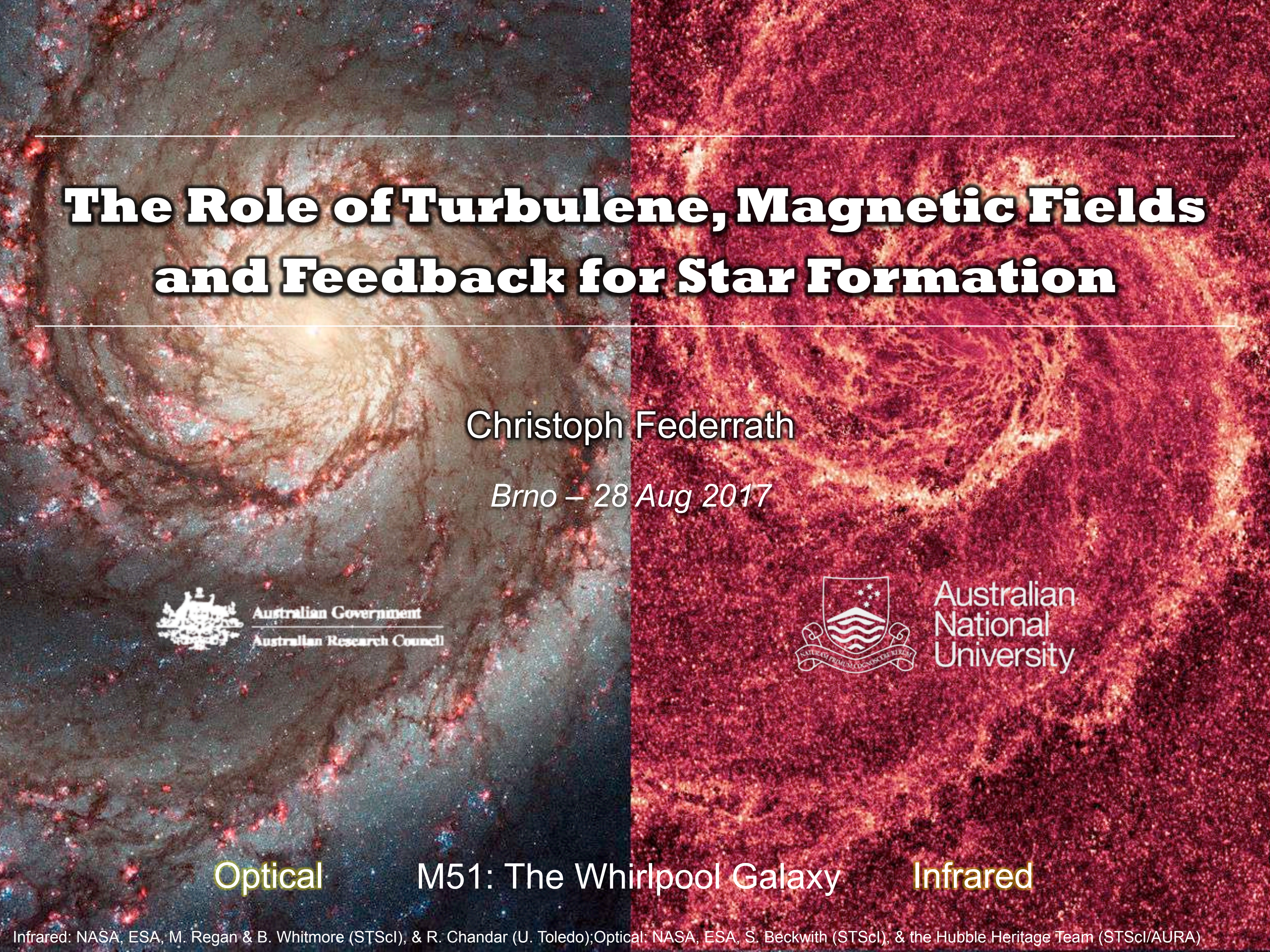
The Role of Turbulene, Magnetic Fields and Feedback for Star Formation

Christoph Federrath

Brno – 28 Aug 2017

Australian Government
Australian Research Council

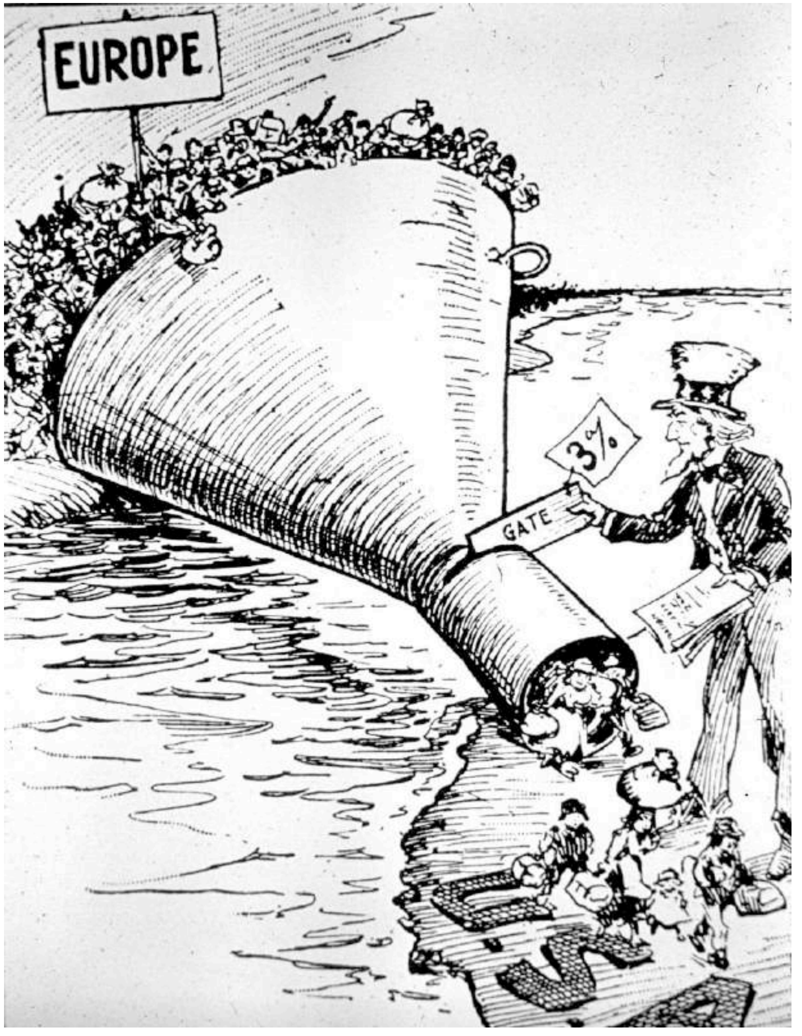
Australian National University



M51: The Whirlpool Galaxy

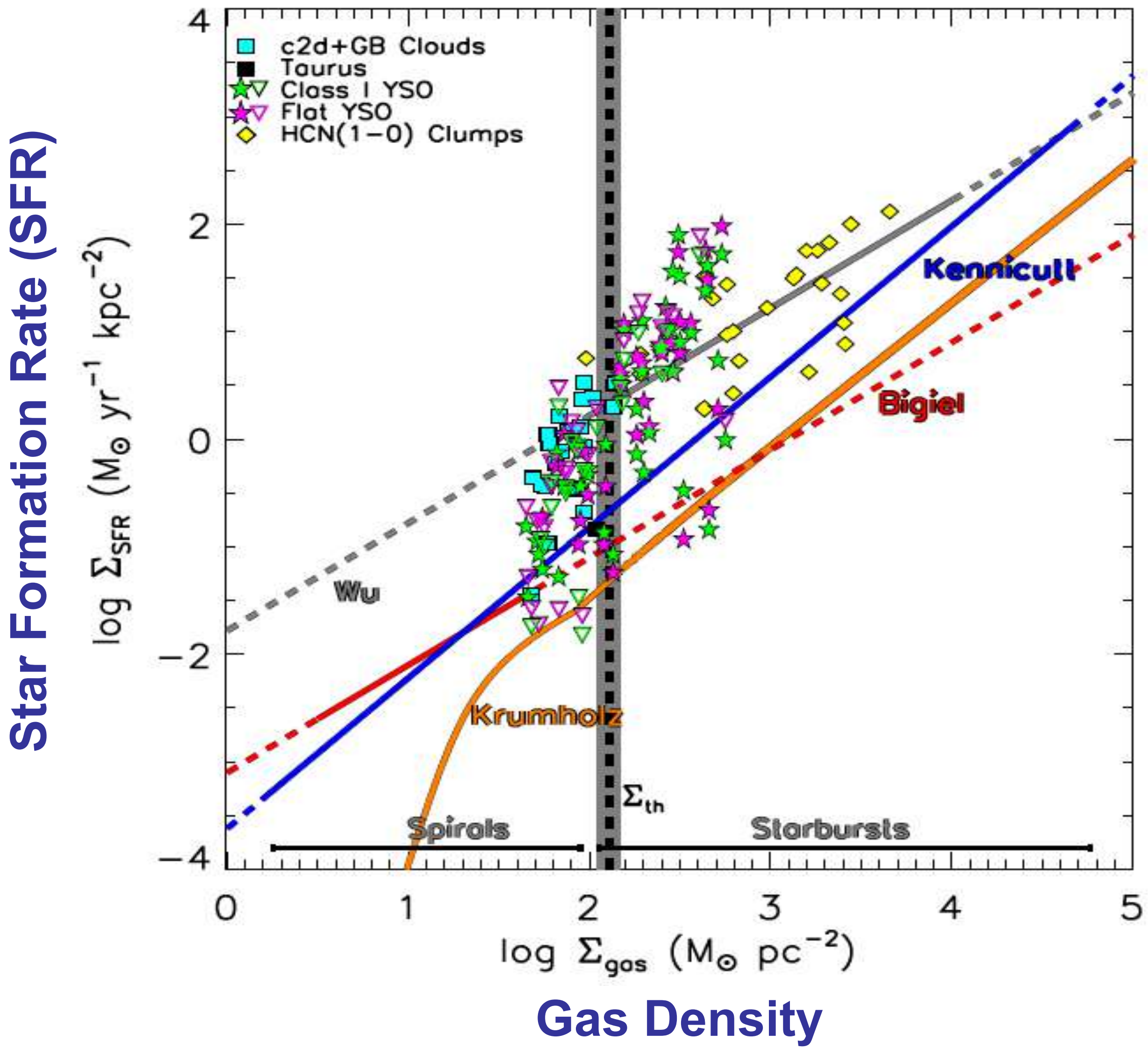
Infrared: NASA, ESA, M. Regan & B. Whitmore (STScI), & R. Chandar (U. Toledo);Optical: NASA, ESA, S. Beckwith (STScI), & the Hubble Heritage Team (STScI/AURA)

Star Formation is inefficient



Turbulence? Magnetic Fields? Feedback?

Universal star formation "law"?

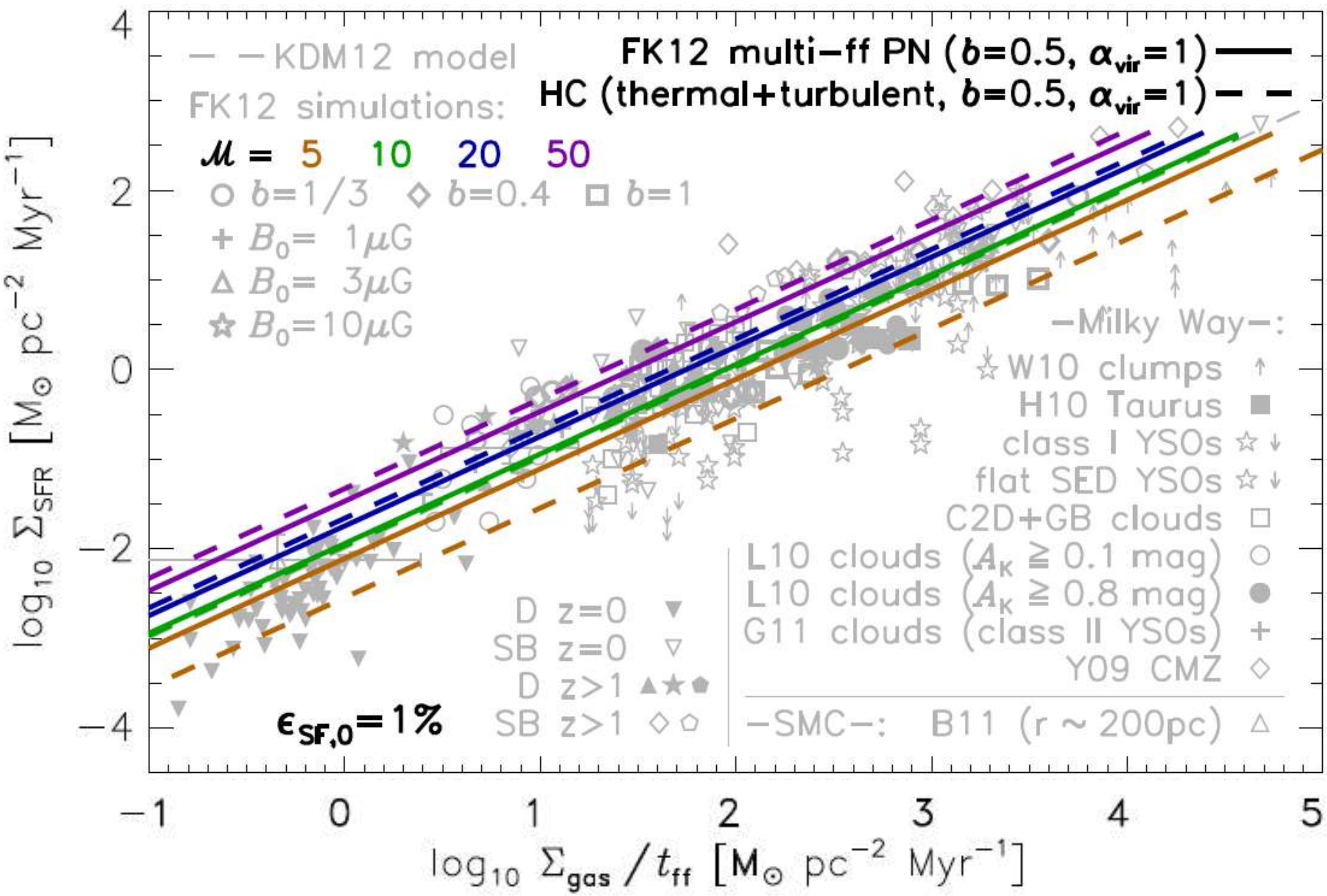


Scatter?

Turbulence

(Heiderman et al. 2010; Lada et al. 2010; Gutermuth et al. 2011; Kennicutt & Evans 2012)

Physical Variations in the Star Formation Law → Turbulence



→ **Scatter caused by variations in the TURBULENCE**
(Mach number, driving, etc.)

Federrath (2013); Salim et al. (2015)

Turbulence is key for Star Formation

(Federrath & Klessen 2012; Federrath et al. 2016)

Turbulence → Stars → Feedback

Magnetic Fields

Dynamics
(shear)

Turbulence driven by

- Shear
- Jets / Outflows
- Cloud-cloud collisions
- Winds / Ionization fronts
- Spiral-arm compression
- Supernova explosions
- Gravity / Accretion

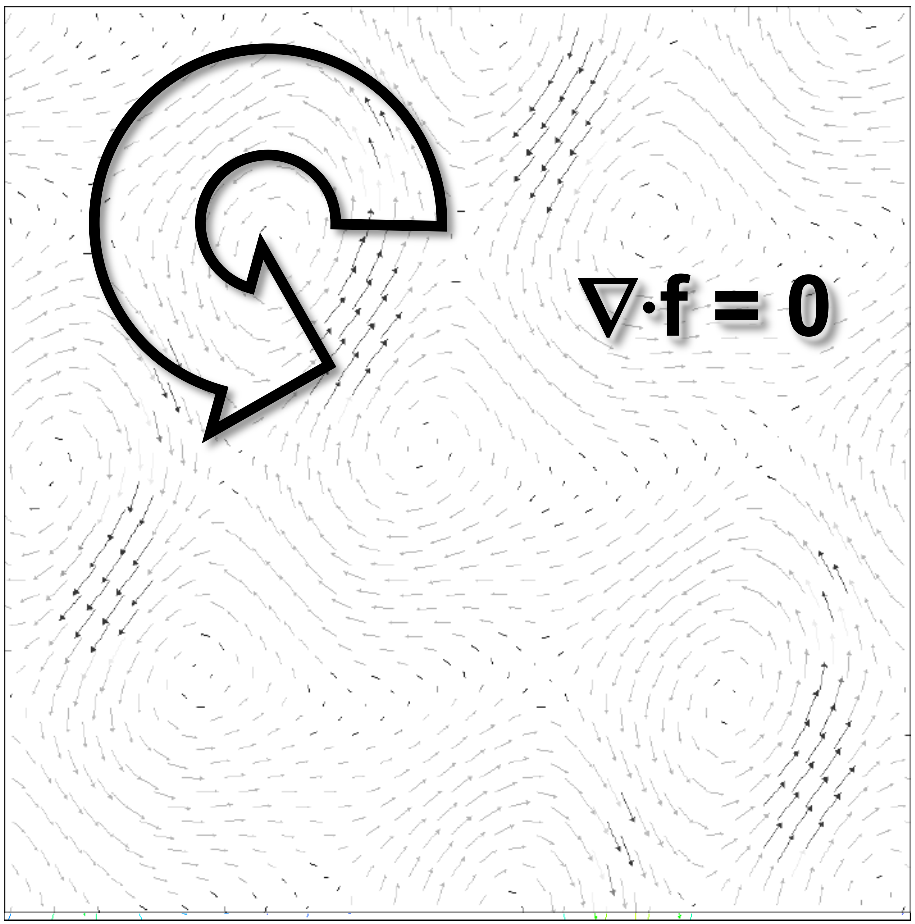
Solenoidal

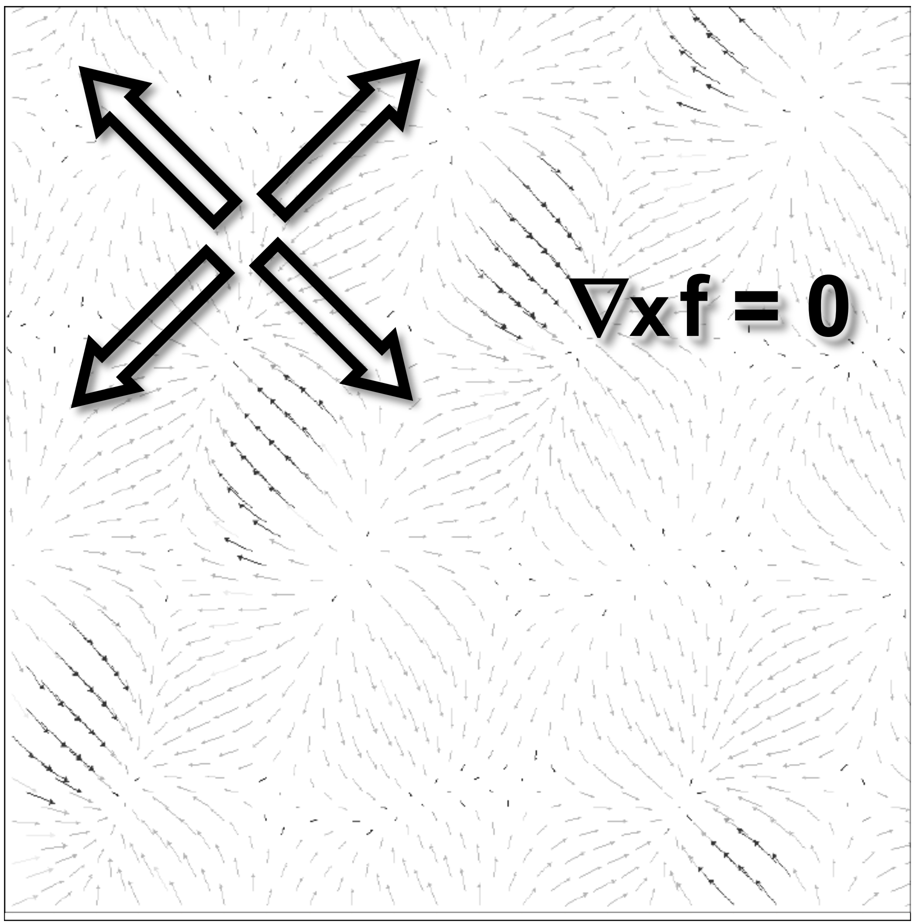
↓

Compressive

Turbulence driving – solenoidal versus compressive

Star Formation depends on how turbulence is driven

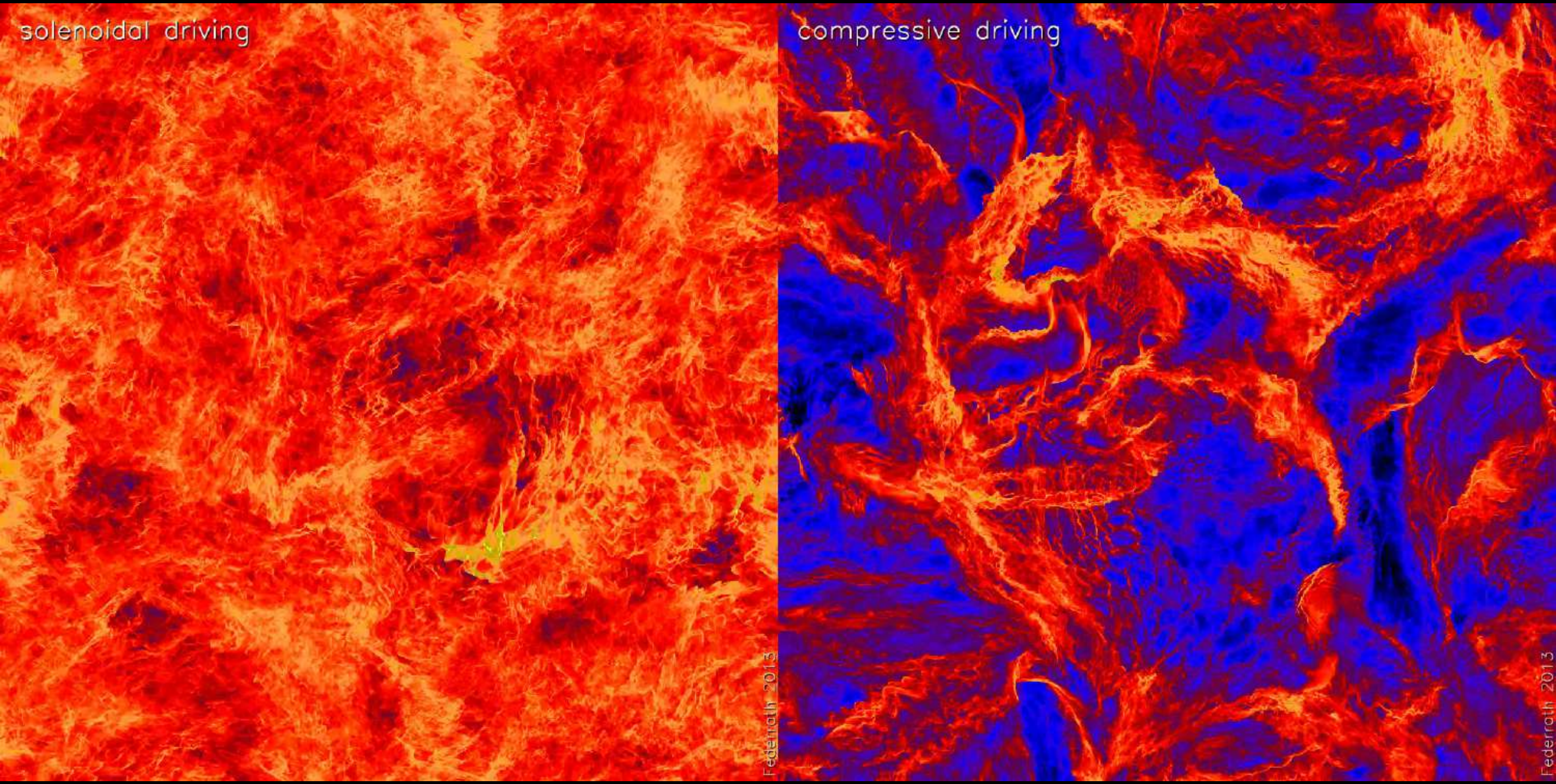




Turbulence driving – solenoidal versus compressive

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

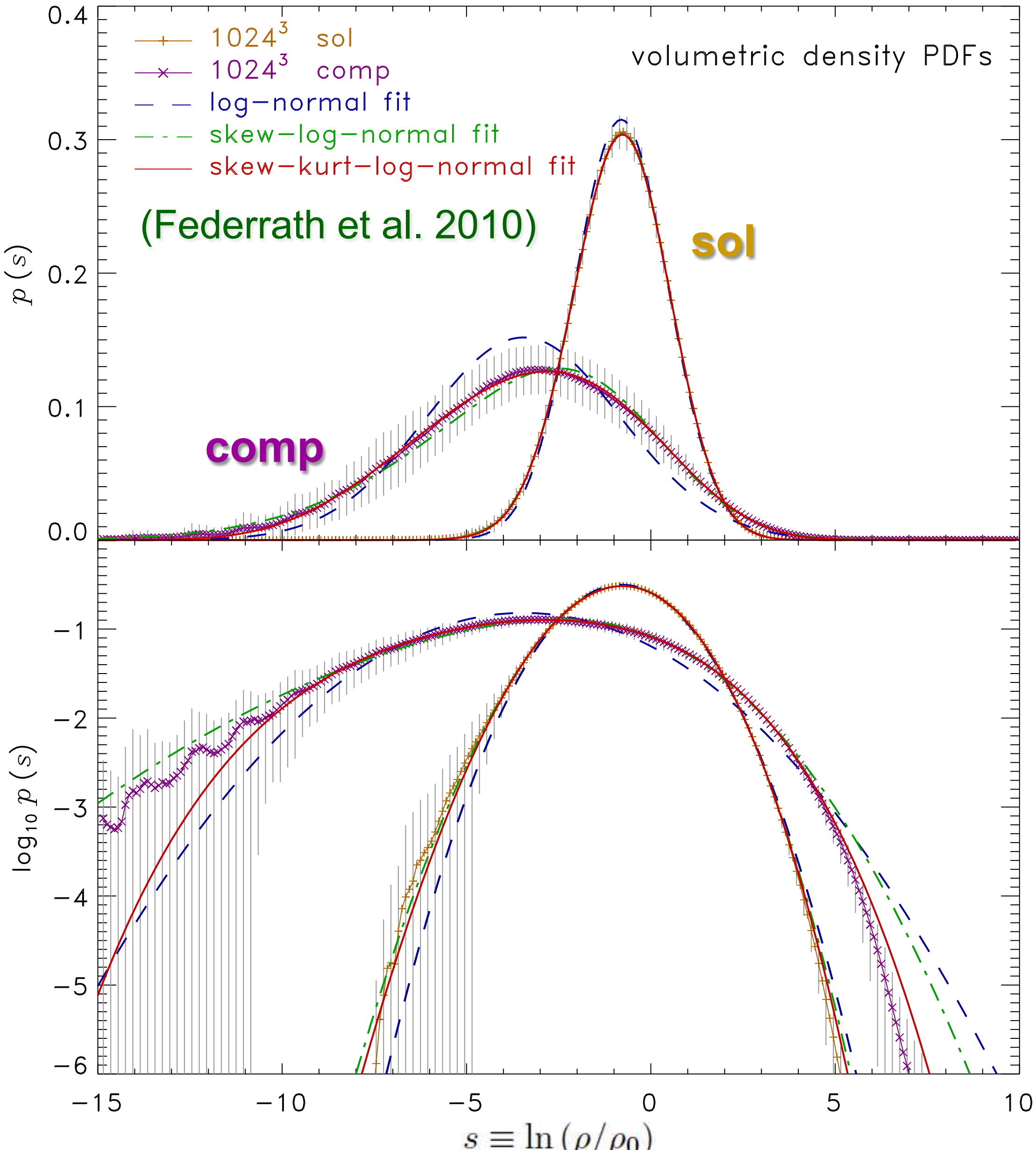
solenoidal driving compressive driving



Compressive driving produces stronger shocks and density enhancements

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

The density PDF → Star Formation



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)

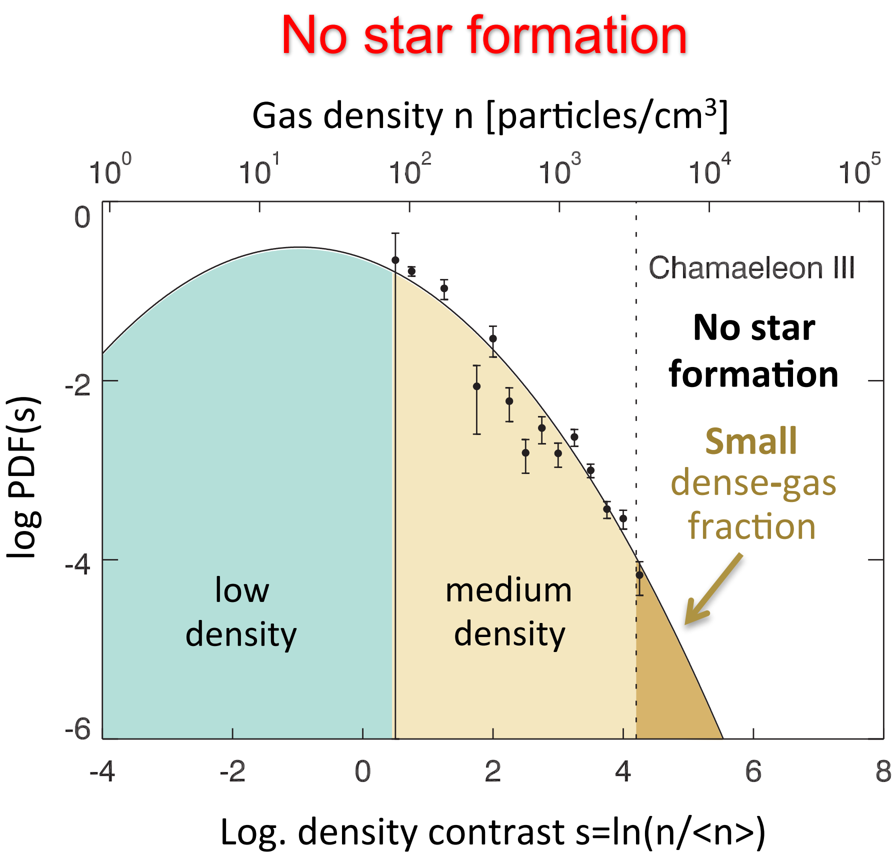
$$\boxed{\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right)}$$

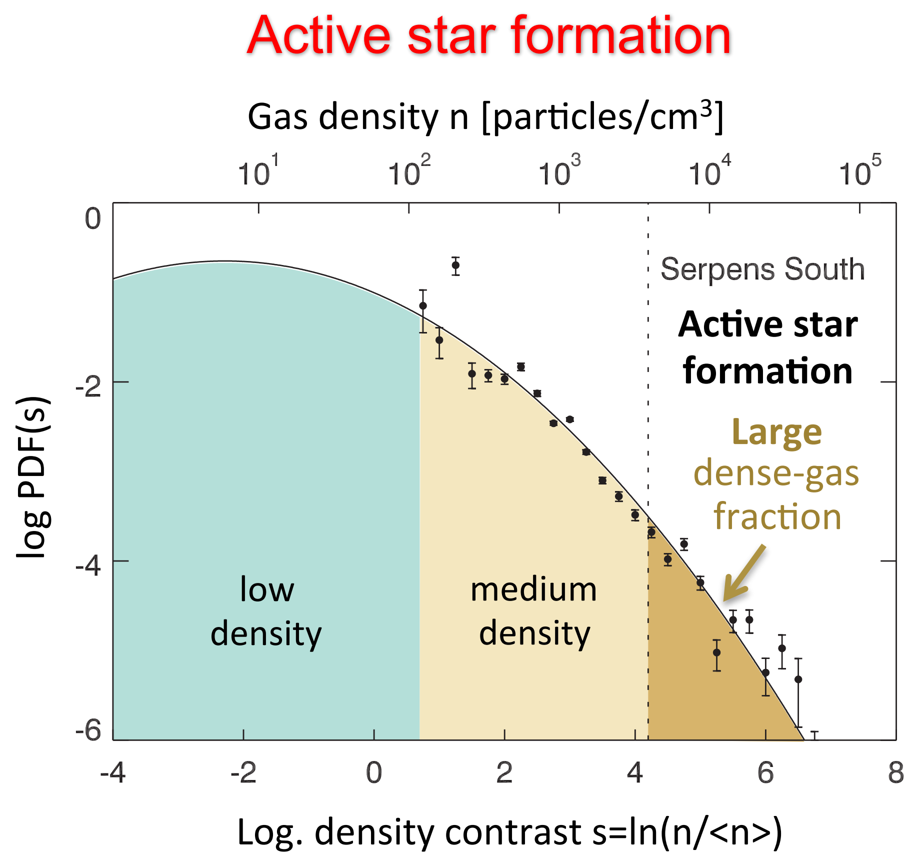
b = 1/3 (sol)

b = 1 (comp)

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

The density PDF → Star Formation



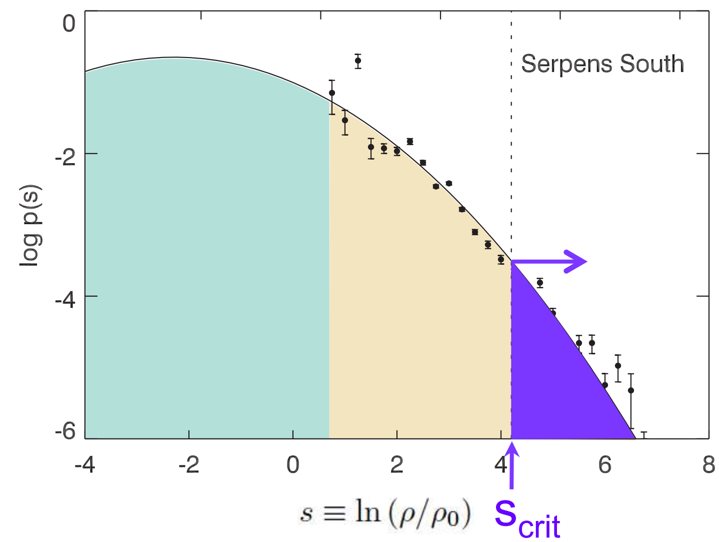


Kainulainen, Federrath, Henning (2014, *Science*)

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

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



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

Federrath & Klessen (2012)

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

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

Hennebelle & Chabrier (2011) : "multi-freefall model"

Federrath & Klessen (2012)

Statistical Theory for the Star Formation Rate:

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

Hennebelle & Chabrier (2011) : "multi-freefall model"

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

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

From sonic and Jeans scales:

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

(Krumholz+McKee 2005; Padoan+Nordlund 2011)

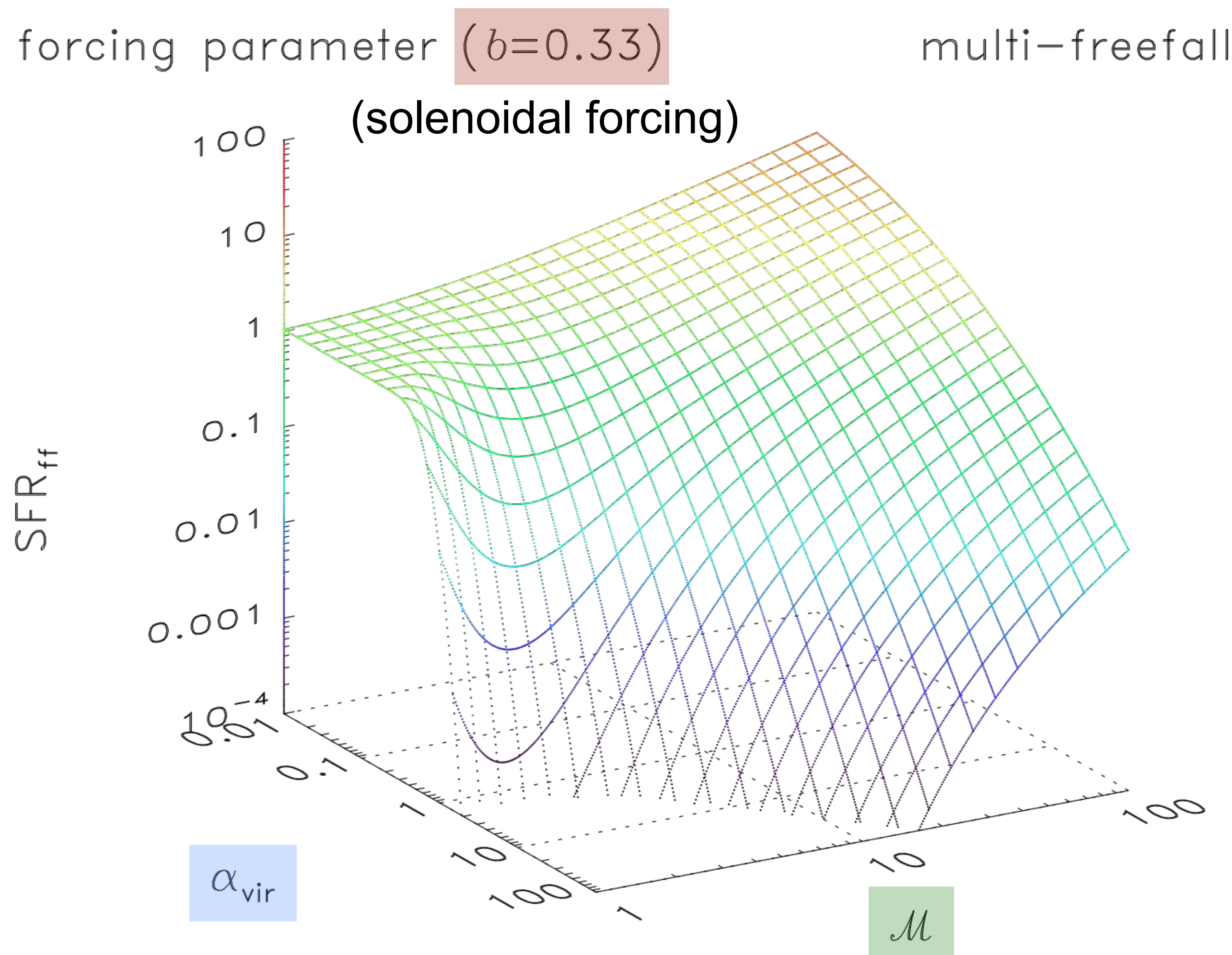
$$\boxed{\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right)}$$

(Federrath+2008; Molina+2012)

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\,(\alpha_{\mathrm{vir}}, b, \mathcal{M})$ 2 E_{kin}/E_{grav} **forcing** **Mach number**

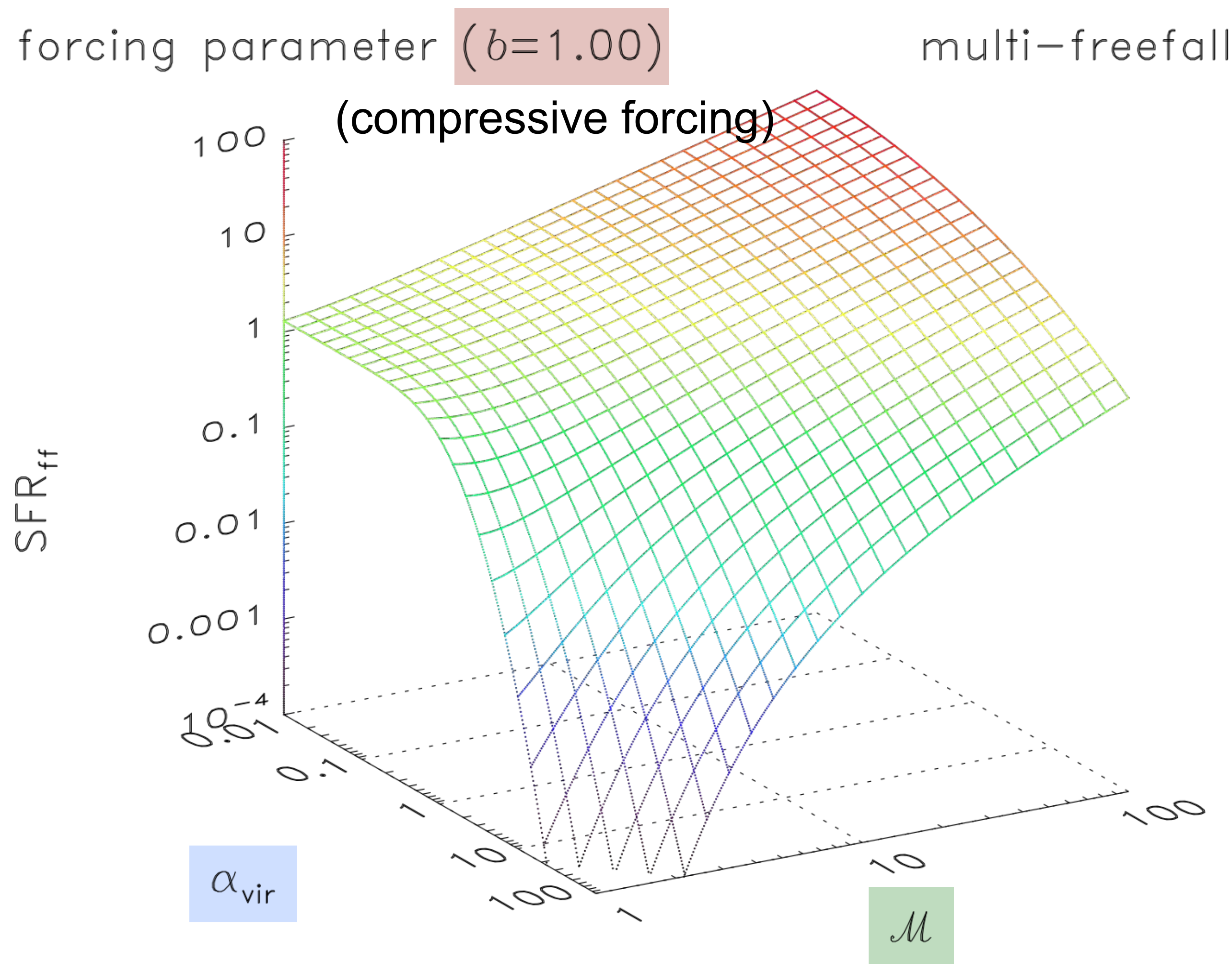


Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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

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



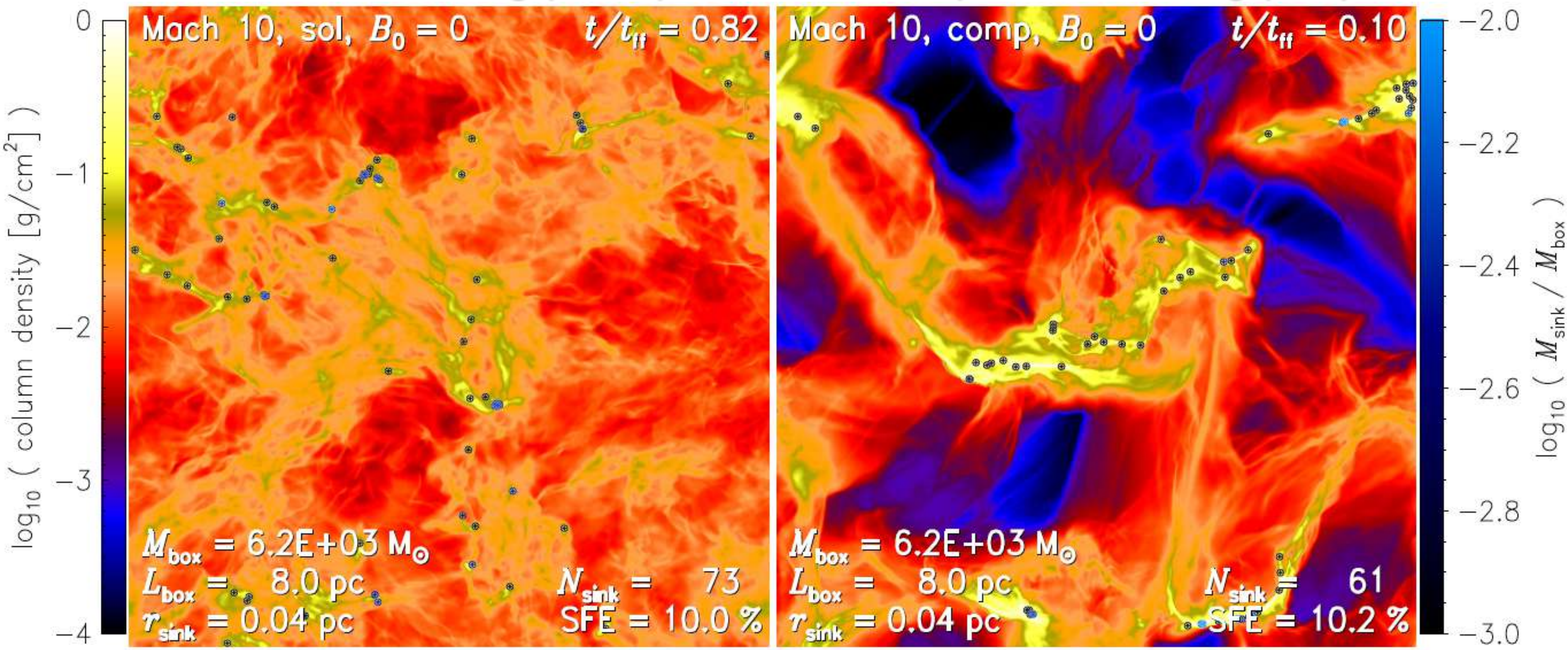
Federrath & Klessen (2012)

Density PDF → Star Formation Rate

Numerical Test for Mach 10 and $\alpha_{vir} \sim 1$

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

Solenoidal Forcing (b=1/3) Compressive Forcing (b=1)



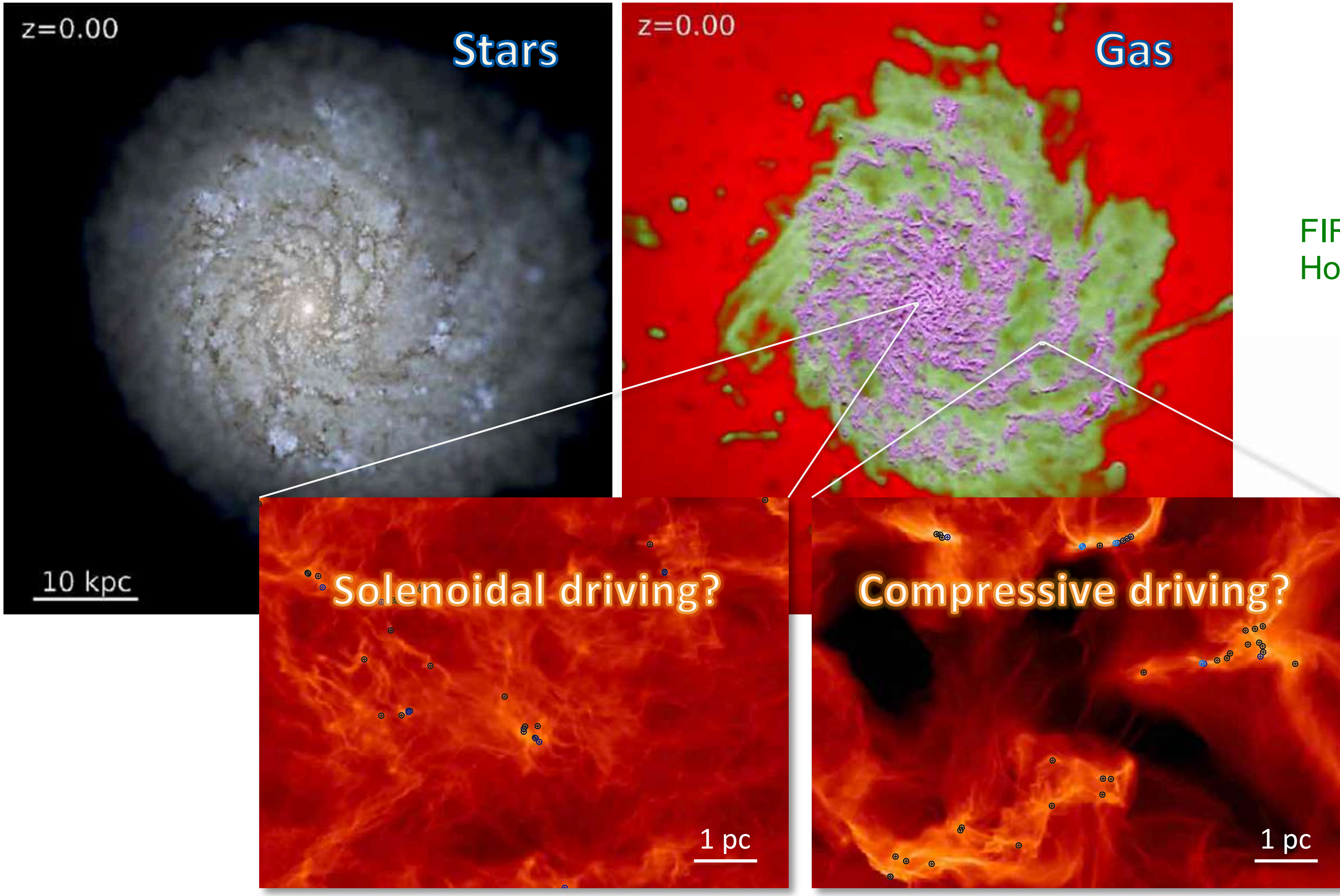
SFR_{ff} (simulation) = **0.14** x**20** SFR_{ff} (simulation) = **2.8**

SFR_{ff} (theory) = **0.15** x**15** SFR_{ff} (theory) = **2.3**

Turbulence driving is a key parameter for star formation

Federrath & Klessen (2012)

Driving of turbulence in different galactic environments



FIRE galaxies:
Hopkins et al. (2013)

FIRE-DRIVE:
DP170100603
CI Federrath

Determine the driving in Galactic Centre (Federrath et al. 2016) vs. Galactic Disc

→ Recently applied to the SAMI galaxy survey (Federrath et al. 2017, MNRAS 468, 3965; Zhou et al. 2017)

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

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

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

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

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

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

From sonic and Jeans scales:

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

(Krumholz+McKee 2005; Padoan+Nordlund 2011)

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

(Federrath+2008; Molina+2012)

MAGNETIC FIELD: $P_{\mathrm{th}} \rightarrow P_{\mathrm{th}} + P_{\mathrm{mag}}$

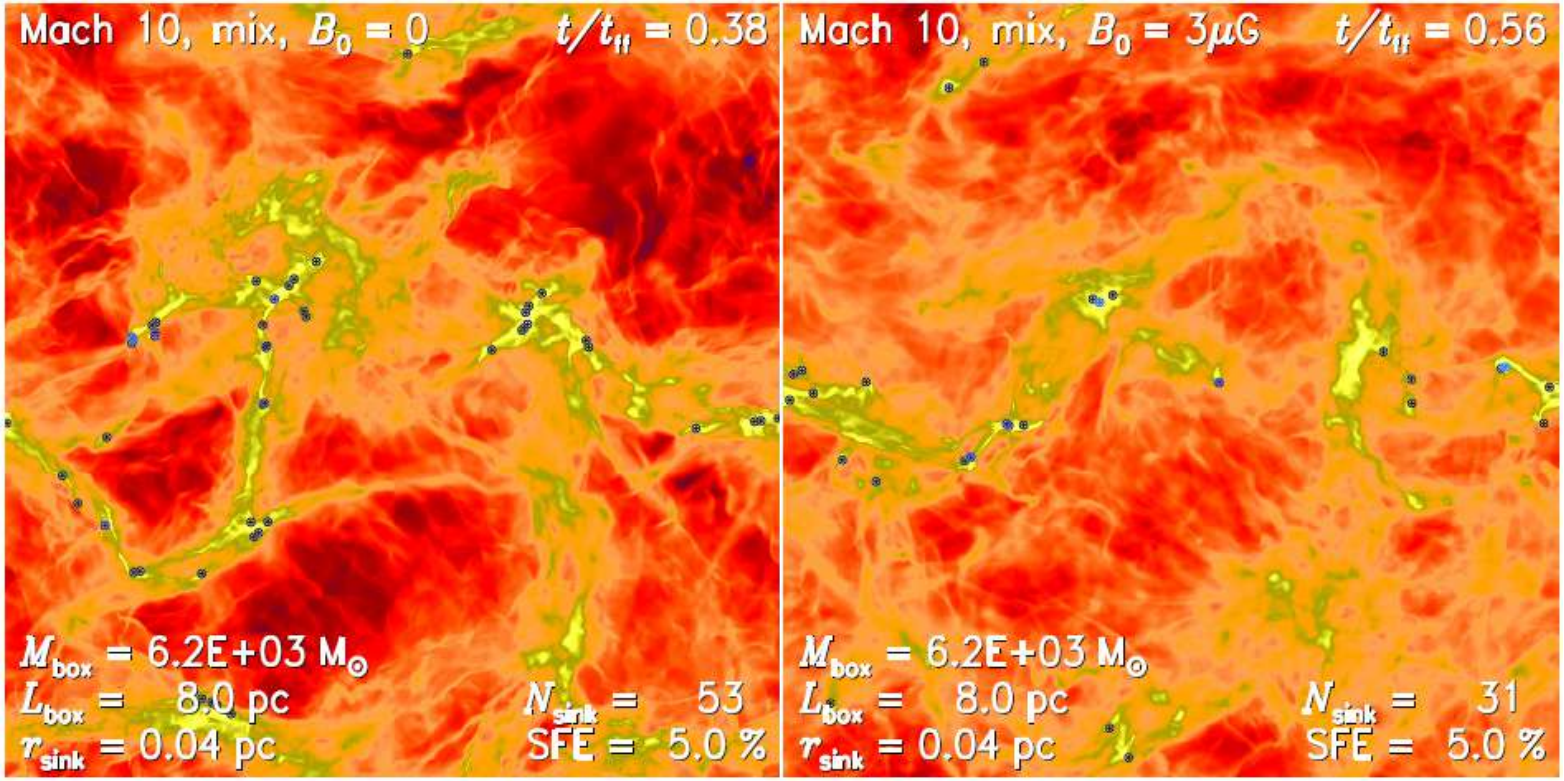
Federrath & Klessen (2012)

The Star Formation Rate – Magnetic fields

Numerical Test for Mach 10 with mixed forcing

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

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



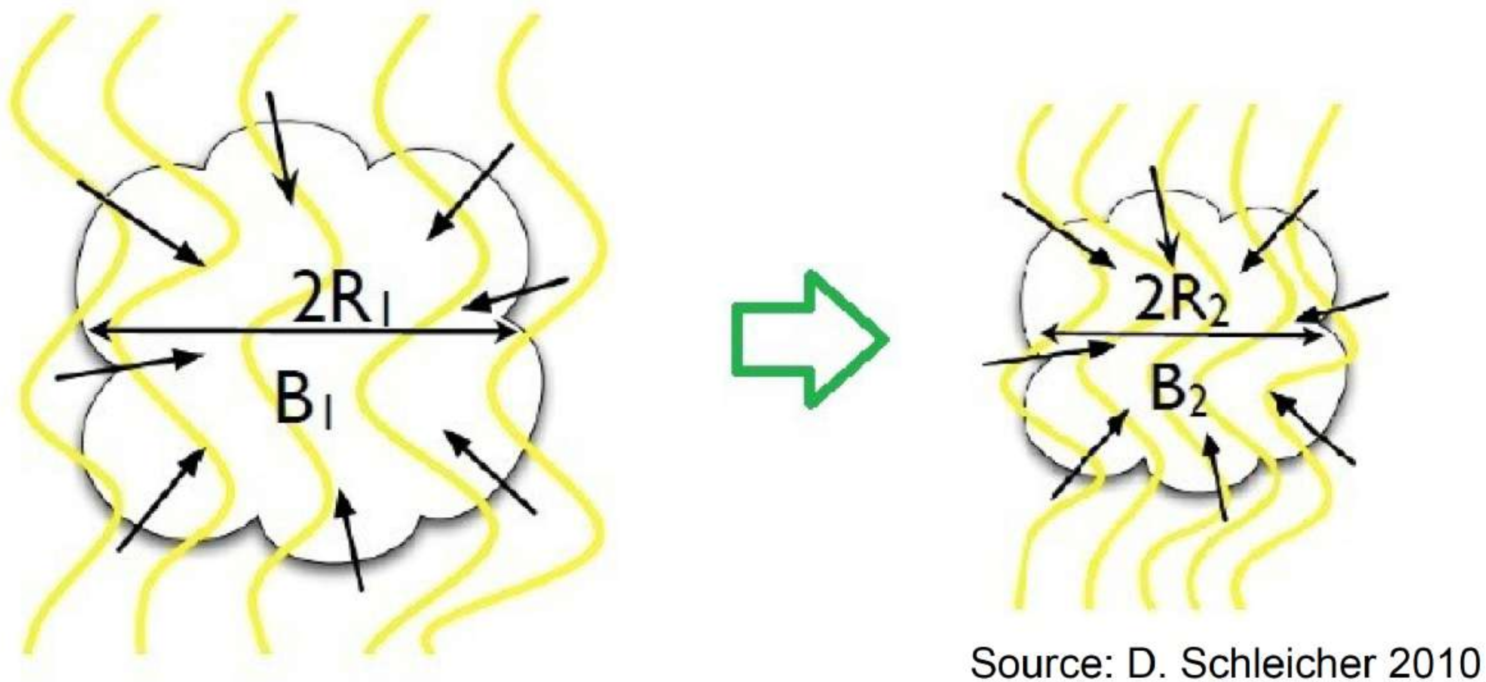
SFR_{ff} (simulation) = **0.46** x **0.63** SFR_{ff} (simulation) = **0.29**

SFR_{ff} (theory) = **0.45** x **0.40** SFR_{ff} (theory) = **0.18**

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

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

Compression of field lines during collapse (flux-freezing):



Source: D. Schleicher 2010

conservation of magnetic flux:

$$R_1^2 \cdot B_1 = R_2^2 \cdot B_2$$

$$\boxed{B \propto \rho^{2/3}}$$

Dynamo:

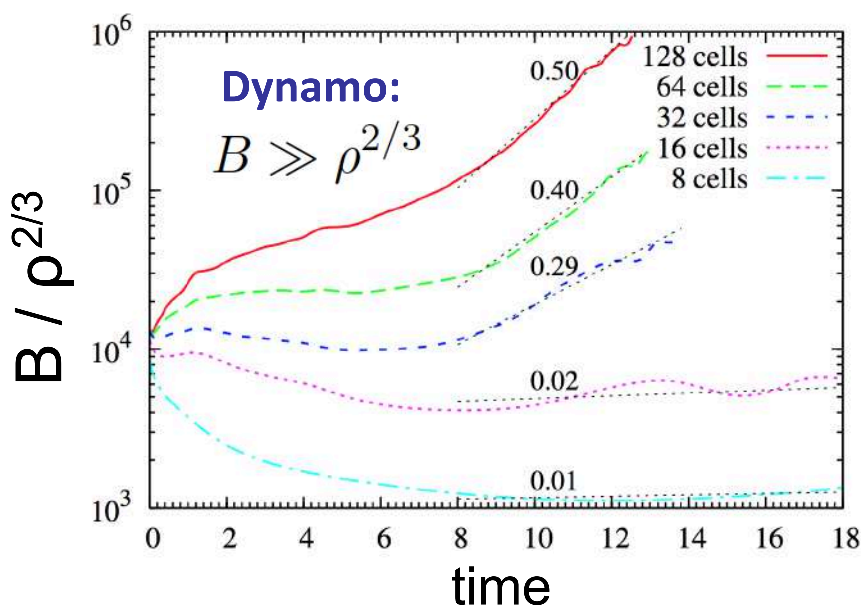
$$B \gg \rho^{2/3}$$

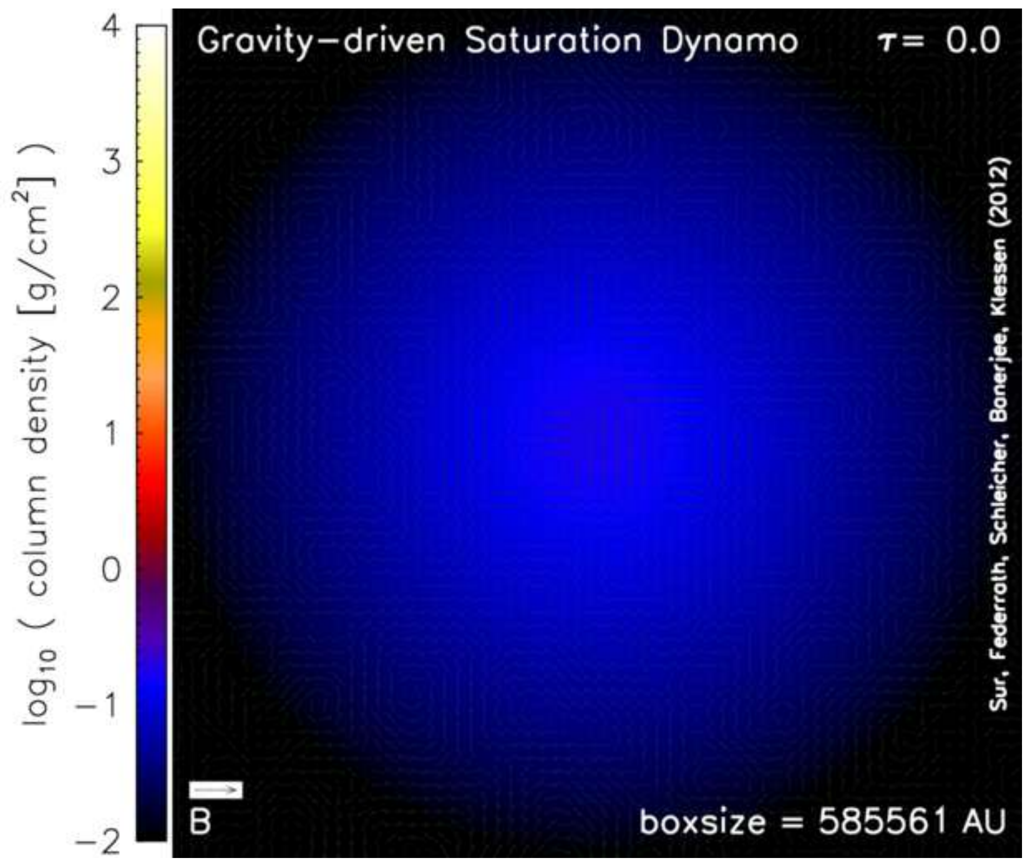
Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/dynamo_grav/dynamo_grav.html

Can dynamo work in a collapsing cloud?

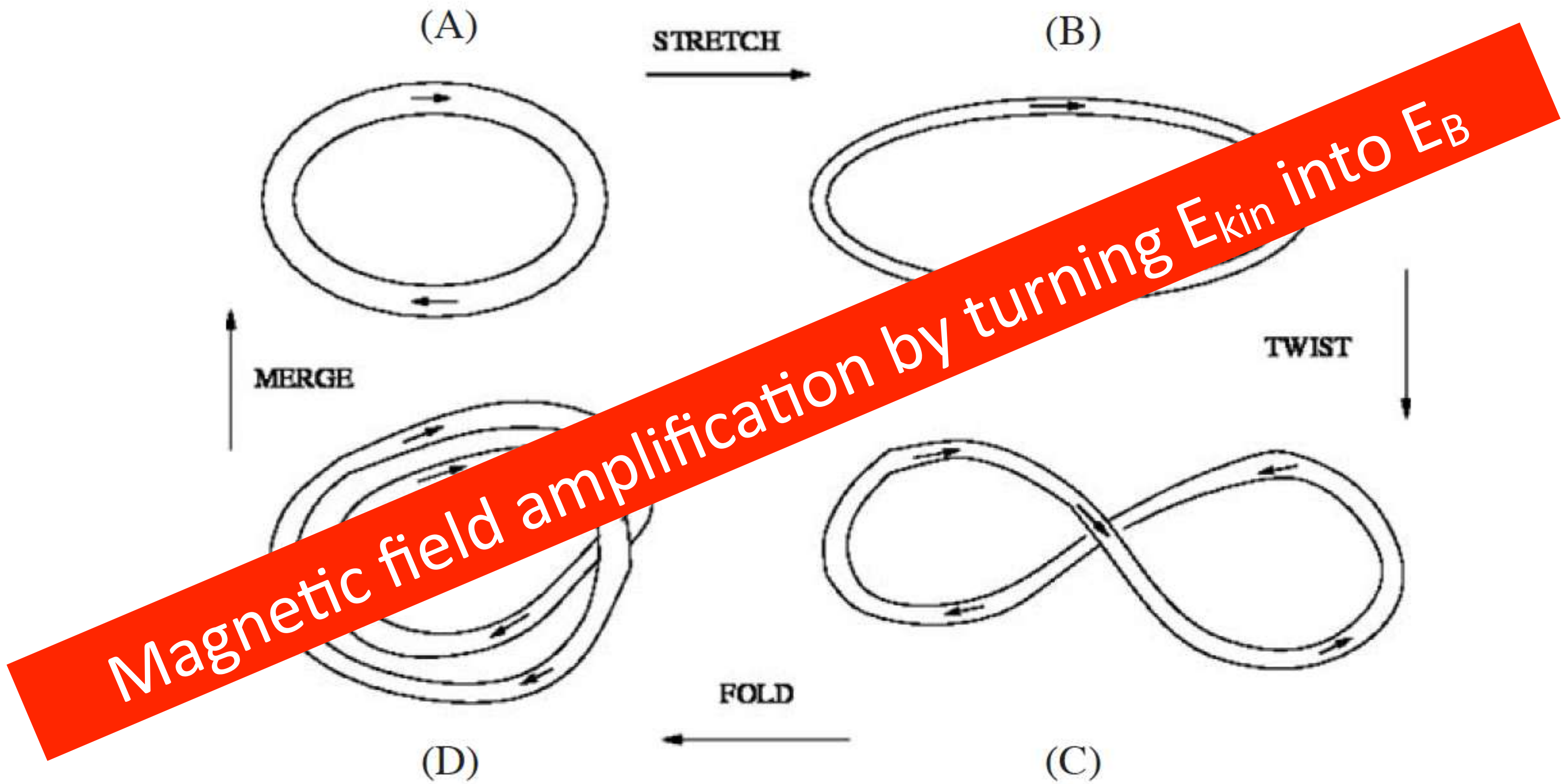
Magnetohydrodynamic simulations by
Sur et al. (2010, 2012); Federrath et al. (2011):

- gravitationally unstable Bonnor-Ebert sphere
- initial large-scale turbulence
- weak intial B = 1 nano Gauss
- Deep adaptive mesh refinement





Stretch-Twist-Fold Dynamo („turbulent dynamo“):



Brandenburg & Subramanian (2005); Federrath (2016, Journal of Plasma Physics 82, 6)

Turbulent dynamo in compressible gases

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\boxed{\nabla \times (\mathbf{v} \times \mathbf{B})}}_{\text{non-linear}} \underbrace{\boxed{+\,\eta \nabla^2 \mathbf{B}}}_{\text{diffusive}}$$

Exponential amplification of B:

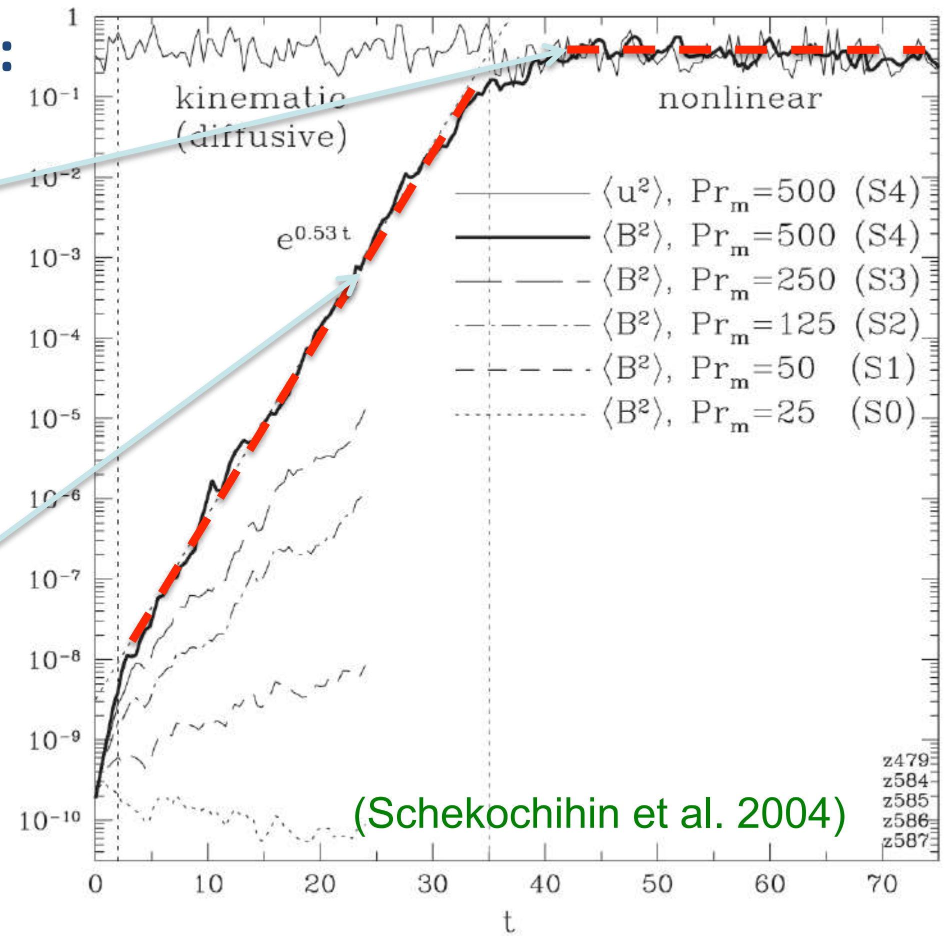
Saturation

$$E_\mathrm{B} \approx E_\mathrm{kin}$$

Exponential growth with

$$B \propto \exp\left(\sqrt{\mathrm{Re}}\,\frac{t}{t_\mathrm{eddy}}\right)$$

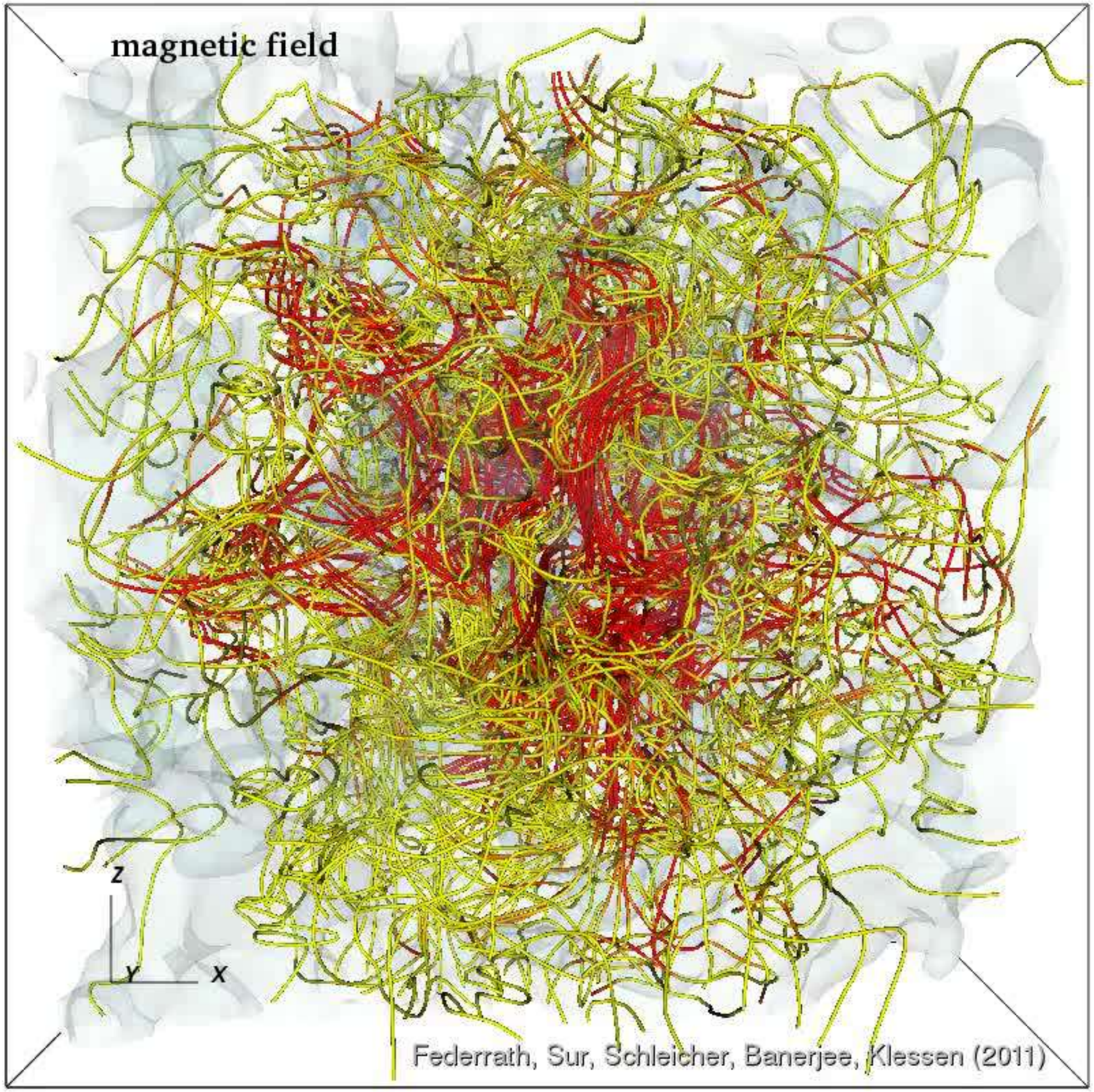
(Schober et al. 2011)



(Schekochihin et al. 2004)

Gravity-driven dynamo

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

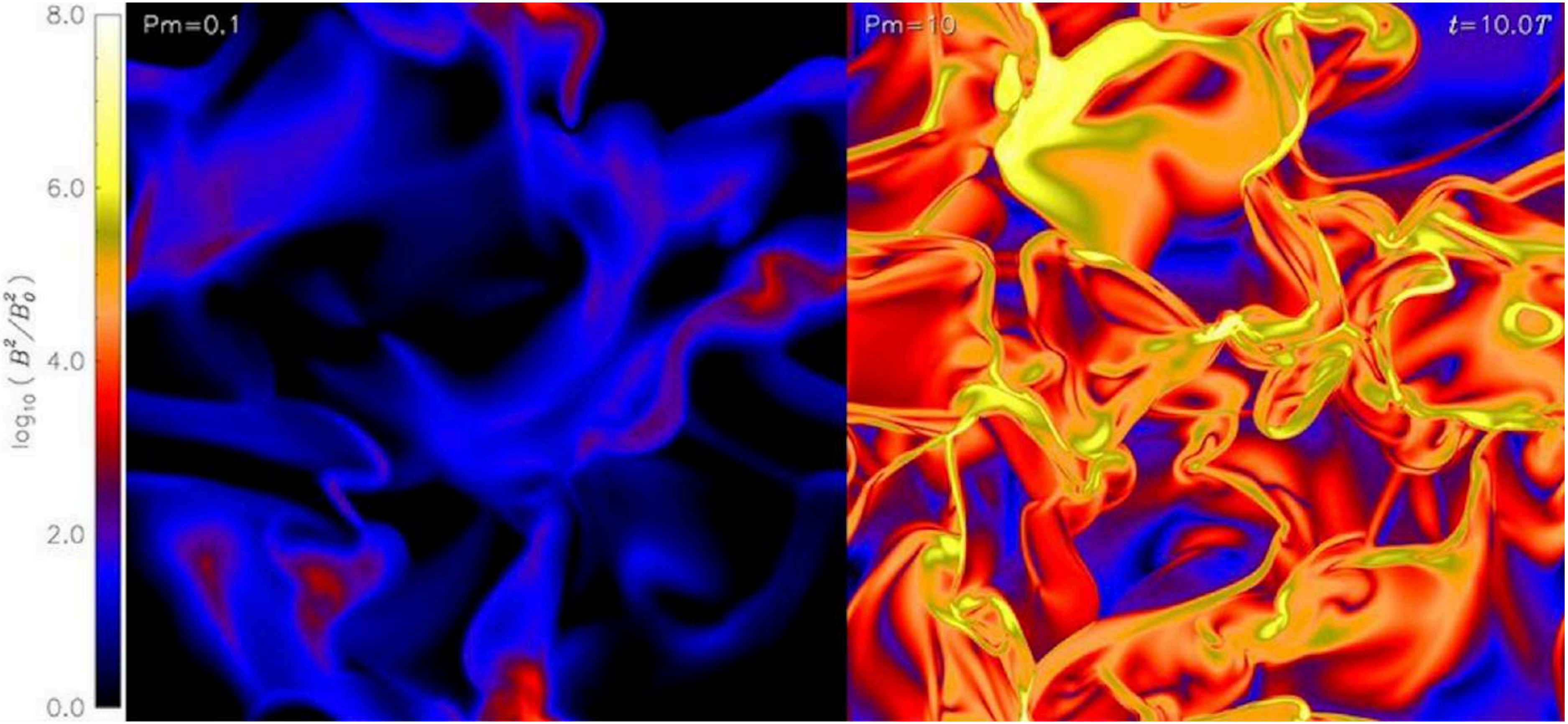


Federrath et al. (2011)

Dependence of dynamo on magnetic Prandtl number

Prandtl number 0.1

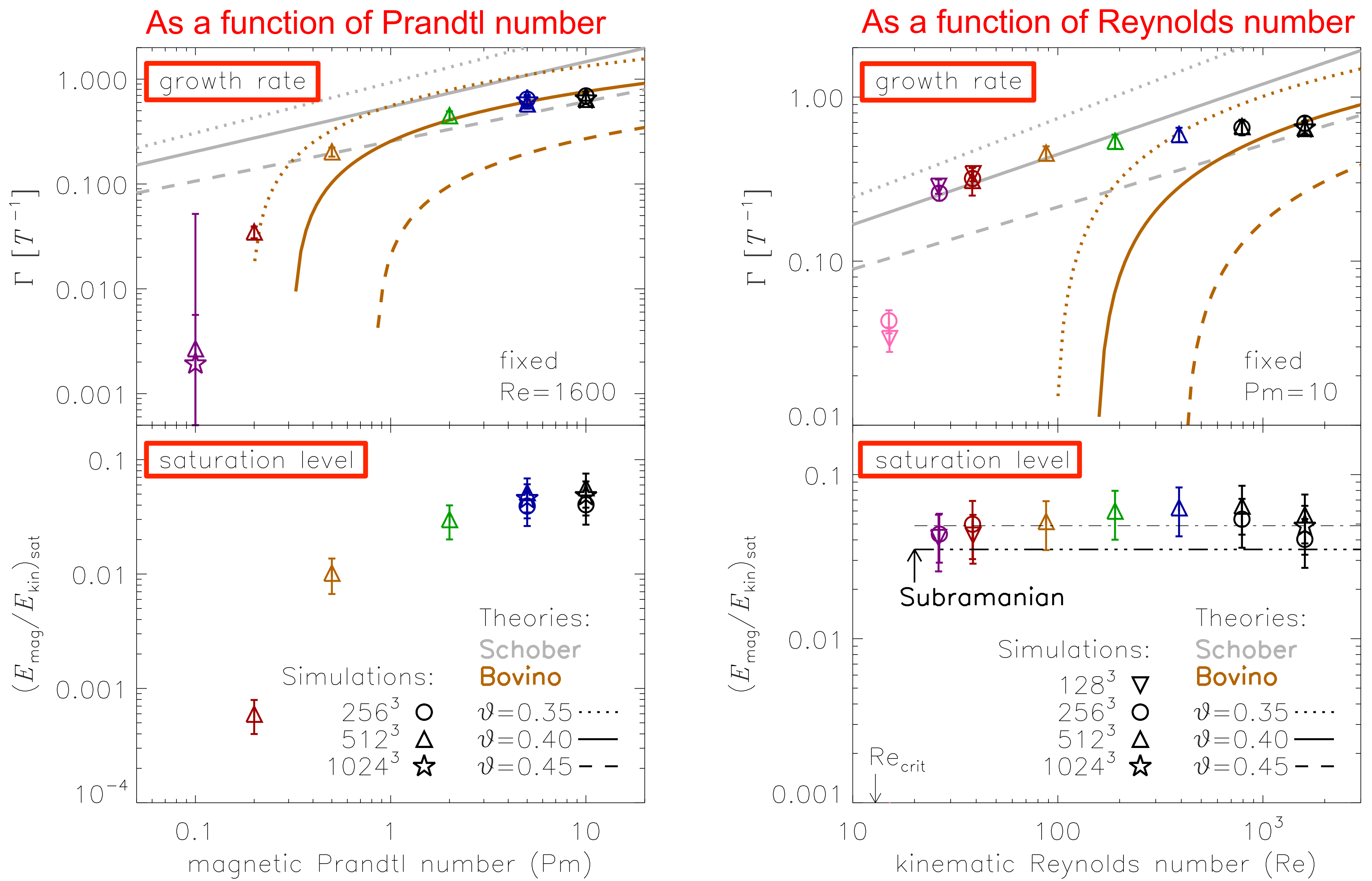
Prandtl number 10



Federrath et al. (2014, ApJ 797, L19)

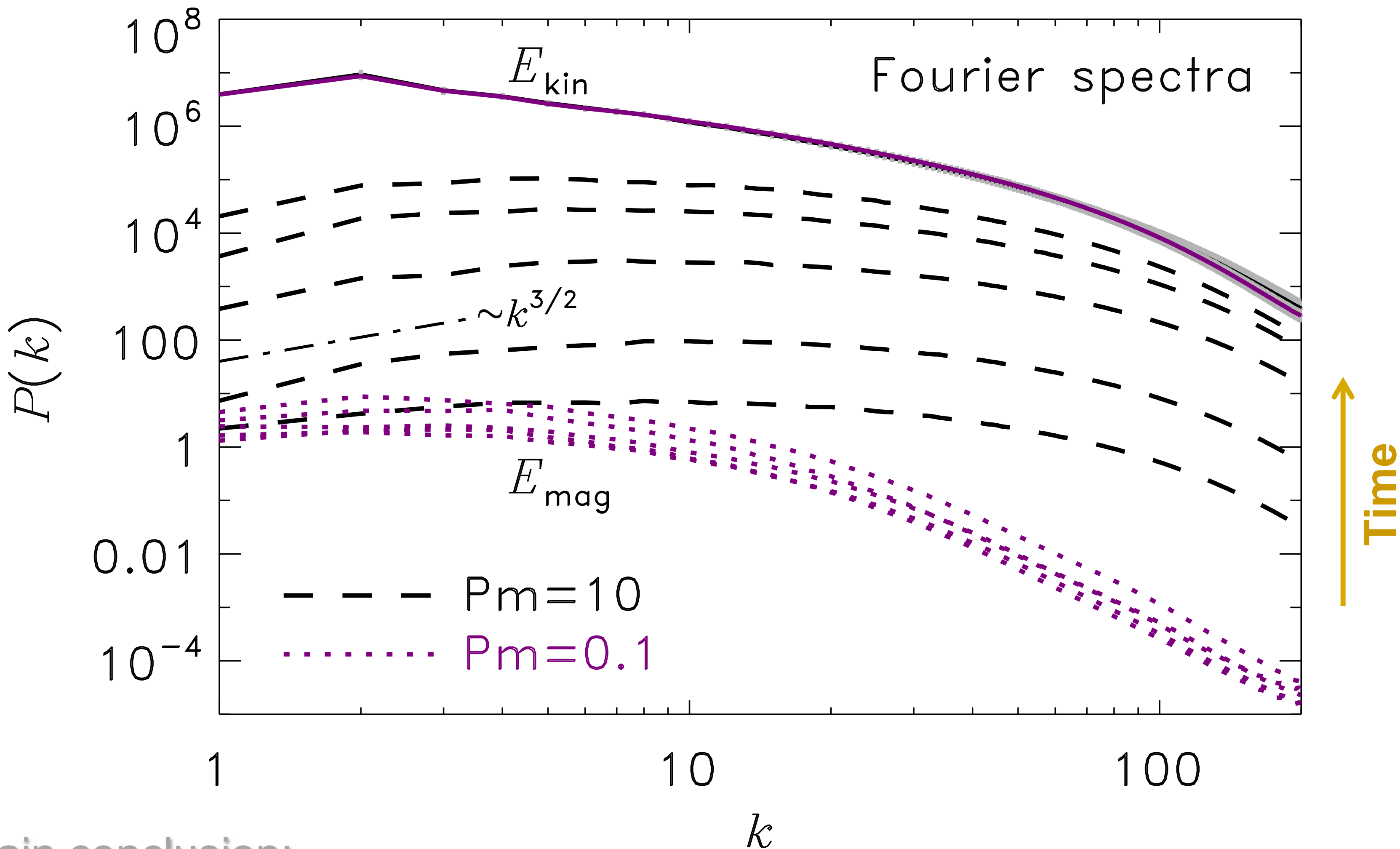
Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/dynamo_pm/dynamo_pm.html

Dependence of supersonic dynamo on Pm and Re



Federrath et al. (2014, ApJ 797, L19)

Supersonic dynamo power spectrum

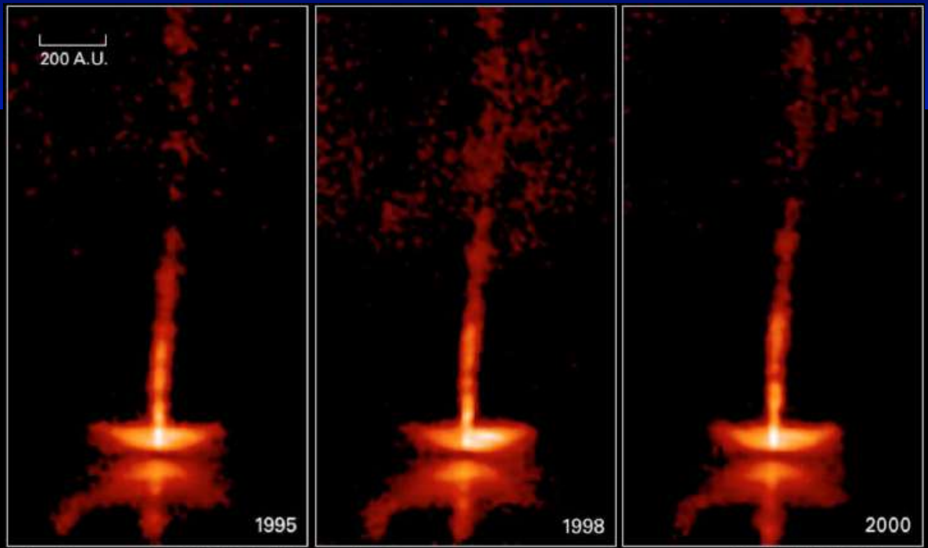


Main conclusion:

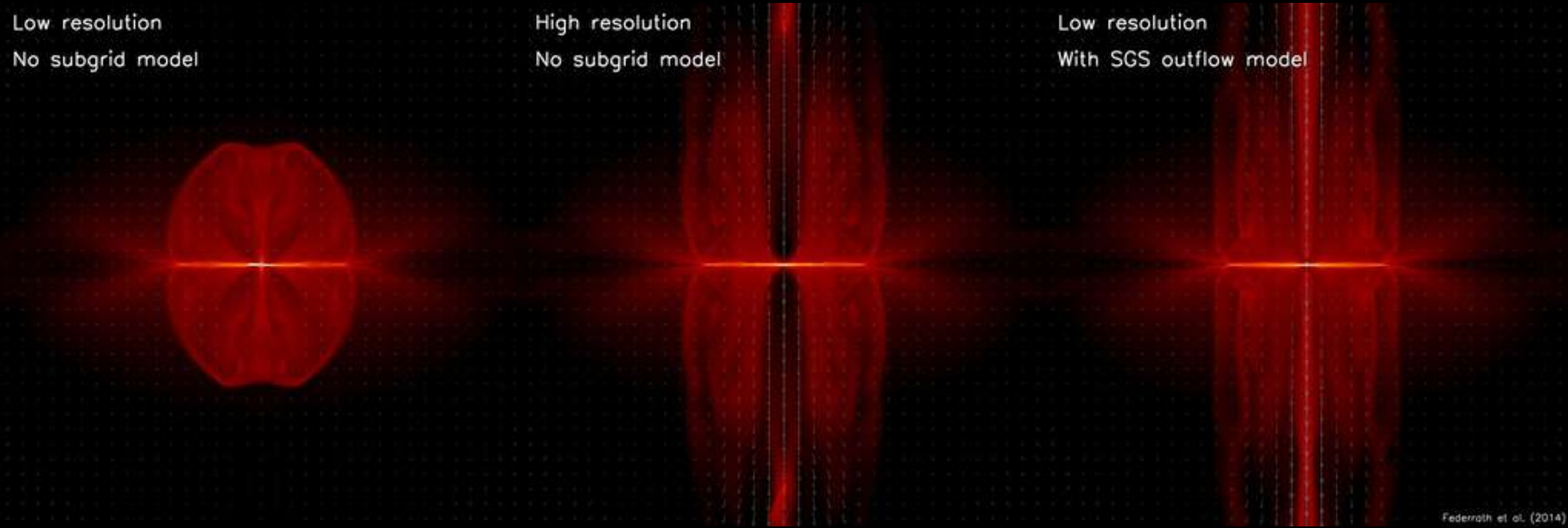
Dynamo works; Magnetic Field important even in Early Universe!

Federrath et al. (2014, ApJ 797, L19); see also Schober et al. (2012)

Jet/Outflow Feedback



The Dynamic HH 30 Disk and Jet HST • WFPC2
NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

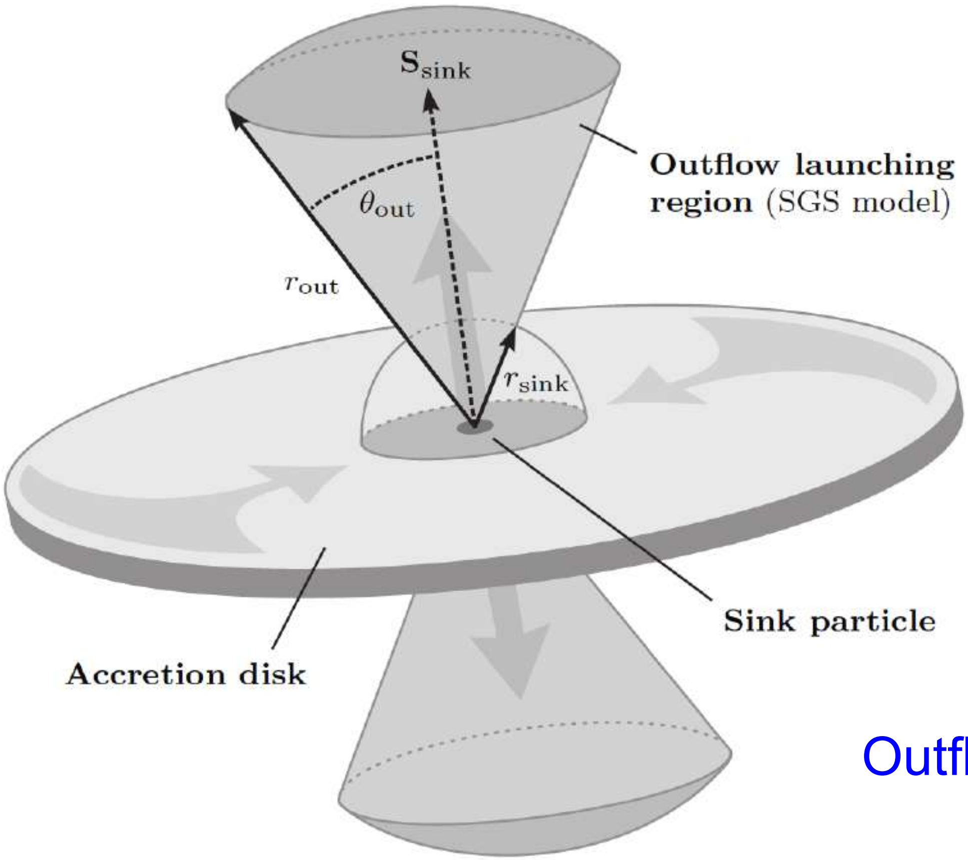


Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

Federrath et al. 2014, ApJ 790, 128

Jet Feedback 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 footpoint of the jet, $|\mathbf{V}_{\rm out}| = 100\,{\rm km\,s^{-1}}(M_{\rm sink}/0.5\,M_\odot)^{1/2}$ (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: $$|\mathbf{V}_{\rm out}| = \left(\frac{G M_{\rm sink}}{10\,R_\odot}\right)^{1/2} = 100\,{\rm km\,s^{-1}} \left(\frac{M_{\rm sink}}{0.5\,M_\odot}\right)^{1/2}$$

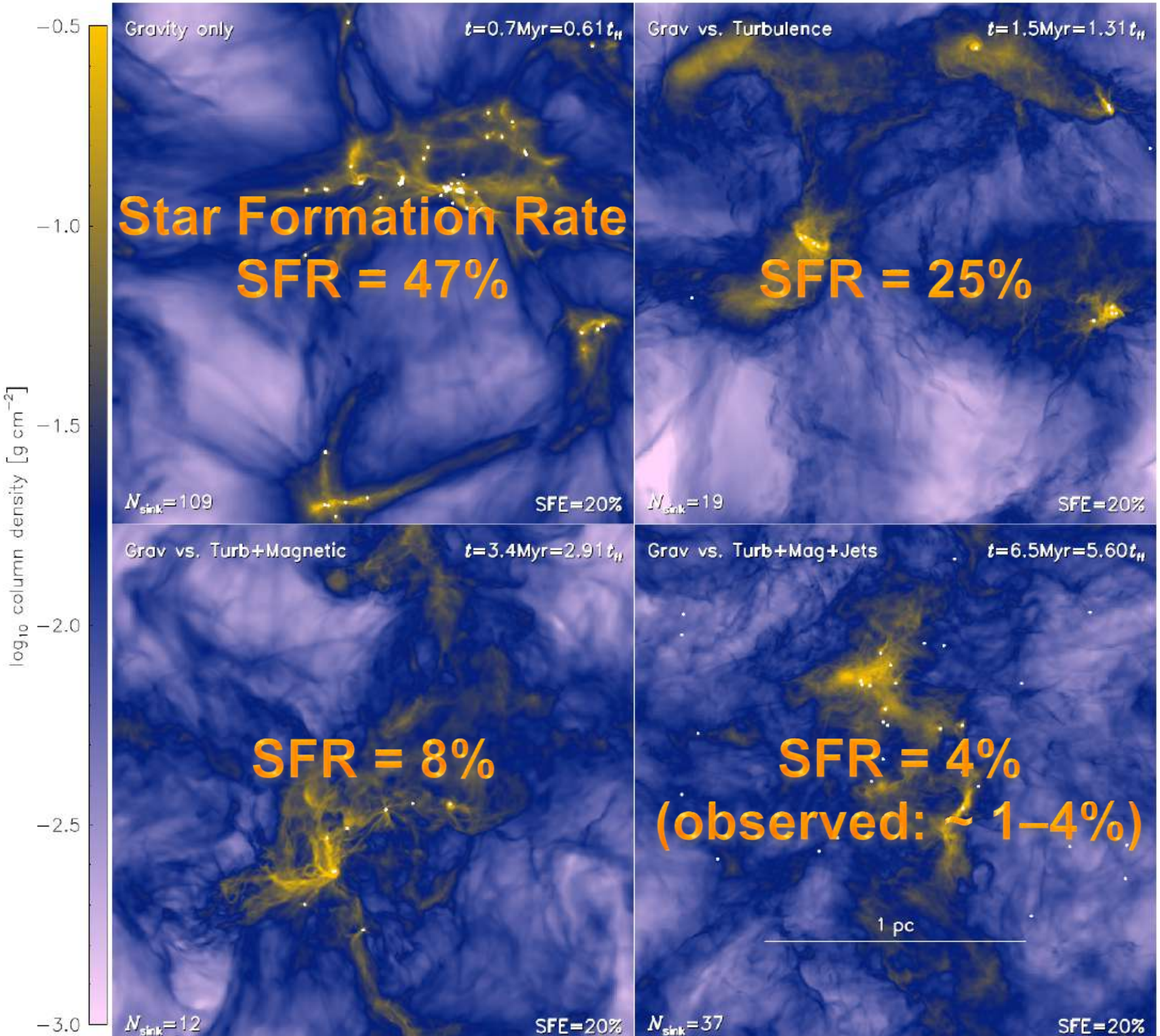
Outflow angular momentum: $$\mathbf{L}_{\rm out} = f_{\rm a}\,(\mathbf{S}'_{\rm sink} - \mathbf{S}_{\rm sink}) \cdot \mathbf{S}'_{\rm sink}/|\mathbf{S}'_{\rm sink}|$$

Why is Star Formation is so Inefficient?

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

Gravity only

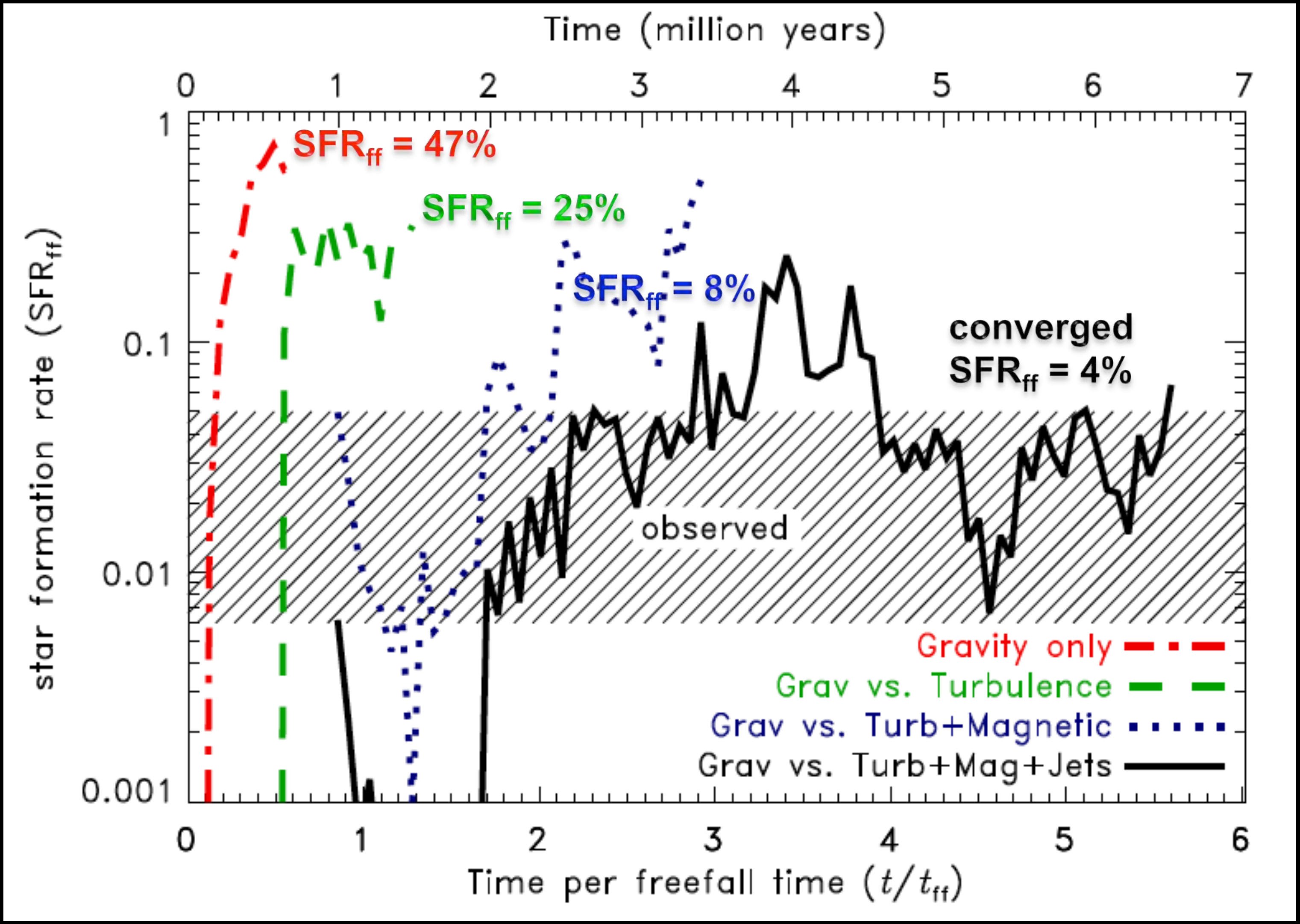
Turb



Turb+ Mag

Turb+ Mag+ Jets

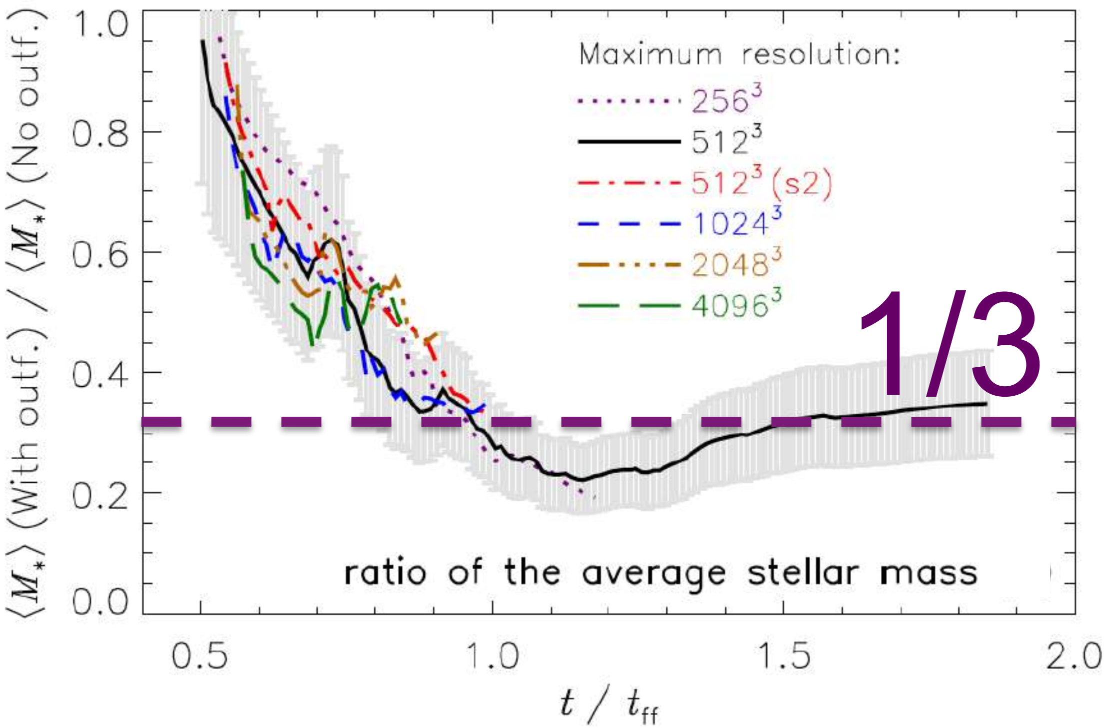
Star Formation is Inefficient

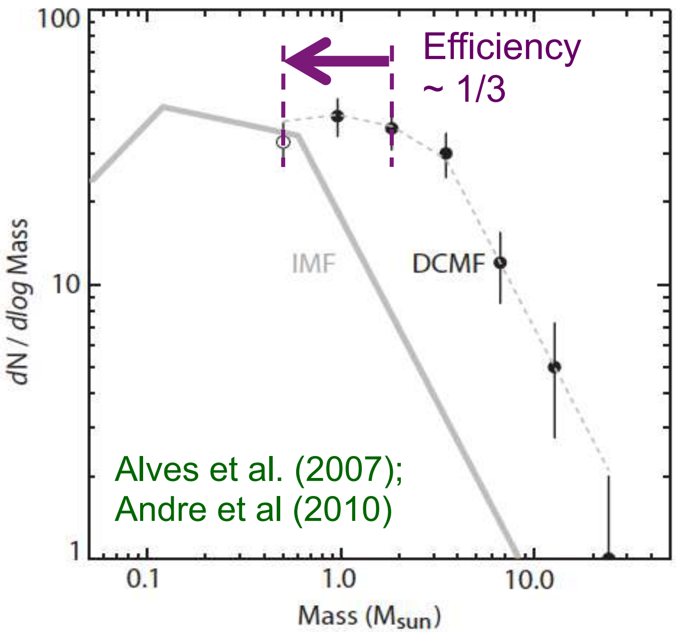


Only the combination of turbulence, magnetic fields and feedback gives realistic SFR

Federrath 2015, MNRAS 450, 4035

Implications for the stellar initial mass function (IMF)





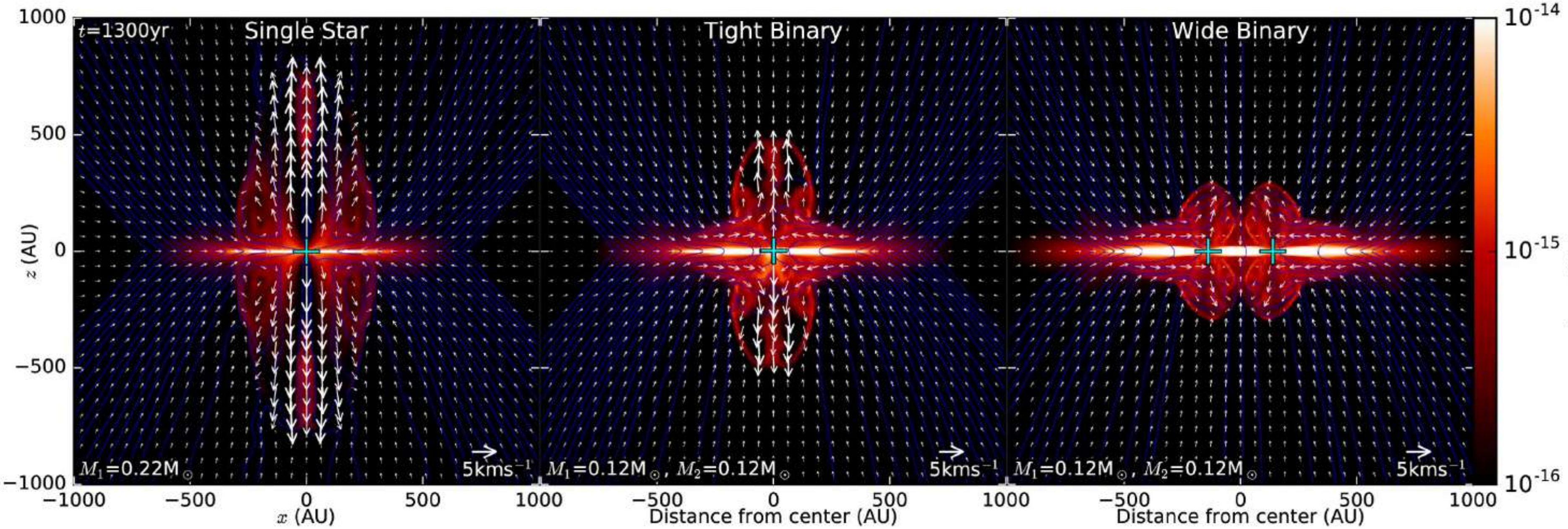
Federrath et al. 2014, ApJ 790, 128

Outflow/Jet feedback reduces average star mass by factor ~ 3 → IMF!

Jet Feedback in Binary Star Formation

Kuruwita, Federrath, Ireland (2017, MNRAS 470, 1626)

Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/binary_jets/binary_jets.html



Jet structure and power depend on binary separation → different star mass

→ Challenge for understanding and modelling the IMF!

Conclusions

1) Star Formation is complex and inefficient →

Only the combination of

Turbulence + Magnetic Fields + Feedback

gives realistic (observed) SFRs

2) Determined dynamo amplification in compressible, supersonic turbulence

→ Dynamo works in supersonic plasmas → B important in early Universe

Dependence on Prandtl and Reynolds number

3) Importance of magnetic fields and feedback for the IMF:

Determine the Initial Mass Function (IMF) of Stars

→ Necessary physics:

turbulence, magnetic fields, and jet feedback (+ radiation feedback)

The End.