Towards Self-consistent Modeling of Star Formation and the Initial Mass Function

Åke Nordlund
Niels Bohr Institute & Centre for Star and Planet Formation
University of Copenhagen

with

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

Fire Down Below, KITP, April 14-18, 2014

Basic Philosophy: Resolve “everything” !

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Time scales:

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Parameter spaces***:***

- ***Avoid*** getting lost in ***multi-dimensional parameter spaces***

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- If we have a theory:
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A: To understand, and to double-check understanding !

- If we have a theory:
  - It needs to be checked = verified | refuted
- If we have no theory:
  - Being able to investigate in 4-D (space + time) is a perfect foundation to build one on

Overview of the rest of this talk

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  - Zoom simulations
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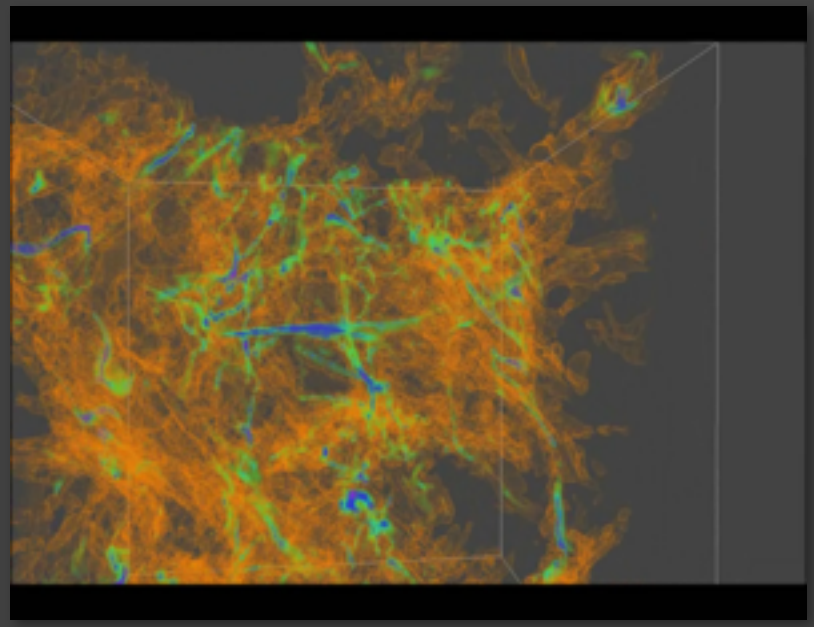
- ***Discussion & Conclusions***
  - What's next / what's missing

Star Formation: Zooming in on solar mass stars

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



- Outer scale 40 pc, inner scale 0.01 AU
  - **Ratio 1 : 2^{29} ≈ 1 : 1 billion**
  - Animations zoom over 7 orders of magnitude

- So far: Proof of concept
  - 4 solar-mass stars
  - **Plan: Get a statistically significant sample of solar mass stars**

On arXiv: astro-ph/1309.2278

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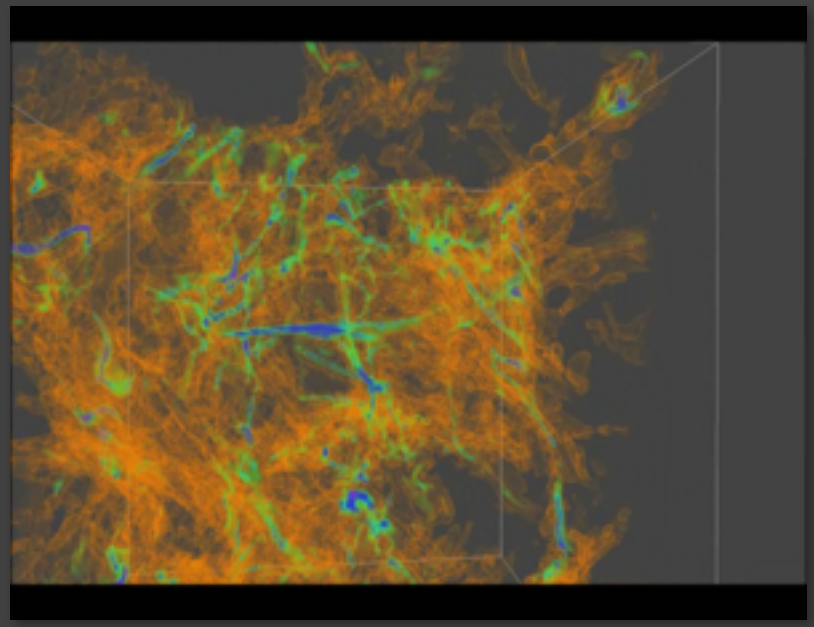

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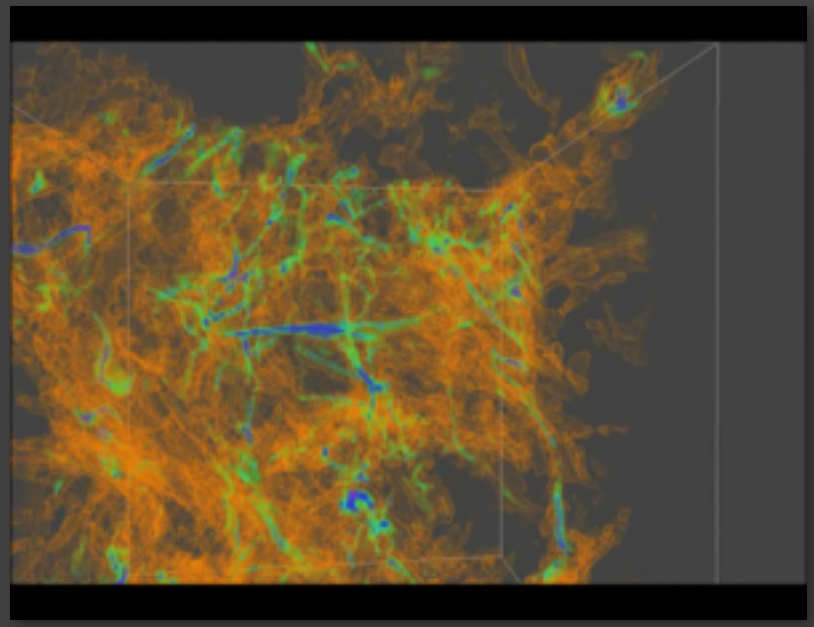

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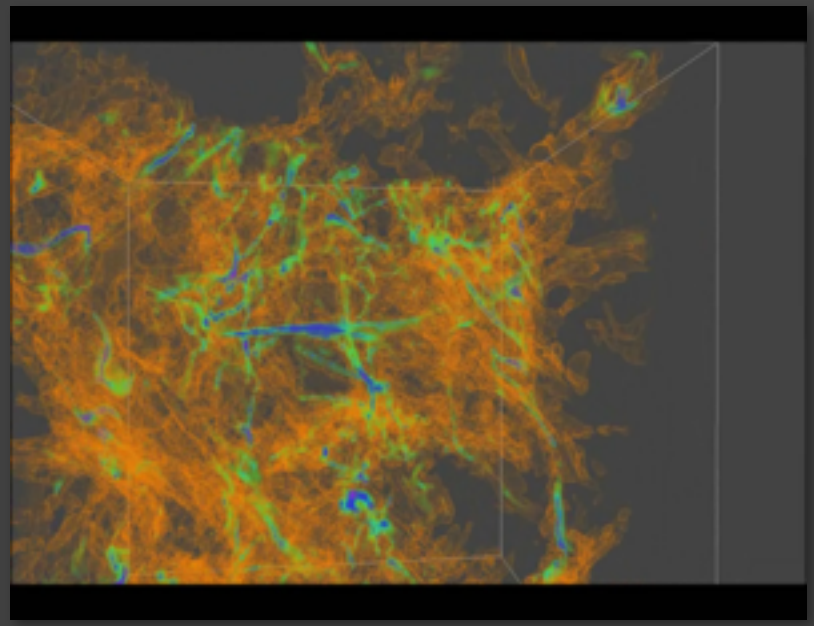

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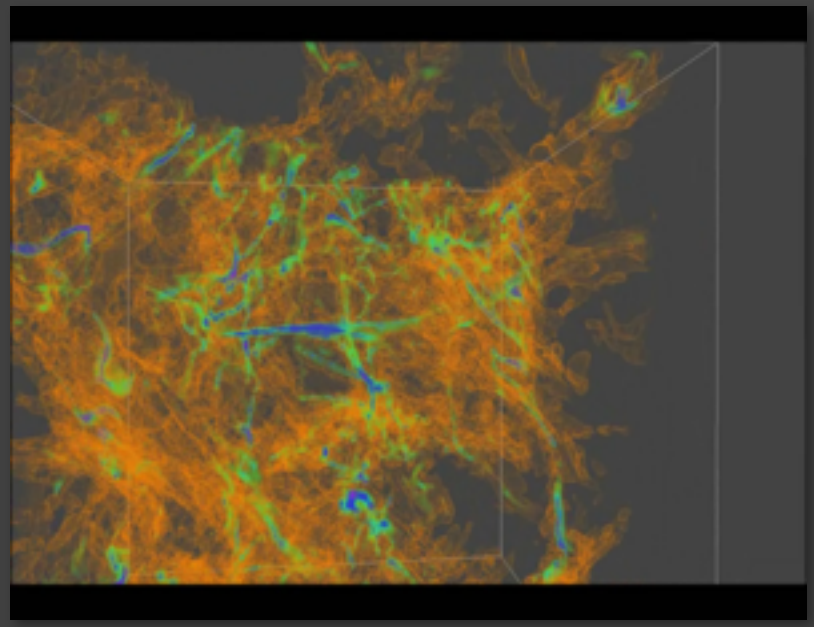

40 pc = 8 10^6 AU

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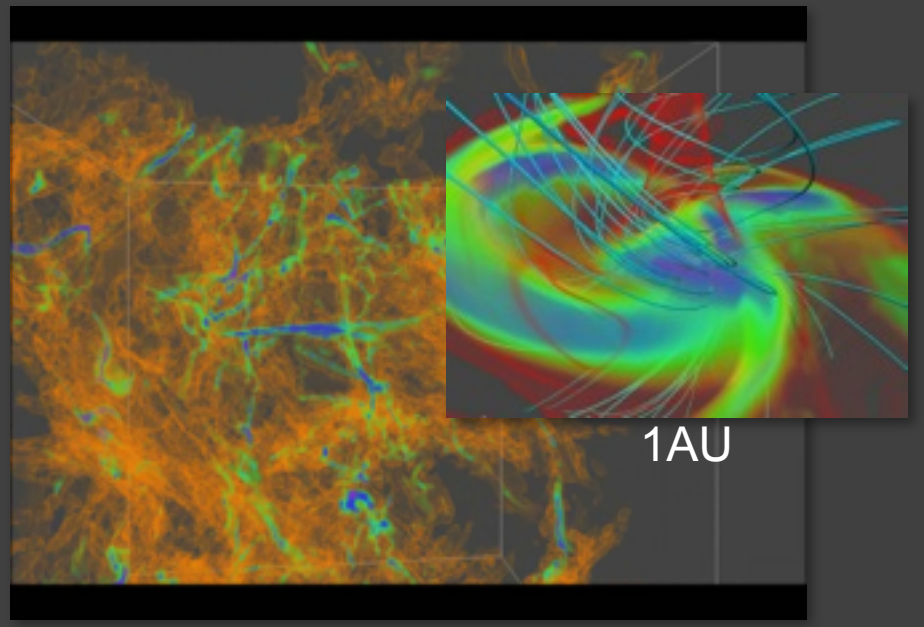

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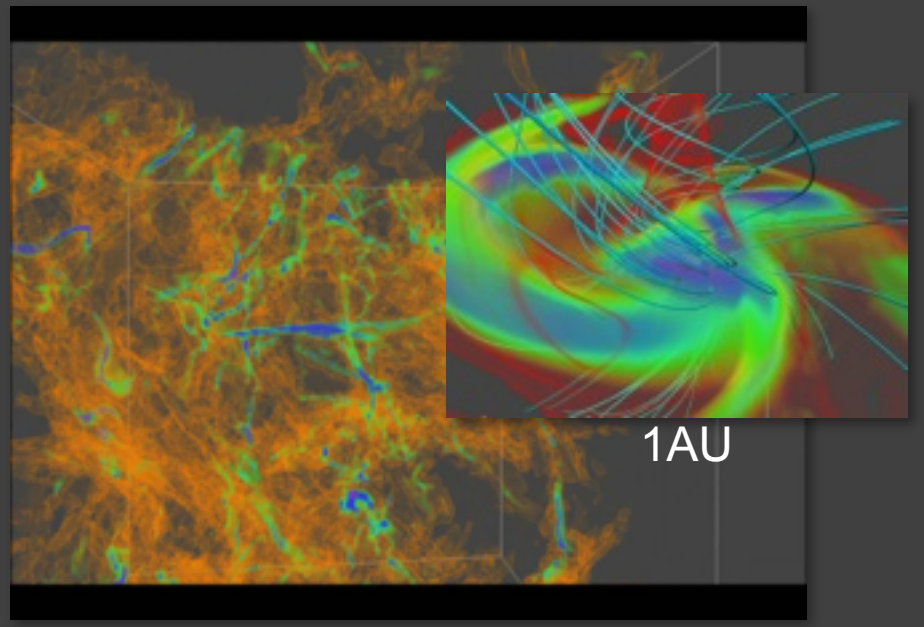

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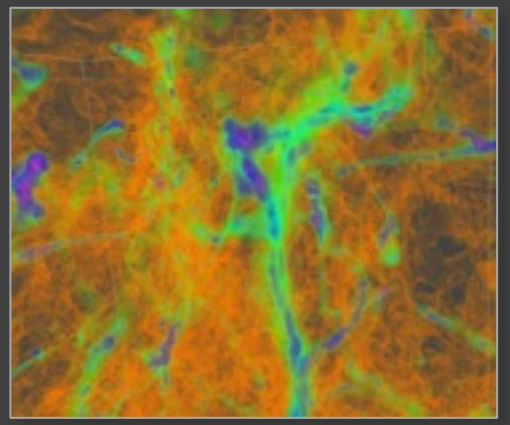

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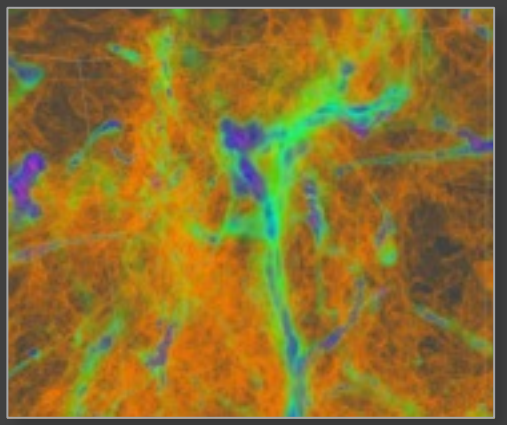

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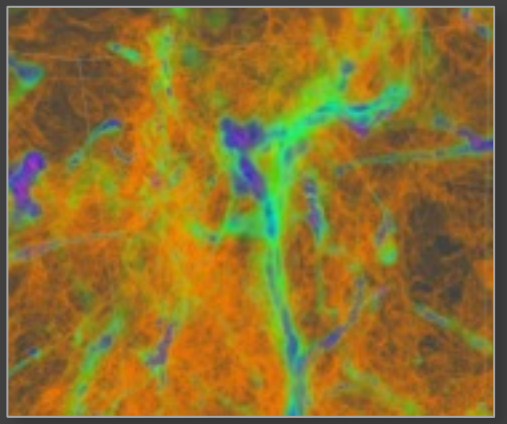

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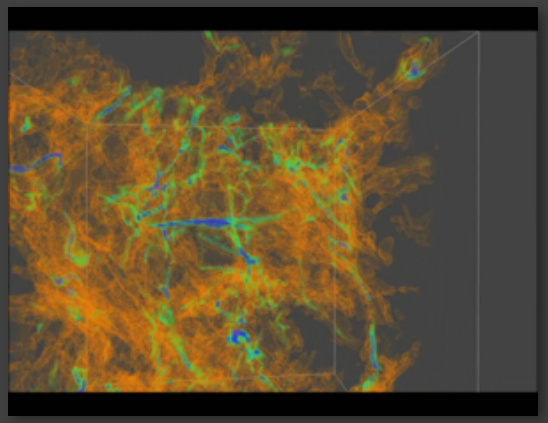
BUT: if Moore's law continues, such an increase with 50 powers of two will take less than 80 years (!)

Basic Zoom 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
- ***Drawback:*** Must cover about 9 orders of magnitude in size
  - From GMC scales to resolving vertical structure of PP disks

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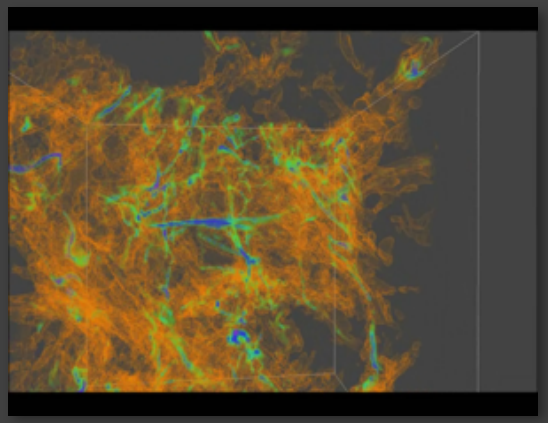

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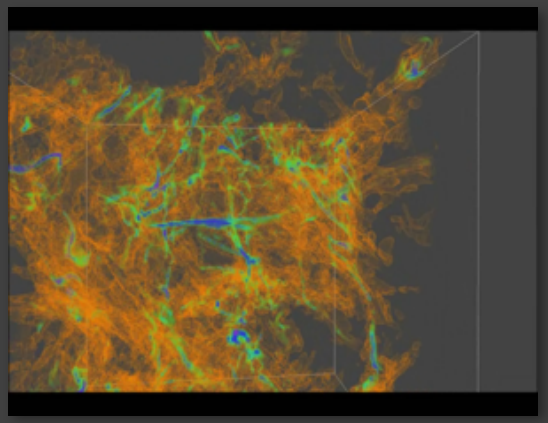

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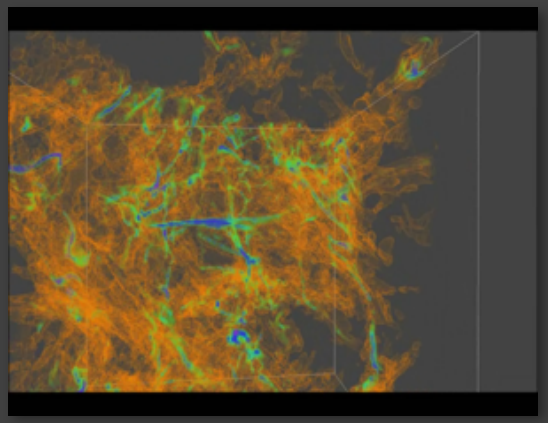

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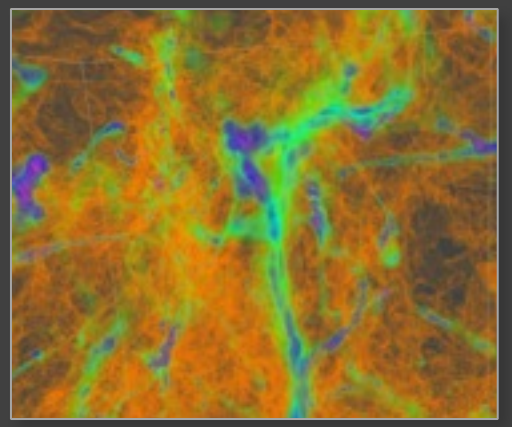
However, even simulating only the PP-disk part would require a scale range from at least ~300 AU to ~0.01 AU – the full range is "only about twice as expensive" (AMR!)

Three Simulation Zoom Levels

- ***Giant Molecular Cloud scales***
  - Size: 40pc
  - Refinement: $2^{16} \Rightarrow$ cell size 120 AU
  - Time duration: $\approx$ 10 Myr



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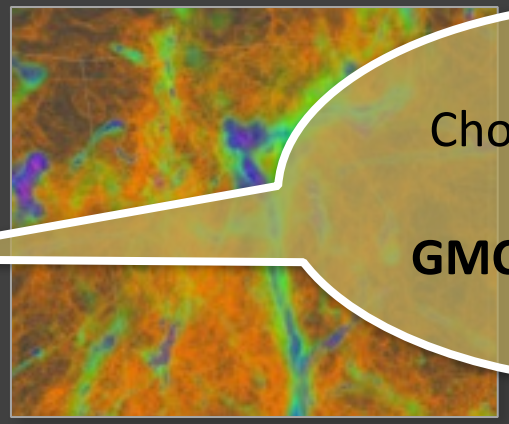

Chosen to be able to afford a few **GMC dynamical times**

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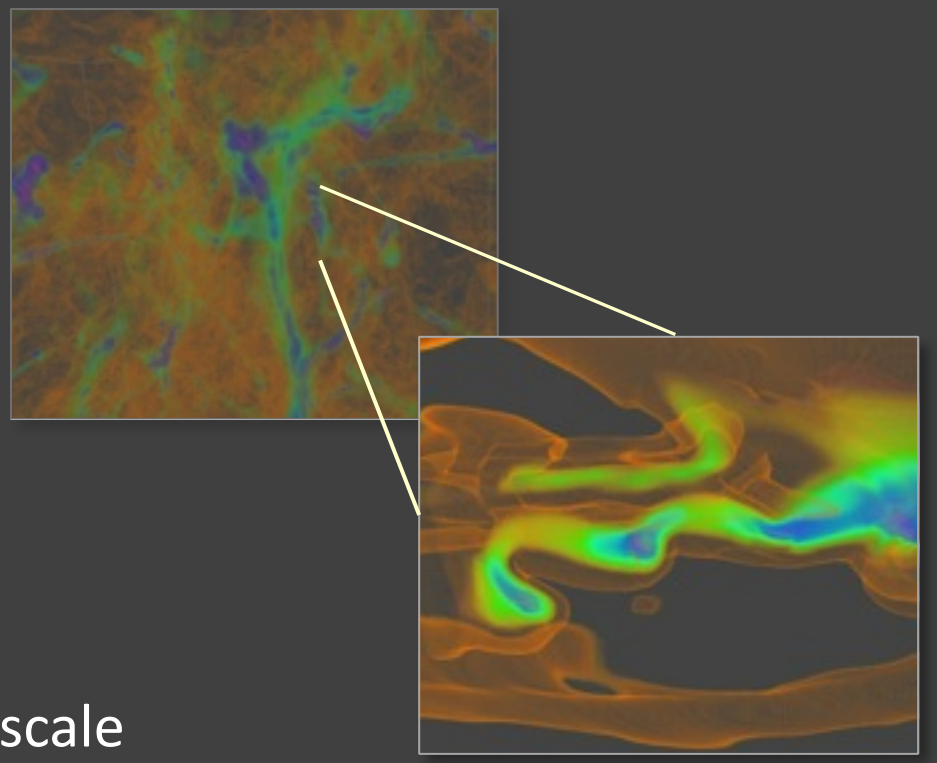
  - Dynamic scale: ~ 0.5 pc
  - Refinement: $2^{22} \Rightarrow$ cell size 2 AU
  - Time duration: $\approx$ 100 kyr $\approx$ accretion time scale



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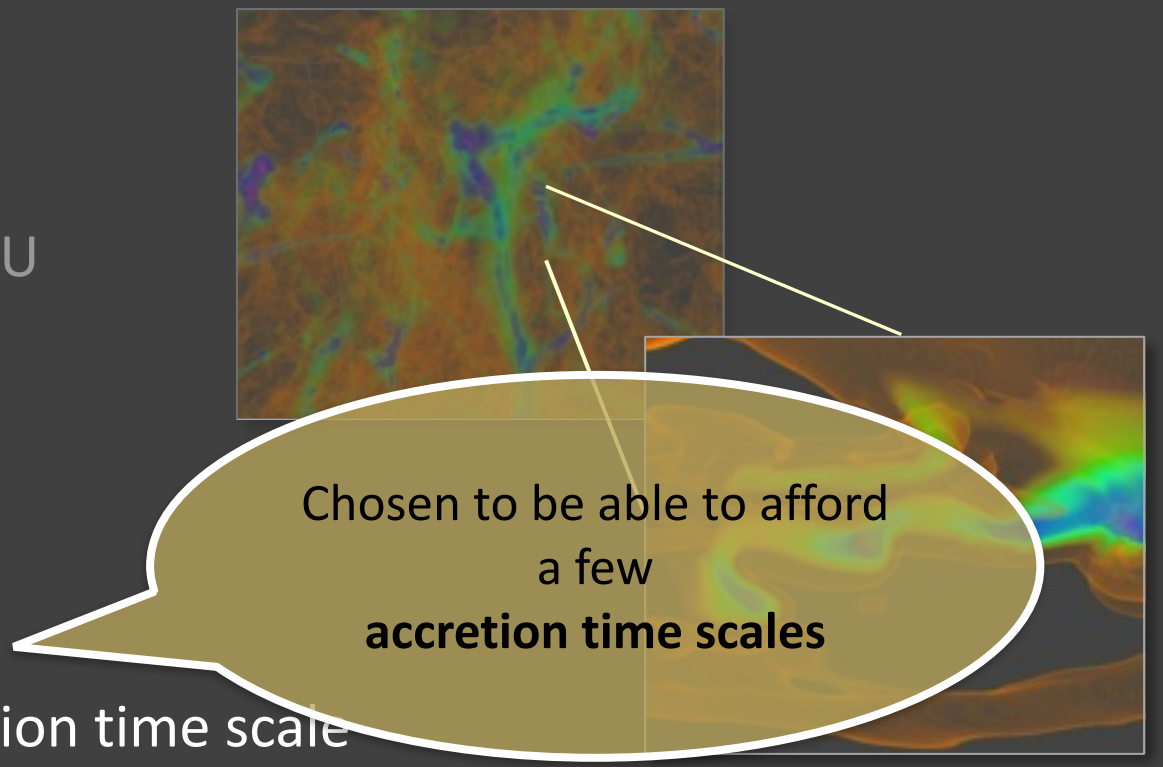

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  - Dynamic scale: ~ 5 AU
  - Refinement: 2^{30} => cell size 0.008 AU (!)
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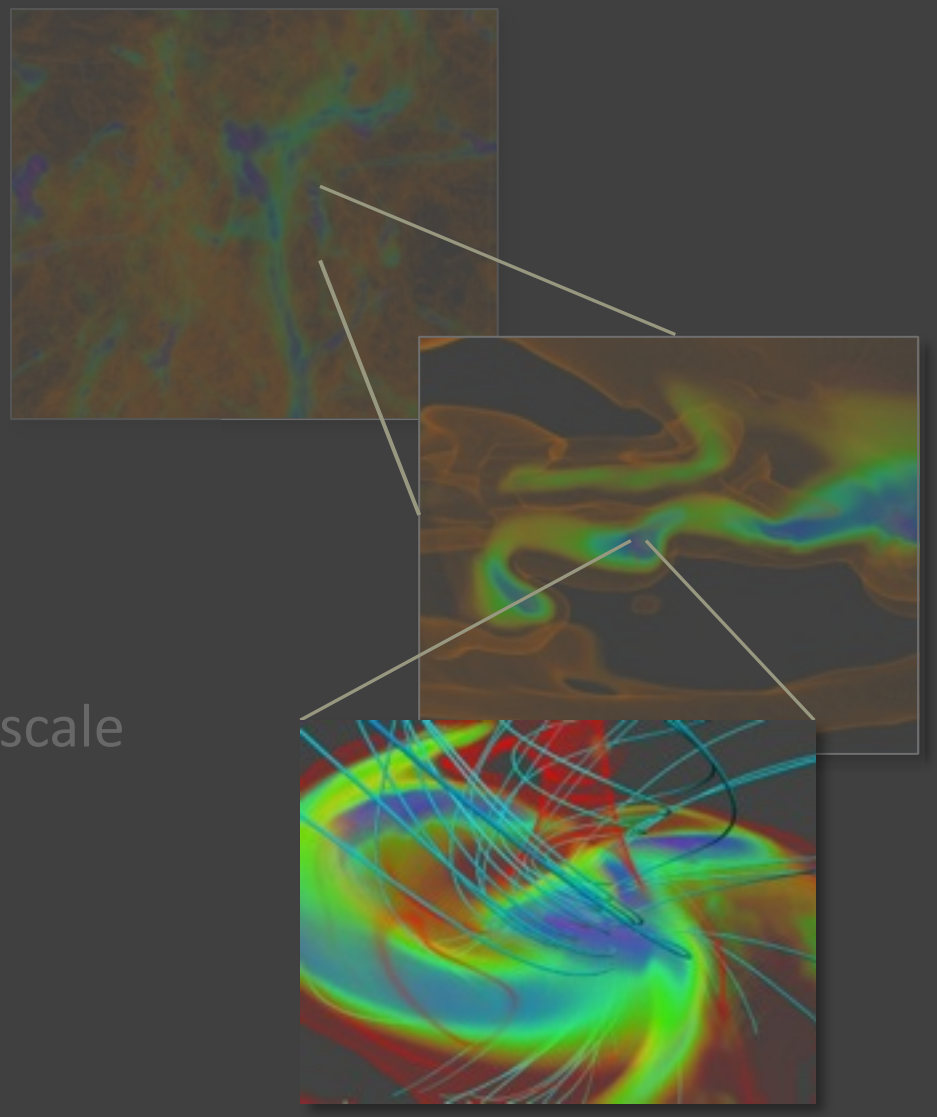

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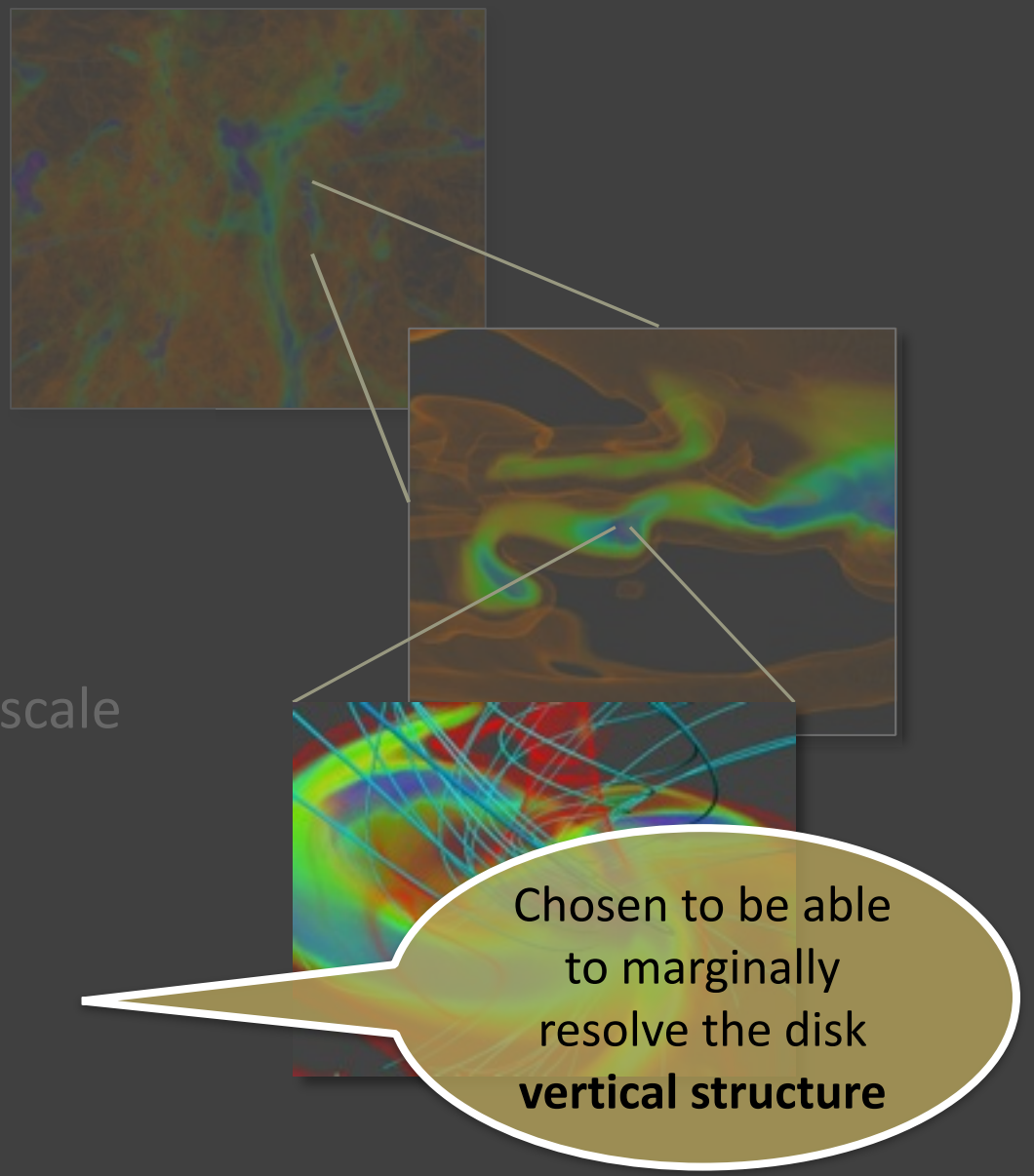

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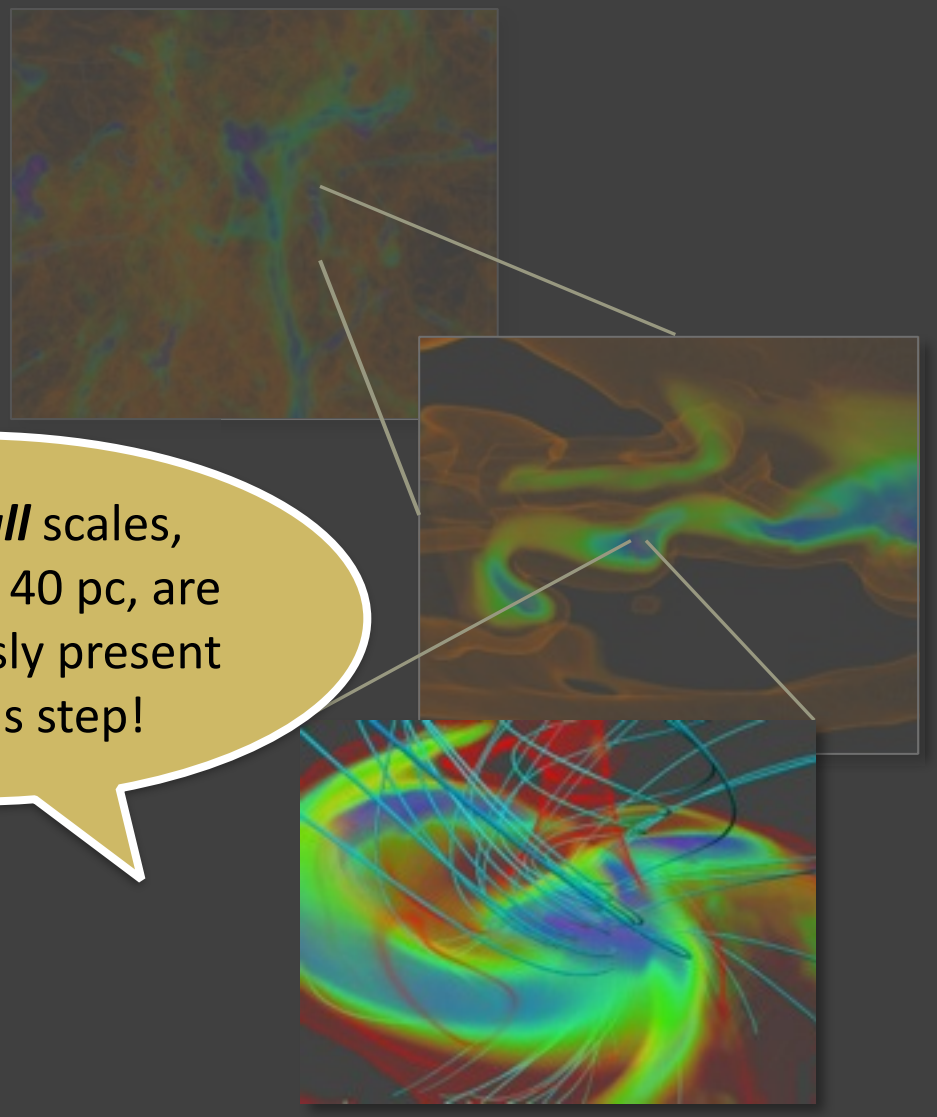
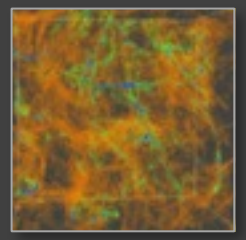
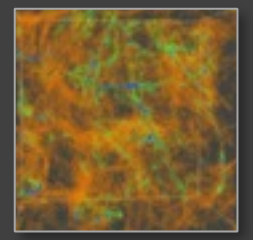


Note that ***all*** scales, up to the full 40 pc, are simultaneously present also in this step!

Time Scale Zoom

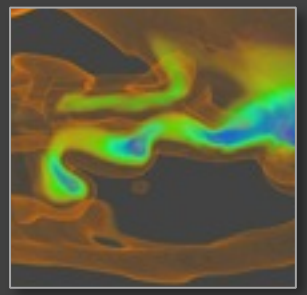
~ 10^7 AU



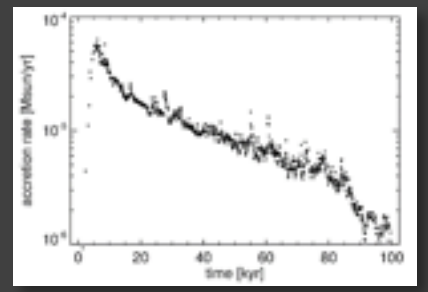


GMC Evolution Time Scale ~ **10 Myr**

~ 10^4 AU



Stellar Accretion Time Scale ~**100 kyr**



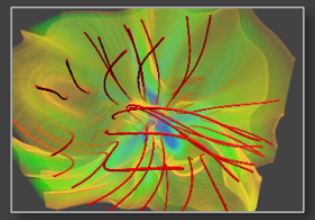
Disk Dynamics Time Scale ~ **1 kyr**

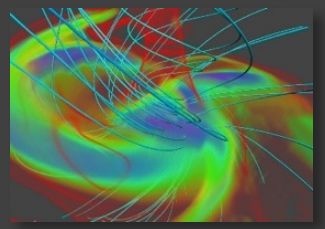
EARLY

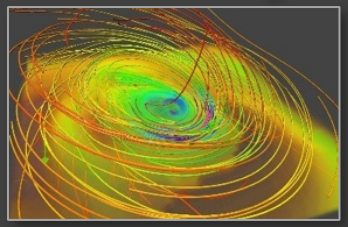
MID

LATE

~ 10 AU







Time Scale Zoom

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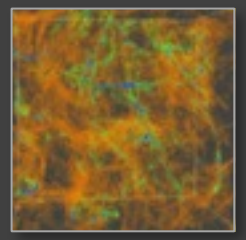

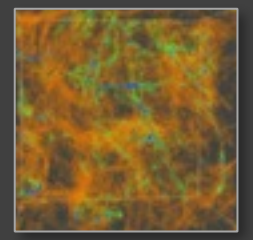

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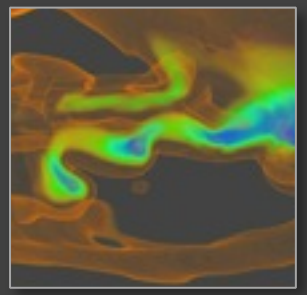
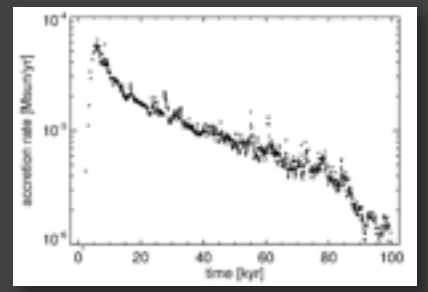


Stellar Accretion Time Scale ~**100 kyr**



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EARLY

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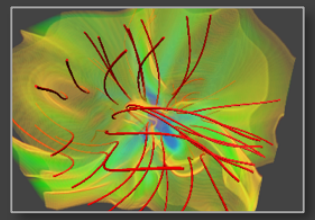
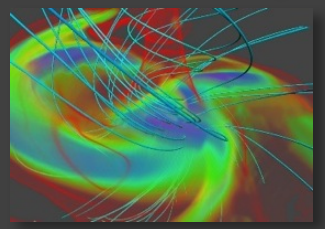
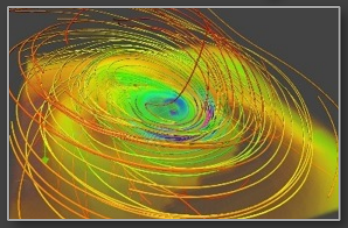
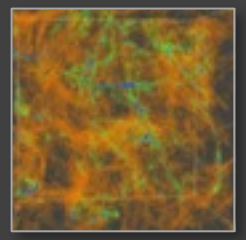


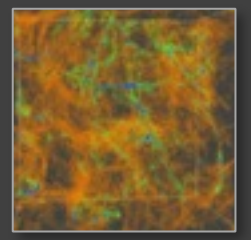




Time Scale Zoom

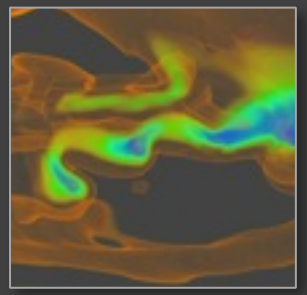
~ 10^7 AU



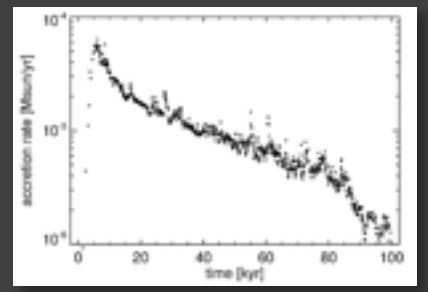


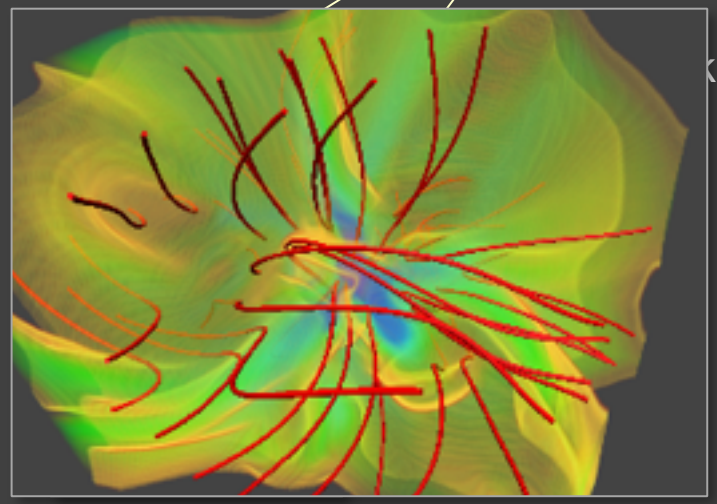
GMC Evolution Time Scale ~ **10 Myr**

~ 10^4 AU



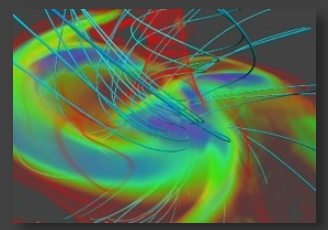
Stellar Accretion Time Scale ~**100 kyr**



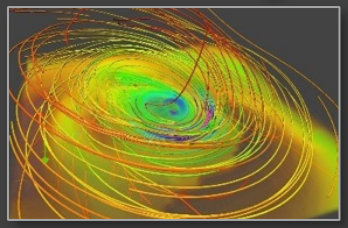


k Dynamics Time Scale ~ **1 kyr**

MID



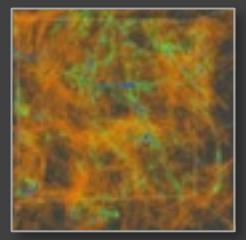
LATE

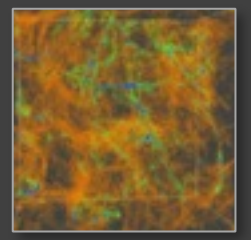


~ 10 AU

Time Scale Zoom

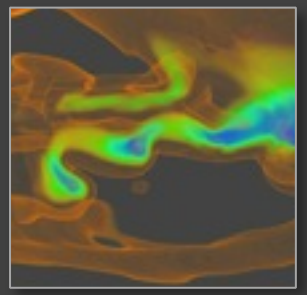
~ 10^7 AU



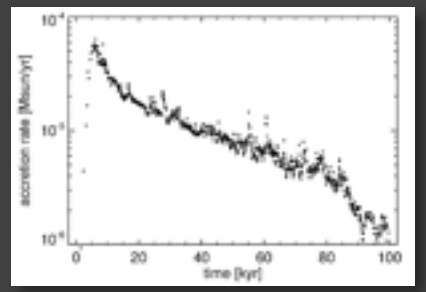


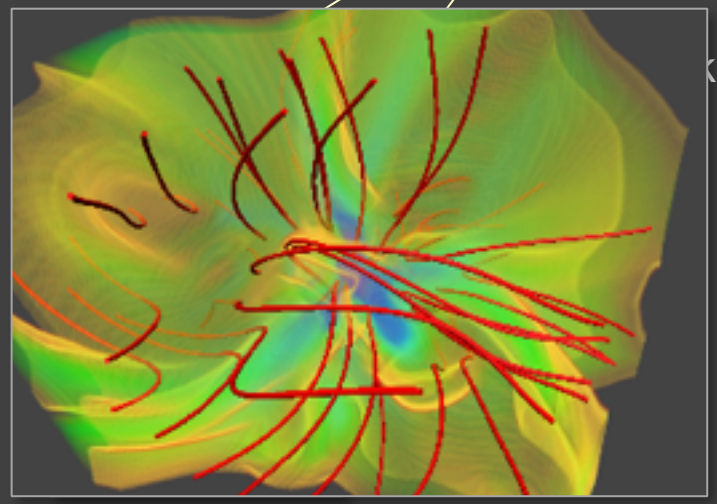
GMC Evolution Time Scale ~ **10 Myr**

~ 10^4 AU



Stellar Accretion Time Scale ~**100 kyr**

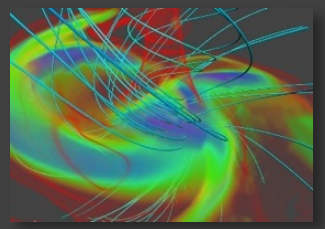


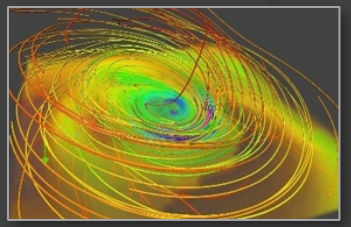


k Dynamics Time Scale ~ **1 kyr**

MID

LATE

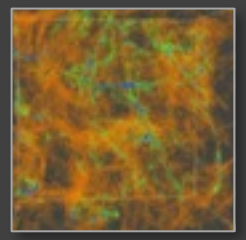


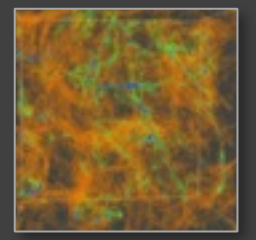


~ 10 AU

Time Scale Zoom

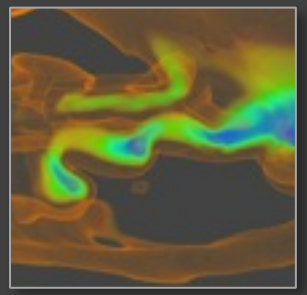
~ 10^7 AU



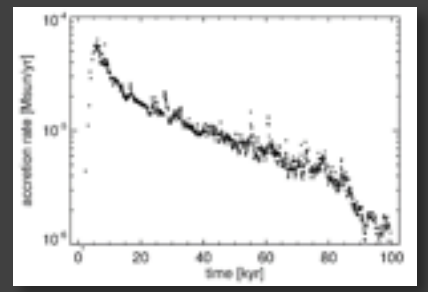


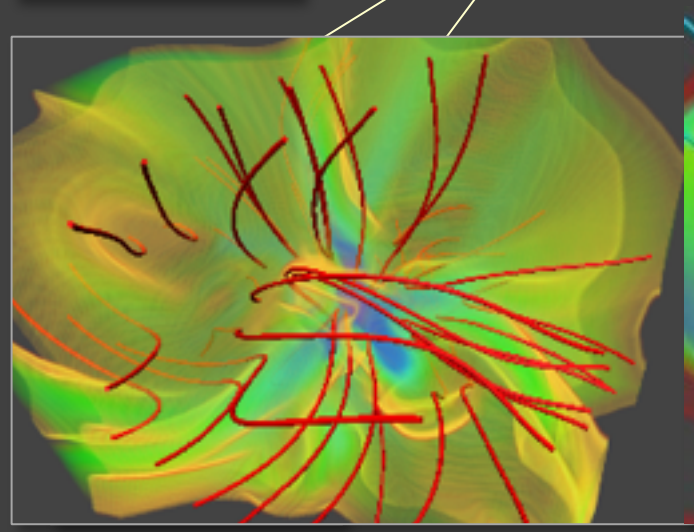
GMC Evolution Time Scale ~ **10 Myr**

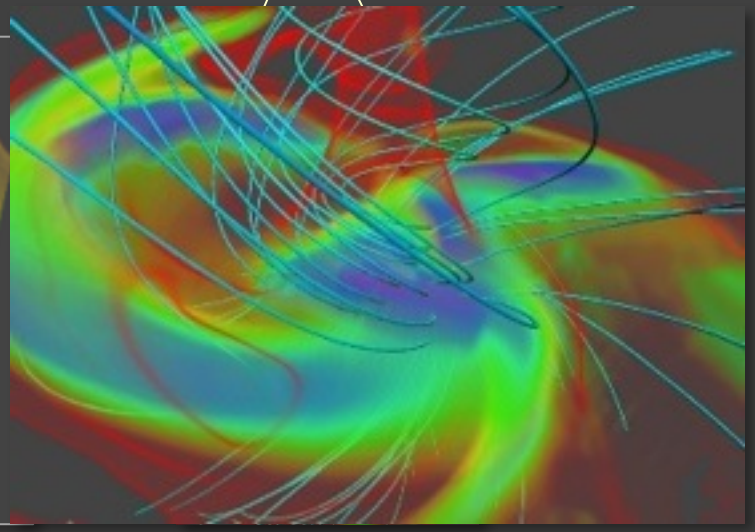
~ 10^4 AU



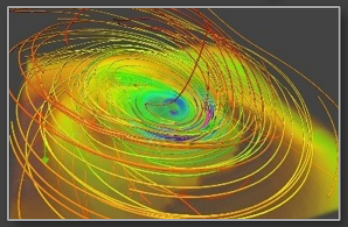
Stellar Accretion Time Scale ~**100 kyr**







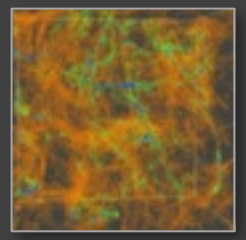
LATE

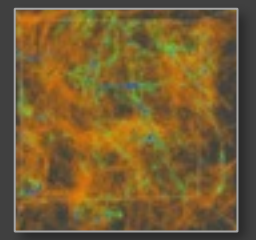


~ 10 AU

Time Scale Zoom

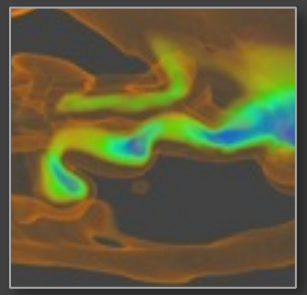
~ 10^7 AU



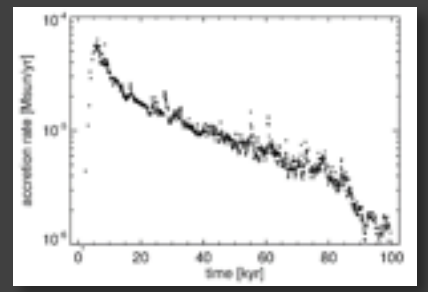


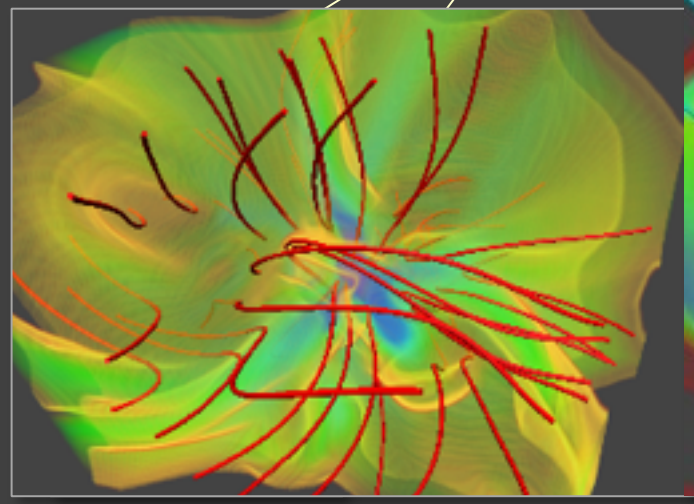
GMC Evolution Time Scale ~ **10 Myr**

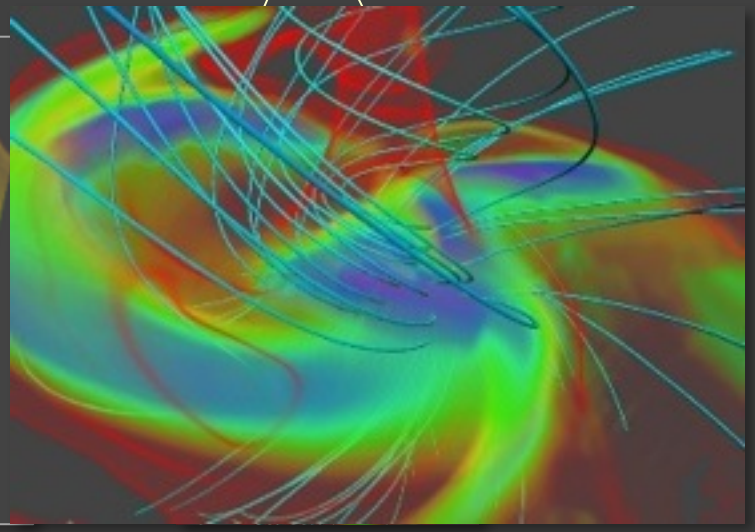
~ 10^4 AU



Stellar Accretion Time Scale **~100 kyr**

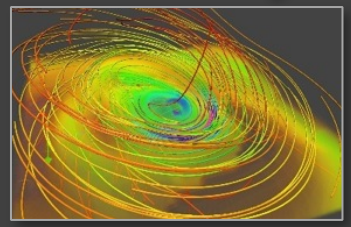






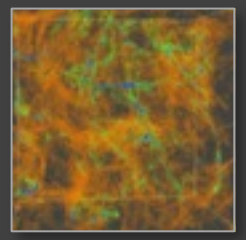
LATE

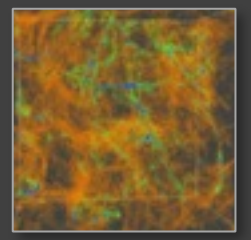
~ 10 AU



Time Scale Zoom

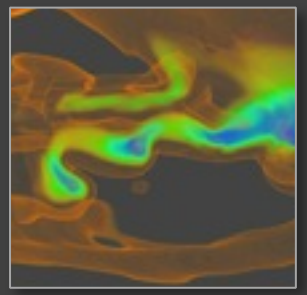
~ 10^7 AU



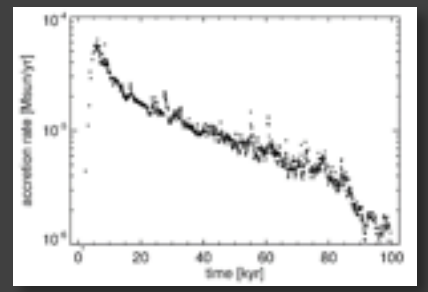


GMC Evolution Time Scale ~ **10 Myr**

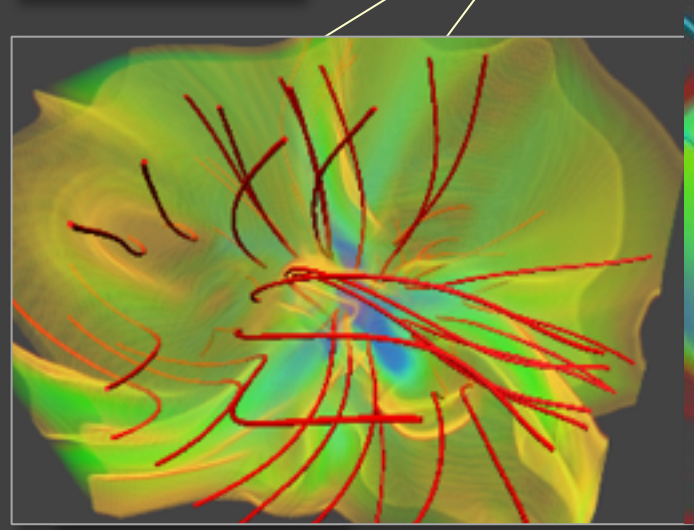
~ 10^4 AU

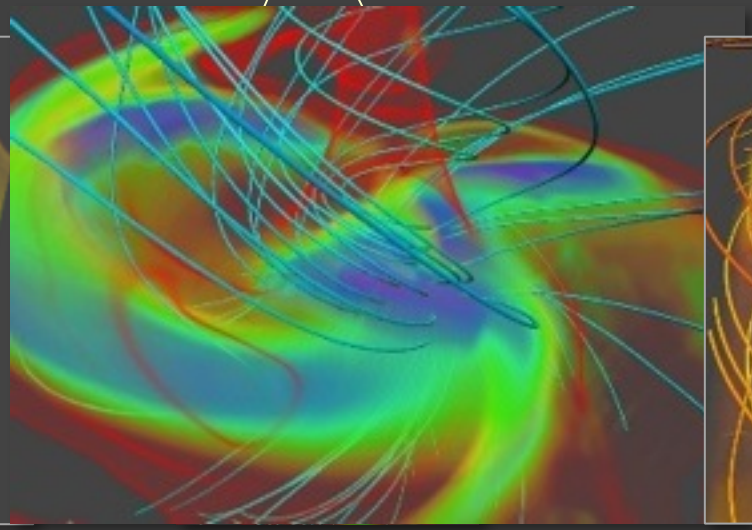


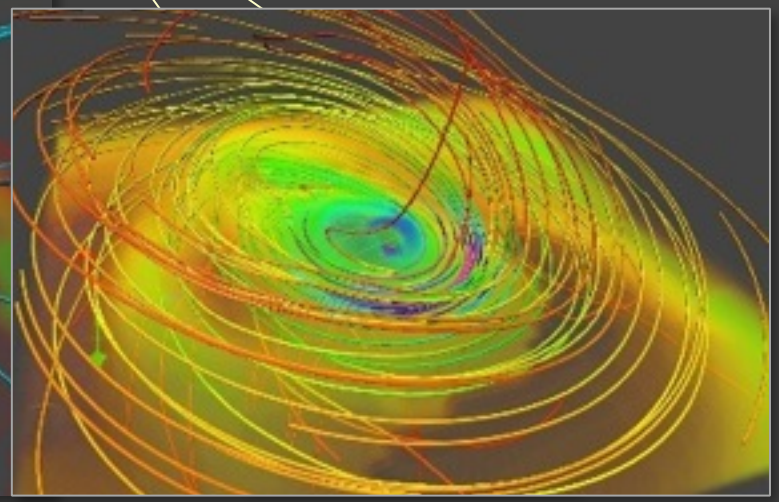
Stellar Accretion Time Scale **~100 kyr**



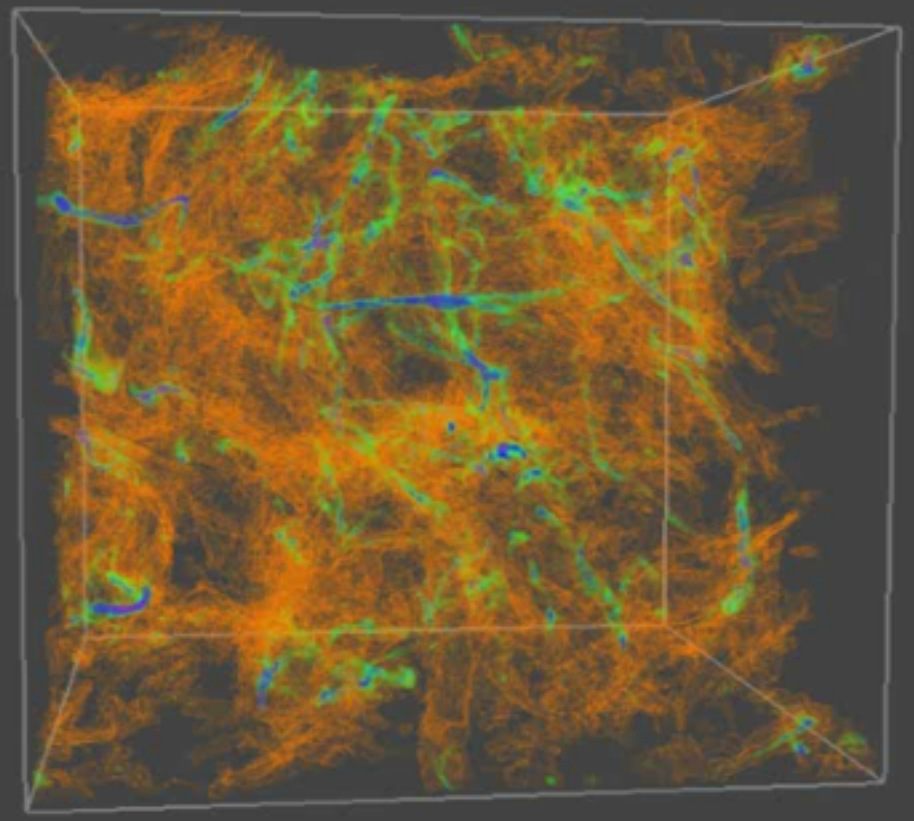
~ 10 AU







From GMC scales to disk with jet and outflow



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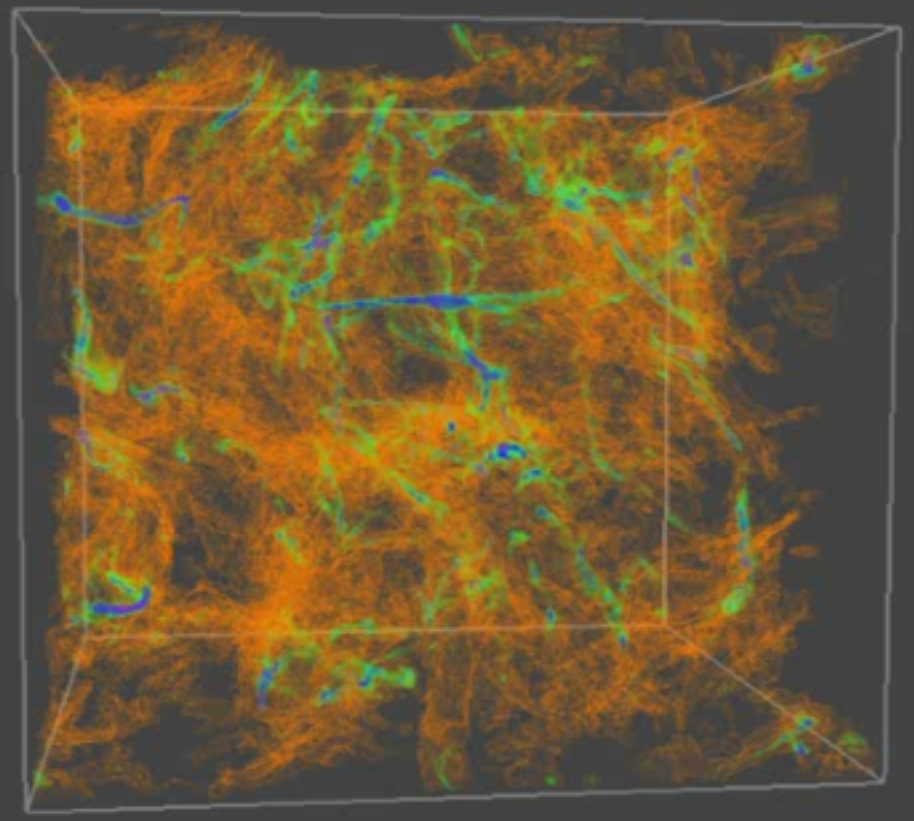
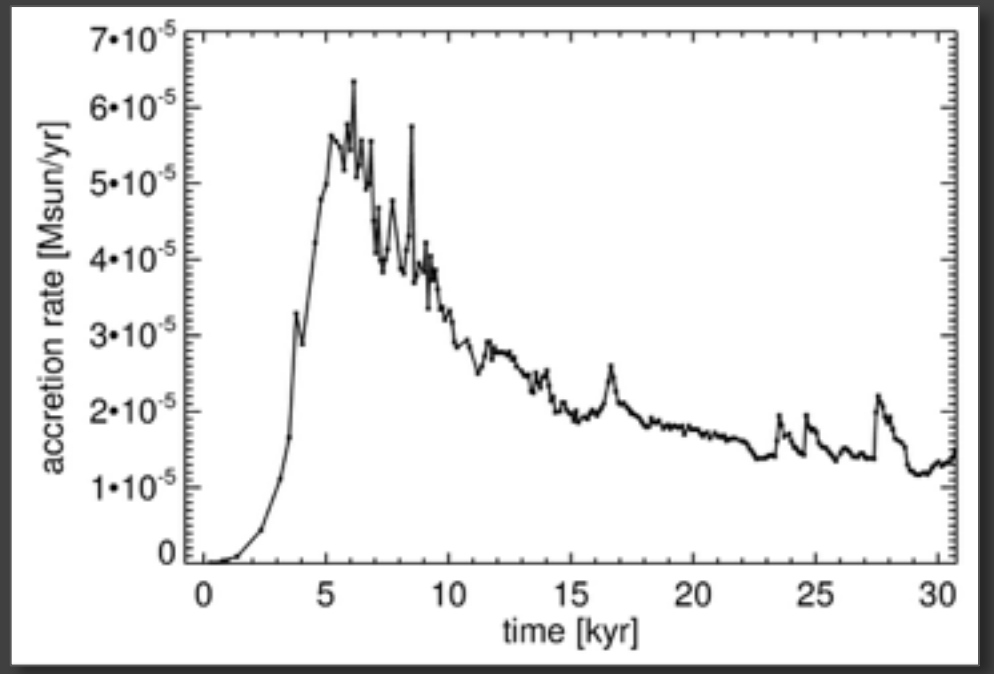
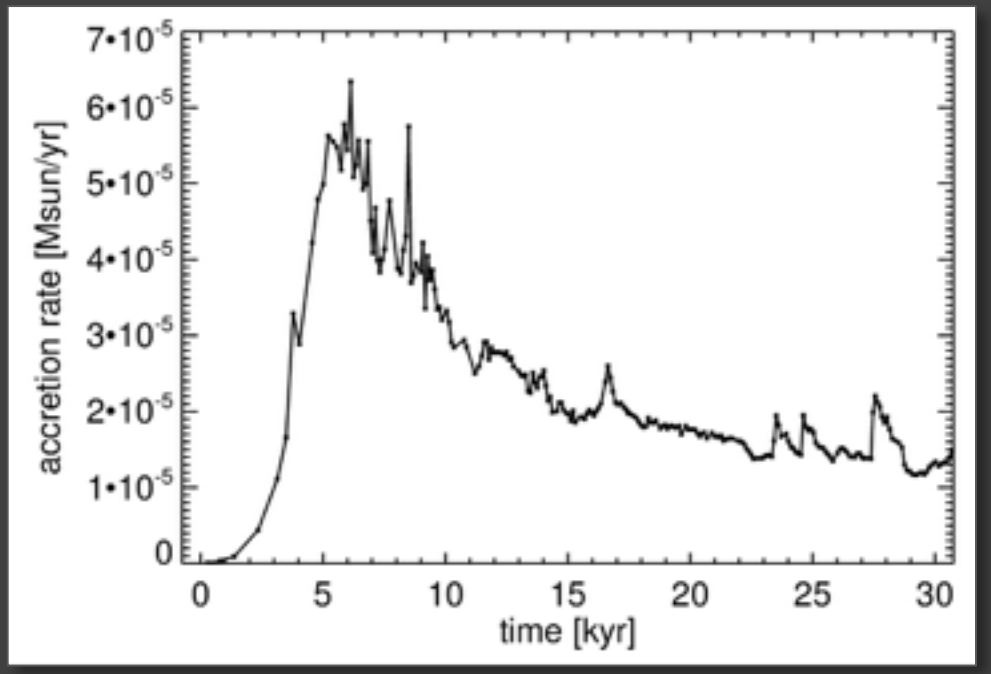


Accretion Rates



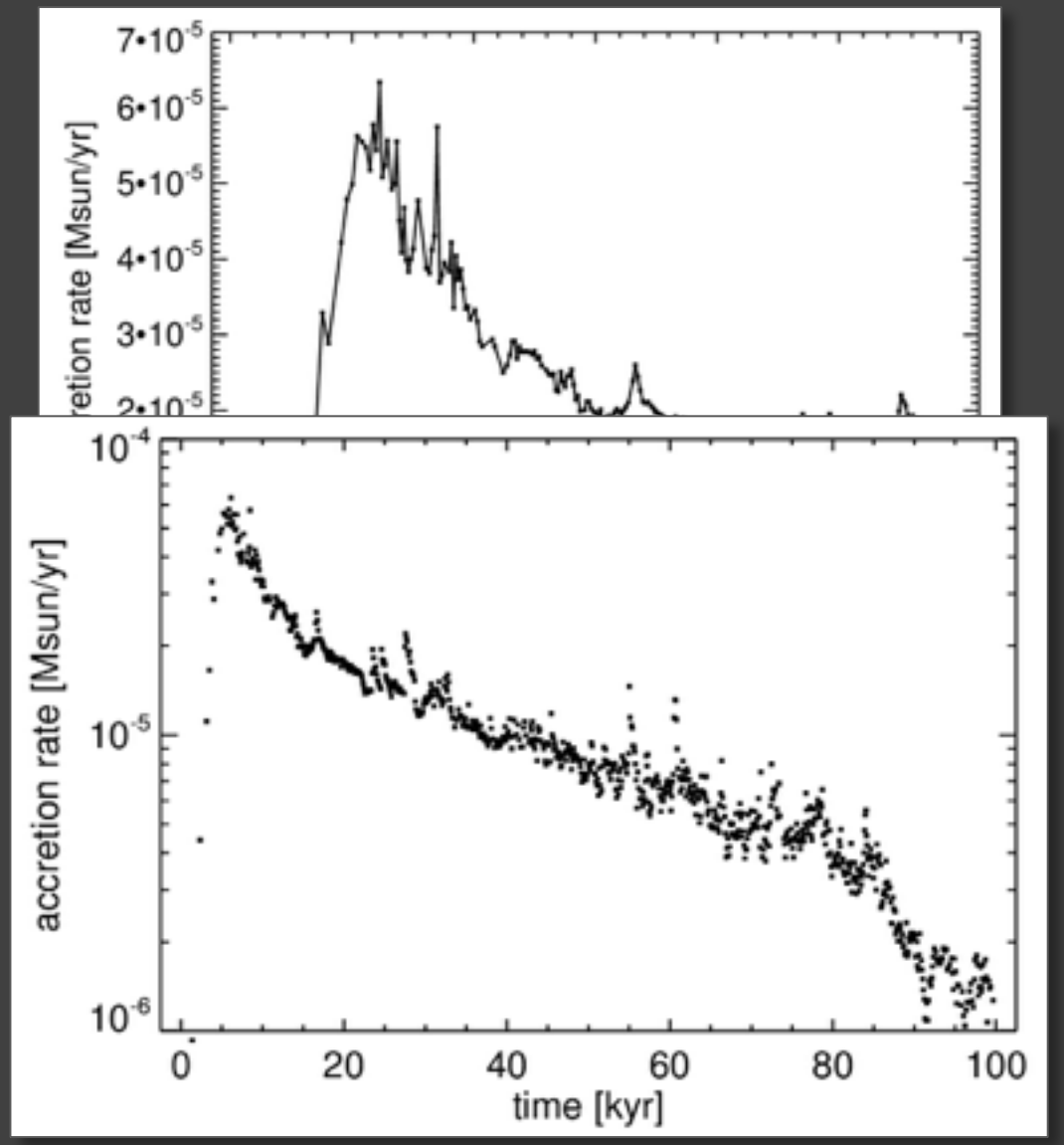
Accretion Rates



Accretion Rates

Instantaneous accretion rate to the central sink particle:

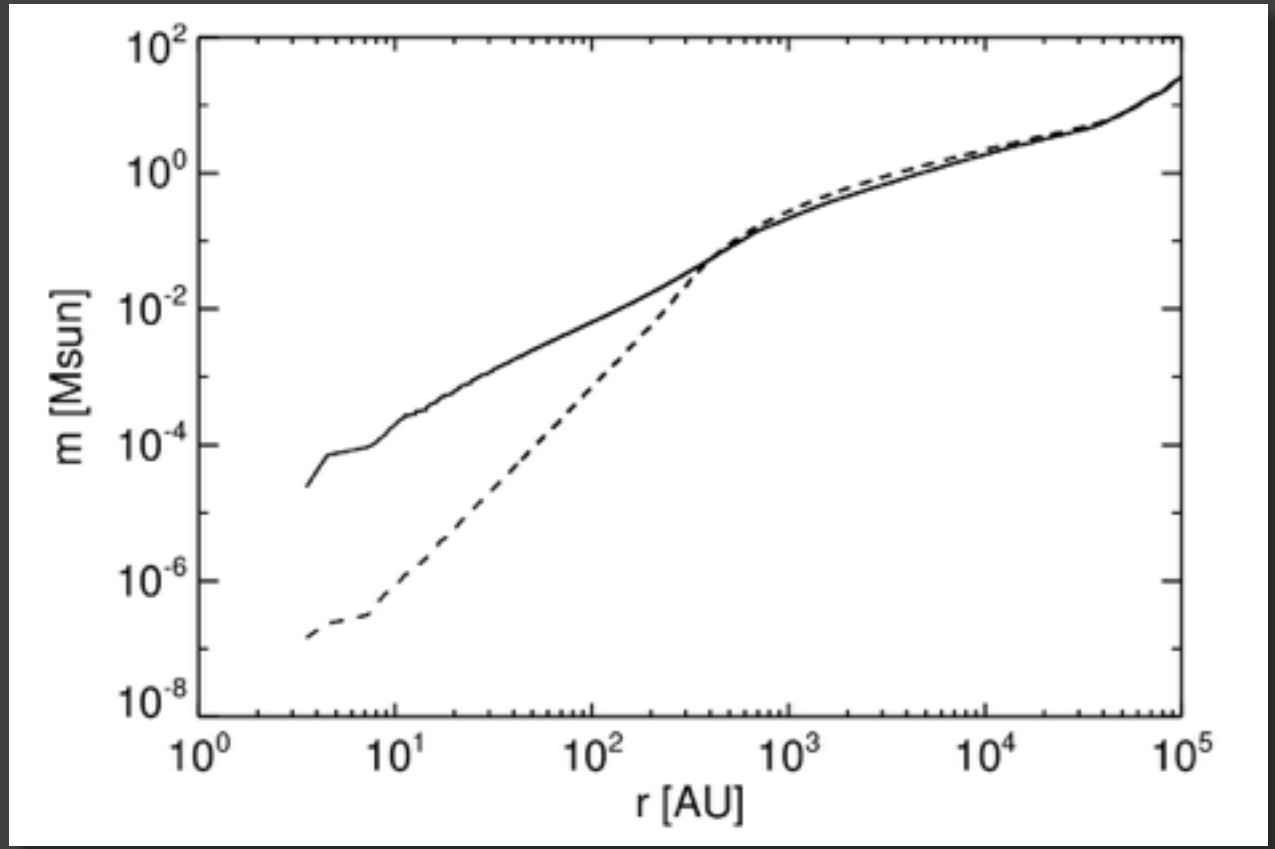
- Peaks after about 5 kyr, fluctuates due to magnetic field topology changes
- Decreases exponentially with time thereafter



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 braking!



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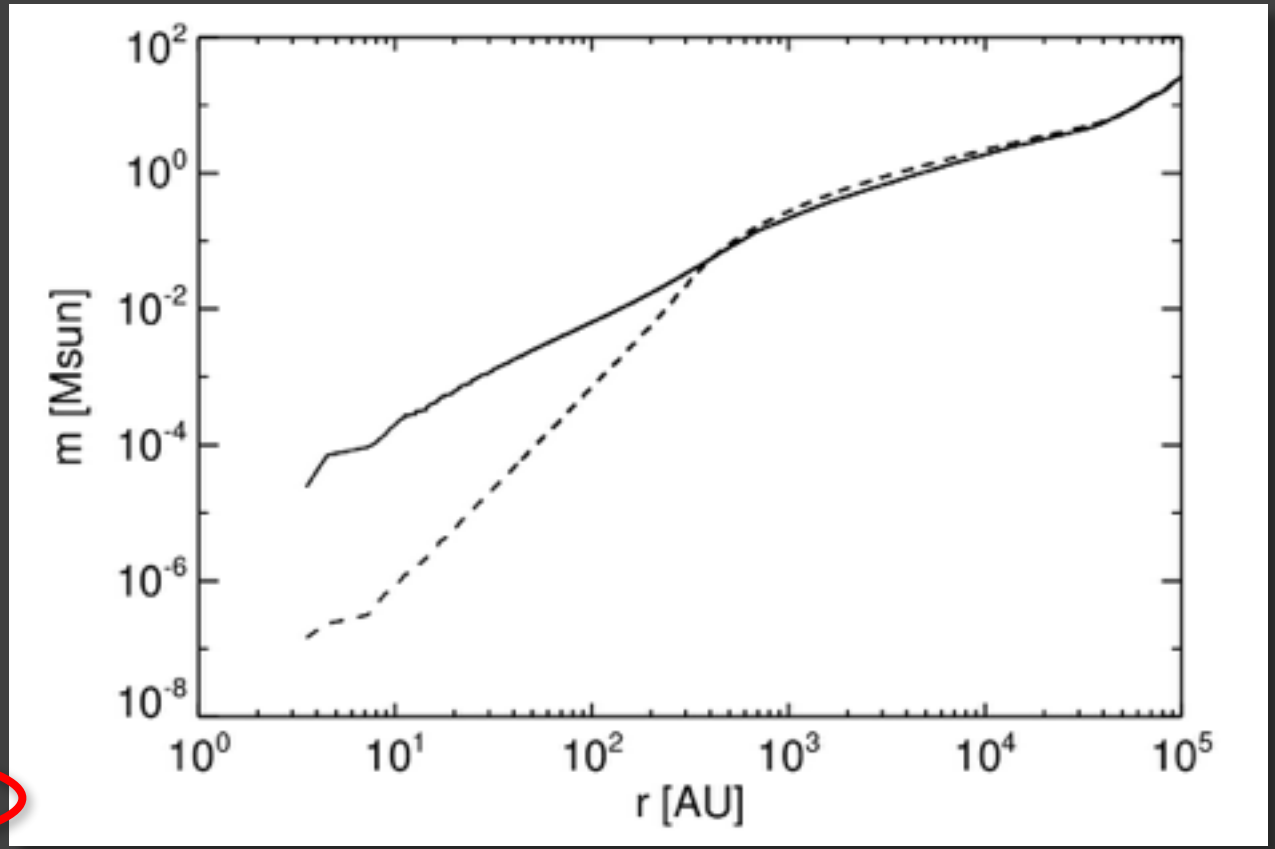
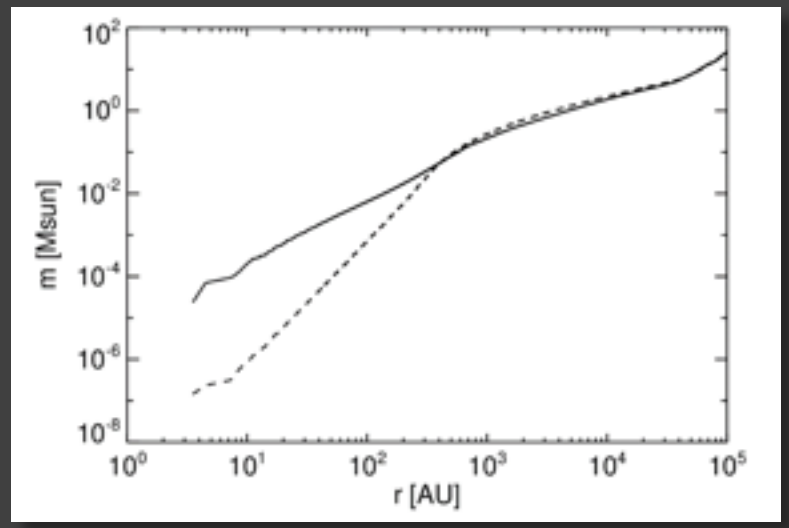
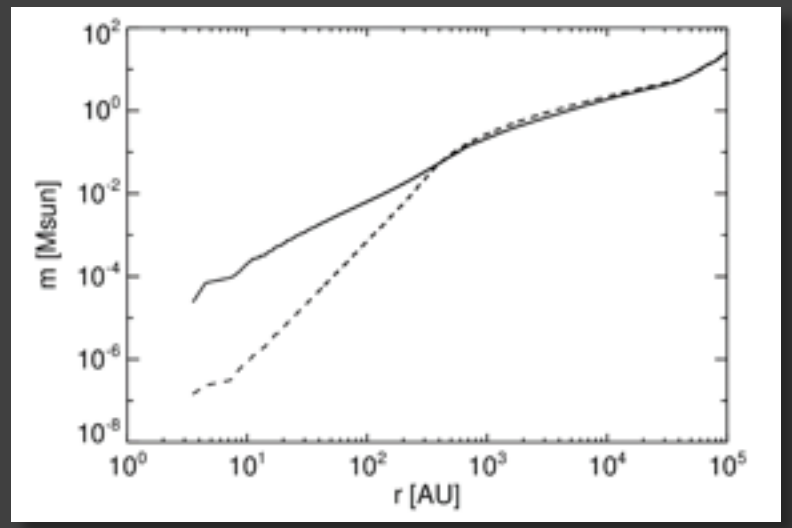
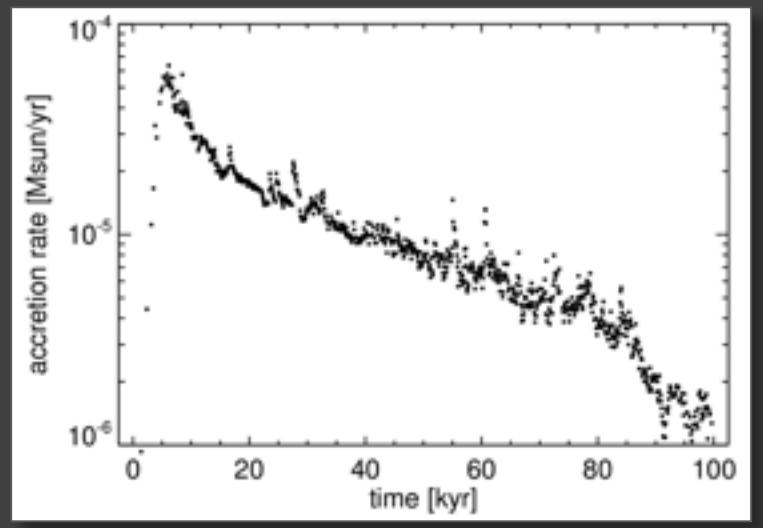


Replenishment Times

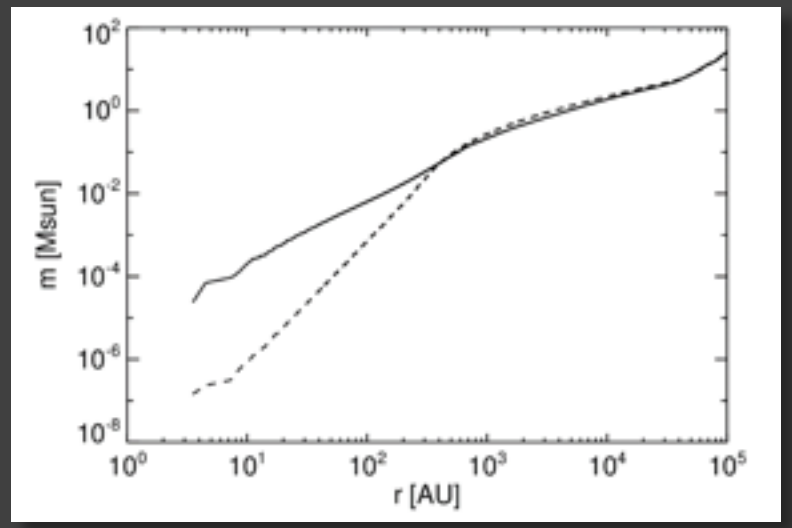


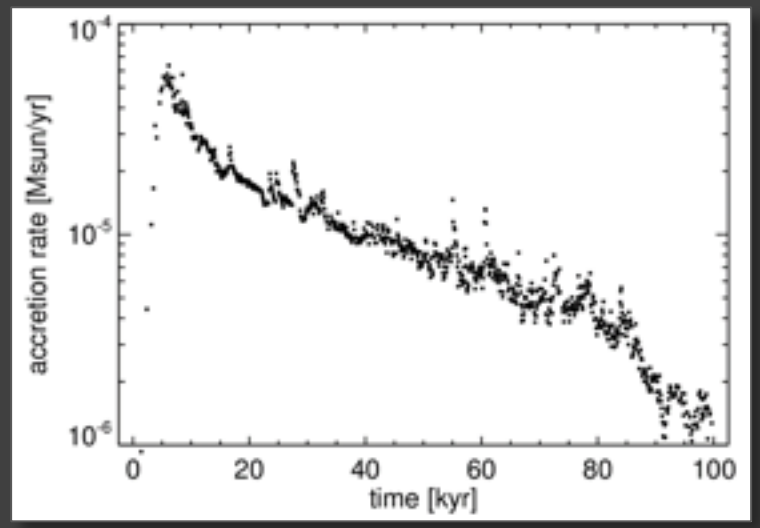
Replenishment Times

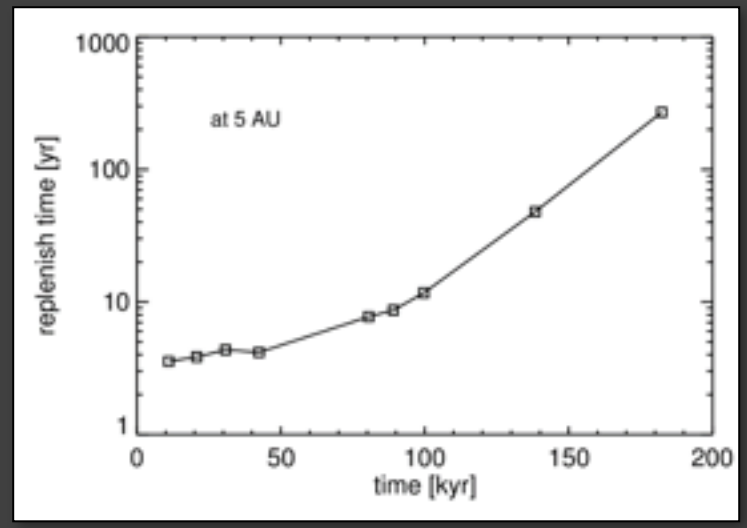




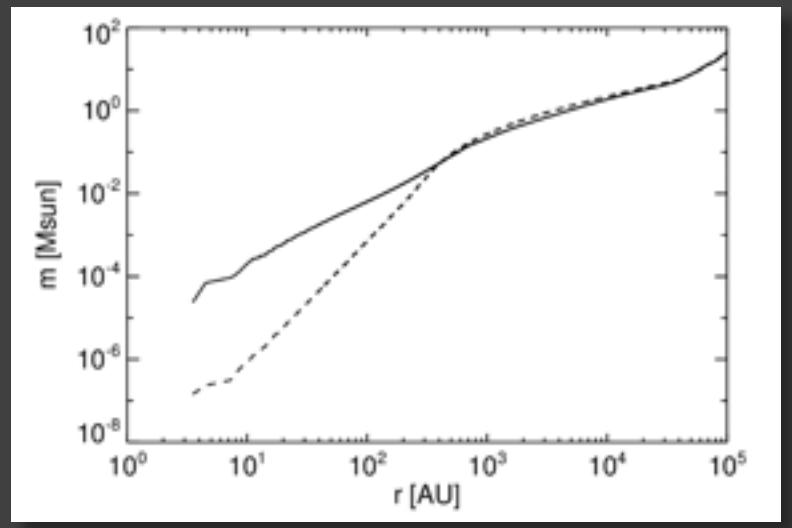
Replenishment Times

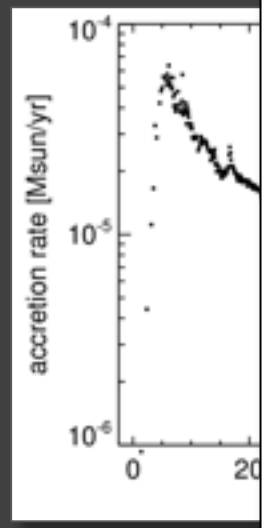


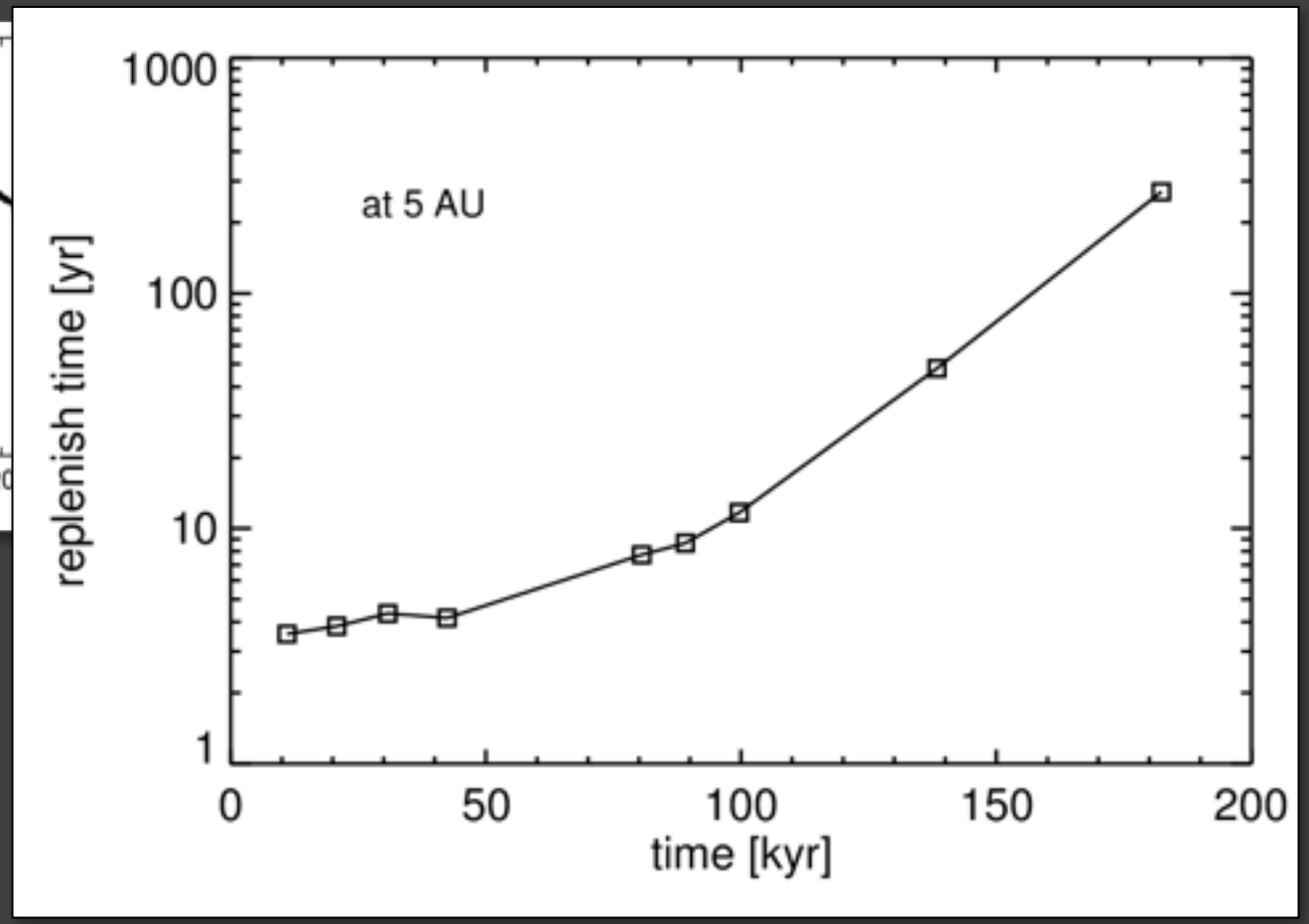




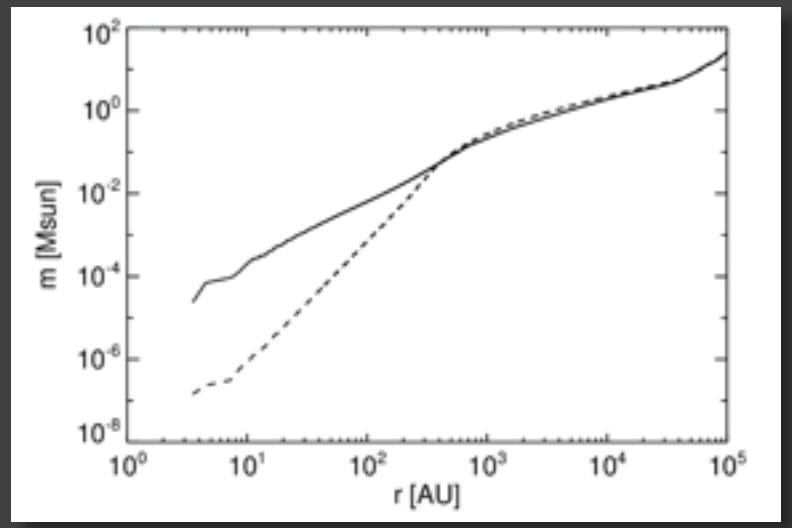
Replenishment Times

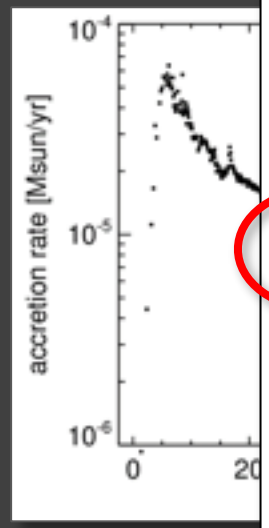


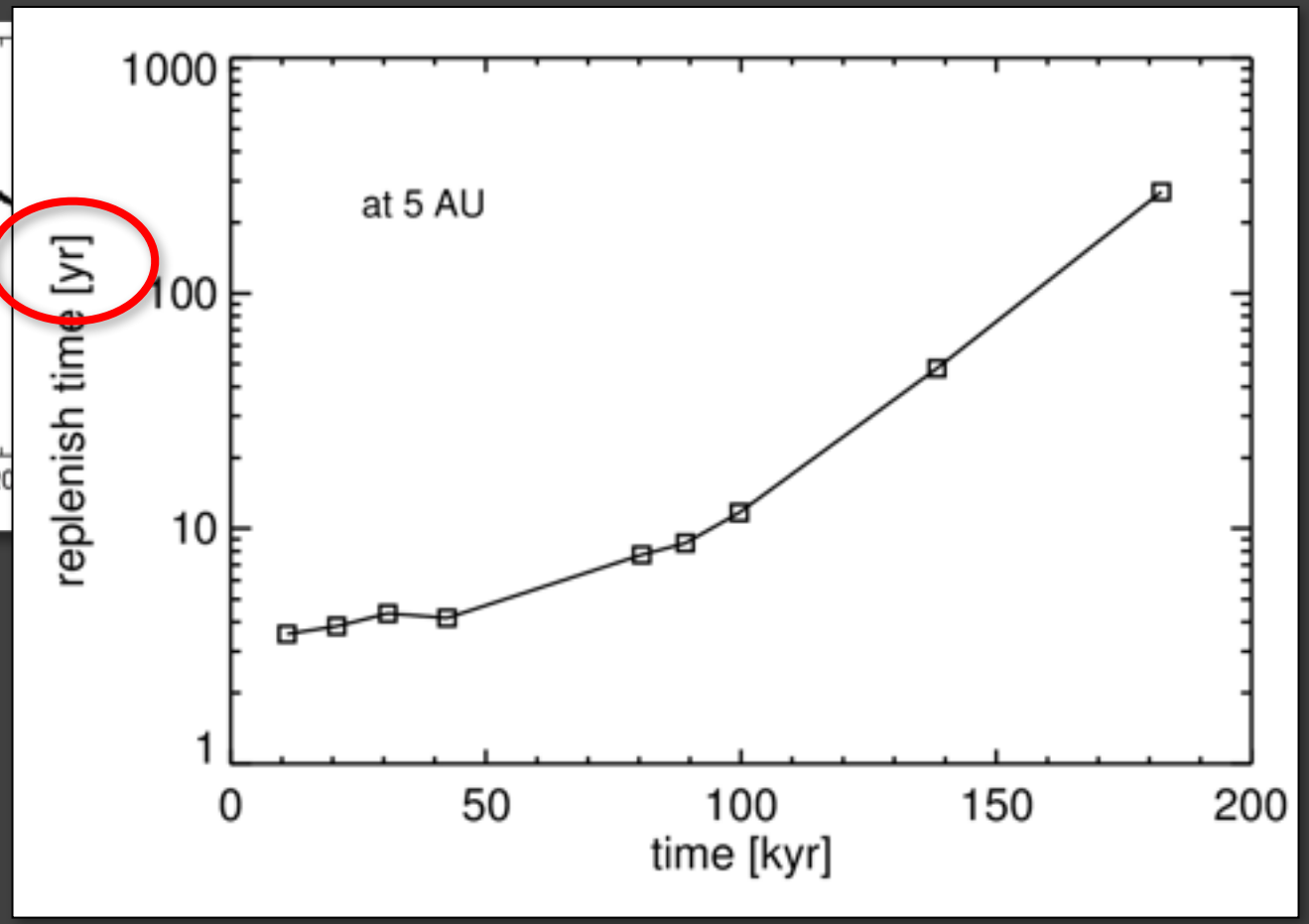




Replenishment Times

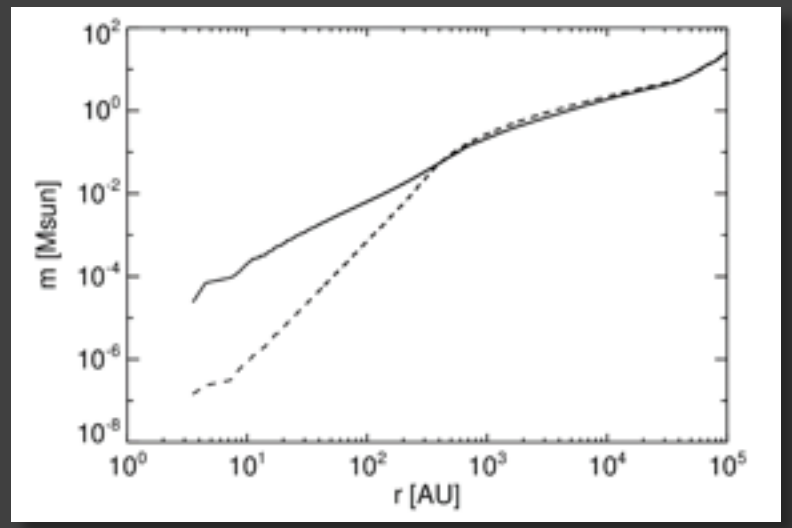


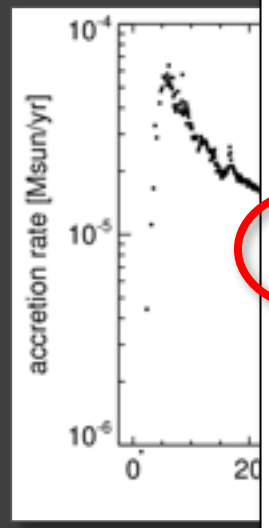


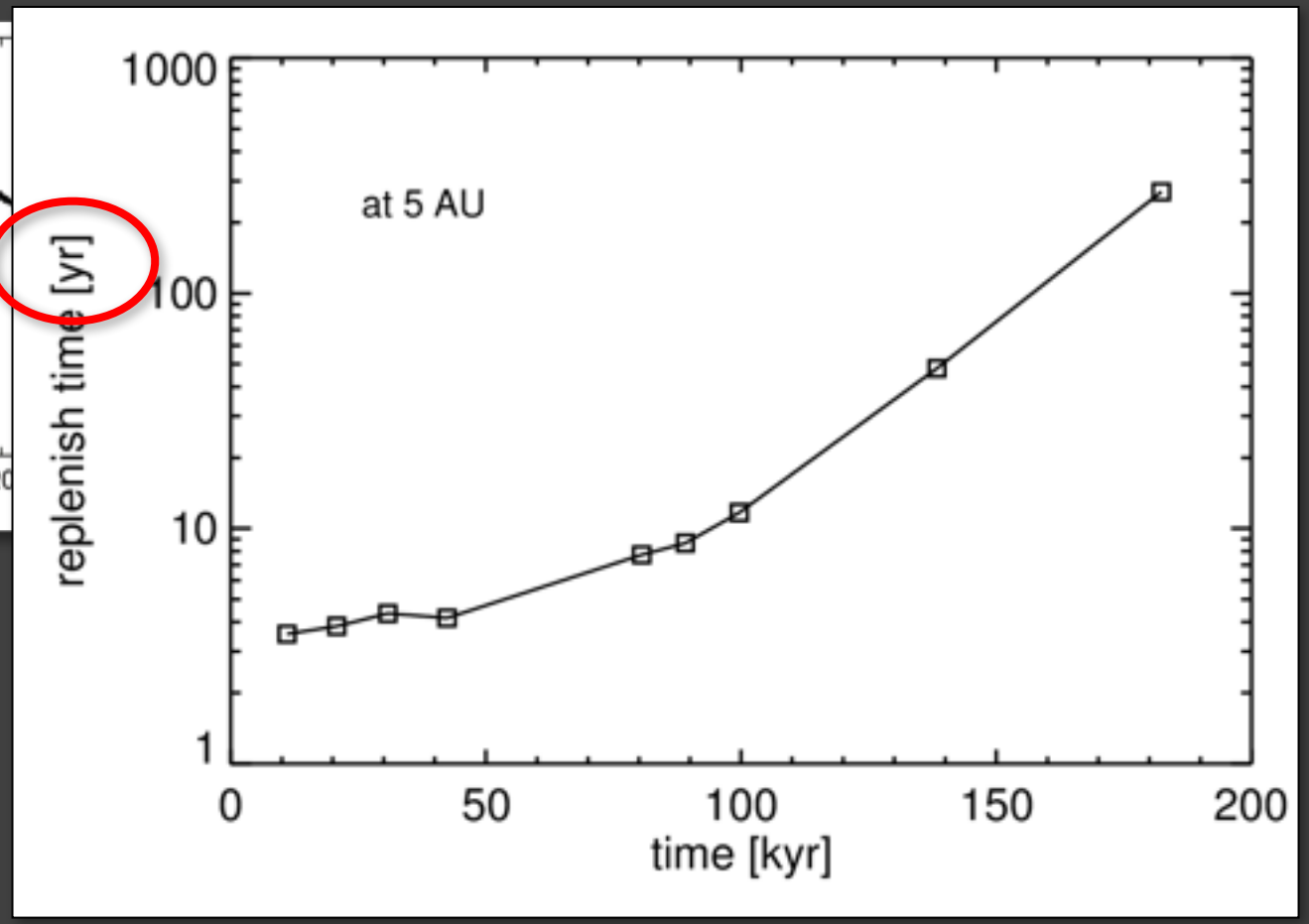


Replenishment Times

(disk mass) / (accretion rate) = time scale







- Spiral angle =
  (Time scale) / (Orbital time)
  ≈ constant !!

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

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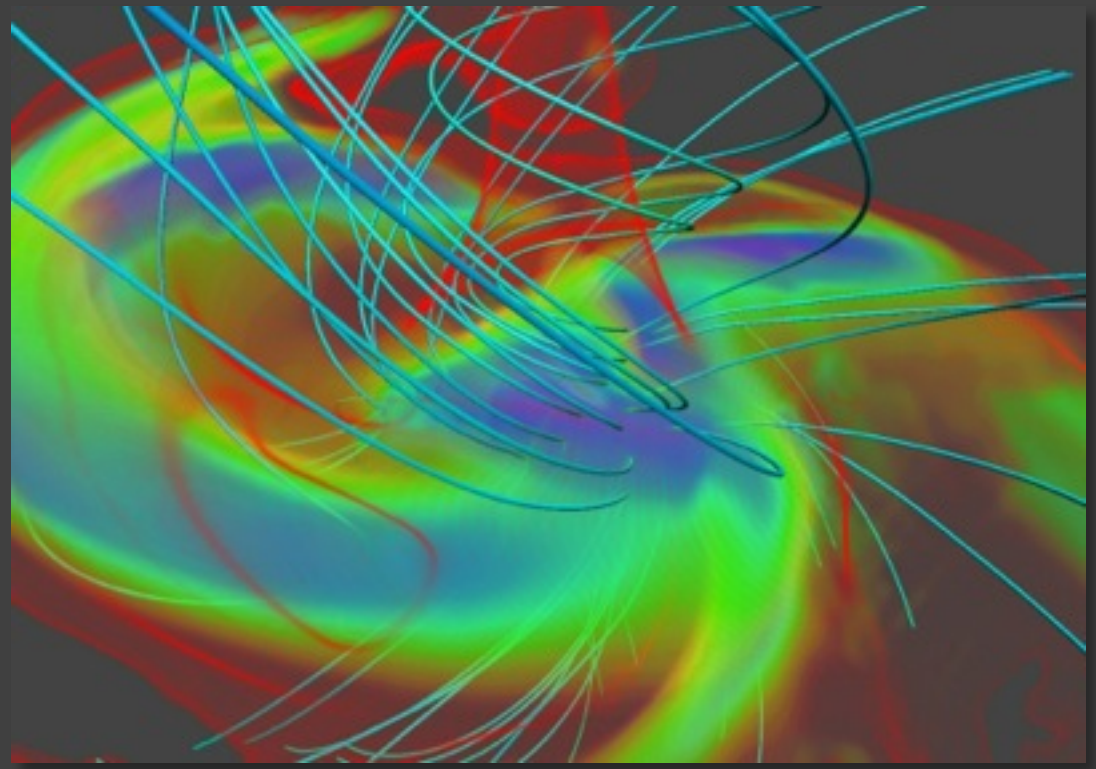

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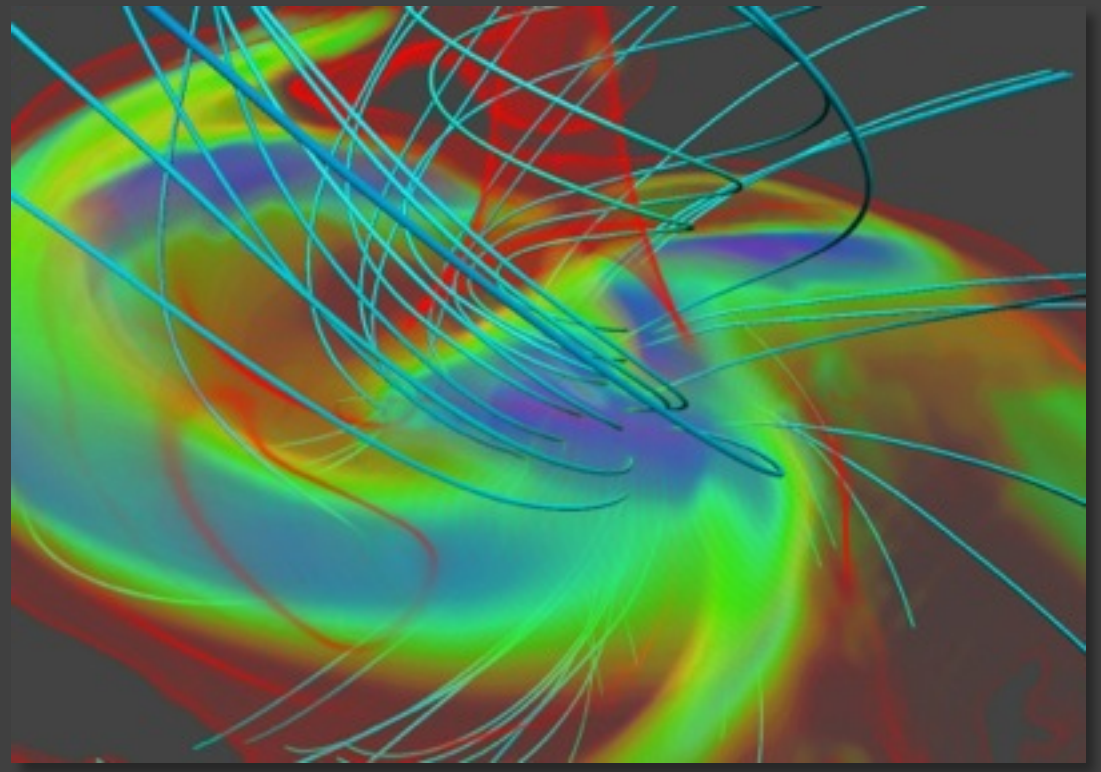

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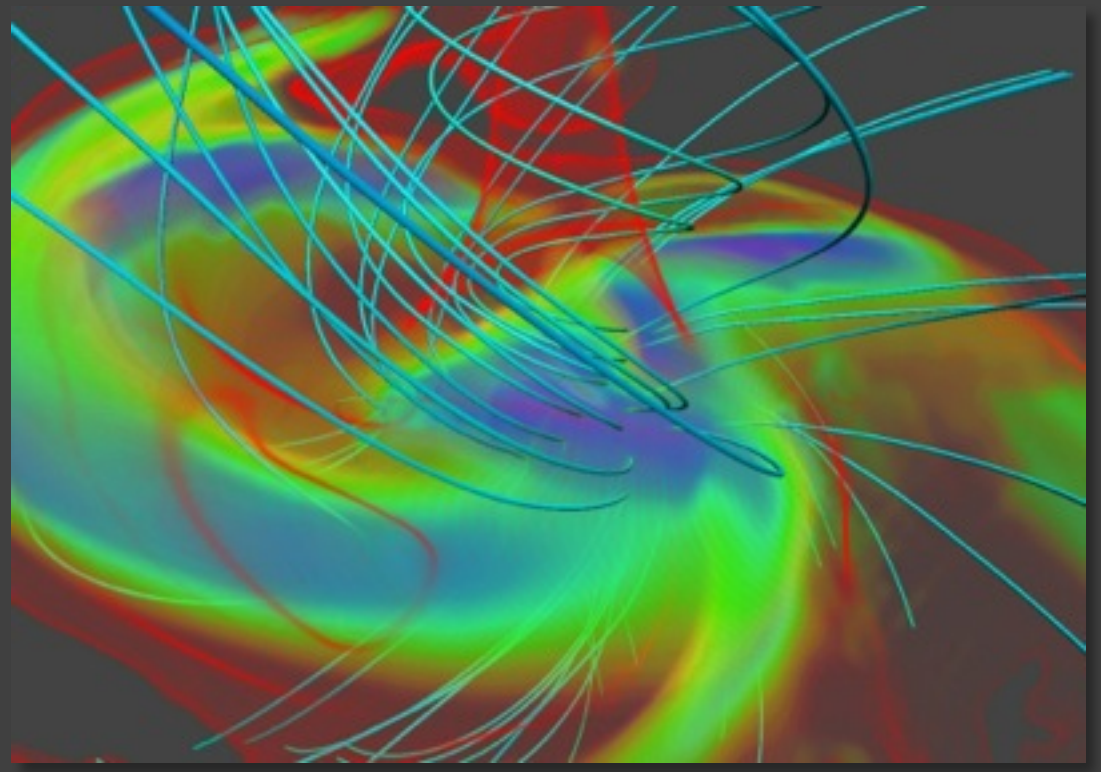

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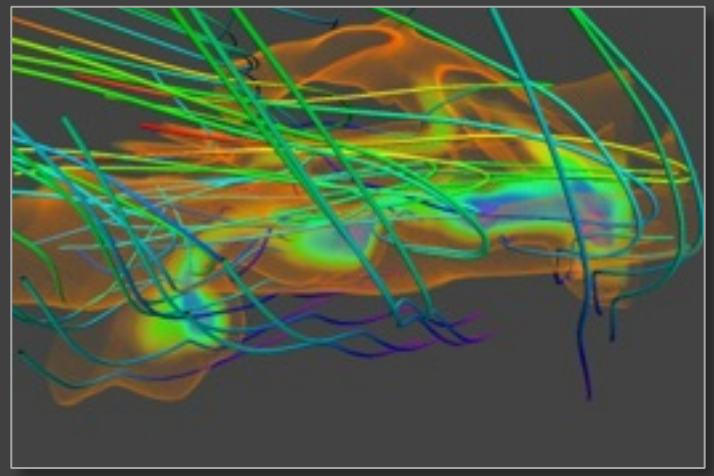
Importance of Magnetic Fields

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



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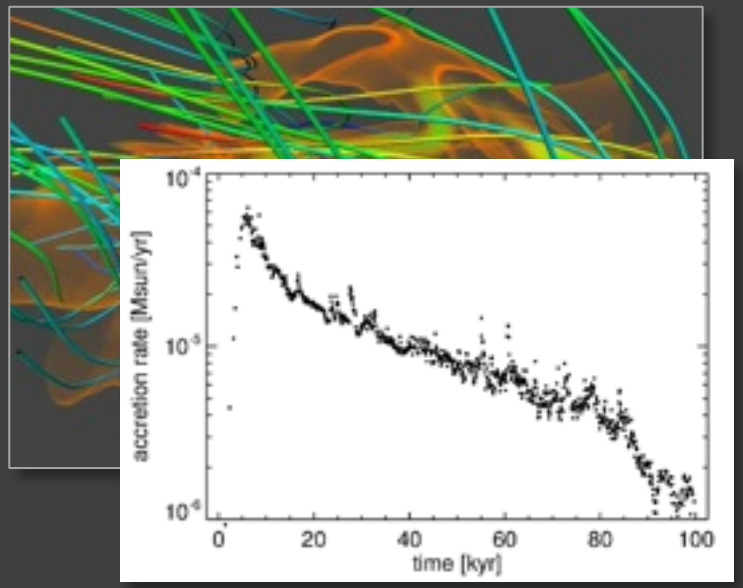

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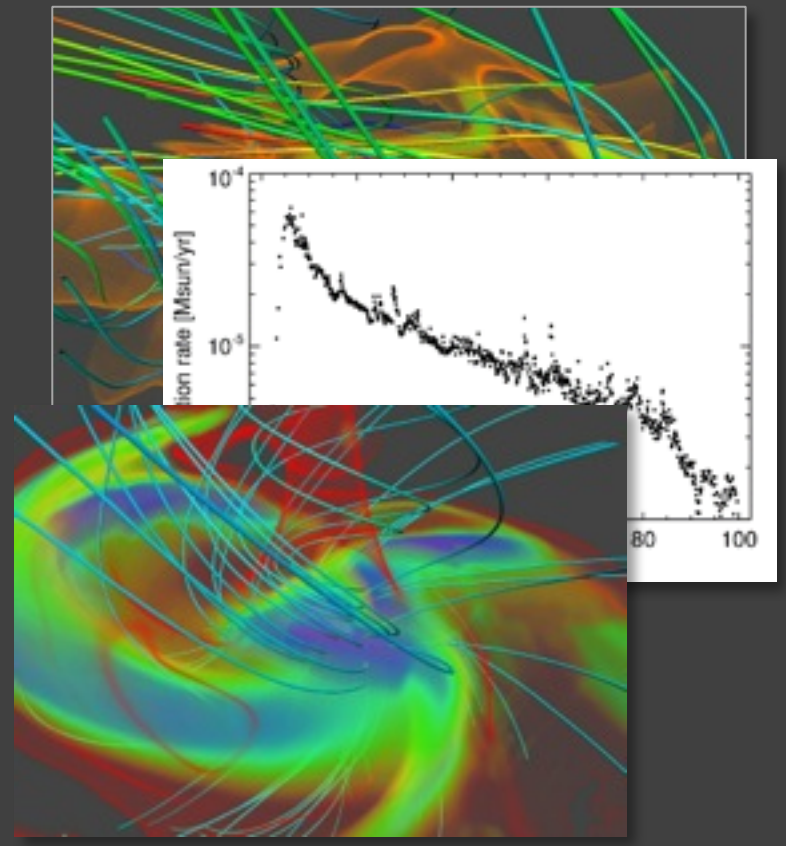

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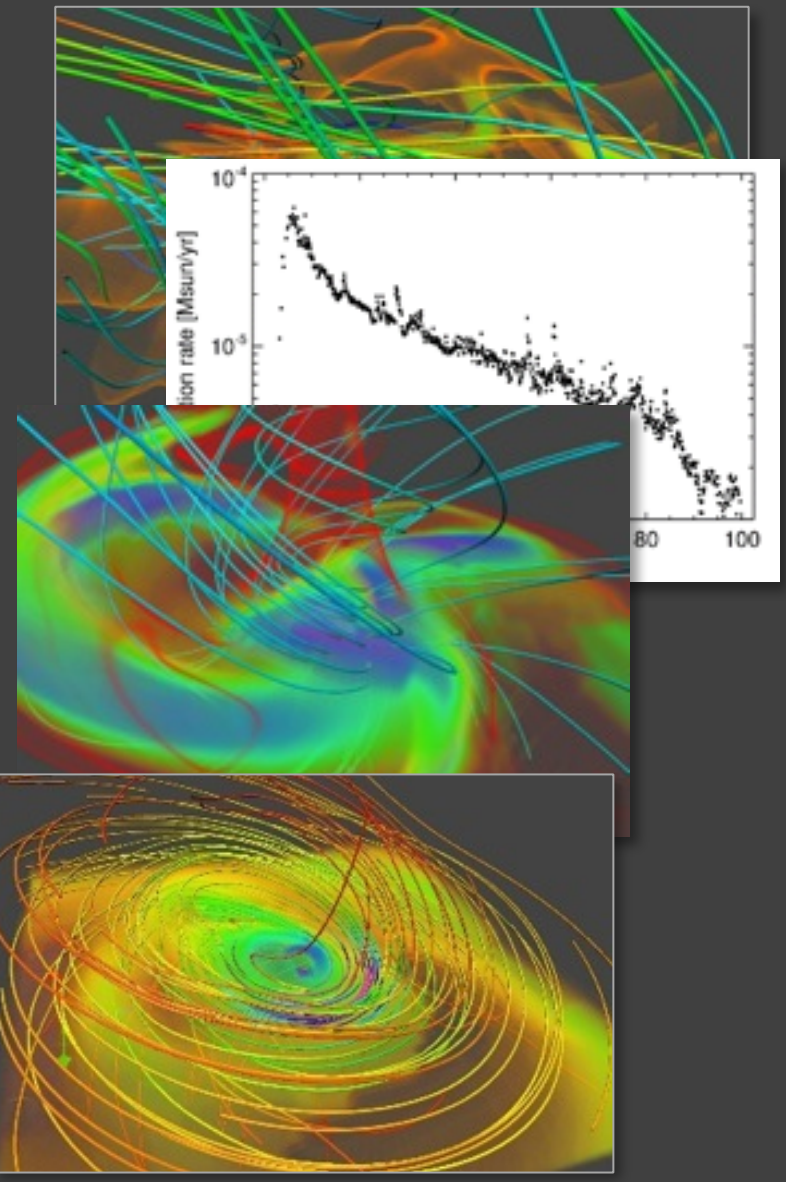

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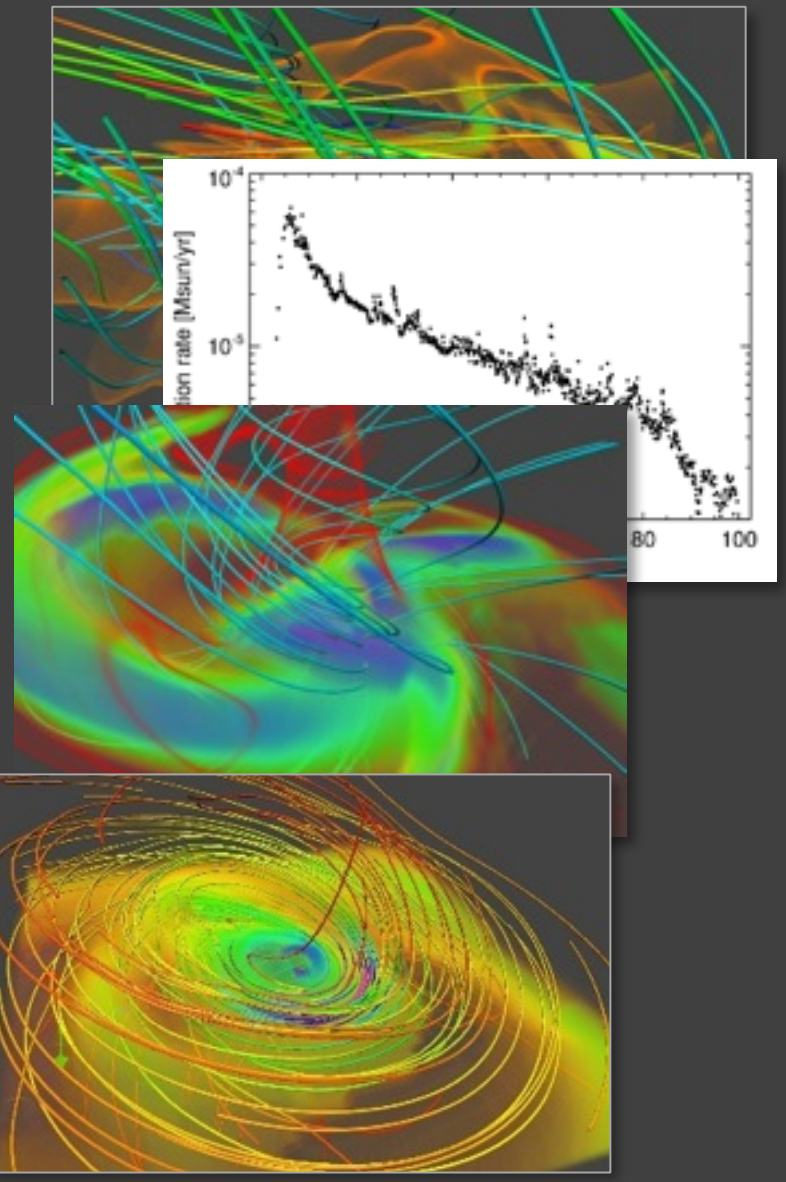

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  - Much MORE of the angular momentum ***and energy***

Conclusions for IMF context

- Resolving the accretion region is affordable
  - Avoids having to define parameters for Bondi-Hoyle type formulae
- Gas pressure gradients should ***not*** be ignored
  - Gas is ***not*** moving ballistically – far from it !
- Sink particle recipes should respect the radial density profile
  - Avoid triggering spurious sink particles in accretion flows
  - Calibrate dimensionless accretion rate from highly resolved examples

Main IMF questions

Which mechanisms control the shape of the IMF?

- What determines the power law slope?
- What determines the peak position?
  - Why does it appear to be so independent of the environment?

Which mechanisms are important, and which are not?

- What is needed to get the IMF right?

Some answers (Padoan & Nordlund 2002, …)

The power law slope:

- The size distribution of fragments created by super-Alfvénic MHD turbulence

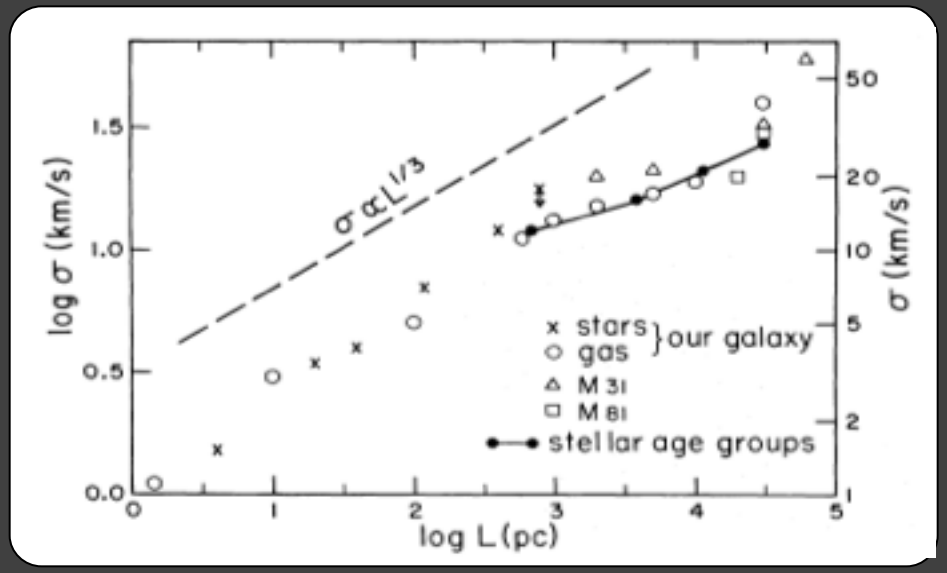
The turn-over and peak:

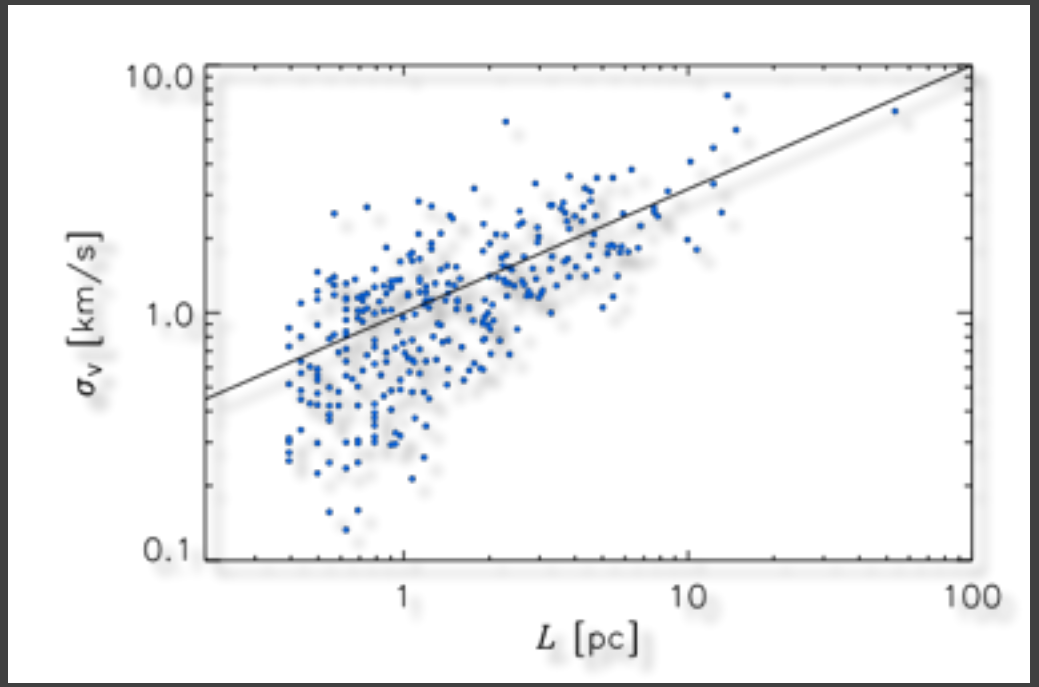
- Rate of failure-to-collapse becomes significant

Peak position:

- Larson's law scalings
- Fortuitous cancellation (follows from Larson's relations)
  - Density dependence vs. Mach number (external ram pressure)

Initial Mass Function Resolved





Initial Mass Function Resolved

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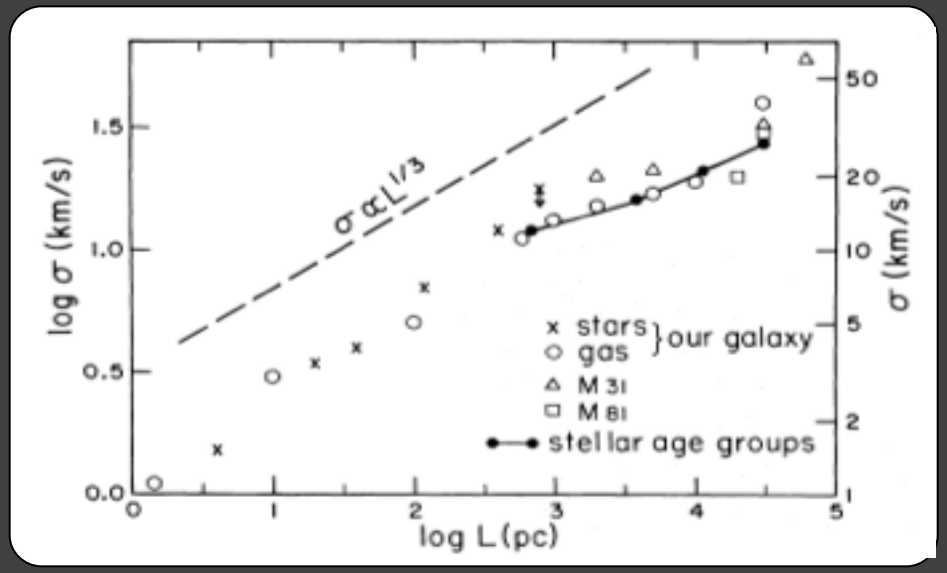

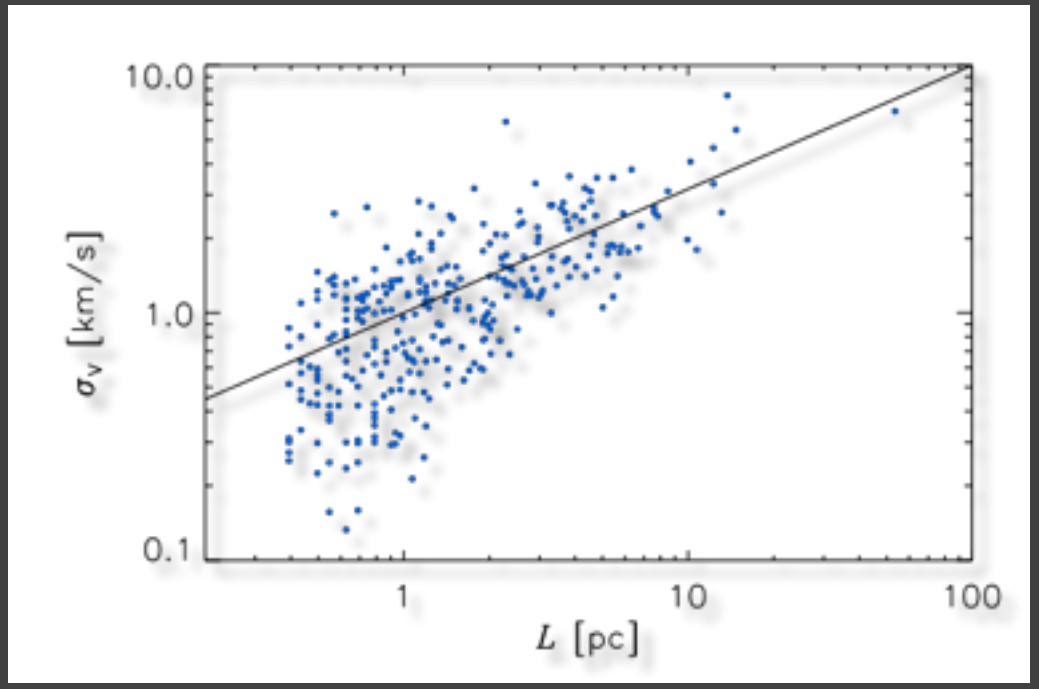

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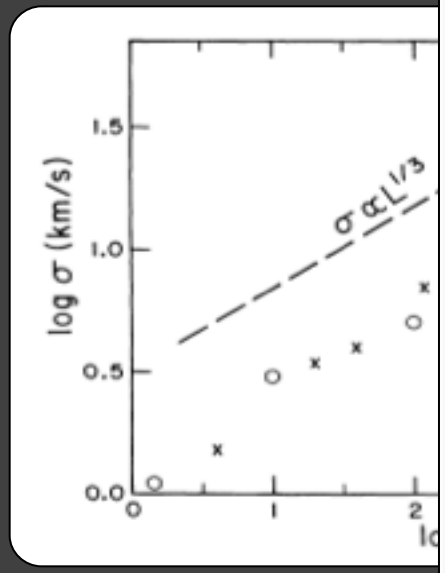

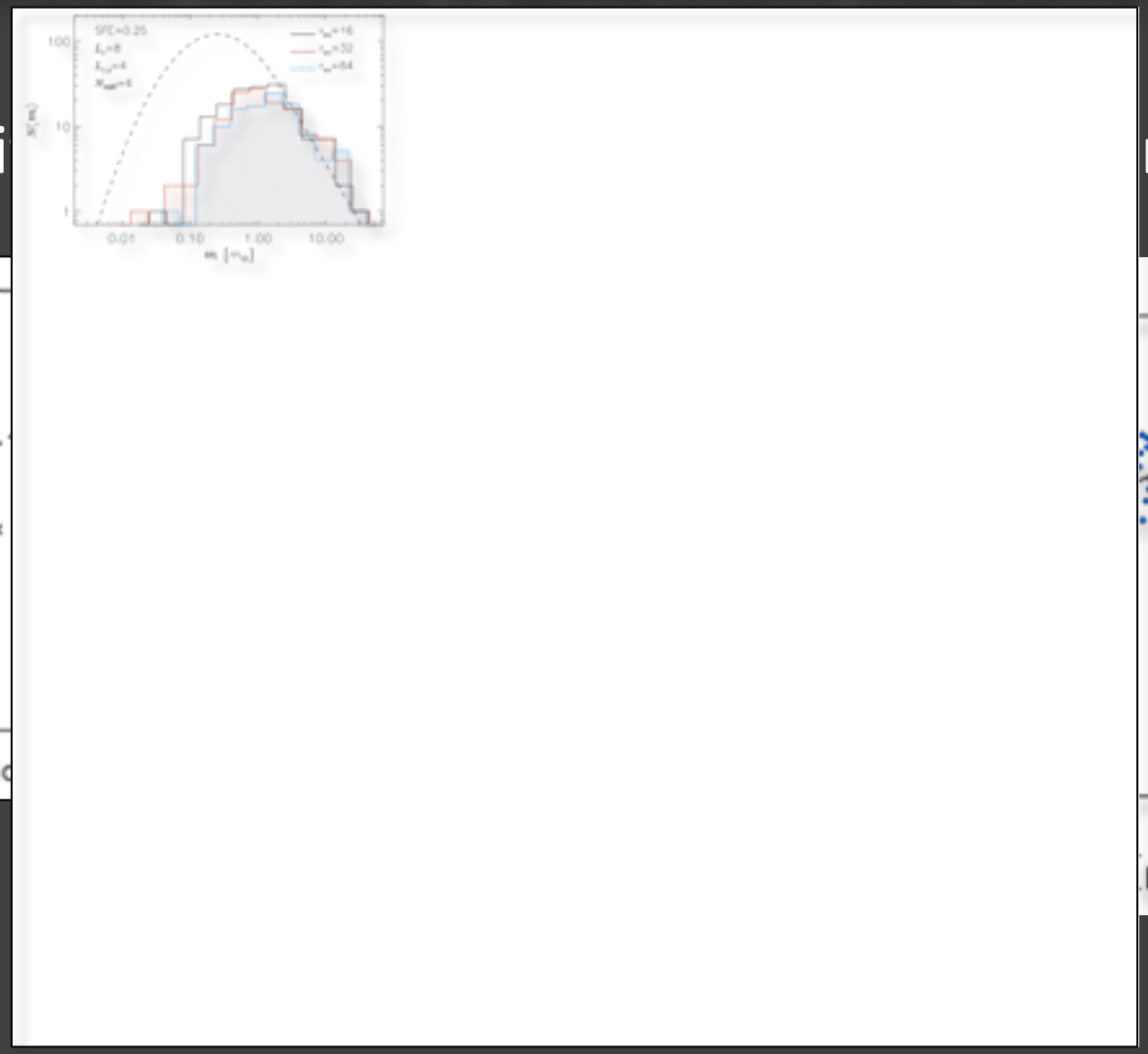

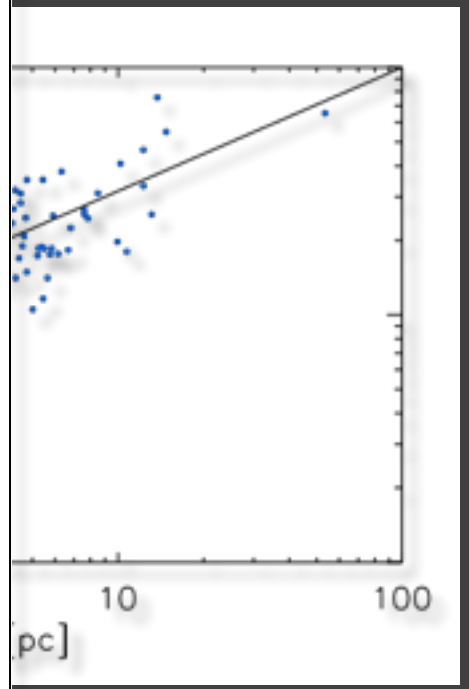

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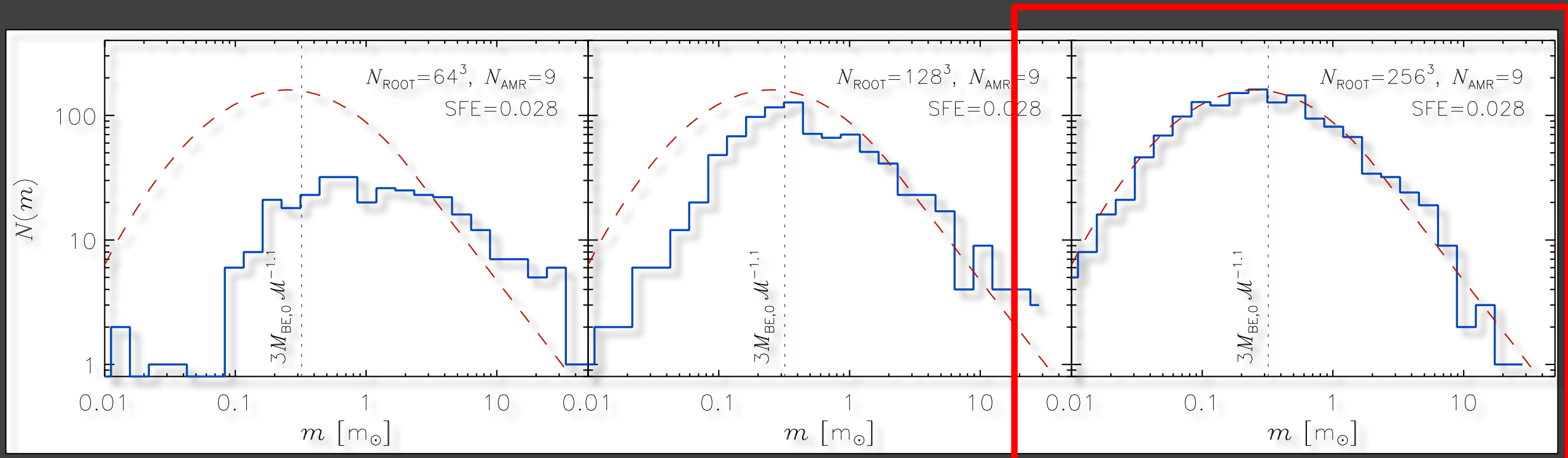

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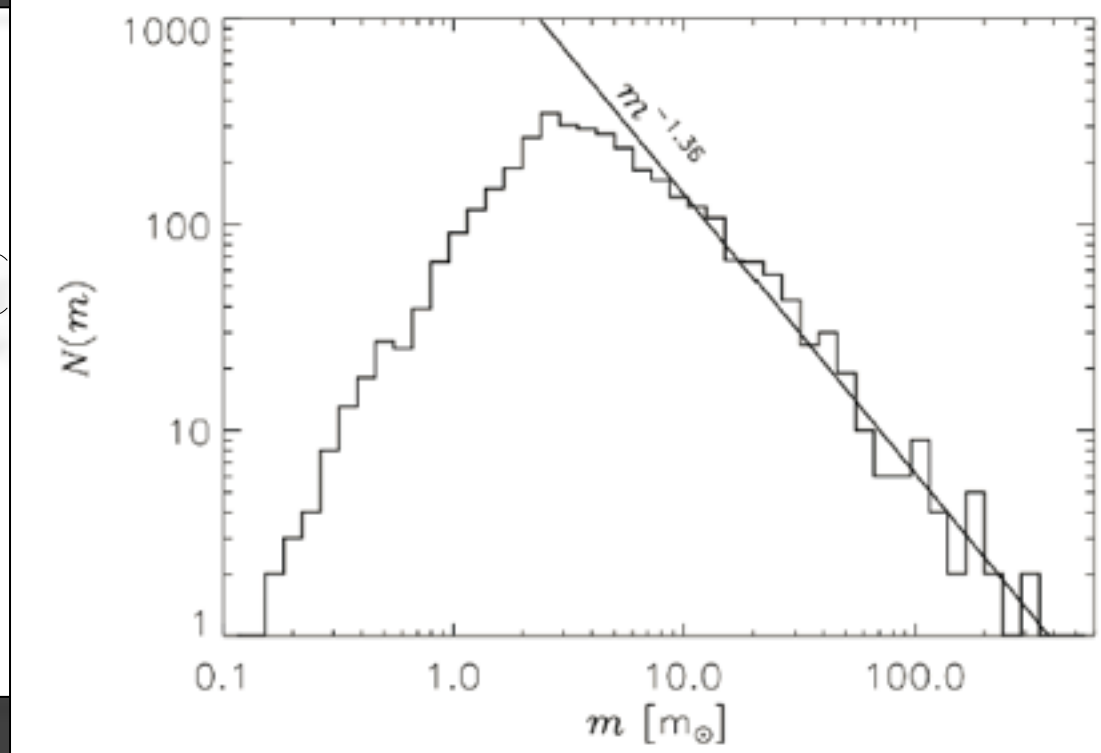
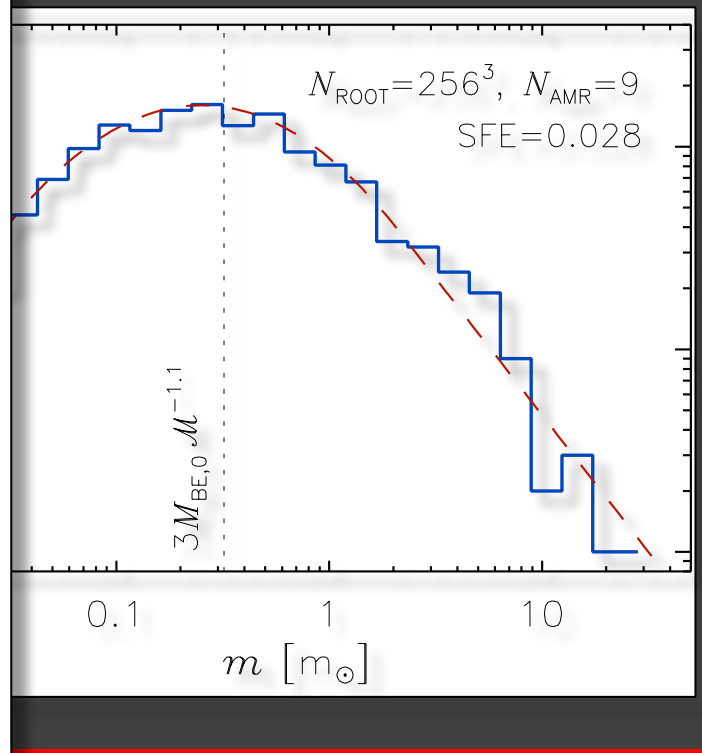


Figure 4: The mass distribution of approximately 4,000 stars from the Fountain1 simulation. Massive stars follow an almost perfect power law, with slope nearly identical to the observed Salpeter value. The power law covers the full range of masses of stars that end their lives as SNae. (*Padoan, Haugbølle and Nordlund, in preparation*).



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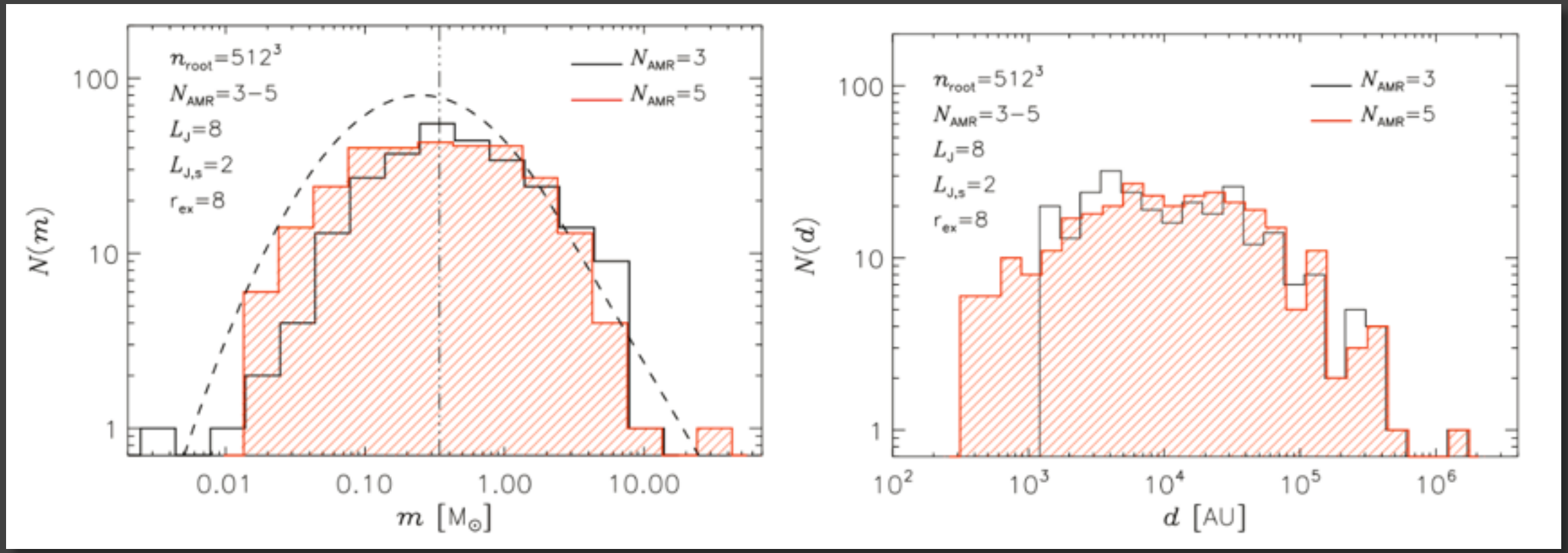
Dependence on max AMR level



Demonstration experiment – 2 days @ 400 cores

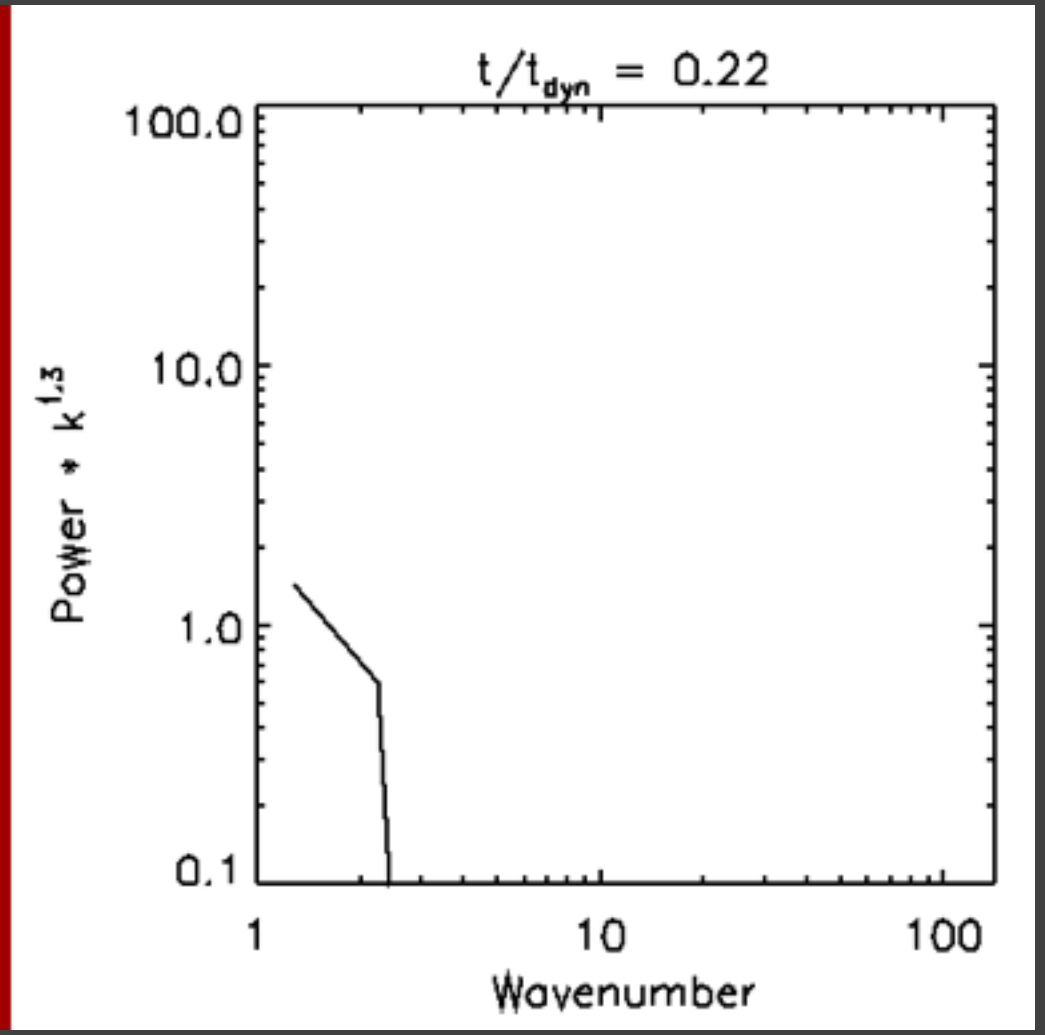
Physical

- Isothermal (T = 10 K, c = 0.18 km/s)
- Box size = 3.33 pc ≈ 0.7 million AU
- Mach number = 12 (consistent with Larson)
- Mean density = 1000 H_2/cm^3 (slightly overdense relative to Larson)

Computational

- RAMSES AMR + locally developed sink particle creation & accretion
- levels = 7-14 (root grid 128^3, min cell size $1/2^{14}$ = 40 AU)
- HLLD solver, locally developed 3-D slope limiter

Initial initial condition– not useful !



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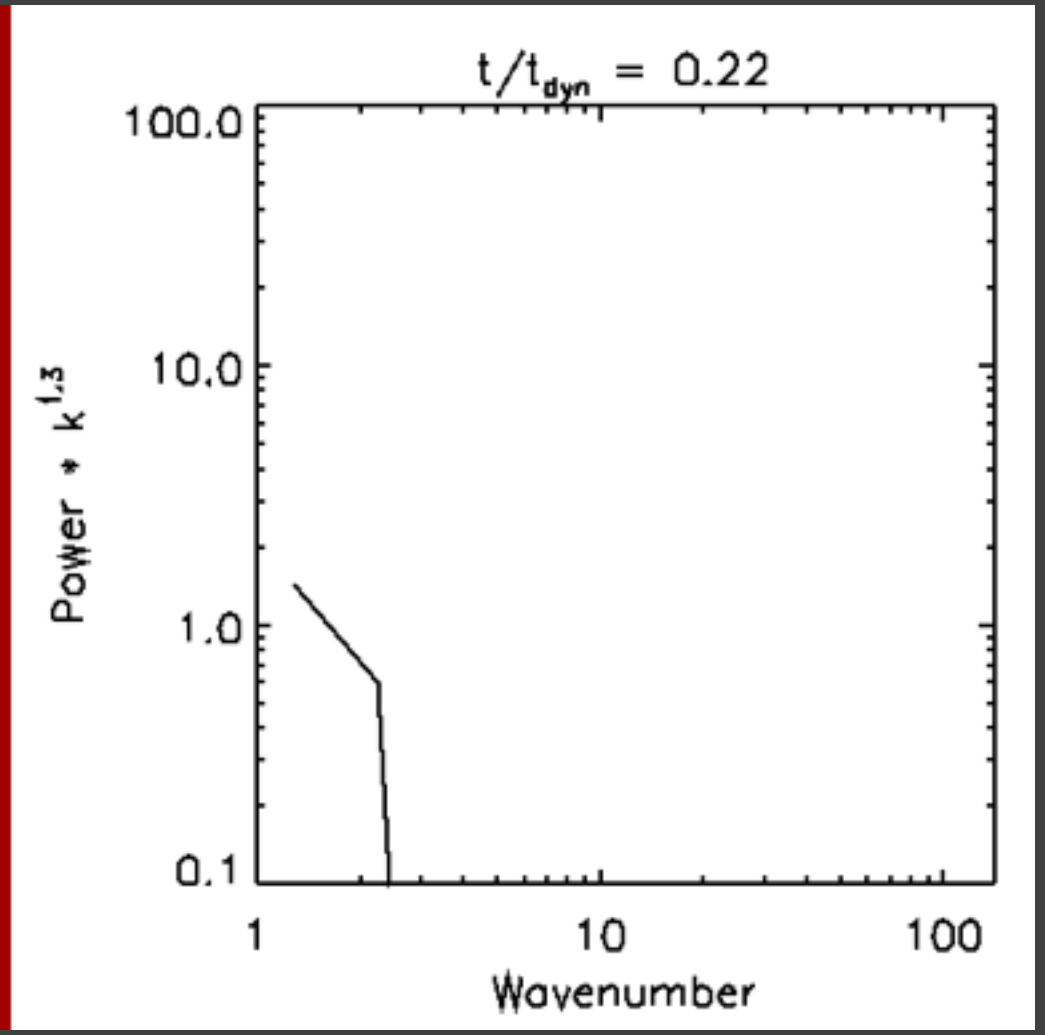
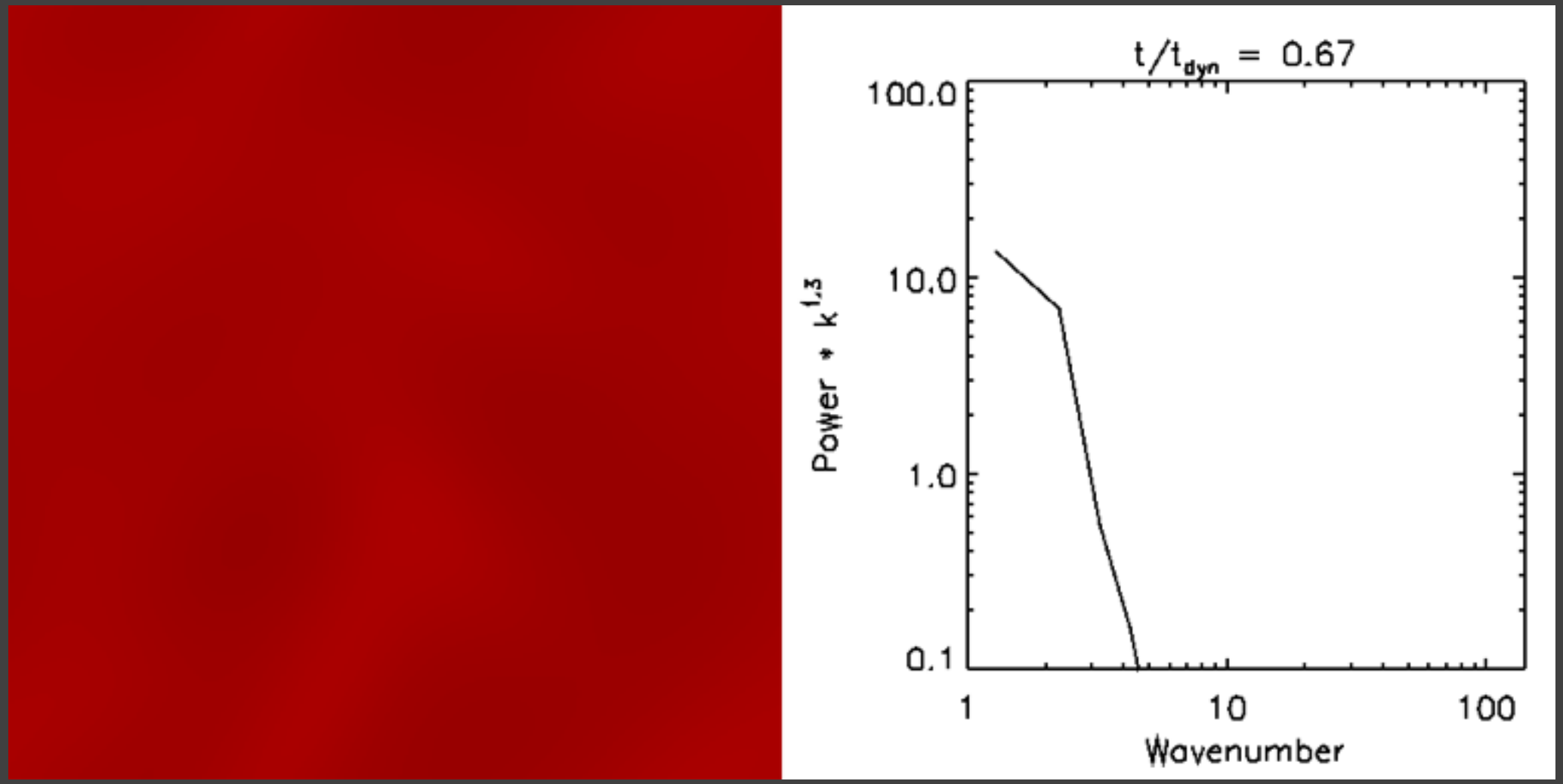
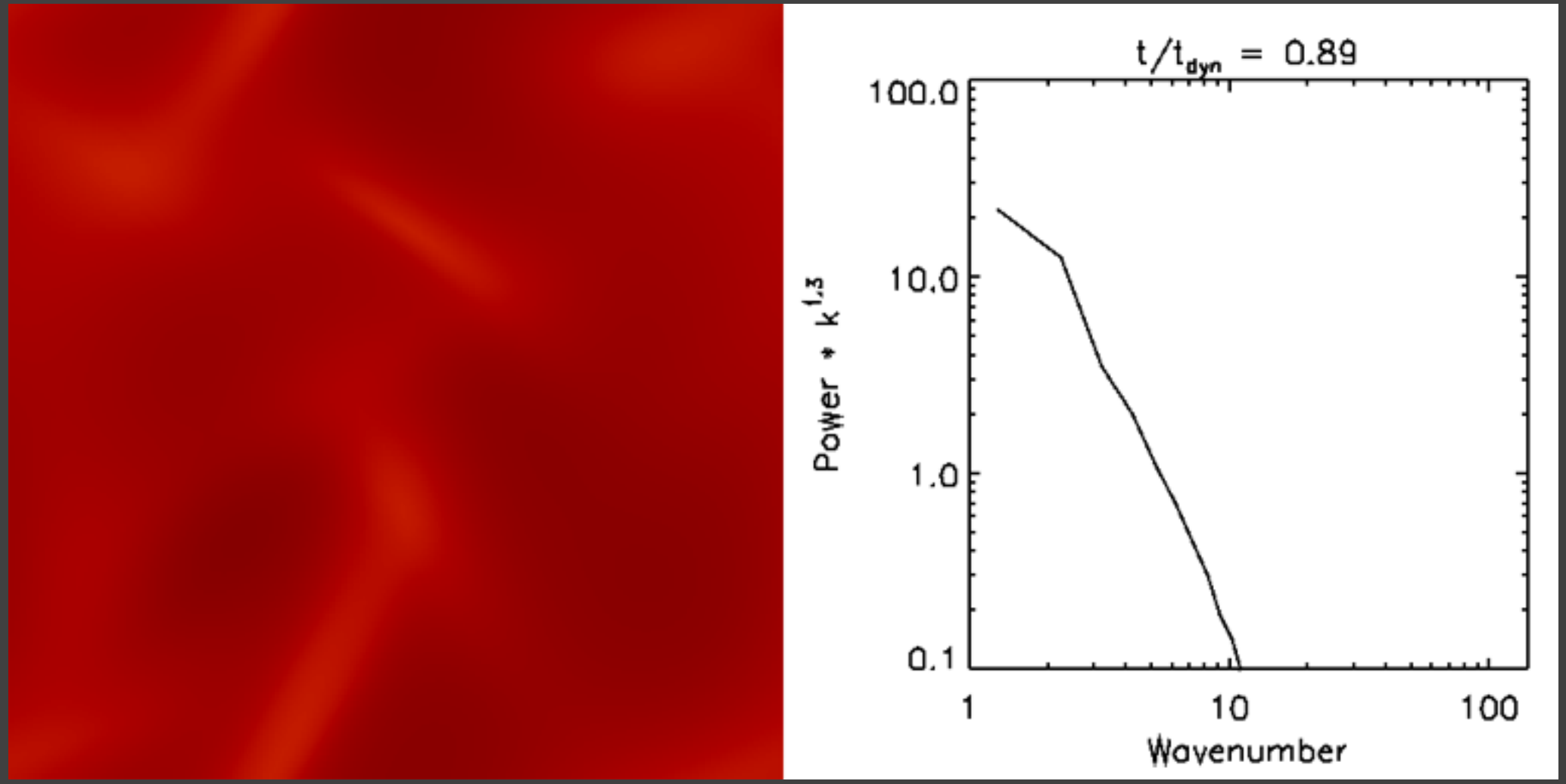
Drive supersonic, super-Alfvenic turbulence (initially no gravity) for about 3 dynamical times



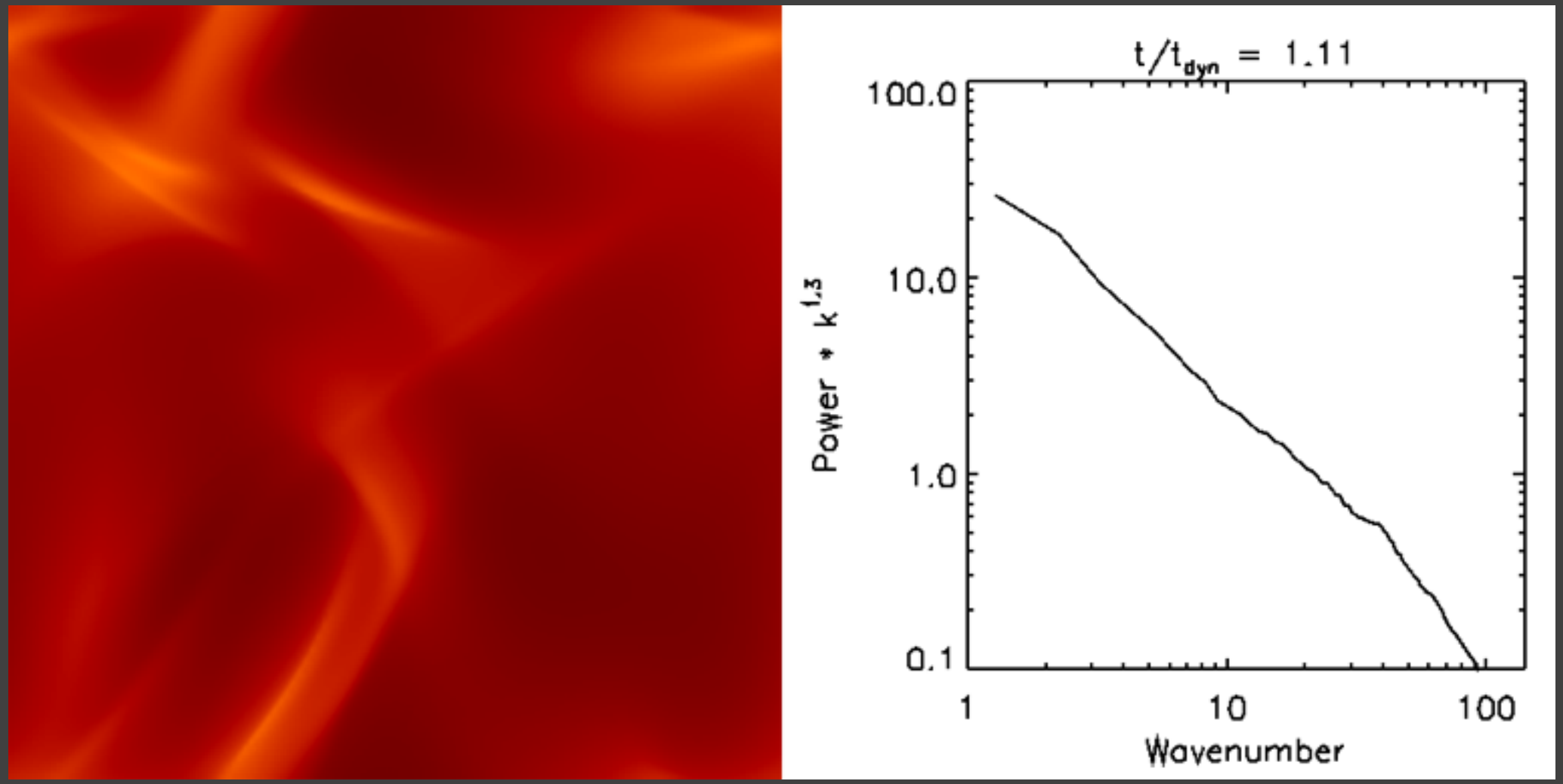
Fraction of dynamic time: weak density fluctuations …



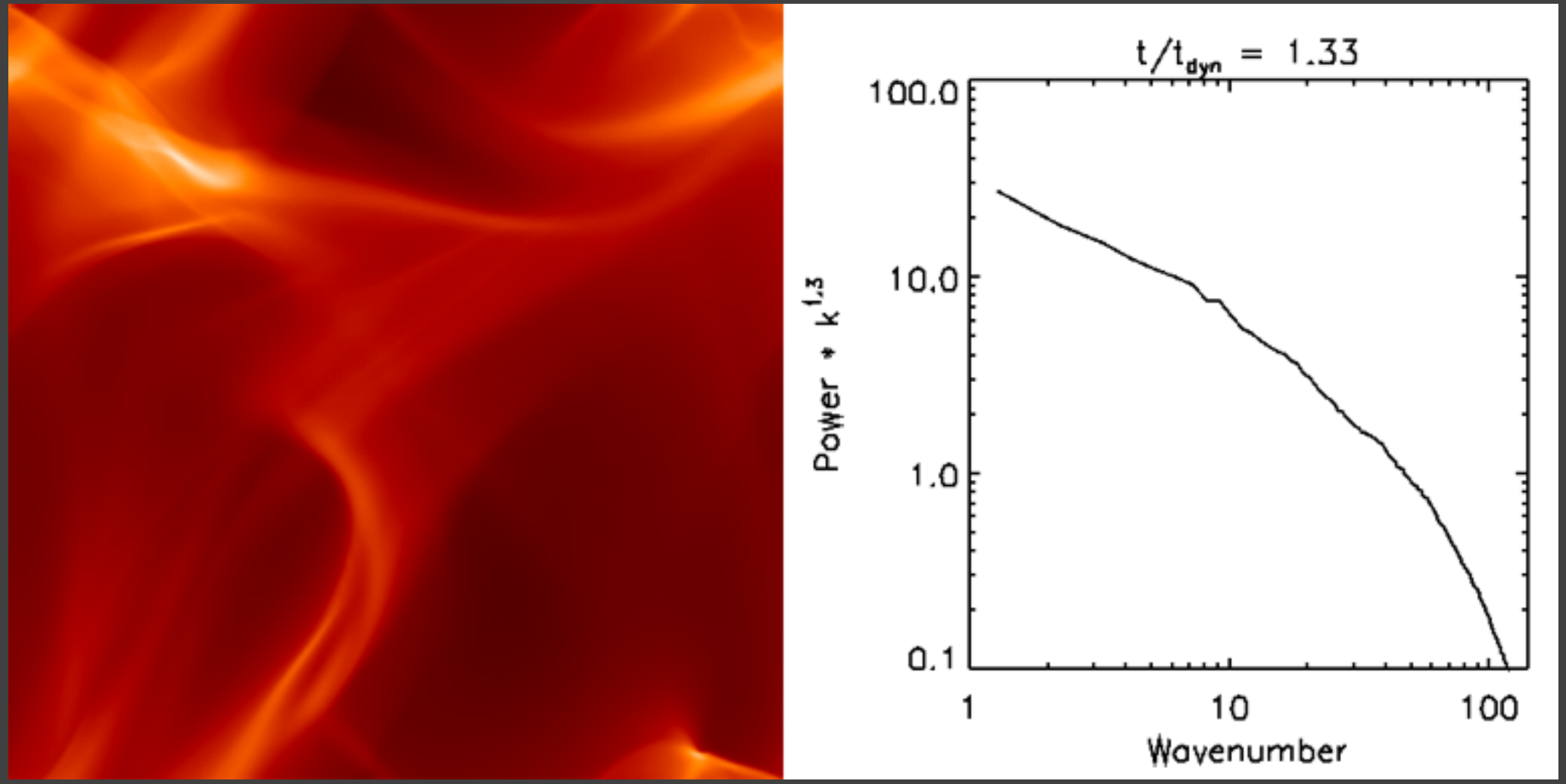
… sharpening …



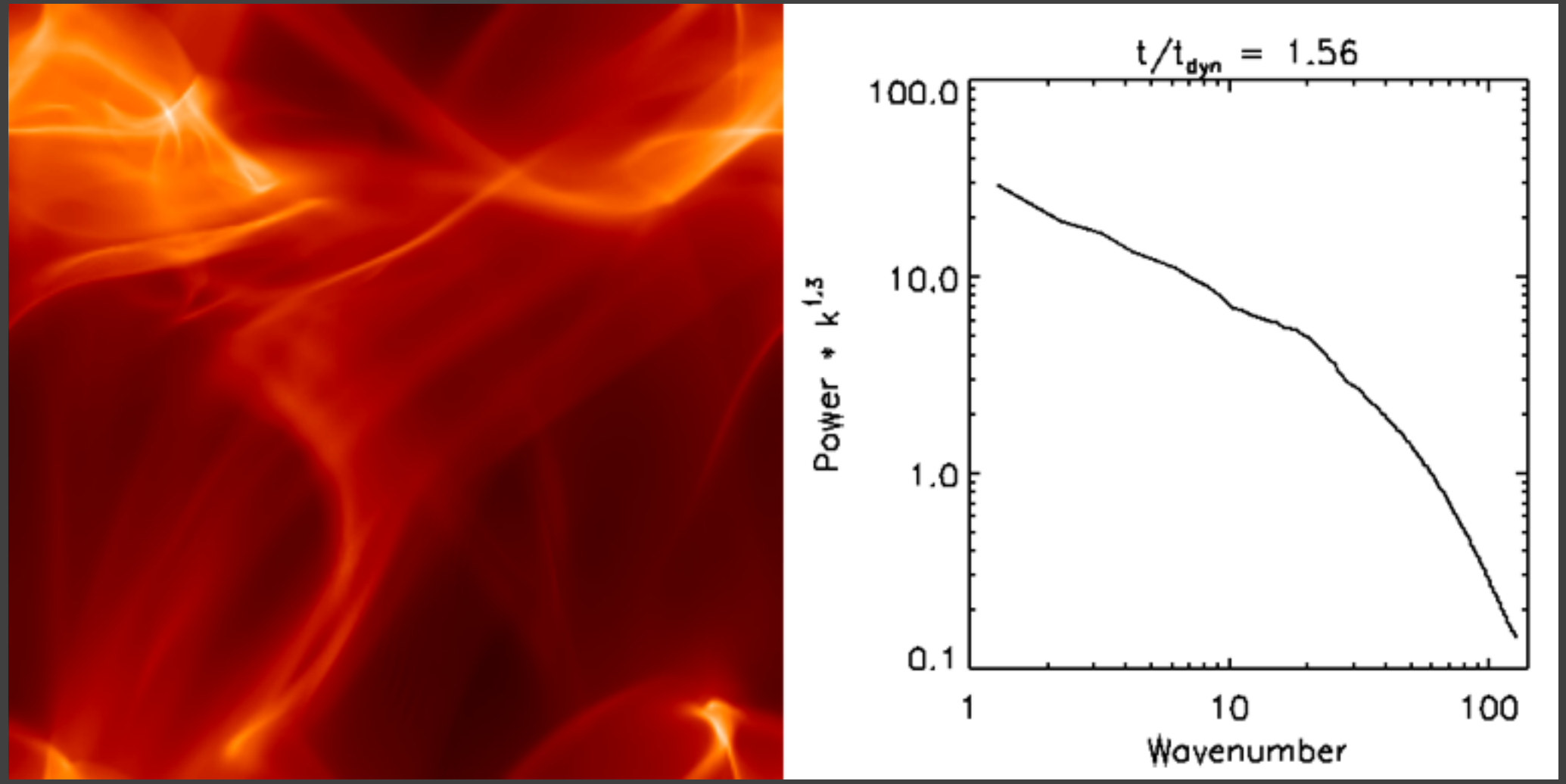
… into shocks at one dynamic time …



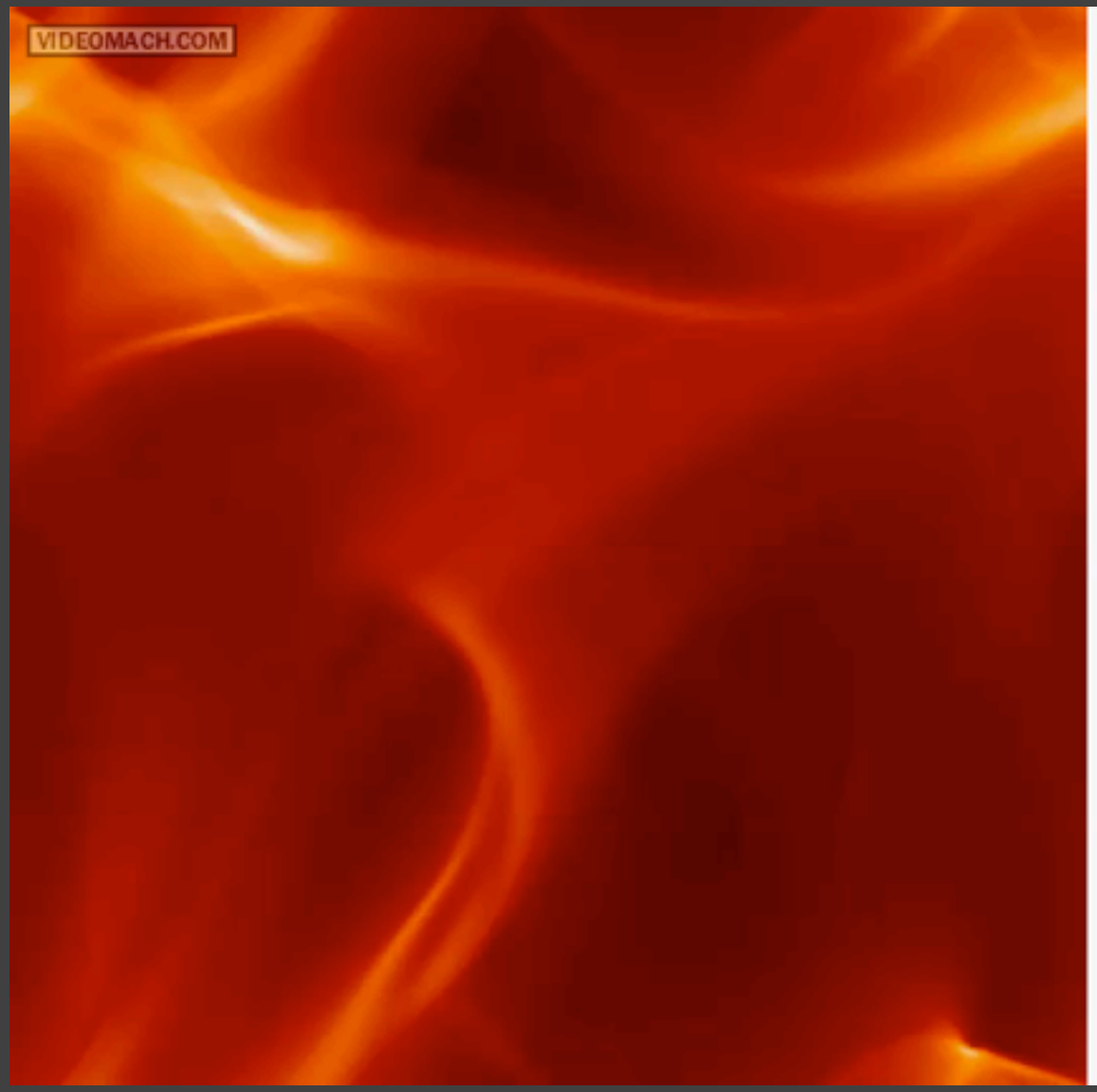
… shock interaction …

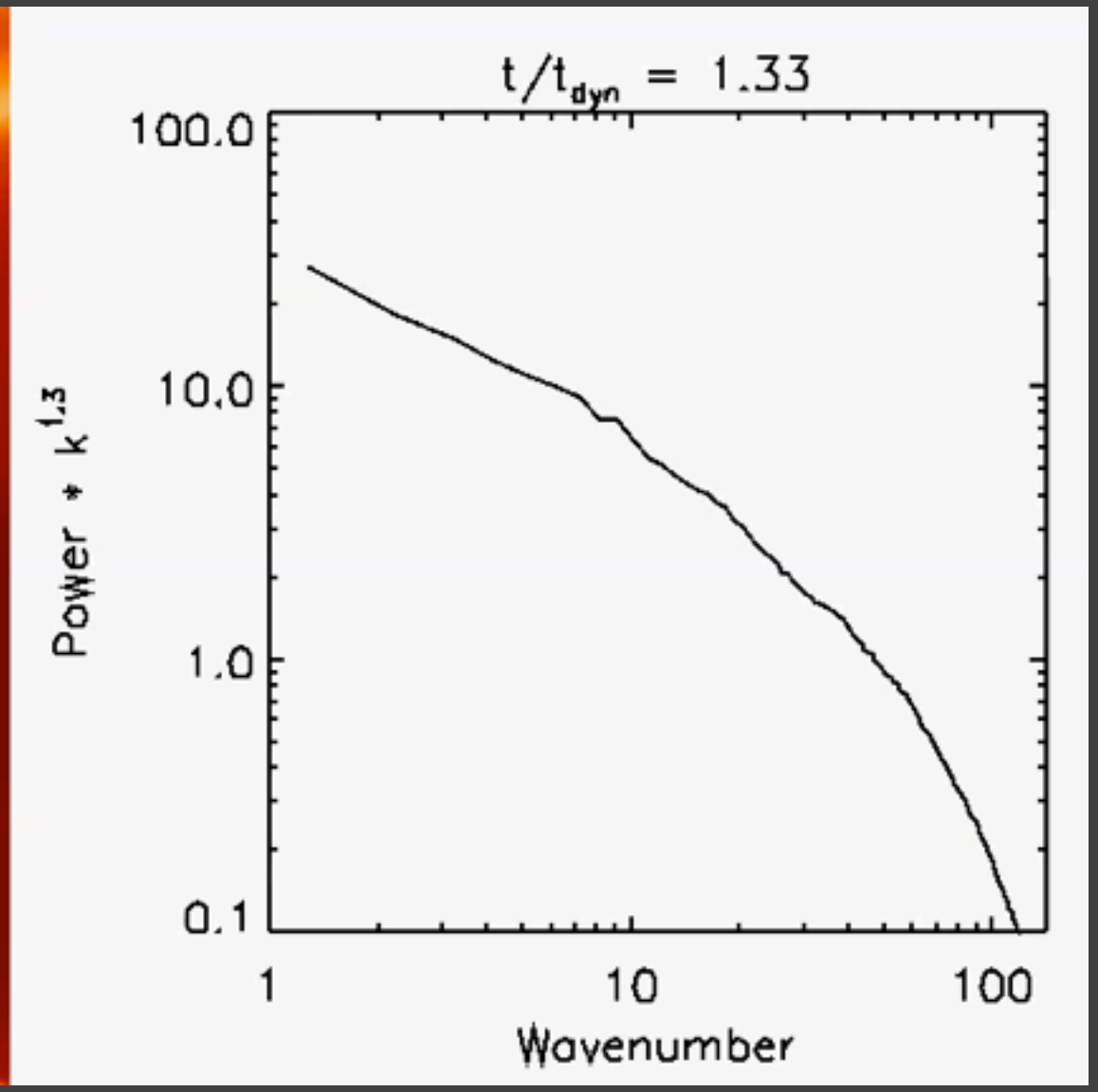


… over to animation …



Increasing fragmentation – cf kinetic energy power





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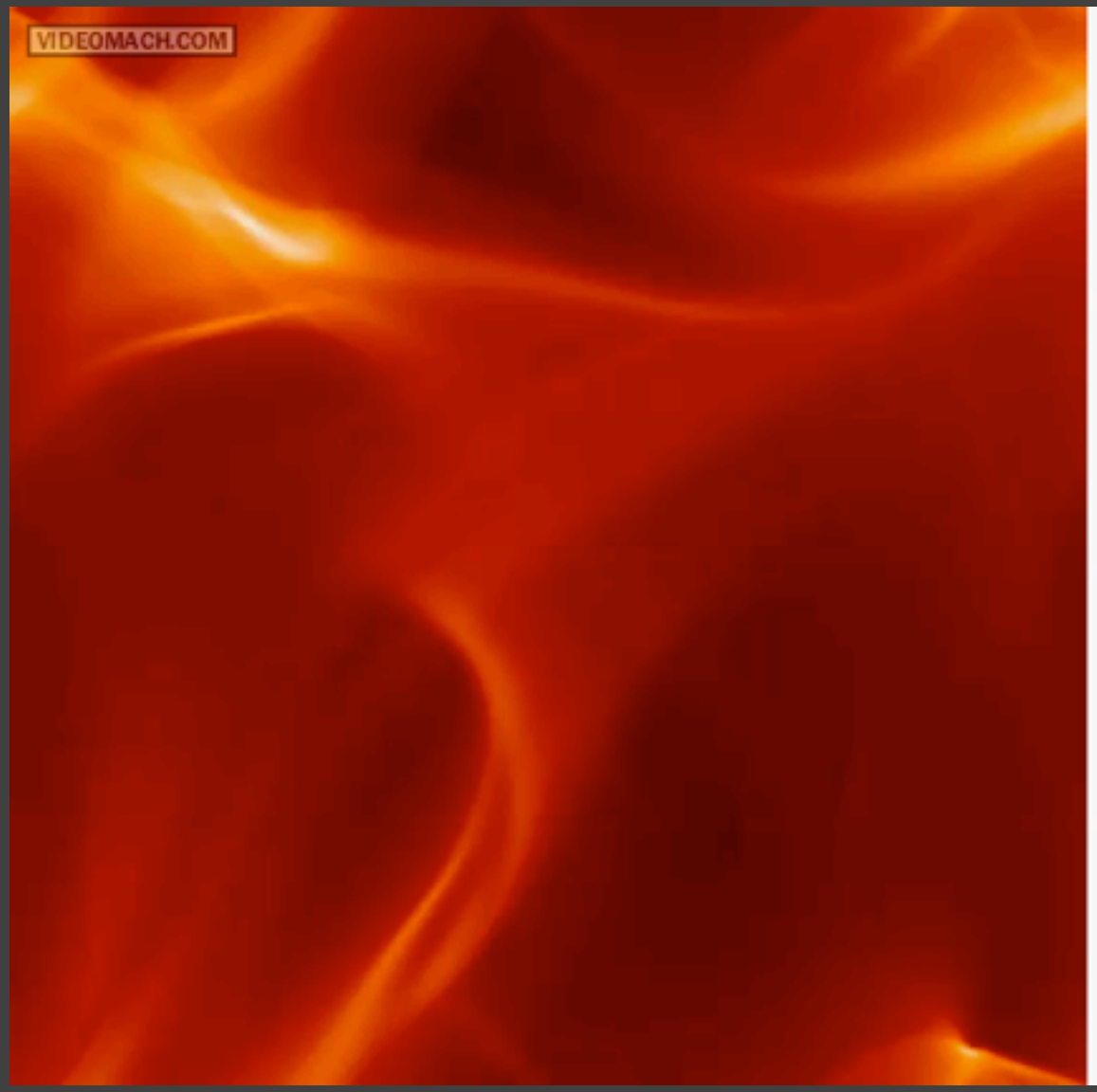
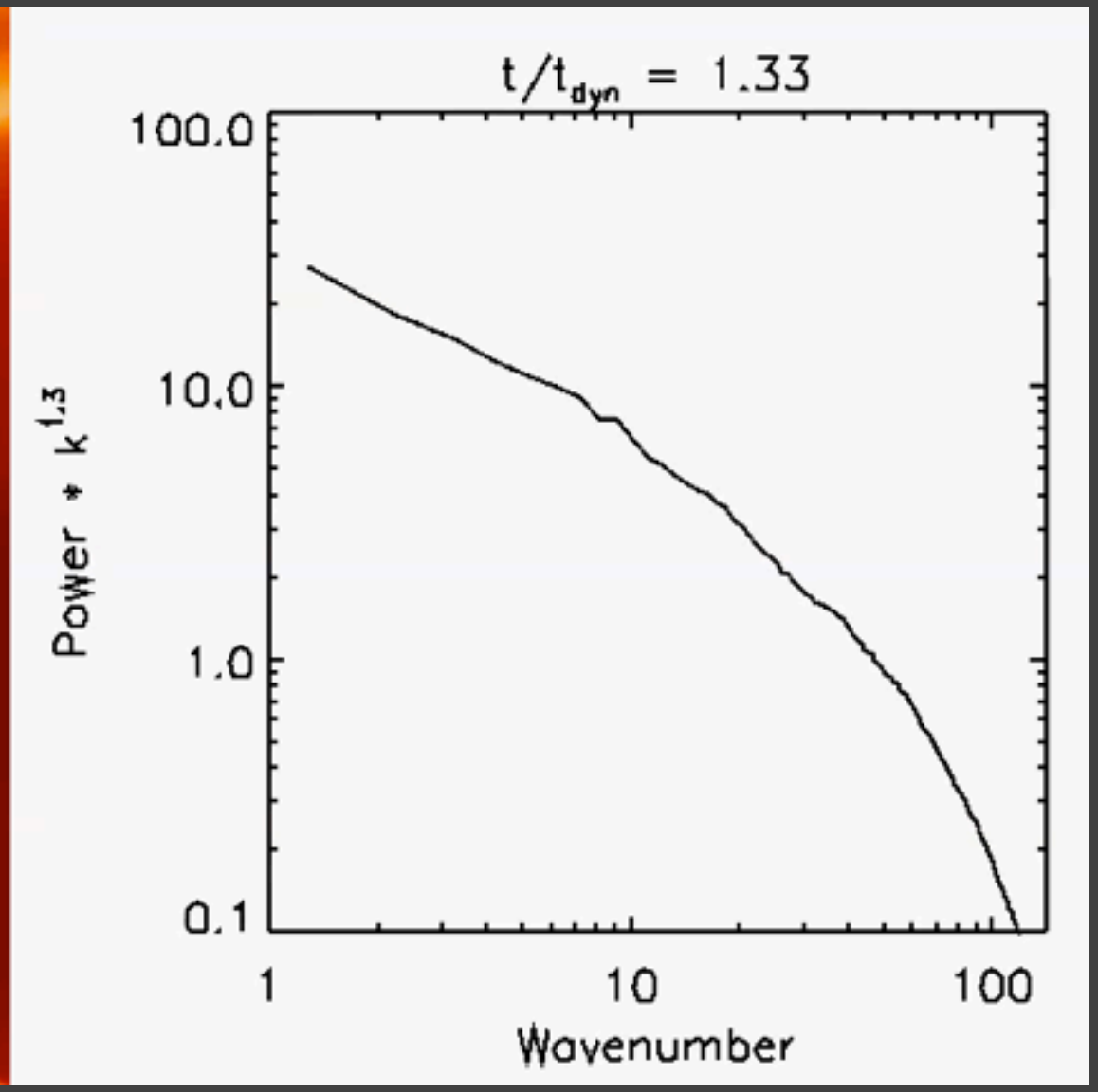
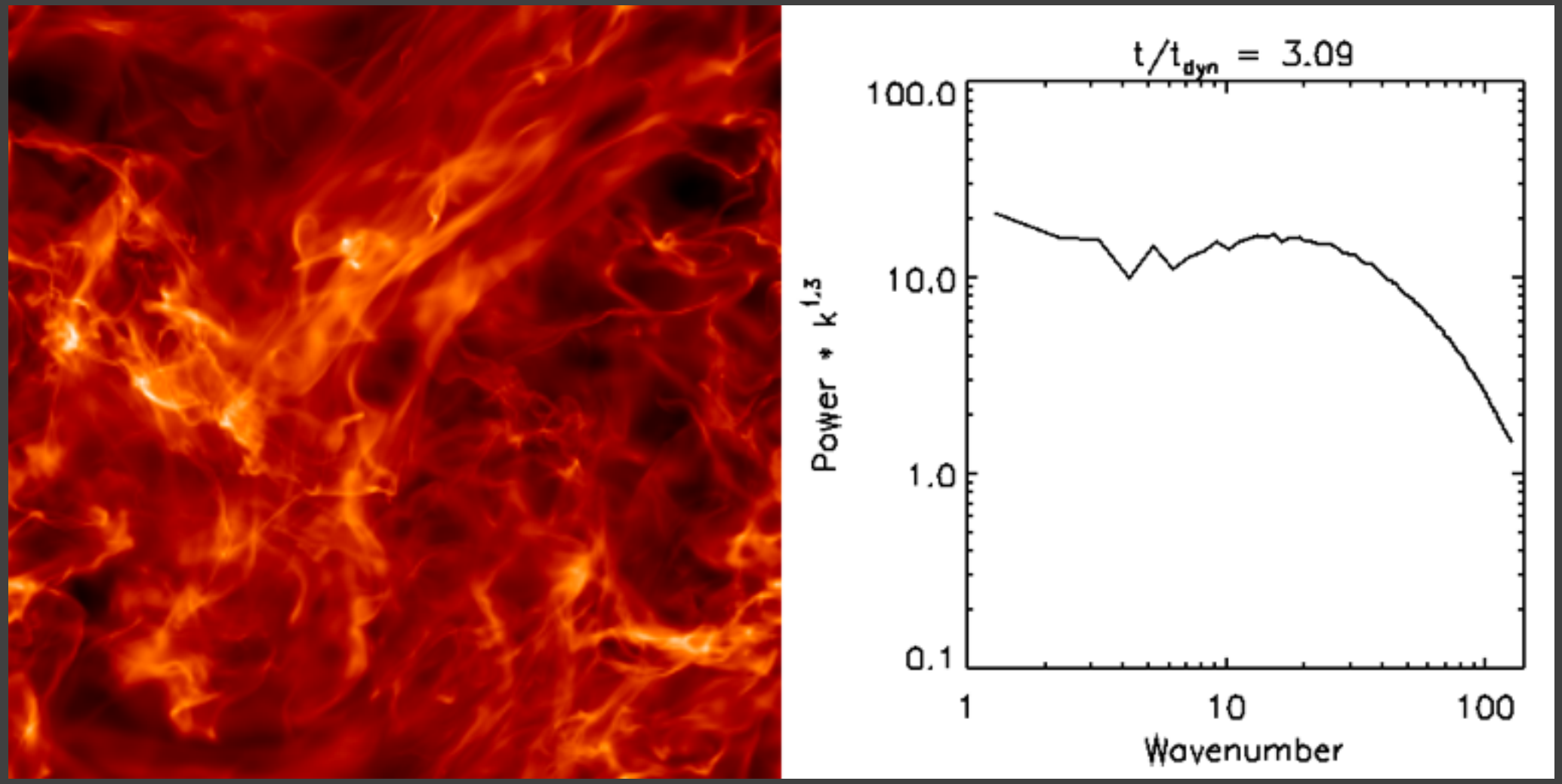




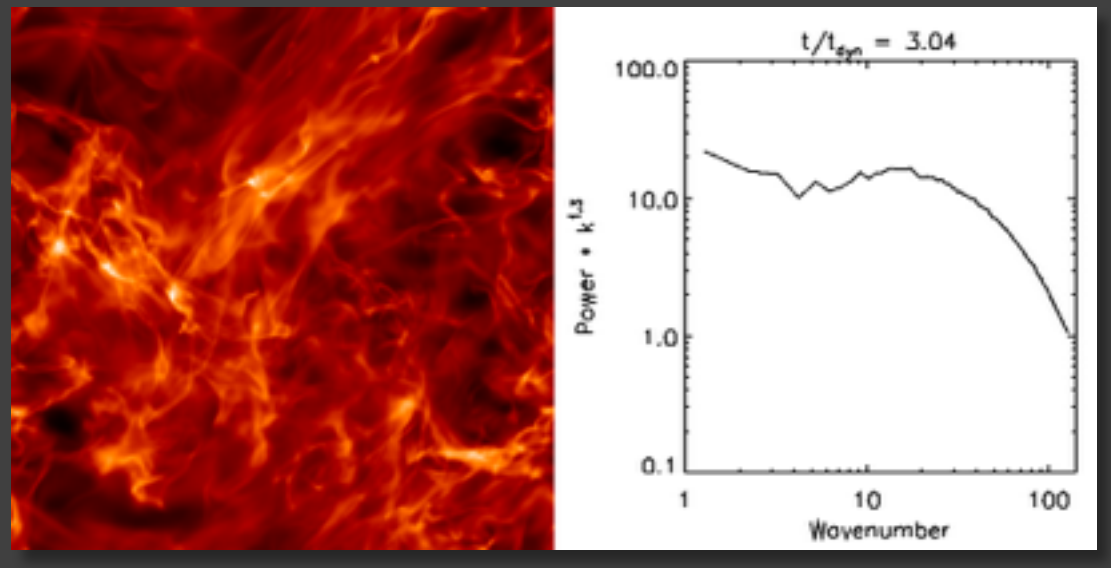
Final Initial Condition for IMF experiment



Turning on gravity

Self-gravity is gradually ramped up to the value consistent with the size and mass (Larson's relations)

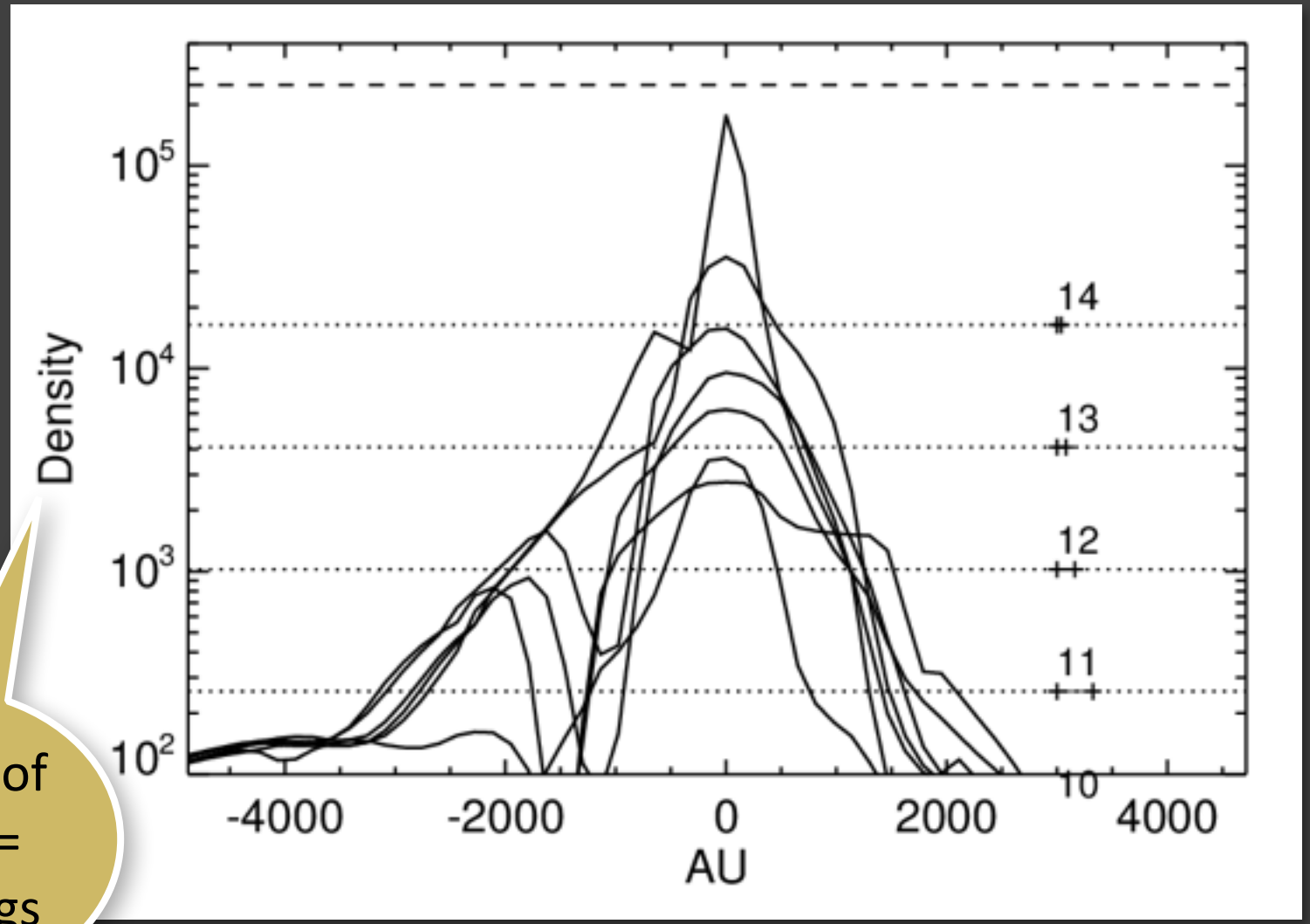
- This corresponds closely to the gradual compression of this MC as it is assembled in a larger (GMC) context



The first star ⟶ a single star IMF !

Mass in the collapsing core ≈ 0.2 solar masses: ***on the IMF peak*** !

- Dotted lines: levels of mass refinement (12 cells per Jeans' length)
- Dashed line: sink tr… level



In units of <rho> = 2e-22 cgs

Conclusions from numerical experiments

Needed for realistic IMF

- MHD-turbulence = ***magnetic fields*** and ***turbulence***
- Supersonic and super-Alfvenic conditions
  - Sound speed ≈ 0.2 km/s (T ≈ 10 K)
- Respecting ***Larson's relations***
  - Driving of some sort (SNe, artificial, …)

Not needed:

- Non-isothermal EOS
- Radiative transfer
- Local feedback

Towards self-consistent experiments

- We have SN-feedback
  - Tables of life-times, stars explode at the time (and place!) appropriate
- Radiative transfer
  - Just finished implementing ray-tracing in Ramses AMR
- Chemistry
  - KROME code has just been integrated

Overall conclusions

What controls the IMF?

- Power law slope: Statistics of super-Alfvenic MHD turbulence
- Peak position: Larson's relations = ISM scaling laws

This begs the question: What controls Larson's relations?

- Self-regulated feedback !
- Cannot be dominated by local feedback

Thanks for your attention!