Astronomical Computing

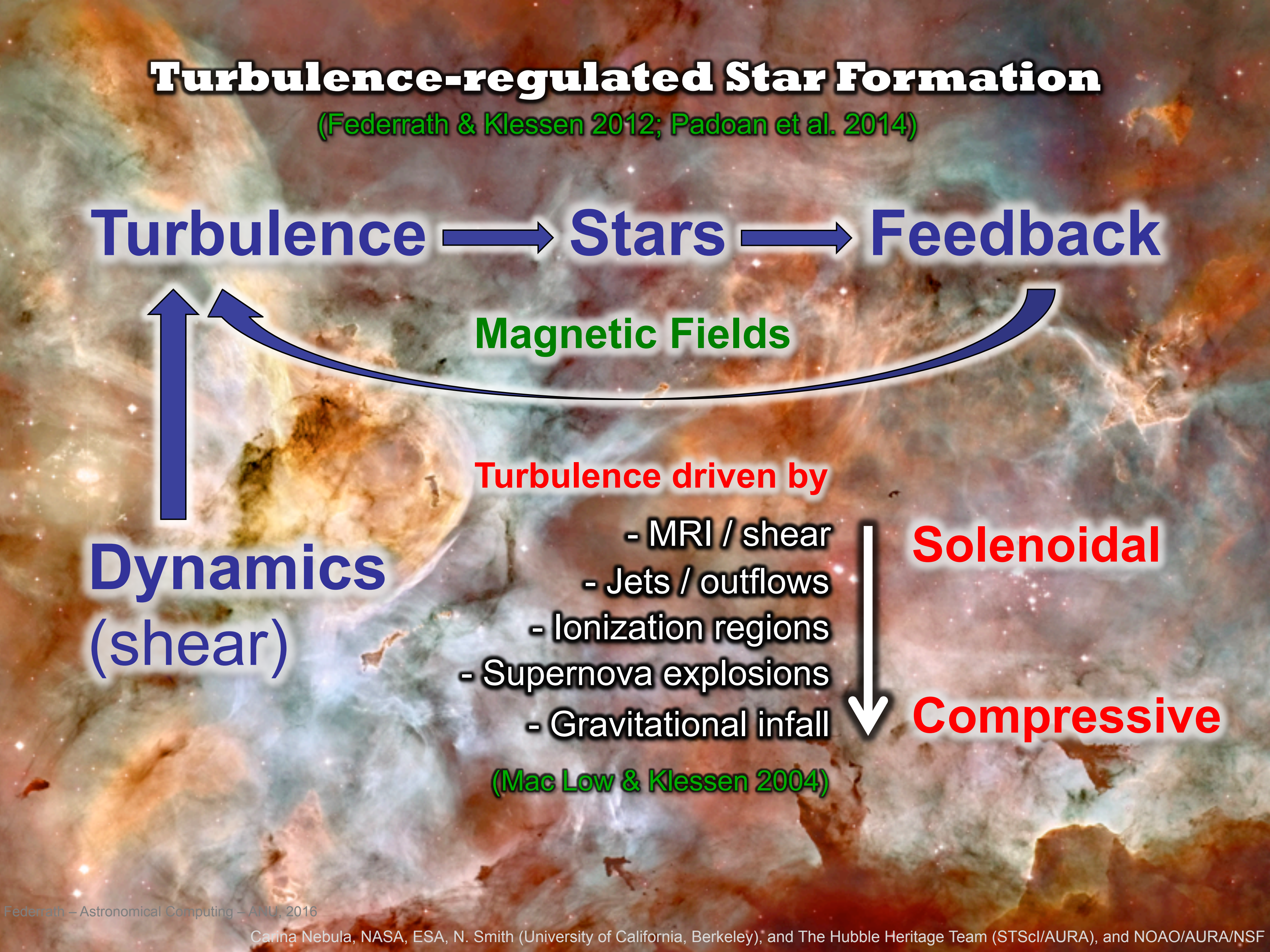
ASTR4004 / ASTR8004

ANU – 2nd semester 2016

Dr Christoph Federrath

Lectures and Tutorials: Tuesdays and Fridays 09:15-10:45

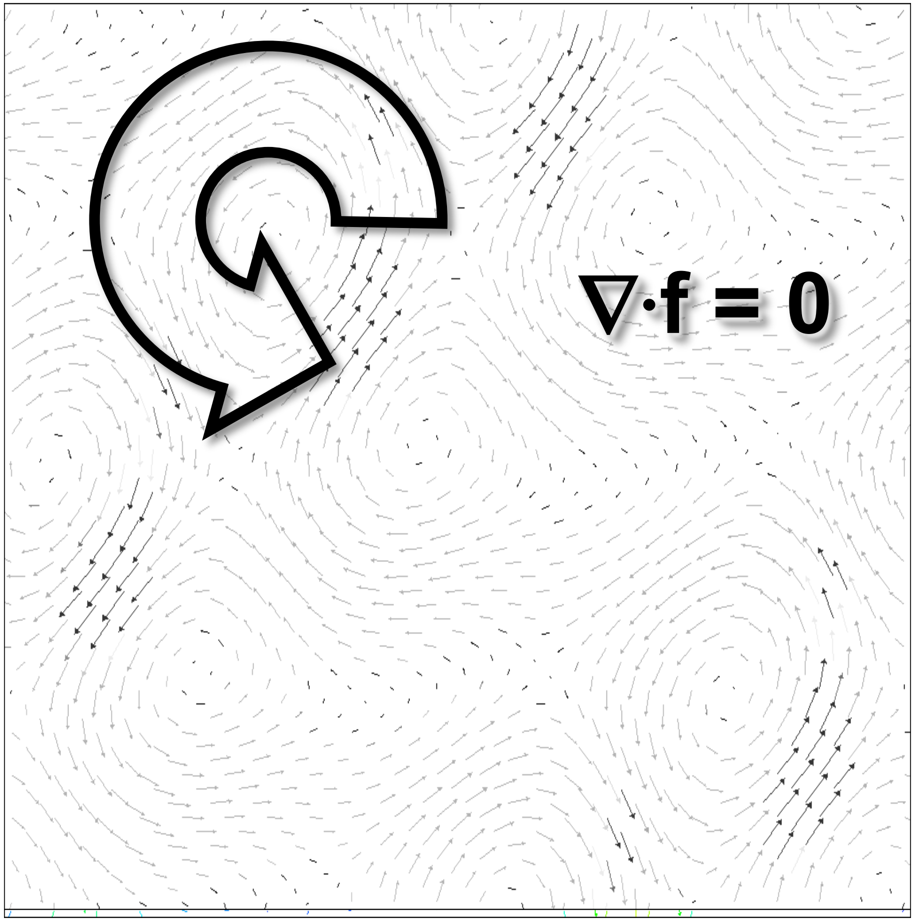
Image credit: M. S. Povich


Turbulence-regulated Star Formation
(Federrath & Klessen 2012; Padoan et al. 2014)
Turbulence
Stars
Feedback
Magnetic Fields
Dynamics
(shear)
Turbulence driven by
- MRI / shear
- Jets / outflows
- Ionization regions
- Supernova explosions
- Gravitational infall
Solenoidal
Compressive
(Mac Low & Klessen 2004)
Federrath – Astronomical Computing – ANU, 2016
Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

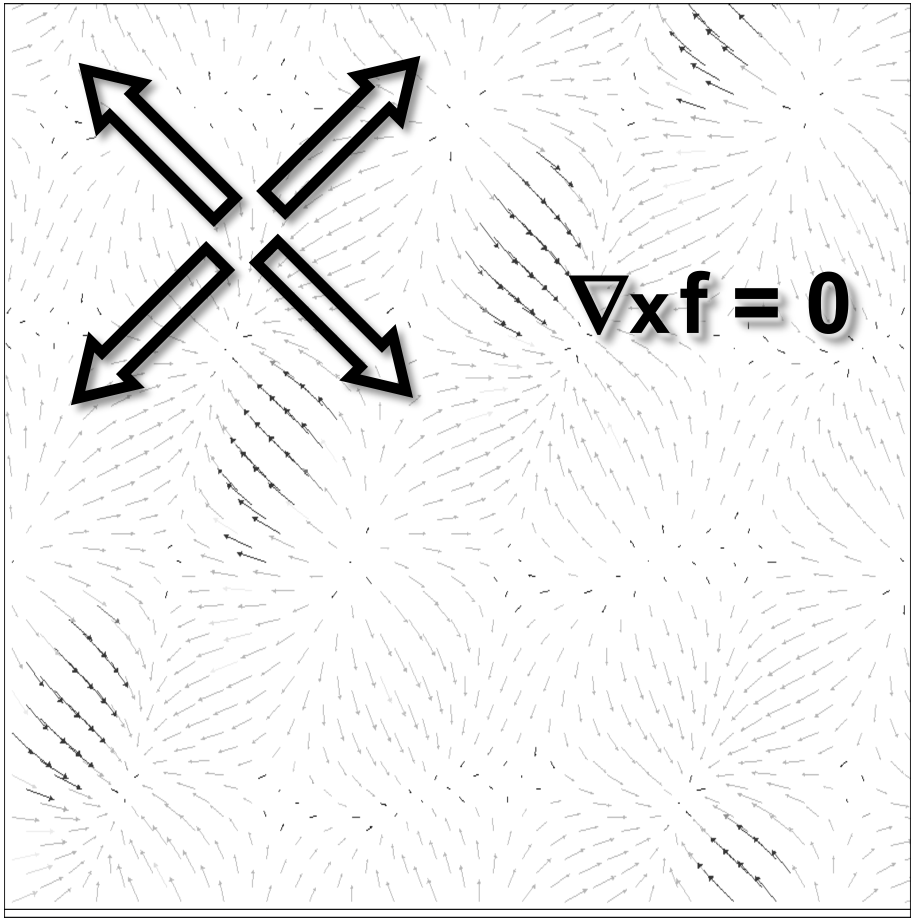
Turbulence driving – solenoidal versus compressive

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

Solenoidal forcing



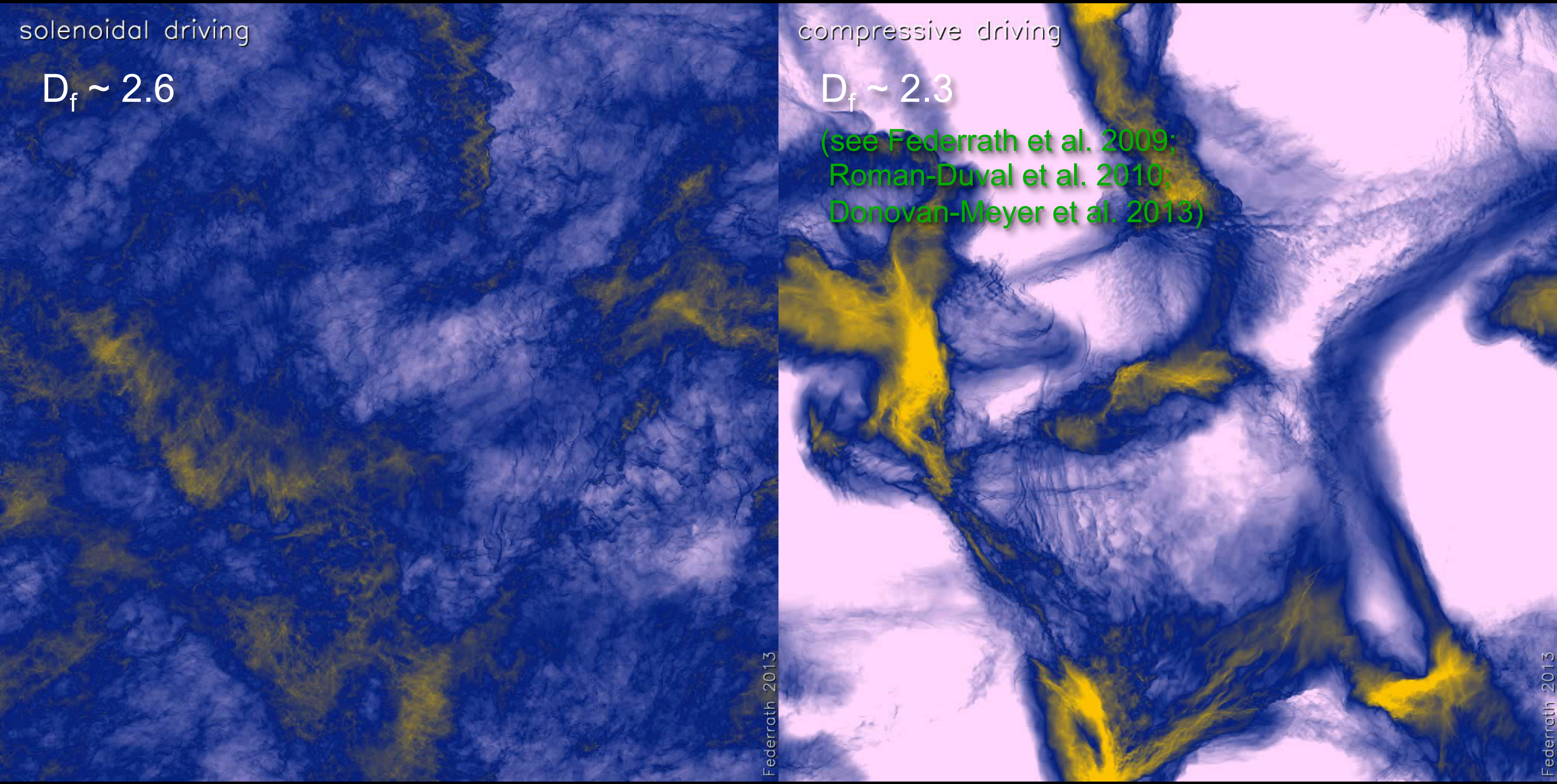
Compressive forcing



Turbulence driving – solenoidal versus compressive

solenoidal forcing | Column Density | compressive forcing

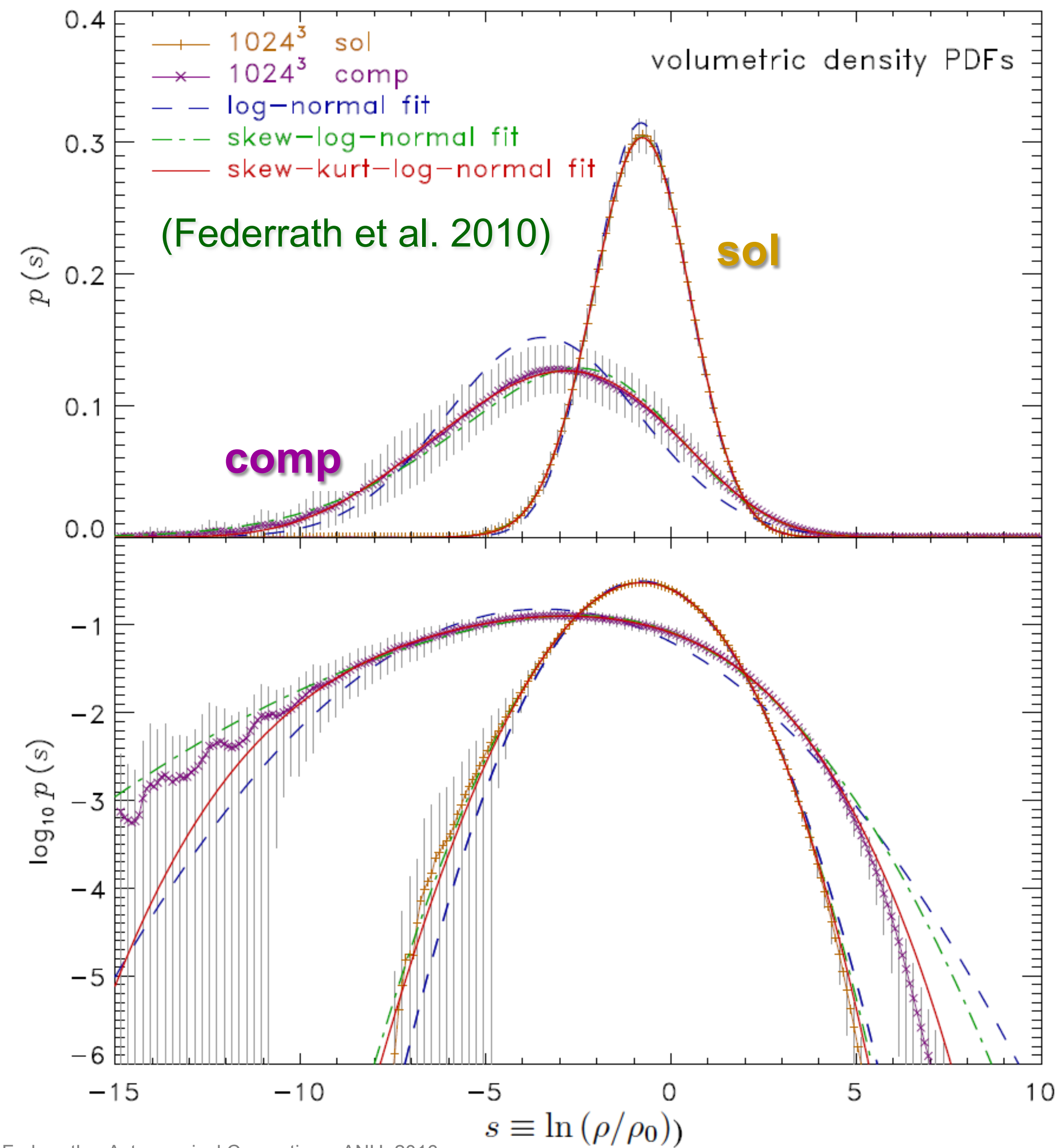
Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/supersonic/supersonic.html



Compressive forcing produces stronger density enhancements

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

The density PDF



Density PDF

log-normal:

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

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

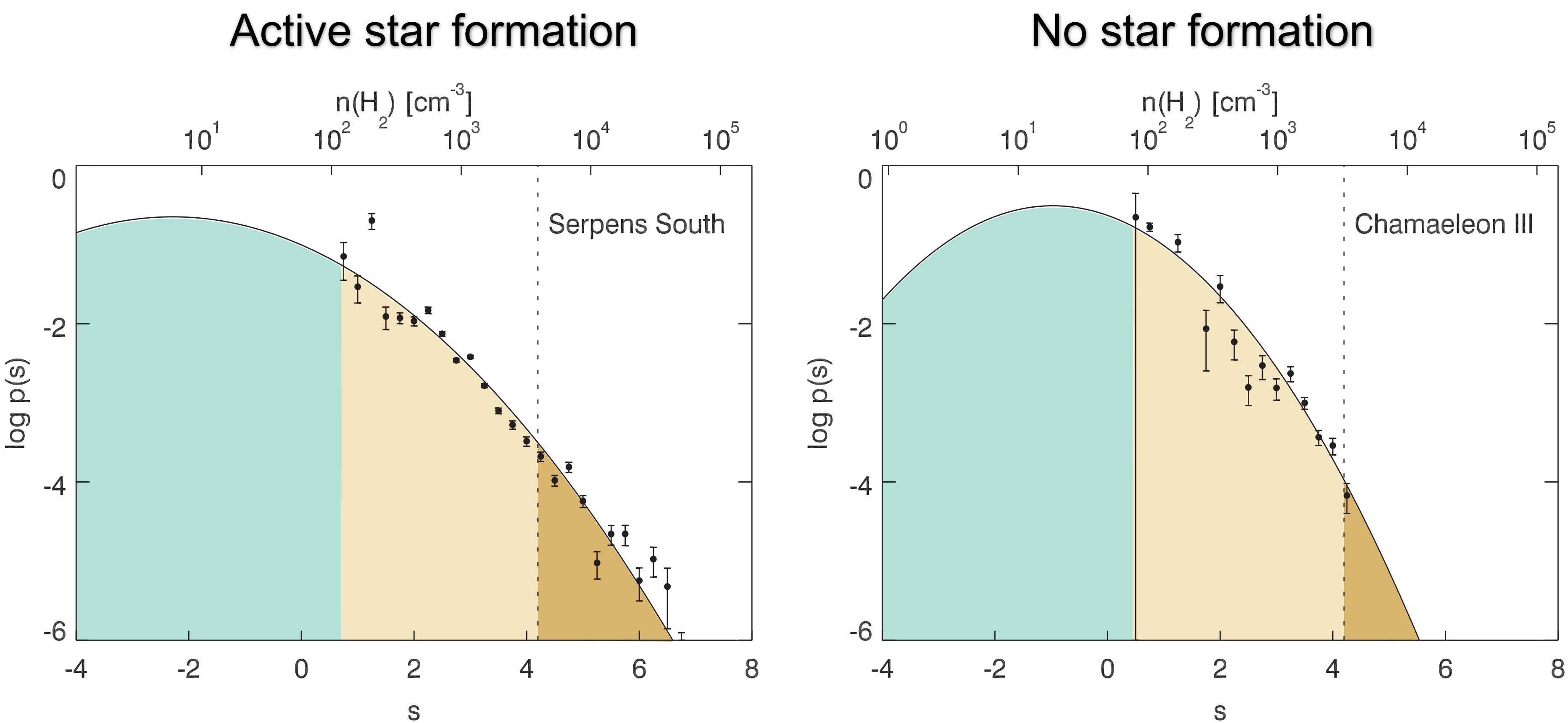
Vazquez-Semadeni (1994); Padoan et al. (1997); Ostriker et al. (2001); Hopkins (2013)

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

⇒ 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)

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; Cunningham et al., in prep.

2D → 3D
conversion

(Brunt et al. 2010a,b)

Turbulence → Density PDF

Density PDF → Star Formation Rate

Why is star formation so inefficient?

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

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

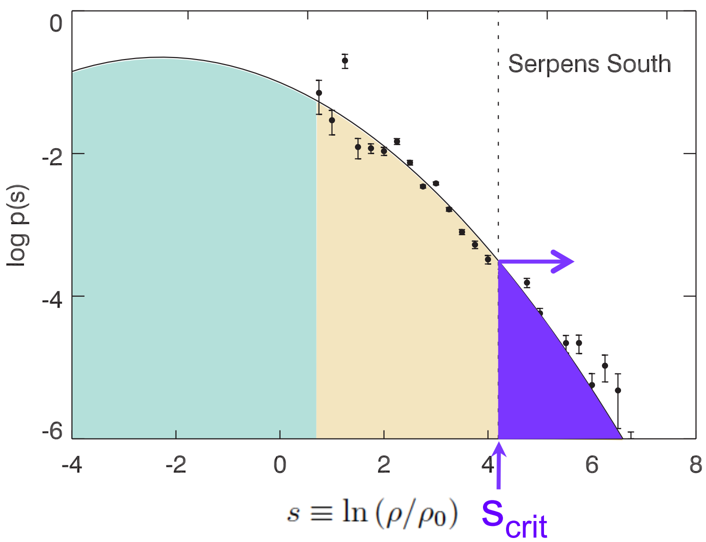
Krumholz & McKee (2005), Padoan & Nordlund (2011); Hennebelle & Chabrier (2011,2013)

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

freefall time — **mass fraction**

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



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

freefall time **mass fraction**

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

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

Federrath & Klessen (2012)

The Star Formation Rate

Statistical Theory for the Star Formation Rate:

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

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

SFR ~ Mass/time

freefall time — **mass fraction**

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

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

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)

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

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

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

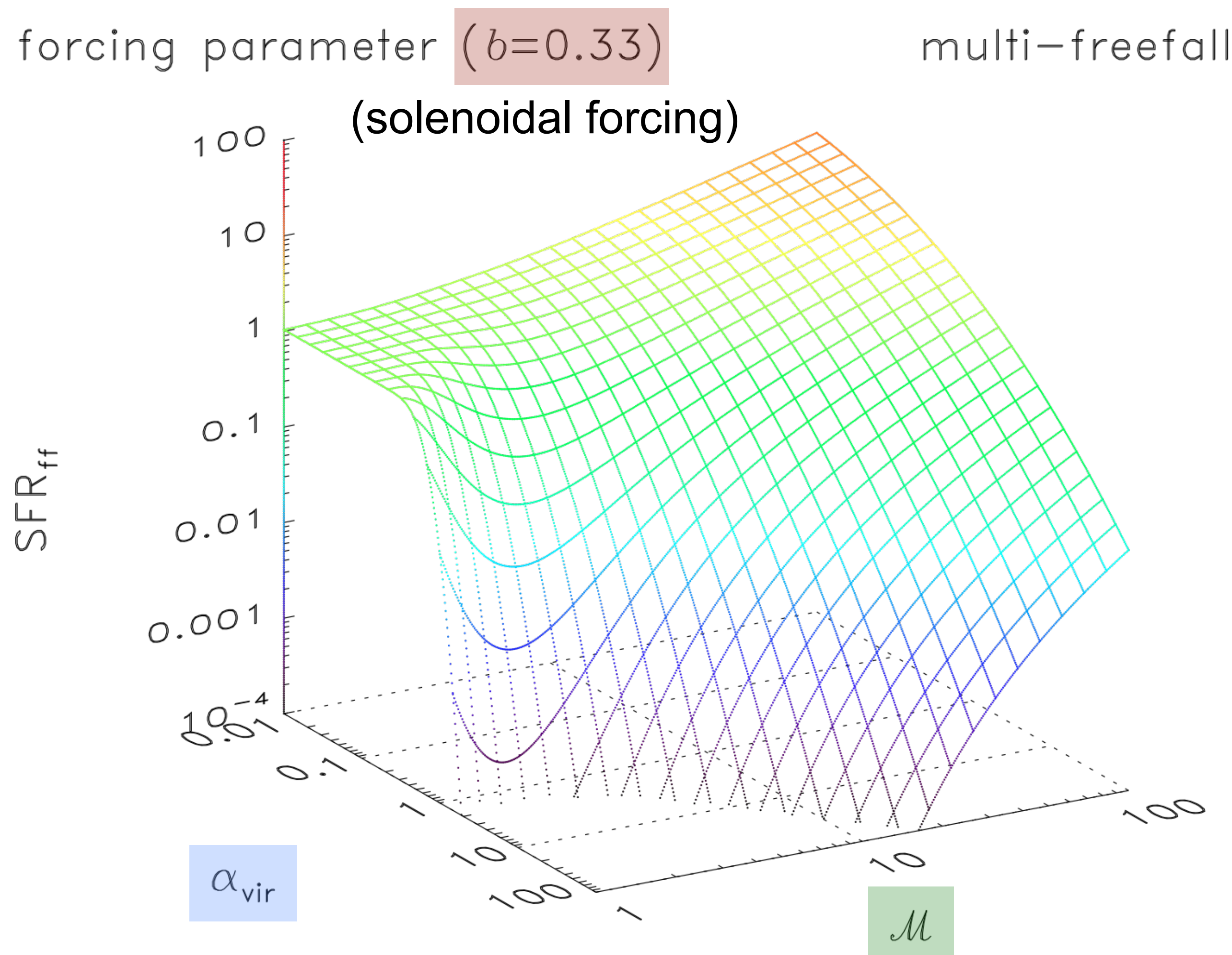
$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ — **forcing** — **Mach number**

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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

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

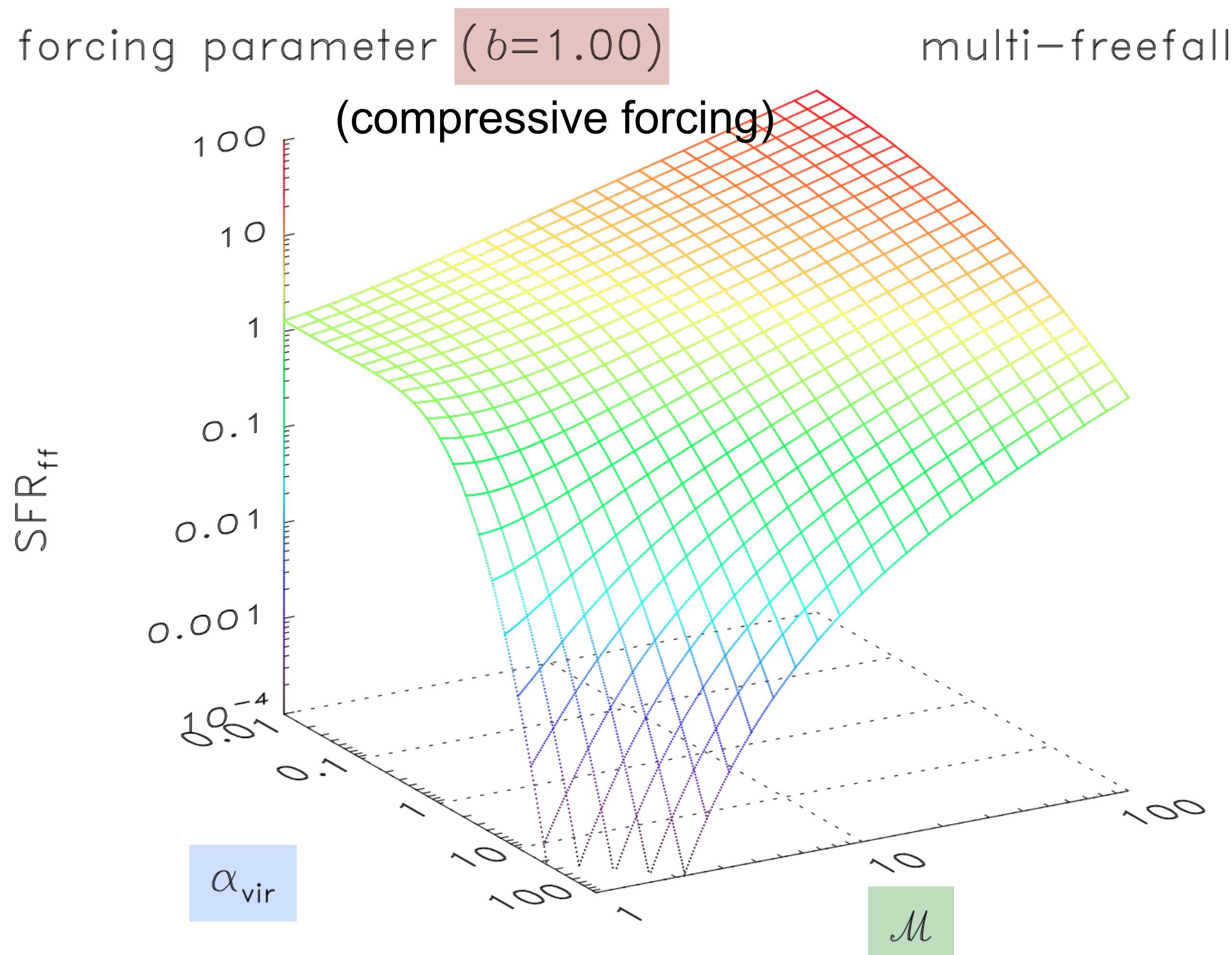


Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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

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



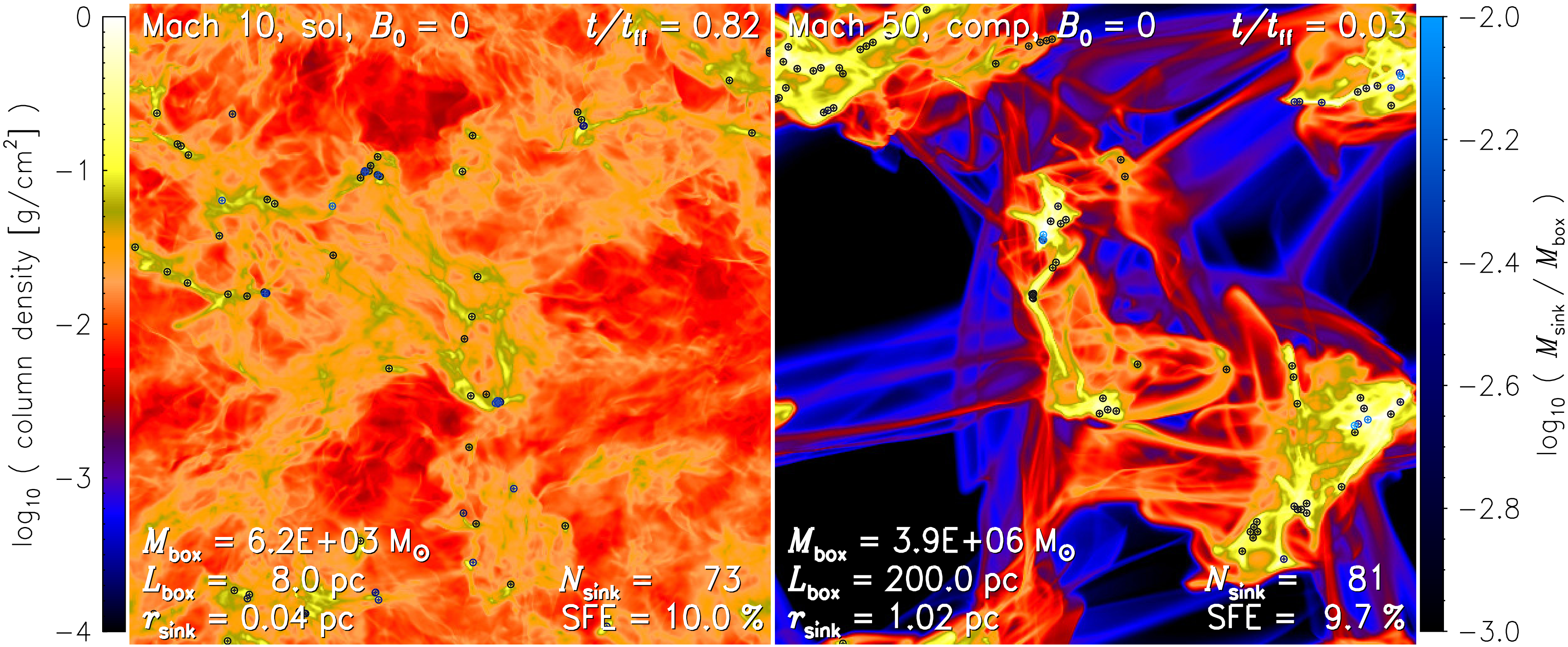
Federrath & Klessen (2012)

Density PDF → Star Formation Rate

Numerical Simulation varying the turbulent Mach number:

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

Mach 10 solenoidal driving — Mach 50 compressive driving



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

SFR_{ff} (theory) = **0.15**   x **52** 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:

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

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

SFR ~ Mass/time

freefall time — **mass fraction**

$$\mathrm{SFR_{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)} \frac{\rho}{\rho_0}\, p(s)\, \mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\, \mathrm{d}s$$

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

MAGNETIC FIELD:

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

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

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

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

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

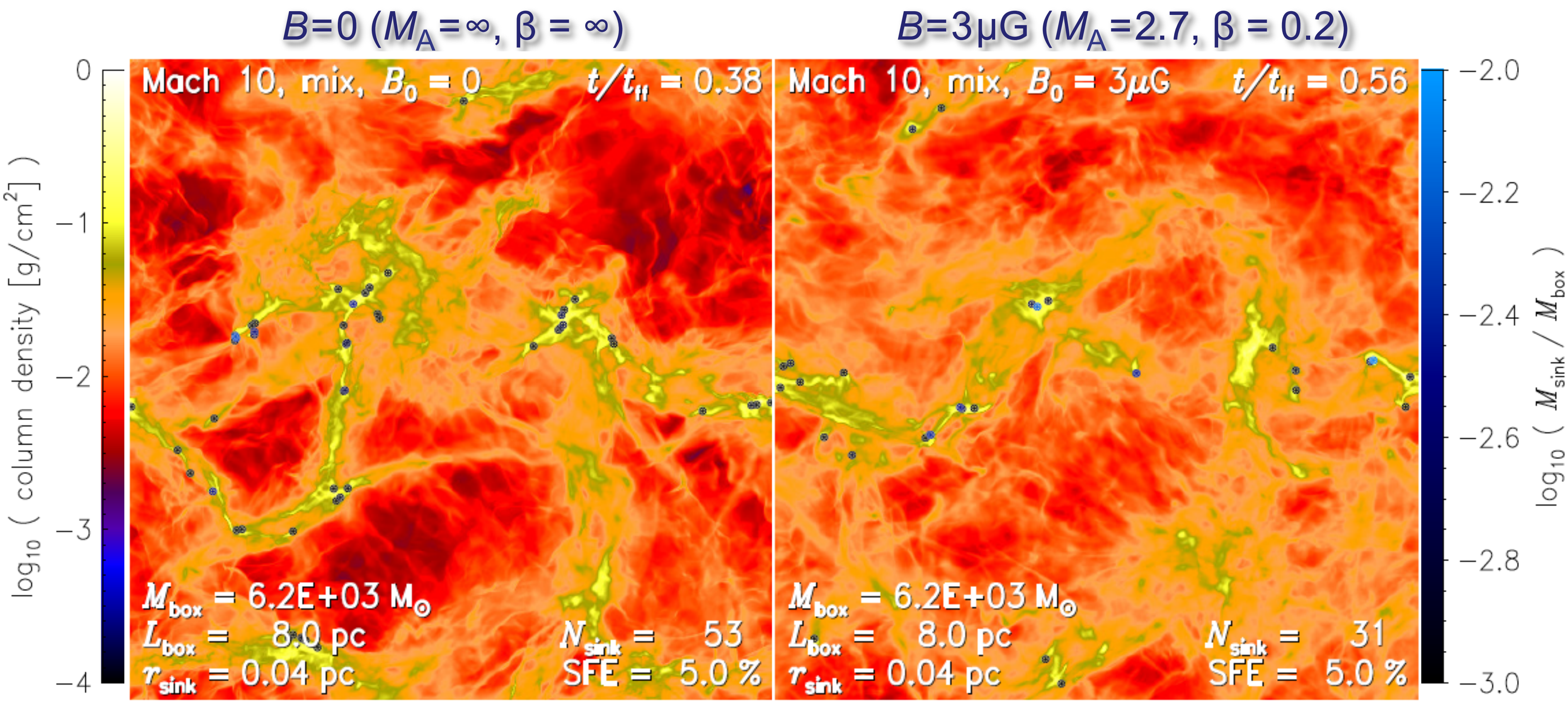
$2E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number** **plasma $\beta = P_{\mathrm{th}}/P_{\mathrm{mag}}$**

Federrath & Klessen (2012)

The Star Formation Rate – Magnetic fields

Numerical Test at Mach 10 with mixed forcing

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



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).

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

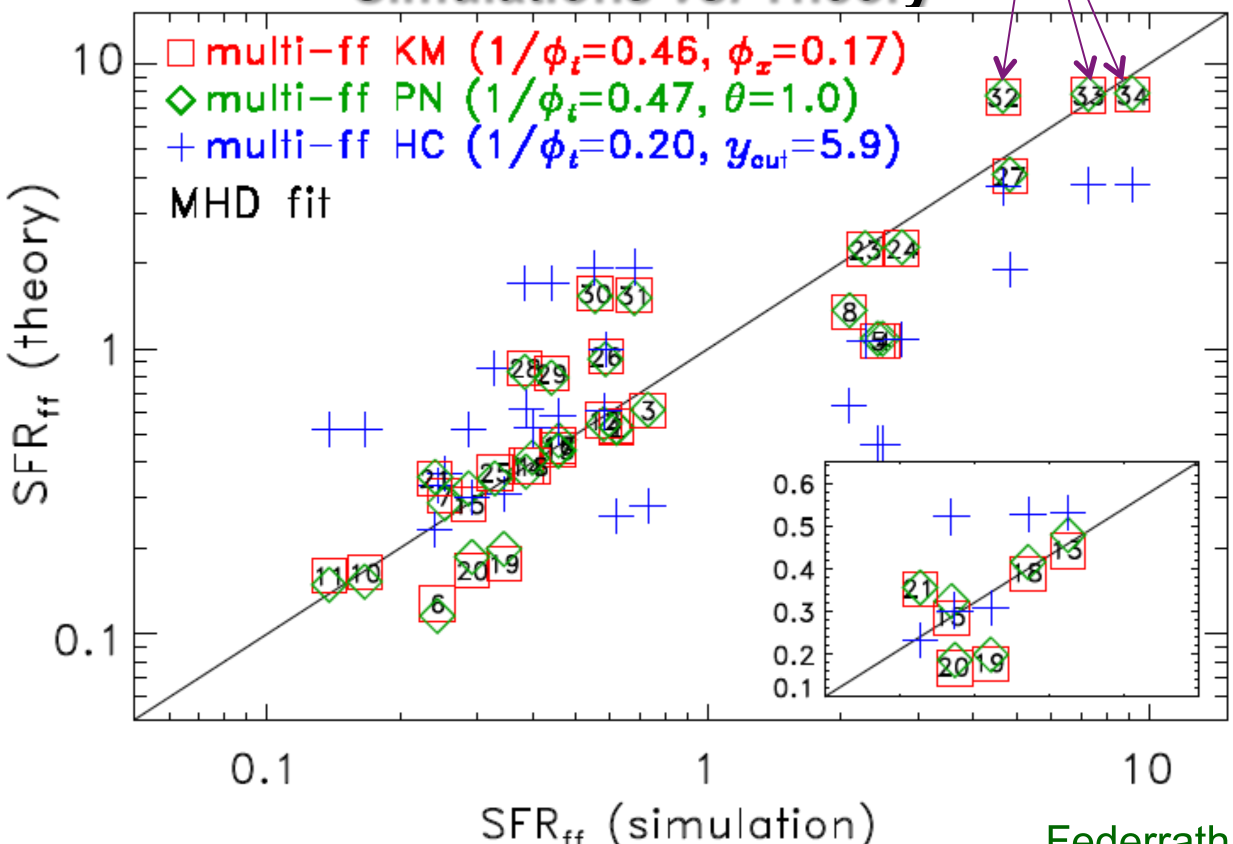
The Star Formation Rate

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

Convergence with numerical resolution

Simulations *vs.* Theory

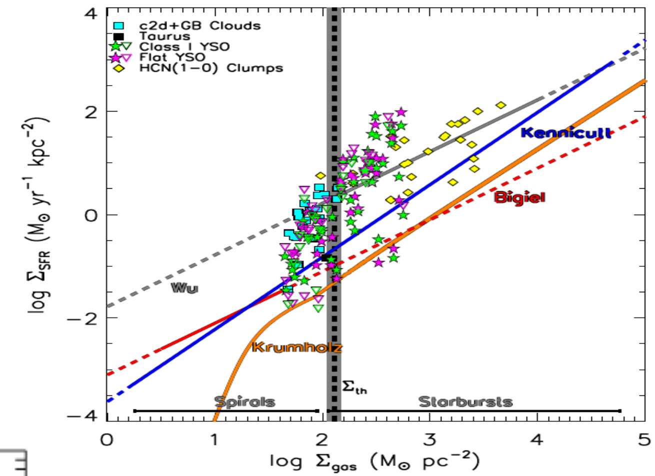


Federrath & Klessen (2012)

The Star Formation Rate

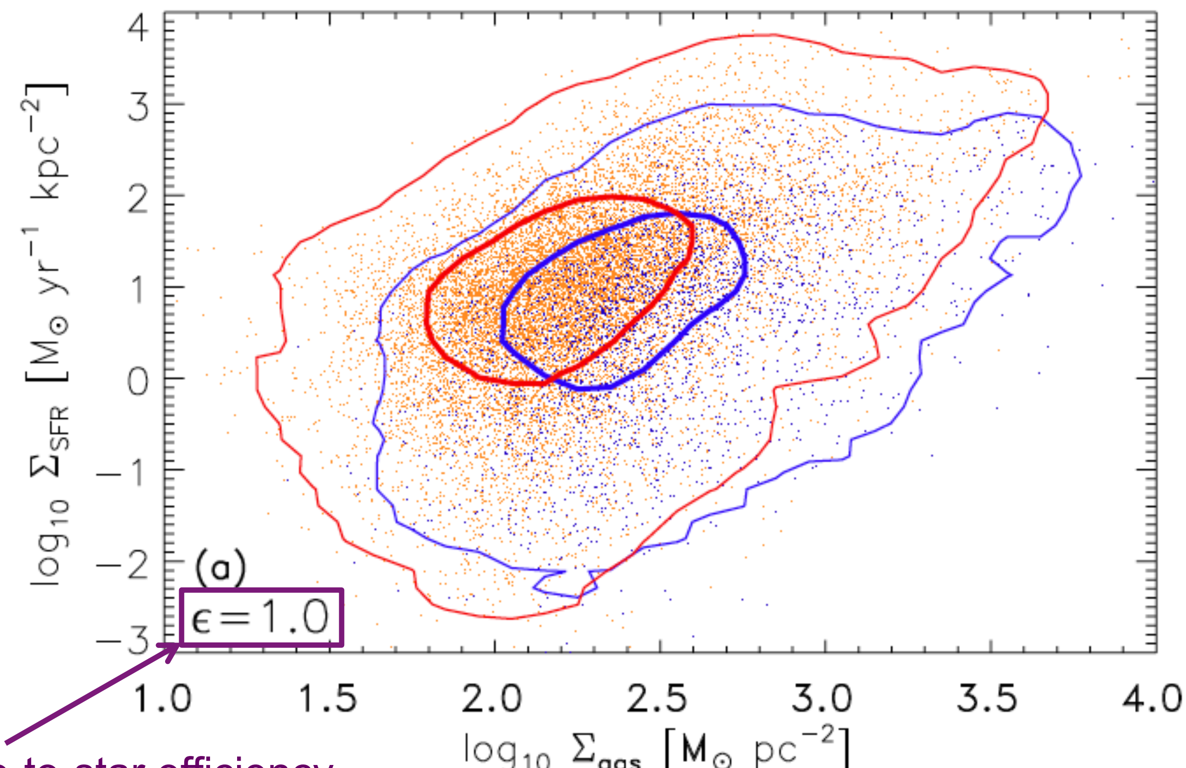
Simulation study with

- 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)

GRAVTURB SFE=10%
GRAVTURB SFE= 1%

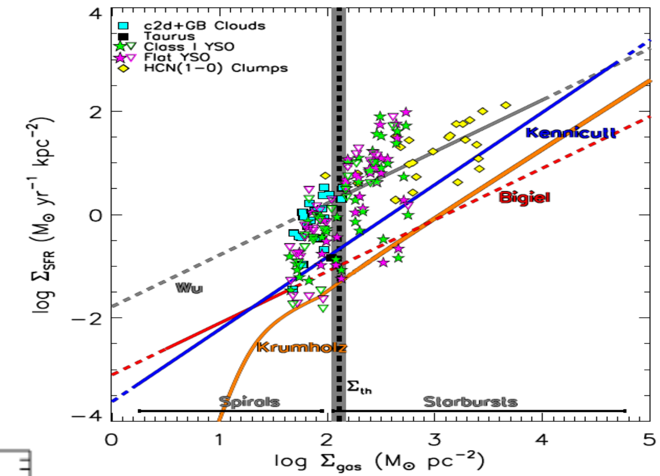
Taurus
Class I YSO
Flat YSO
HCN(1−0) Clumps
C2D+GB Clouds

Federrath & Klessen (2012)

The Star Formation Rate

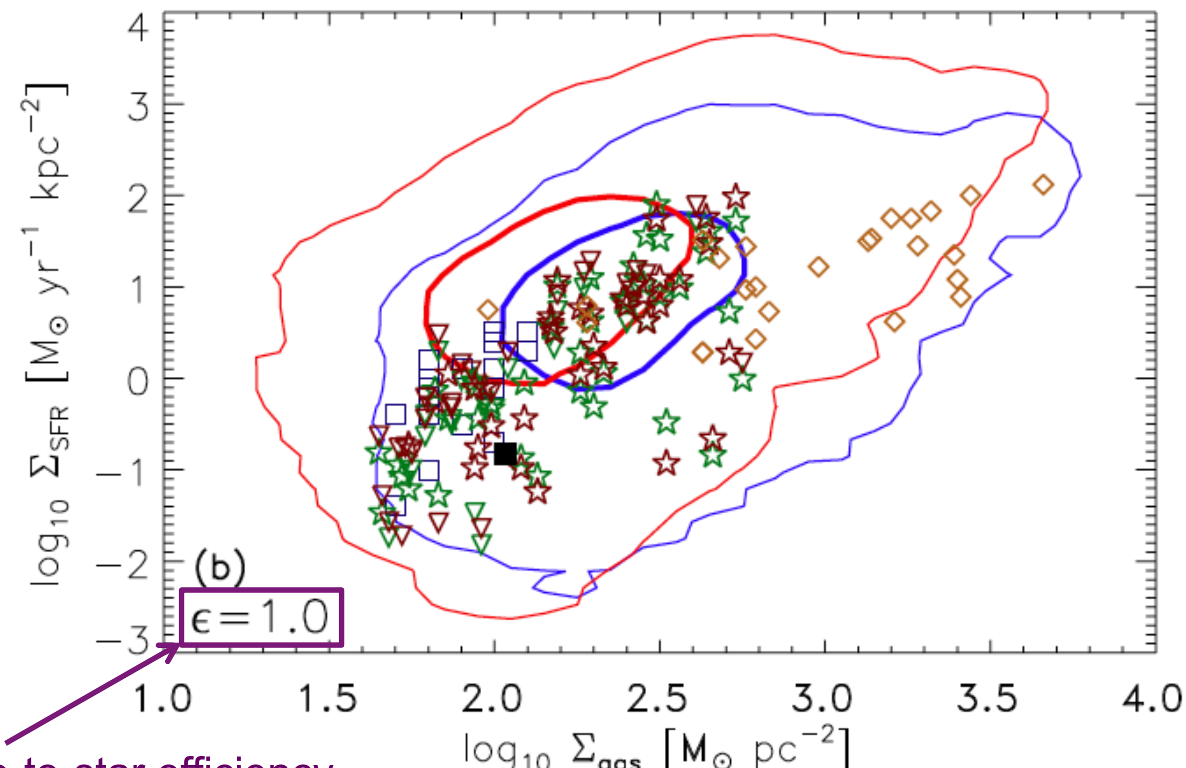
Simulation study with

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



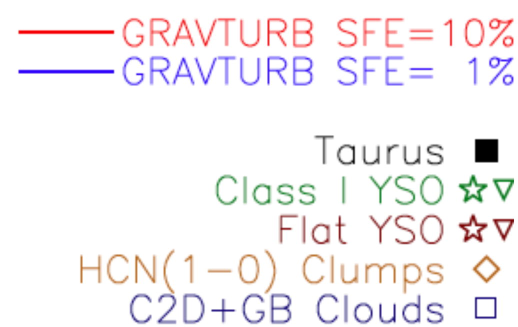
(Heiderman et al. 2010)

Simulations *vs.* Observations



core-to-star efficiency

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

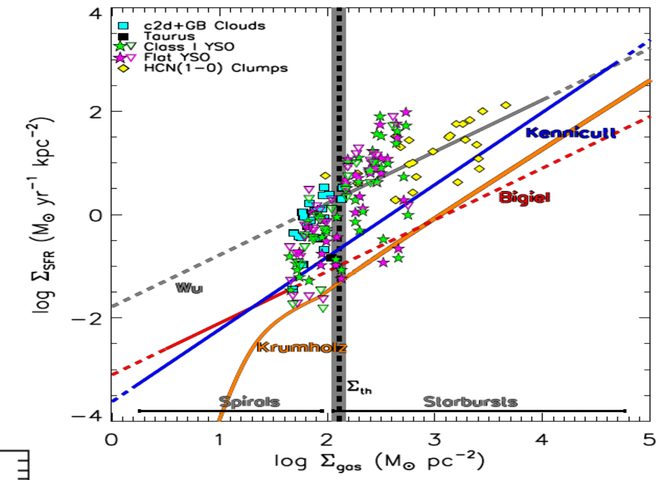


Federrath & Klessen (2012)

The Star Formation Rate

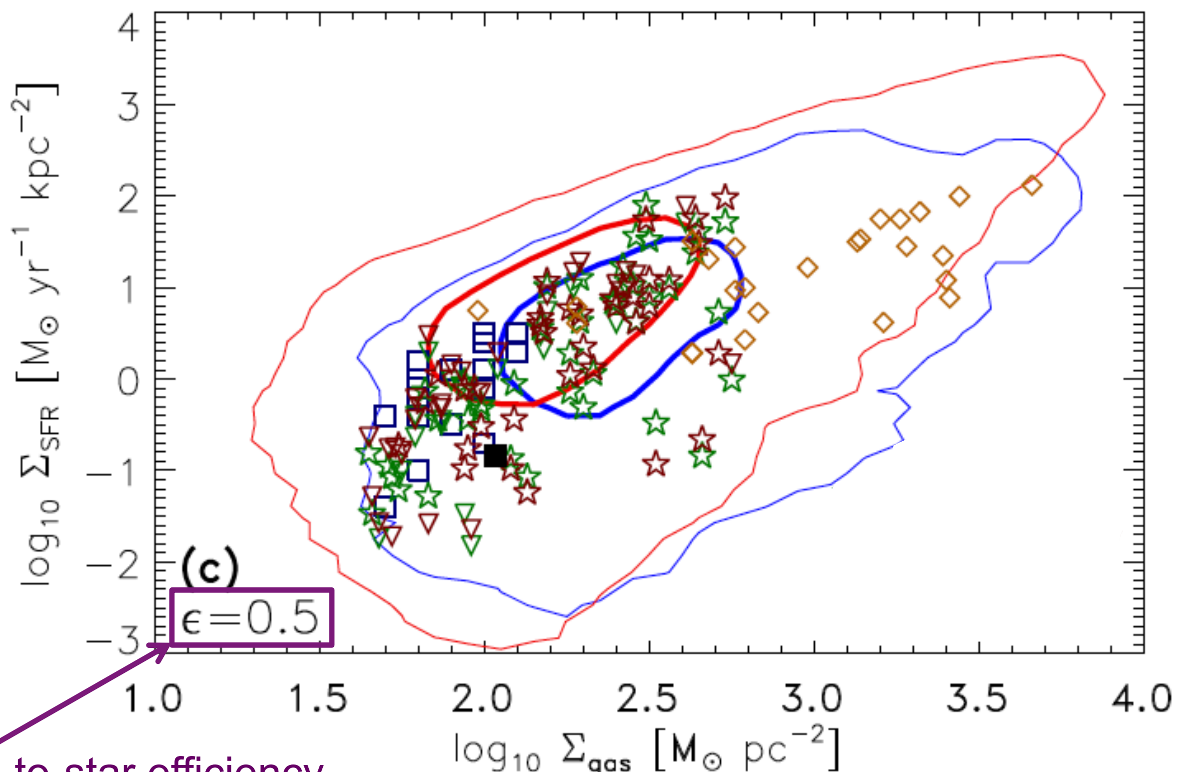
Simulation study with

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



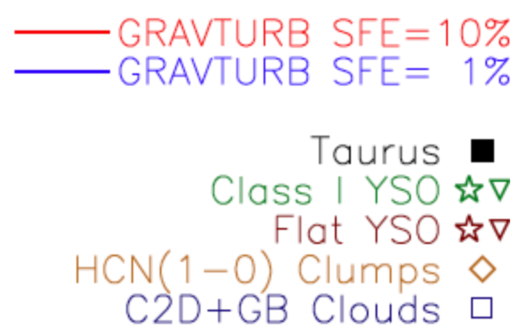
(Heiderman et al. 2010)

Simulations *vs.* Observations



core-to-star efficiency

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

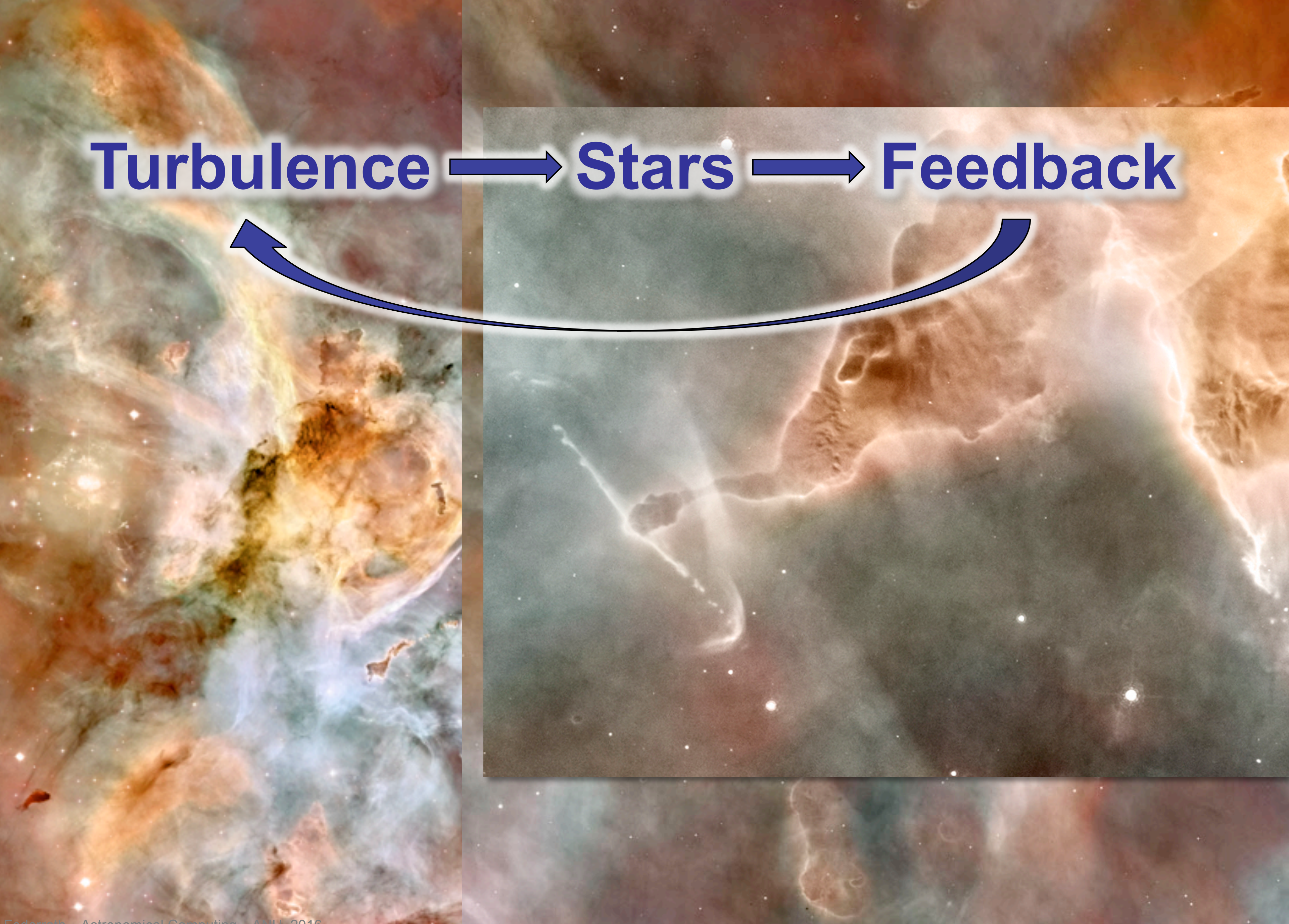


Federrath & Klessen (2012)

Turbulence → Density PDF

Density PDF → Star Formation Rate

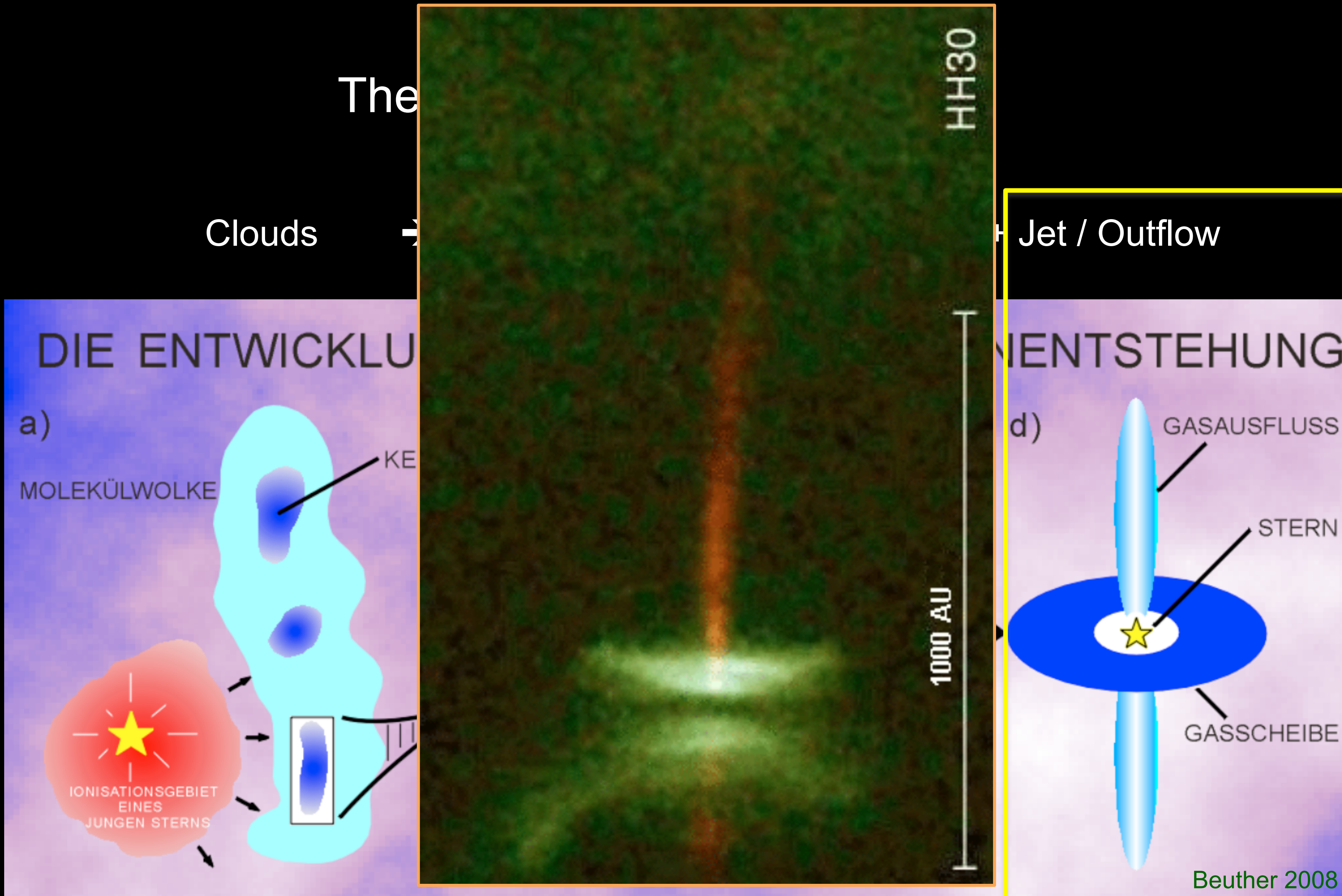
Why is star formation so inefficient?



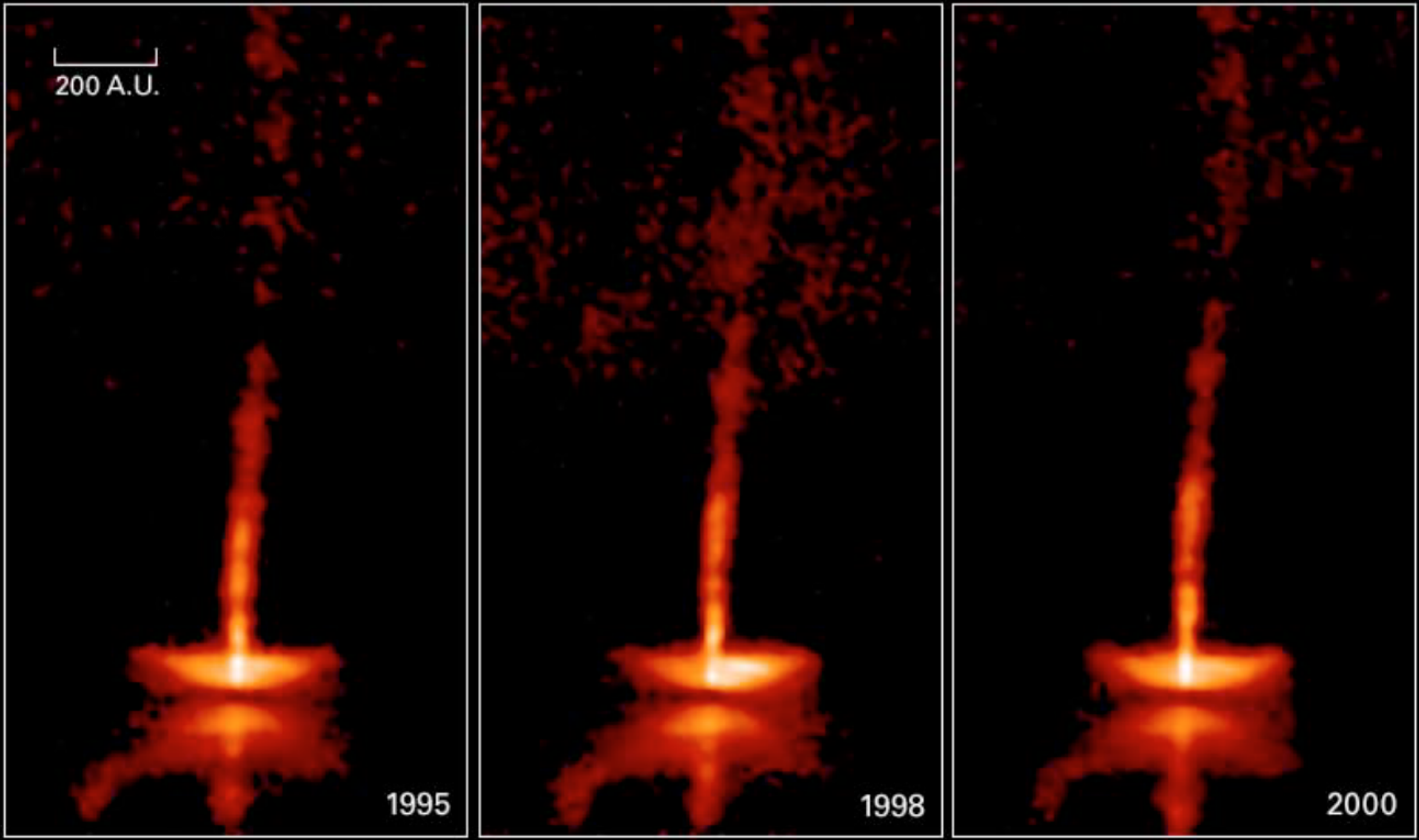
Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

The

Clouds → … → Jet / Outflow



Jets and Outflows



The Dynamic HH 30 Disk and Jet

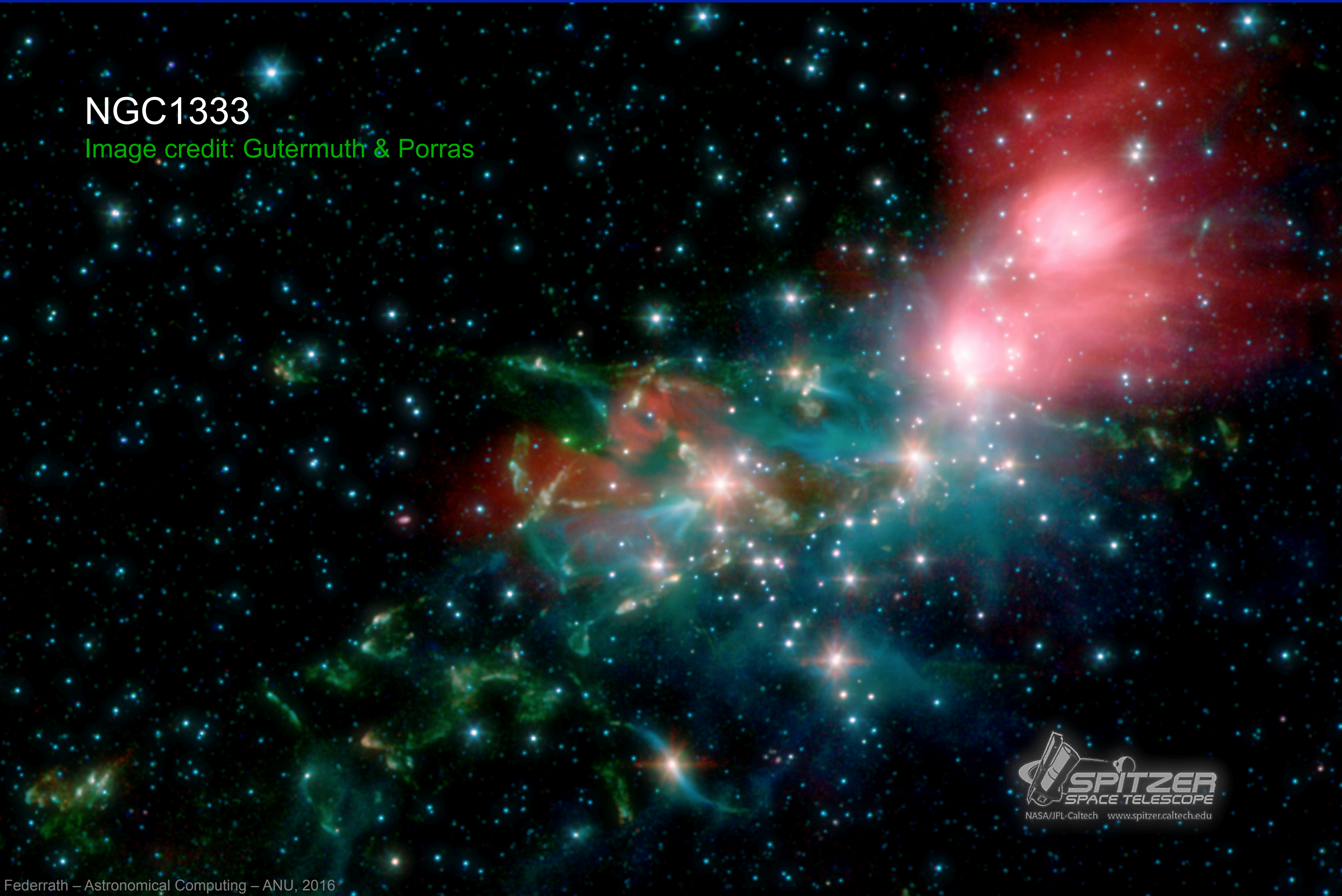
HST • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

Star Formation – Outflow/Jet Feedback

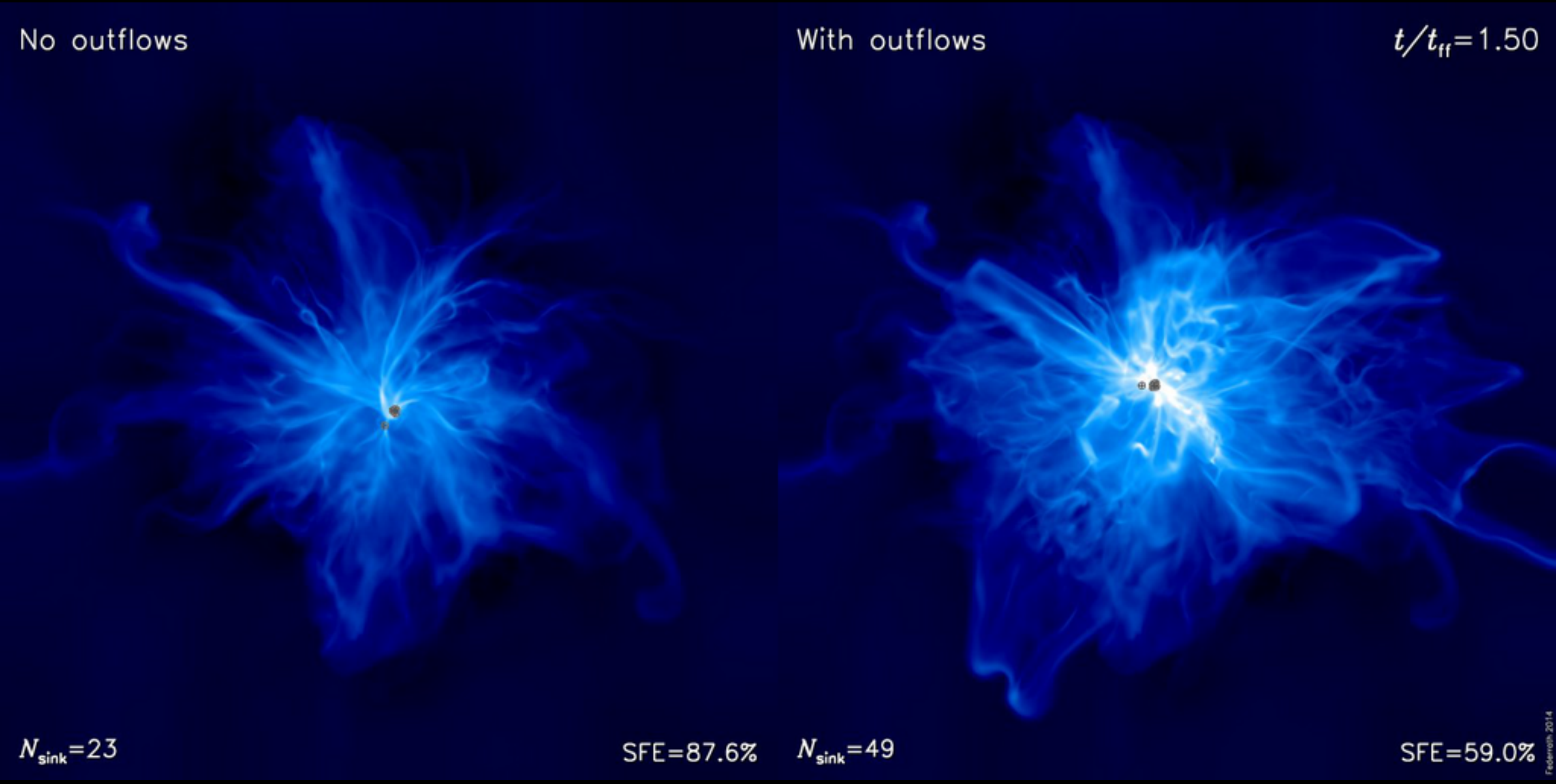
NGC1333

Image credit: Gutermuth & Porras



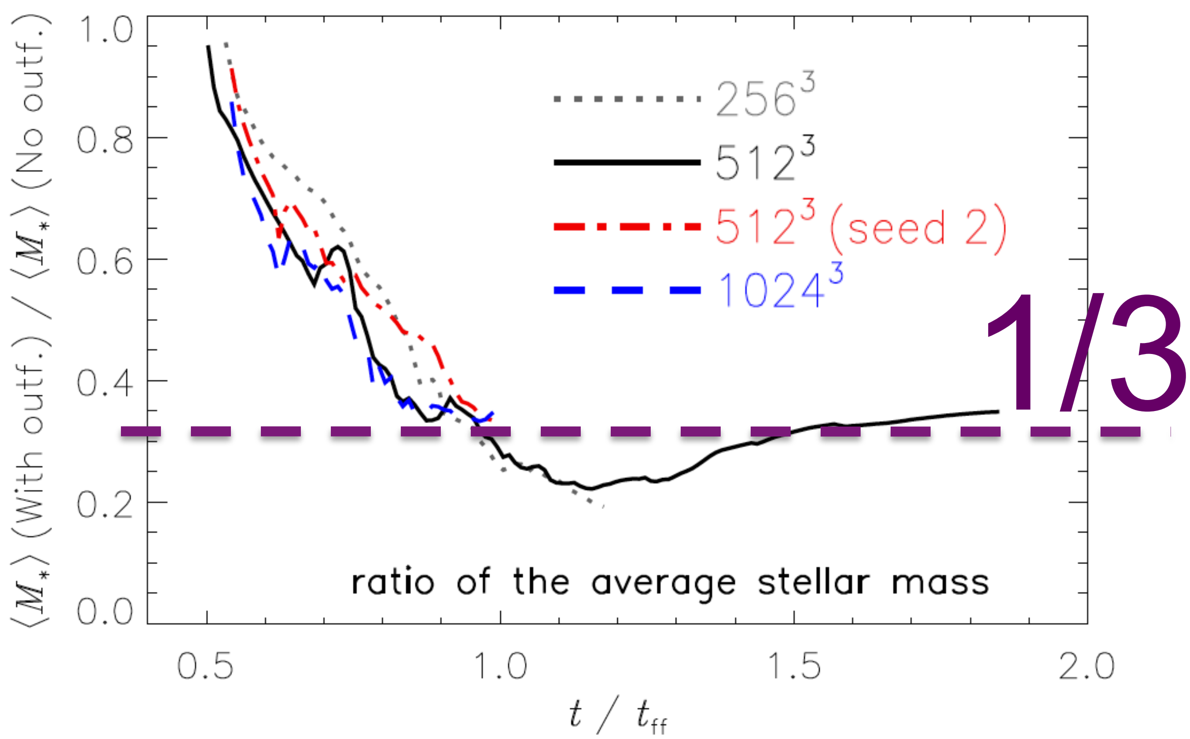
Star Formation – Outflow/Jet Feedback

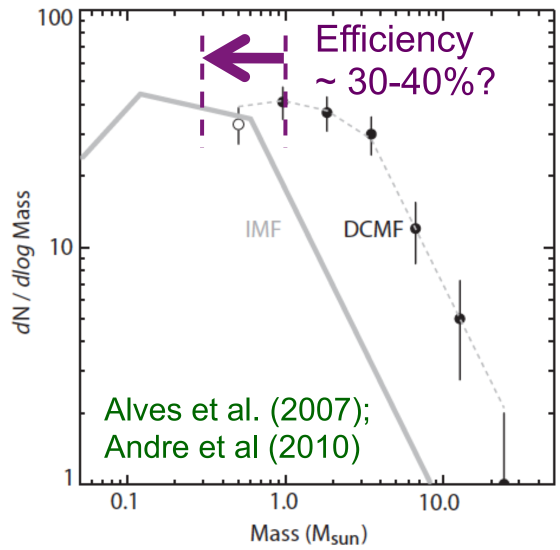
Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html



Federrath et al. 2014, ApJ 790, 128

The role of outflow/jet feedback for star cluster formation



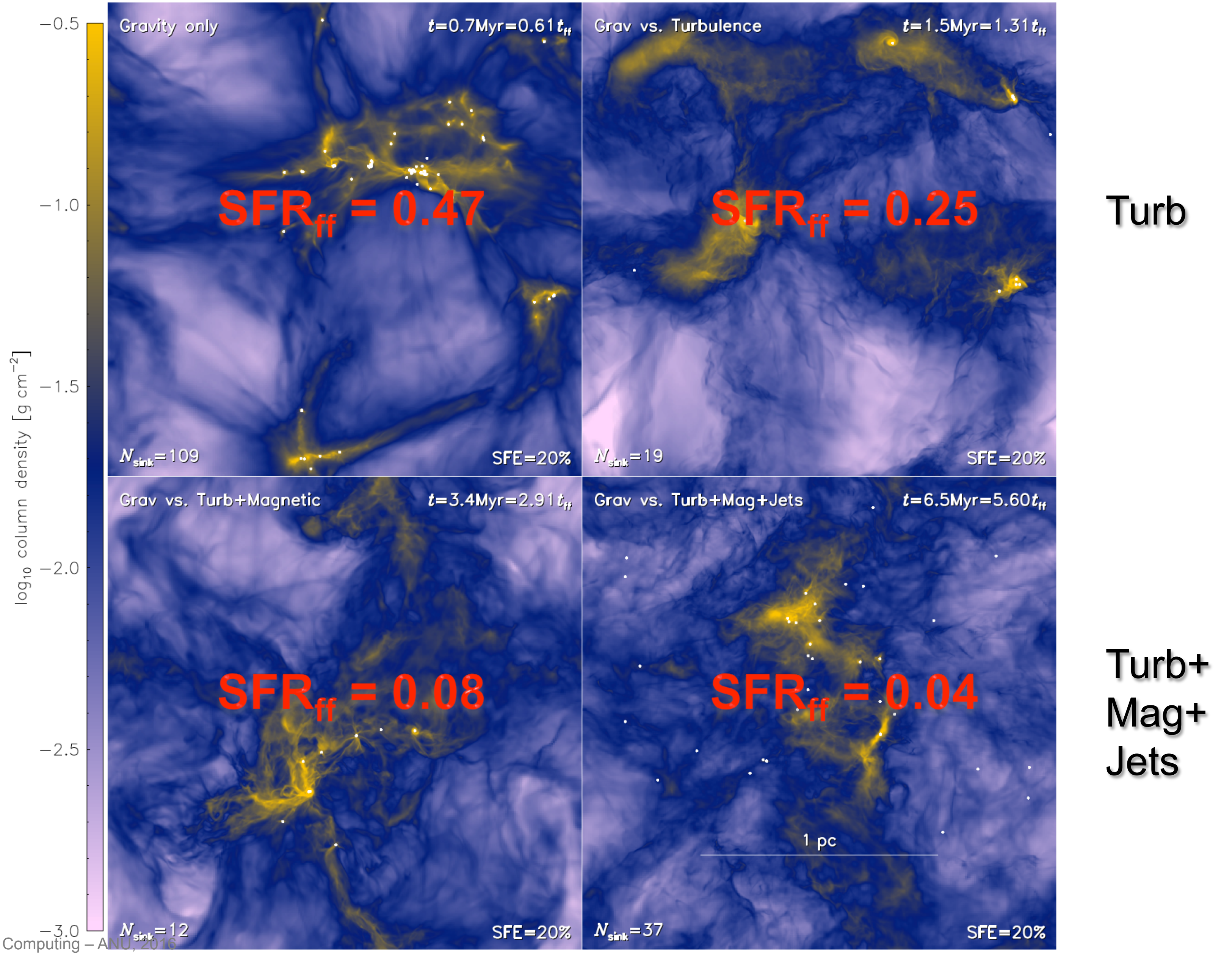


RESULTS:

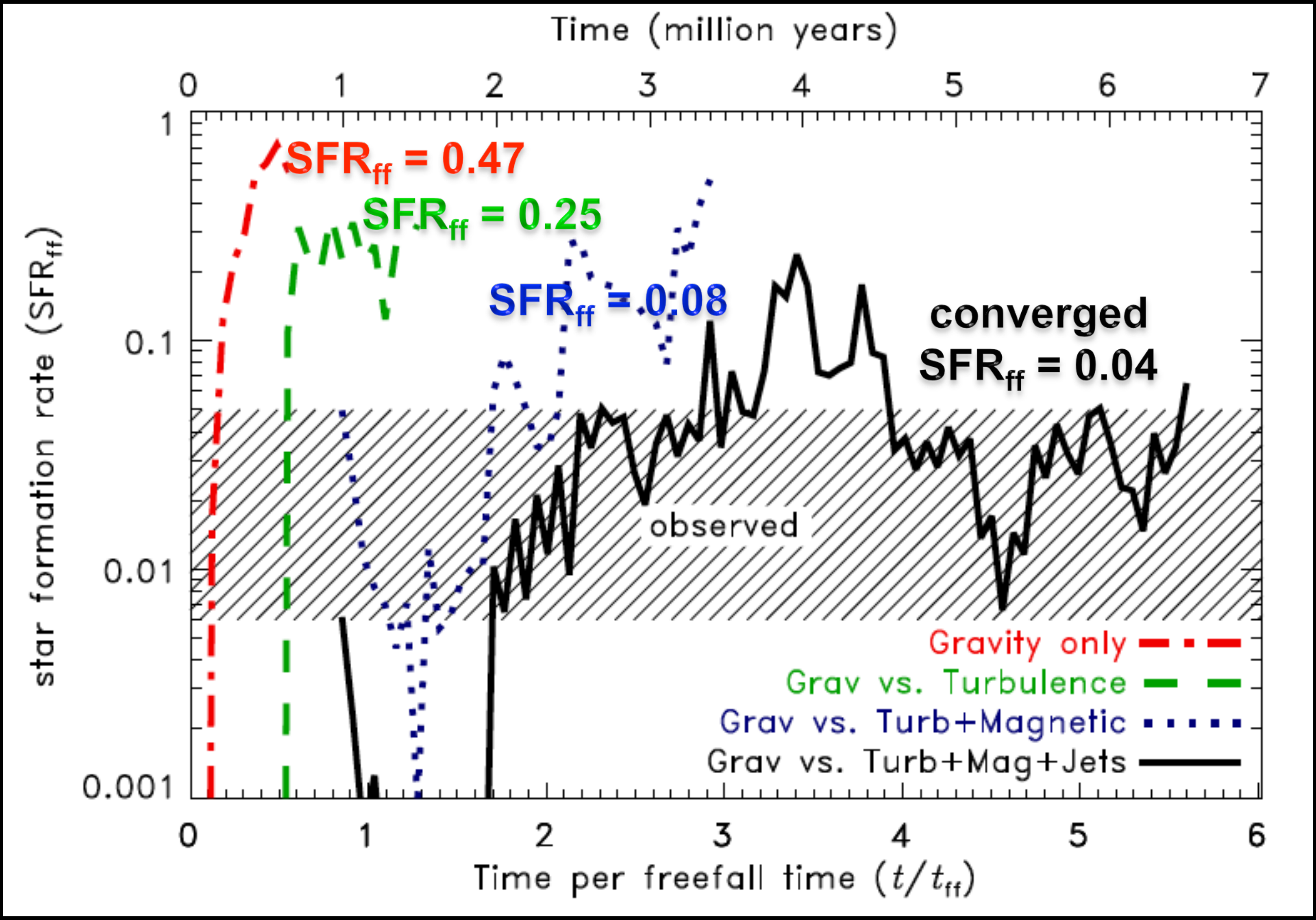
- Outflow/Jet feedback reduces the SFR by factor ~ 2
- Outflow/Jet feedback reduces average star mass by factor ~ 3

Why is Star Formation is so Inefficient?

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



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

- Jet/outflow feedback in star cluster formation:

  - Star formation rate reduced by ~2x

  - Average star mass reduced by ~3x → Initial Mass Function!

- Star Formation is inefficient →

  Only combination of Turb+Mag+Feedback gives realistic SFRs

Astronomical Computing

Introduction to Bash and shell scripting

Bash is a shell program designed to listen to my commands and do what I tell it to.

Bash is a simple tool in a vast toolbox of programs that lets me interact with my system using a text-based interface.

Distinguish *Interactive* and *Non-interactive* mode

Useful shell commands:

grep, rsync, redirect stdout/stderr, top, tail, cat, wc, nohup, screen, nice

Good Bash introduction: http://guide.bash.academy

Astronomical Computing

ASTR4004 / ASTR8004

NEXT (FRIDAY 05/08): plotting with gnuplot,
remote computing (ssh, scp, rsync, nohup, ...)

Image credit: M. S. Povich