Star Formation – local processes

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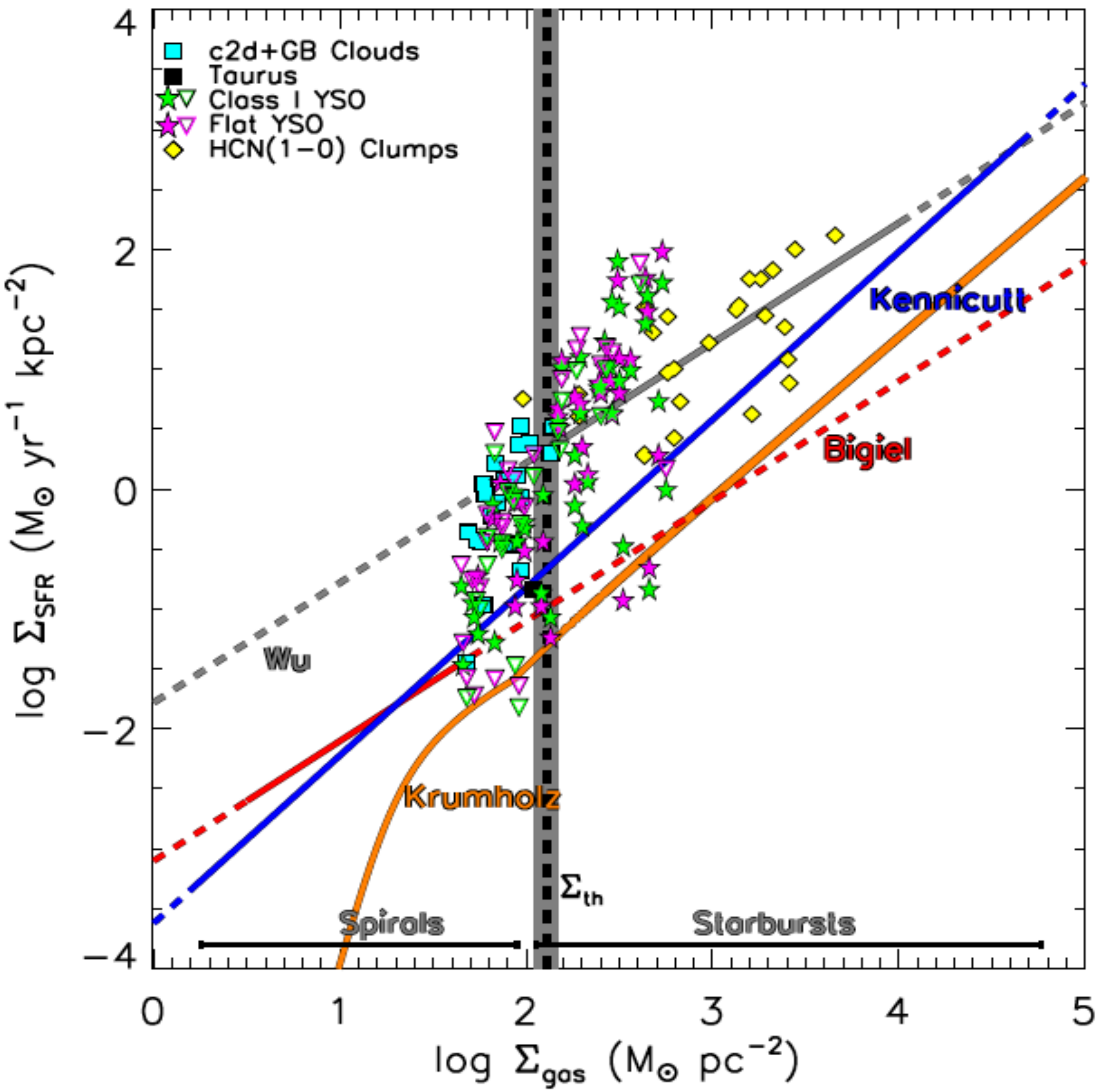
MoCA
Monash Centre for Astrophysics

DFG Priority Program 1573
ISM-SPP
Interstellar Medium

Australian Government
Australian Research Council

Image Credit: ESA and the HFI Consortium, IRAS 2010

Universal star formation "law"?



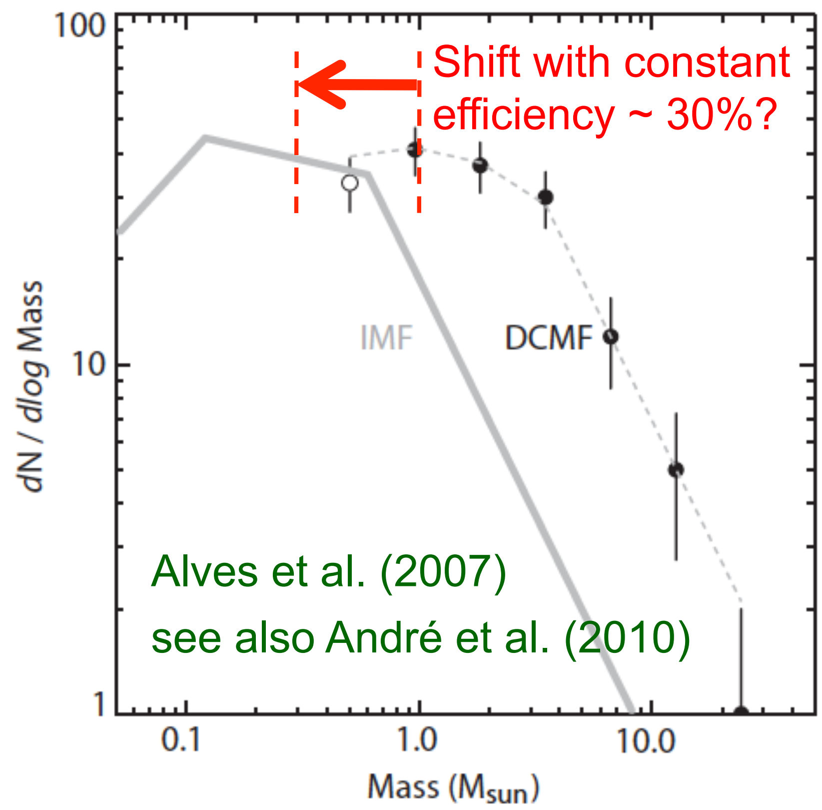
- Relation?
- Offset?
- Scatter?

Galactic clouds (Heiderman+10; see also Lada+10, Guthermuth+11)

Star Formation – Local processes

Local processes

- Radiation / Ionization / Winds
- Magnetic Fields
- Outflows / Jets



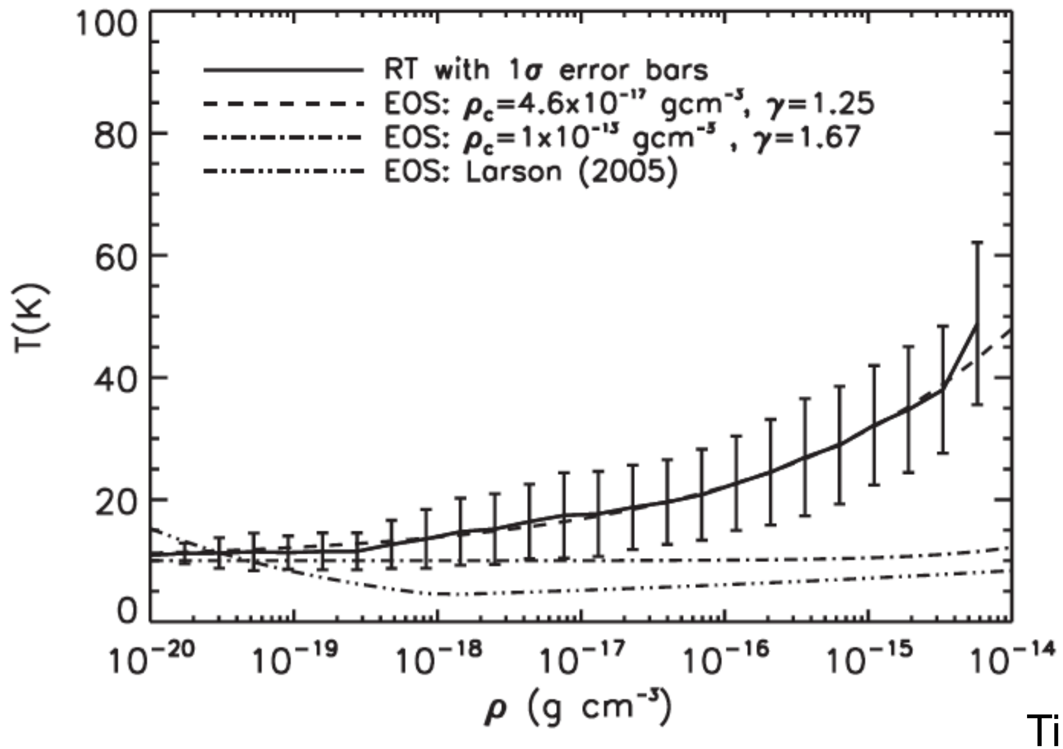
Reduce SFR and SFE
(local core formation efficiency ~ 0.3–0.7)

(see also Matzner & McKee 2002)

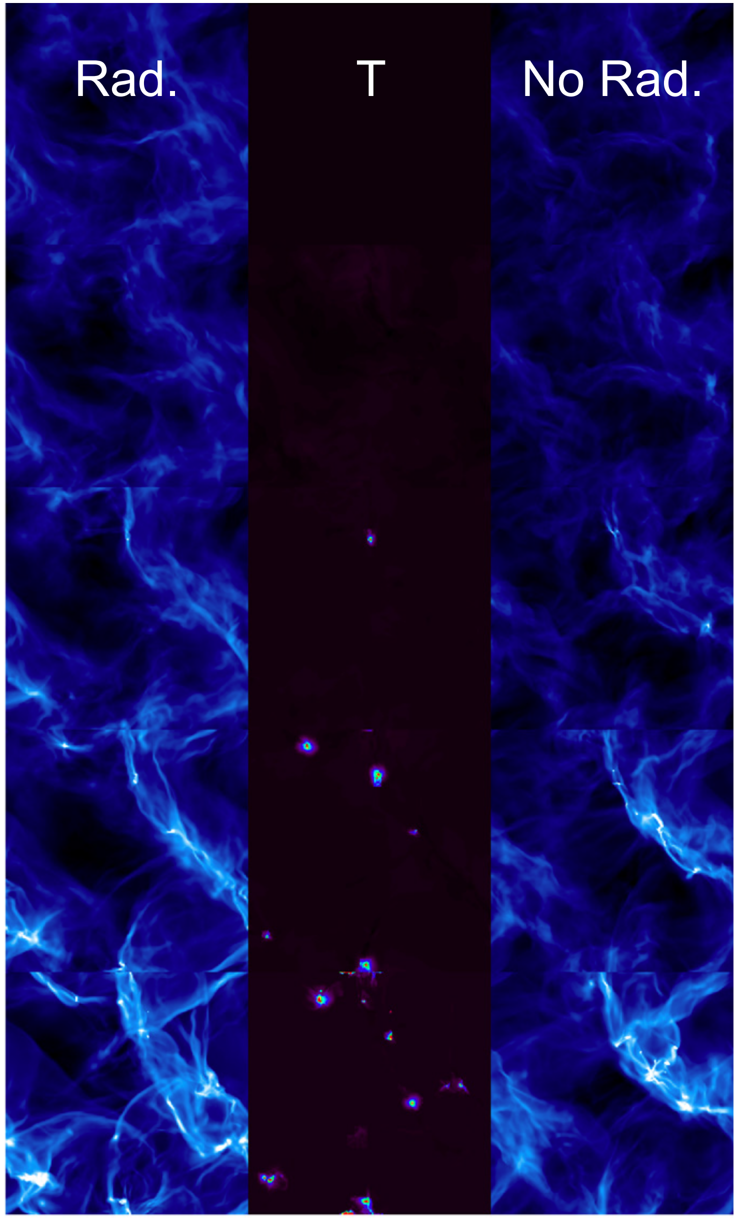
Star Formation – Radiation

Radiation: (Dale+05, Krumholz+07, Bate 09)

- Important on small scales and at high density
- High-mass stars → Ionization → Turbulence
  (J. Dale's talk)
- Outflows unlikely driven by ionization
  (Peters et al. 2012)



Time

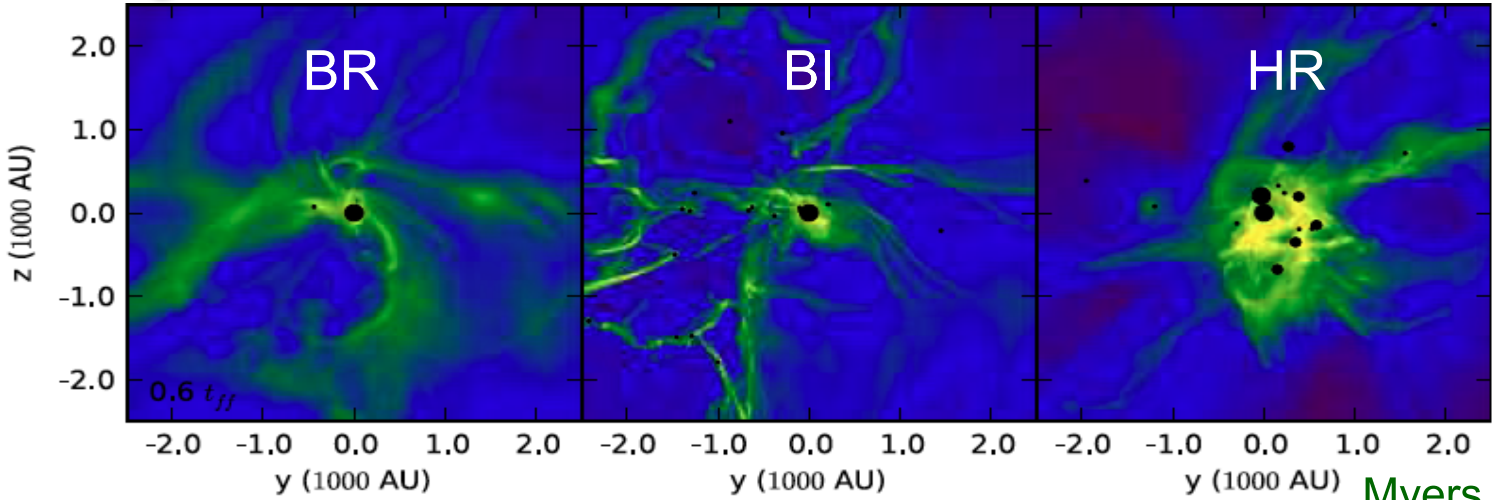


0.6 pc

(Offner et al. 2009)

Star Formation – Magnetic fields

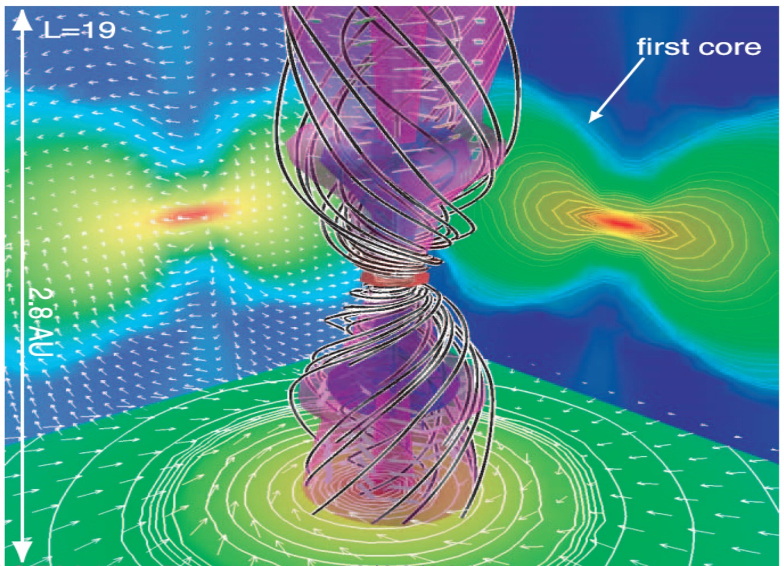
Reduce fragmentation (Hennebelle & Tyessier 2008, Bürzle+08, Federrath & Klessen 2012)

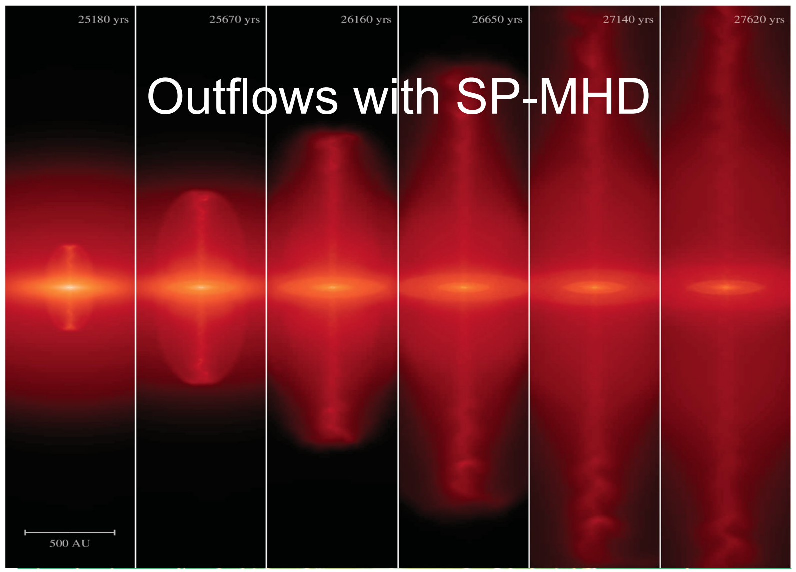


Myers et al. (2013)

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

Machida et al. (2008)





Price et al. (2012)

Star Formation – Jets / Outflows

Jets / outflows:

EFFECTS

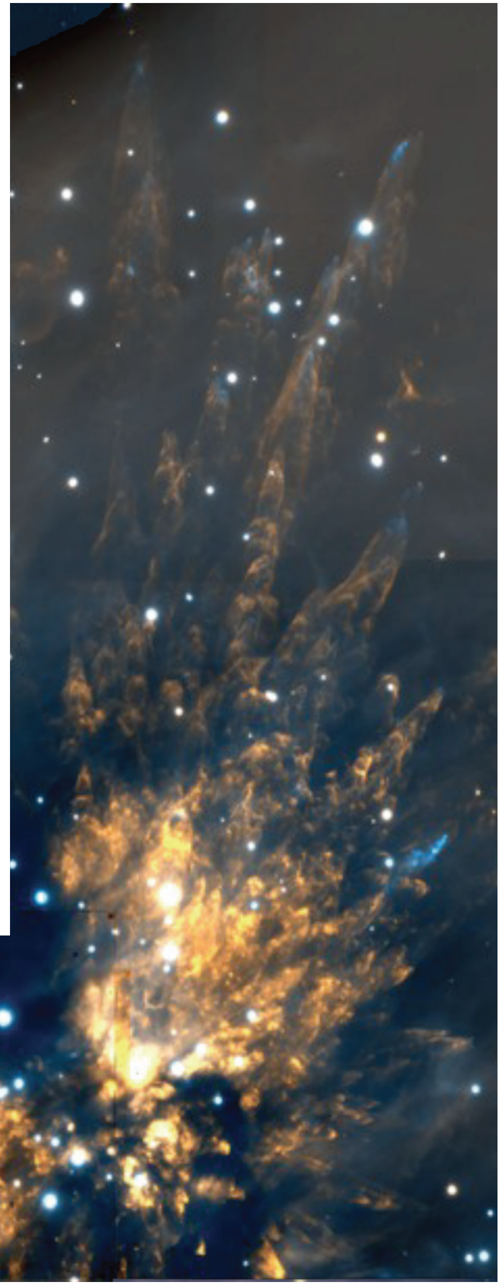
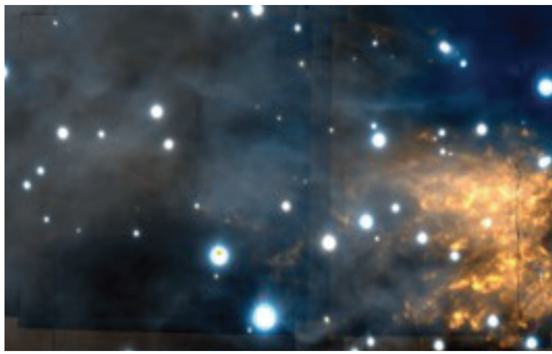
DIRECT

Reduce core mass

SFR, SFE, IMF

INDIRECT

Drive turbulence
→
1) Further reduce core mass
2) Trigger SF

Orion BN/KL

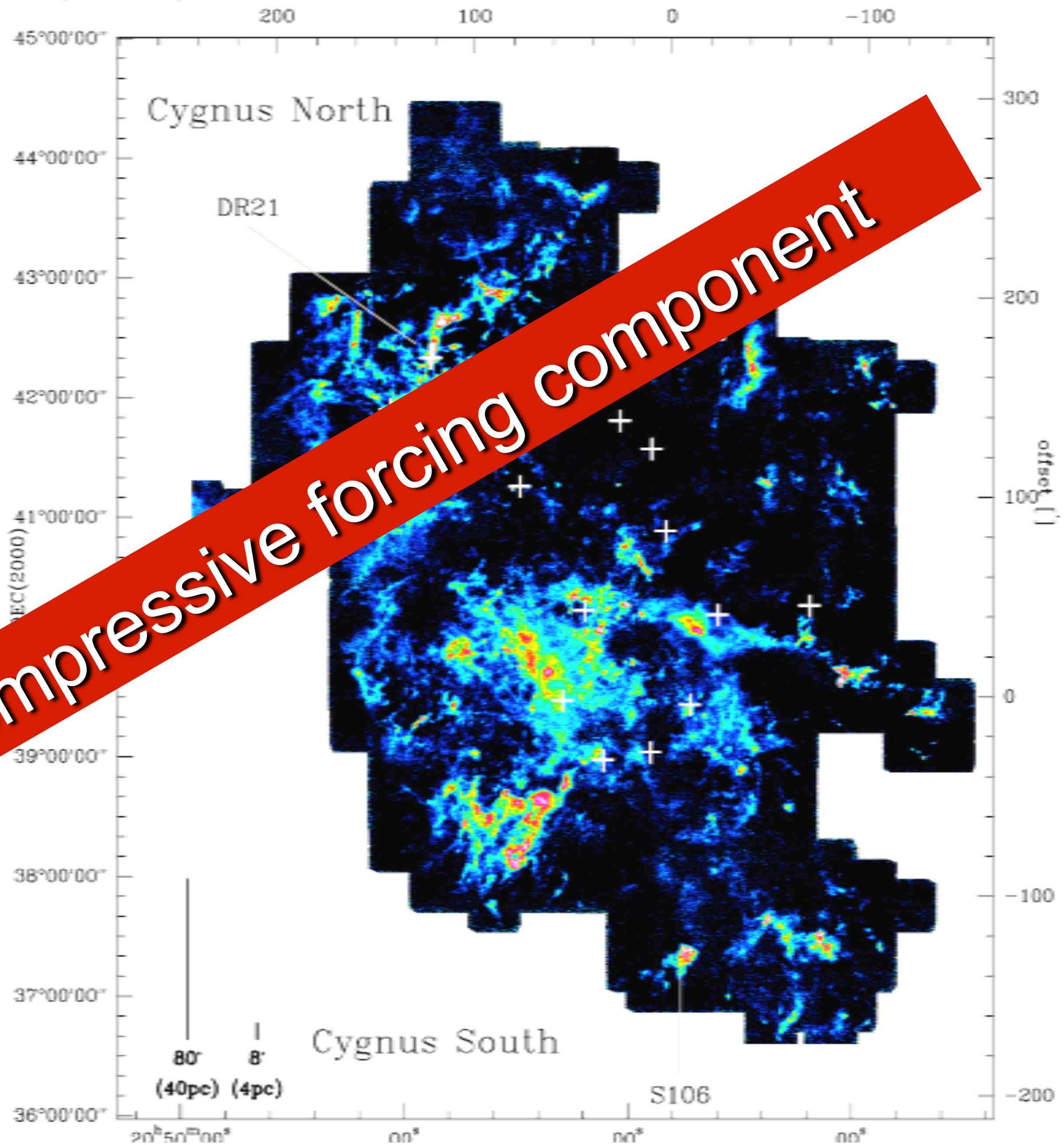
Bally et al.
(from A. Ginsburg thesis)

Cygnus X: **Schneider et al. (2011)**

Giant molecular cloud complex

Turbulence driven by

- **Supernova explosions?**
- **Ionization fronts?**
- **Protostellar jets/winds?**
- **MRI / shear?**
- **Gravitational infall?**
- **Galactic sprial shock?**



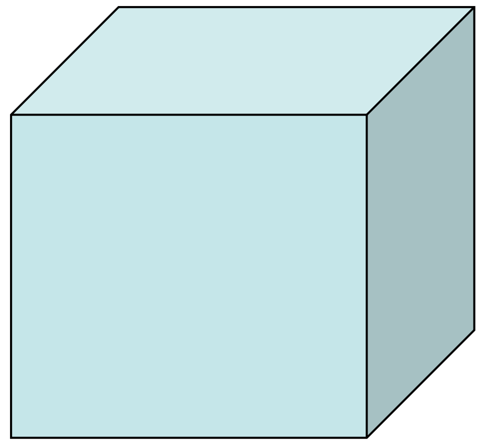
Significant compressive forcing component

of thermal HII regions, the well-known star-forming regions DR21 and S106 are labelled

Turbulence driving – solenoidal versus compressive

"Turbulence in a box"

- 3D, periodic boundary conditions
- Isothermal gas: $P = c_s^2 \rho$
- Driven to supersonic speeds (Mach 2 - 50)
- Large-scale **Forcing Term f**

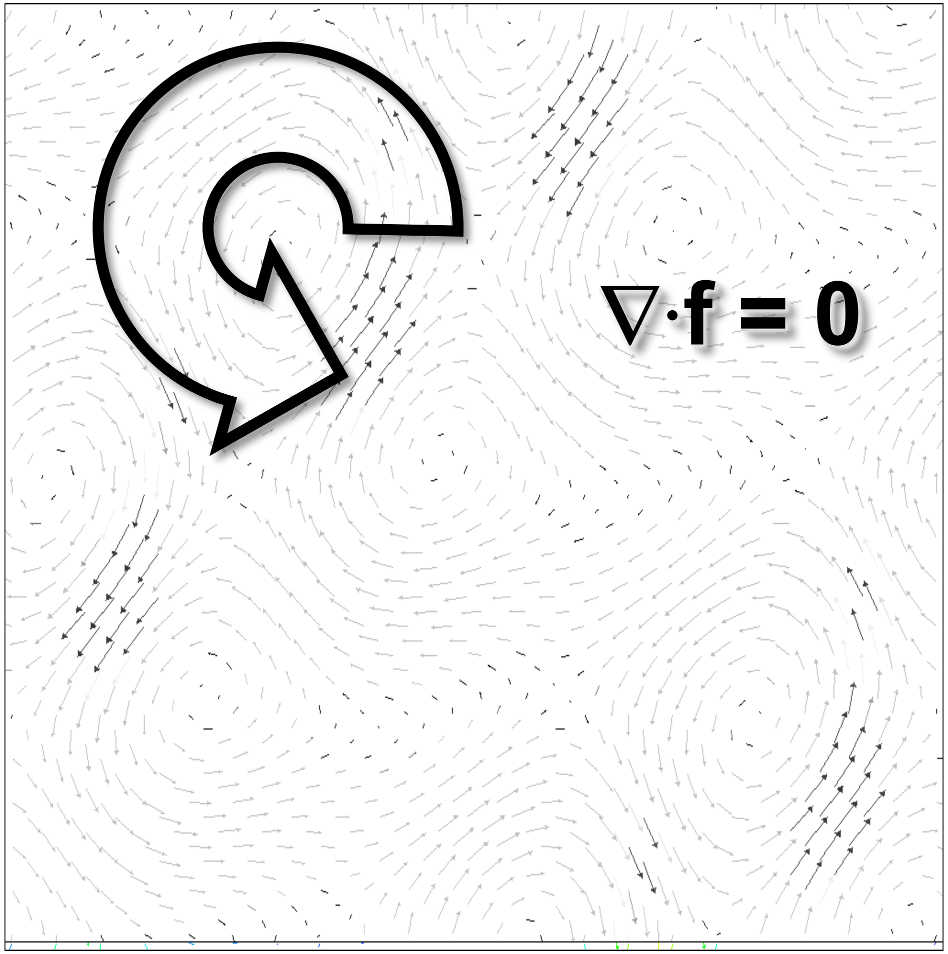


e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Dib+2008, Offner+2008, Kowal+2008, Schmidt+2009, Cho+2009,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

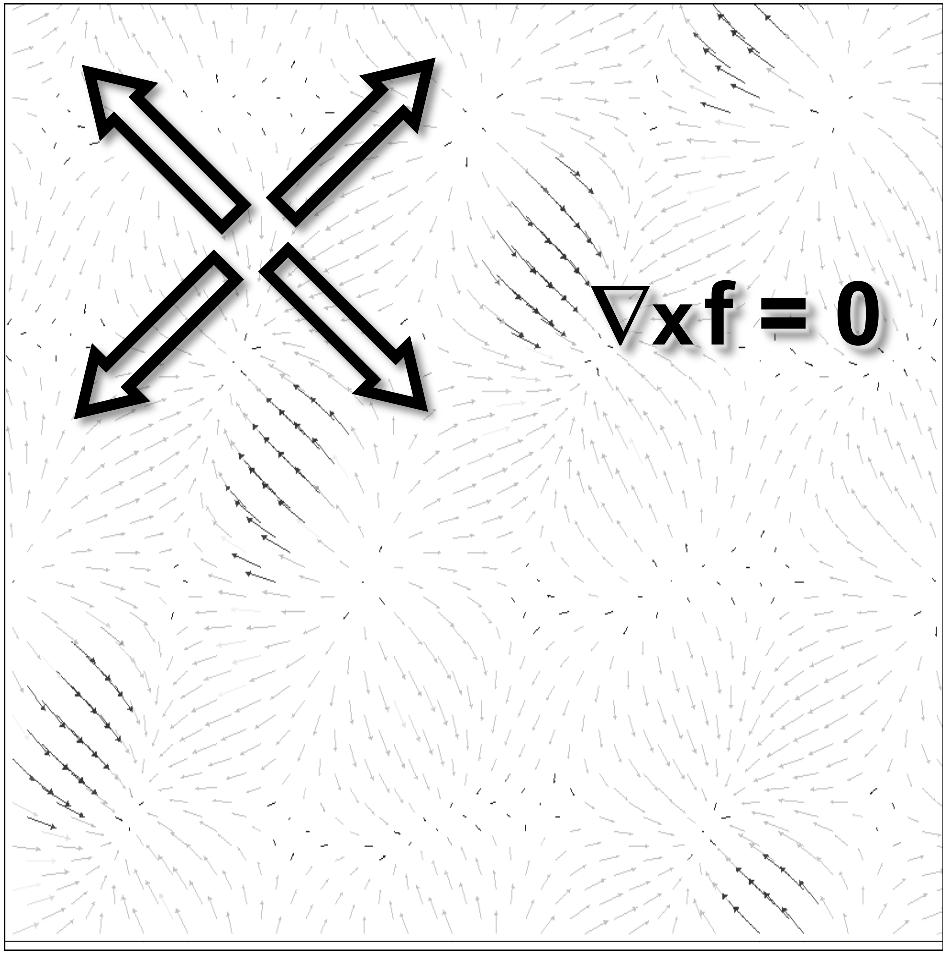
Turbulence driving – solenoidal versus compressive

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

Solenoidal forcing



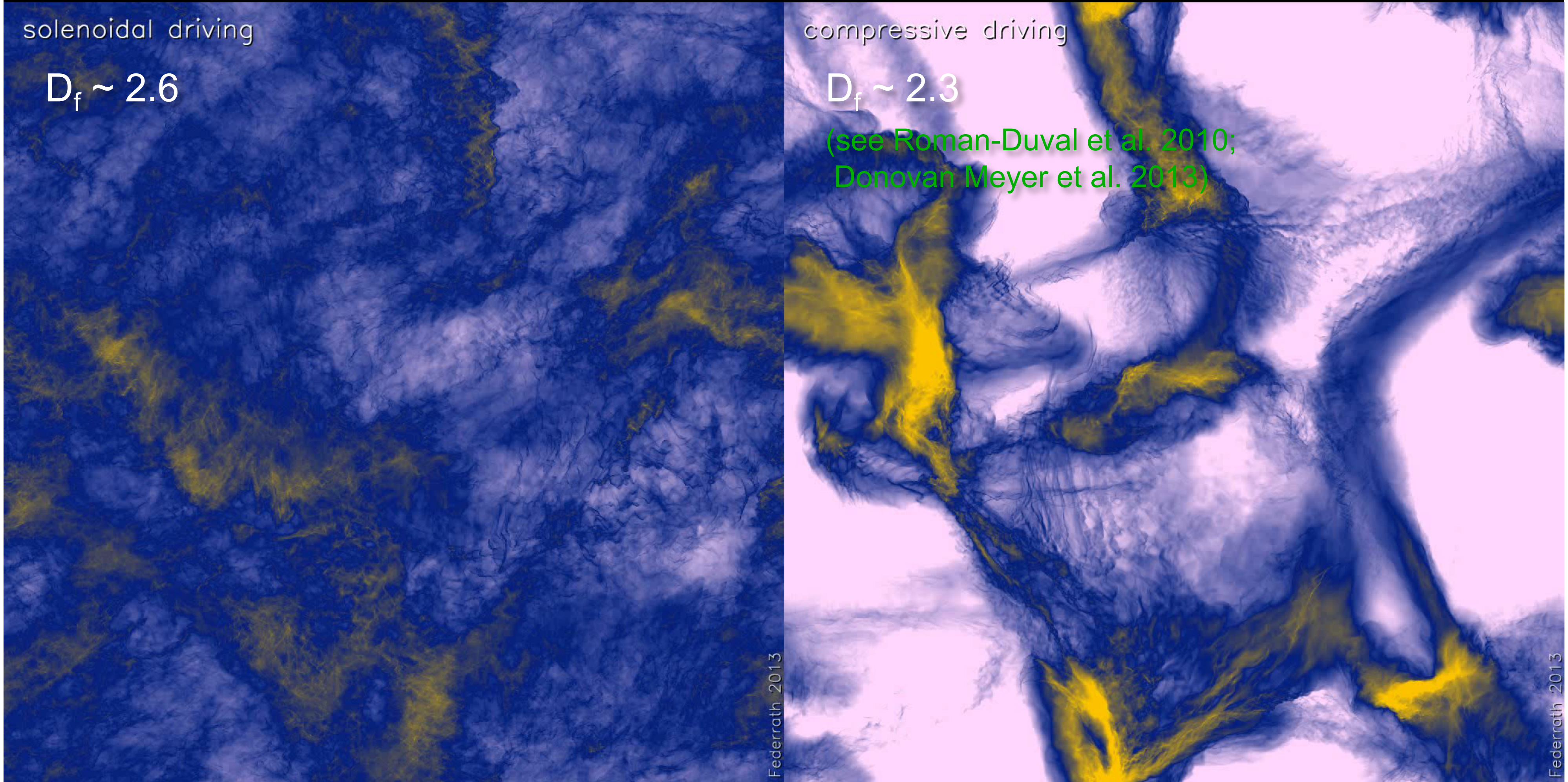
Compressive forcing



Turbulence driving – solenoidal versus compressive

Column Density

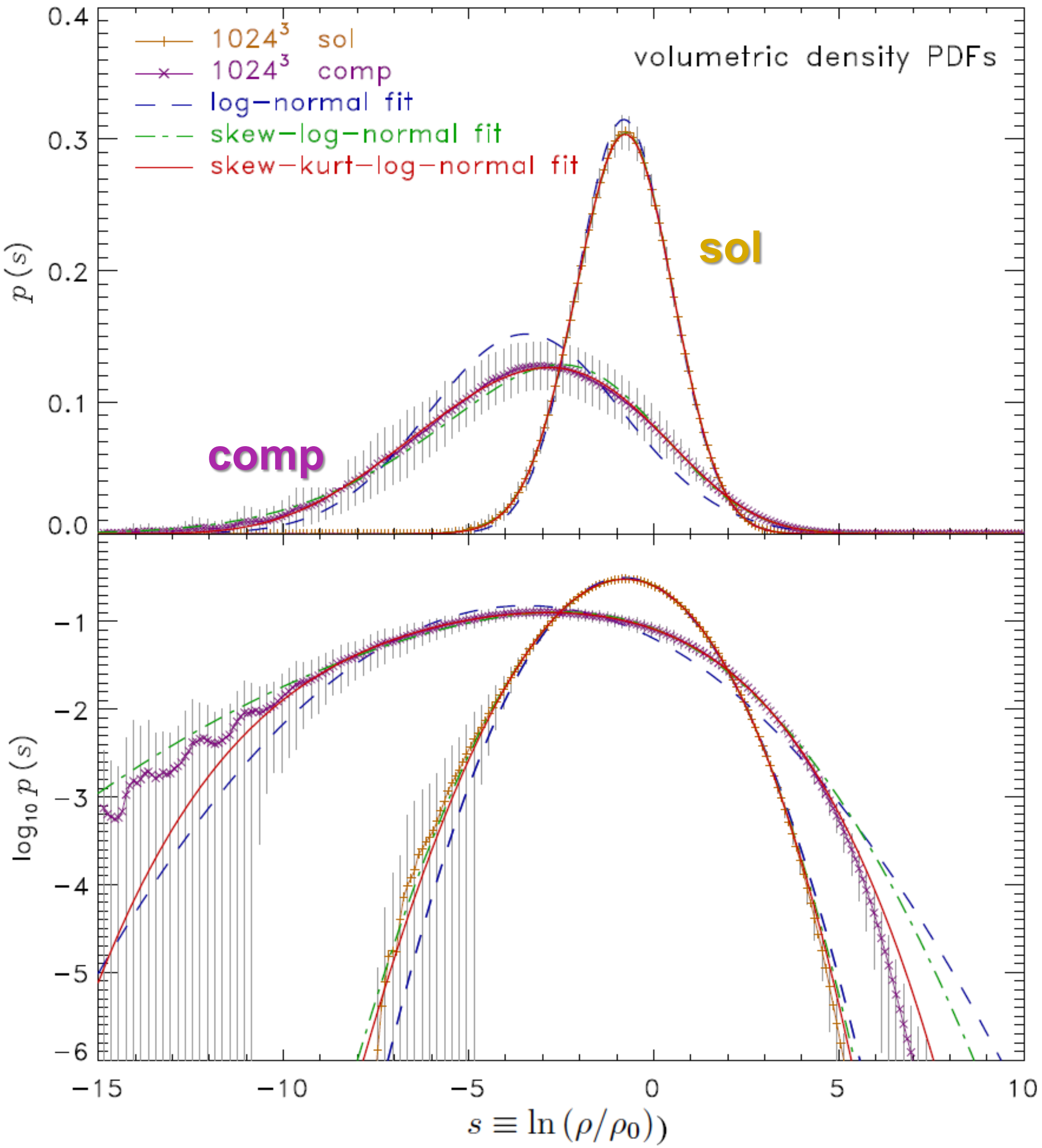
Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/supersonic/supersonic.shtml



Compressive forcing produces stronger density enhancements

(Federrath 2013, arXiv:1306.3989)

The density PDF



gas density PDF

PDFs are close to log-normals:

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

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

Vazquez-Semadeni (1994)
Padoan et al. 1997, Ostriker et al. (2001)

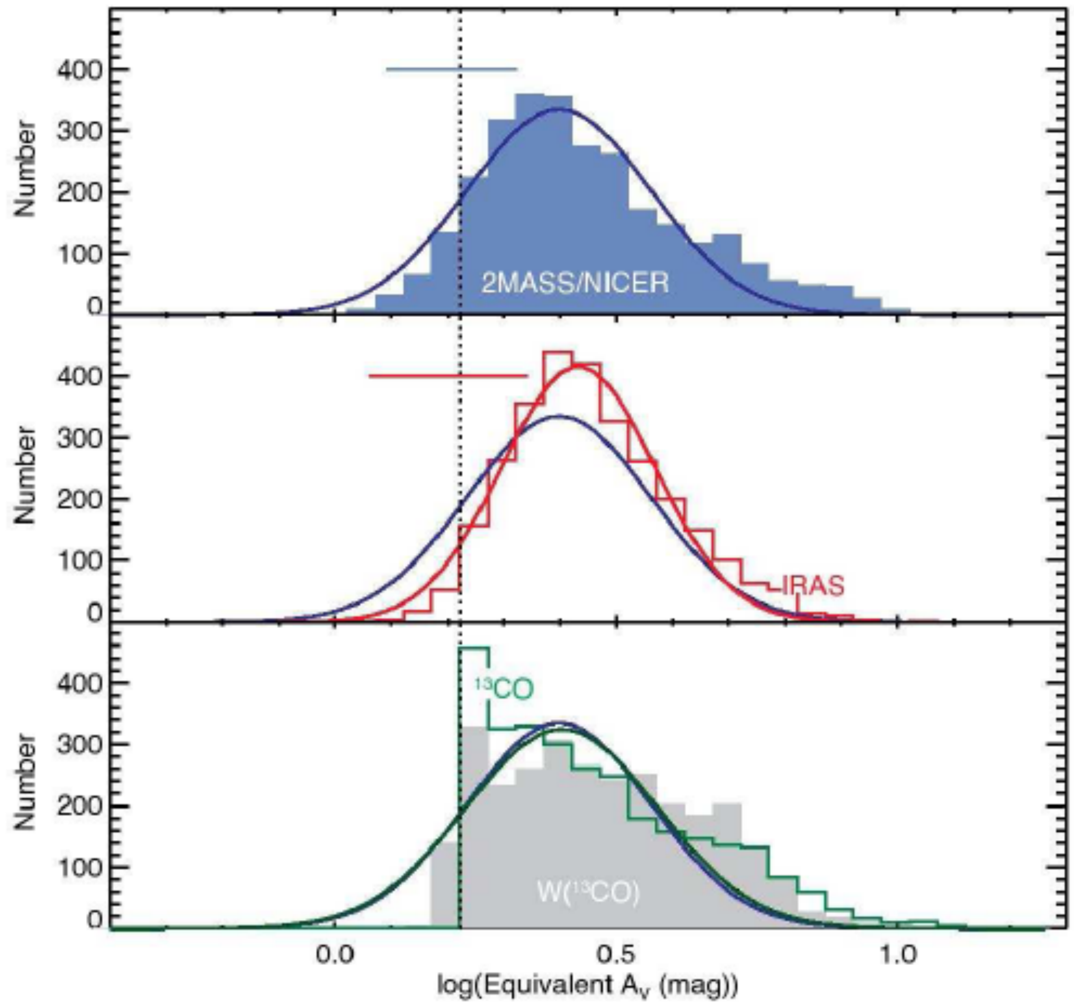
$$\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right)$$

b = 1/3 (sol)
b = 1 (comp)

Federrath+08,10; Price+11, Konstandin+12

The density PDF

Comparison with observations (Perseus MC): Goodman, Pineda, & Schnee (2009)



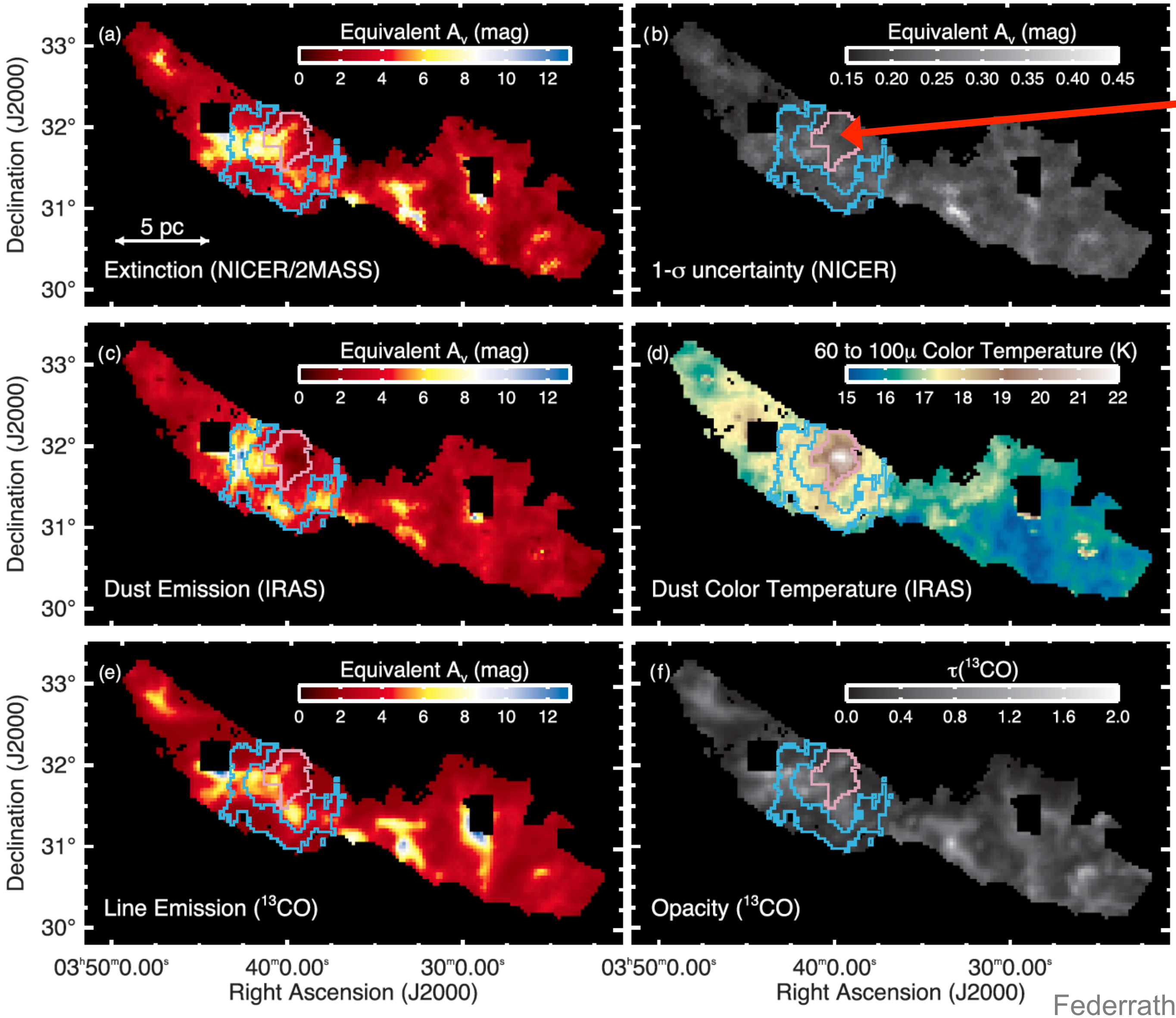
dust extinction

dust emission

^{13}CO line emission

→ **Column density PDFs are near log-normal distributions**

Comparison with observations: Goodman, Pineda, & Schnee (2009)



Expanding shell around massive B star

↓

Dominance of compressive modes expected

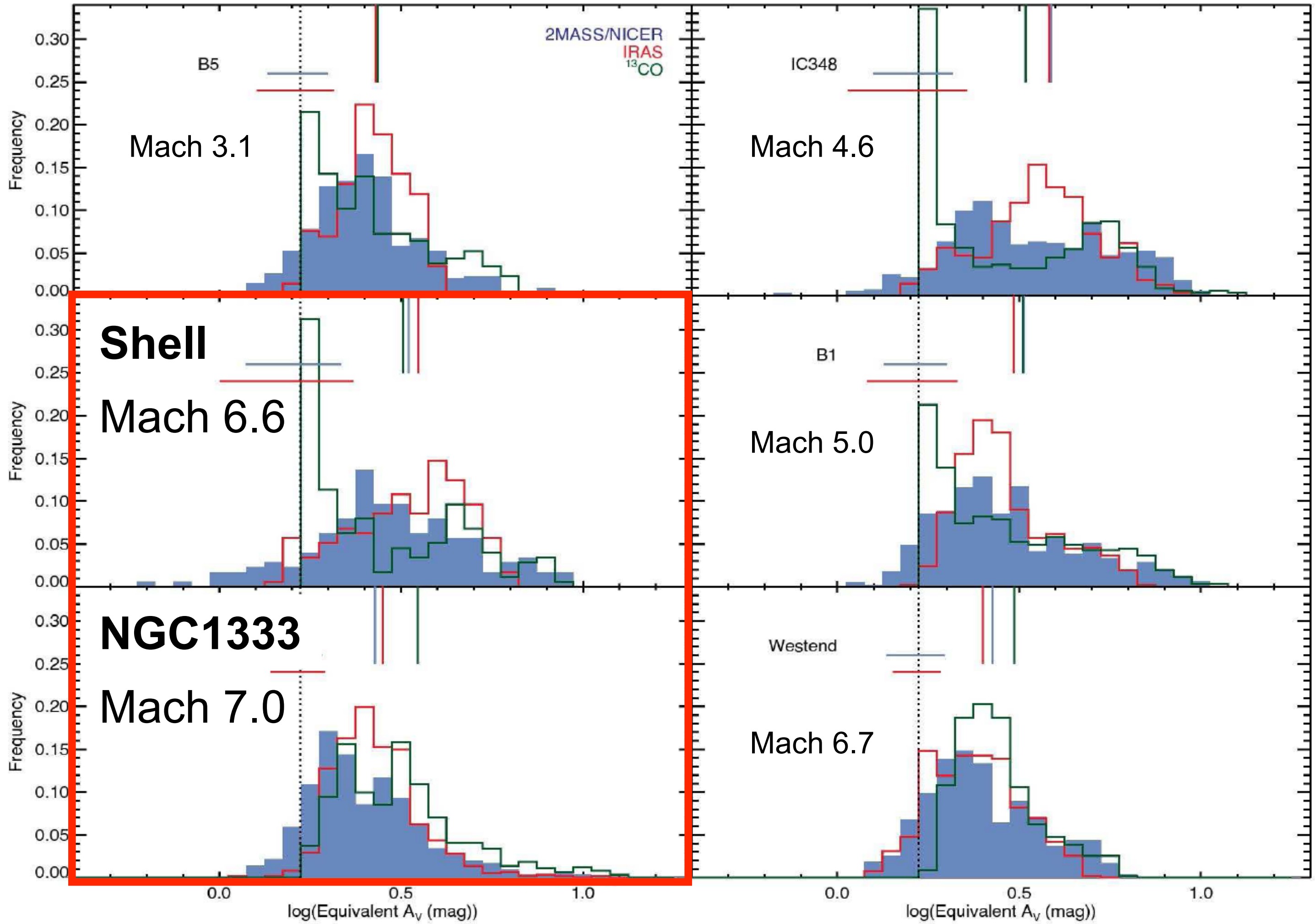
↓

Largest density dispersion in all of Perseus

Perseus MC

The density PDF

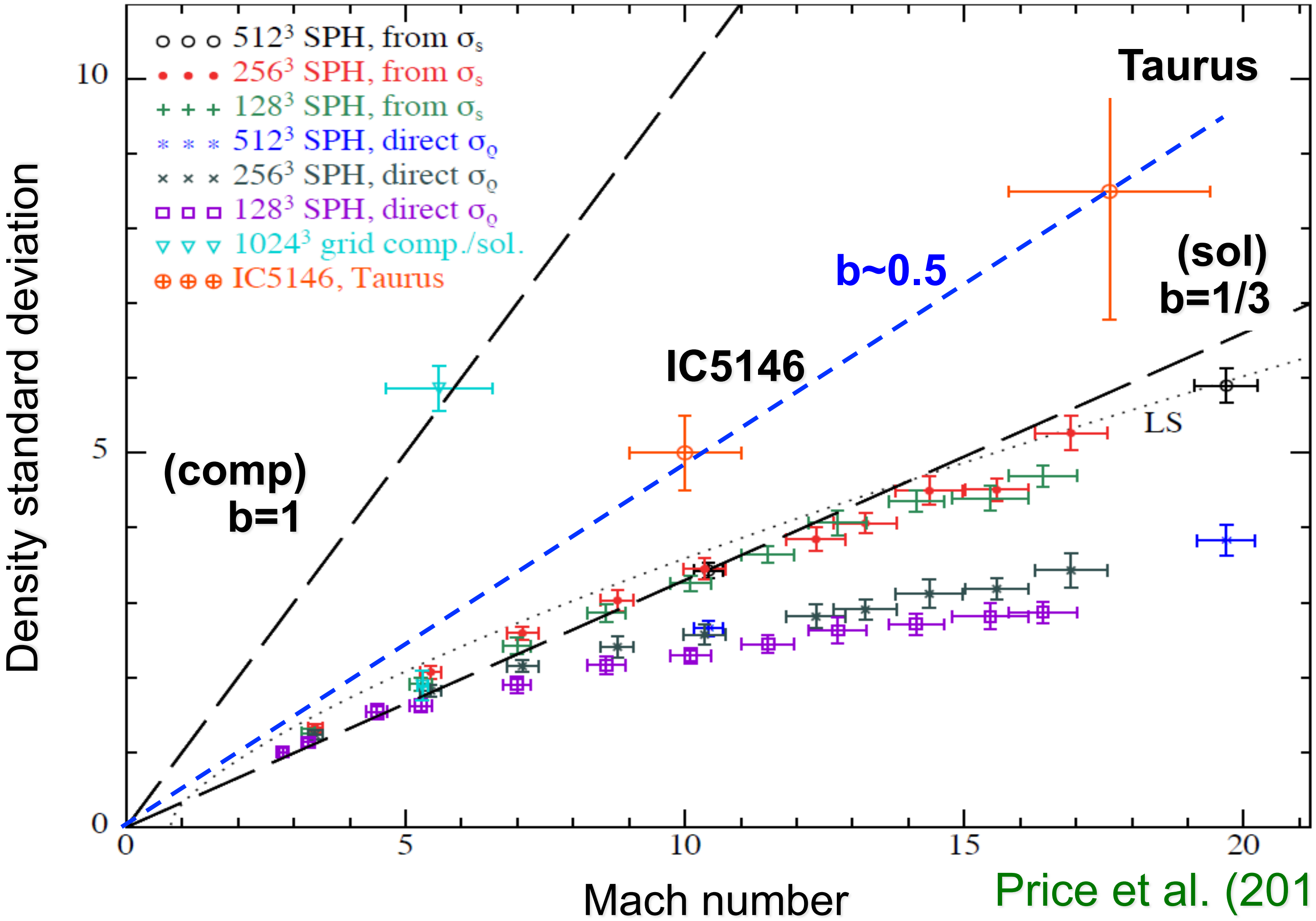
Comparison with observations: Goodman, Pineda, & Schnee 2009



Density variance depends on Mach number AND forcing:

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

The density PDF



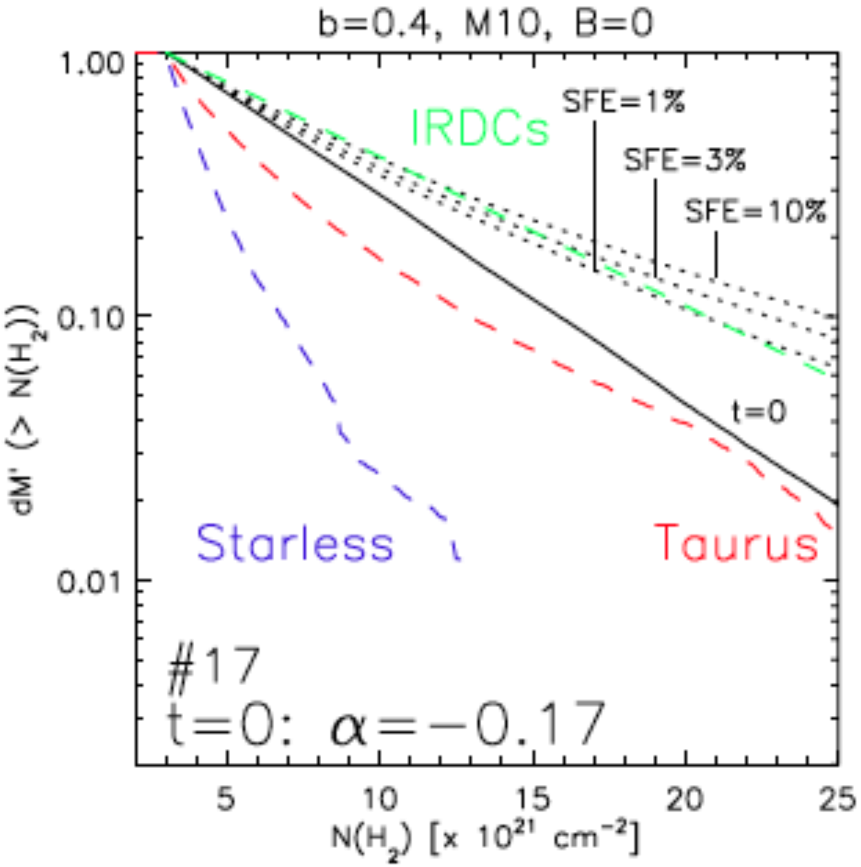
Price et al. (2011)
Brunt et al. (2010)
Burkhart & Lazarian (2012)

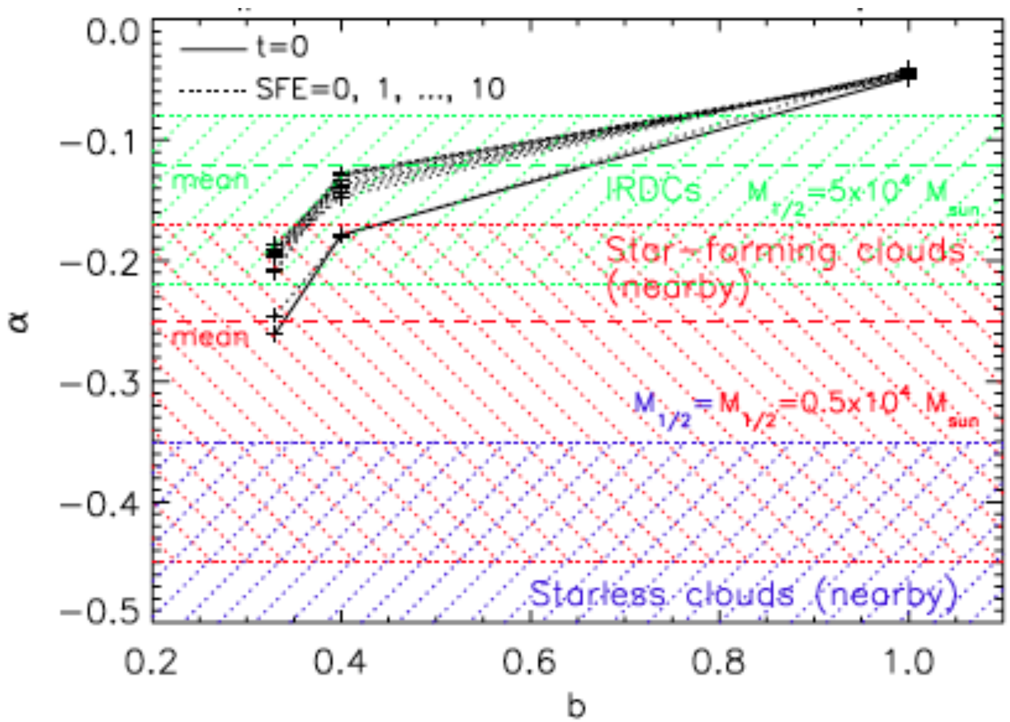
$$\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right) \xrightarrow{p(s)} \sigma_{\rho/\rho_0} = b\,\mathcal{M}$$

Compressive forcing and/or gravity required to explain observations

The dense gas mass fraction

Kainulainen et al. (2013)



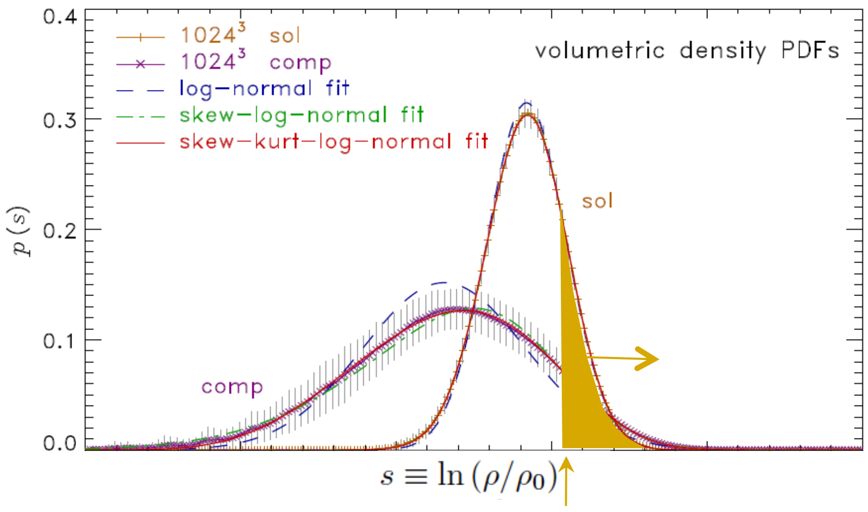


Sequence: Starless → Star-forming (nearby) → IRDCs

Density PDF → The Star Formation Rate

Density PDF → Star Formation Rate

Density PDF is key for star formation theories



- **Initial Mass Function** (Padoan & Nordlund 02, Hennebelle & Chabrier 08,09, Elmegreen 11, Veltchev+12, Hopkins 12)
- **Star Formation Efficiency** (Elmegreen 08)
- **Kennicutt-Schmidt relation** (Elmegreen 02, Krumholz & McKee 05, Tassis 07)
- **Star Formation Rate** (Krumholz & McKee 05, Padoan & Nordlund 11, Renaud et al. 12)

All based on integrals over the turbulent density PDF

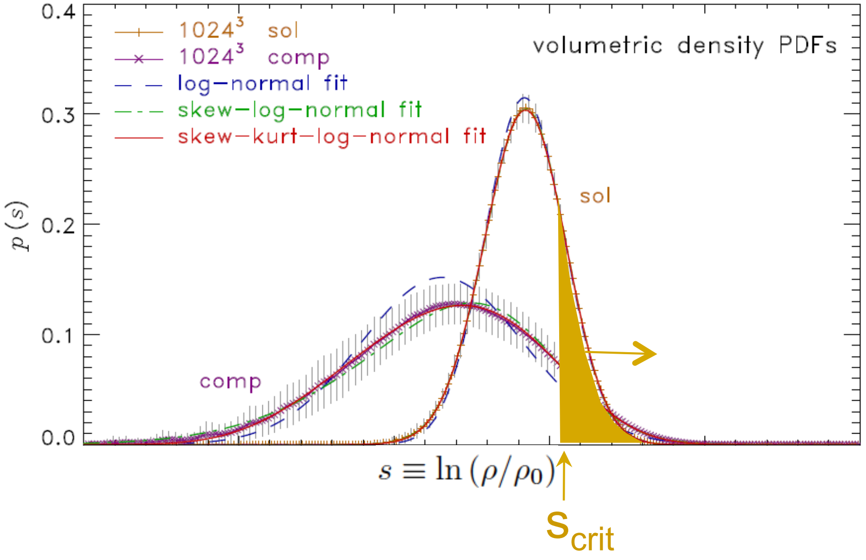
$$\mathrm{SFR}_{\mathrm{ff}} = \frac{\epsilon_{\mathrm{core}}}{\phi_t} \int_{x_{\mathrm{crit}}}^{\infty} x p(x)\, dx$$

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

Density PDF → Star Formation Rate

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time



freefall time **mass fraction**

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

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

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

Statistical Theory for the Star Formation Rate:

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

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

SFR ~ Mass/time

freefall time **mass fraction**

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

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

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

(see Eve’s / Paolo’s talk)

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

(KM05, PN11)

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

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

(PN97, PV98, F08,10; Price+11)

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

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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

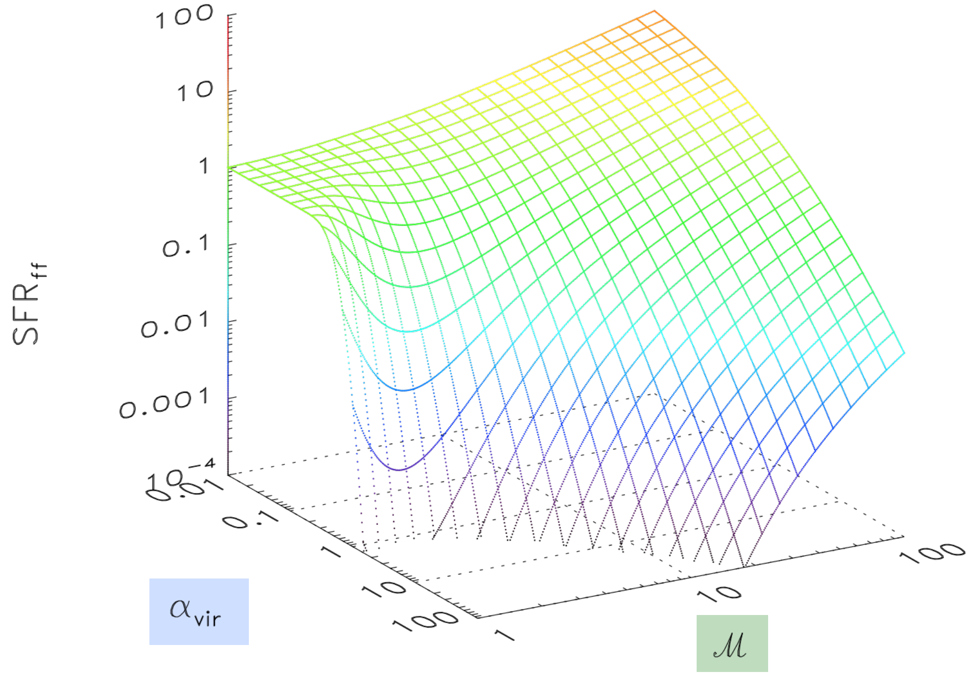
$2\,E_{kin}/E_{grav}$ **forcing** **Mach number**

---

multi-freefall model (HC11)

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

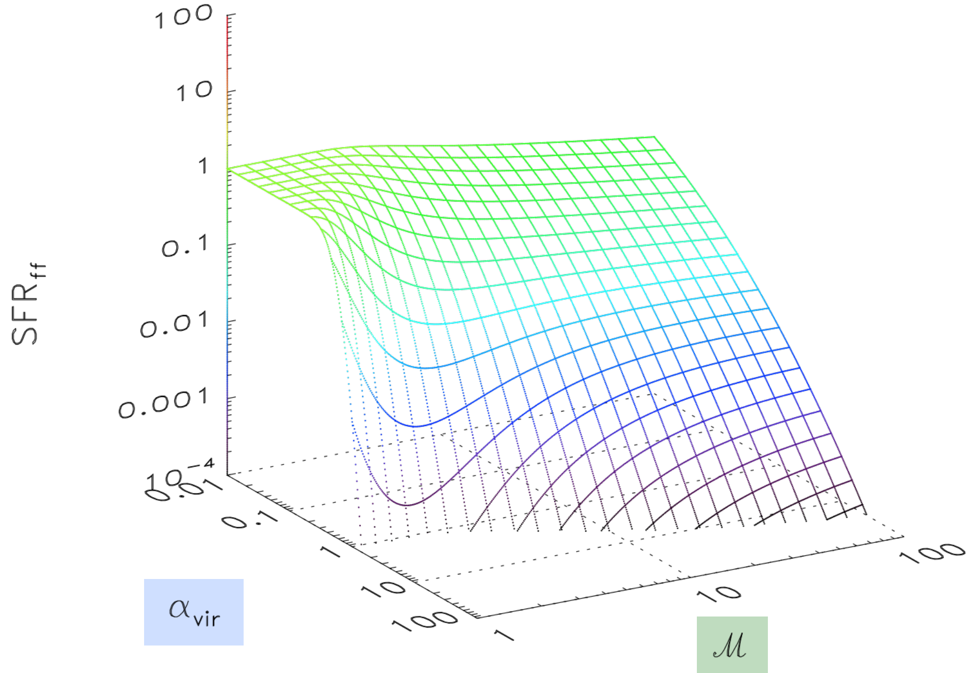
(b=0.33)



single-freefall model (KM05)

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

(b=0.33)



Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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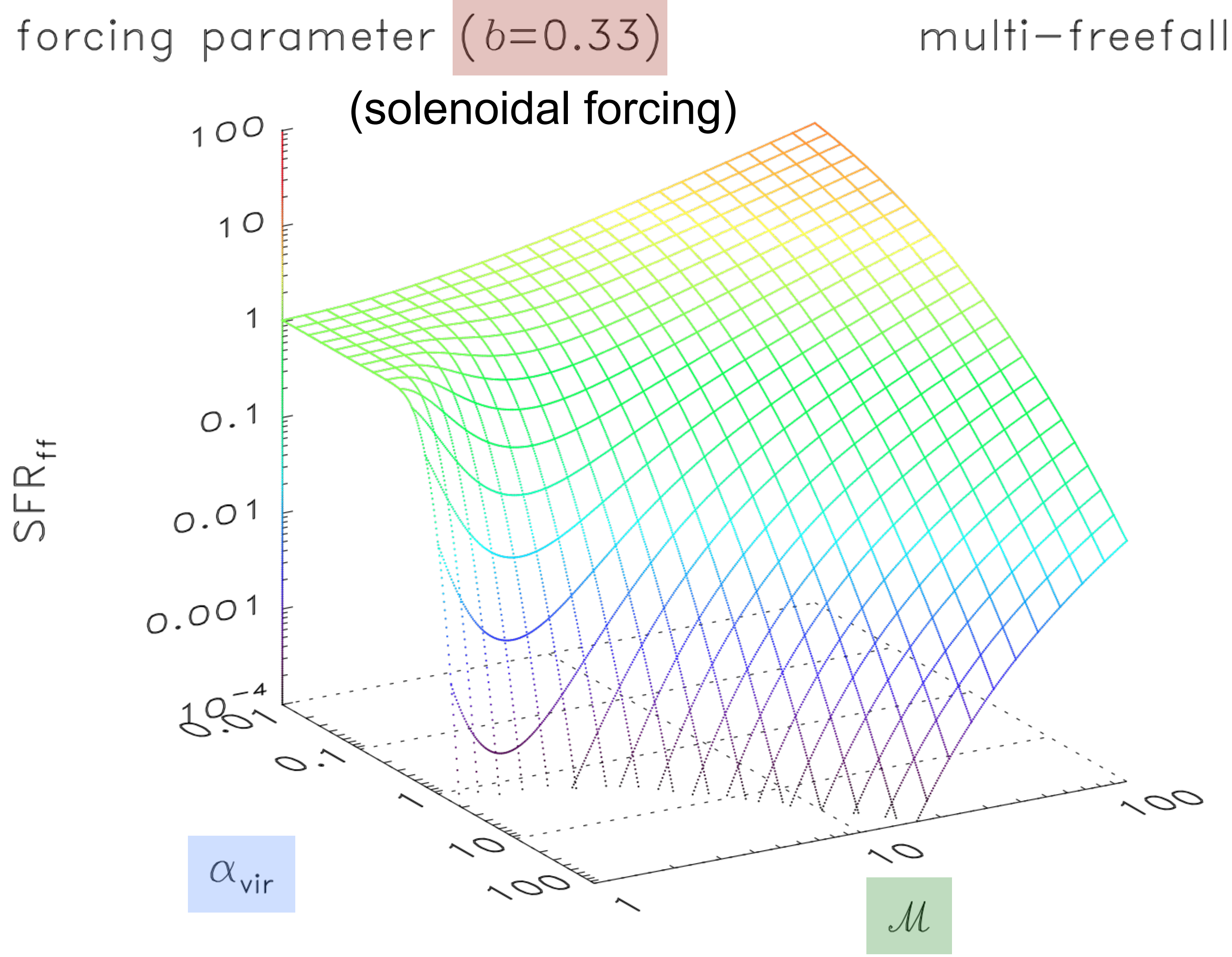

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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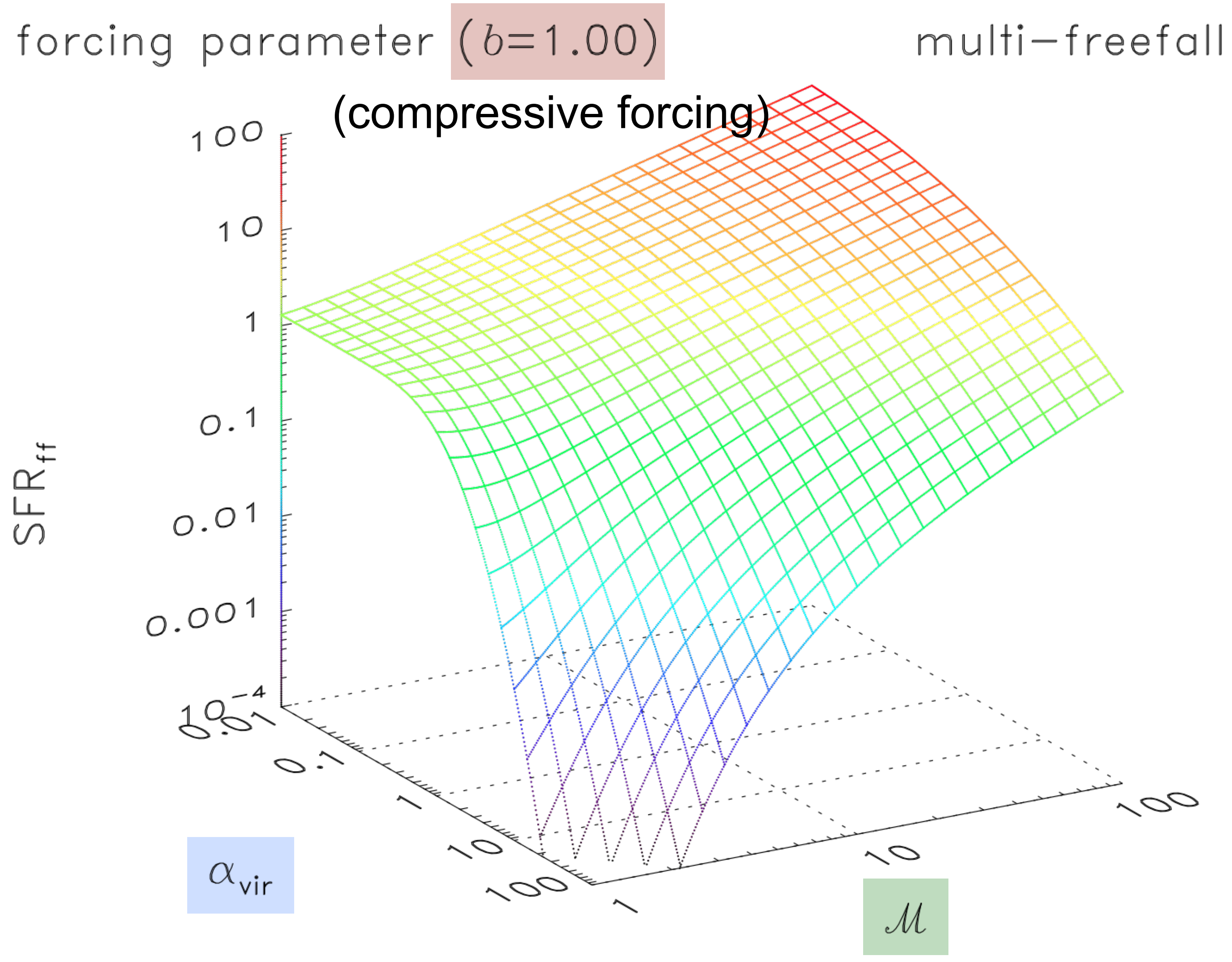


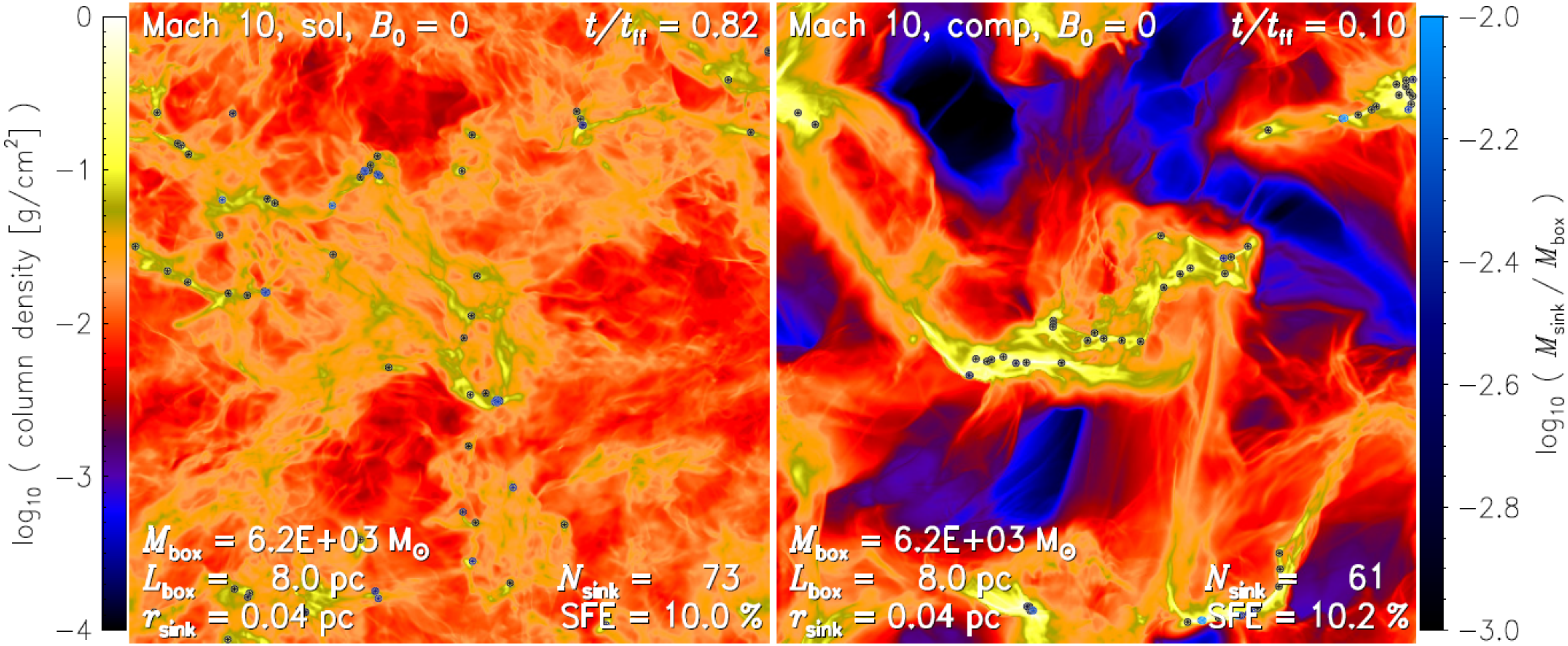
Federrath & Klessen (2012)

Density PDF → Star Formation Rate

Numerical Test at Mach 10

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

Solenoidal Forcing | Compressive Forcing



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

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

Theory and Simulation 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

freefall time **mass fraction**

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

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

MAGNETIC FIELD:

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

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

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

(PN11; Molina+2012)

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

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

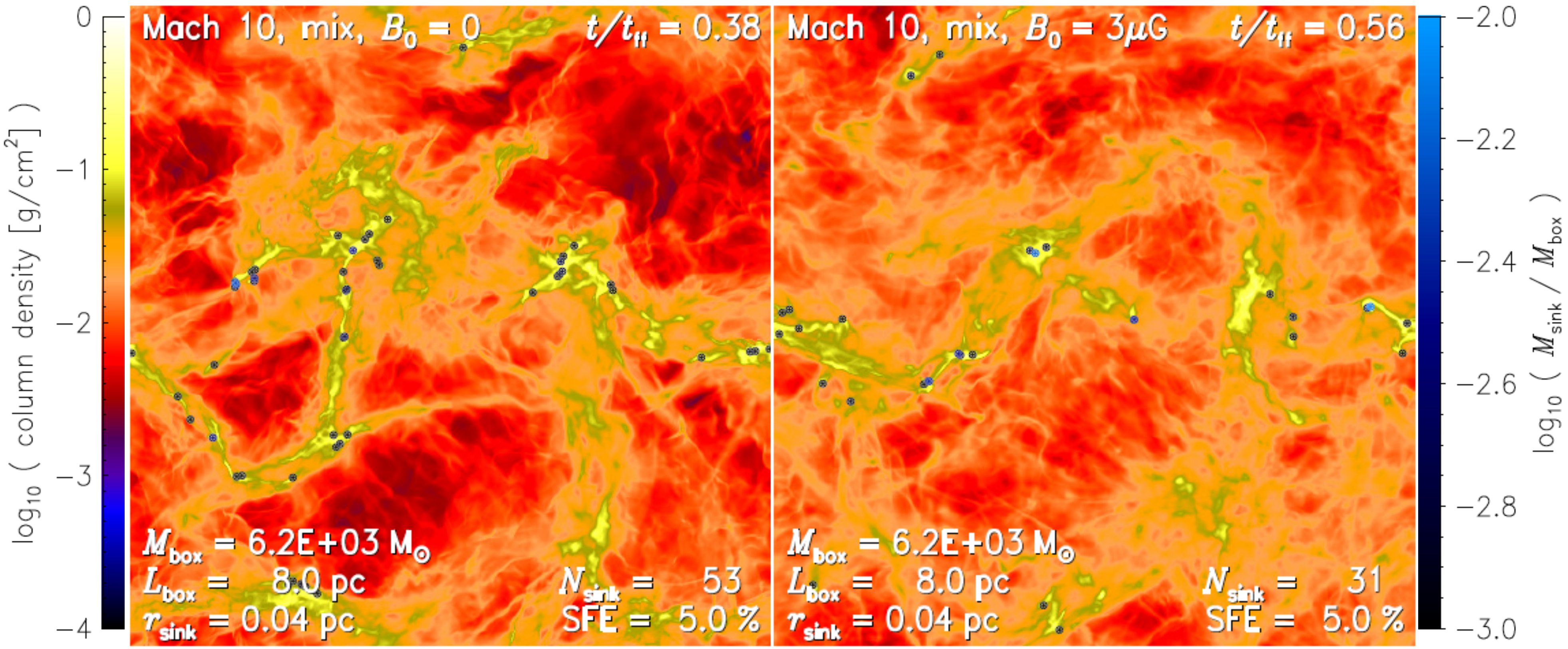
Federrath & Klessen (2012)

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)



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)

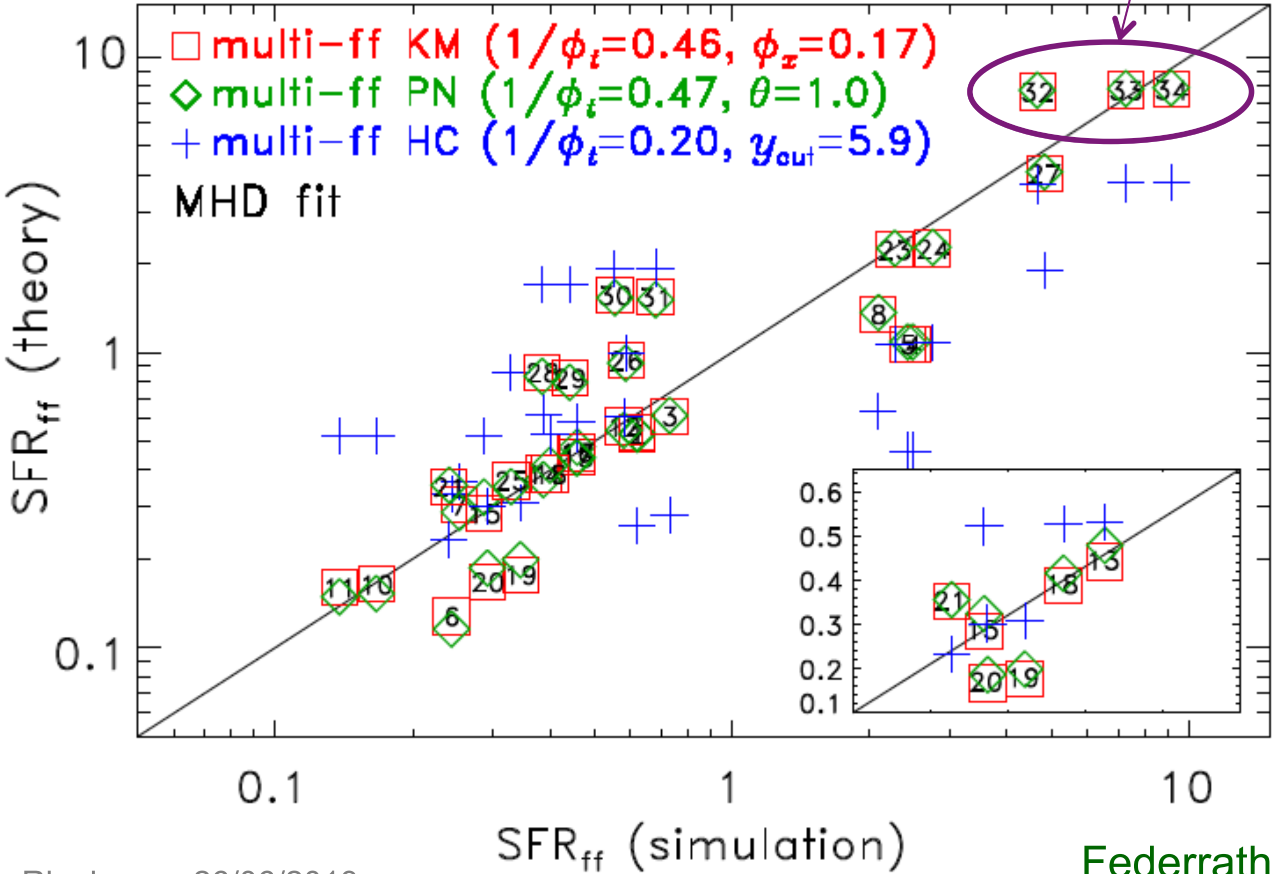
The Star Formation Rate of MHD turbulence

Compare simulations 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)

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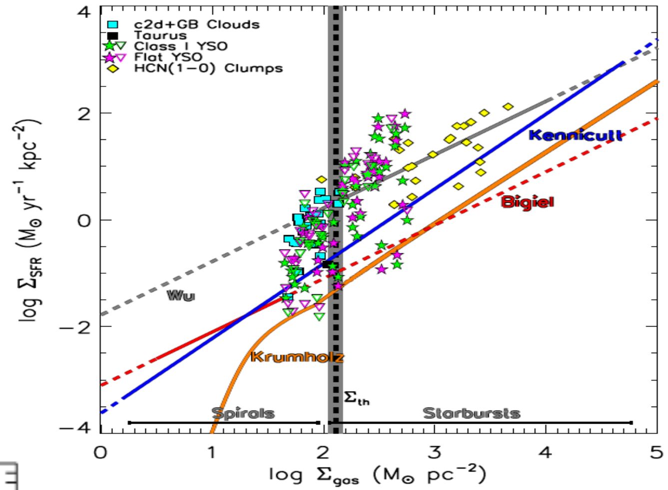
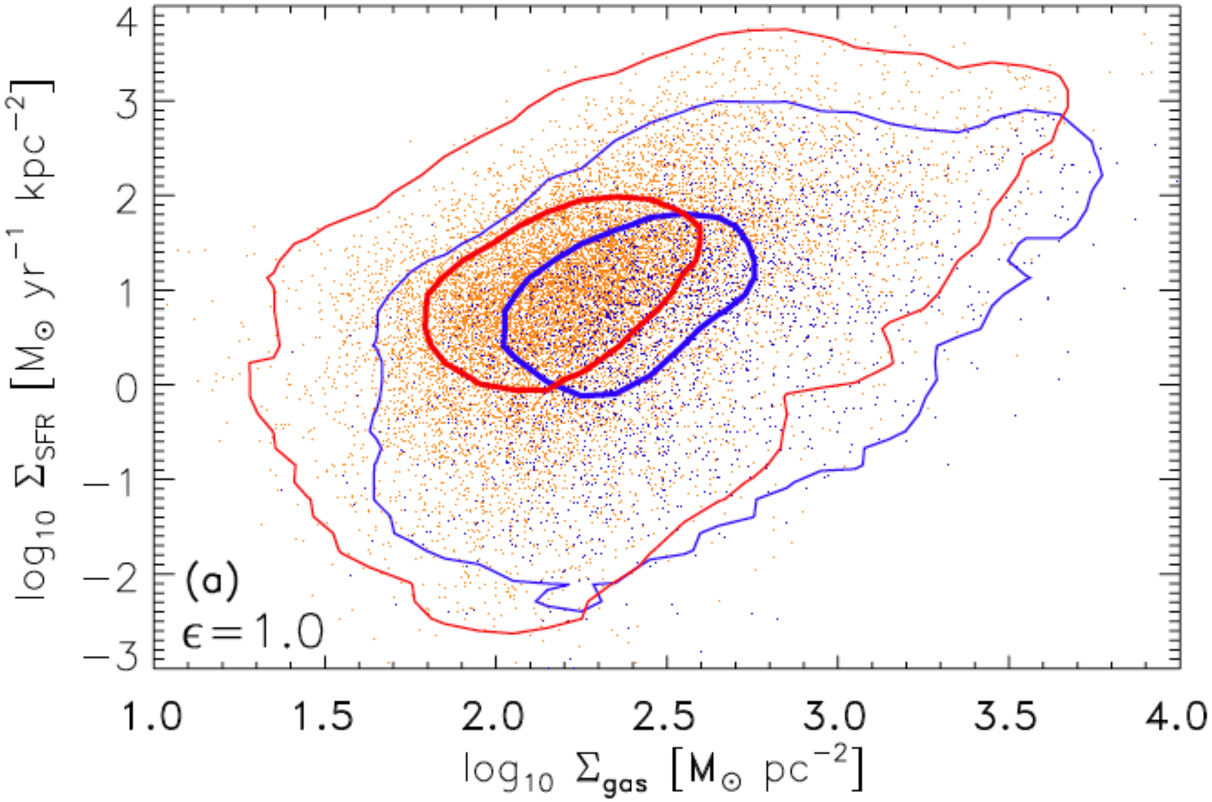


(Heiderman et al. 2010)

Simulations *vs.* Observations



SFEs ~ 1-10% (Evans+09, Burkert & Hartmann 2013 Federrath & Klessen 2013)

Federrath & Klessen (2012)

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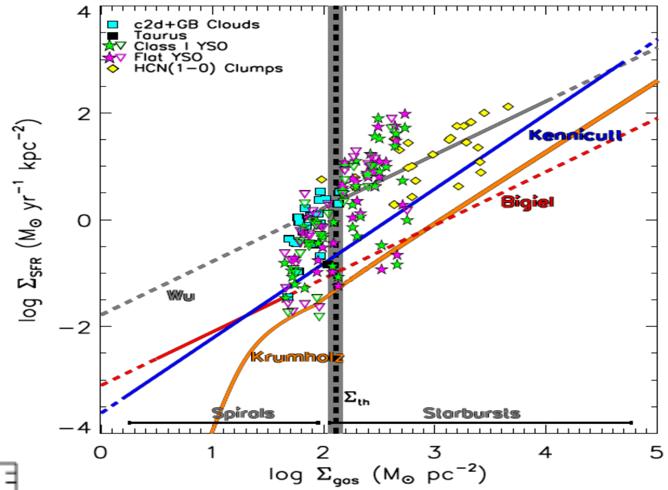

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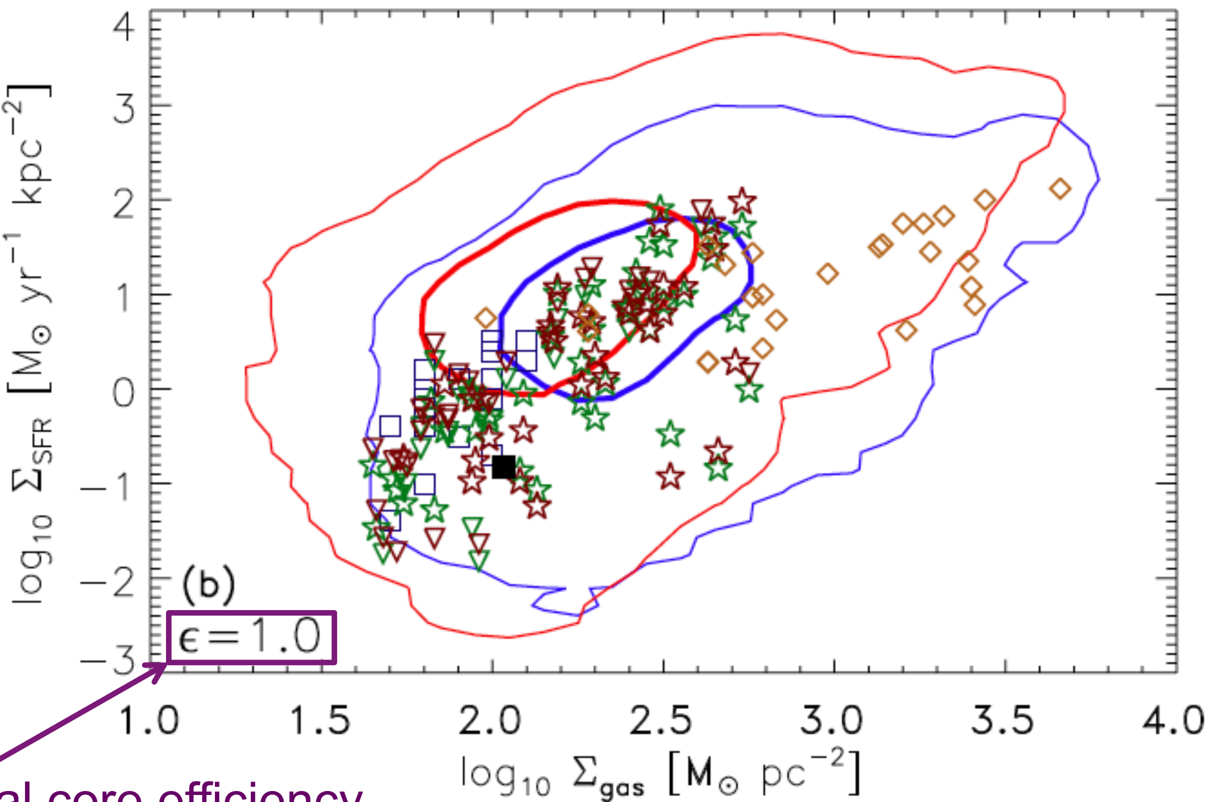
Simulations *vs.* Observations



Local core efficiency

SFEs ~ 1-10% (Evans+09, Burkert & Hartmann 2013 Federrath & Klessen 2013)

Federrath & Klessen (2012)

The Star Formation Rate of MHD turbulence

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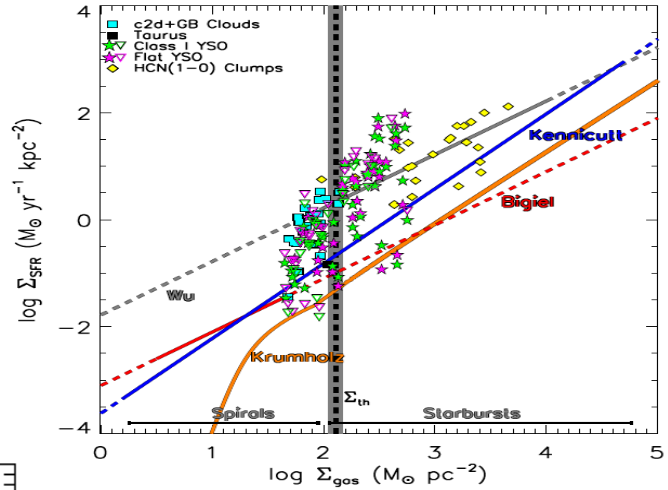
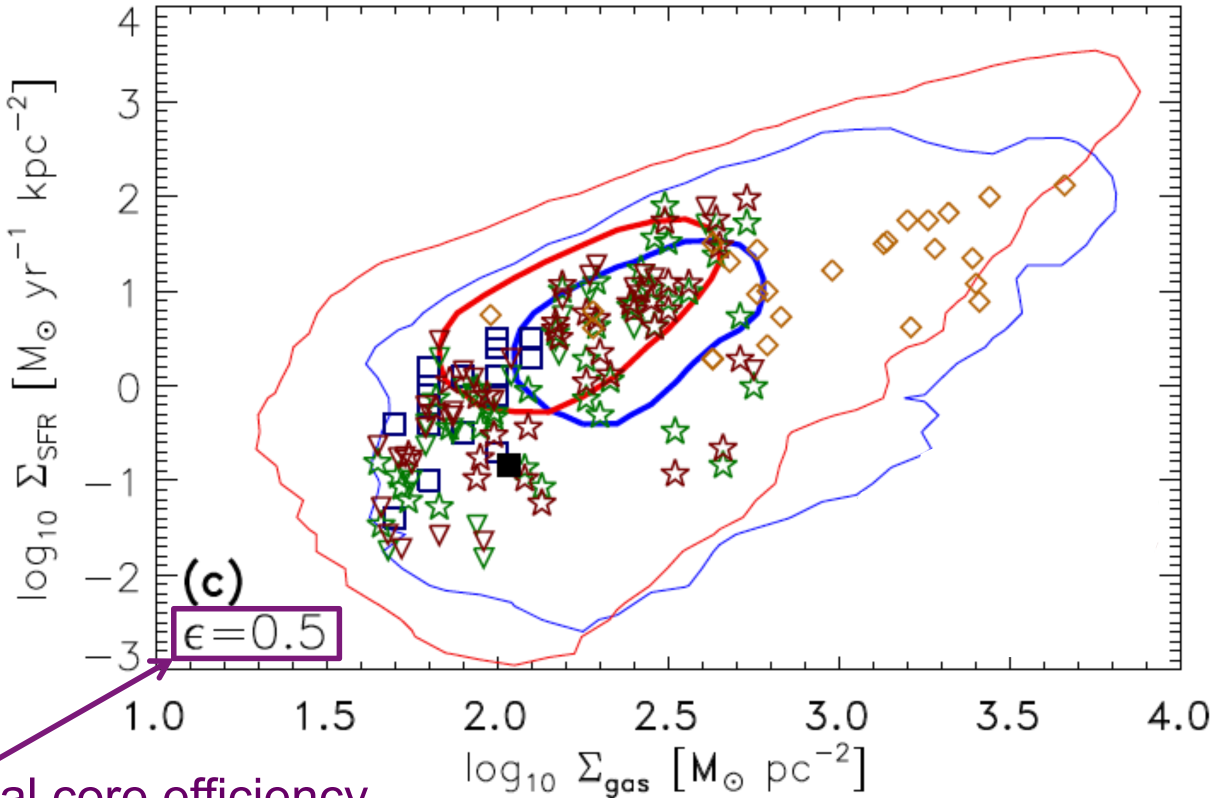


(Heiderman et al. 2010)

Simulations *vs.* Observations



Local core efficiency

SFEs ~ 1-10% (Evans+09, Burkert & Hartmann 2013 Federrath & Klessen 2013)

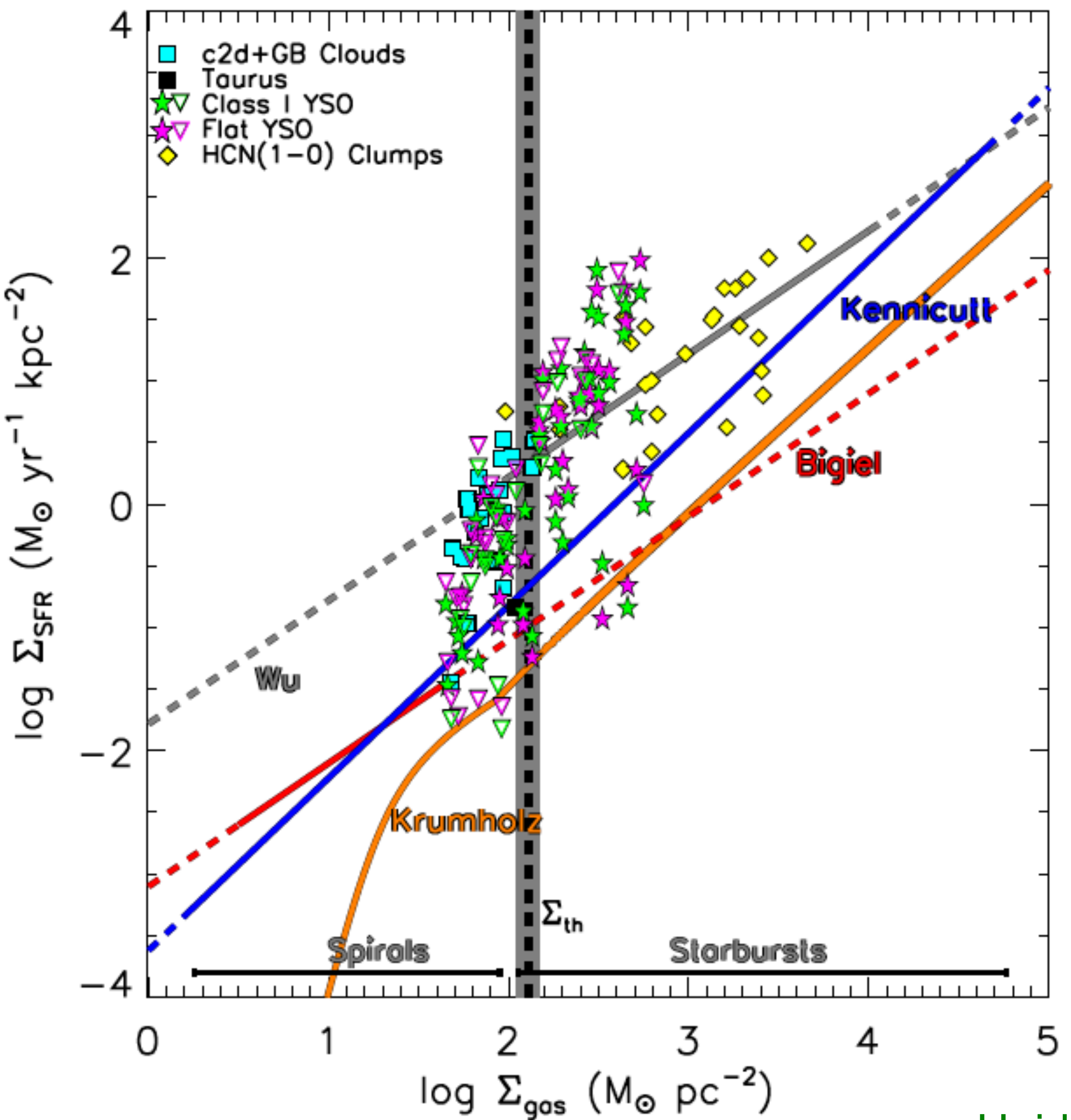
GRAVTURB SFE=10%
GRAVTURB SFE= 1%

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

Federrath & Klessen (2012)

Application to Extra-Galactic Star Formation

Extra-Galactic Star Formation

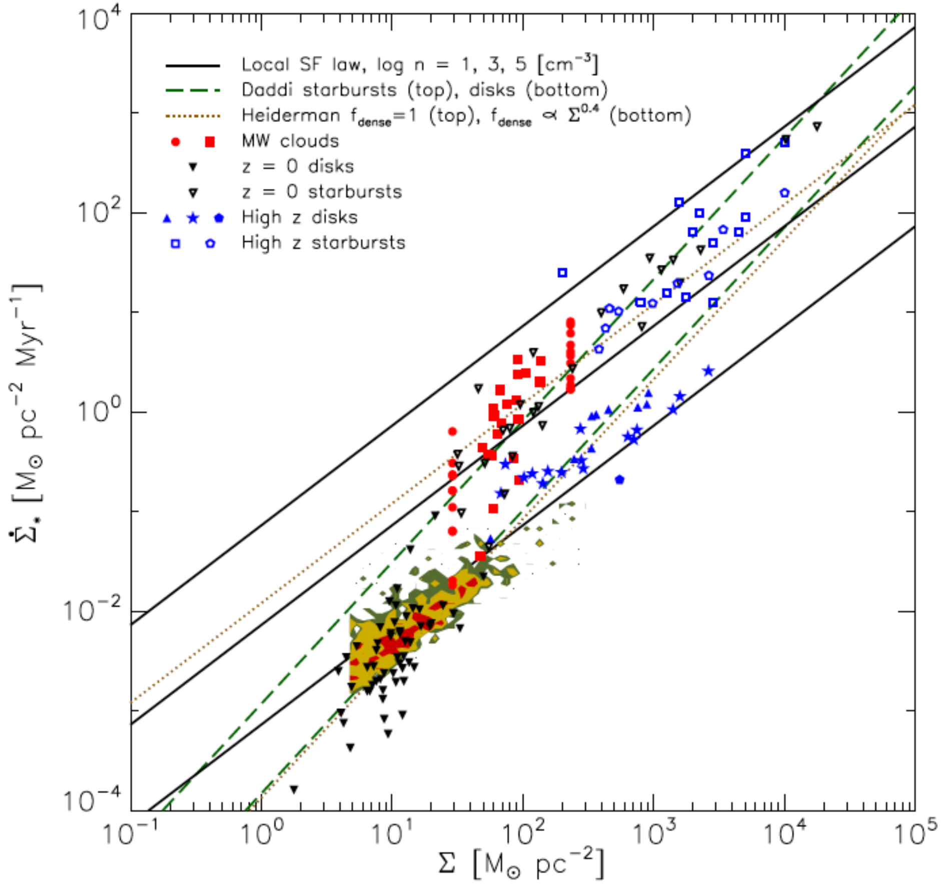


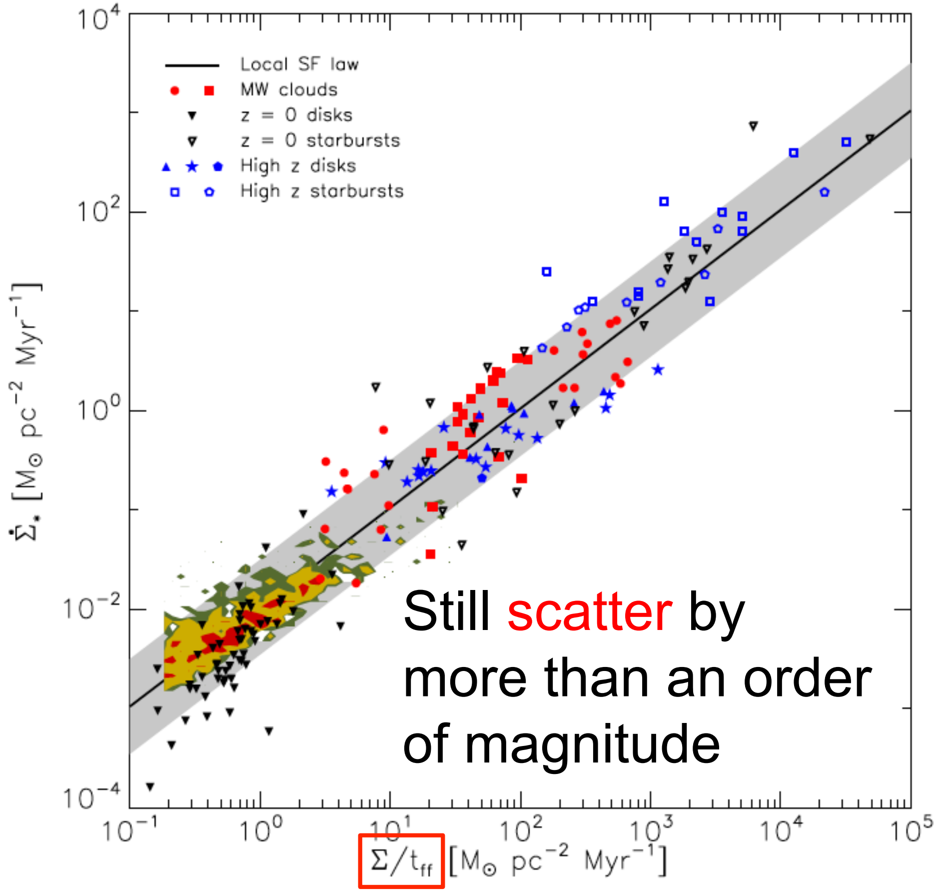
Scatter !

See also
S. Ragan's and
A. Leroy's talks

Heiderman et al. (2010)

A more universal star formation "law"?

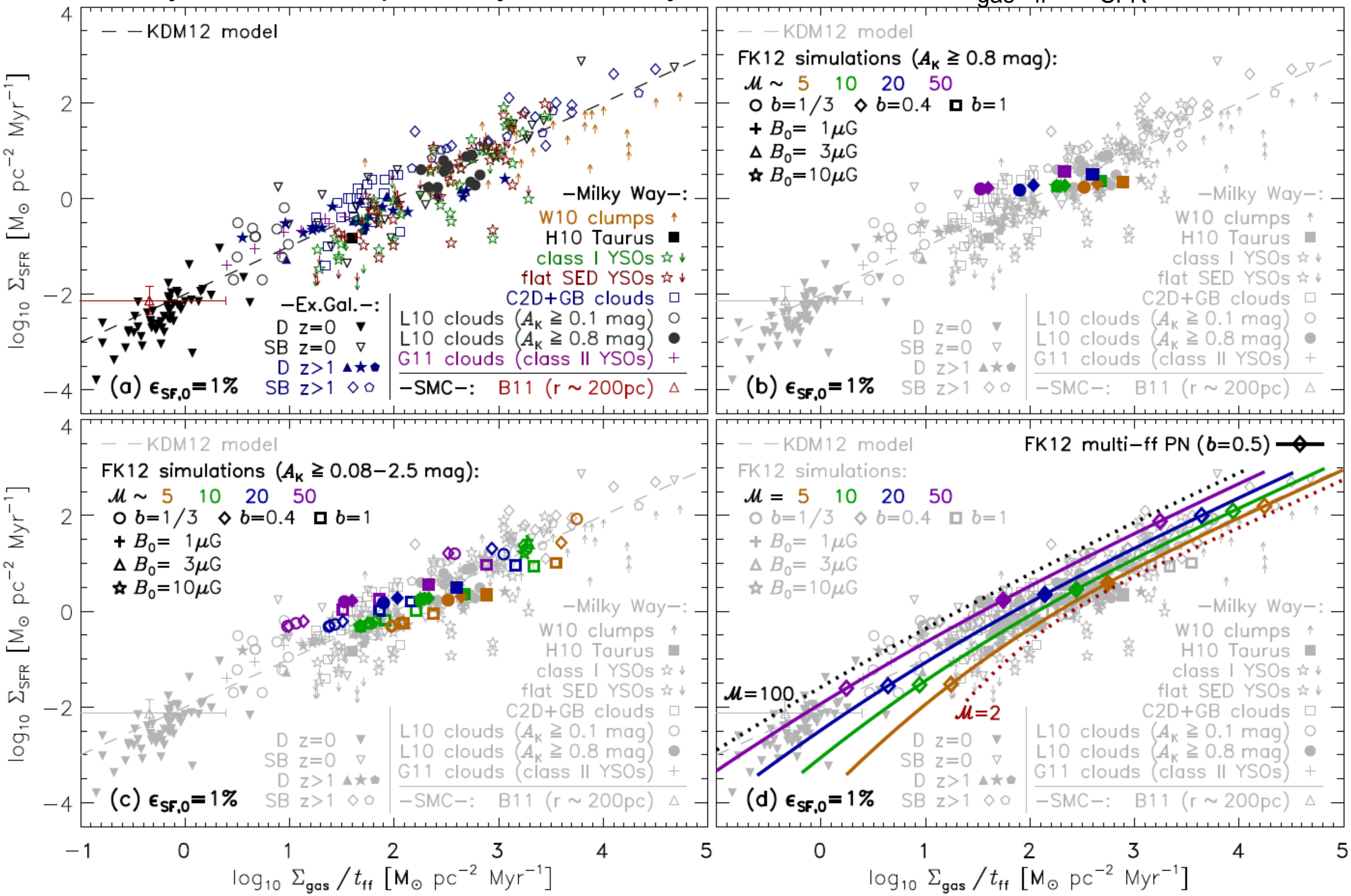




divide Σ_{gas} by local freefall time t_{ff}

Krumholz, Dekel, McKee (2012)

Physical scatter primarily caused by Mach number in Σ_{gas}/t_{ff} - Σ_{SFR} relation?



Federrath (2013, submitted)

Conclusions

Star Formation Rate (SFR) from supersonic, magnetized turbulence:

- MHD turbulence is key for star formation (see e.g., Federrath & Klessen 2012)
- $\mathrm{SFR}_{(\text{compressive forcing})} > 10 \times \mathrm{SFR}_{(\text{solenoidal forcing})}$
- SFR as integral over density distribution (PDF) depends on
  - virial parameter
  - turbulent forcing parameter
  - sonic Mach number
  - plasma beta
- Magnetic fields reduce SFR, consistent with theoretical model prediction
- Good agreement between theory, simulations and observations