Modeling jet and outflow feedback in star cluster formation: *Impact on the SFR and IMF*

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Monash Centre for Astrophysics

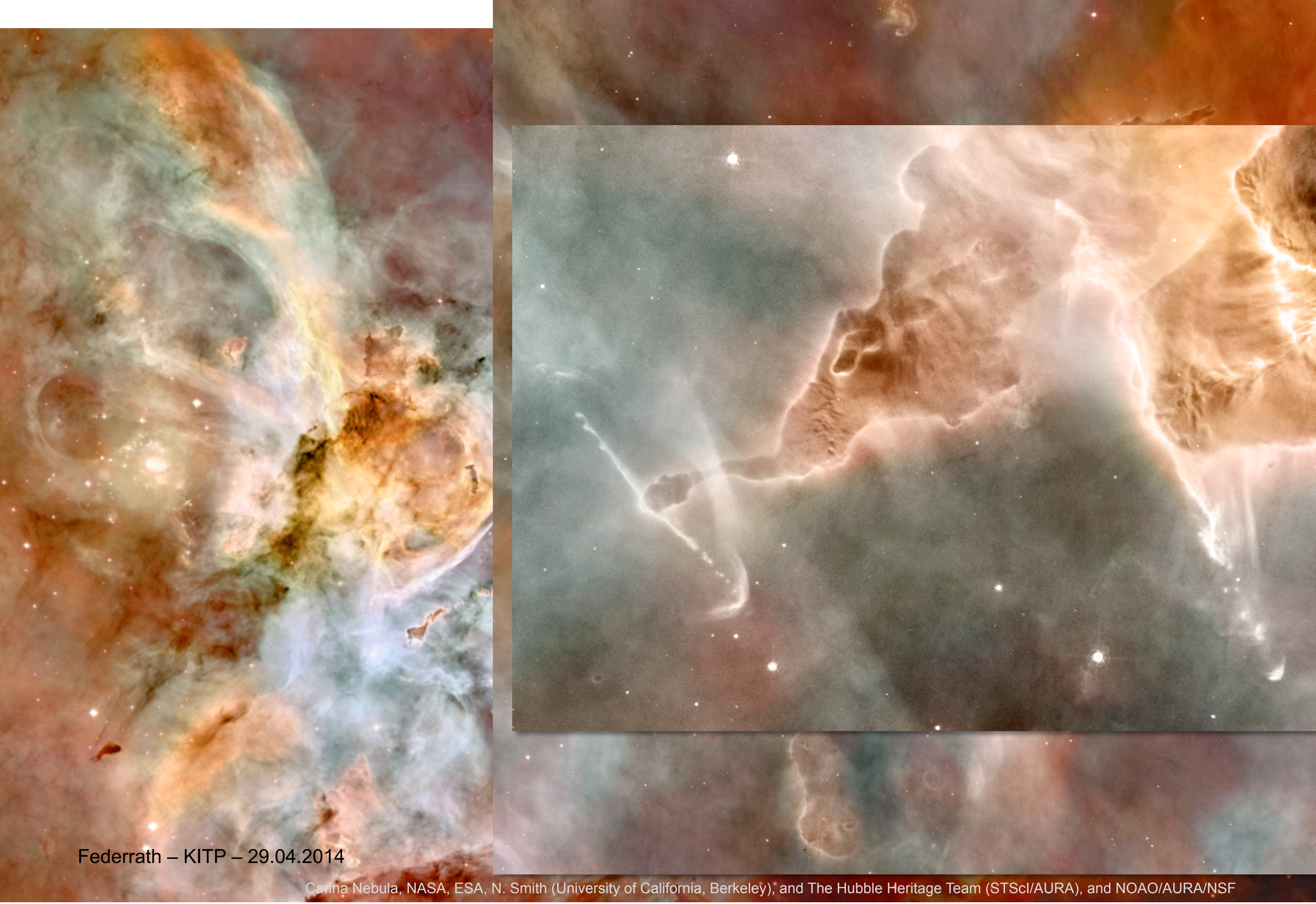
Australian Government
Australian Research Council

Image Credit: ESA and the HFI Consortium, IRAS 2010

Modeling jet and outflow feedback

Turbulence → Density PDF

Density PDF → Star Formation Rate

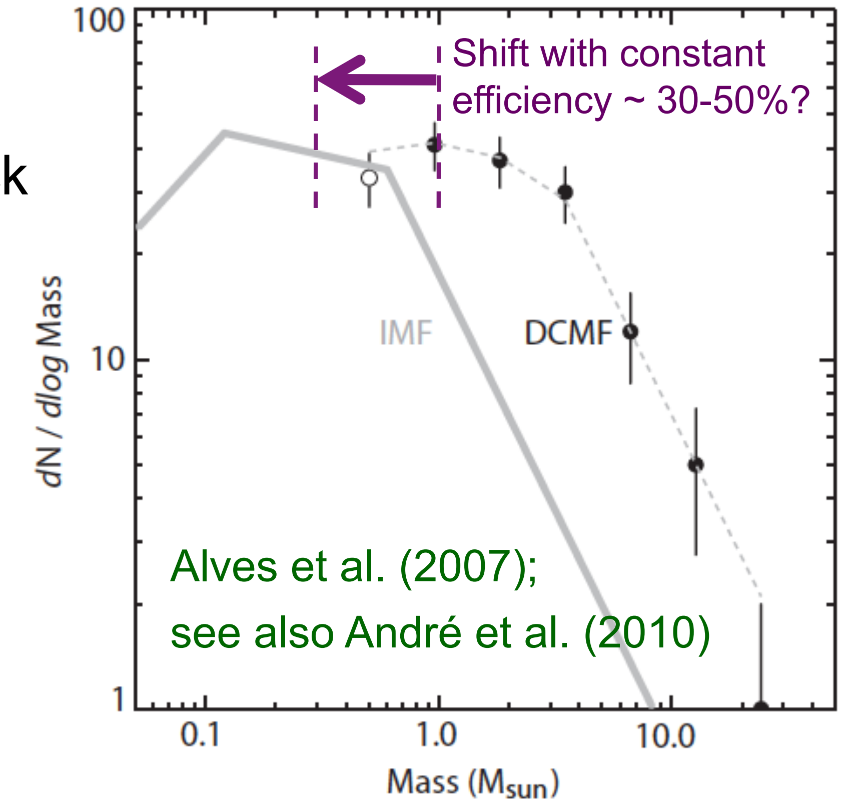


Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

Star Formation – Outflows/Jets

Outflows/Jets

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

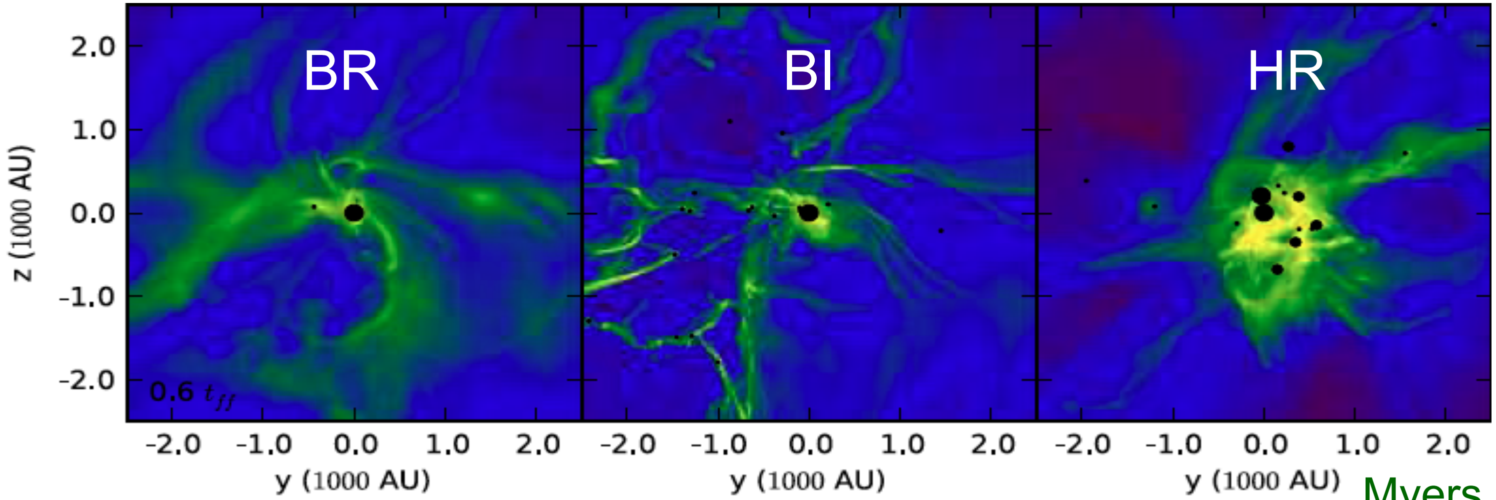


Impact on SFR and IMF:
core-to-star efficiency ε ~ 0.3–0.5

(see also Matzner & McKee 2002)

Star Formation – Magnetic Fields

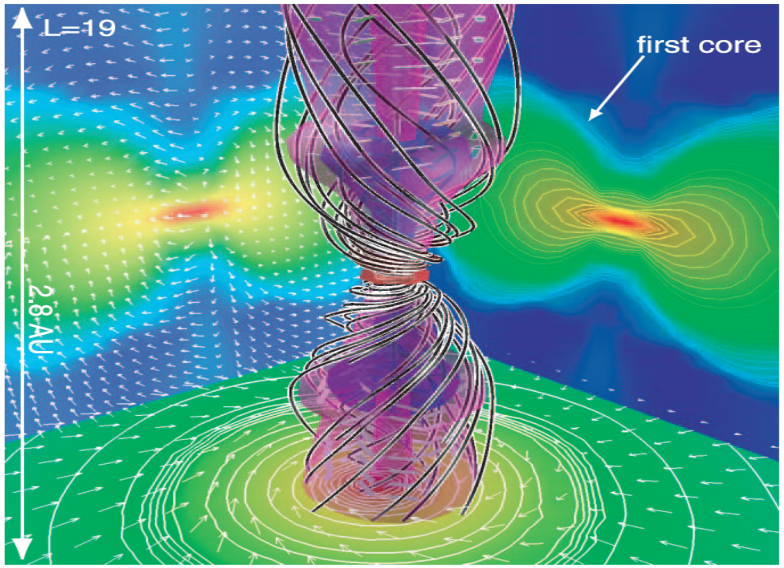
Reduce fragmentation (Hennebelle & Tyessier 08, Bürzle+11, Federrath & Klessen 12)

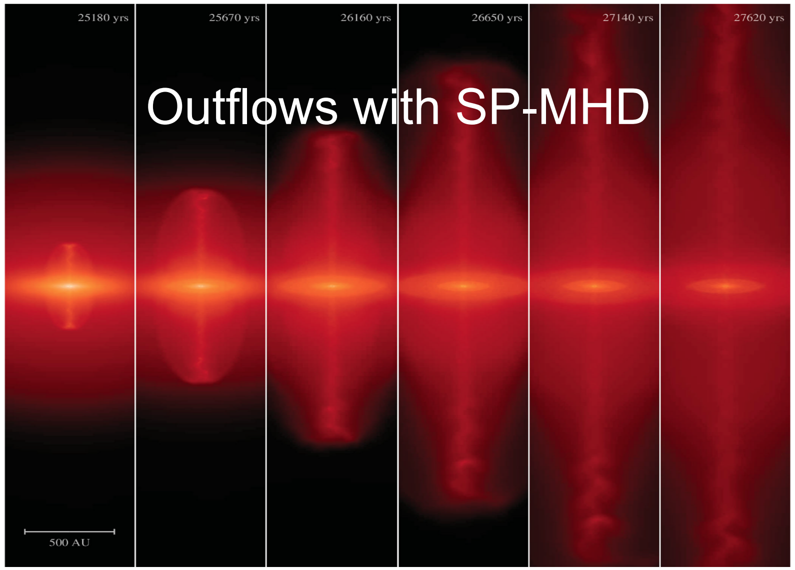


Myers et al. (2013)

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

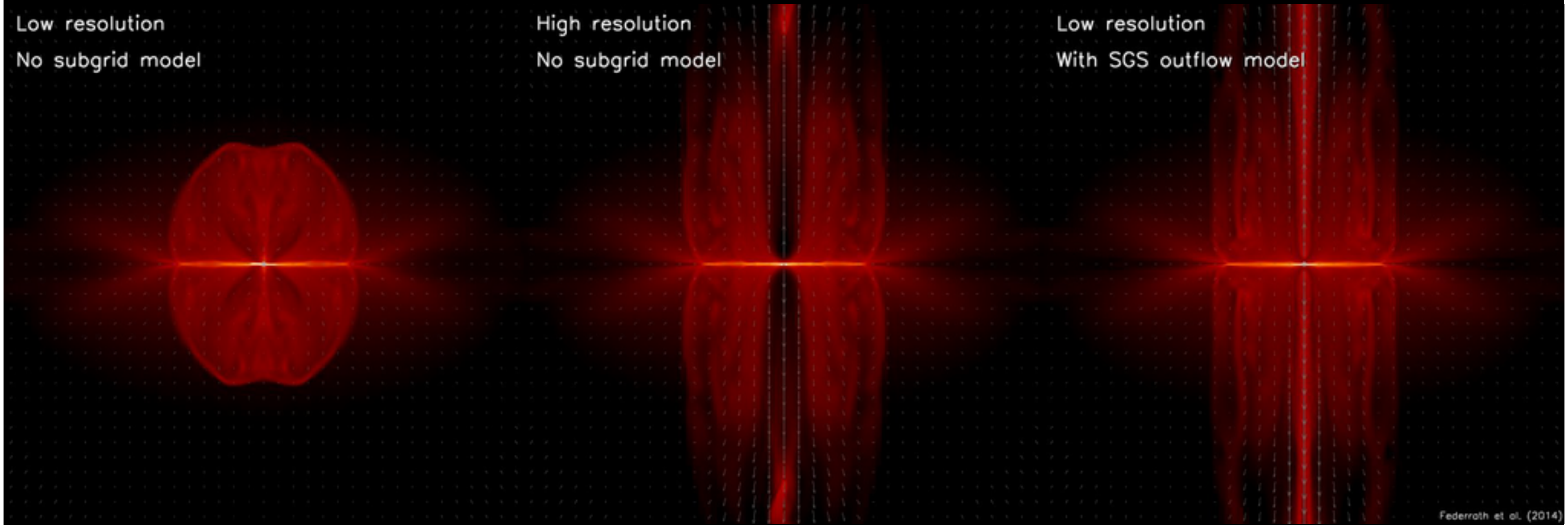
Machida et al. (2008)





Price et al. (2012)

Modeling jets/outflows



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

Sink particles

- Quantify fragmentation and accretion
- Prevent code from stalling

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

- Resolve Jeans length

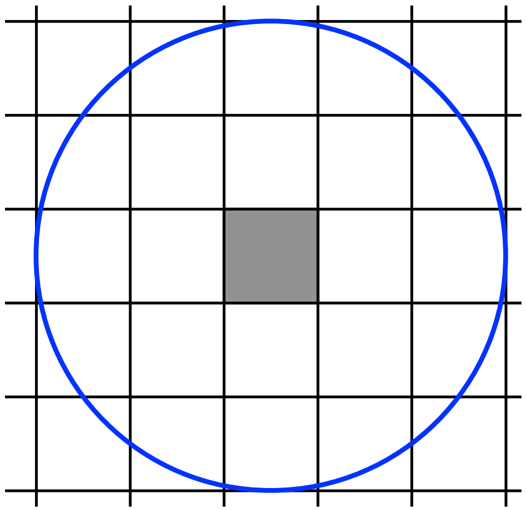
$$\lambda_{\mathrm{J}} = \left(\frac{\pi c_{\mathrm{s}}^2}{G\rho}\right)^{1/2} \quad \rightarrow \quad \rho_{\mathrm{res}}$$ (resolution criterion)

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

Sink particle implementation in FLASH

Collapse checks to avoid spurious sink creation

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

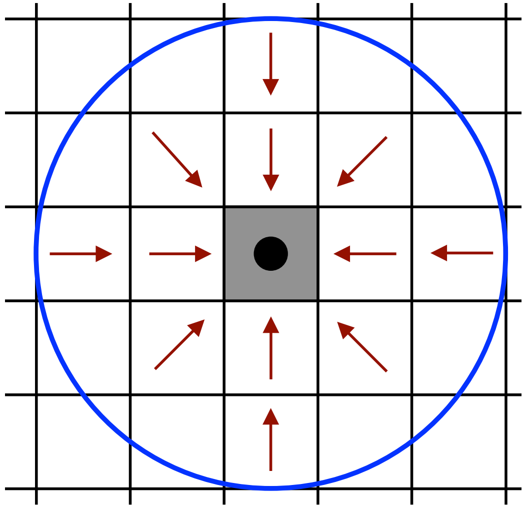


Federrath, Banerjee, Clark, Klessen (2010, ApJ 713, 269)

Sink particle implementation in FLASH

Collapse checks to avoid spurious sink creation

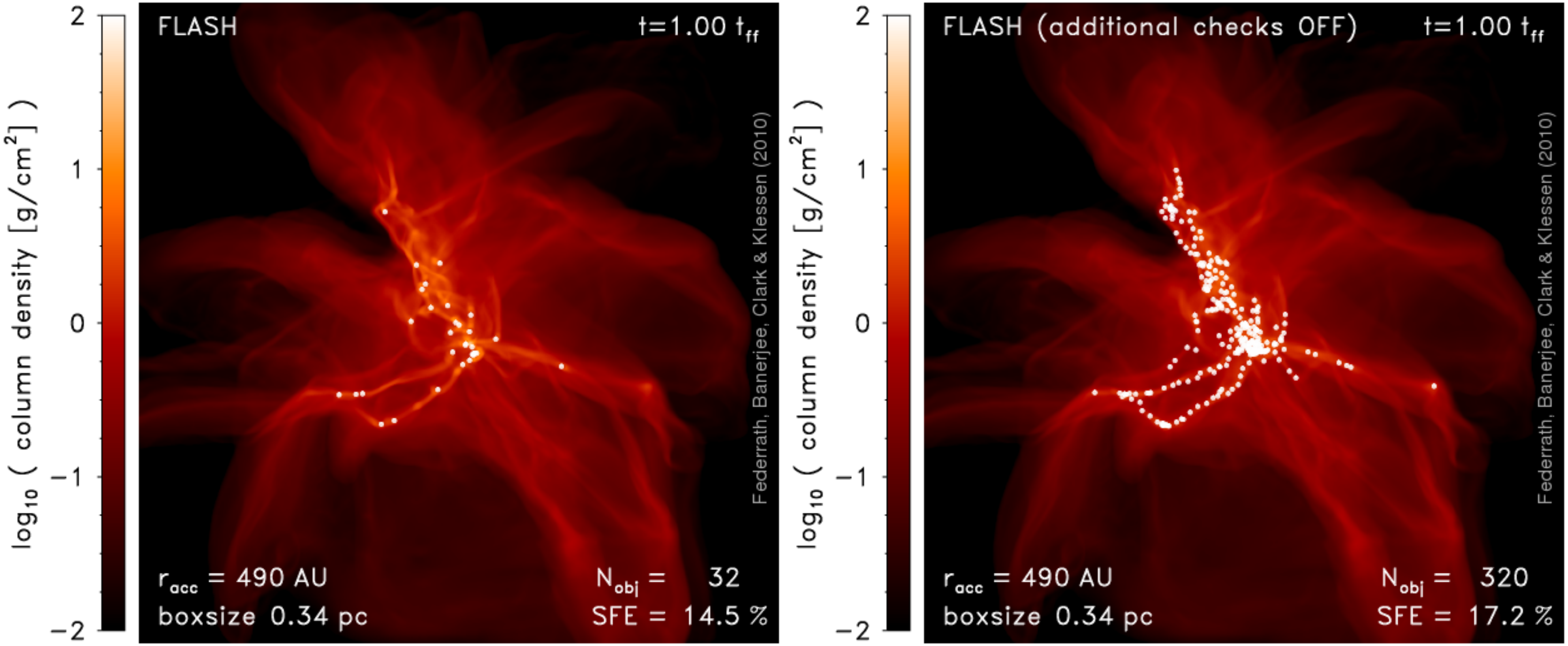
1. Cell exceeds density threshold, $\rho > \rho_{\mathrm{res}}$
2. Highest level of AMR
3. Converging towards the center
4. Central minimum in gravitational potential
5. Jeans unstable, $|E_{\mathrm{grav}}| > 2E_{\mathrm{th}}$
6. Bound, $E_{\mathrm{grav}} + E_{\mathrm{th}} + E_{\mathrm{kin}} + E_{\mathrm{mag}}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



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

Sink particle implementation in FLASH

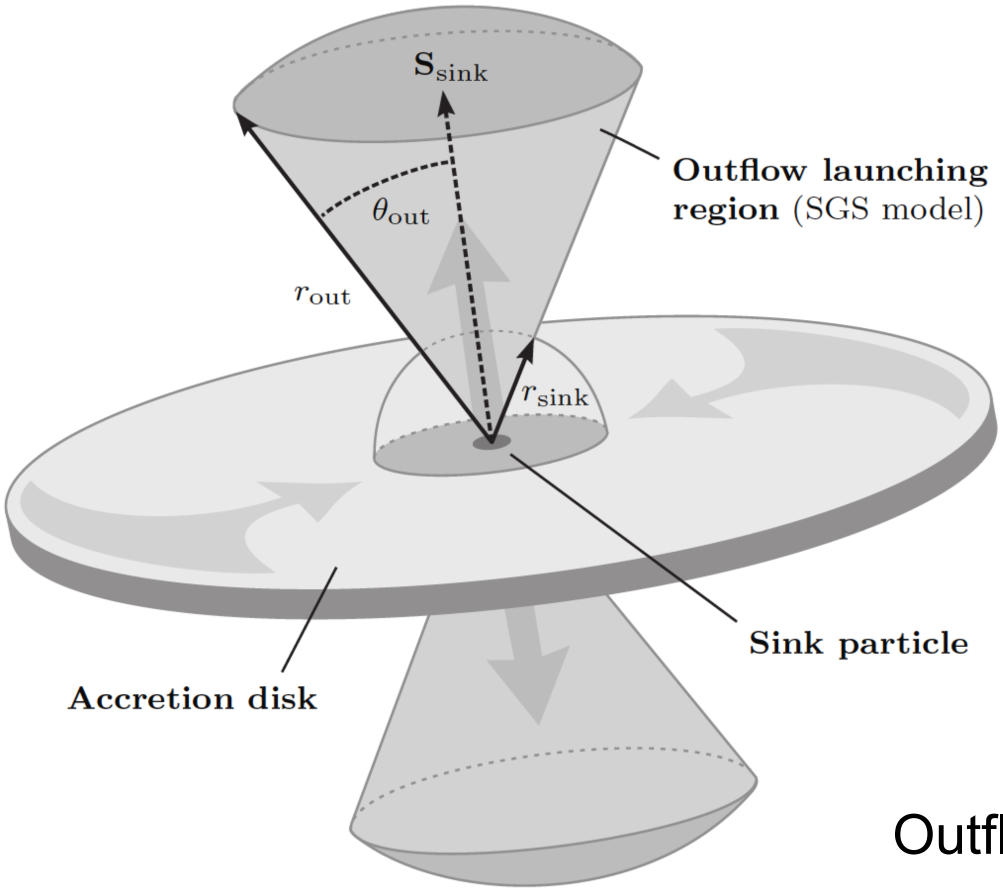
Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/sinks/sinks.shtml



all checks ON $\rho > \rho_{res}$ **only**

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

A subgrid model for jets/outflows



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).

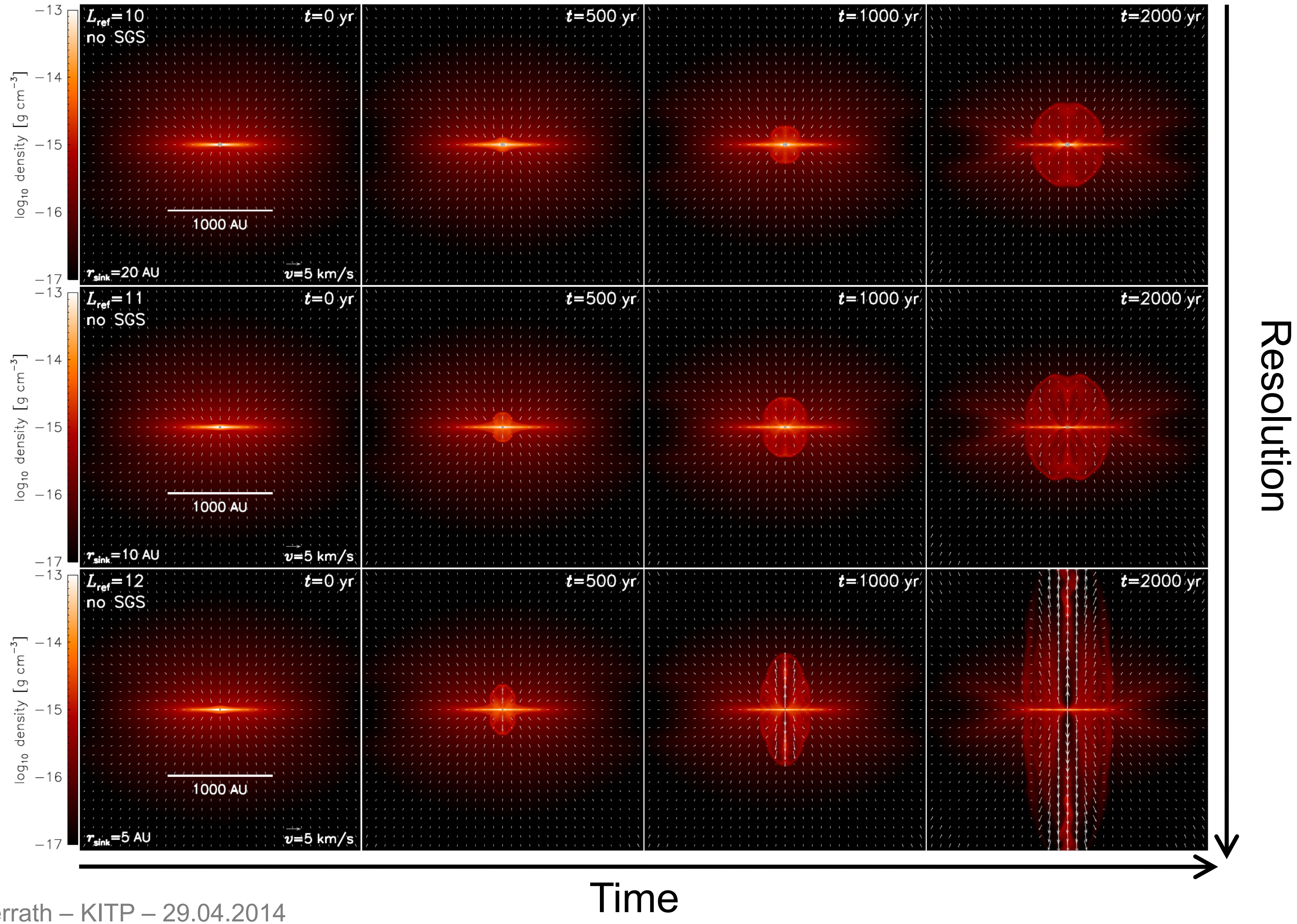
Outflow mass: $$M_{\rm out} = f_{\rm m}\dot{M}_{\rm acc}\Delta t$$

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

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

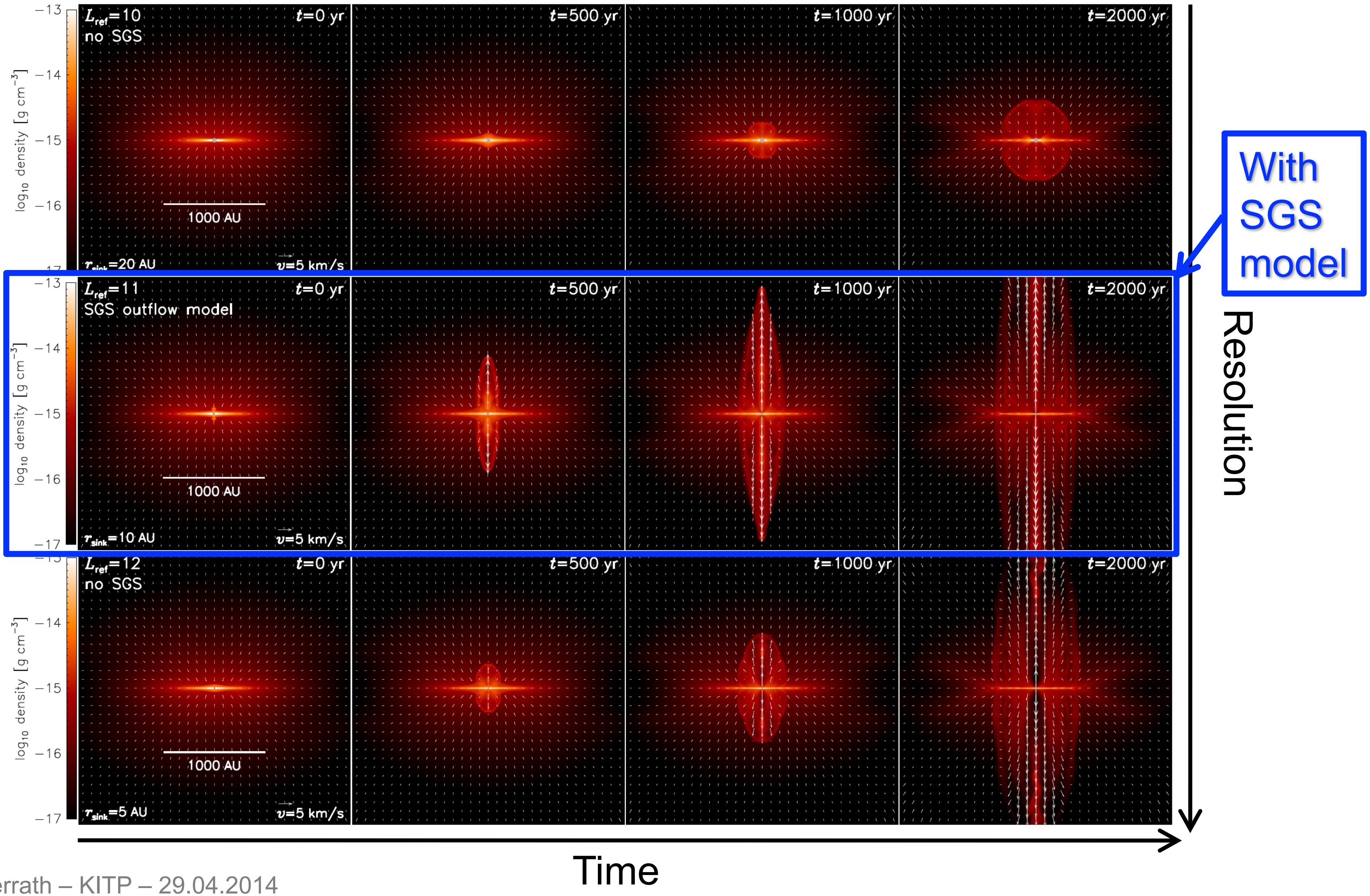
A subgrid model for jets/outflows

Resolution study *without* SGS model:



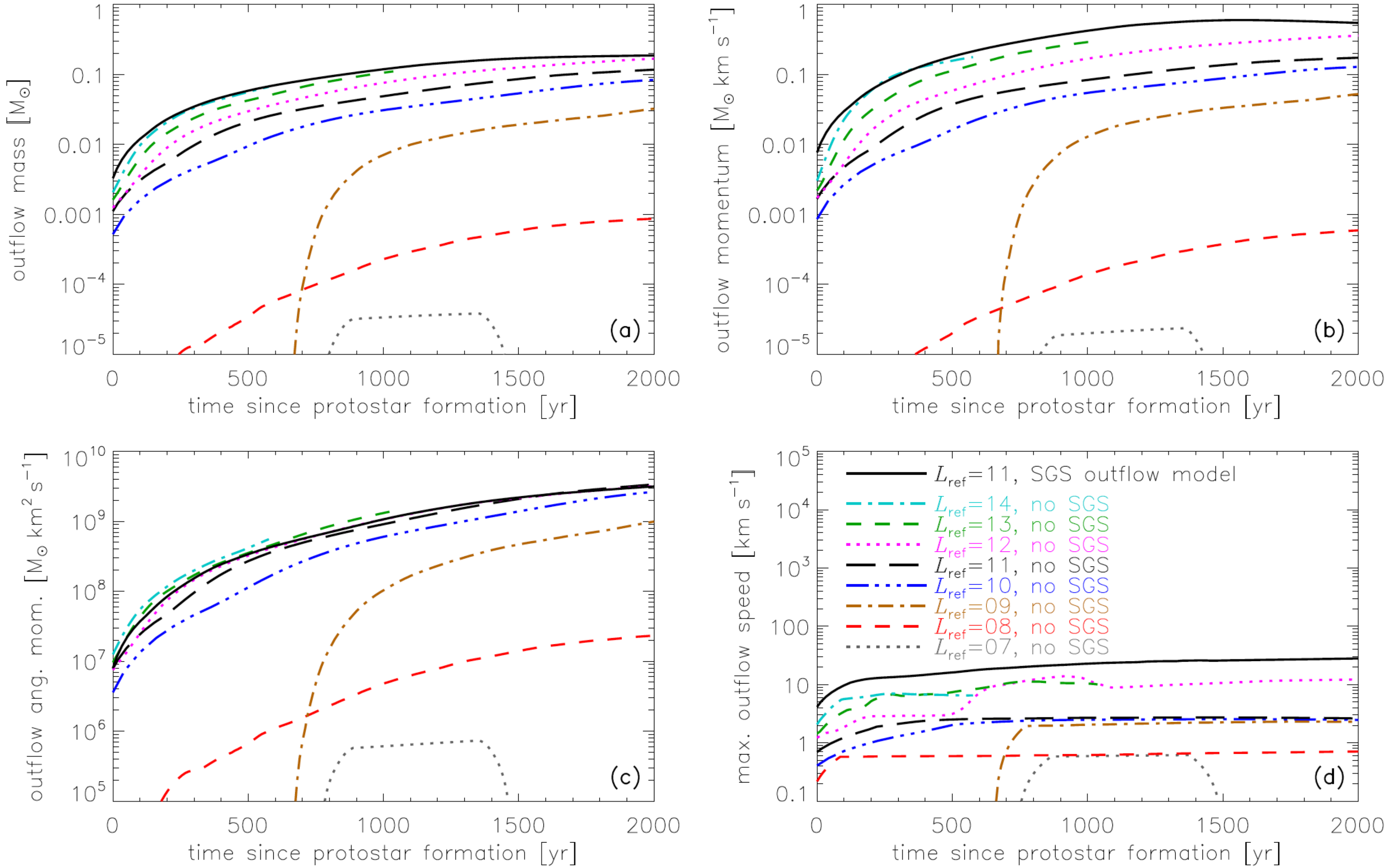
A subgrid model for jets/outflows

Resolution study without SGS model:



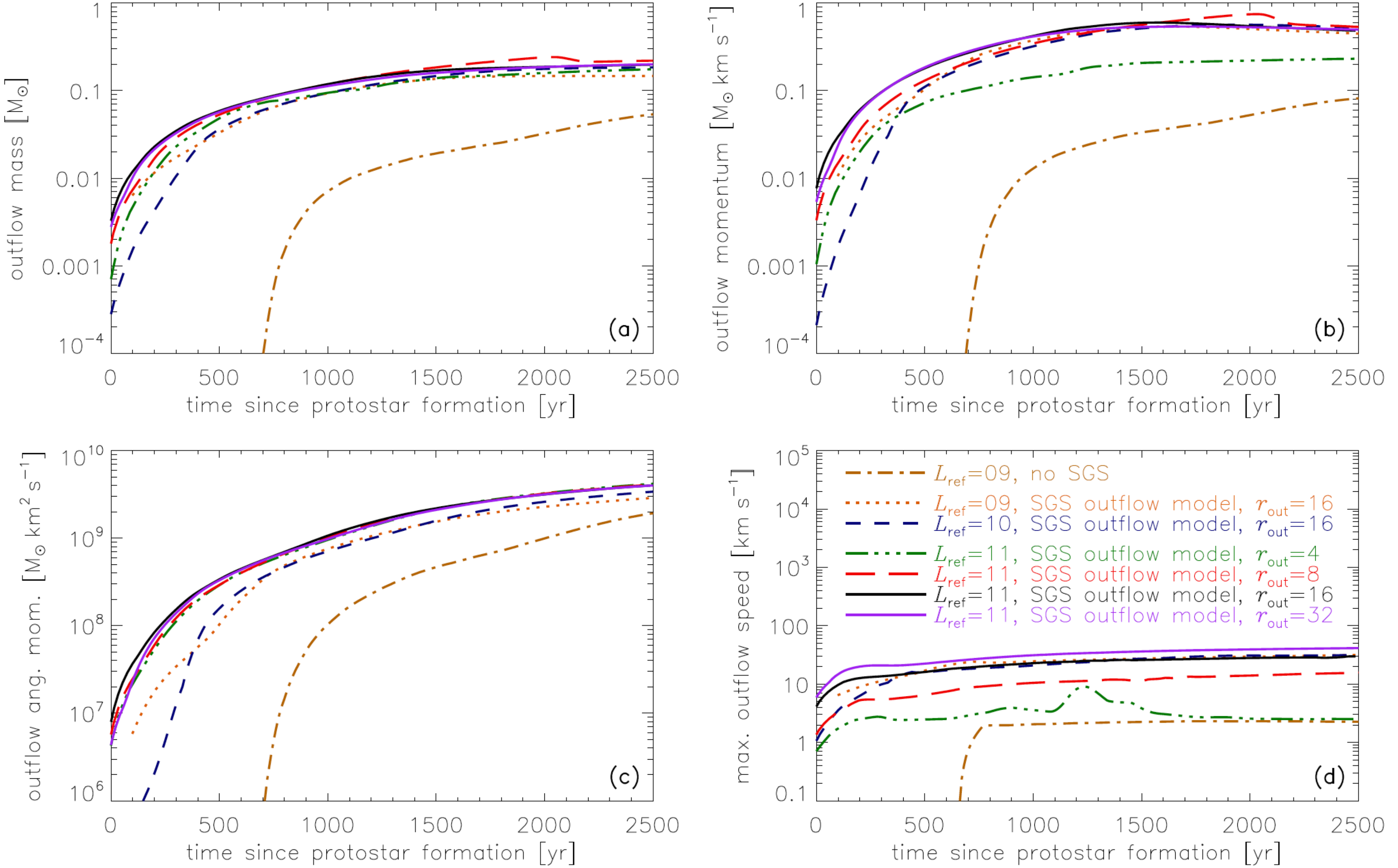
A subgrid model for jets/outflows

SGS model must reproduce small-scale physics:



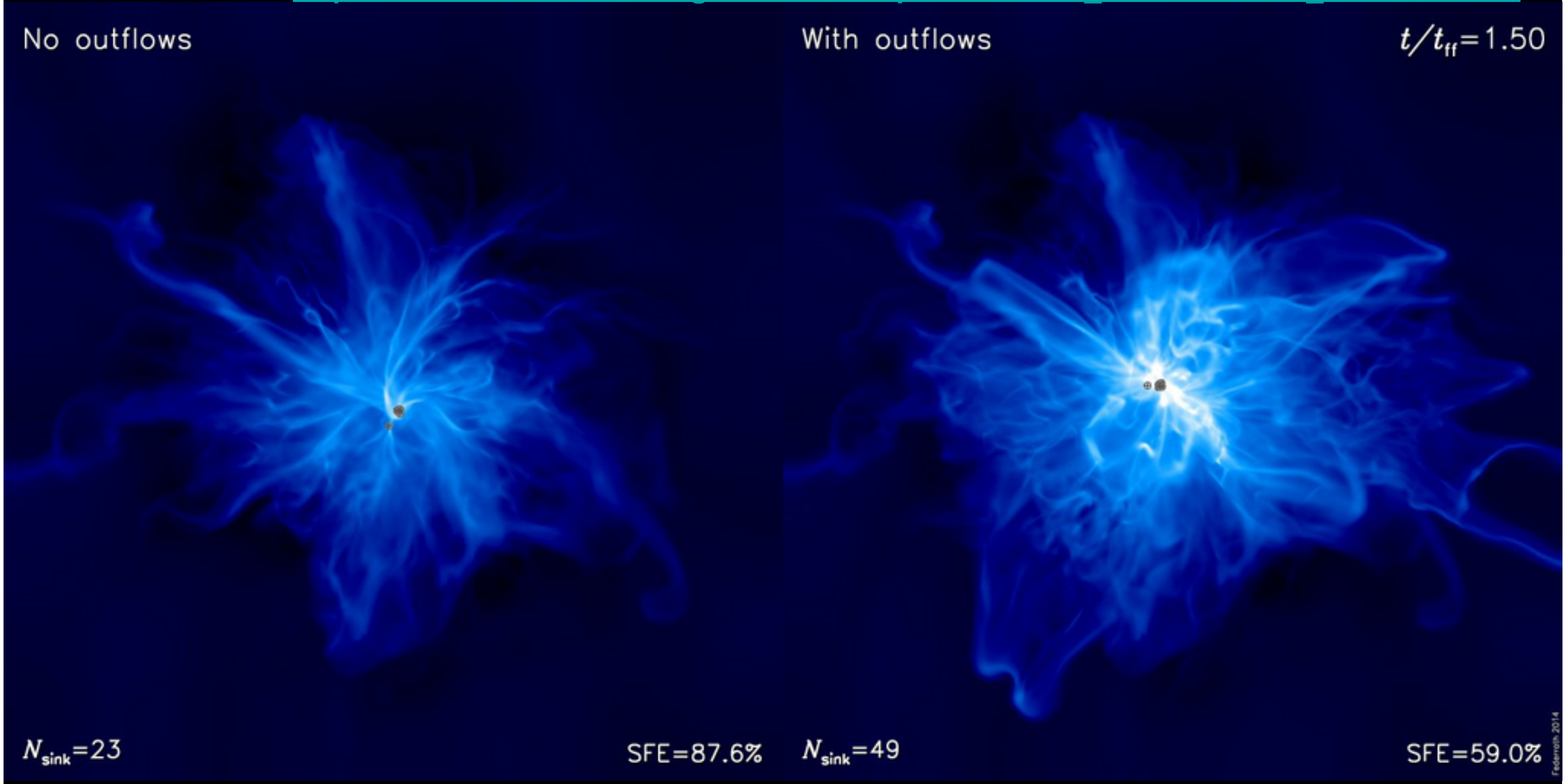
A subgrid model for jets/outflows

SGS model must converge:



The role of outflow/jet feedback for star cluster formation

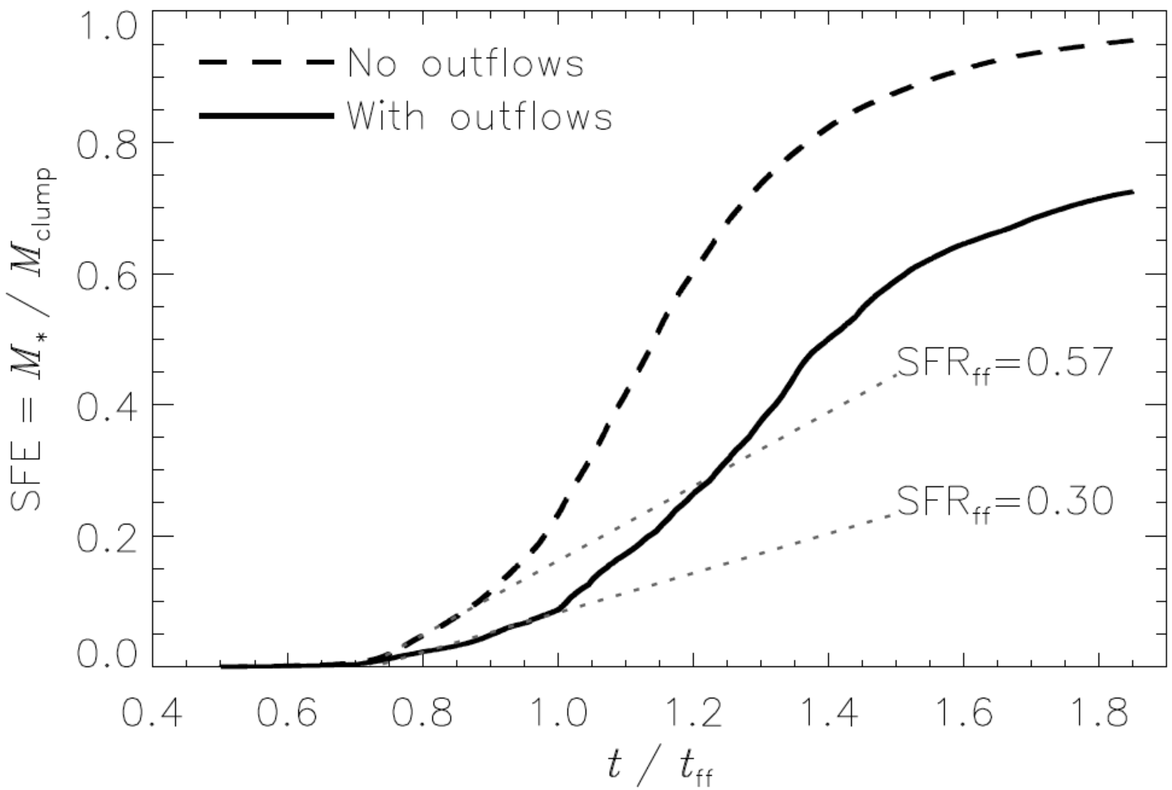
Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/outflow_model/outflow_models.shtml



SGS off

SGS on

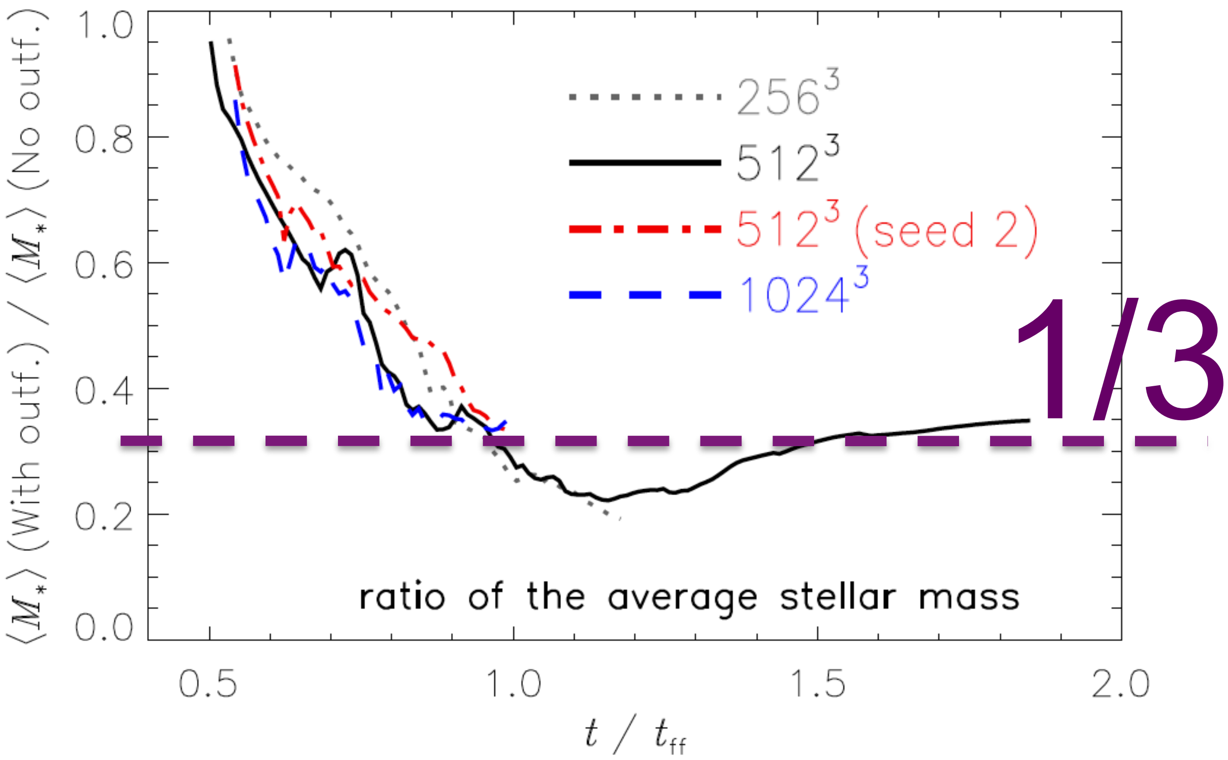
The role of outflow/jet feedback for star cluster formation

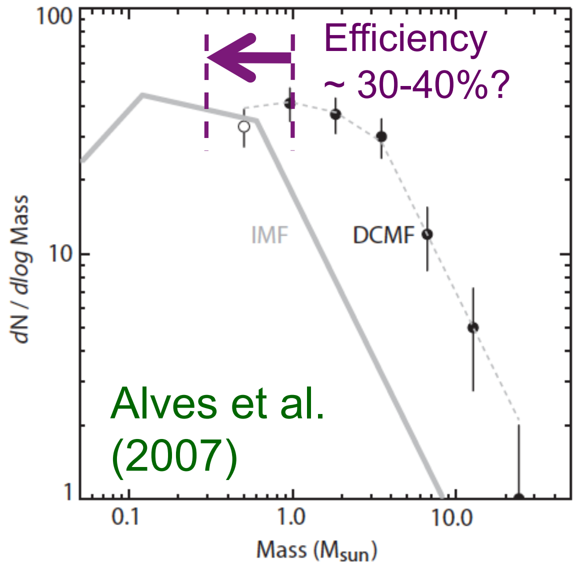


RESULTS:

- 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





RESULTS:

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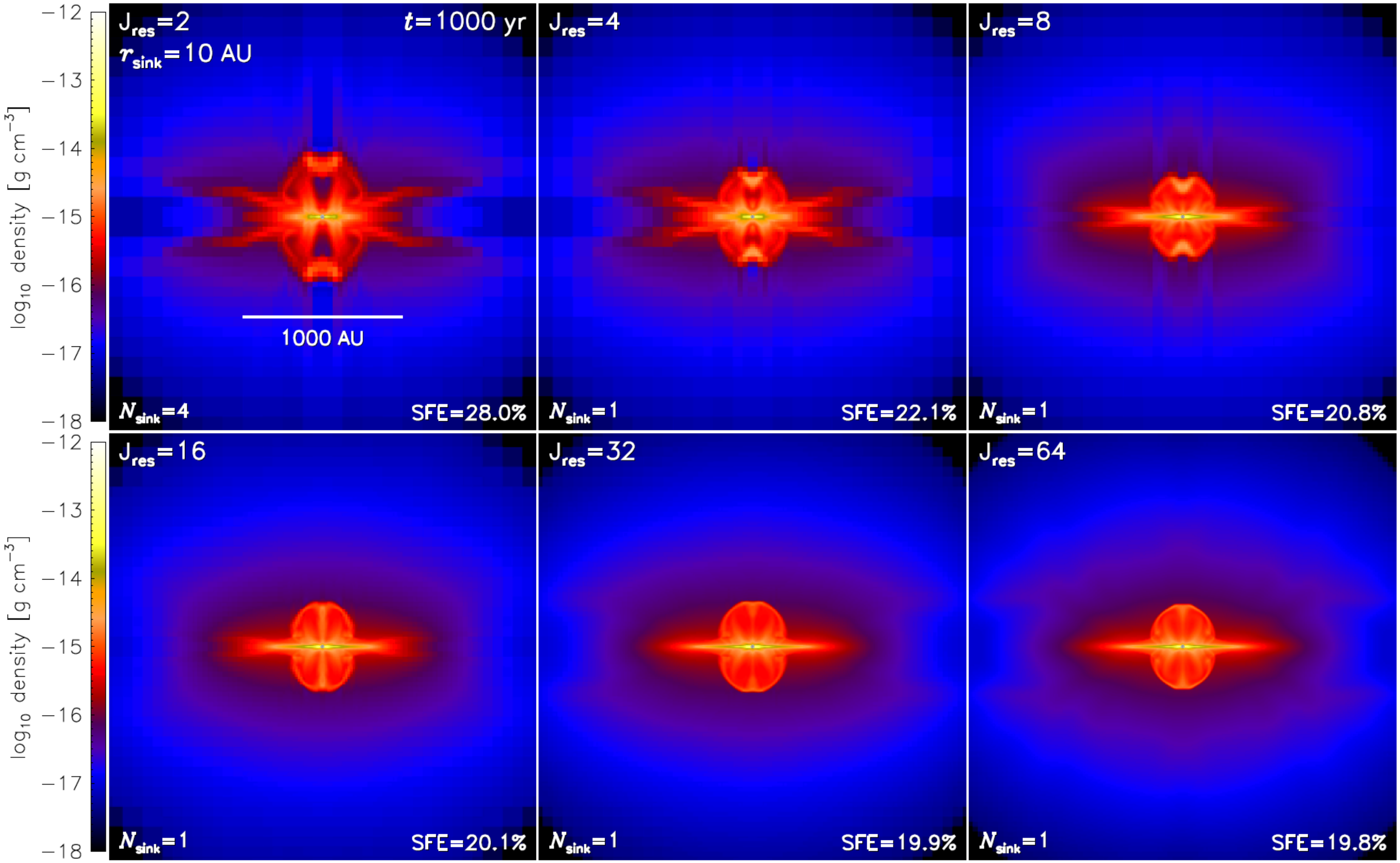
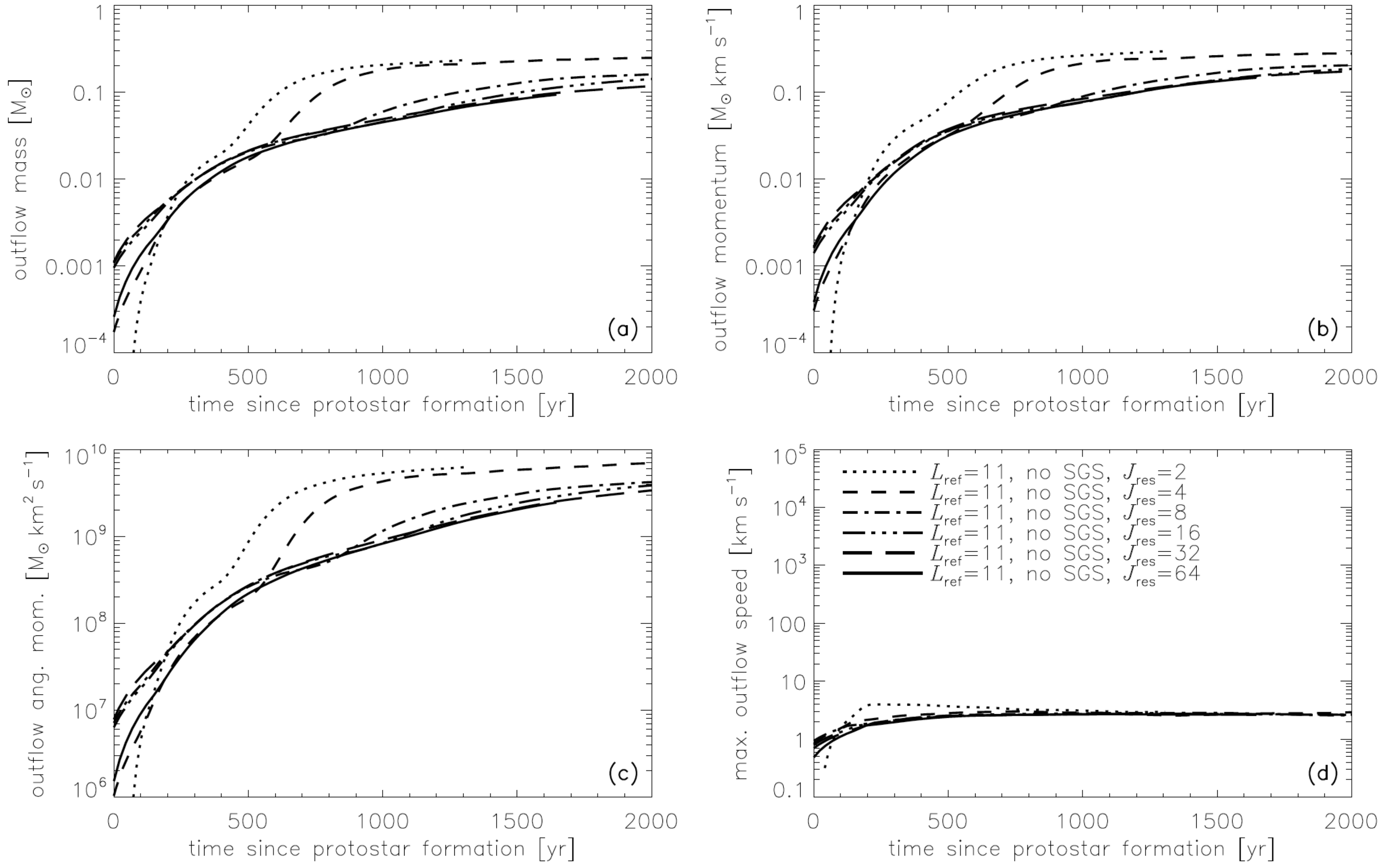
Jeans resolution study



“The answer is 42” – roughly…

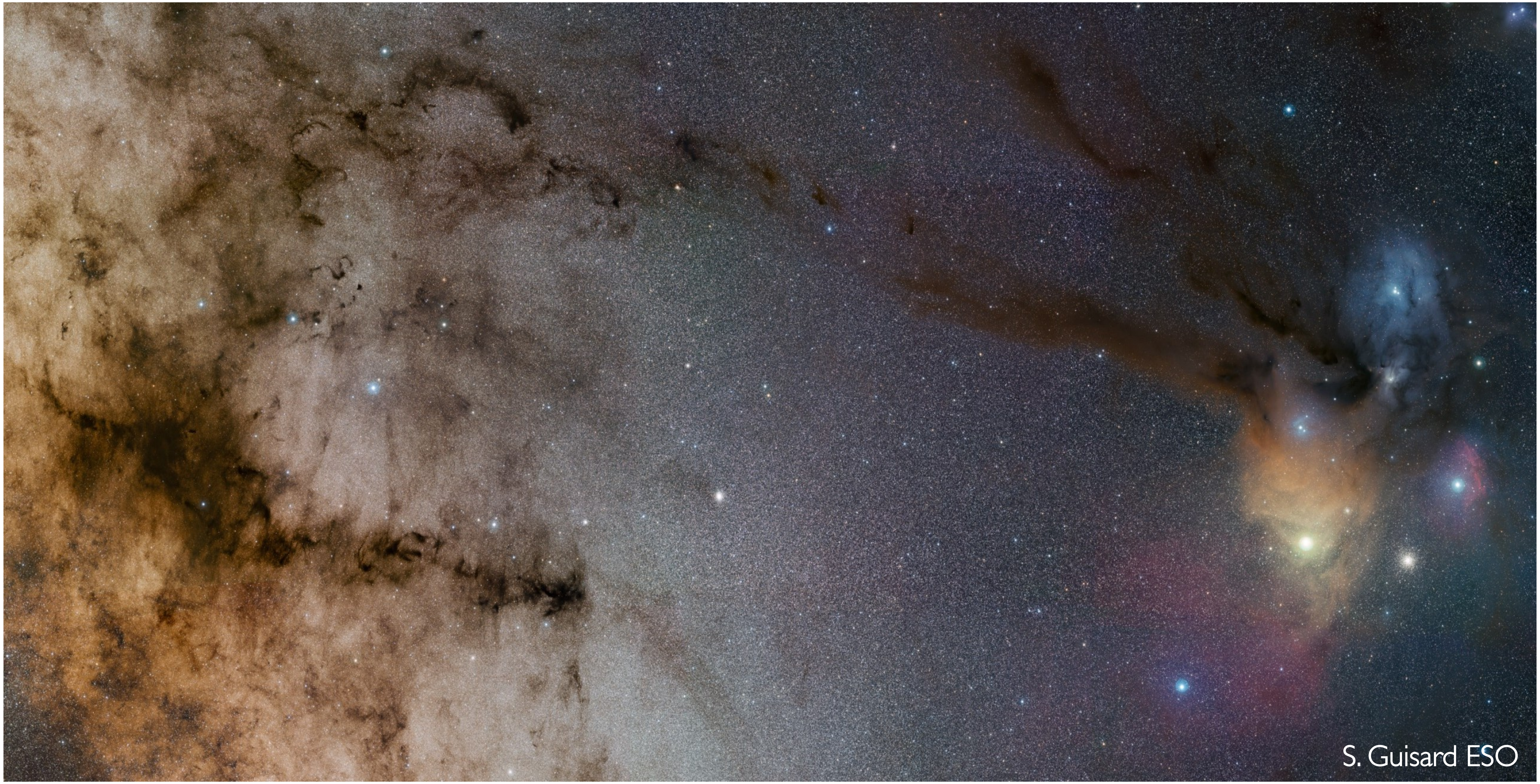


→ At least 30 grid cells per Jeans length required (see also Federrath et al. 2011, ApJ)

Modeling jet and outflow feedback

Turbulence → Density PDF

Density PDF → Star Formation Rate



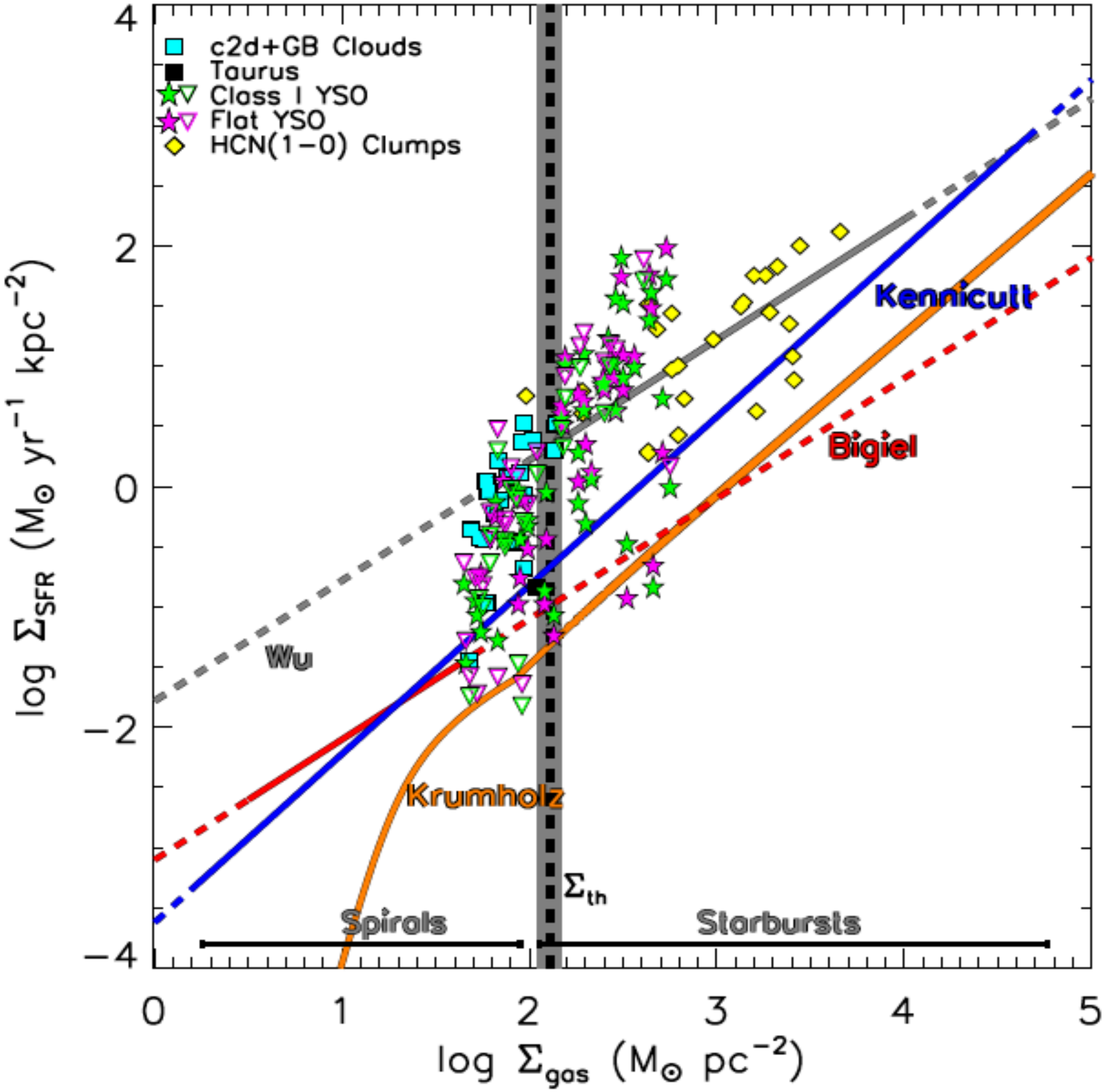
Pipe Nebula

Rho Ophiuchi Cloud

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

(Lada et al. 2010)

Universal star formation "law"?



- Relation?
- Offset?
- Scatter?

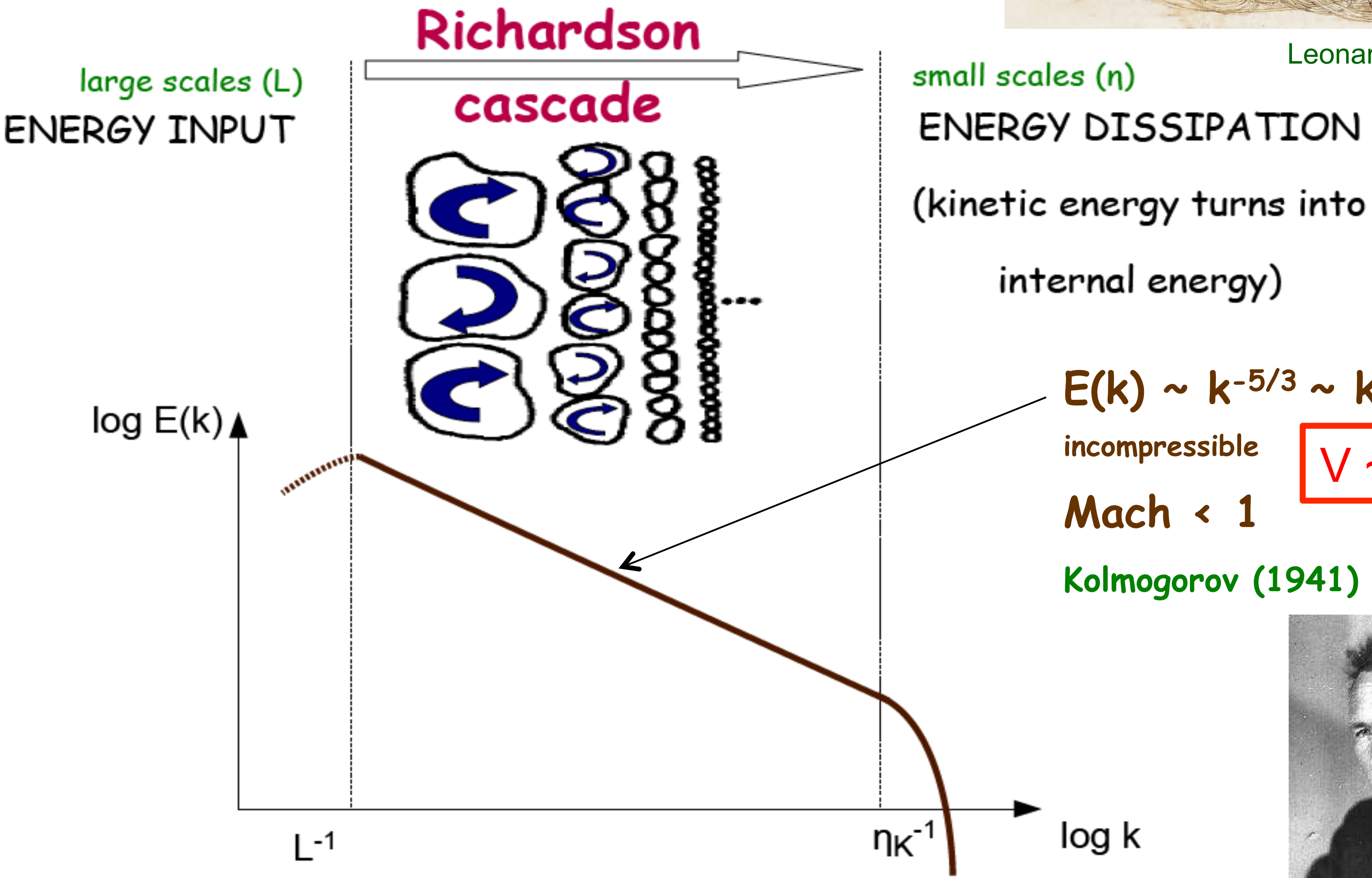
Observational scatter and physical variations: Turbulence

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

Turbulence


Leonardo da Vinci

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



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

incompressible

Mach < 1

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

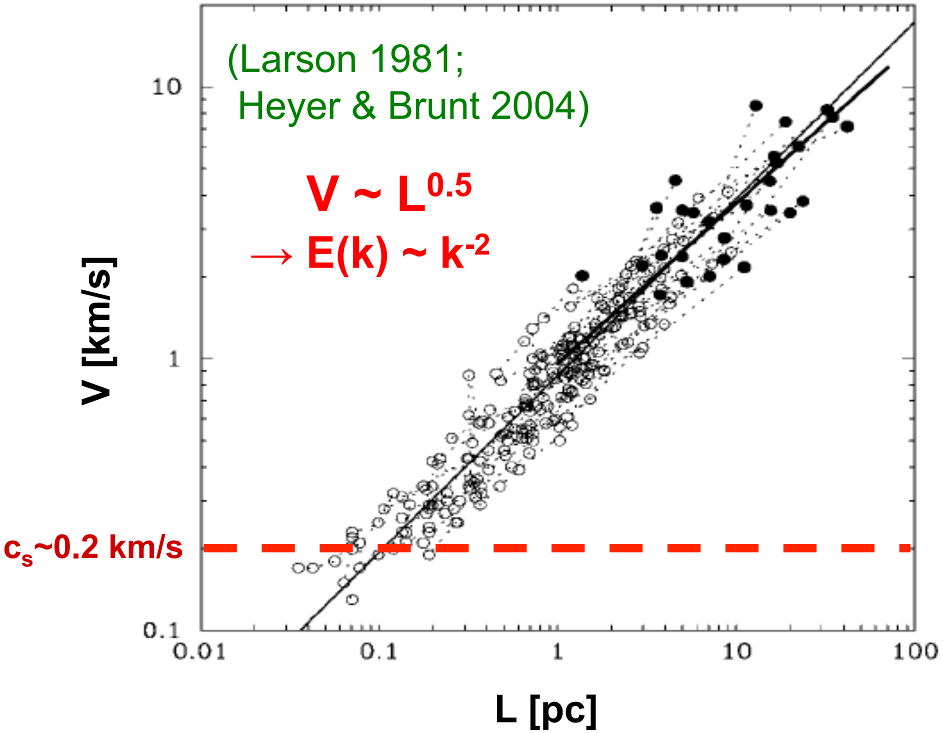
Kolmogorov (1941)

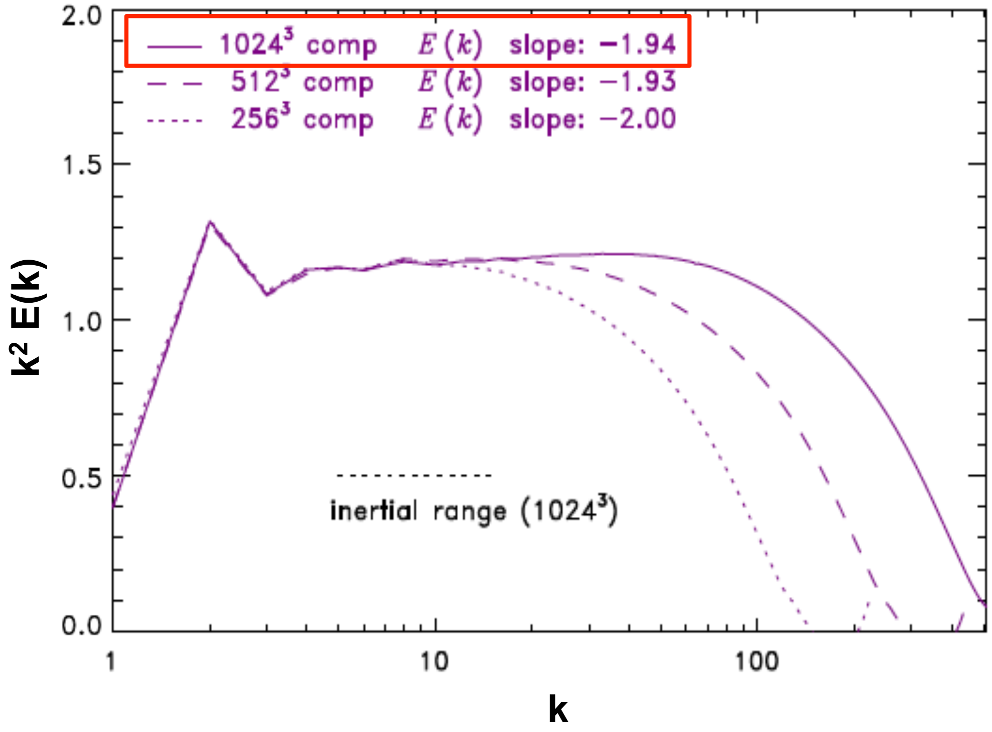
Interstellar Turbulence – scaling

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**

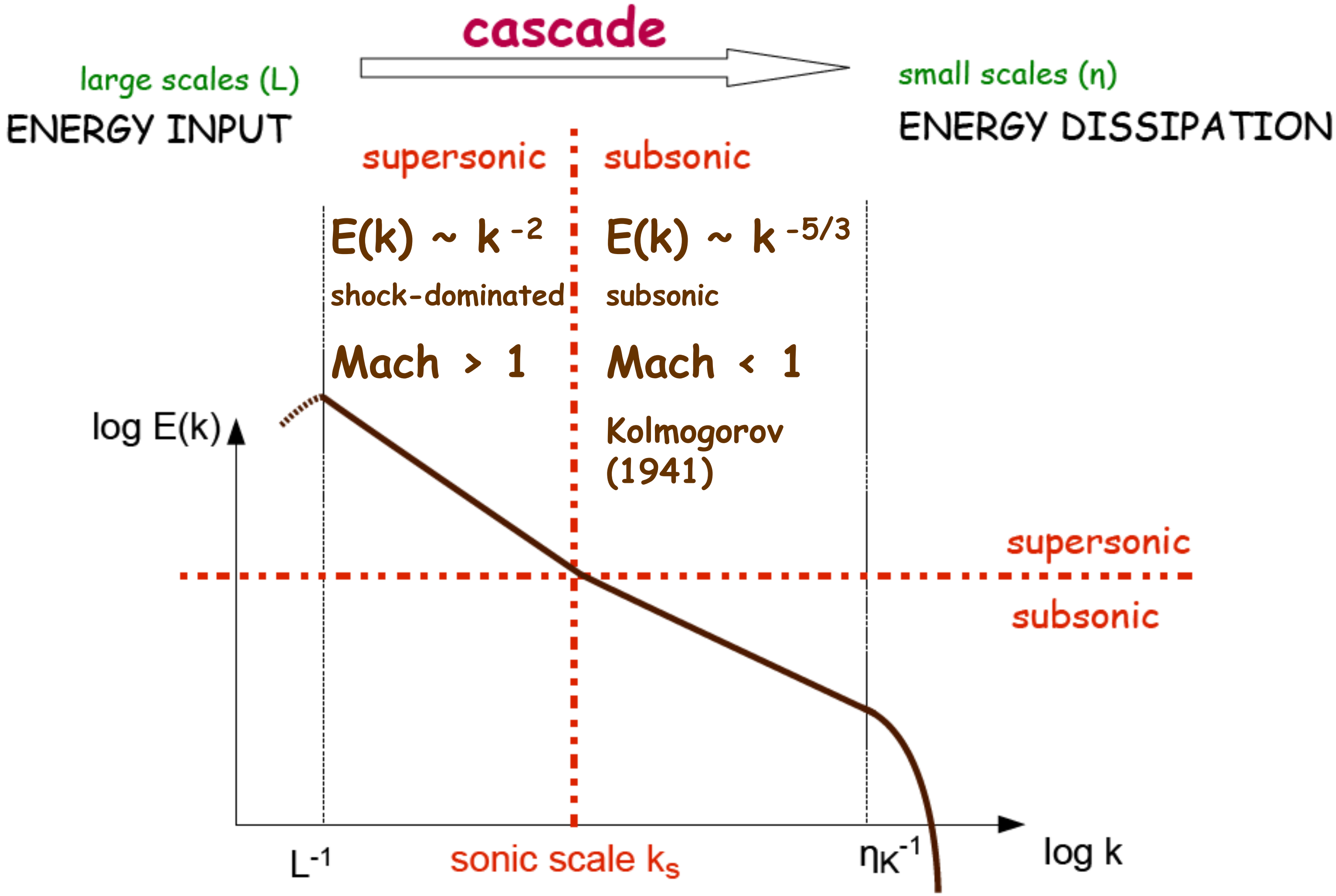




Supersonic, compressible turbulence has steeper $E(k) \sim k^{-1.9}$ than Kolmogorov ($E \sim k^{-5/3}$)

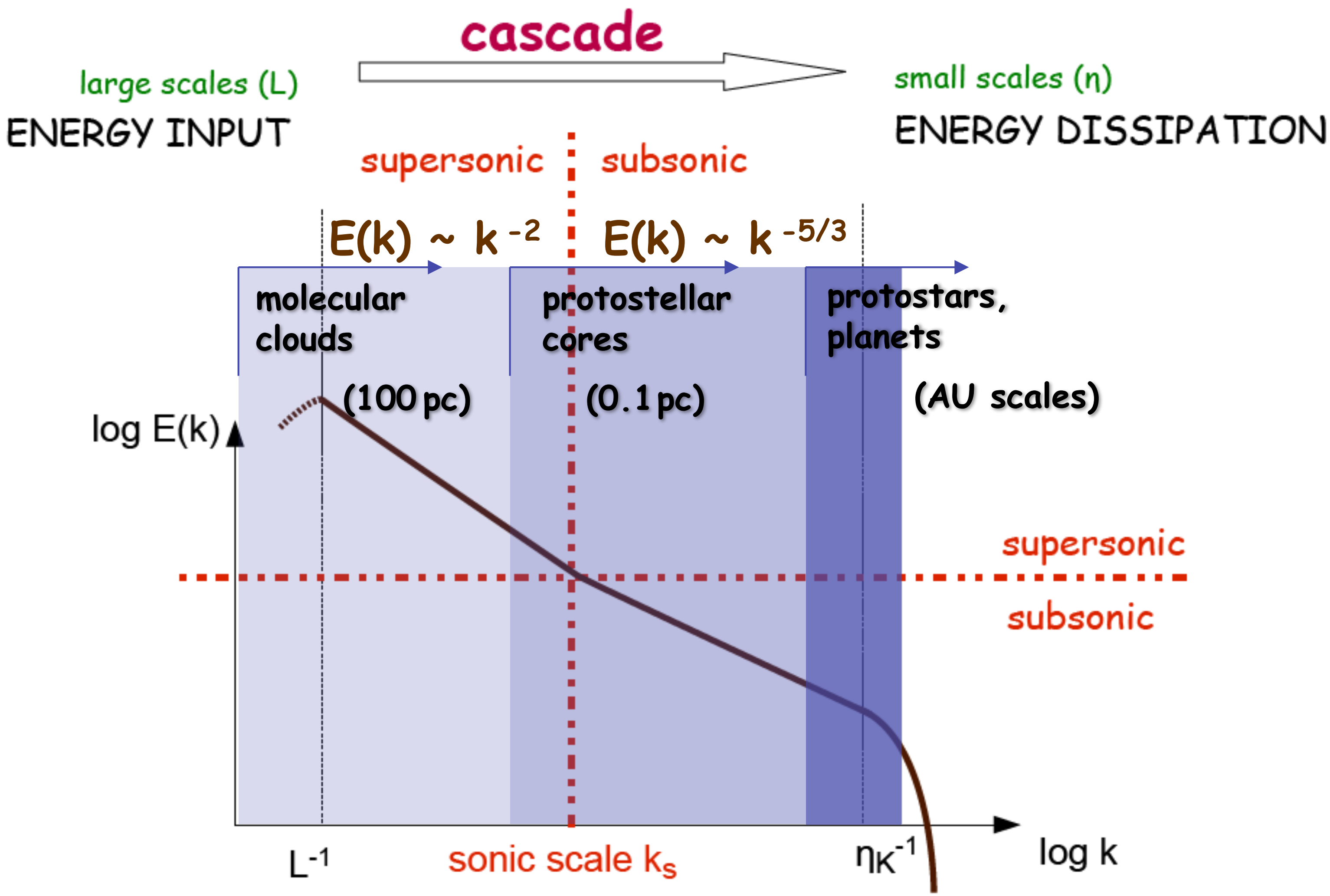
Federrath et al. (2010); see also Kritsuk et al. (2007)

- Reynolds numbers > 1000
- Kinetic energy cascade



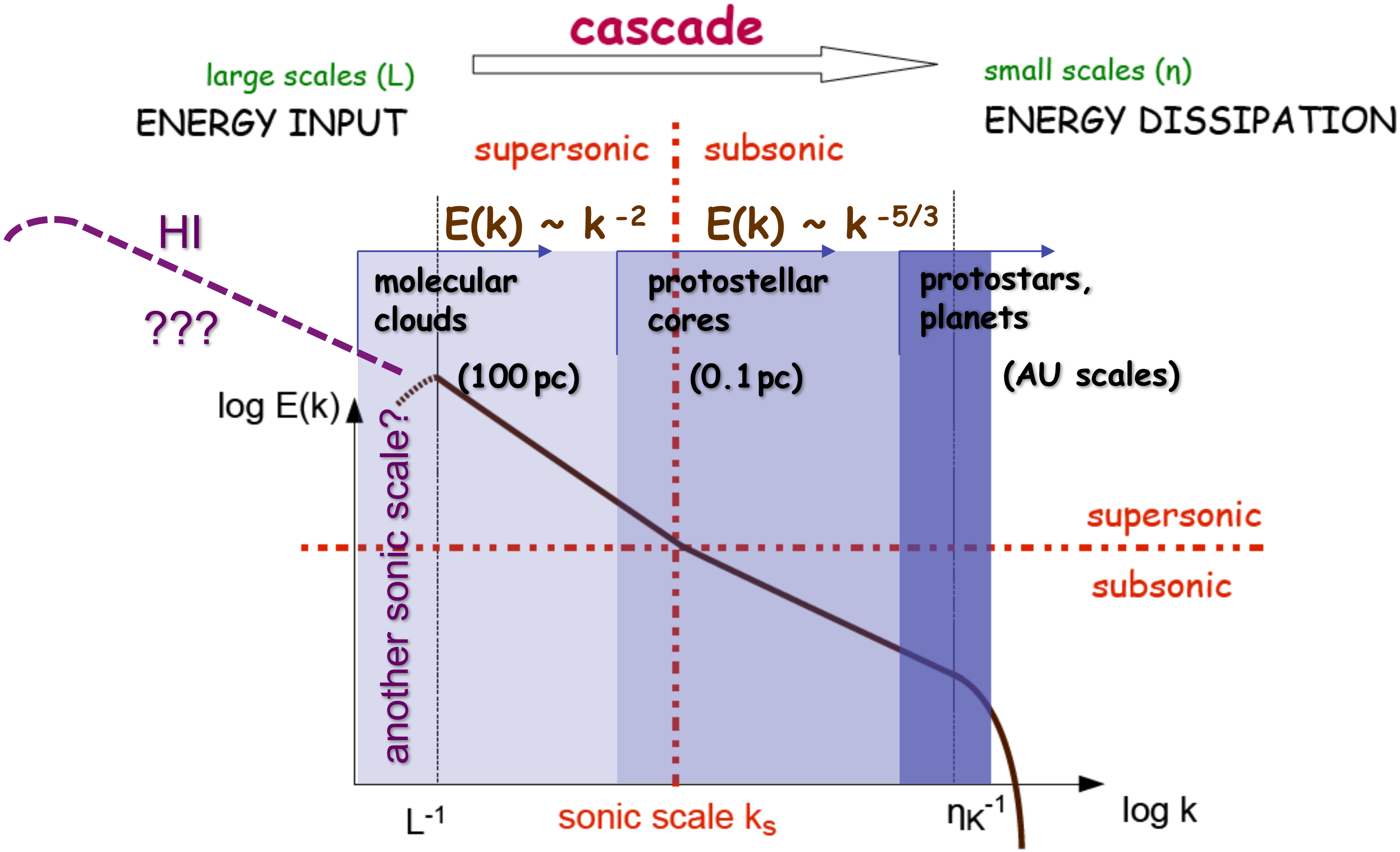
Interstellar Turbulence

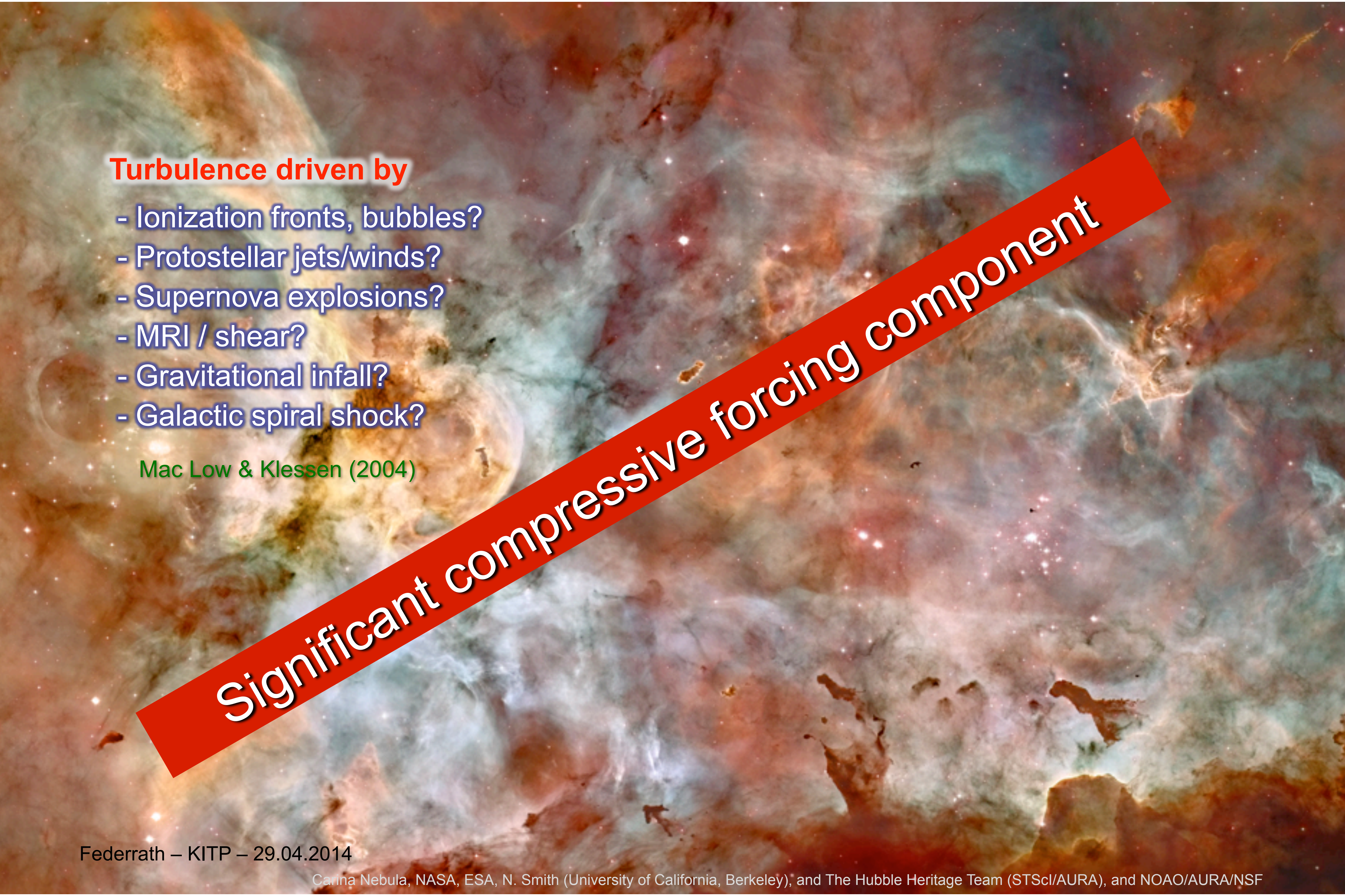
- **Reynolds numbers > 1000**
- **Kinetic energy cascade**



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?

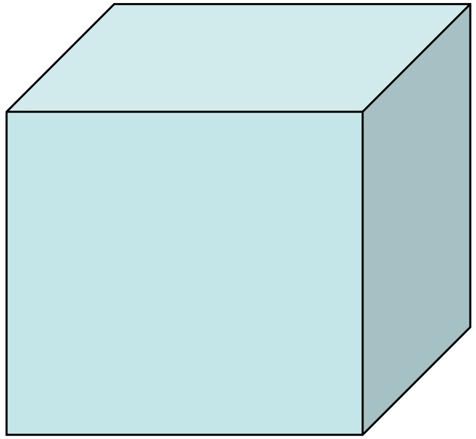
Mac Low & Klessen (2004)

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**

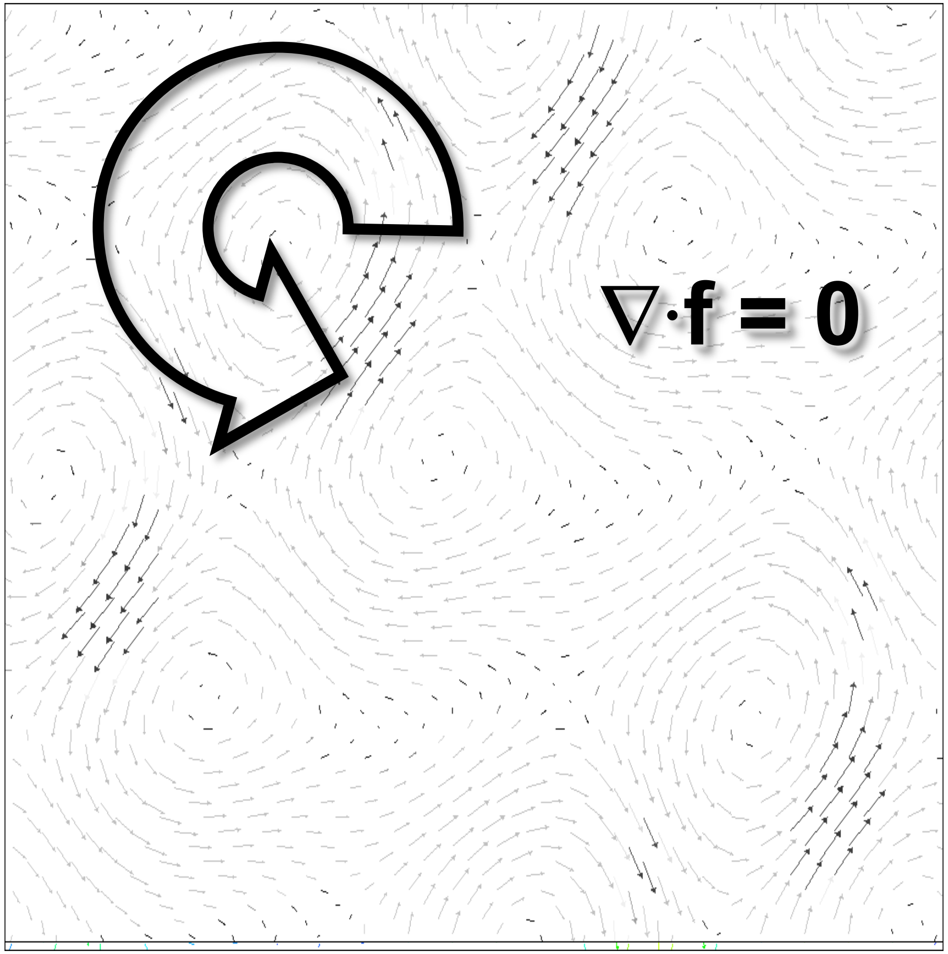
e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Kowal+2007, Dib+2008, Offner+2008, Schmidt+2009, Burkhart +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 +++

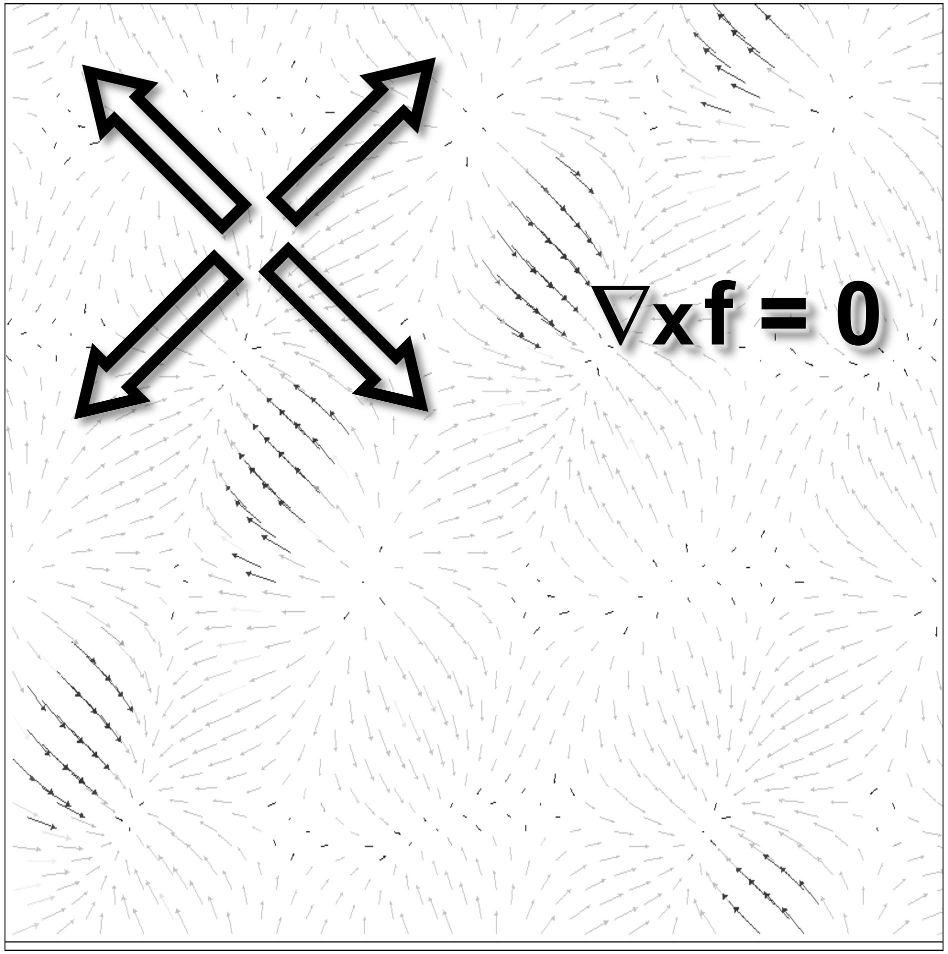
Turbulence driving – solenoidal versus compressive

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

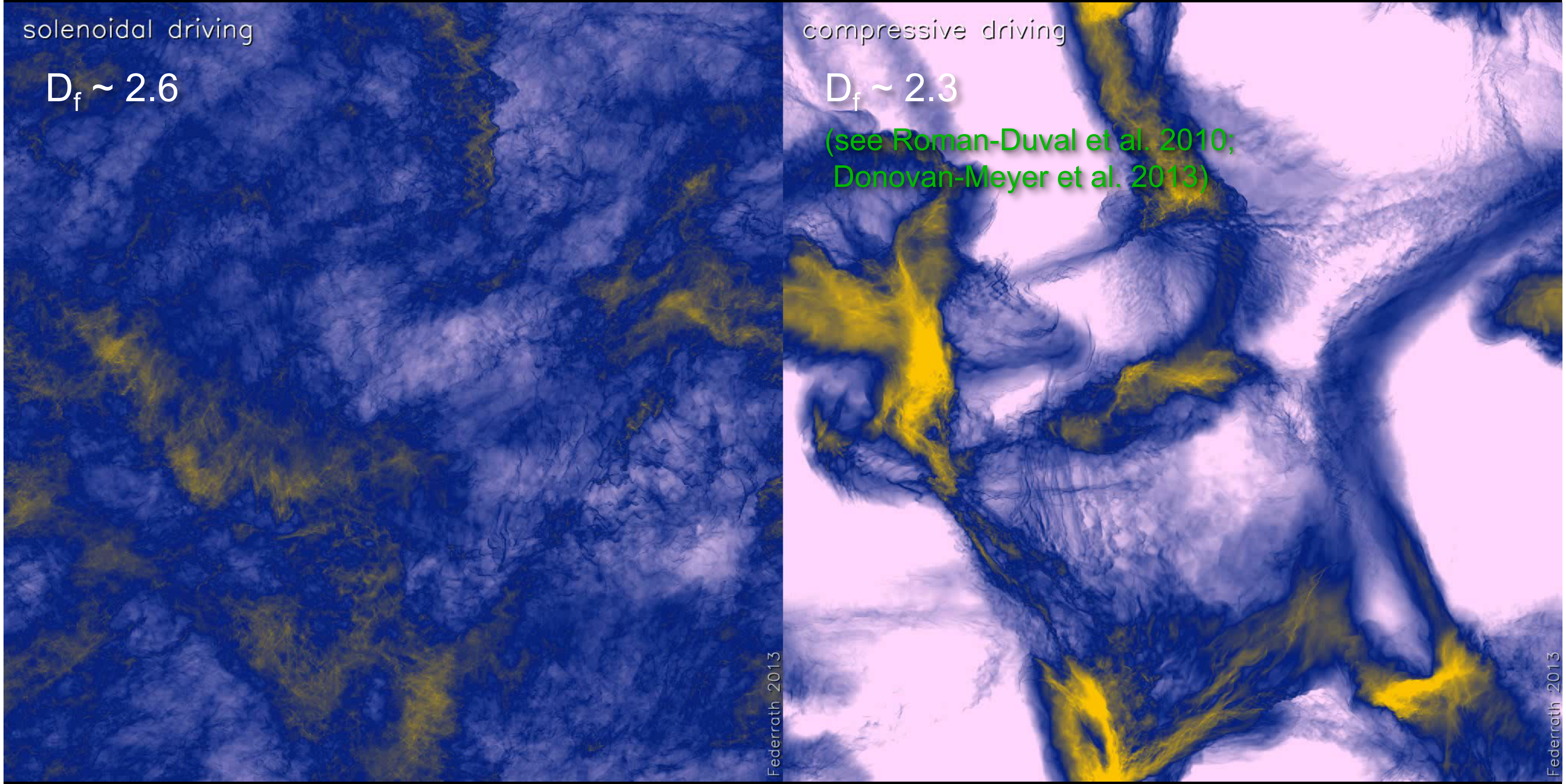




Turbulence driving – solenoidal versus compressive

Column Density

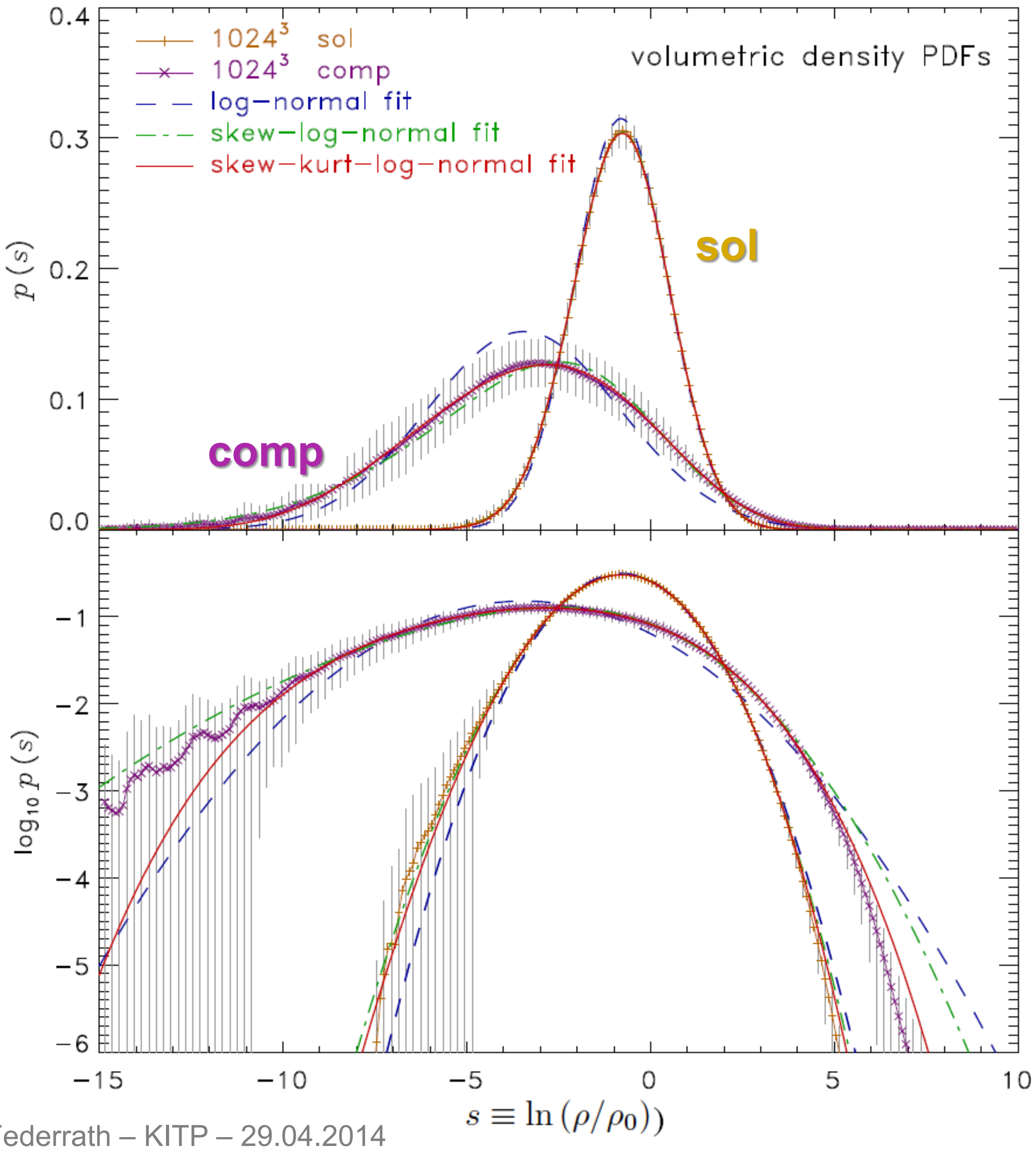
Movies available: http://www.ita.uni-heidelberg.de/~chfeder/pubs/supersonic/supersonic.shtml



Compressive forcing produces stronger density enhancements

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

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); Hopkins (2013)

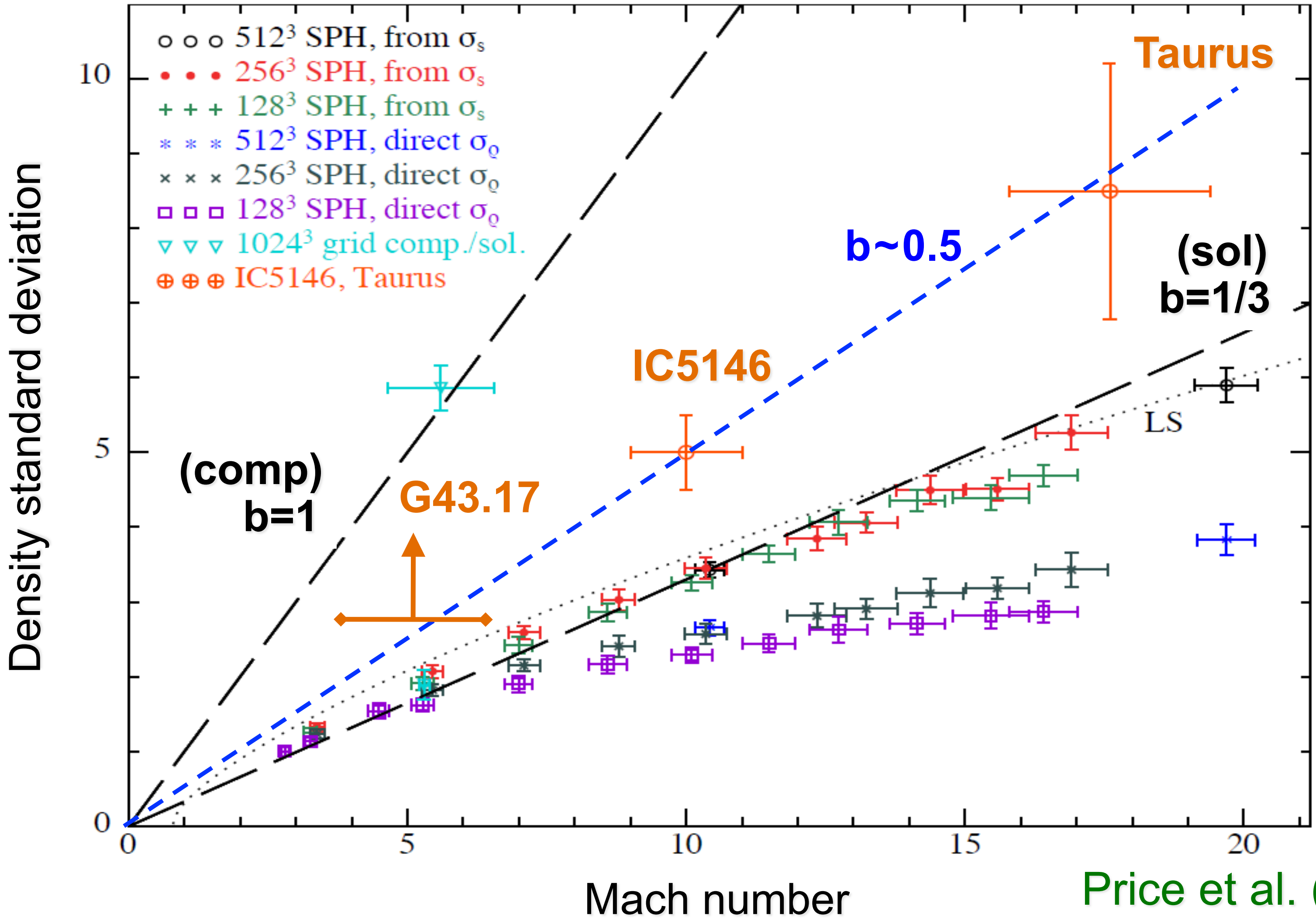
$$\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right)$$

b = 1/3 (sol)

b = 1 (comp)

Federrath et al. (2008, 2010); Konstandin et al. (2012)

The density PDF



2D → 3D conversion

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

(Brunt et al. 2010a,b)

Price et al. (2011)

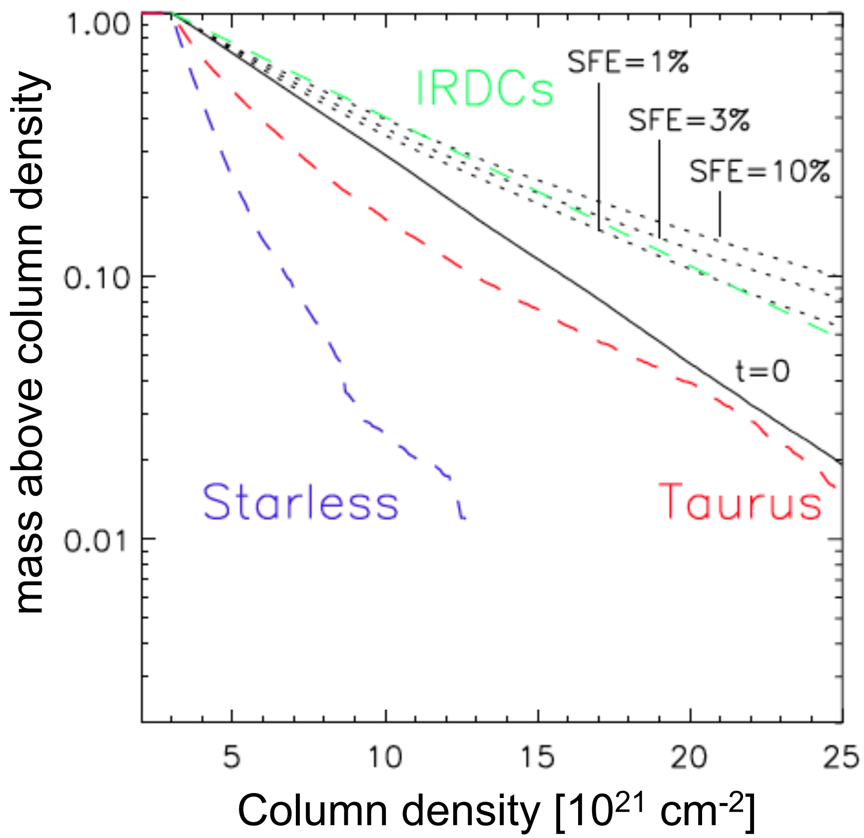
Padoan et al. (1997), Brunt (2010), Burkhart & Lazarian (2012), Ginsburg et al. (2013)

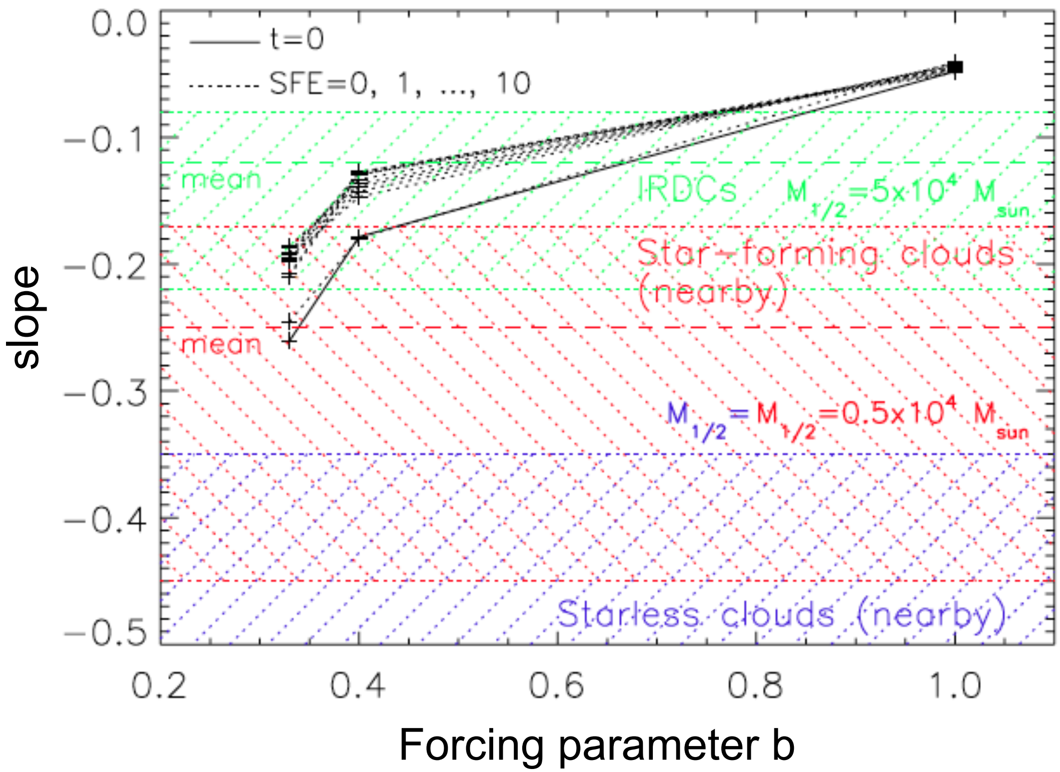
$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right) \xrightarrow{p(s)} \sigma_{\rho/\rho_0} = b\,\mathcal{M}$$

Compressive forcing and/or gravity required to explain observations

PDF → The dense gas mass fraction

Kainulainen et al. (2013); See also
Kainulainen et al. (2014, *Science Vol. 344 no. 6180 pp. 183-185*)





Sequence: Starless → Star-forming (nearby) → IRDCs → more massive clouds?

(5×10^3 $M_\odot$) (5×10^4 $M_\odot$)

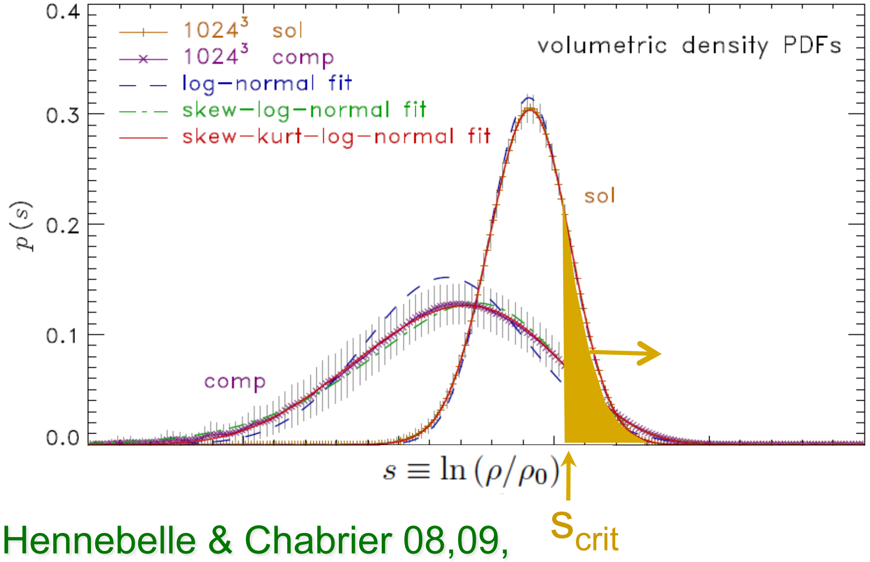
Modeling jet and outflow feedback

Turbulence → Density PDF

Density PDF → 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+11, Hopkins 12)
- **Star Formation Efficiency** (Elmegreen 08, Federrath & Klessen 13)
- **Kennicutt-Schmidt relation** (Elmegreen 02, Krumholz & McKee 05, Tassis 07, Ostriker+10)
- **Star Formation Rate** (Krumholz & McKee 05, Padoan & Nordlund 11, Renaud+12)

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)

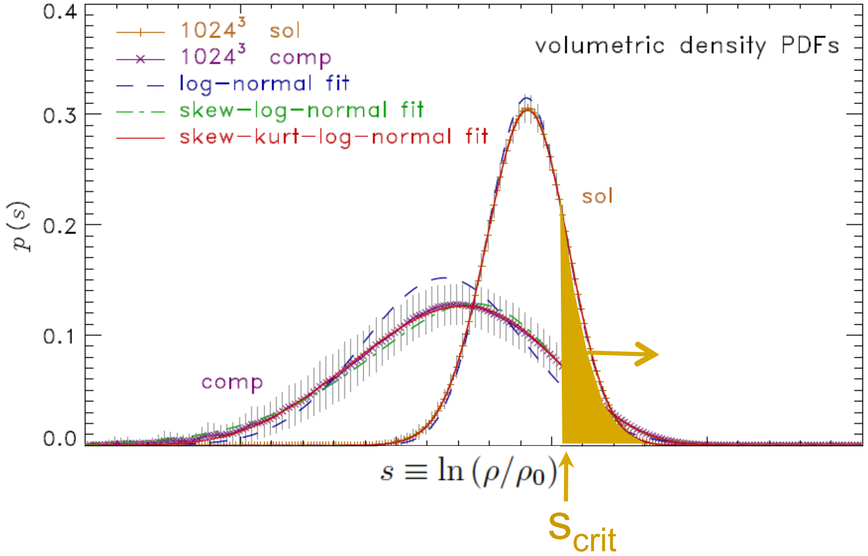
Density PDF → Star Formation Rate

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

freefall time | **mass fraction**

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



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

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

Statistical Theory for the Star Formation Rate:

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

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

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”

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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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”

From sonic and Jeans scales:

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

(Krumholz & McKee 2005, Padoan & Nordlund 2011)

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

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

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

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

Federrath & Klessen (2012)

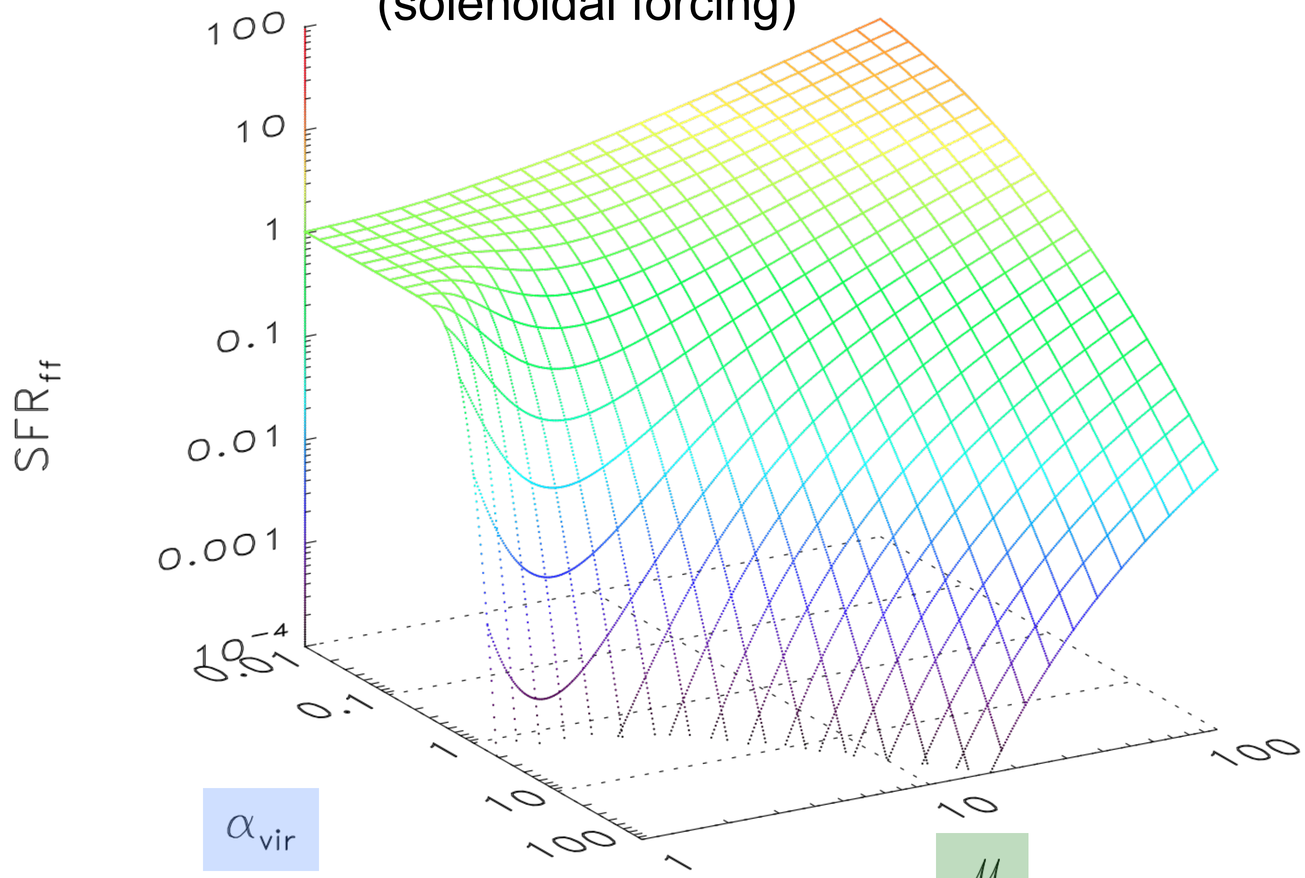
Density PDF → Star Formation Rate

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

---

forcing parameter (b=0.33) multi−freefall

(solenoidal forcing)



If α_{vir}↑ then SFR↓

If $\mathcal{M}$↑ then SFR↑

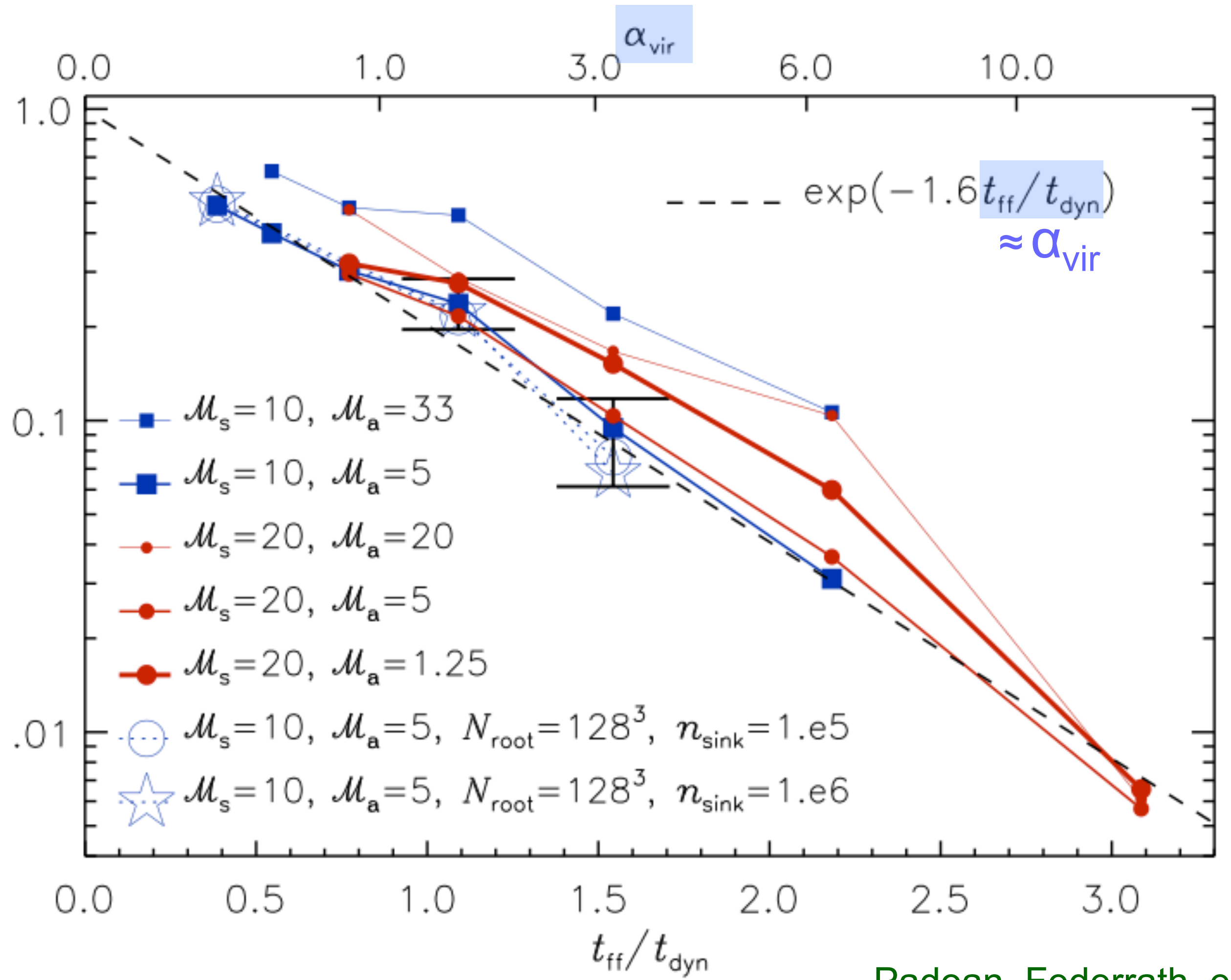
Federrath & Klessen (2012)

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**

Numerical simulations varying α_{vir}



Padoan, Federrath, et al. (2014, PPVI)

Density PDF → Star Formation Rate

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

---

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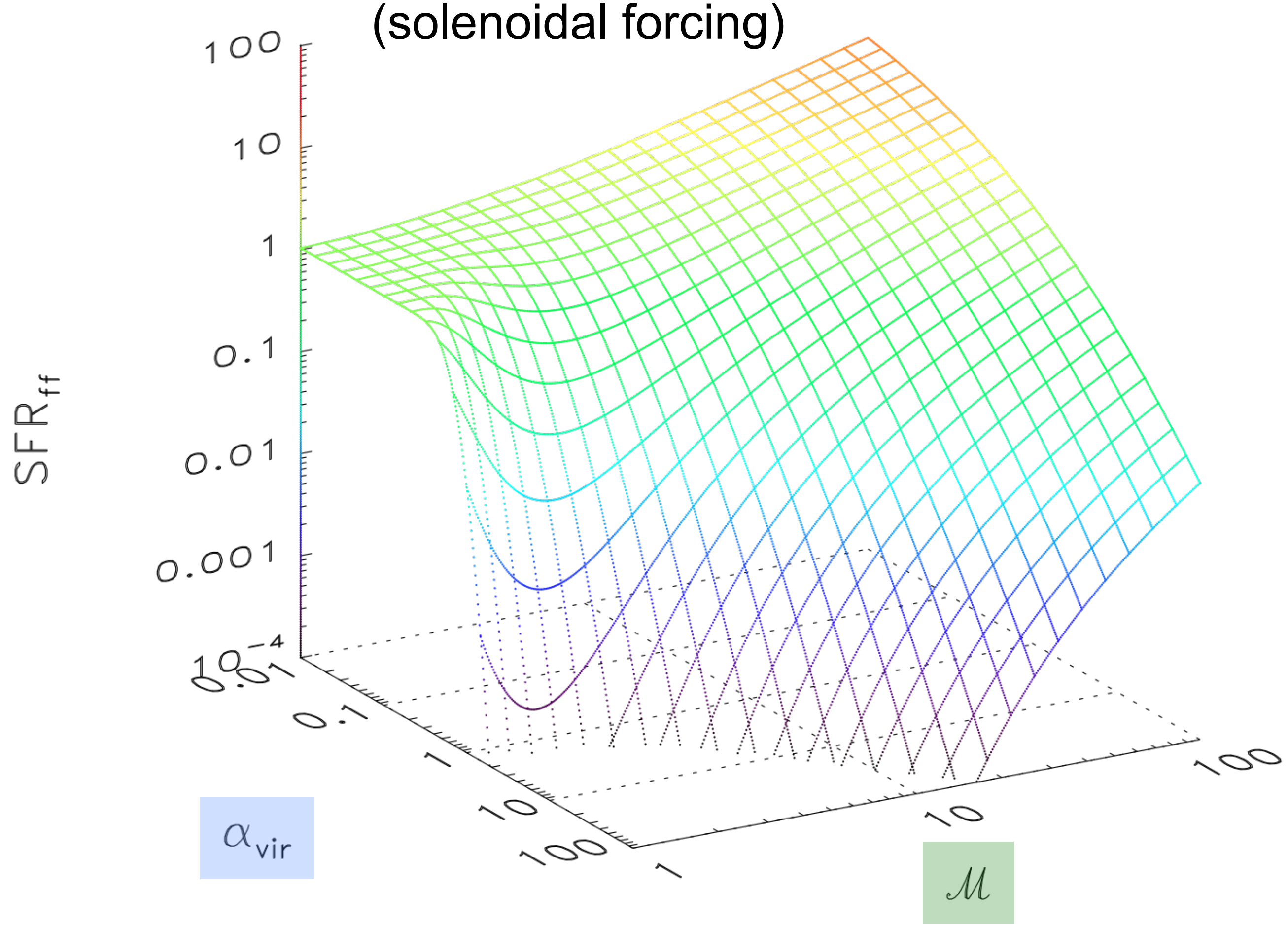
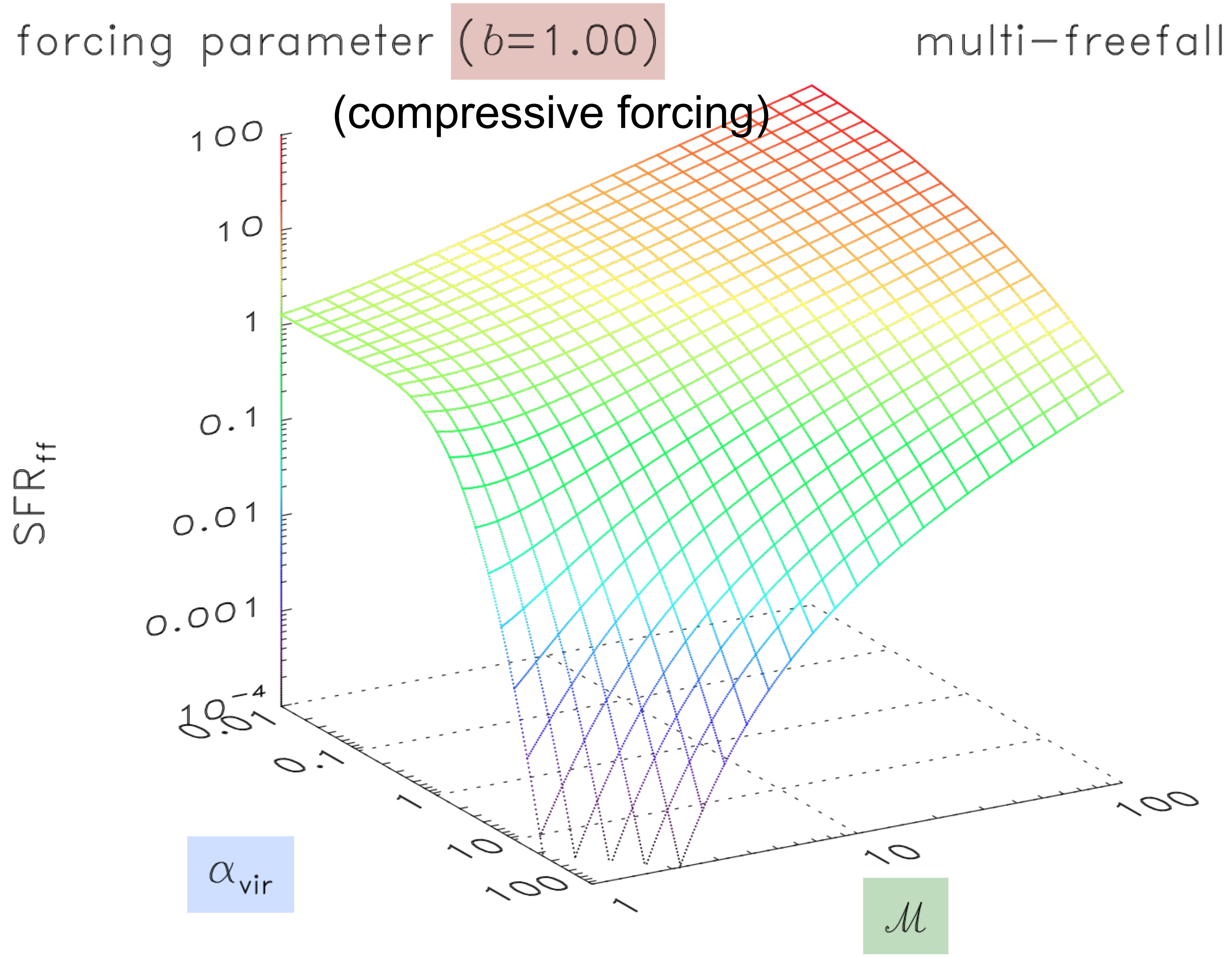


Federrath & Klessen (2012)

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**

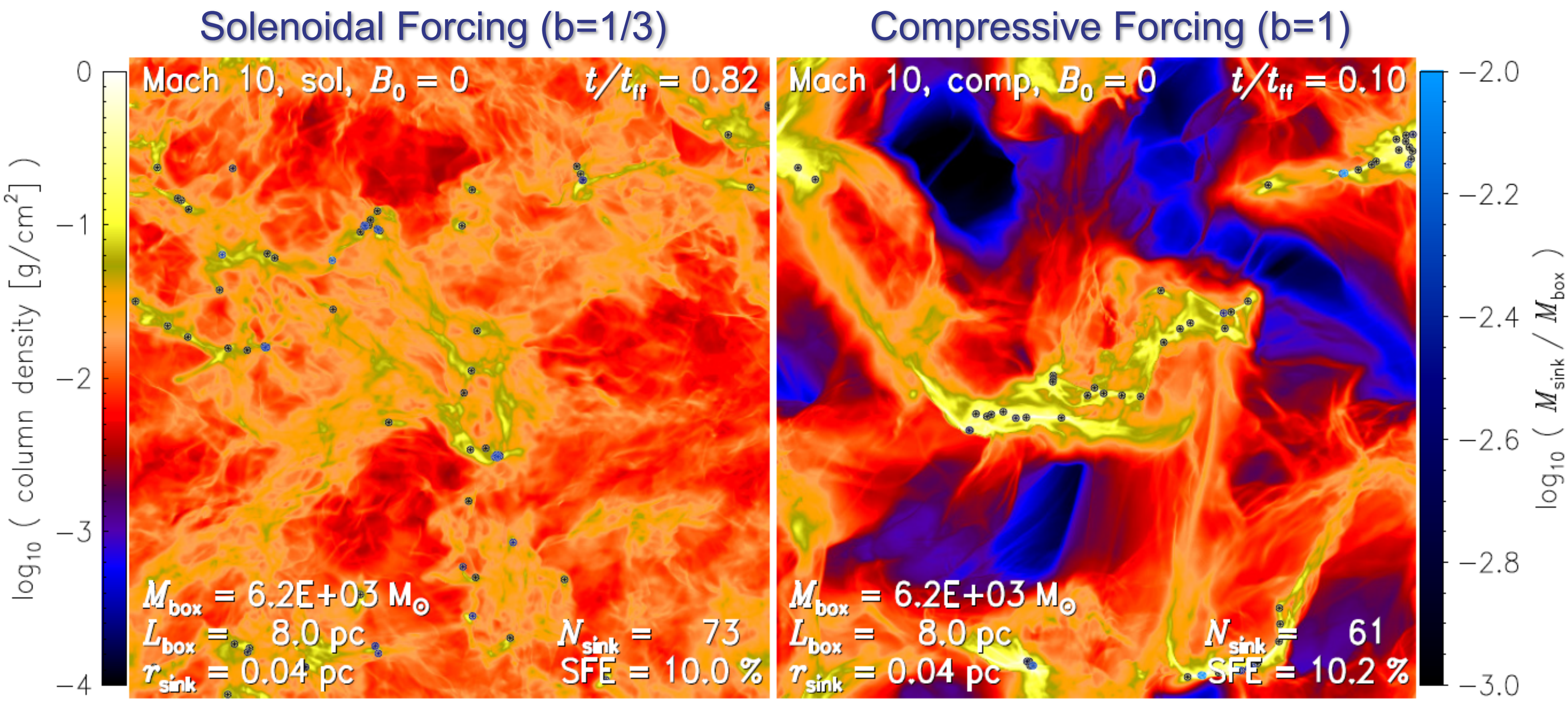


Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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

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



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:

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

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

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

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

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

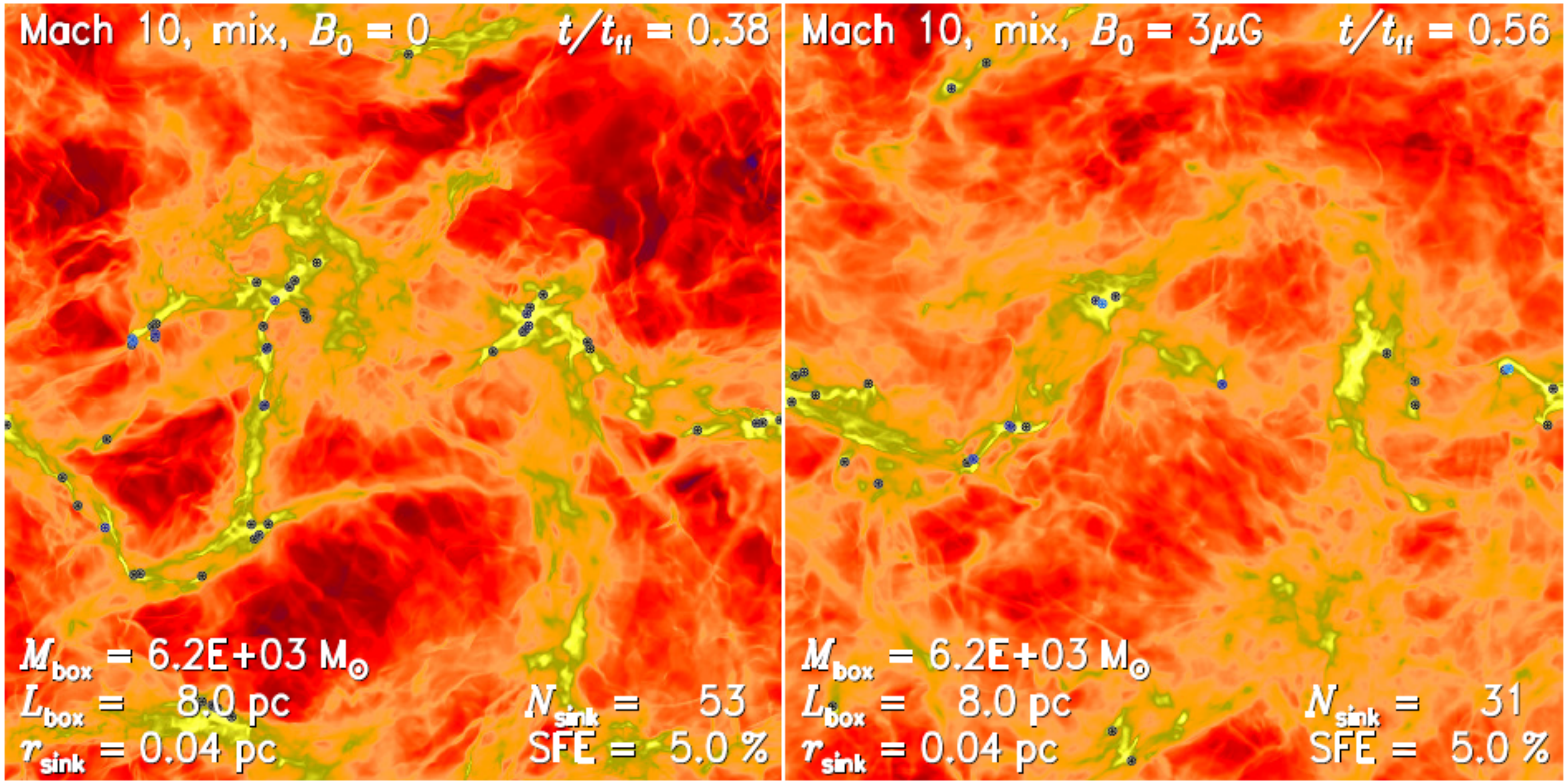
$2\,E_{kin}/E_{grav}$ **forcing** **Mach number** **plasma $\beta = P_{th}/P_{mag}$**

Federrath & Klessen (2012)

Numerical Test for 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).

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

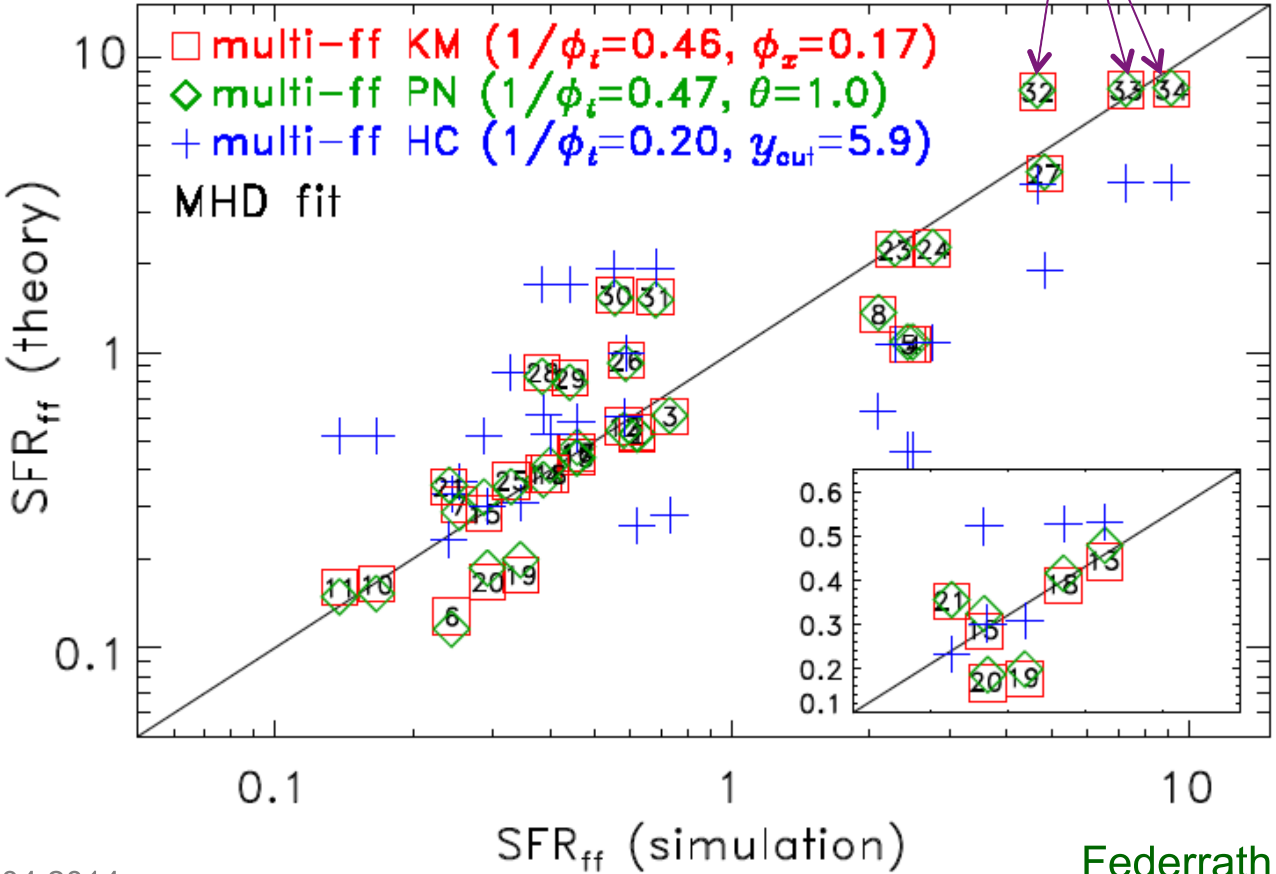
The Star Formation Rate of MHD turbulence

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)

The Star Formation Rate of MHD turbulence

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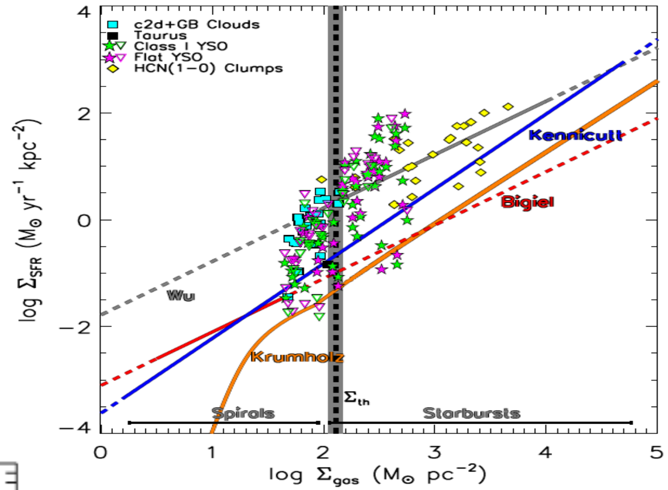
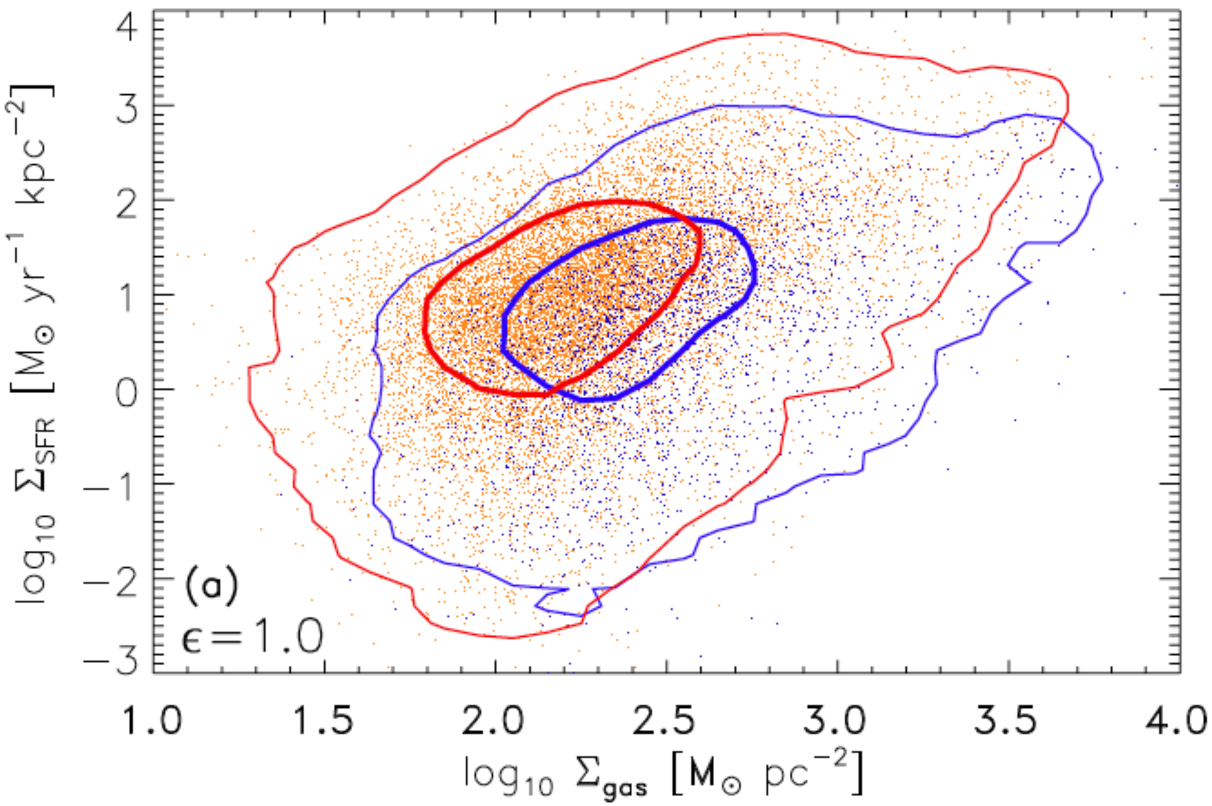


(Heiderman et al. 2010)

Simulations *vs.* Observations



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 of MHD turbulence

Compare simulations with

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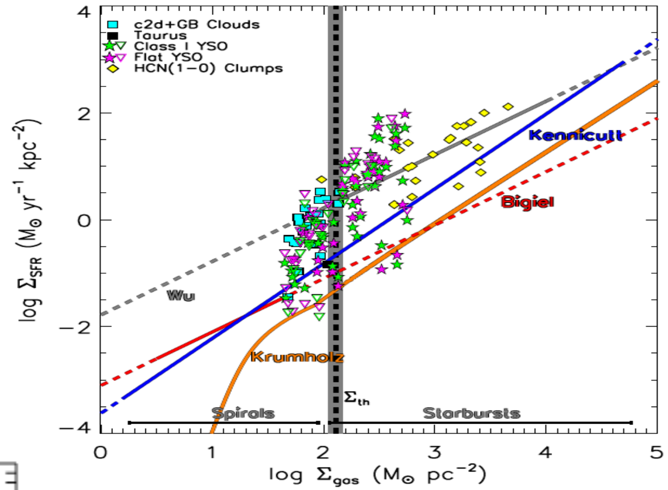
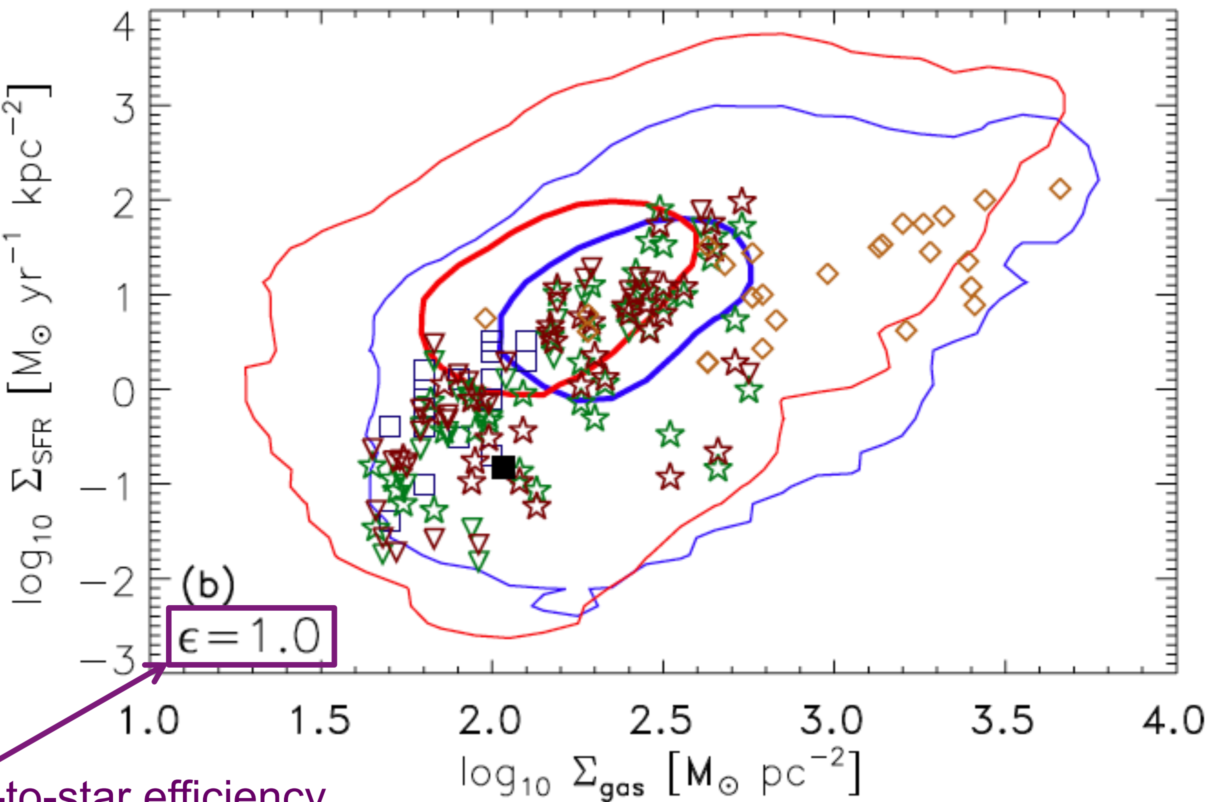


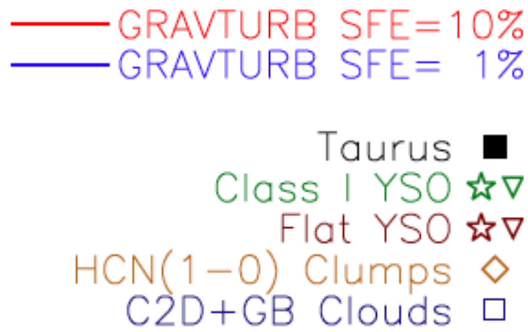
(Heiderman et al. 2010)

Simulations *vs.* Observations



core-to-star efficiency

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



Federrath & Klessen (2012)

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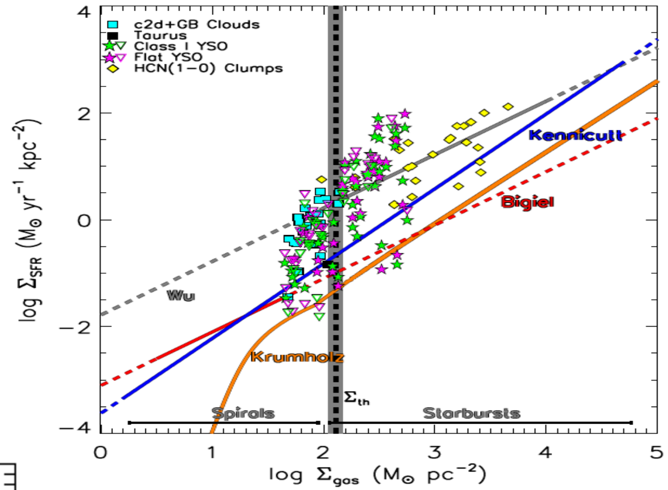

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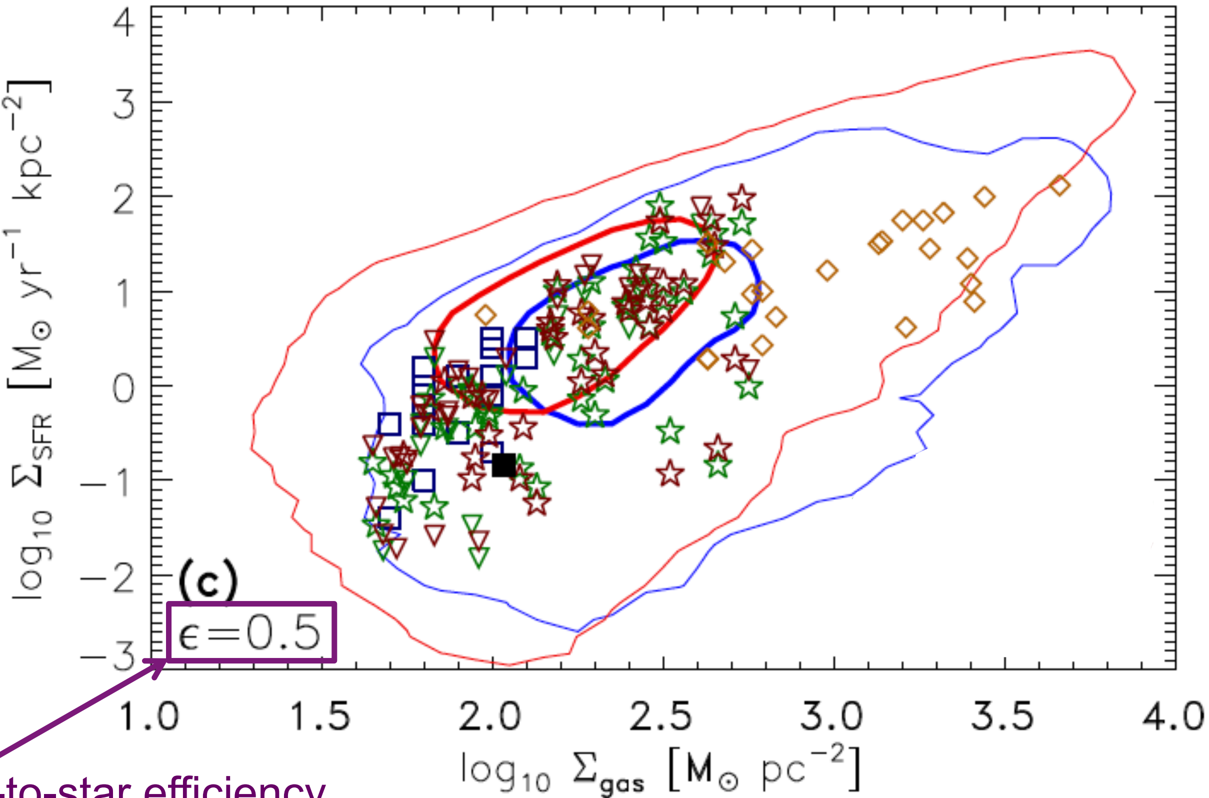
Simulations *vs.* Observations



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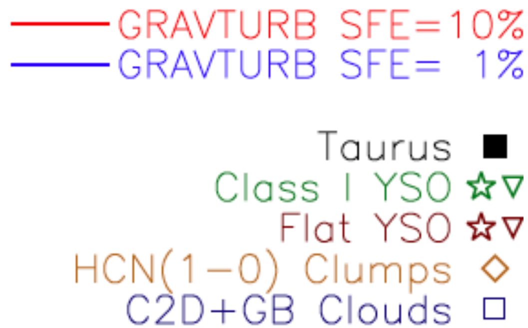


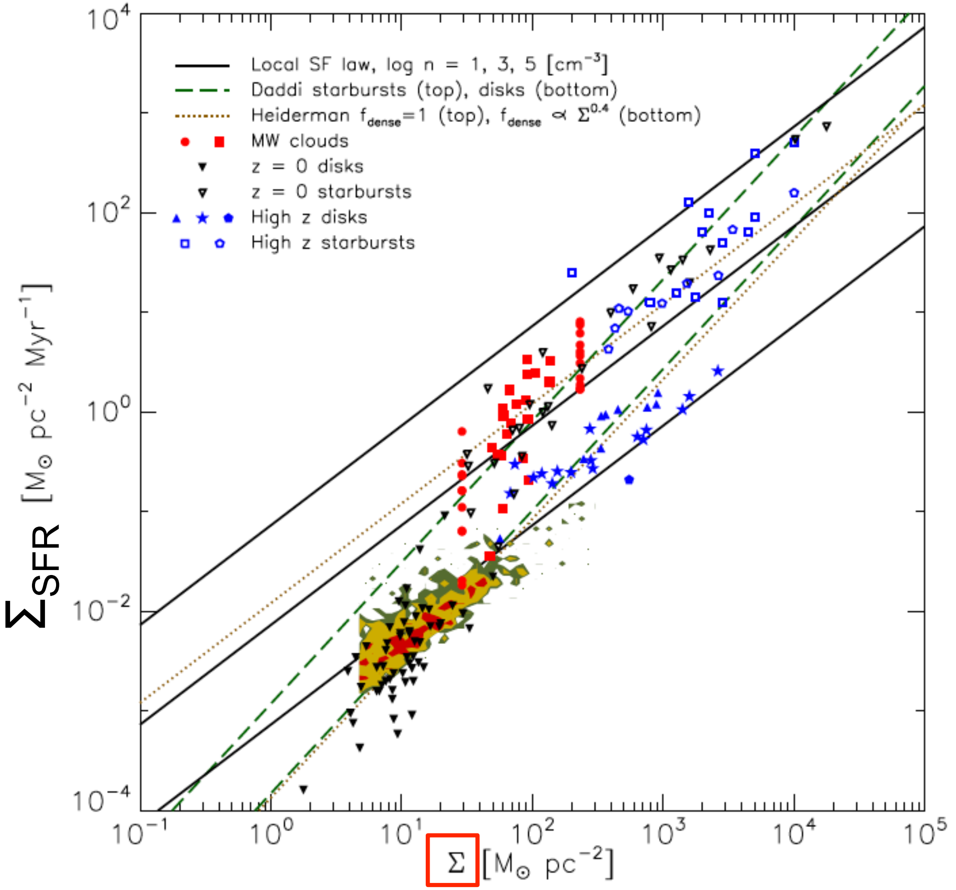
Federrath & Klessen (2012)

Application to Extra-Galactic Star Formation

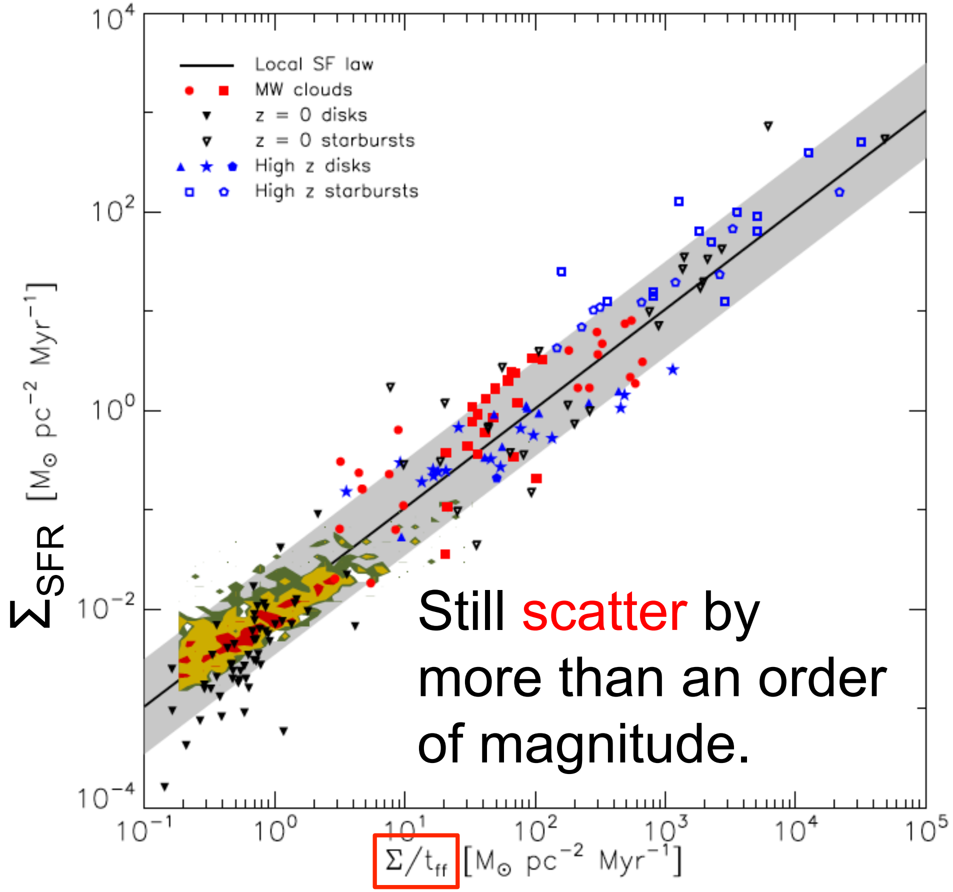
Physical Variations in the Universal Star Formation Law

Krumholz, Dekel, McKee (2012)

A more universal star formation "law"?

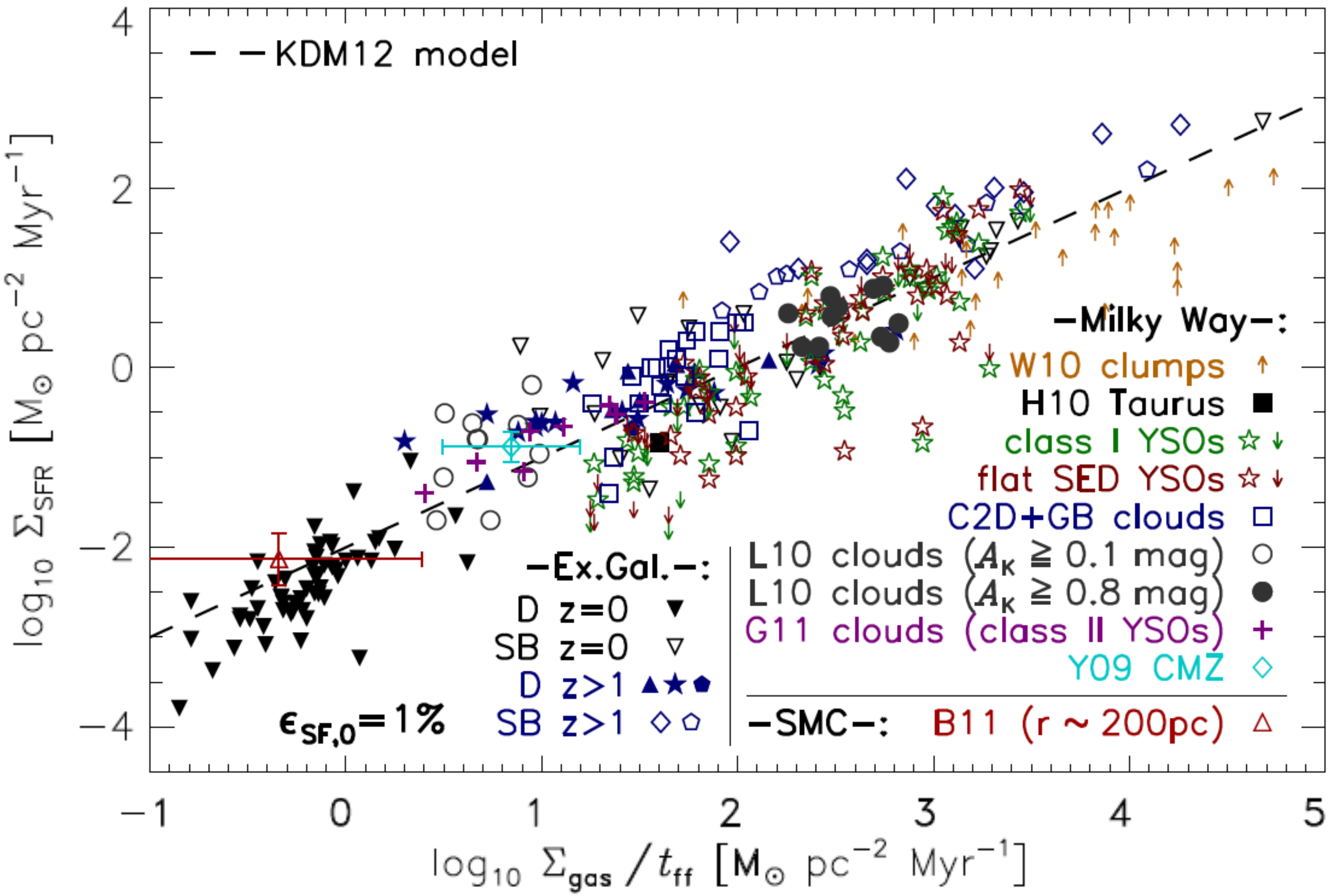


just Σ_{gas}
(classical Kennicutt-Schmidt relation)



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

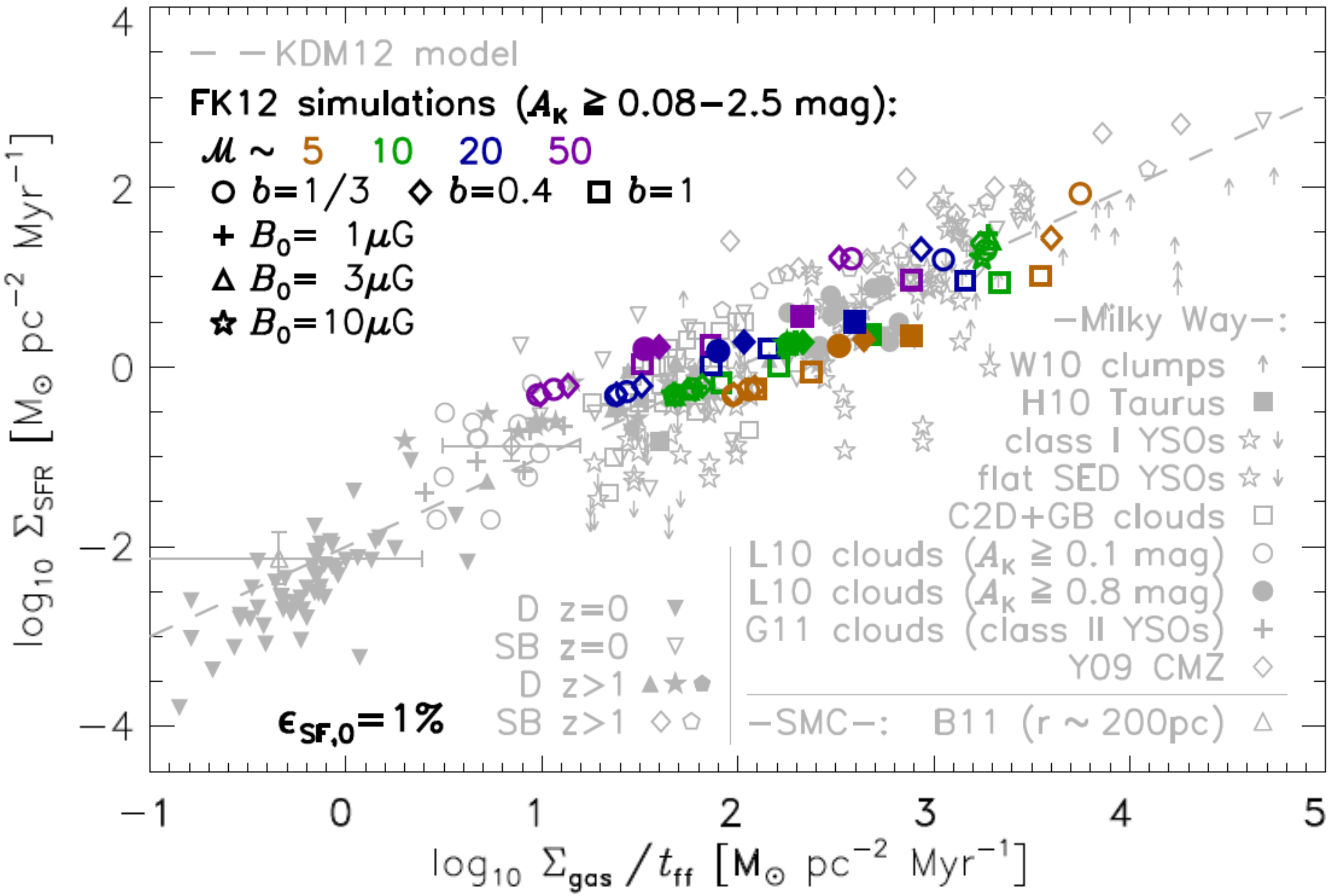
Physical Variations in the Universal Star Formation Law



Scatter caused by variations in the turbulence (Mach number, driving)

Federrath (2013, MNRAS 436, 3167)

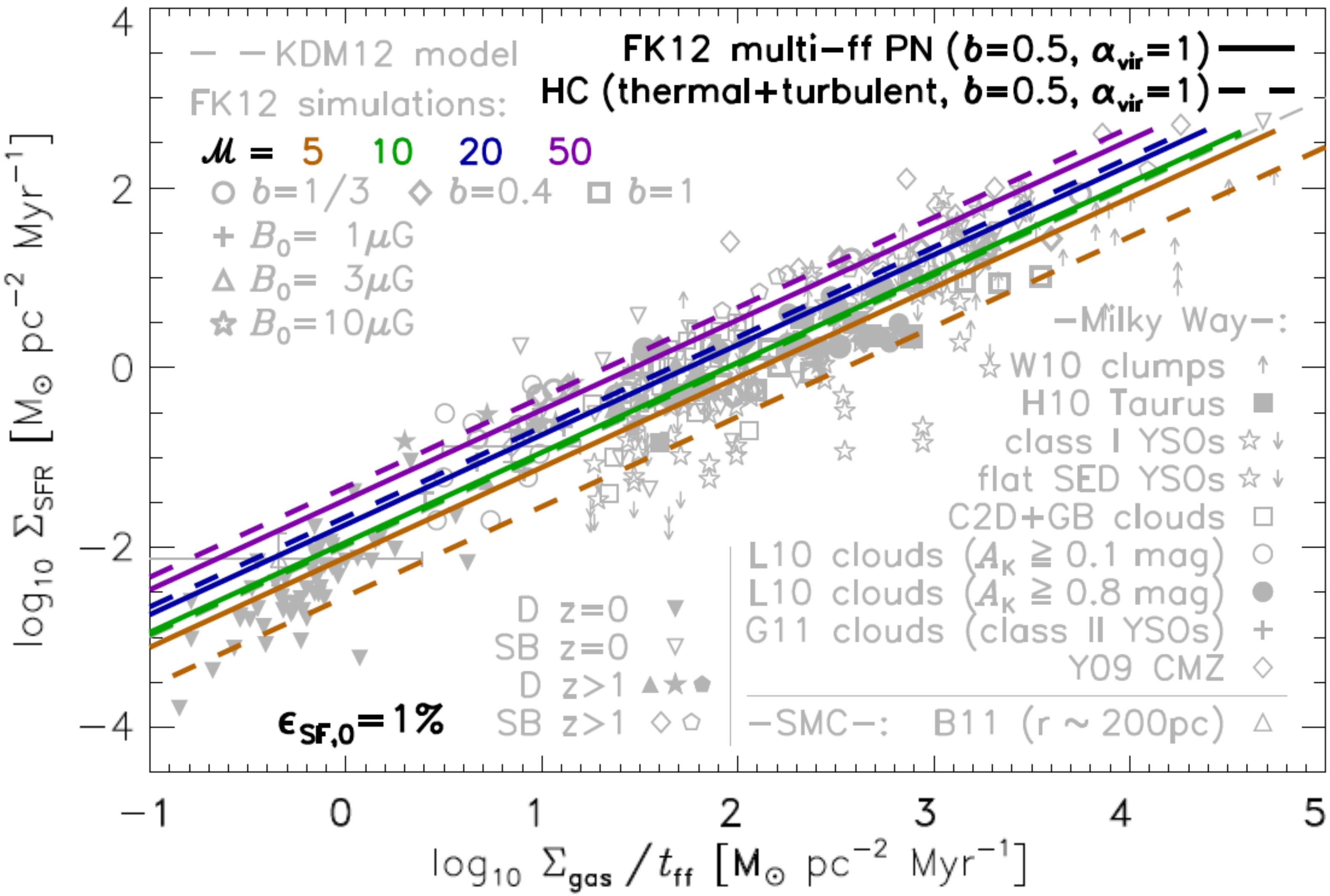
Physical Variations in the Universal Star Formation Law



Scatter caused by variations in the turbulence (Mach number, driving)

Federrath (2013, MNRAS 436, 3167)

Physical Variations in the Universal Star Formation Law



Scatter caused by variations in the turbulence (Mach number, driving)

Federrath (2013, MNRAS 436, 3167)

Conclusions

- 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
- 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
- Scatter in star formation relations → potentially caused by variations in the turbulence