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

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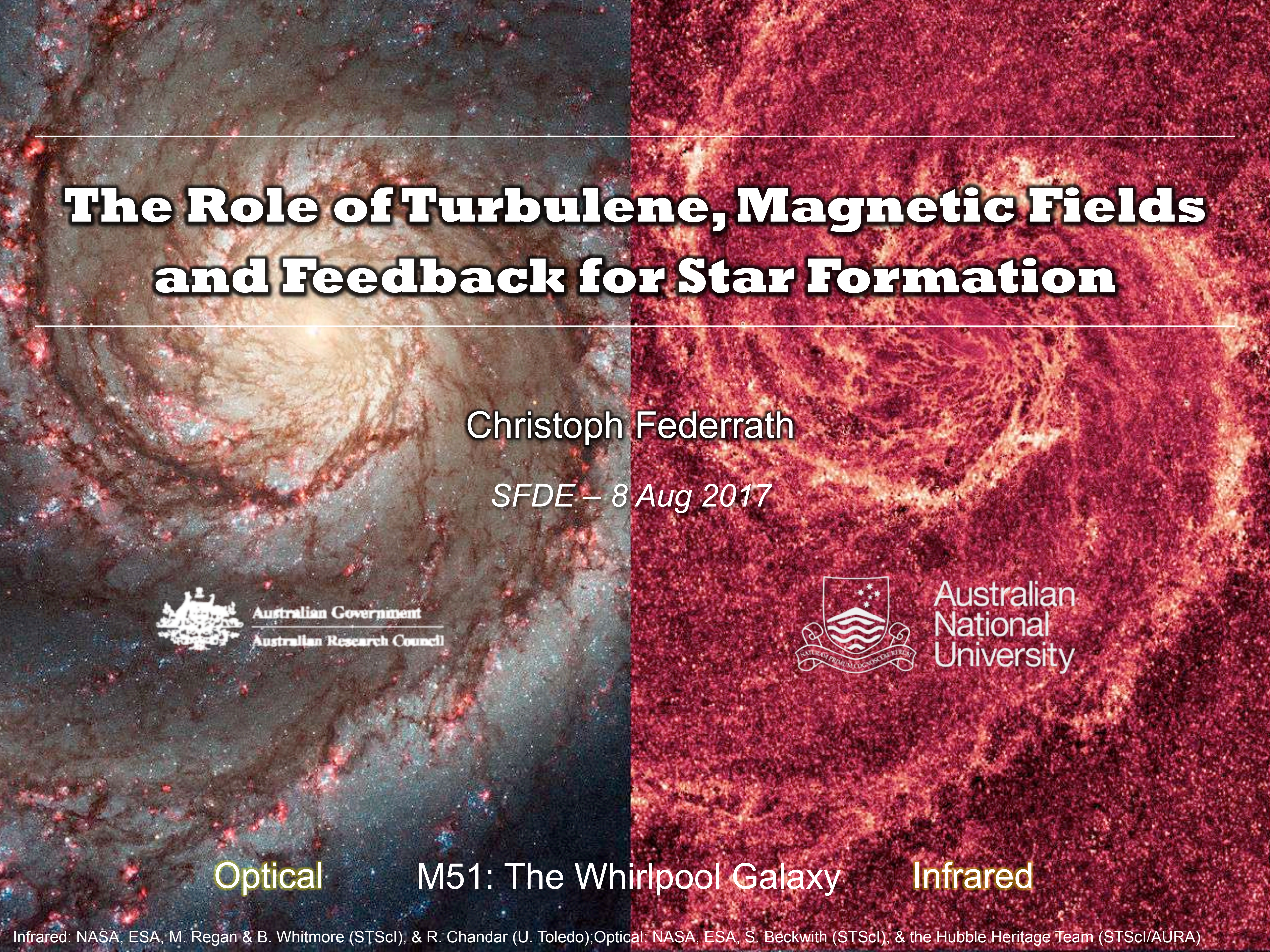
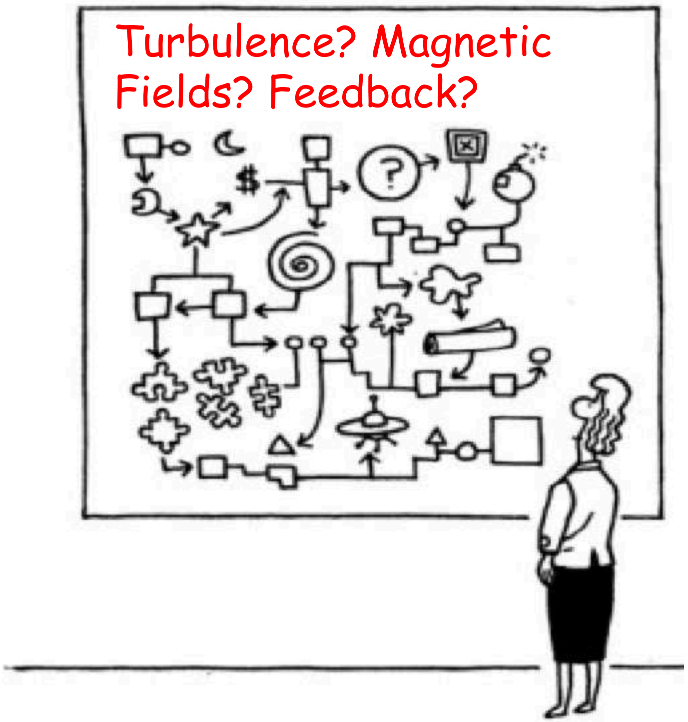
Australian Government
Australian Research Council

Australian National University

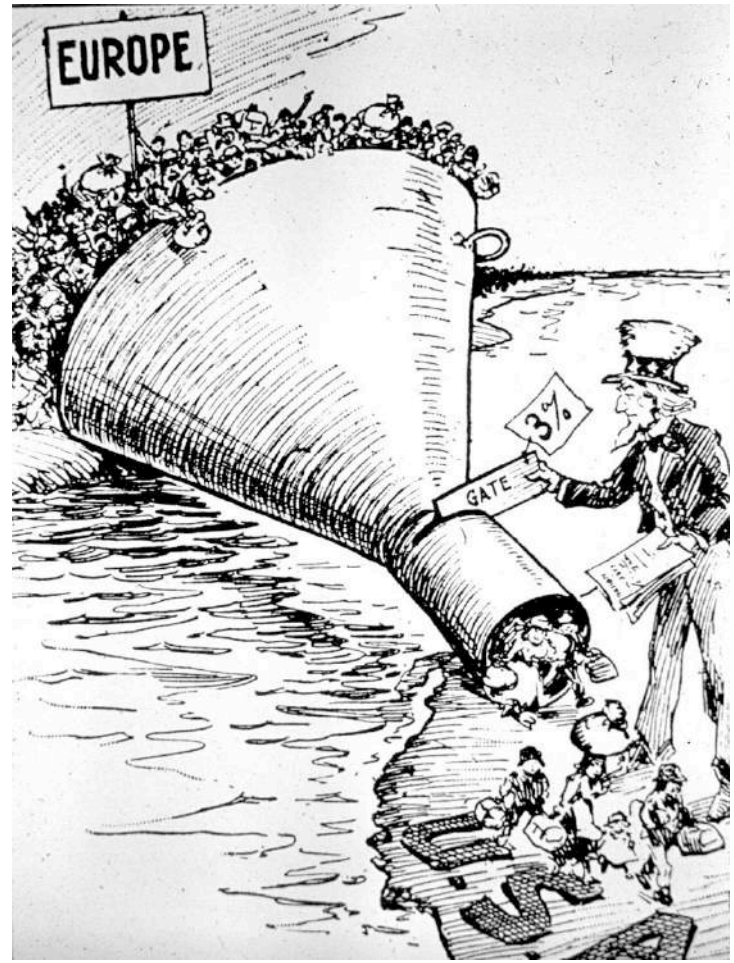


Infrared: NASA, ESA, M. Regan & B. Whitmore (STScI), & R. Chandar (U. Toledo);Optical: NASA, ESA, S. Beckwith (STScI), & the Hubble Heritage Team (STScI/AURA)

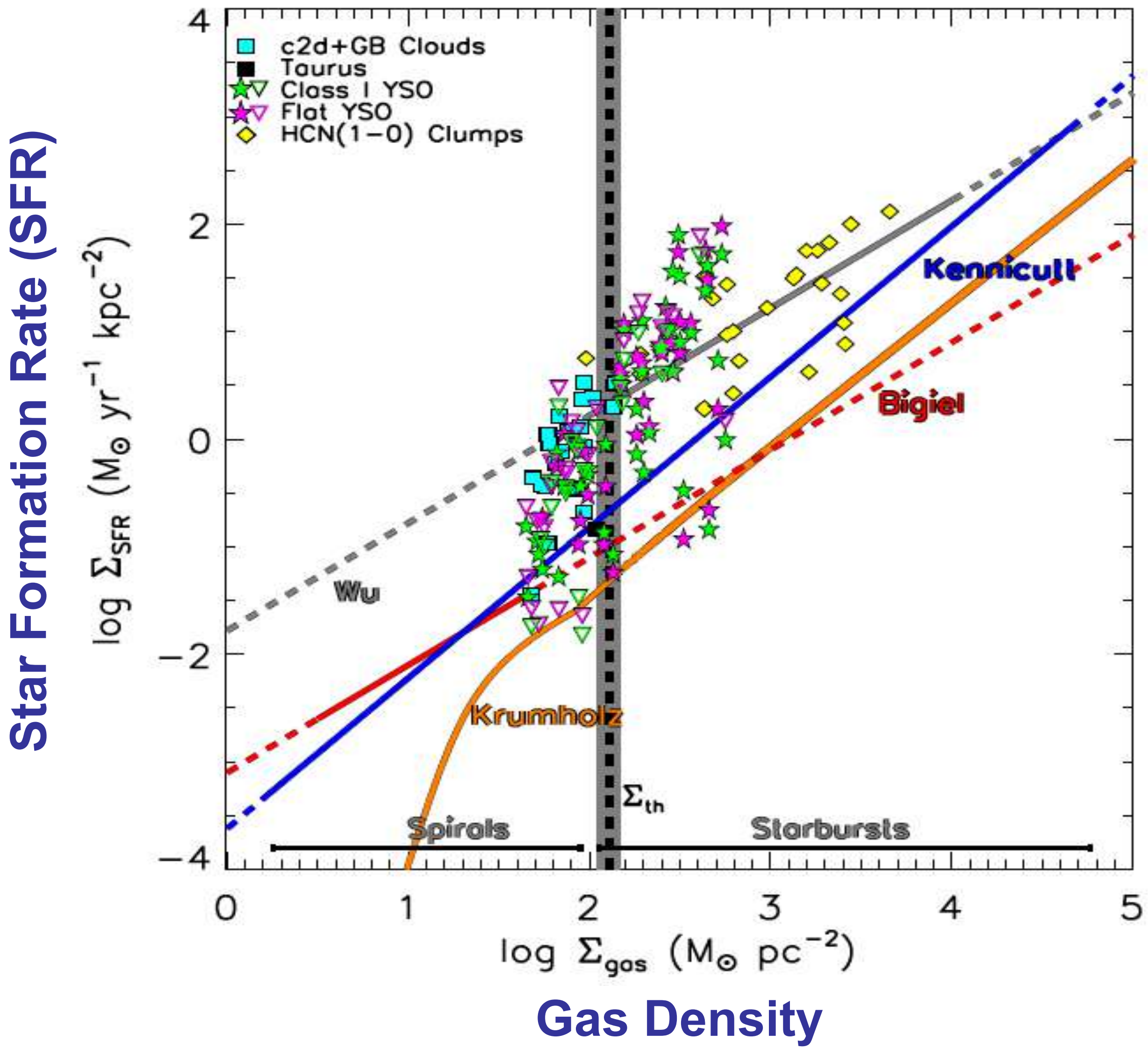
Star Formation is messy.



Star Formation is Inefficient. – Why?



Universal star formation "law"?

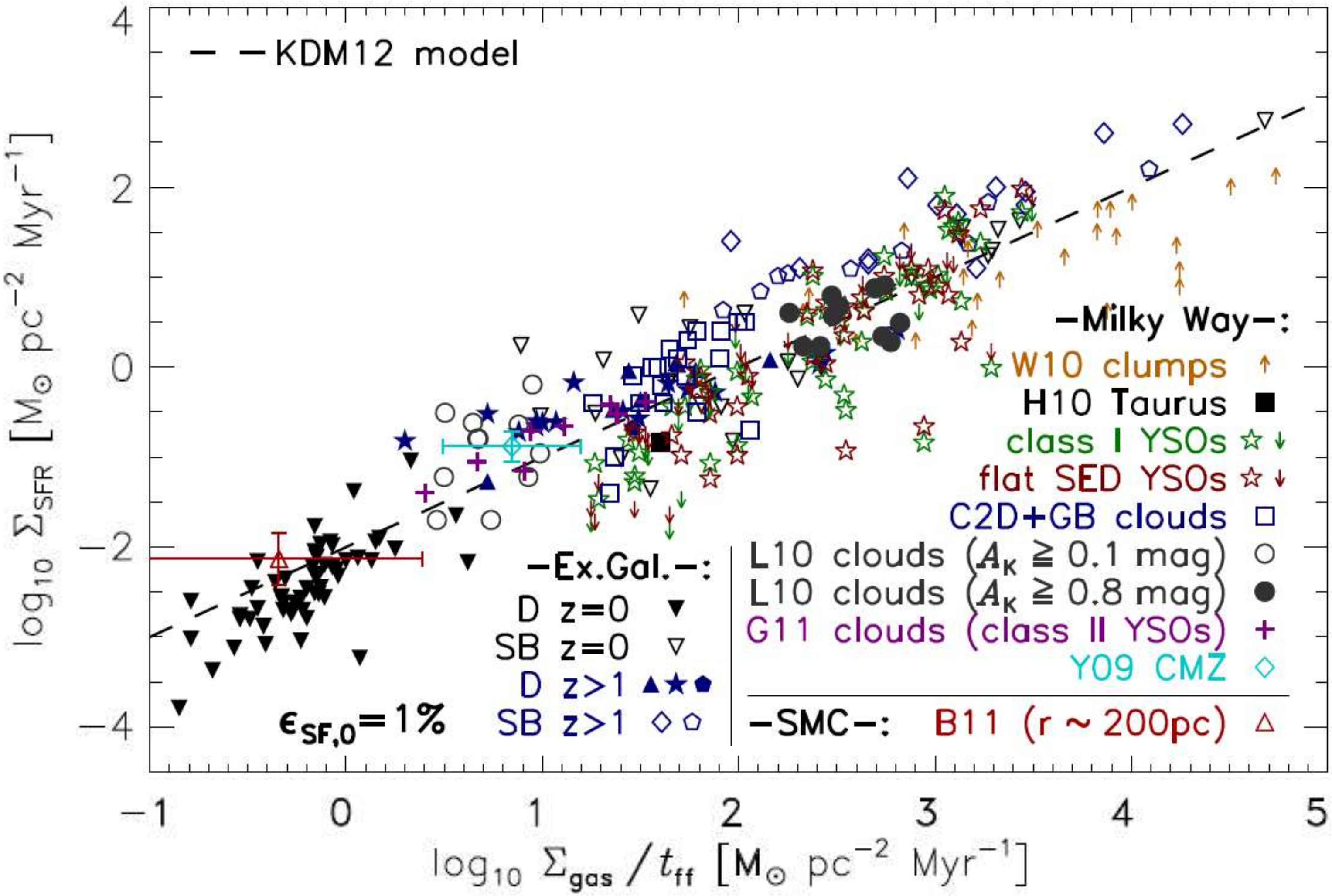


Scatter?

Turbulence

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

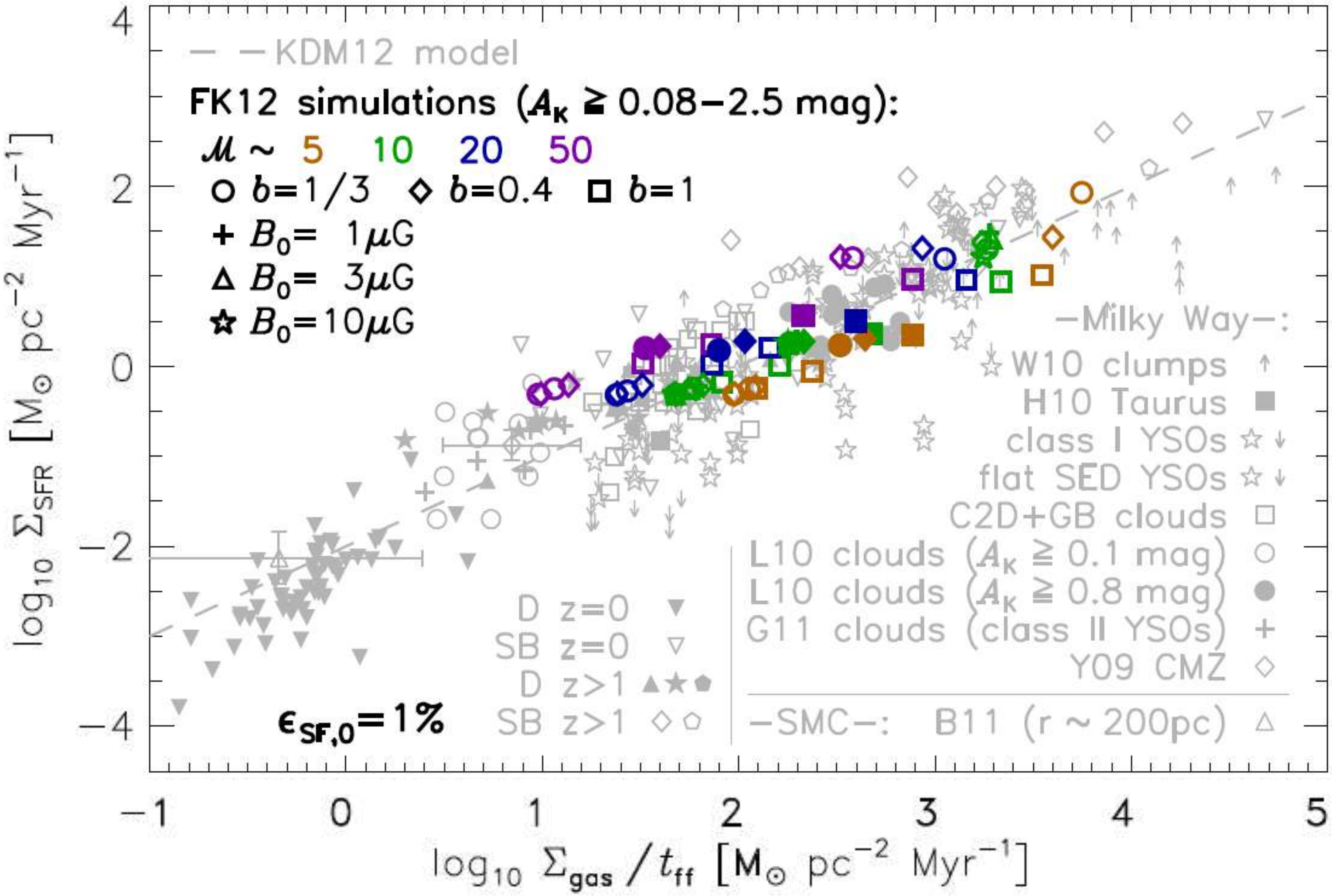
Physical Variations in the Star Formation Law → Turbulence



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

Federrath (2013, MNRAS 436, 3167)

Physical Variations in the Star Formation Law → Turbulence



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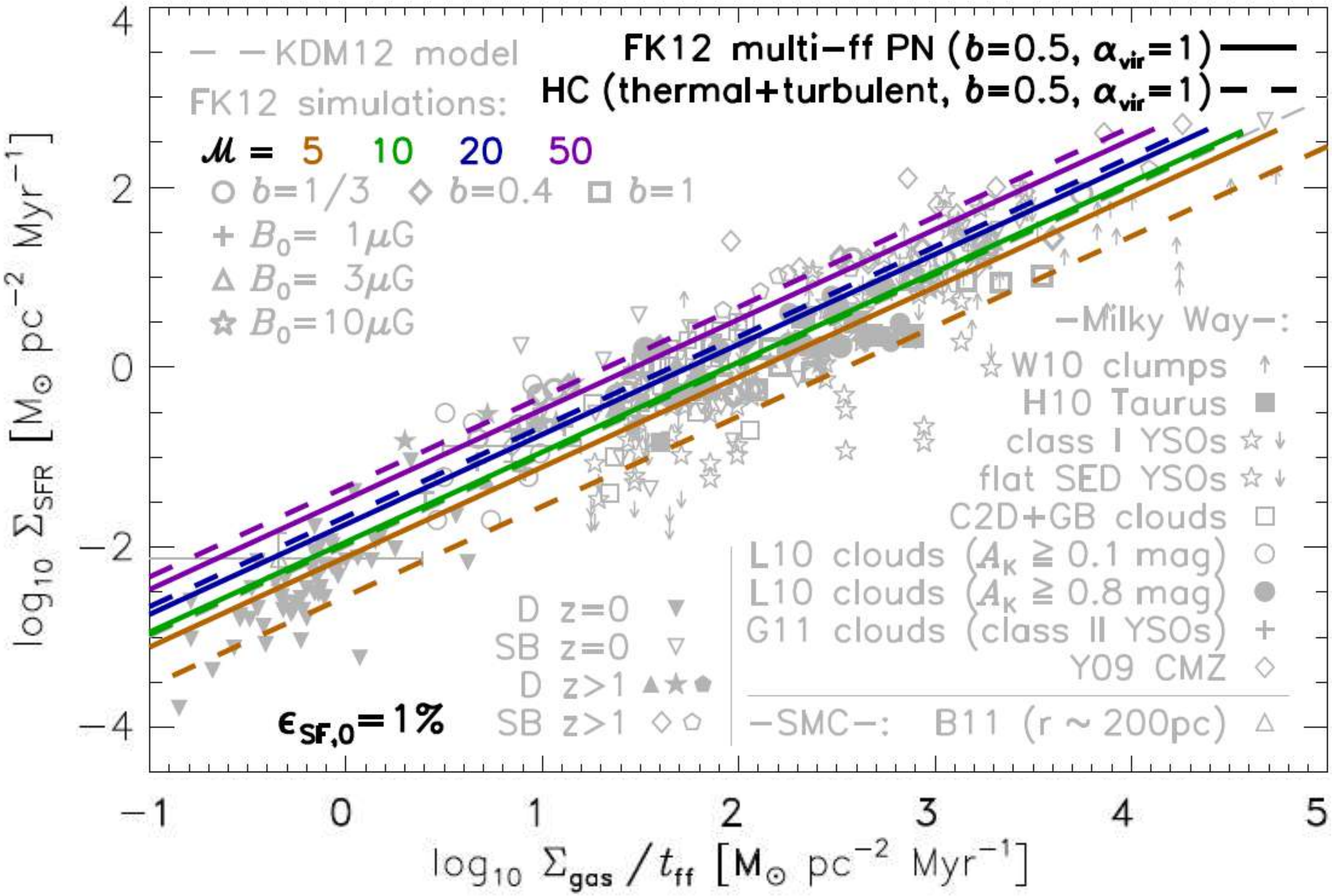
Physical Variations in the Star Formation Law → Turbulence

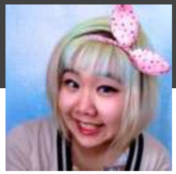


→ Scatter/Non-Universality caused by variations of the Turbulence (Mach number, Driving, Virial parameter)

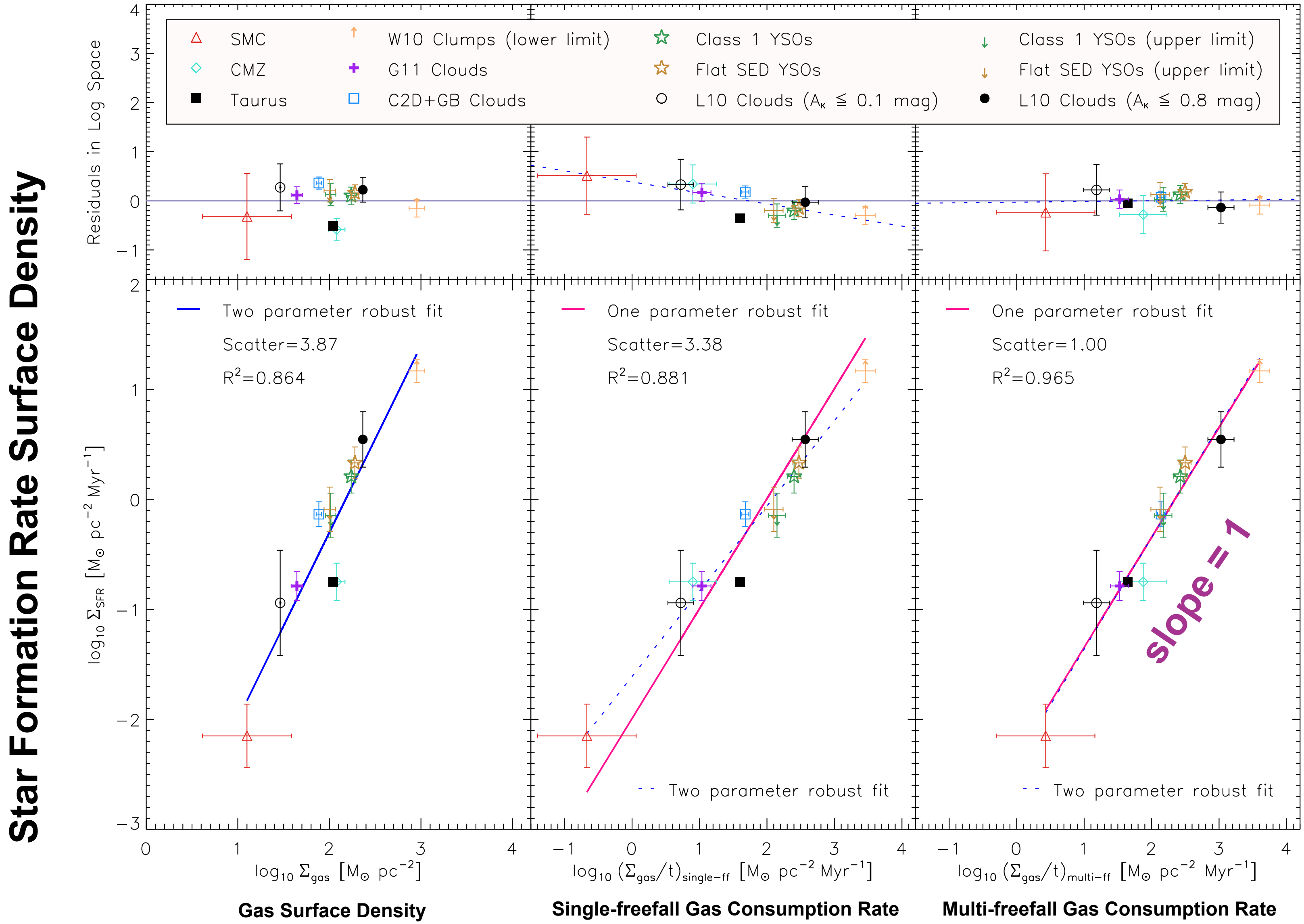
Federrath (2013, MNRAS 436, 3167)

Australian National University

A Multi-Freefall Star Formation Law



Salim, Federrath, Kewley 2015, ApJL 806, L36



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

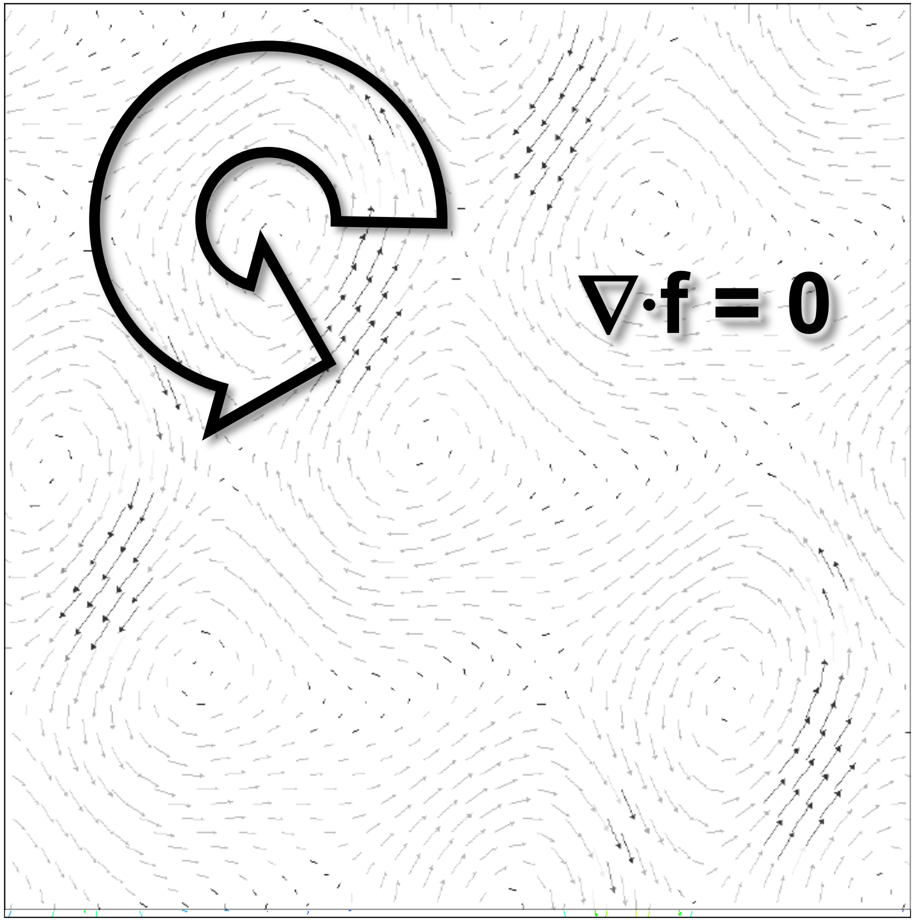
Solenoidal ↓ Compressive

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

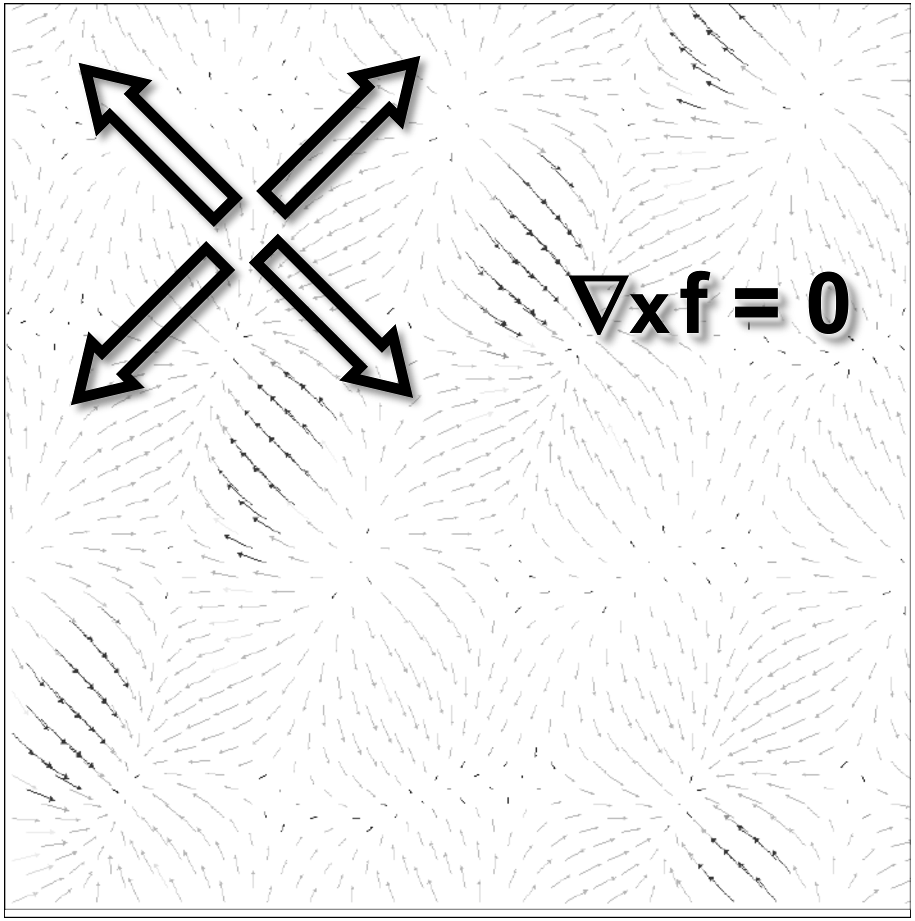
Turbulence driving – solenoidal versus compressive

Star Formation depends on how turbulence is driven

Solenoidal driving



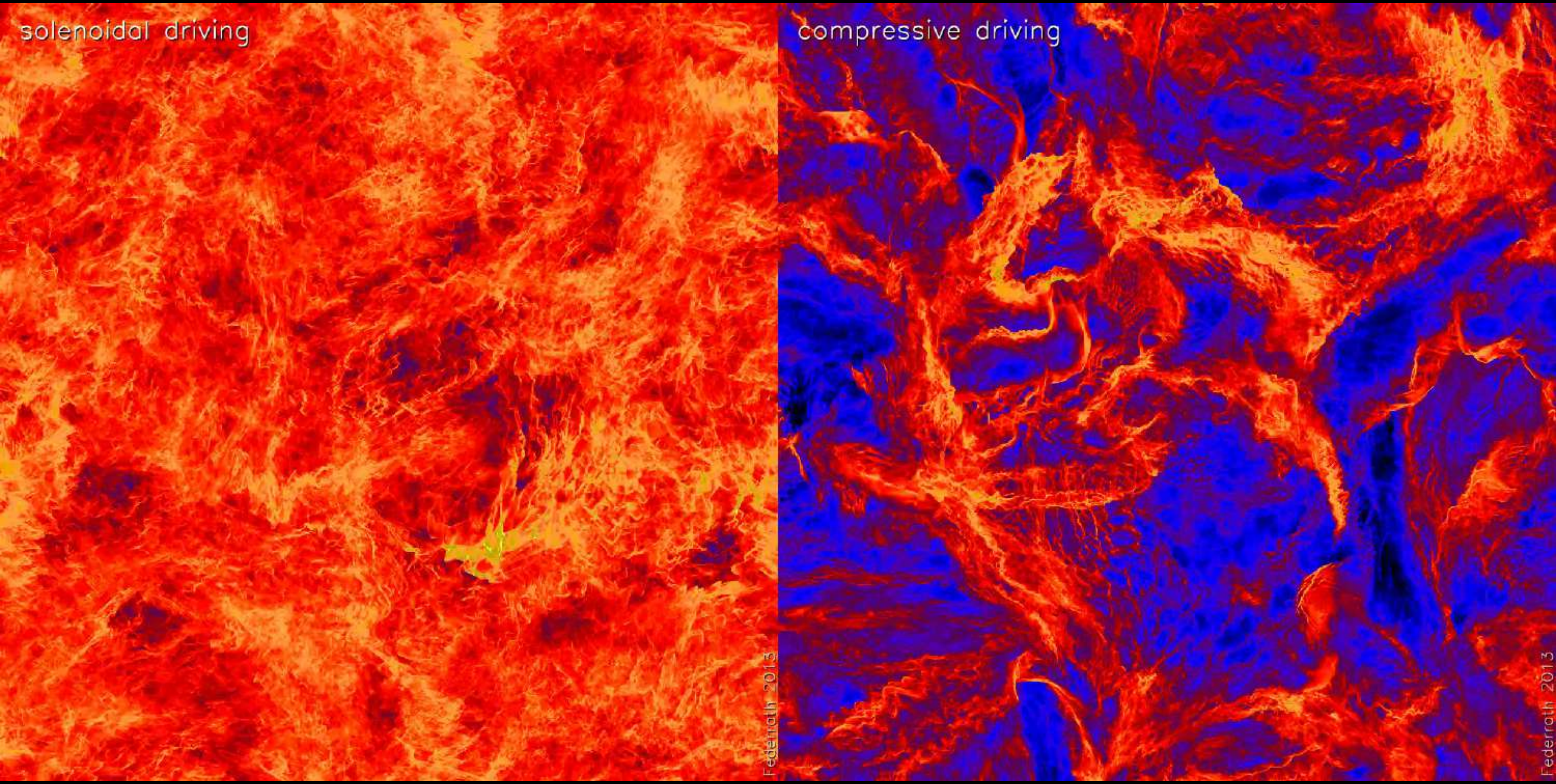
Compressive driving



Turbulence driving – solenoidal versus compressive

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

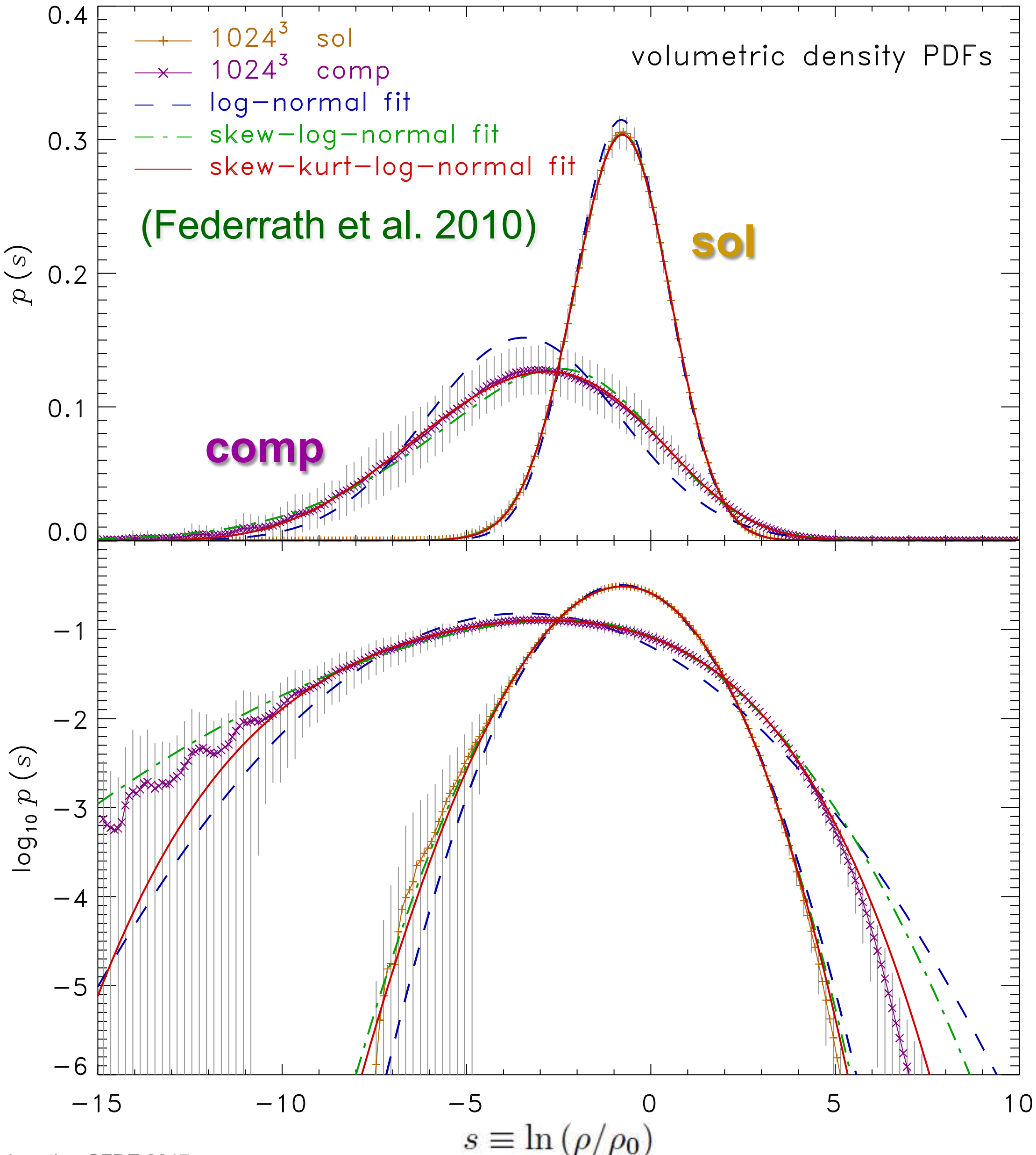
solenoidal driving compressive driving



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)

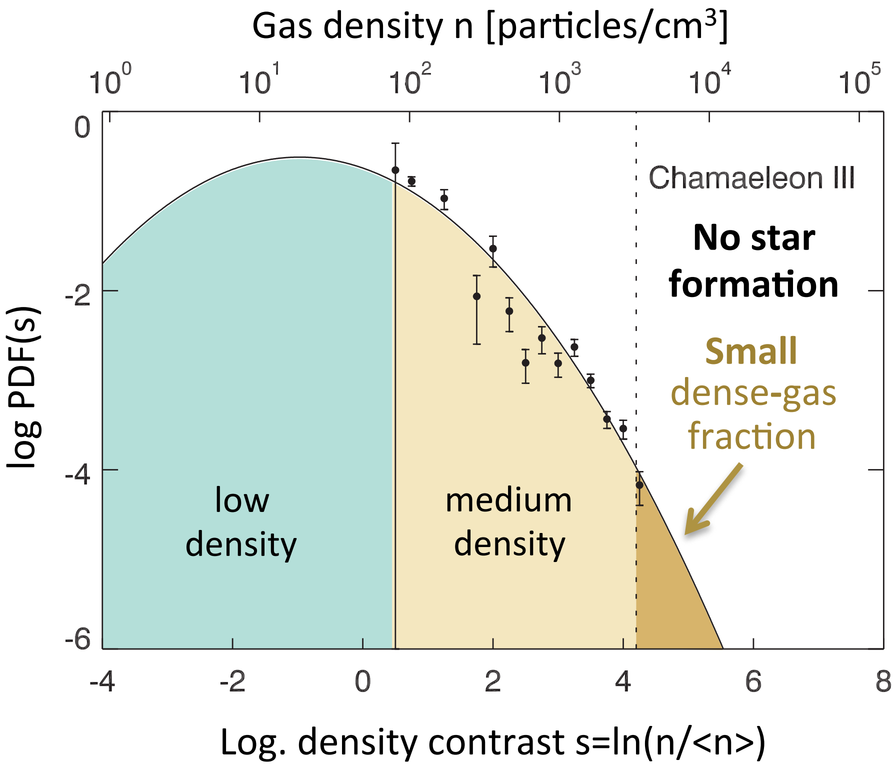
$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right)$$

⇒ b = 1/3 (sol)
b = 1 (comp)

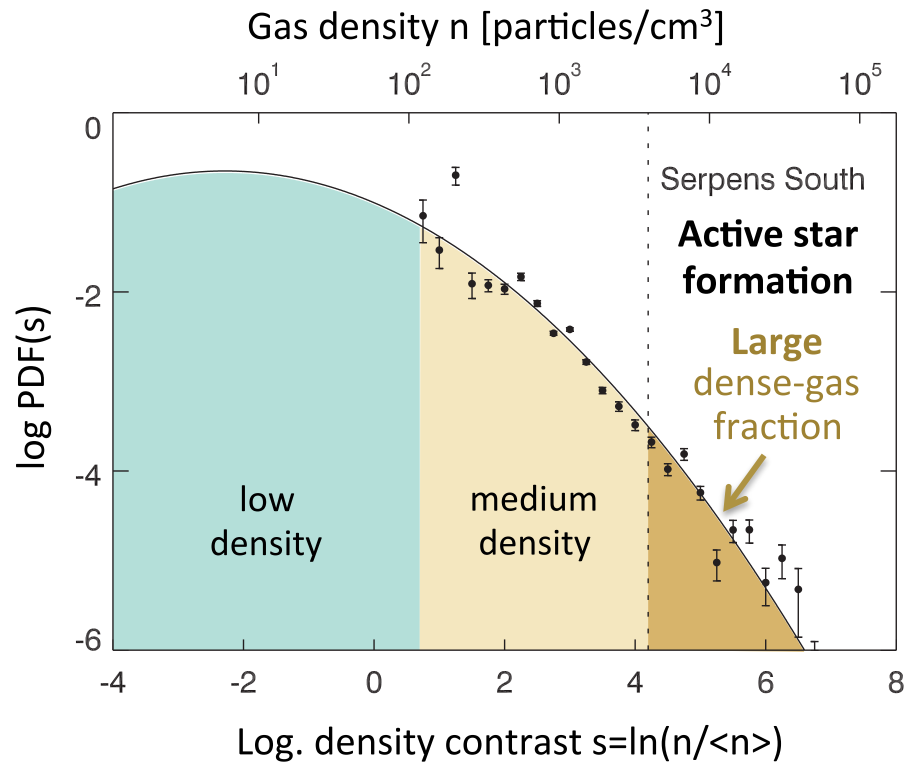
Federrath et al. (2008, 2010); Price et al. (2011); Konstandin et al. (2012); Molina et al. (2012); Federrath & Banerjee (2015); Nolan et al. (2015)

The density PDF → Star Formation

No star formation



Active star formation



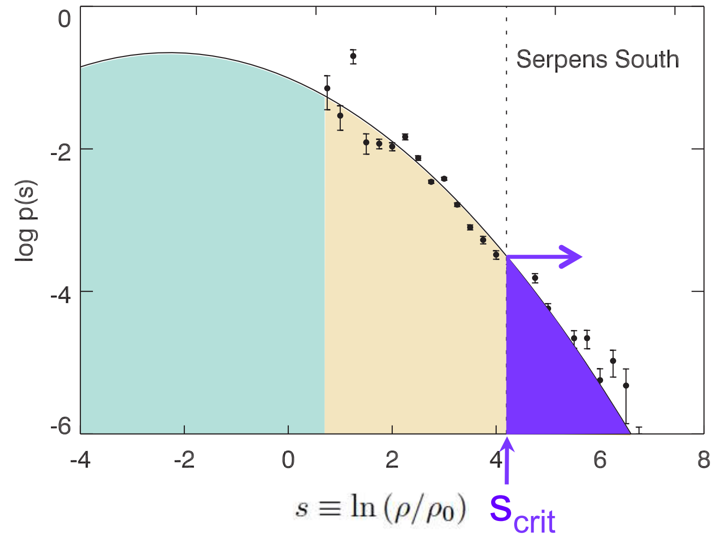
Kainulainen, Federrath, Henning (2014, *Science*)

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

freefall time — **mass fraction**

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



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**

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

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

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

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freefall time **mass fraction**

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

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

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

From sonic and Jeans scales:

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

(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: $P_{\rm th} \rightarrow P_{\rm th} + P_{\rm mag}$

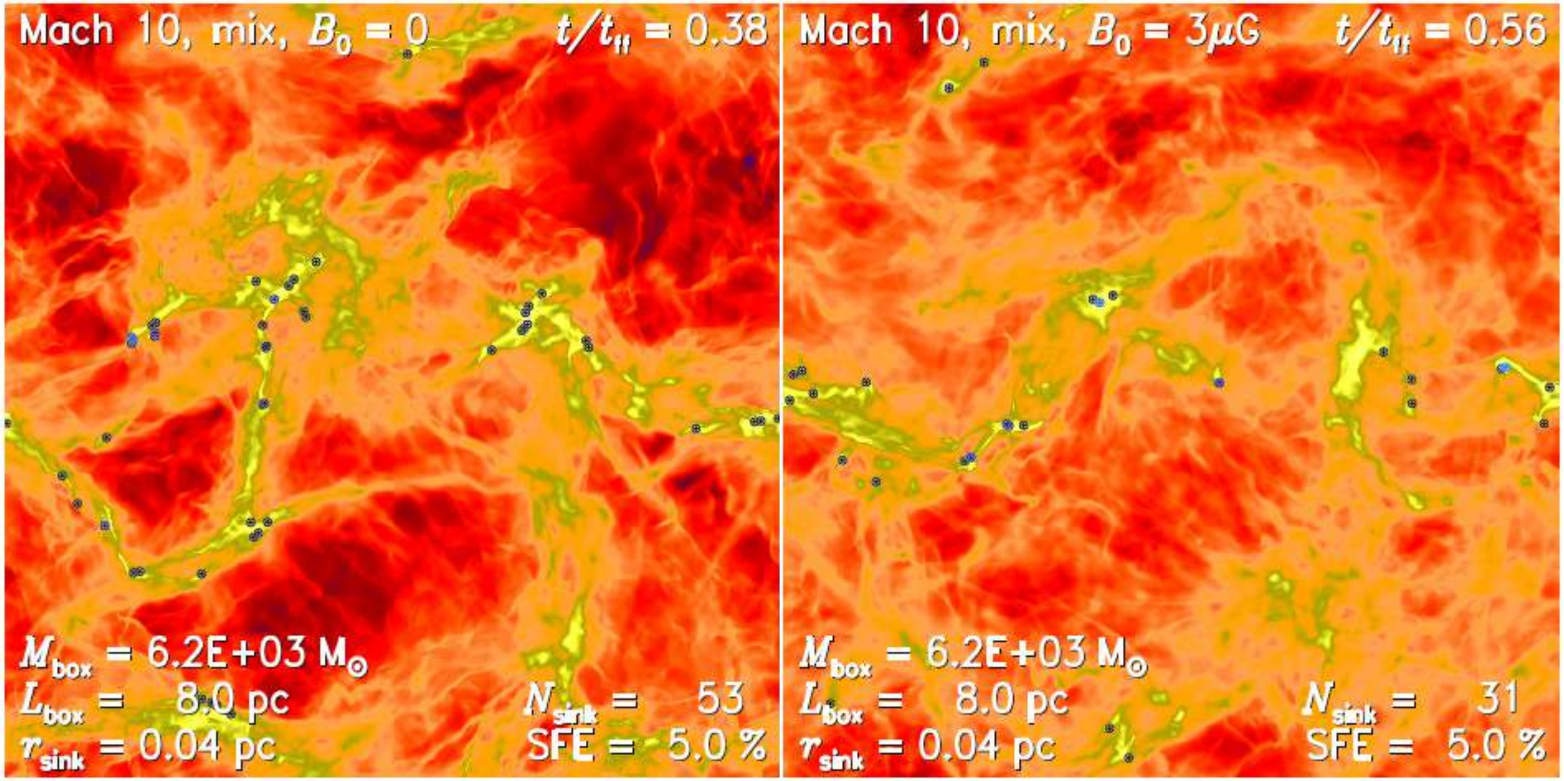
Federrath & Klessen (2012)

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)

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**

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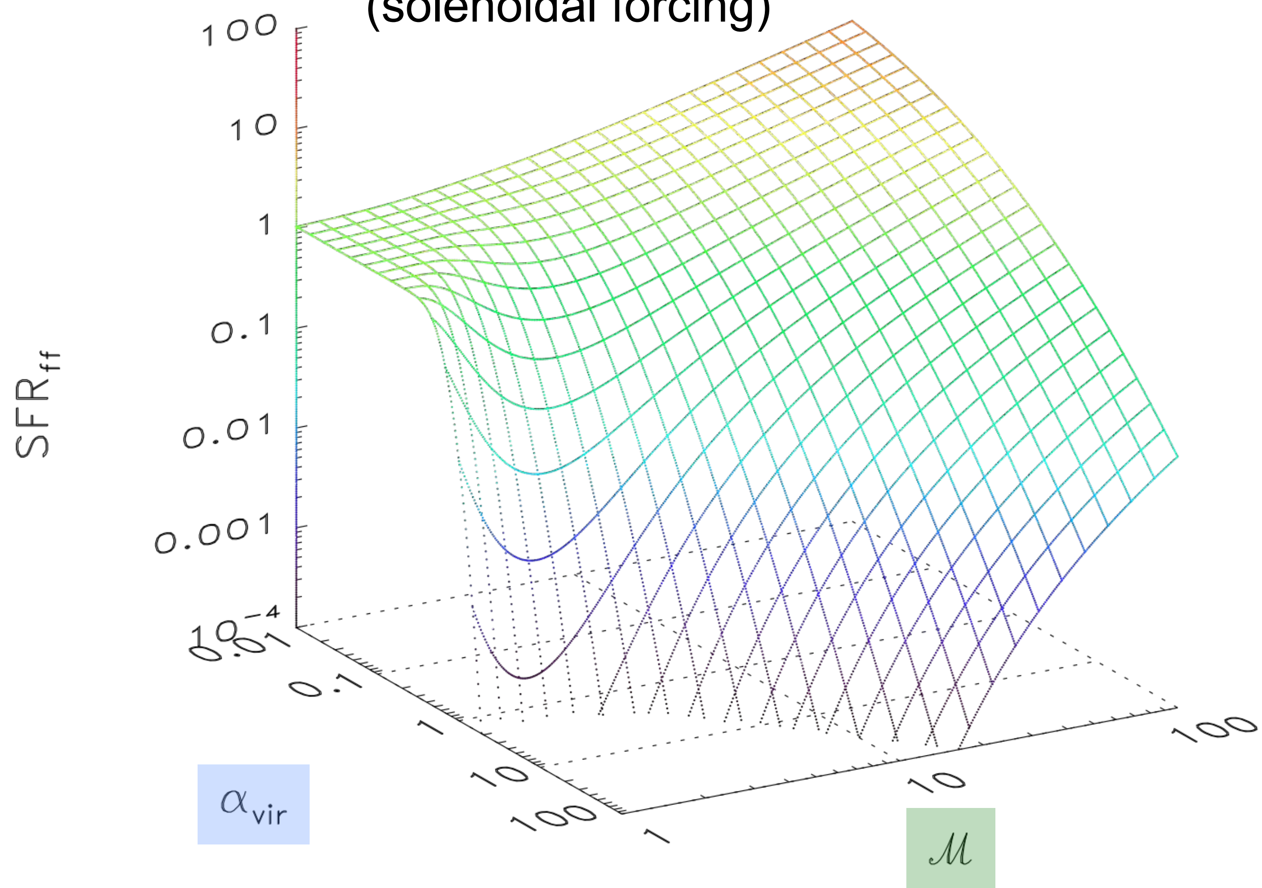
forcing parameter $(b=0.33)$ multi−freefall

(solenoidal forcing)

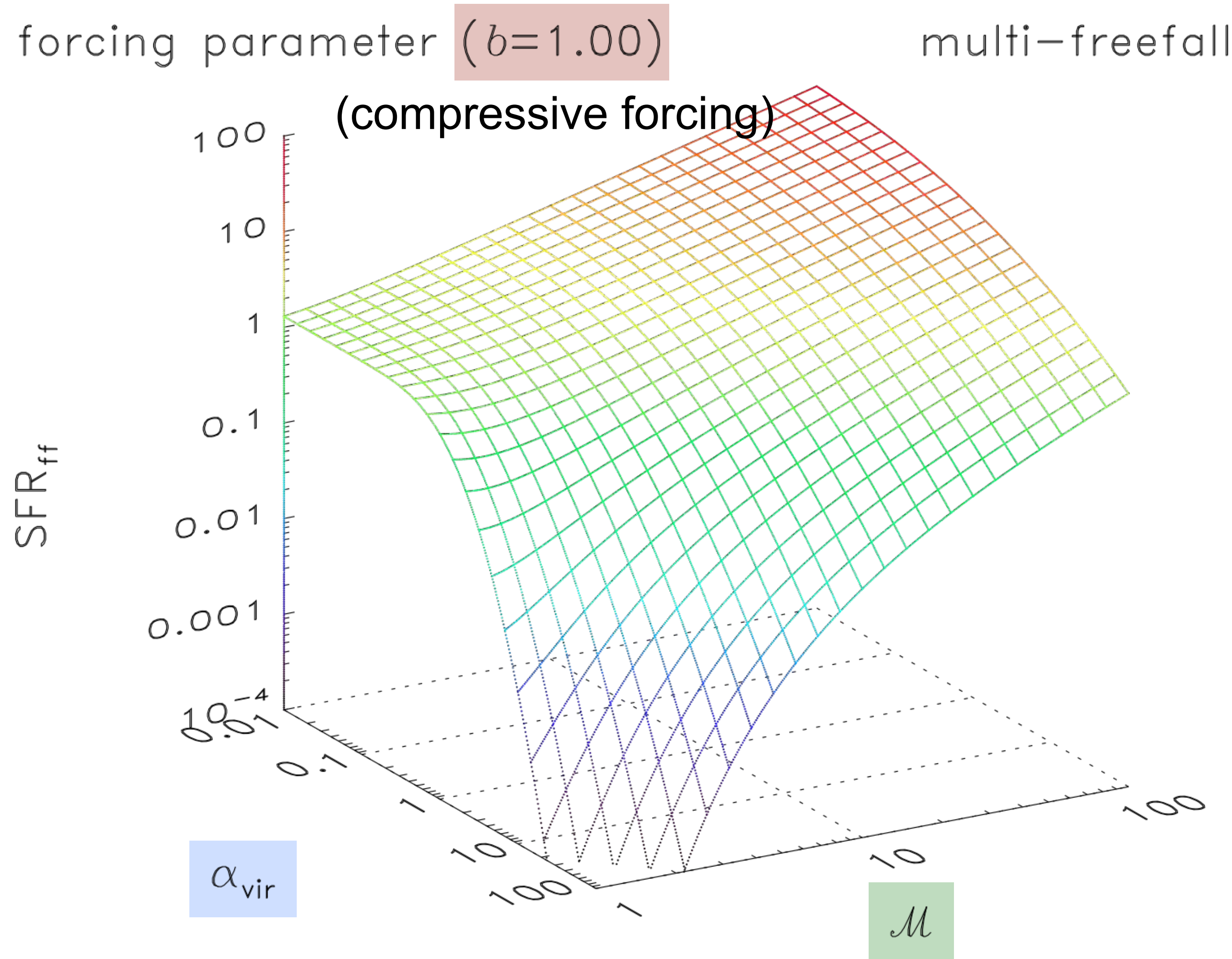


Federrath & Klessen (2012)

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**



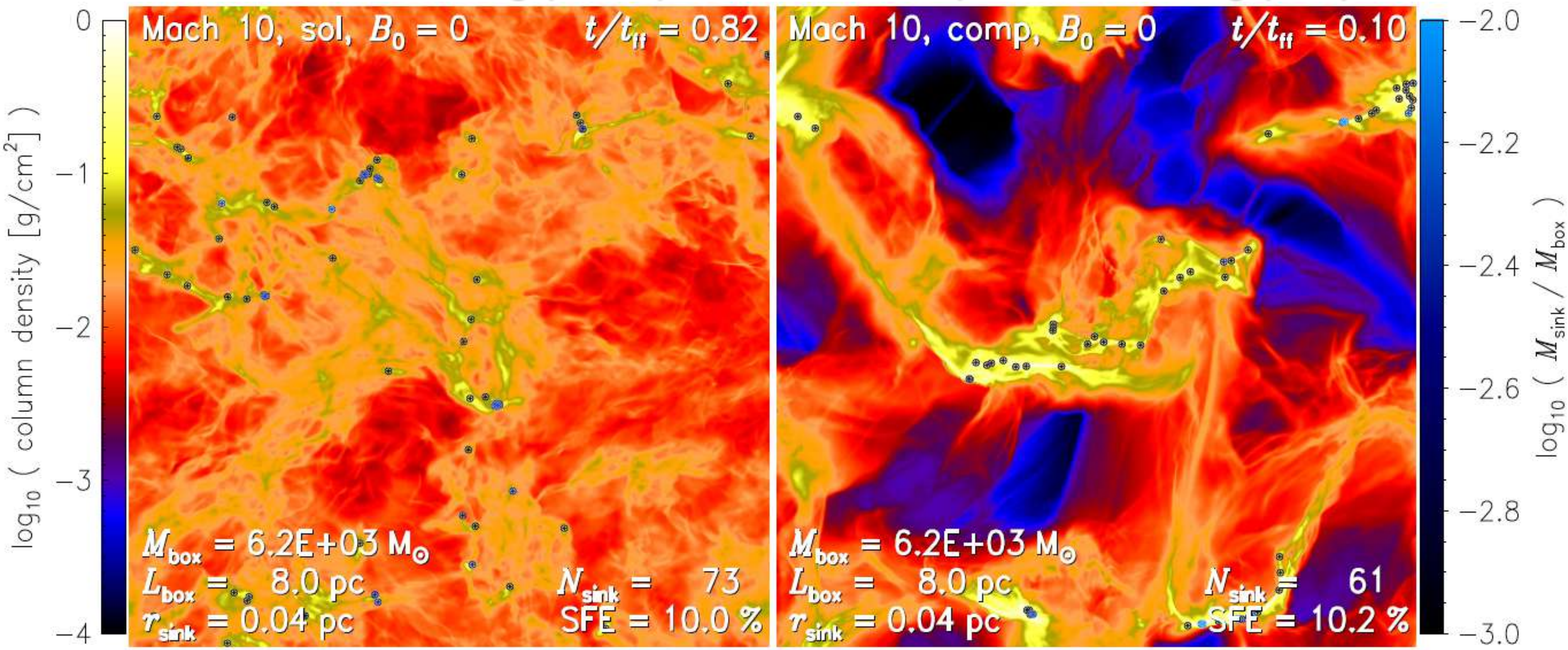
Federrath & Klessen (2012)

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)**

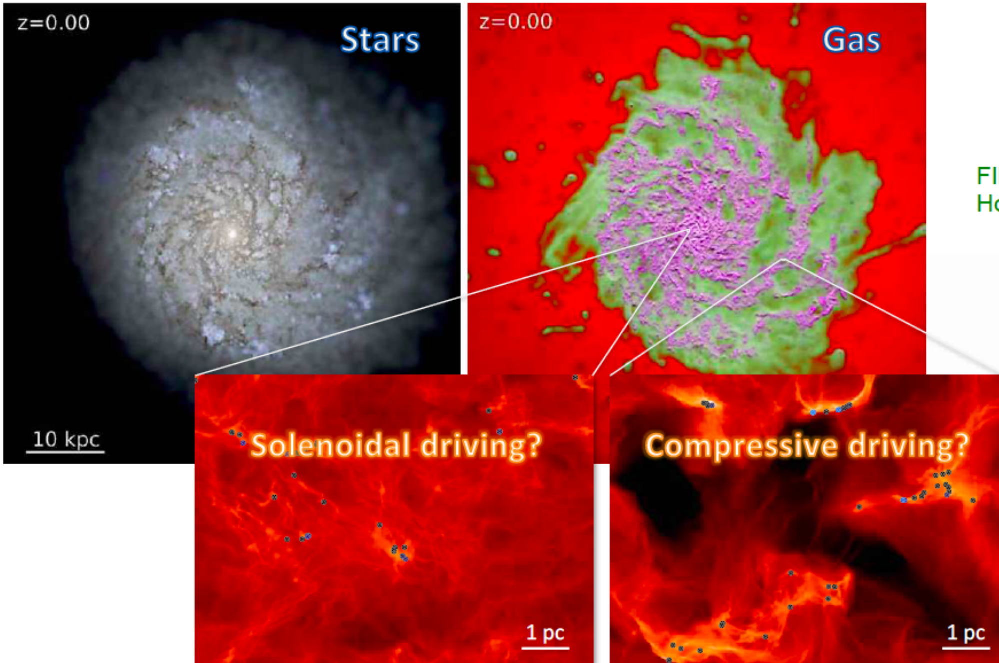


SFR_{ff} (simulation) = **0.14**	x **20**	SFR_{ff} (simulation) = **2.8**
SFR_{ff} (theory) = **0.15**	x **15**	SFR_{ff} (theory) = **2.3**

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)

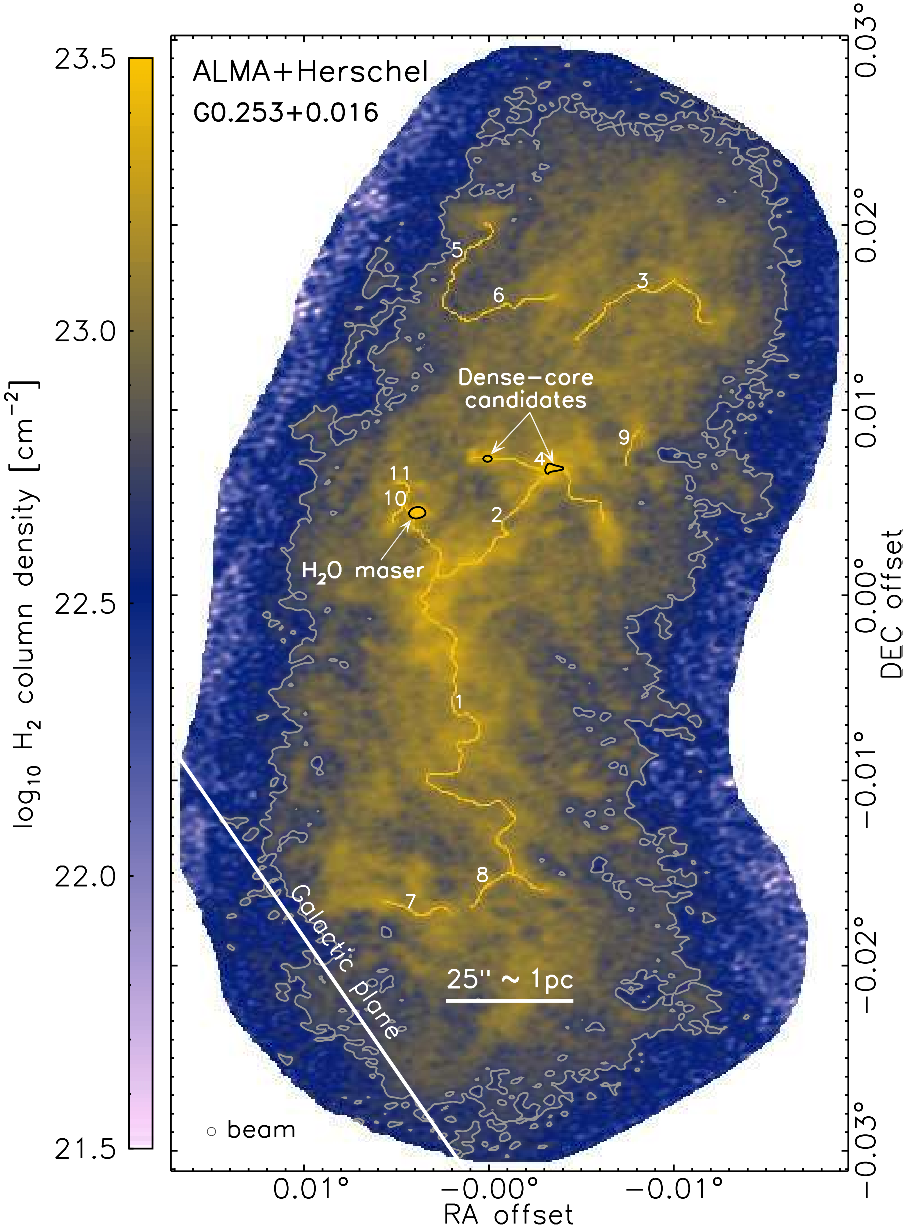
FIRE-DRIVE:
DP170100603
CI Federrath

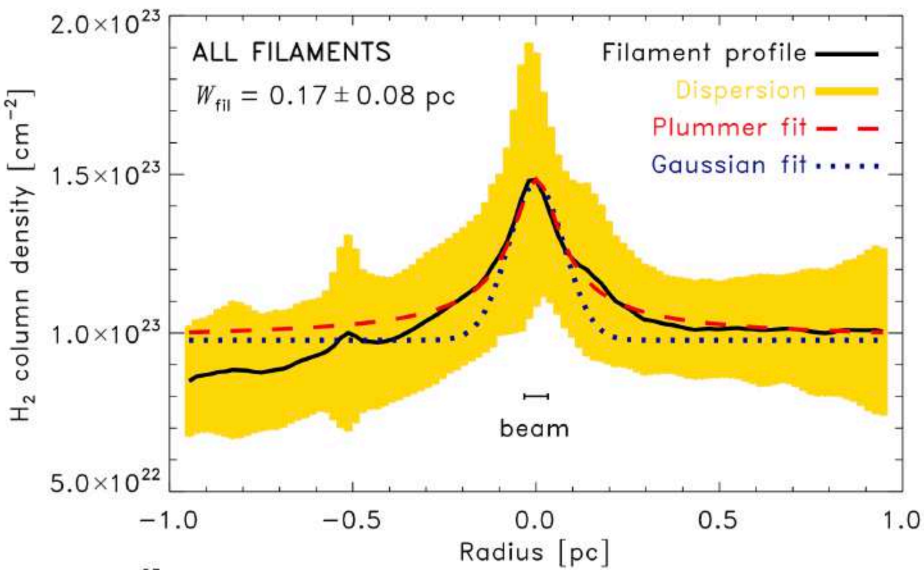
Determine the driving in Galactic Centre (Federrath et al. 2016) vs. Galactic Disc

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

$$b = \sigma_{\rho/\rho_0} \mathcal{M}^{-1} (1 + \beta^{-1})^{1/2}$$

Brick (CMZ) – 1. Density PDF

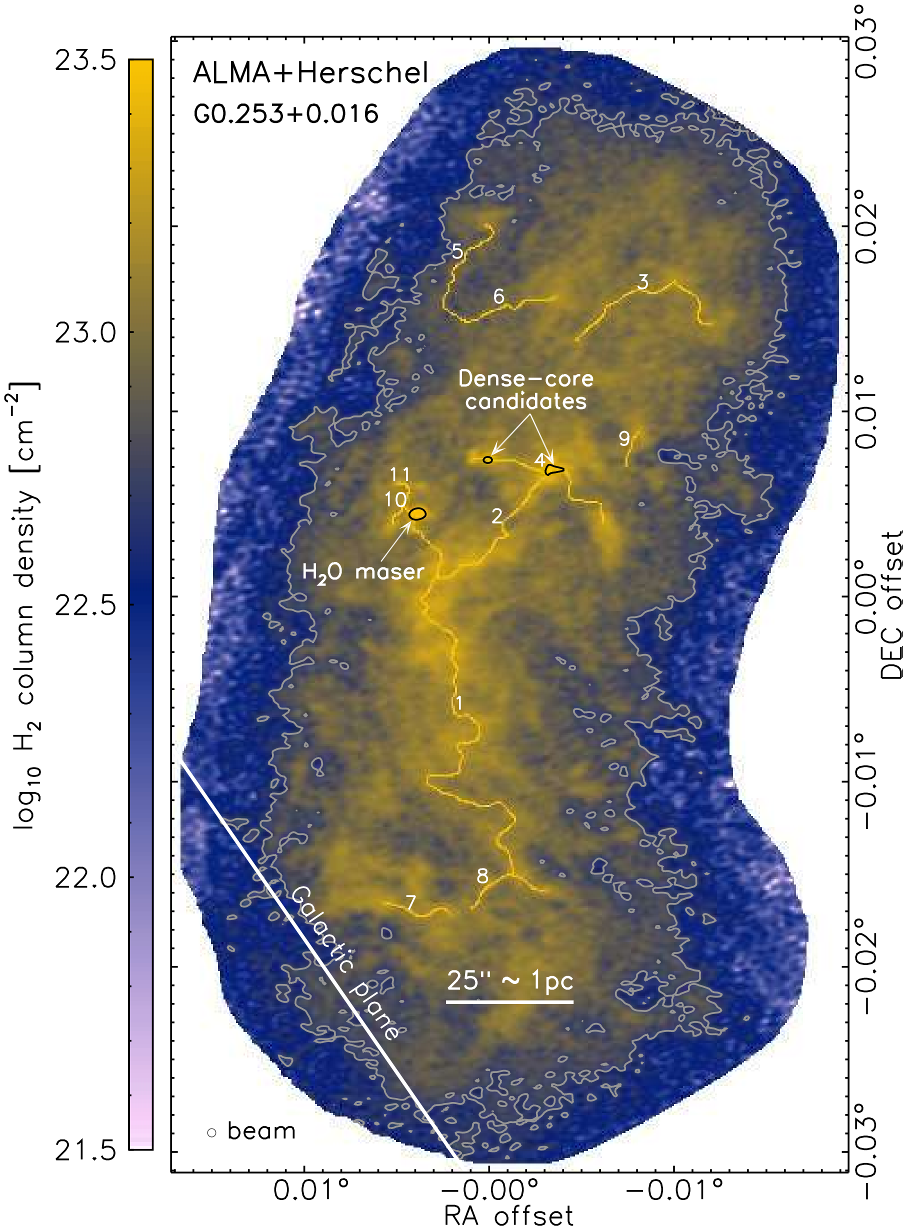




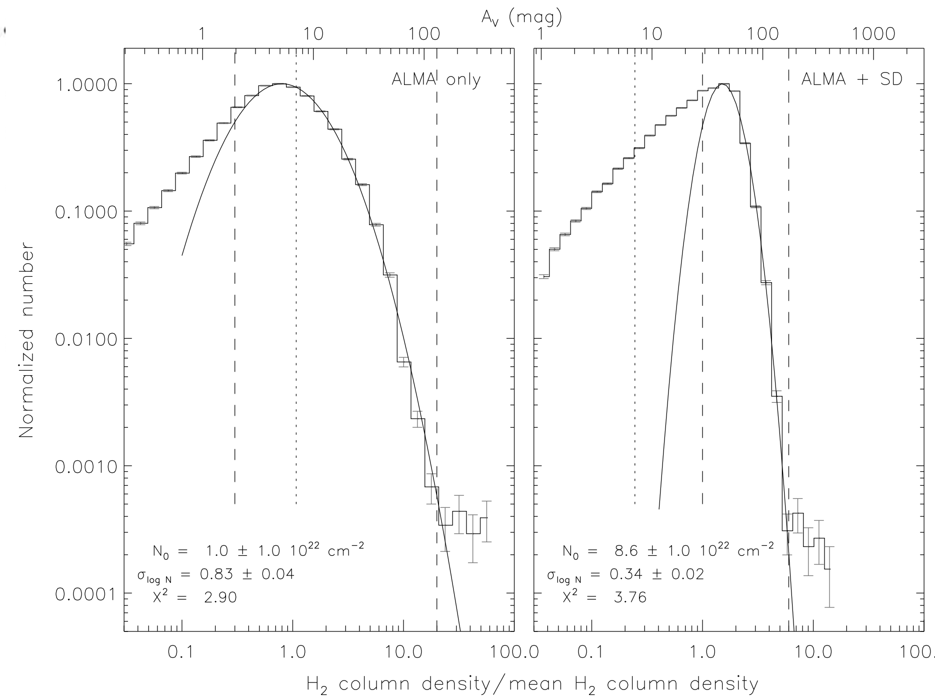
Federrath et al. (2016)

$b = \sigma_{\rho/\rho_0} \mathcal{M}^{-1} (1 + \beta^{-1})^{1/2}$

Brick (CMZ) – 1. Density PDF



Column density PDF



(Rathborne et al. 2014)

→ 2D density dispersion $\sigma_{N/N0}$ = 0.35 ± 0.02

Using 2D-to-3D conversion method by Brunt et al. (2010):

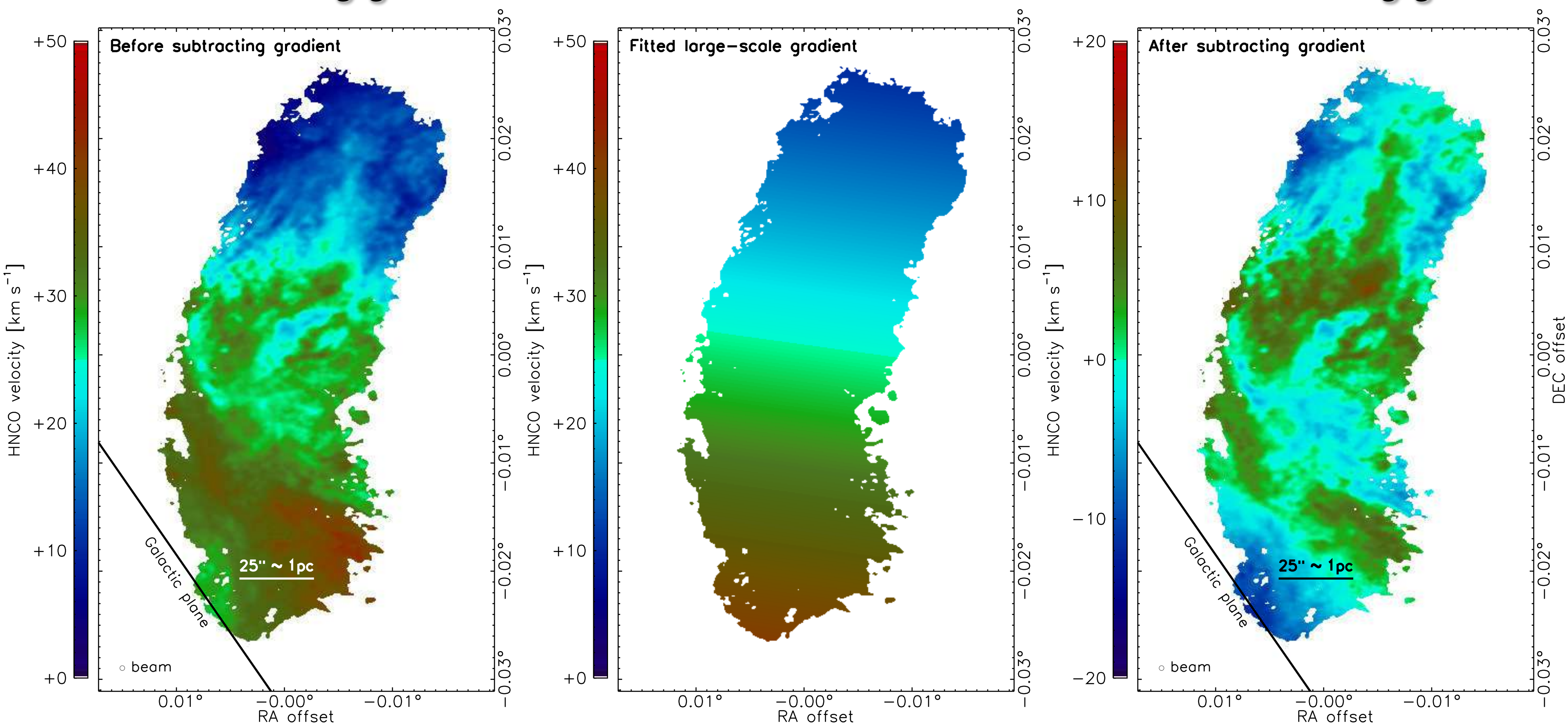
→ **3D density dispersion $\sigma_{\rho/\rho0}$ = 1.3 ± 0.5**

Federrath et al. (2016)

$$b = \sigma_{\rho/\rho_0} \mathcal{M}^{-1} (1 + \beta^{-1})^{1/2}$$

Brick (CMZ) – 2. Mach number

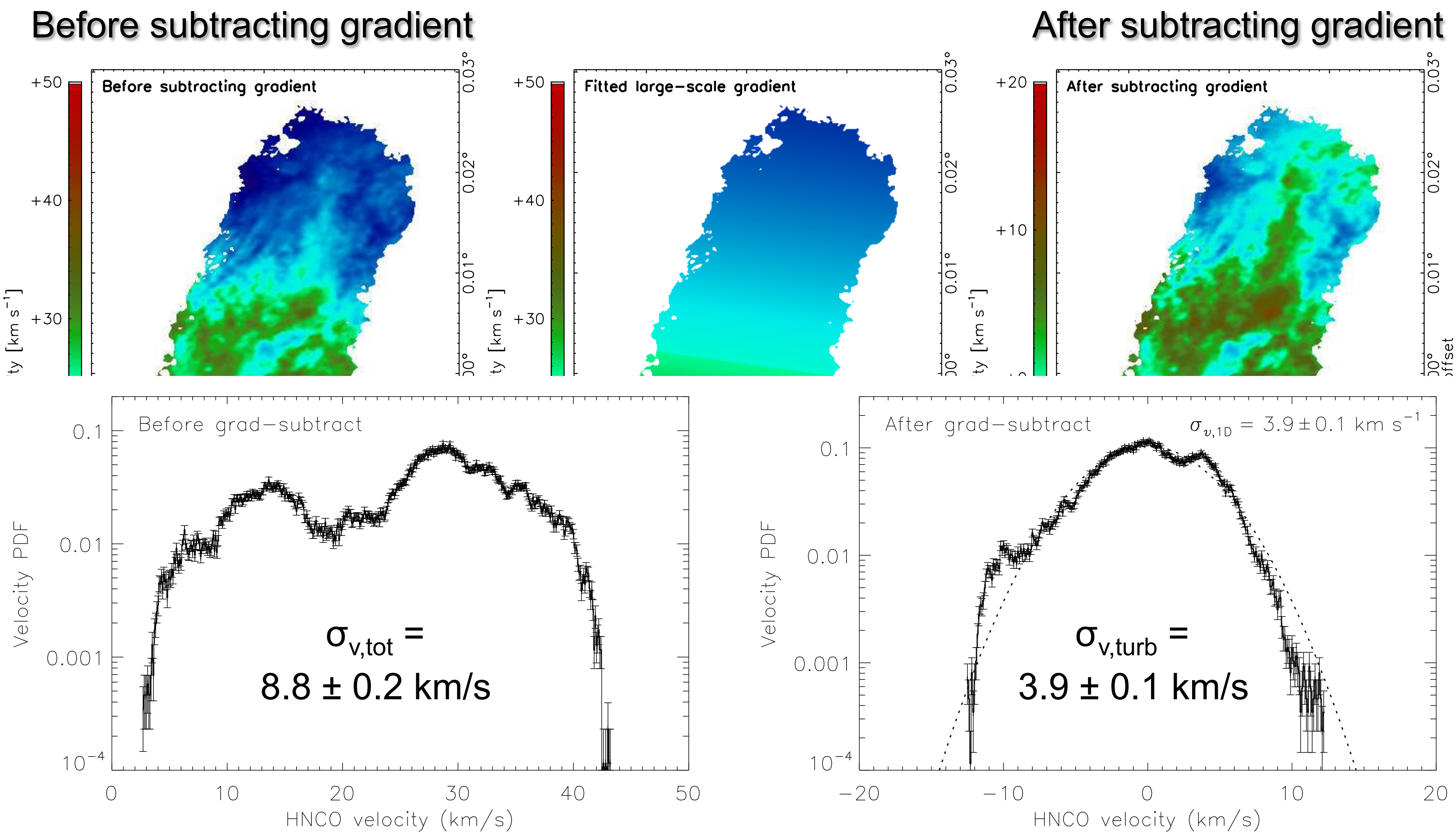
Before subtracting gradient | **After subtracting gradient**



Federrath et al. (2016)

$b = \sigma_{\rho/\rho_0} \mathcal{M}^{-1} (1 + \beta^{-1})^{1/2}$

Brick (CMZ) – 2. Mach number



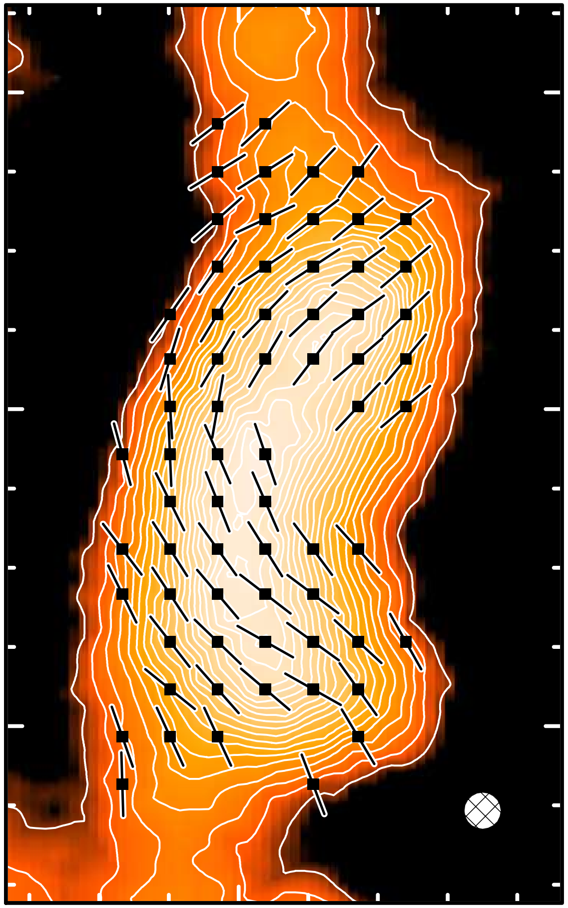
→ 1D turbulent velocity dispersion 3.9 ± 0.1 km/s → **3D turbulent Mach number 11 ± 3**

Federrath et al. (2016)

$$b = \sigma_{\rho/\rho_0} \mathcal{M}^{-1} (1 + \beta^{-1})^{1/2}$$

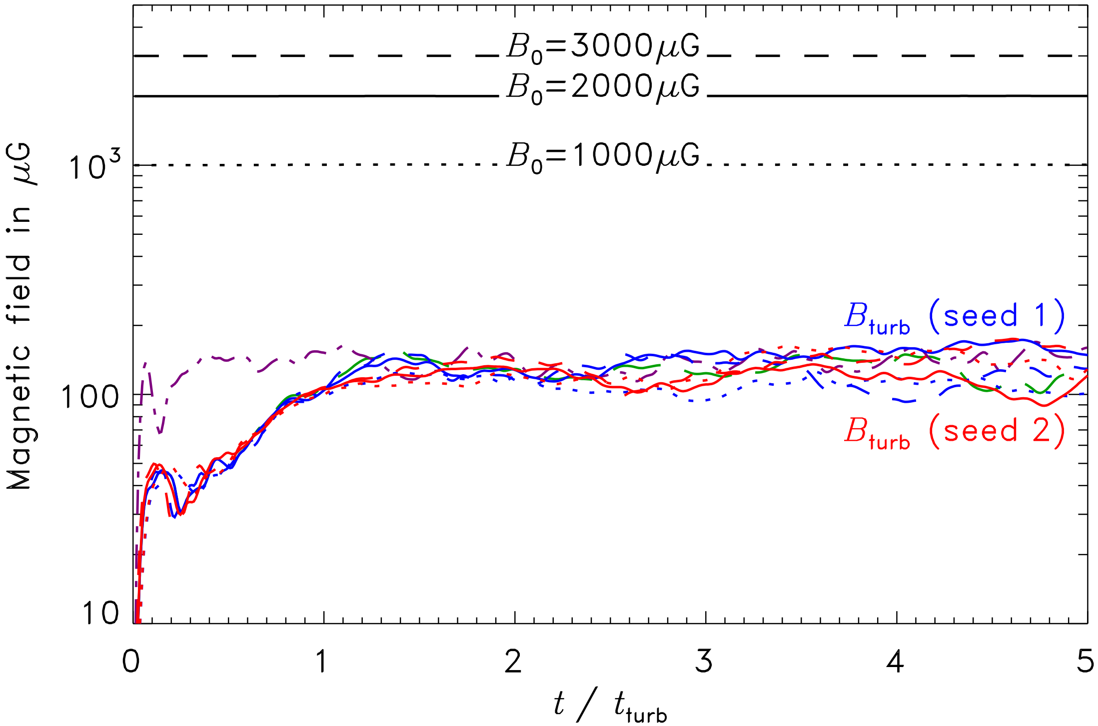
Brick (CMZ) – 3. Magnetic field

Ordered (large-scale) B_0



Pillai, Kauffmann, et al. (2015)

Un-ordered (turbulent) B_{turb}



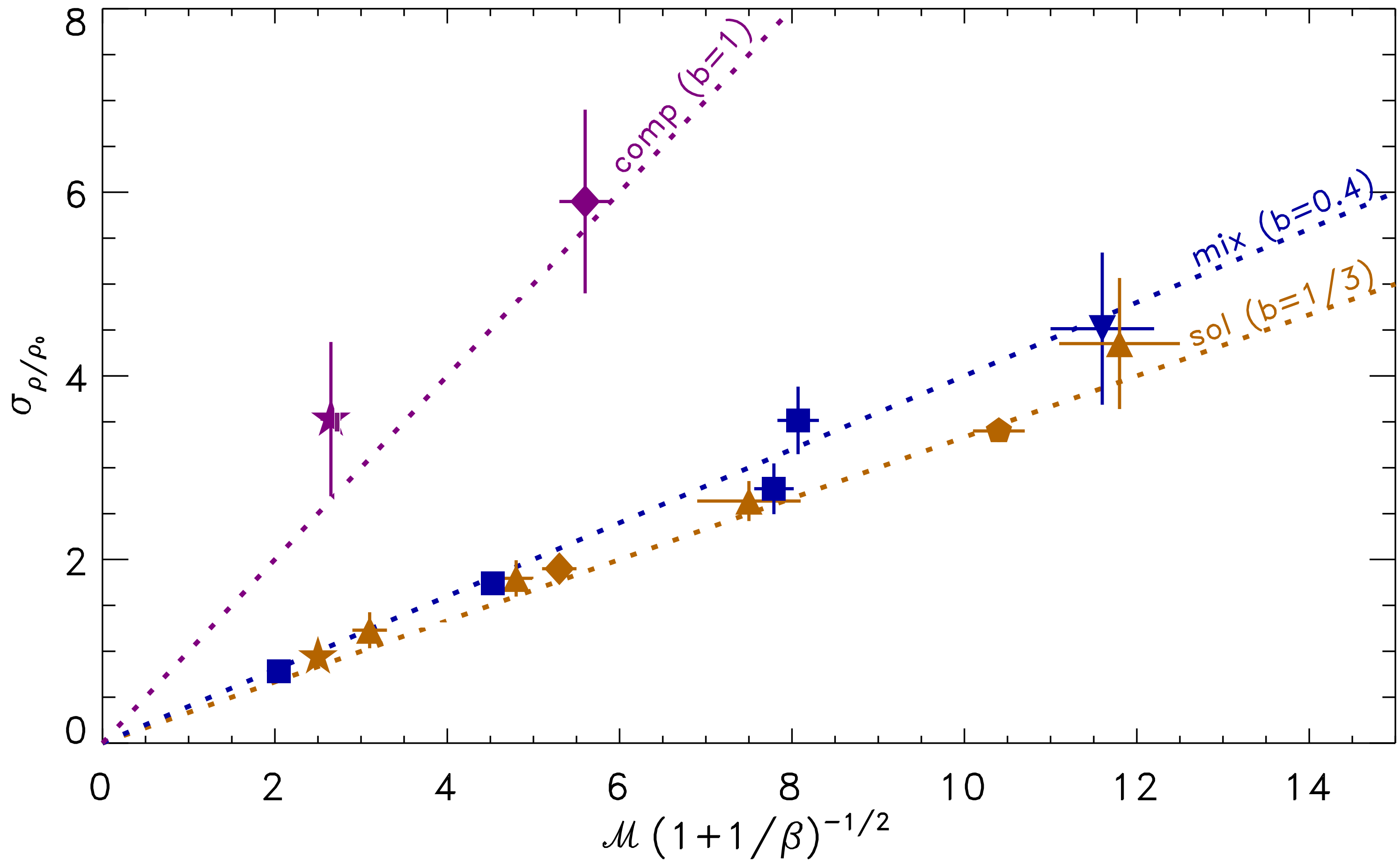
→ B_{turb} ≈ 1/10 B_0 ≈ 130 ± 50 μG

→ turbulent plasma β ≈ 0.34

Federrath et al. (2016)

Brick (Central Molecular Zone) – Turbulence driving

$$b = \sigma_{\rho/\rho_0} \mathcal{M}^{-1}(1 + \beta^{-1})^{1/2} = 0.22 \pm 0.12$$



→ **Solenoidal driving of the turbulence in the Brick (most likely *shear*)**

Federrath et al. (2016)

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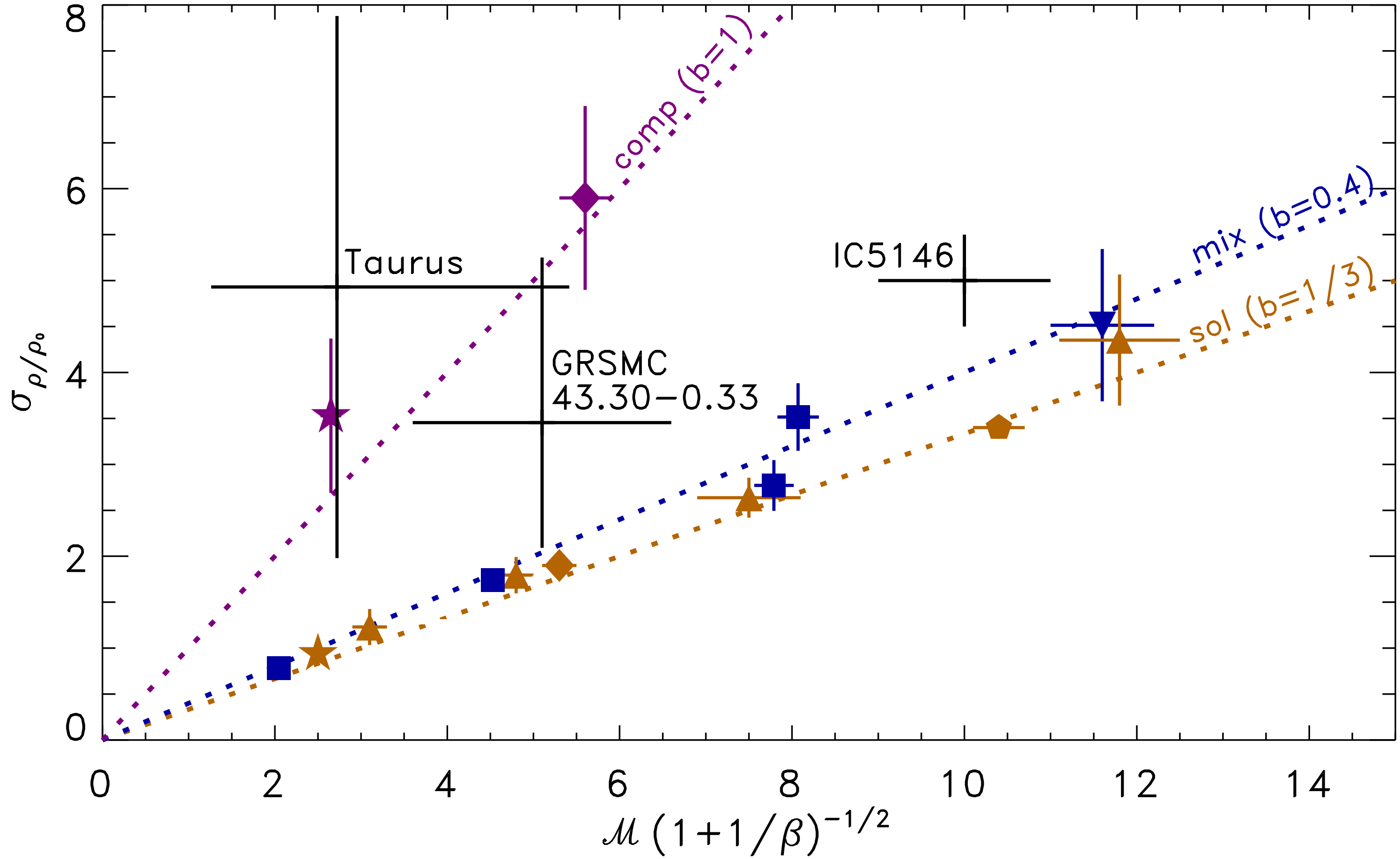

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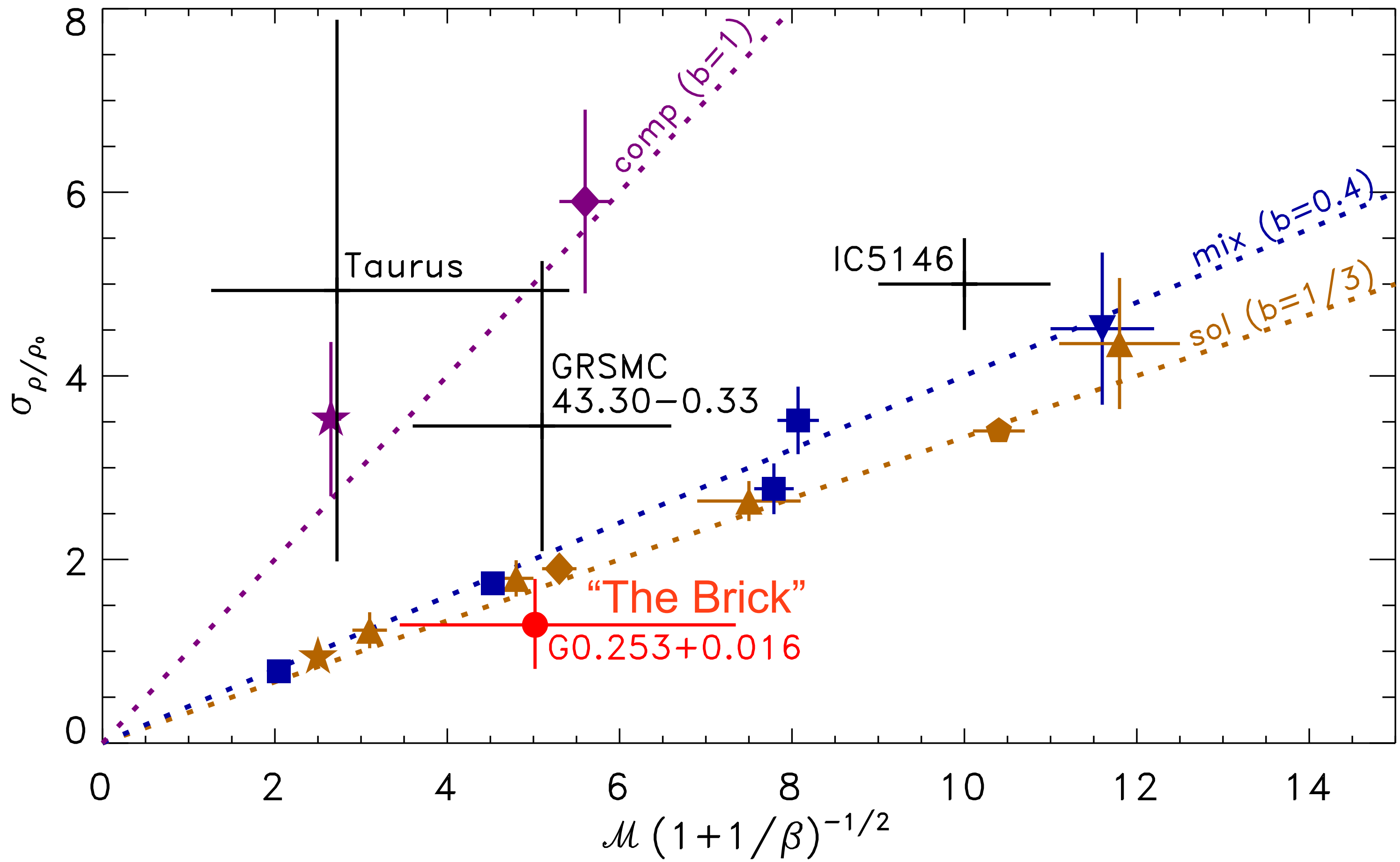


→ **Solenoidal driving of the turbulence in the Brick (most likely *shear*)**

Federrath et al. (2016)

Brick (Central Molecular Zone) – Star formation

Implications for Star Formation in Different Environments (SFDE)

→ Theoretical prediction for SFR in Brick with measured b = 0.22:

$$\mathrm{SFR} = (1.1 \pm 0.8) \times 10^{-2}\, M_{\odot}\, \mathrm{yr}^{-1}$$

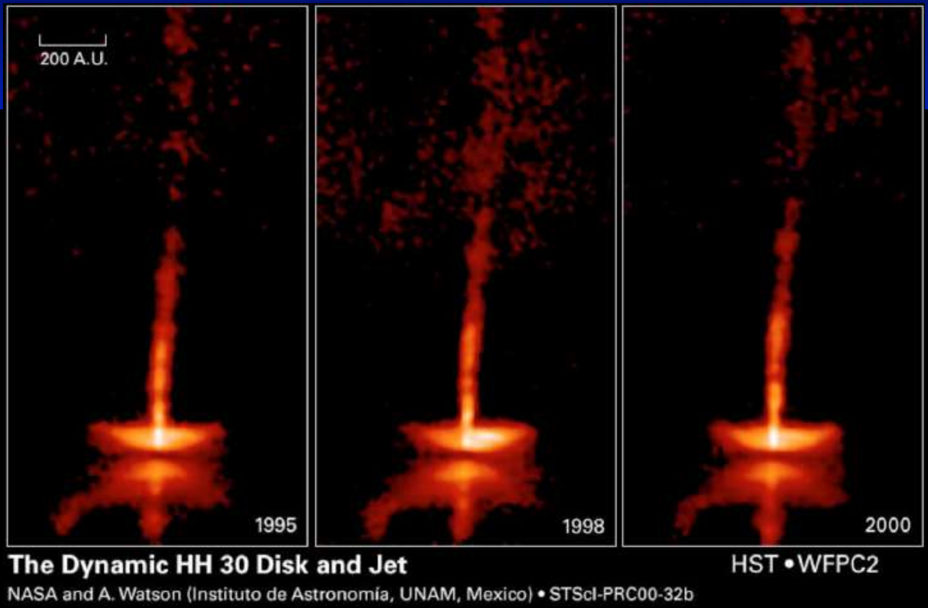
Later measured for Brick: SFR = 0.7 x 10^{-2} $M_{\odot}$ yr^{-1} (Barnes et al. (2017)

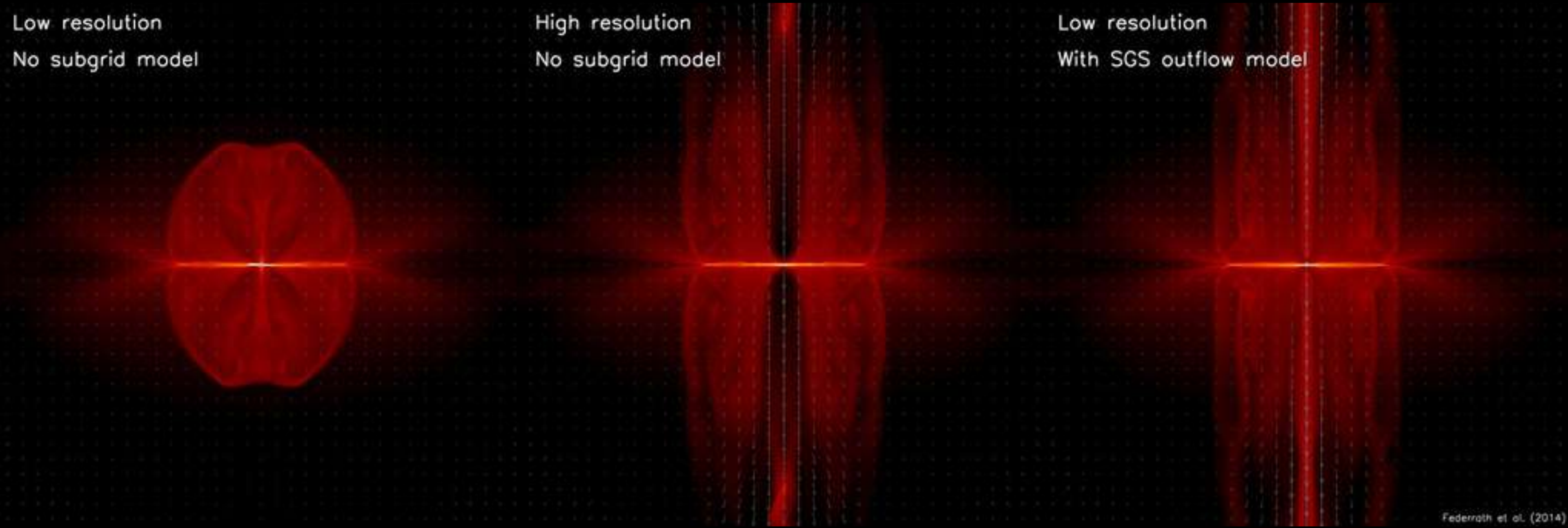
If driving parameter b were 0.5 (as in many nearby clouds),

then SFR would be factor 7 higher!

Federrath et al. (2016)

Jet/Outflow Feedback



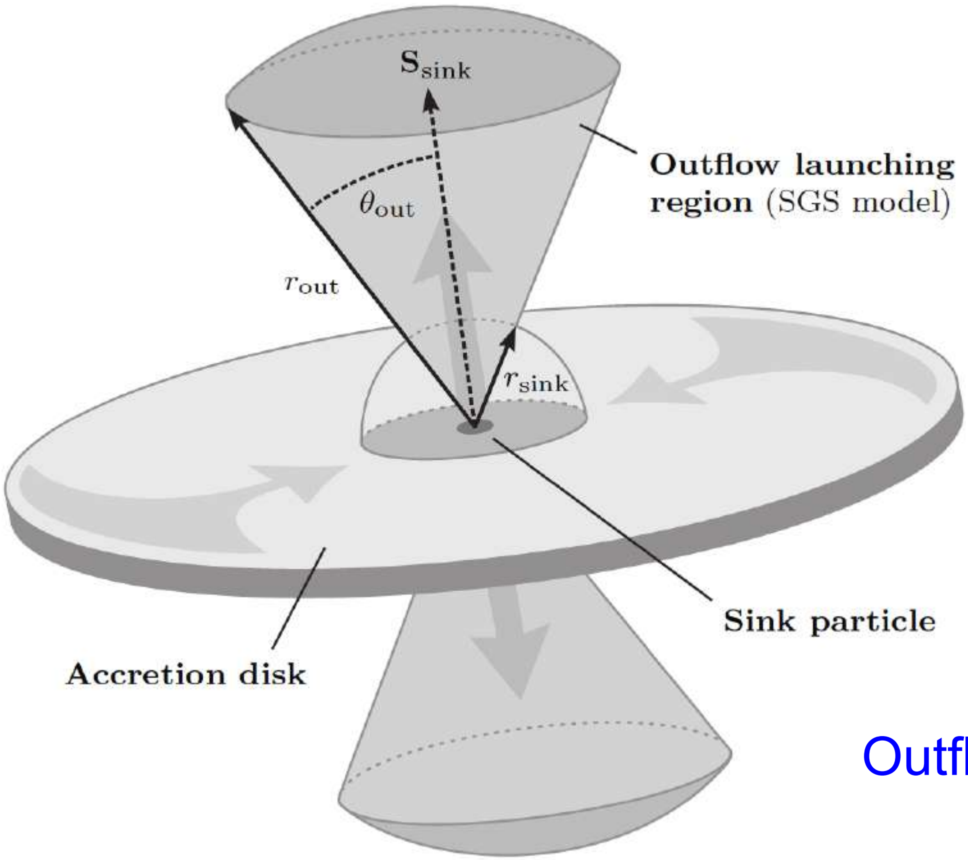


Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

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, $\lvert\mathbf{V}_{\rm out}\rvert = 100\,{\rm km\,s^{-1}}(M_{\rm sink}/0.5\,M_\odot)^{1/2}$ (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).

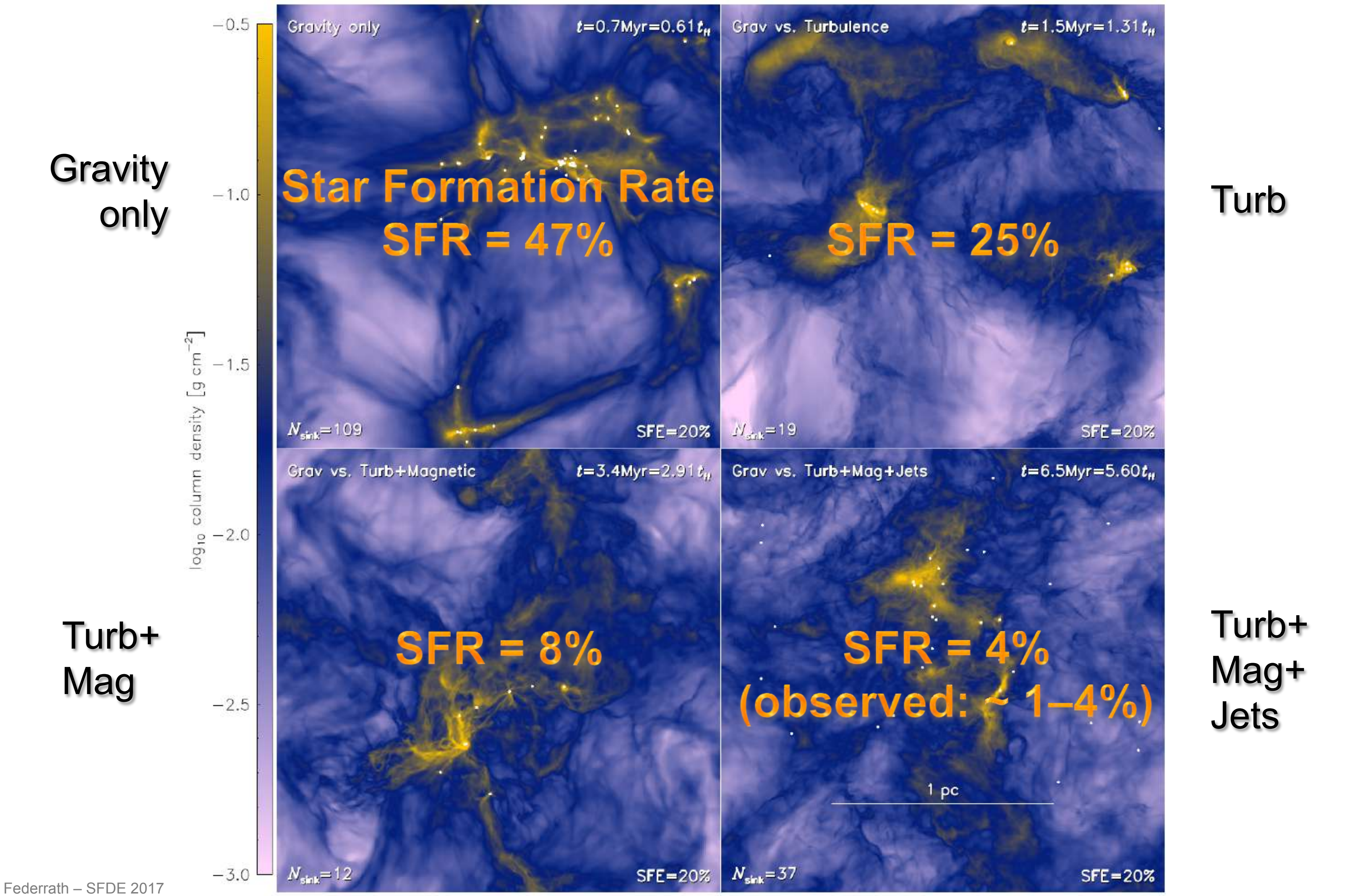
Outflow mass: $$M_{\rm out} = f_{\rm m} \dot{M}_{\rm acc} \Delta t$$

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

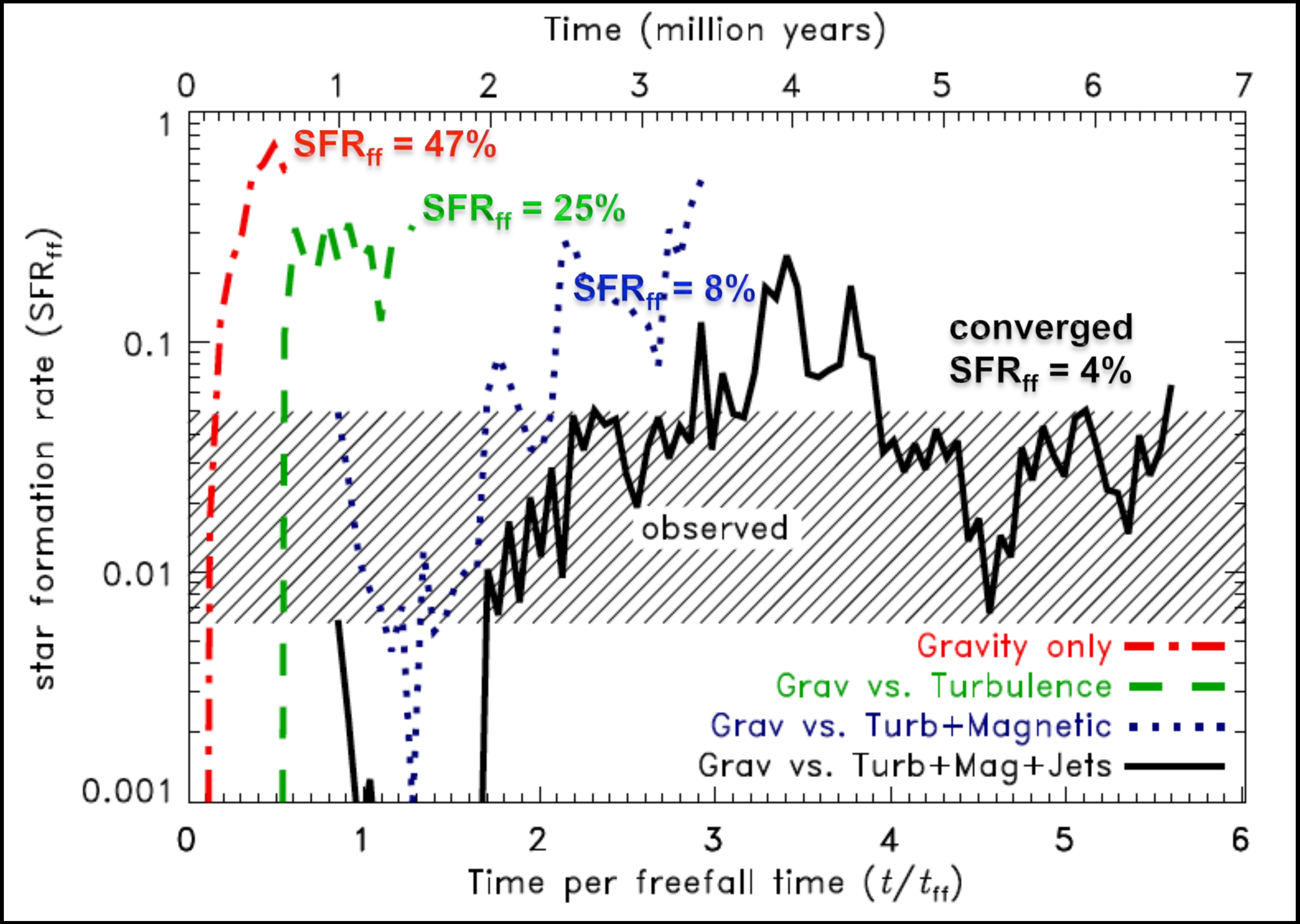
Outflow angular momentum: $$\mathbf{L}_{\rm out} = f_{\rm a}\,(\mathbf{S}'_{\rm sink} - \mathbf{S}_{\rm sink}) \cdot \mathbf{S}'_{\rm sink}/\lvert\mathbf{S}'_{\rm sink}\rvert$$

Why is Star Formation is so Inefficient?

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



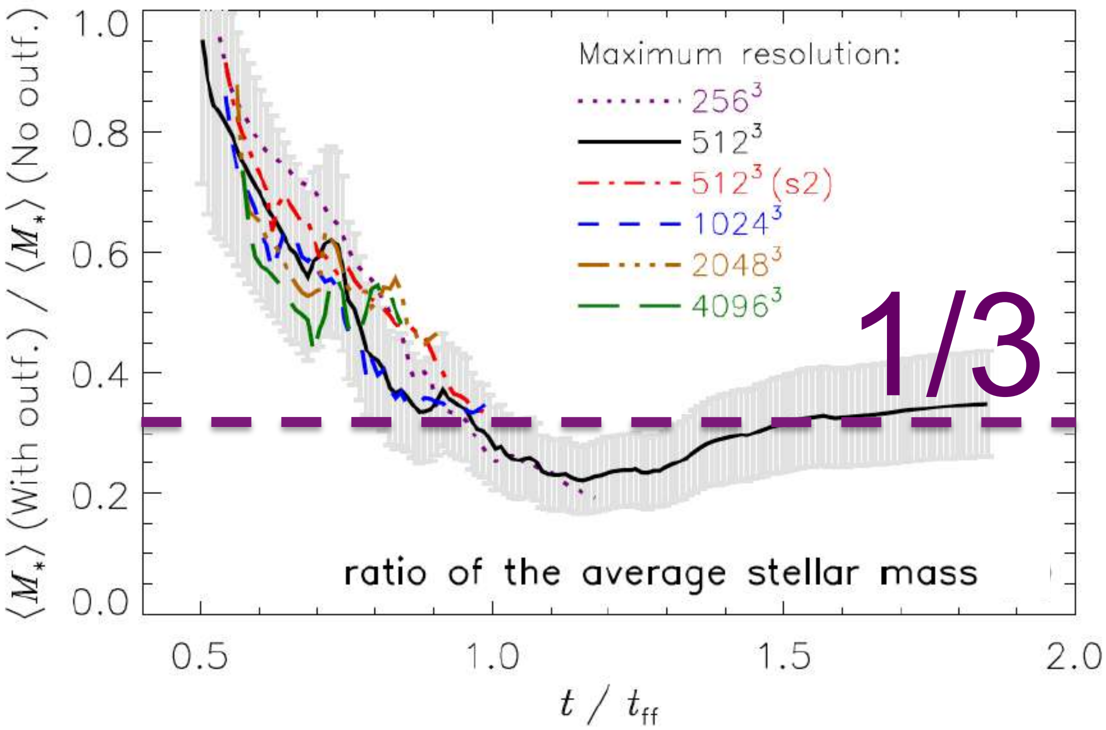
Star Formation is Inefficient



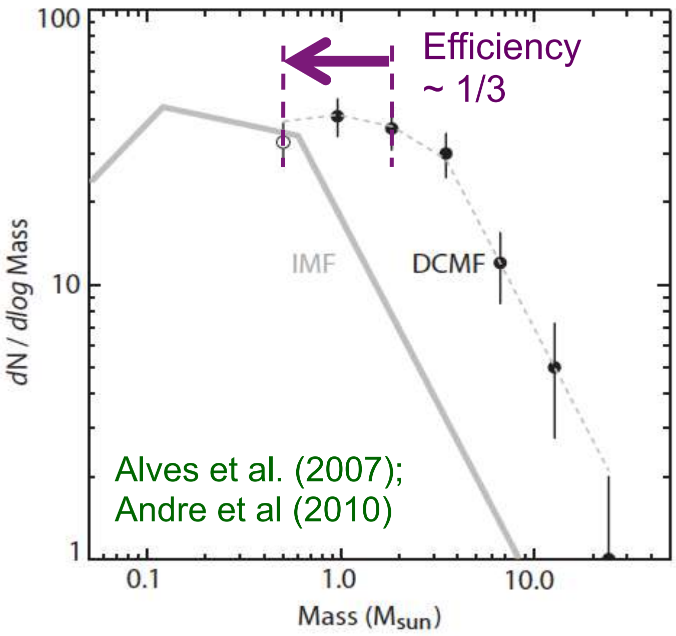
Only the combination of turbulence, magnetic fields and feedback gives realistic SFR

Federrath 2015, MNRAS 450, 4035

Implications for the stellar initial mass function (IMF)



Federrath et al. 2014, ApJ 790, 128

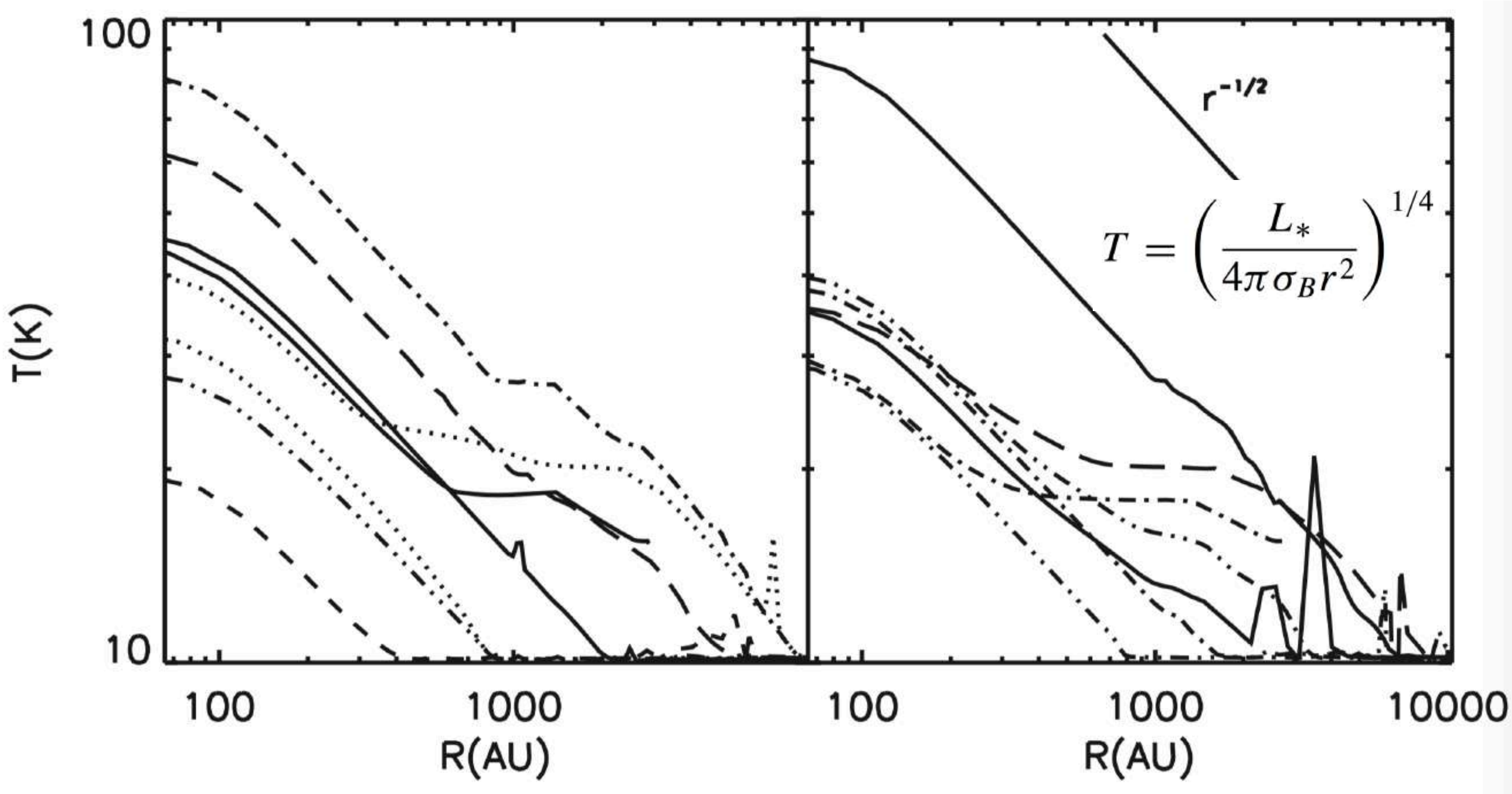


Outflow/Jet feedback reduces average star mass by factor ~ 3 → IMF!

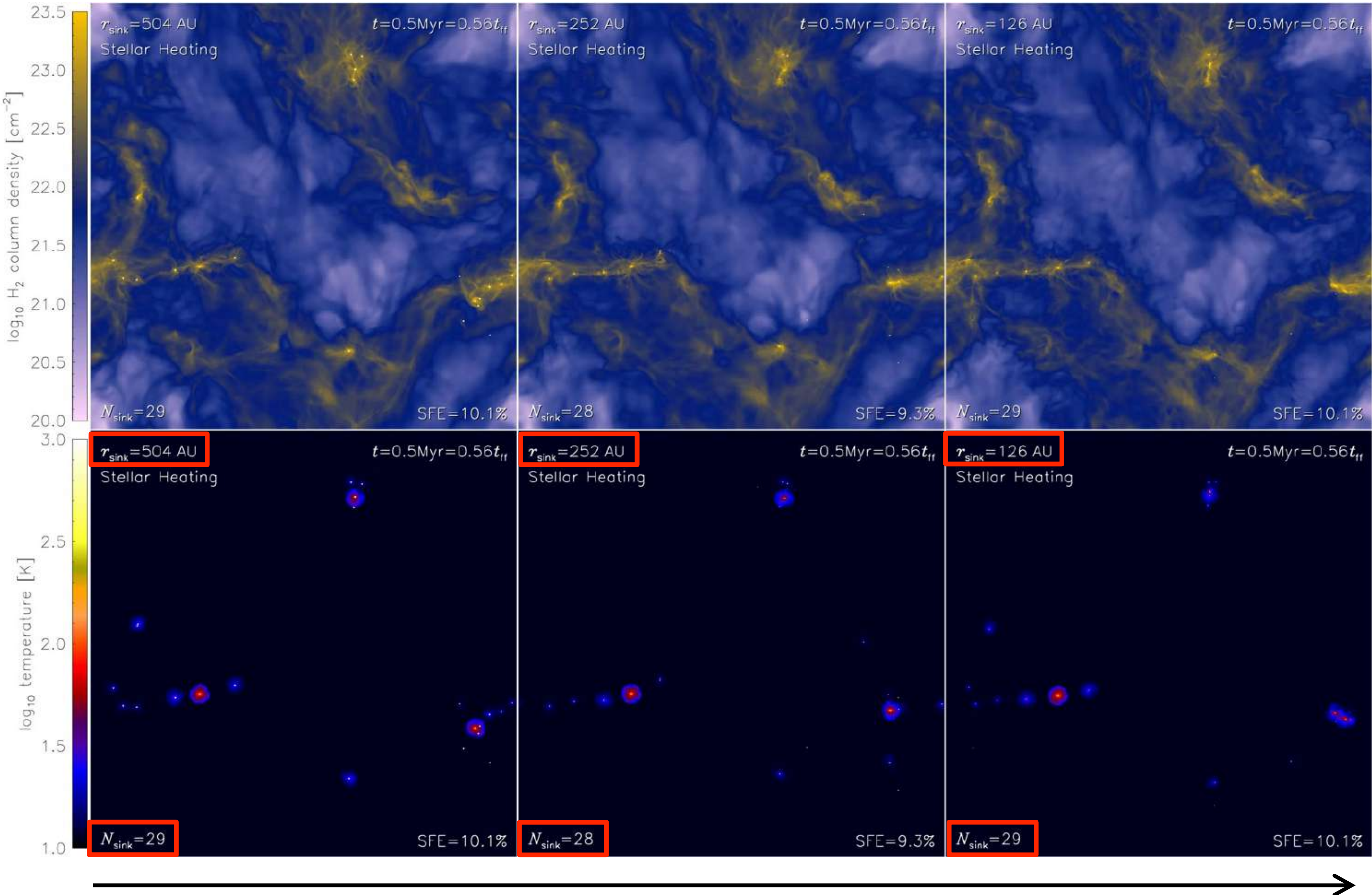
...but, IMF also needs stellar **heating feedback**!

Proto-/stellar evolution → accretion/stellar luminosity → heating

Offner et al. (2009)



A simple radiation feedback model



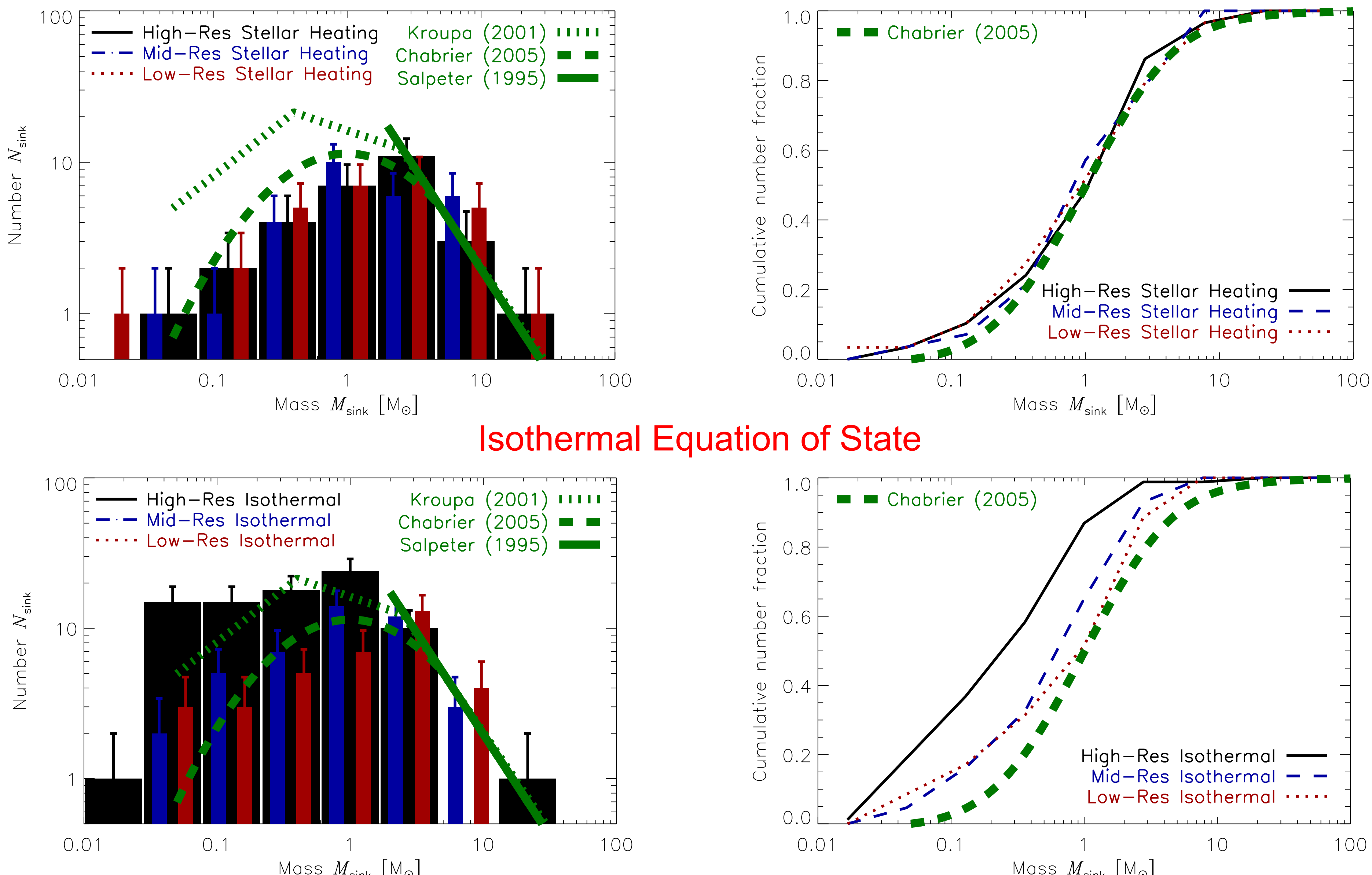
(Federrath, Krumholz, Hopkins 2017)

Increasing resolution → convergence

Radiation feedback → Converging on the IMF

Stellar Heating Feedback

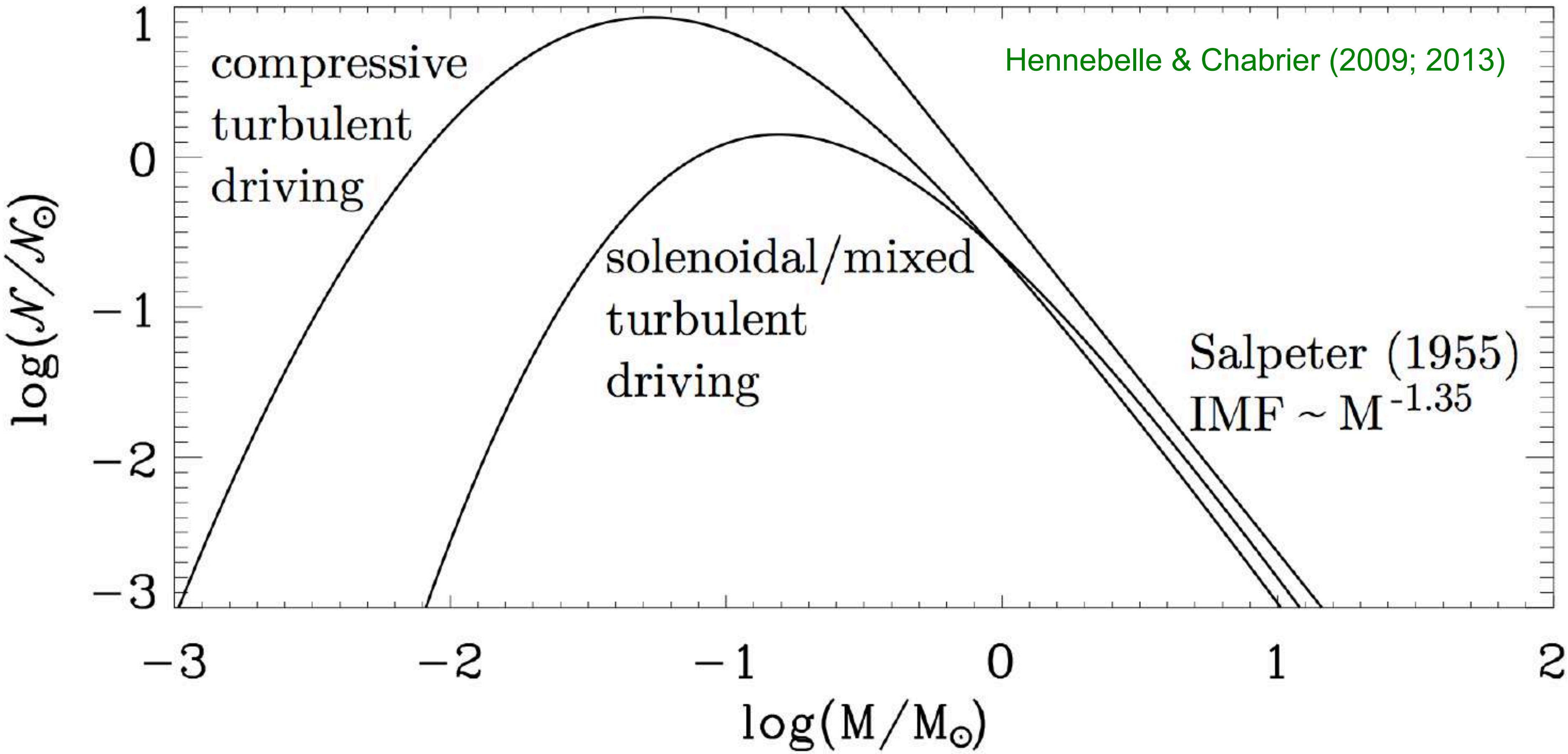
Isothermal Equation of State



(Federrath et al., in prep.)

A new calibrated radiation feedback model → IMF

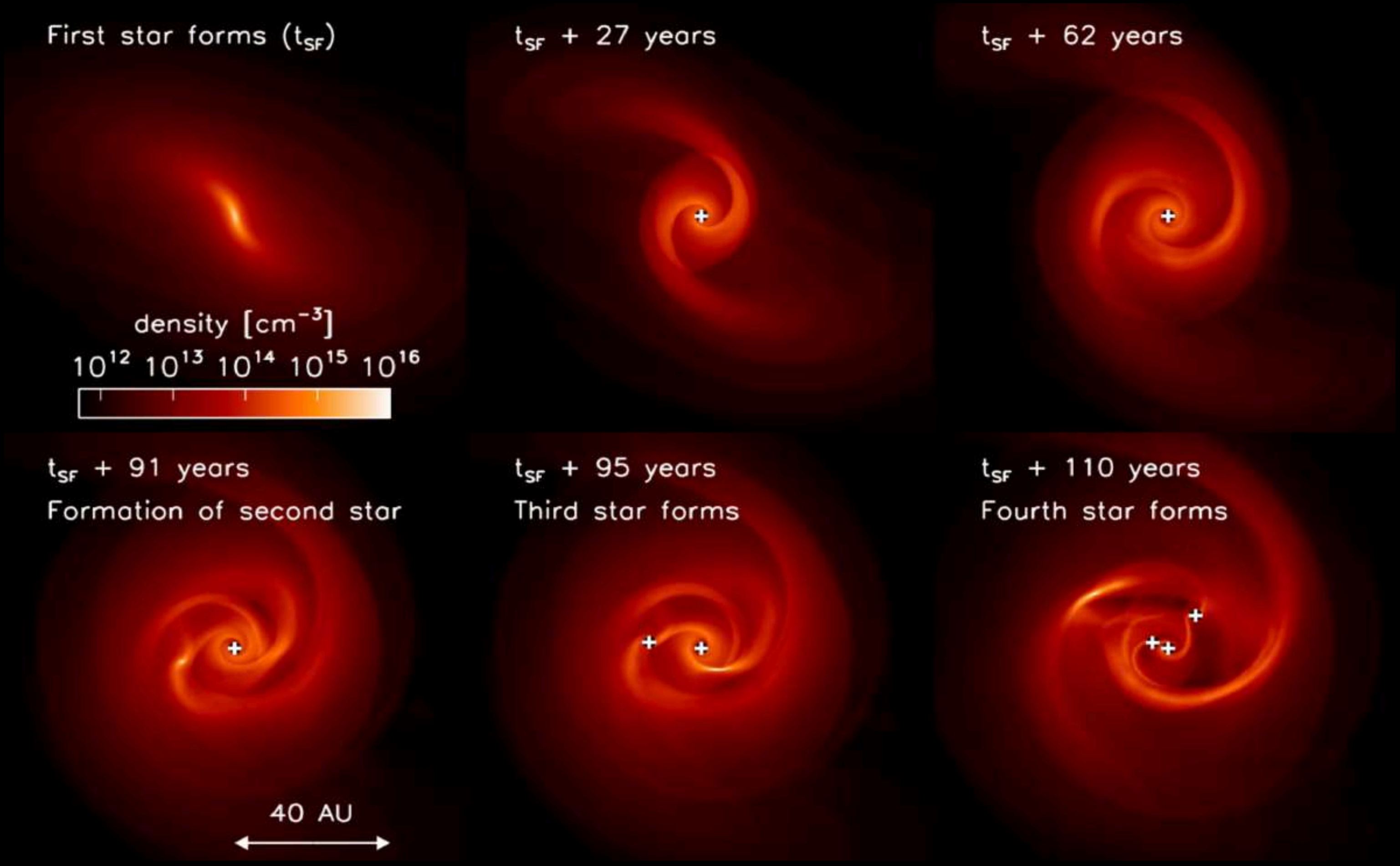
Theoretical prediction:



→ We can determine the IMF

Primordial Star Formation (IMF of Population III Stars)

Clark et al. 2011, Science



Important physics missing: no magnetic fields, no jet feedback

→ **Our simulation methods allow us to predict the Pop III IMF**

→ Indirect constraints on Pop III IMF: e.g., Norris et al. (2013)

and near future observations with **LSST, JWST, GMT, E-ELT**

Conclusions and new challenges

1) Star Formation is complex and inefficient →

   Only the combination of

   Turbulence + Magnetic Fields + Feedback

   gives realistic (observed) SFRs

2) Measured turbulence driving parameter in *The Brick (CMZ)*

   → Solenoidal driving (probably caused by shear) may explain low SFR

   (predicted SFR ≈ 0.01 $M_{\odot}$/yr ≈ 4% per freefall time)

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

   Determine the Initial Mass Function (IMF) of Stars

   → Necessary physics:

   turbulence, magnetic fields, jet feedback and radiation feedback

   …probably relevant also for Population III IMF

The End.