# *Star formation regulation: from clouds to the cosmos*

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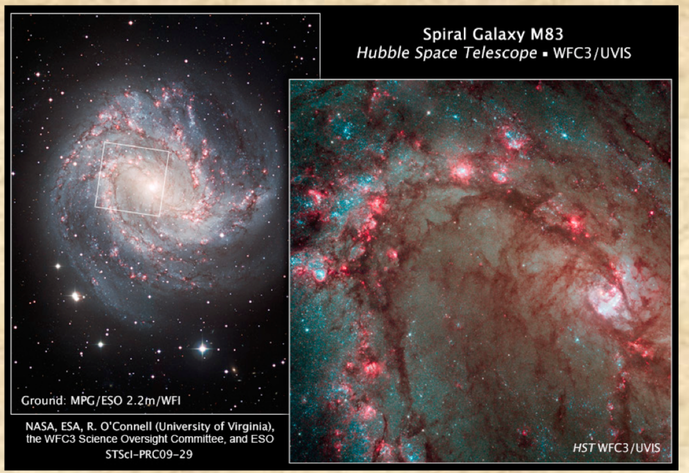
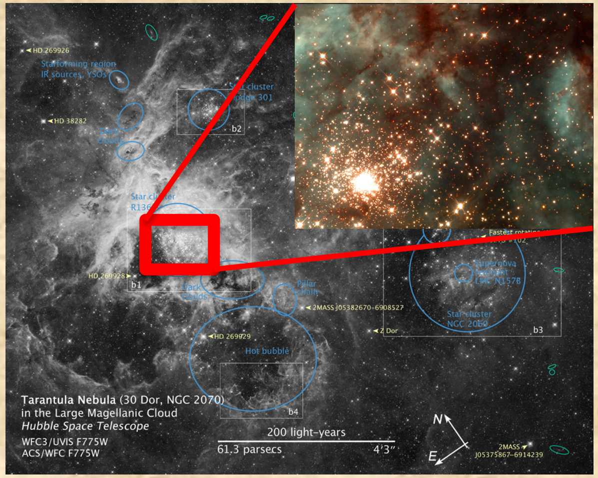
# *Multi-scale self-regulated SF*

- Large-scale SF regulation by feedback
- GMCs and SFRs
- Galactic winds





# *The ISM, SF, and feedback*

- ISM dissipation and losses are rapid, so large-scale self-consistent ISM state/SF regulation theory must account for *source terms*
- Energy source terms are mainly from *young massive stars*

⇒ *self-regulated, feedback-modulated, quasi-equilibrium on large scales*

⇒ *extreme time-dependent cycling on small scales*

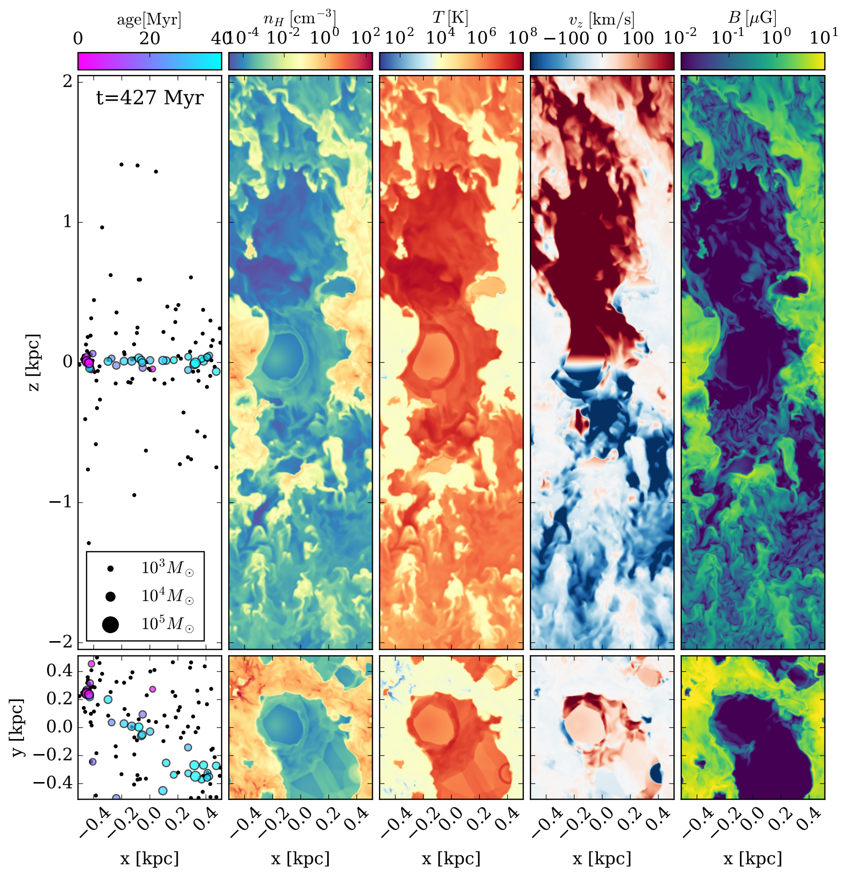
## Self-regulation concept

*When some gas in a system collapses*

- new short-lived, high-mass stars are born
- these stars inject energy, momentum to their surroundings
- transforms state of ISM (phase changes), accelerates motions on a range of scales
- may limit further collapse and may remove "fuel" from system

*Star formation* ***now*** *regulates* ***future*** *star formation*

# *TIGRESS**



C.-G. Kim & Ostriker (2017, 2018)

*Three-phase **I**SM **R**esolving **E**volution with **S**tar formation and **S**upernovae

## Physics

- MHD, shearing box, FFT self-gravity
- External potential for old stars + DM
- Sink particles = star clusters
- Cluster particles set time-dependent FUV field, SN rate/location
- Warm-cold ISM heated by PE effect
- Hot ISM created by SN shocks with resolved Sedov phase
- SN in clusters + OB runaways yields realistic space-time correlation of SNe with different ISM phases

➢ With local box, high resolution everywhere

➢ Tall box to quantify fountain vs. wind

➢ Efficiently explore range of galactic environments

# *Feedback "yields"*

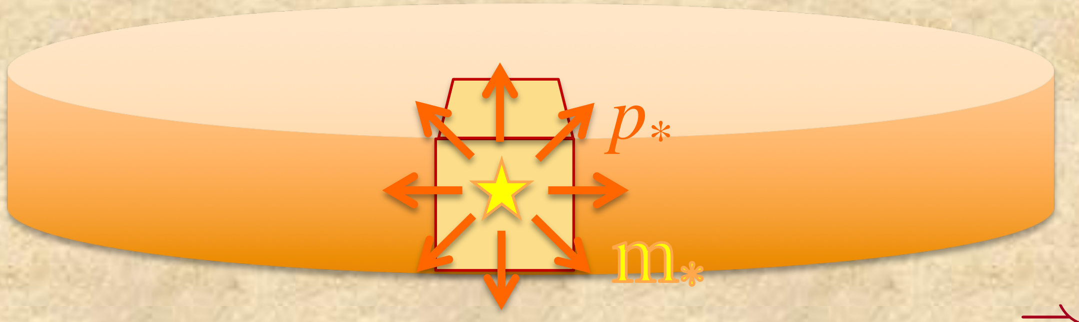
- Sets pressure ($P_{th}$, $P_{turb}$, $P_{mag}$, $P_{CR}$) in ISM
  - Higher PE heating rate from higher $J_{FUV}$ ⇒higher $P_{th}$ in WNM and CNM

    *Wolfire et al (1995, 2003)*
    *Ostriker et al (2010)*

    *If both warm and cold gas are present, expect*

    $P_{th} \sim P_{\text{two-phase}} \propto J_{FUV} Z_d / Z_g \Rightarrow P_{th} = \eta_{th,FUV} \Sigma_{SFR}$
  - Higher driving rate from higher SN explosion rate ⇒higher $P_{turb}$ *(kinetic & magnetic)*, $P_{CR}$

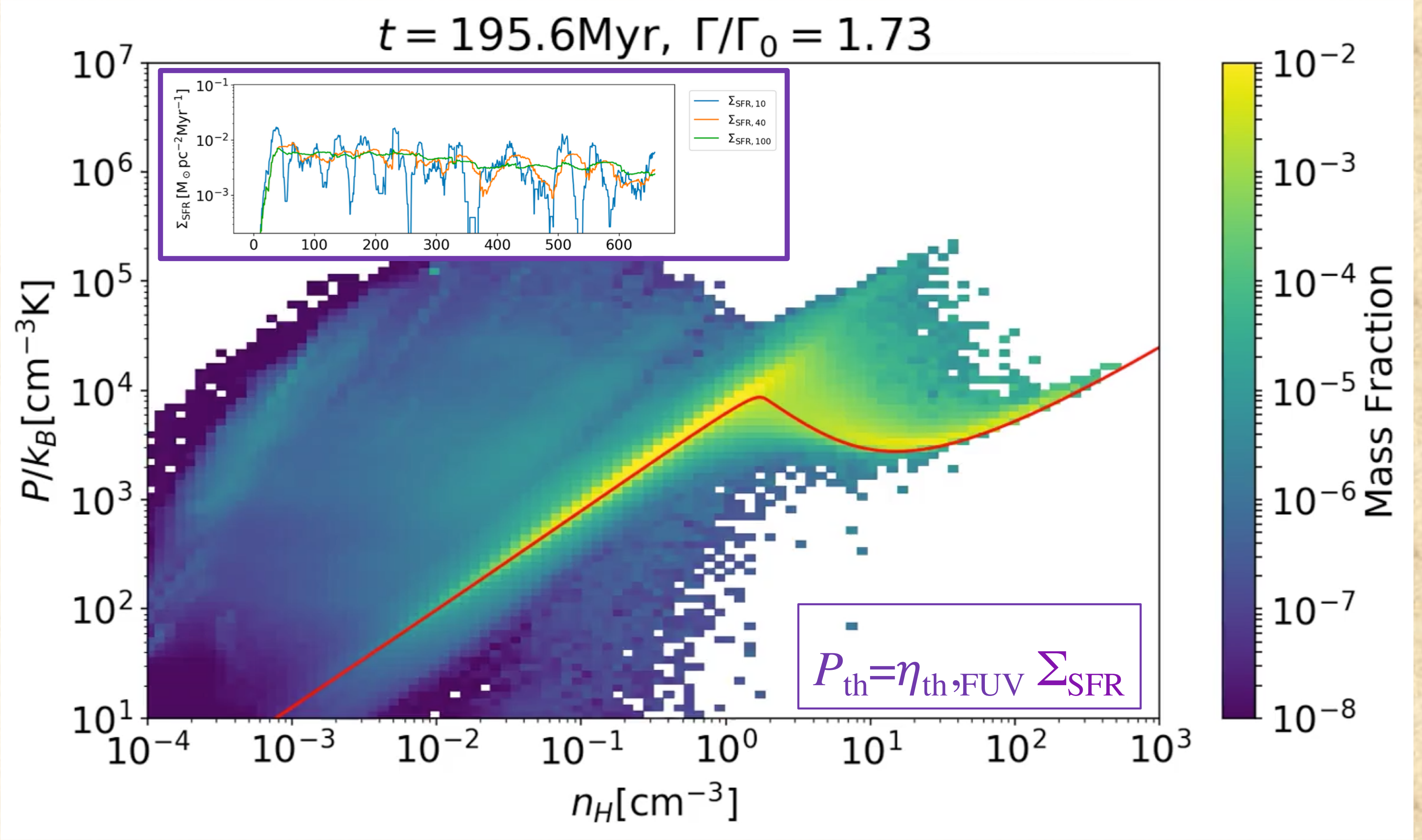
    *Ostriker & Shetty (2011)*



$$P_{\rm turb} \sim F_z = \frac{1}{4}\frac{p_*}{m_*}\Sigma_{SFR}$$

$$\Rightarrow P_{\rm turb} = \eta_{turb,SN}\Sigma_{SFR}$$

# *Thermal equilibrium*

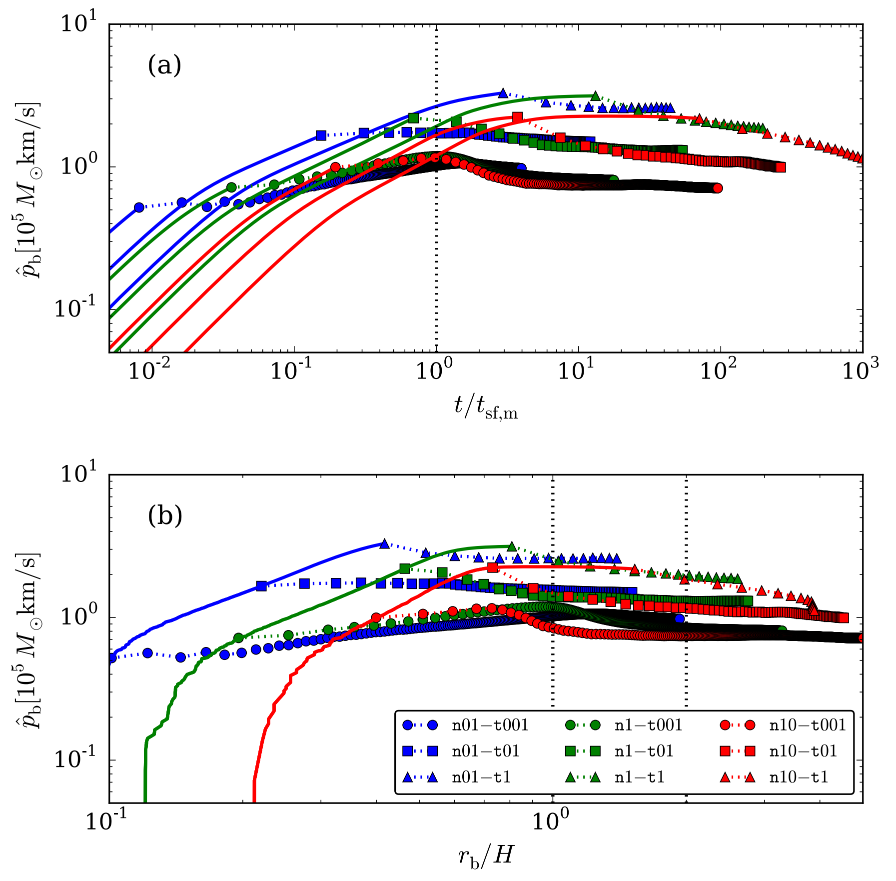


$P_{\mathrm{th}} = \eta_{\mathrm{th,FUV}}\,\Sigma_{\mathrm{SFR}}$

C.-G. Kim & Ostriker (2017)

# *SNR/Superbubble momentum*

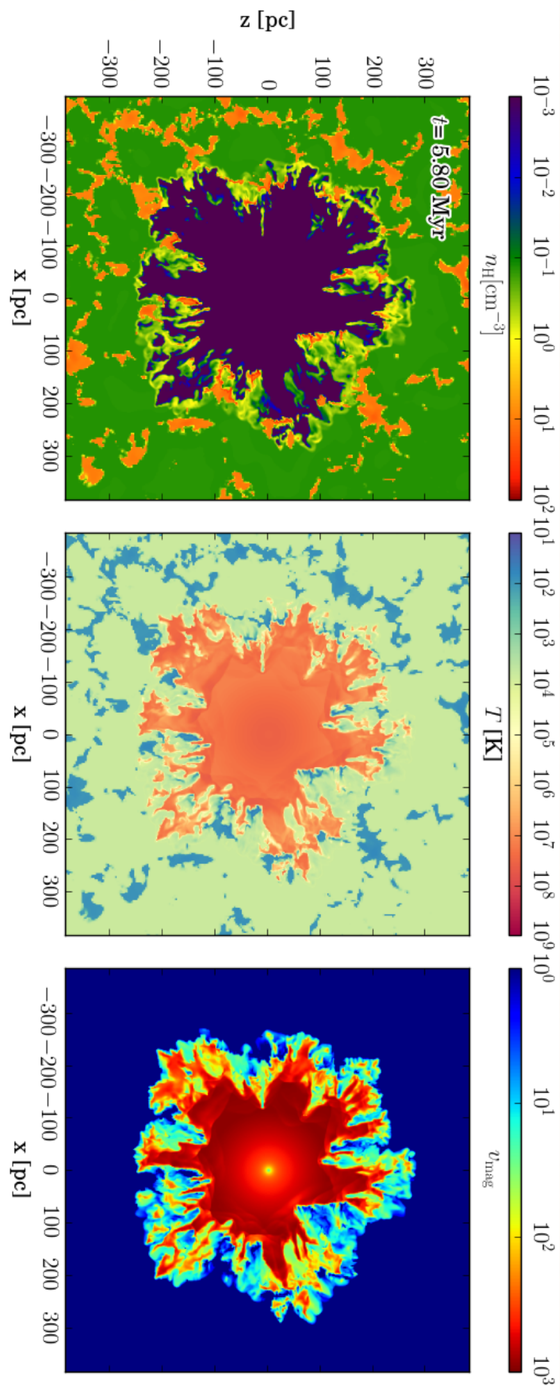
C.-G. Kim, Ostriker, & Raileanu (2017)



- Superbubble has similar momentum/SN to individual SNR: $p_{*,\rm SNR} = 2.8\times10^5\ M_\odot{\rm km/s}\ \langle n_0\rangle^{-0.17}$

  *C.-G. Kim & Ostriker (2015), Iffrig & Hennebelle (2015), Martizzi et al (2015), Walch & Naab (2015)*

Feedback momentum/mass from SNe: $p_*/m_* \sim (1\text{-}3)\times10^3$ km/s



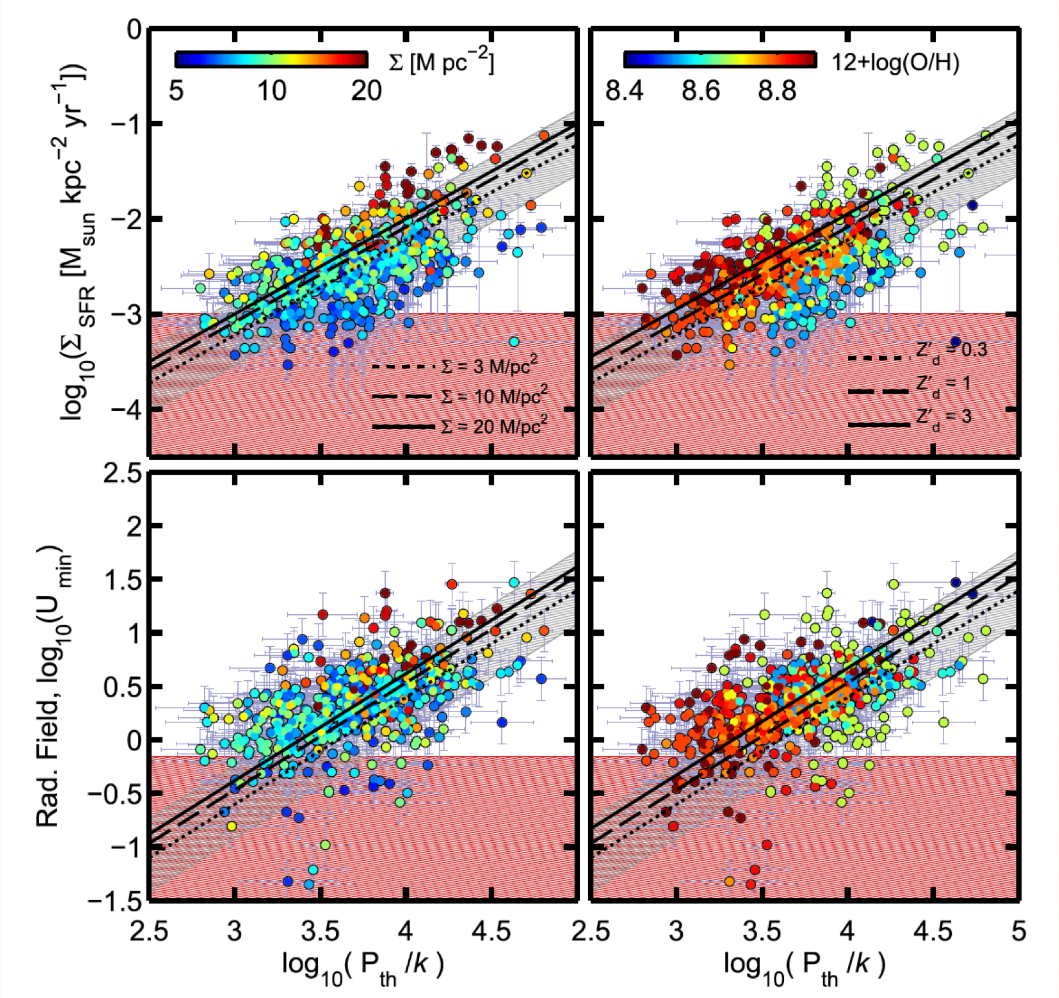
# $P_{th}$ vs $\Sigma_{SFR}$ in observations

- From Herschel/KINGFISH, use [CII] 158μ emission to obtain thermal pressure of primarily-atomic gas
- Sample of 31 galaxies also in THINGS and HERACLES
- kpc-scale resolution pointings
- Consistent with the prediction

$P_{th}=P_{\text{two-phase}}\propto\Sigma_{SFR}$

from Wolfire et al (2003)

$$\frac{P_{\text{two-phase}}}{k} \simeq 3.5\times10^{6}\mathrm{K\,cm^{-3}}\left(\frac{P_{\max}}{P_{\min}}\right)^{1/2} \times\frac{\Sigma_{\rm SFR}}{M_{\odot}\,\mathrm{yr^{-1}\,kpc^{-2}}}\times\frac{1}{1+3.1\,(Z_d'\Sigma_{\rm gas}/\Sigma_{\rm gas,0})^{0.365}}.$$



Herrera-Camus et al (2017)

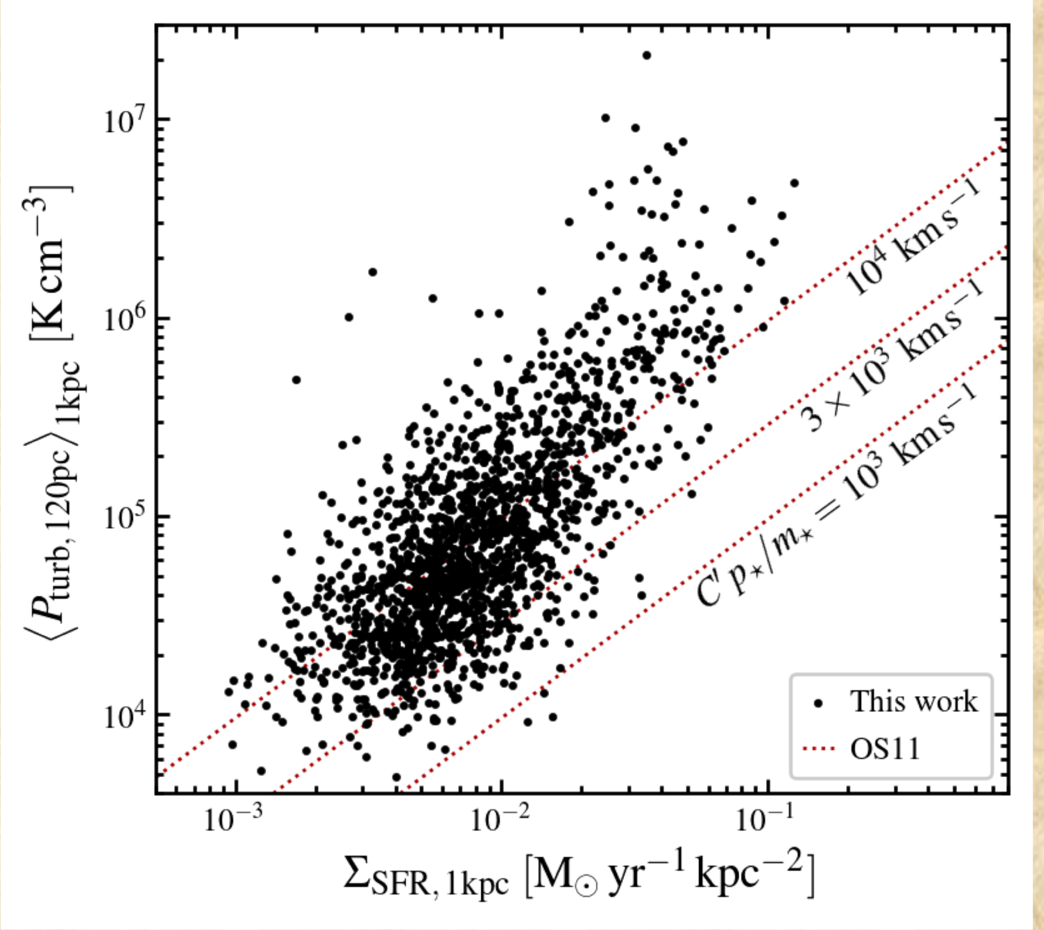
# $P_{turb}$ vs $\Sigma_{SFR}$ in observations

- Prediction from feedback:

$$P_{\rm turb} \sim F_z = \frac{1}{4}\frac{p_*}{m_*}\Sigma_{SFR}$$

on large scales

- Concentration of SF in clouds increases the momentum input/time/area relative to kpc-scale average



Jiayi Sun + PHANGS (2019, in prep)

# *Self-regulated $\Sigma_{SFR}$ in disk galaxies*

- Allowing for *thermal*, *turbulent*, and *magnetic* pressure as driven by star formation feedback:

$$P_{\mathrm{th}} = \eta_{\mathrm{th}}\,\Sigma_{\mathrm{SFR}},\; P_{\mathrm{turb}} = \eta_{\mathrm{turb}}\,\Sigma_{\mathrm{SFR}},\; P_{\mathrm{mag}} = \eta_{\mathrm{mag}}\,\Sigma_{\mathrm{SFR}}$$

$$P_{\mathrm{tot}} = (\eta_{\mathrm{th}} + \eta_{\mathrm{turb}} + \eta_{\mathrm{mag}})\Sigma_{\mathrm{SFR}} = \eta_{\mathrm{tot}}\Sigma_{\mathrm{SFR}}$$

- Vertical force balance: $P_{tot} \approx \mathcal{W} = \int \rho g_z dz = \Sigma_{\mathrm{gas}}\langle g_z\rangle/2 \equiv P_{\mathrm{DE}}$

$$P_{\mathrm{DE}} = \Sigma_{gas}\frac{\langle g_z\rangle}{2} \approx \frac{\pi G \Sigma_{gas}^2}{2} + \Sigma_{gas}(2G\rho_*)^{1/2}\sigma_{gas,z}$$

- Self-regulated equilibrium star formation rate:

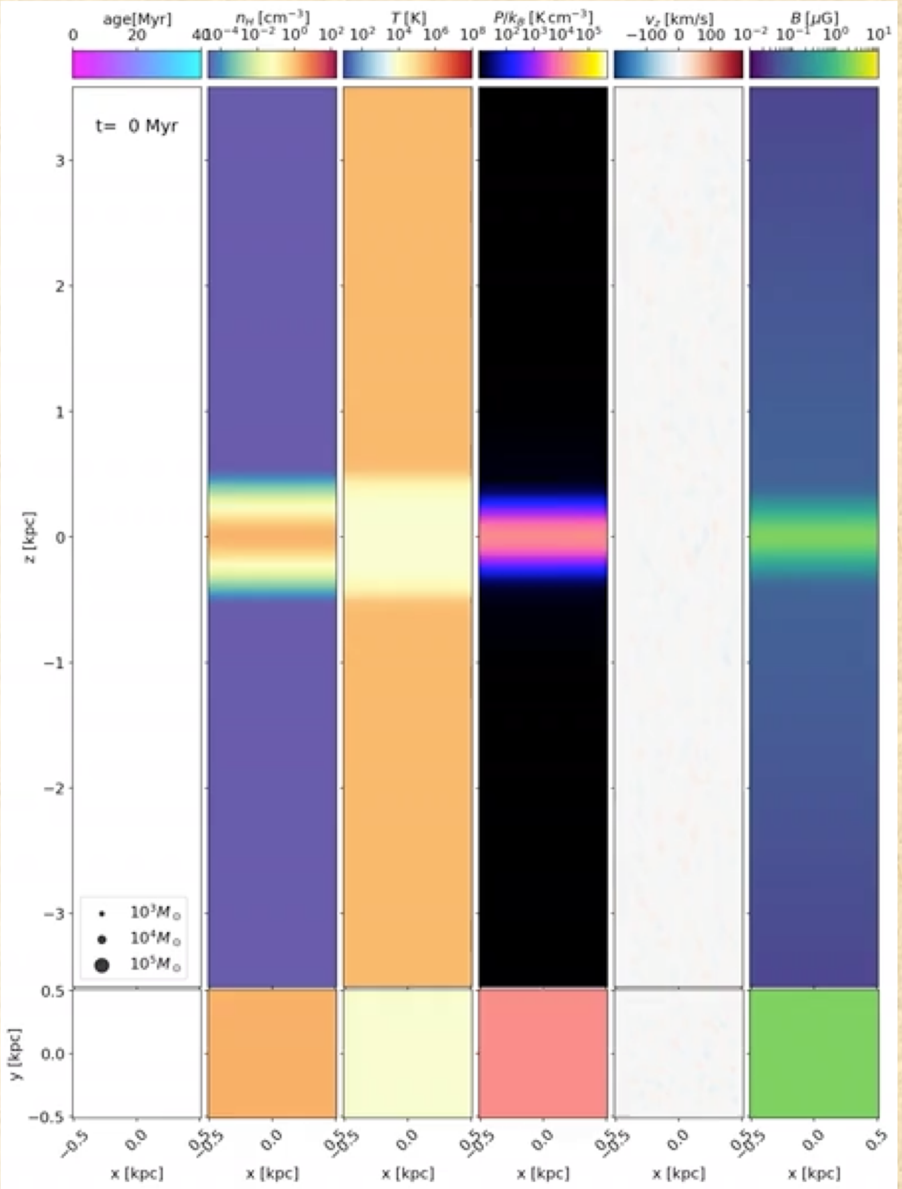
$$\langle \Sigma_{\mathrm{SFR}} \rangle = \langle P_{\mathrm{tot}} \rangle / \eta_{\mathrm{tot}} = P_{\mathrm{DE}} / \eta_{\mathrm{tot}}$$

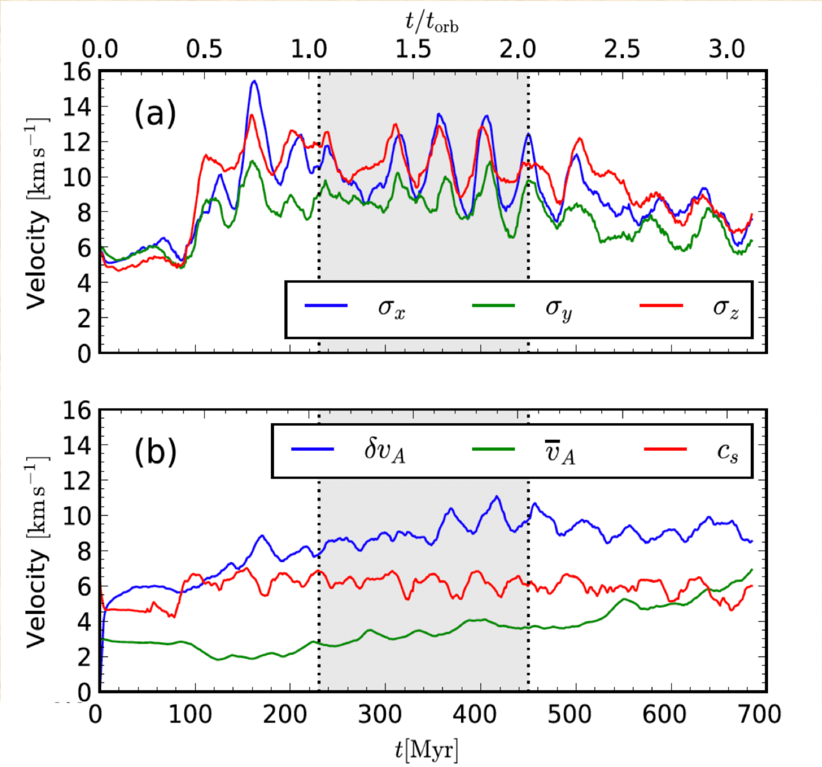
- Calibrating $\eta$ values with numerical simulations, result is $\eta_{\mathrm{tot}} \sim 1000$ km/s ⇒

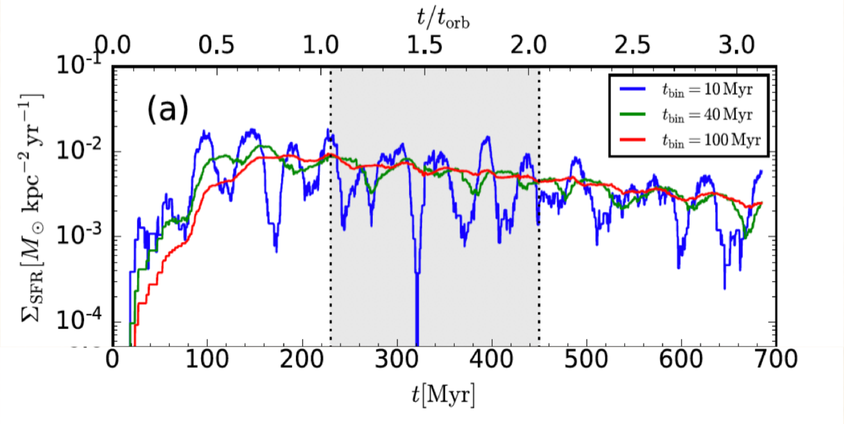
$$\Sigma_{SFR} = 2 \times 10^{-3} M_\odot \ \mathrm{kpc}^{-2}\ \mathrm{yr}^{-1} \left( \frac{P/k}{10^4 \mathrm{cm}^{-3} K} \right) = f(\Sigma_{gas}, g_z)$$

Ostriker, McKee, & Leroy (2010); Ostriker & Shetty (2011); C.-G. Kim, Kim, & Ostriker (2011)
Shetty & Ostriker (2012); C.-G. Kim, Ostriker, Kim (2013); C.-G. Kim & Ostriker (2015,2017)

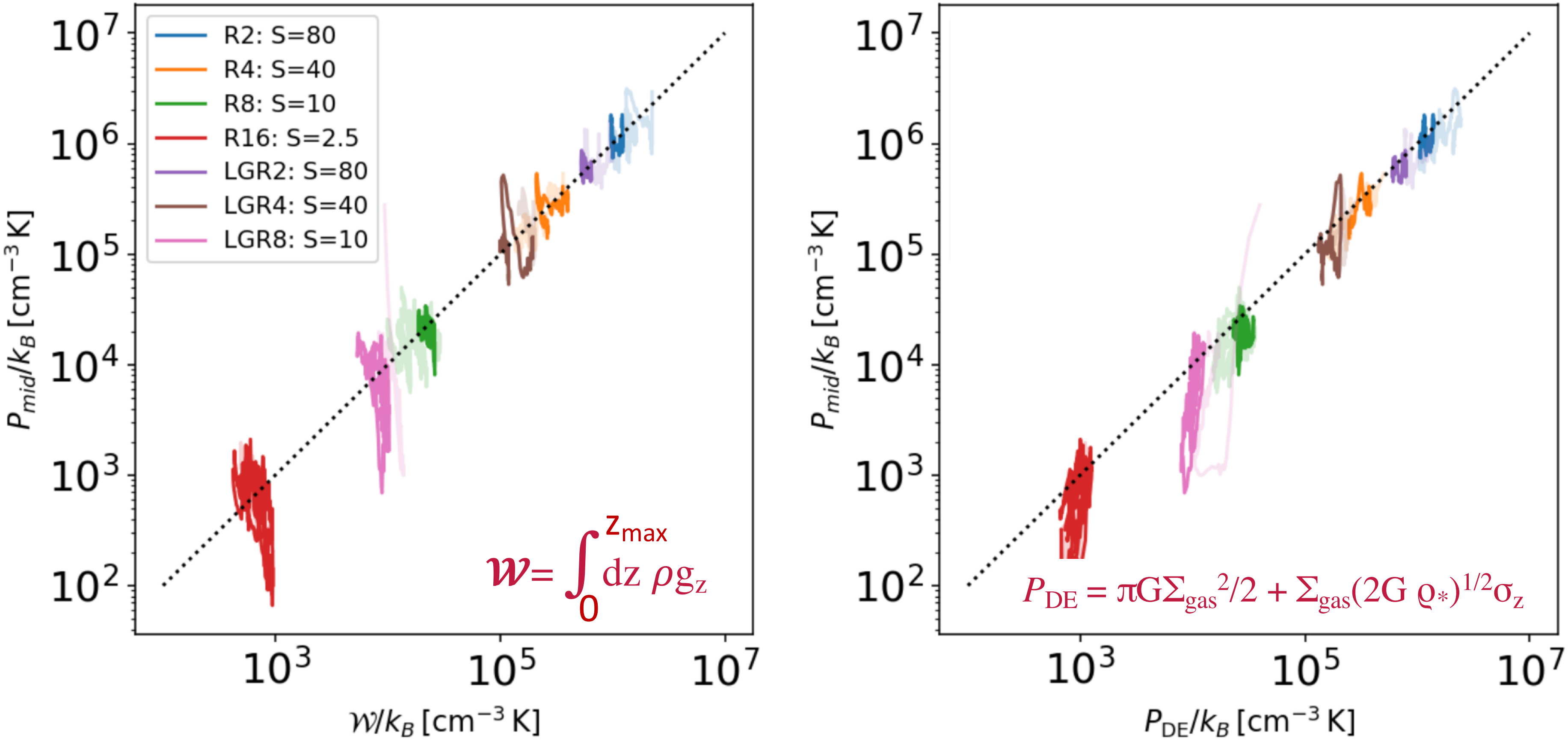
# *TIGRESS Evolution*







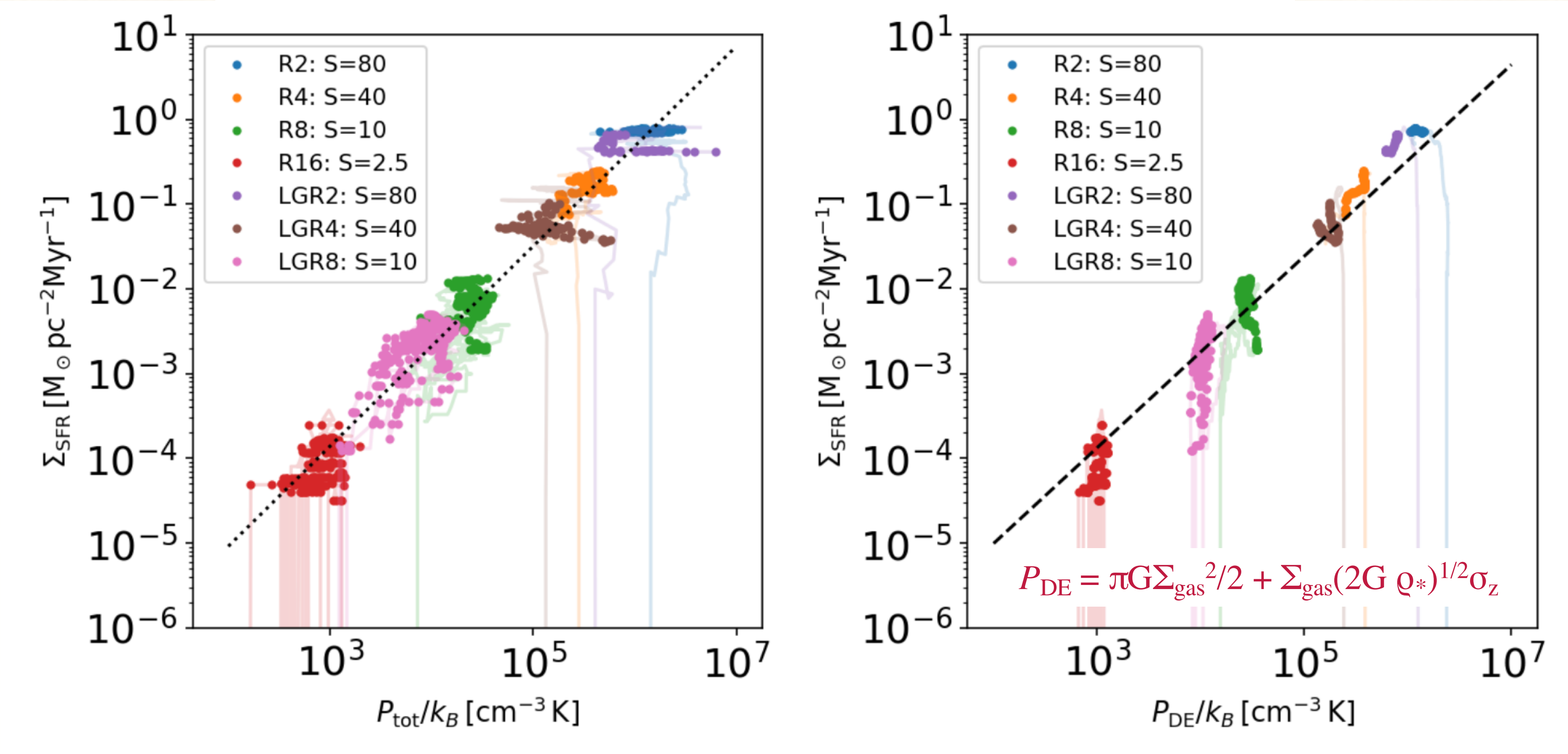
# *Dynamical equilibrium*



*Varying galactic environment with TIGRESS:*
*the required average equilibrium pressure is maintained*

See also: C.-G. Kim, W.-T. Kim, & Ostriker (2011), C.-G. Kim, Ostriker, W.-T. Kim, (2013)

# *Pressure vs. $\Sigma_{SFR}$*

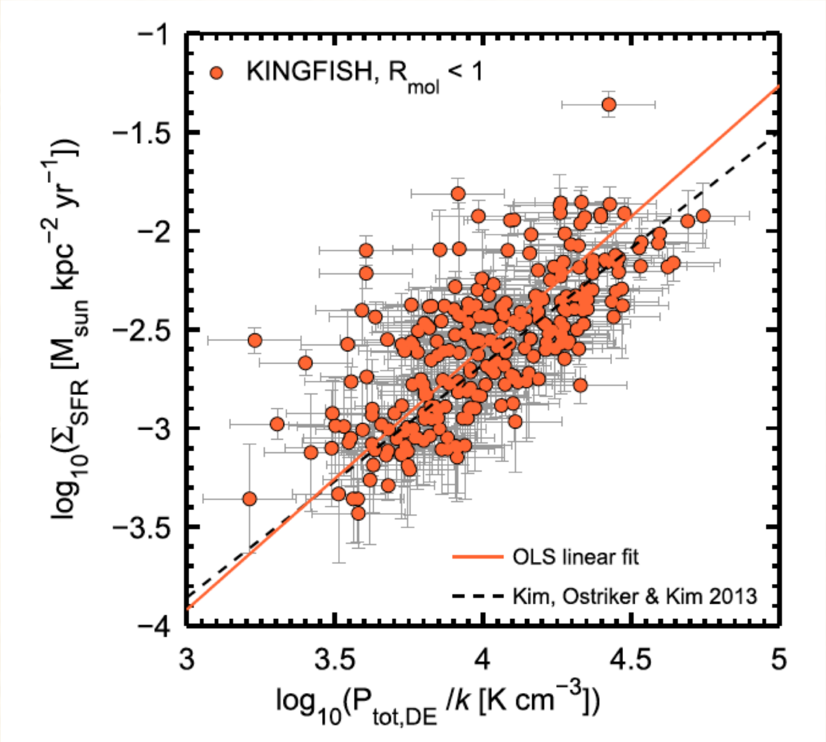


$P_{DE} = \pi G\Sigma_{gas}^2/2 + \Sigma_{gas}(2G\,\rho_*)^{1/2}\sigma_z$

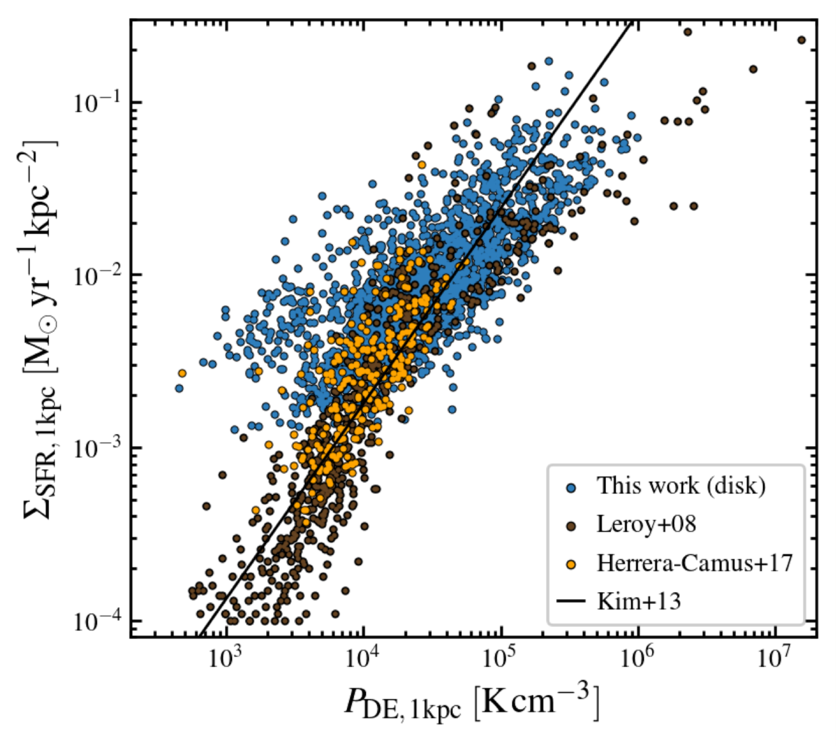
Colors: new TIGRESS simulations; lines from C.-G. Kim, Ostriker & W.-T. Kim (2013)

$$\Sigma_{SFR} \approx 2\times 10^{-3} M_\odot \text{ kpc}^{-2}\text{yr}^{-1}\left(\frac{P/k}{10^4\text{cm}^{-3}\text{K}}\right)$$

# $P_{DE}$ *vs.* $\Sigma_{SFR}$ *in observations*



Herrera-Camus et al (2017)



Jiayi Sun + PHANGS (2019 in prep)

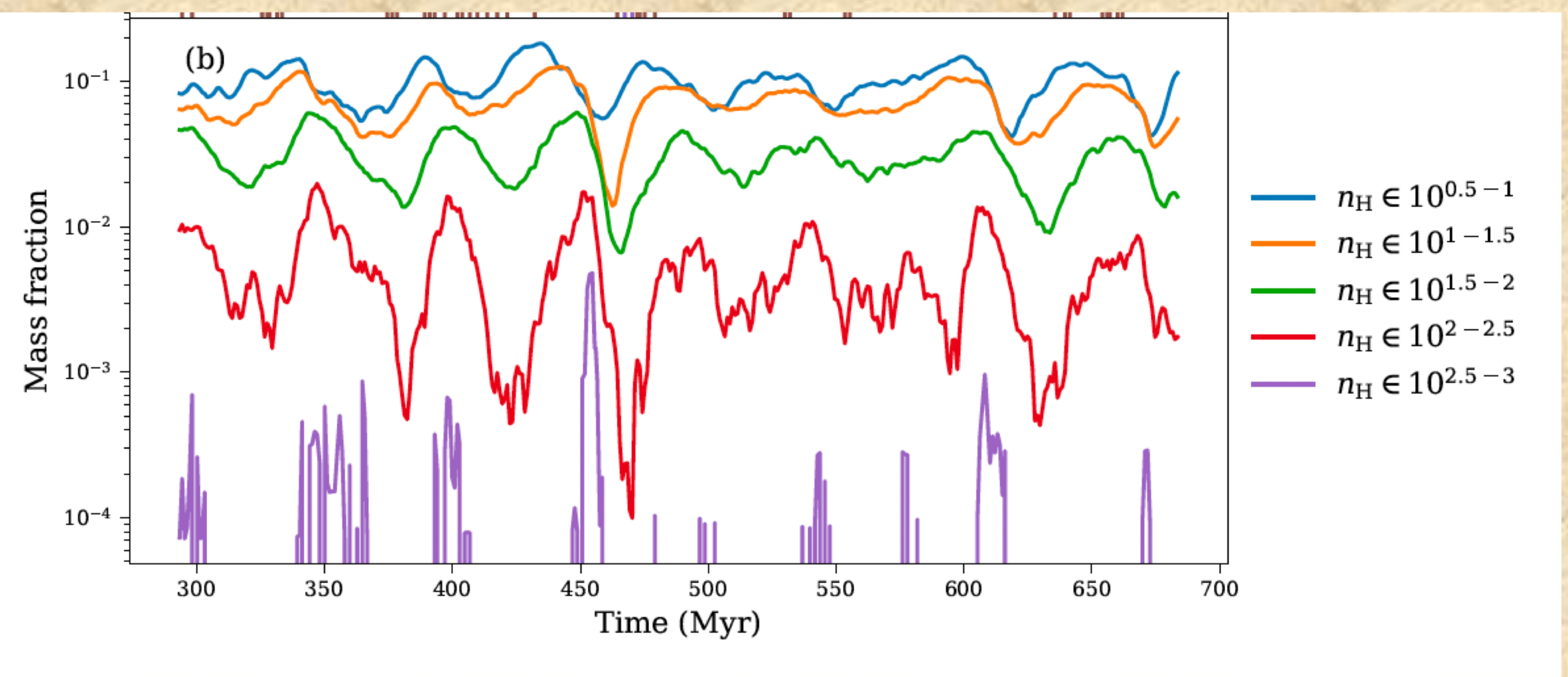
$$P_{DE} = \pi G \Sigma_{gas}^{2}/2 + \Sigma_{gas}(2G\,\varrho_*)^{1/2}\sigma_z$$

See also: Blitz & Rosolowsky (2006), Leroy et al (2008)

# *Connecting to small-scale star formation*

# *Dense gas evolution*

Mao, Ostriker, & C.-G. Kim (2019)



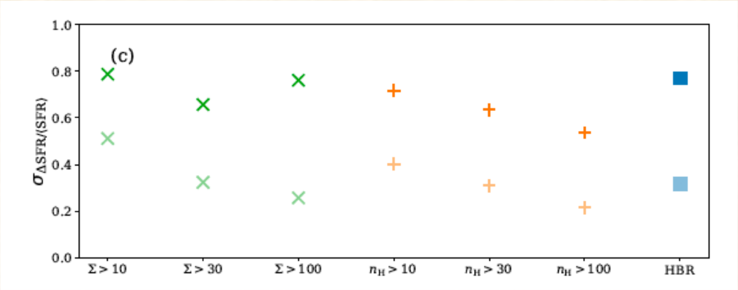
- Temporal phase shift in peaks of mass in different density regimes:

  $t_{shift} \propto t_{ff}(\rho)$

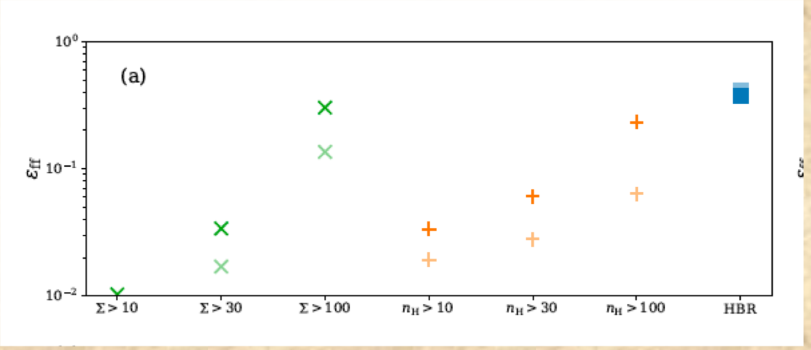
- Indication of *hierarchical formation of self-gravitating structure*

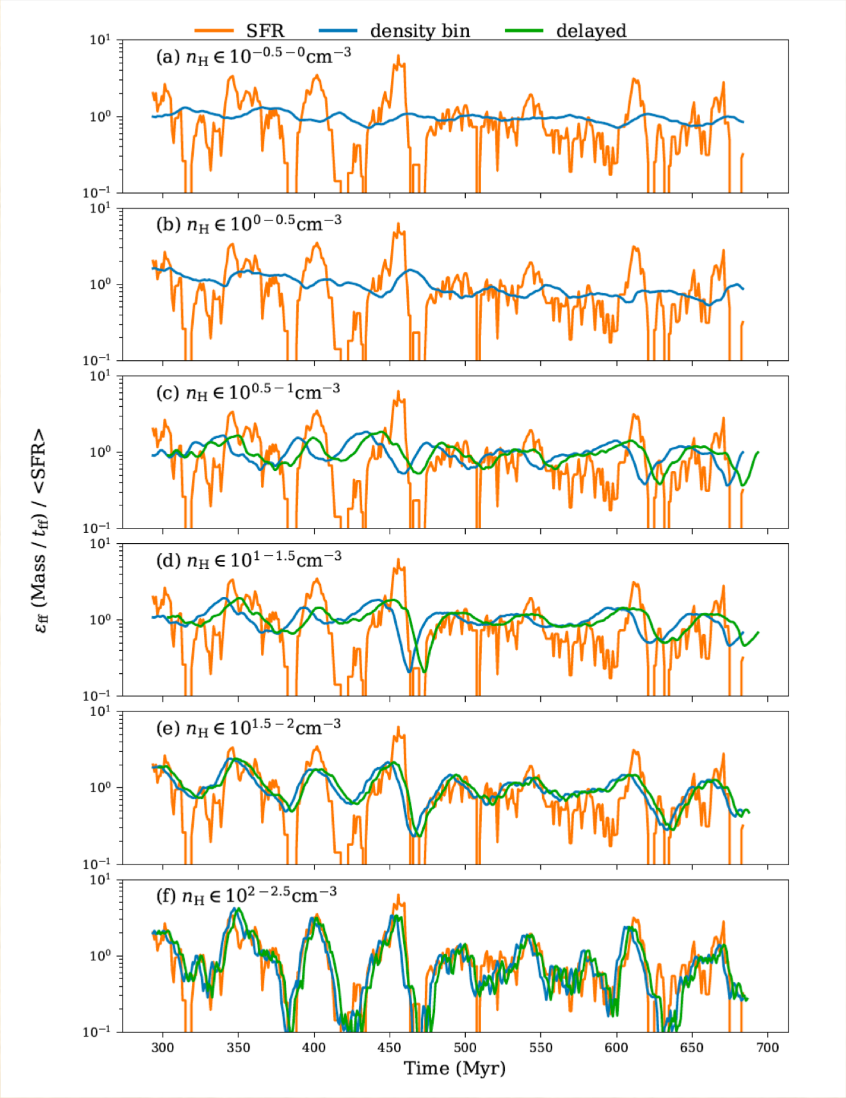
# *Dense gas and SFRs*

- Detailed correlation between gas mass and SFR secularly improves with density



- With $\varepsilon_{ff} \equiv \Sigma_{SFR}\,(t+ t_{shift})\; t_{ff}\; / \Sigma_{gas}(t)$ $\varepsilon_{ff}$ increases with density



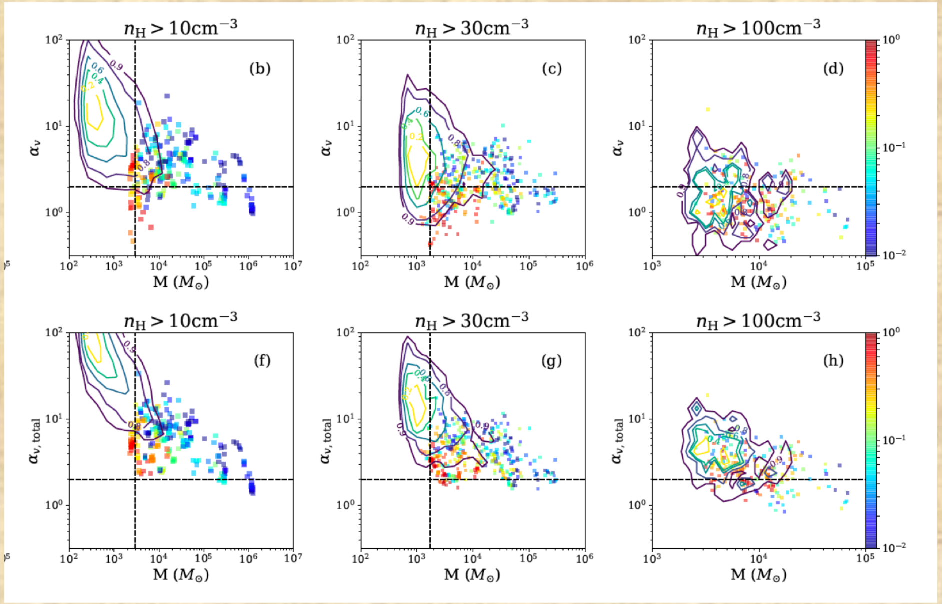


# *Dense gas=bound gas?*

- Most structures, especially at low mass, are unbound
- No fixed density threshold for becoming bound: bound fraction increases with density threshold
- Simple virial parameter typically overestimates true "boundedness"
- Massive clouds are typically not bound even if $\alpha_{vir}$ <2

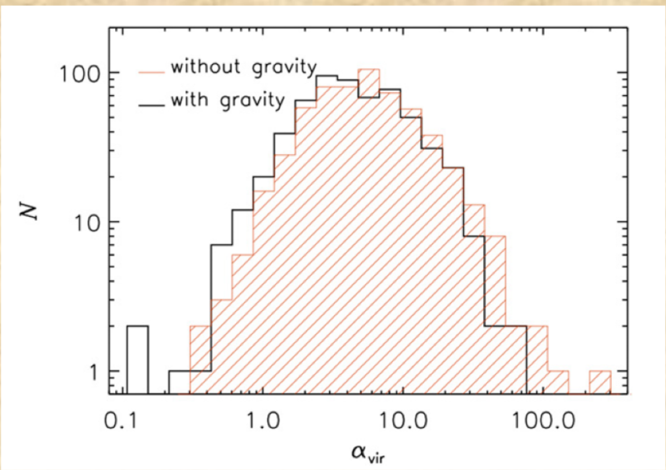
*Fraction of cloud mass that is bound*

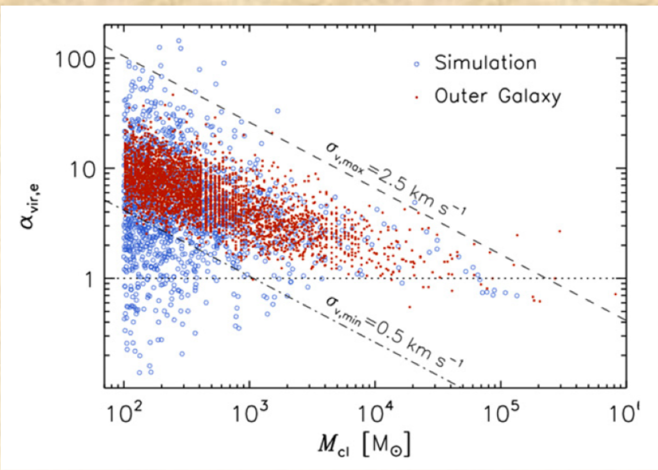
$\alpha_v \equiv 5\sigma_v^2 R/(GM)$



Mass

Mao, Ostriker, & C.-G. Kim (2019)





Padoan, Pan, Haugbolle, & Nordlund (2016)

# *SF efficiency per free-fall time*

Can test how well analytic SF models fit numerical results using time series

$$\mathrm{SFR}_m(t) = \sum_{\mathrm{object}} \epsilon_{\mathrm{ff}}(\alpha_{v,i}) M_i / t_{\mathrm{ff},i}.$$

[1] constant

$$\epsilon_{\mathrm{ff}}(\alpha_v) = \epsilon_{\mathrm{ff},0}.$$

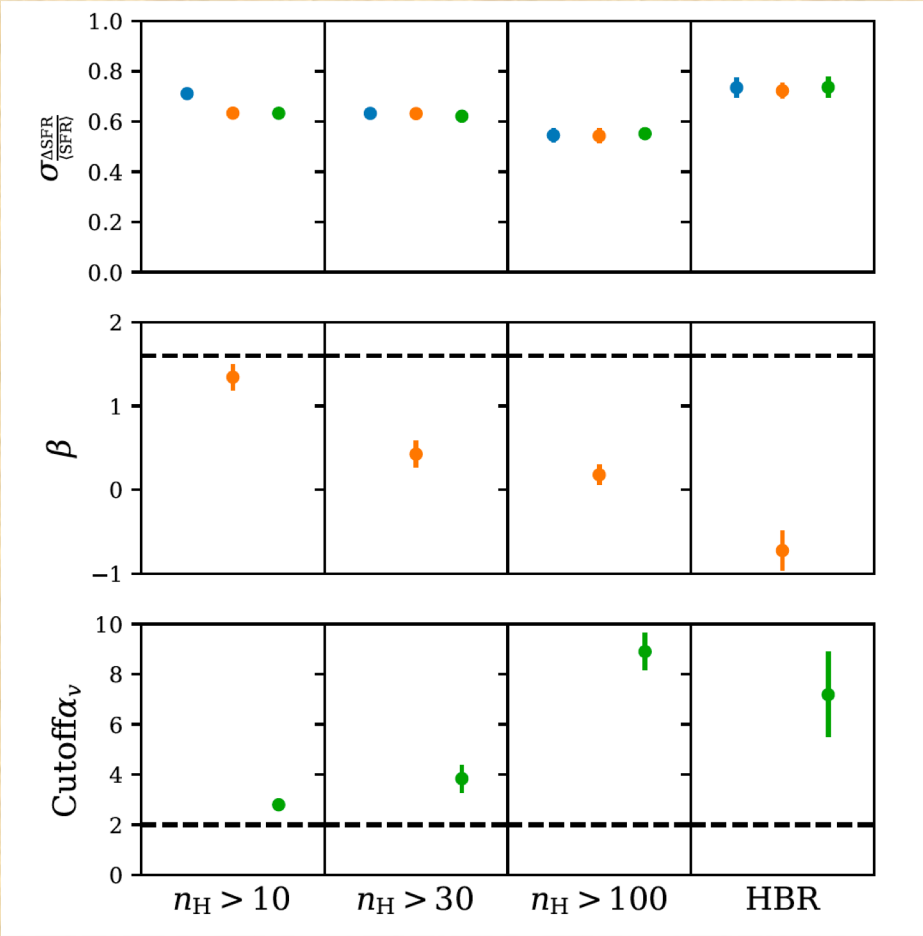
[2] exponential

$$\epsilon_{\mathrm{ff}}(\alpha_v) = \epsilon_{\mathrm{ff},0} \exp(-\beta \sqrt{3\pi^2/40\alpha_v})$$

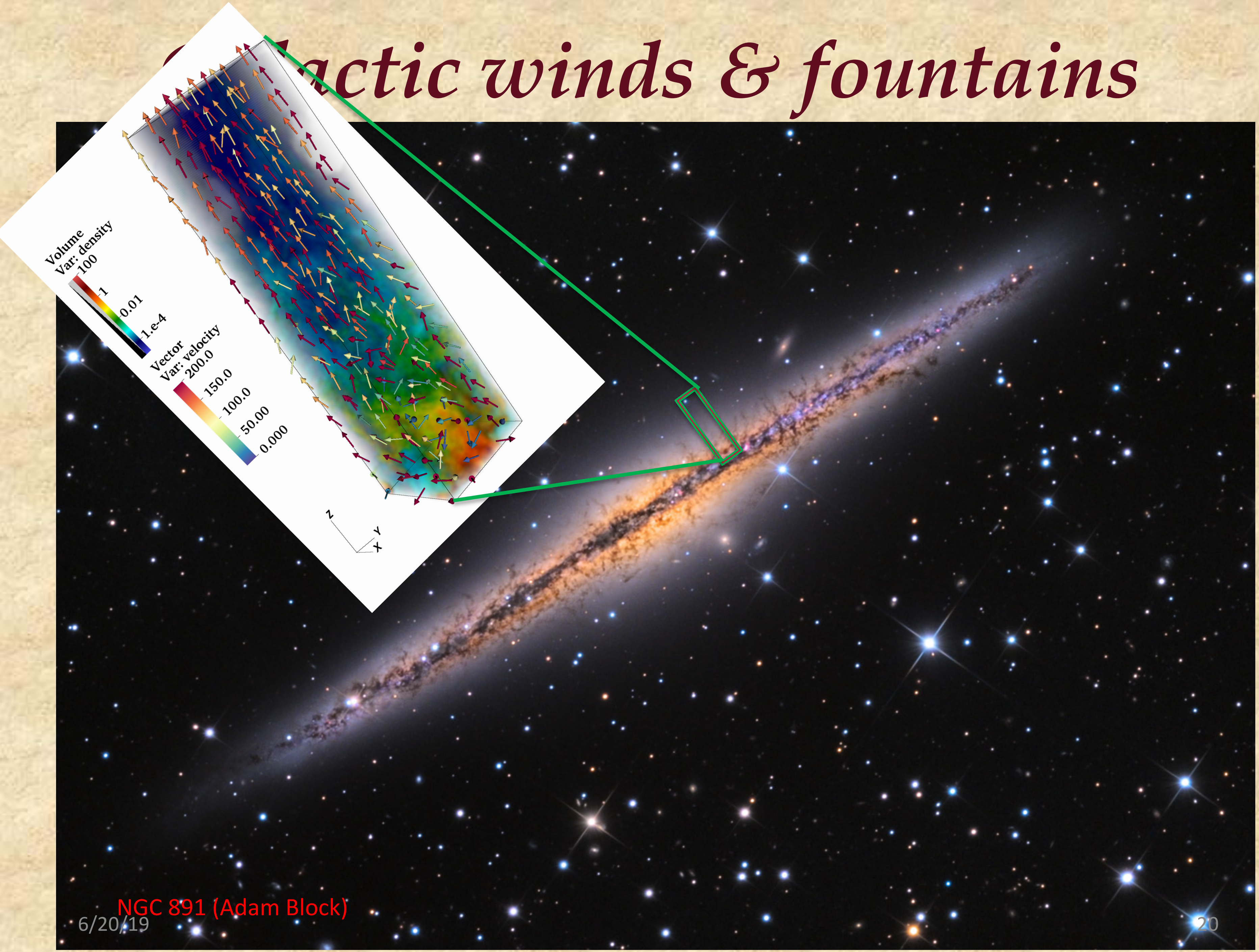
Padoan, Haugbolle, & Nordlund (2012): $\beta$=1.6

[3] threshold

$$\epsilon_{\mathrm{ff}}(\alpha_v) = \epsilon_{\mathrm{ff},0} H(\alpha_{v,\mathrm{cutoff}} - \alpha_v),$$



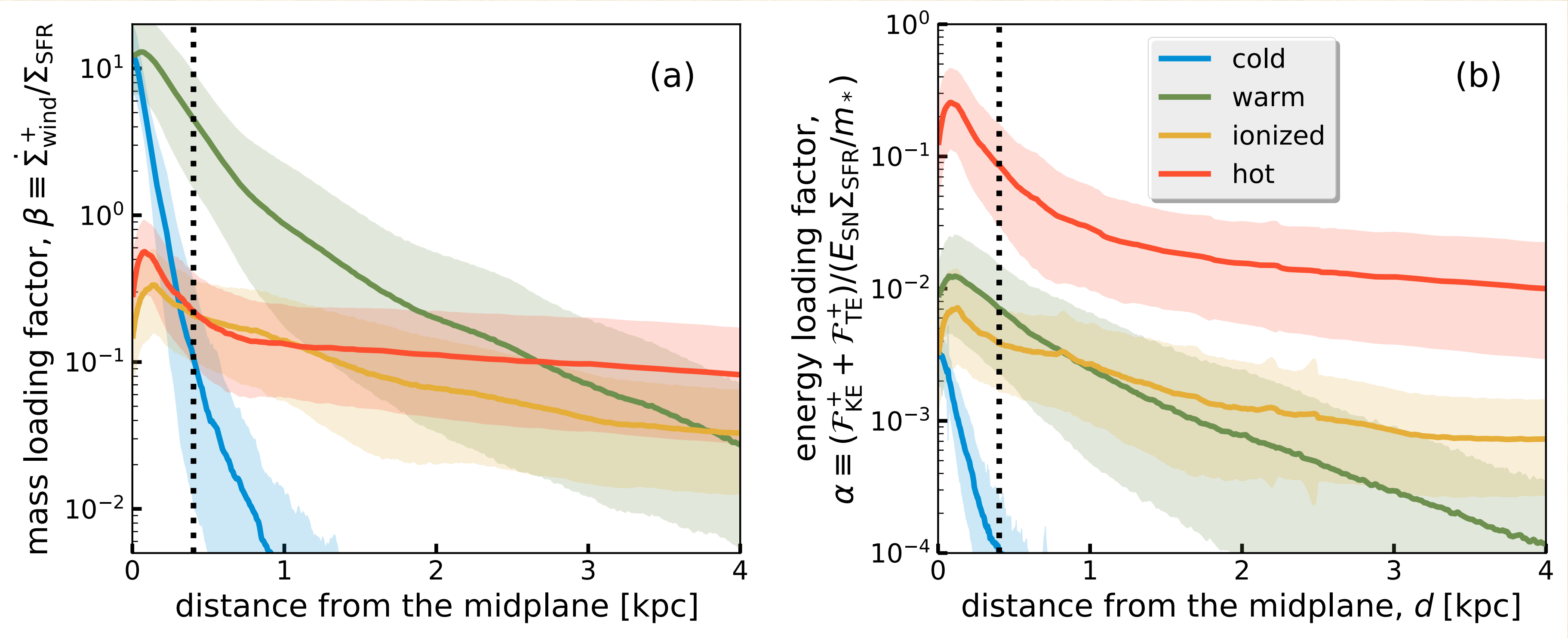
# Galactic winds & fountains



NGC 891 (Adam Block)

# *Outflows driven by SNe: hot wind*

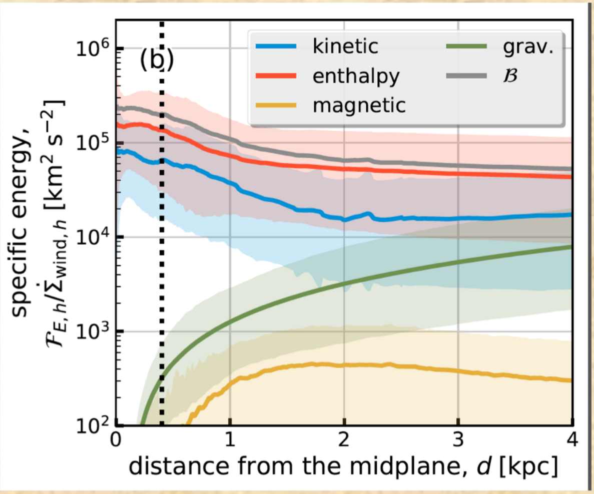
- From TIGRESS simulations of Solar nbhd:
  - Hot gas escapes as nearly adiabatic wind carrying 10% of the mass converted to stars, 1% of energy in SNe
  - Warm gas has more mass, less energy: creates "fountain"

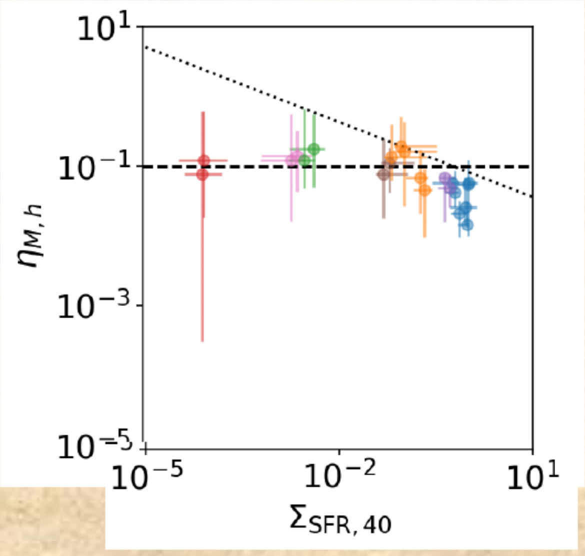


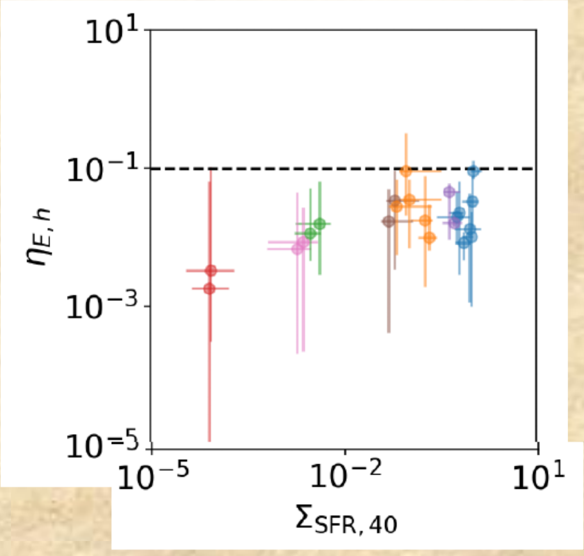
C.-G. Kim & Ostriker (2018)

# *Outflows driven by SNe: hot wind*

- From TIGRESS simulations across environments:
  - Bernoulli implies asymptotic speed $v_{\mathrm{hot}} \sim$ 300-500 km/s
  - Mass loading insensitive to SFR
  - Energy loading increases weakly with SFR





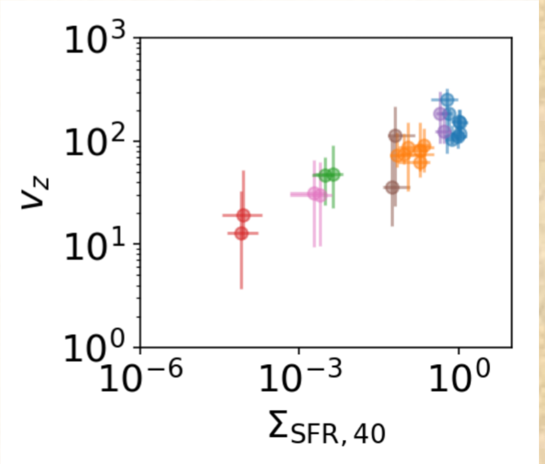


C.-G. Kim & Ostriker (2018)

# *Outflows driven by SNe: warm fountain*

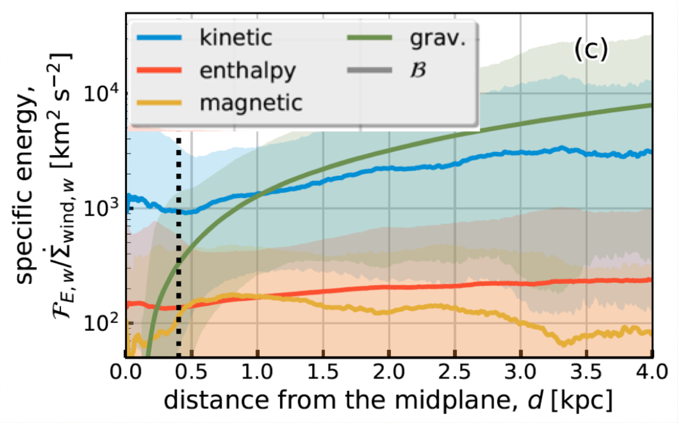
- Warm gas accelerated to v ~ 20-200 km/s, increases with SFR
- Exponential distribution $dM/dv_z$
- Creates fountain in massive galaxies ($v_z < v_{esc}$)

For dwarf galaxy, gas could escape ($v_z > v_{esc}$)

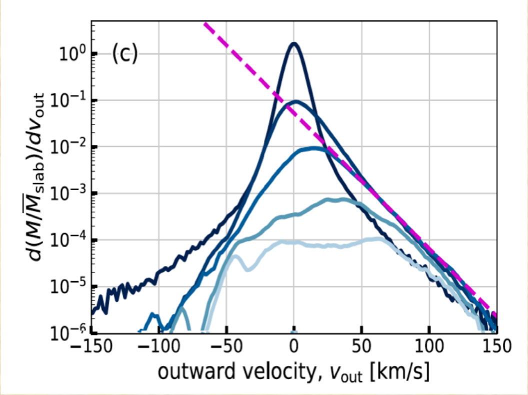


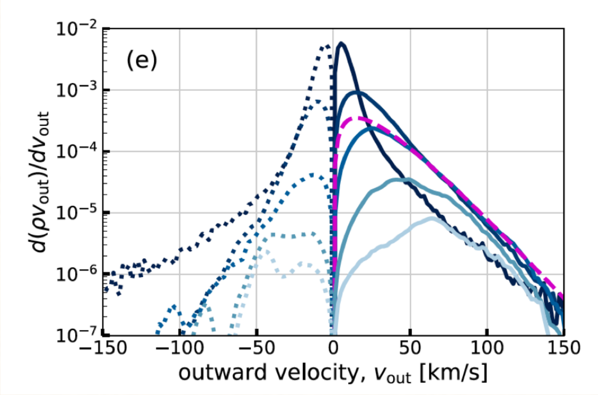
*Warm "fountain" gas may be further accelerated out of galaxy by cosmic ray pressure gradients when CR fluid streams at $v_A$*

C.G. Kim & Ostriker (2018)



Warm component





d=0,0.5,1,2,3 kpc

# *Carrying capacity for CR-driven wind*

Mao & Ostriker (2018)

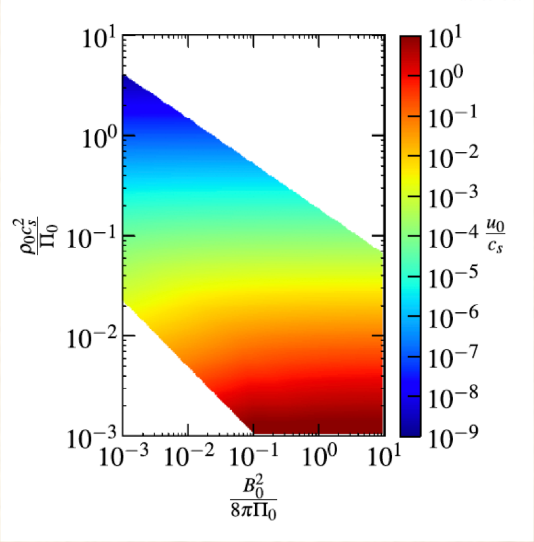
- Mass-loss rate/area in disk:

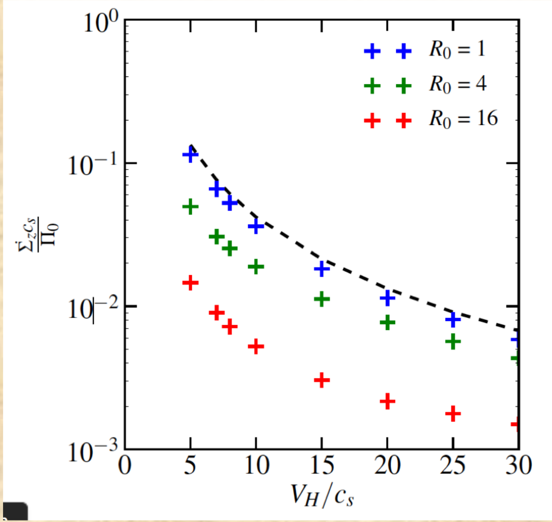
$$\dot{\Sigma} \sim 3\times10^{-3}\ M_\odot\ \mathrm{kpc}^{-2}\ \mathrm{yr}^{-1}\left(\frac{\Pi_0}{1\mathrm{eV\ cm}^{-3}}\right)\left(\frac{V_H}{200\mathrm{kms}^{-1}}\right)^{-5/3}\left(\frac{u_0}{50\mathrm{kms}^{-1}}\right)^{2/3}$$

- Mass-loss rate compared to SFR:

$$\frac{\dot{\Sigma}_{\mathrm{wind,cr}}}{\Sigma_{\mathrm{SFR}}} = \frac{\eta_{\mathrm{cr}}}{c_s}\frac{\dot{\Sigma}_z c_s}{\Pi_0} \sim 0.8\left(\frac{\eta_{\mathrm{cr}}}{600\ \mathrm{km\ s}^{-1}}\right)\left(\frac{V_H}{200\mathrm{kms}^{-1}}\right)^{-5/3}\left(\frac{u_0}{50\mathrm{kms}^{-1}}\right)^{2/3}\left(\frac{A_c}{A_0}\right)^{1/3}\hat{z}\cdot\hat{s}.$$

- $u_0$ ~ 20-200 km/s for SN-driven "fountain" ⇒ wind mass-loss could exceed SFR for $V_H$<200 km/s





# *Summary*

- Star formation is self-regulated by feedback at wide range of scales:
  - turbulent, thermal, radiation, magnetic, and cosmic ray energy densities are sustained by ***energy input from massive stars***
  - these stresses ***control SF rates and efficiencies*** by mitigating or reversing gravitationally-induced collapse
- For disk galaxies, mean SFR adjusts so that turbulent, thermal, & magnetic pressure allow quasi-steady equilibrium in energy equation (gains=losses) and momentum equation (force balance)
- Most dense structures appear to be unbound, when taking into account full gravitational potential (tidal effects)
- Structures at higher density are increasingly correlated with SF; varying models for $\varepsilon_{ff}$ fit SFR comparably
- Outflows driven by SNe create galactic winds and fountains
  - hot winds have mass loading ~ 0.1, energy loading ~ 0.01 - 0.1
  - warm fountains have v~ 20-200 km/s, mass loading ~ 1 at z~ kpc
  - Streaming cosmic rays may accelerate warm fountains into warm winds to produce mass loading >1 when $v_H \lesssim 200$ km/s