Role of Turbulence, Magnetic Fields, and Feedback for Star Formation

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Guillermo Haro Workshop – INAOE Puebla – 14 July 2015

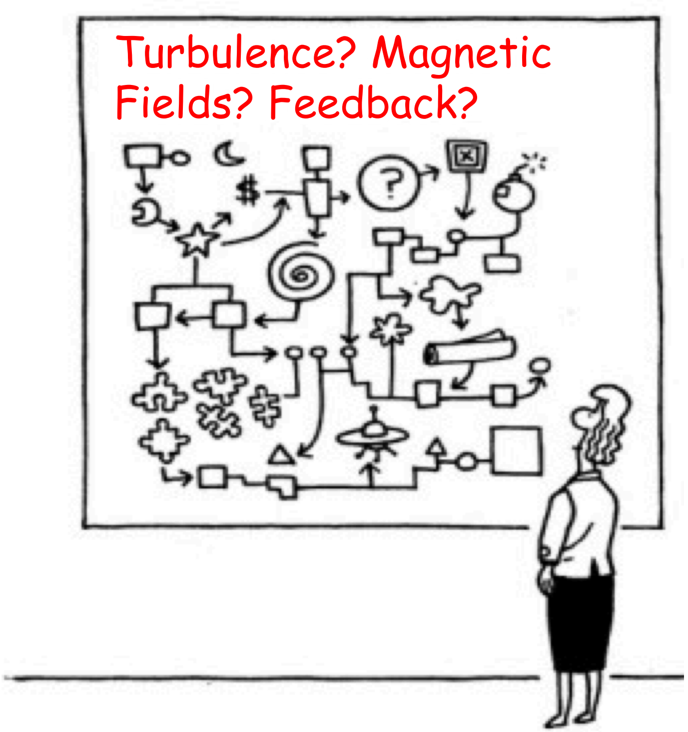
Australian
National
University

Australian Government
Australian Research Council

Image Credit: ESA and the HFI Consortium, IRAS 2010

Two Points

1) Star Formation is Messy


Turbulence? Magnetic Fields? Feedback?

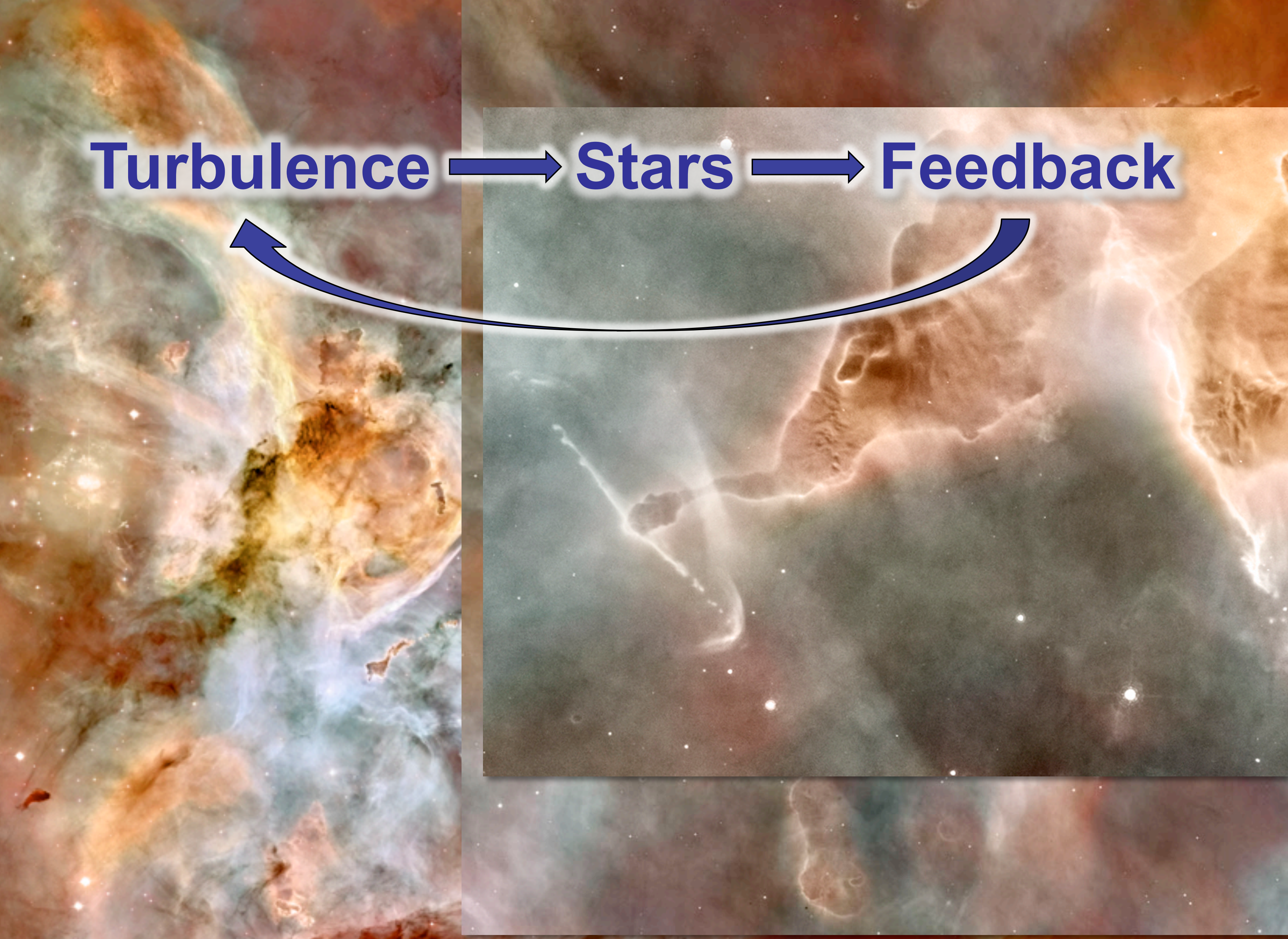
...unless you can come up with a theory

2) Star Formation is Inefficient

Turbulence → Density PDF

Density PDF → Star Formation Rate

Modeling jet and outflow feedback



Turbulence → Stars → Feedback

Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

Star Formation Rate

S. Guisard ESO

Pipe Nebula

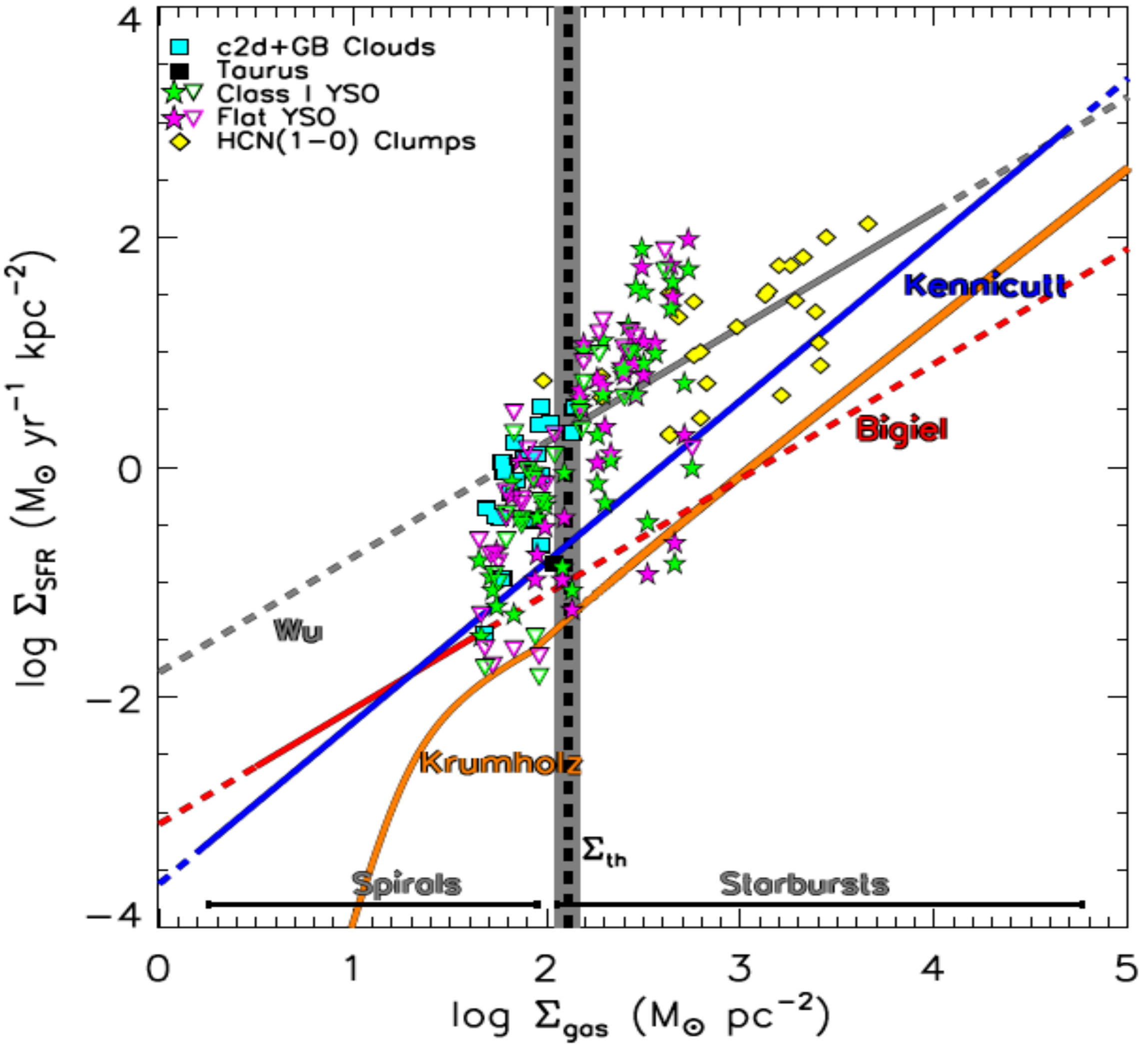
Rho Ophiuchi Cloud

$$\mathbf{SFR_{Oph} = 15 \times SFR_{Pipe}}$$

(Lada et al. 2010)

Universal star formation "law"?

Star Formation Rate (SFR)



Gas Density

Scatter?

↓

Observational scatter and physical variations caused by

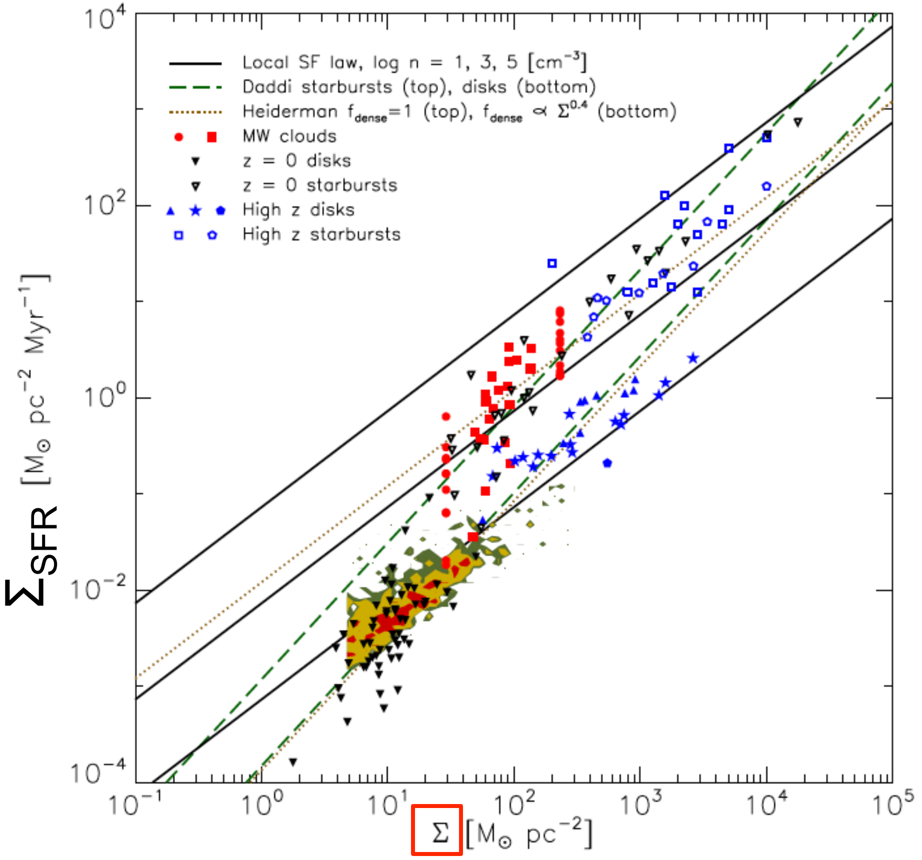
Turbulence

(Heiderman et al. 2010; Lada et al. 2010, Gutermuth et al. 2011)

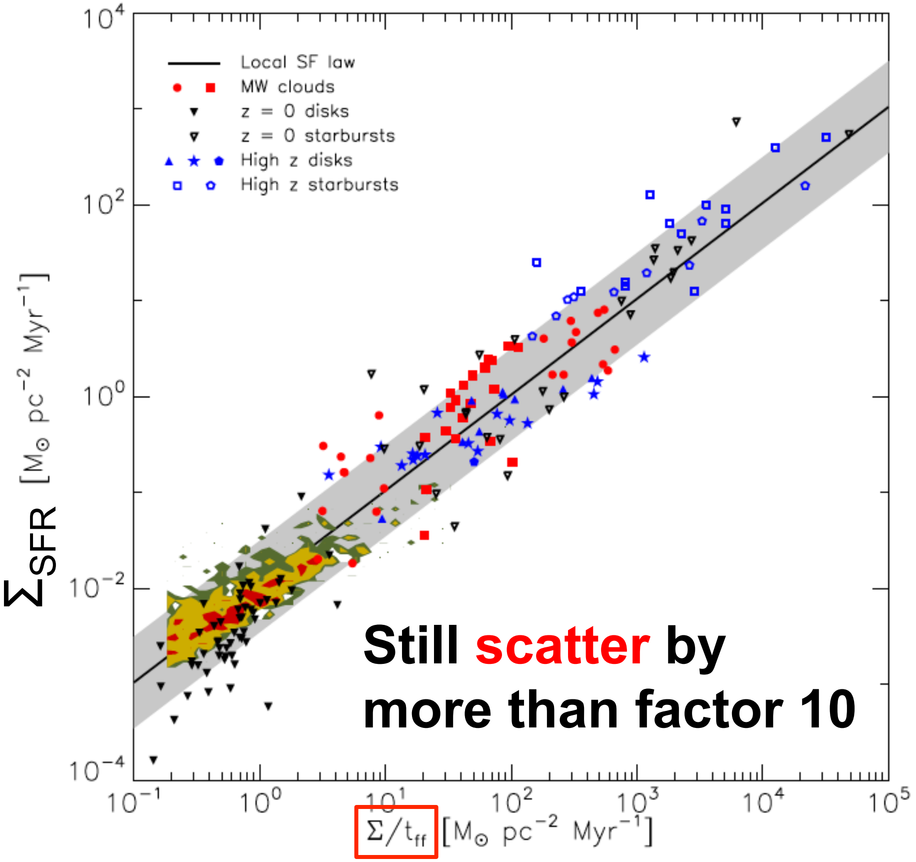
Physical Variations in the Universal Star Formation Law

Krumholz, Dekel, McKee (2012)

A more universal star formation "law" →



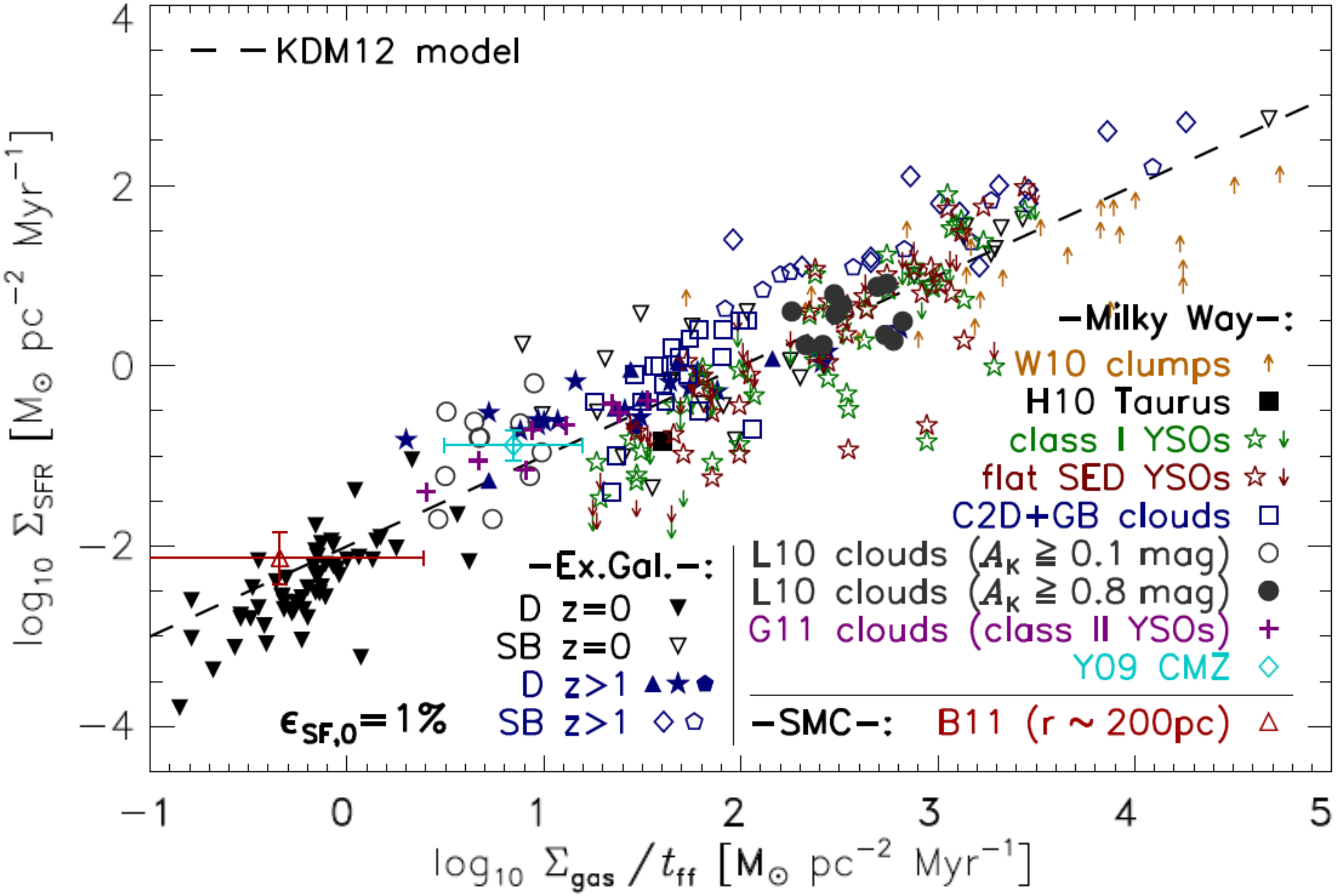
just Σ_{gas}
(classical Kennicutt-Schmidt relation)



Still scatter by more than factor 10

divide Σ_{gas}
by single (mean)
freefall time t_{ff}

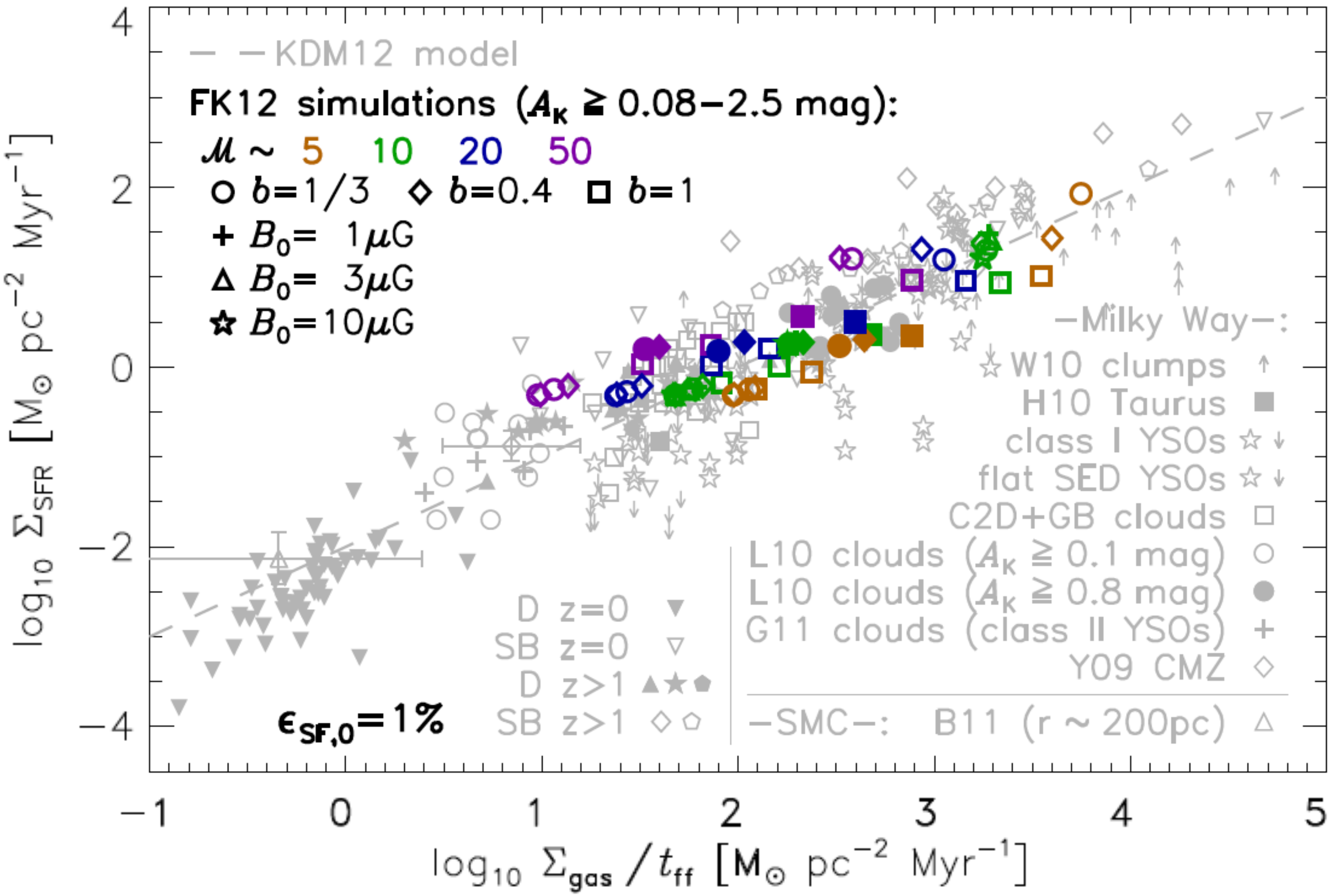
Physical Variations in the Universal Star Formation Law



→ Scatter/Non-Universality caused by variations of the Turbulence (Mach number, Driving, Virial parameter)

Federrath (2013, MNRAS 436, 3167)

Physical Variations in the Universal Star Formation Law



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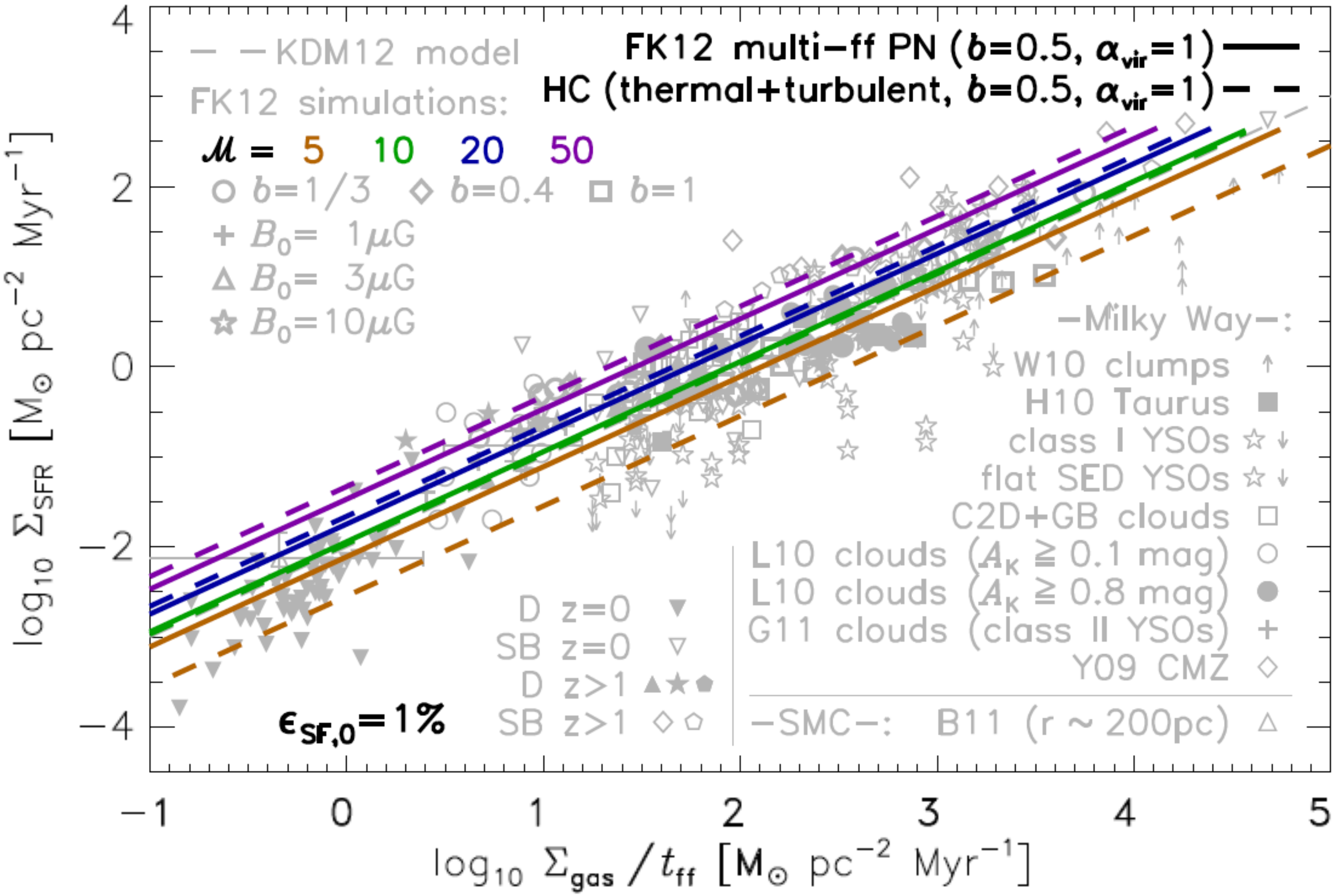
Physical Variations in the Universal Star Formation Law



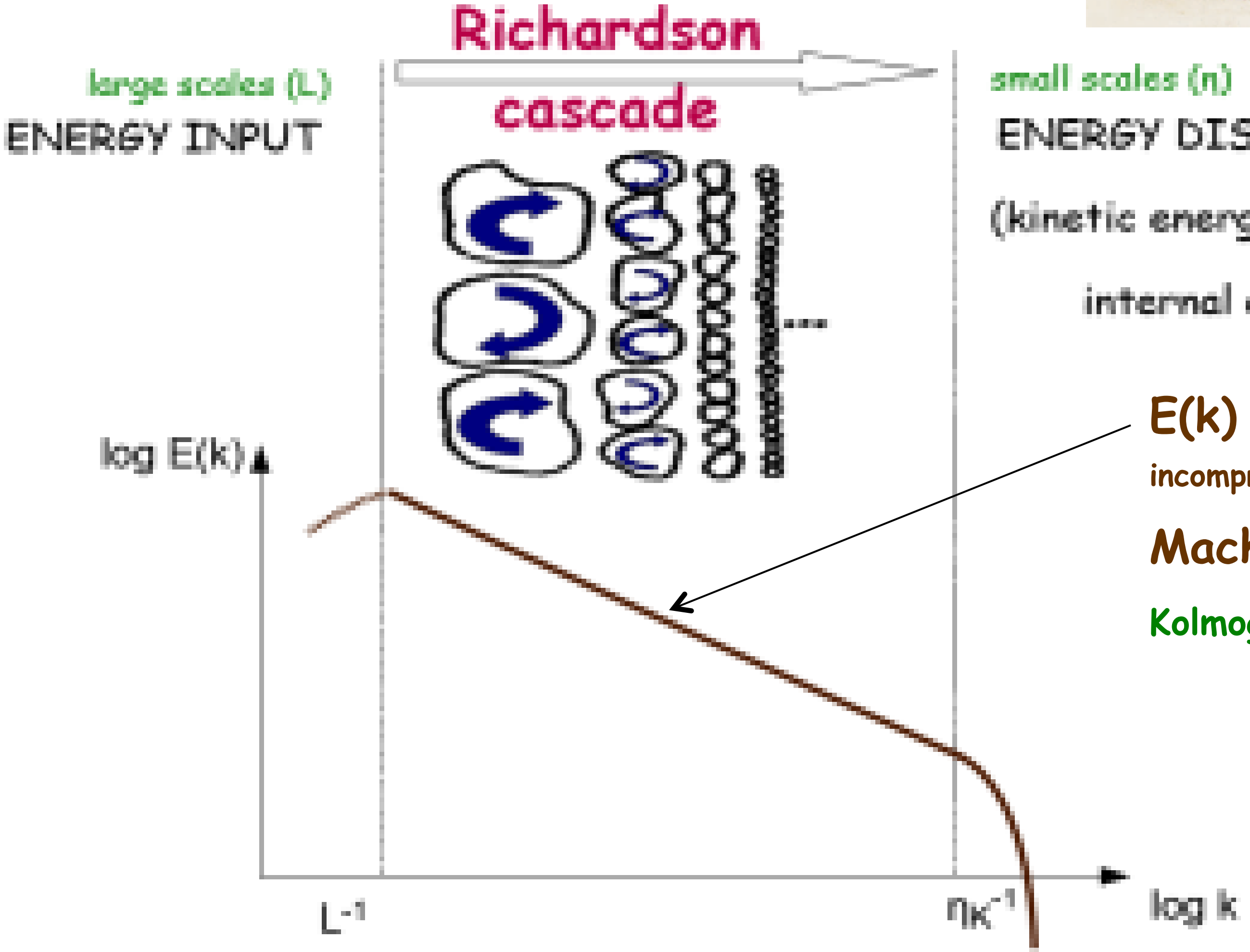
→ Scatter/Non-Universality caused by variations of the Turbulence
(Mach number, Driving, Virial parameter)

Federrath (2013, MNRAS 436, 3167)

Turbulence

- **Reynolds numbers > 1000**
- **Kinetic energy cascade**

Leonardo da Vinci



$E(k) \sim k^{-5/3} \sim k^{-1.67}$

incompressible

$\boxed{V \sim L^{1/3}}$

Mach < 1

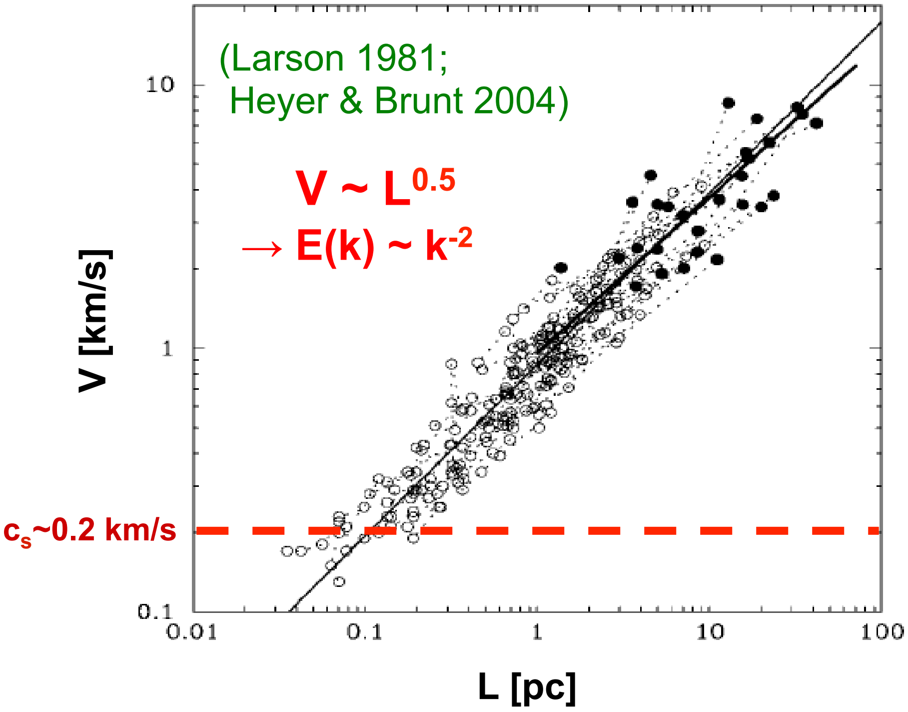
Kolmogorov (1941)

Interstellar Turbulence – scaling

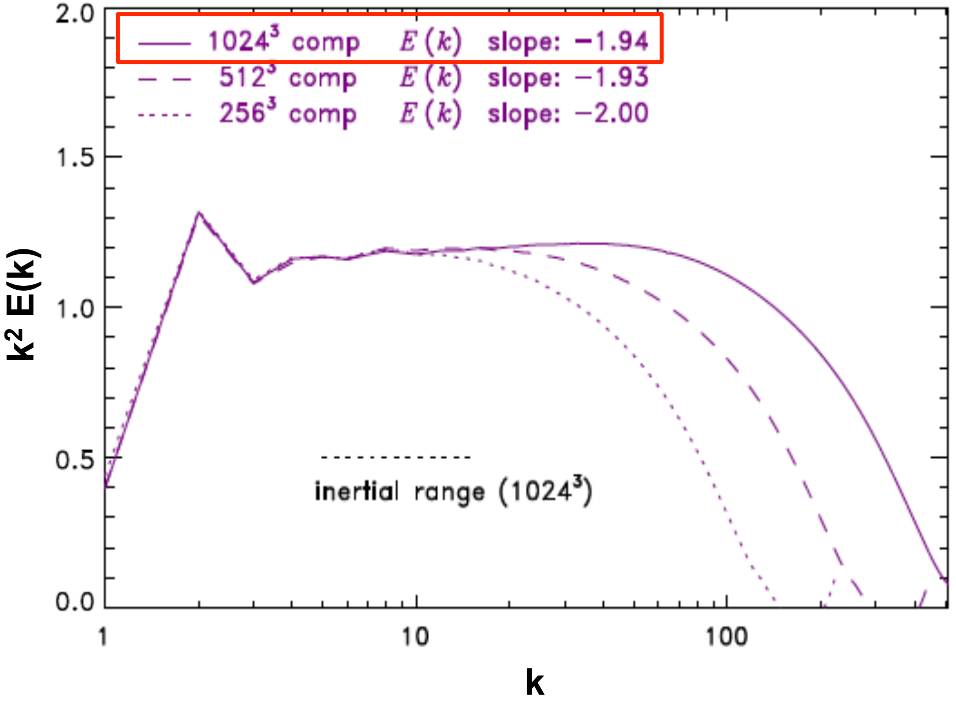
BUT: **Larson (1981) relation:** $E(k) \sim k^{-1.8\text{–}2.0}$

(see also Heyer & Brunt 2004; Roman-Duval et al. 2011)

Observation



Simulation

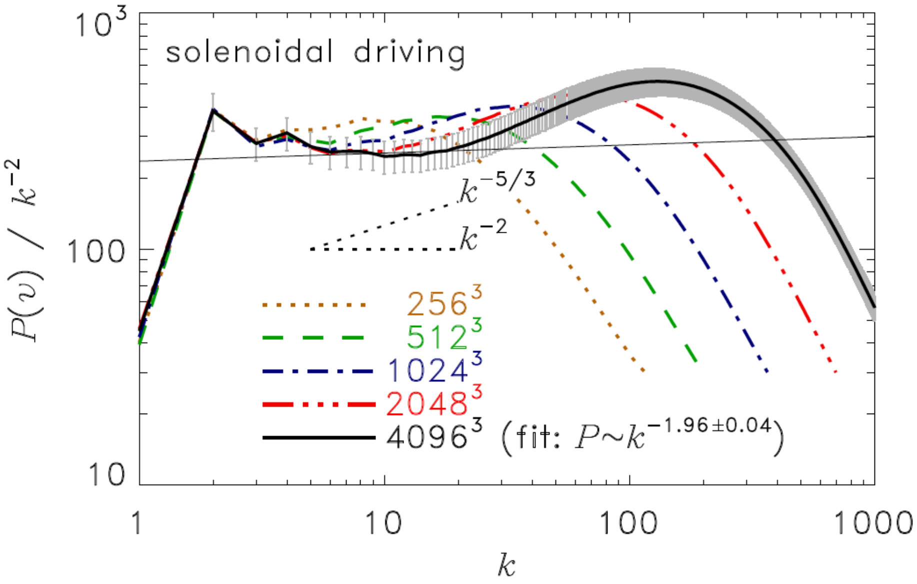


Supersonic, compressible turbulence has steeper $E(k) \sim k^{-1.9}$ than Kolmogorov ($E \sim k^{-5/3}$)

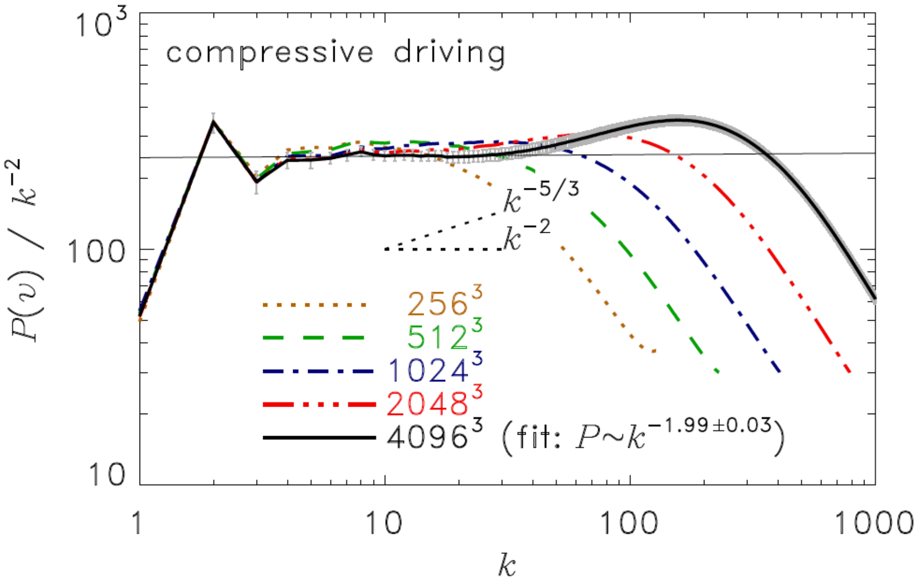
Federrath et al. (2010); see also Kritsuk et al. (2007)

Supersonic turbulence @4096^3 grid cells

Solenoidal forcing



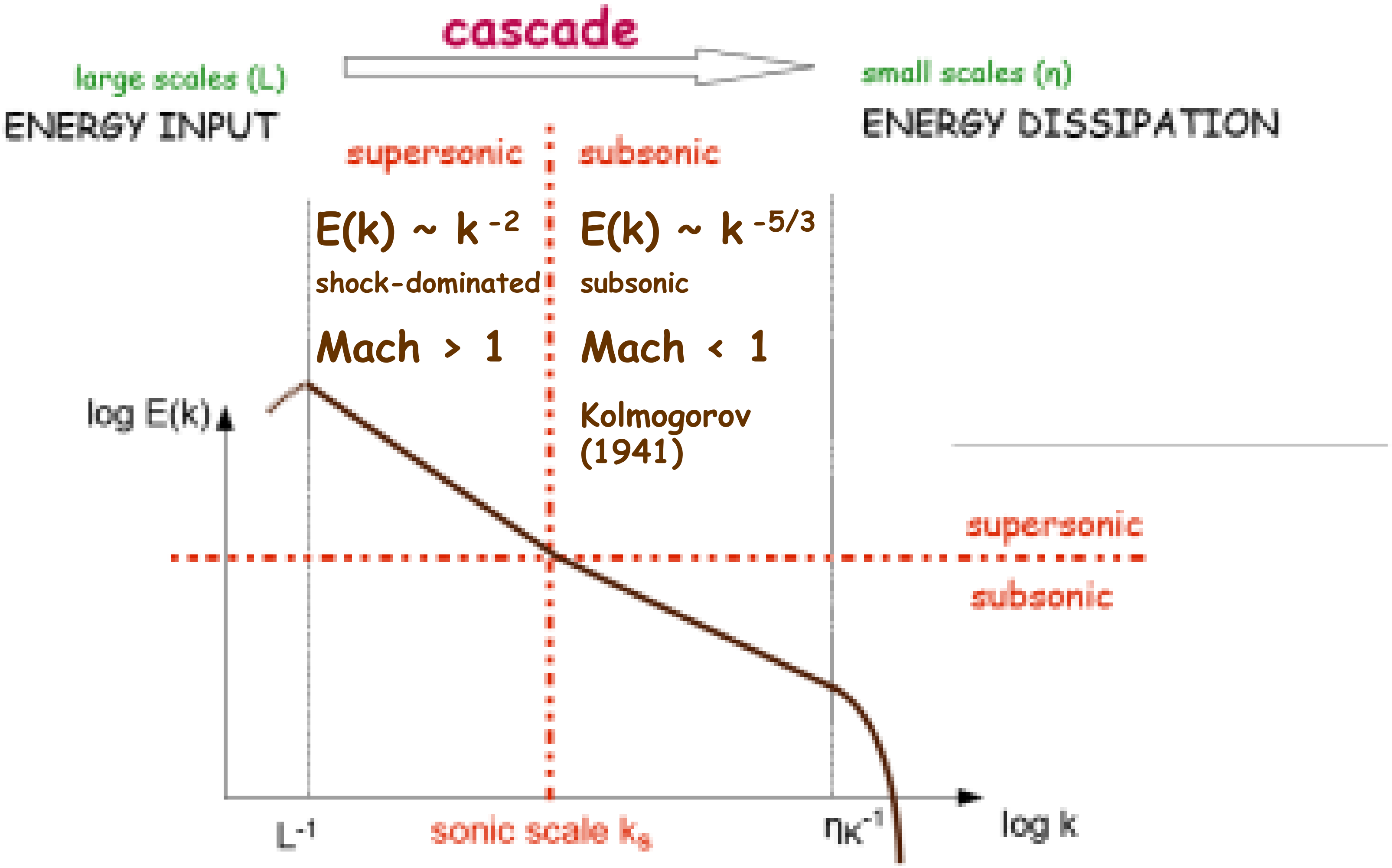
Compressive forcing



Federrath 2013, MNRAS 436, 1245

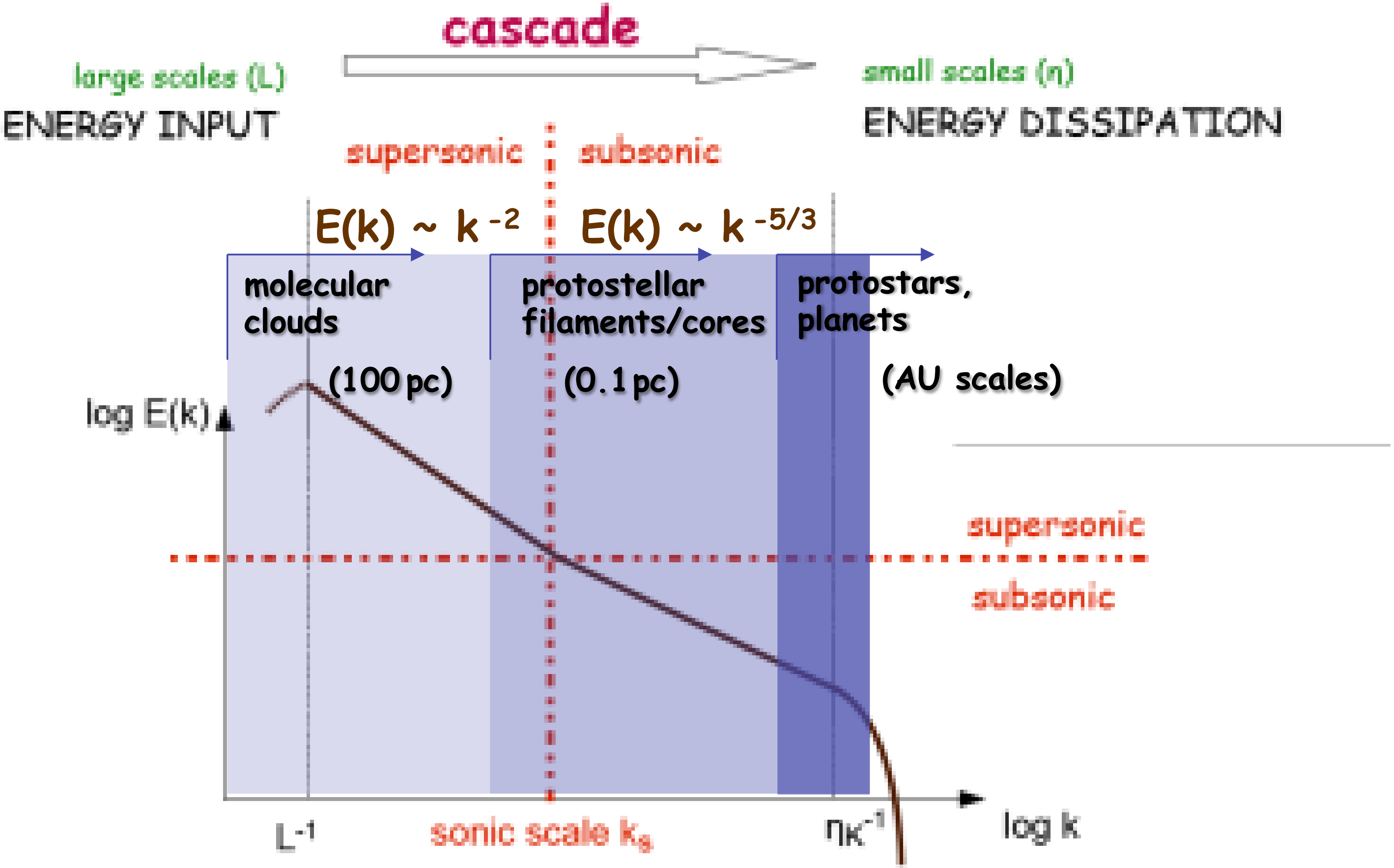
Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



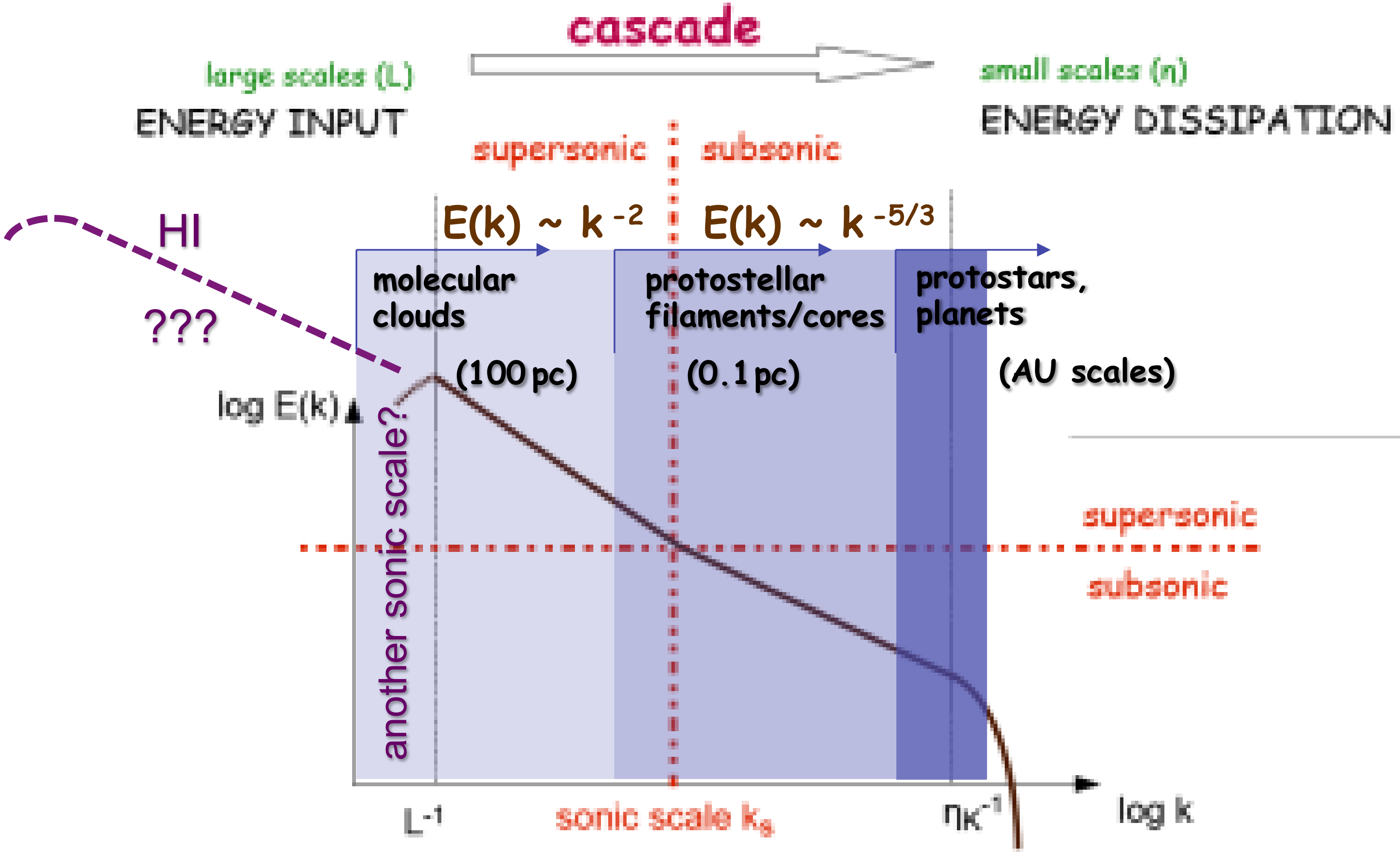
Interstellar Turbulence

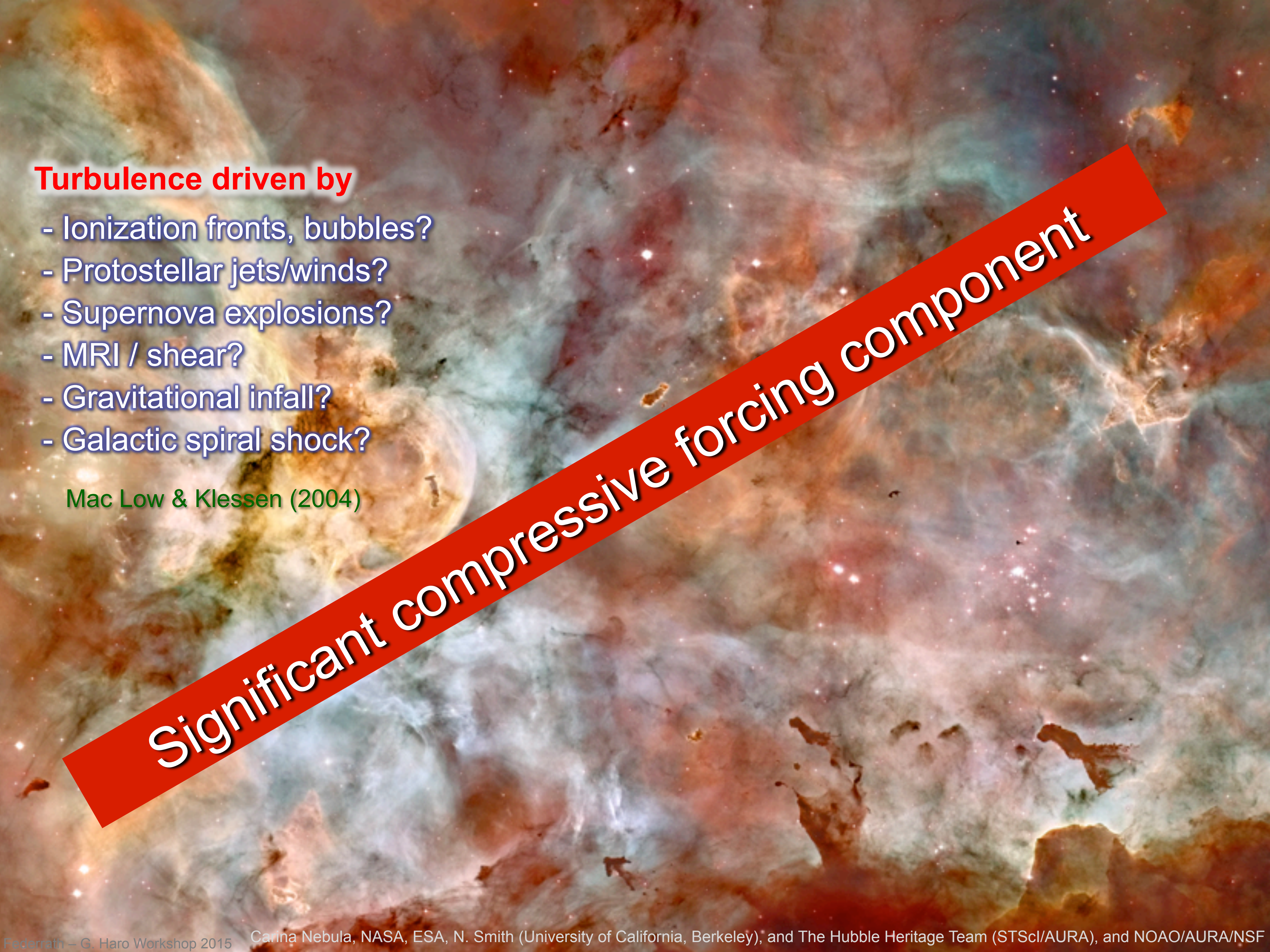
- Reynolds numbers > 1000
- Kinetic energy cascade



Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade





Turbulence driven by

- Ionization fronts, bubbles?
- Protostellar jets/winds?
- Supernova explosions?
- MRI / shear?
- Gravitational infall?
- Galactic spiral shock?

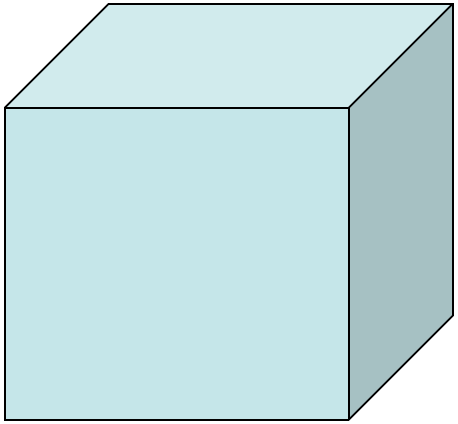
Mac Low & Klessen (2004)

Significant compressive forcing component

Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

Turbulence driving – solenoidal versus compressive

“Turbulence in a box”



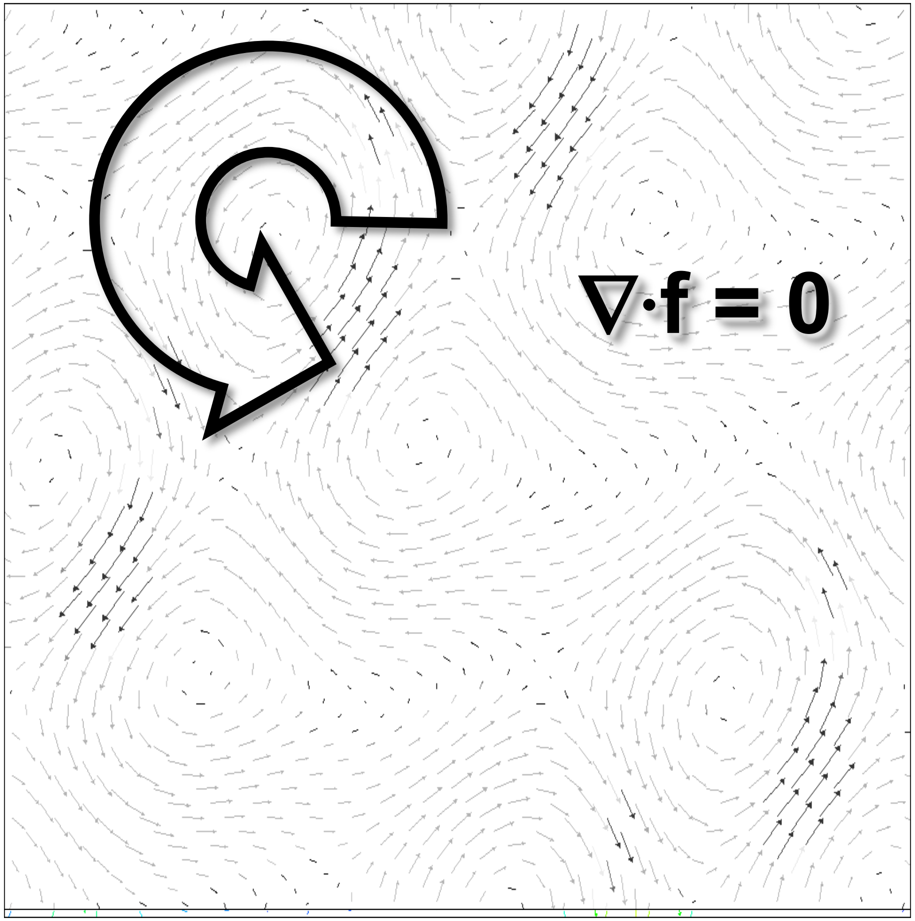
- 3D, periodic boundaries
- Driven to supersonic speeds (Mach 2 - 50)
- Large-scale **Forcing Term f**

e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Kowal+2007, Dib+2008, Offner+2008, Schmidt+2009, Burkhart +2009, Cho+2009, Lemaster+2009, Glover+2010, Price+2011, DelSordo+2011, Collins +2012, Walch+2012, Scannapieco+2012, Pan+2012, Micic+2012, Robertson+2012, Price+2012, Bauer+2012 +++

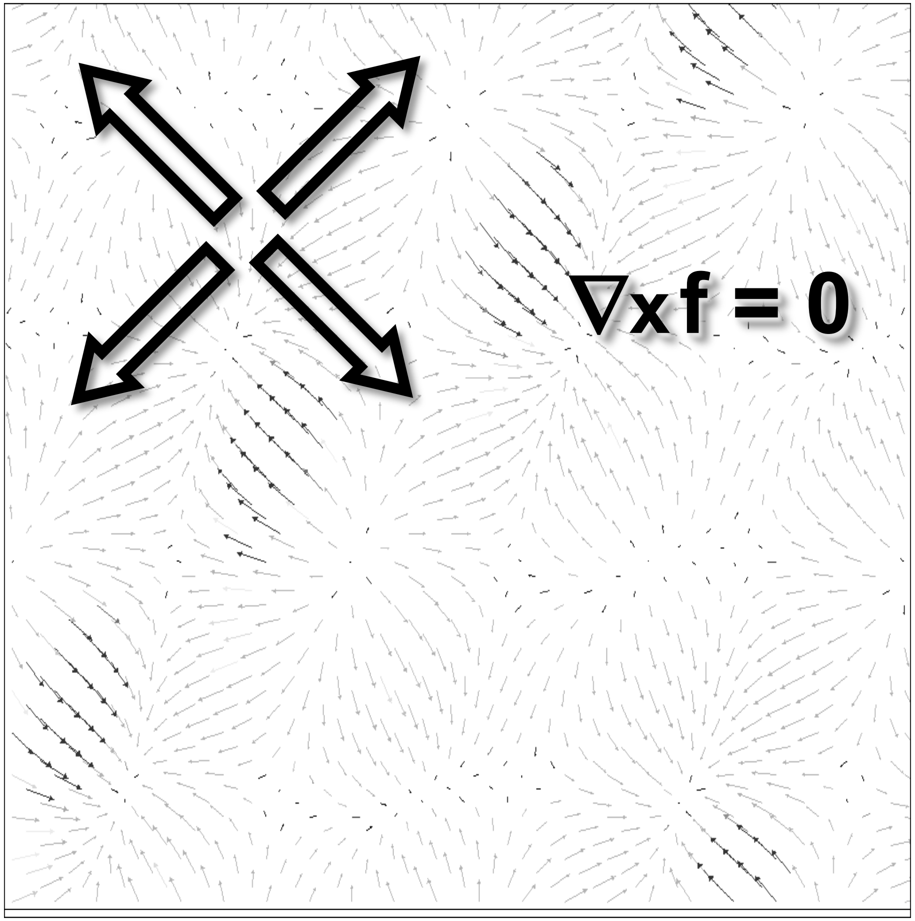
Turbulence driving – solenoidal versus compressive

Ornstein-Uhlenbeck process (stochastic process with autocorrelation time)
→ **forcing varies smoothly in space and time,**
following a well-defined random process

Solenoidal forcing



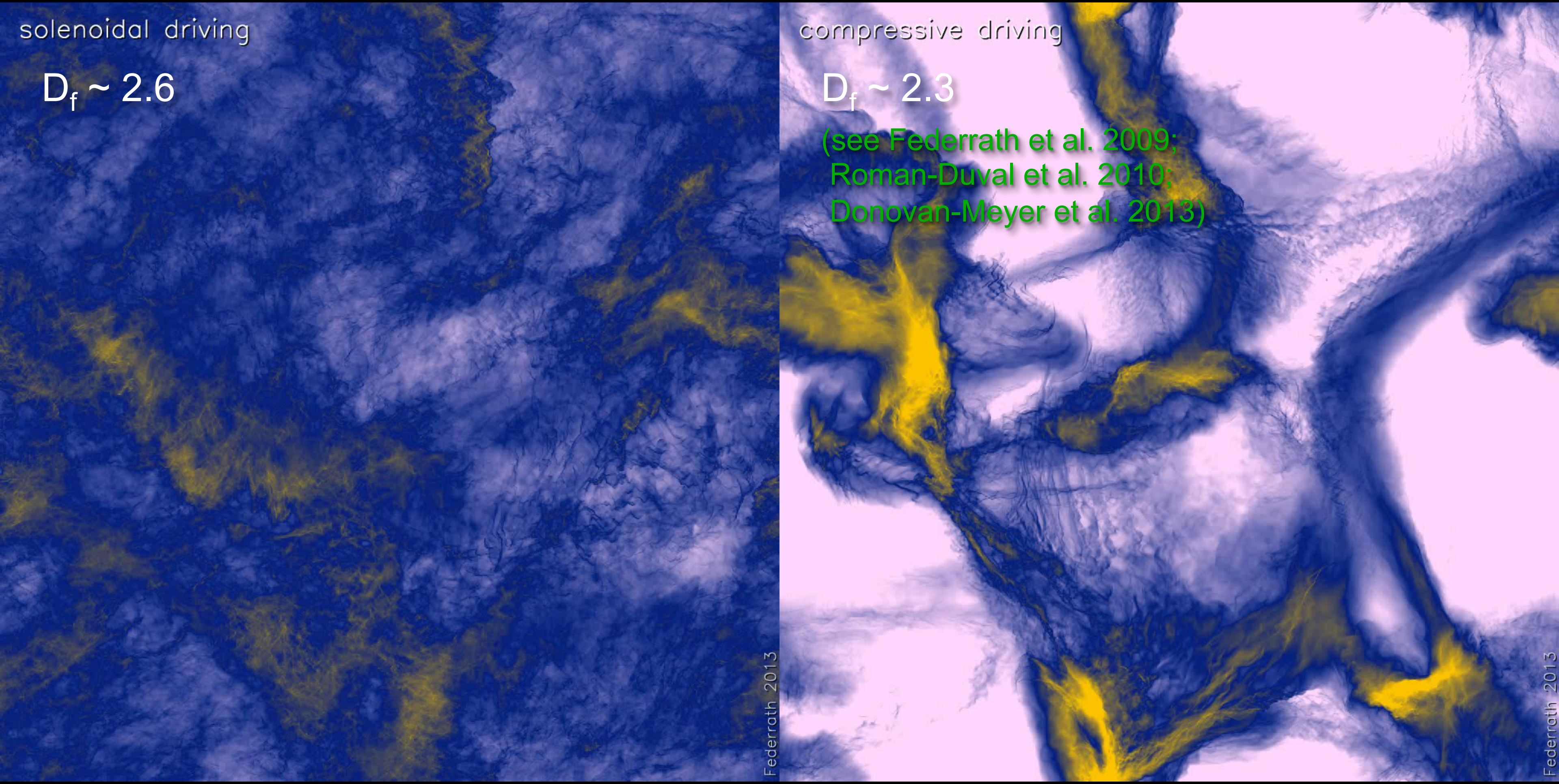
Compressive forcing



Turbulence driving – solenoidal versus compressive

solenoidal forcing Column Density compressive forcing

Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/supersonic/supersonic.shtml



$D_f \sim 2.6$

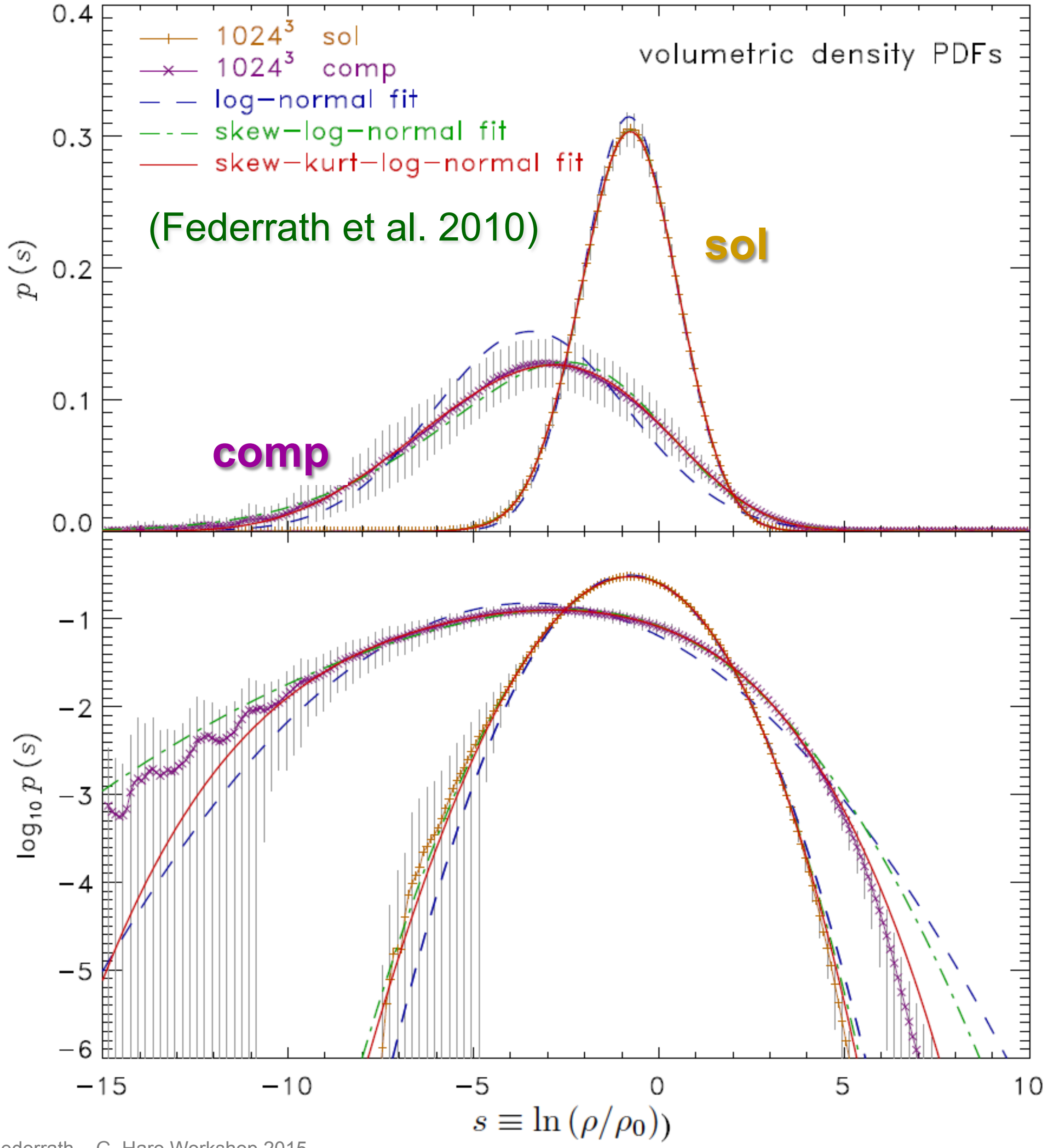
$D_f \sim 2.3$

(see Federrath et al. 2009; Roman-Duval et al. 2010; Donovan-Meyer et al. 2013)

Compressive forcing produces stronger density enhancements

(Federrath 2013, MNRAS 436, 1245: Supersonic turbulence @ 4096^3 grid cells)

The density PDF



Density PDF

log-normal:

$$p_s\,\mathrm{d}s = \frac{1}{\sqrt{2\pi\sigma_s^2}}\exp\left[-\frac{(s-\langle s\rangle)^2}{2\sigma_s^2}\right]\mathrm{d}s$$

$$s \equiv \ln(\rho/\rho_0)$$

Vazquez-Semadeni (1994); Padoan et al. (1997); Ostriker et al. (2001); Hopkins (2013)

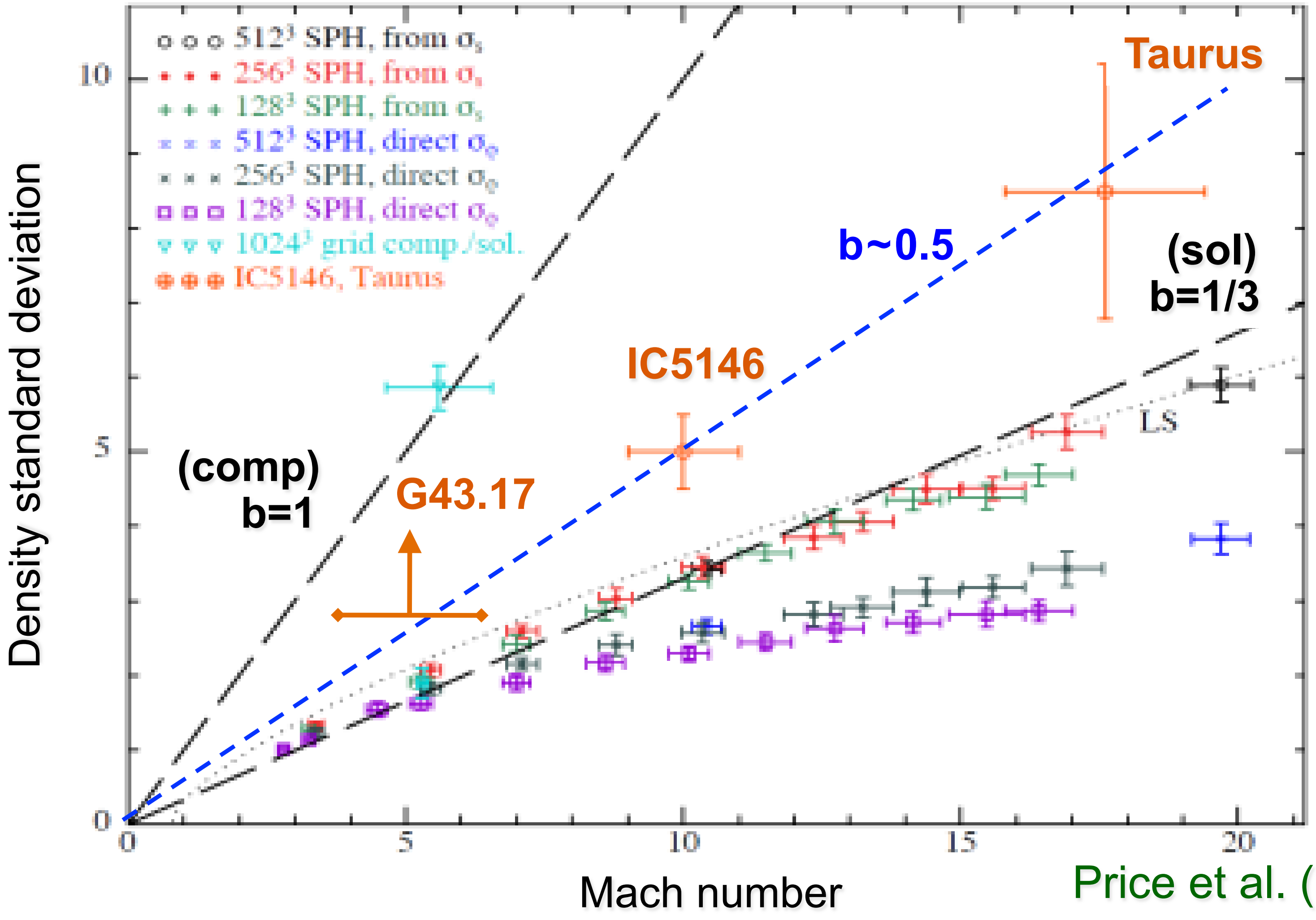
$$\boxed{\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right)}$$

b = 1/3 (sol)

b = 1 (comp)

Federrath et al. (2008, 2010); Price et al. (2011); Konstandin et al. (2012); Molina et al. (2012); Federrath & Banerjee (2014); Nolan et al. (2015)

The density PDF



2D → 3D conversion

$\sigma_{N/N_0} \rightarrow \sigma_{\rho/\rho_0}$

(Brunt et al. 2010a,b)

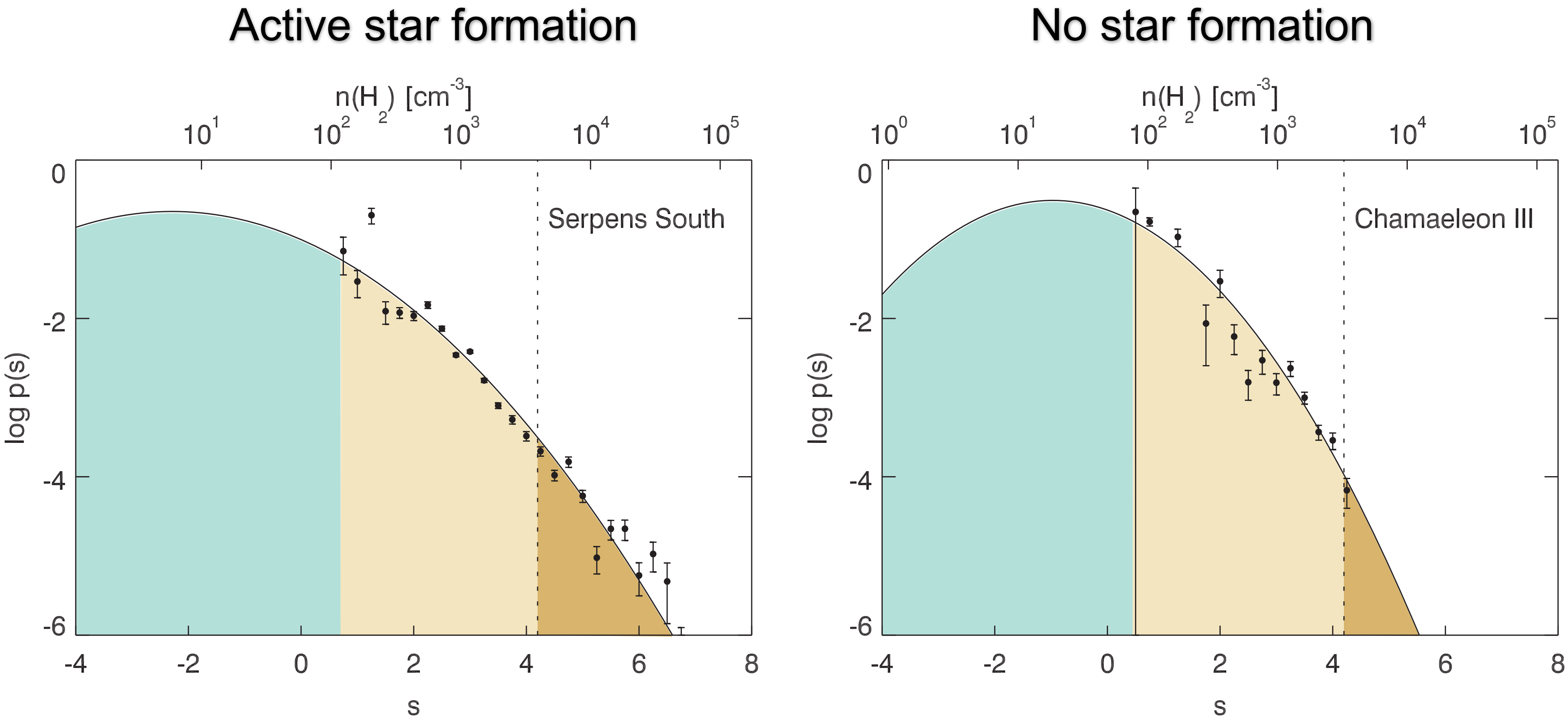
Price et al. (2011)

Padoan et al. (1997), Brunt (2010), Burkhart & Lazarian (2012), Ginsburg et al. (2013)

$$\boxed{\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right)} \xrightarrow{p(s)} \boxed{\sigma_{\rho/\rho_0} = b\,\mathcal{M}}$$

Compressive forcing and/or gravity required to explain observations

PDF → The dense gas fraction



Kainulainen, Federrath, Henning (2014, *Science* 344, 183)

Power-law tails →
gravitational collapse

Schneider et al. 2012–2015; Federrath & Klessen 2013;
Girichidis et al. 2014; Sadavoy et al. 2014, Myers 2015

2D → 3D
conversion

(Brunt et al. 2010a,b)

Turbulence → Density PDF

Density PDF → Star Formation Rate

Modeling jet and outflow feedback

Density PDF → Star Formation Rate

Density PDF is key for star formation theories:

- **Initial Mass Function** (Padoan & Nordlund 02, Hennebelle & Chabrier 08,09,
- **Star Formation Efficiency** (Elmegreen 08, Federrath & Klessen 13)
- **Kennicutt-Schmidt relation** (Elmegreen 02, Krumholz & McKee 05, Tassis 07, Ostriker+10, Elmegreen 11, Veltchev+11, Hopkins 12, Federrath 13, Salim+15)
- **Star Formation Rate** (Krumholz & McKee 05, Padoan & Nordlund 11, Renaud+12, Federrath & Klessen 2012)

All based on integrals over the turbulent density PDF

$$\mathrm{SFR}_{\mathrm{ff}} = \frac{\epsilon_{\mathrm{core}}}{\phi_t} \int_{x_{\mathrm{crit}}}^{\infty} x p(x)\, dx$$

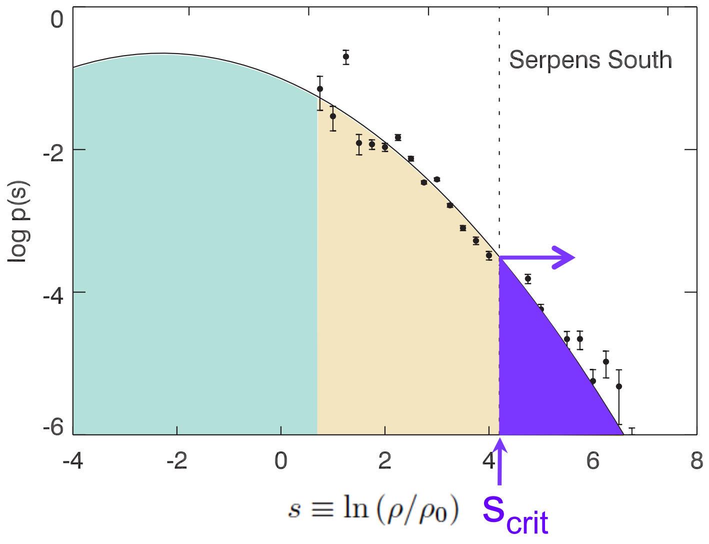
Krumholz & McKee (2005), Padoan & Nordlund (2011); Hennebelle & Chabrier (2011,2013)

The Star Formation Rate

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \overbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}^{\textbf{freefall time}} \overbrace{\frac{\rho}{\rho_0}}^{\textbf{mass fraction}} p(s)\,\mathrm{d}s$$



Hennebelle & Chabrier (2011) : “multi-freefall model”

Federrath & Klessen (2012)

The Star Formation Rate

Statistical Theory for the Star Formation Rate:

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s-s_0)^2}{2\sigma_s^2}\right)$$

$$s = \ln(\rho/\rho_0) \qquad t_{\mathrm{ff}}(\rho) = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

SFR ~ Mass/time

$$\begin{aligned}
\mathrm{SFR}_{\mathrm{ff}} &= \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \overbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}^{\textbf{freefall time}} \overbrace{\frac{\rho}{\rho_0}}^{\textbf{mass fraction}} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s \\
&= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right)\left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\mathrm{crit}}}{\sqrt{2\sigma_s^2}}\right)\right]
\end{aligned}$$

Hennebelle & Chabrier (2011) : “multi-freefall model”

Federrath & Klessen (2012)

The Star Formation Rate

Statistical Theory for the Star Formation Rate:

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s-s_0)^2}{2\sigma_s^2}\right)$$

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SFR ~ Mass/time

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \overbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}^{\textbf{freefall time}} \overbrace{\frac{\rho}{\rho_0}}^{\textbf{mass fraction}} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s$$

$$= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\mathrm{crit}}}{\sqrt{2\sigma_s^2}}\right)\right]$$

Hennebelle & Chabrier (2011) : “multi-freefall model”

From sonic and Jeans scales:

$$s_{\mathrm{crit}} \propto \ln\left(\alpha_{\mathrm{vir}}\,\mathcal{M}^2\right)$$

(Krumholz & McKee 2005, Padoan & Nordlund 2011)

$$\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right)$$

(e.g., Federrath et al. 2008)

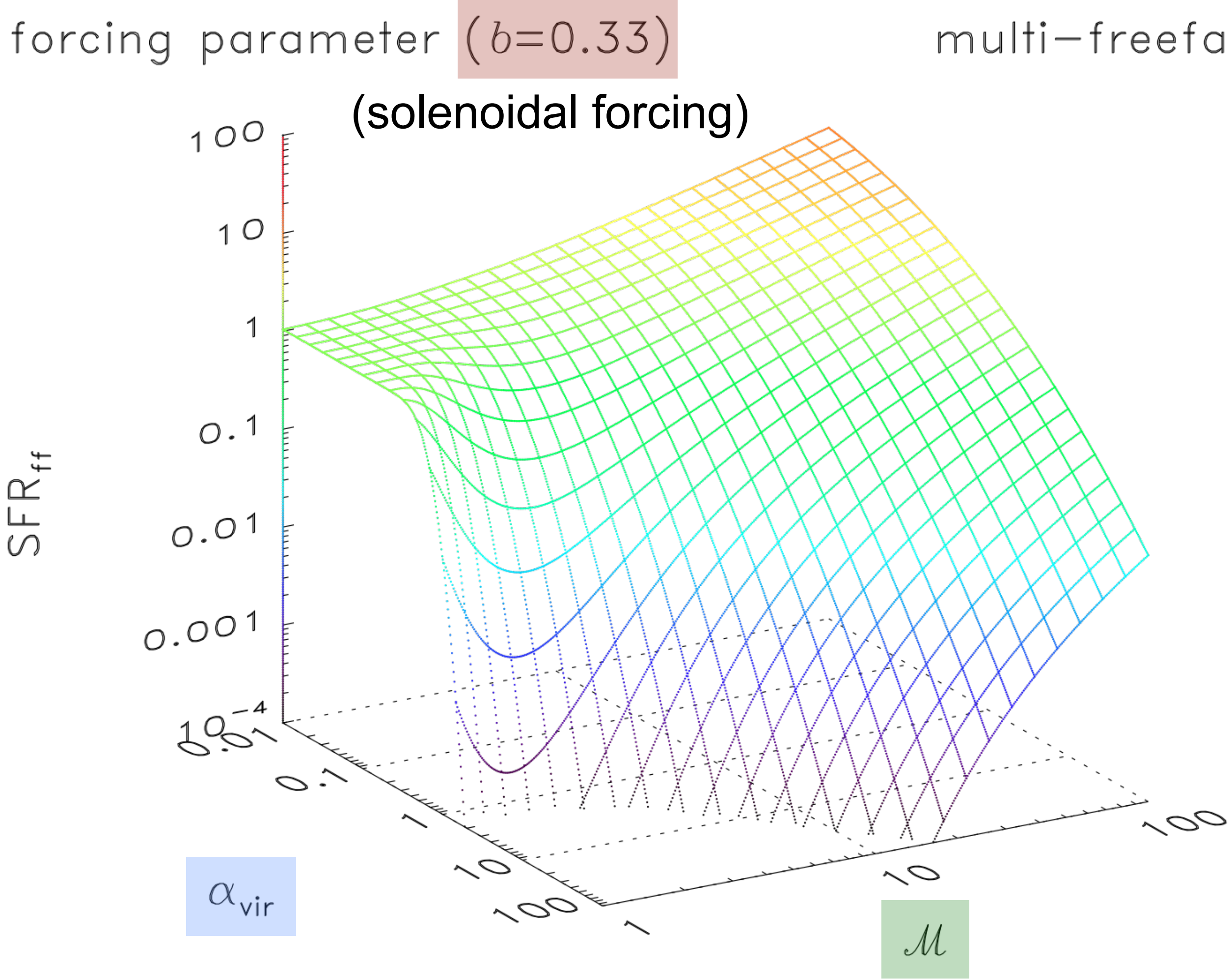
$$\mathrm{SFR}_{\mathrm{ff}} = \mathrm{SFR}_{\mathrm{ff}}\,(\underbrace{\alpha_{\mathrm{vir}}}_{2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}}, \underbrace{b}_{\textbf{forcing}}, \underbrace{\mathcal{M}}_{\textbf{Mach number}})$$

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

$$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\,(\alpha_{\mathrm{vir}}, b, \mathcal{M})$$

$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number**


forcing parameter (b=0.33)

multi−freefall

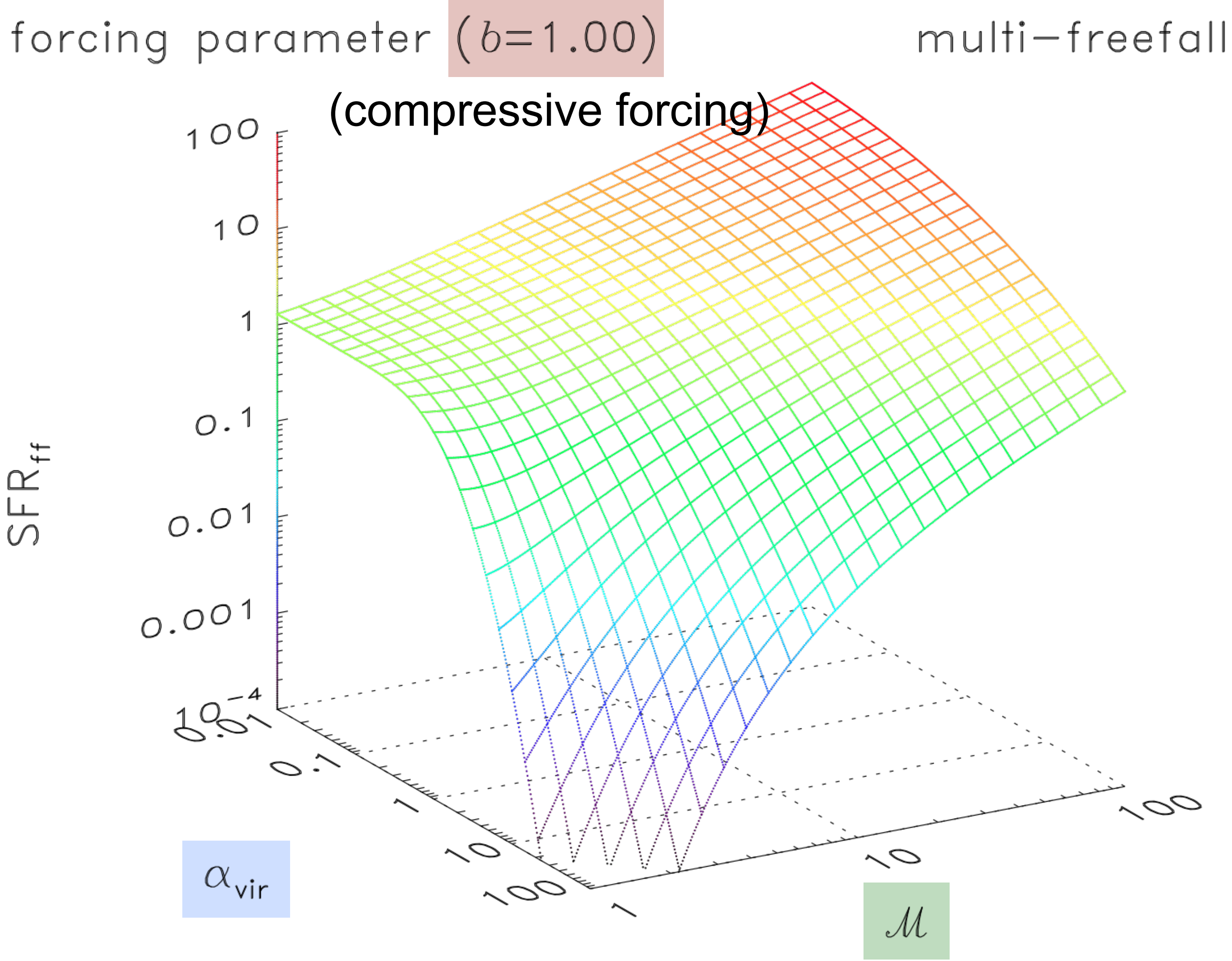
(solenoidal forcing)

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

$$\mathrm{SFR}_{\mathrm{ff}} = \mathrm{SFR}_{\mathrm{ff}}\left(\alpha_{\mathrm{vir}}, b, \mathcal{M}\right)$$

$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number**



(compressive forcing)

Federrath & Klessen (2012)

$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\left(\alpha_{\mathrm{vir}}, b, \mathcal{M}\right)$

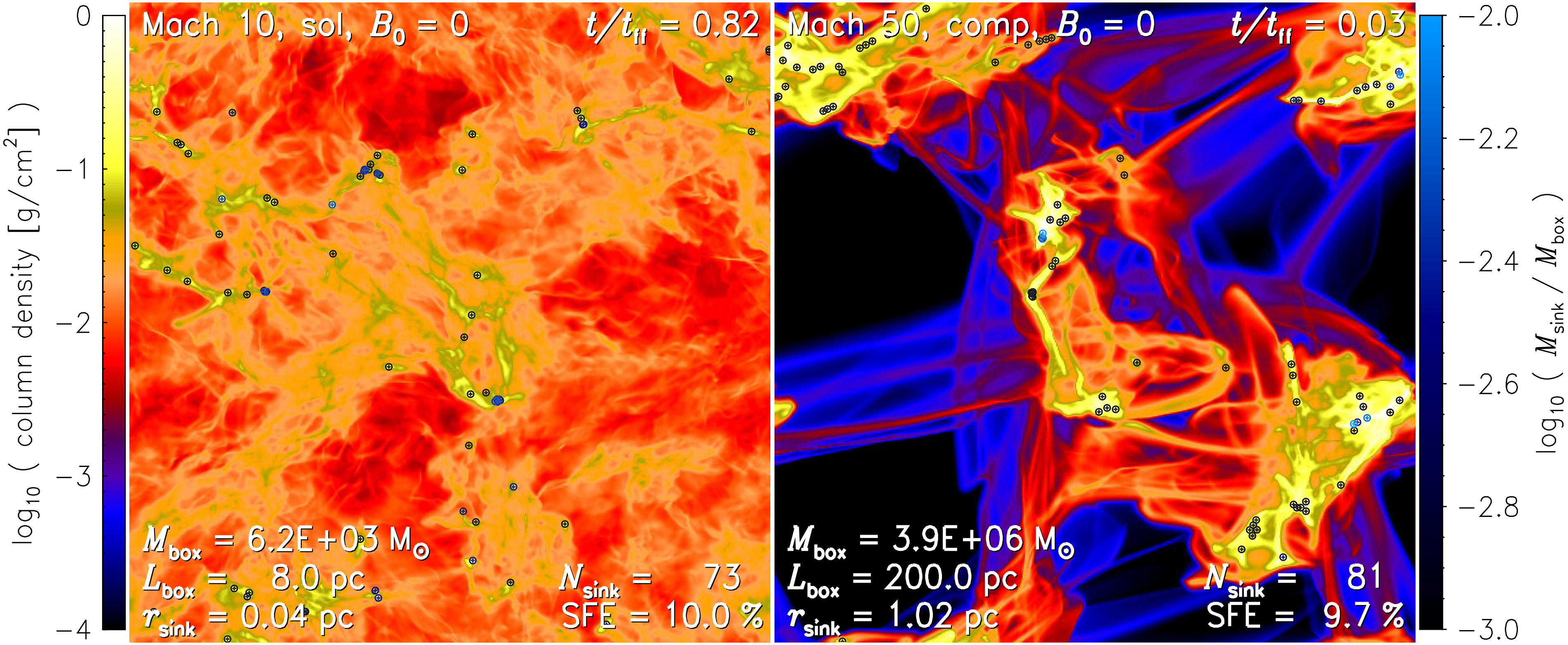
Density PDF → Star Formation Rate

Numerical Simulation varying the turbulent Mach number:

Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/sfr/sfr.shtml

Mach 10 solenoidal driving

Mach 50 compressive driving



$\mathrm{SFR_{ff}}$ (simulation) = **0.14** x **52** $\mathrm{SFR_{ff}}$ (simulation) = **7.3**

$\mathrm{SFR_{ff}}$ (theory) = **0.15** x **52** $\mathrm{SFR_{ff}}$ (theory) = **7.8**

Theory and Simulations agree well.

Federrath & Klessen (2012)

The Star Formation Rate – Magnetic fields

Statistical Theory for the Star Formation Rate:

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s-s_0)^2}{2\sigma_s^2}\right)$$

$$s = \ln(\rho/\rho_0) \qquad t_{\mathrm{ff}}(\rho) = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

SFR ~ Mass/time

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \overbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}^{\textbf{freefall time}} \overbrace{\frac{\rho}{\rho_0}}^{\textbf{mass fraction}} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s$$

$$= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\mathrm{crit}}}{\sqrt{2\sigma_s^2}}\right)\right]$$

MAGNETIC FIELD:

$$P_{\mathrm{th}} \rightarrow P_{\mathrm{th}} + P_{\mathrm{mag}} \qquad \mathcal{M} \rightarrow \mathcal{M}\left(1+\beta^{-1}\right)^{-1/2}$$

$$s_{\mathrm{crit}} \propto \ln\left(\alpha_{\mathrm{vir}}\, \mathcal{M}^2 \frac{\beta}{\beta+1}\right.$$

$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2 \frac{\beta}{\beta+1}\right.$$

$$\mathrm{SFR}_{\mathrm{ff}} = \mathrm{SFR}_{\mathrm{ff}}\left(\alpha_{\mathrm{vir}}, b, \mathcal{M}, \beta\right)$$

(Padoan & Nordlund 2011; Molina et al. 2012)

$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number** **plasma $\beta = P_{\mathrm{th}}/P_{\mathrm{mag}}$**

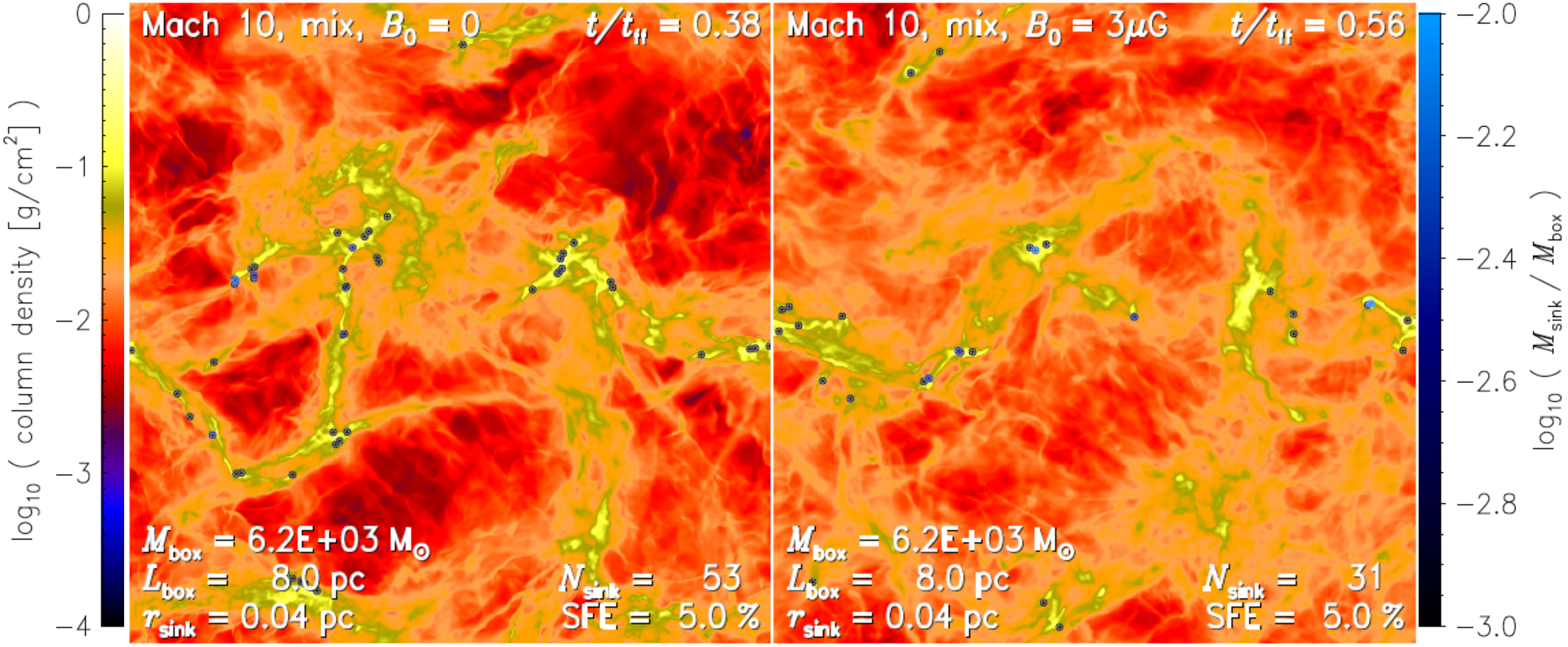
Federrath & Klessen (2012)

The Star Formation Rate – Magnetic fields

Numerical Test at Mach 10 with mixed forcing

Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/sfr/sfr.shtml

B=0 (M_A=∞, β = ∞) B=3μG (M_A=2.7, β = 0.2)



$\mathrm{SFR}_{\mathrm{ff}}$ (simulation) = **0.46** x**0.63** $\mathrm{SFR}_{\mathrm{ff}}$ (simulation) = **0.29**

$\mathrm{SFR}_{\mathrm{ff}}$ (theory) = **0.45** x**0.40** $\mathrm{SFR}_{\mathrm{ff}}$ (theory) = **0.18**

Magnetic field reduces SFR and fragmentation (by factor ~2).

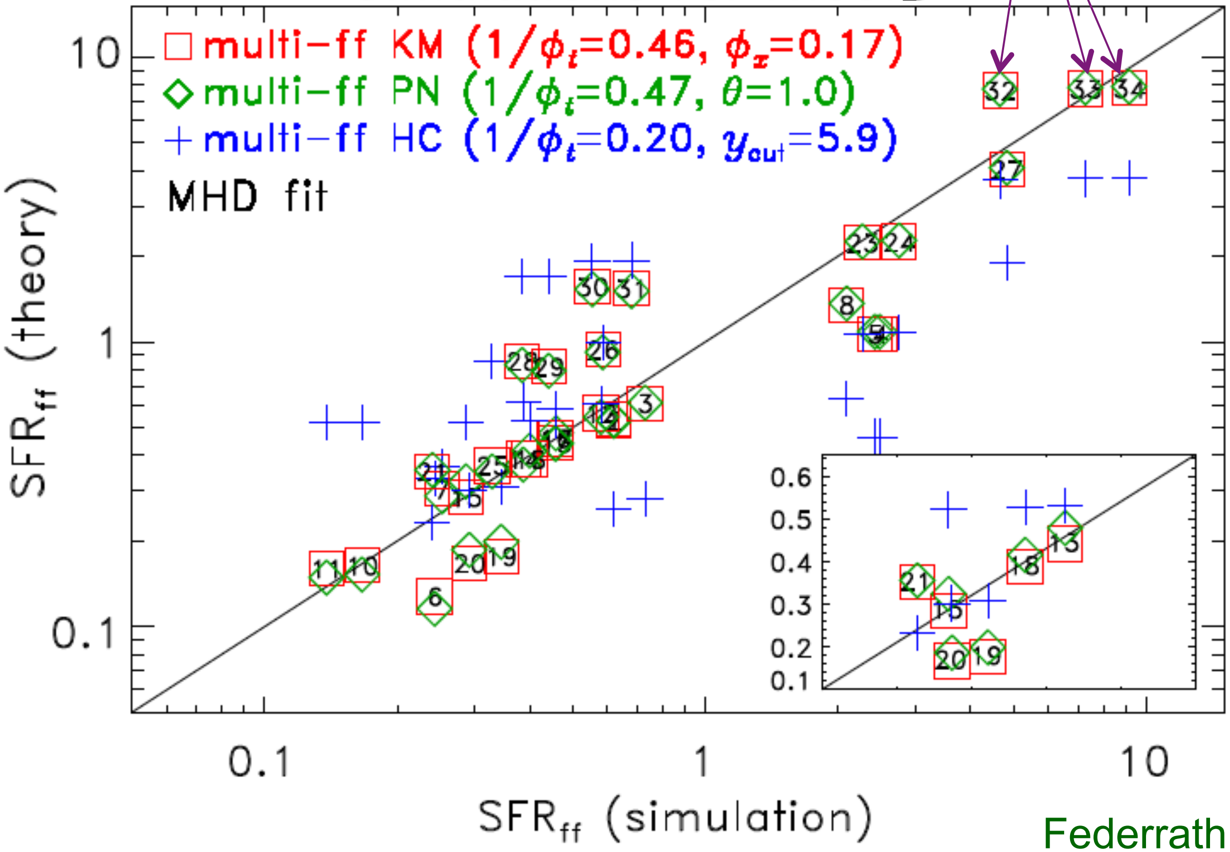
Federrath & Klessen (2012); see also Padoan & Nordlund (2011), Padoan et al. (2012)

The Star Formation Rate

Simulation study with

- cloud masses of 300 – 4×10^6 M$_\odot$
- solenoidal, mixed, and compressive forcing
- sonic Mach numbers 3 – 50
- Alfvén Mach numbers 1 – infinity

Simulations *vs.* Theory



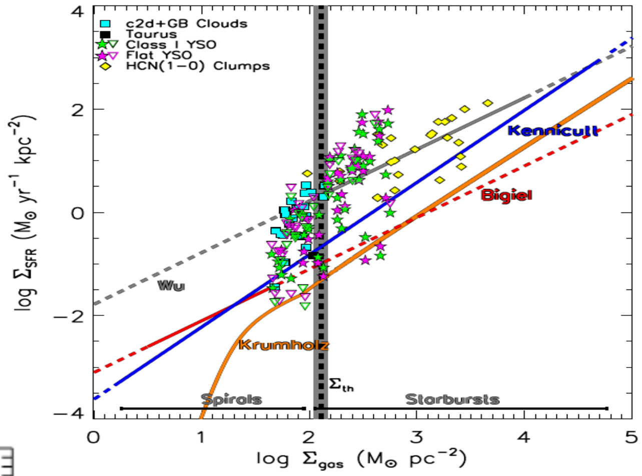
Convergence with numerical resolution

Federrath & Klessen (2012)

The Star Formation Rate

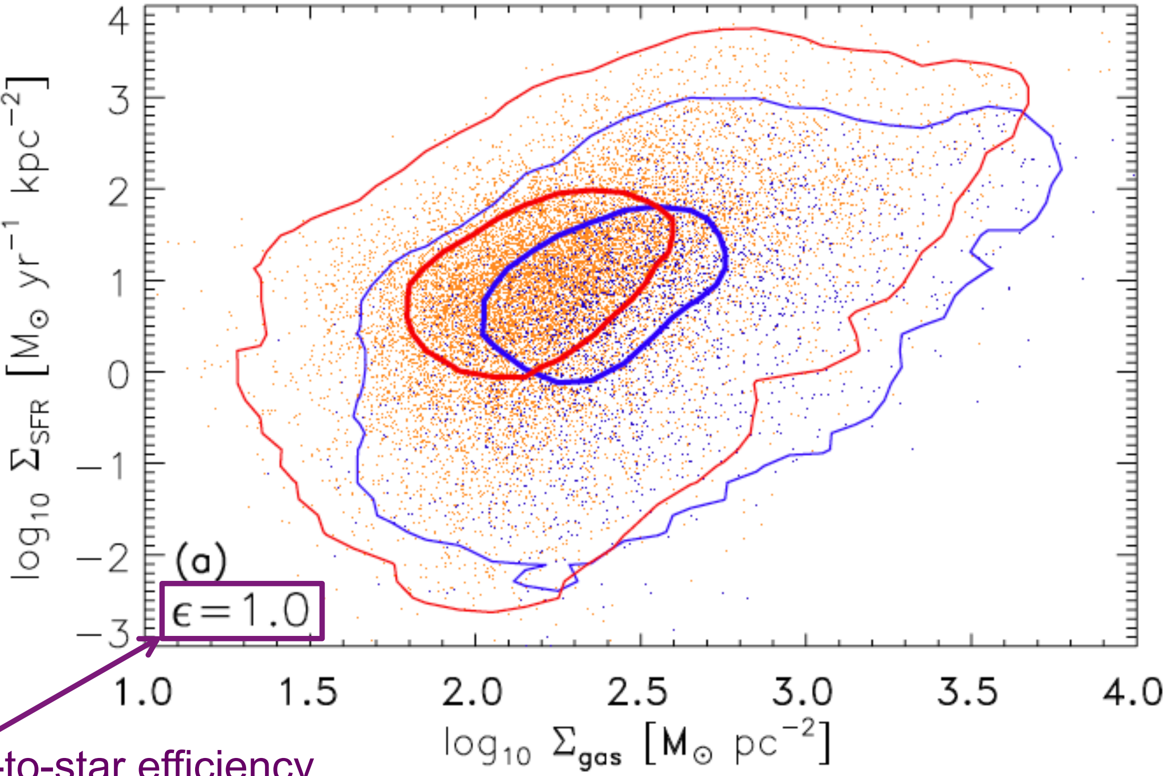
Simulation study with

- cloud masses of 300 – 4×10⁶ $M_\odot$
- solenoidal, mixed, and compressive forcing
- sonic Mach numbers 3 – 50
- Alfvén Mach numbers 1 – infinity



(Heiderman et al. 2010)

Simulations *vs.* Observations



core-to-star efficiency

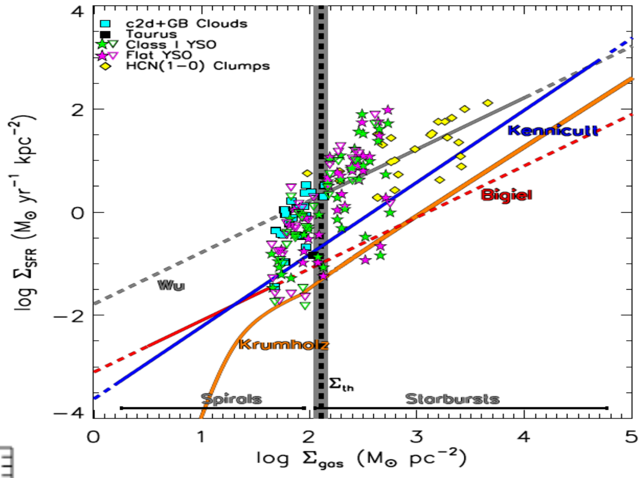
SFEs ~ 1-10% (Evans+2009; Burkert & Hartmann 2013; Federrath & Klessen 2013)

Federrath & Klessen (2012)

The Star Formation Rate

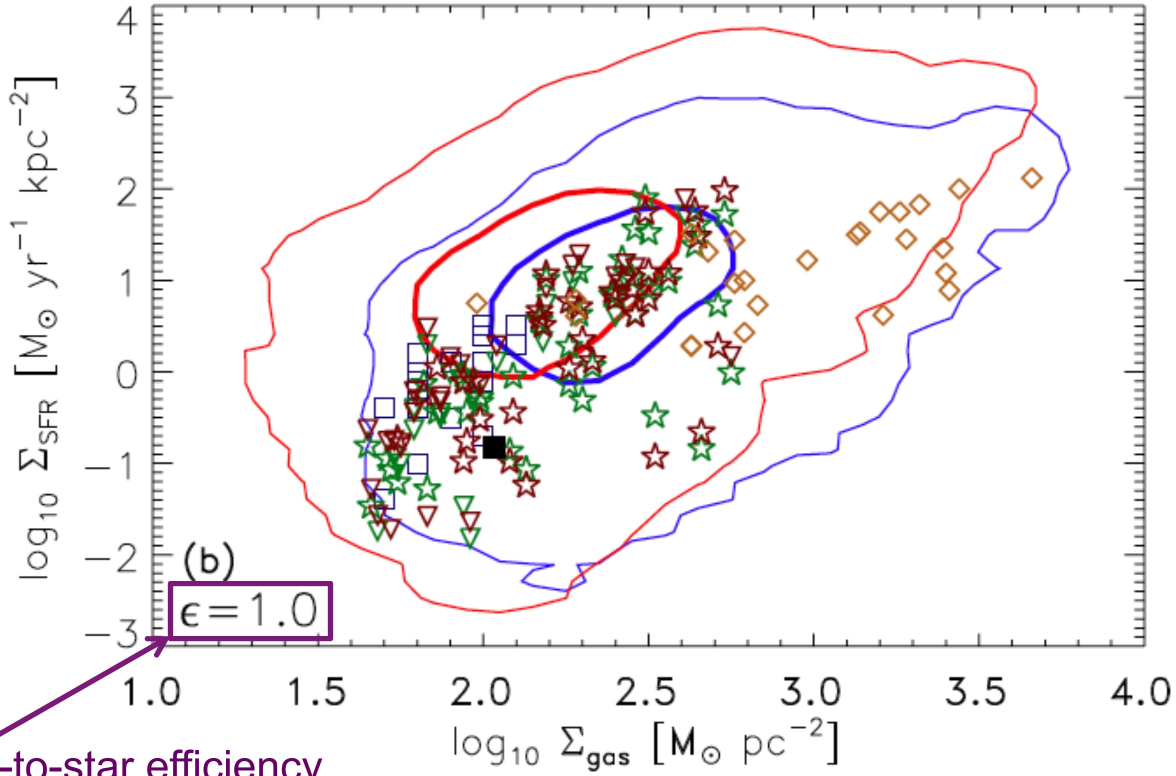
Simulation study with

- cloud masses of 300 – 4×10^6 M$_\odot$
- solenoidal, mixed, and compressive forcing
- sonic Mach numbers 3 – 50
- Alfvén Mach numbers 1 – infinity



(Heiderman et al. 2010)

Simulations *vs.* Observations



core-to-star efficiency

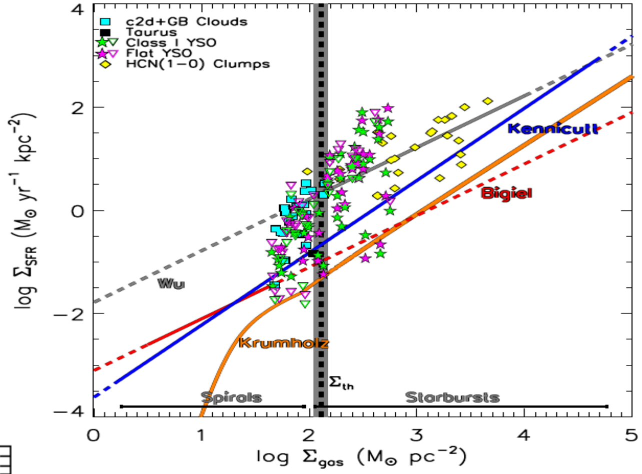
SFEs ~ 1-10% (Evans+2009; Burkert & Hartmann 2013; Federrath & Klessen 2013)

Federrath & Klessen (2012)

The Star Formation Rate

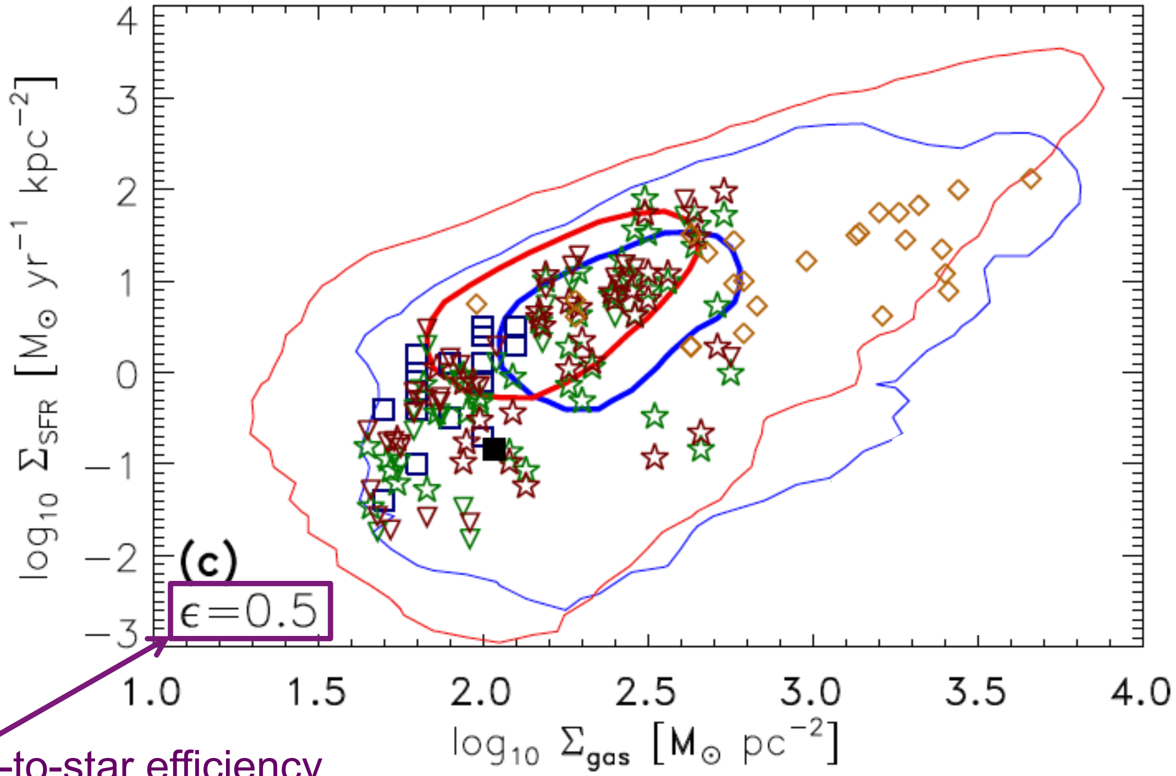
Simulation study with

- cloud masses of 300 – 4×10^6 M$_\odot$
- solenoidal, mixed, and compressive forcing
- sonic Mach numbers 3 – 50
- Alfvén Mach numbers 1 – infinity



(Heiderman et al. 2010)

Simulations *vs.* Observations



core-to-star efficiency

SFEs ~ 1-10% (Evans+2009; Burkert & Hartmann 2013; Federrath & Klessen 2013)

Federrath & Klessen (2012)

Turbulence → Density PDF

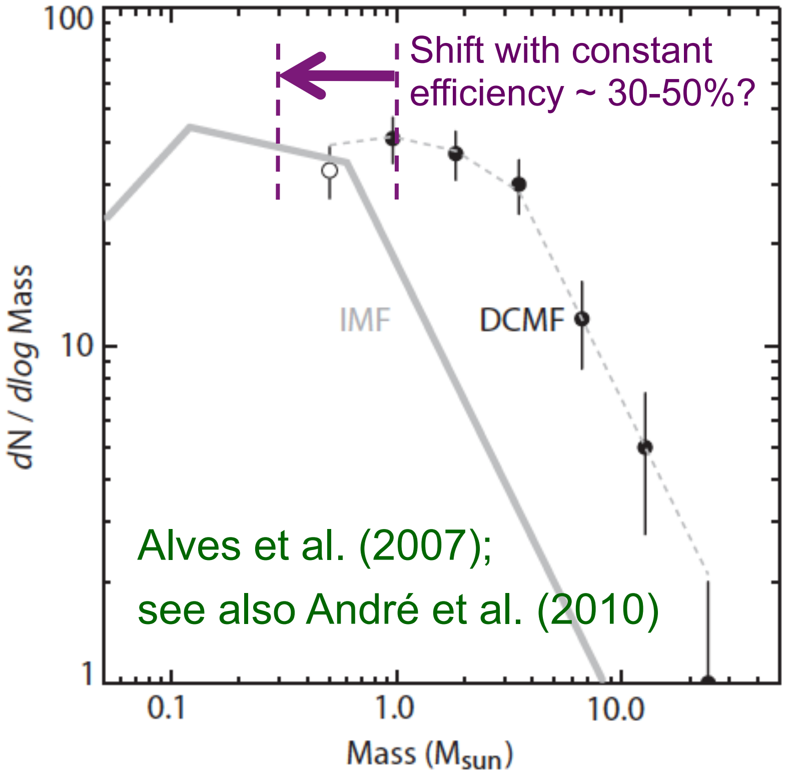
Density PDF → Star Formation Rate

Modeling jet and outflow feedback

Star Formation – Jets and Outflows

Outflows/Jets

- Energy comparable to other feedback
  (Mac Low & Klessen 2004; Nakamura & Li 2014; Krumholz et al. 2014)
- Driven by magnetic field
  (Blandford & Payne 1982; Lynden-Bell 2003)



Shift with constant efficiency ~ 30-50%?

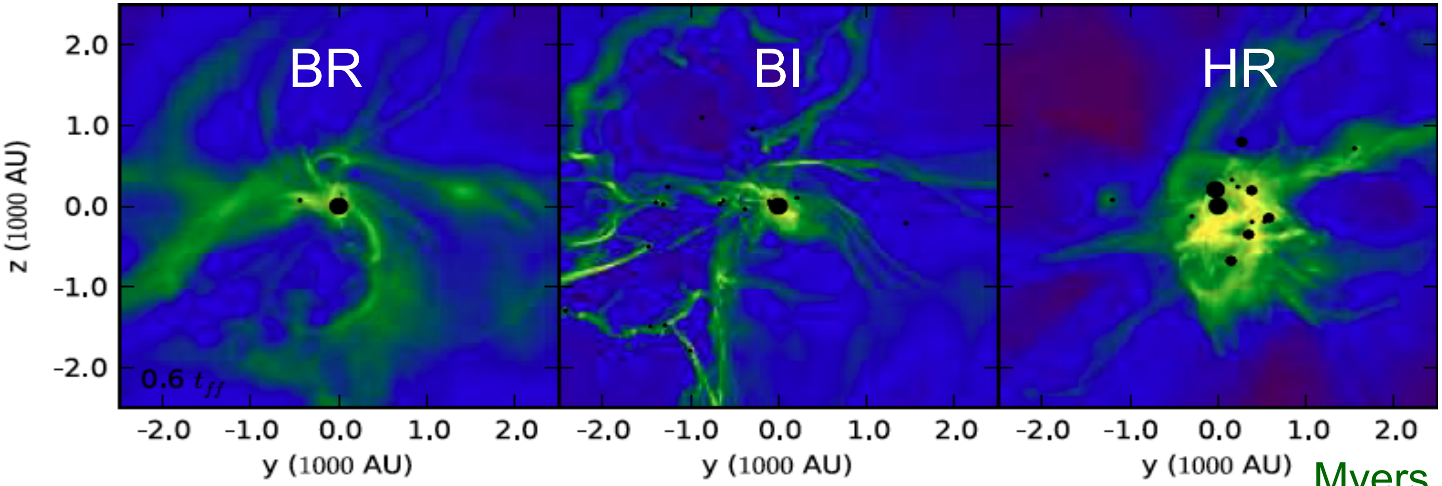
Alves et al. (2007);
see also André et al. (2010)

Impact on SFR and IMF:
core-to-star efficiency ε ~ 0.3–0.5

(see also Matzner & McKee 2002)

Star Formation – Jets and Outflows

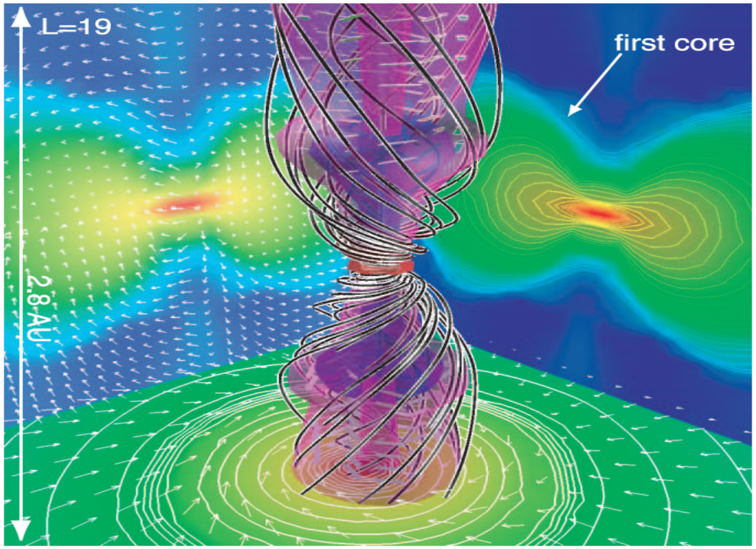
Reduce fragmentation (Hennebelle & Tyessier 08, Bürzle+11, Federrath & Klessen 12)

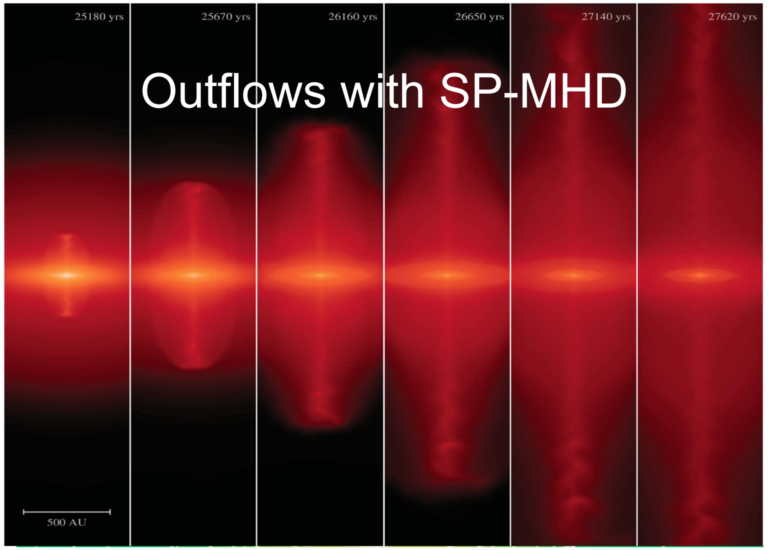


Myers et al. (2013)

Drive jets / outflows (Banerjee & Pudritz 2006, Seifried et al. 2012, Moraghan et al. 2013)

Machida et al. (2008)





Outflows with SP-MHD

Price et al. (2012)

Why sink particles?

Sink particles

- Quantify fragmentation and accretion
- Prevent code from stalling

$$t_{\mathrm{ff}} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

- Resolve Jeans length

$$\lambda_{\mathrm{J}} = \left(\frac{\pi c_{\mathrm{s}}^2}{G\rho}\right)^{1/2} \quad \rightarrow \quad \rho_{\mathrm{res}}$$

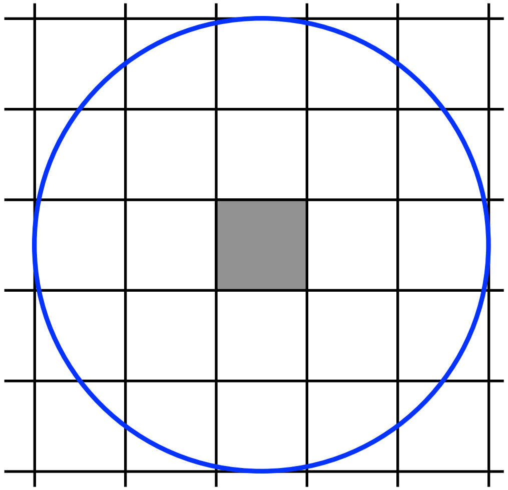
(resolution criterion)

Truelove et al. (1997)
(see also Bate & Burkert 1997)

Sink Particles as Star Formation Subgrid Model

Collapse checks to avoid spurious sink creation

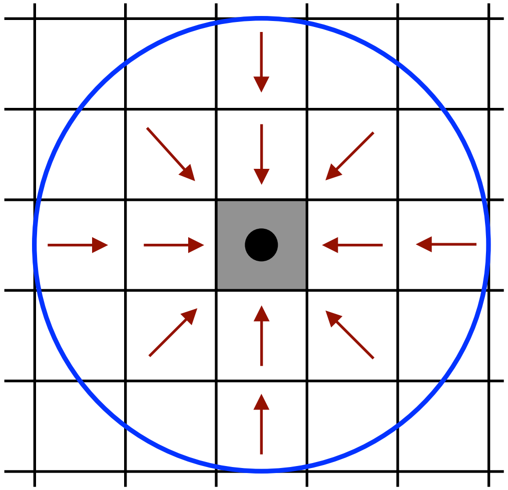
1. Cell exceeds density threshold, $\rho > \rho_{\mathrm{res}}$



Federrath, Banerjee, Clark, Klessen (2010, ApJ 713, 269)

Sink Particles as Star Formation Subgrid Model

Collapse checks to avoid spurious sink creation

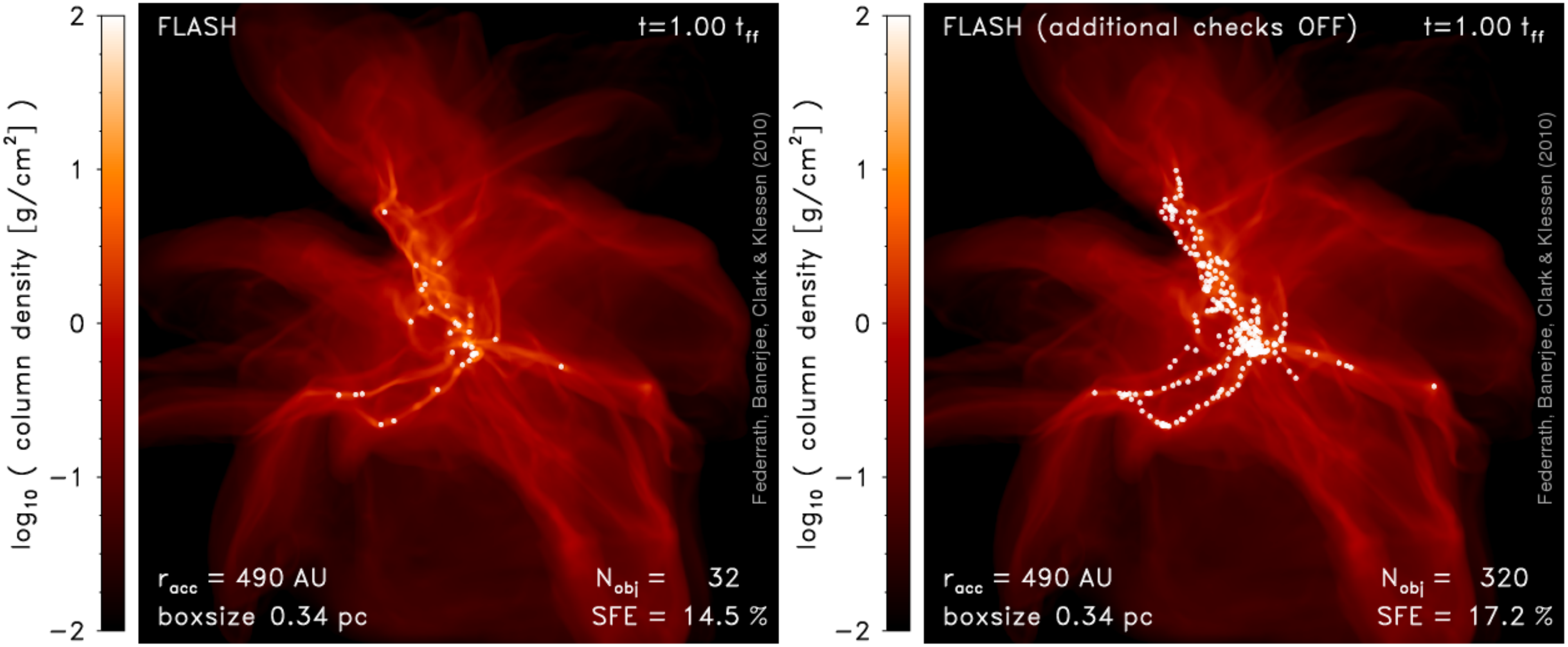


1. Cell exceeds density threshold, $\rho > \rho_{\mathrm{res}}$
2. Highest level of AMR
3. Converging towards the center
4. Central minimum in gravitational potential
5. Jeans unstable, $|E_{\mathrm{grav}}| > 2E_{\mathrm{th}}$
6. Bound, $E_{\mathrm{grav}} + E_{\mathrm{th}} + E_{\mathrm{kin}} + E_{\mathrm{mag}} < 0$
7. Not within the accretion radius of an existing sink particle

Federrath, Banerjee, Clark, Klessen (2010, ApJ 713, 269)

Sink particle implementation in FLASH

Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/sinks/sinks.shtml



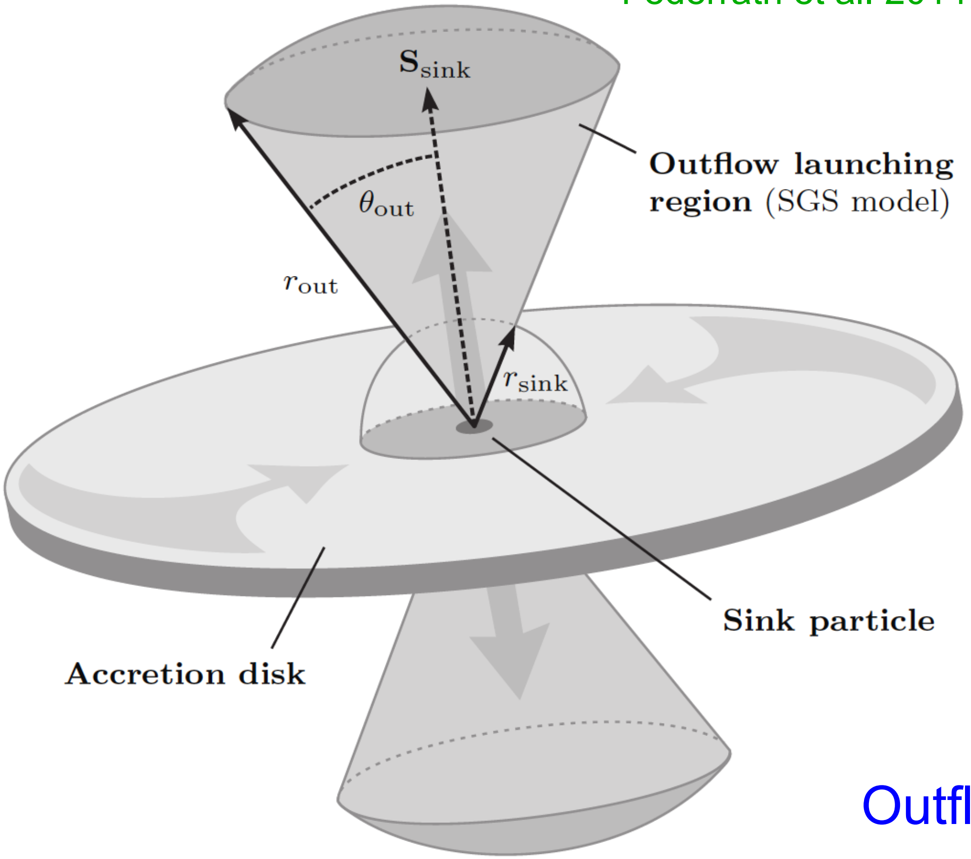
all checks ON

$\rho > \rho_{\mathrm{res}}$ **only**

Federrath, Banerjee, Clark, Klessen (2010, ApJ 713, 269)

Sink Particles as Star Formation Subgrid Model

Federrath et al. 2014, ApJ 790, 128



List of SGS outflow parameters.

SGS Parameter	Symbol	Default	Reference
Outflow Opening Angle	$\theta_{\rm out}$	30°	[1]
Mass Transfer Fraction	$f_{\rm m}$	0.3	[2]
Jet Speed Normalization[a]	$\lvert\mathbf{V}_{\rm out}\rvert$	$100\,{\rm km\,s^{-1}}$	[3]
Angular Momentum Fraction	$f_{\rm a}$	0.9	[4]
Outflow Radius	$r_{\rm out}$	$16\,\Delta x$	Section 4

Notes. [a] The outflow velocities are dynamically computed according to the Kepler speed at the footprint of the jet, $\lvert\mathbf{V}_{\rm out}\rvert = 100\,{\rm km\,s^{-1}}(M_{\rm sink}/0.5\,M_\odot)^{1/2}$ (see Equation 13).
References: [1] Blandford & Payne (1982); Appenzeller & Mundt (1989); Camenzind (1990); [2] Hartmann & Calvet (1995); Calvet (1998); Tomisaka (1998); Bacciotti et al. (2002); Tomisaka (2002); Lee et al. (2006); Cabrit et al. (2007); Lee et al. (2007); Hennebelle & Fromang (2008); Duffin & Pudritz (2009); Bacciotti et al. (2011); Price et al. (2012); Seifried et al. (2012); [3] Herbig (1962); Snell et al. (1980); Blandford & Payne (1982); Draine (1983); Uchida & Shibata (1985); Shibata & Uchida (1985, 1986); Pudritz & Norman (1986); Wardle & Königl (1993); Bacciotti et al. (2000); Königl & Pudritz (2000); Bacciotti et al. (2002); Banerjee & Pudritz (2006); Machida et al. (2008); [4] Pelletier & Pudritz (1992); Bacciotti et al. (2002); Banerjee & Pudritz (2006); Hennebelle & Fromang (2008).

Outflow mass: $M_{\rm out} = f_{\rm m}\dot{M}_{\rm acc}\Delta t$

Outflow velocity: $\lvert\mathbf{V}_{\rm out}\rvert = \left(\frac{GM_{\rm sink}}{10\,R_\odot}\right)^{1/2} = 100\,{\rm km\,s^{-1}}\,\left(\frac{M_{\rm sink}}{0.5\,M_\odot}\right)^{1/2}$

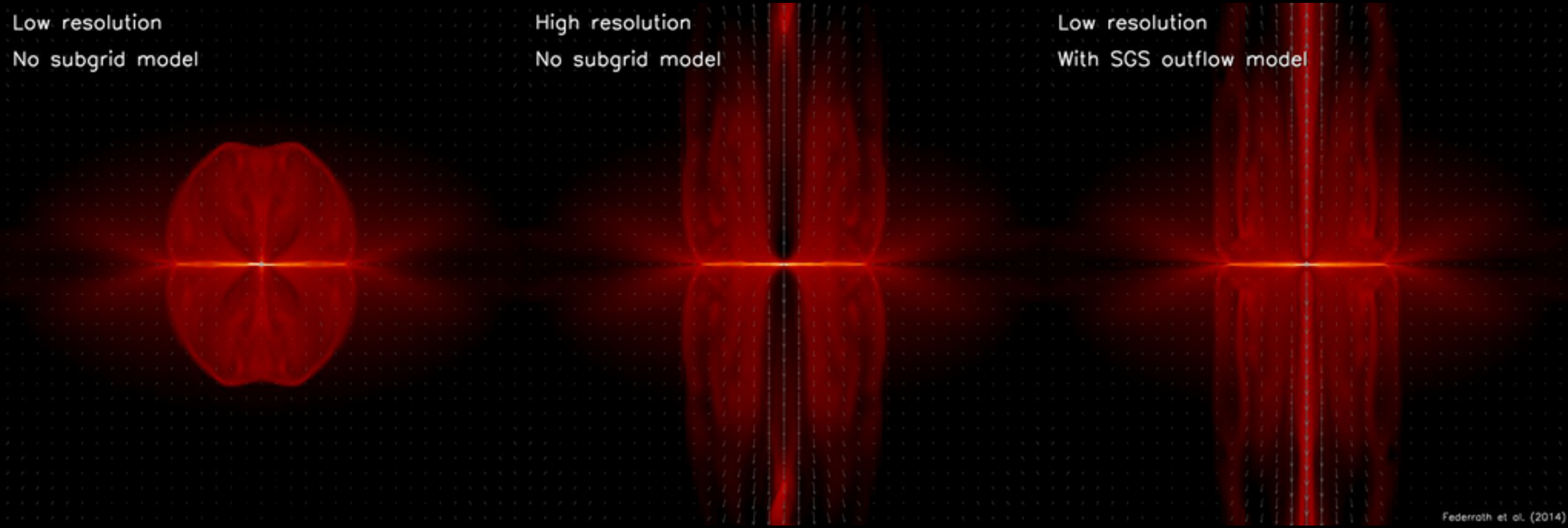
Outflow angular momentum: $\mathbf{L}_{\rm out} = f_{\rm a}\,(\mathbf{S}'_{\rm sink} - \mathbf{S}_{\rm sink})\cdot\mathbf{S}'_{\rm sink}/\lvert\mathbf{S}'_{\rm sink}\rvert$

Modeling jets/outflows

Without Subgrid Model (low res)

Without Subgrid Model (mid res)

With Subgrid Model (low res)

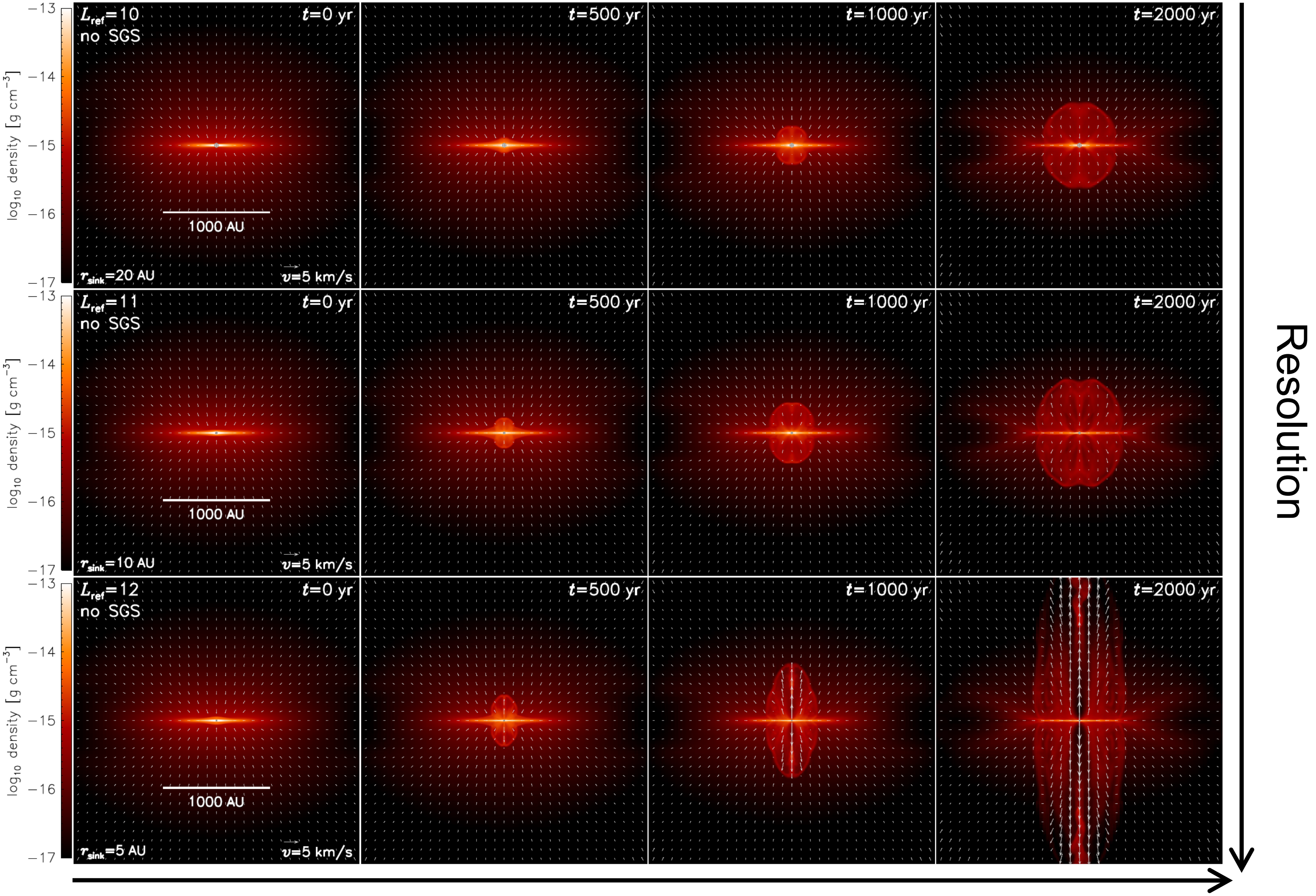


Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/outflow_model/outflow_model.shtml

Federrath et al. 2014, ApJ 790, 128

Sink Particles as Star Formation Subgrid Model

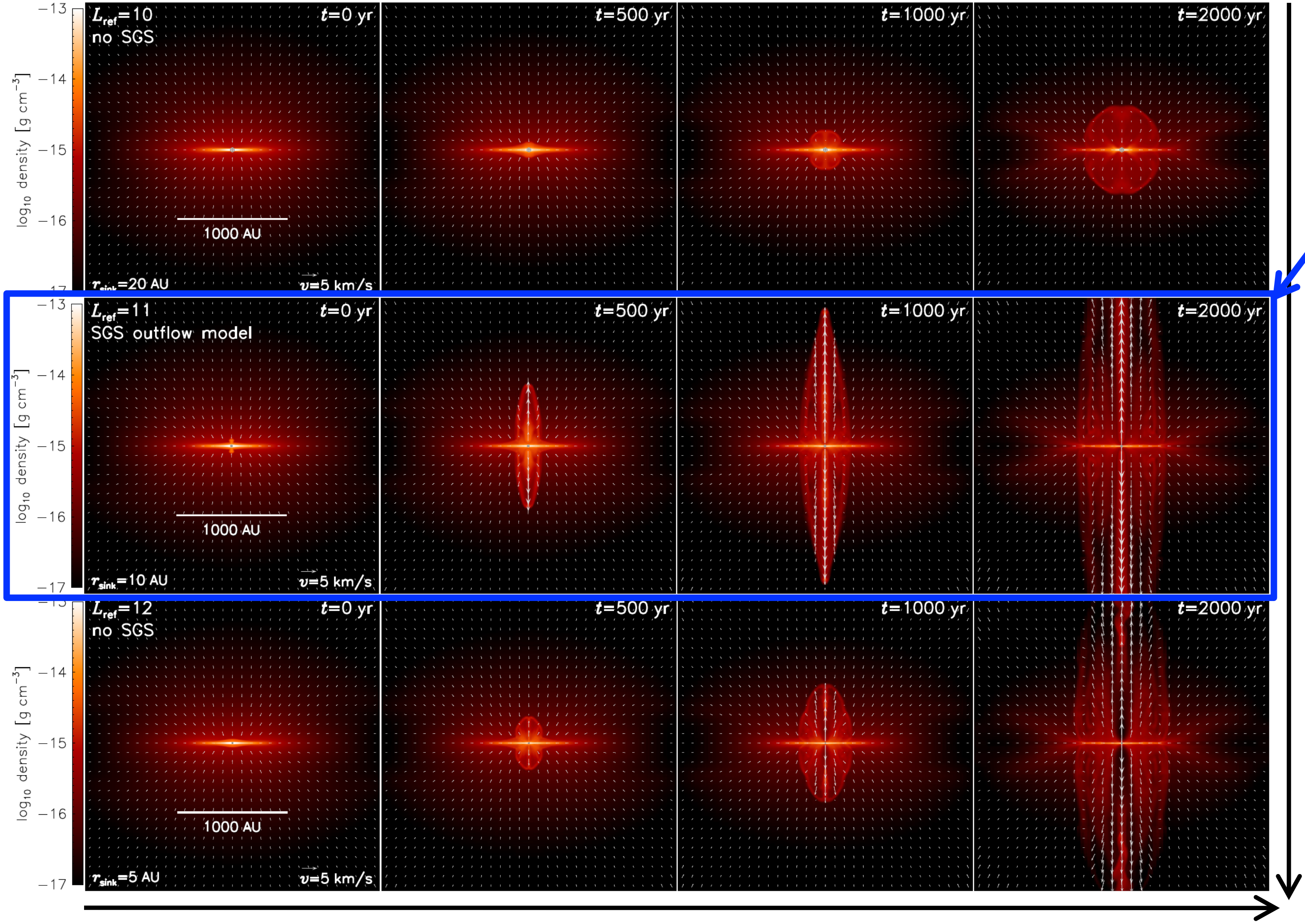
Resolution study *without* SGS model:



Federrath et al. 2014, ApJ 790, 128

Sink Particles as Star Formation Subgrid Model

Resolution study without SGS model:



With SGS model

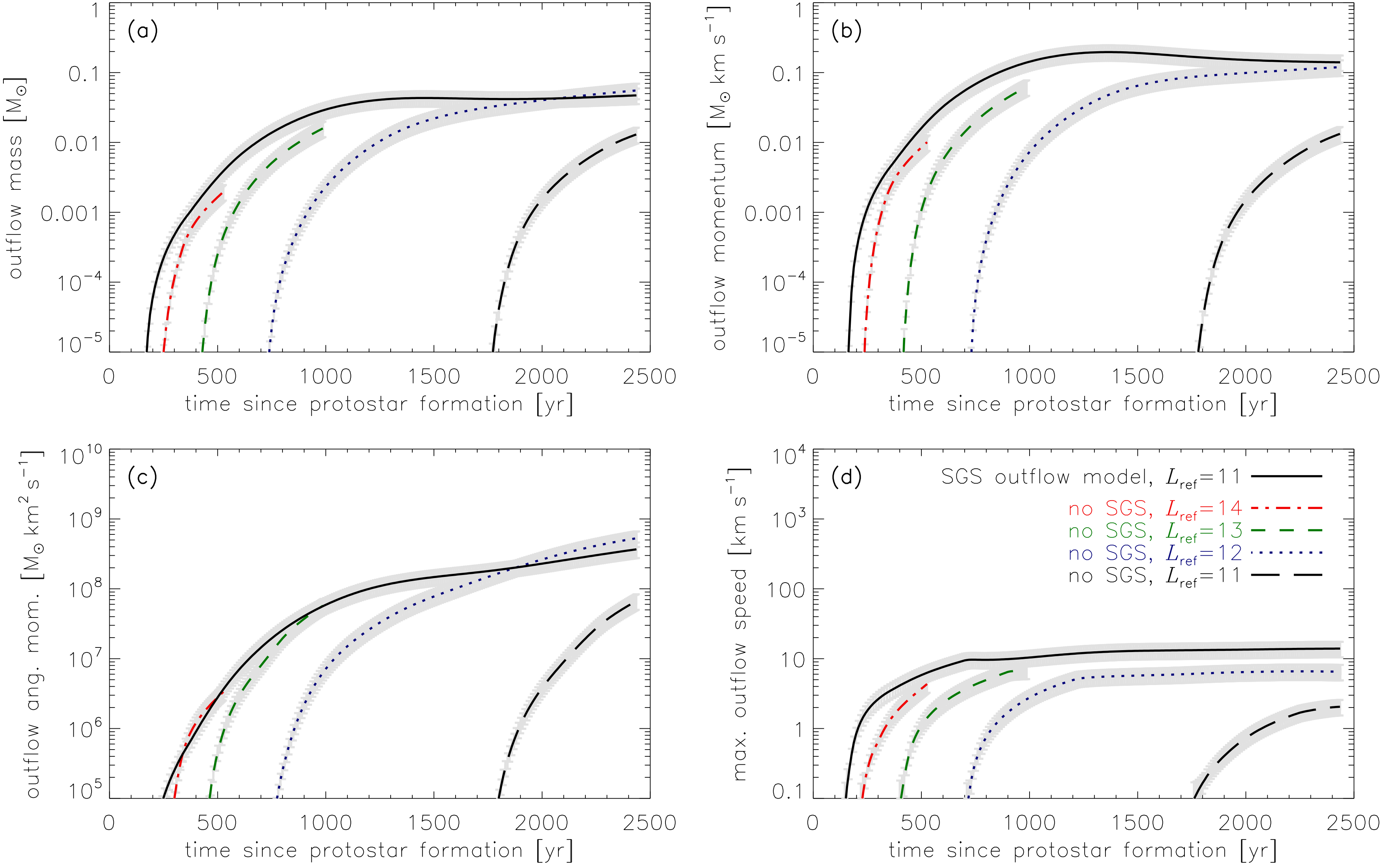
Resolution

Time

Federrath et al. 2014, ApJ 790, 128

Sink Particles as Star Formation Subgrid Model

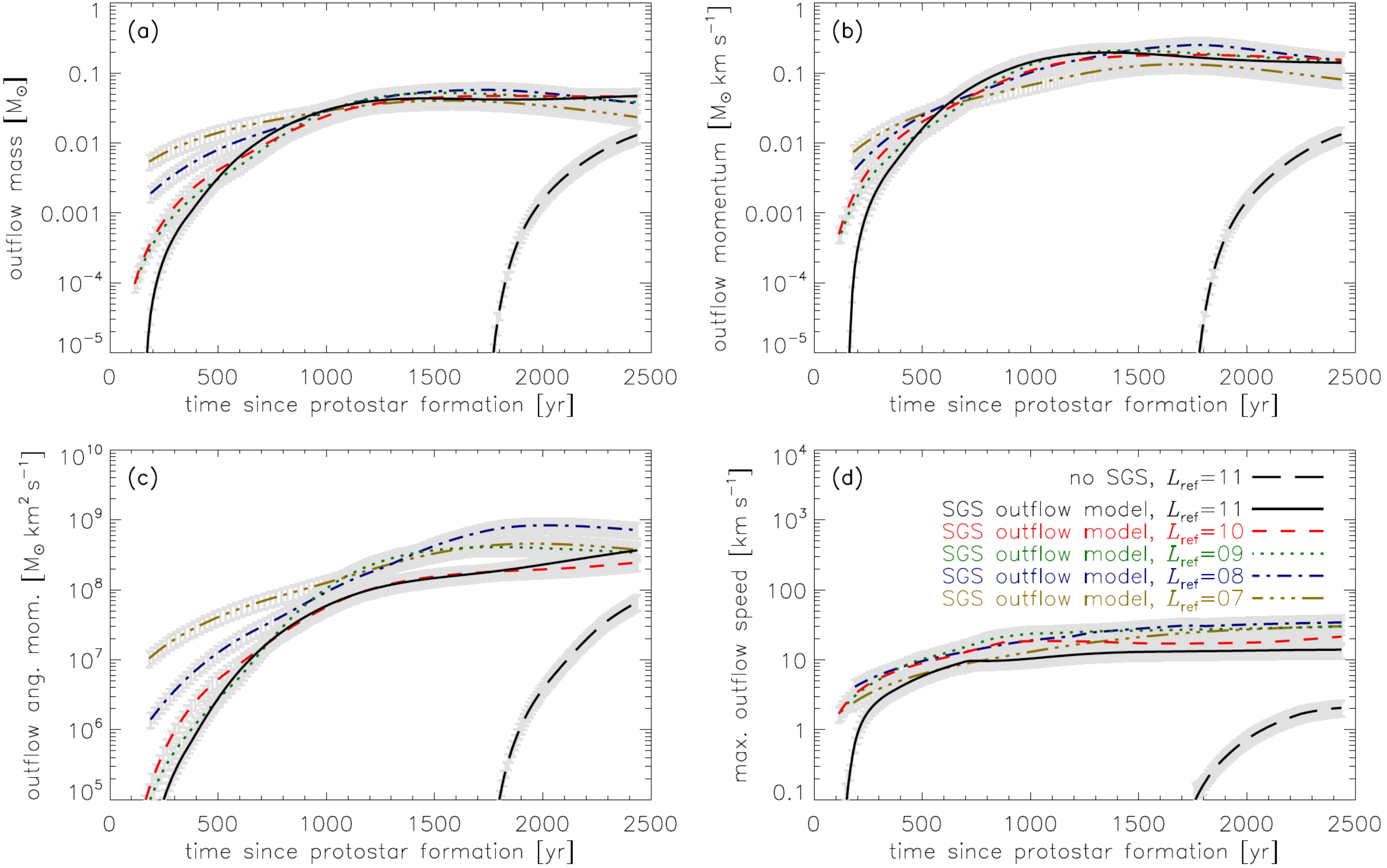
Subgrid model reproduces observations and theory



Federrath et al. 2014, ApJ 790, 128

Sink Particles as Star Formation Subgrid Model

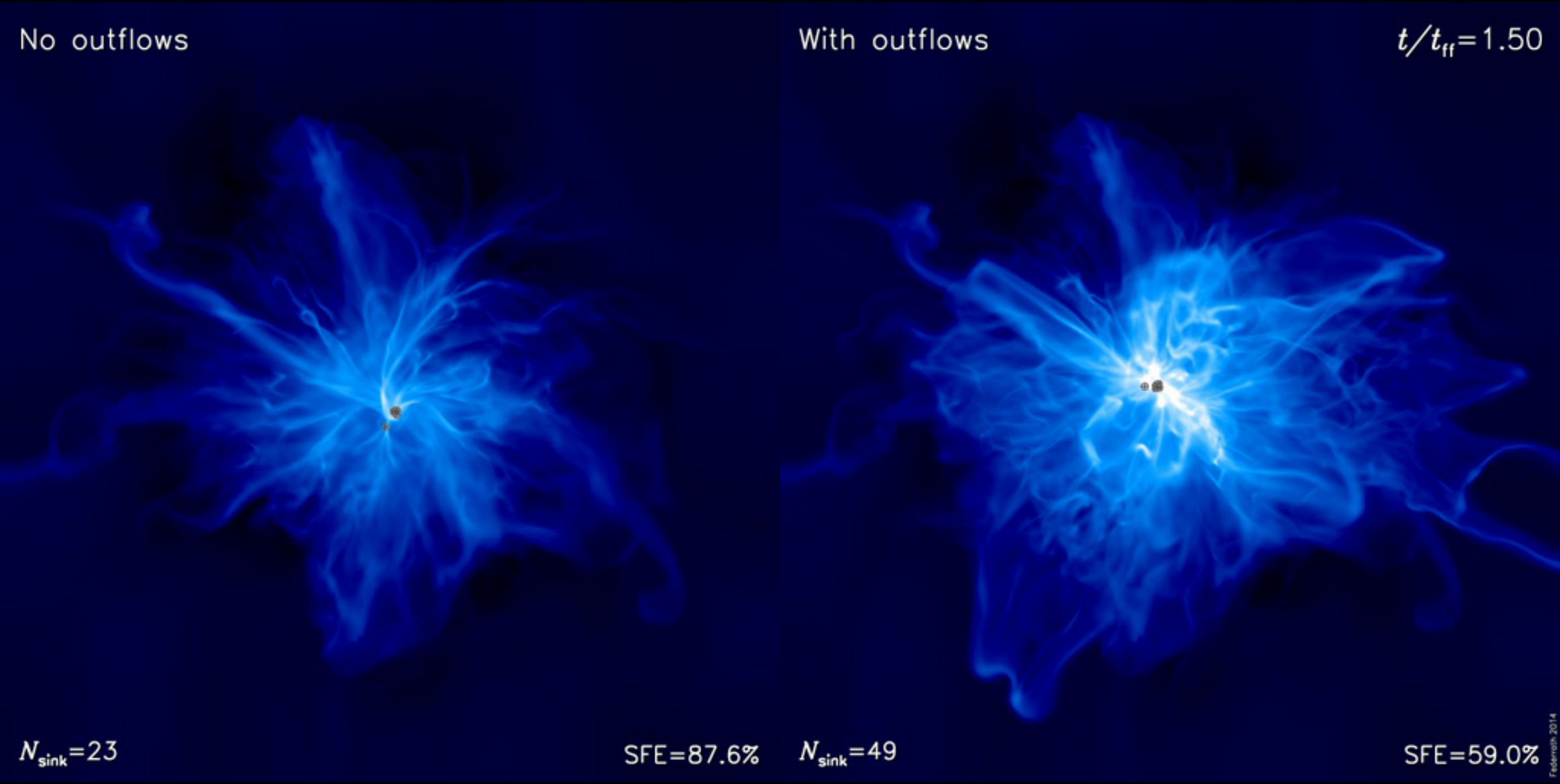
Subgrid model is automatically adaptive



Federrath et al. 2014, ApJ 790, 128

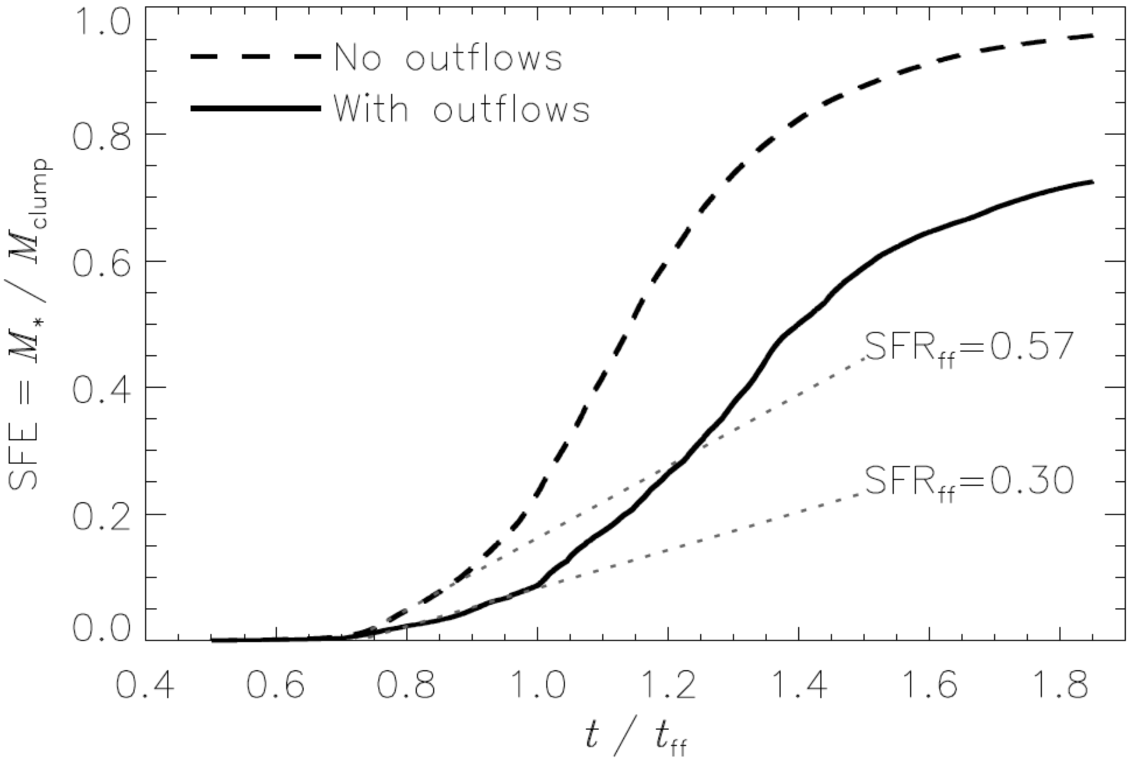
Star Formation – Outflow/Jet Feedback

Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/outflow_model/outflow_model.shtml



Federrath et al. 2014, ApJ 790, 128

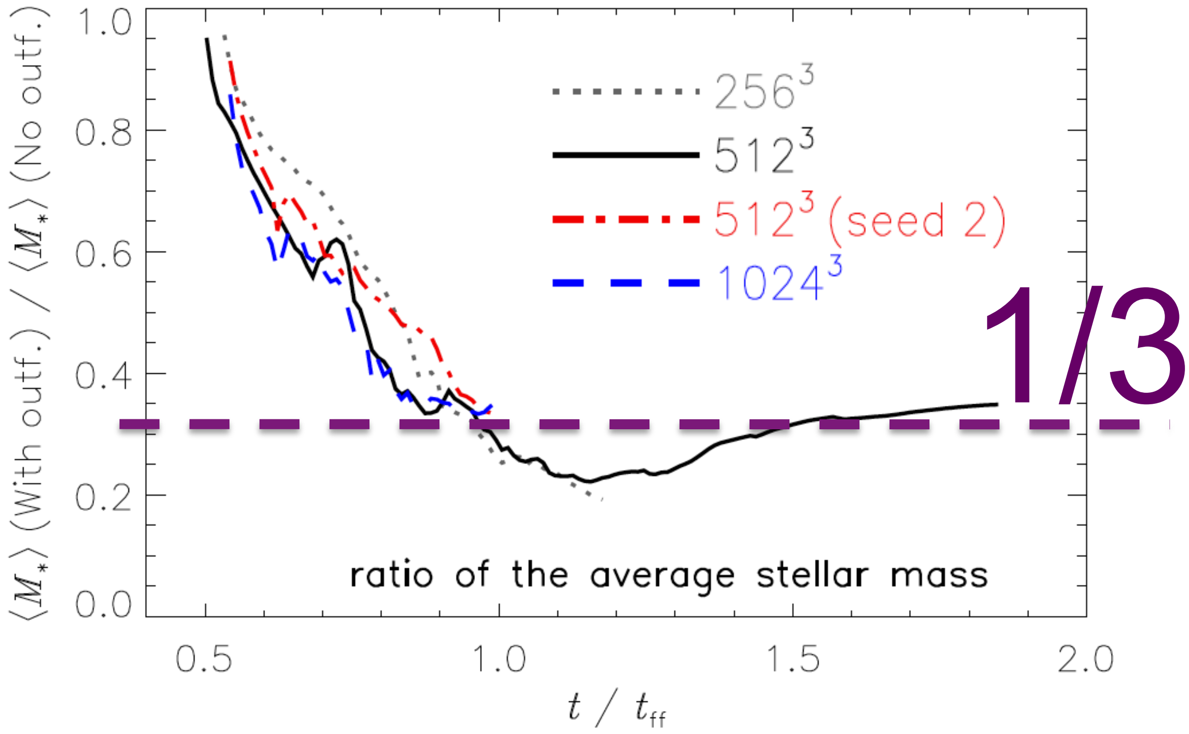
The role of outflow/jet feedback for star cluster formation



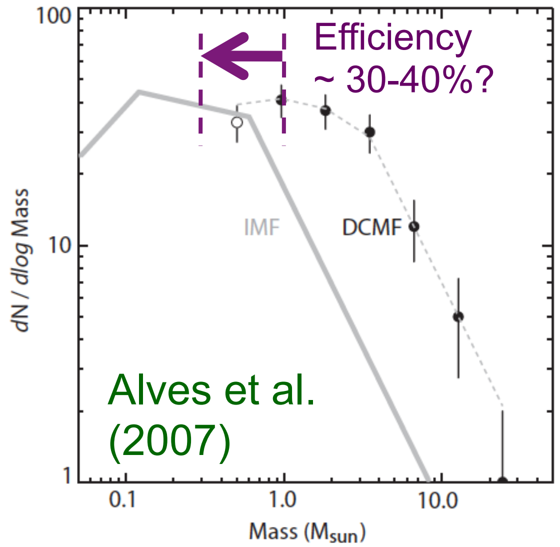
RESULTS:

- Outflow/Jet feedback reduces the SFR by factor ~ 2
- Outflow/Jet feedback reduces average star mass by factor ~ 3

The role of outflow/jet feedback for star cluster formation



1/3



Efficiency
~ 30-40%?

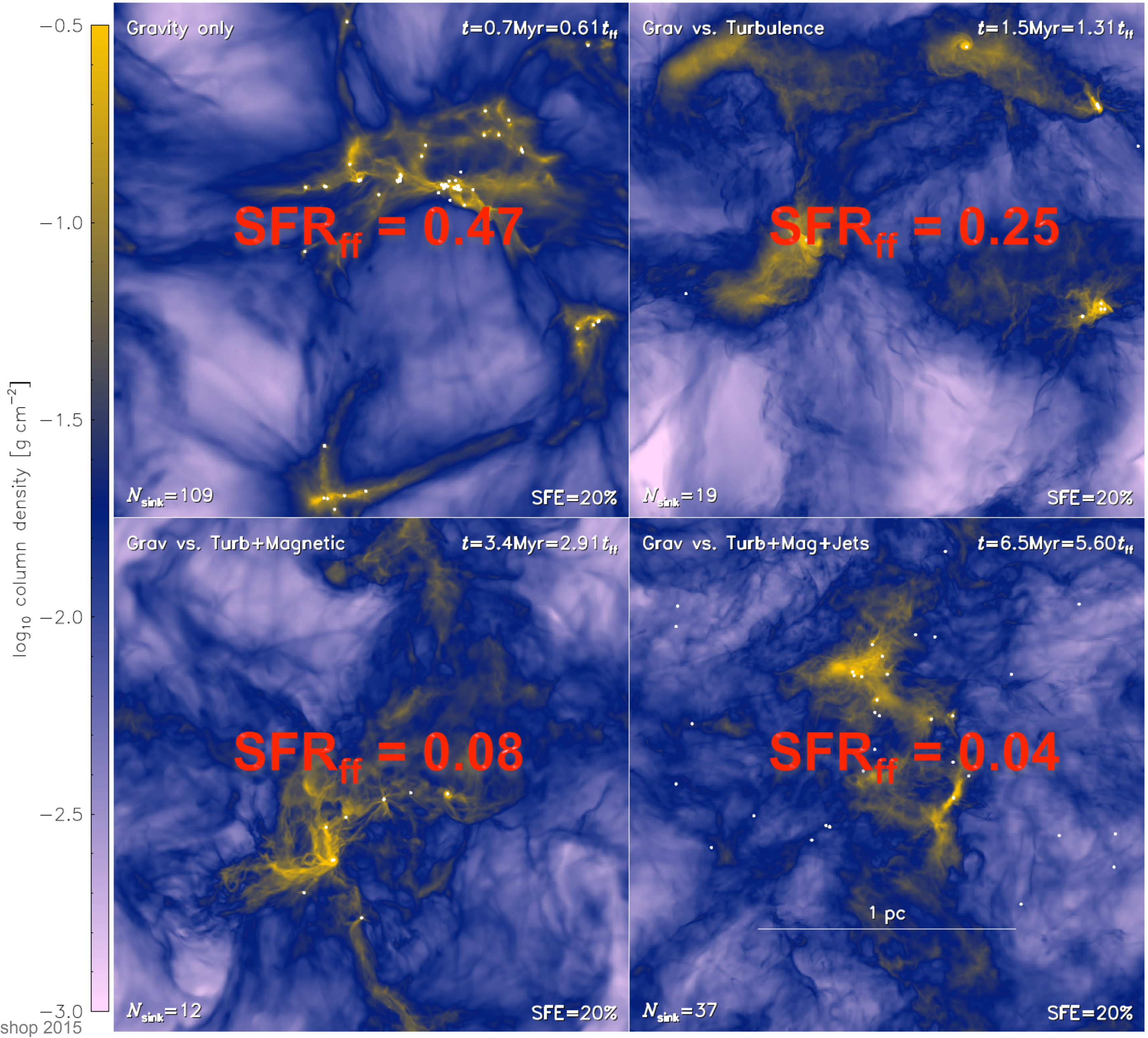
Alves et al.
(2007)

RESULTS:

- Outflow/Jet feedback reduces the SFR by factor ~ 2
- Outflow/Jet feedback reduces average star mass by factor ~ 3

Why is Star Formation is so Inefficient?

Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/ineff_sf/ineff_sf.html



Gravity only

$SFR_{ff} = 0.47$

Turb

$SFR_{ff} = 0.25$

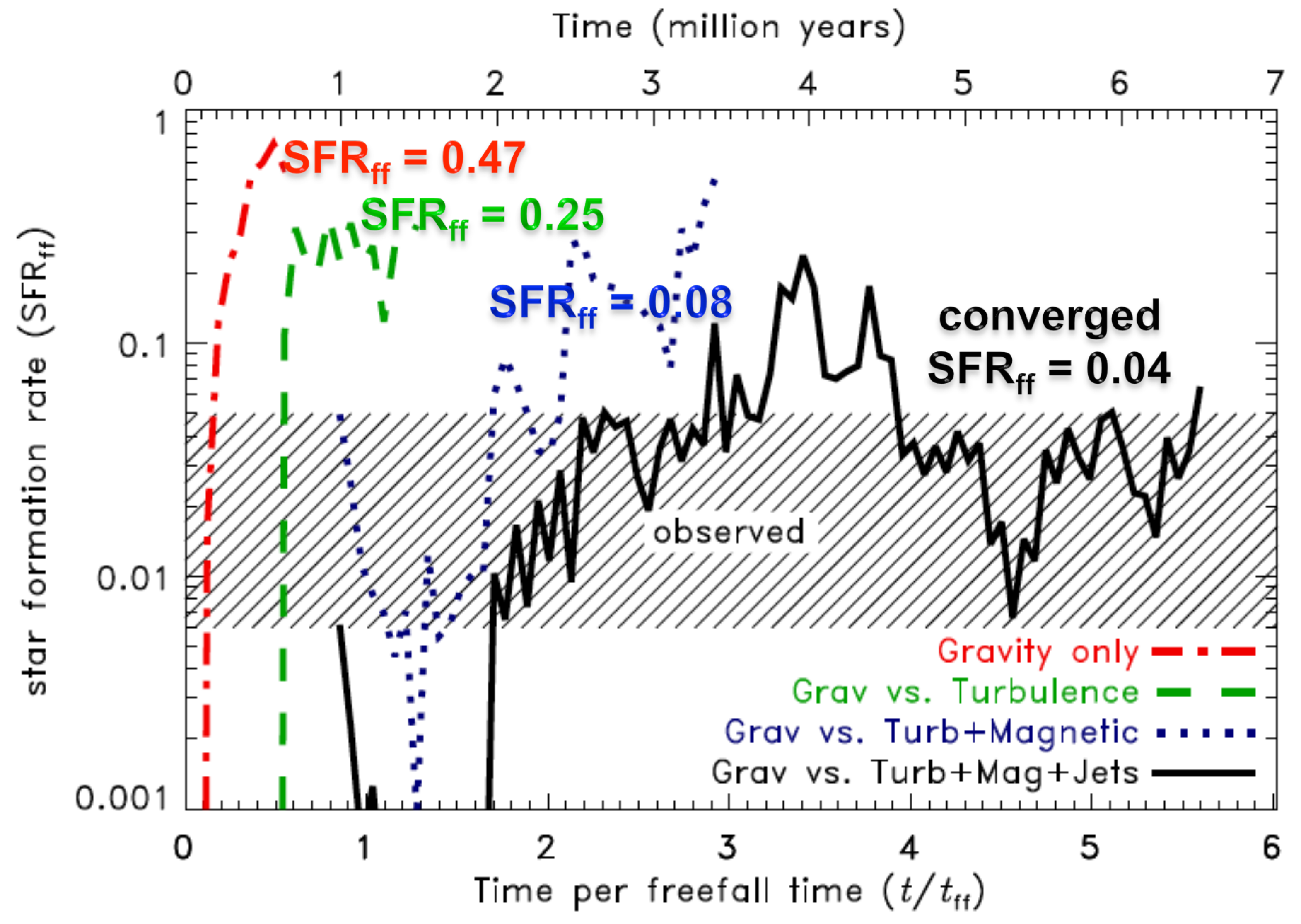
Turb+ Mag

$SFR_{ff} = 0.08$

Turb+ Mag+ Jets

$SFR_{ff} = 0.04$

Star Formation is Inefficient



Federrath 2015, MNRAS 450, 4035

Conclusions

- Supersonic, magnetized turbulence is key for star formation
  - SFR from density PDF depends on
    virial parameter, forcing parameter, Mach number, plasma beta
  - Very good agreement between theory, simulations and observations

- Subgrid model for jet/outflow feedback in star cluster formation:
  - Implemented for AMR, tested, and demonstrated convergence
  - Star formation rate reduced by ~2x
  - Average star mass reduced by ~3x → IMF

- Star Formation is inefficient →

  Only combination of Turb+Mag+Feedback gives realistic SFRs