rpSPH

Star Formation

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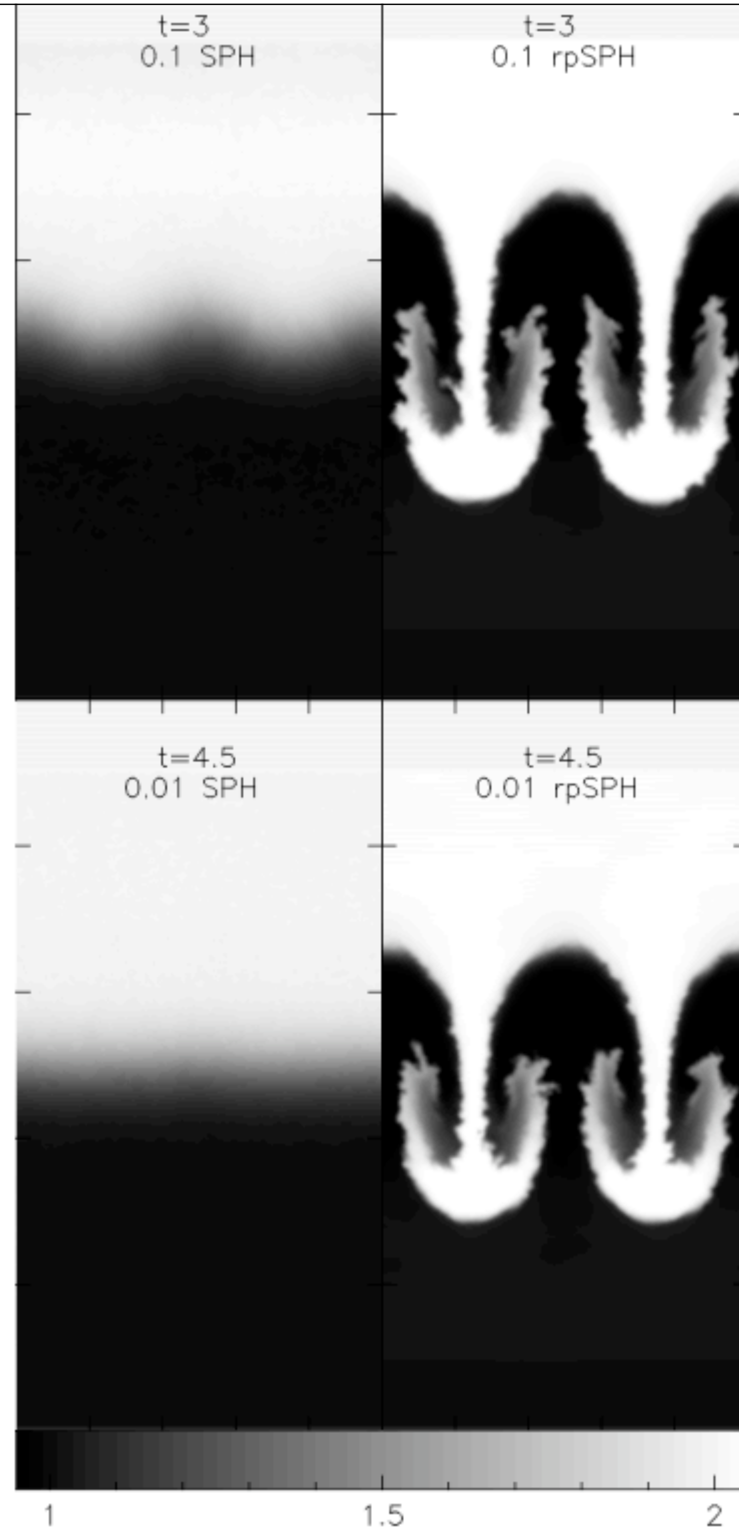
rpSPH

- Novel discretization of the SPH equation

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

- Avoids or dramatically reduces
  - pairing instability
  - unphysical shear dissipation
  - “Brownian Motion”
  - unphysical “surface tension”
- Better handles contact discontinuities
- Does not conserve momentum (individual time-stepping SPH does not either)



[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

SPH discretization

- Standard formalism

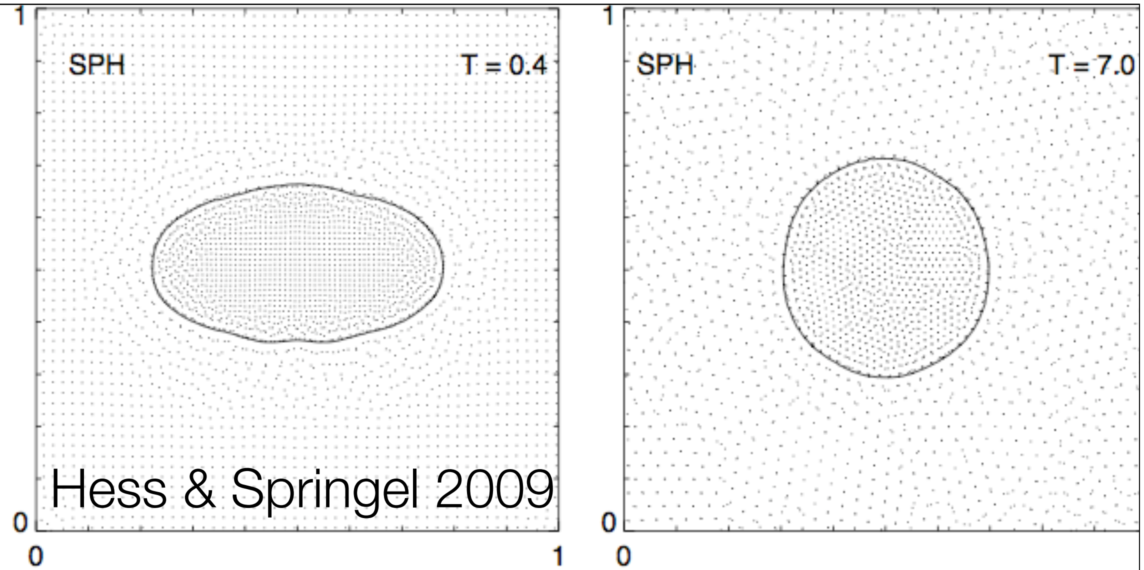
$$\frac{dv}{dt} = -\frac{1}{\rho}\nabla p$$

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

Gadget

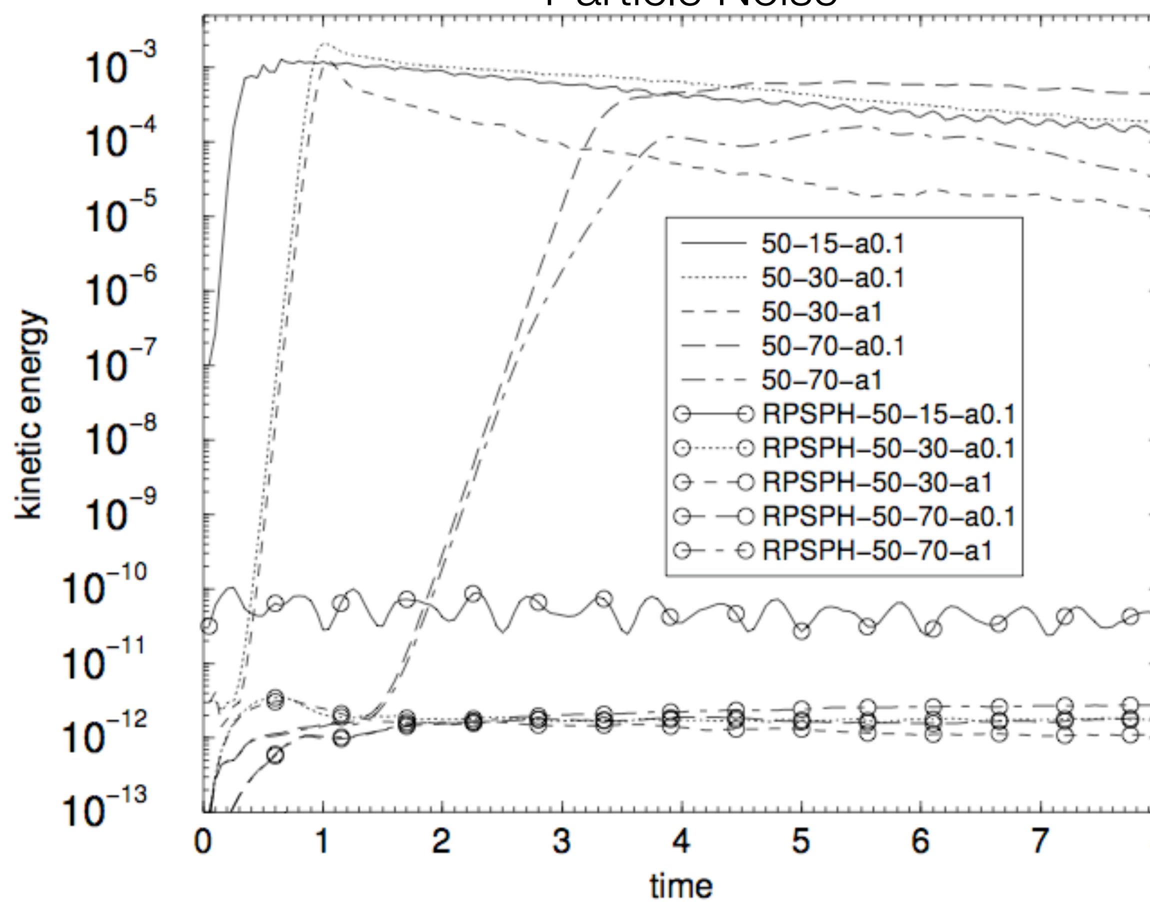
Selected SPH shortcomings

- Surface Tension
- Pairing Instability



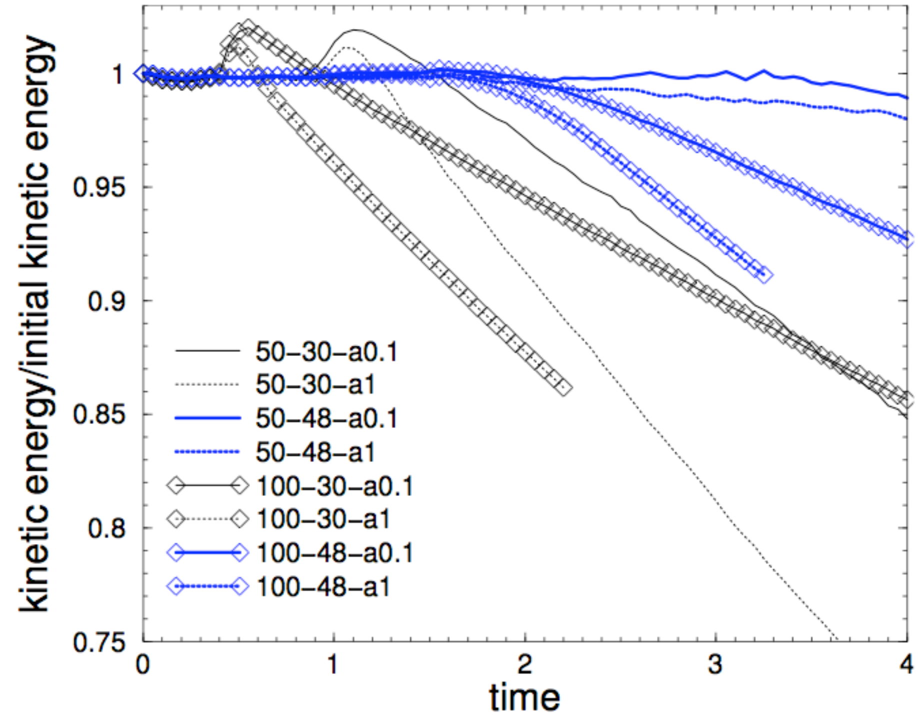
Hess & Springel 2009

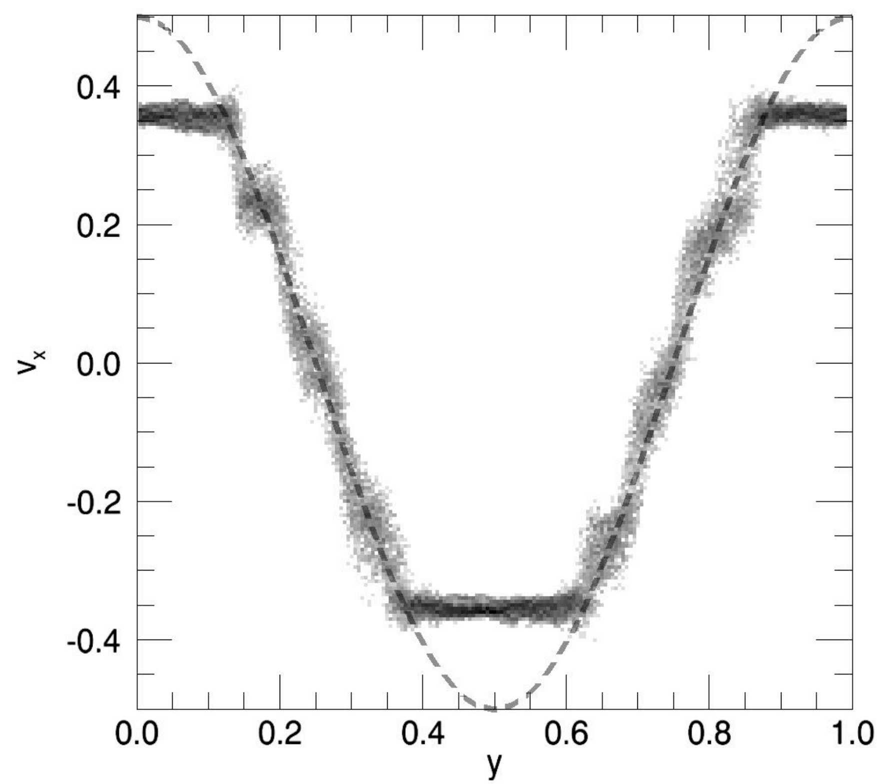
Particle Noise



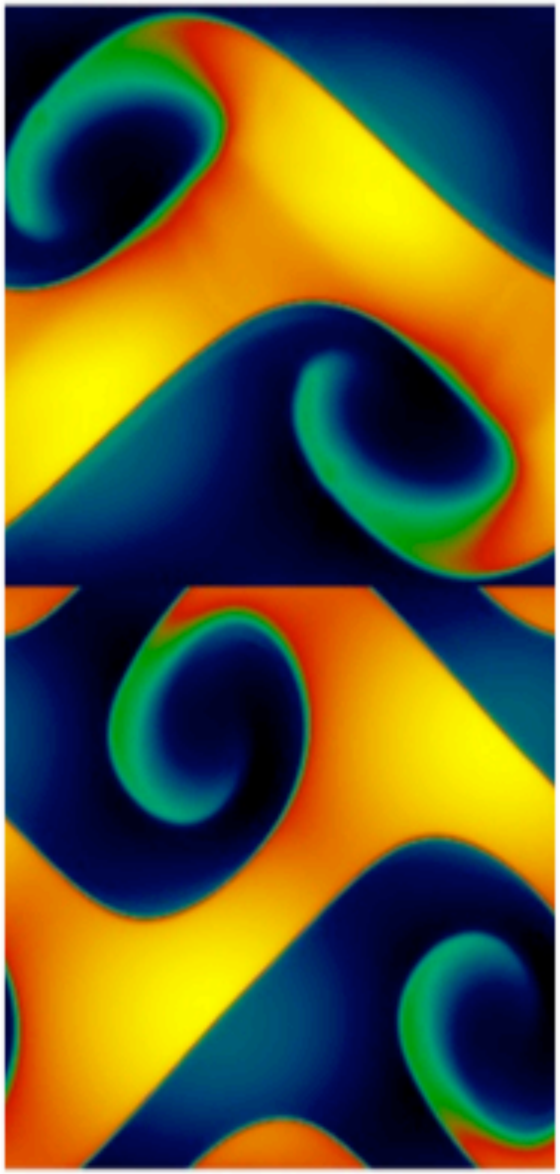
Selected SPH shortcomings (cont.)

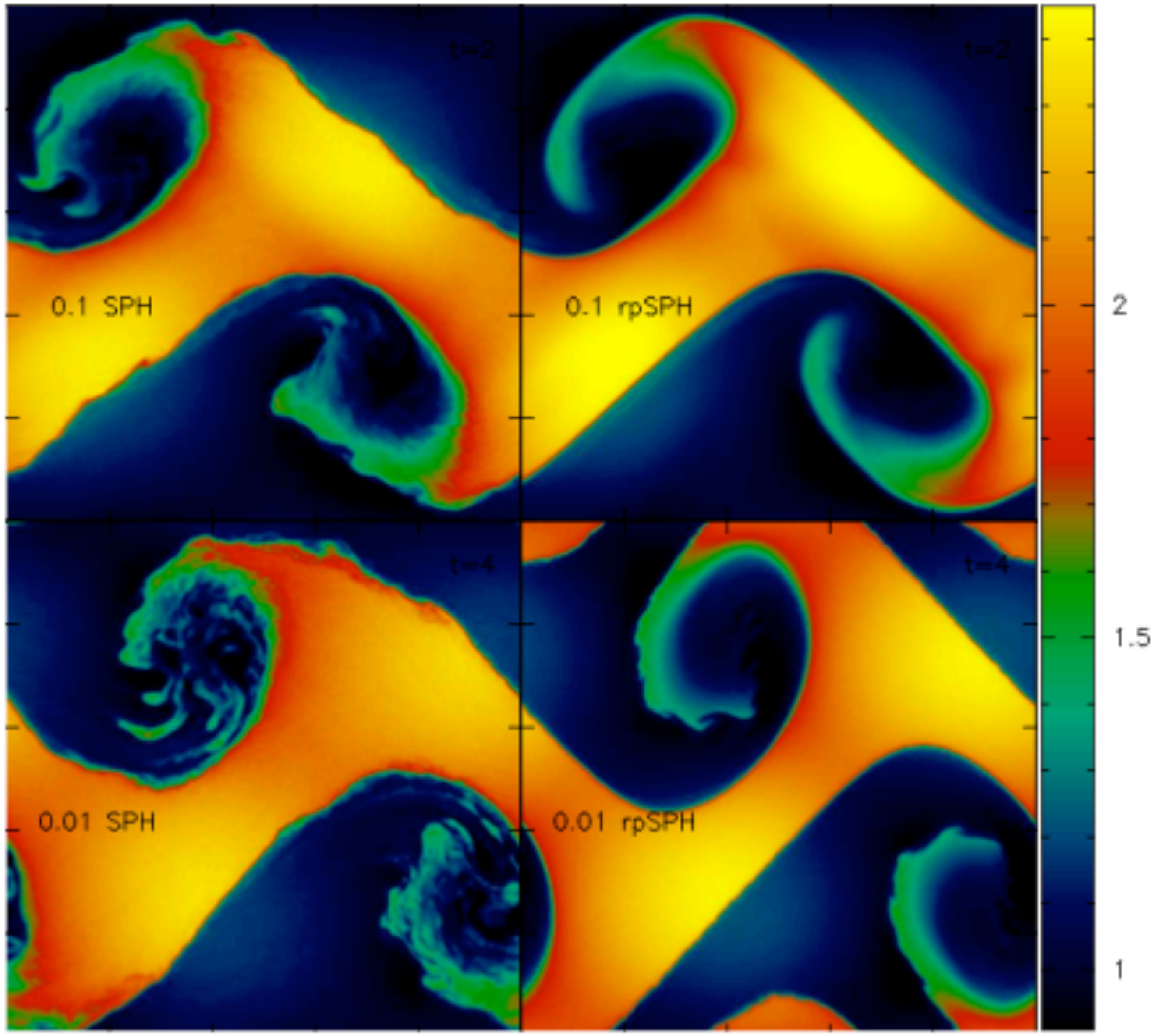
- Unphysical dissipation of shear flows
- Large Non-Newtonian viscosity
- Numerical dissipation does *not* decrease with numerical resolution
- Maximum Reynolds number of order ~100
- Turbulence typically at Re > 1e5 (> 1e~4 in pipes)
- Convergence study impossible





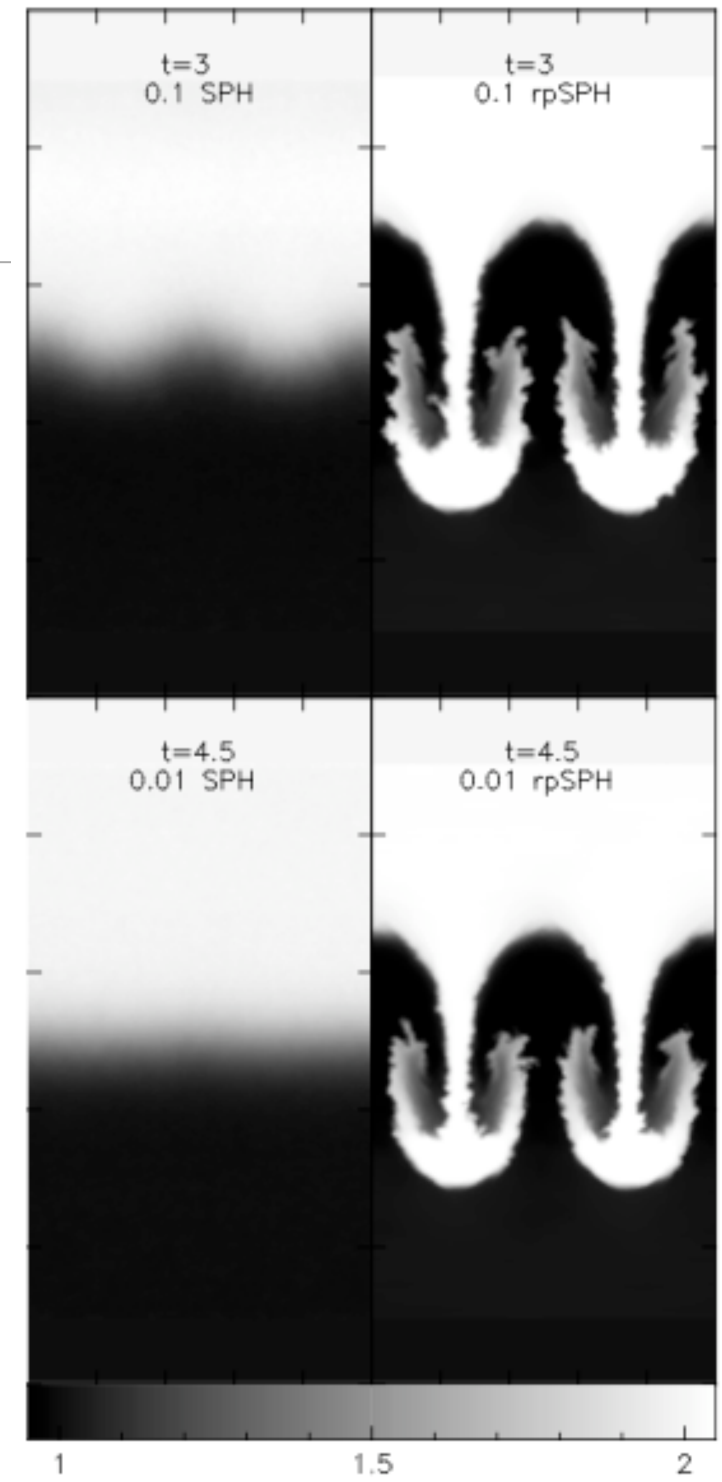
Kelvin Helmholtz Instability





Rayleigh Taylor Instability

- Impossible with standard SPH
- More physical behaviour with *rpSPH*



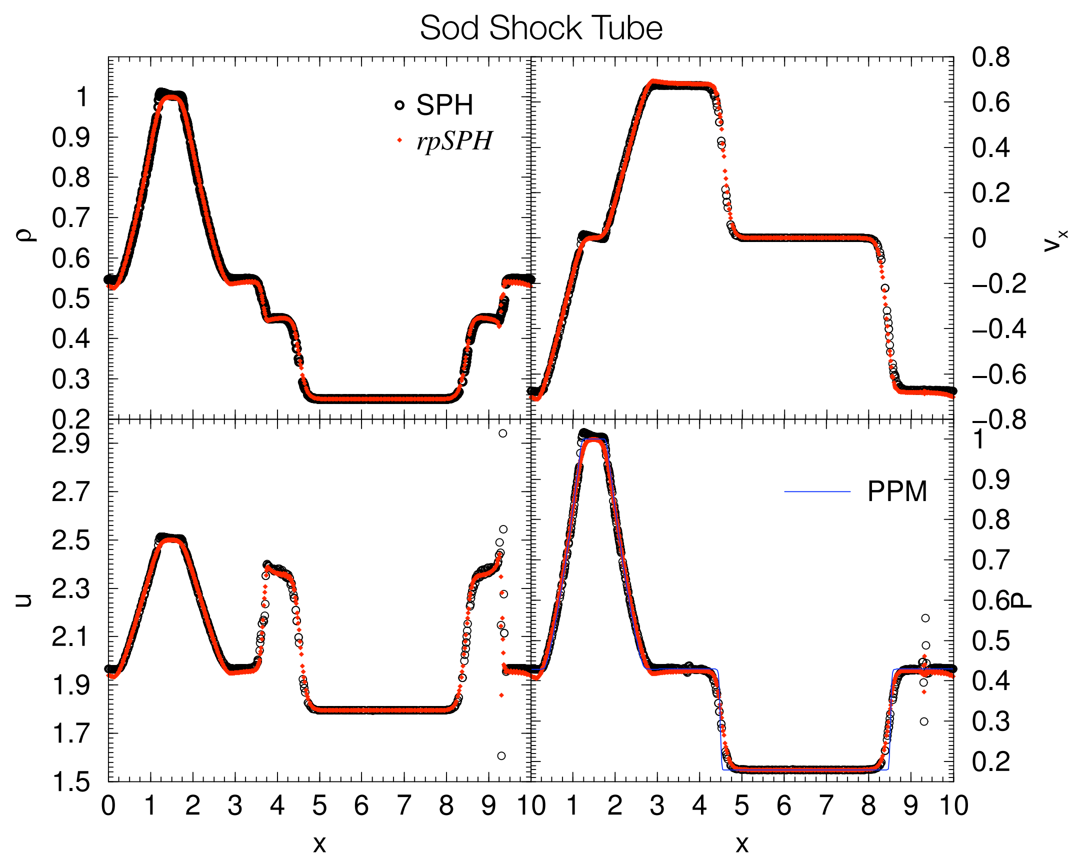
$$\frac{dv}{dt} = -\frac{1}{\rho}\nabla p$$

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

rpSPH

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

- 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*:

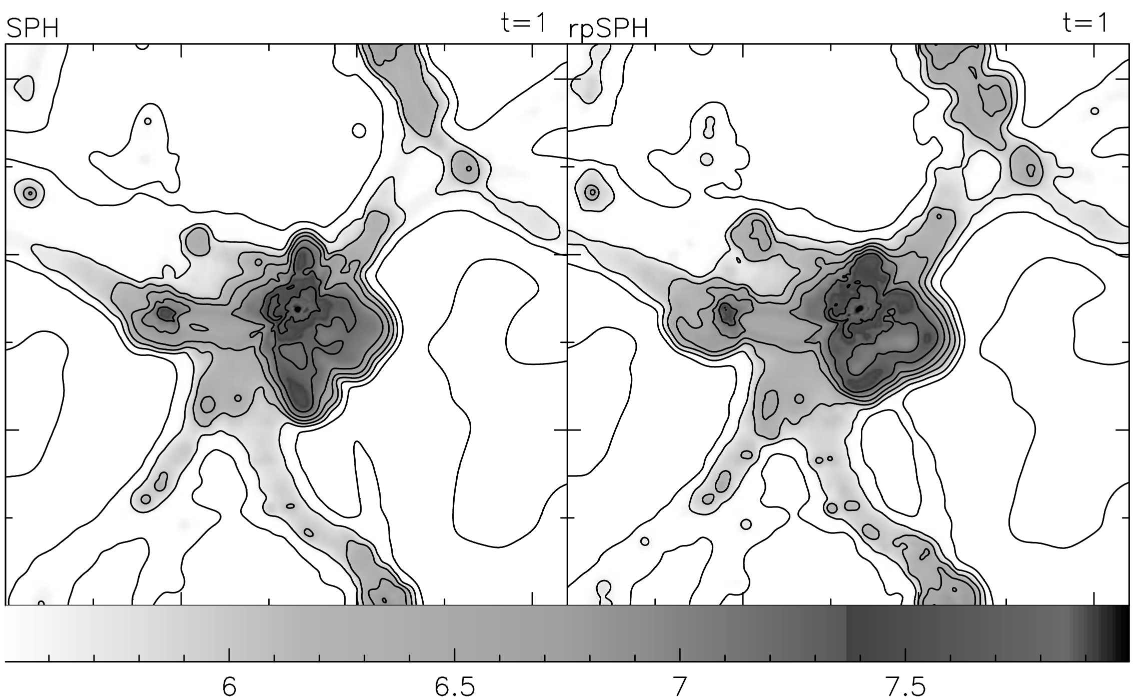
```
hfc = hfc_visc + P[j].Mass*(p_over_rho2_i*dwk_i
        + p_over_rho2_j*dwk_j)/r;
```

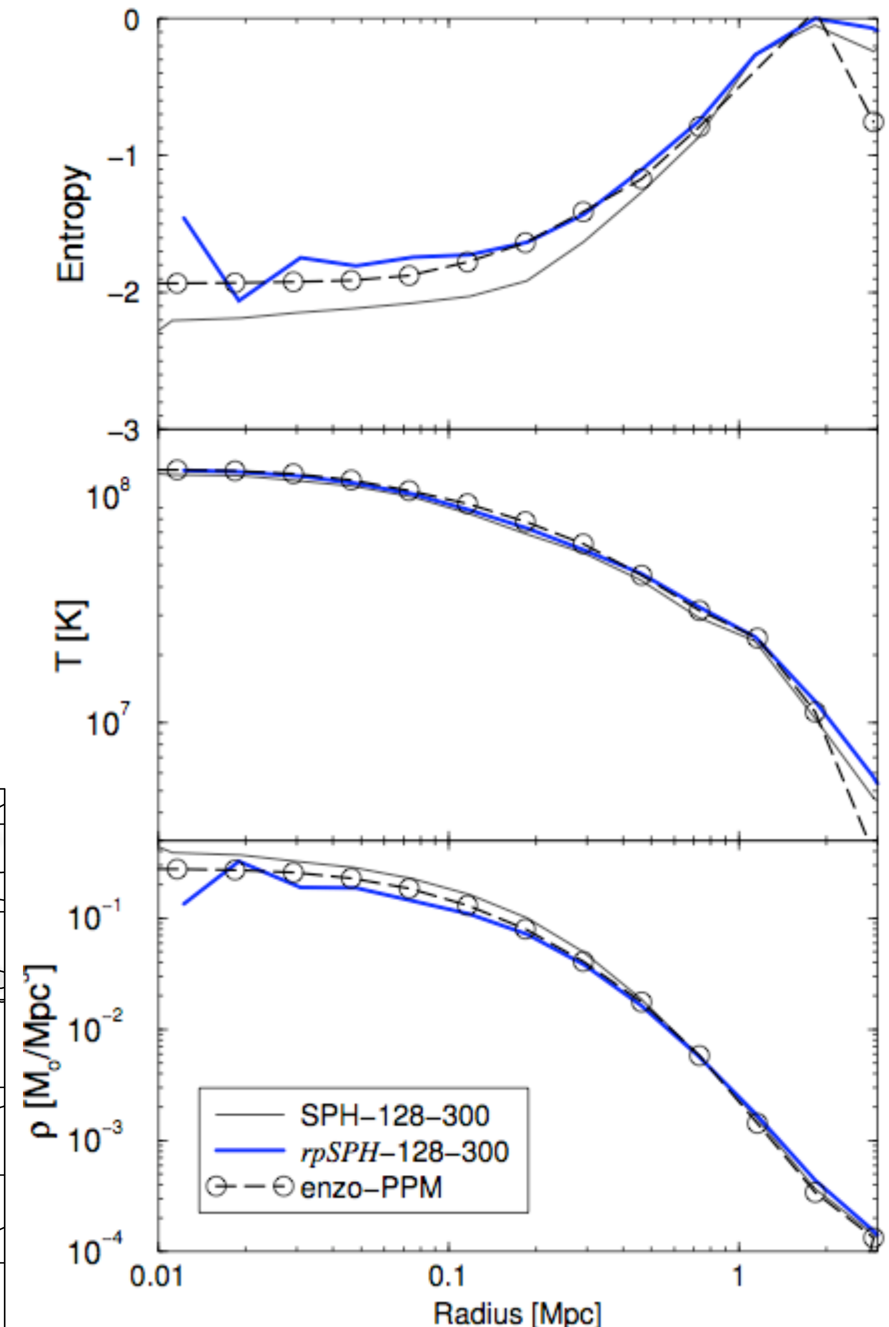
and change it to

```
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 standard SPH





Breaking rpSPH

- Use low resolution and self-gravity: wrong results with rpSPH

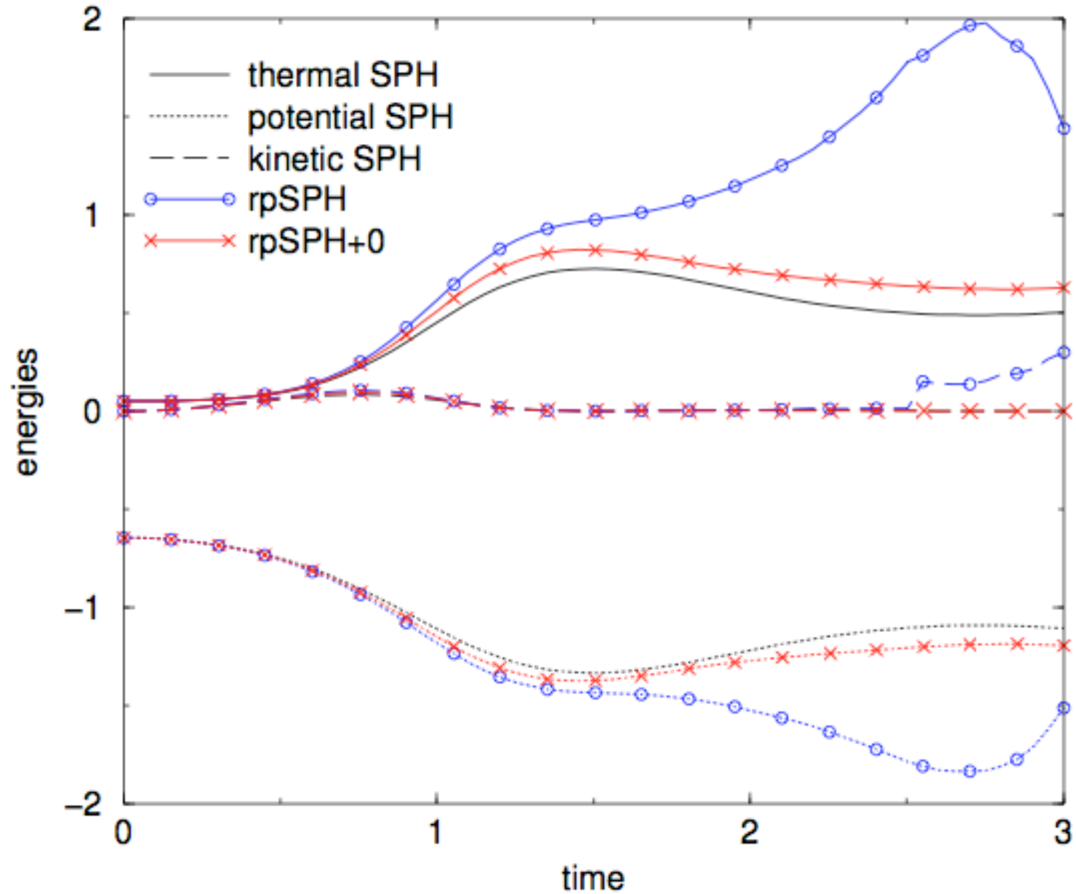


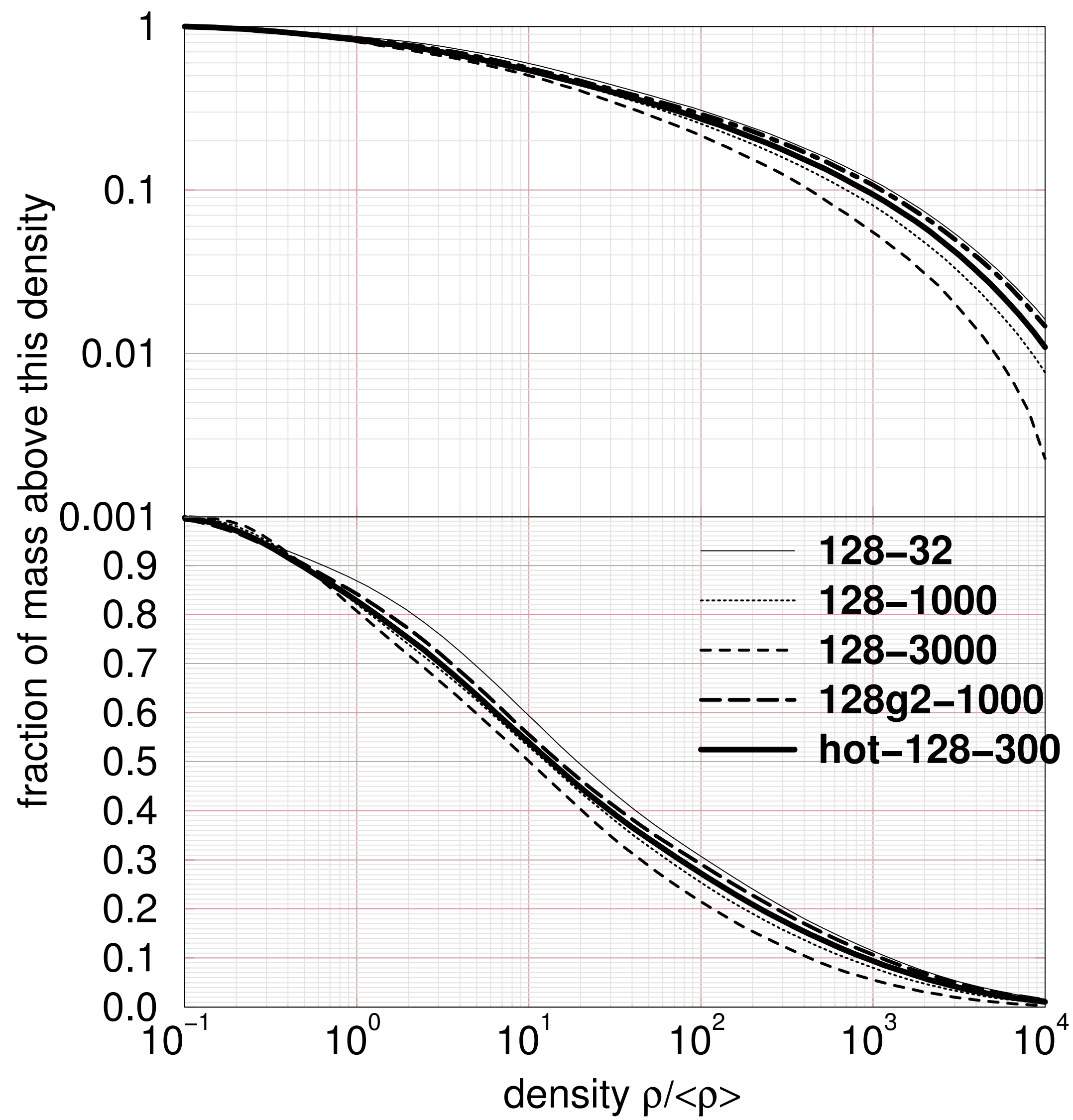
Figure 13. Energies in the Evrard gas collapse test.

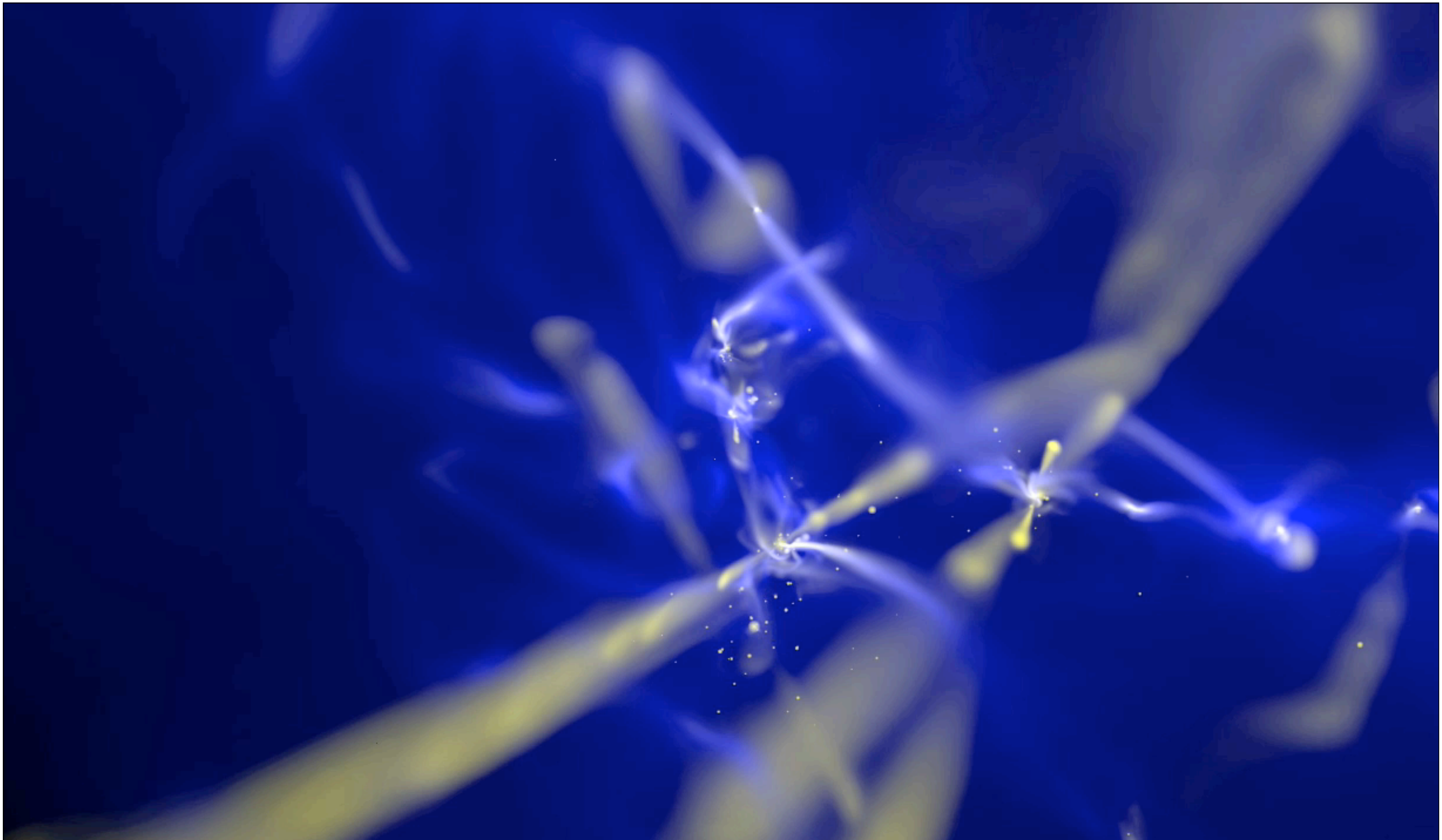
Useful Trick: Volume conservation

- SPH does not conserve Volume
- Easy way to monitor whether you're resolving the density field and your sim is accurate

$$\rho \equiv \frac{dm}{dV}$$

$$V = \sum_{N_{part}} \frac{1}{\rho} dm$$



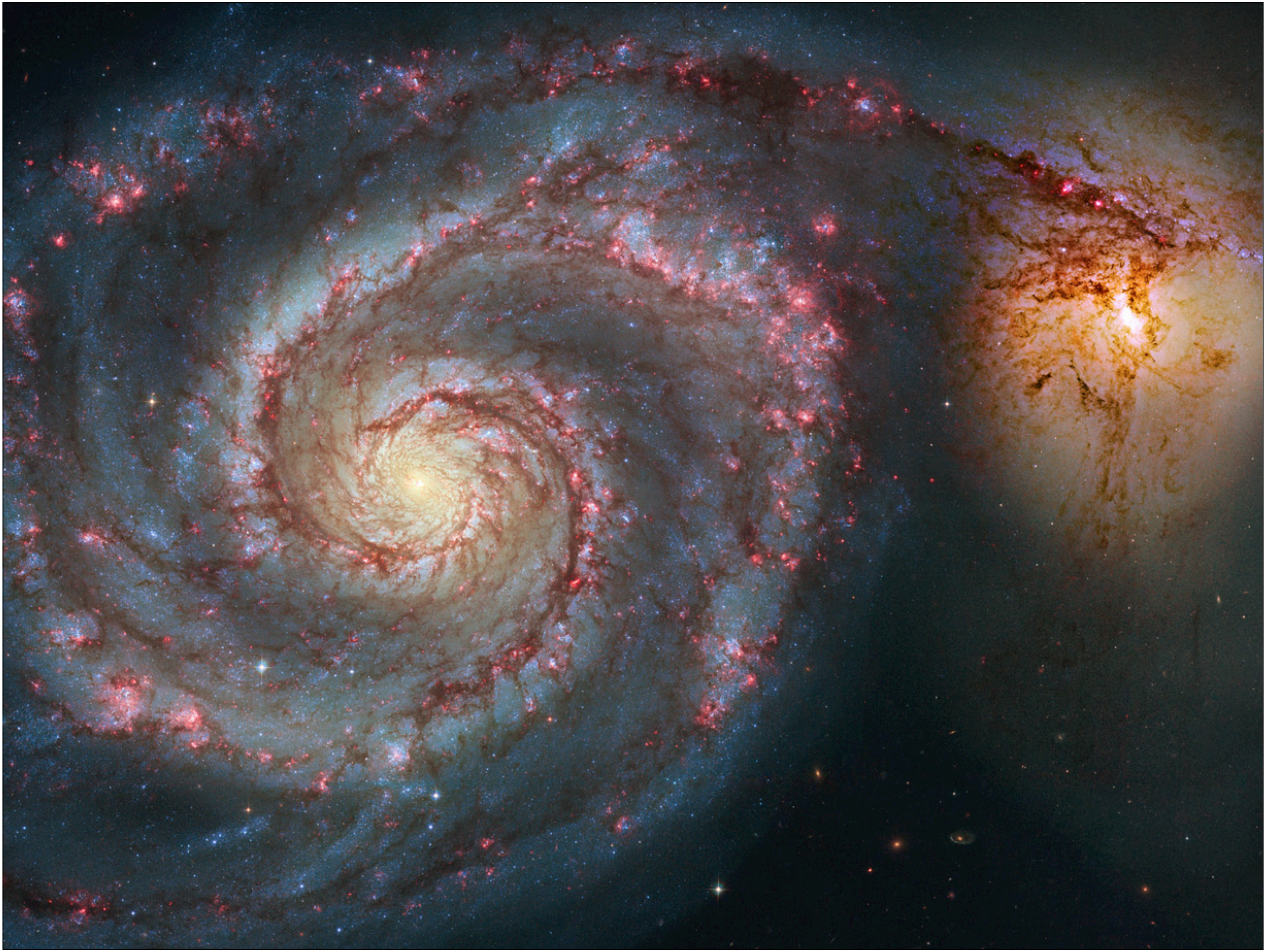


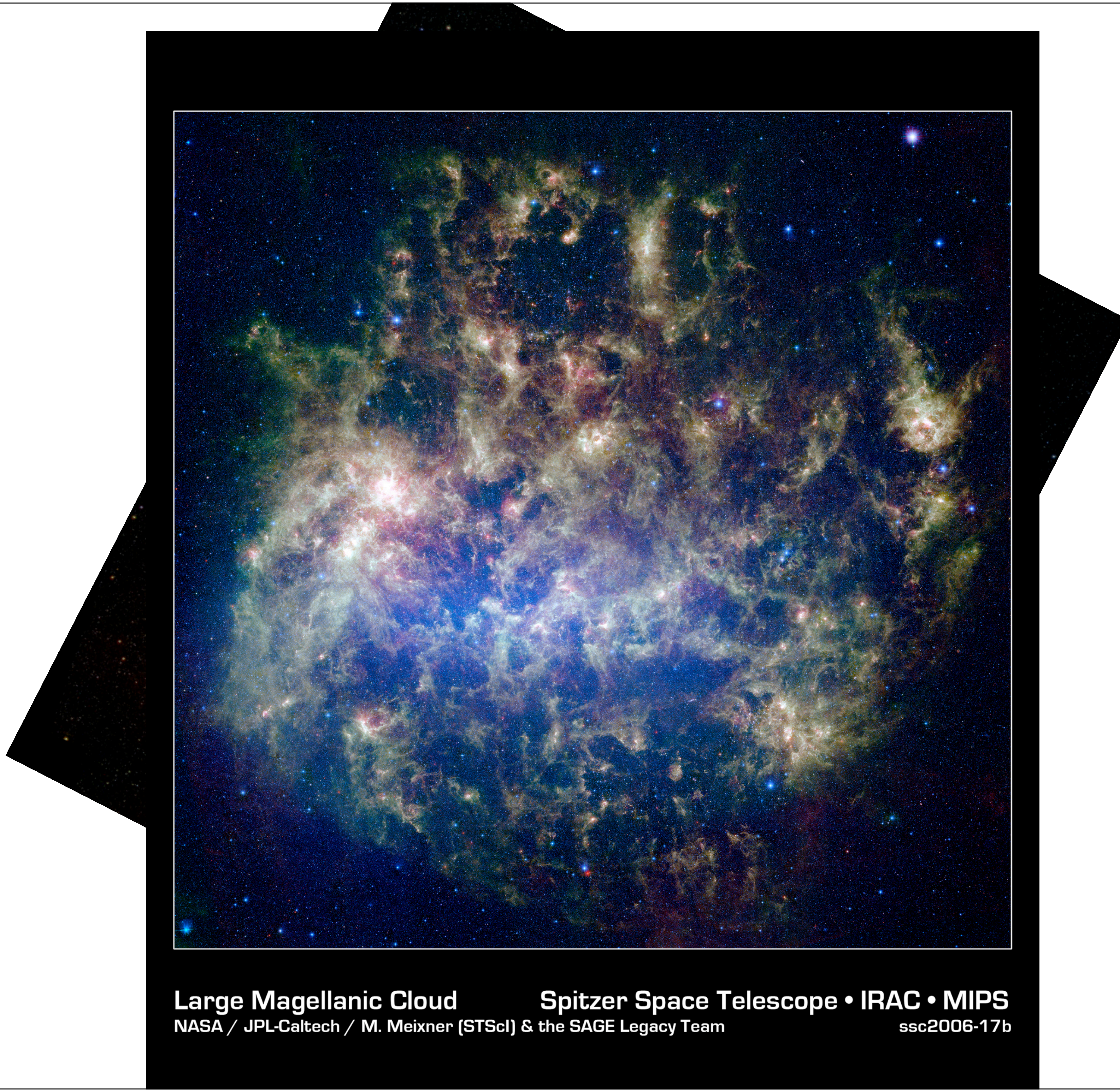
Tom Abel
KIPAC, Stanford

Star Formation

Star Formation for
“Galaxy Formation“

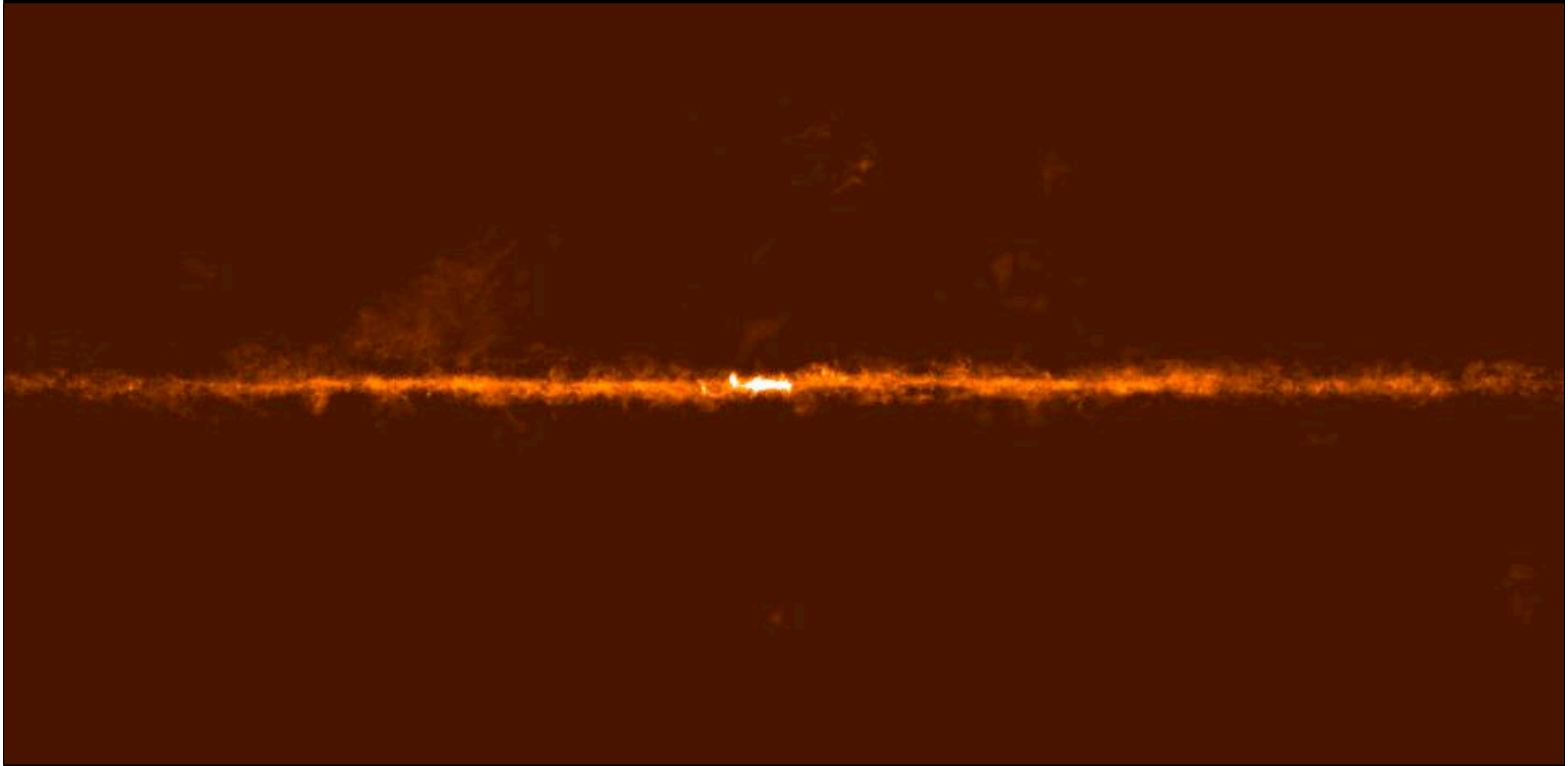
- “Galaxies are the building blocks of structure in the Universe”
- Stars are the building blocks of galaxies
- They are the dominant source of radiation, heavy elements, dust in the Universe. Their supernovae, winds, outflows, magnetic fields profoundly impact their surroundings and future star formation.
- Star Formation
  - essentially is one of the most important aspects of galaxy formation
  - at the heart of understanding properties und physical processes in galaxies at all redshifts





Large Magellanic Cloud
Spitzer Space Telescope • IRAC • MIPS
NASA / JPL-Caltech / M. Meixner (STScI) & the SAGE Legacy Team
ssc2006-17b

Galactic plane: CO J=1-0 (115 GHz = 2.6 mm)



224 KENNICUTT

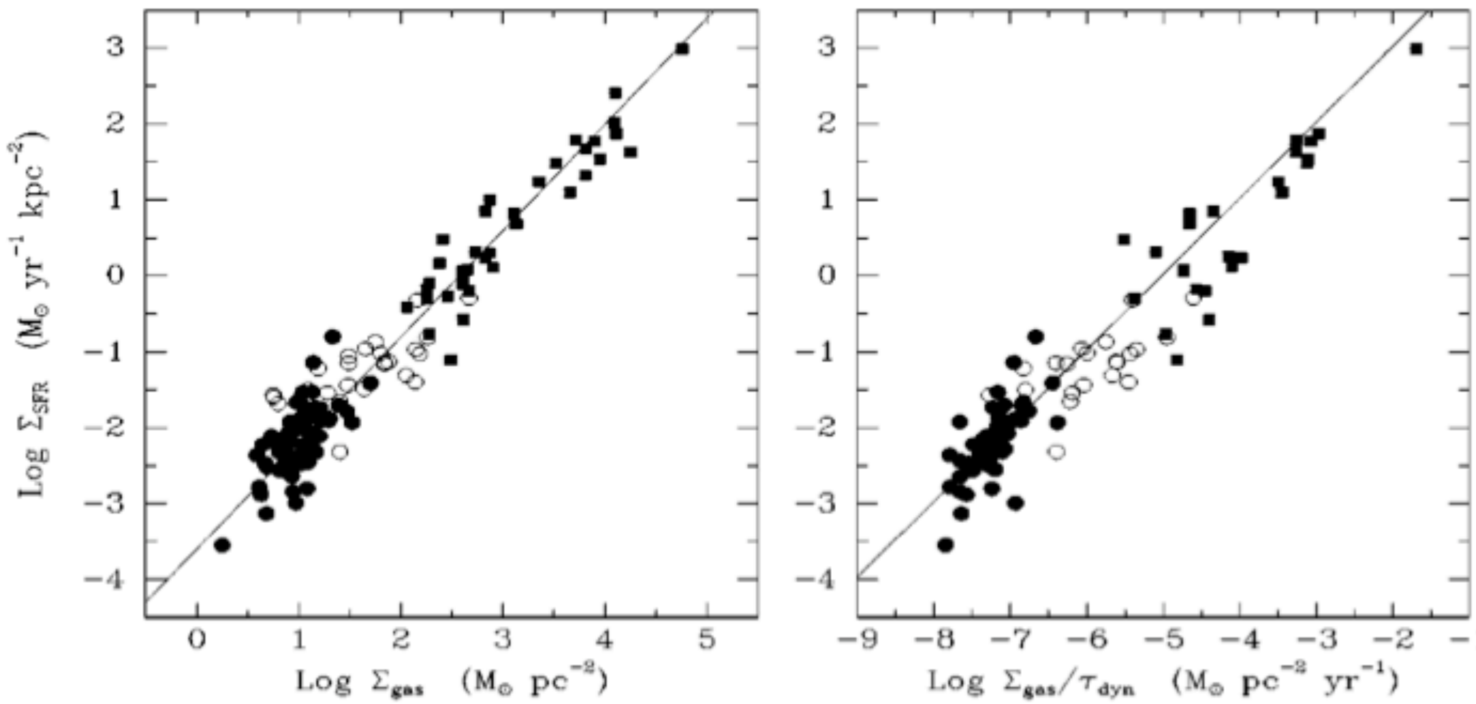


Figure 9 (*Left*) The global Schmidt law in galaxies. *Solid points* denote the normal spirals in Figure 5, *squares* denote the circumnuclear starbursts in Figure 7. The *open circles* show the SFRs and gas densities of the central regions of the normal disks. (*Right*) The same SFR data but plotted against the ratio of the gas density to the average orbital time in the disk. Both plots are adapted from Kennicutt (1998).

Star Formation in Galaxy Formation Models

Relied on Kennicutt-Schmidt law to encapsulate most relevant physics

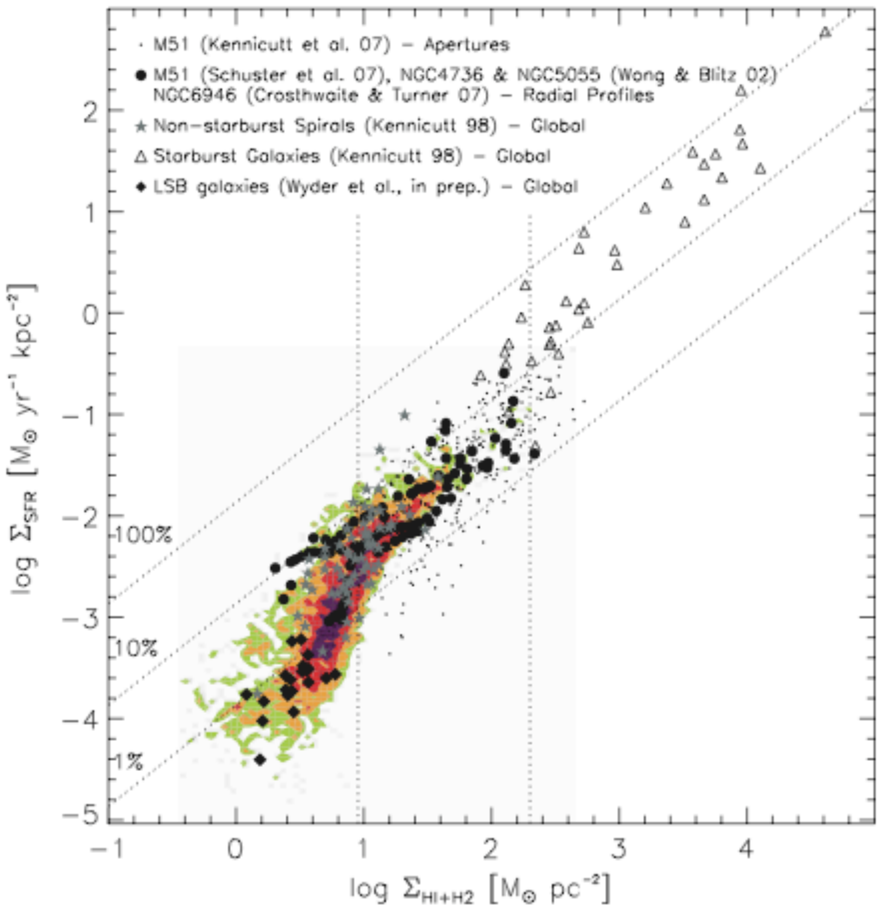


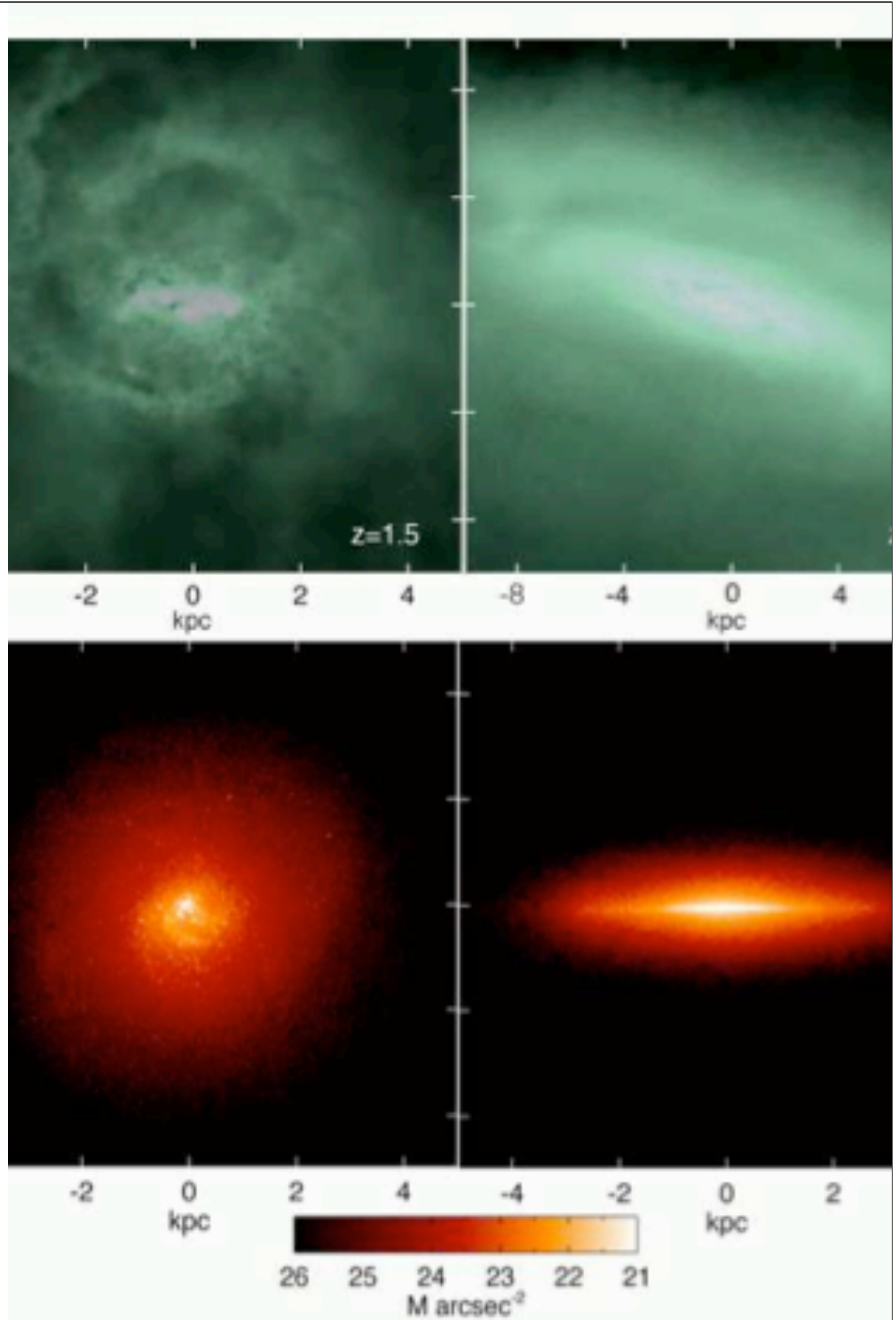
Figure 15. Σ_{SFR} vs. Σ_{gas} from this paper in colored contours (compare the middle-right panel of Figure 8) and for individual galaxies from other analyses (see Figure 14). The diagonal dotted lines and all other plot parameters are the same as in Figure 4. Overplotted as black dots are data from measurements in individual apertures in M51 (Kennicutt et al. 2007). Data points from radial profiles from M51 (Schuster et al. 2007), NGC 4736, and NGC 5055 (Wong & Blitz 2002) and from NGC 6946 (Crosthwaite & Turner 2007) are shown as black filled circles. Furthermore, we show disk-averaged measurements from 61 normal spiral galaxies (filled gray stars) and 36 starburst galaxies (triangles) from K98. The black filled diamonds show global measurements from 20 low surface brightness galaxies (Wyder et al. 2008). Data from other authors were adjusted to match our assumptions on the underlying IMF, CO line ratio, CO-to-H_2 conversion factor and galaxy inclinations where applicable. One finds good qualitative agreement between our data and the measurements from other studies despite a variety of applied SFR tracers. This combined data distribution is indicative of three distinctly different regimes (indicated by the vertical lines) for the SF law (see discussion in the text).

Perhaps three different regimes?

Bigiel et al. Leroy et al 2008-

Governato, Brook, Mayer, et al. 2010

- Bulgeless disk in a cosmological setting
- Star formation threshold above 100 cm^{-3} made all the difference (and turning off cooling selectively)



Agertz, Teyssier, Moore 2010

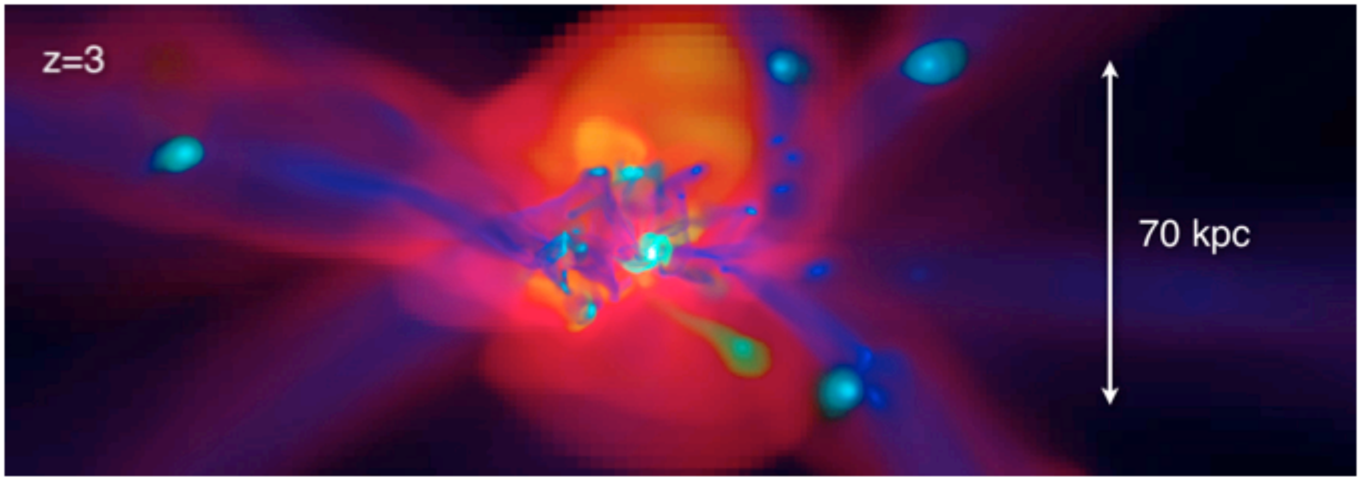
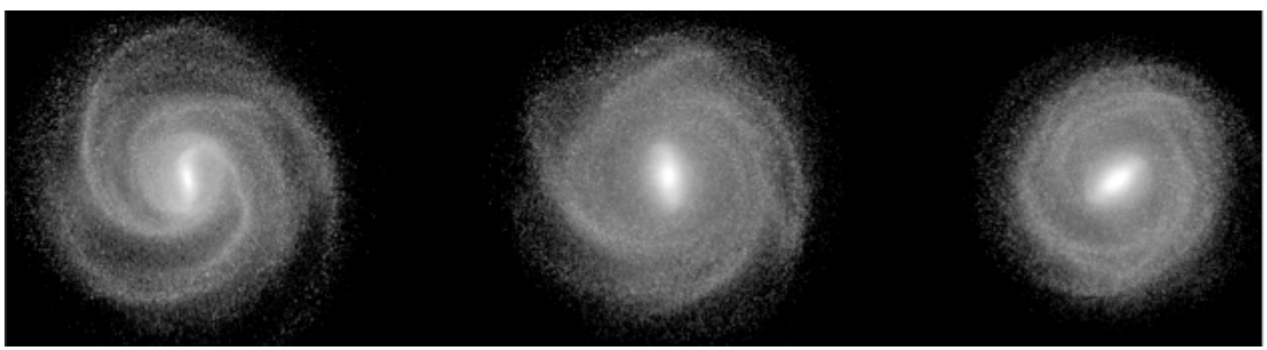
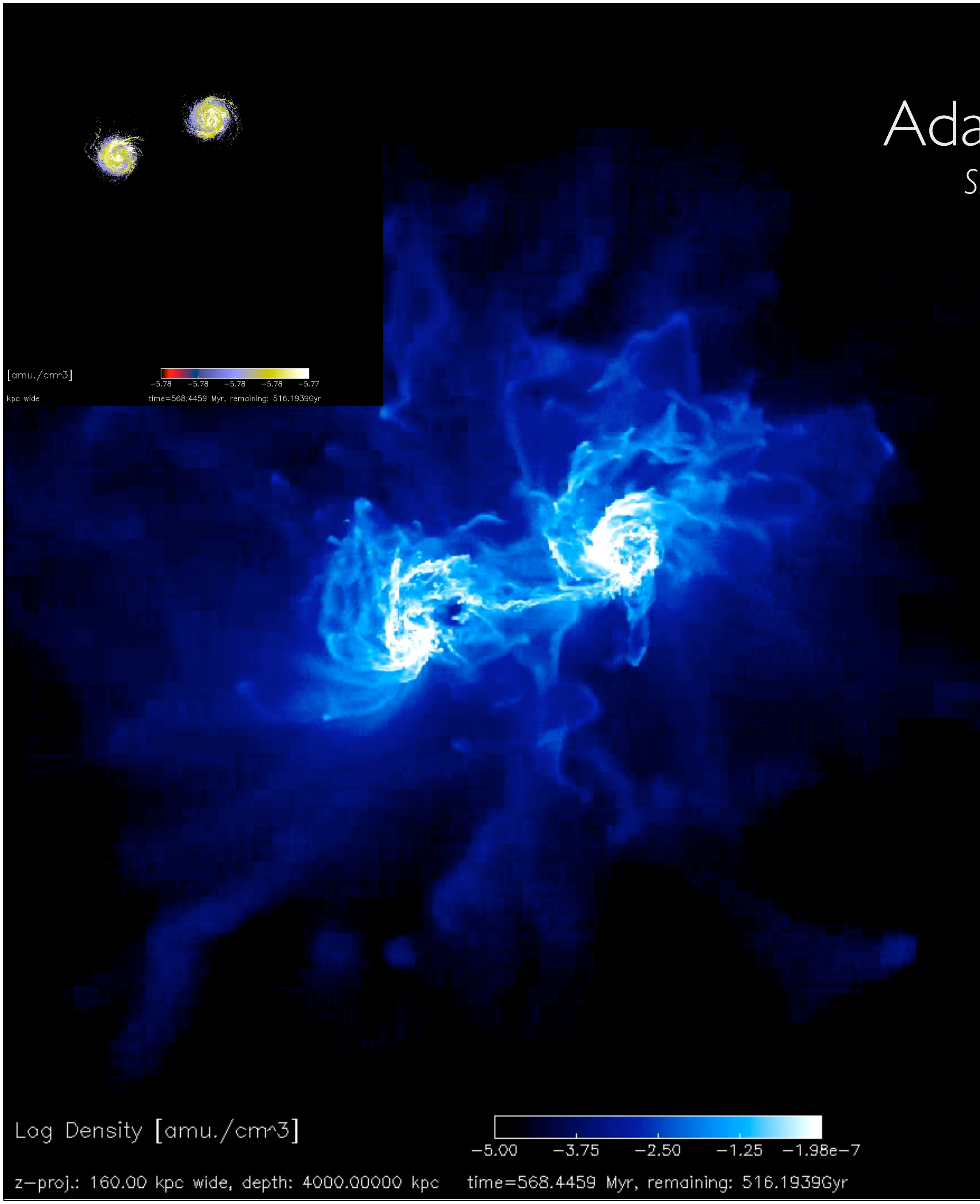


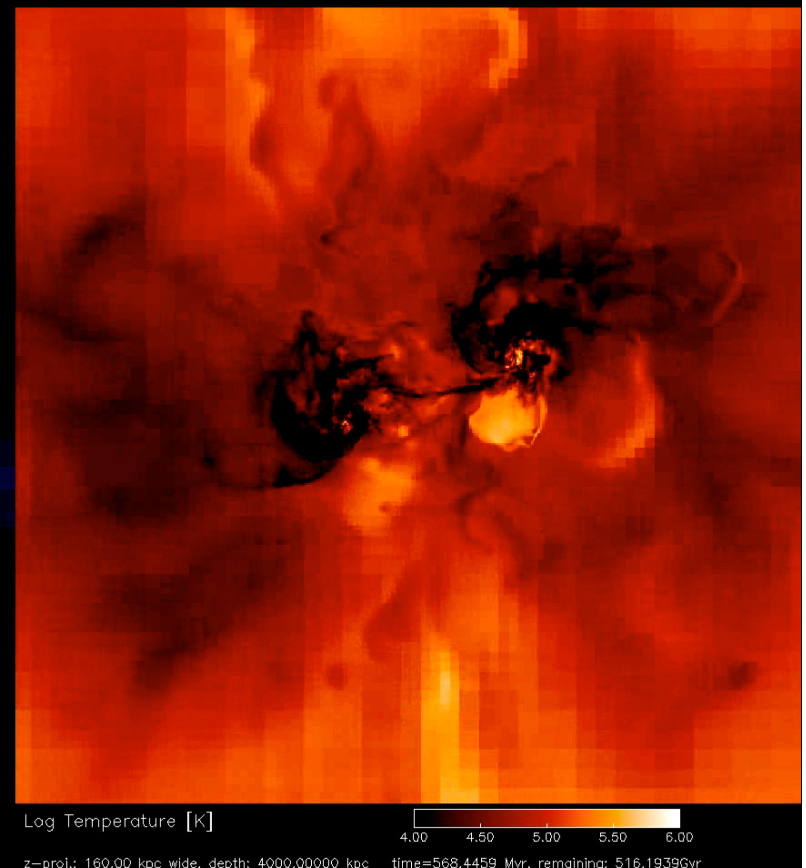
Figure 9. A large scale view of the assembling spiral galaxy from the SR5 simulation at $z \sim 3$: the most intense epoch of star formation for this system. The *RGB*-image displays only the gas component using *red*=temperature, *green*=metals and *blue*=density. We can clearly distinguish accretion via streams of cold pristine gas in blue penetrating the shock heated gas in red, reaching the heart of the halo. Dwarf galaxies outside of the large gaseous halo are surrounded by puffy enriched gas originating from stellar outflows. Gas is efficiently lost via tidal and ram-pressure as the dwarfs interact with the main halo galaxy the hot gaseous halo, enriching it in the process. The distance measure is in physical units.



Galaxy Mergers with Adaptive Mesh Refinement

Sim: Ji-hoon Kim, John Wise, Tom Abel 2009
Viz: Kim & Abel 2009





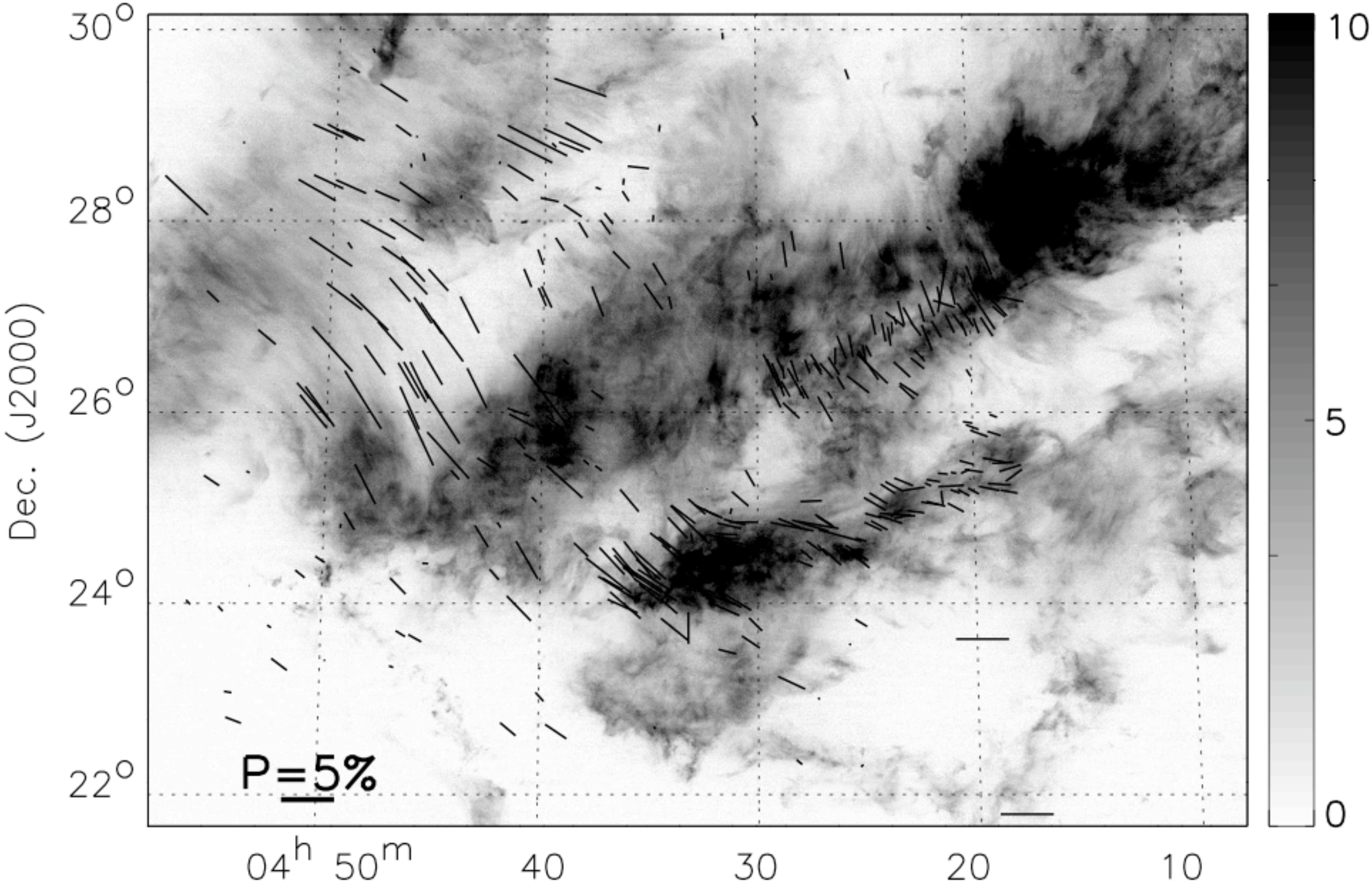
2 galaxies: 2e11 solar mass each
Evolving over 2 Gyrs
Follow star formation, supernova feedback @ 10pc
few hundred million resolution elements

UK Astrophysical Fluids Facility

dynamical processes relevant
in star formation are sub parsec scale
0.4 pc in radius
190,000 years dynamical time
took 10 months on 16 processors

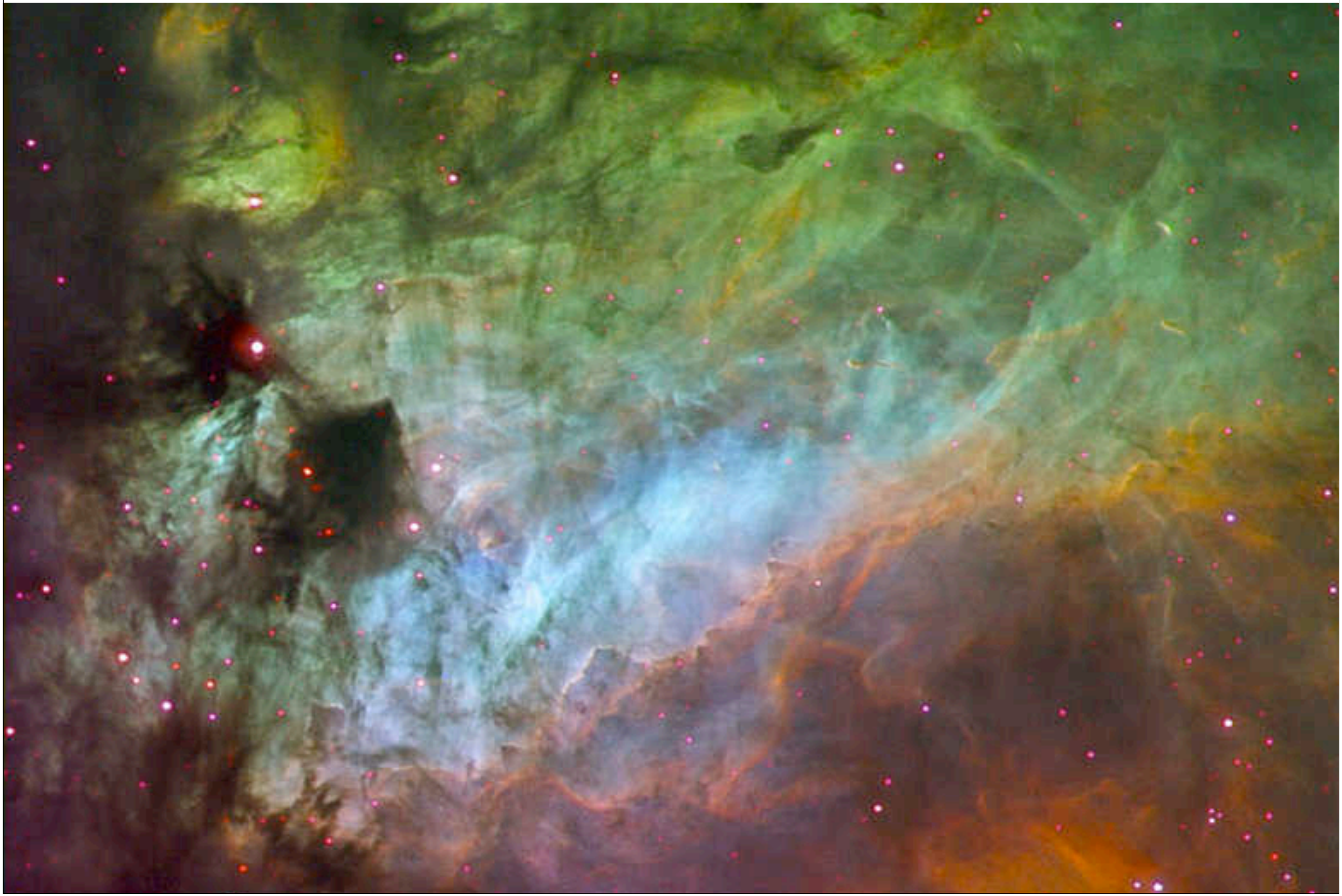
Matthew Bate

University of Exeter

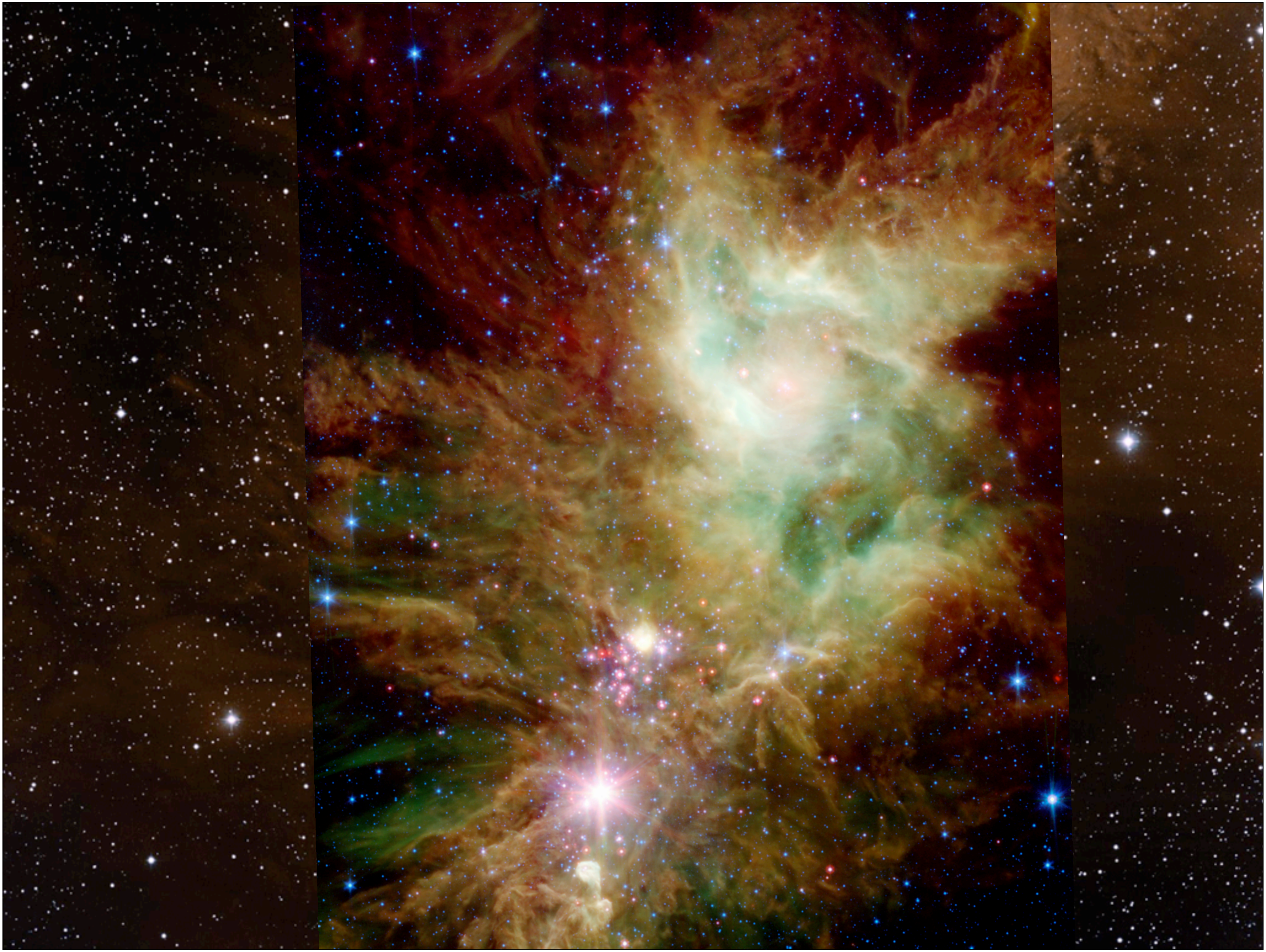


Taurus, Goldsmith et al. 2008

Somewhere in Orion



Somewhere else in Orion



The "Nessie" Nebula: Cluster Formation in a Filamentary Infrared Dark Cloud

The "Nessie" Nebula is a filamentary infrared dark cloud (IRDC) with a large aspect ratio of over 150:1 (1.5°× 0.01°, or 80 pc × 0.5 pc at a kinematic distance of 3.1 kpc). Maps of HNC (1–0) emission, a tracer of dense molecular gas, made with the Australia Telescope National Facility Mopra telescope, show an excellent morphological match to the mid-IR extinction. Moreover, because the molecular line emission from the entire nebula has the same radial velocity to within ±3.4 $\mathrm{km\,s^{-1}}$, the nebula is a single, coherent cloud and not the chance alignment of multiple unrelated clouds along the line of sight.

80pc x 0.5pc

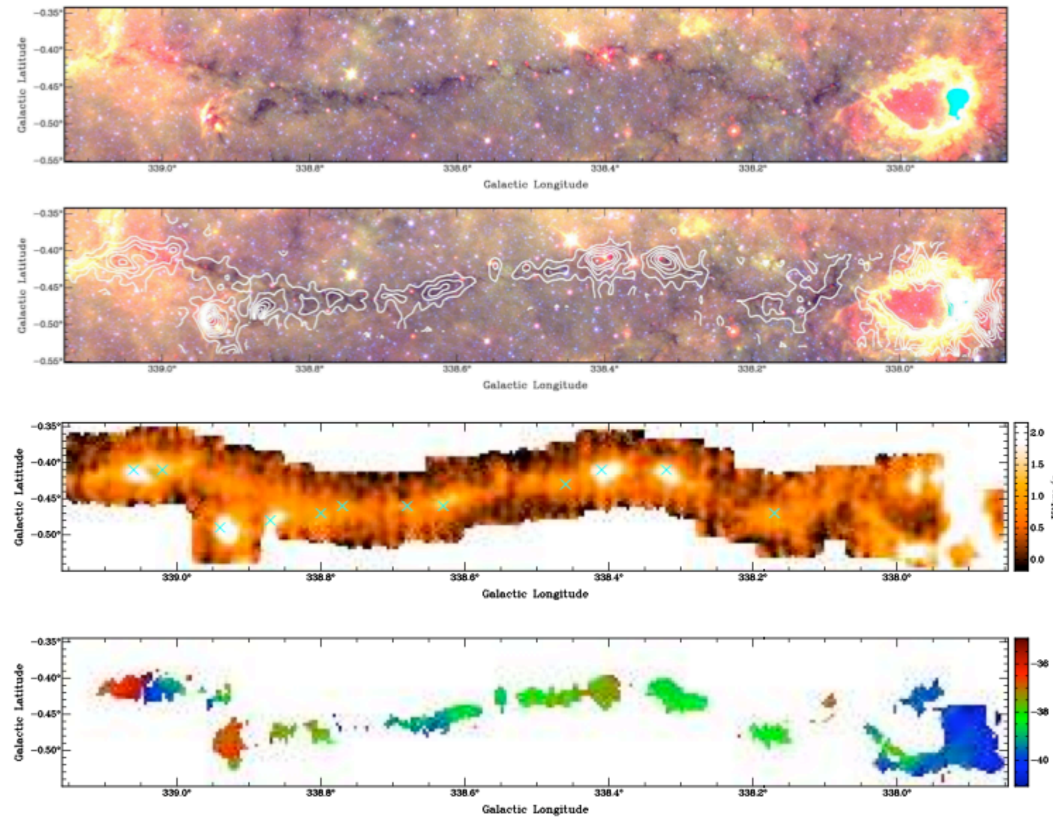
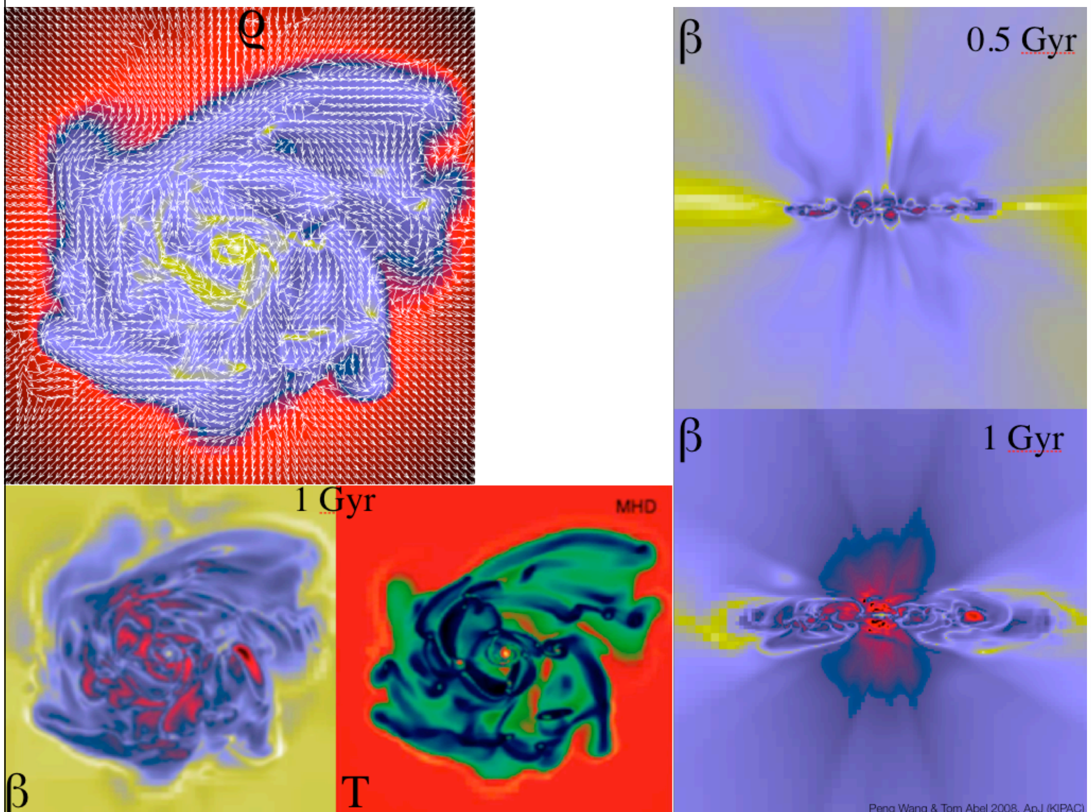


Fig. 1.— Top panel: a false three-color image of the Nessie Nebula. The 3.6 μm (blue) and 8.0 μm (green) emission is from GLIMPSE, and the 24 μm (red) emission is from MIPSGAL. Second panel: the false three-color mid-IR image of the Nessie Nebula from the top panel overlaid with integrated HNC (1-0) contours from the Mopra telescope. Note the excellent correspondence between the HNC emission and the 8 μm extinction. Third panel: an HNC (1-0) integrated intensity map from the Mopra telescope with core positions marked with cyan crosses. Bottom panel: a velocity-field (first moment) map from the HNC (1-0) map of the Nessie Nebula. All of the molecular emission is at the same velocity to within ±3.4 $\mathrm{km\,s^{-1}}$, demonstrating that the filament is a single coherent object.

Jackson et al astro-ph today



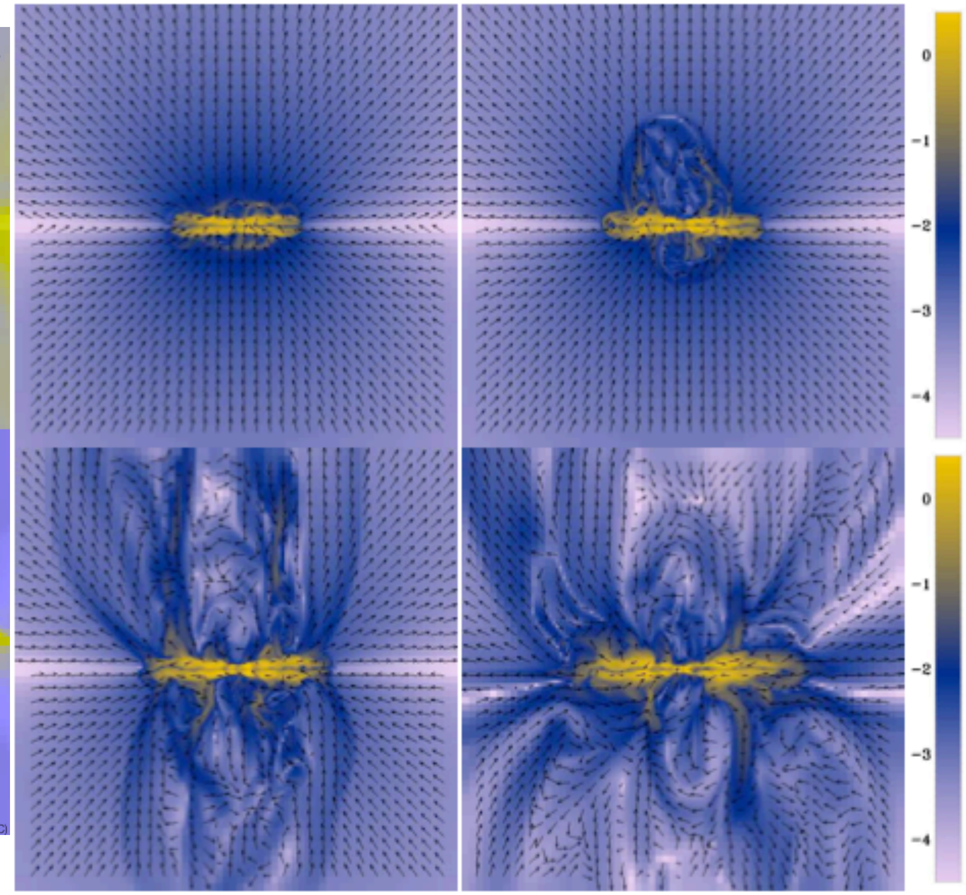


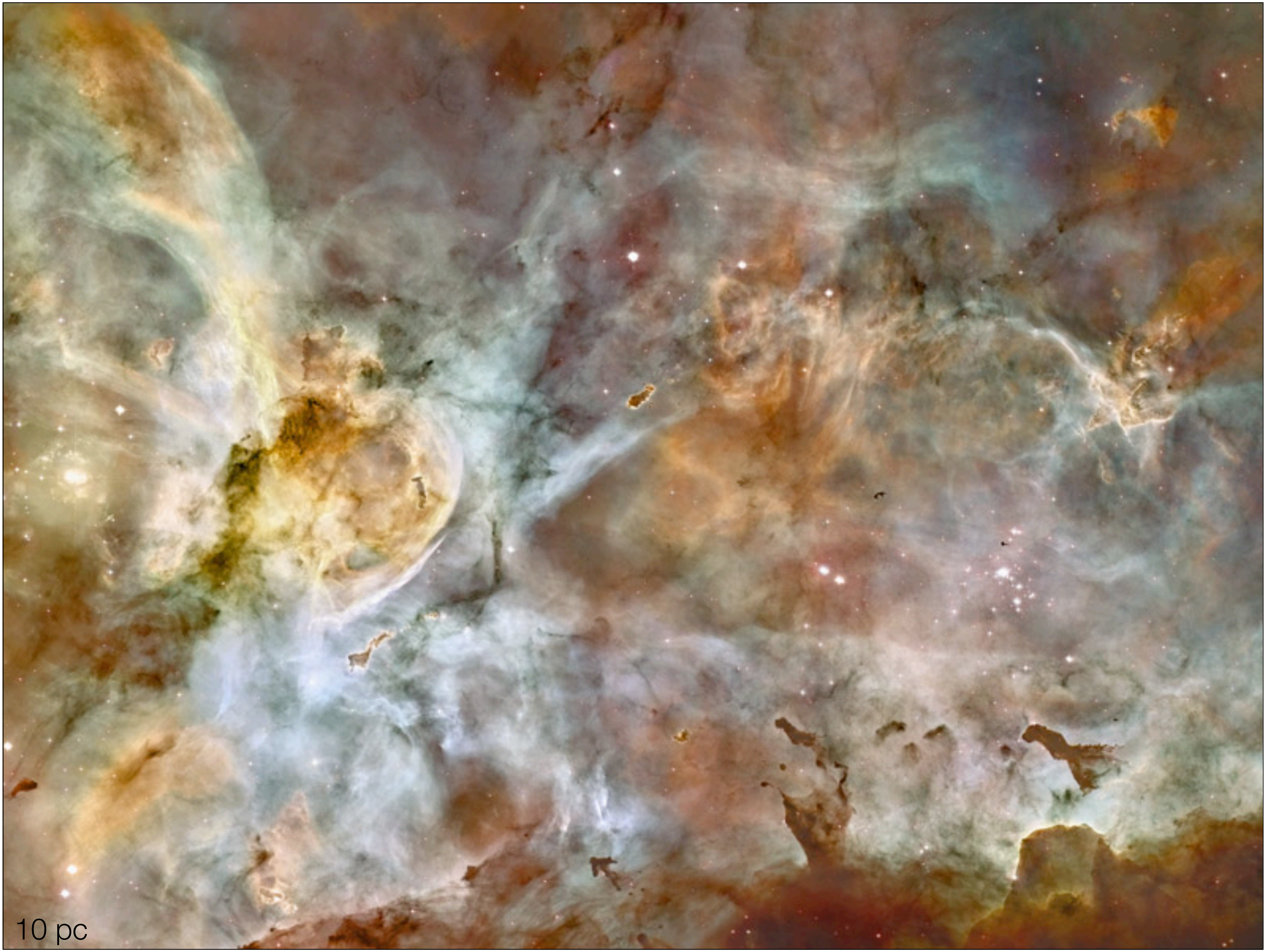
Fig. 7. Magnetic field in log μG units for the galaxy with star formation and supernova feedback with $B_{IGM} = 10^{-5}\,\mu$G at differe epochs $t = 1$ Gyr (upper left), $t = 1.5$ Gyr (upper right), $t = 2$ Gyr (bottom left) and $t = 3$ Gyr (bottom right). Picture size is 4 kpc.

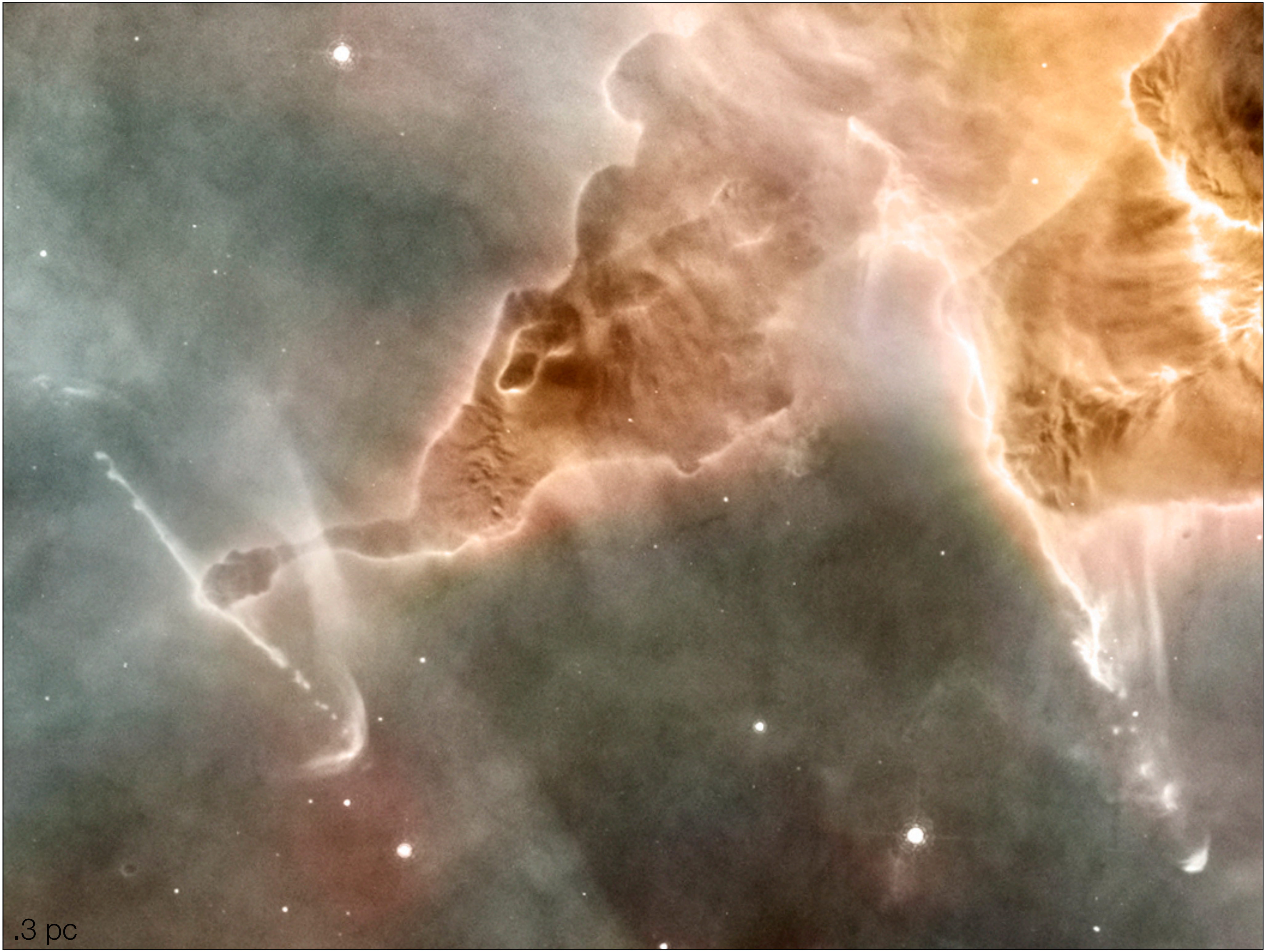
Wang & Abel 2008

Dubois & Teyssier 2009

Magnetic field amplifies very rapidly
Fills halo material and affects gas accretion
Hierarchical model gives many dynamical times in small objects allowing a cosmic dynamo to act quickly

Magnetic Fields amplify quickly!

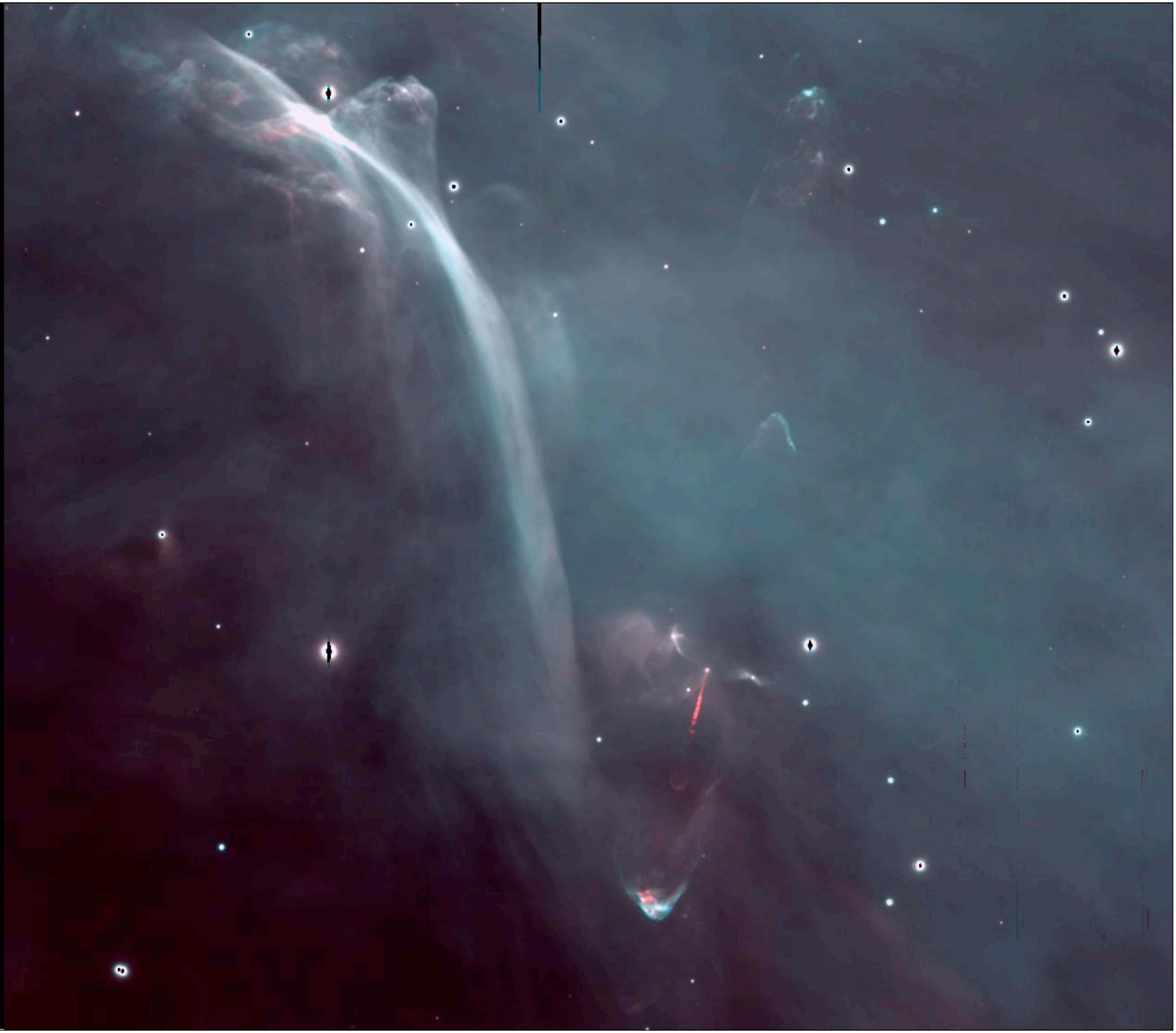

10 pc

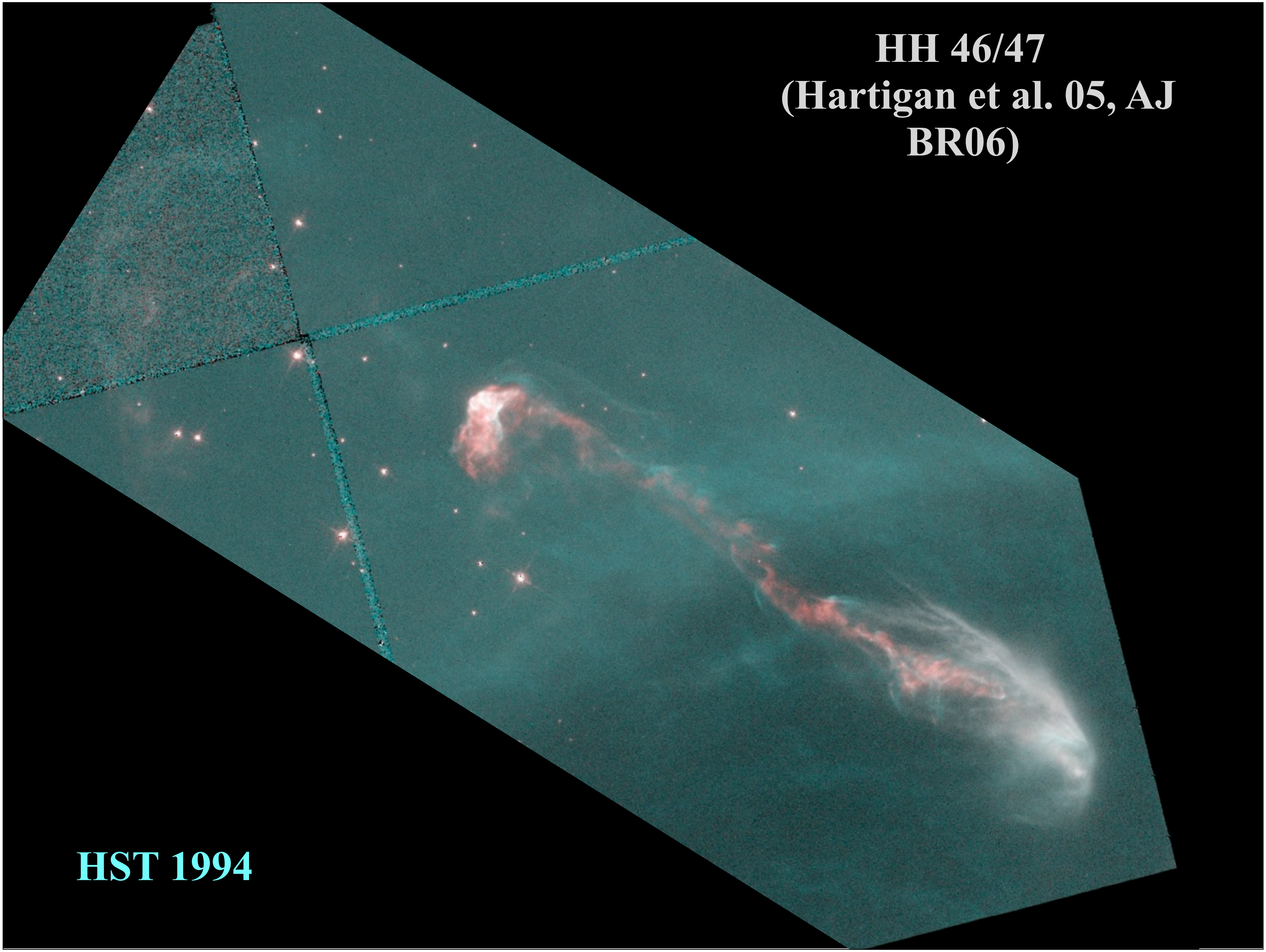

.3 pc

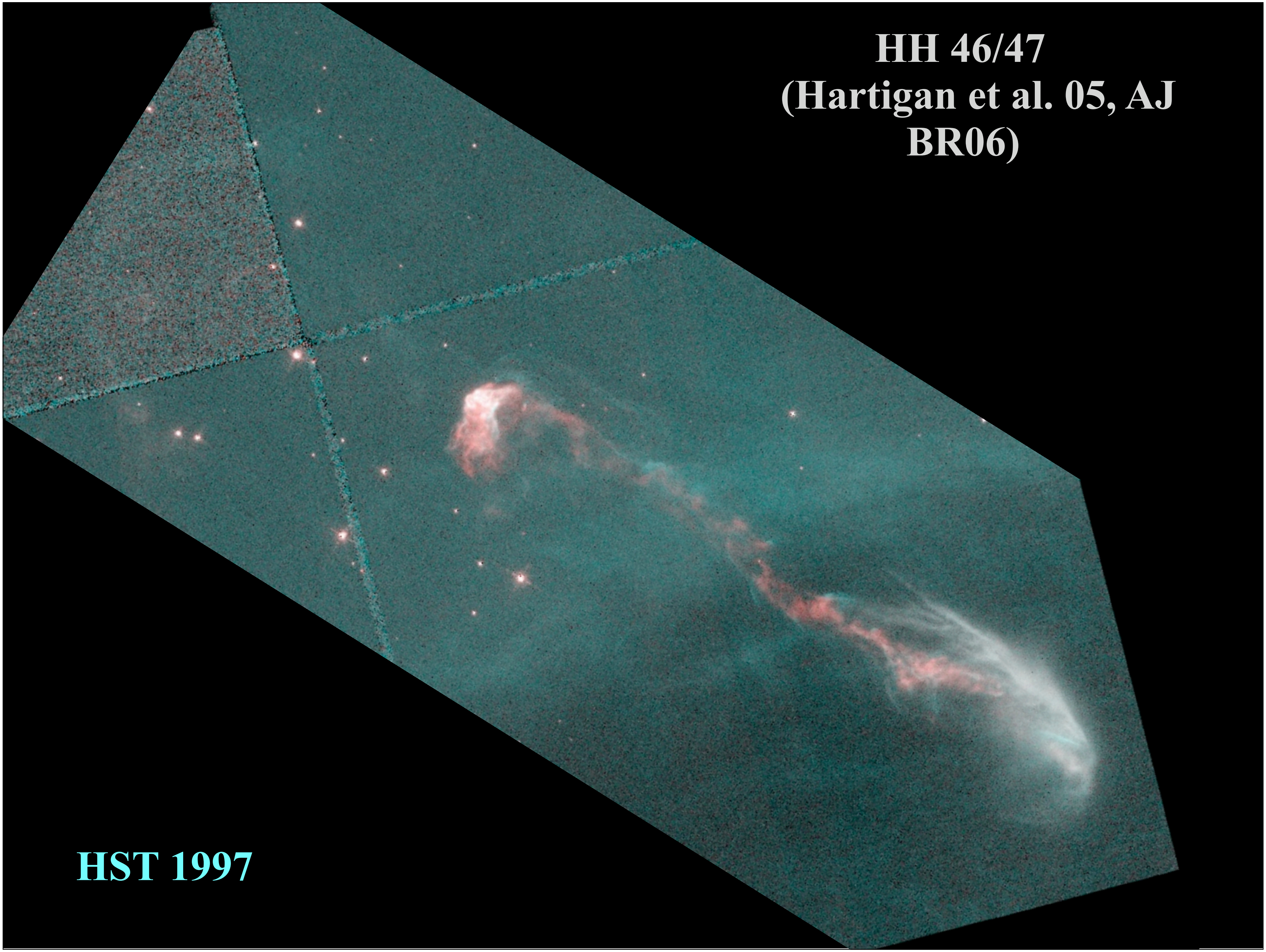
HH 34
(Orion)

Subaru
8.4 m

Hα
[SII]



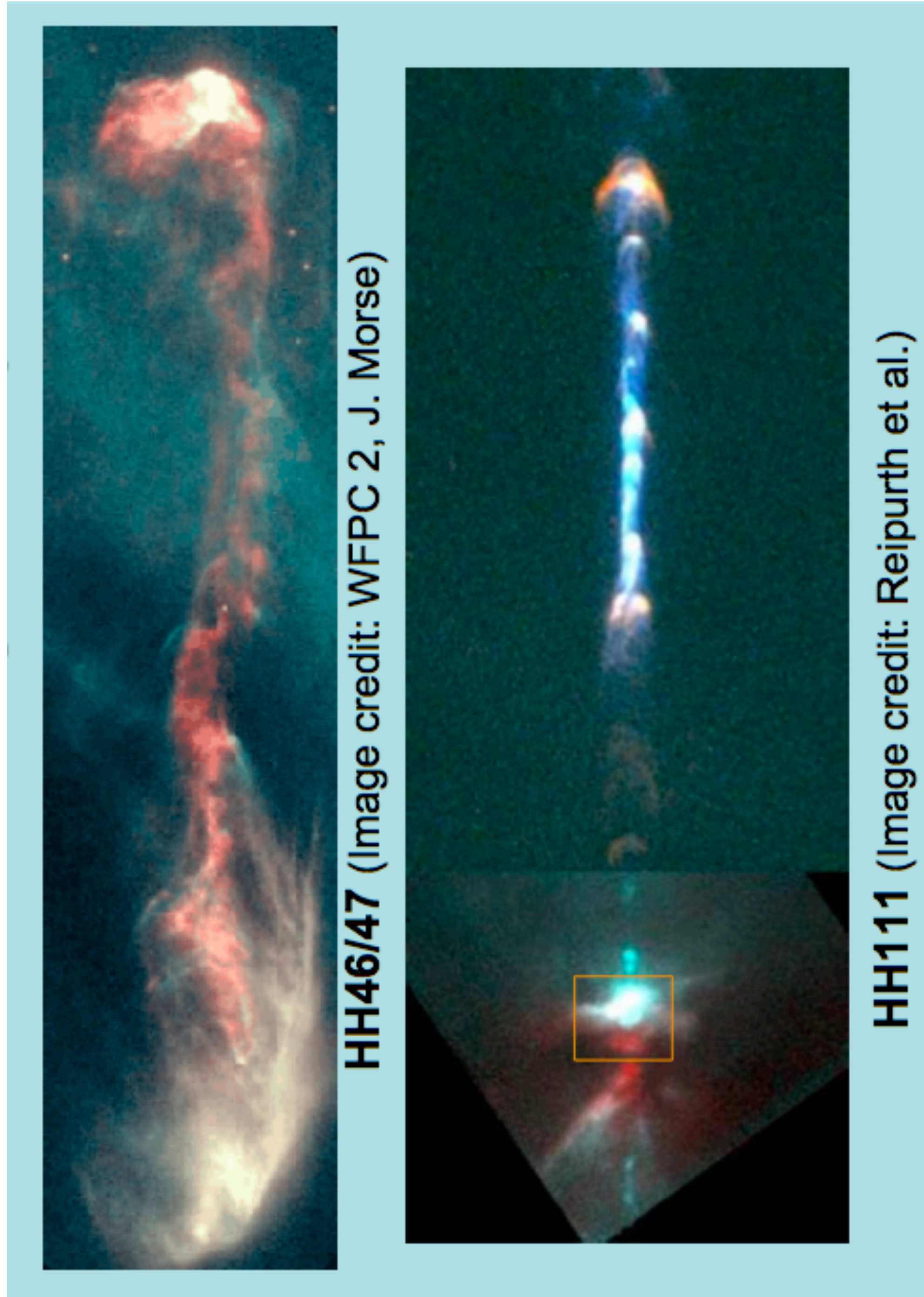

HH 46/47
(Hartigan et al. 05, AJ
BR06)
HST 1994


HH 46/47
(Hartigan et al. 05, AJ
BR06)
HST 1997

Outflows carry momentum

- Typical outflow momentum 50 Msun km/s per stellar mass

- so if 5% of mass turns into stars, then the outflow momentum feedback is already enough to keep the whole cloud at 2.5 km/s turbulence level.



HH46/47 (Image credit: WFPC 2, J. Morse)

HH111 (Image credit: Reipurth et al.)

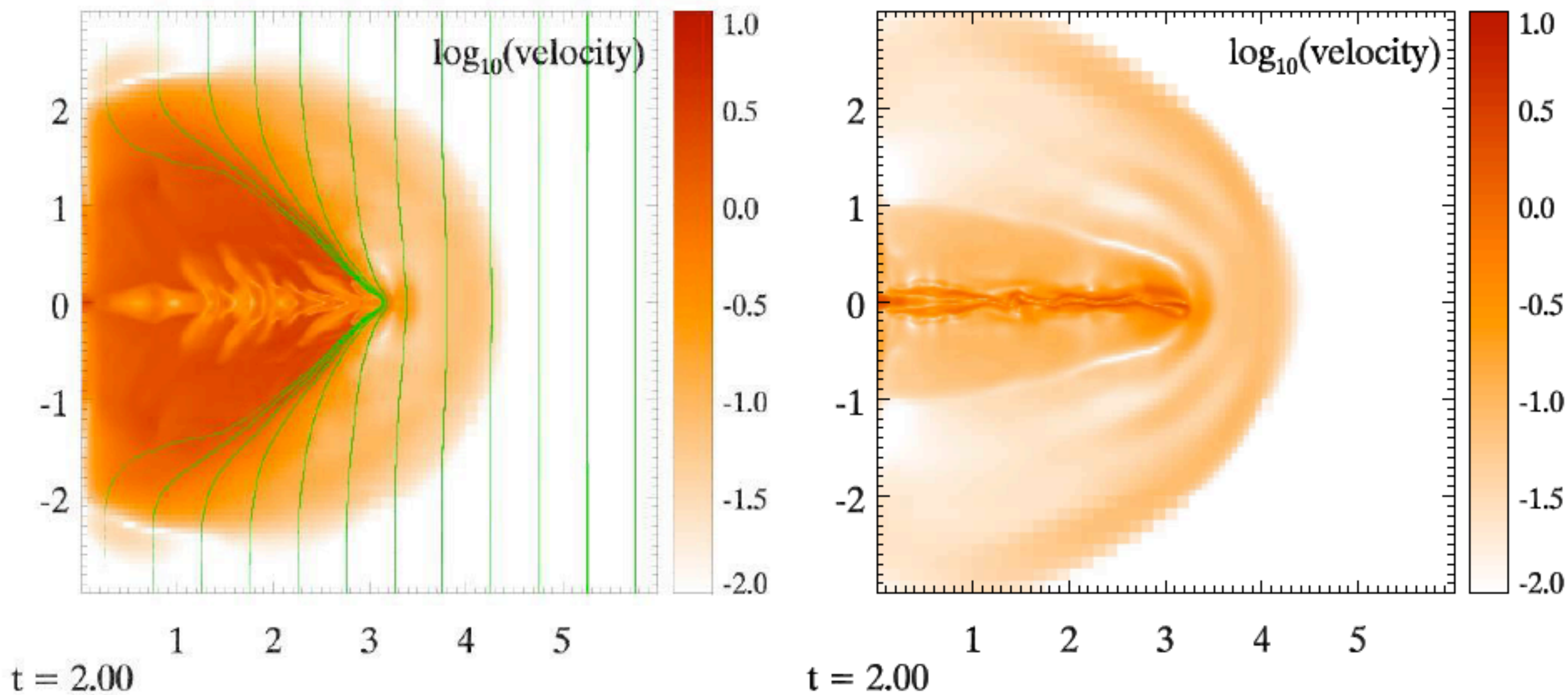
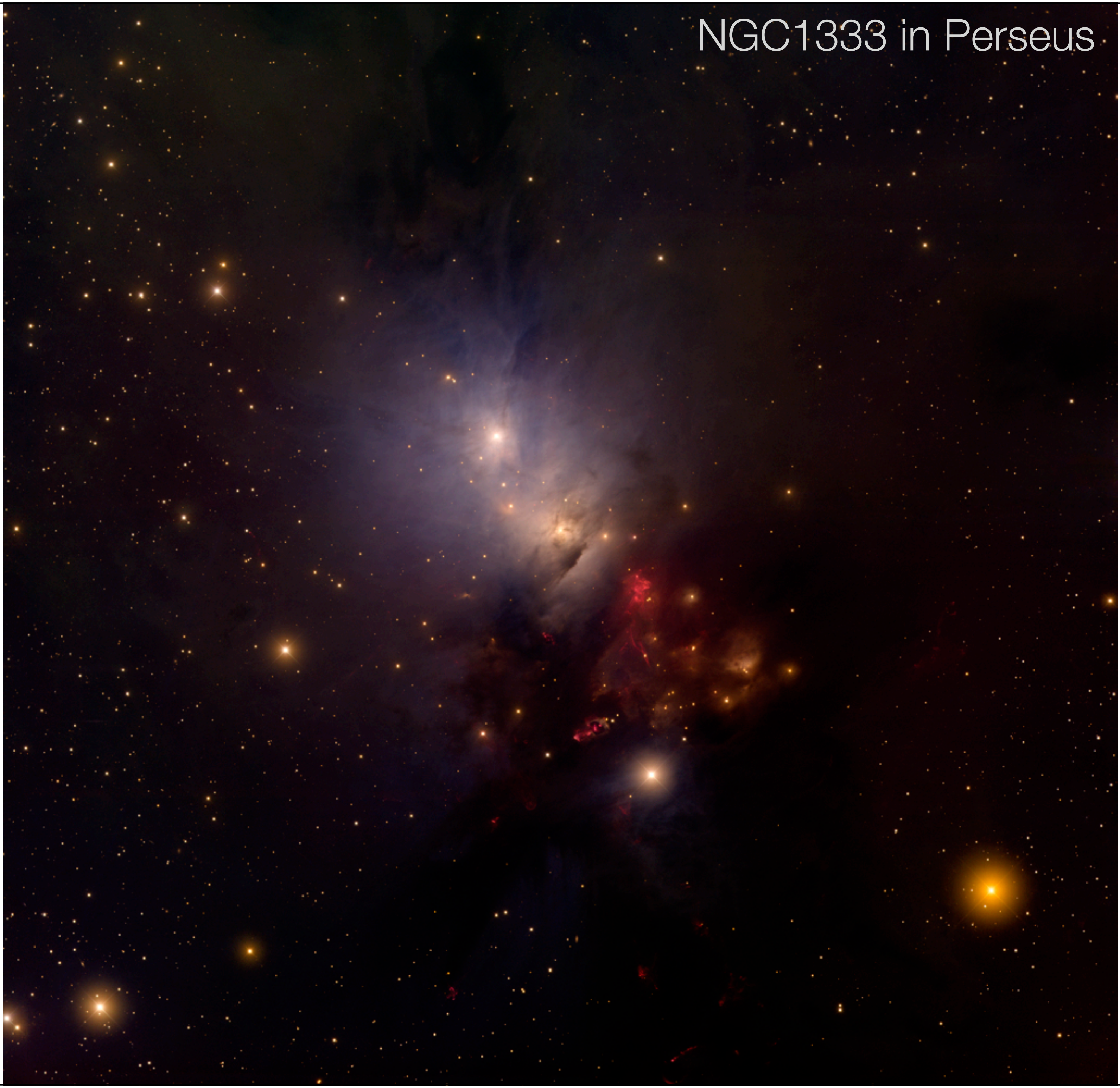


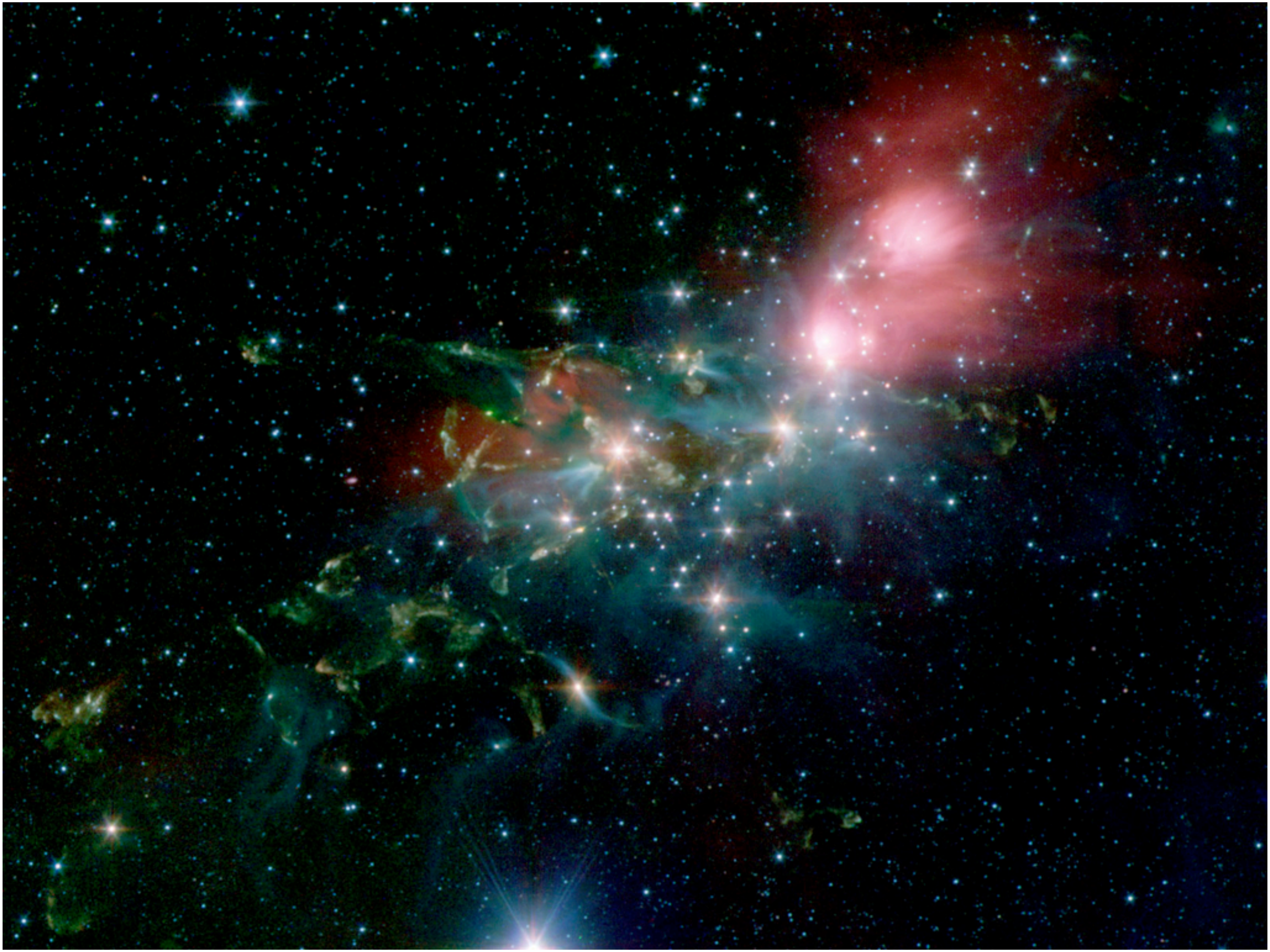
Fig. 17.— Shows the velocity structure form simulation M10tMpe3D (initial homogeneous magnetic field perpendicular to the jet axis). The left panel shows the speed distribution in a 2D slice through the xy plane and the right panel is an image through the xz plane. The jet compresses and distorts the magnetic field whose pressure and tension accelerates gas off the jet axis as seen in the left panel.

Banerjee, Klessen et al. 2008

Outflows effect surrounding cloud or do they?

Jets can slow in dark clouds


NGC1333 in Perseus



Sink Outflow Feedback

Momentum feedback according to sink particle accretion rate:

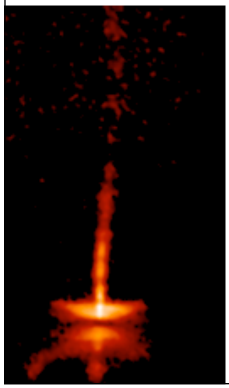
$$\Delta P = P_* \Delta M$$

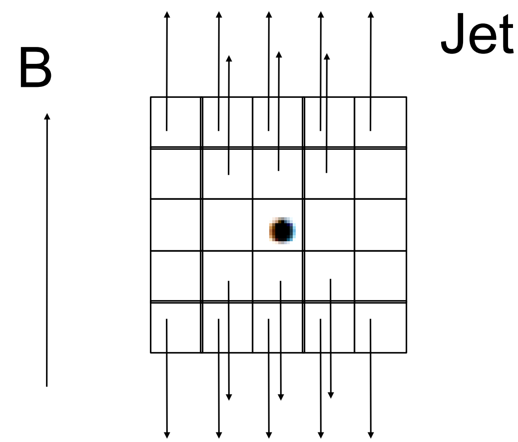
$$P_* = P_0 (M_*/M_0)^{1/2}$$

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

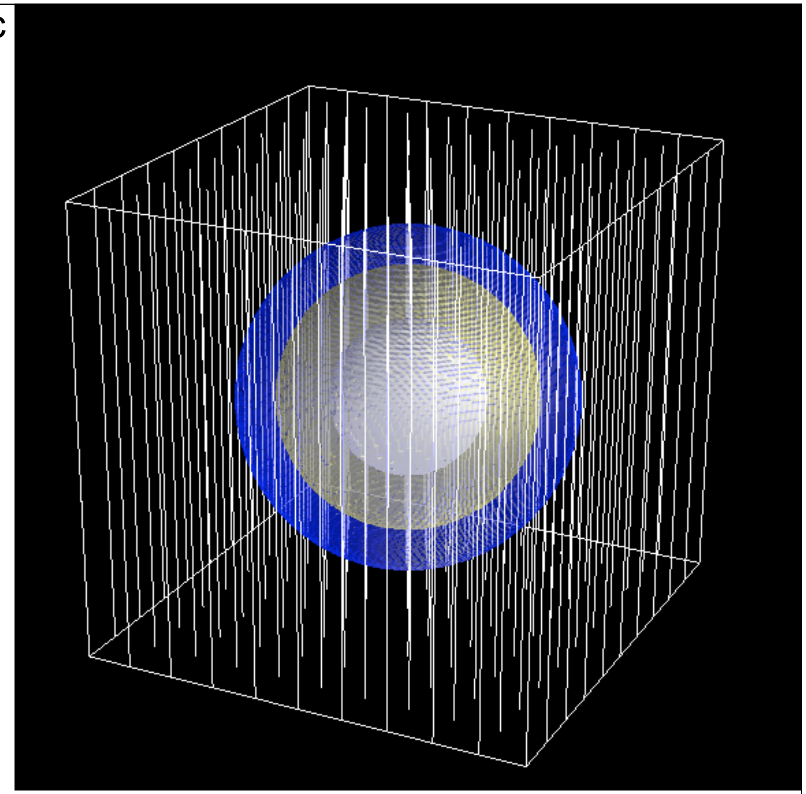
Note: this is ~ 1/3 of the observed value for low mass stars:
~ 16 km/s per accreted solar mass

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





Box size: 2 pc



Numerical experiments: Model Setup

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

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

- c_s = 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 particles to model star formation designed to give more or less the known answer

- Protostellar outflow feedback.

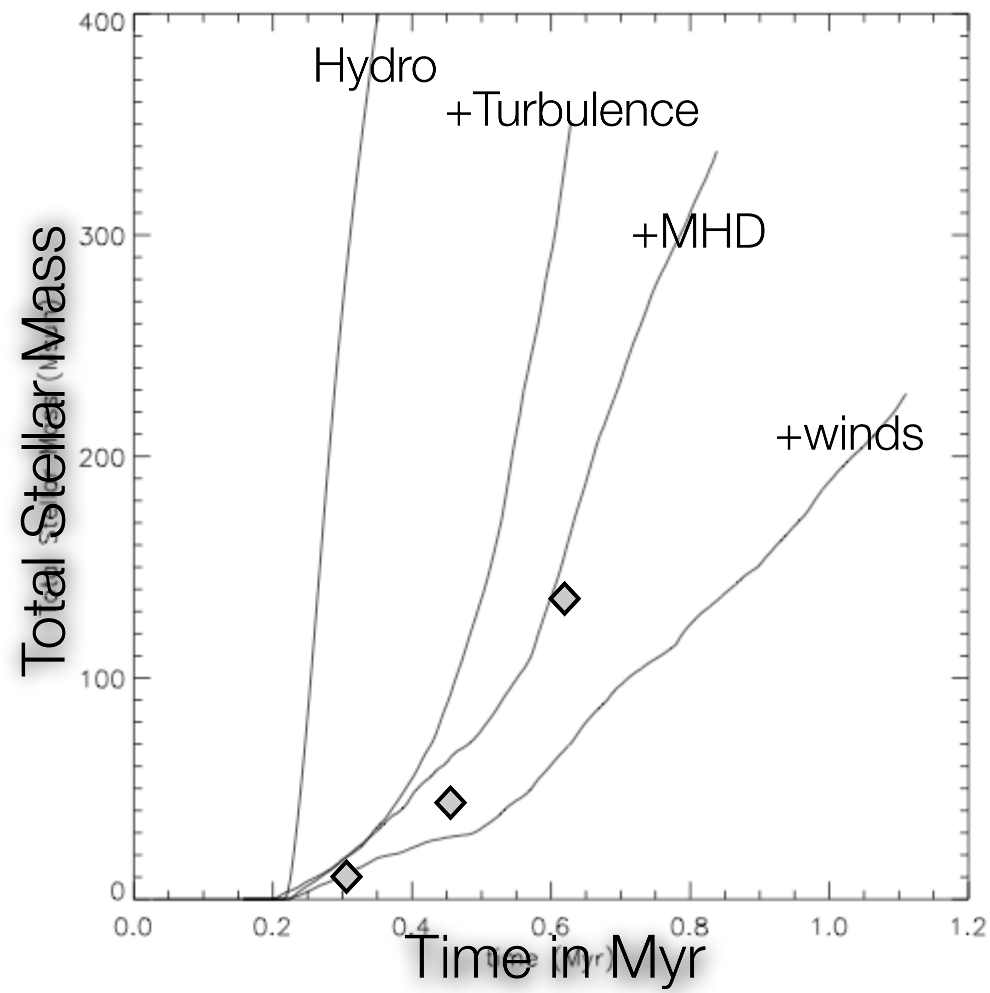
- Top grid 128^3, 4 levels of refinement by 2, maximum resolution 100 AU 2048 dynamic range .

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

Wang, Li, Abel, Nakamura 2010 ApJ

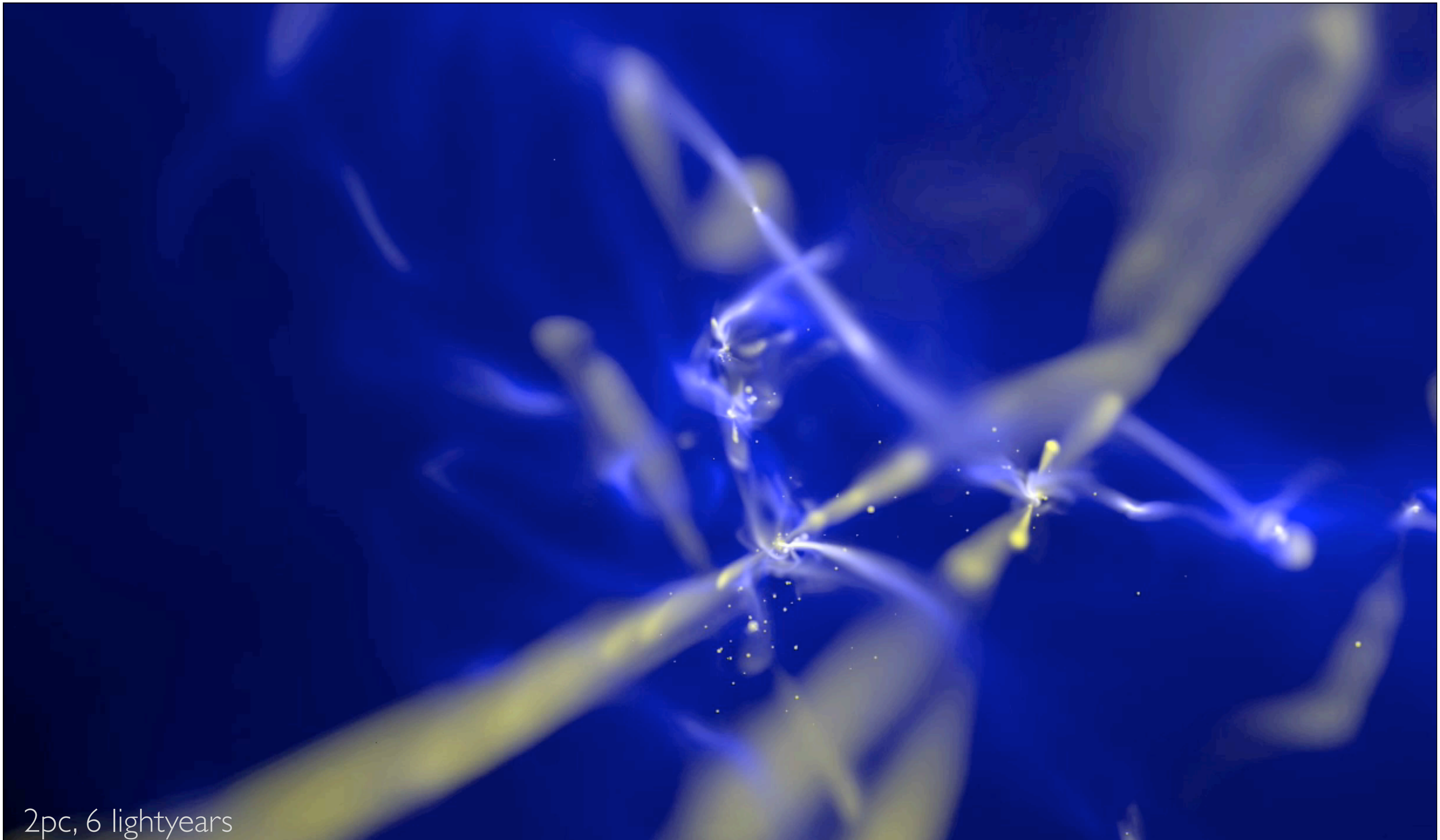
Relevant physics in star formation

- Hydro/MHD models form stars much to quickly and very accelerated ...
- With proto-stellar outflows and MHD one gets const. star formation rate
- 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)

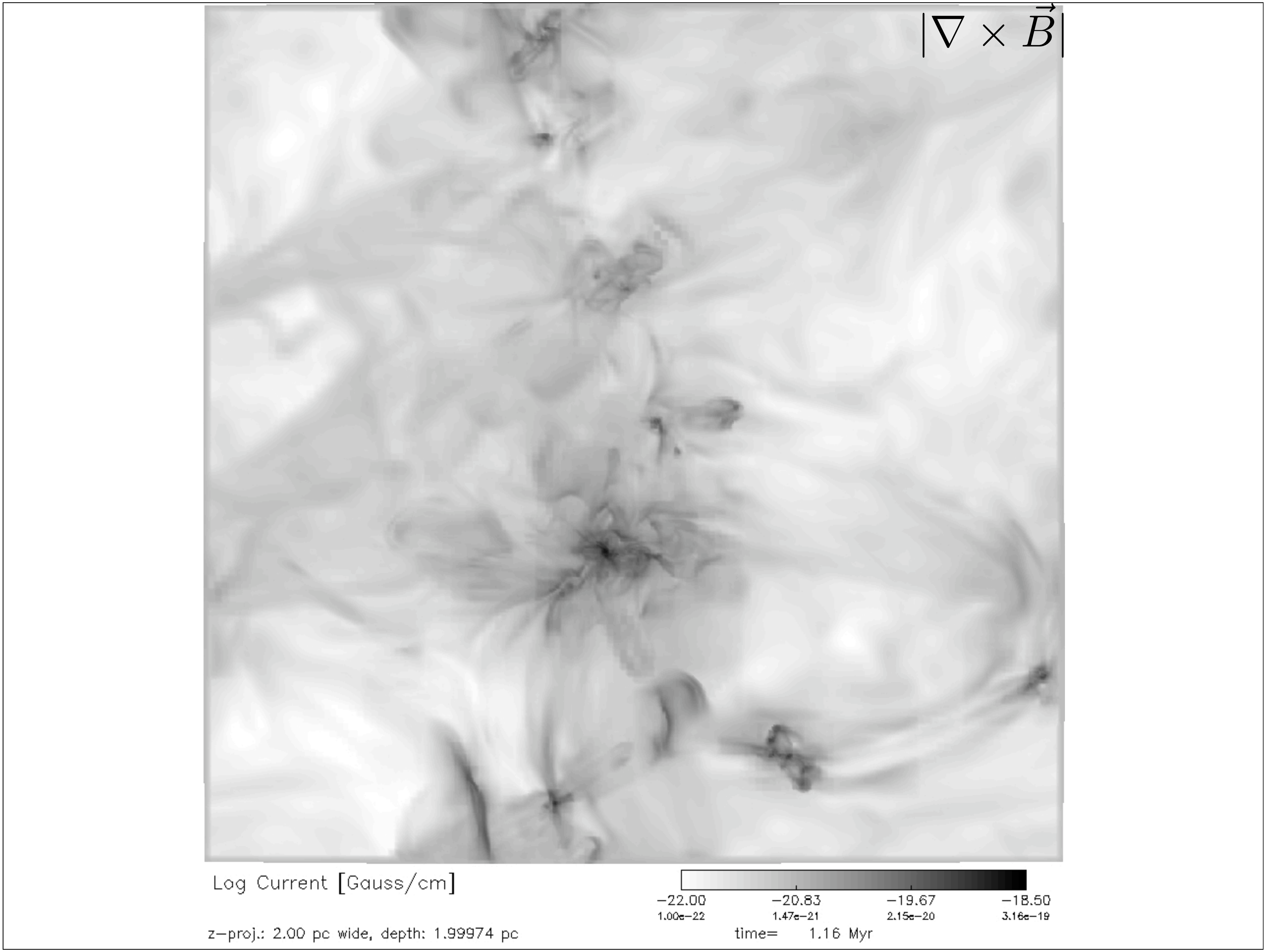


Formation of a Star Cluster in the Milky Way

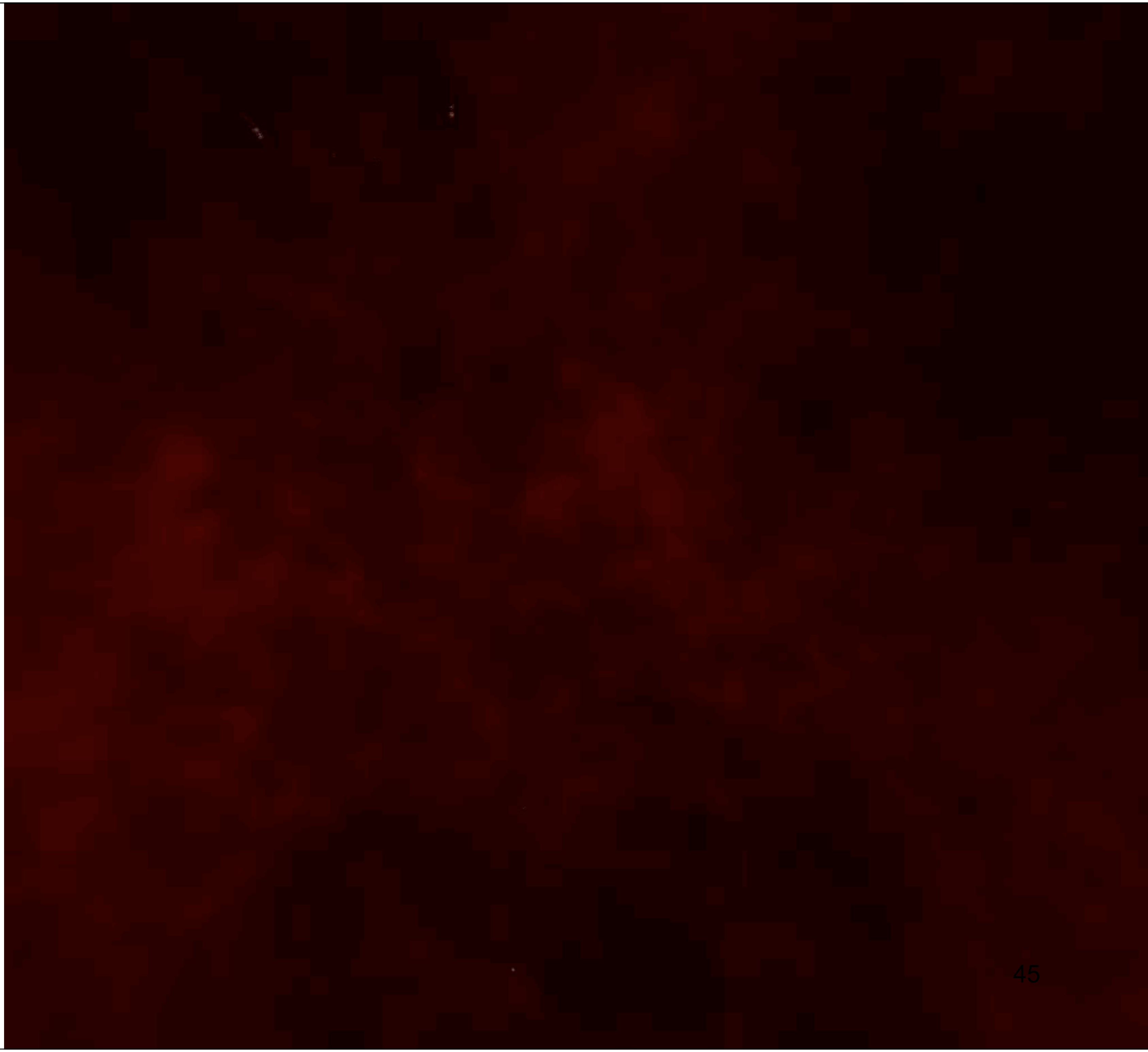
Sim: Wang, Li, Abel, Nakamura 2009 ApJ, submitted.

Viz: Kähler & Abel 2009

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

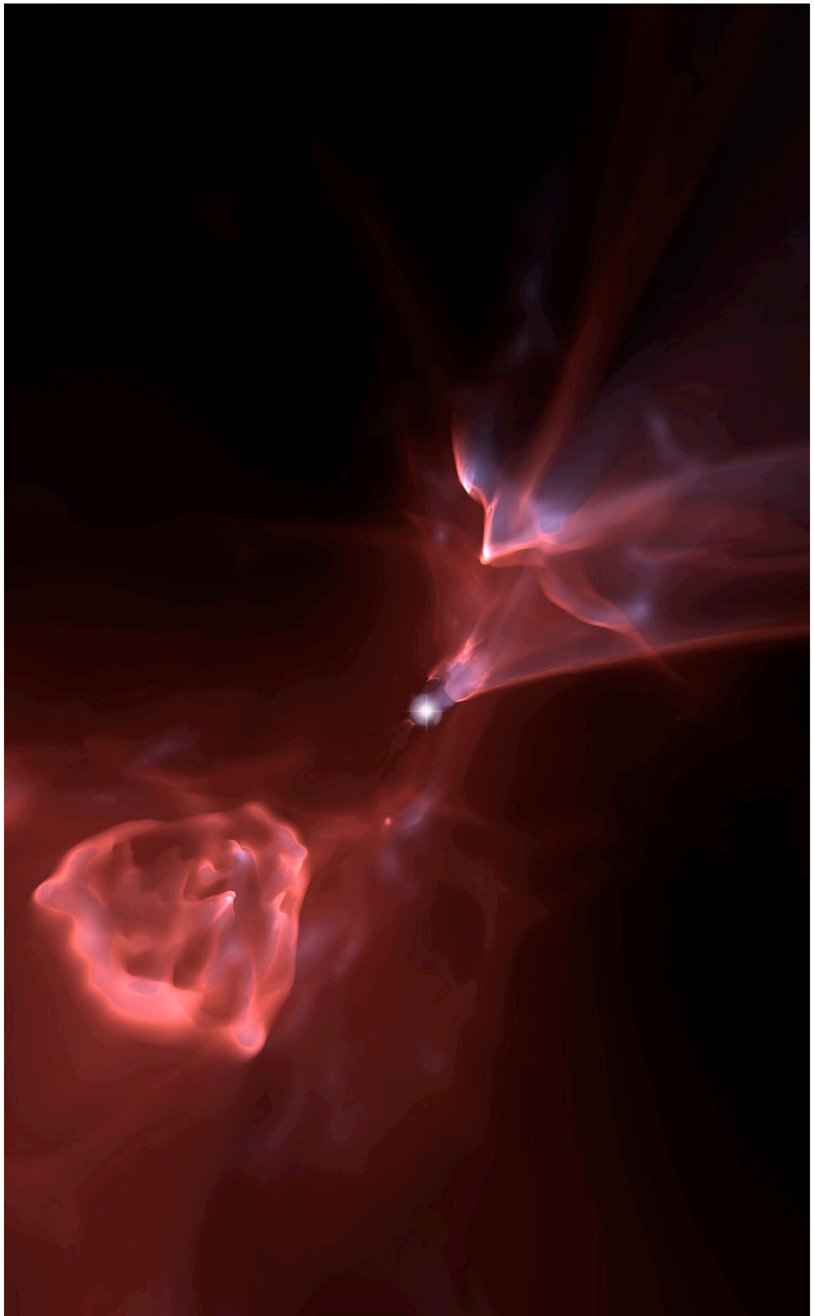

$|\nabla \times \vec{B}|$
Log Current [Gauss/cm]
−22.00
1.00e−22
−20.83
1.47e−21
−19.67
2.15e−20
−18.50
3.16e−19
z−proj.: 2.00 pc wide, depth: 1.99974 pc
time= 1.16 Myr

Ji-hoon Kim

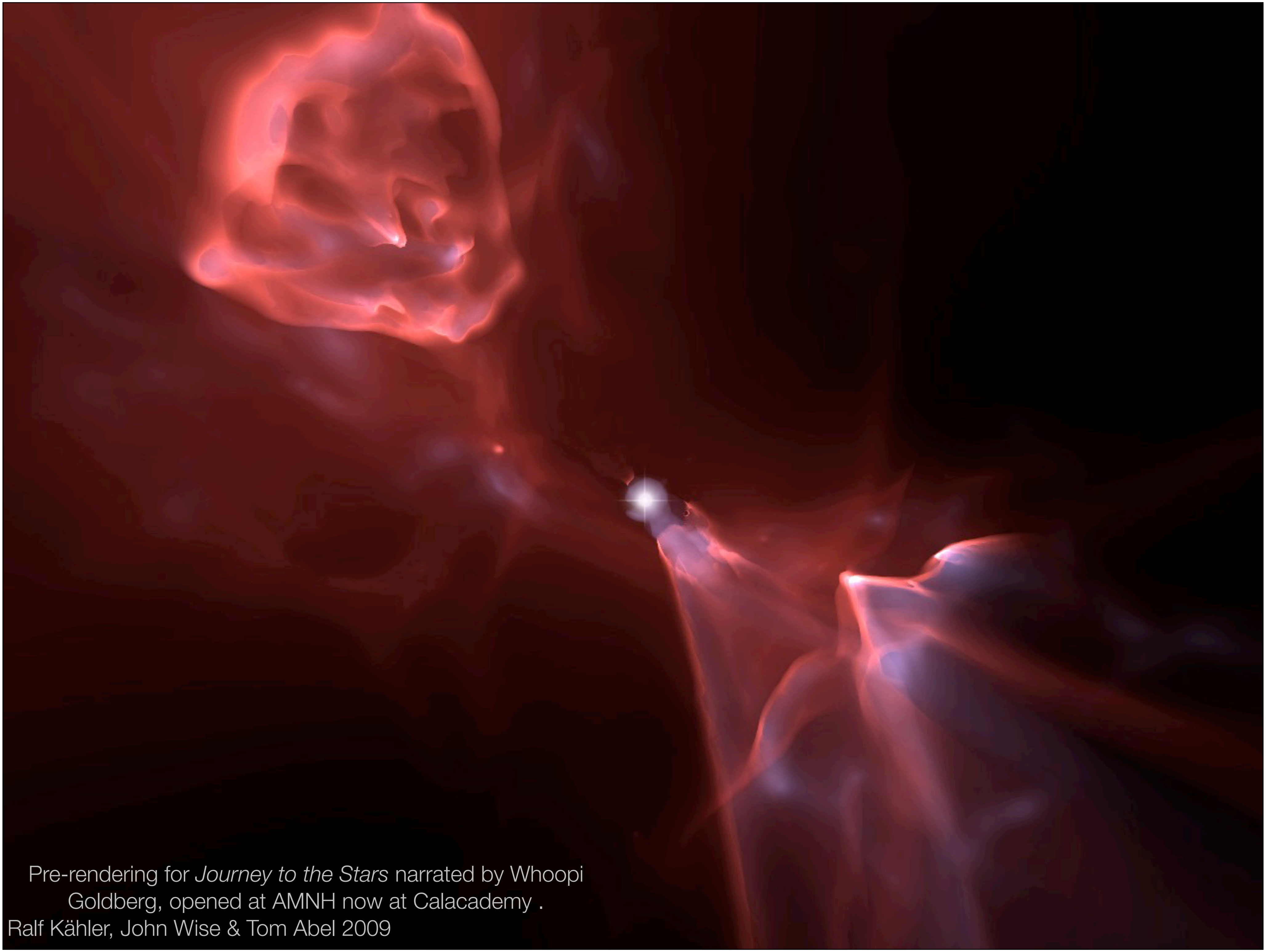


Summary

- SPH does not model inviscid fluids properly
- rpSPH allows to study weakly compressible flows but is non-conserving
- Galaxy formation models start to inform star formation studies and vice versa
- Exciting times ahead as computational power within reach to combine the two things meaning fully.
- Outflows likely to play an important role in star formation
- Magnetic fields relevant very quickly.



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