Outflows from young stellar objects and their impact on star formation

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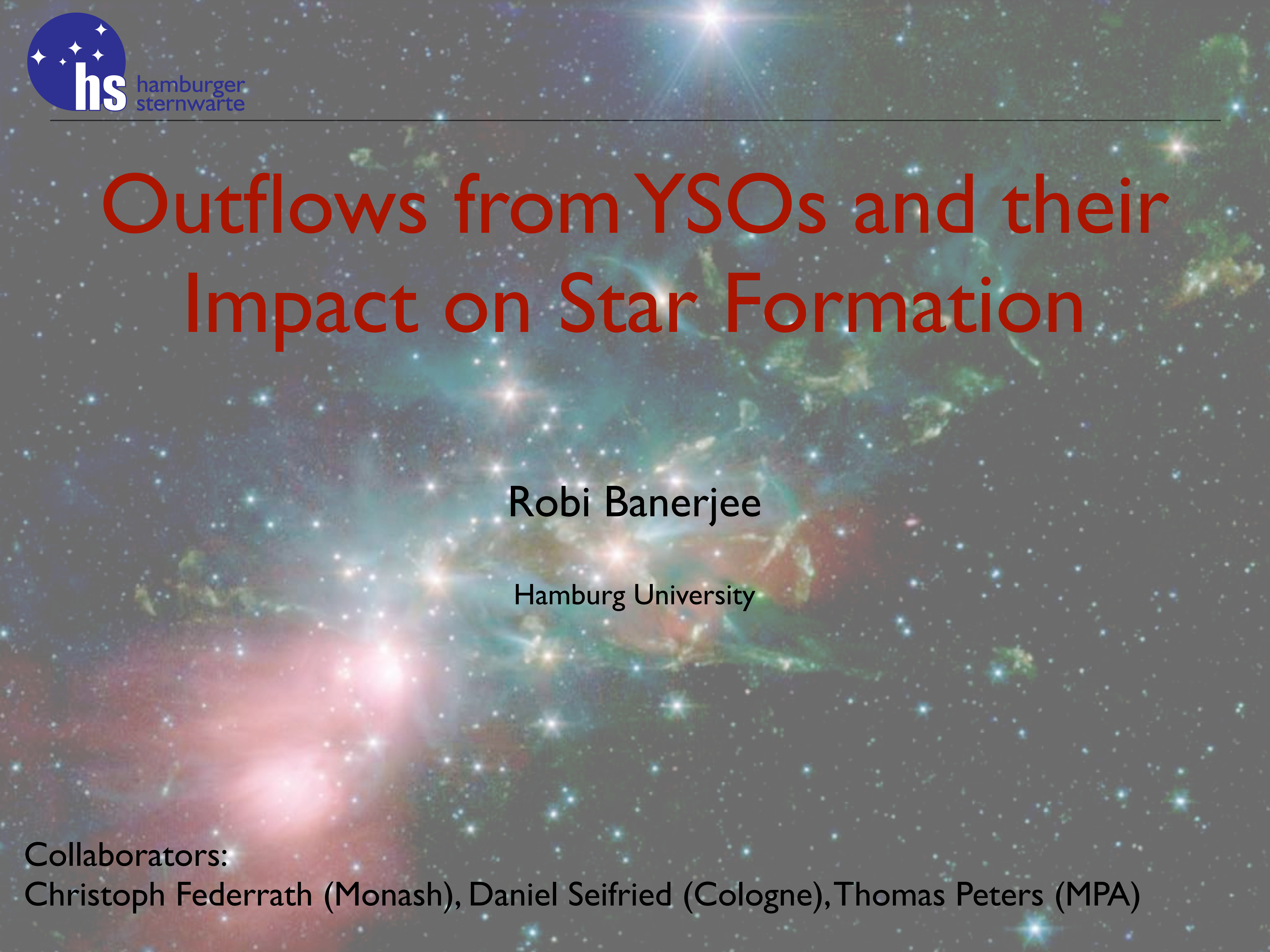
Jets and outflows are observed around young stellar objects over the whole stellar spectrum, from brown dwarfs to high-mass stars. Those outflows are most likely driven by the coupling of magnetic fields that thread the underlying accretion disc. If this is a universal mechanism, such a disc-wind configuration should be self-consistently build up during the collapse of individual cloud cores. Additionally, jets and outflows feed back energy and momentum to the ambient gas in star-forming regions. Yet, it is still controversial whether feedback from outflows are able to regulate star formation in molecular clouds.

In this talk, I will summarise recent results from numerical simulations on outflow launching during the birth of stars and their impact on star-forming regions based on sub-grid modells of outflows.

Subject :	:	oral
Topics	:	Astrophysics
Topics	:	Numerical simulations



Outflows from YSOs and their Impact on Star Formation

Robi Banerjee

Hamburg University

Collaborators:
Christoph Federrath (Monash), Daniel Seifried (Cologne), Thomas Peters (MPA)

Outflows & Jets

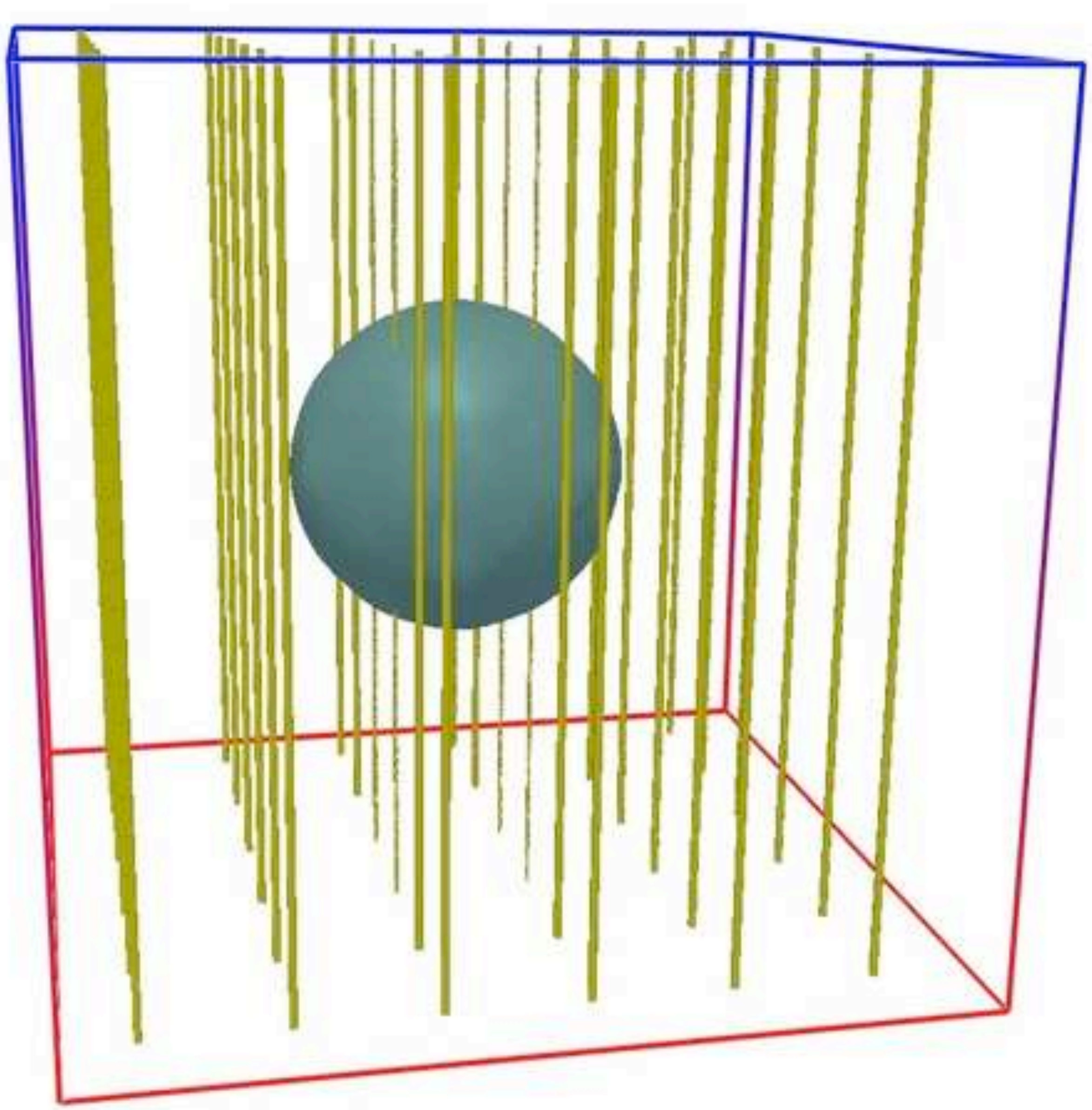
- Outflows & Jets are ultimately linked to the formation of stars

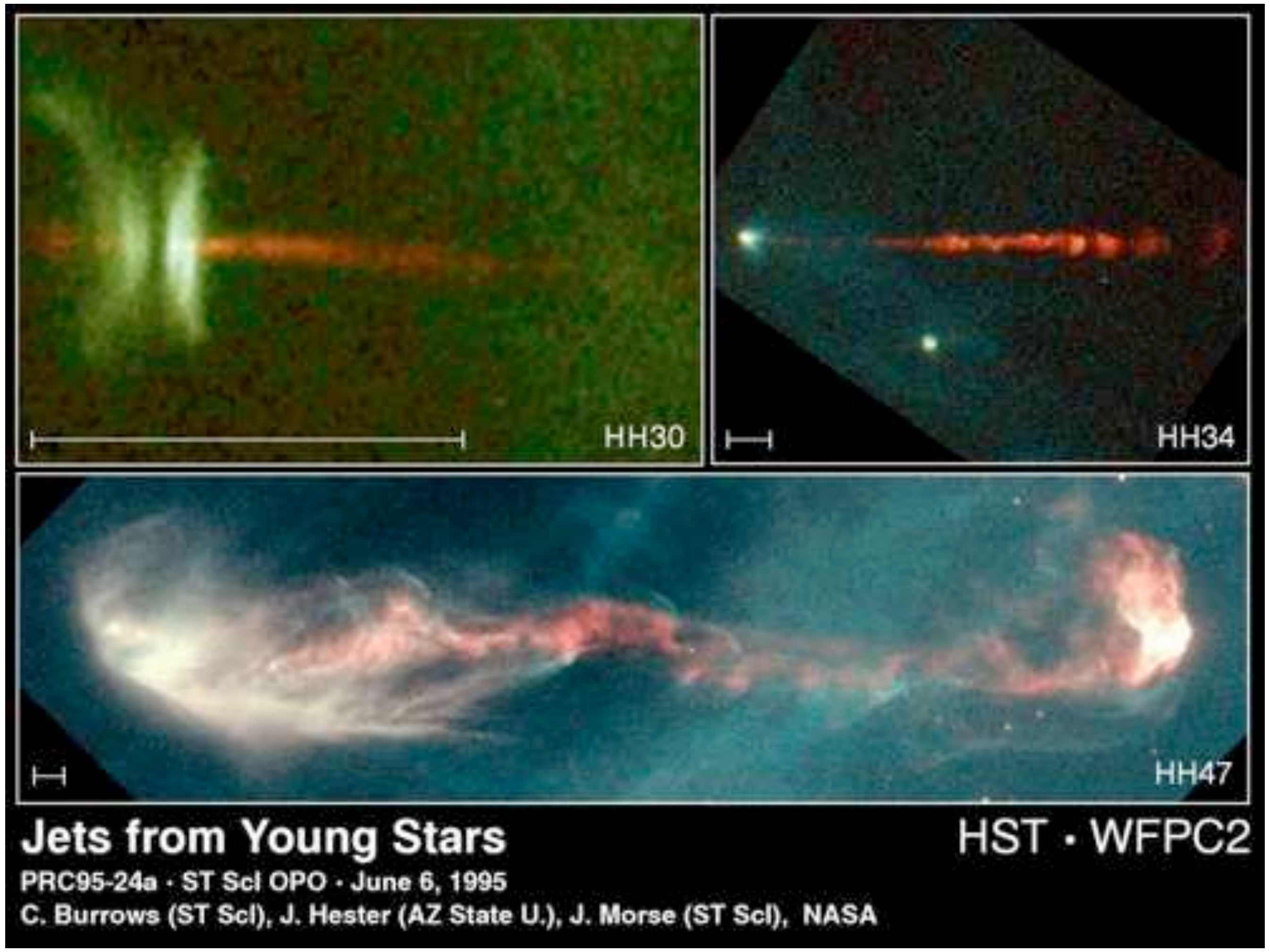
⇒ what's their impact on this process?

⇒ how to model it self-consistently?

NGC 1333, R.Gutemuth, Spitzer IRAC

Collapse of Magnetised Cloud Cores





- magnetically driven Jets / Outflow from YSOs

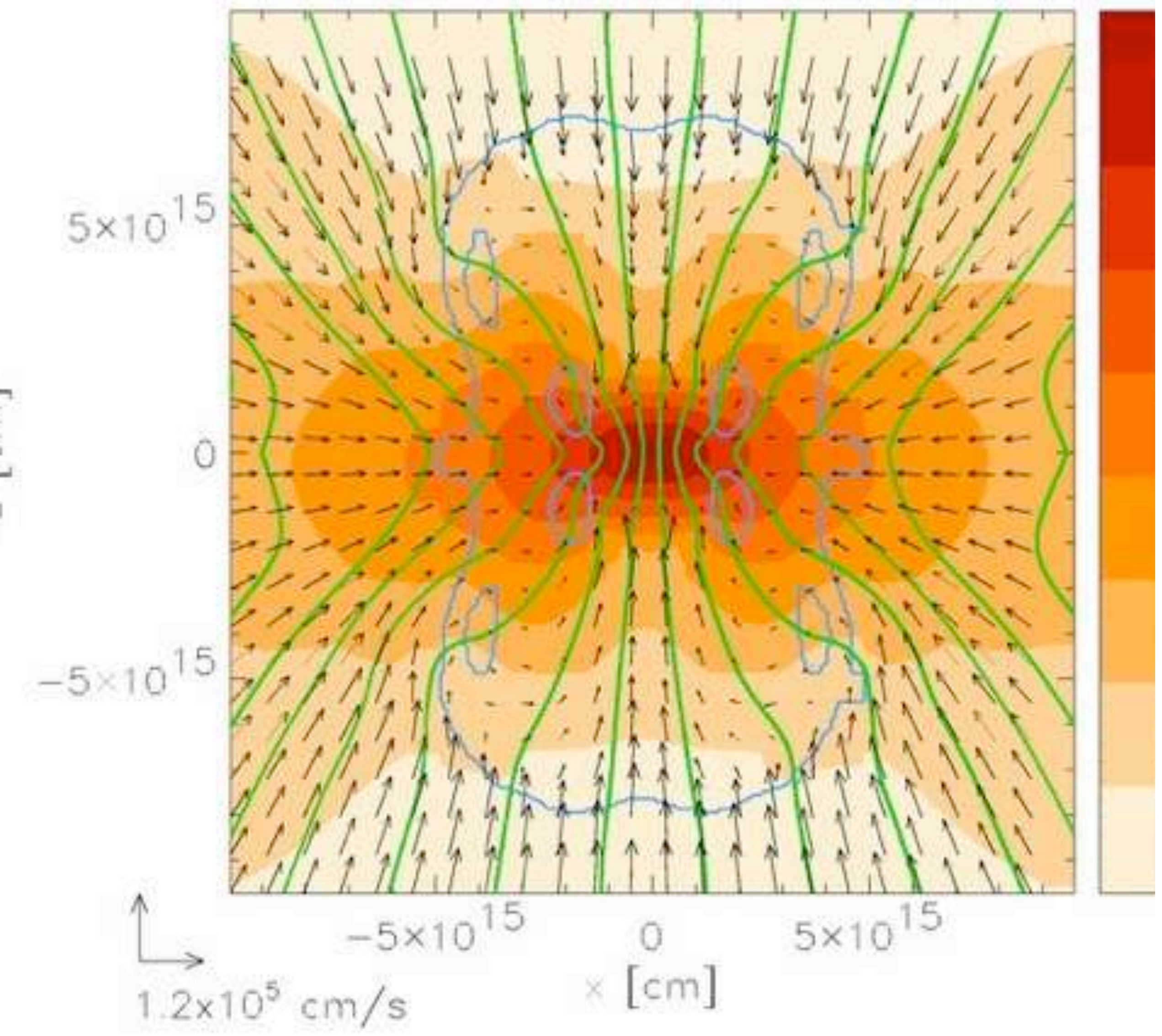
Outflows from Collapse of Magnetised Cores

Onset of large scale outflow:

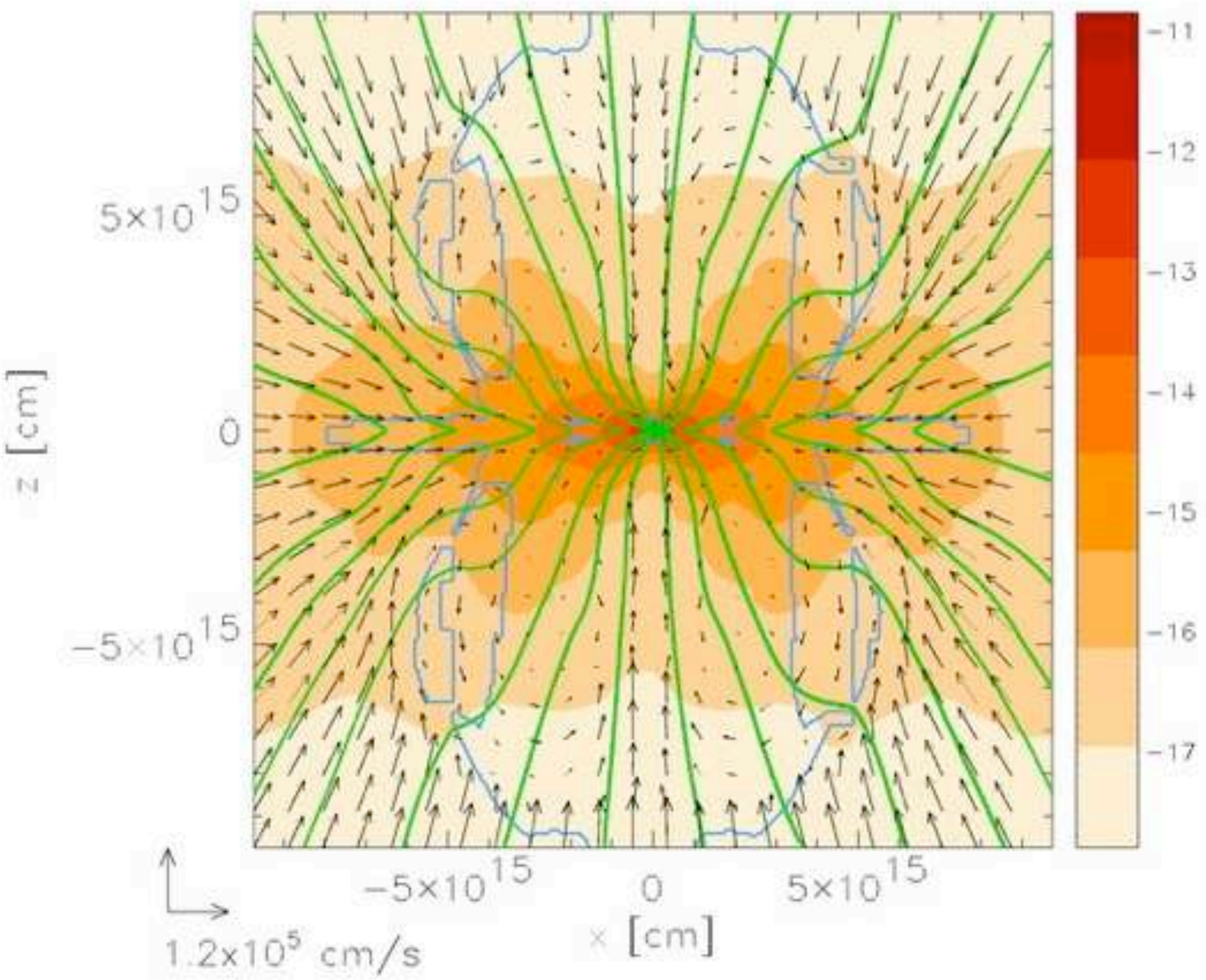
at few 100 AU

magnetic tower configuration (e.g. *Lynden-Bell 2003*)

Banerjee & Pudritz 2006



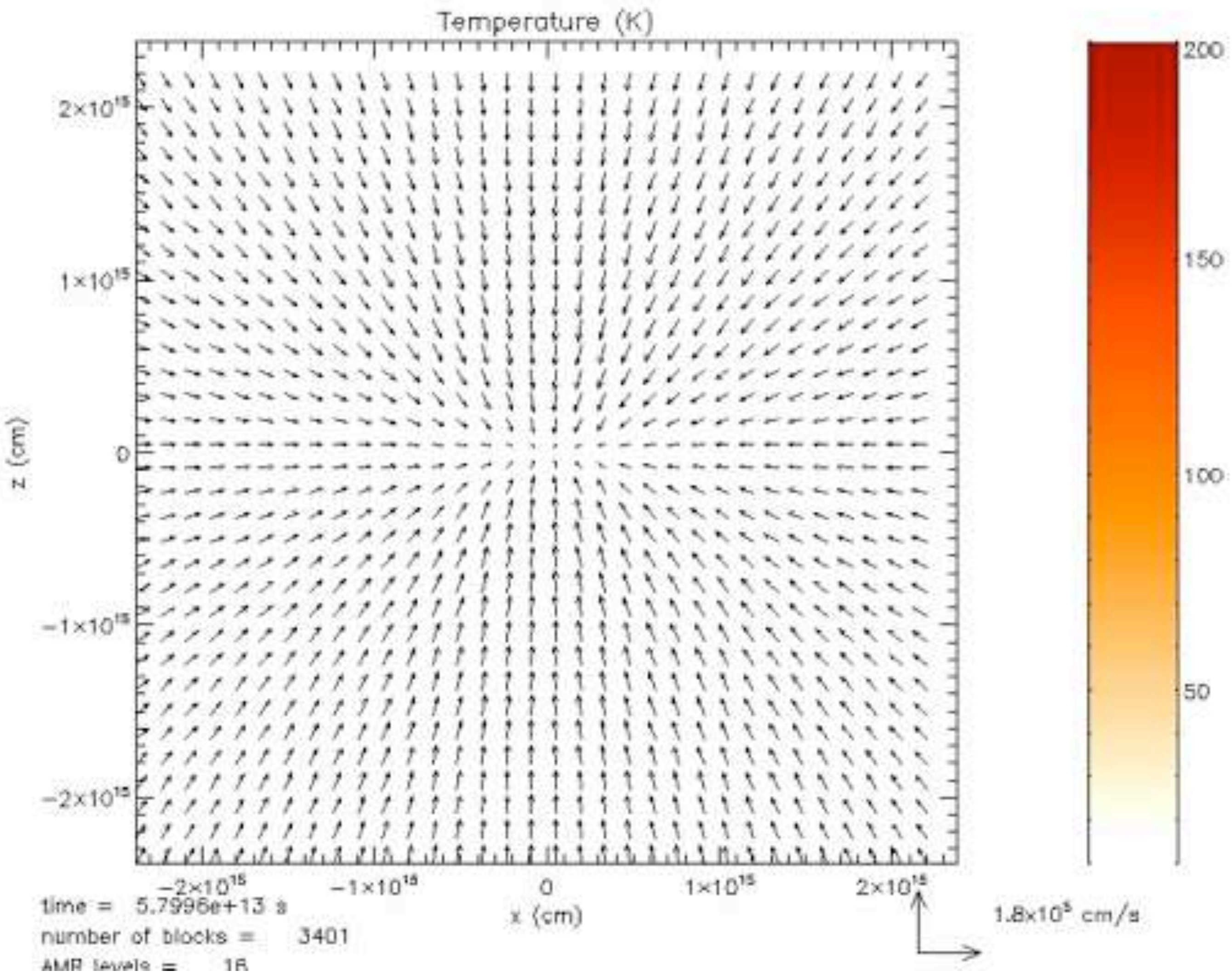
collapse phase
pinched in magnetic field



.... 1430 years later:
onset of a large scale outflow

Outflows from Collapse of Magnetised Cores

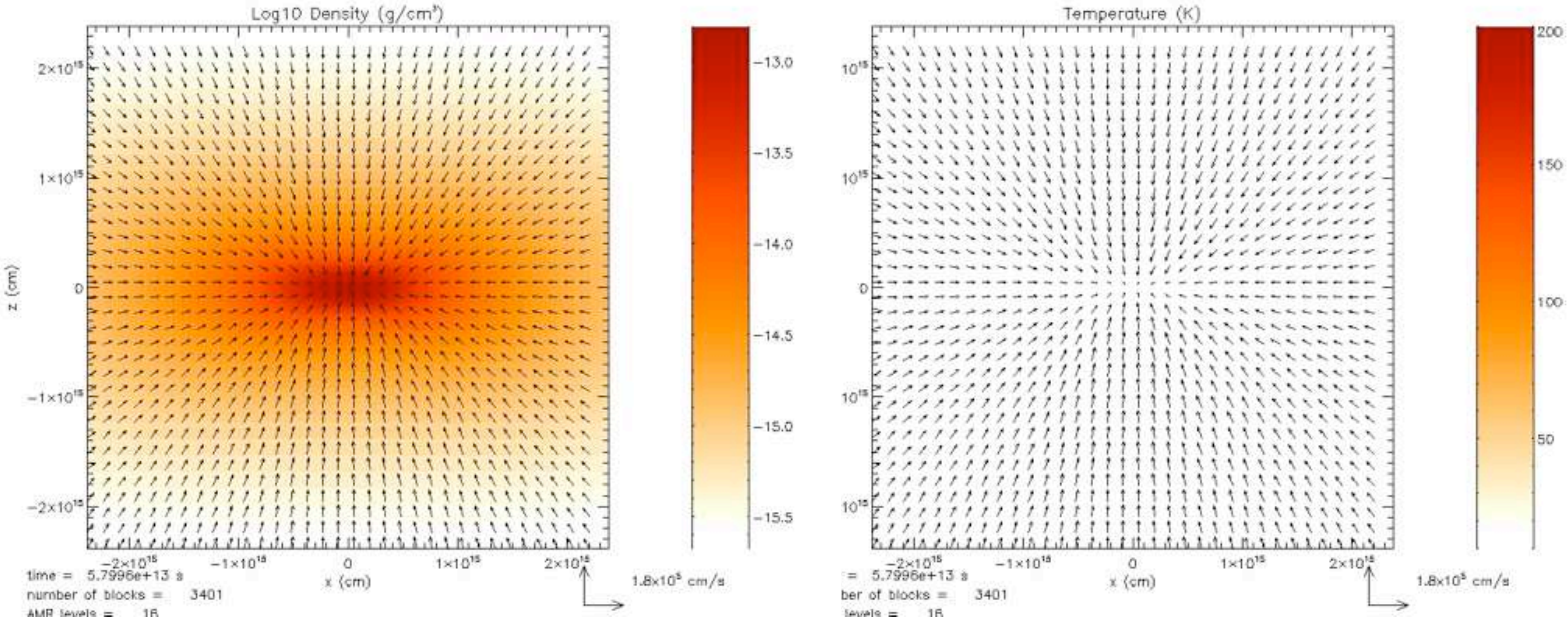
Magnetic tower flow



- build up of toroidal field → magnetic pressure
- outward propagation of shock fronts
- magnetic bubble

Outflows from Collapse of Magnetised Cores

Magnetic tower flow



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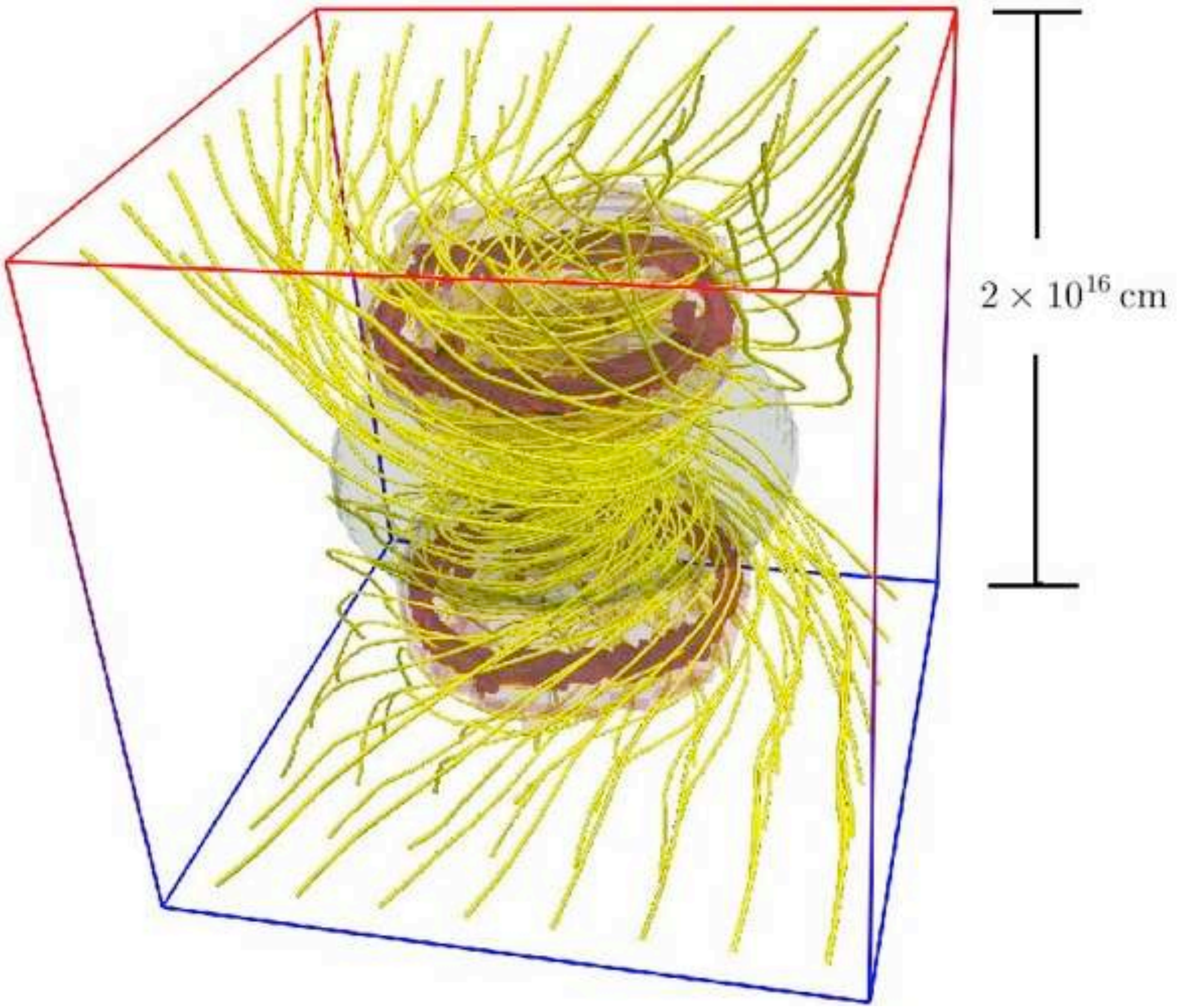
Outflows from Collapse of Magnetised Cores

Large scale outflow



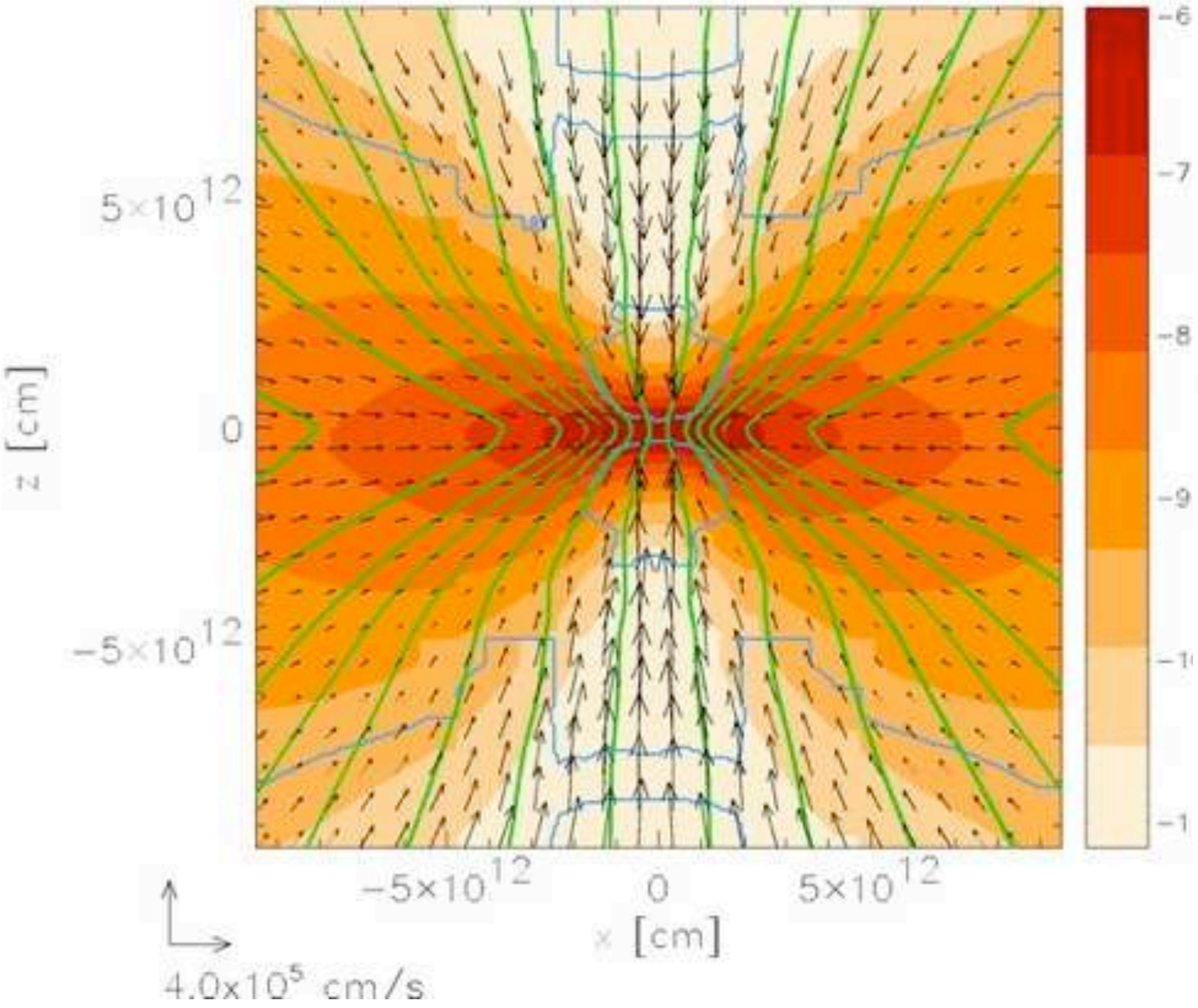
- Magnetic field is **compressed** with the gas
- Rotating disk generates **toroidal** magnetic field ⇒**outflow**

- Shock fronts are pushed outwards (magnetic tower)
- Outflow velocities v ~ 0.4 km/sec, M ~ 2-3
- Accretion: funneled along the rotation axis, through disk

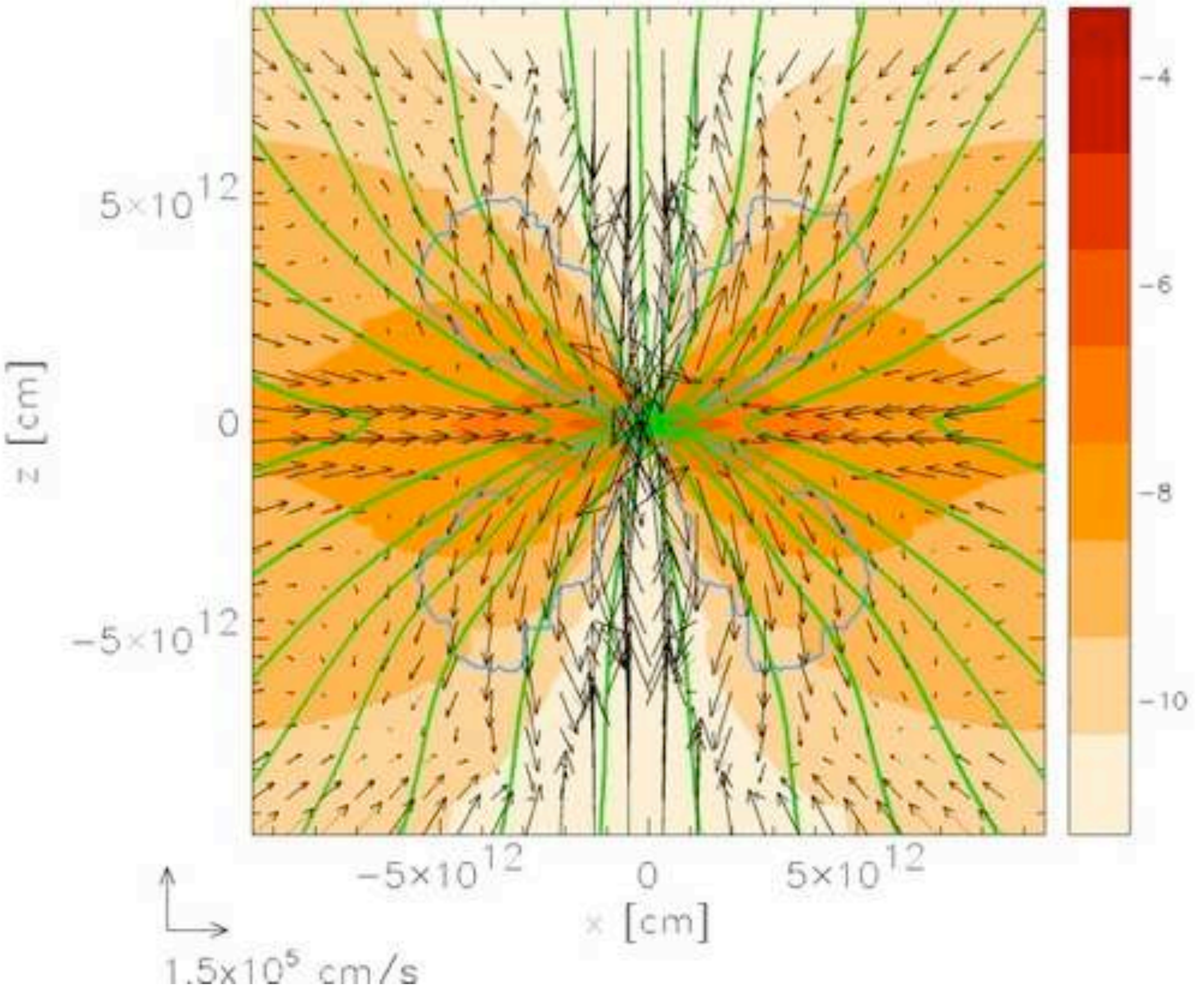
Outflows from Collapse of Magnetised Cores

$\Delta x \approx 5\times10^9$ cm (0.07 R_{sol}) **at** $l_{ref} = 27$

$\Longrightarrow$ Onset of inner disk jet



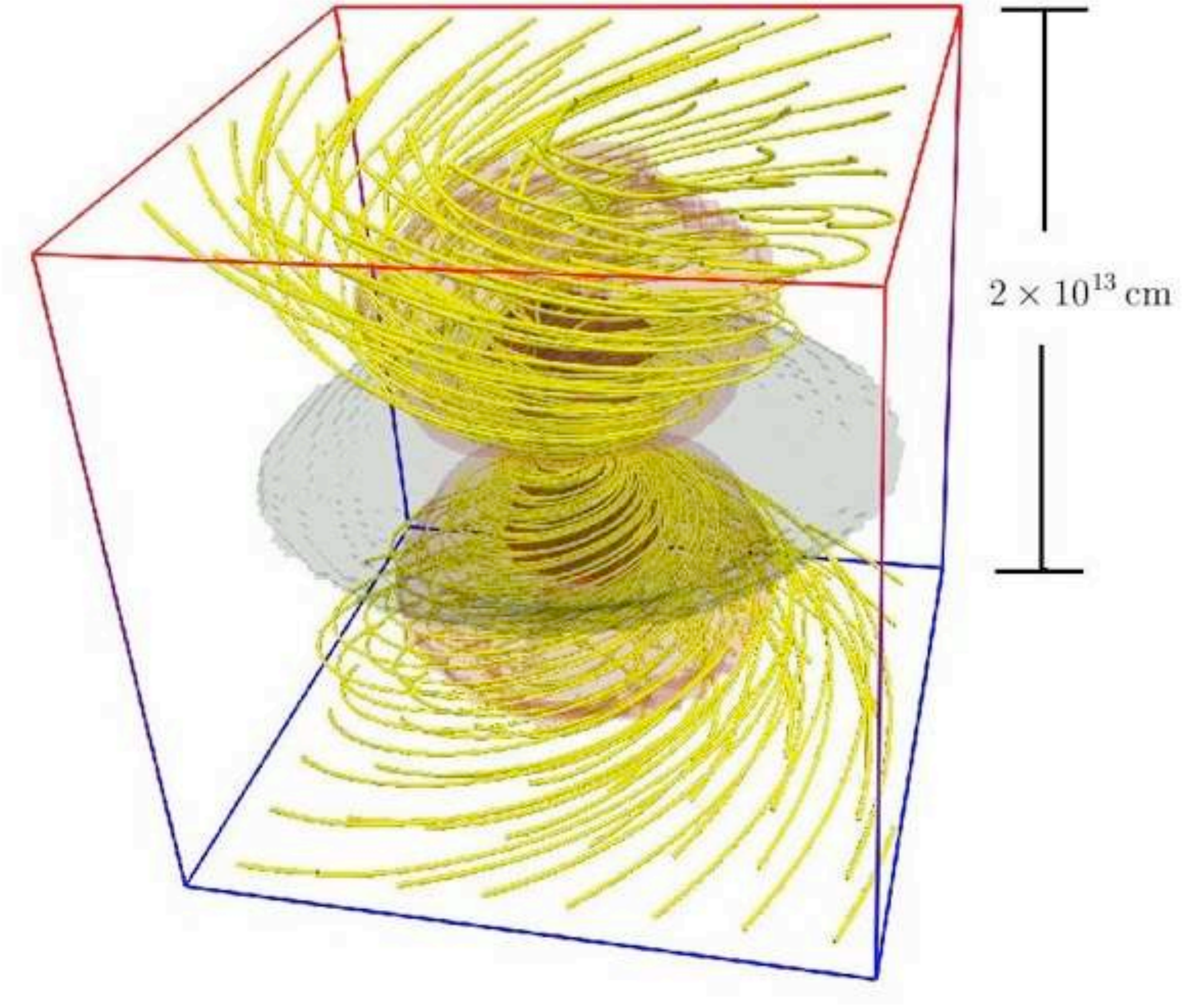
infall only



… 5 month later: flow reversal

Outflows from Collapse of Magnetised Cores

small scale disk jet



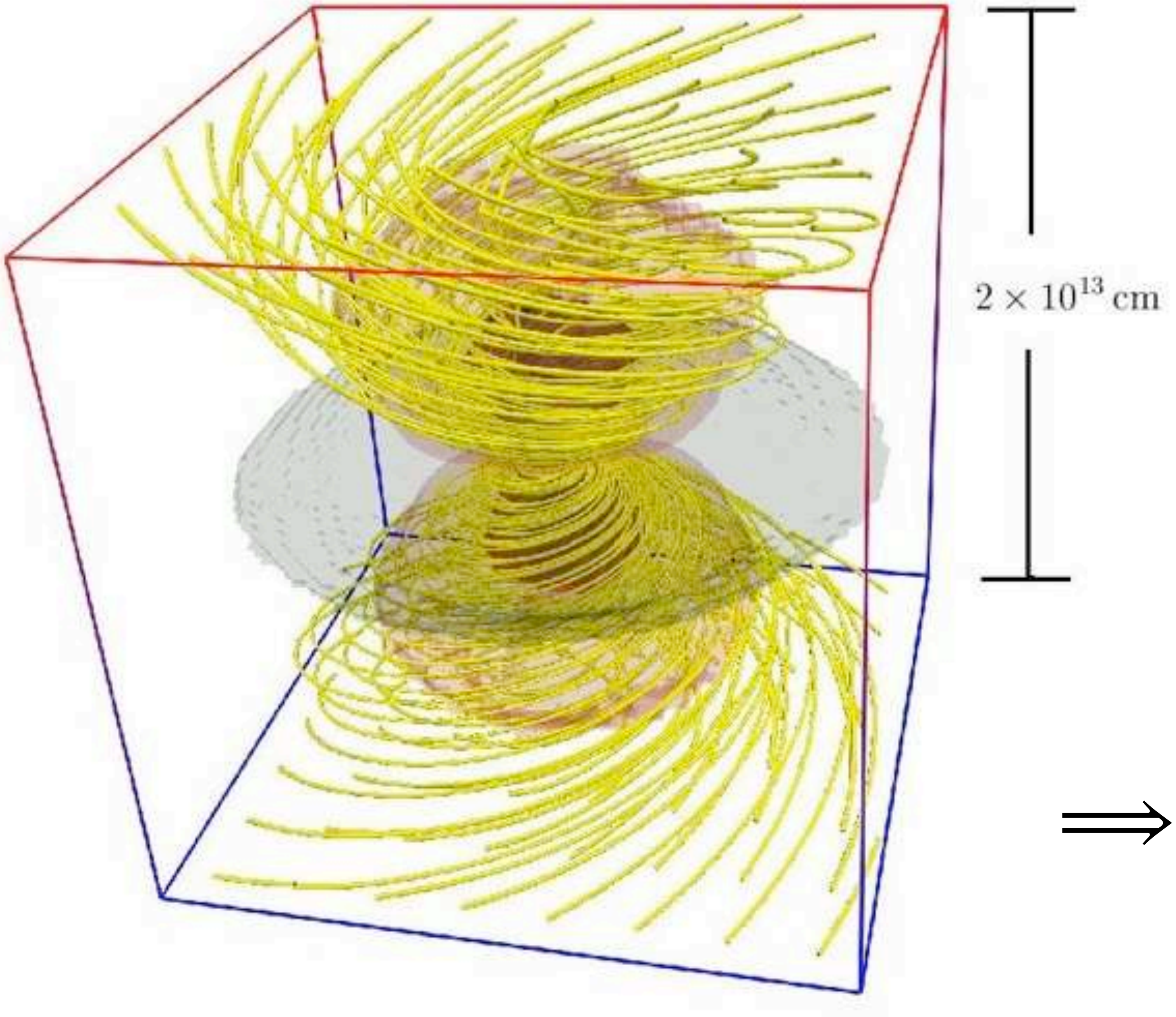
- Magnetic field strongly pinched and warped
- Angle with disk plane < 60°

  → magneto-centrifugal jet launch *(Blandford & Payne 1982)*
- "Onion" shaped velocity structure
- Outflow velocities

  v ~ 4 - 5 km/sec, Mach ~ 4

Outflows from Collapse of Magnetised Cores

small scale disk jet



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- Angle with disk plane < 60°
  → magneto-centrifugal jet launch *(Blandford & Payne 1982)*
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- Outflow velocities
  v ~ 4 - 5 km/sec, Mach ~ 4

$\Longrightarrow$ can not follow long-term, large-scale evolution

Sink Particles for the FLASH code

- AMR/SPH simulations can't cover the full spatial range for star formation $\Longrightarrow$ introduce "black boxes" = *Sink Particles*

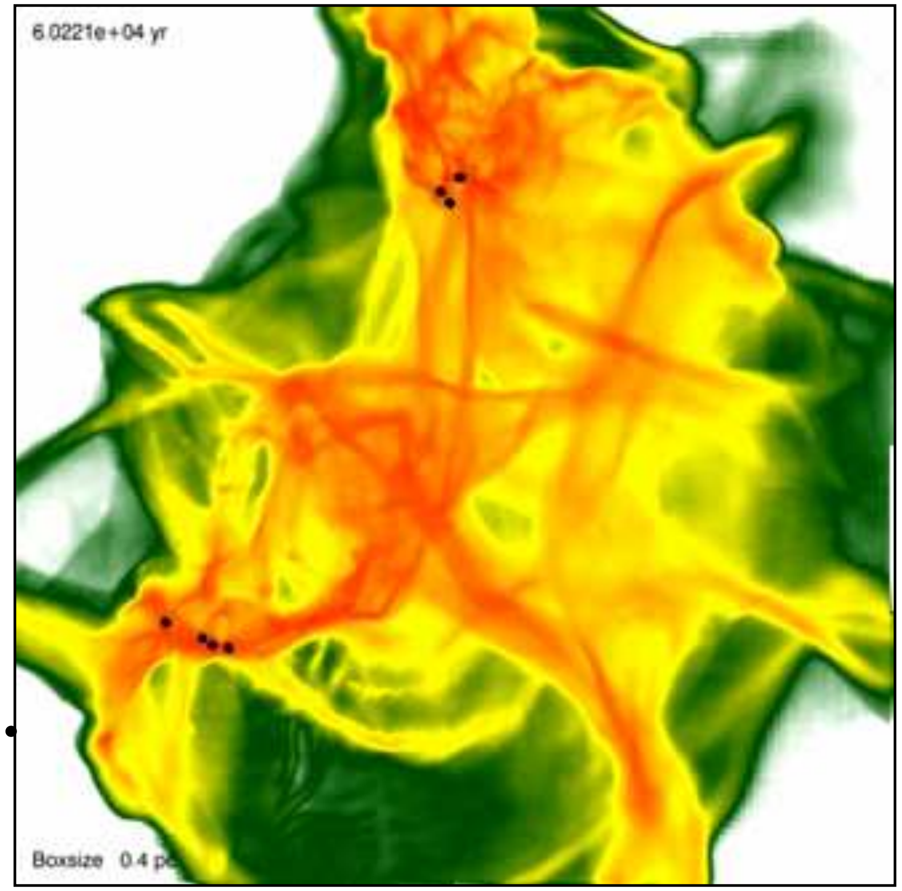
Sink Particles for the FLASH code

- AMR/SPH simulations can't cover the full spatial range for star formation ⟹ introduce "black boxes" = *Sink Particles*

  ⟹ modeling of dense regions in **collapse** simulations,
  e.g. star formation (*M.Bate et al.* 1995)

  - 'controlled' violation of the Truelove criterion (*Truelove et al. 1997*):
    preventing artificial fragmentation by resolving the *Jeans length*
  - allows long term runs of star forming regions:
    binaries, stellar clusters, outflows
    also: feedback, drag forces, ...

  - **BUT:** 'arithmetic' part of the system, i.e.
    ⇒ physical interpretation?



Sink Particles

Based on the particle module in FLASH 2.x (Paul Ricker):

- handles boundaries
- moves particles across CPUs/blocks
- mapping of grid variables onto particles and vice versa
- advances particles

Extensions / modifications:

- creation of particles on the 'fly'
- gravity: use $1/r^2$ acceleration for particle contribution
- time dependent particle masses: accretion / loss
- momentum transfer onto the particles
- back-reaction onto the grid (feedback)
- MPI communication of global particle list

Sink Particles

- Gravity

originally:
1. mapping of particle density onto grid (CIC, NGP, TSC)
2. solve Poisson’s equation with gas-density + particle-density
3. map acceleration to particle
4. advance particle (Euler, Leapfrog)

Sink Particle Module:

- use direct acceleration from particles

⇒ more accurate (e.g. binary system)

⇒ faster for small particle numbers

Sink Particles

- Gravity

1. gas–gas (g–g)
2. gas–sinks (g–s)
3. sinks–gas (s–g)
4. sinks–sinks (s–s)

$$\mathbf{g}_{\mathrm{g-g}} = -\nabla\Phi_{\mathrm{gas}}$$

$$\mathbf{g}_{\mathrm{g-s}} = -\sum_{i}^{\text{grid}} \frac{G\,M_i}{|\mathbf{r}_i(i,j,k)|^3}\mathbf{r}_i(i,j,k)$$

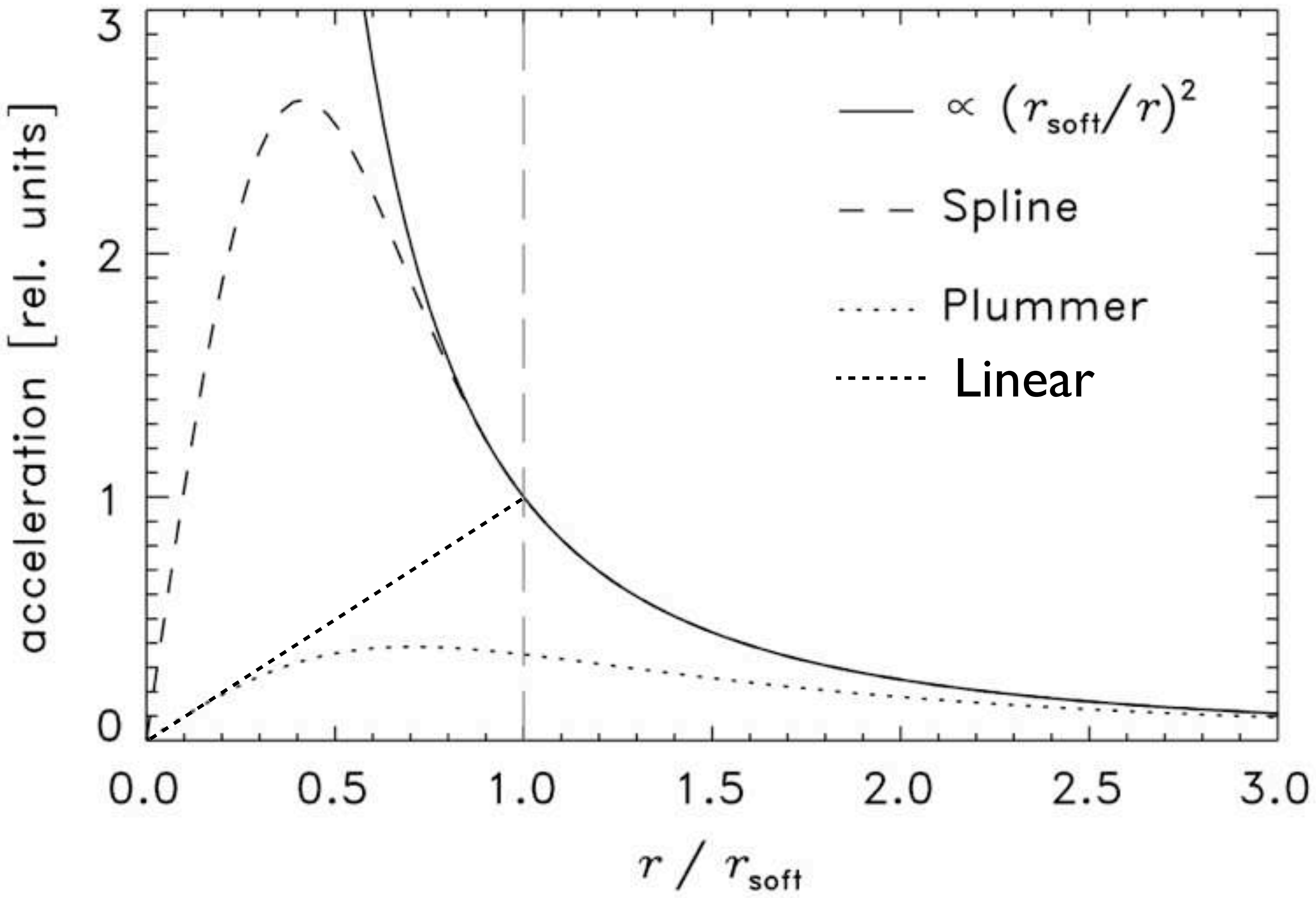
$$\mathbf{g}_{\mathrm{s-g}}(i,j,k) = -\sum_{n}^{\text{particles}} \frac{G M_n}{|\mathbf{r}_n(i,j,k)|^3}\,\mathbf{r}_n(i,j,k)$$

$$\mathbf{g}_{\mathrm{s-s},\,n} = -\sum_{m\neq n} \frac{G M_m}{|\mathbf{r}_{nm}|^3}\,\mathbf{r}_{nm}$$

with $1/\mathrm{r}^2 \rightarrow \mathrm{f}(\mathrm{r},\mathrm{r}_{\mathrm{soft}})$: gravitational softening

Sink Particles

- Gravitational softening



Sink Particles

- Sub-Cycling
  - close "binary" interaction can limit time step:

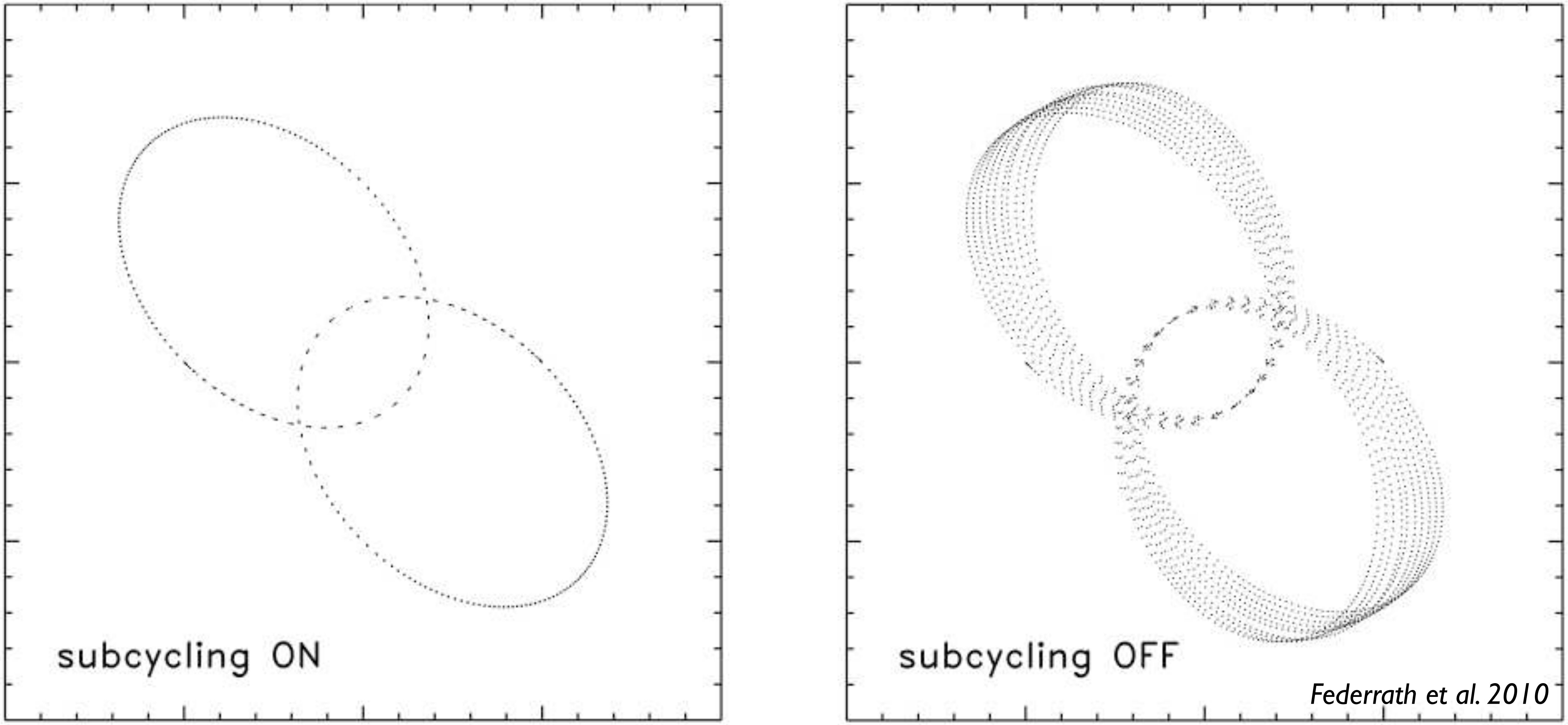
$$\Delta t_{\mathrm{gs}} = C_{\mathrm{gs}} \min_{n,m} \left(\frac{\min(|\mathbf{r}_{nm}|, \Delta x)}{|\mathbf{g}_{\mathrm{sinks},\, n}|} \right)^{1/2}$$

$\Rightarrow$ sub-cycle on particle-particle interaction till:

$$N_{\mathrm{cycles}}\, \Delta t_{\mathrm{gs}} = \Delta t_{\mathrm{hydro}}$$

Sink Particles

- Sub-Cycling

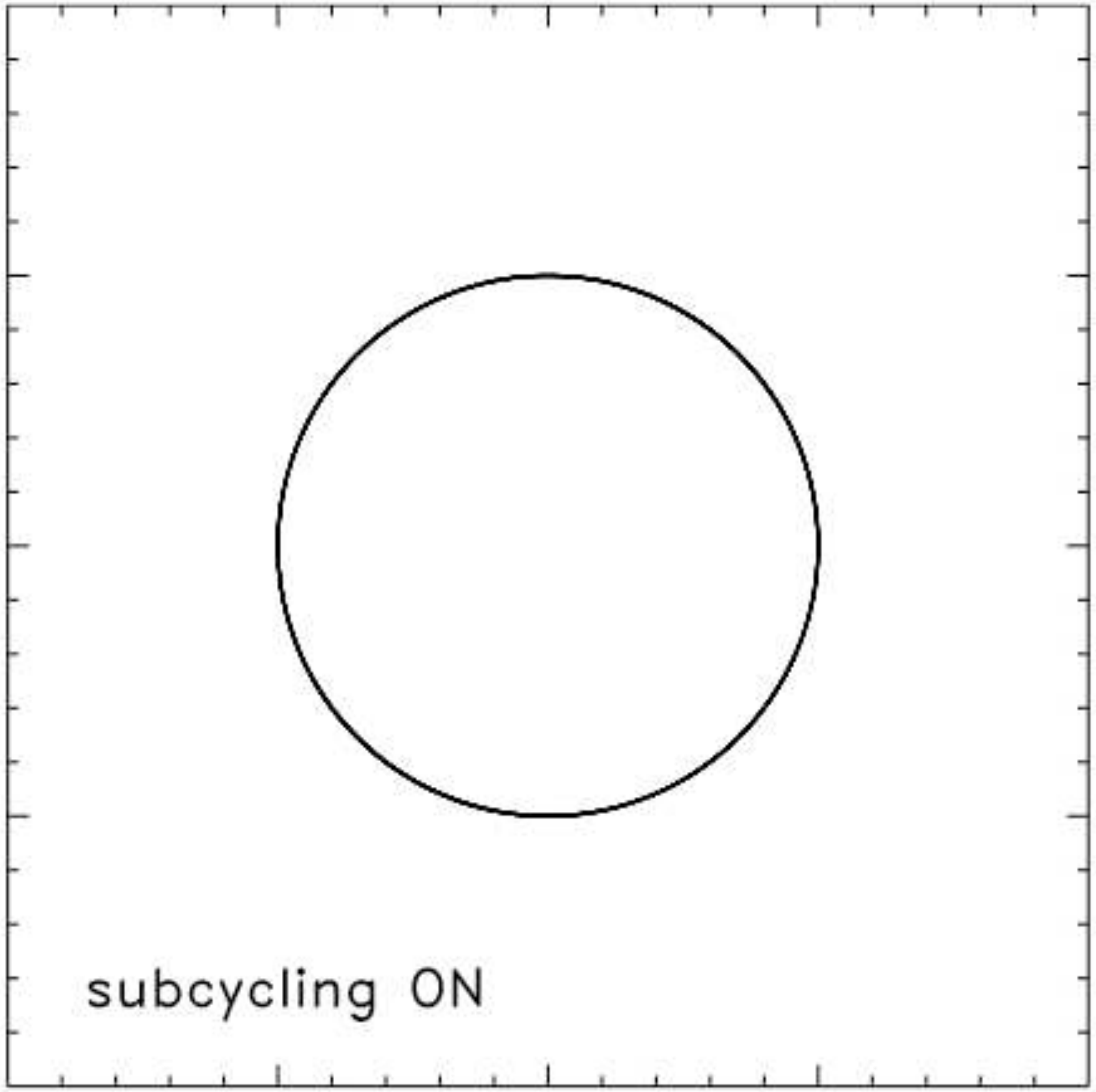


Federrath et al. 2010

⇒ after 10 orbits

Sub-Cycling

- Sub-Cycling



⇒ after 1000 orbits:

two particles around the common center

Sink Particles

Particle creation

Conditions by gravitational **collapse**:

0. Density criterion (within accretion radius r_{accr}):

$$\rho_{\mathrm{gas}} > \rho_{\mathrm{crit}} \quad (\rho_{\mathrm{crit}} \text{ parameter})$$

⇒ choose ρ_{crit} so that Truelove criterion is not violated:

$$\lambda_J > N_J \, \Delta x_{\min}$$

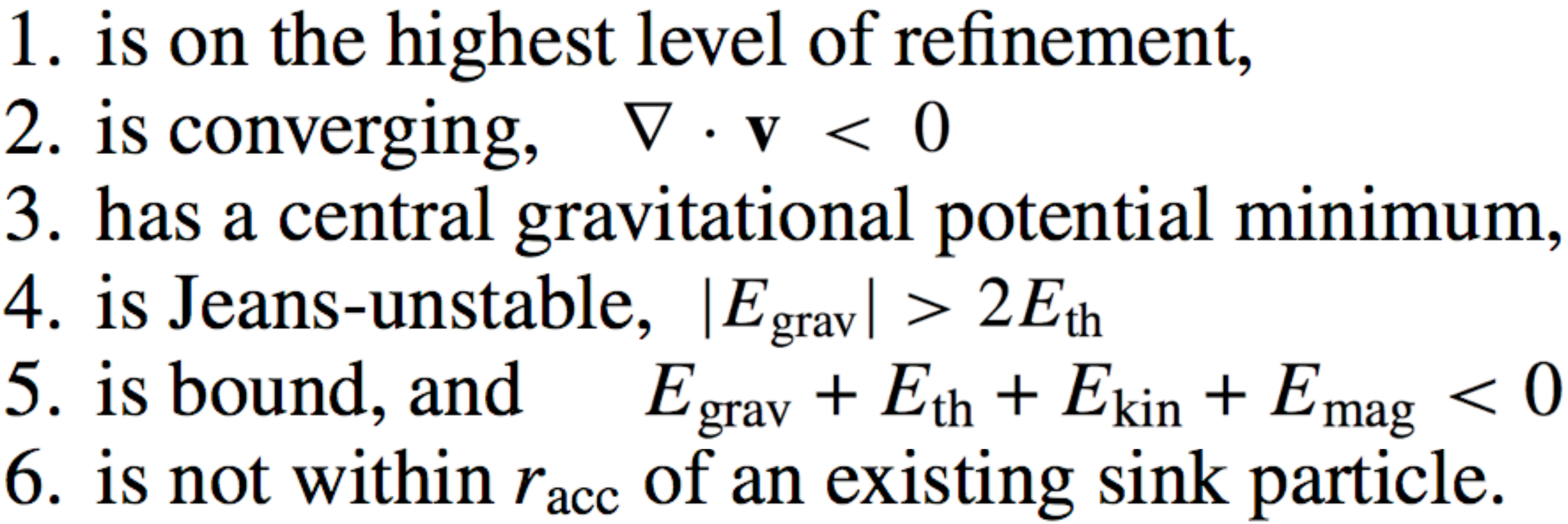
+ Jeans refinement condition ($\lambda J = (\pi c2/G\rho)^{1/2}$)

Sink Particles in FLASH

Particle creation

Conditions by gravitational collapse:

0. Density criterion: $\rho_{\mathrm{gas}} > \rho_{\mathrm{crit}}$ (ρ_{crit} parameter)

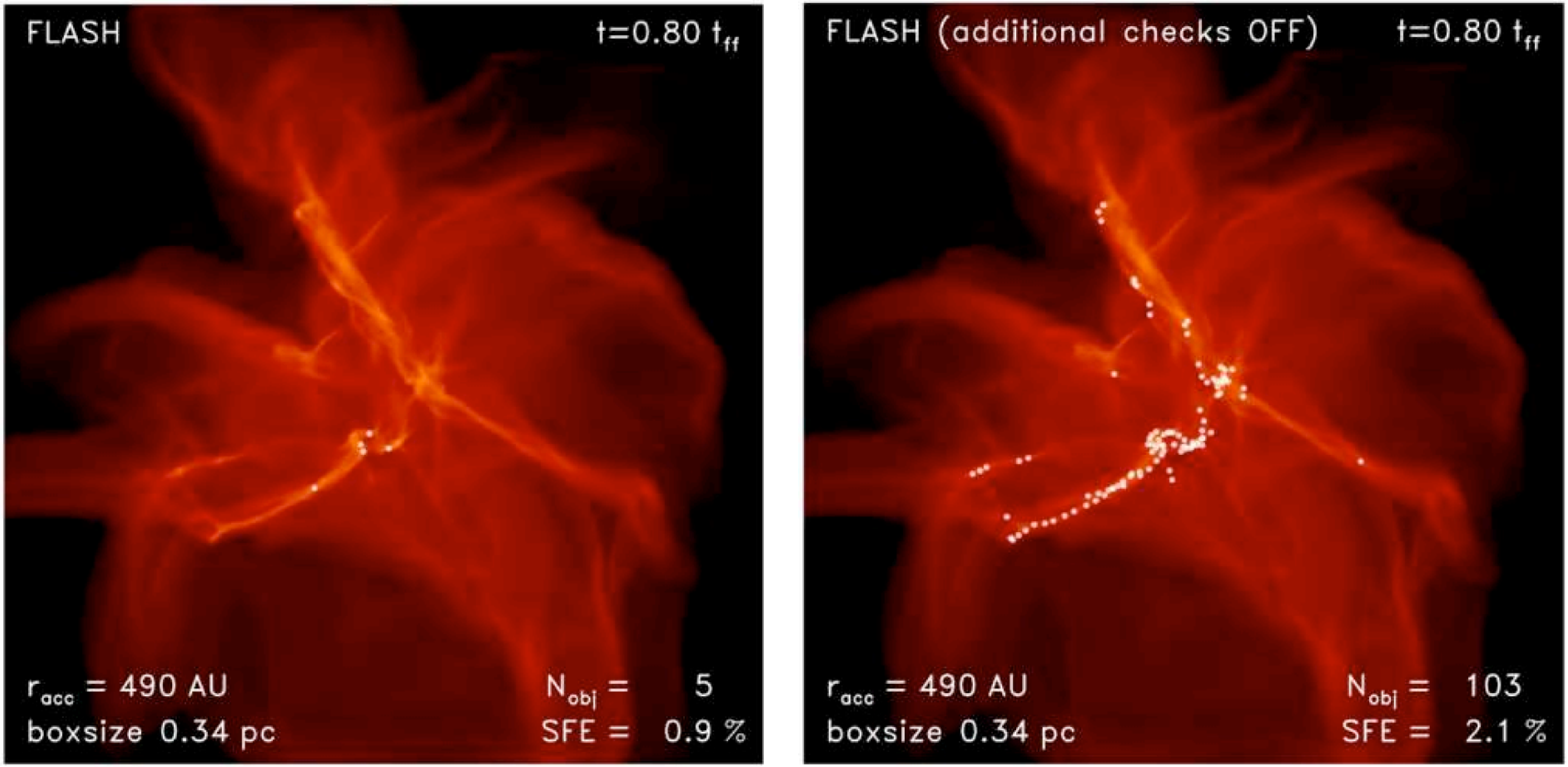


1. is on the highest level of refinement,
2. is converging, $\nabla \cdot \mathbf{v} < 0$
3. has a central gravitational potential minimum,
4. is Jeans-unstable, $|E_{\mathrm{grav}}| > 2E_{\mathrm{th}}$
5. is bound, and $E_{\mathrm{grav}} + E_{\mathrm{th}} + E_{\mathrm{kin}} + E_{\mathrm{mag}} < 0$
6. is not within r_{acc} of an existing sink particle.

Federrath, RB, Clark & Klessen et al. 2010

Sink Particles in FLASH

Particle creation



Sink Particles in FLASH

Mass accretion & linear momentum

Mass accretion from excess gas density within $r_i < r_{\mathrm{accr}}$:

$$\mathrm{M}_i = \mathrm{M}_i + \Sigma_j \, \Delta\mathrm{Vol}_j \, (\rho_j - \rho_{\mathrm{crit}})$$

additional check for convergent flow, i.e. $\mathrm{v}_{\mathrm{rad}} < 0$

Mass conservation ensured

+ linear momentum conservation:

$$\mathrm{P}_i = \mathrm{P}_i + \Sigma_j \, \Delta\mathrm{m}_j \, \mathrm{v}_j$$

Sink Particles in FLASH

angular momentum

no unique solution for angular momentum conservation:

$$\mathbf{R} \times \mathbf{v}_{\rm cm} = \frac{1}{M}\,\mathbf{L}$$

⇒ internal spin:

$$\mathbf{L}_{\rm spin} = \mathbf{L}'_{\rm gas} - \mathbf{L}_{\rm gas}$$

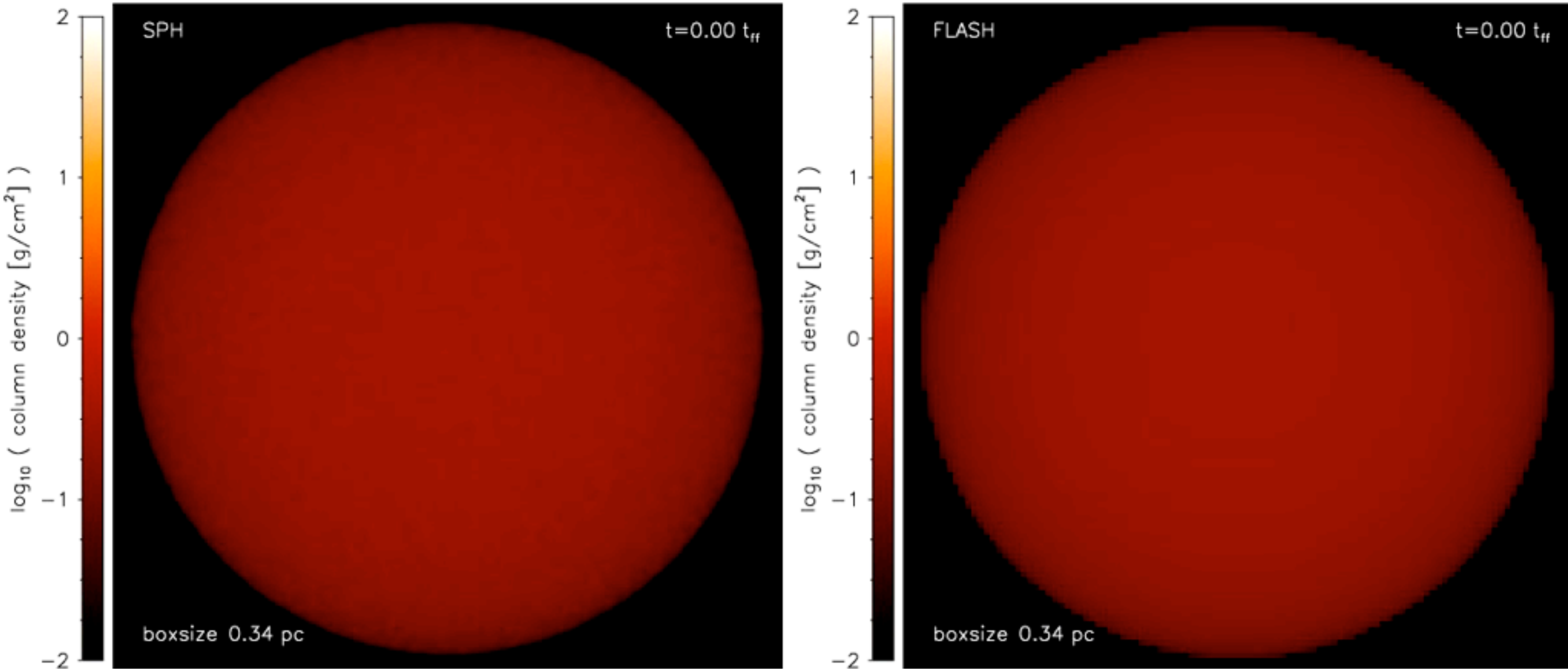
use for sub-grid-scale modelling, e.g. outflows & jets

Comparison to SPH Simulations

Federrath et al. 2010

- collapse of **turbulent** cloud cores

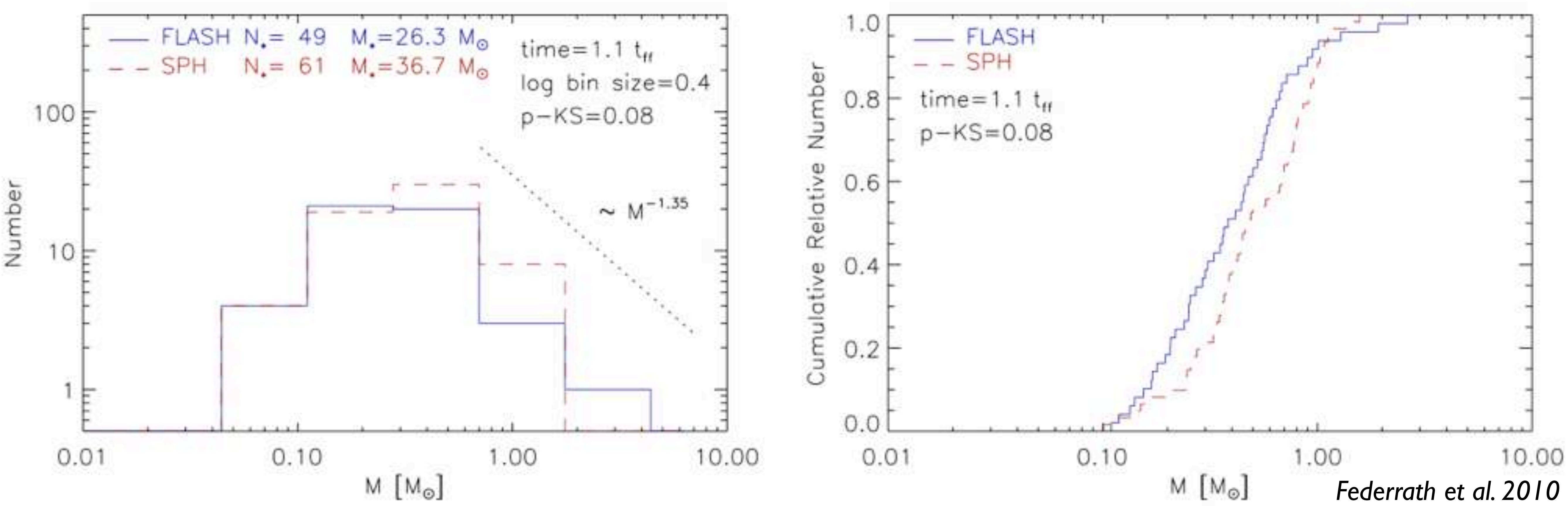
Comparison to SPH Simulations



Federrath et al. 2010

- collapse of **turbulent** cloud cores

Comparison to SPH Simulations

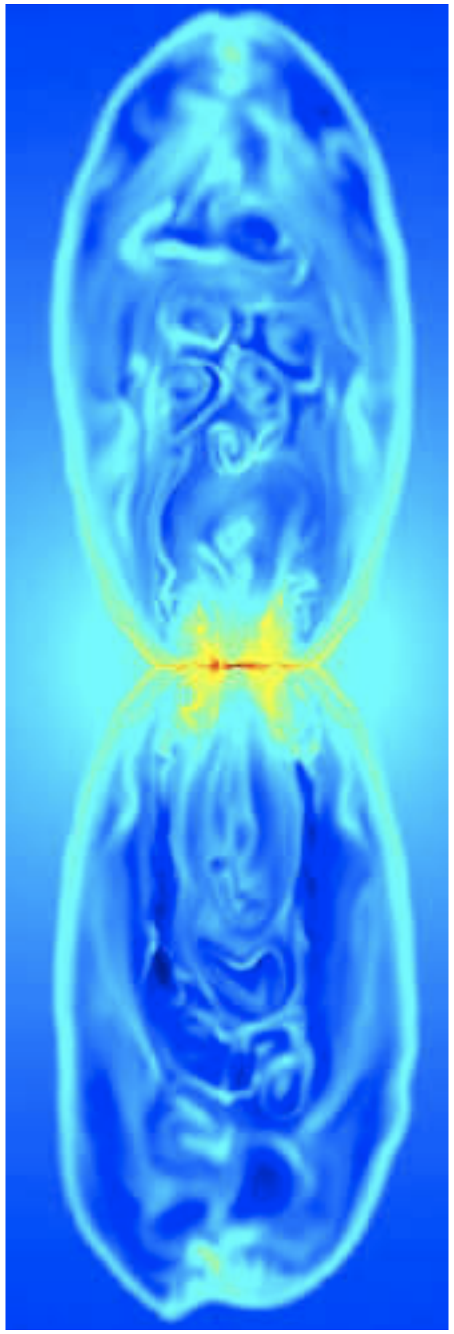


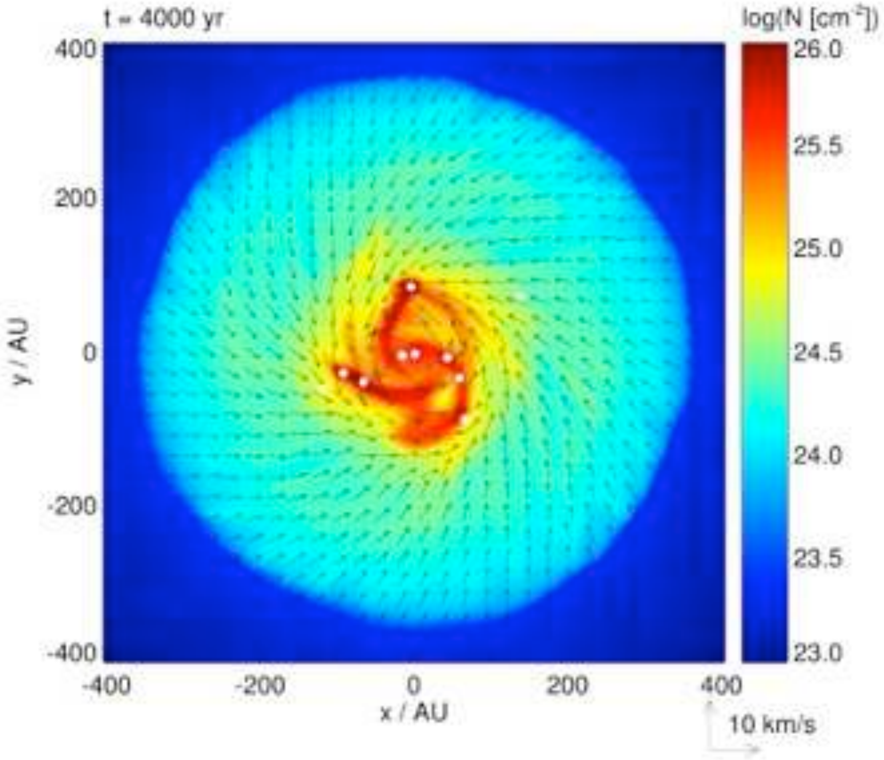
Federrath et al. 2010

- good agreement
- differences due to hydro
  ⇒ SPH slightly more dissipative

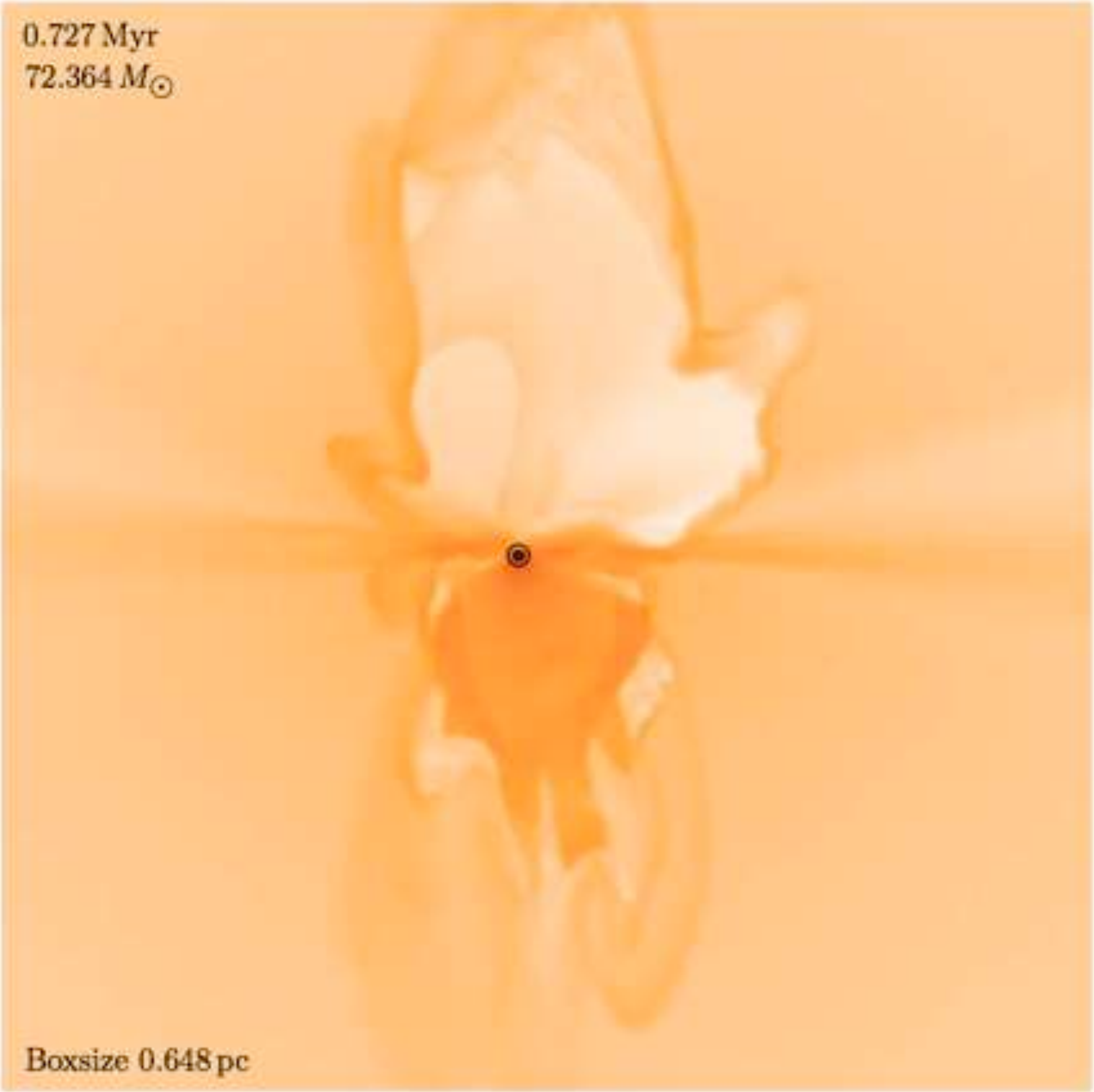
  ⇒ cluster more centrally condensed

Applications





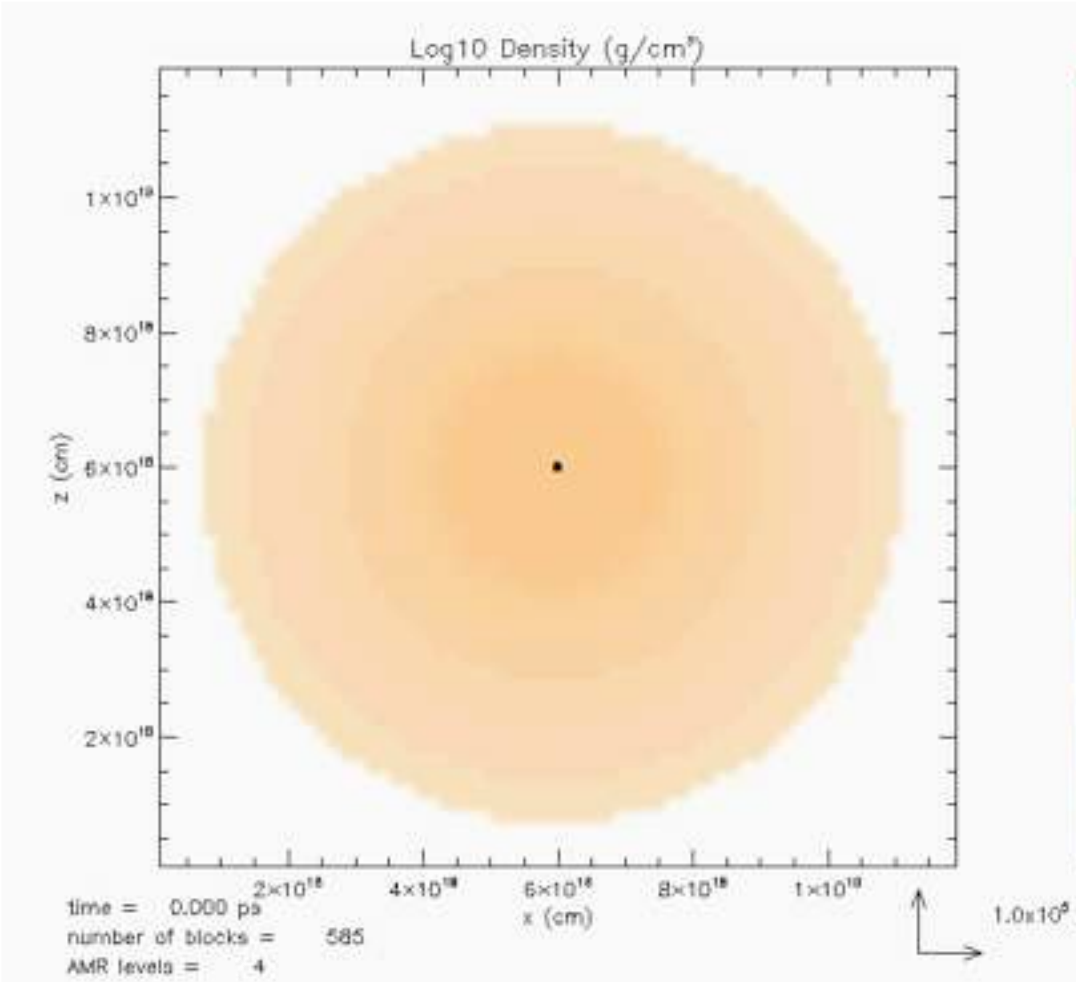
disc formation and jet launching by *Daniel Seifried*



feedback from ionizing radiation by *Thomas Peters*

Outflows from Massive Stars: Young HII Regions

3D Simulations of collapsing cloud cores with ionization feedback from young massive stars (*Thomas Peters*, ITA)

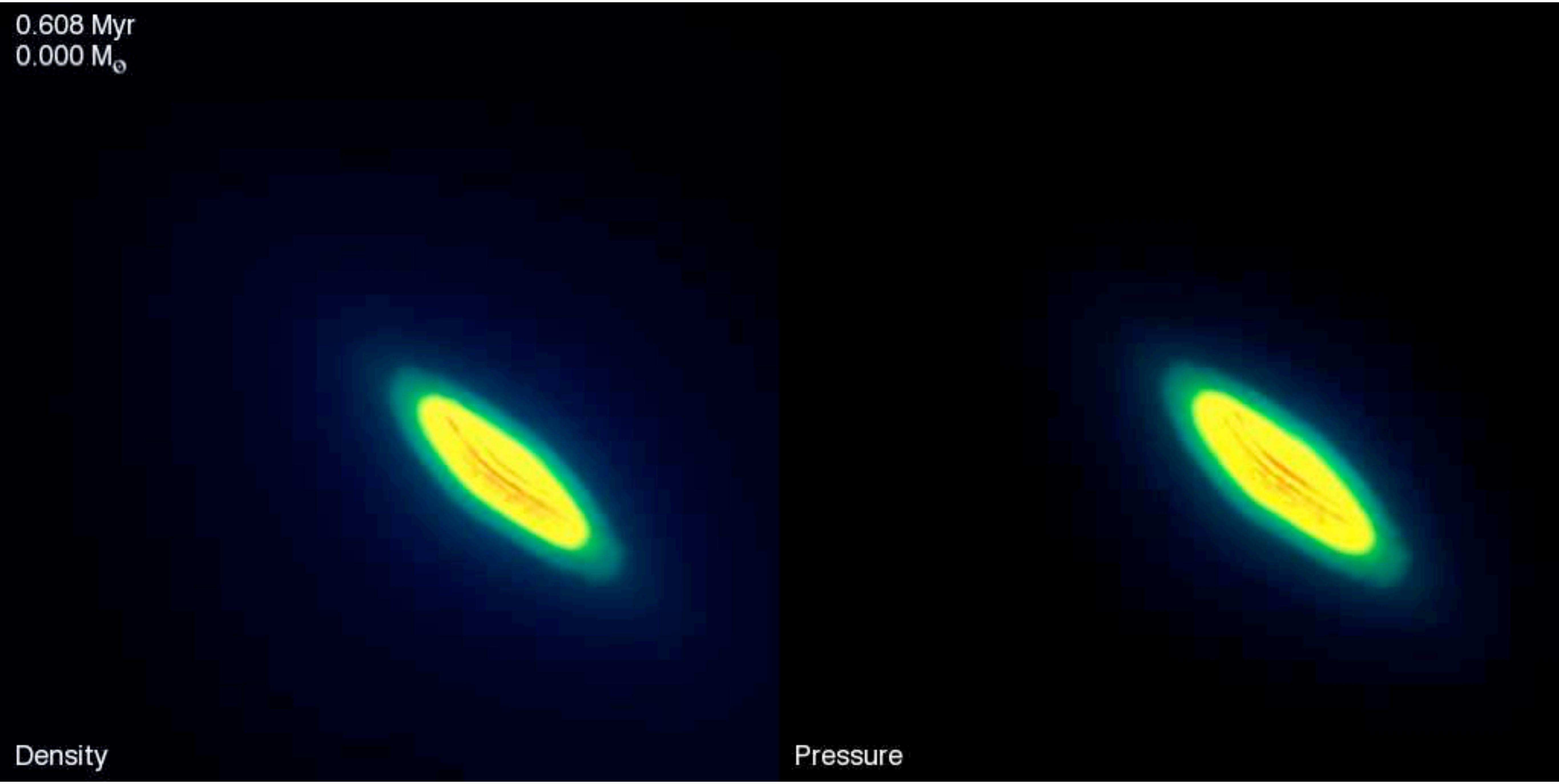


- **massive core with $M_{\mathrm{core}} = 1000\ M_\odot$**
- $R_{\mathrm{core}} = 1.6$ pc
- $\rho_{\mathrm{core}} = 1.27\mathrm{x}10^{-20}$ g cm^{-3}; $\rho \sim r^{-1.5}$
- initial core rotation with $\beta = 0.05$
- magnetized case: $\mu = 14\ \mu_{\mathrm{crit}}$ ($B = 10\ \mu$G)

- accreting sink particles ⇒ luminosity and temperature using ZAMS (*Paxton* 2004) + protostellar accretion luminosity (*Hosokawa & Omukai* 2009)
- highest grid resolution ~ 100 AU
- ray-tracing based on *Rijkhorst et al.* 2006

Massive Star Formation: Dynamics of HII Regions

Run B: formation of multiple stars

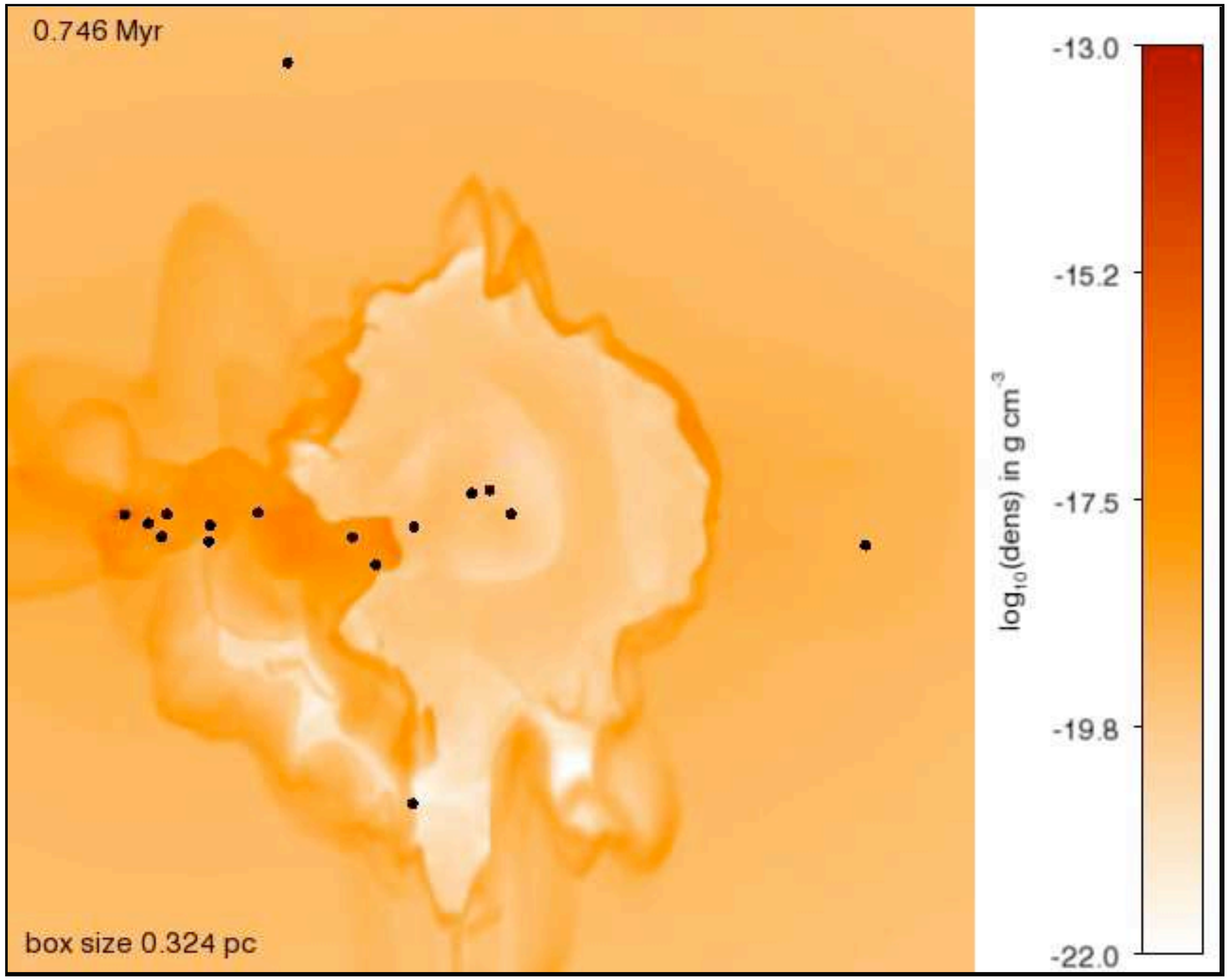


courtesy: Zilken, NIC, Jülich

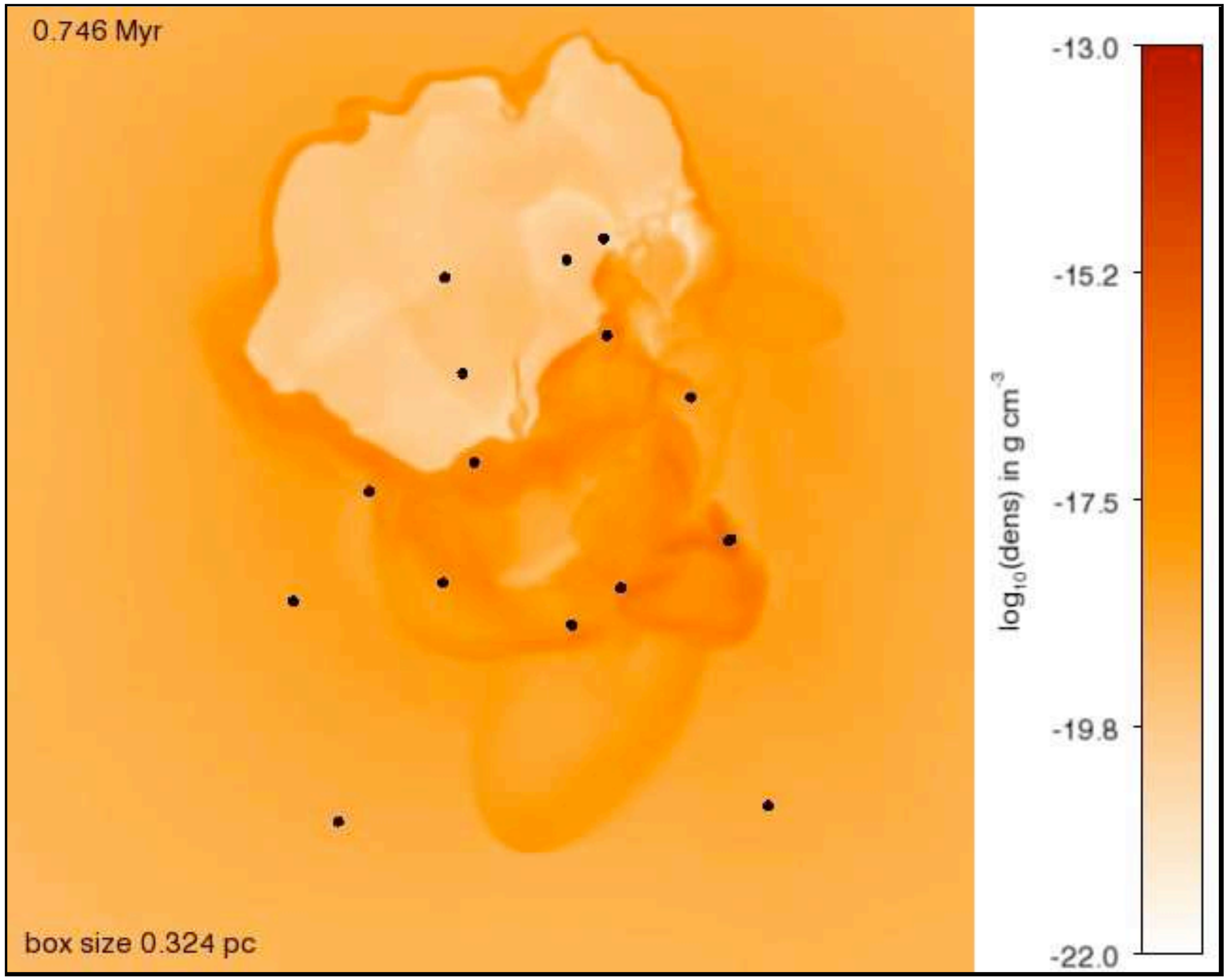
Massive Star Formation: Dynamics of HII Regions

Collapse of a massive, rotating cloud core
(M_{core} = 1000 M_{sol}) + ionization feedback

Simulations by Thomas Peters

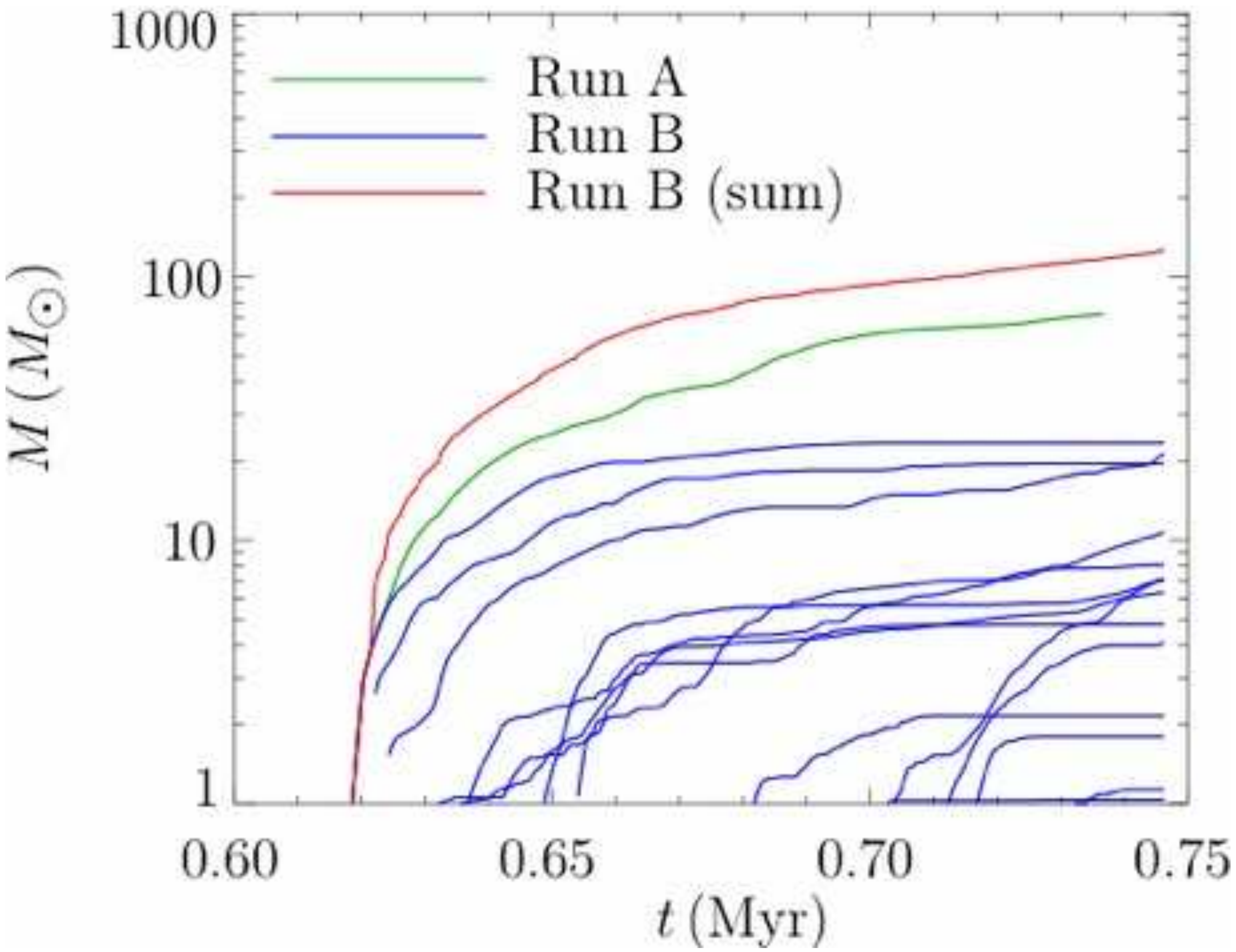


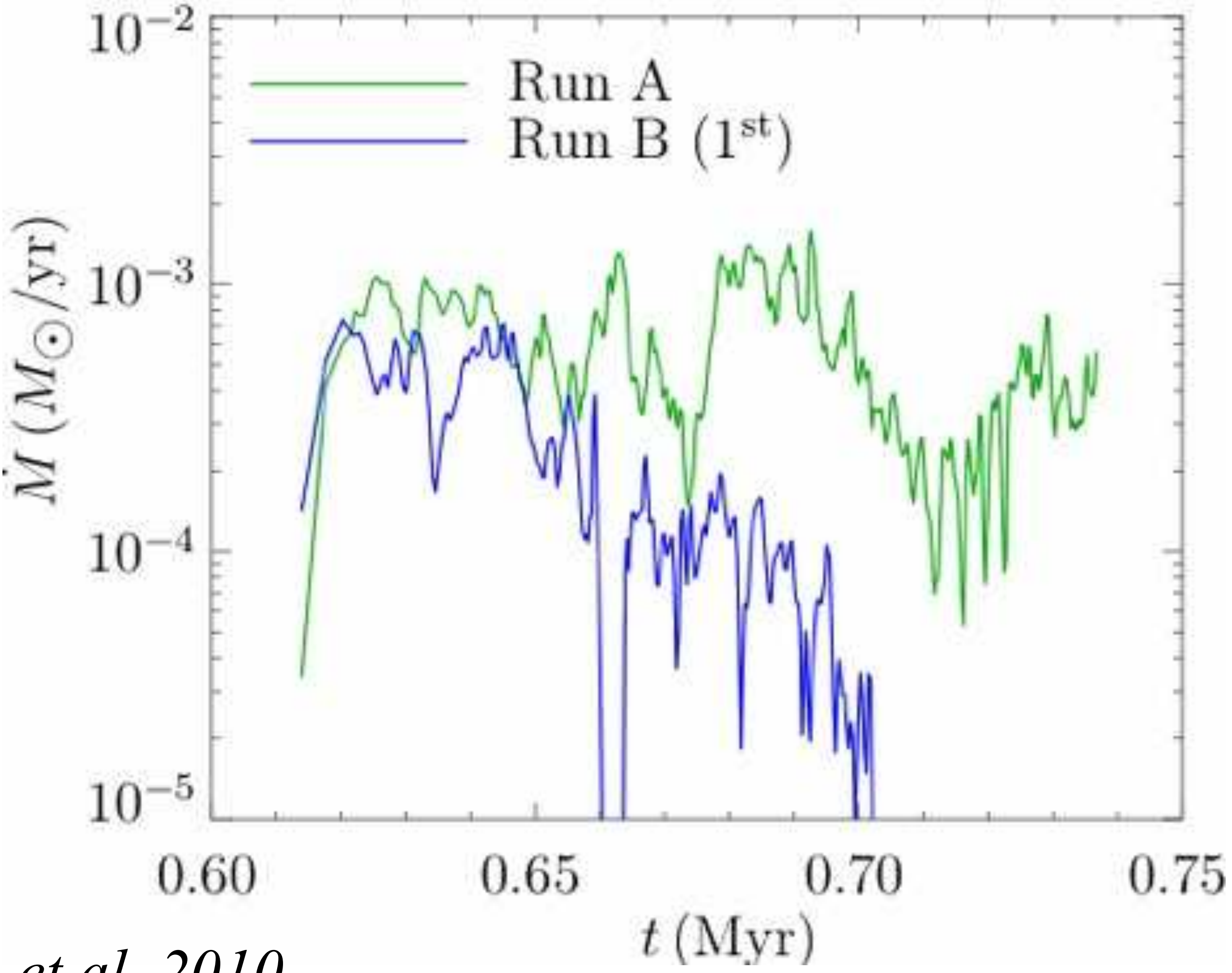
Disk edge on



Disk plane

Massive Star Formation: Dynamics of HII Regions

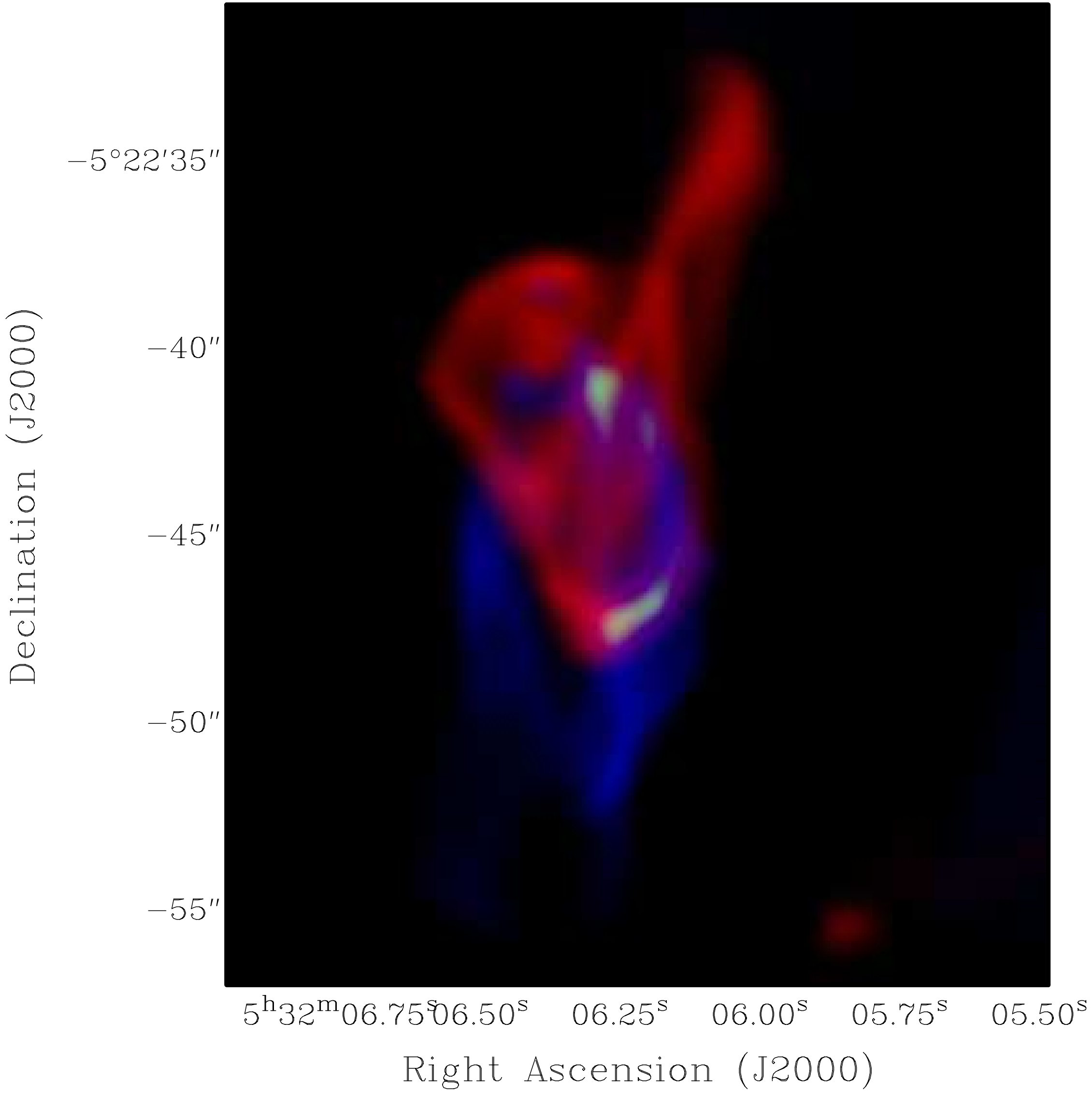


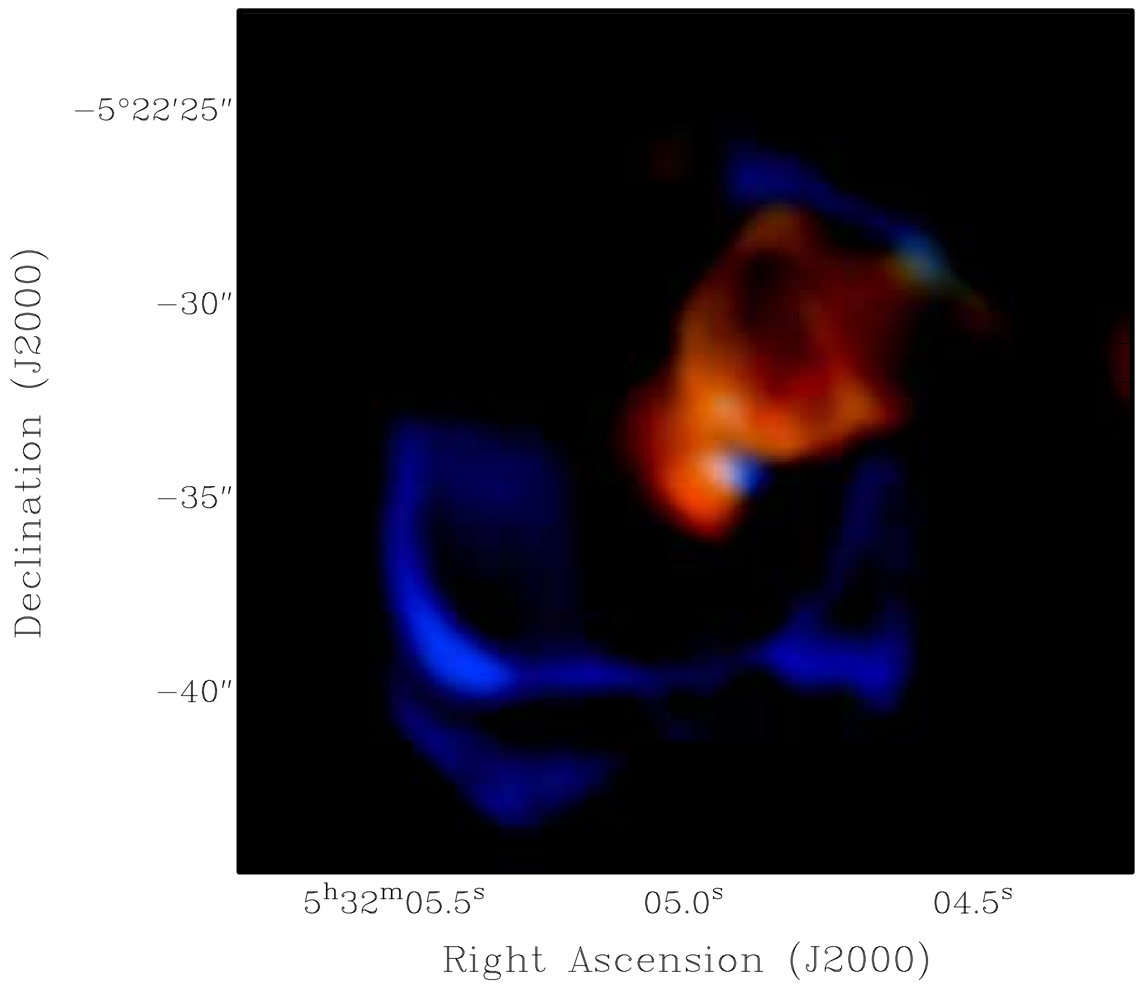


Peters et al. 2010

- Ionization feedback does not shut off star formation
- accretion onto the most massive star is cut off by ***fragmentation induced starvation*** *(Peters et al.* 2010)

Comparison with Observations: Outflows


Run B (left)


Run A

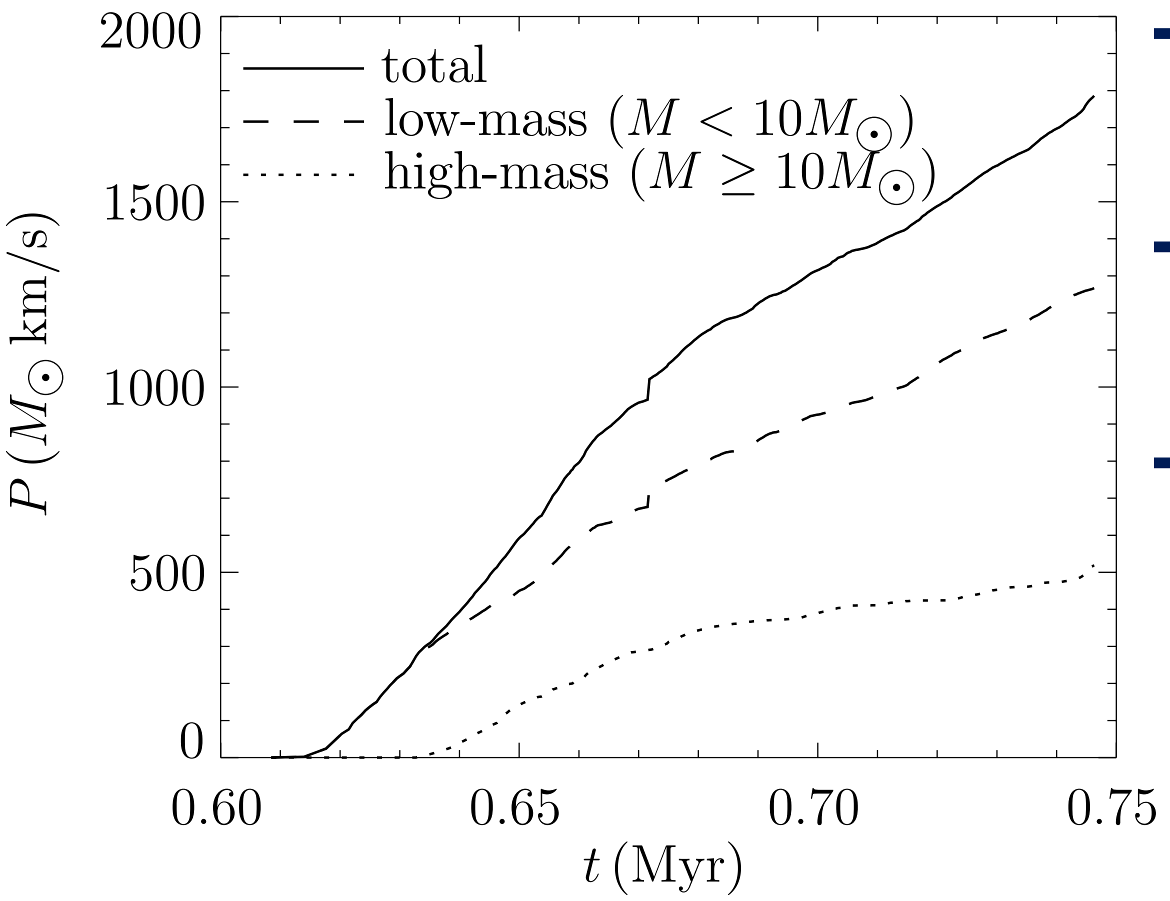
- Synthetic CO maps with the ALMA simulator CASA @ Orion distance: 414 pc

Comparison with Observations: Outflows

TABLE 1
OUTFLOW PARAMETERS DERIVED FROM ALMA SIMULATIONS

		M ($M_\odot$)	V (km s^{-1})	P ($M_\odot$ km s^{-1})	E (10^{44} erg)	L ($L_\odot$)	$\dot{M}$ (10^{-3} $M_\odot$ yr^{-1})	T (yr)	R (AU)
Run A	blue	2.50±0.26	3.9±0.9	9.93±3.32	3.94±2.22	8.15±6.23	6.26±1.91	400	4100
	red	1.80±0.18	3.8±0.9	6.82±2.30	2.58±1.48	5.33±4.12	4.51±1.37	400	4100
Run B (left)	blue	1.12±0.13	3.3±0.4	3.68±0.87	1.21±0.43	2.51±1.39	2.80±0.89	400	3300
	red	2.08±0.12	3.5±0.5	7.26±1.55	2.53±0.93	5.24±2.98	5.21±1.35	400	2100
Run B (right)	blue	1.31±0.12	3.3±0.4	4.29±0.91	1.41±0.47	2.92±1.55	3.26±0.95	400	5000
	red	0.75±0.08	3.5±0.5	2.62±0.69	0.91±0.38	1.89±1.17	1.88±0.58	400	4100

Peters, Klaassen et al. 2012



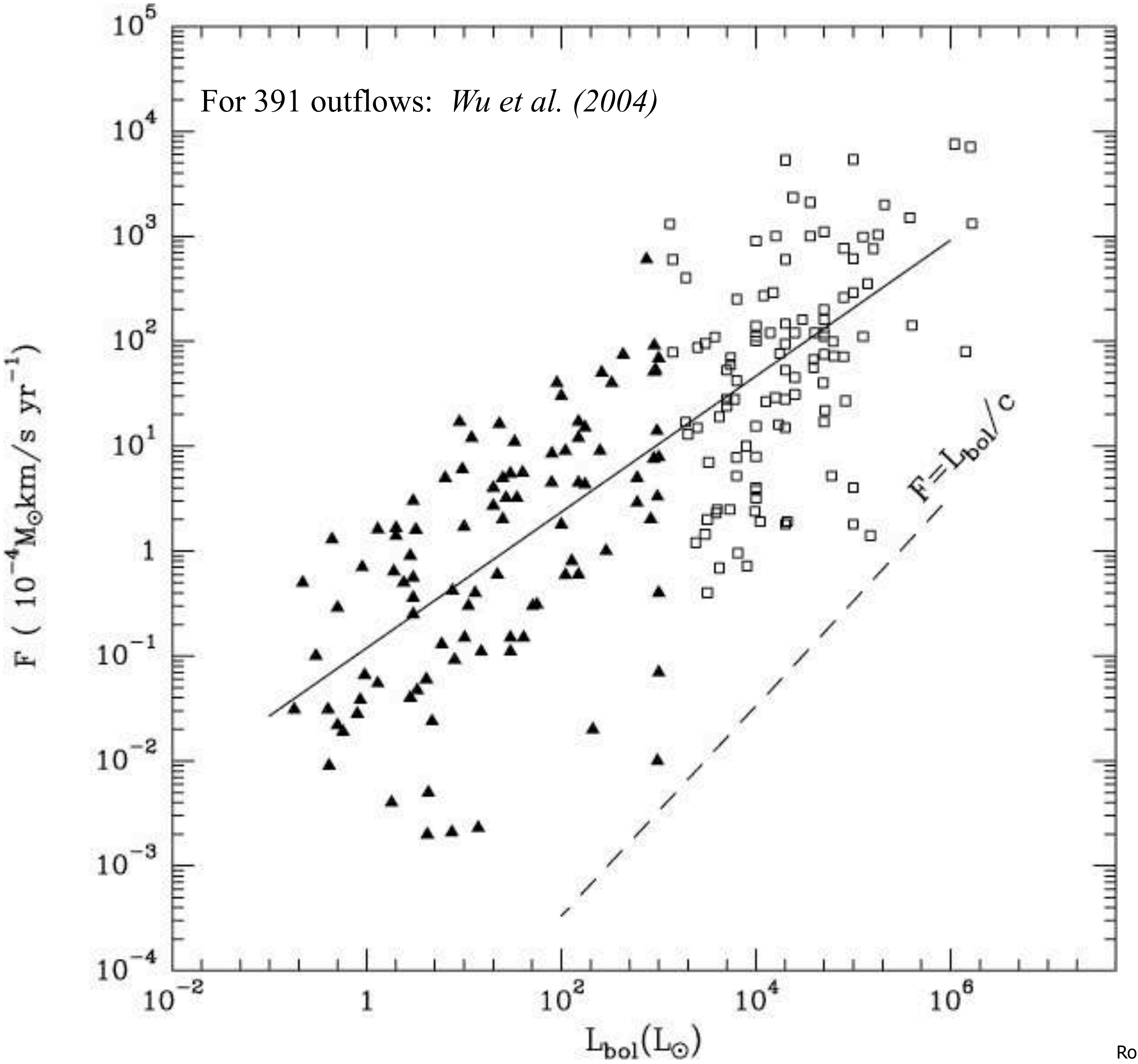
→ derived outflow parameters are on the **low** end of observations

→ Ionisation feedback is **not** the main driver of molecular outflows

→ common **low** mass companions drive large scale molecular outflows?

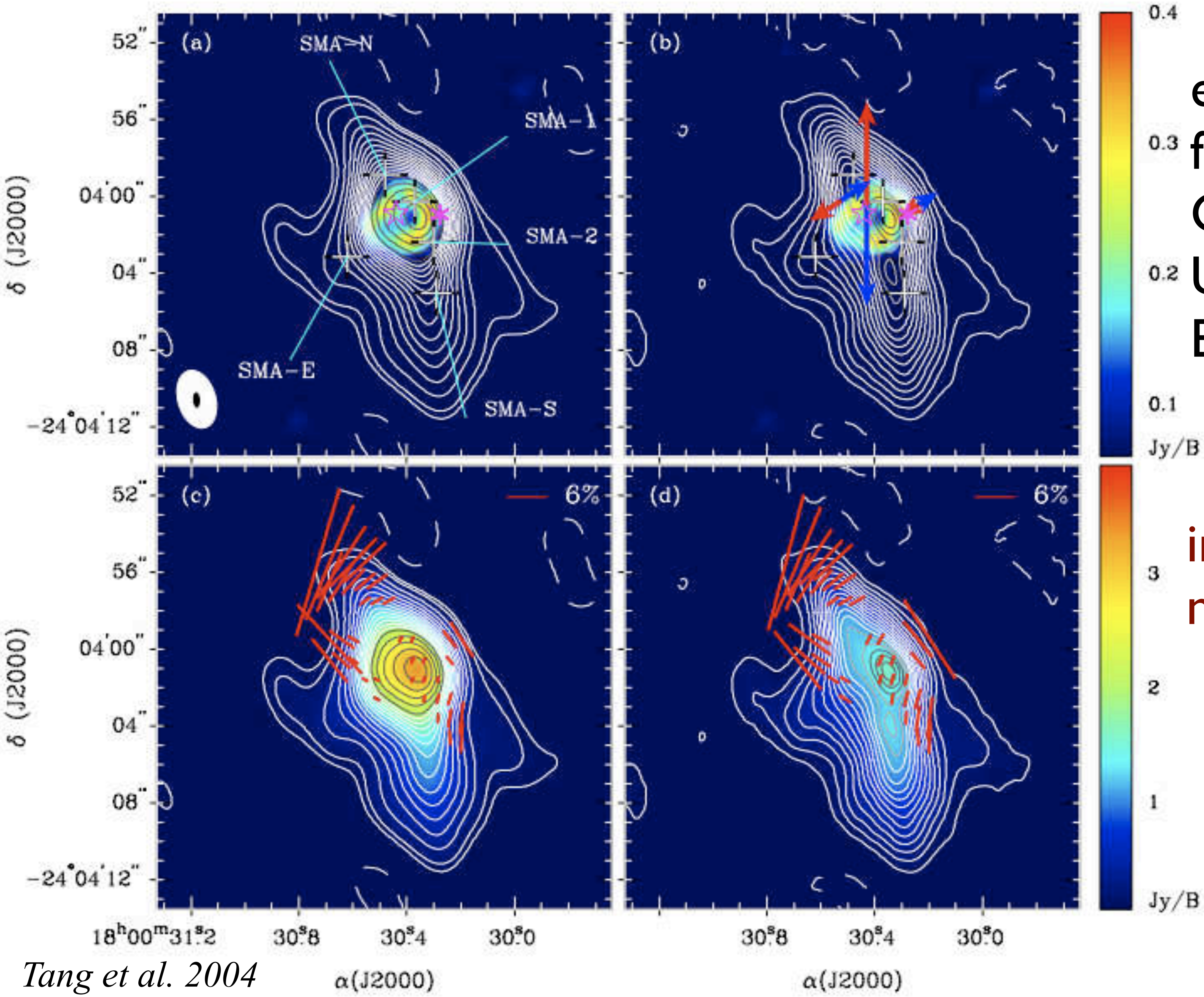
(see also *Peters et al.* 2014, *Collective Outflows* ...)

Magnetic fields during Massive Star Formation?



outflows
launched by
magnetic fields?

Magnetic fields during Massive Star Formation?



e.g. Massive star forming region G5.89-0.39 UHII

B ~ 2-3 mG

influence of magnetic fields?

Tang et al. 2004

Jet Launching

Ideal MHD equations + (self-)gravity

references: eg. *Chandrasekhar 1956; Mestel 1969; Blandford&Payne 1982; Pudritz&Norman 1983*
reviews: eg. Königl&Pudritz 1999 (PPIV); Heyvaerts 2000; Pudritz et al. 2007 (PPV)

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\mathbf{v} \rho) &= 0 \\
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} &= -\frac{1}{\rho} \nabla p - \nabla \Phi + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi\rho} \\
\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v} \times \mathbf{B}) \\
\nabla \cdot \mathbf{B} &= 0
\end{aligned}
$$

$$\Delta \Phi = 4\pi G \rho$$

Jet Launching

Lorentz force:

(assume axi-symmetry, i.e. $\partial_\Phi \mathbf{B} = 0$)

$$\mathbf{j} \times \mathbf{B} \quad = \quad -\frac{1}{2}\nabla\mathbf{B}^2 + \left(\mathbf{B}_\mathrm{p} \cdot \nabla\right)\left(\mathbf{B}_\mathrm{p} + B_\phi \mathbf{e}_\phi\right) \underbrace{-\frac{B_\phi^2}{R}\mathbf{e}_R}_{}$$

hoop stress
(jet collimation)

Jet Launching

Lorentz force:

(assume axi-symmetry, i.e. $\partial_\Phi \mathbf{B} = 0$)

$$\mathbf{j} \times \mathbf{B} = -\frac{1}{2}\nabla \mathbf{B}^2 + (\mathbf{B}_\mathrm{p} \cdot \nabla)\left(\mathbf{B}_\mathrm{p} + B_\phi \mathbf{e}_\phi\right) \underbrace{-\frac{B_\phi^2}{R}\mathbf{e}_R}_{\substack{\text{hoop stress} \\ \text{(jet collimation)}}}$$

different force types:

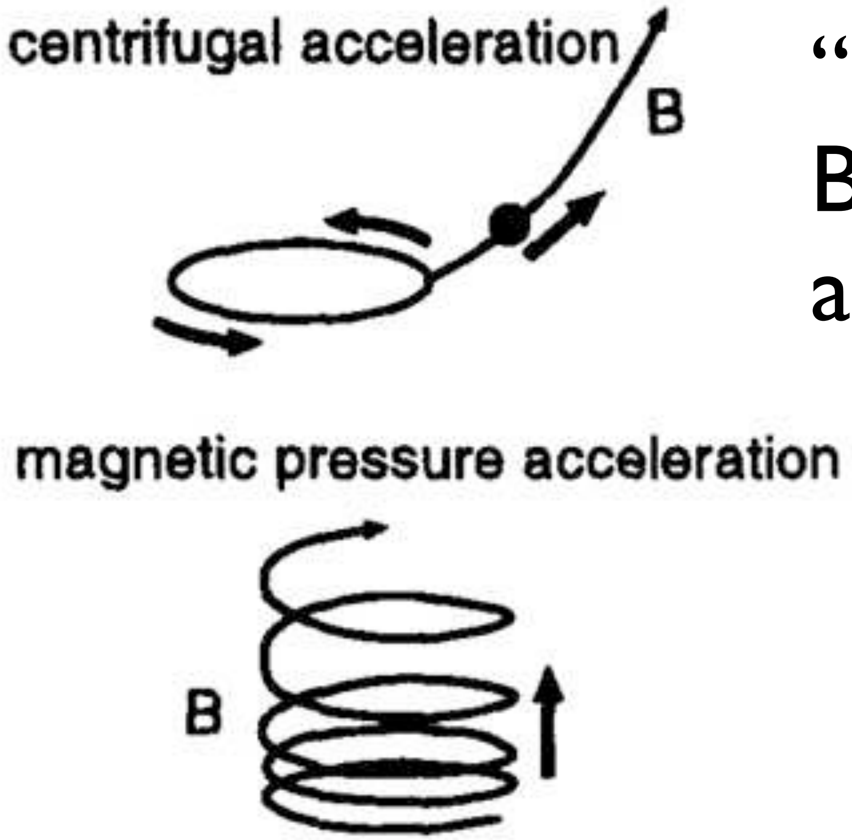
- **magnetic pressure**: force along gradient
- **tension**: force along magnetic field lines
- **hoop stress**: force towards axis

Jet Launching

Lorentz force:

(assume axi-symmetry, i.e. $\partial_\Phi \mathbf{B} = 0$)

$$\mathbf{j} \times \mathbf{B} \quad = \quad -\frac{1}{2}\nabla \mathbf{B}^2 + (\mathbf{B}_\mathrm{p} \cdot \nabla)\left(\mathbf{B}_\mathrm{p} + B_\phi \mathbf{e}_\phi\right) \underbrace{-\frac{B_\phi^2}{R}\mathbf{e}_R}_{\text{hoop stress (jet collimation)}}$$



"beads on a wire"
Blandford-Payne type
acceleration

courtesy *Matsumoto & Shibata, 1999*

Jet & Outflow Launching

Specific energy conserved along field lines

with separation of poloidal and toroidal velocity and field components:

$$
\begin{aligned}
\epsilon &= \frac{1}{2}v^2 + \Phi + h - \frac{r\omega B_\phi}{4\pi k} \\
&= \frac{1}{2}v_{\mathrm{pol}}^2 + \frac{1}{2}v_\phi^2 + \Phi + h - \frac{v_\phi}{v_{\mathrm{pol}}}\frac{1}{4\pi}\frac{B_\phi B_{\mathrm{pol}}}{\rho} + \frac{1}{4\pi}\frac{B_\phi^2}{\rho}
\end{aligned}
$$

$\Longrightarrow$ new, generalised outflow criterion

to distinguish between tower and centrifugal launching

Jet & Outflow Launching

$\Longrightarrow$ new, generalised outflow criterion

to distinguish between tower and centrifugal launching

$\Longrightarrow$ magneto-centrifugal launching (a-la Blanford & Payne):

$$\frac{r}{z}\frac{1}{GM}\left(\frac{v_\phi^2}{r^2}(r^2+z^2)^{3/2}-GM\right)\Big/\left(\frac{B_\mathrm{z}}{B_\mathrm{r}}\right) > 1$$

$\Longrightarrow$ any outward acceleration:

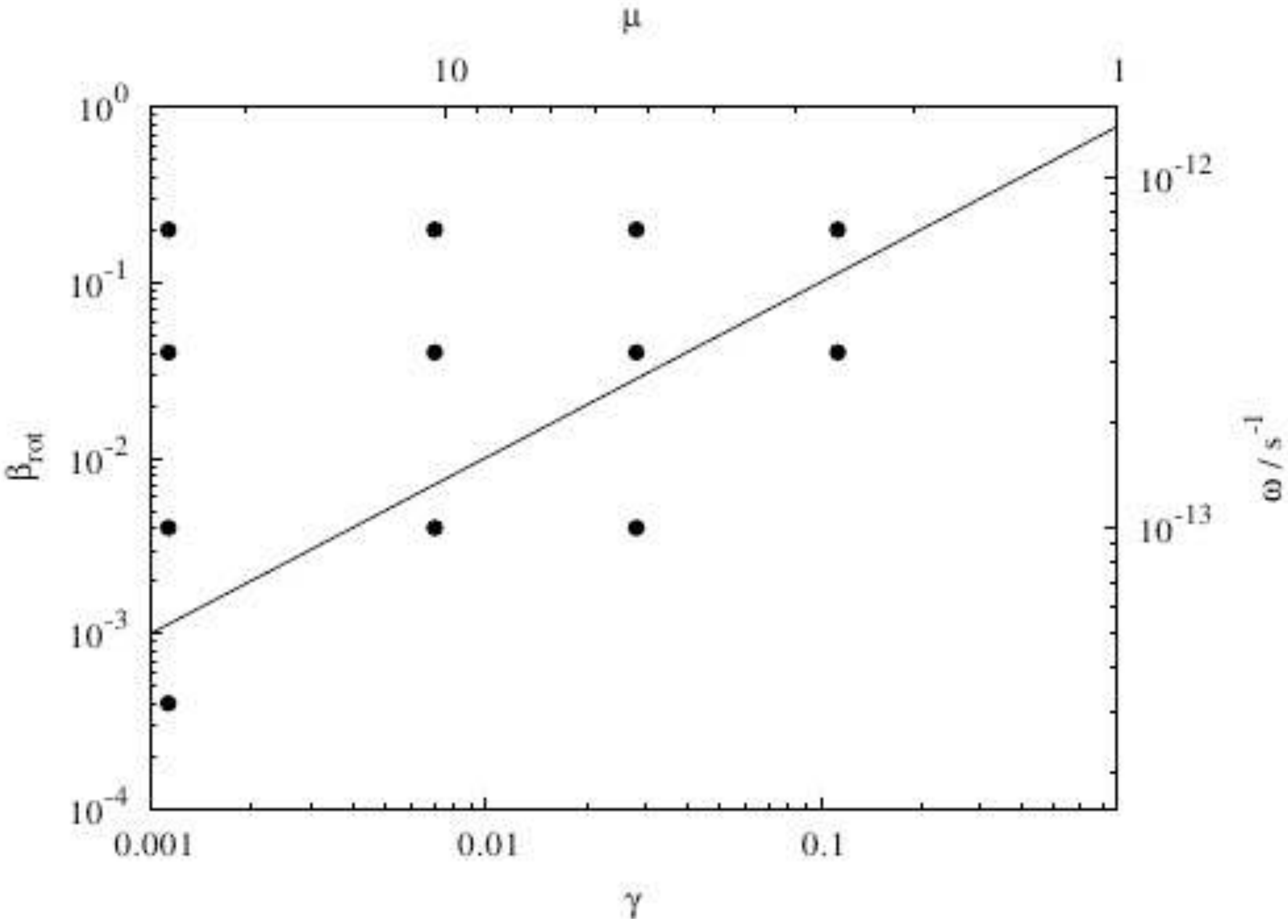
$$\partial_\mathrm{pol}\left(\frac{1}{2}v_\phi^2+\Phi-\frac{v_\phi}{v_\mathrm{pol}}\frac{1}{4\pi}\frac{B_\phi B_\mathrm{pol}}{\rho}+\frac{1}{4\pi}\frac{B_\phi^2}{\rho}\right) < 0$$

Seifried et al. 2012

Collapse of Massive Cloud Cores

Parameter study with 3D Simulations of massive collapsing cloud cores with Sink Particles

- $M_{core} = 100\ M_\odot$
- $R_{core} = 0.125$ pc
- density profile: $\rho \sim r^{-1.5}$
- $\rho_{core} = 2.3 \mathrm{x} 10^{-17}$ g cm^{-3}
- rotation with $\beta = 0.0004 - 0.2$
- mass-to-flux: $\mu = 2.6 \ldots 26\ \mu_{crit}$
- $B_z = 1.3 - 0.13$ mG aligned with rotation axis
- resolution: 4.7 AU

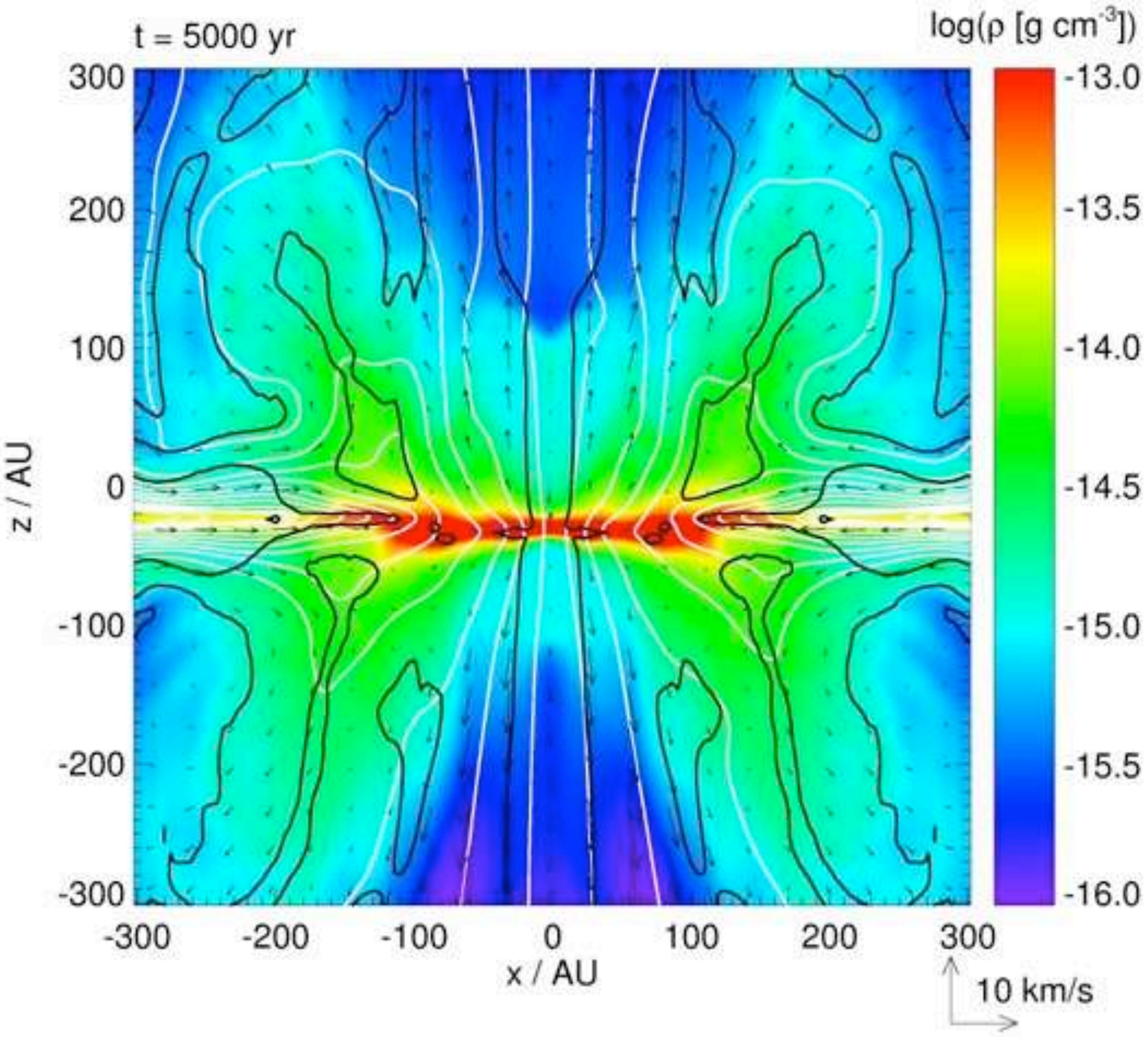


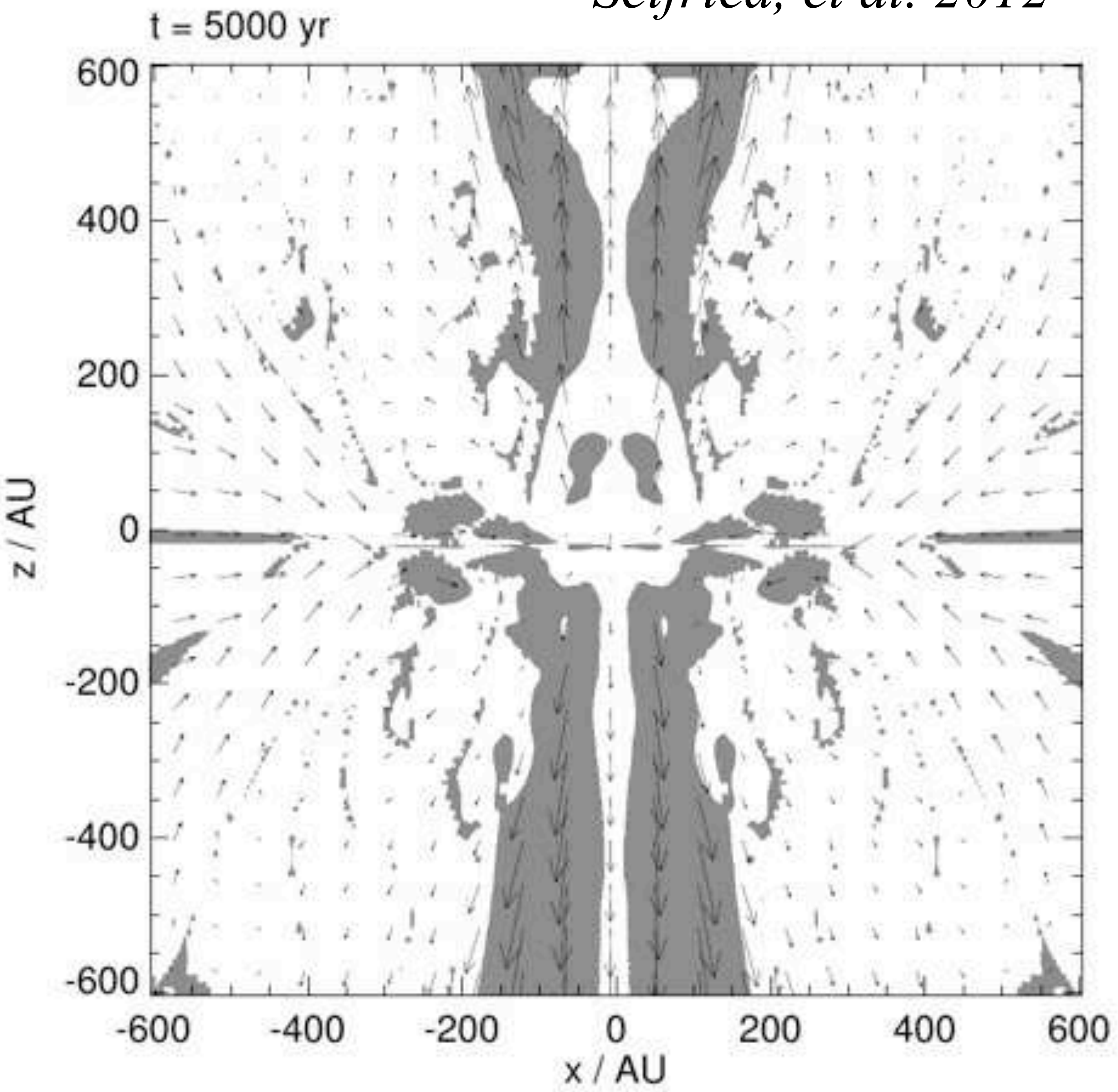
Seifried, RB, Klessen, Duffin, Pudritz 2011

A Generalised Outflow Criterion

Outflow / Lauchning mechanism

Seifried, et al. 2012





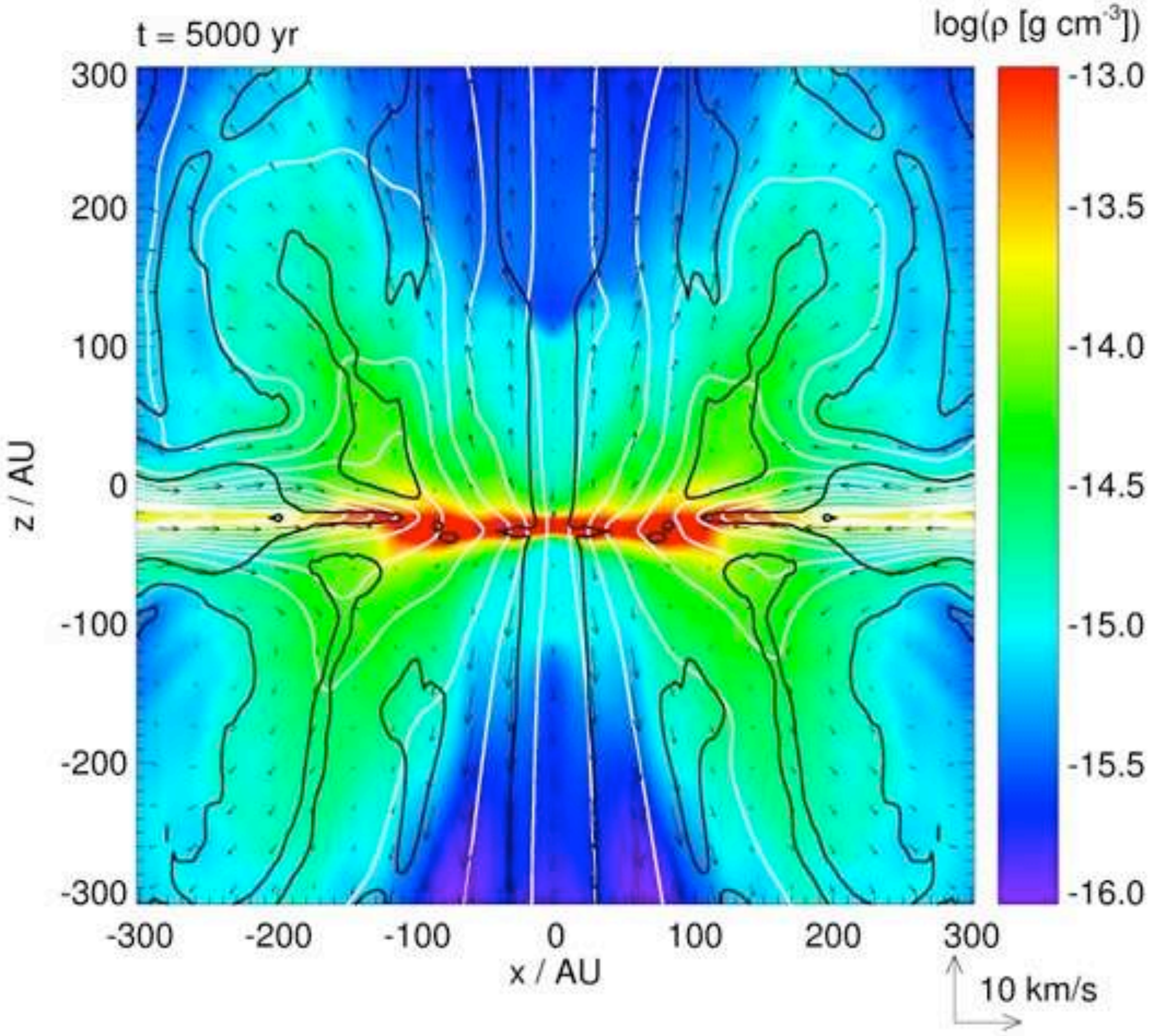
$\mu = 26\ \mu_{\mathrm{crit}}$

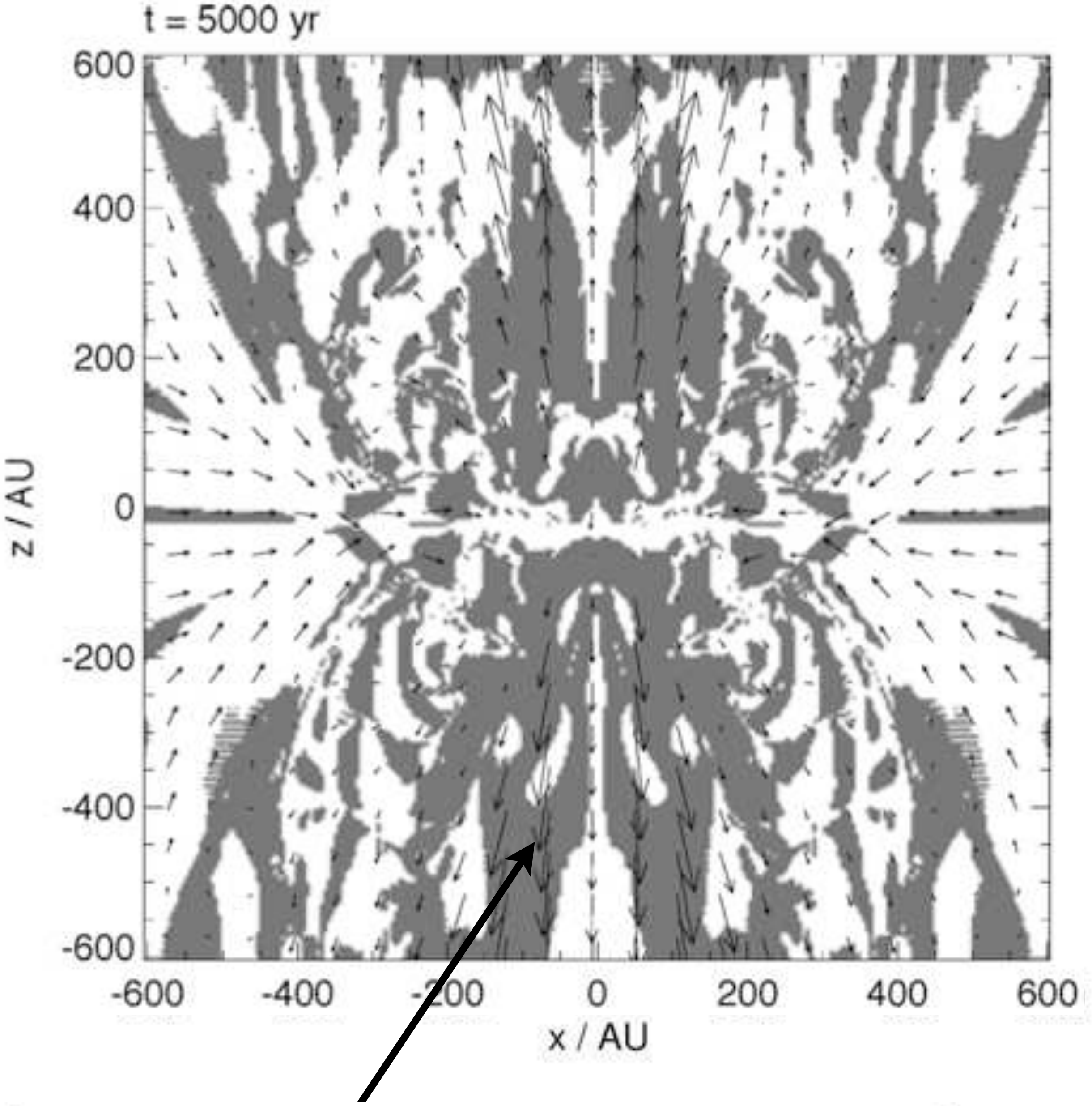
gray: magnetocentrifugal launching (*Blandford & Payne* 1982)

A Generalised Outflow Criterion

Outflow / Lauchning mechanism

Seifried, et al. 2012





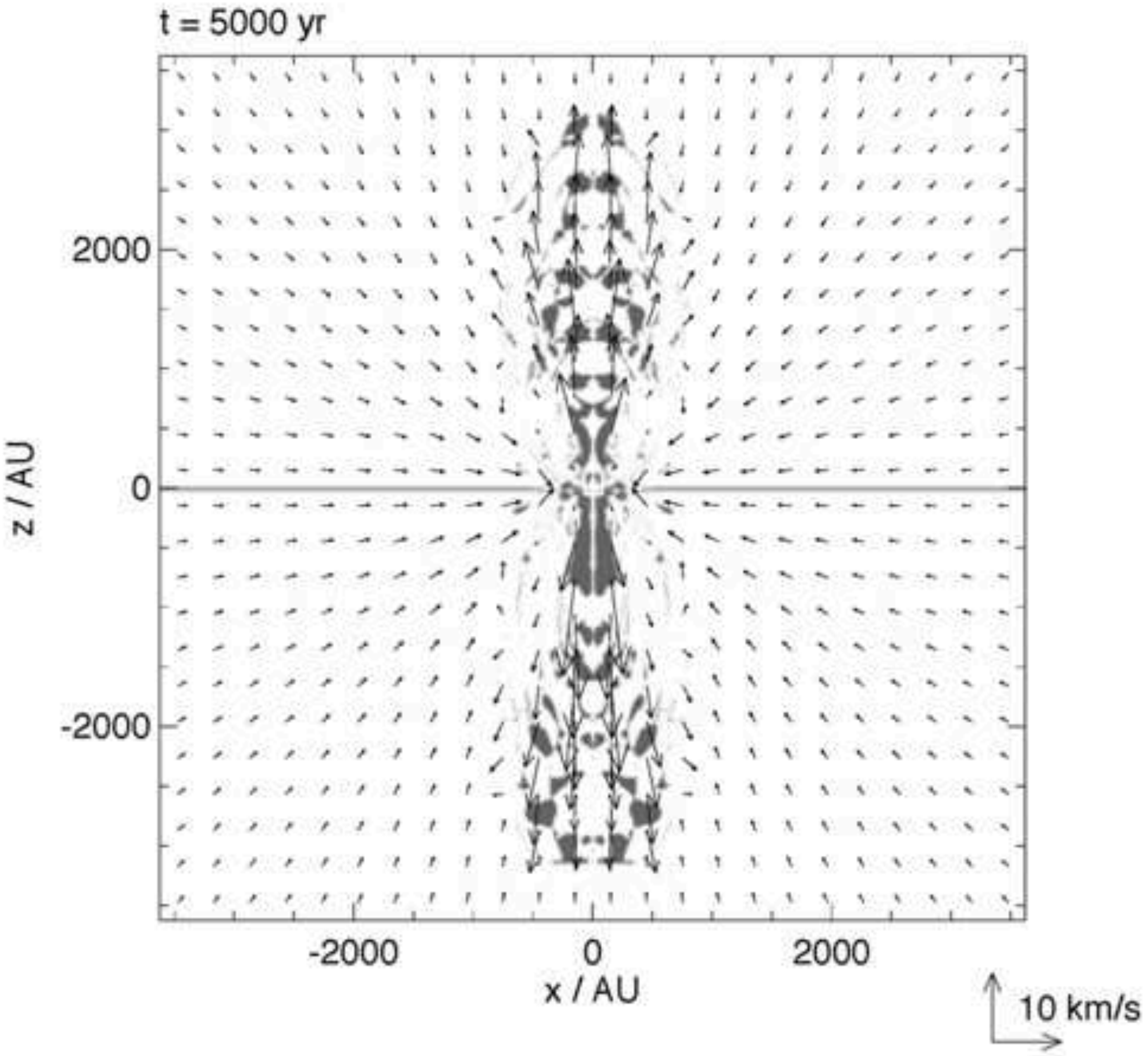
$\mu = 26\ \mu_{\rm crit}$

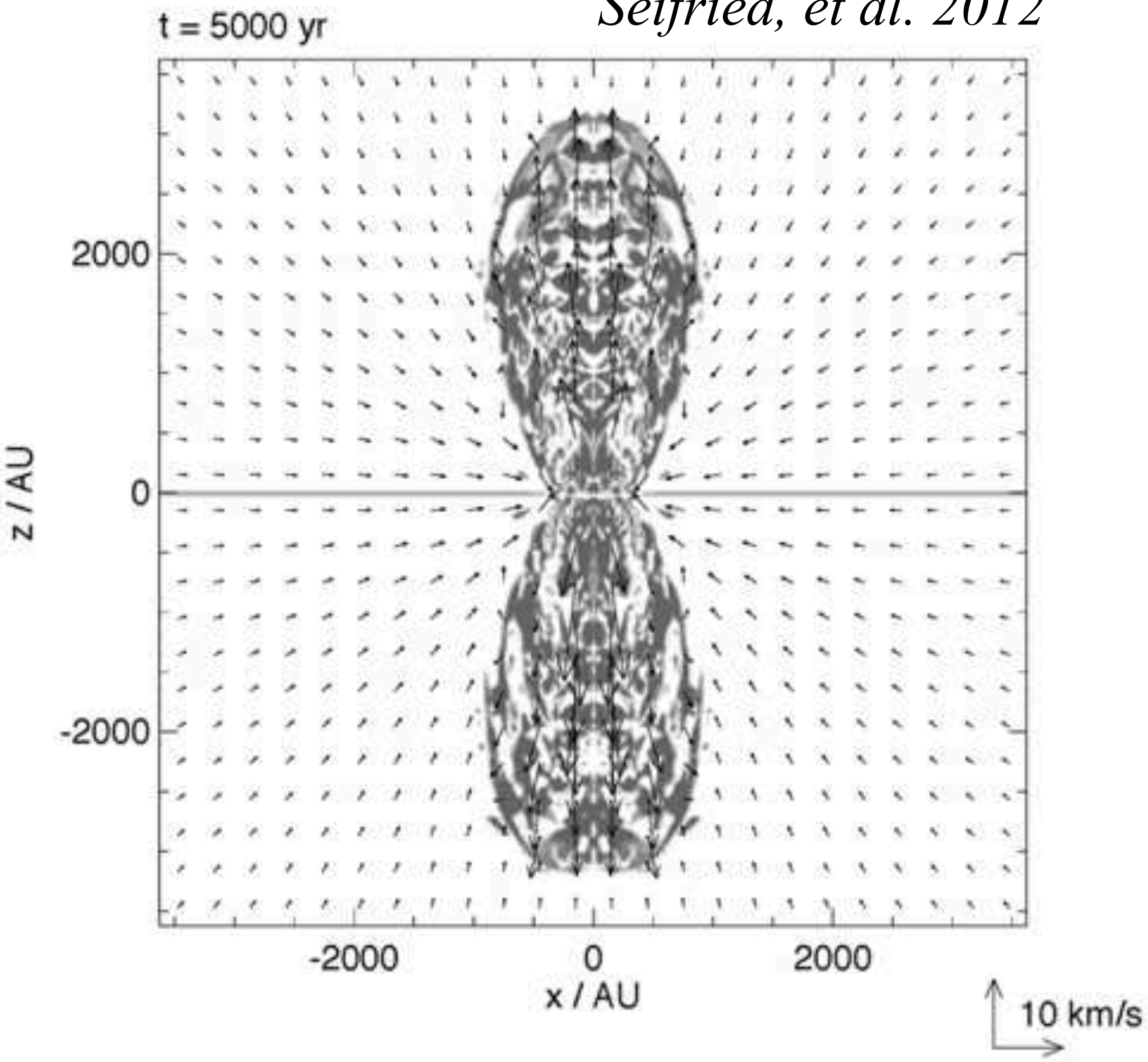
$$\partial_{\rm pol}\left(\frac{1}{2}v_\phi^2 + \Phi - \frac{v_\phi}{v_{\rm pol}}\frac{1}{4\pi}\frac{B_\phi B_{\rm pol}}{\rho} + \frac{1}{4\pi}\frac{B_\phi^2}{\rho}\right) < 0$$

A Generalised Outflow Criterion

Outflow / Lauchning mechanism

Seifried, et al. 2012





magnetocentrifugal launching:

$$\frac{r}{z}\frac{1}{GM}\left(\frac{v_\phi^2}{r^2}(r^2+z^2)^{3/2}-GM\right)\Big/\left(\frac{B_z}{B_r}\right) > 1$$

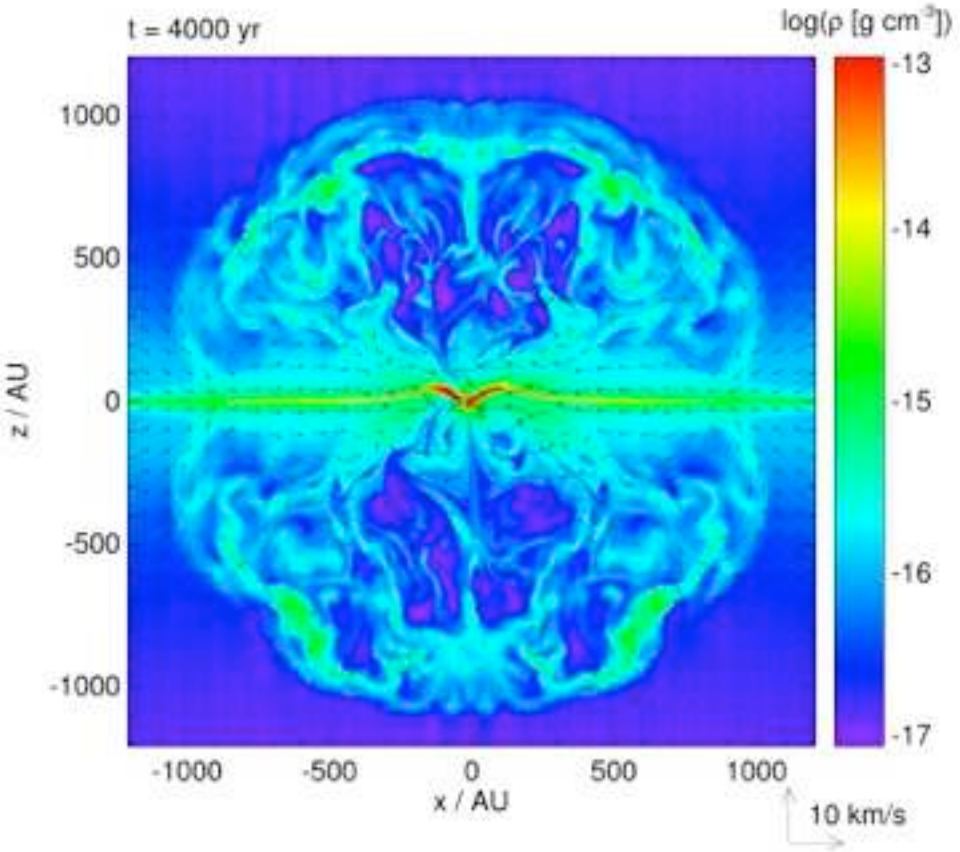
generalised criterion:

$$\partial_{\mathrm{pol}}\left(\frac{1}{2}v_\phi^2+\Phi-\frac{v_\phi}{v_{\mathrm{pol}}}\frac{1}{4\pi}\frac{B_\phi B_{\mathrm{pol}}}{\rho}+\frac{1}{4\pi}\frac{B_\phi^2}{\rho}\right) < 0$$

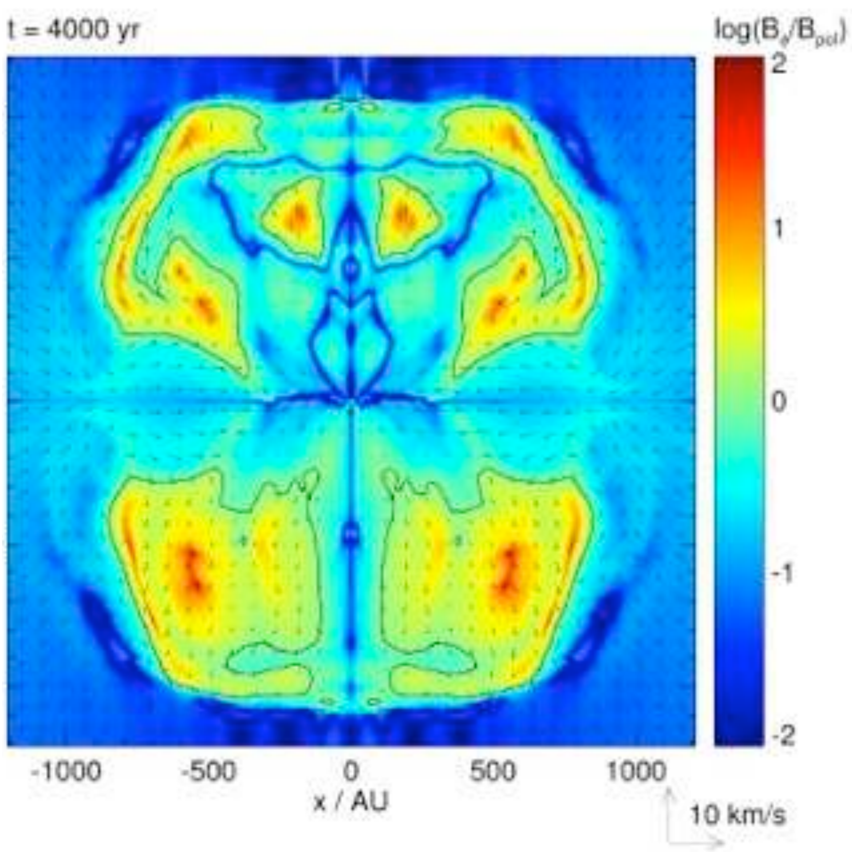
Parameter study of collapsing cores

Outflow / Launching mechanism

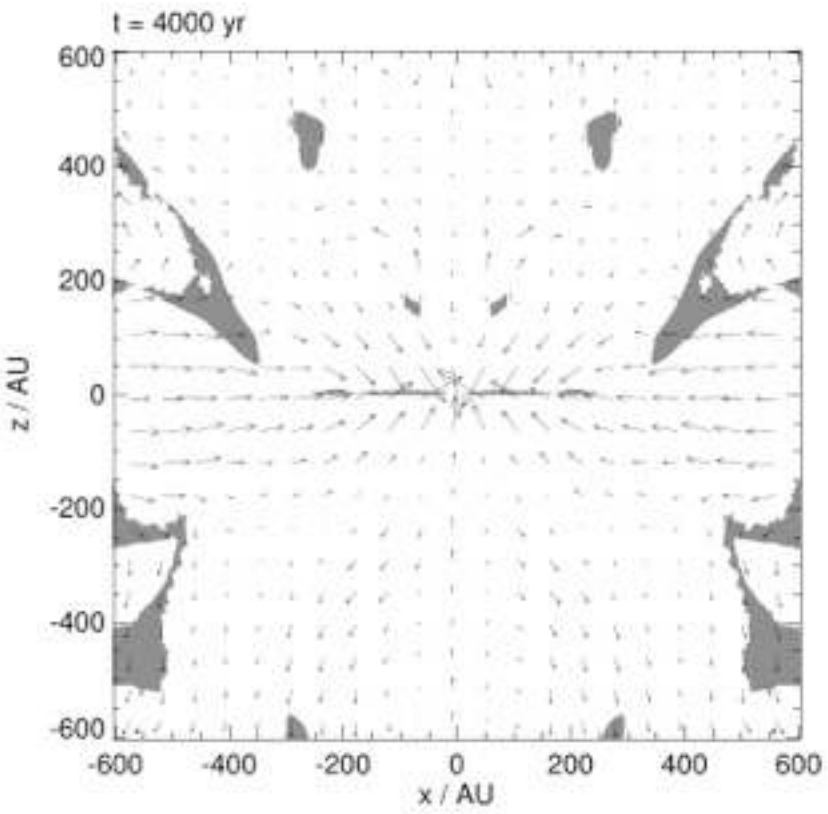
stronger magnetic field: $\mu = 5.2\ \mu_{\mathrm{crit}}$



density



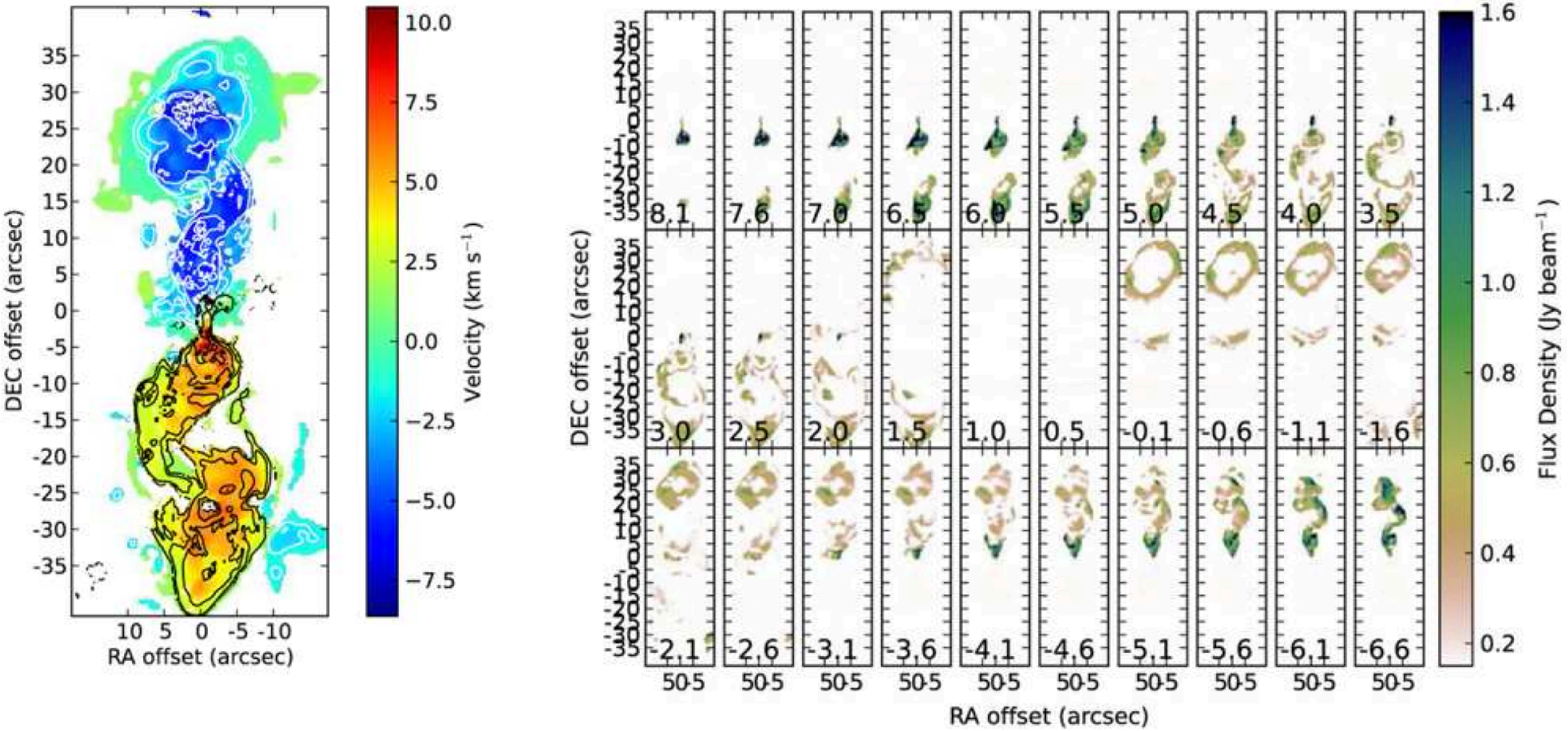
B_φ / B_p



$\frac{r}{z}\frac{1}{GM}\left(\frac{v_\phi^2}{r^2}(r^2+z^2)^{3/2}-GM\right)/\left(\frac{B_z}{B_r}\right)>1$

- inefficient magneto-centrifugal launching
- bubble like “outflow”

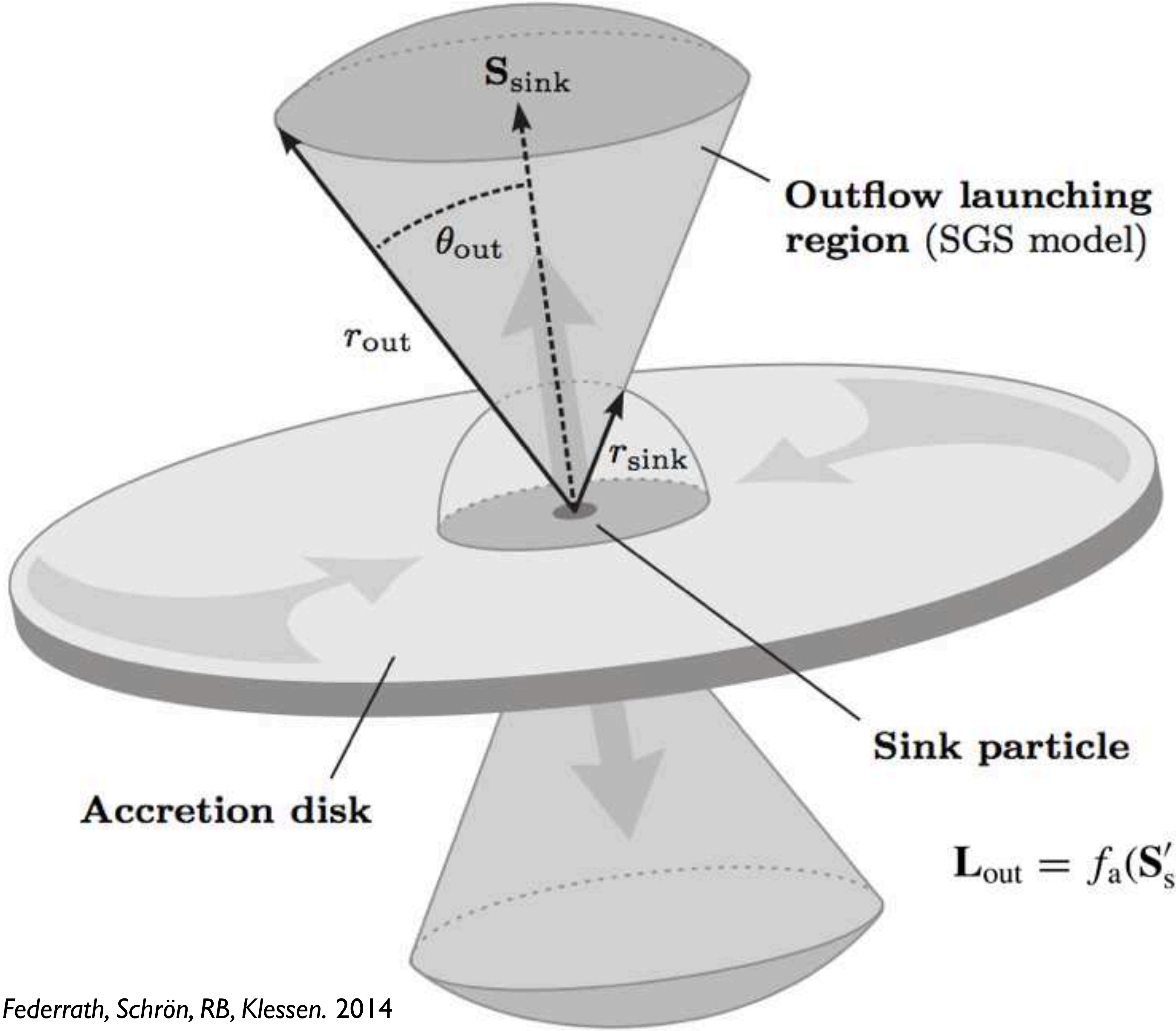
Synthetic Observations



Peters, Klaassen, Seifried, RB, Klessen 2014

$\Longrightarrow$ Helical structure similar to outflow around the A-type star HD 163296 (D = 122 pc)

Sub-Grid-Scale Model



Federrath, Schrön, RB, Klessen. 2014

outflow direction determined from sink spin axis

- parameters:

outflow angle: Θ_{out}

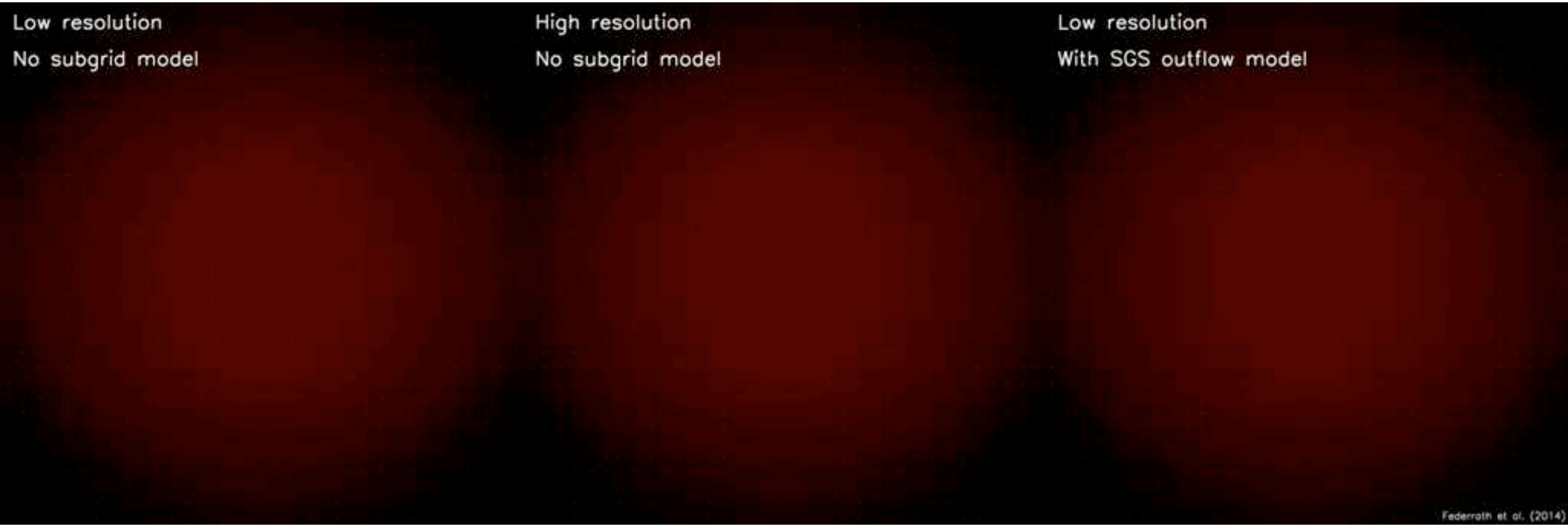
f_{m}:

$$M_{\mathrm{out}} = f_{\mathrm{m}} \dot{M}_{\mathrm{acc}} \Delta t$$

f_{a}:

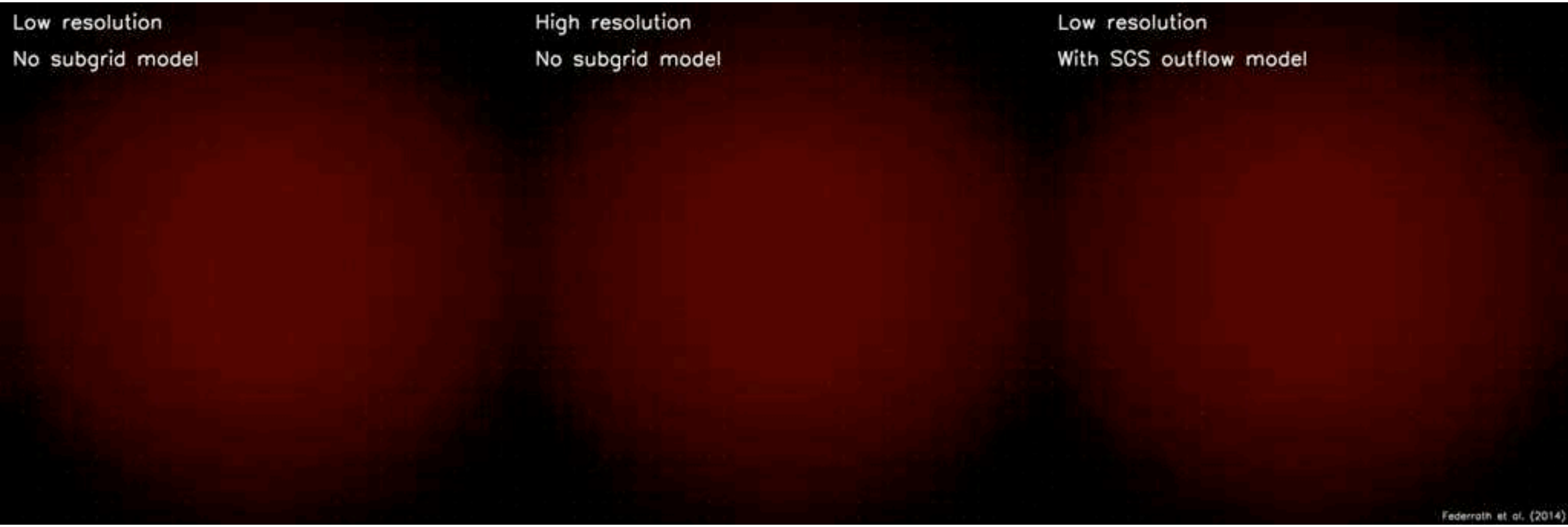
$$\mathbf{L}_{\mathrm{out}} = f_{\mathrm{a}}(\mathbf{S}'_{\mathrm{sink}} - \mathbf{S}_{\mathrm{sink}}) \cdot \mathbf{S}'_{\mathrm{sink}} / |\mathbf{S}'_{\mathrm{sink}}|$$

SGS Model: Single Outflow

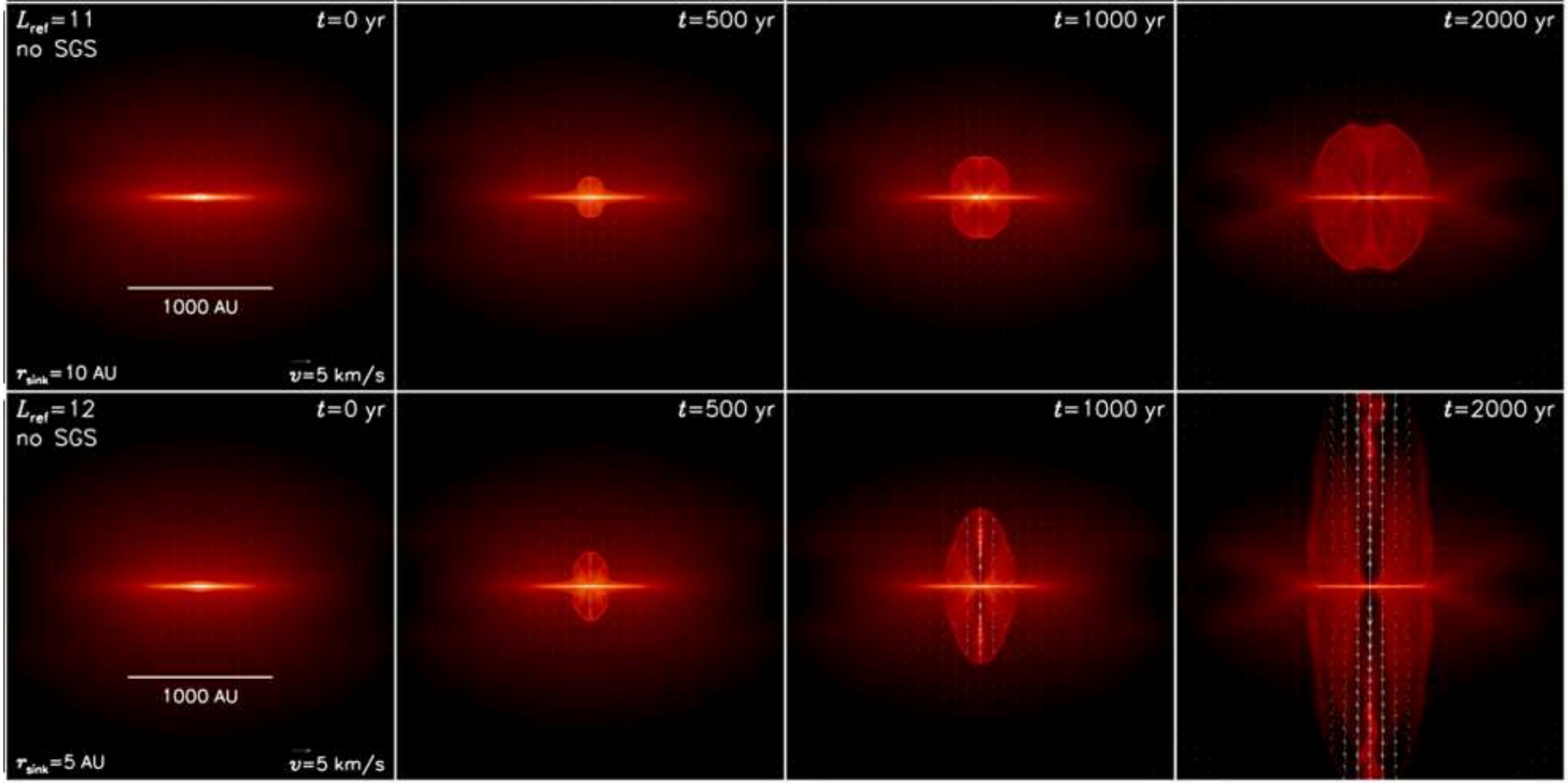


Federrath et al. (2014)

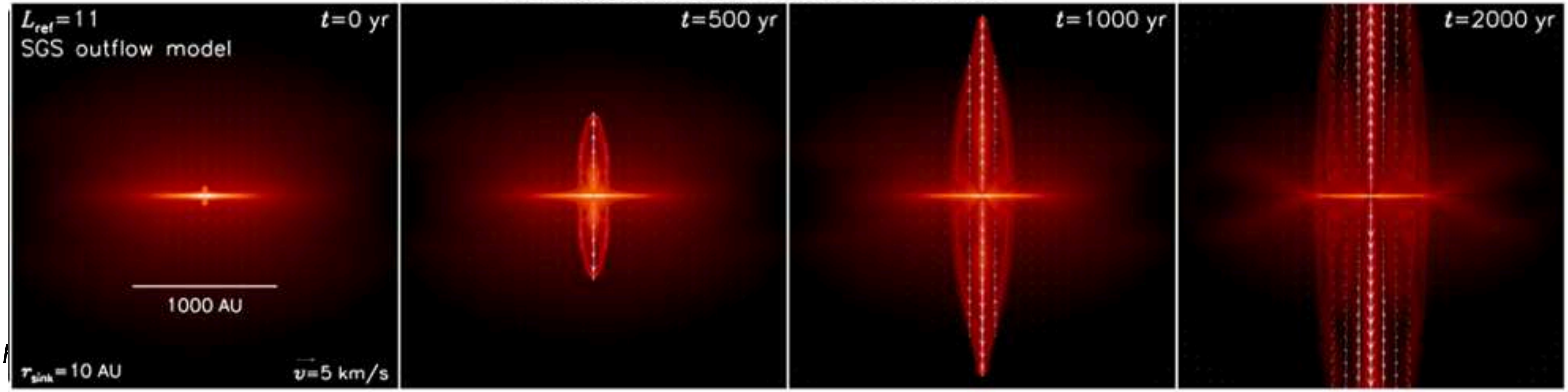
SGS Model: Single Outflow



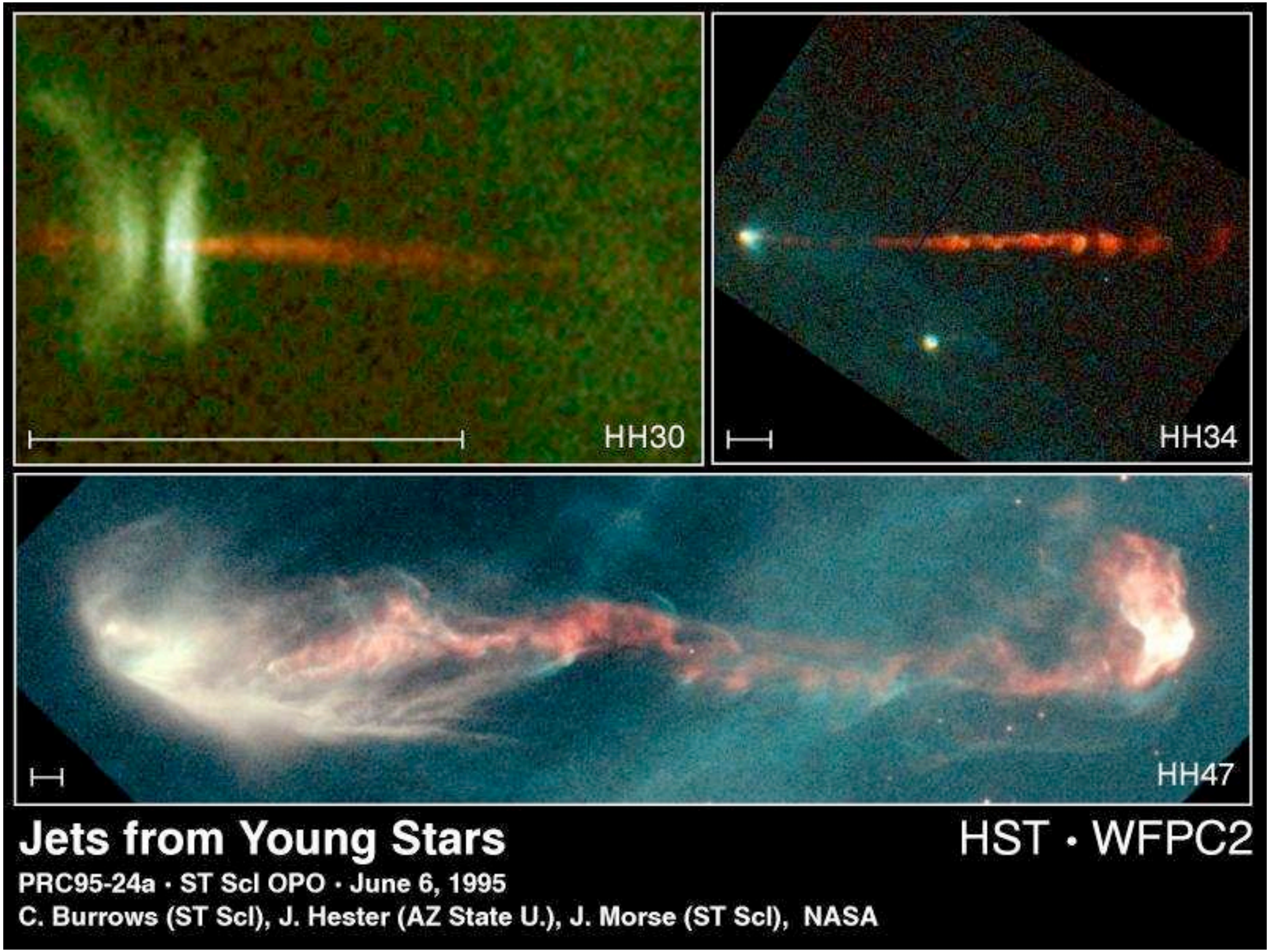
$\Longrightarrow$ low resolution SGS outflow model recovers fast jet of high resolution self-consistent outflow simulation



With SGS outflow model activated:



Feedback: Impact of Jets & Outflows



Jets from Young Stars

PRC95-24a · ST ScI OPO · June 6, 1995

C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

Feedback: Impact of Jets & Outflows

- Jets are powerful:

$$L_{\rm jet} = \frac{\dot{M}_{\rm jet} v_{\rm jet}^2}{2} \approx 2.9 \times 10^{32} \left(\frac{\dot{M}_{\rm jet}}{10^{-8}\ M_\odot\ {\rm yr}^{-1}} \right) \times \left(\frac{v_{\rm jet}}{300\ {\rm km\ s}^{-1}} \right)^2 {\rm ergs\ s}^{-1}$$

$\sim 8\%\ L_\odot$

$$E_{\rm jet} = L_{\rm jet} \tau_{\rm jet} \approx 10^{44}\ {\rm ergs}$$

with $\tau_{\rm jet} = 10^4$ yrs

$\Longrightarrow$ cf. $E_{\rm turb} \sim 10^{46}$ ergs

$\Longrightarrow$ Jets from a little stellar cluster ***could*** maintain the turbulence

Feedback: Impact of Jets & Outflows

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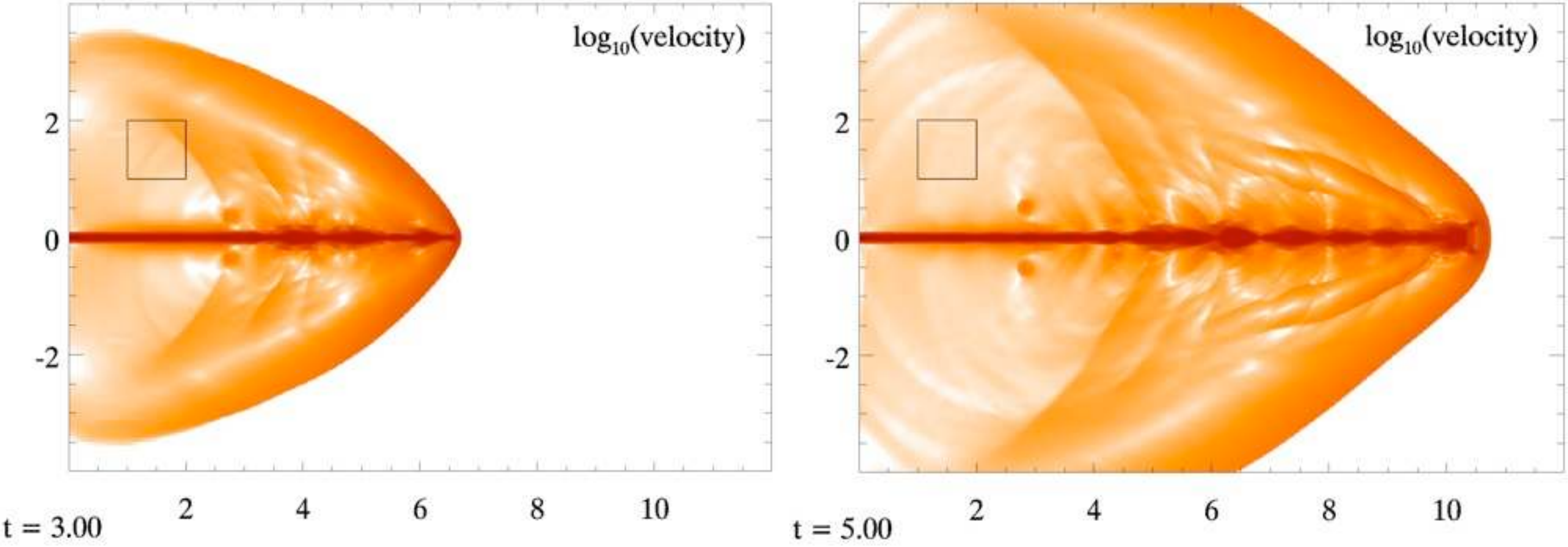
$\Longrightarrow$ Jets from a little stellar cluster ***could*** maintain the turbulence

$\Longrightarrow$ But how **efficient** do they couple to the ISM?

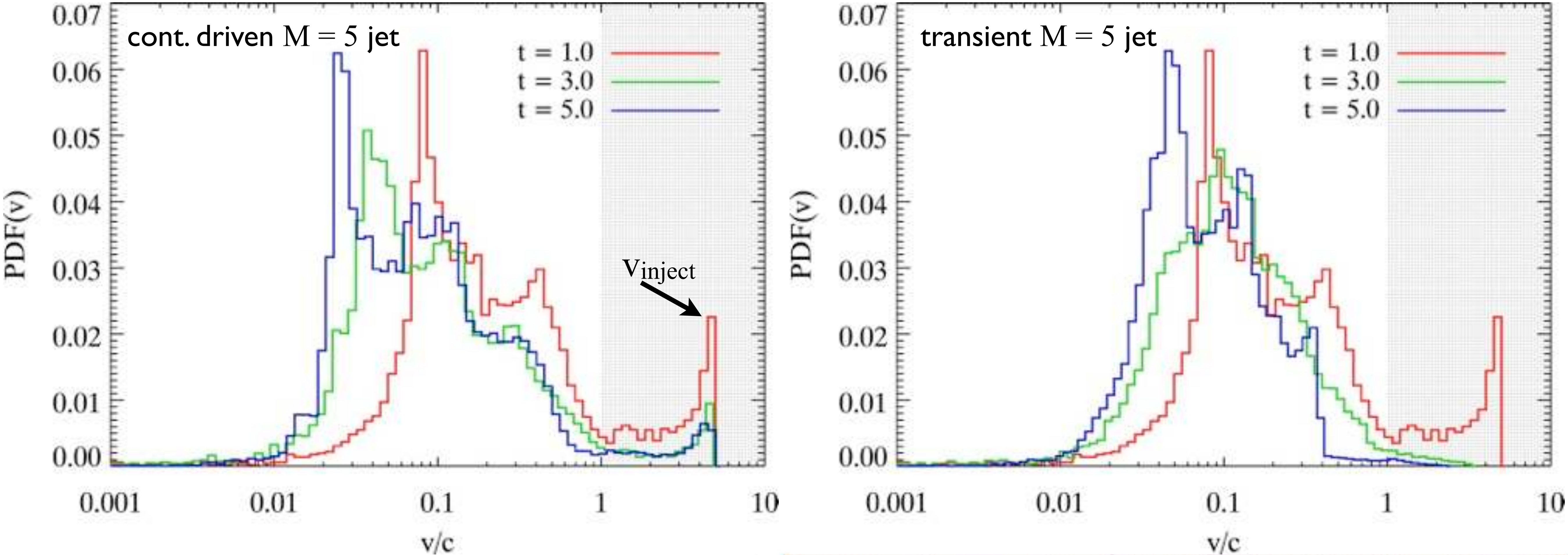
Feedback: Impact of Jets & Outflows

- numerical experiments with **single**, high Mach number jets (momentum injection)
- detailed analysis with velocity PDFs



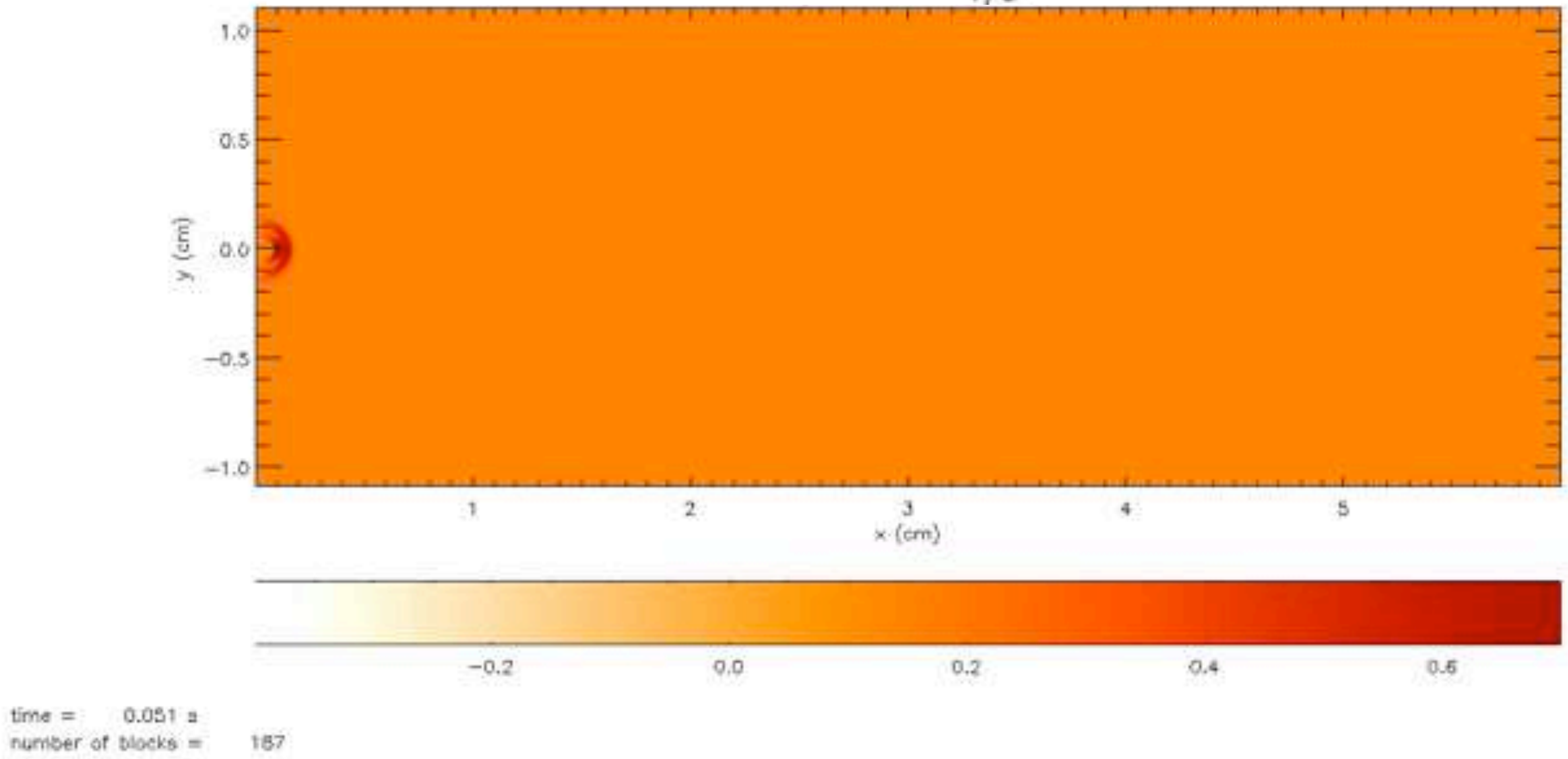
RB, Klessen & Fendt 2007

Feedback: Impact of Jets & Outflows

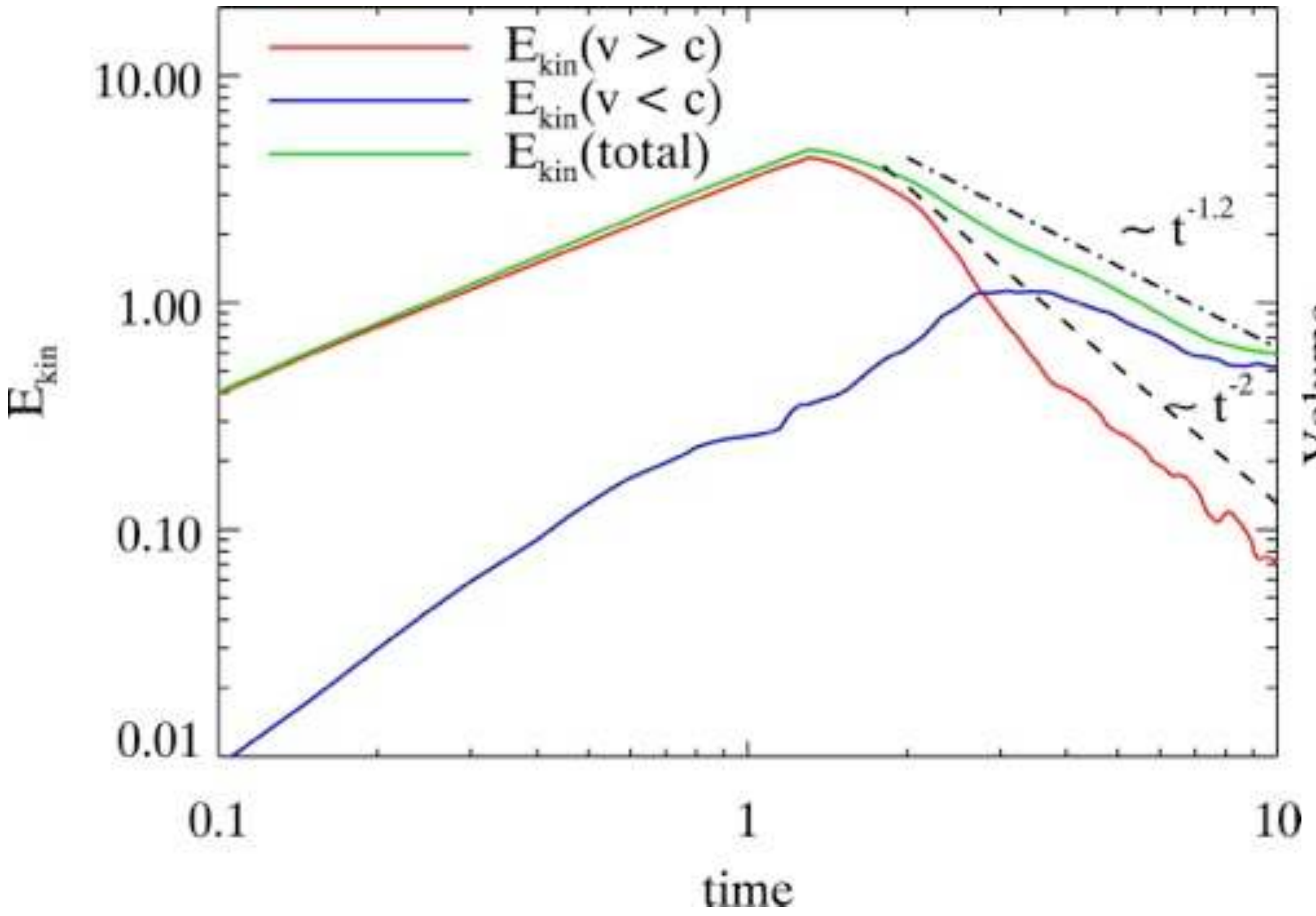


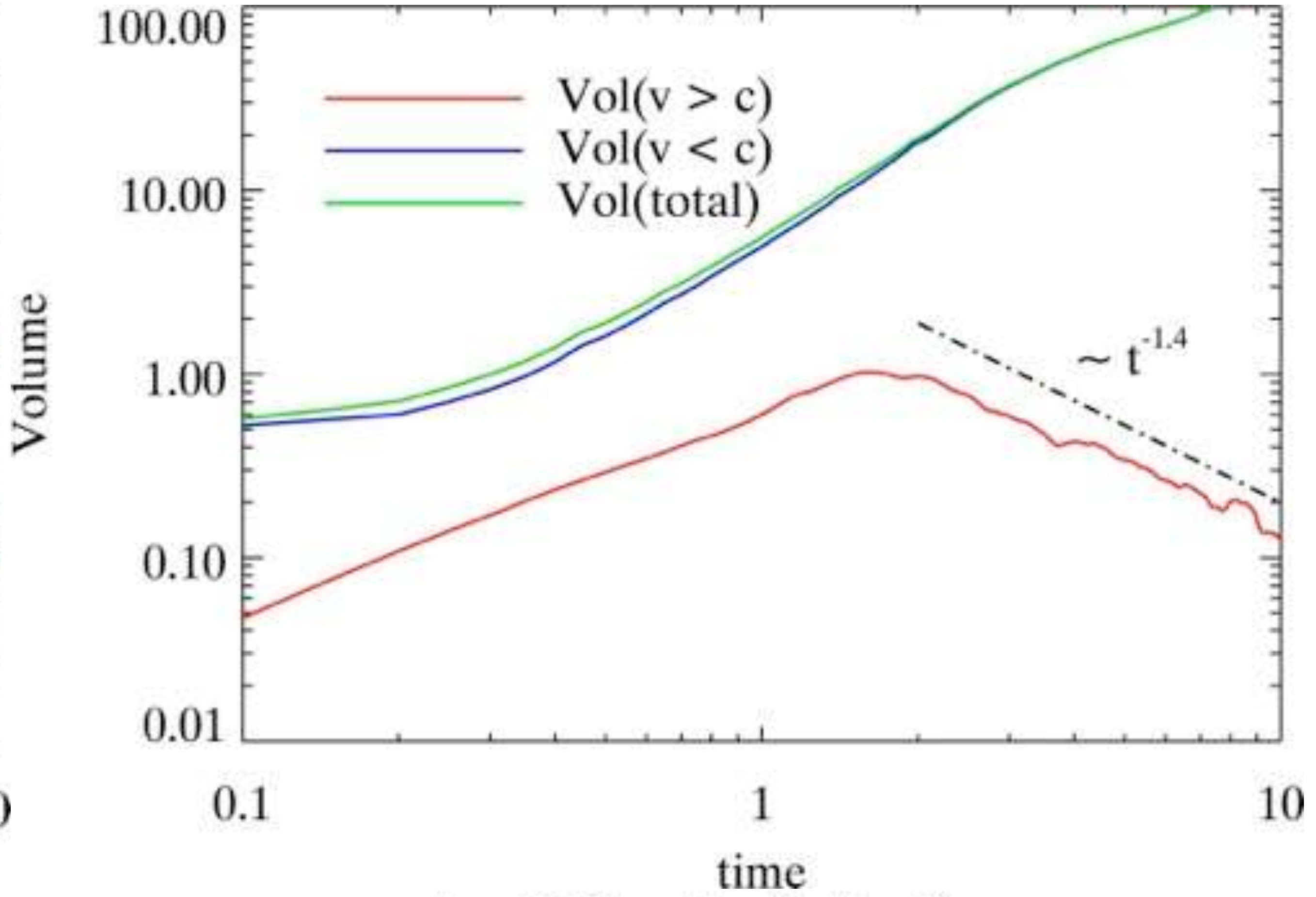
- turbulent motions are sub-sonic
- very **little** supersonic fluctuations

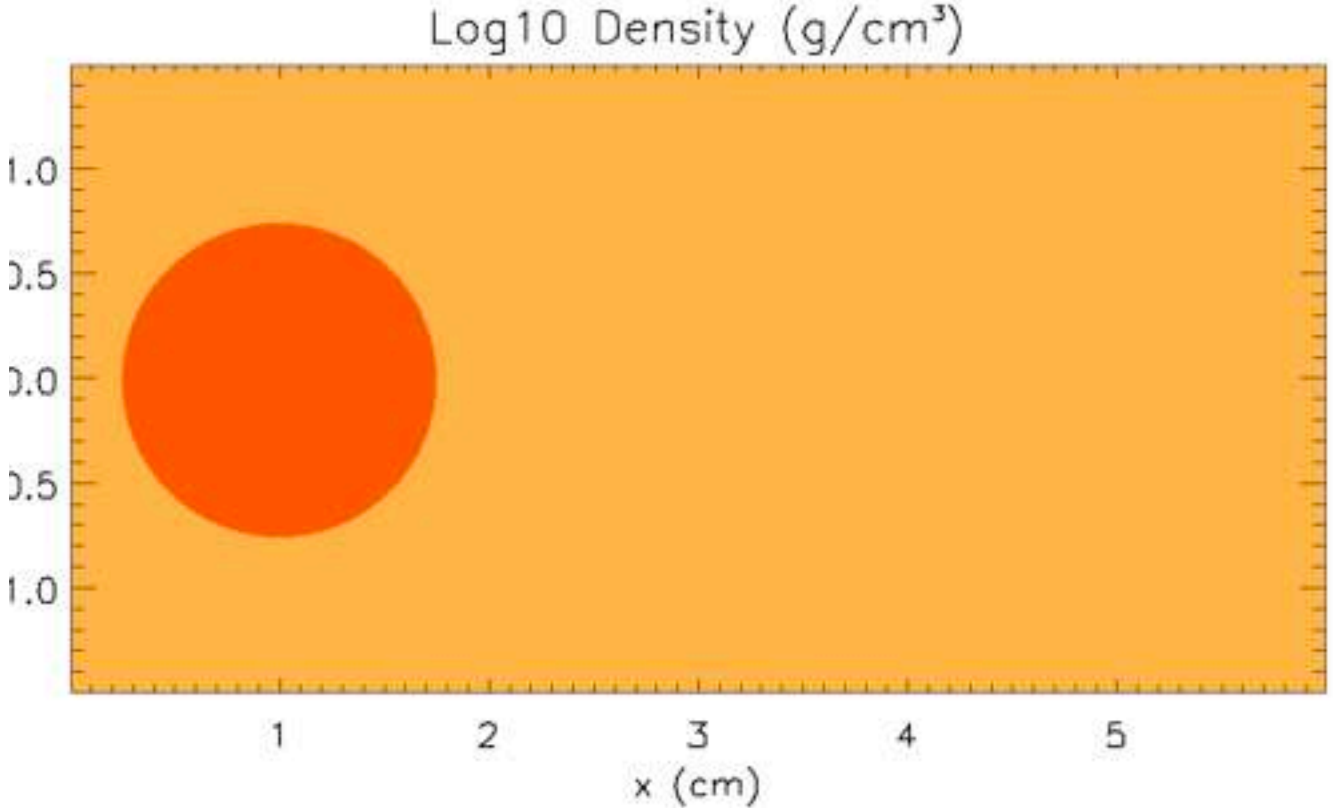
$\Longrightarrow$ “supersonic desert”



Feedback: Impact of Jets & Outflows



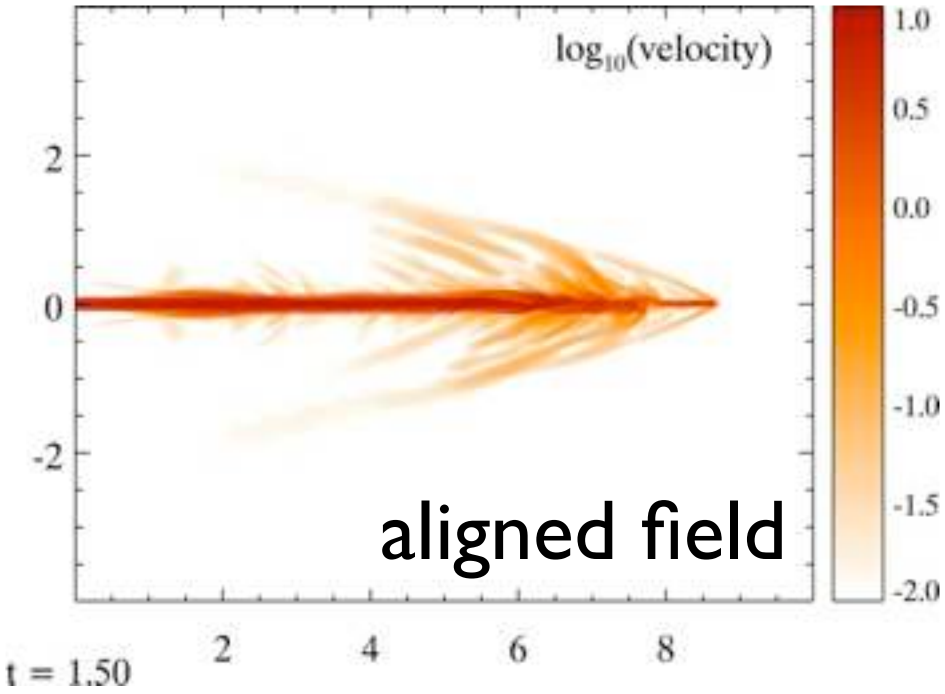




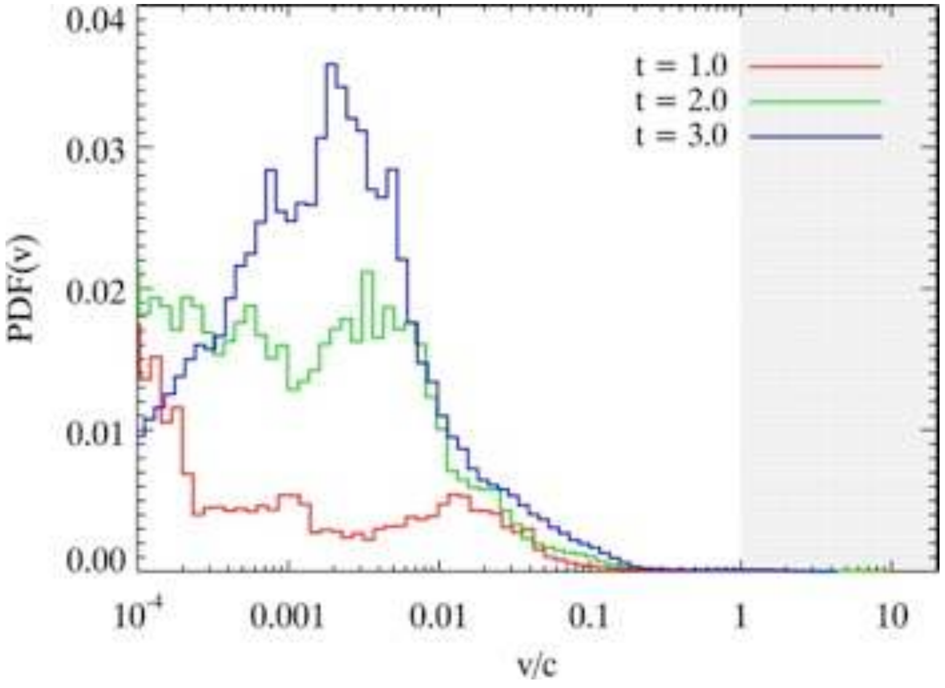
- supersonic fluctuations decay **quickly**: $E \propto t^{-2}$ (*Mac Low et al. '98*)
- supersonic fluctuations occupy only a **small** fraction of all fluctuations

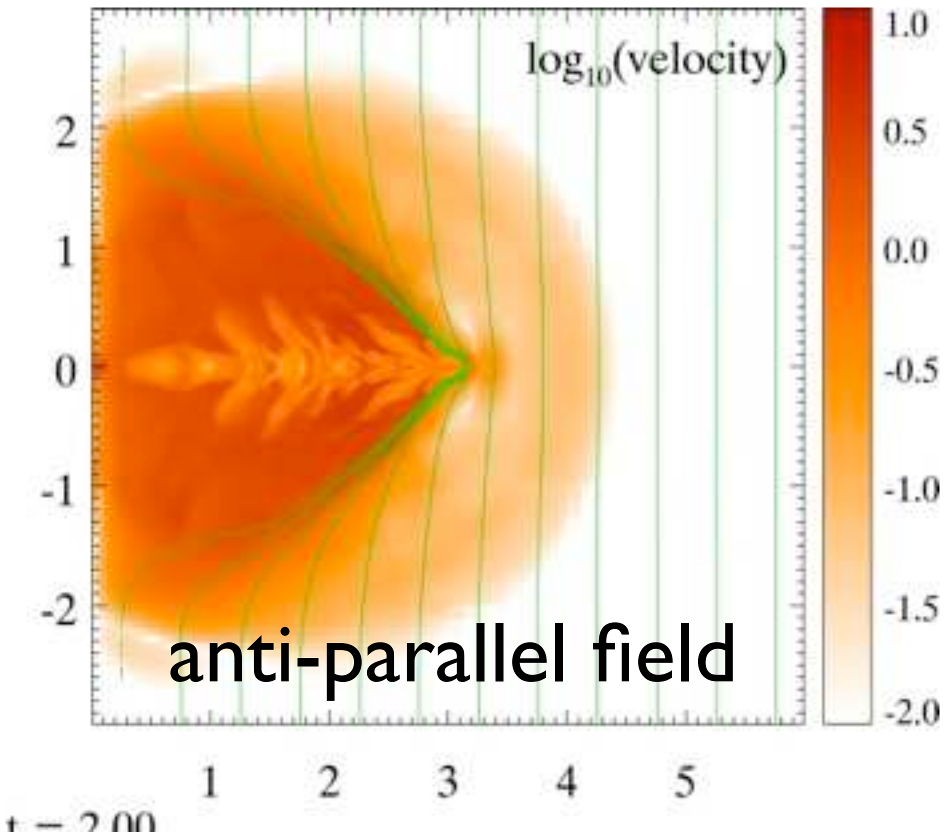
Feedback: Impact of Jets & Outflows

Influence of Magnetic Fields

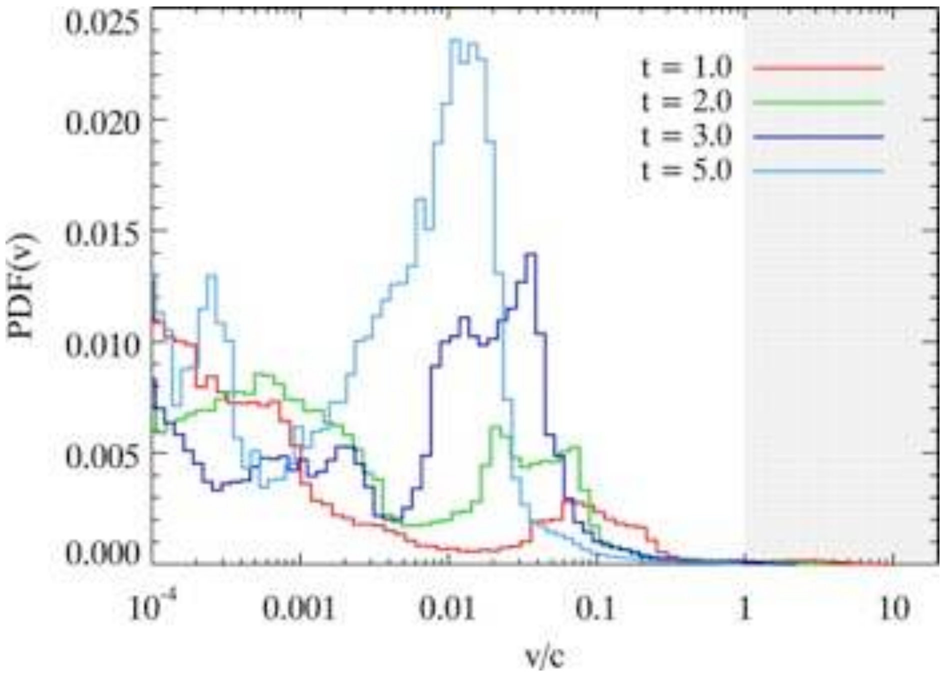


aligned field





anti-parallel field

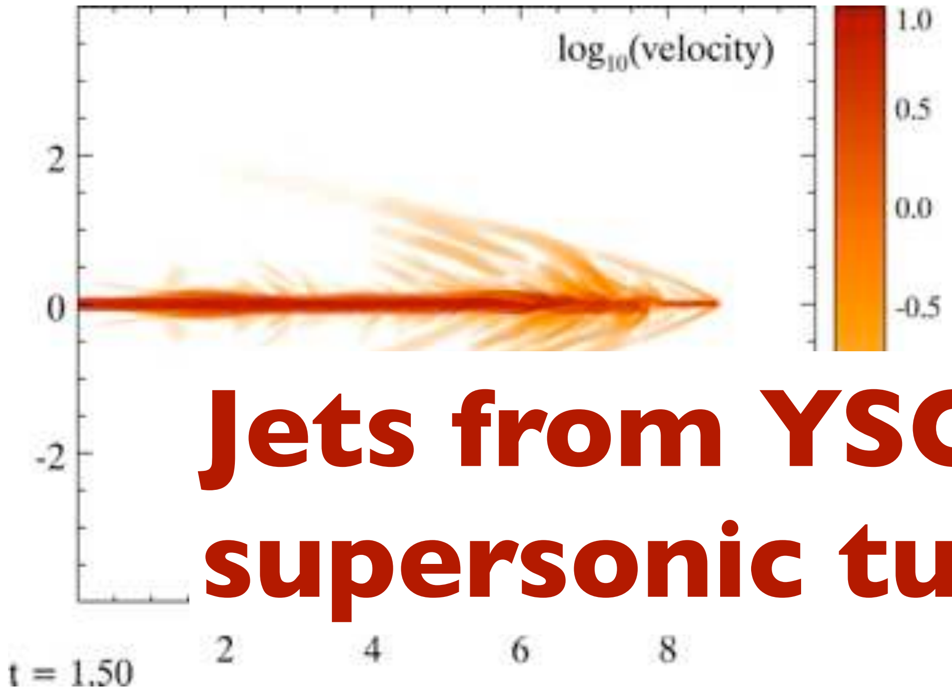


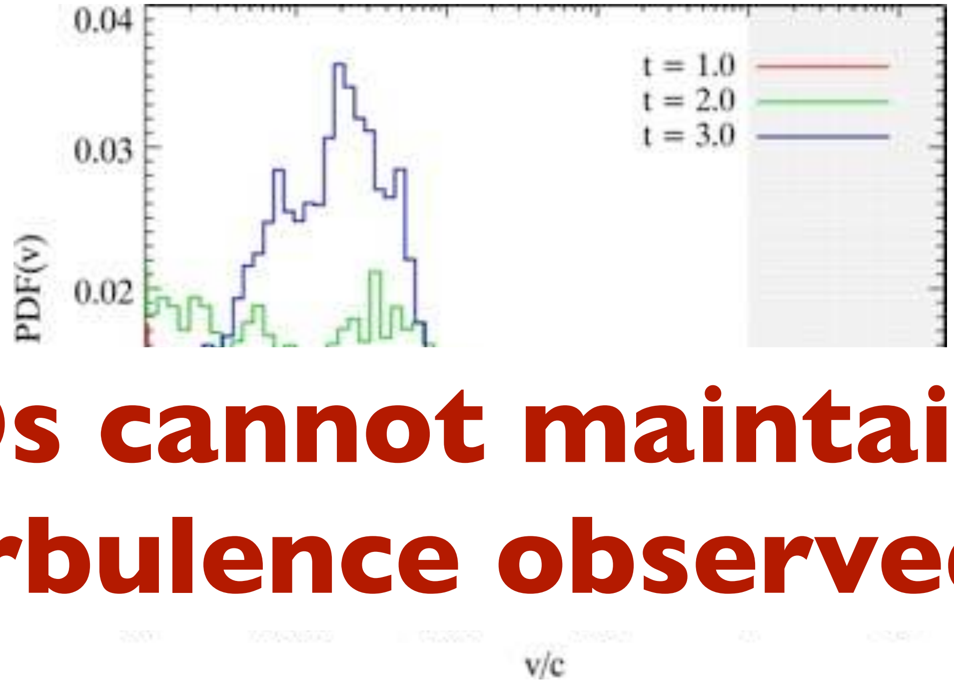
magnetic fields **suppress** the propagation of large amplitude velocity fluctuations

stabilize jet (aligned field)

Feedback: Impact of Jets & Outflows

Influence of Magnetic Fields





Jets from YSOs cannot maintain the supersonic turbulence observed in MCs

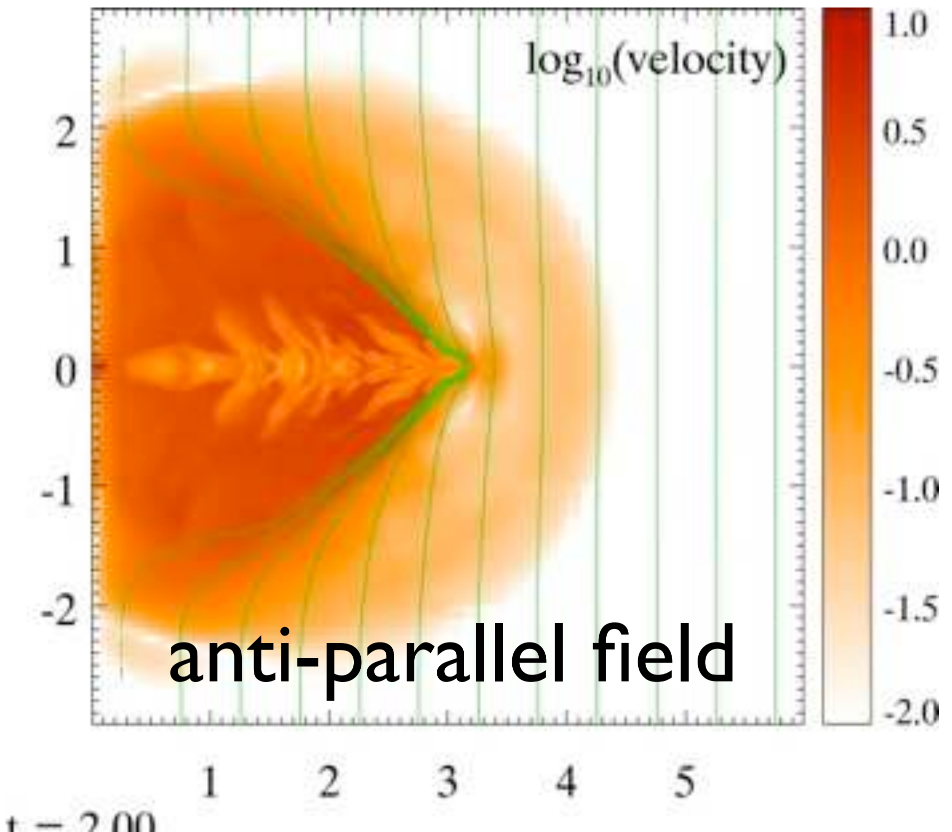
magnetic fields **suppress** the

n of

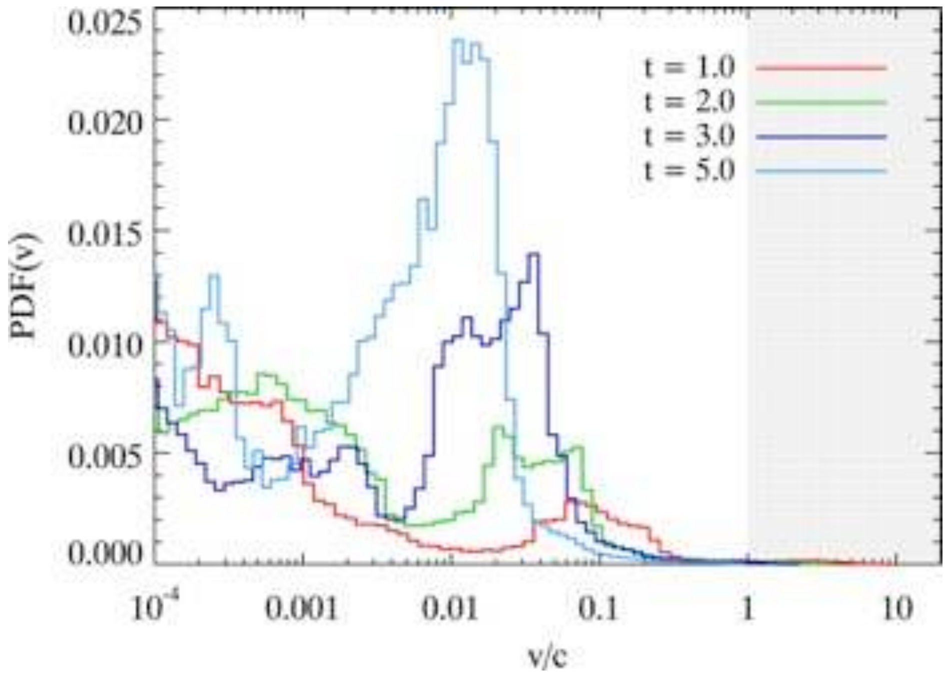
ude

velocity

fluctuations



anti-parallel field



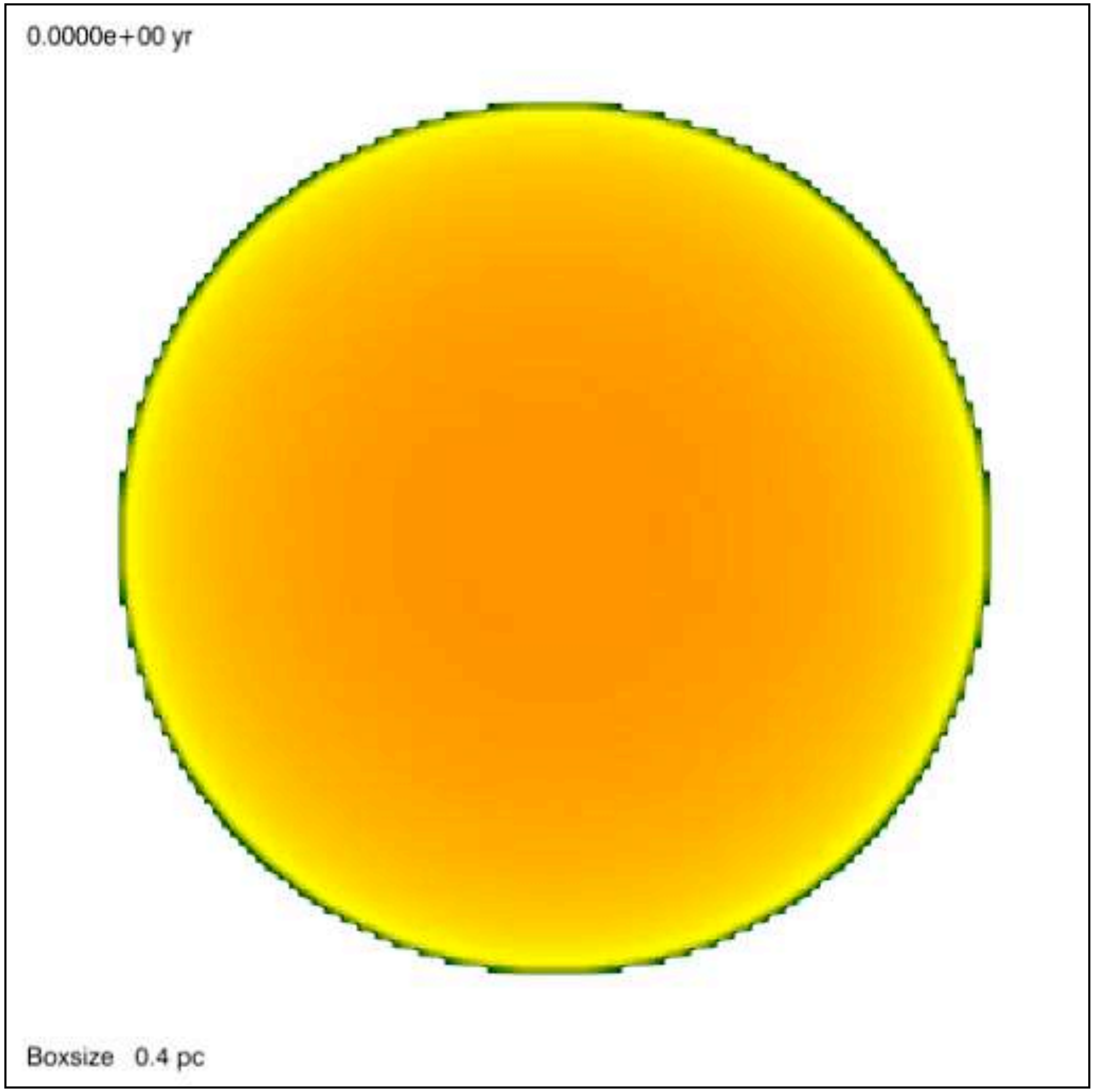
stabilize jet (aligned field)

Feedback: Impact of Jets & Outflows

Global simulation

- collapse of a turbulent cloud core (*Li&Nakamura* 2006; *Carroll et al.* 2008, *Dale & Bonnell* 2008, *Wang et al.* 2010, *Federrath et al.* 2014)

Feedback: Impact of Jets & Outflows



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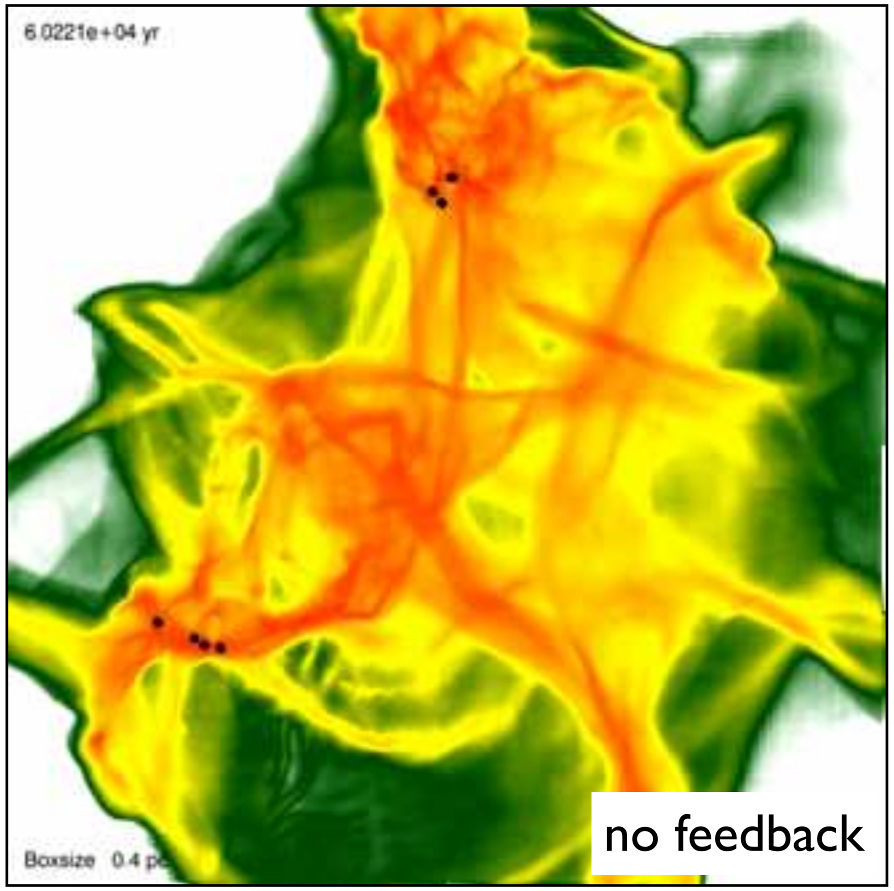
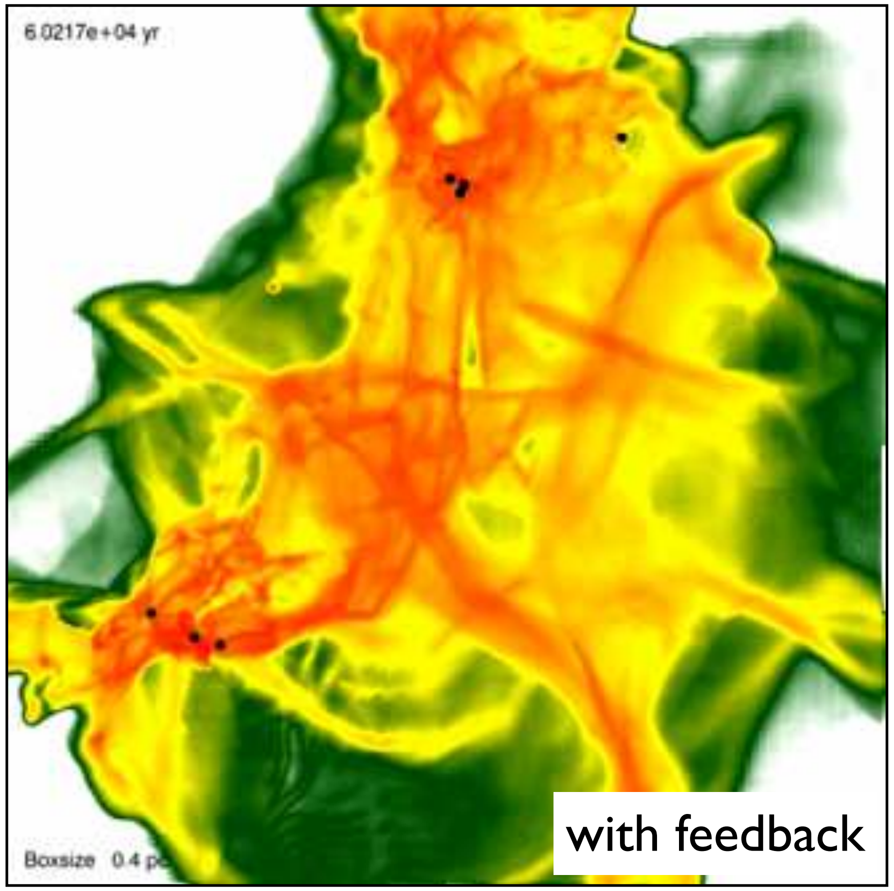
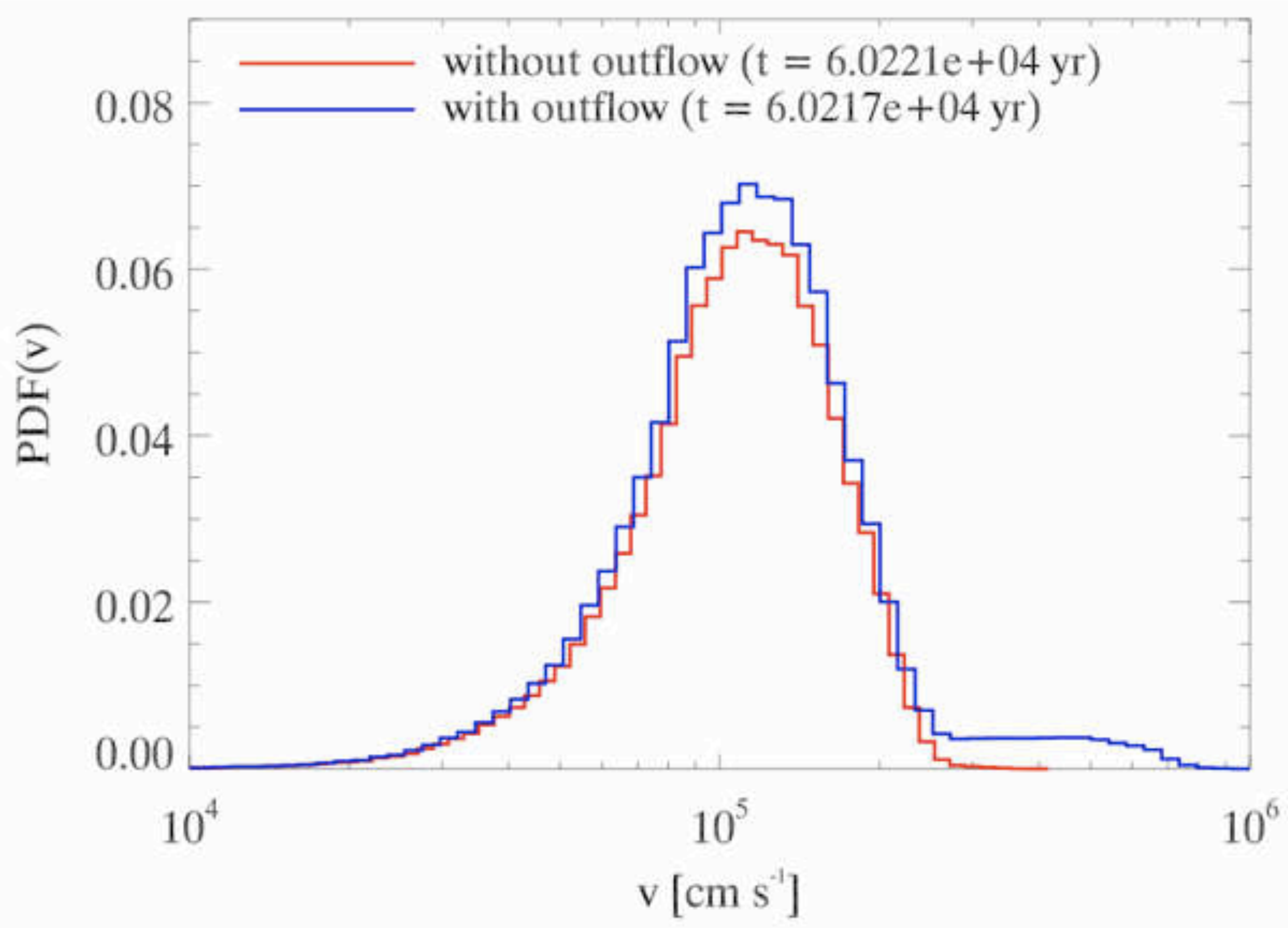
Feedback: Impact of Jets & Outflows



no feedback

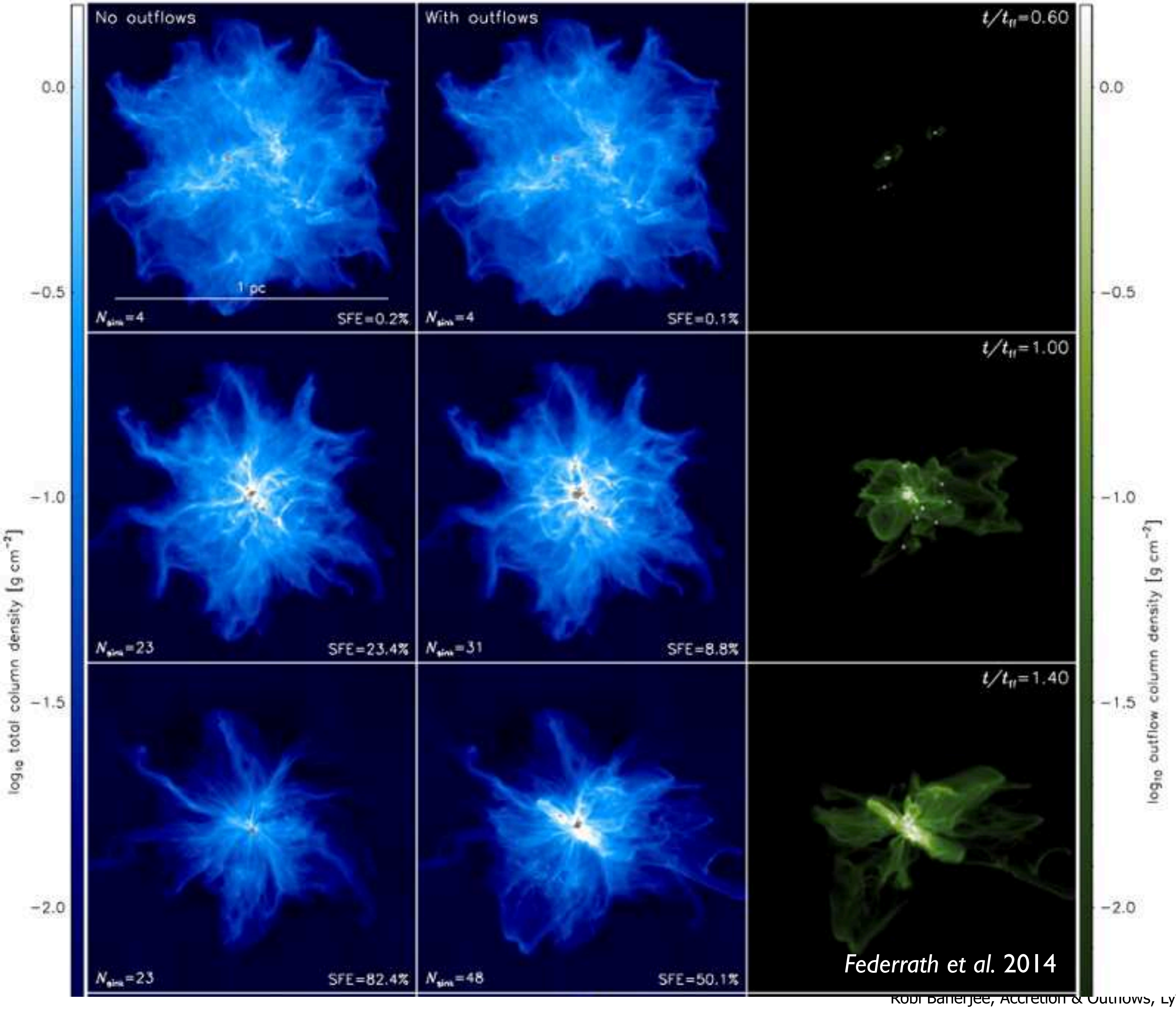


with feedback



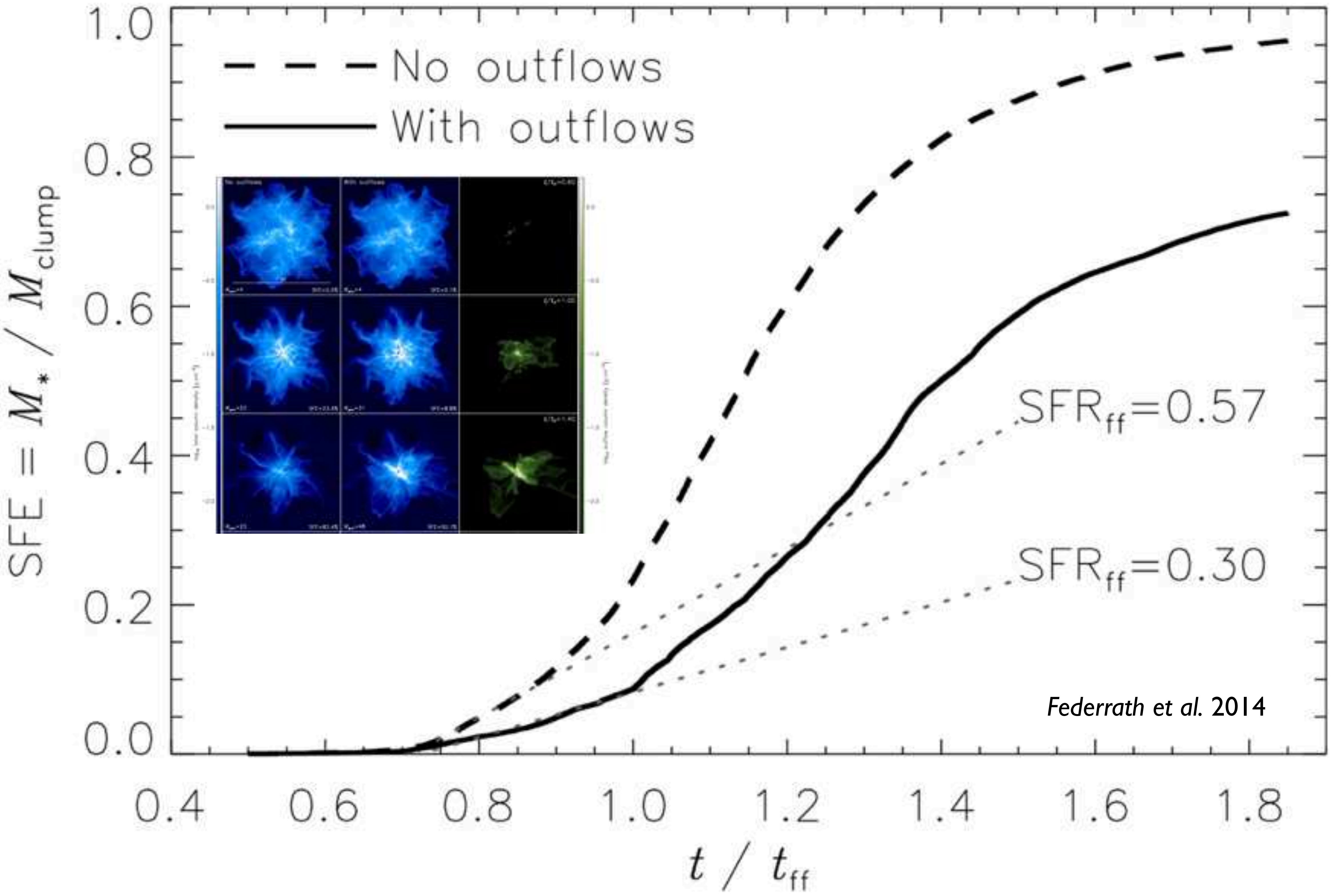
- influence on small scales
- self-regulated SF?
- large scale turbulence?

SGS Model: Outflows during Cluster Formation



Federrath et al. 2014

SGS Model: Outflows during Cluster Formation

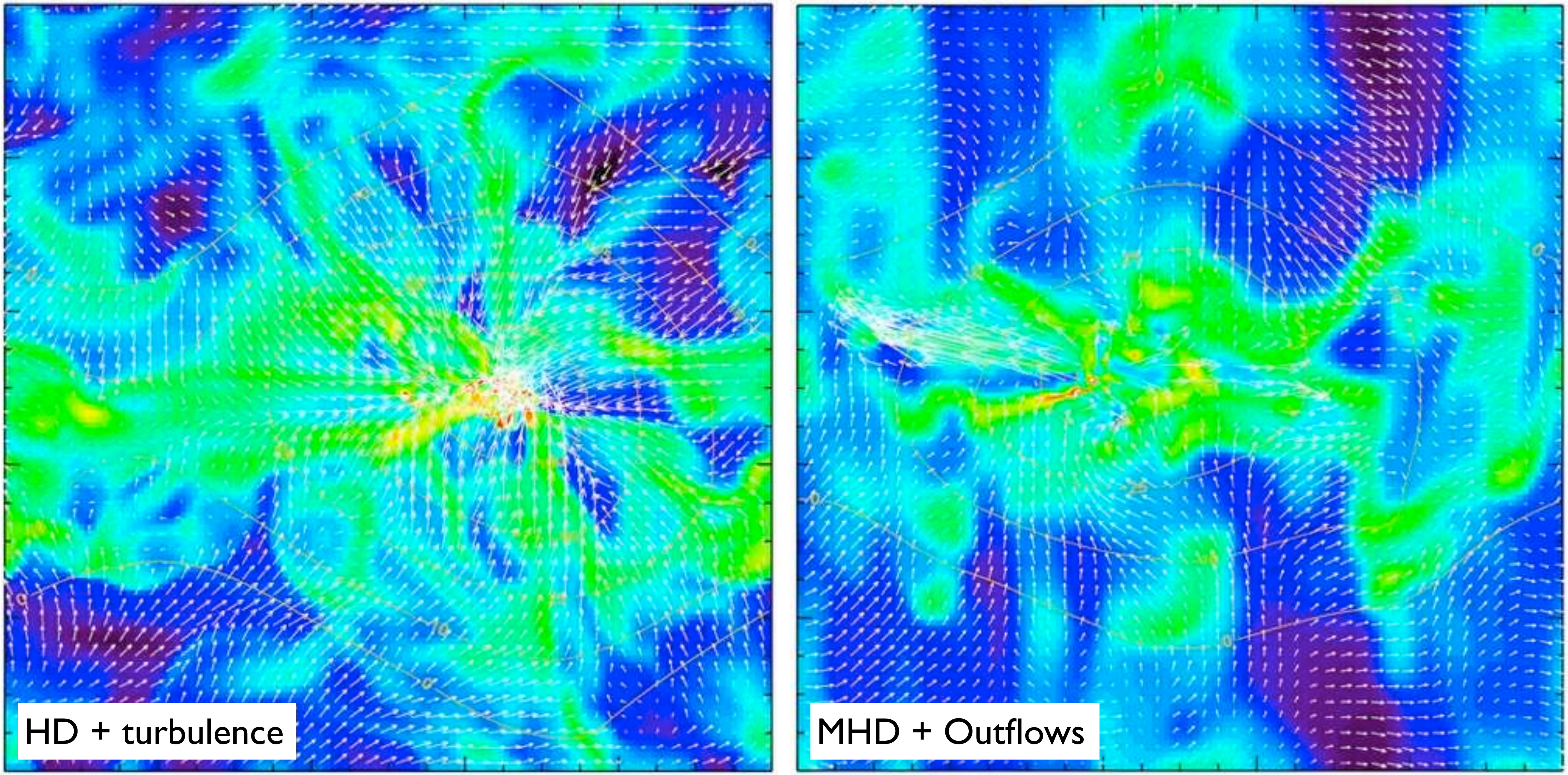


Federrath et al. 2014

$\Longrightarrow$ Outflows & Jets do not stop star formation

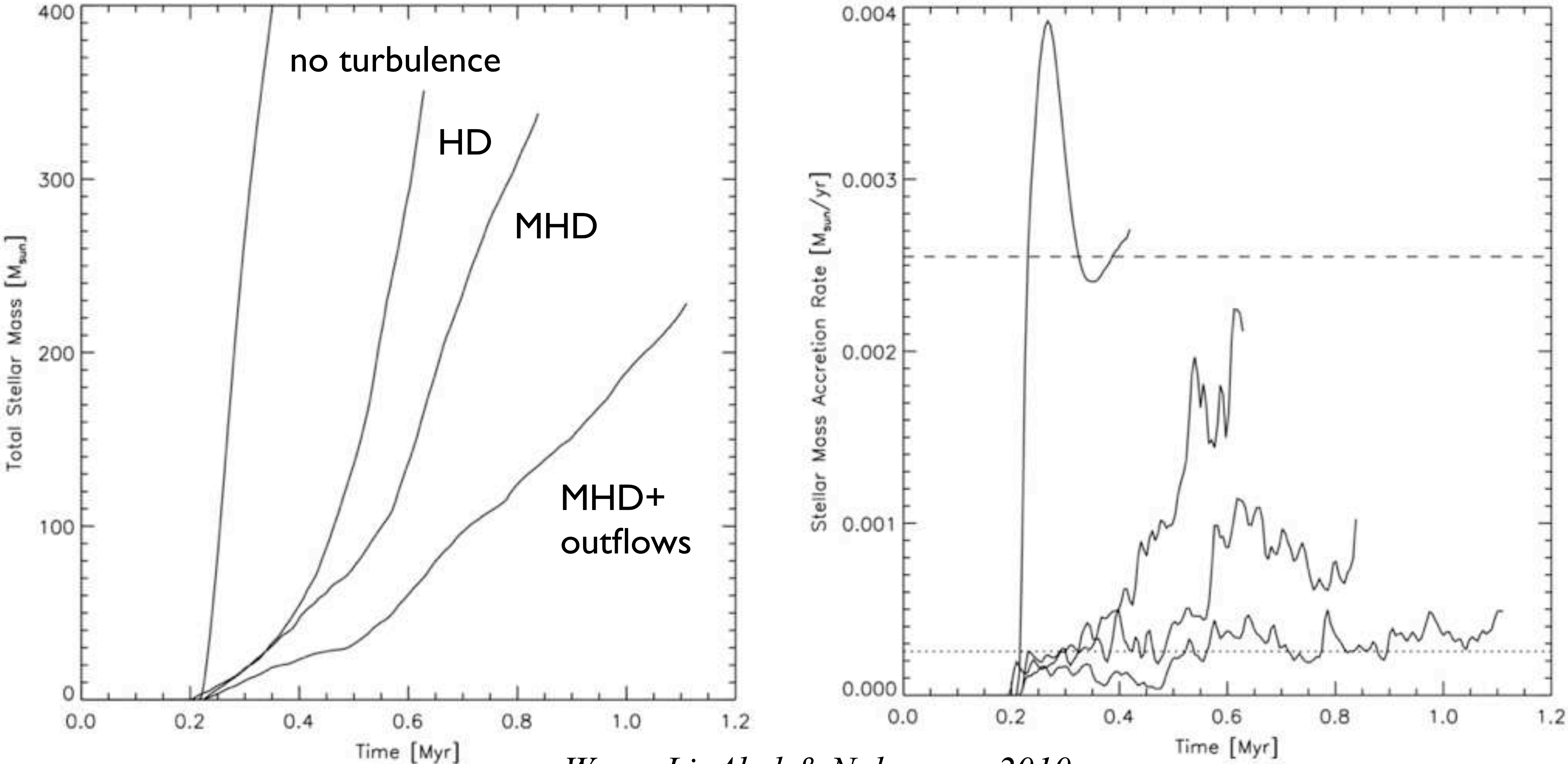
Feedback: Impact of Jets & Outflows

Wang et al. (2010): Collapse of a massive, turbulent cloud core (M_{core} = 1600 M_{sol}) + feedback from jets & outflows



Wang, Li, Abel & Nakamura 2010

Feedback: Impact of Jets & Outflows

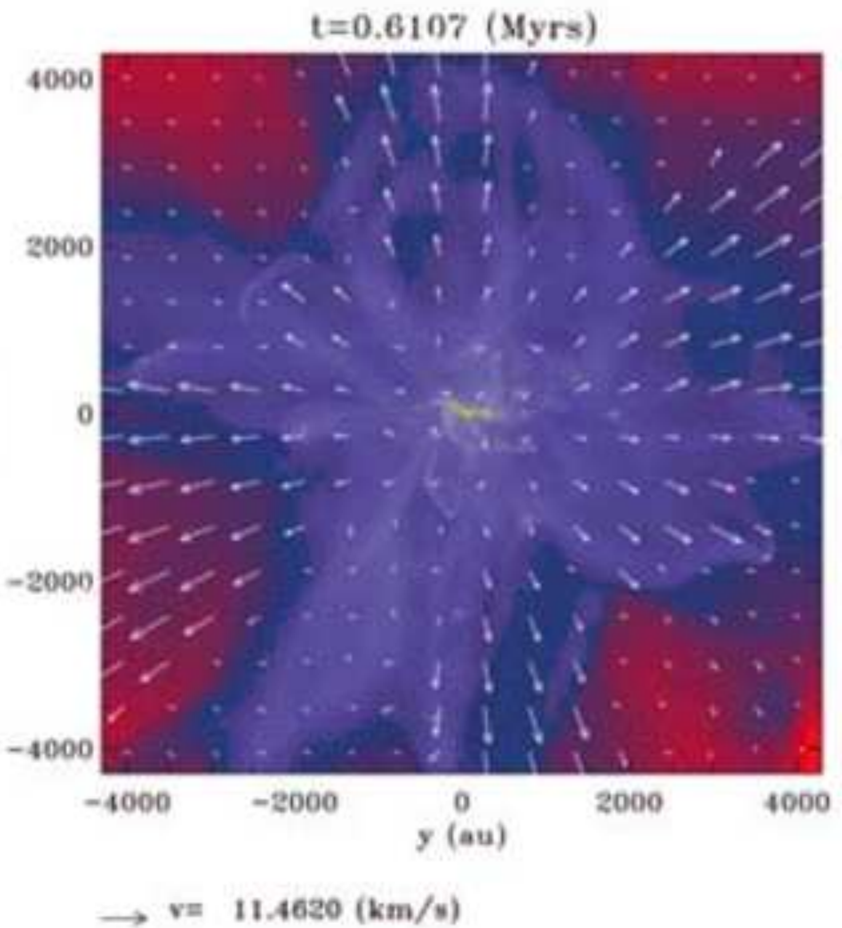


Wang, Li, Abel & Nakamura 2010

$\Longrightarrow$ Outflows & Jets do not stop star formation

Conclusion

- Jets & Outflows:
  self-consistent treatment in
  collapse simulation
  is still challenging
  (but see Hennebelle et al.)



Hennebelle et al. 2011

- SGS models allow to scan a
  larger parameter space (at lower resolution)

- Influence of Outflow feedback?
  $\Longrightarrow$ not conclusive:

  $\Longrightarrow$ might not be too important on cloud scales