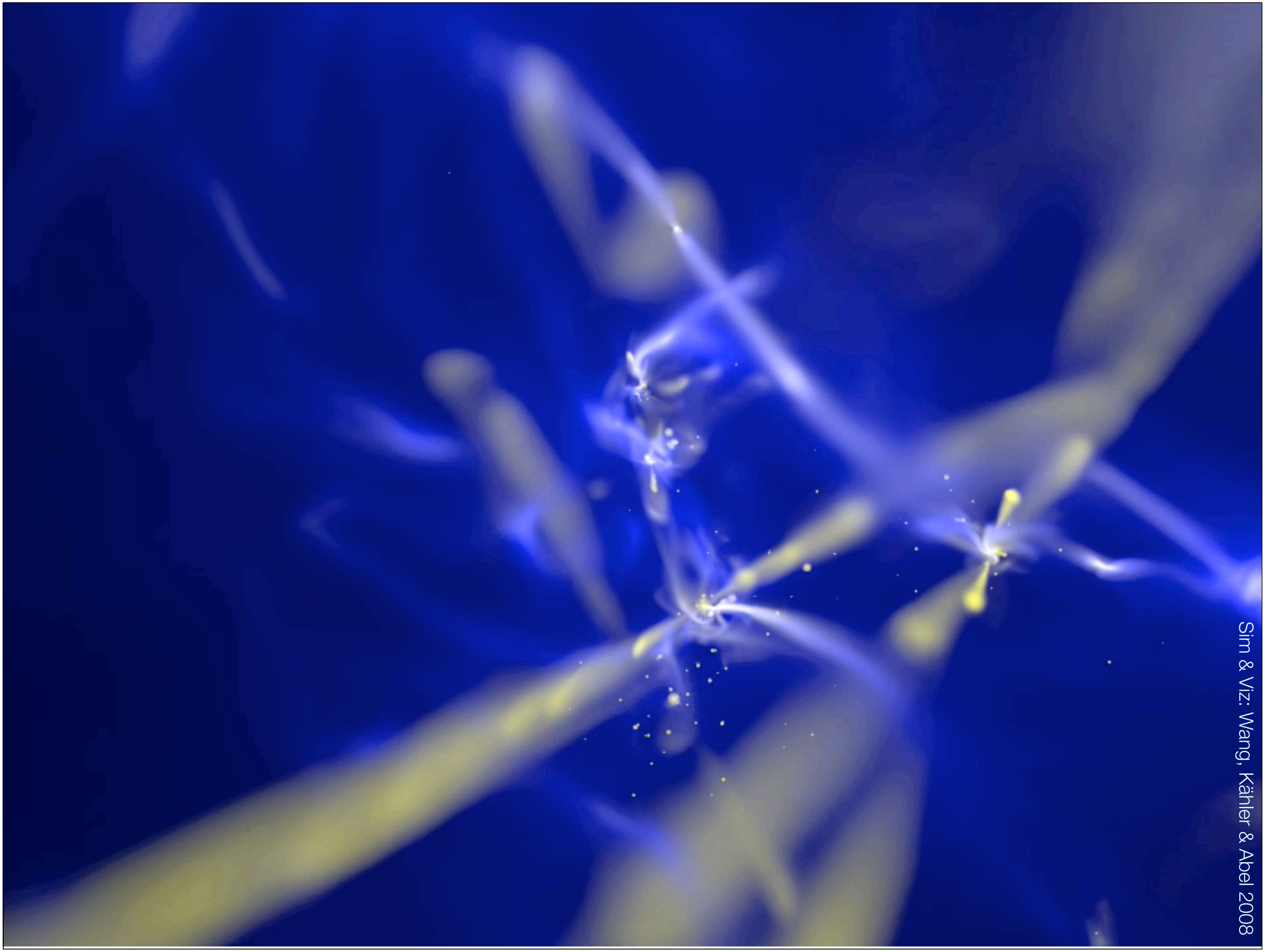
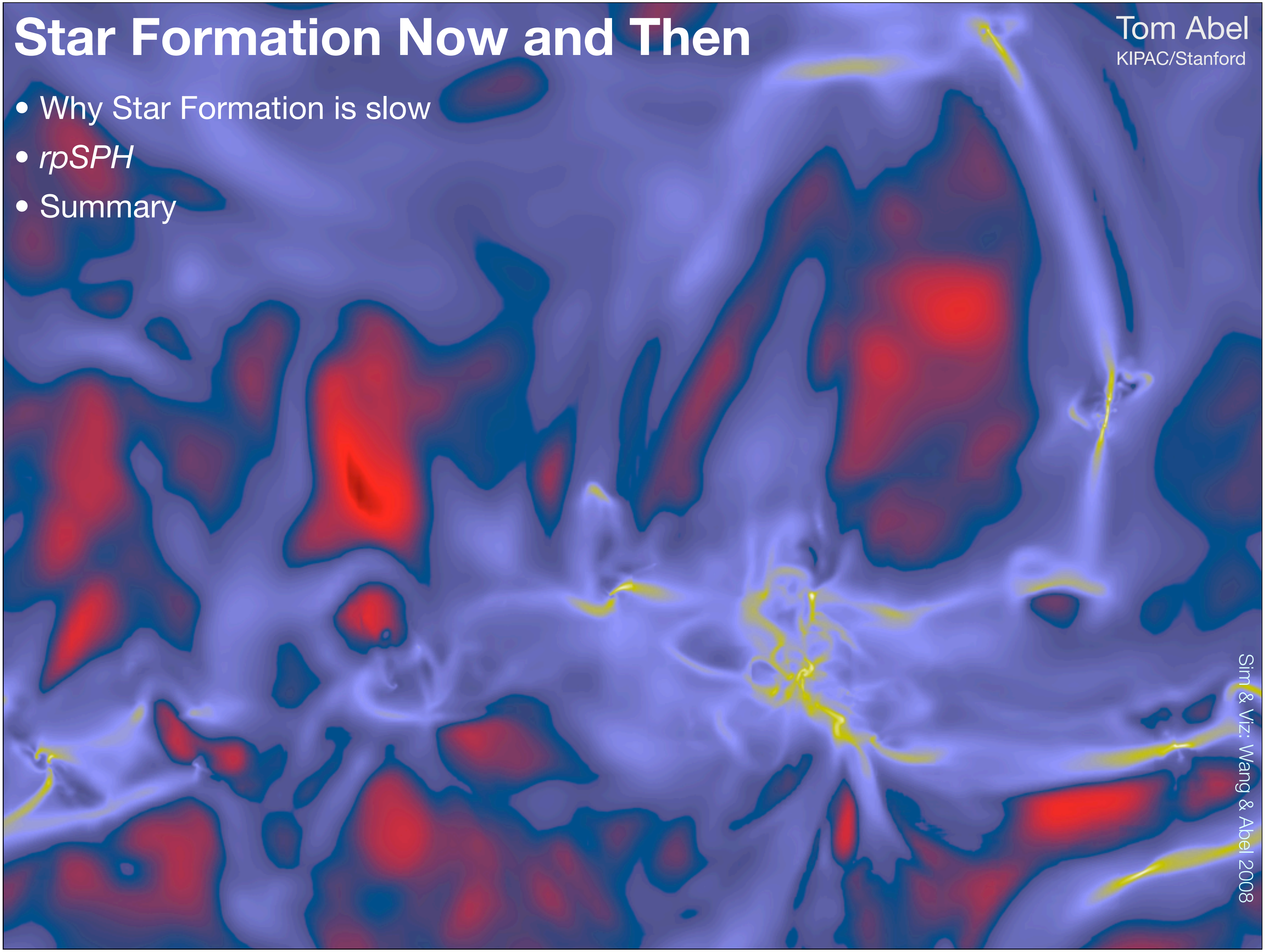
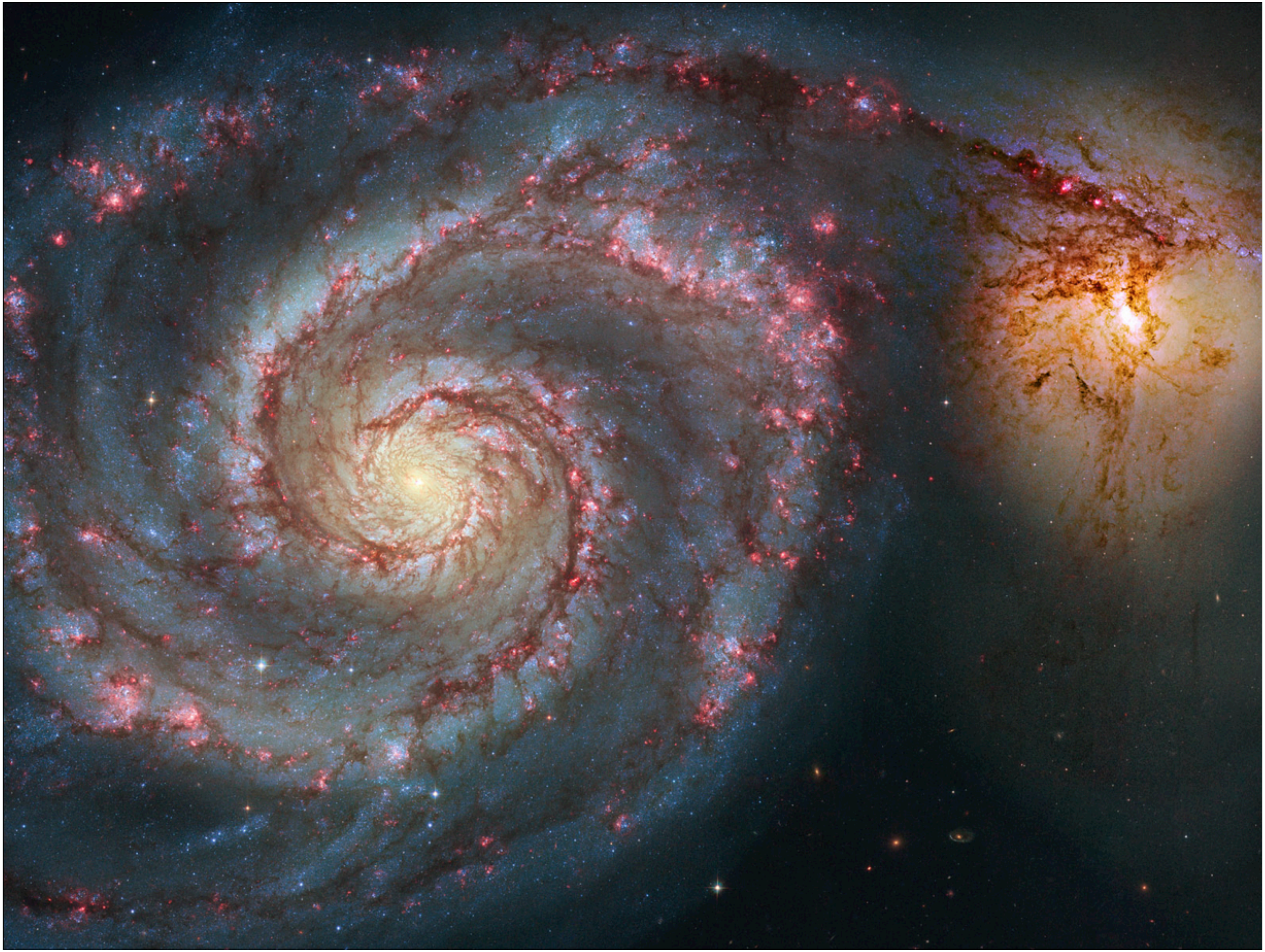

Sim & Viz: Wang, Kähler & Abel 2008

Star Formation Now and Then

Tom Abel
KIPAC/Stanford

- Why Star Formation is slow
- *rpSPH*
- Summary

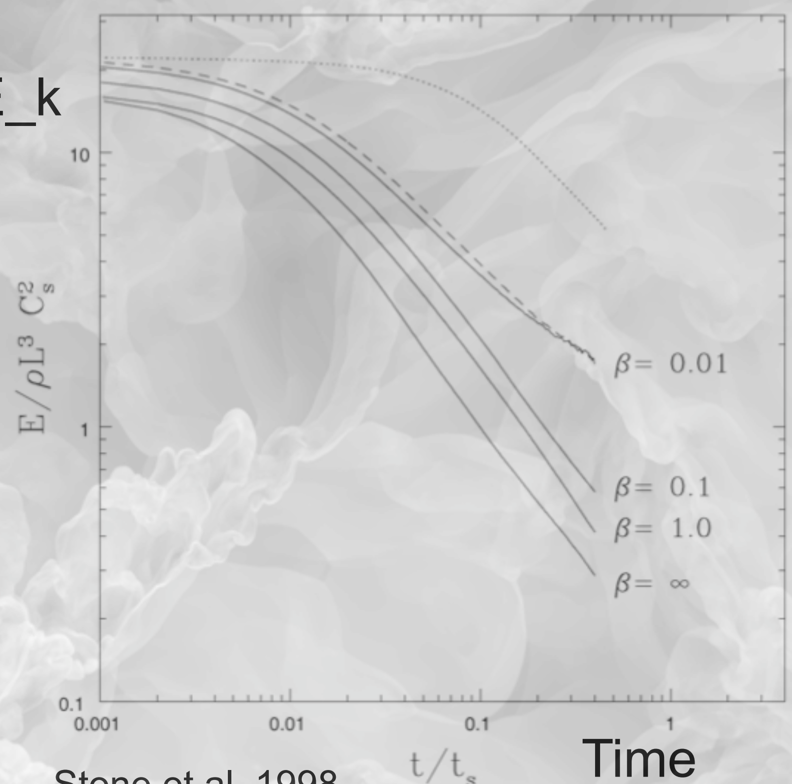




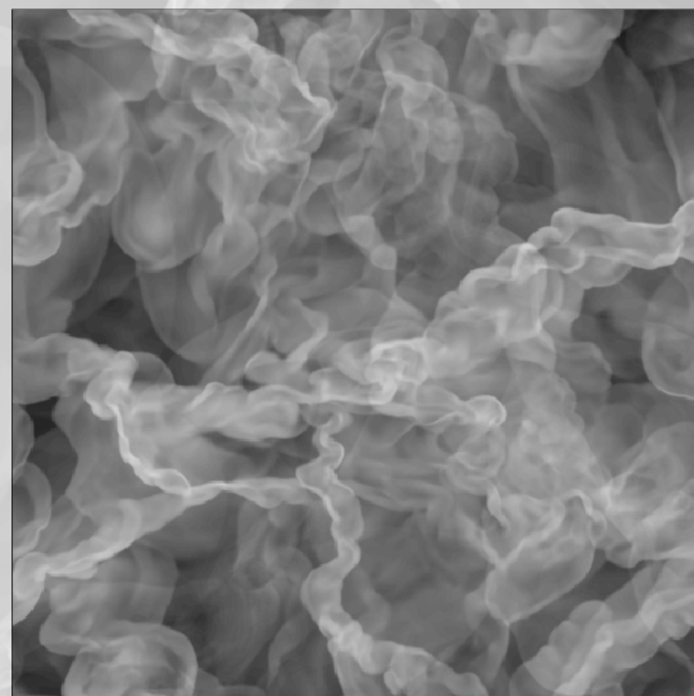
Star Formation is Slow

- There are a billion solar mass of gas in Giant Molecular Clouds. (Bronfman et al. 2000) in our Galaxy.
- GMCs have typical number densities ~ 100 per cubic centimeter. Hence the gravitational free fall time is about 4 million years (1/sqrt(G rho)) (Solomon 1987)
- So M_{MC}/t_{ff} ~ 250 Myr This would be the star formation rate if only gravity would be the relevant physics.
- Observed rate of star formation is 3 solar masses per year (McKee & Williams 1987)
- Also true in nearby disk galaxies and even in Starburst galaxies which have 100 times denser molecular gas and observed star formations rates ~ 50 solar masses per year

Rapid Decay of Supersonic Turbulence



Stone et al. 1998



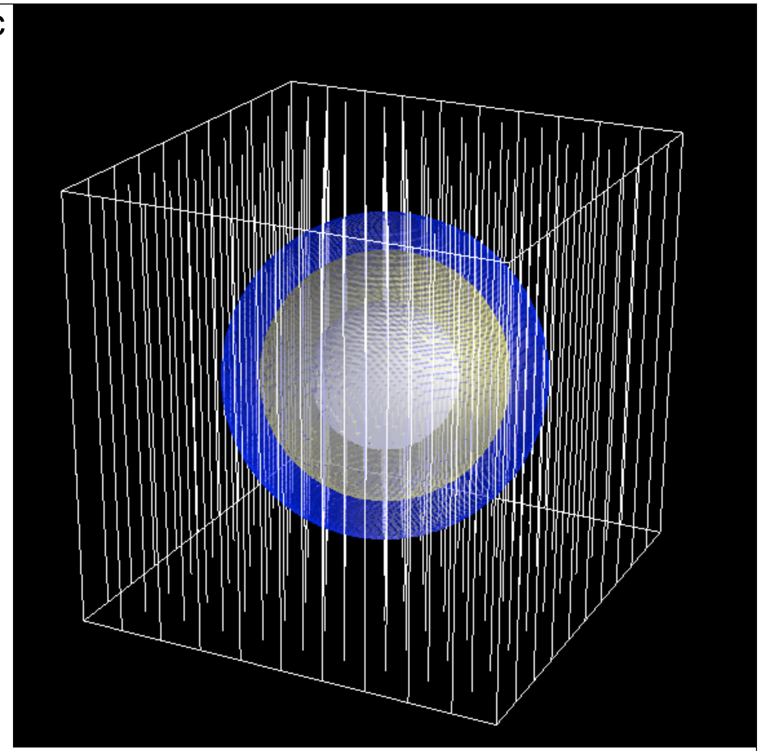
MHD 512^3, Wang & Abel 2009
with 16 graphics cards this takes 16 hours
on the 40 node cluster in Heidelberg

This result is inconsistent with the observed slow star formation and supersonic turbulence!

So how is turbulence driven in molecular cloud?

Model Setup

Box size: 2 pc



- Spherical cloud with total mass = 1200 Msun with total of 1641 Msun in the box and density profile:

$$\rho(r) = \frac{\rho_c}{1 + (r/r_c)^2},$$

- Cs=0.265 km/s (T=20 K);

- Initial turbulence has k^{-2} Burger's power spectrum with M=9

- Uniform magnetic field in z direction. Mass-to-flux ratio: overall: 1.4; central: 3.3.

- Sink particle to model star formation

- Protostellar outflow feedback.

- Top grid 128^3, 4 levels of refinement by 2, maximum resolution 100 AU 2048 dynamic range .

	Turbulence	Magnetic field	Wind
Base	0	0	No
HD	virial	0	No
MHD	virial	1e-4 G	No
Wind	virial	1e-4 G	Yes

Wang, Li, Abel, Nakamura 2010 ApJ

Sink Outflow Feedback

Momentum feedback according to sink particle accretion rate:

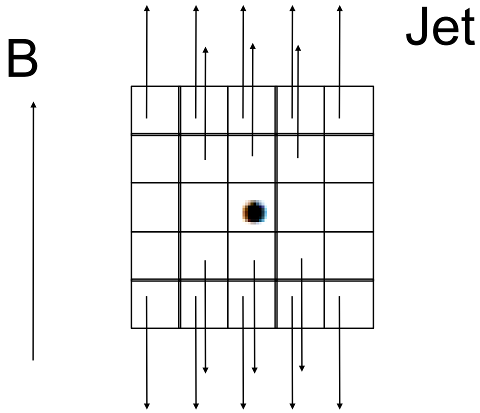
$$\Delta P = P_* \Delta M$$

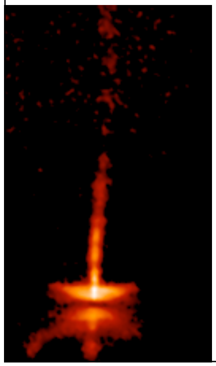
$$P_* = P_0 (M_* / M_0)^{1/2}$$

where $P_0 = 50$ km/s and $M_0 = 10\ \mathrm{M}_\odot$. $\Delta M = 0.1\ \mathrm{M}_\odot$.

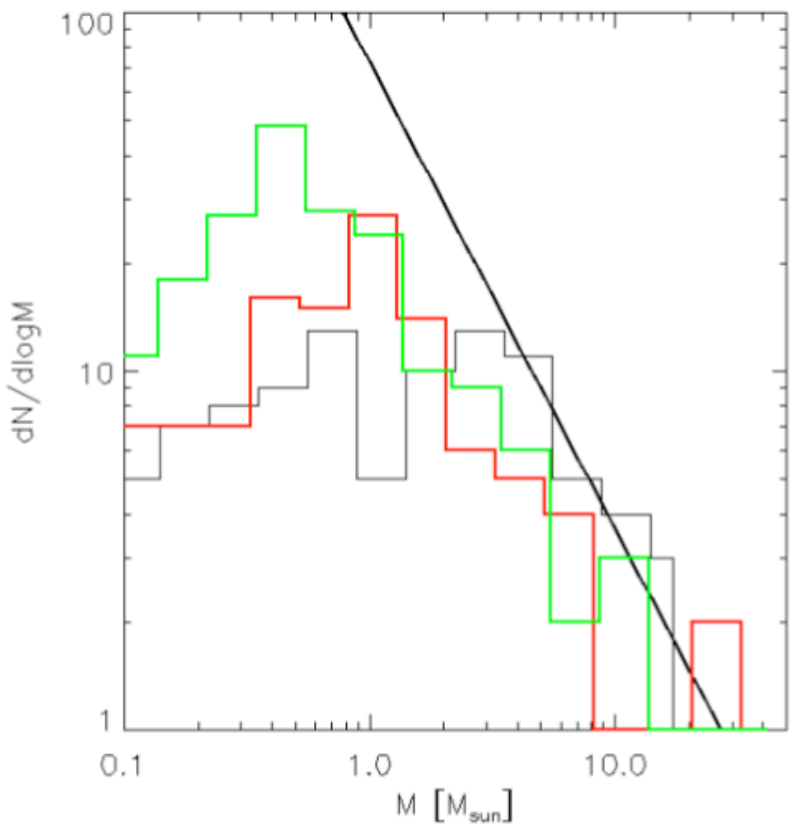
Note: this is ~ 1/3 of the observed value for low mass stars:
~ 16 km/s per accreted solar mass

Jet injected parallel with 3-5 cells across; direction is the B field direction of the host cell at the first injection, subsequent direction is fixed to the initial direction





Final Sink Particle Mass Function (FSPMF - IMF?)



High mass slope consistent with Salpeter in all cases.

Wind case:
- observed turn over mass correct
- twice as many stars as initial Jeans masses within the initial cloud

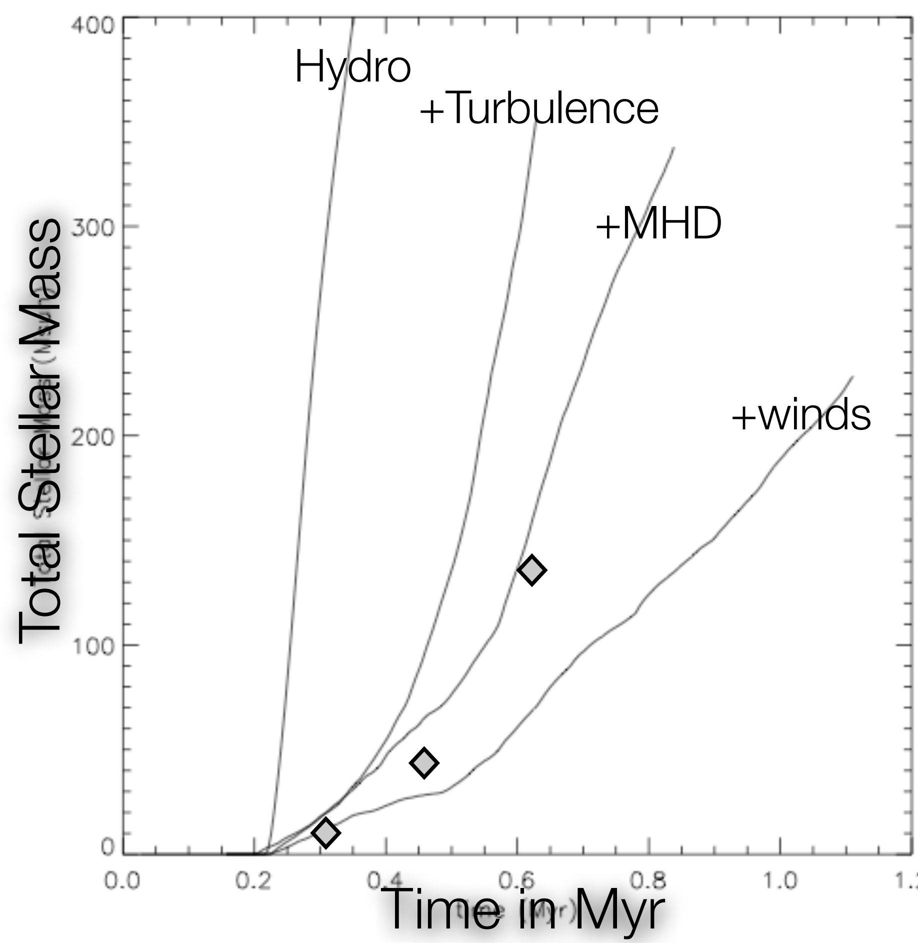
This is more of an input than an output of the calculation because it is a direct consequence of the myriad choices of how to implement sink particles. We should recall that we make an order unity error at and around sink particles. Even after a few time-steps we cannot guarantee an exact solution. At the same time we sacrificed the ability of doing resolution studies.

Fig. 2.12.— The sink particle IMF for HD (black), MHD (red) and WIND (green) when they have the same SFE $\sim 16\%$. The thick black line gives the Salpeter IMF slope of -2.35.

k run.

Relevant physics in star formation

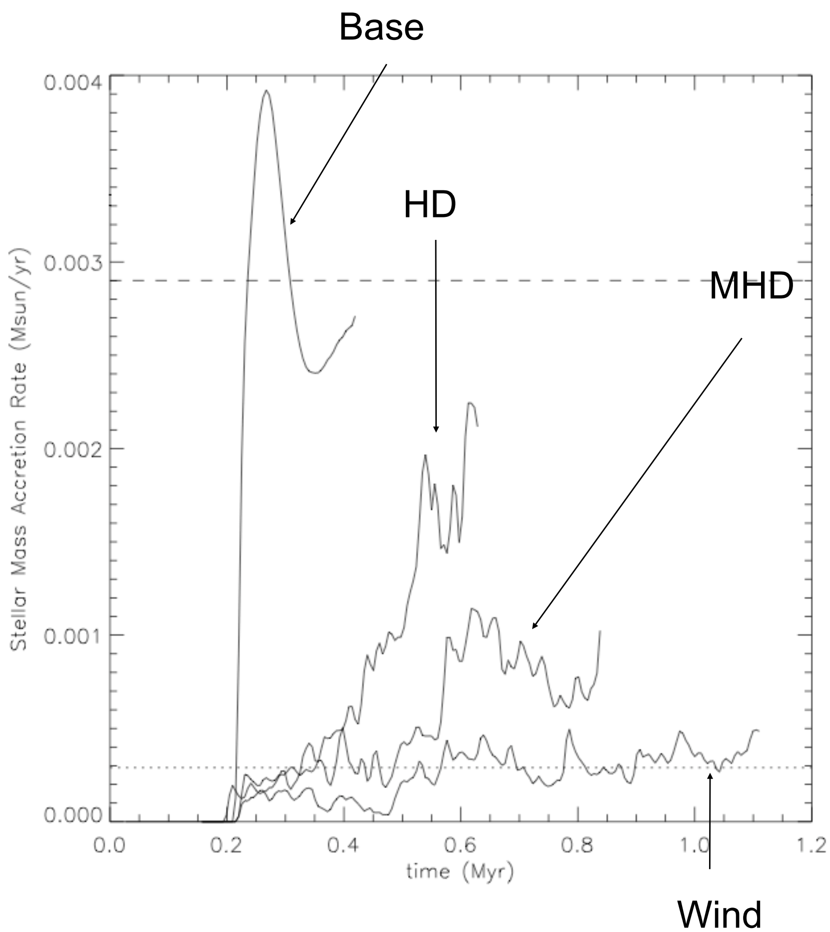
- Hydro/MHD models form stars much to quickly
- Only with proto-stellar outflows and MHD one gets any reasonable
- Winds keep turbulence allow cloud to form stars for many dynamical times
- First Model with sustained star formation over many dynamical times without large scale driving
- “primordial” turbulence decays fast, most of the mass
  of a star cluster is built during outflow-driven turbulence phase.
- Our models still are missing
  - ambipolar diffusion
  - IR radiation



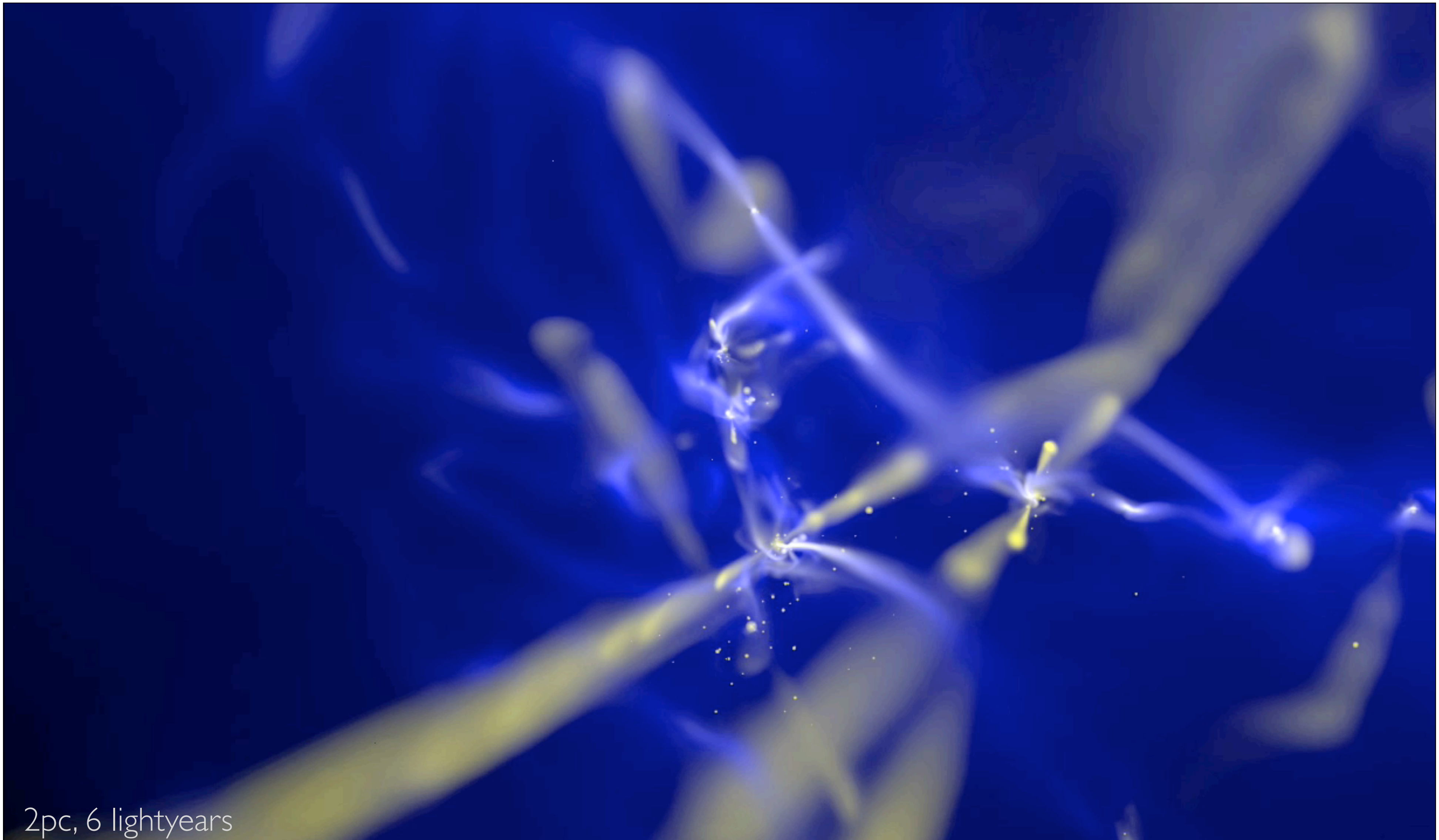
Wang, Li, Abel, Nakamura 2010 ApJ

◇ turbulence + winds (no MHD)

Global star formation rate



Outflow can lead to slow star formation!
=> Since "primordial" turbulence decays fast, <u>most of the mass of a star cluster is built during outflow-driven turbulence phase.</u>
So it's crucial for massive star formation, initial mass function, etc.



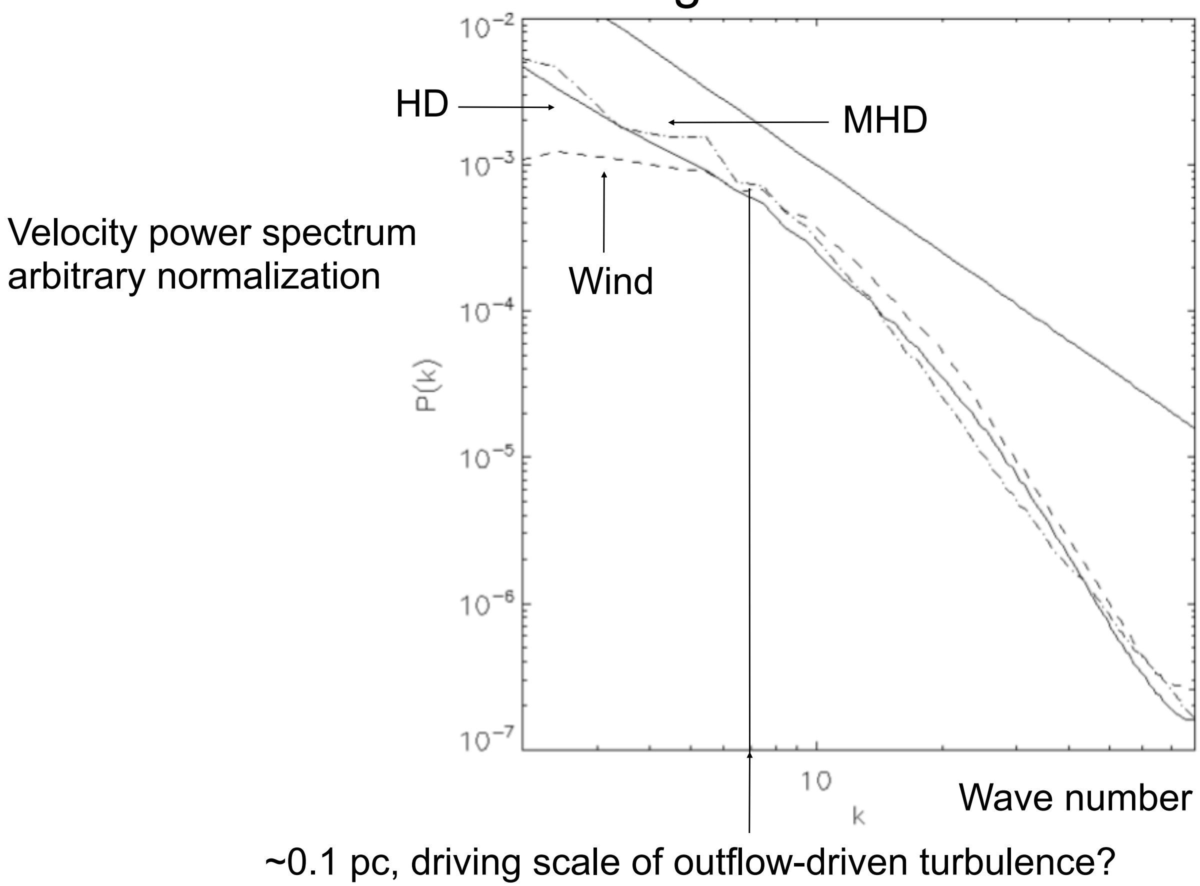
Formation of a Star Cluster in the Milky Way

Sim: Wang, Li, Abel, Nakamura 2010 ApJ.
Viz: Kähler & Abel 2009

Log of column density: blue-white
yellow: kinetic energy - jets from young stars

Velocity Power Spectrum

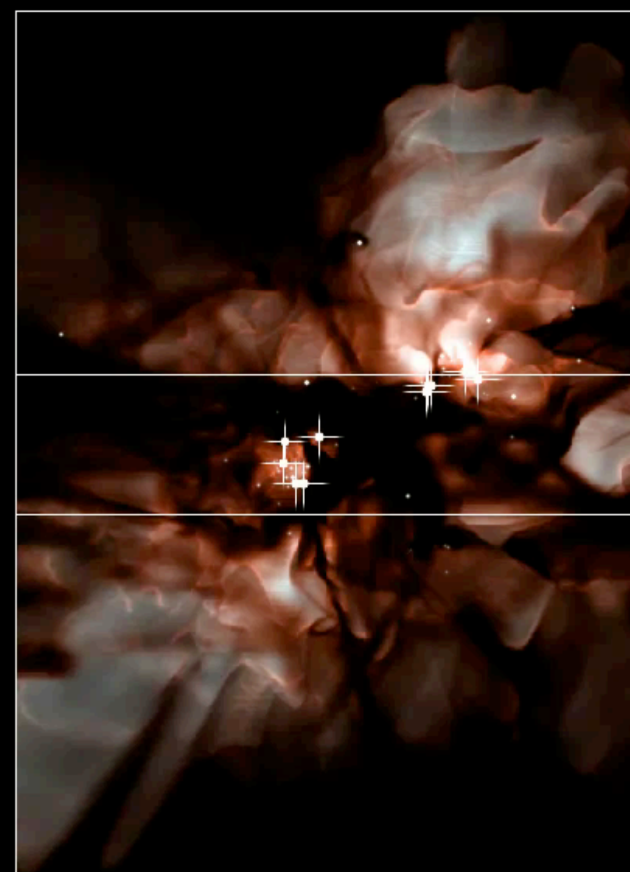
Outflow-driven turbulence's velocity spectrum slope is much flatter than -2 above core scale and indistinguishable at small scales!



- A spectrum flattening at ~ 0.05 pc is recently seen in L1551 (Swift 2008) (also found in Orion if when linear large scale velocity gradient is removed)
- Many analytical works have tried to explained IMF using -2 law.

Molecular Cloud Dispersal

- Driven by Massive Stars
  - Winds
  - HII regions
  - Supernovae



Vis: Iannucci, Wang & Abel in progress
Sim: Wang & Abel

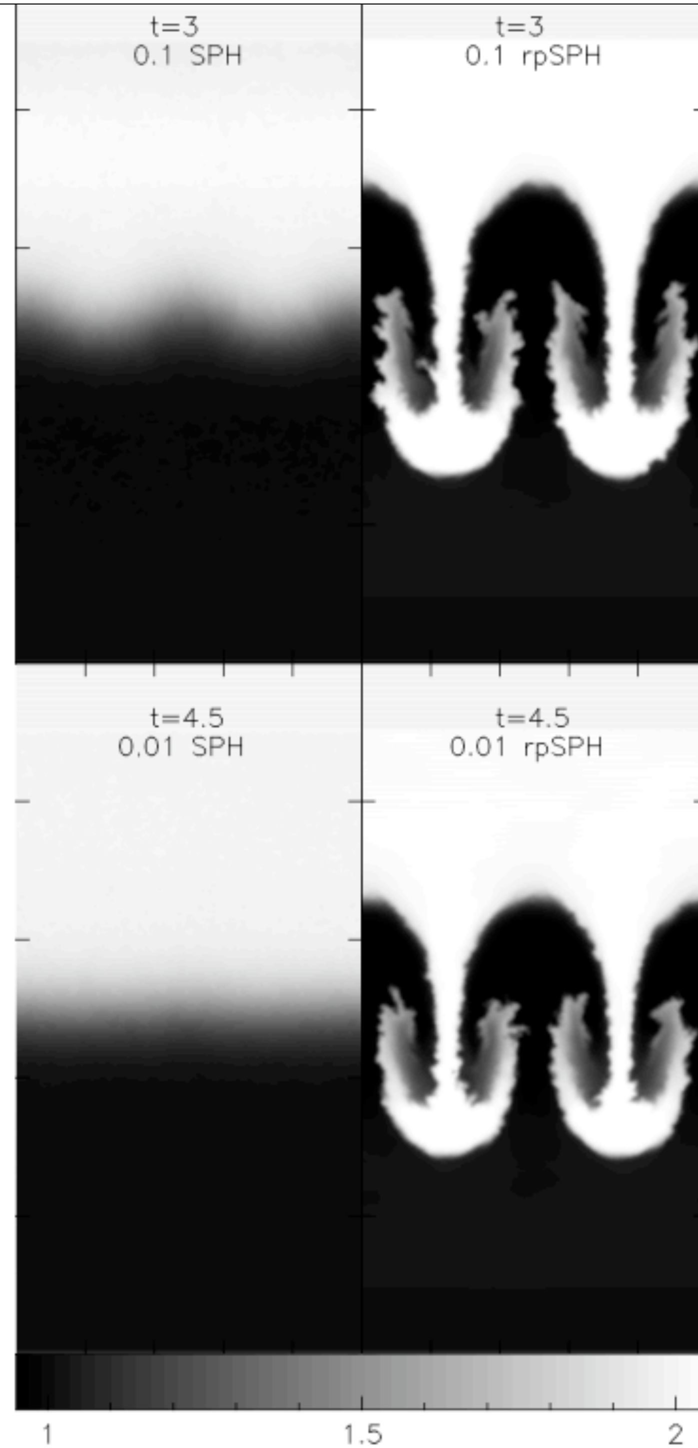
rpSPH

- Novel discretization of the SPH equation

$$\frac{dv}{dt} = -\frac{1}{\rho}\nabla p$$

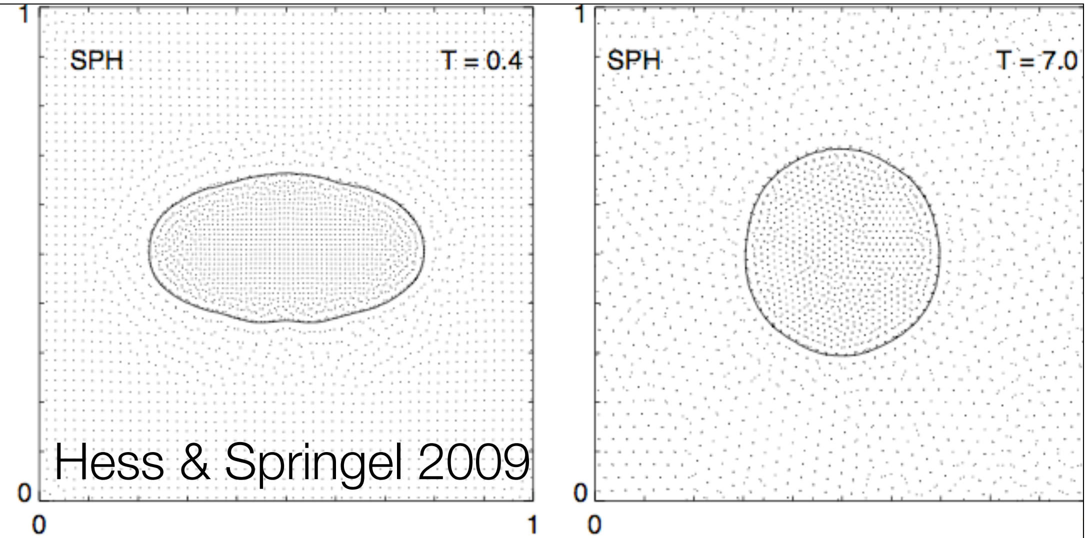
- Avoids or dramatically reduces
  - clumping instability
  - unphysical dissipation
  - "Brownian Motion"
  - unphysical "surface tension"
- Better handles contact discontinuities

[11] arXiv:1003.0937 [pdf, other]
rpSPH: a much improved Smoothed Particle Hydrodynamics Algorithm
Tom Abel
Comments: 14 pages, 11 figures, submitted to MNRAS. Comments welcome

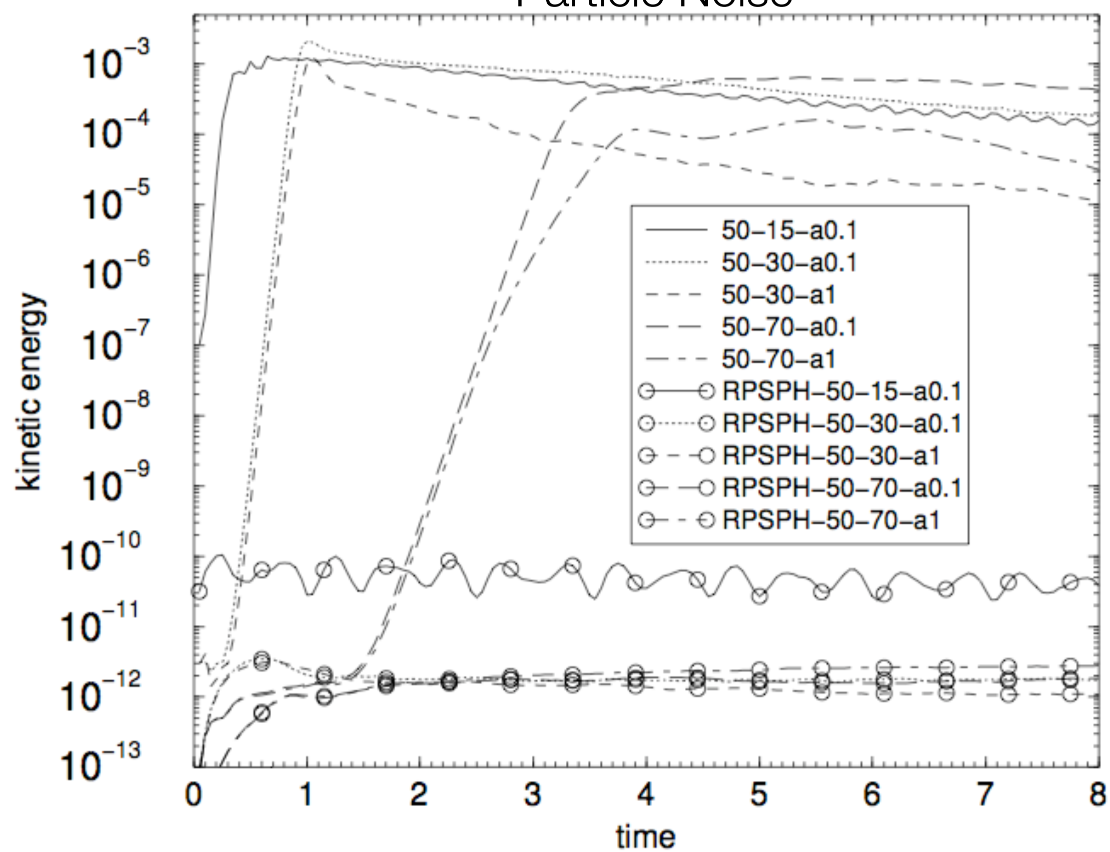


Selected SPH shortcomings

- Surface Tension
- Clumping Instability

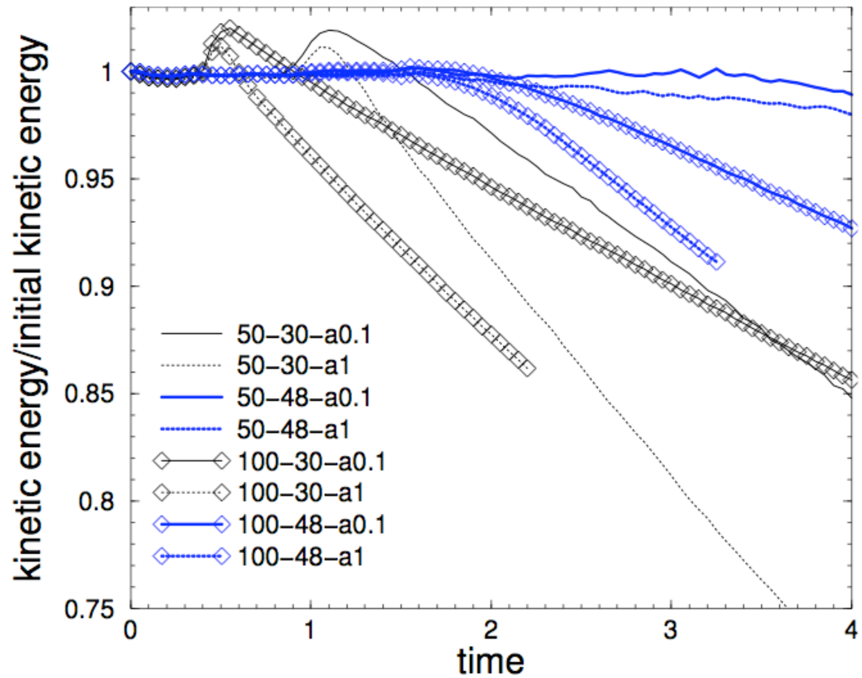


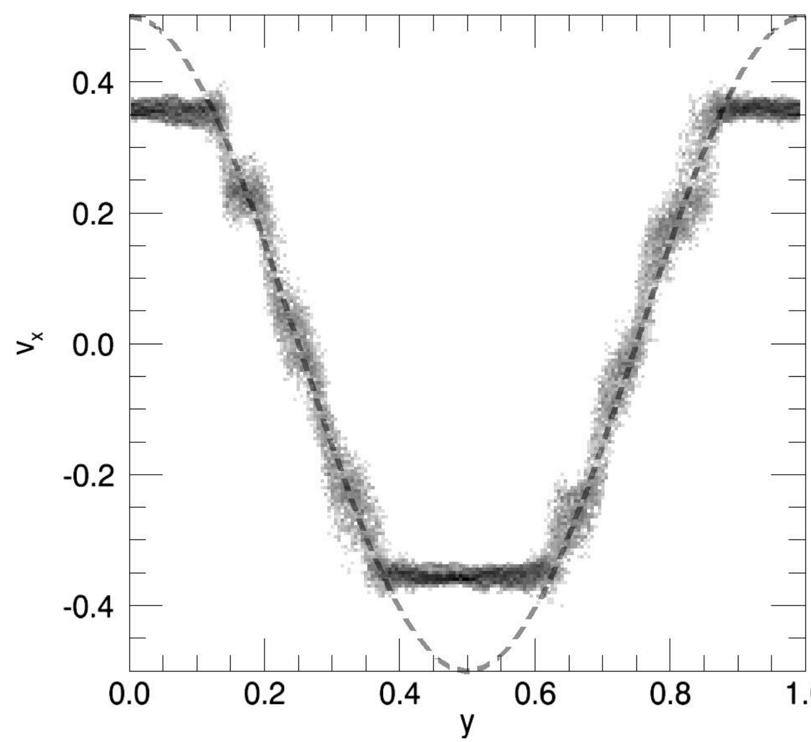
Particle Noise



Selected SPH shortcomings (cont.)

- Unphysical dissipation of shear flows
- Large Non-Newtonian viscosity
- Numerical dissipation does *not* decrease with numerical resolution
- Maximum Reynolds number of order ~100
- Turbulence typically at Re > 1e5 (> 1e~4 in pipes)
- Convergence study impossible





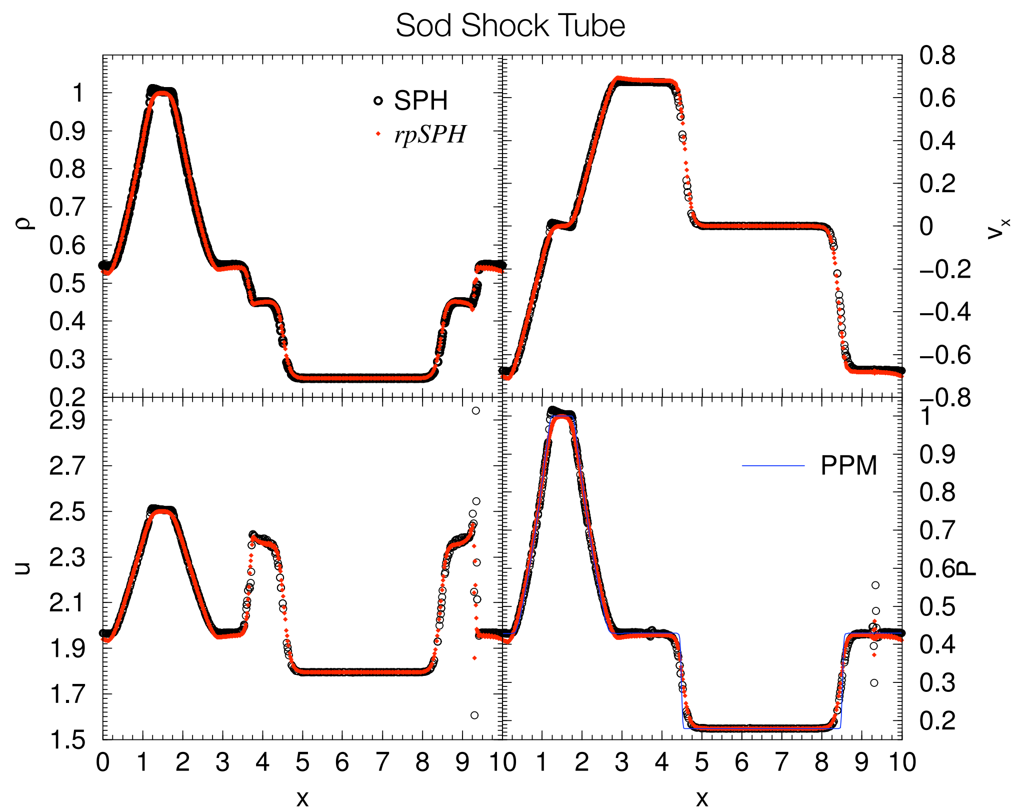
rpSPH

$$\frac{dv}{dt} = -\frac{1}{\rho}\nabla p$$

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} = -\sum_{j=1}^{N} m_j \left[f_i \frac{P_i}{\rho_i^2} \nabla_i W_{ij}(h_i) + f_j \frac{P_j}{\rho_j^2} \nabla_i W_{ij}(h_j) \right]$$

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} = -\sum_{j=1}^{N} m_j \left[f_j \frac{P_j - P_i}{\rho_j^2} \nabla_i \bar{W} \right]$$

- Overcomes all the above problems
- Respects Newtons first instead of third law of mechanics
- Works for viscous flow
- Same idea for MHD looks very promising



To convert Gadget to *rpSPH*:

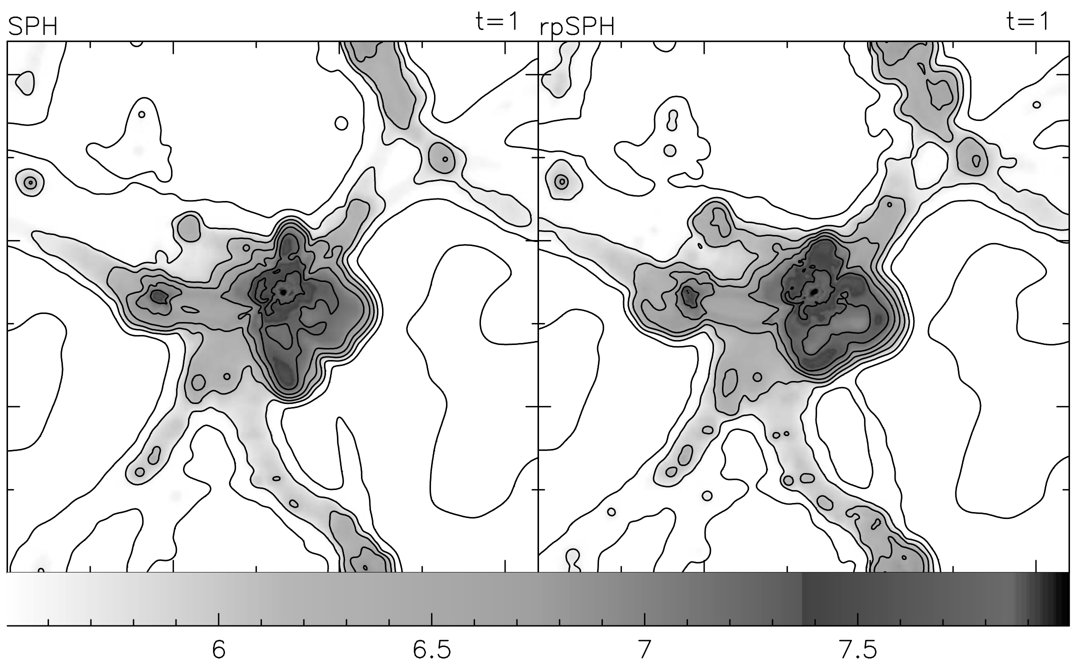
```
hfc = hfc_visc + P[j].Mass*(p_over_rho2_i*dwk_i
        + p_over_rho2_j*dwk_j)/r;
```

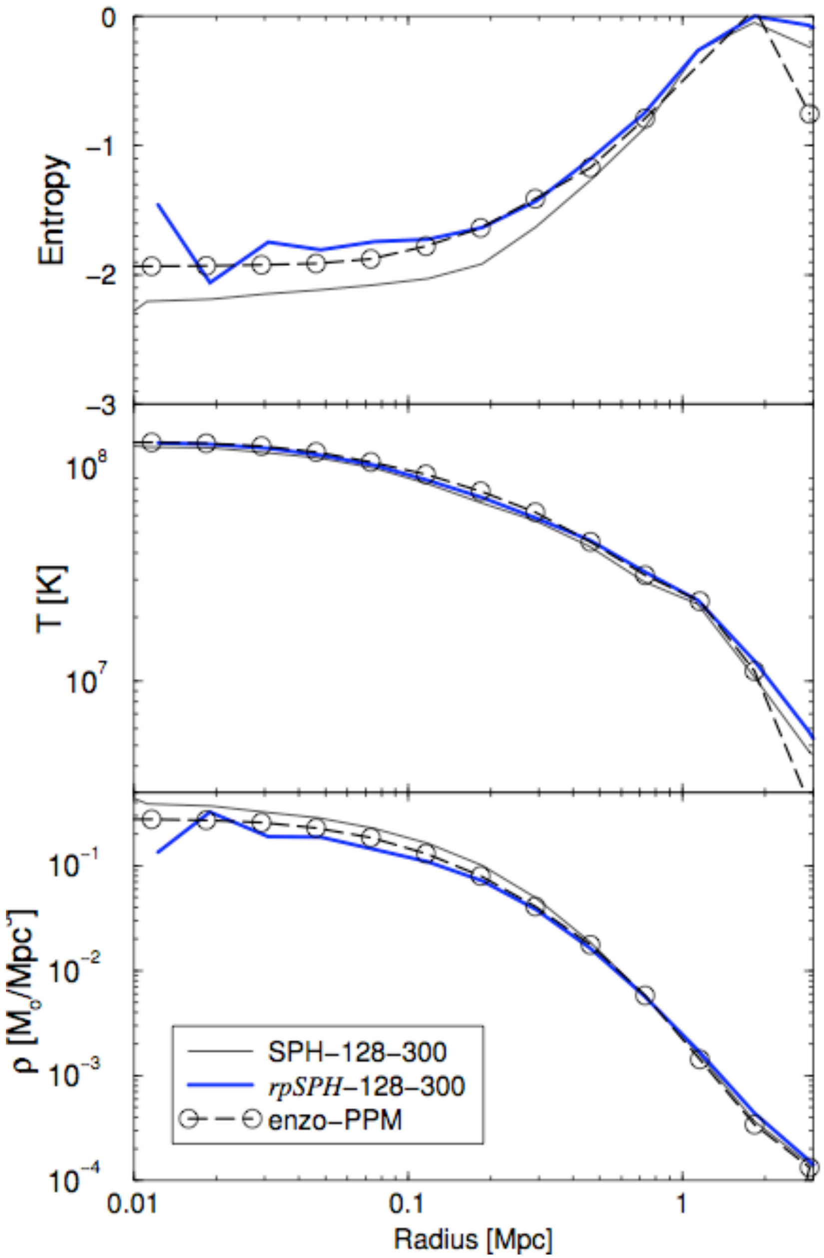
and change it to

```
hfc = hfc_visc+P[j].Mass/SphP[j].Density*
  (SphP[j].Pressure-pressure)/SphP[j].Density*
  (dwk_j+dwk_i)/r/2;
```

Santa Barbara test looks ok

- Easy problem since DM is dominant source of gravity
- rpSPH agrees better with AMR than with SPH

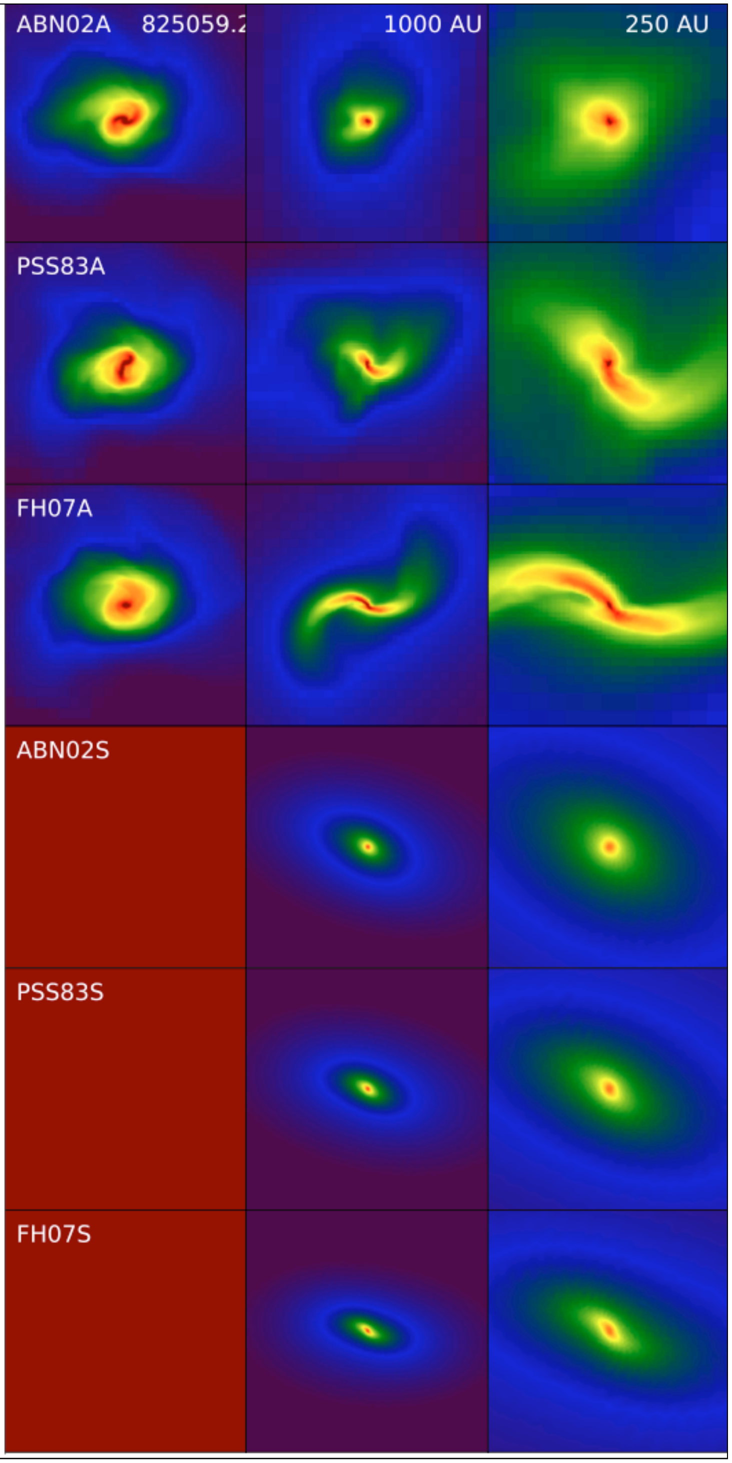


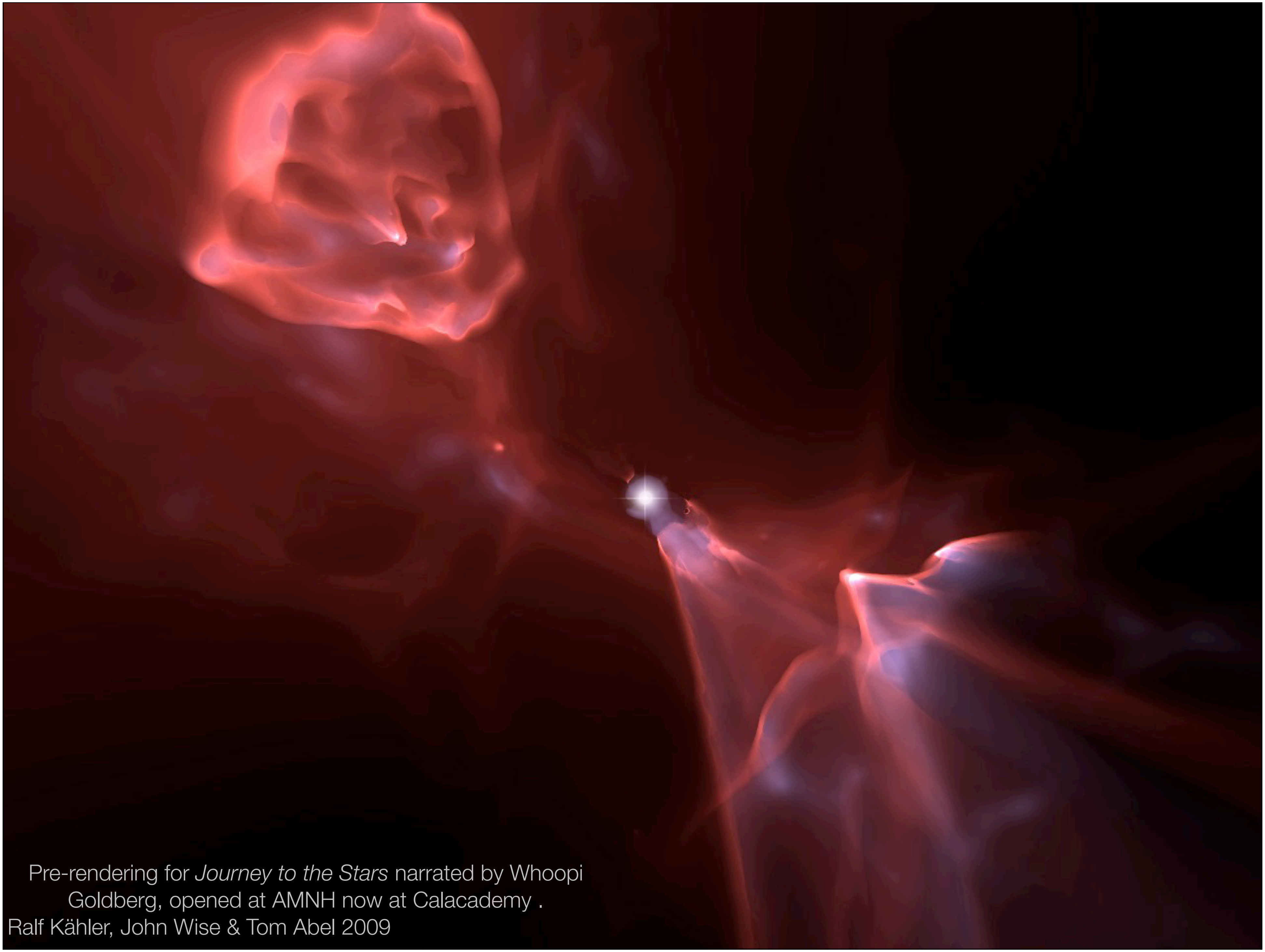


Summary

- Turbulence in Molecular clouds on parsec scales is regulated by outflows.
  - Magnetization of cloud is if crucial importance
  - Likely a parameter at least as important as metallicity for Pop III to Pop II transition
- SPH has significant flaws in the regime of Pop III conditions
- *rpSPH* may be one way forward to do proper Lagrangian Hydrodynamics limiting numerical dissipation

Turk et al 2010





Pre-rendering for *Journey to the Stars* narrated by Whoopi Goldberg, opened at AMNH now at Calacademy .
Ralf Kähler, John Wise & Tom Abel 2009