Title: Feedback-regulated star formation on galactic and cosmological scales

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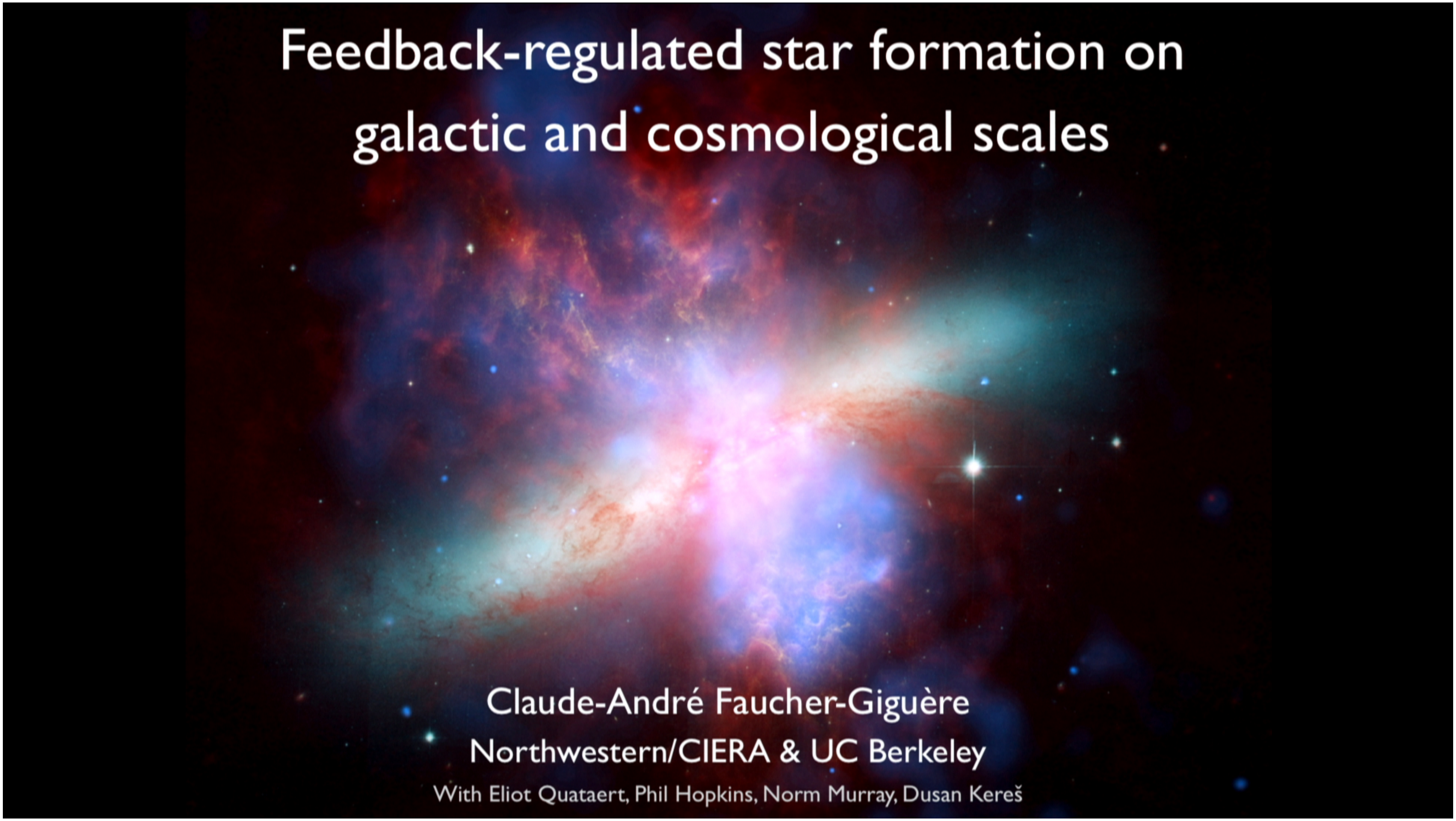
Abstract: A central problem in galaxy formation is to understand why star formation is so inefficient. Within individual galaxies, gas is converted into stars at a rate two orders of magnitude slower than unimpeded gravitational collapse predicts, a fact embodied in the low normalization of the observed Kennicutt-Schmidt (K-S) relationship between star formation rate surface density and gas surface density. Star formation in galaxies is also globally inefficient in the sense that the stellar mass in dark matter halos is a small fraction of the universal baryon fraction. I will show that these two facts can be explained by the self-regulation of star formation by feedback from massive stars. Within galaxies, stellar feedback drives turbulence that supports the interstellar medium against collapse and the K-S law is set by the low strength of gravity relative to stellar feedback. The energy input from the same stellar feedback processes drive powerful galactic outflows that remove most of the gas accreted from the intergalactic medium before it has time to turn into stars. Using cosmological hydrodynamical simulations from our FIRE project ("Feedback In Realistic Environments"), I will show that gas removal by star formation-driven galactic winds successfully explains the observed galaxy stellar mass function, at least for galaxies less massive than the Milky Way. Feedback from massive black holes may be required to explain the quenching of more massive galaxies. Motivated by recent observations, I will discuss the physics of galactic winds driven by active galactic nuclei.

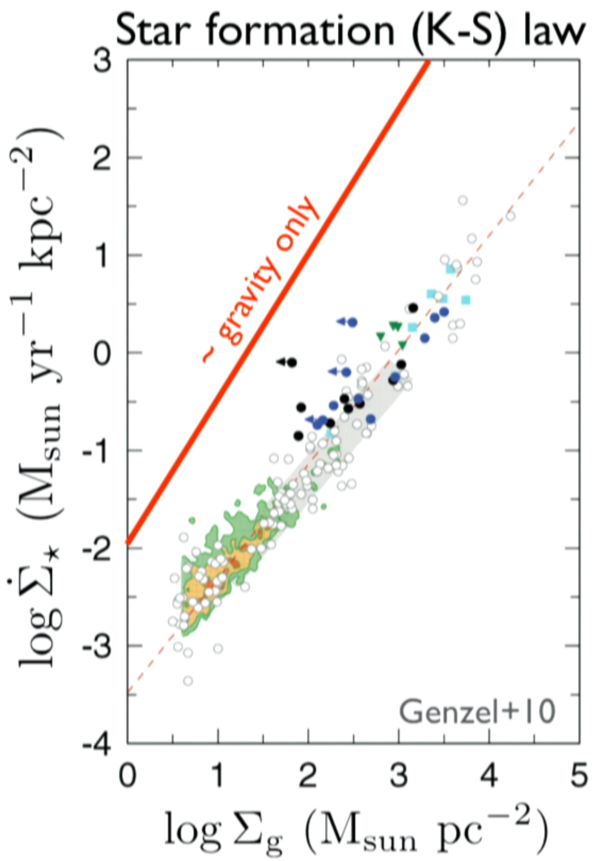

Feedback-regulated star formation on galactic and cosmological scales
Claude-André Faucher-Giguère
Northwestern/CIERA & UC Berkeley
With Eliot Quataert, Phil Hopkins, Norm Murray, Dusan Kereš

Star formation is very slow on galactic scales

- Within individual galaxies, expect

$$\text{Star form. rate} \approx \frac{\text{Gas mass}}{\text{Free fall time}}$$

- Observationally, ~50× slower, i.e. SF efficiency *per free fall time* ε_{ff}^{gal}~0.02



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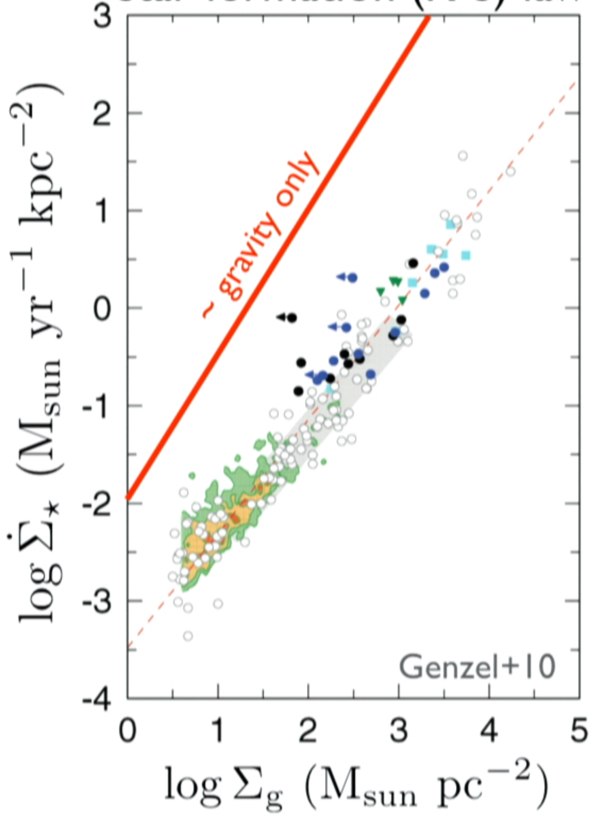
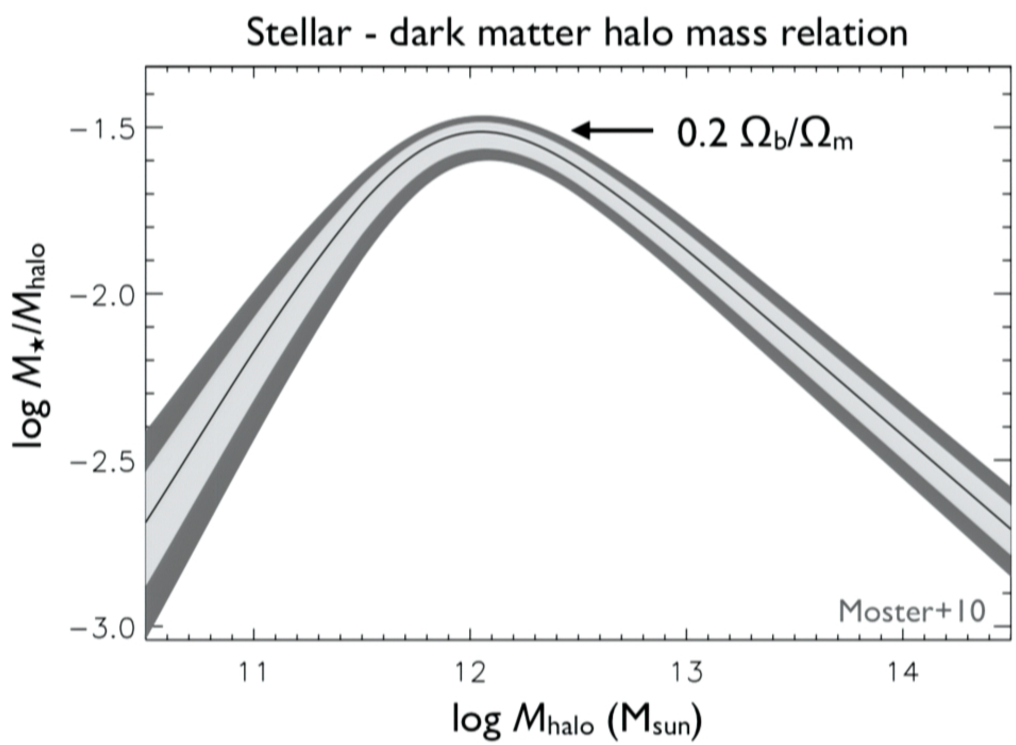
Star formation (K-S) law



Star formation is also cosmologically inefficient



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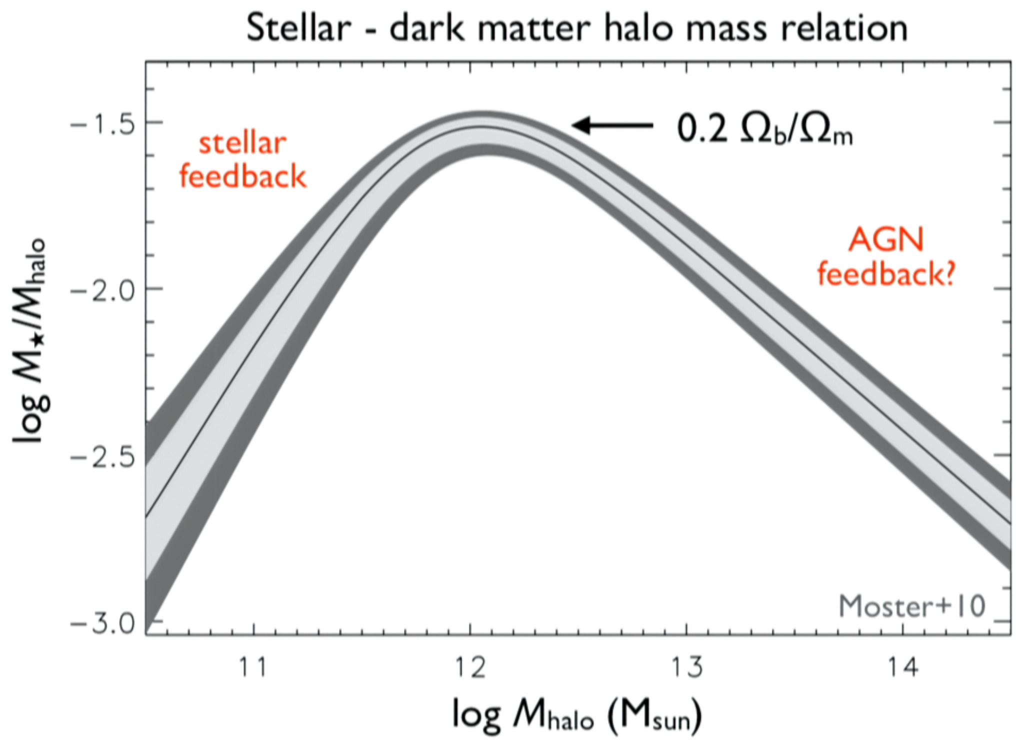
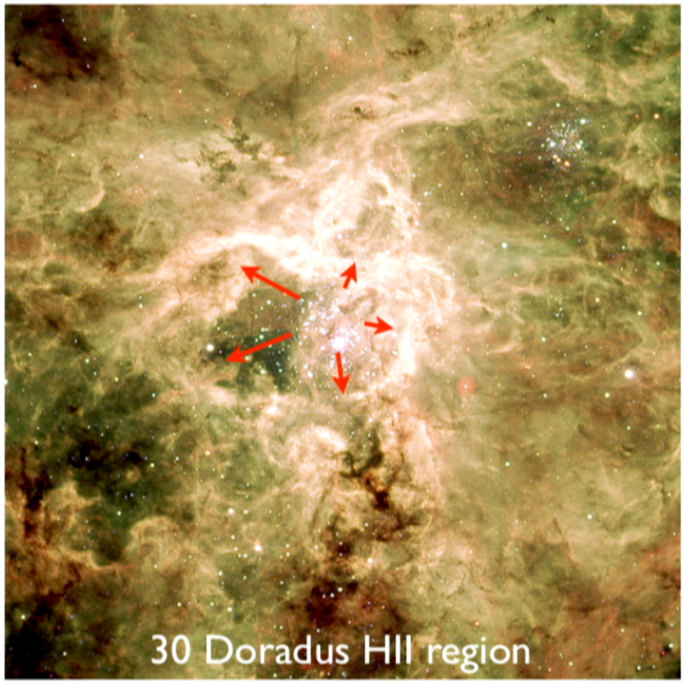
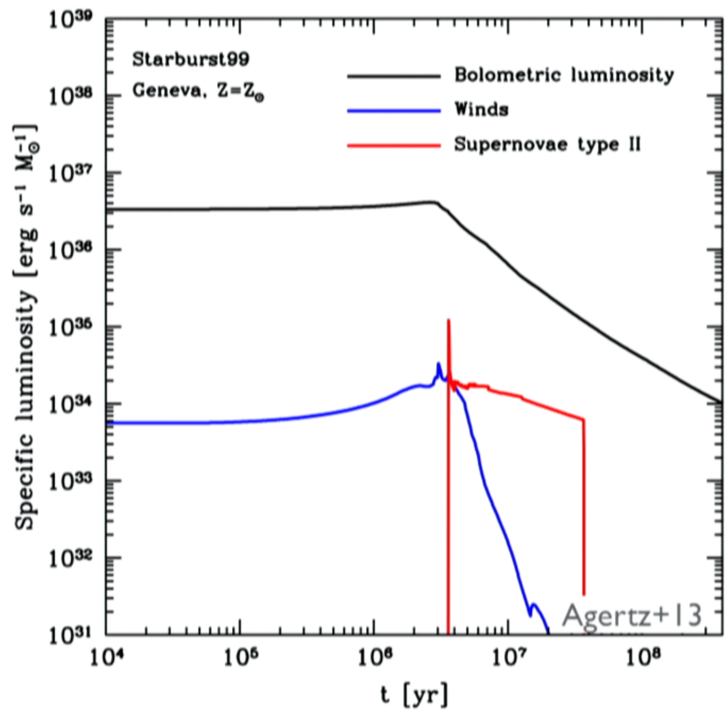


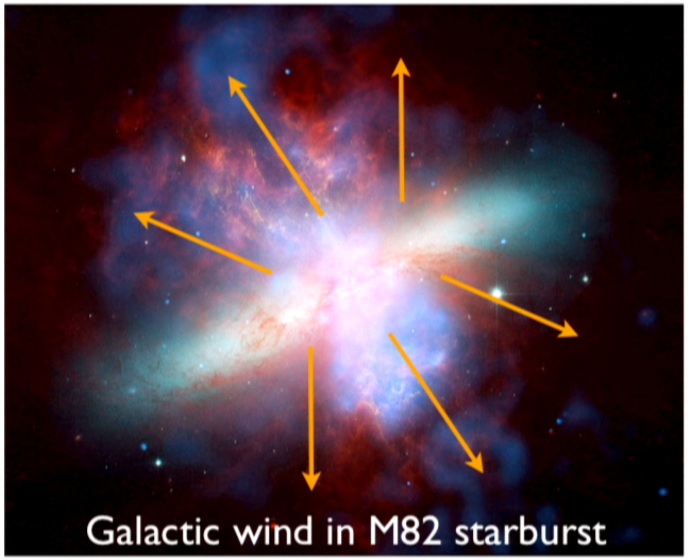
Since free fall time in galaxies ≪ Hubble, two problems are independent

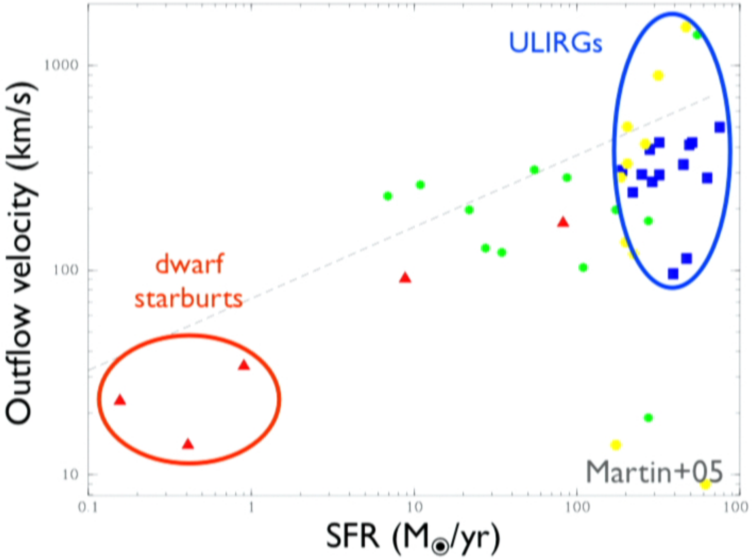
Stellar feedback: massive stars emit ionizing radiation, drive winds, explode in supernovae





Collectively, stellar feedback processes drive interstellar turbulence and galactic winds





Outline

- **Feedback-regulated star formation in galaxies**
  - ➡ origin of the galaxy-averaged $\dot{\Sigma}_\star - \Sigma_{\rm g}$ relation (K-S law)
  - ➡ GMCs as the rate-limiting step
  - ➡ contrast with 'supersonic turbulence' models

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- Star formation and feedback in the FIRE cosmological simulations
    - ➡ project description and early results on $M_{\star}$ - $M_{\rm halo}$ and halo gas

Feedback-regulation via hydrostatic balance

In a disk of thickness *h*, mean gas density $\bar{\rho}$, surface gas density $\Sigma_{\rm g}$, the star formation rate surface density is $\dot{\Sigma}_\star$.

Feedback processes return a momentum per stellar mass formed $P_\star/m_\star$ in the ISM, generating turbulent eddies with velocity $v_{\rm turb}$.

Disk is in vertical hydrostatic balance when turbulent pressure $p_{\rm turb}$ equals weight of the disk gas $p_{\rm grav}$.

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Turbulent pressure in galactic disk

Rate of turbulent energy injection by feedback:

$$\dot{e}_{\rm in} \approx \frac{\dot{\Sigma}_\star}{h}\left(\frac{P_\star}{m_\star}\right)\frac{v_{\rm turb}}{2}$$

Dissipation rate of turbulent energy:

$$\dot{e}_{\rm diss} \approx \frac{\bar{\rho} v_{\rm turb}^2}{t_{\rm diss}}$$

Turbulence dissipation time:

e.g., Stone+98, MacLow 99

$$t_{\rm diss} \approx \frac{h}{v_{\rm turb}}$$

Equilibrium turbulent pressure:

$$\dot{e}_{\rm in} = \dot{e}_{\rm diss} \Rightarrow$$

$$p_{\rm turb} \approx \bar{\rho} v_{\rm turb}^2 \sim \dot{\Sigma}_\star \left(\frac{P_\star}{m_\star}\right)$$

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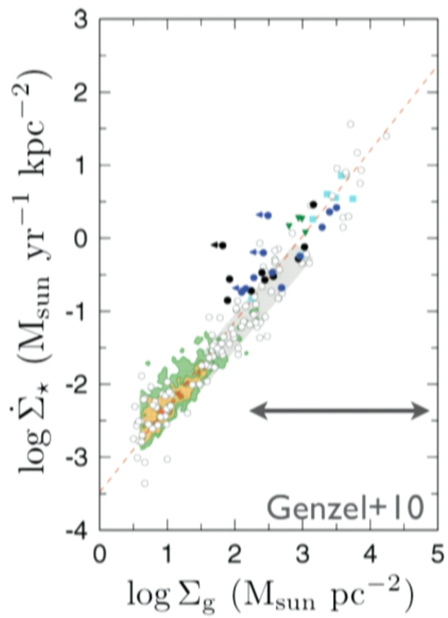
Balancing turbulent pressure and gravity

- Focus on galaxies with $\Sigma_{\rm g} \geq 100\ {\rm M_\odot\ pc^{-2}}$
  - ~fully molecular, so neglect chemistry
  - local mergers, ordinary high-z galaxies
  - SNe dominate momentum injection in volume-filling ISM:

$$\left(\frac{P_\star}{m_\star}\right)_{\rm SNe} \approx 3,000\ {\rm km\ s^{-1}} \left(\frac{n_{\rm H}}{1\ {\rm cm^{-3}}}\right)^{-1/7}$$



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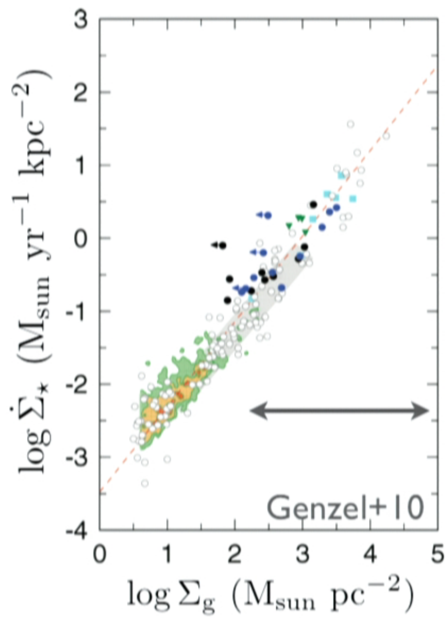

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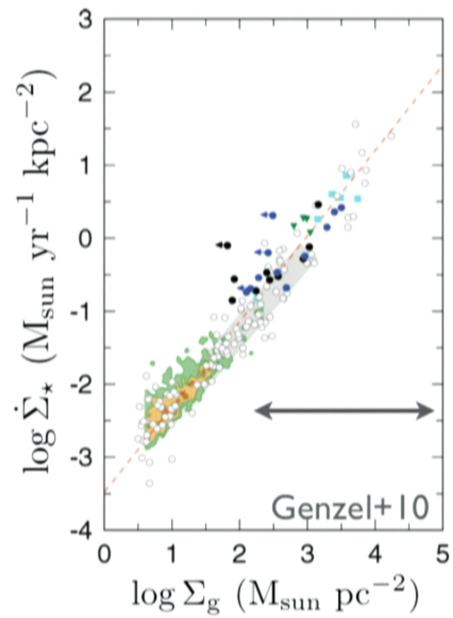

- Weight of disk gas, for Toomre *Q*≈1: $p_{\rm grav} \sim G\Sigma_{\rm g}^2$

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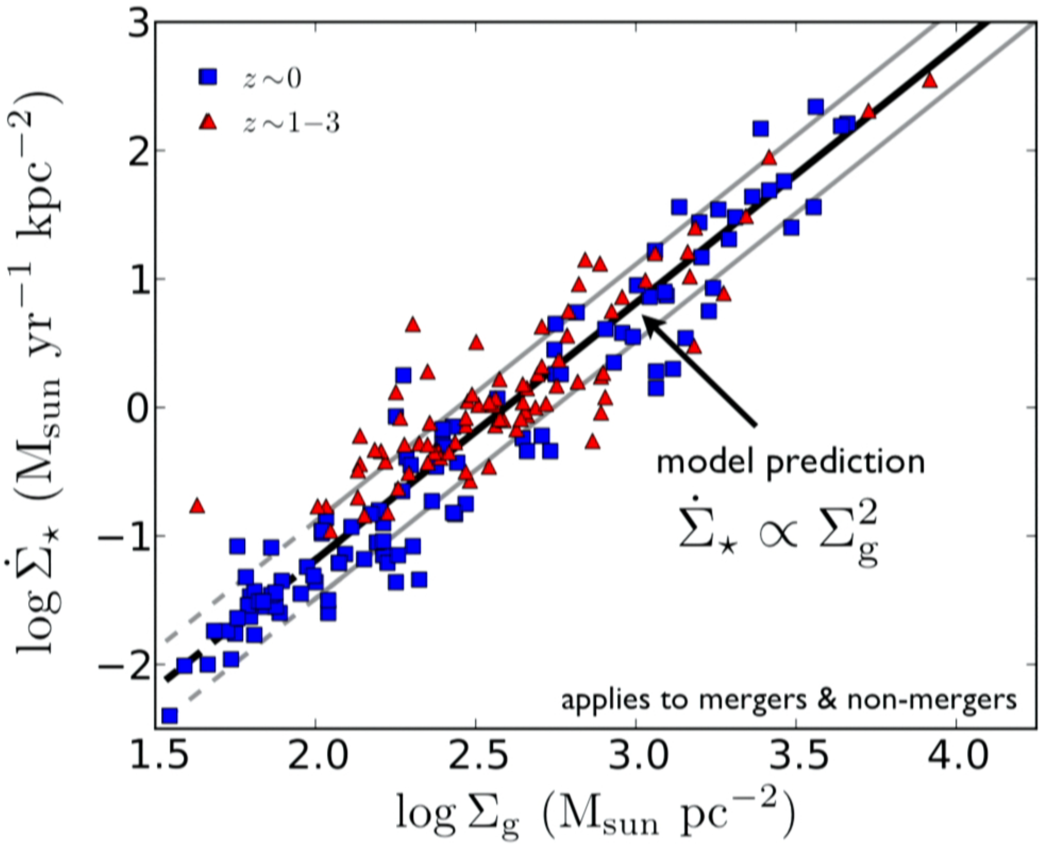
Hydrostatic balance explains observed SF law



Observations from Genzel+10, Tacconi+13;
X_{CO} from Ostriker & Shetty 11, Narayanan+12

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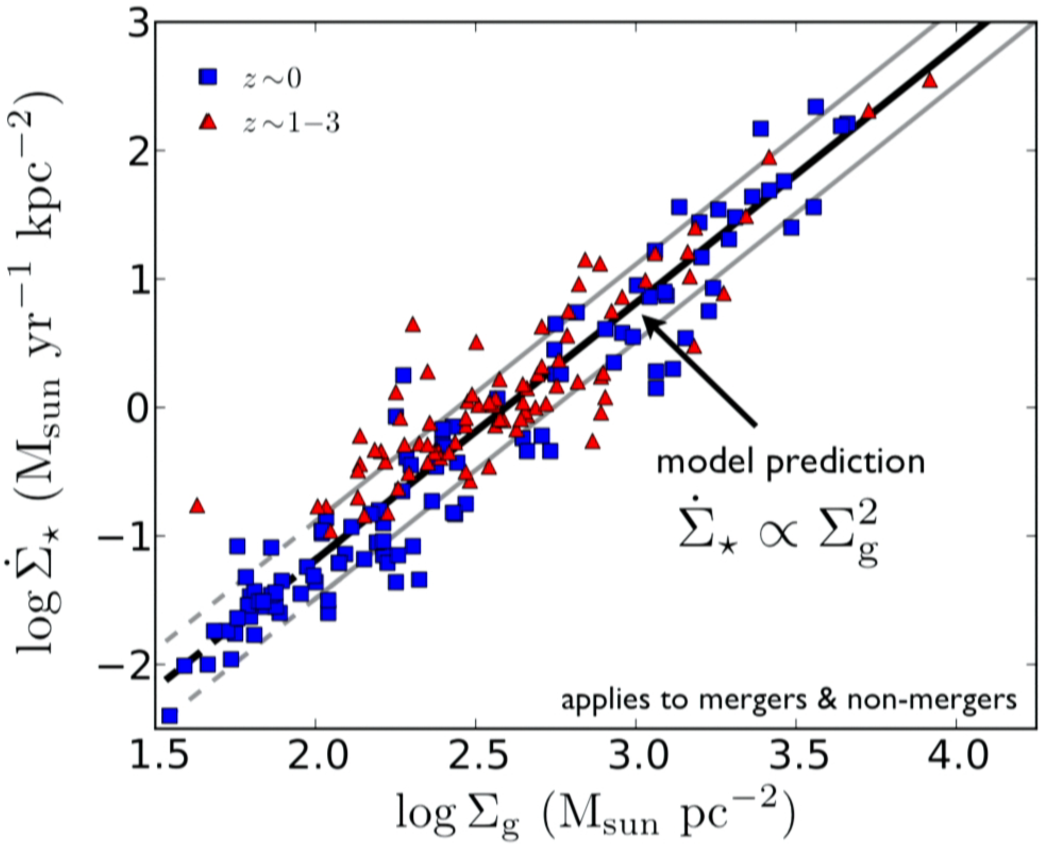

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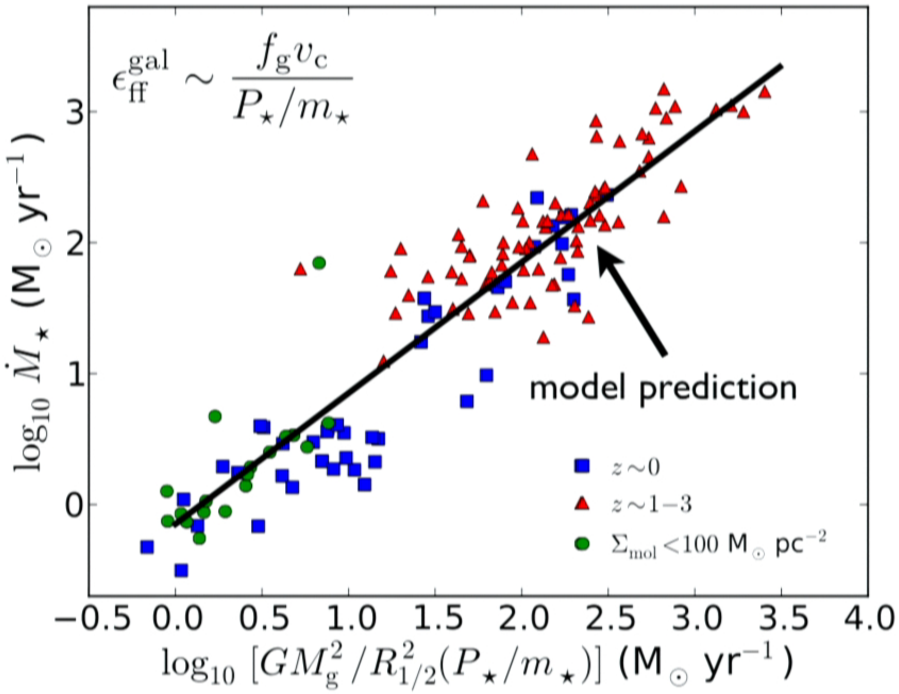
The star formation efficiency scales with gas fraction f_g, *not* universal



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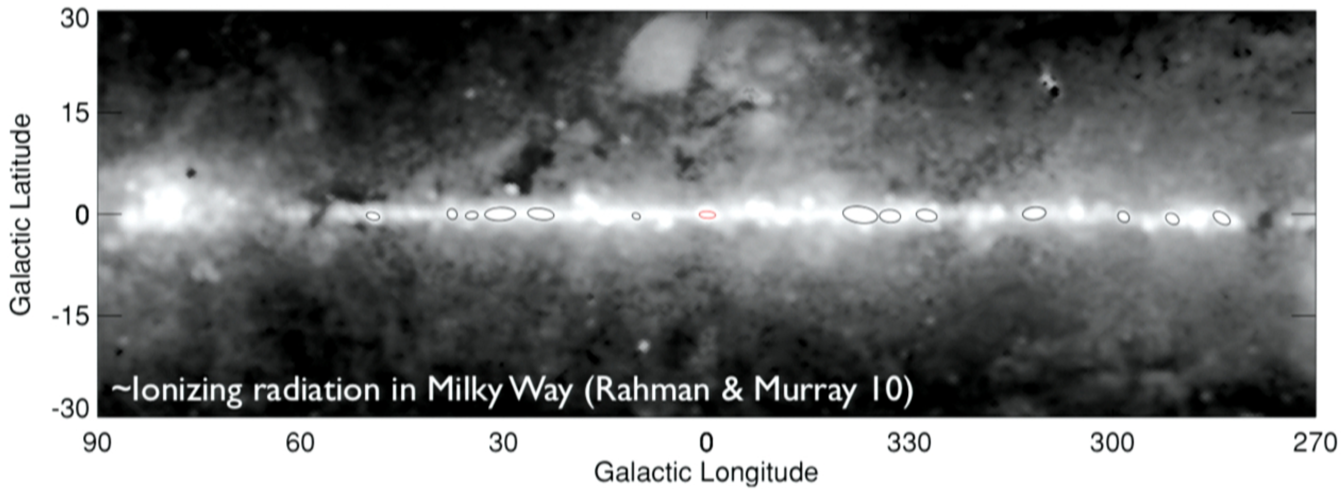
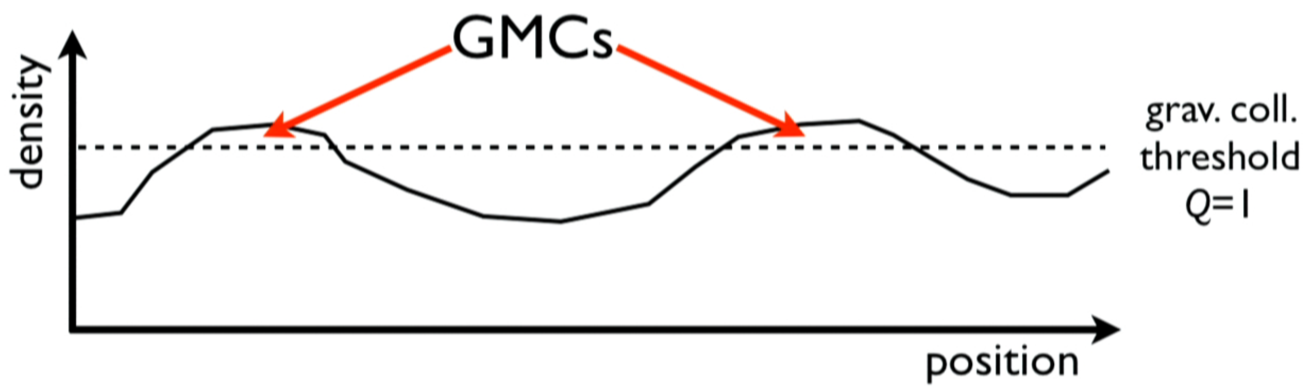
Stars form in giant molecular clouds

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



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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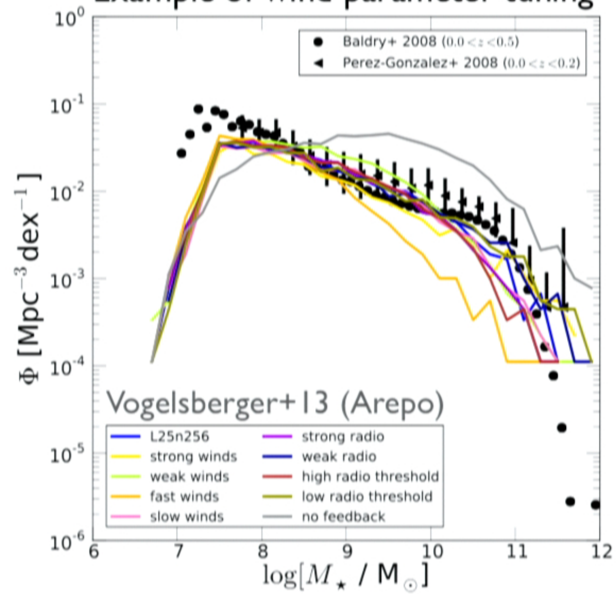
State of the art in cosmological simulations of galaxy formation

- Simulations have relied on important approximations:
  - ➡ decouple hydro (e.g., Springel & Hernquist, Oppenheimer & Davé, Vogelsberger+, ...)
  - ➡ turn off cooling (e.g., Governato+, Stinson+, Shen+, ...)
  - ➡ usually SNe-only (no radiation pressure, stellar winds, photoionization)

- Limit predictive power, so simulations tuned to match, e.g., stellar mass function

- SNe-only models require unrealistic energy; unreliable phase structure, interactions with galaxy/CGM

Example of wind parameter tuning



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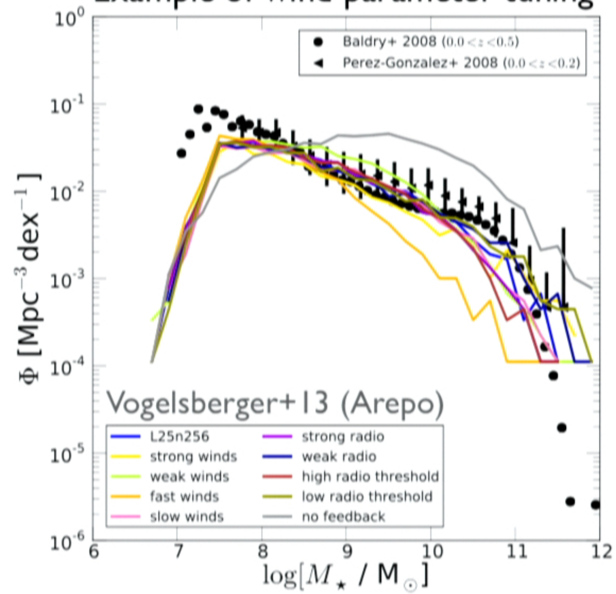

FIRE: Feedback In Realistic Environments

- Cosmological zoom-ins resolving GMCs at all redshifts

- Metal and molecular line cooling to *T*~10 K; SF in mol., self-grav. gas

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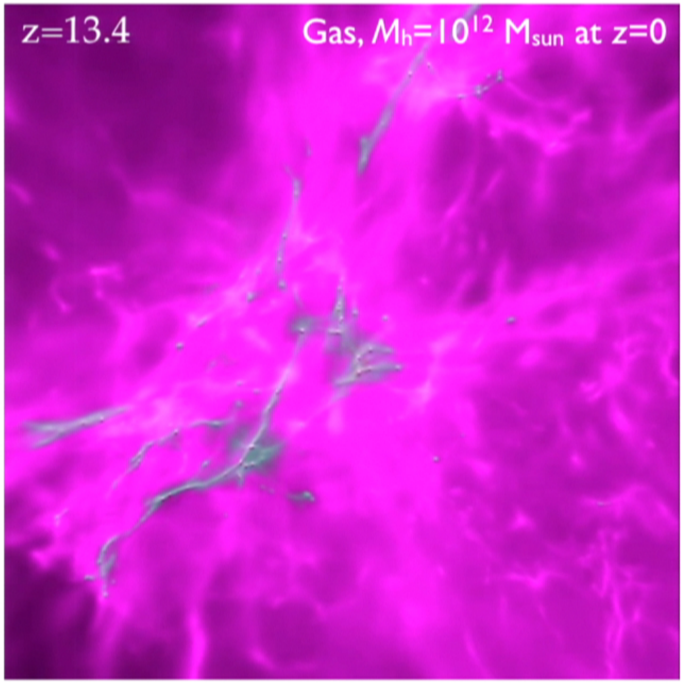
- *No parameter tuning!*

  ➡ K-S law, outflows, etc. emerge from the calculation



w/ Hopkins, Kereš, Quataert, Murray

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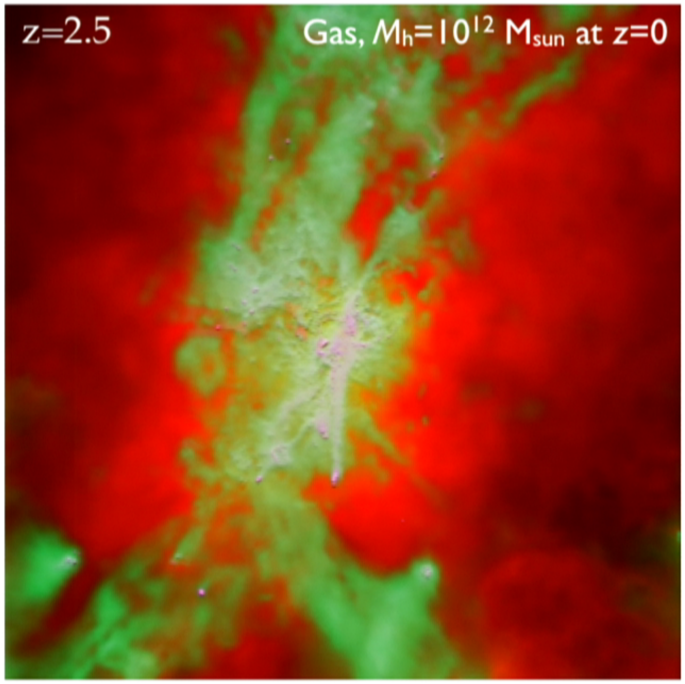

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FIRE overview

- Improved Gadget-3:
  - ➡ resolves historical discrepancies between SPH and grid-based codes
- Sample includes dwarfs, Milky Way analogs, group; being expanded
- E.g., Milky Way analog sim:
  - ➡ m_{gas}=7×10^3 M_{sun}
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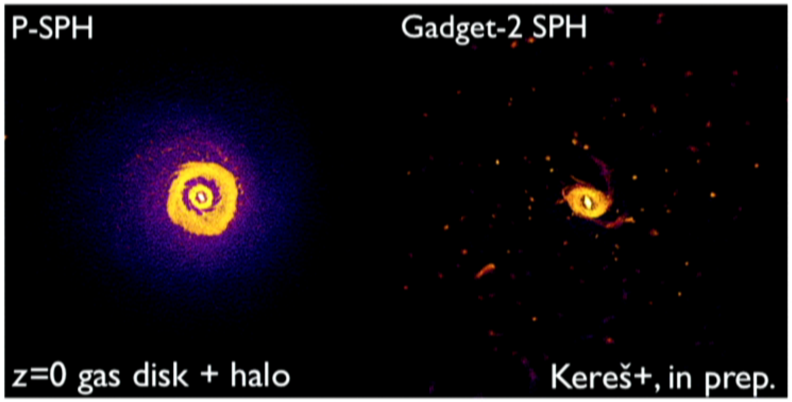

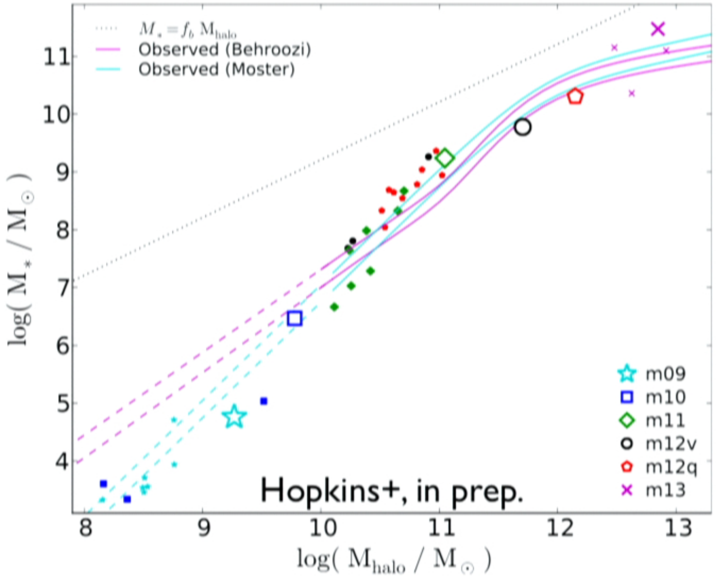

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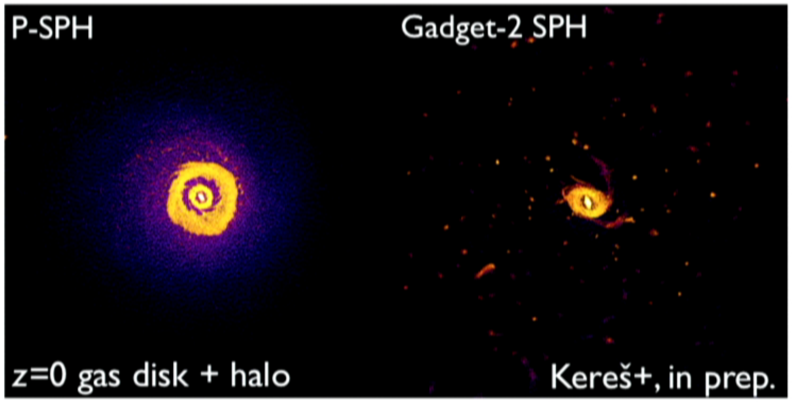
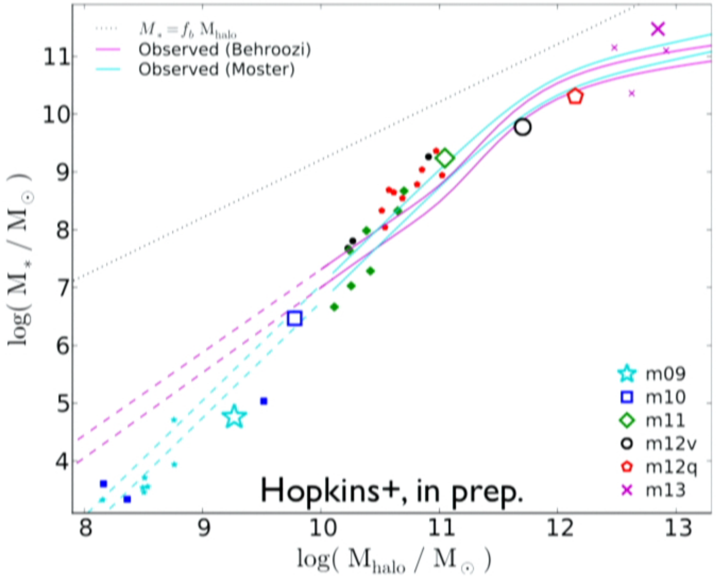
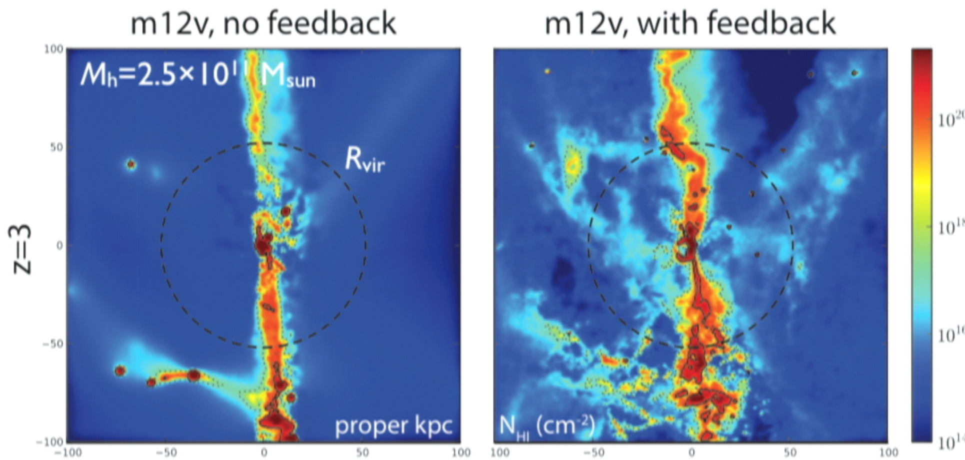


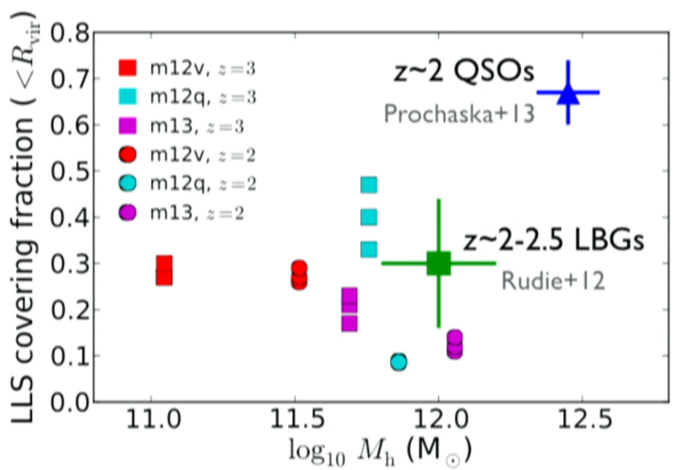


Inflows and outflows in FIRE: HI

- Ionizing RT following CAFG+10, CAFG & Kereš 11



- Star formation-driven galactic winds increase covering fractions of cool halo gas



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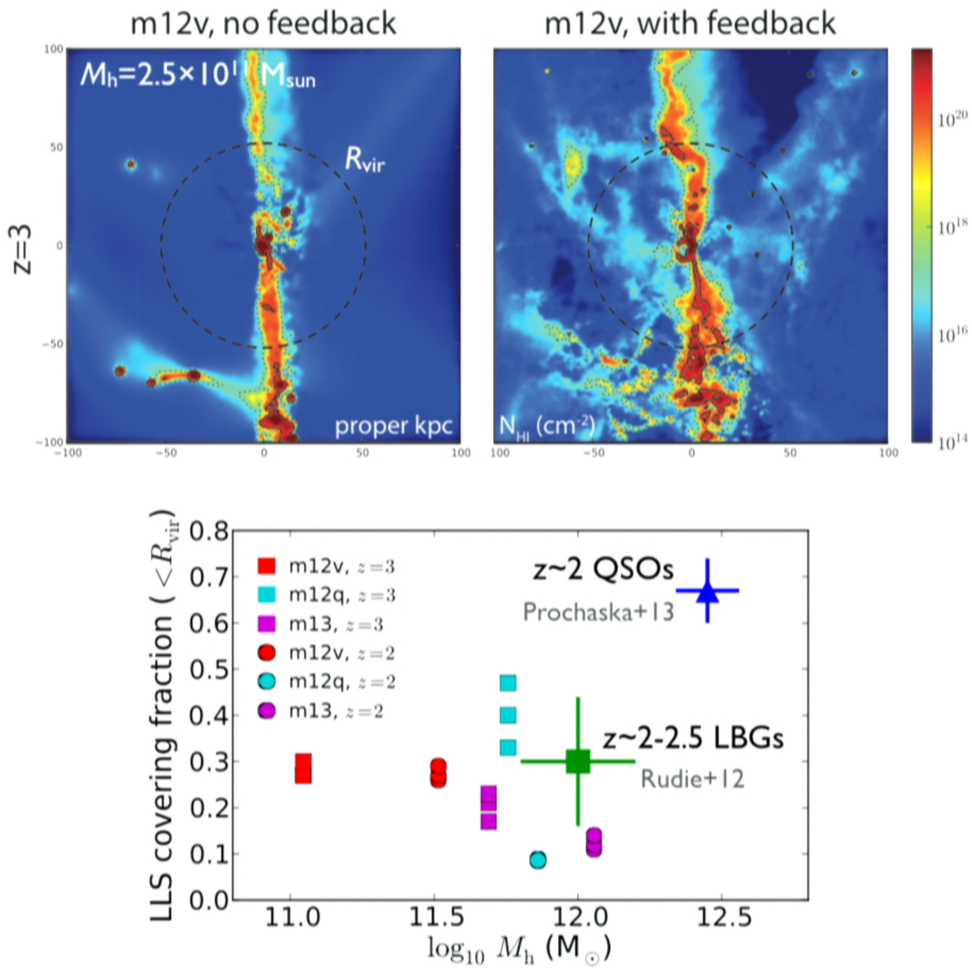

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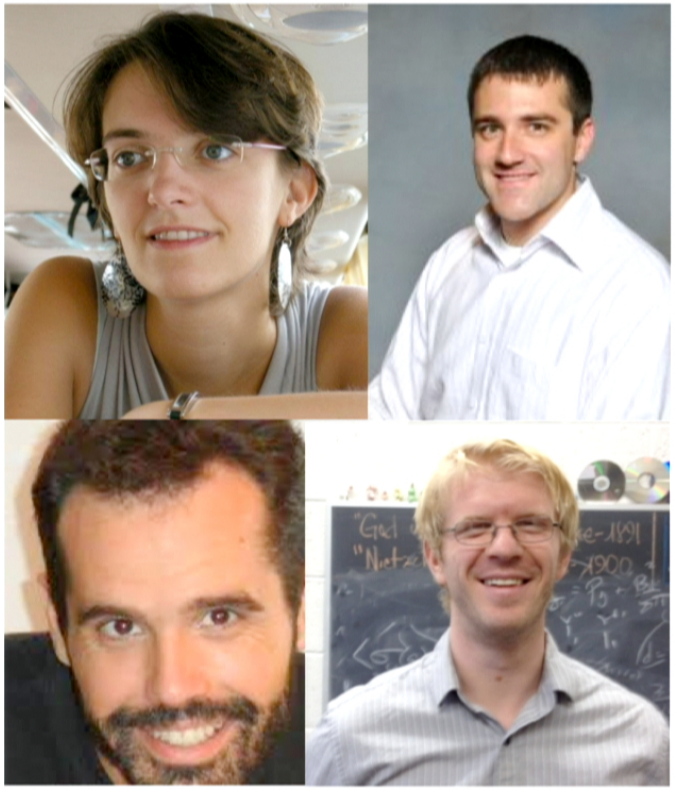
Future of FIRE

- More predictive approach enabling range of new studies:
  - ➡ halo gas in all phases with realistic inflows/outflows
  - ➡ heavy element enrichment
  - ➡ assembly of stellar pops and morphological transformations
  - ➡ formation and evolution of star clusters
  - ➡ dark matter cusp-core transformation
  - ➡ quenching of star formation
  - ➡ ...



Collaborators
Freeke van de Voort, Ian Parrish,
Jose Onorbe, Sasha Muratov

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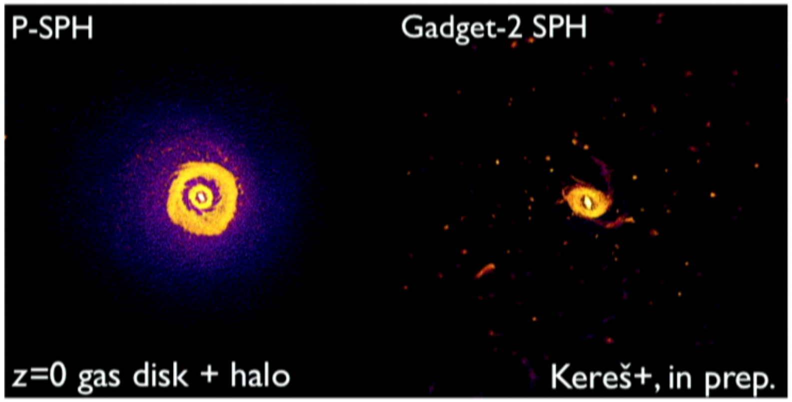
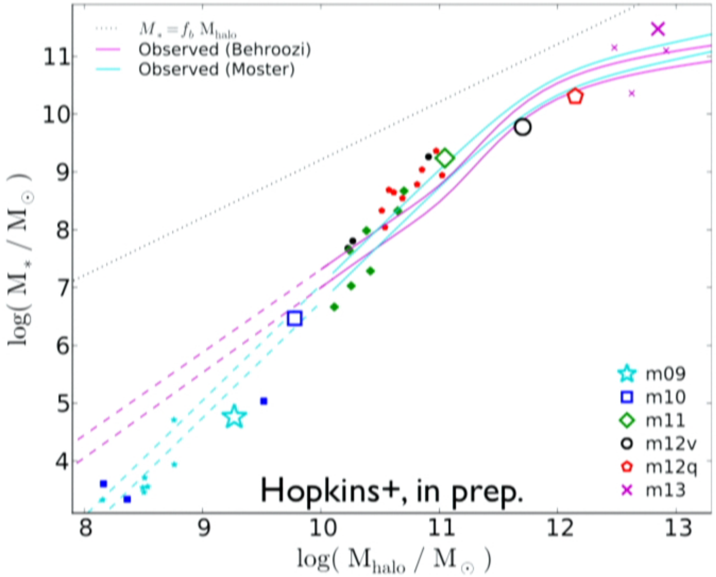
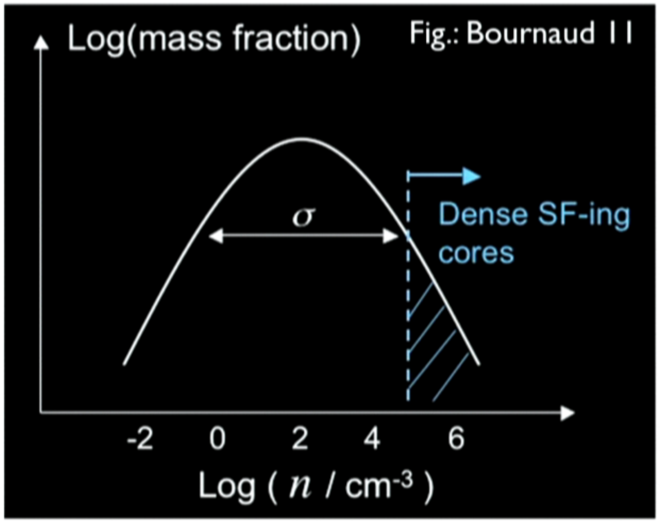




Contrast with 'supersonic turbulence' theories

- Low ε_{ff} identified with mass fraction in self-gravitating tail of turbulent gas density PDF



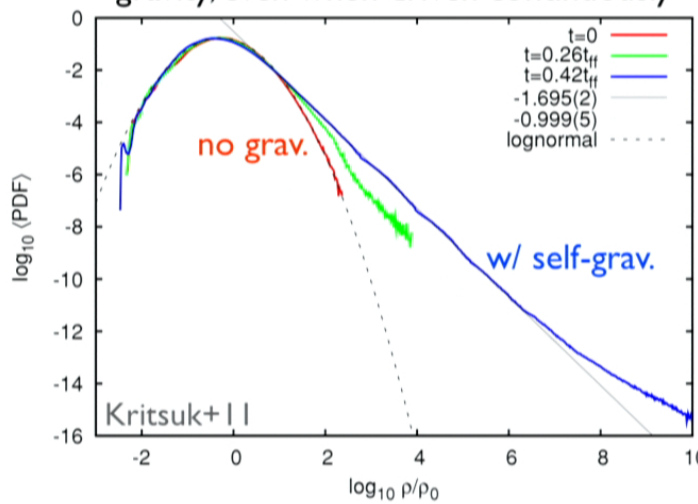
- Krumholz & McKee 05 (KM05): for driven isothermal turb., absent self-gravity, PDF ~lognormal and ε_{ff}~*0.01* universal (but see Padoan & Nordlund 12, Federrath & Klessen 12)

- KM05 and Krumholz, McKee & Tumlinson 09 (KMT09) assume that ε_{ff}~*0.01* everywhere in molecular gas and the low ε_{ff} on galaxy scales (K-S law) derives from low ε_{ff} in molecular clouds

Theoretical problems with supersonic turbulence models

- Do not specify how lognormal PDF is sustained
- Most likely, it does not happen as envisioned by KM05, KMT09, etc.

Power-law tails in turbulence with self-gravity, even when driven continuously



ε_{ff} increases with t, can be $\gtrsim 0.5$