Feedback-regulated star formation:
More and cosmological

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Take home messages

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• In cosmo sims: resolve GMC formation, explicitly model feedback
Gravitational weight of disk gas = momentum/time from supernovae

\[ \dot{\Sigma}_* \propto \Sigma_g^2 \]

applies to molecule-dominated galaxies, mergers & non-mergers

\[ \log \dot{\Sigma}_* \left( \frac{M_{\odot}}{\text{yr}^{-1} \text{kpc}^{-2}} \right) \]

\[ \log \Sigma_g \left( \frac{M_{\odot}}{\text{pc}^{-2}} \right) \]
The SFE is *not* universal, scales with gas fraction $f_g$

Feedback-regulated prediction vs. observations

$$c_{\text{gal}}^{\text{eff}} \sim \frac{f_g v_c}{P_*/m_*} \quad (Q \sim 1)$$

- $z \sim 0$
- $z \sim 1-3$
- $\Sigma_{\text{mol}} < 100 \, M_\odot \, \text{pc}^{-2}$

CAFG, Quataert, & Hopkins 13, CAFG+, in prep.
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Feedback-regulated prediction vs. observations

Also: $c_T \sim f_g v_c / 2 \Rightarrow$ high $c_T$ in ULIRGs, high-z SFGs

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Stars form in giant molecular clouds

- In Milky Way, 1/3 of current star formation occurs in 33 GMCs

~~Ionizing radiation in Milky Way (Rahman & Murray 10)~~
Stars form in giant molecular clouds

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- Gravitational instability forms GMCs and sets their mass $M_T \sim h^2 \Sigma_g$
  
  $\Rightarrow$ $\sim 10^6 \, M_{\text{sun}}$ in Milky Way

  $\Rightarrow$ $\sim 10^9 \, M_{\text{sun}}$ in gas-rich $z \sim 2$ star-forming galaxies
GMC formation is rate limiting step for SF

- Feedback-driven turbulence keeps disk marginally grav. stable, throttles *formation rate of GMCs* and thus galaxy star formation rate
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- To capture essential physics of star formation, resolve GMC formation and model stellar feedback
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- Feedback-driven turbulence keeps disk marginally grav. stable, throttles formation rate of GMCs and thus galaxy star formation rate
- To capture essential physics of star formation, resolve GMC formation and model stellar feedback
- Galaxy SFR weakly dependent on SF prescription on scales ≪ GMCs
**Contrast with ‘supersonic turbulence’ theories**

- *In SST theories,* low $\varepsilon_{\text{ff}}$ identified with mass fraction in self-gravitating tail of $\sim$lognormal density PDF

![Graph showing lognormal distribution](image)
Contrast with ‘supersonic turbulence’ theories

- In SST theories, low $\varepsilon_{\text{ff}}$ identified with mass fraction in self-gravitating tail of $\sim$lognormal density PDF

- Universal $\varepsilon_{\text{ff}} \sim 0.01$ for isothermal gas, absent self-gravity
  (Krumholz & McKee 05; see also Padoan, Nordlund, Federrath, Klessen, ...)

Fig.: Bournaud 11
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- Problem: with self-gravity, PDF doesn’t stay lognormal, get runaway collapse (e.g., Murray & Chang 12)
Universal SFE predictions of SST theories are inconsistent with observations

Universal $\epsilon_{\text{ff}}$ predictions for disks

$\log_{10} \dot{M}_* (M_\odot \text{ yr}^{-1})$

$\log_{10} \left[ M_g v_c / 1.14 R_{1/2} \right] (M_\odot \text{ yr}^{-1})$

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- $\Sigma_{\text{mol}} < 100 M_\odot \text{ pc}^{-2}$

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Milky Way GMC efficiencies

- CAFG+, in prep.
- $z \sim 0$
- $z \sim 1-3$
- $\Sigma_{\text{mol}} < 100 \, M_\odot \, \text{pc}^{-2}$

- K&M05 SST
- MW avg
- Murray II

$\log_{10} [M_g v_c / 1.14 R_{1/2}]$ (M$_\odot$ yr$^{-1}$)

$(M_{\text{GMC}} + M_*) / M_\odot$
What about Krumholz, Dekel, & McKee 2012?

The scatter given is a multiplicative factor, so a scatter of unity indicates perfect scatter. The failure of a power-law fit between the extragalactic data including both disks and starbursts is 

\[ \frac{\dot{\Sigma}}{t_{\text{ff}}} \] 

is far different and far worse: slope \( \eta = 0.8 \), factor of 20, missing Norm's clouds!

KDM12

\[ \Sigma \] 

\[ t_{\text{ff}} \]

\[ \dot{\Sigma} \] 

\[ M_\odot \text{ pc}^{-2} \text{ Myr}^{-1} \]
What about Krumholz, Dekel, & McKee 2012?

- Factor $\sim 100$ in $\varepsilon_{\text{eff}}^{\text{gal}}$ scatter is not random about universal value: reduced by $\sim 1$ dex when plotted against $f_g \nu_c$
FIRE: Feedback In Realistic Environments

- Cosmo zoom-ins directly resolving GMC formation at all redshifts
- Metal and molecular line cooling, UVB, SF in self-gravitating gas
- Stellar feedback (SNe, photoion, stellar winds, rad. P) based on SB99
- P-SPH, resolving main discrepancies between grid and standard SPH
- SF law, winds, etc. predicted, not put in

w/ Hopkins, Kereš, Quataert, Murray
First FIRE results

Code comparison

Halo gas covering fractions

Preliminary comparisons with obs. very promising; much more to come!

CAFG+, Hopkins+, Kereš+, in prep.