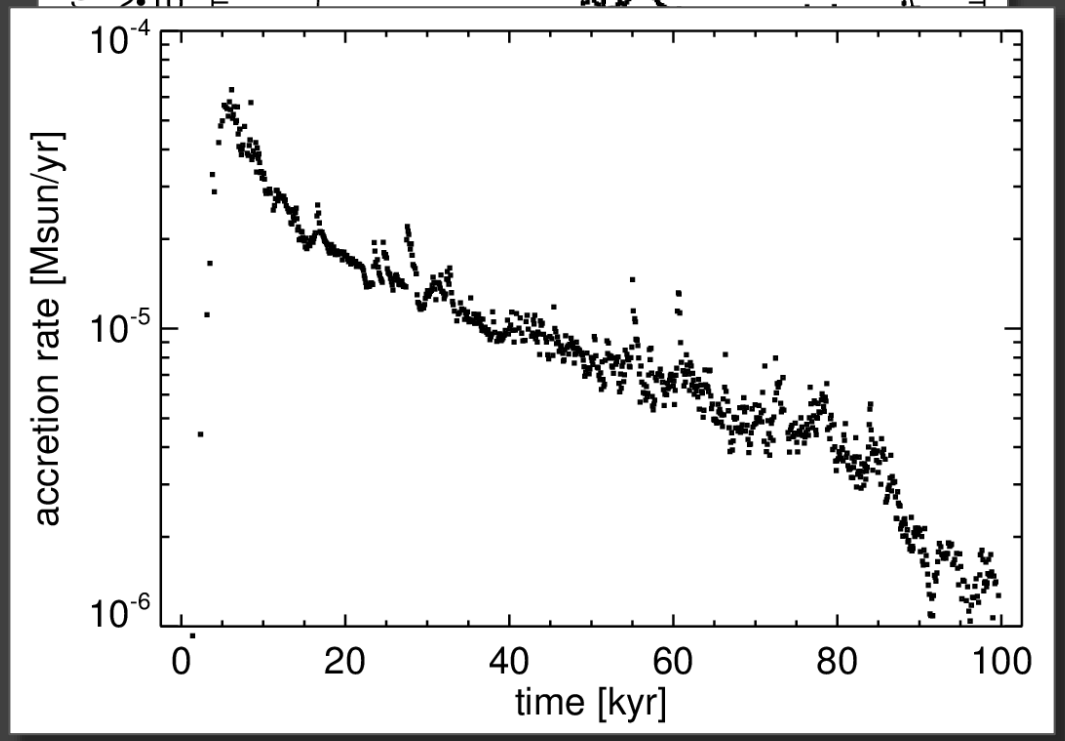
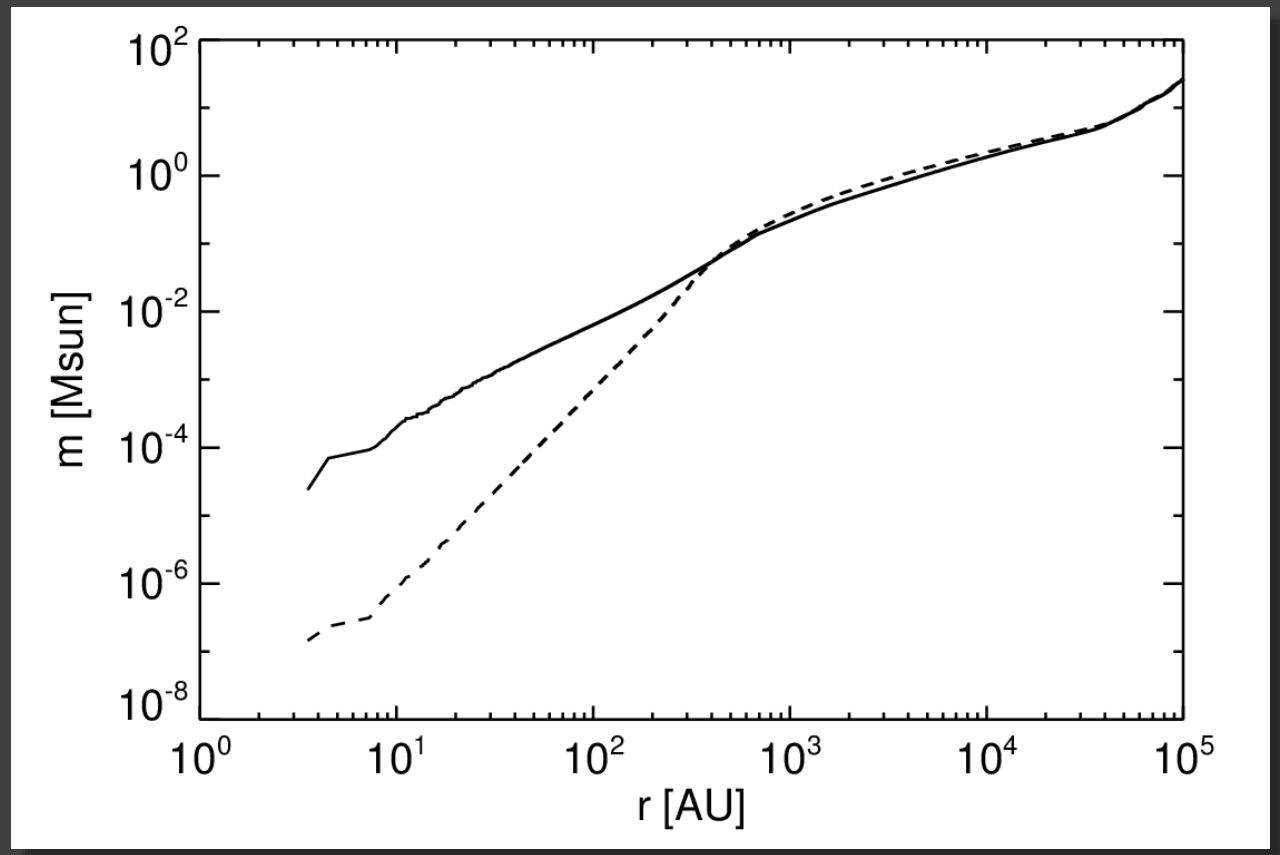




Mass Distribution with Radius

Integrated mass as a function of distance from the central sink particle (star)

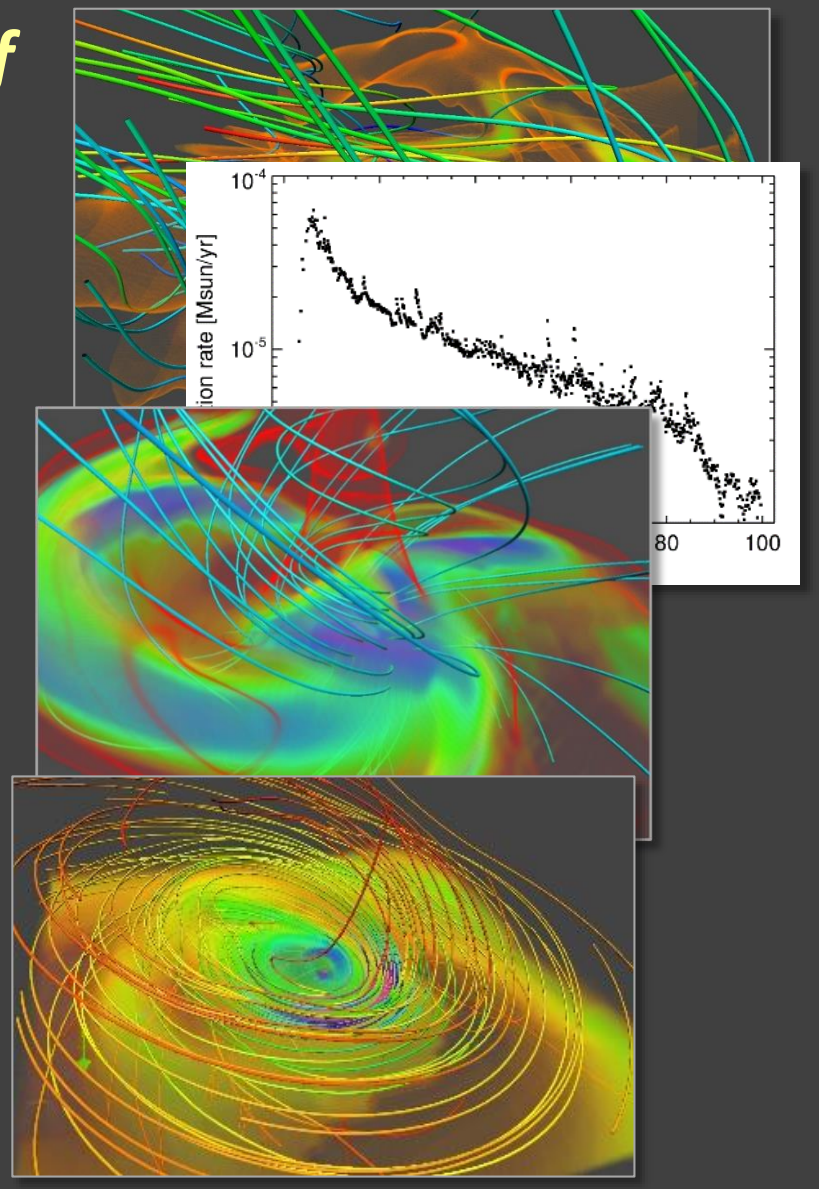
- Initially (dashed) very steep
- Quickly develops power law dependence $m \sim r^{3/2}$, ***characteristic of "free fall"***
  - Consequence of magnetic field braking!



Importance of Magnetic Fields

The simulations illustrate the ***crucial importance of magnetic fields***

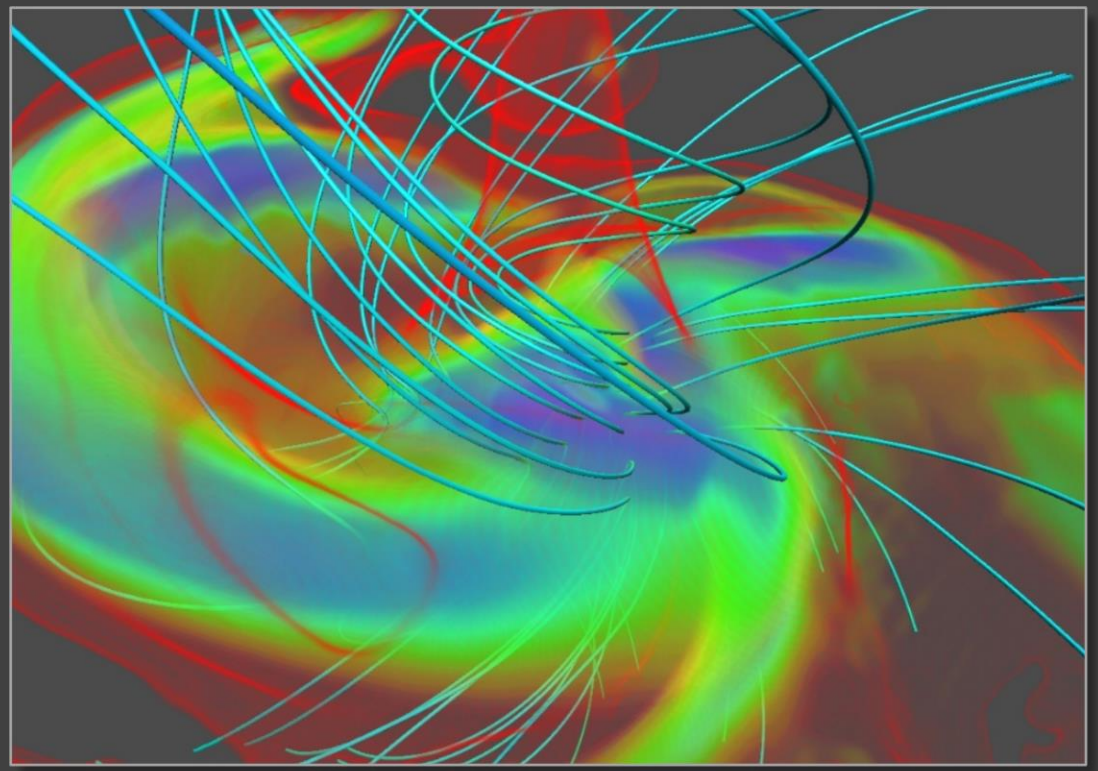
- Making fast and efficient accretion possible
  - m(r) follows free-fall scaling relation
- Producing bipolar outflows
  - Major sink of angular momentum ***and energy*** (!!!)
- Suppressing turbulence in disks
  - ***Re-enabling Goldreich & Ward ?!***



Jets and Disk Wind Outflows

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

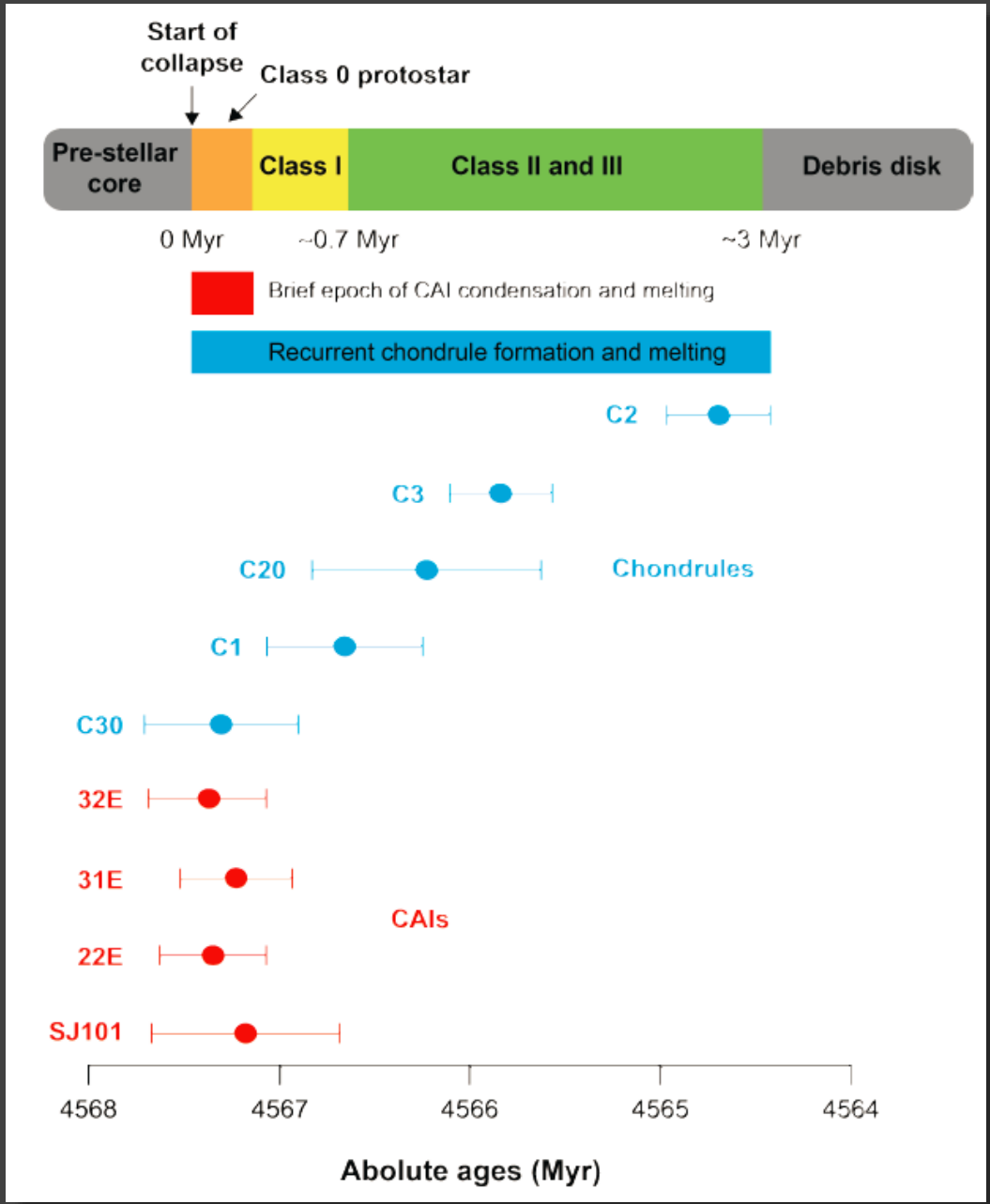
- Outer parts: disk wind with speeds ~ 10 km/s
  - Driven by inclined magnetic fields
- Inner parts: jet with outflow speeds ~ 100 km/s
  - Resolving the near-star environment is ***not*** necessary for jet formation



Impact on Understanding Early Minerals

A recent paper by Connelly et al (Science 2012) shows simultaneous presence in parent bodies formed several Myr after t = 0 of chondrules spanning a range of ages from t=0.

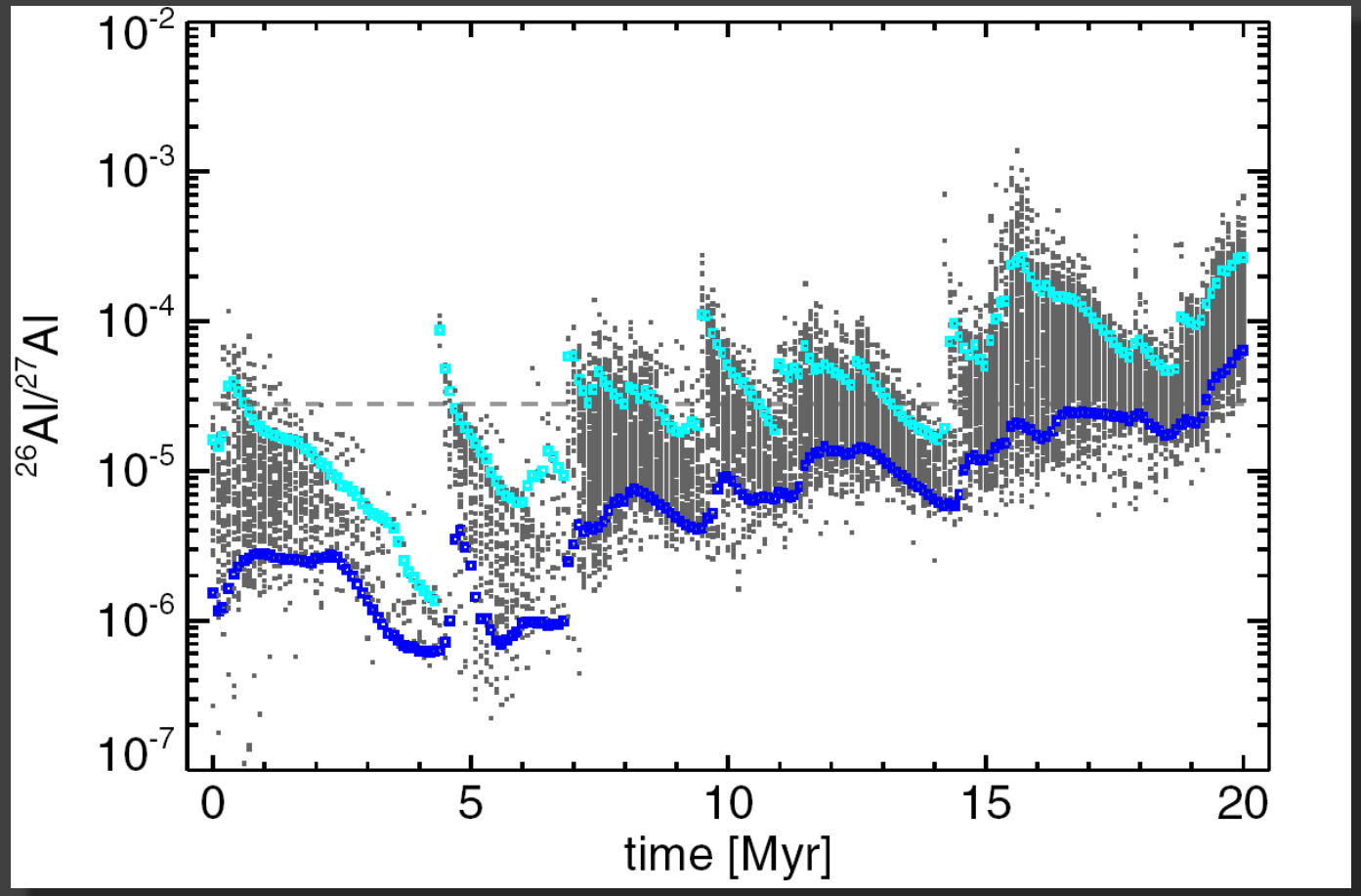
- Can only be achieved by storing chondrules for millions of years
- Large scale outflows can do this !



Transport of Short Lived Radionuclids (SLRs)

See paper by Vasileiades et al, ***ApJL, May 2013*** (also on arXiv)

- Transport from SNe is rapid enough to ***explain initial abundance of ^{26}Al in the Solar System***



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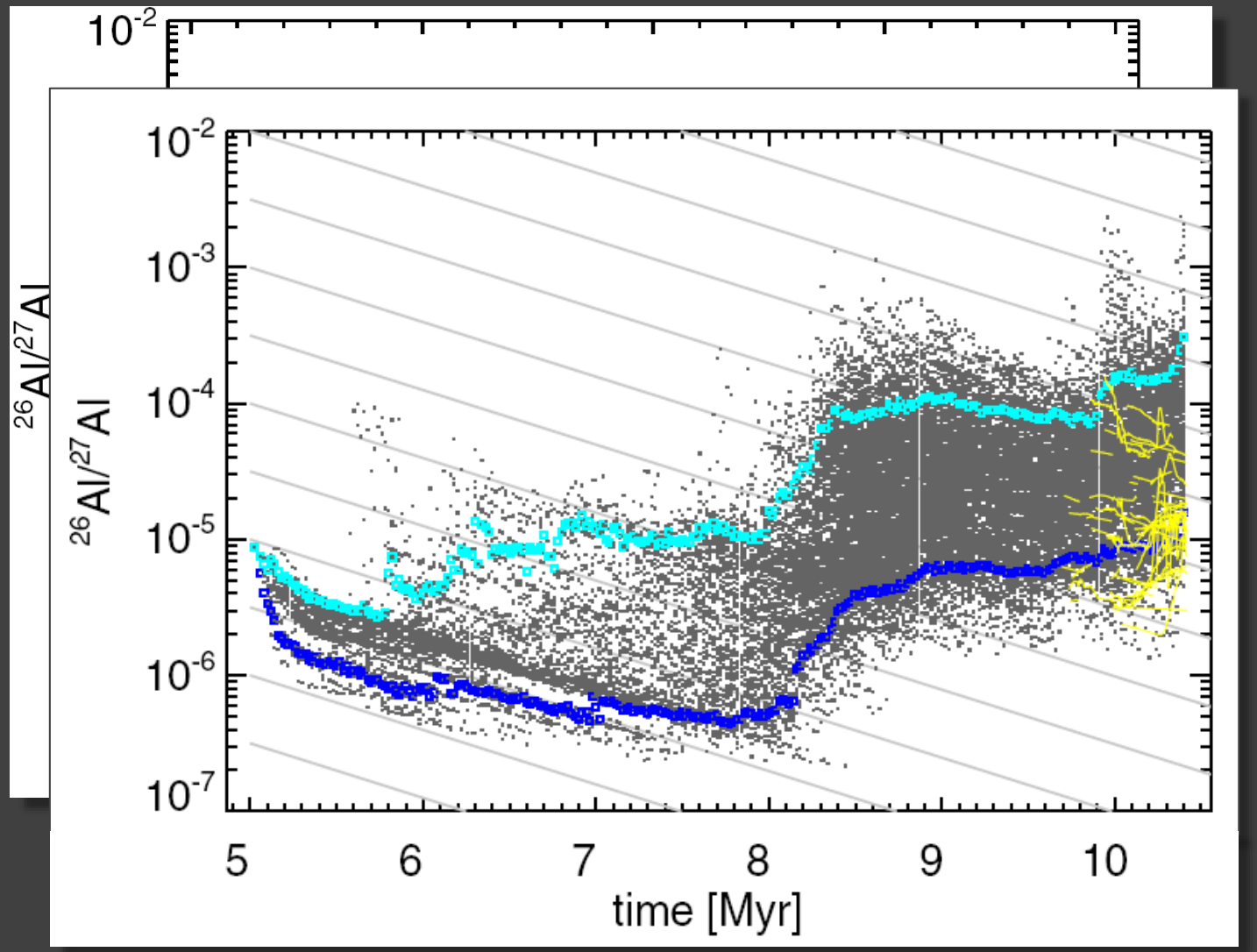
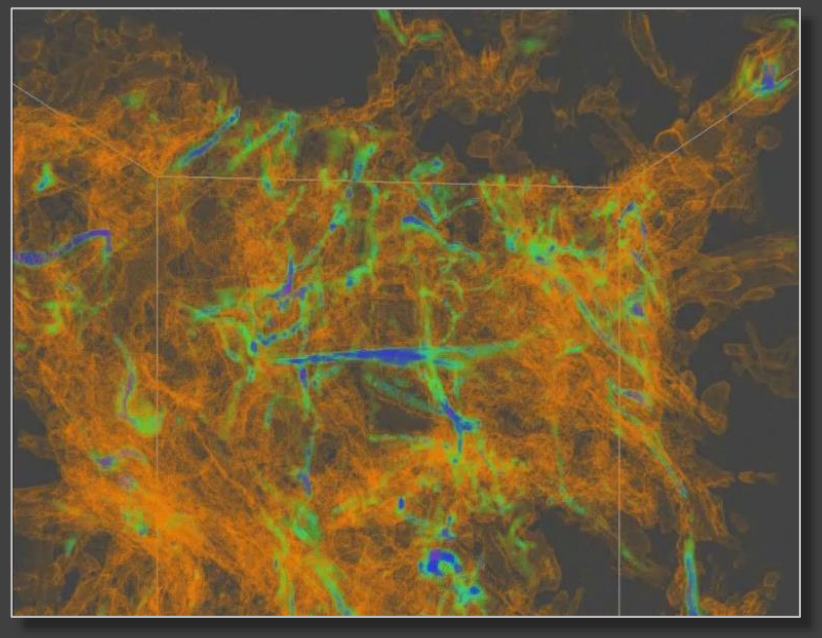


Summary

First of a kind; *ab initio* simulations of the formation of circumstellar disks



- Outer scale 40 pc, inner scale 0.016 AU
  - Scale range ~ ***9 orders of magnitude***
  - *Ab initio* modeling, ***anchored in GMC scales***
- So far: Proof of concept
  - ***Plan: Get a stastically significant sample***
- Already demonstrates crucial importance of
  - ***Magnetic fields***, mediating large scale flows and interactions
  - Those ***large scale flows*** can transport and store early minerals from $t \approx 0$

Thanks for your attention!