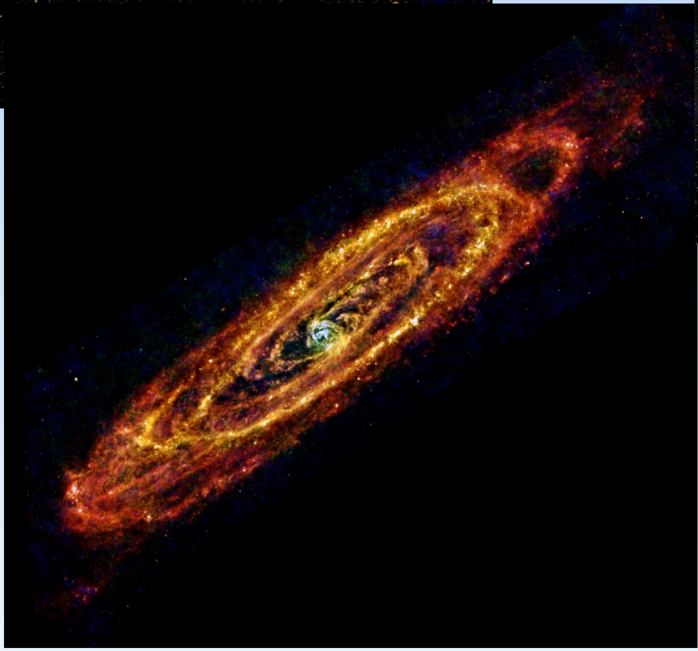
Galactic-scale star formation

Eve Ostriker
Princeton University

Observations: *where do we stand?*

UV: GALEX



IR : Herschel
X-ray: XMM

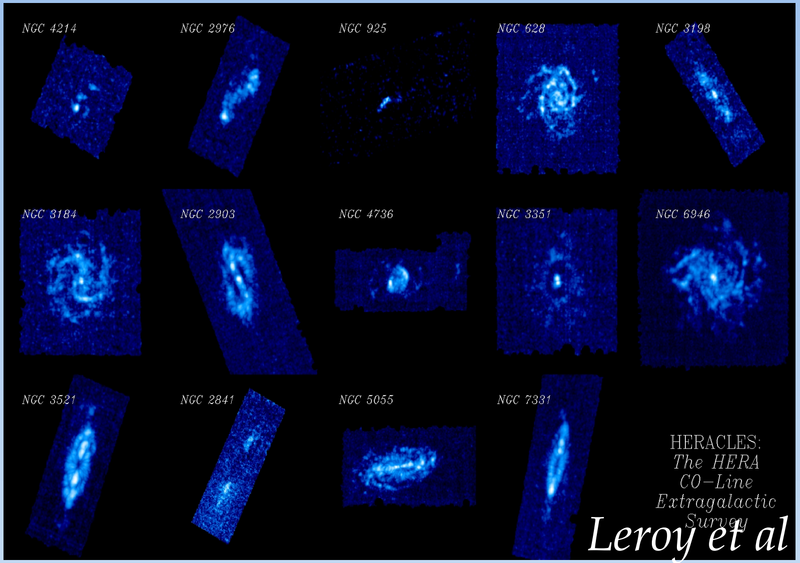
Optical: Gendler + PHAT

High resolution Andromeda

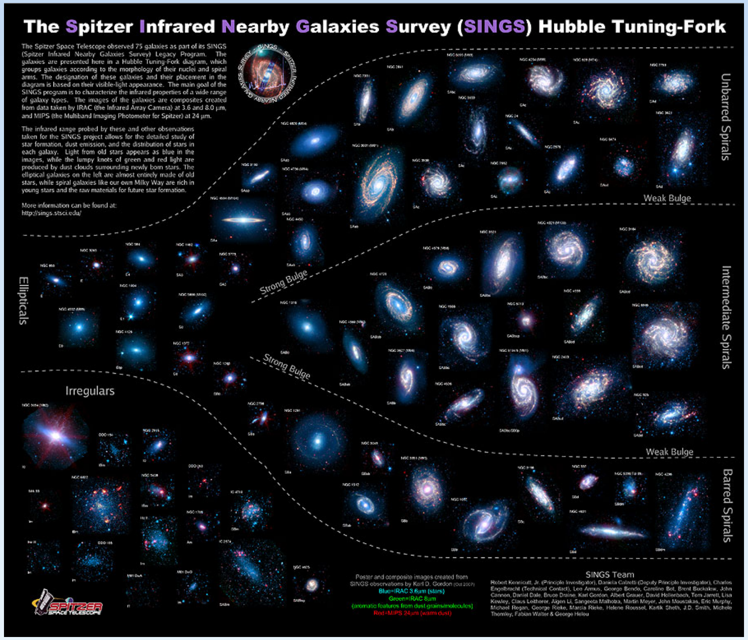
Other high-res. surveys:

- *CO (1-0) (CARMA, Schruba)*
- *21cm, RC (EVLA, Leroy)*

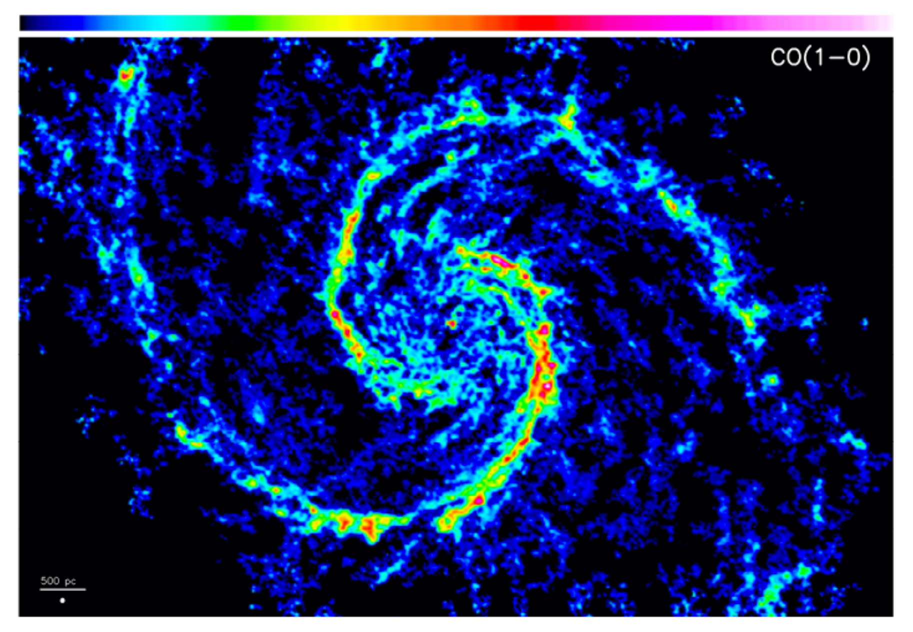
Large-scale gas and SFR

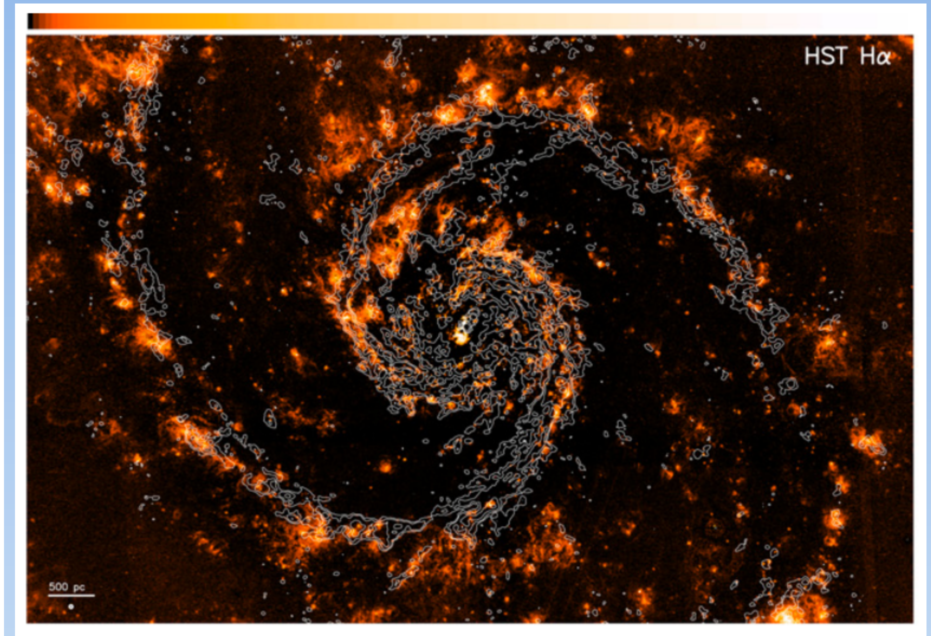


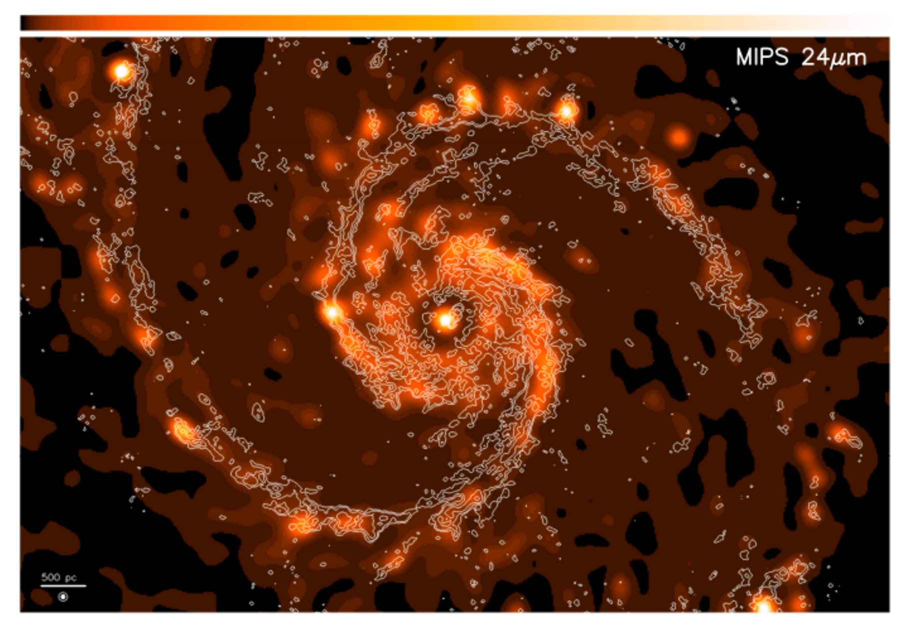
Leroy et al

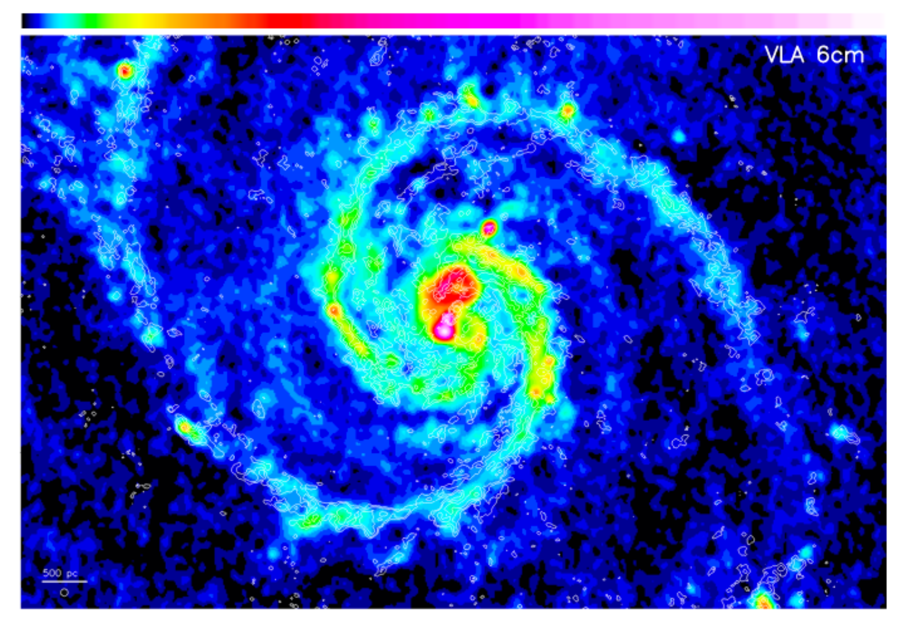


kpc-scale surveys





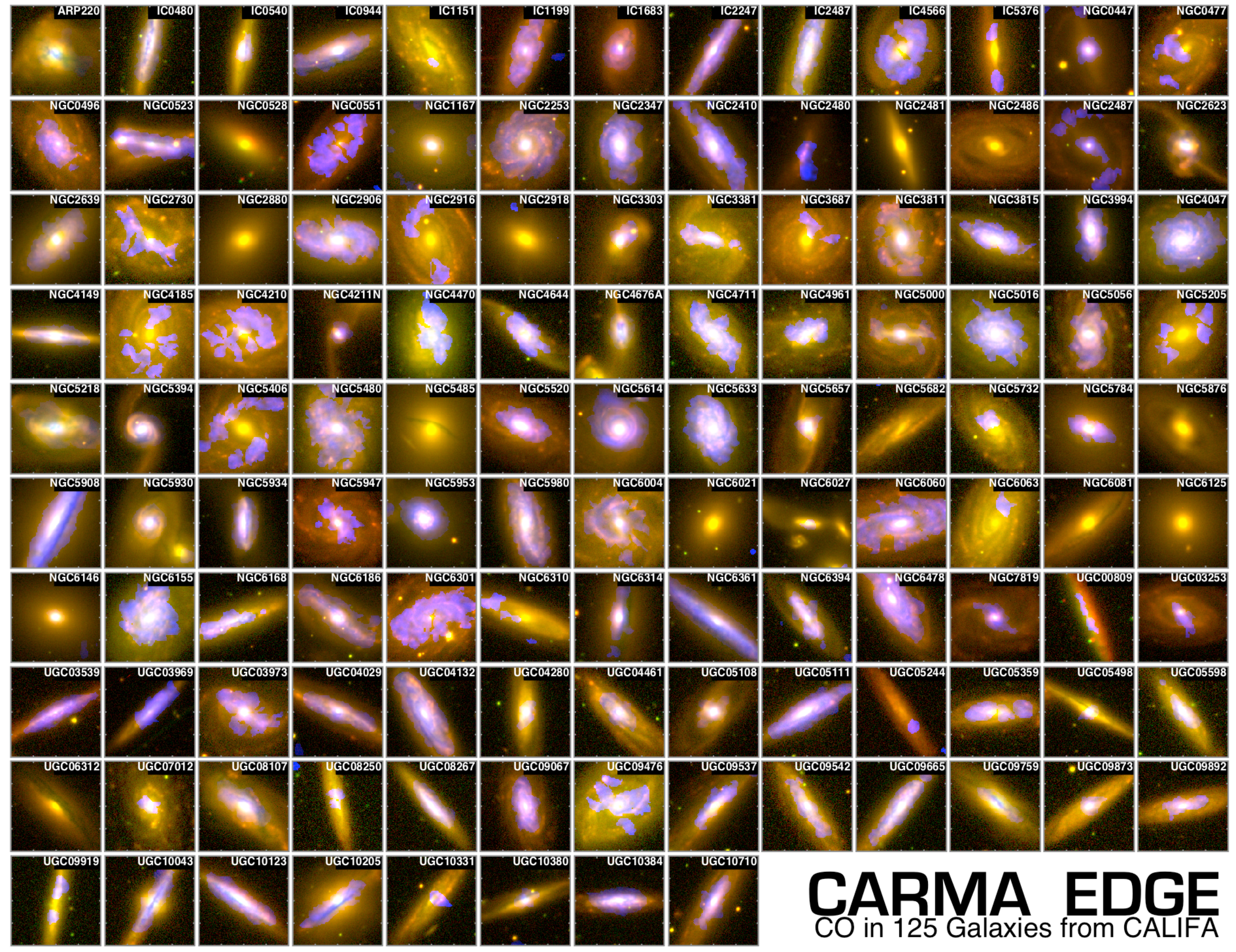




PAWS: M51 at GMC-scale resolution

Schinnerer et al (2013)

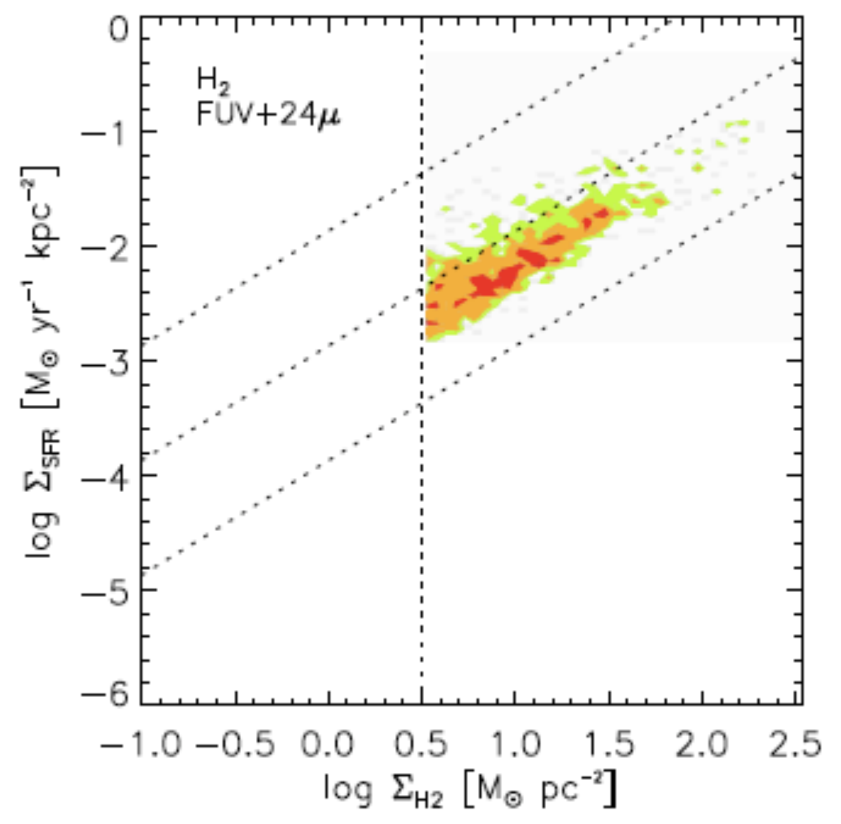
EDGE+CALIFA


ARP220
IC0480
IC0540
IC0944
IC1151
IC1199
IC1683
IC2247
IC2487
IC4566
IC5376
NGC0447
NGC0477
NGC0496
NGC0523
NGC0528
NGC0551
NGC1167
NGC2253
NGC2347
NGC2410
NGC2480
NGC2481
NGC2486
NGC2487
NGC2623
NGC2639
NGC2730
NGC2880
NGC2906
NGC2916
NGC2918
NGC3303
NGC3381
NGC3687
NGC3811
NGC3815
NGC3994
NGC4047
NGC4149
NGC4185
NGC4210
NGC4211N
NGC4470
NGC4644
NGC4676A
NGC4711
NGC4961
NGC5000
NGC5016
NGC5056
NGC5205
NGC5218
NGC5394
NGC5406
NGC5480
NGC5485
NGC5520
NGC5614
NGC5633
NGC5657
NGC5682
NGC5732
NGC5784
NGC5876
NGC5908
NGC5930
NGC5934
NGC5947
NGC5953
NGC5980
NGC6004
NGC6021
NGC6027
NGC6060
NGC6063
NGC6081
NGC6125
NGC6146
NGC6155
NGC6168
NGC6186
NGC6301
NGC6310
NGC6314
NGC6361
NGC6394
NGC6478
NGC7819
UGC00809
UGC03253
UGC03539
UGC03969
UGC03973
UGC04029
UGC04132
UGC04280
UGC04461
UGC05108
UGC05111
UGC05244
UGC05359
UGC05498
UGC05598
UGC06312
UGC07012
UGC08107
UGC08250
UGC08267
UGC09067
UGC09476
UGC09537
UGC09542
UGC09665
UGC09759
UGC09873
UGC09892
UGC09919
UGC10043
UGC10123
UGC10205
UGC10331
UGC10380
UGC10384
UGC10710
CARMA EDGE
CO in 125 Galaxies from CALIFA

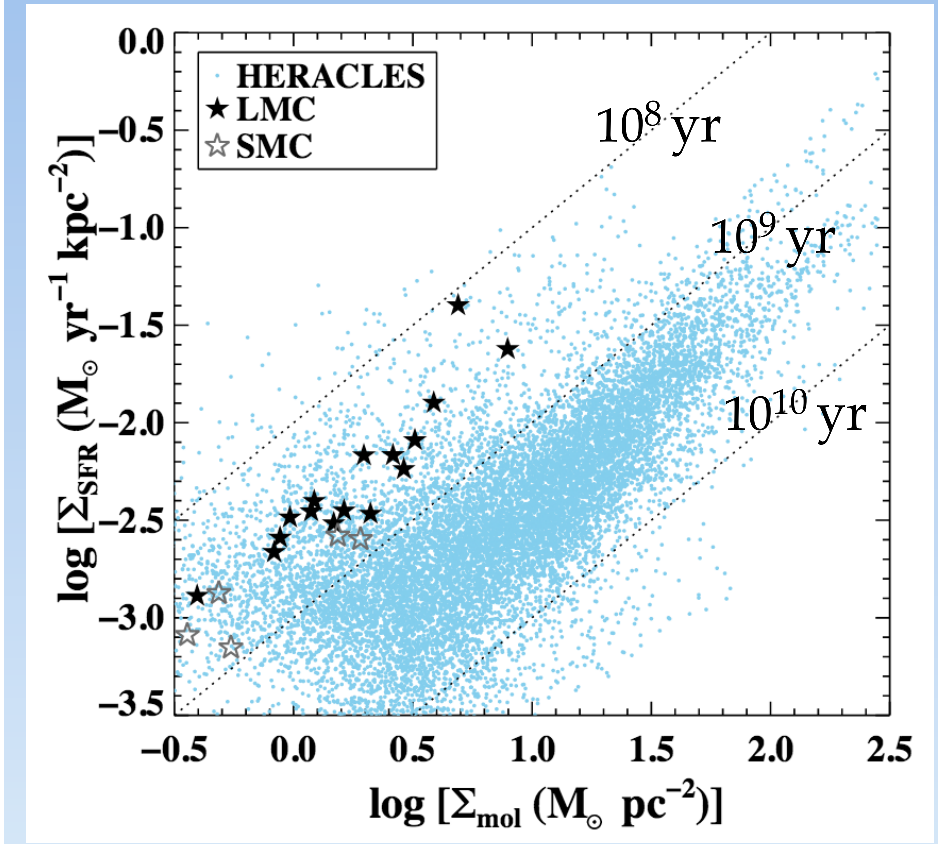
"first order": $\Sigma_{SFR}/\Sigma_{H2} \sim$ const.

Schruba et al (2011)

Bigiel et al (2008)



HERACLES

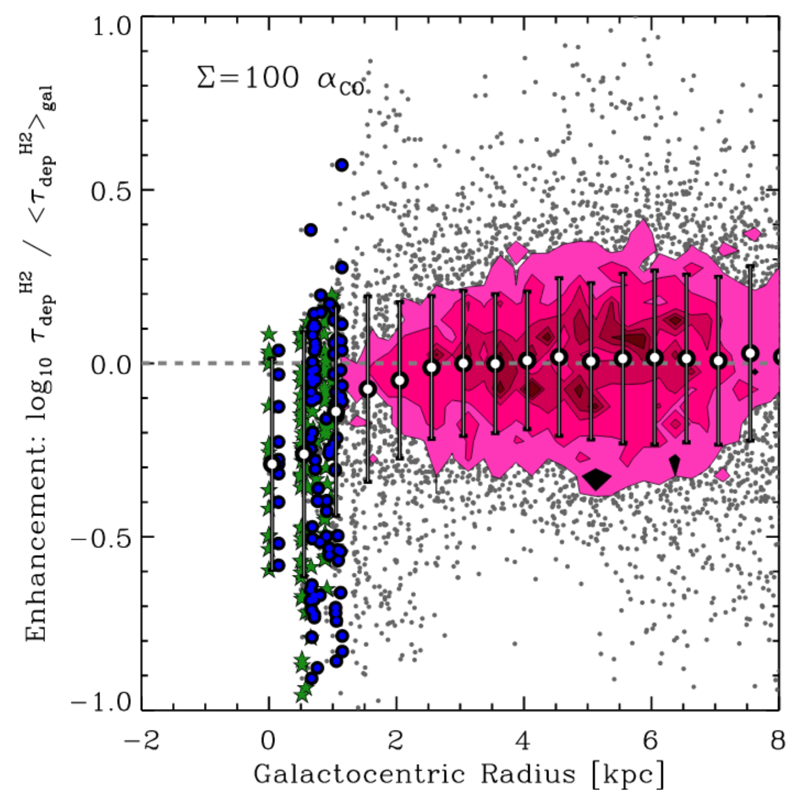


Jameson et al (2015)

- SFR linear in H_2 at moderate $\Sigma_{H2} \lesssim 100 M_\odot\,pc^{-2}$:

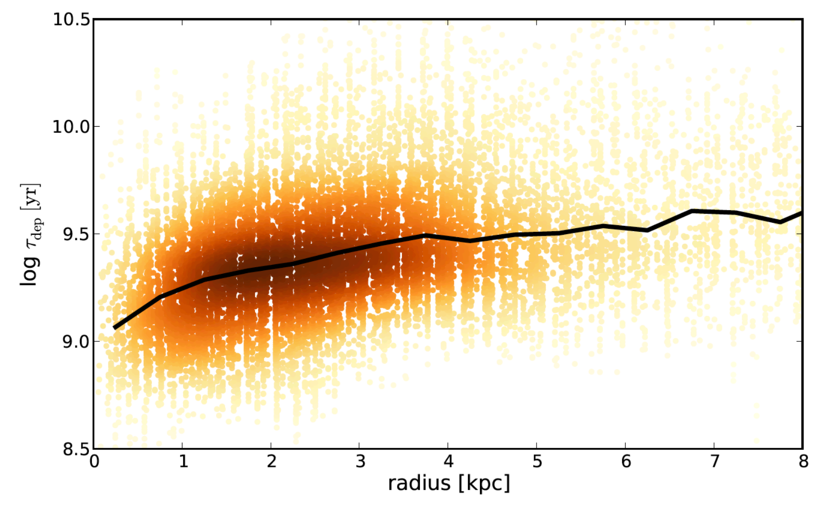
$\Sigma_{SFR} = \Sigma_{H2}/t_{dep,mol}$ with $t_{dep,mol} \sim 10^9$ yr

Next order: variations in $t_{dep,mol}$



Leroy et al (2013)

Effect enhanced by lower central X_{CO} (Sandstrom et al 2013)

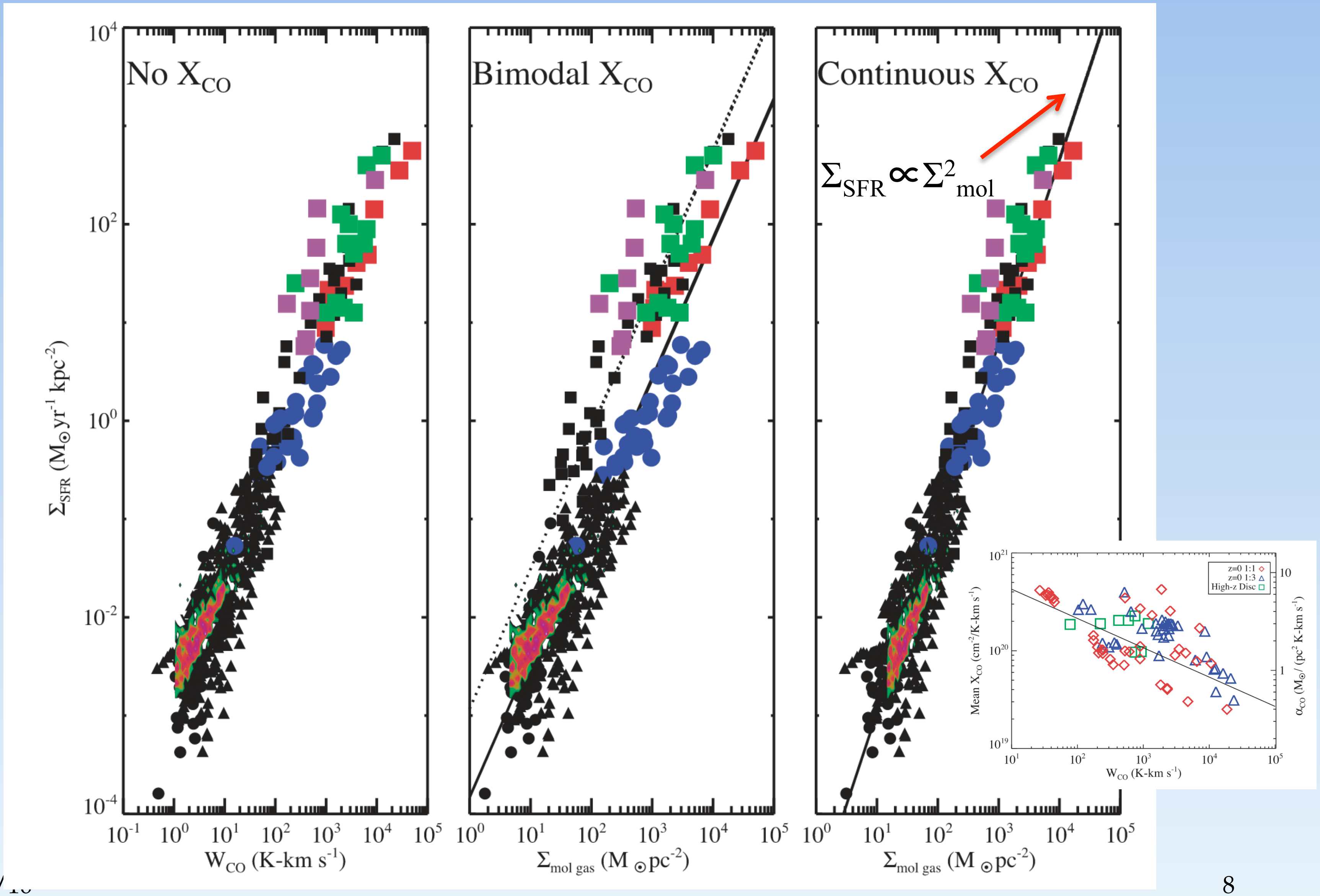


Utomo + EDGE/CALIFA team (2016)

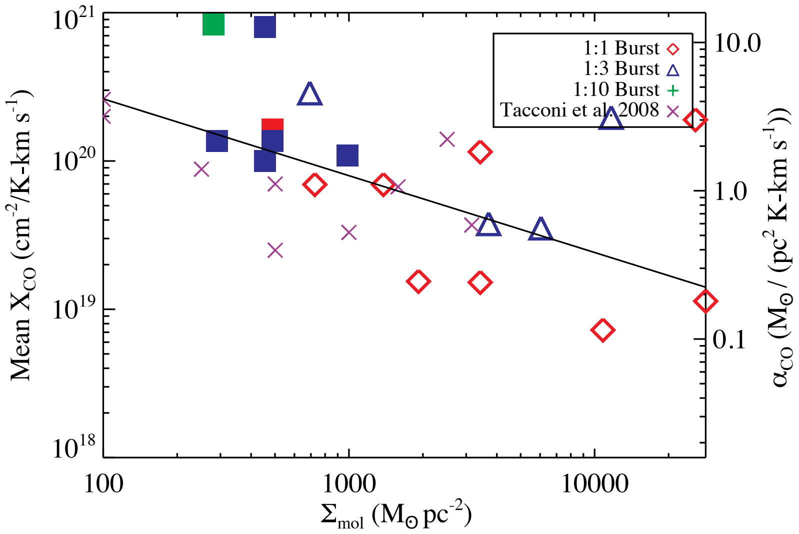
Lower $t_{dep,mol\,=}=\Sigma_{mol}/\Sigma_{SFR}$ *in centers of normal galaxies*

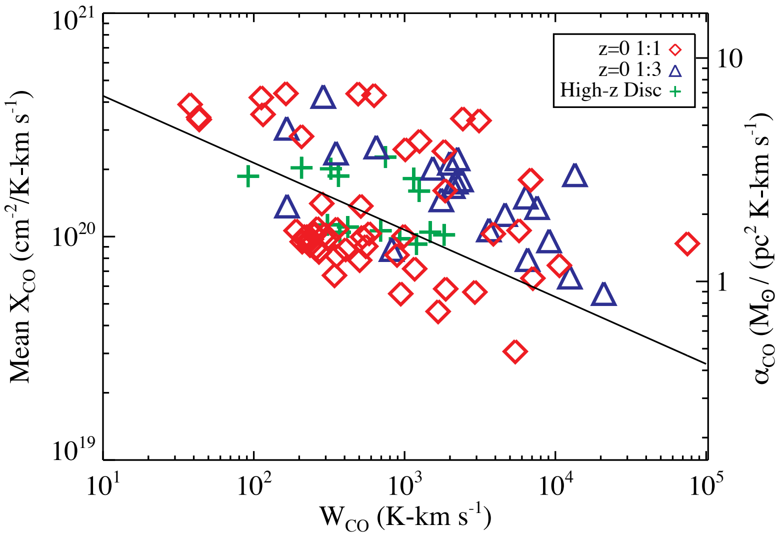
High-Σ_{H2} regime: strongly nonlinear

Narayanan et al (2102)



$X_{CO} = \Sigma_{H2}/W_{CO}$

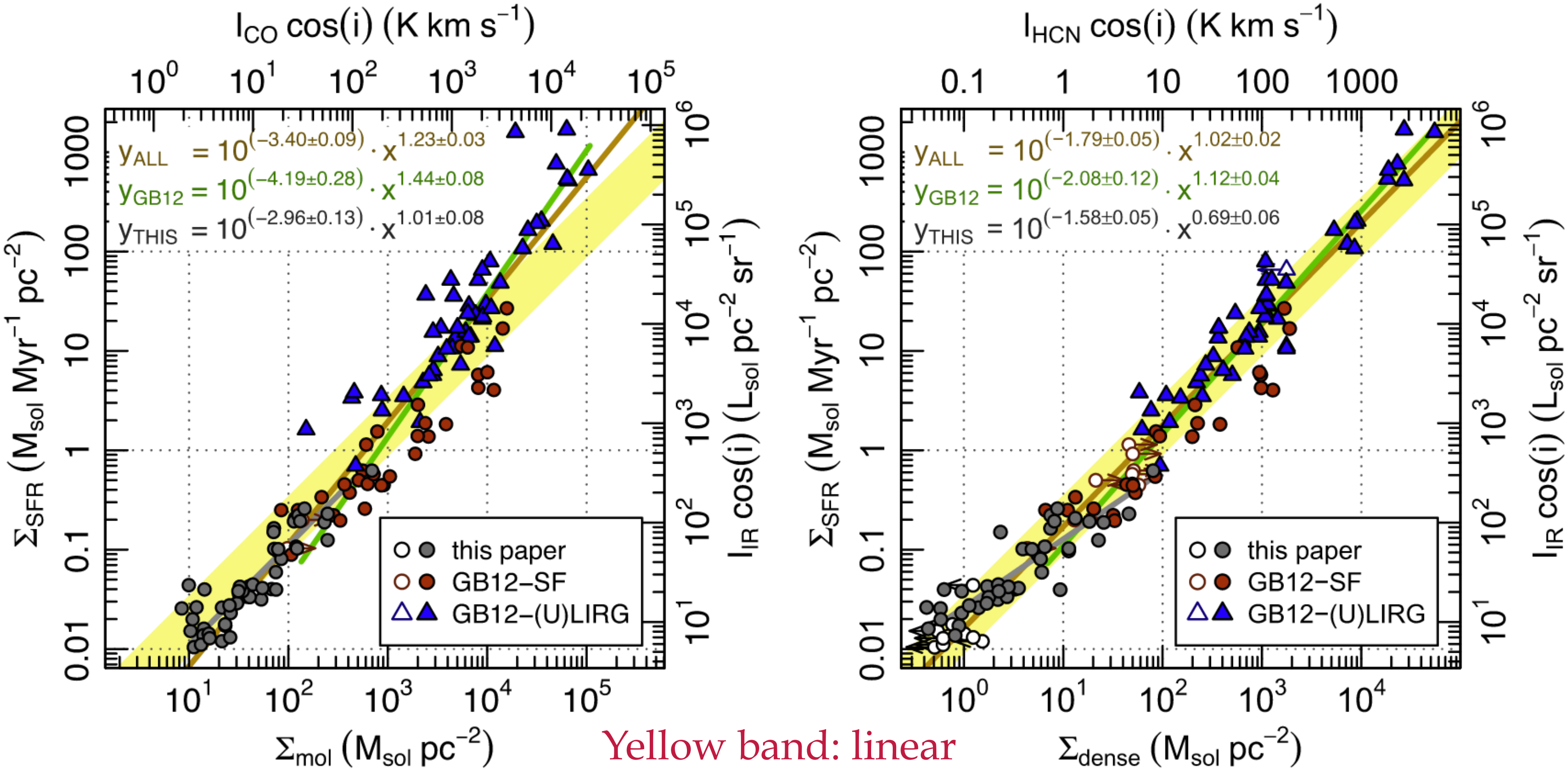




Narayanan, Krumholz, Ostriker, & Hernquist (2012)

$$X_{CO} = 1.3\times10^{21}/[Z'\Sigma_{H2}^{0.5}] \qquad X_{CO} = 6.8\times10^{20}/[Z'^{0.65}W_{CO}^{0.32}]$$

SF in dense gas



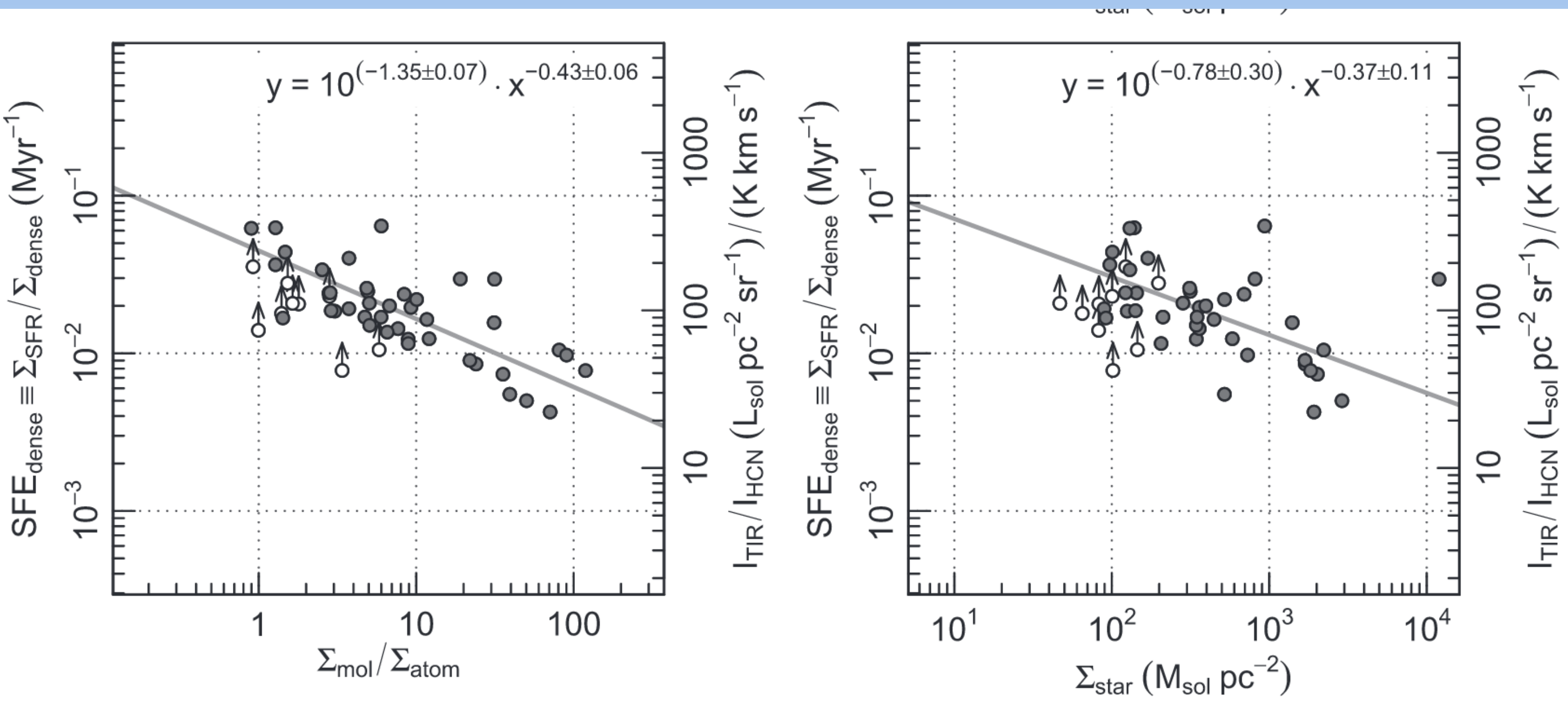
Yellow band: linear

Shallower relation at low Σ, esp. for HCN ⇒ relatively more efficient SF in HCN-emitting gas at low Σ

Usero et al (2015)

See also: Gao & Solomon (2004), Garcia-Burillo et al (2012); Wu et al (2005)

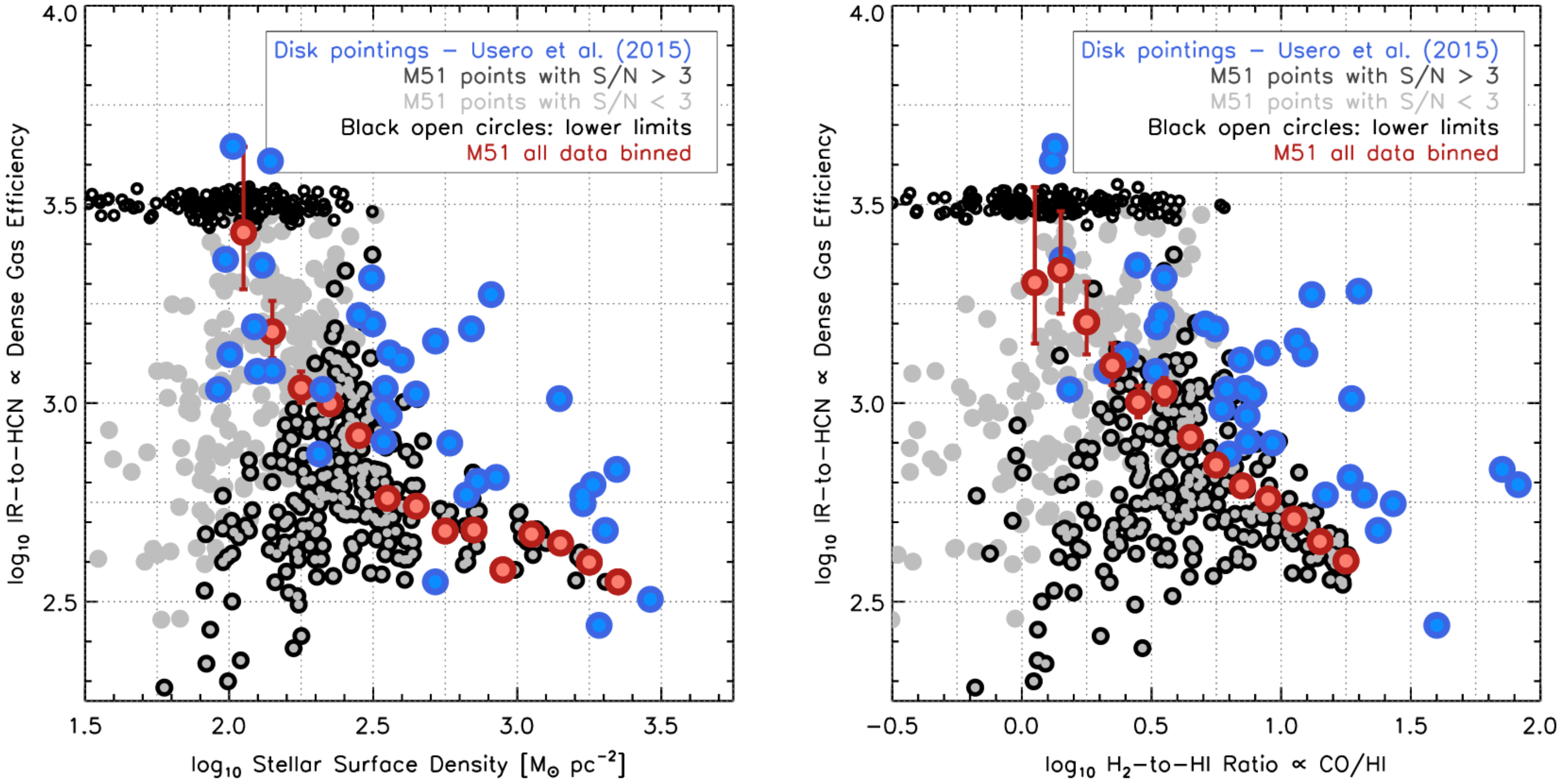
SF in dense gas



relatively more efficient SF in HCN-emitting gas at low Σ_{gas} and Σ_{star}

Usero et al (2015)

SF in dense gas



Bigiel et al (2016)

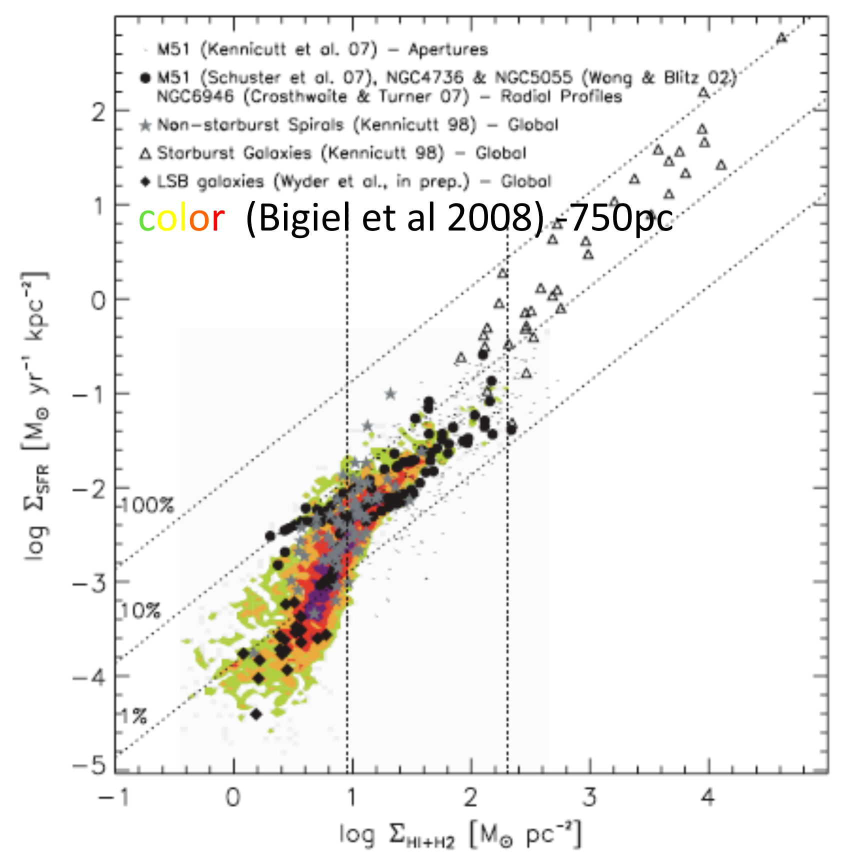
Similar result holds for multiple pointings within M51

SF vs. total gas

- Increase of Σ_{SFR} with total
  $\Sigma_{gas} = \Sigma_{HI} + \Sigma_{H2}$:
  - Superlinear at high end:
    - $\Sigma_{gas} \approx \Sigma_{H2} \gtrsim 100\ M_{\odot}\ pc^{-2}$
  - Close to linear for
  - $10 M_{\odot}\ pc^{-2} \lesssim \Sigma_{gas} \approx \Sigma_{H2} \lesssim 100\ M_{\odot}\ pc^{-2}$

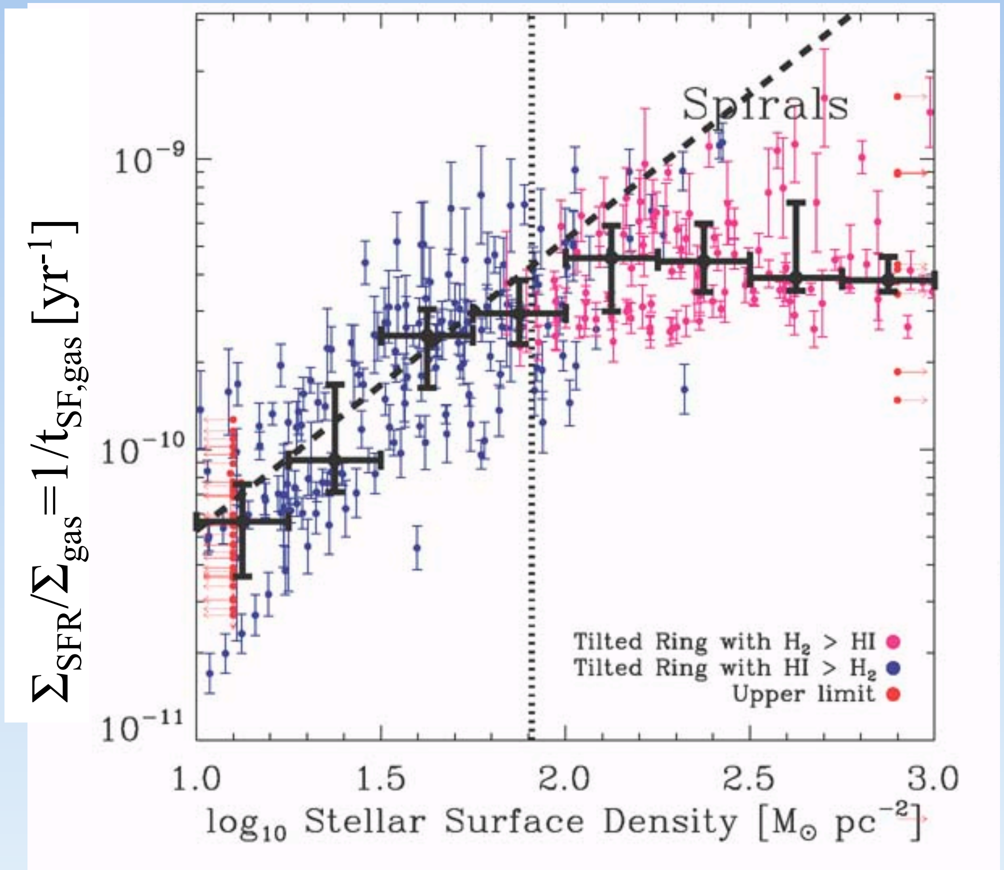
    with $t_{SF,H2} = 2\times10^{9}$ yr
- Superlinear and significant scatter at low end:
  - $\Sigma \approx \Sigma_{HI} \lesssim 10 M_{\odot}\ pc^{-2}$

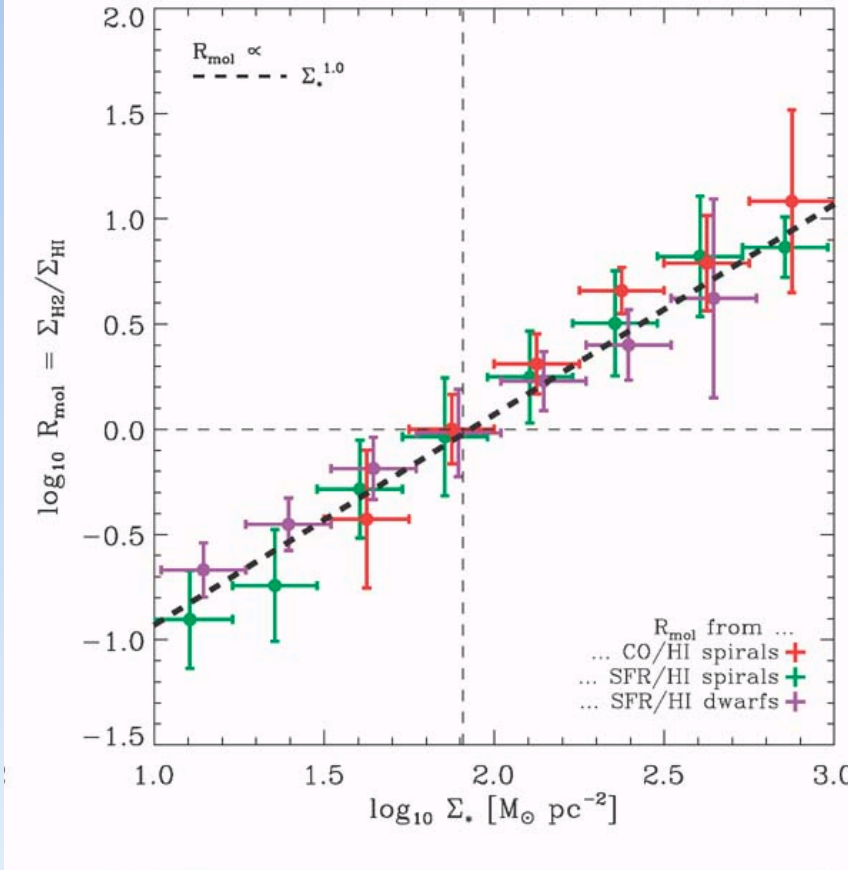
  ⇒ *parameter other than Σ_{gas} is important!*



Local and global Kennicutt-Schmidt relations

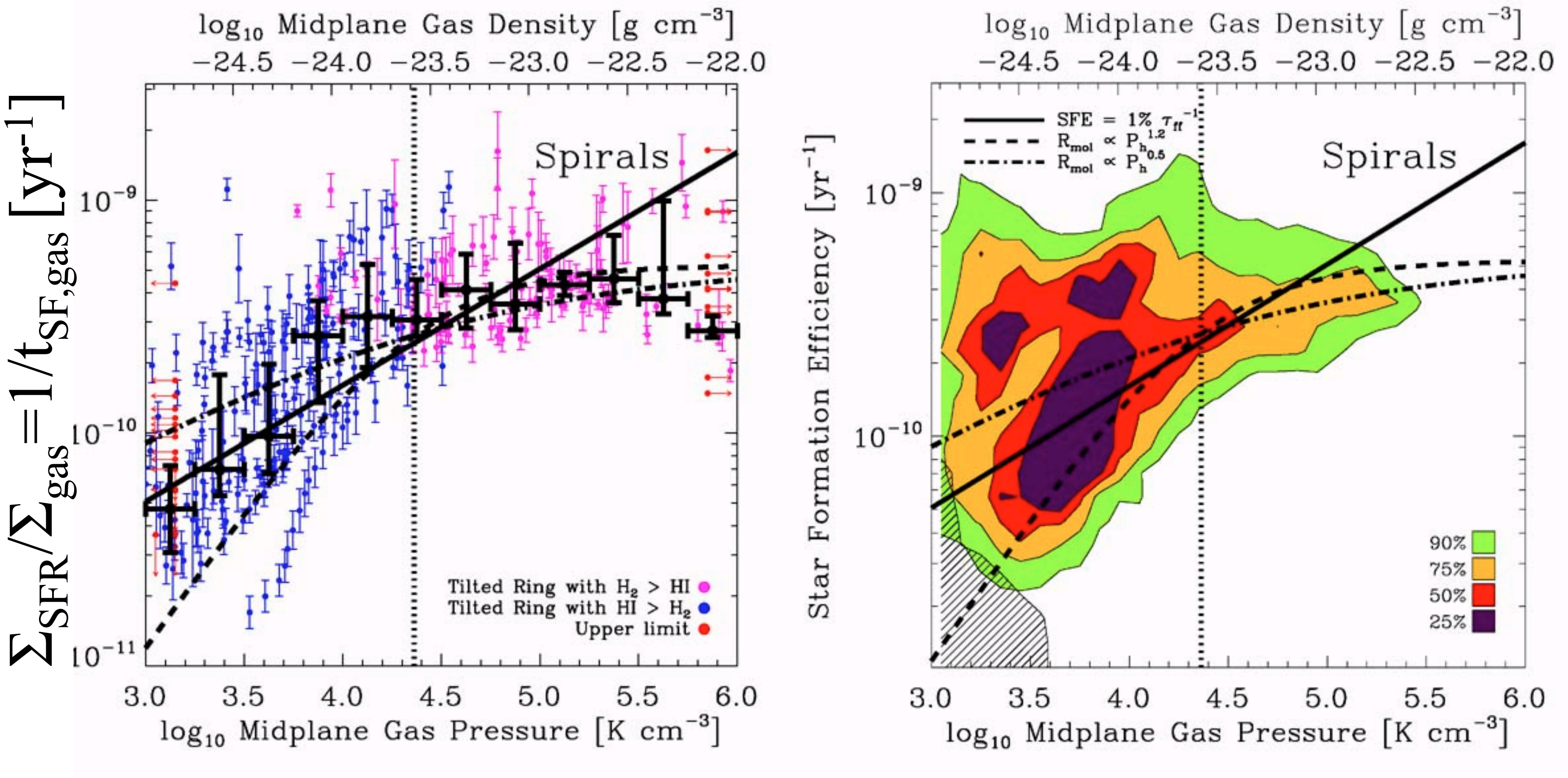
SFR and H_2/HI correlations with stellar content





Leroy et al (2008)

SFR and pressure correlation



Leroy et al (2008)

See also Blitz & Rosolowsky (2006): $R_{mol} \propto P_{DE}$

Gas consumption efficiency

- Interpretation of mid-disk obs. with $t_{SF}(H_2)$= const. : "isolated" GMCs have ~uniform properties and SFE

$$\dot{M}_* = \varepsilon_{\rm GMC} \frac{M_{\rm GMC}}{t_{\rm GMC}} = \varepsilon_{\rm ff} \frac{M_{\rm GMC}}{t_{\rm ff}} \quad \Rightarrow \quad \Sigma_{\rm SFR} = \varepsilon_{\rm GMC} \frac{\Sigma_{\rm mol}}{t_{\rm GMC}} = \varepsilon_{\rm ff} \frac{\Sigma_{\rm mol}}{t_{\rm ff}}$$

$t_{SF}(H_2) = 2\times10^9$ yr requires $\varepsilon_{\rm GMC} = 0.01$ if $t_{\rm GMC} = 20$ Myr,
$\varepsilon_{\rm ff} = 0.003$ if $\langle n_H\rangle \sim 50\ {\rm cm}^{-3}$

- Starburst regime: using t_{ff} for all-H_2 disk in vertical equilibrium,

$$\Sigma_{\rm SFR} \equiv \varepsilon_{\rm ff} \frac{\Sigma}{t_{\rm ff}} = \varepsilon_{\rm ff} \frac{4G\Sigma^2}{\sqrt{3}v_z}$$

  - Comparison to coefficient of $\Sigma_{SFR} \propto \Sigma^2$ from observations ⇒

$$\varepsilon_{\rm ff} = 0.001 v_z/{\rm km\ s}^{-1} \sim 0.01$$

for $v_z \sim 10$ *km/s*

Note: $t_{osc} = (\pi/G\rho_{tot})^{1/2}$; $t_{ff} = (3\pi/32G\rho_{gas})^{1/2} \sim t_{osc}/2$; $t_{ver} = H/v_z = t_{osc}/(2\pi)$

- *Star formation is inefficient at consuming gas, over timescales relevant to the ISM dynamics*

Questions for theory

- Why is SF correlated with molecular gas?
- Why is $\varepsilon_{\mathrm{ff}}$ so small and $t_{\mathrm{dep,mol}}$ so large?
- Why do inner galaxies/high-Σ_* /high P regions have higher efficiency/lower $t_{\mathrm{dep,mol}}$?
- What is responsible for the scaling $\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{mol}}^2$ in starburst regions?
- Is star formation as “inefficient” as it seems?

Questions for theory

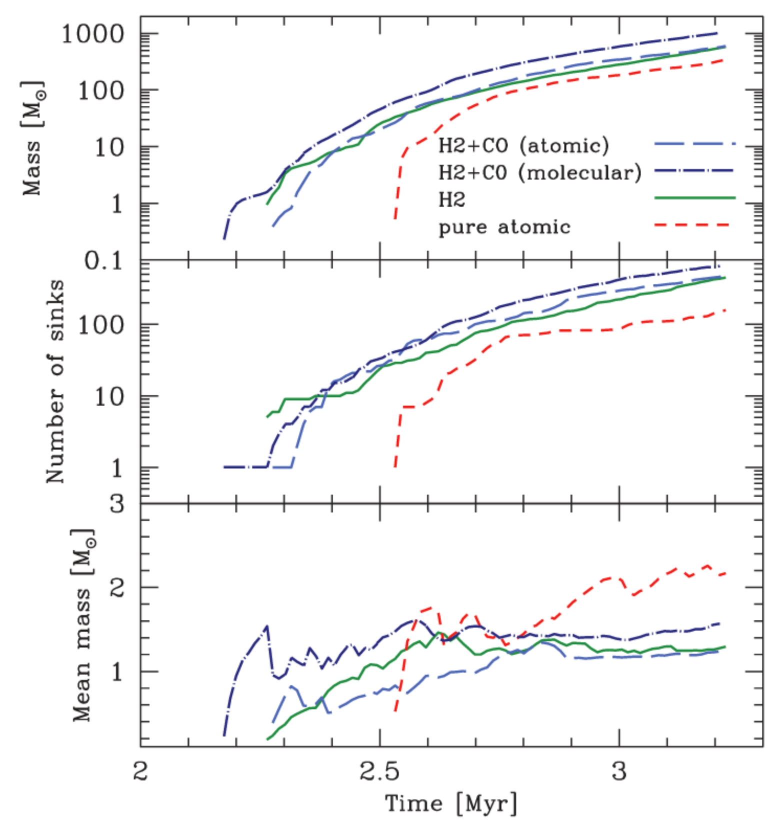
- Why is SF correlated with molecular gas?
- Why is ε_{ff} so small and $t_{dep,mol}$ so large?
- Why do inner galaxies/high-Σ_* /high P regions have higher efficiency/lower $t_{dep,mol}$?
- What is responsible for the scaling $\Sigma_{SFR} \propto \Sigma_{mol}^2$ in starburst regions?
- Is star formation as "inefficient" as it seems?

SF/molecular correlation?

- Causality or coincidence?

Krumholz, Leroy, McKee (2011), Glover & Clark (2012)

  - Low *T* required for small-scale collapse, but H_2 does not cool
  - Molecule formation and self-gravity timescales both shorter at high *n*
  - Photodissociation, photoheating, gravity/pressure all reduced at high *N*
  - CO best coolant but C^+, and C nearly as good

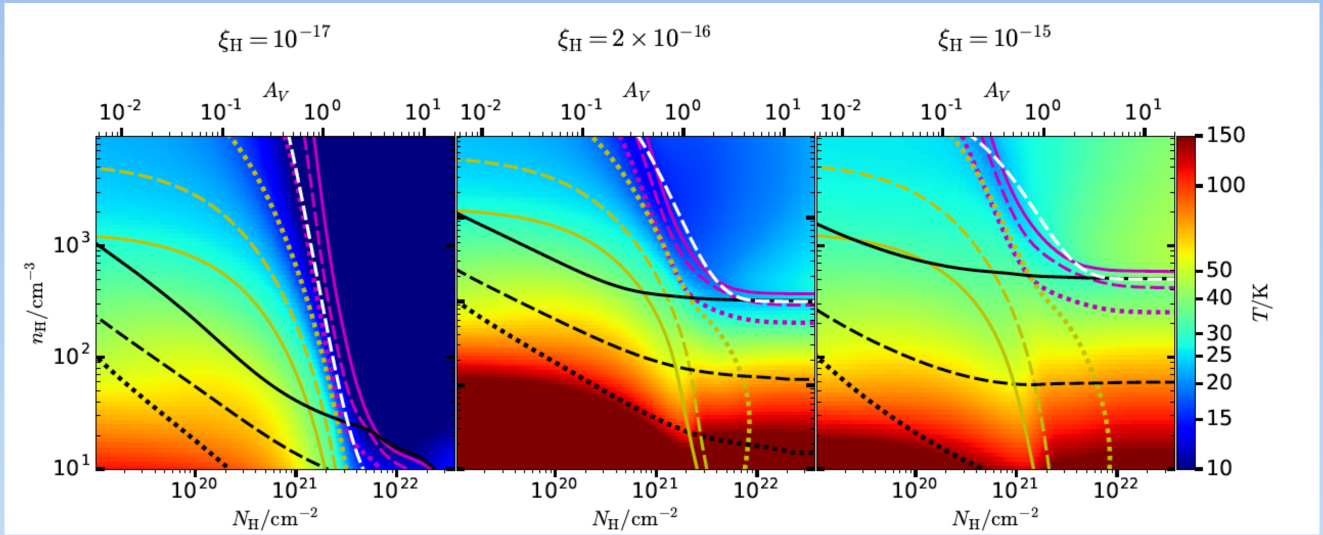


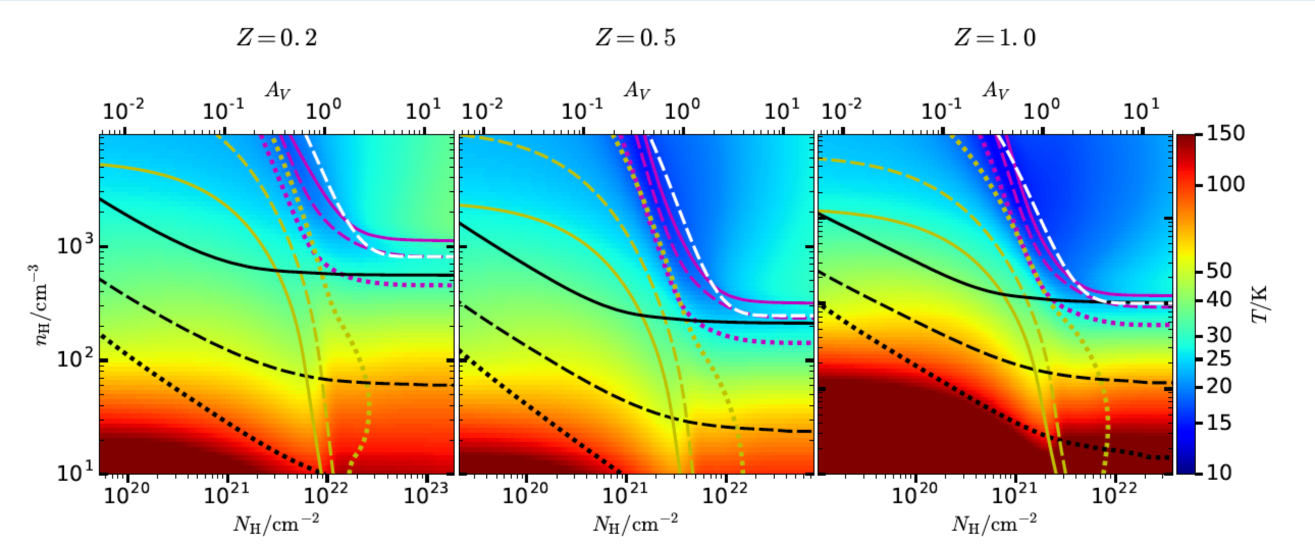
Glover & Clark (2012)

Red: no chemistry
Green: H chemistry only
Blue: all chemistry

Temperature & chemistry

Gong, Ostriker, & Wolfire (2016)

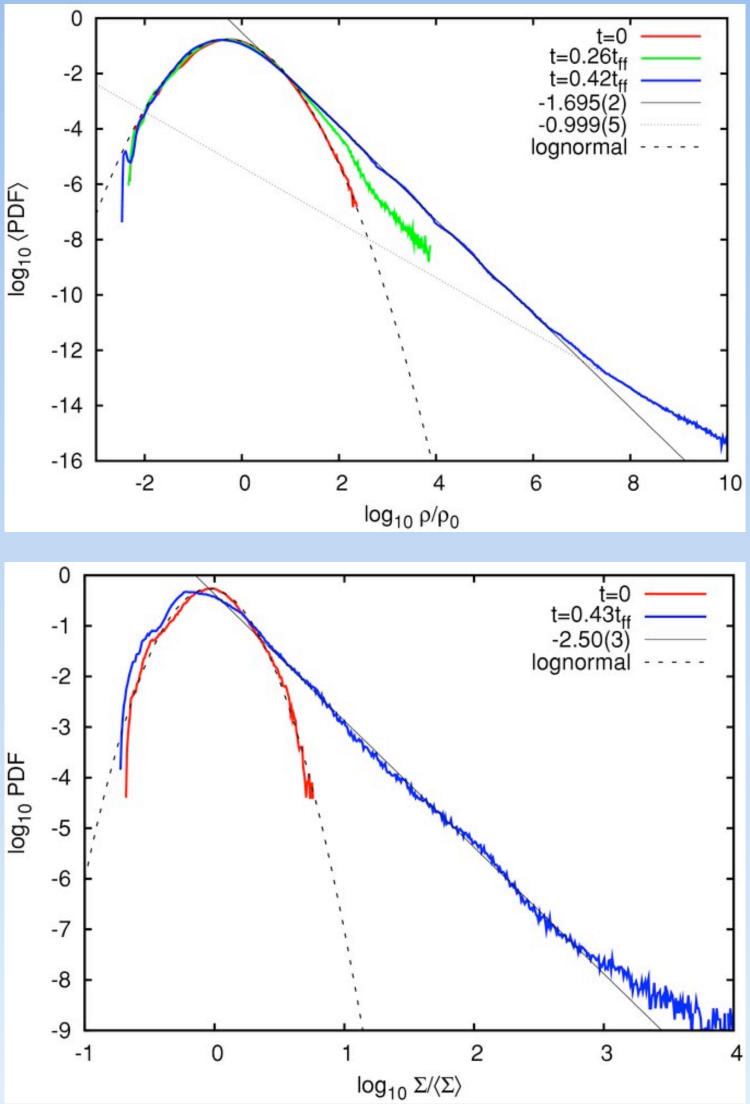




Questions for theory

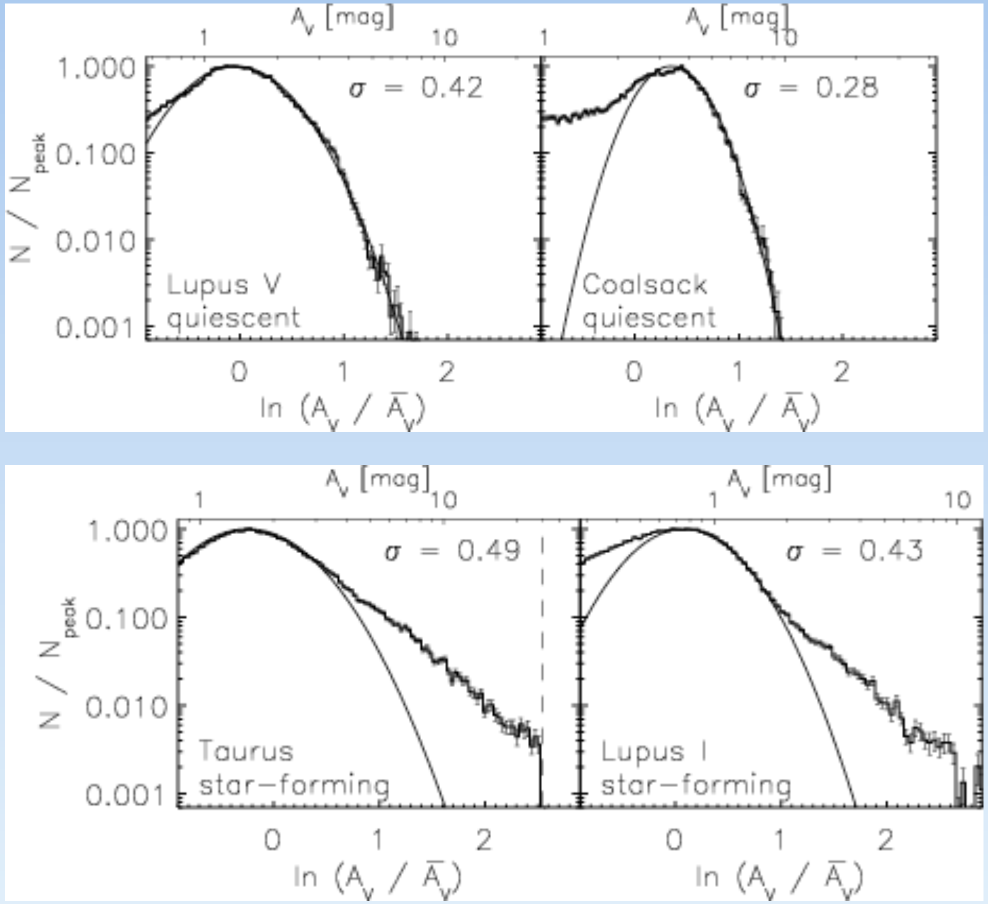
- Why is SF correlated with molecular gas?
- Why is ε_{ff} so small and $t_{dep,mol}$ so large?
- Why do inner galaxies/high-Σ_*/high P regions have higher efficiency/lower $t_{dep,mol}$?
- What is responsible for the scaling $\Sigma_{SFR} \propto \Sigma_{mol}^2$ in starburst regions?
- Is star formation as "inefficient" as it seems?

PDFs: lognormal + power-law tail



Power-law tail develops from gravitational collapse (Kritsuk et al 2011)

Power-law tail seen in star-forming regions



Kainulainen et al (2009)

Critical density for SF

- General idea: only sufficiently dense gas, as drawn from log-normal PDF, can collapse
- Krumholz & McKee (2005): for neither thermal nor turbulent support, $L_{\mathrm{Jeans}}(\rho_{\mathrm{crit}}) = L_{\mathrm{sonic}}$ for GMC

➔ $\rho_{\mathrm{crit}} / \rho_0 \sim \alpha_{\mathrm{vir}} (v/c_s)^2$

- $\mathrm{SFR}/M \sim \varepsilon_{\mathrm{core}}\, t_{\mathrm{ff}}(\rho_0)^{-1} \times$(mass fraction above ρ_{crit})

$$\begin{aligned}\mathrm{SFR_{ff}} &= \frac{\epsilon_{\mathrm{core}}}{\phi_t}\int_{x_{\mathrm{crit}}}^{\infty} x p(x)\, dx \\ &= \frac{\epsilon_{\mathrm{core}}}{2\phi_t}\left[1 + \mathrm{erf}\left(\frac{-2\ln x_{\mathrm{crit}} + \sigma_\rho^2}{2^{3/2}\sigma_\rho}\right)\right].\end{aligned}$$

$$\mathrm{SFR_{ff}} \approx 0.014\left(\frac{\alpha_{\mathrm{vir}}}{1.3}\right)^{-0.68}\left(\frac{\mathcal{M}}{100}\right)^{-0.32}.$$

- Weak dependence on Mach number v/c_s
- Low efficiency for large Mach number
- Efficiency decreases for increasing $\alpha_{\mathrm{vir}} \sim (t_{\mathrm{ff}}/t_{\mathrm{dyn}})^2$

Padoan & Nordlund 2011

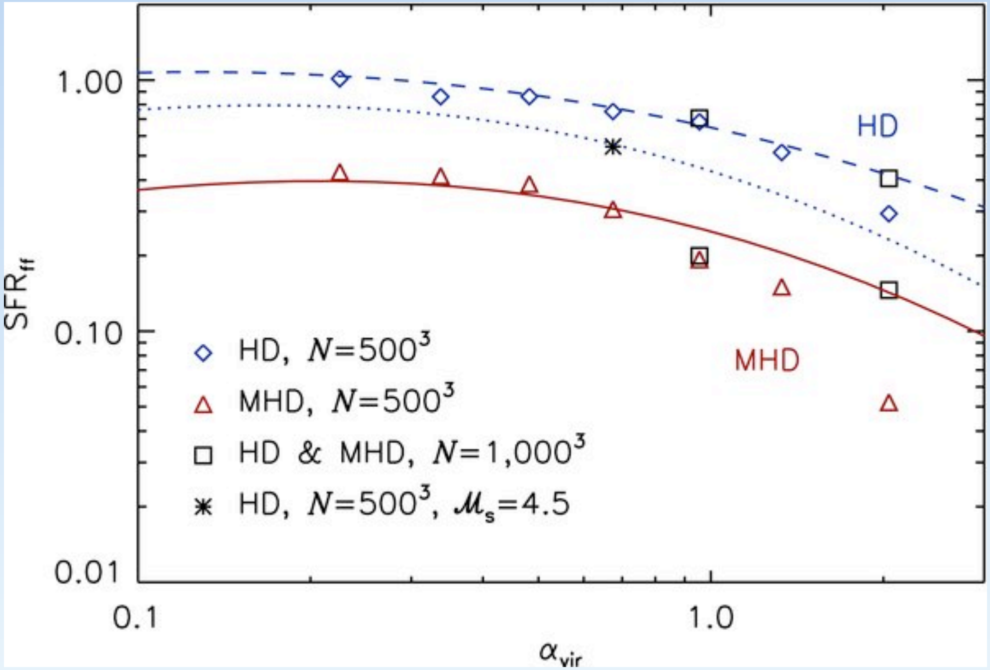
Model similar to KM05, but

$\mathrm{SFR} \propto 1/t_{ff}(\rho_{crit}) \times (\text{fraction above } \rho_{crit})$ instead of

$\mathrm{SFR} \propto 1/t_{ff}(\rho_0) \times (\text{fraction above } \rho_{crit})$

⇒ change ε_{ff} by factor $\propto (\rho_{crit} / \rho_0)^{1/2} \sim \alpha_{vir}^{\ 1/2} (v/c_s)$

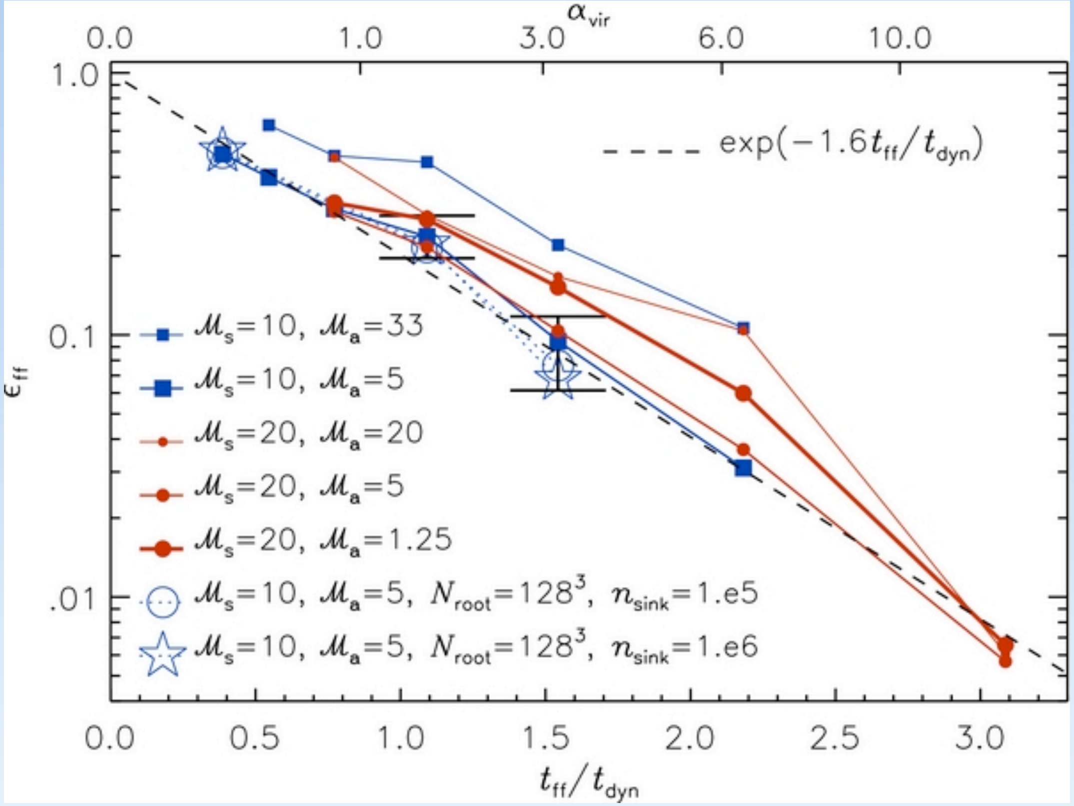
⇒ ε_{ff} increases with v/c_s and decreases with α_{vir}



Padoan et al (2012)

- Simulations extend range of α_{vir} , magnetic field, Mach number
- Conclude that ε_{ff} depends primarily on $\alpha_{\rm vir} \sim \left(\frac{t_{\rm ff}}{t_{\rm dyn}}\right)^2$

Larger efficiency than original KM05 expectation:
$\varepsilon_{ff} > 0.1$ for $\alpha_{vir} < 3$



Padoan, Haugbølle,Nordlund (2012)

Summary: ε_{ff} in turbulent gas

- Simulations and models suggest that

  $\varepsilon_{ff} = dM/dt\ (M/t_{ff}(\rho_0))^{-1}$ or $= \Sigma_{SFR}/[\Sigma_{H2}/t_{ff}(\rho_0)]$

can be low for molecule-dominated conditions largely because of turbulence, secondarily from *B*

Krumholz & McKee 2005; Padoan et al 2011, 2012; Hennebelle & Chabrier 2011; Federrath & Klessen 2012; Hopkins 2013

- From simulations, $\varepsilon_{ff} \sim 0.1\text{-}0.3$ for $\alpha_{vir} \sim 1 - 3$
- For SG galactic disk supported by turbulence, $\alpha_{vir} \sim (t_{ff}/t_{dyn})^2 \sim 2$; would imply $\varepsilon_{ff} >> 0.01$
  - Discrepancy of simulations with observations may depend on details of turbulent driving
- Questions: what sets molecular fraction, v/c_s ?

Questions for theory

- Why is SF correlated with molecular gas?
- Why is ε_{ff} so small and $t_{dep,mol}$ so large?
- Why do inner galaxies/high-Σ_*/high P regions have higher efficiency/lower $t_{dep,mol}$?
- What is responsible for the scaling $\Sigma_{SFR} \propto \Sigma_{mol}^2$ in starburst regions?
- Is star formation as “inefficient” as it seems?

ISM energetics and feedback

- Timescales for cooling and turbulent dissipation in the diffuse ISM are short
- To maintain equilibrium, energy must be replenished
- High-mass stars efficiently:
  - heat the ISM with photoelectric effect from FUV
  - destroy parent GMCs through radiation, winds
  - drive turbulence in the ISM with expanding SN shells
- Midplane pressure ∝ energy density must support weight of diffuse ISM
  - weight depends on gravity of gas, stars, dark matter
- *ISM equilibrium* ***demands*** *a certain level of feedback*

Thermal and dynamical equilibrium

Ostriker, McKee, & Leroy (2010), Ostriker & Shetty (2011)

- Thermal equilibrium:

$$n\Lambda(T) = \Gamma \Rightarrow P_{th}\,\Lambda(T)/T \propto J_{FUV} \Rightarrow P_{th} \propto \Sigma_{SFR}$$

- Turbulent equilibrium:

$$P_{turb}=v_z^2\rho \sim v_z^2\Sigma/H \sim v_z\Sigma/(H/v_z) \sim (\text{momentum}/\text{area})/t_{ver}$$

dissipation=driving ⇒

$$P_{turb} \sim (1/4)p_*\Sigma_{SFR}/m_* \quad \Rightarrow P_{turb} \propto \Sigma_{SFR}$$

p_*/m_*= radial momentum per mass of stars formed

- Vertical "hydrostatic" equilibrium:

$$P_{turb}+P_{th} \approx P_{DE} = \Sigma\langle g_z\rangle/2 \approx \Sigma(2G\,\rho_*)^{1/2}v_z + \pi G\Sigma^2/2$$

$$\Rightarrow P_{th}+P_{turb} \propto \Sigma_{SFR}\ \textit{and}\ P_{th}+P_{turb} \approx P_{DE}$$

Thermal and dynamical equilibrium

Ostriker, McKee, & Leroy (2010), Ostriker & Shetty (2011)

- Thermal equilibrium:

$$n\Lambda(T) = \Gamma \Rightarrow P_{th}\,\Lambda(T)/T \propto J_{FUV} \Rightarrow P_{th} \propto \Sigma_{SFR}$$

- Turbulent equilibrium:

$$P_{turb} = v_z^2 \rho \sim v_z^2 \Sigma / H \sim v_z \Sigma / (H/v_z) \sim (\text{momentum/area})/t_{ver}$$

dissipation=driving ⇒

$$P_{turb} \sim (1/4) p_* \Sigma_{SFR} / m_* \quad \Rightarrow P_{turb} \propto \Sigma_{SFR}$$

p_*/m_* = radial momentum per mass of stars formed

- Vertical "hydrostatic" equilibrium:

$$P_{turb} + P_{th} \approx P_{DE} = \Sigma \langle g_z \rangle / 2 \approx \Sigma (2G\,\rho_*)^{1/2} v_z + \pi G \Sigma^2/2$$

$$\Rightarrow \boxed{\Sigma_{SFR} \propto P_{DE} \approx \Sigma (2G\,\rho_*)^{1/2} v_z + \pi G \Sigma^2/2}$$

Momentum Injection by SNe

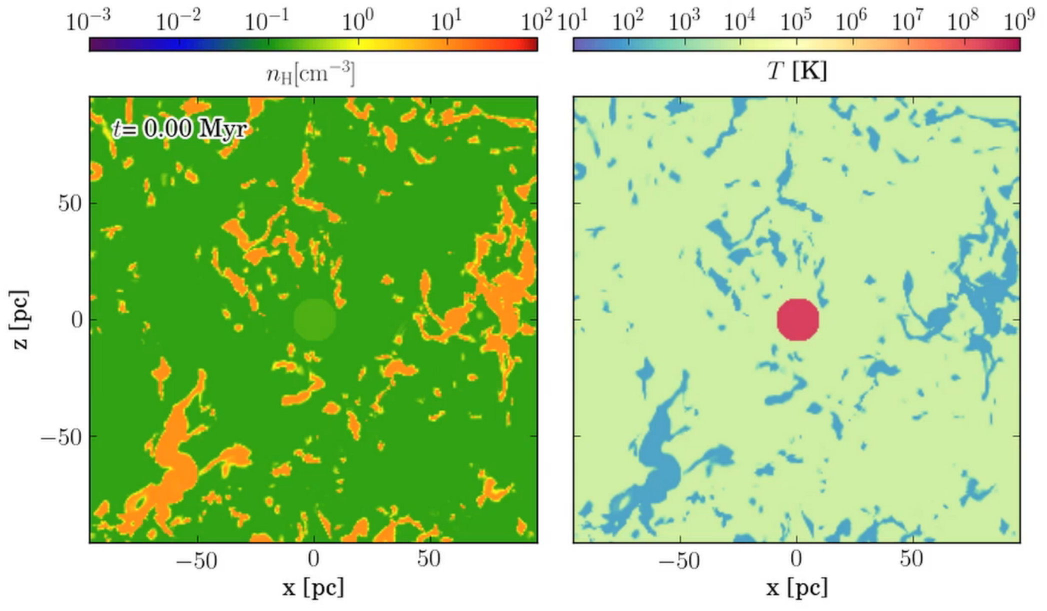
- Key feedback parameter is the net momentum injection/mass p_*/m_*
- SNR classical evolution stages :
  - Free expansion, Sedov-Taylor, Pressure-Driven Snowplow, Momentum-Conserving Snowplow

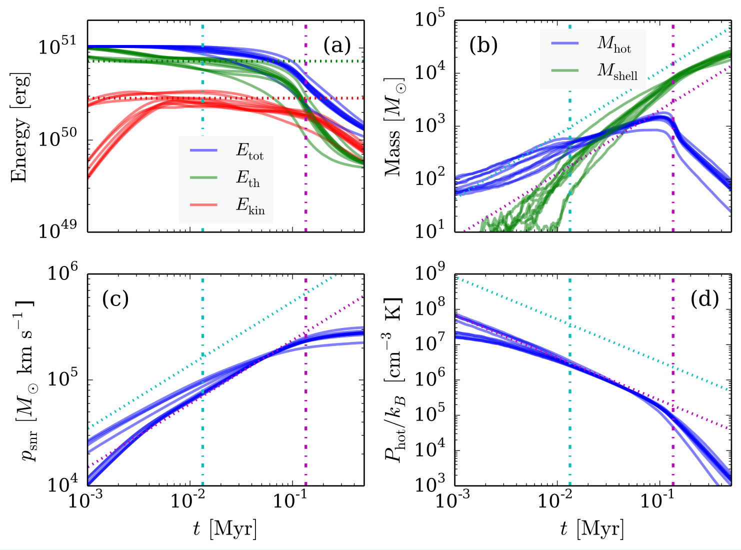
Spherical simulations: Cioffi et al 1988, Blondin et al 1998, Thornton et al 1998

- New simulations: **3D; inhomogenous medium**

Kim & Ostriker (2015), Iffrig & Hennebelle (2015), Martizzi et al (2015), Walch & Naab (2015)

  - All find p_* similar to value in homogeneous medium
  - Insensitive to mean ambient density: $p_{\rm final} = 3\times10^5\ M_\odot \text{km/s}\ \langle n_0\rangle^{-0.17}$

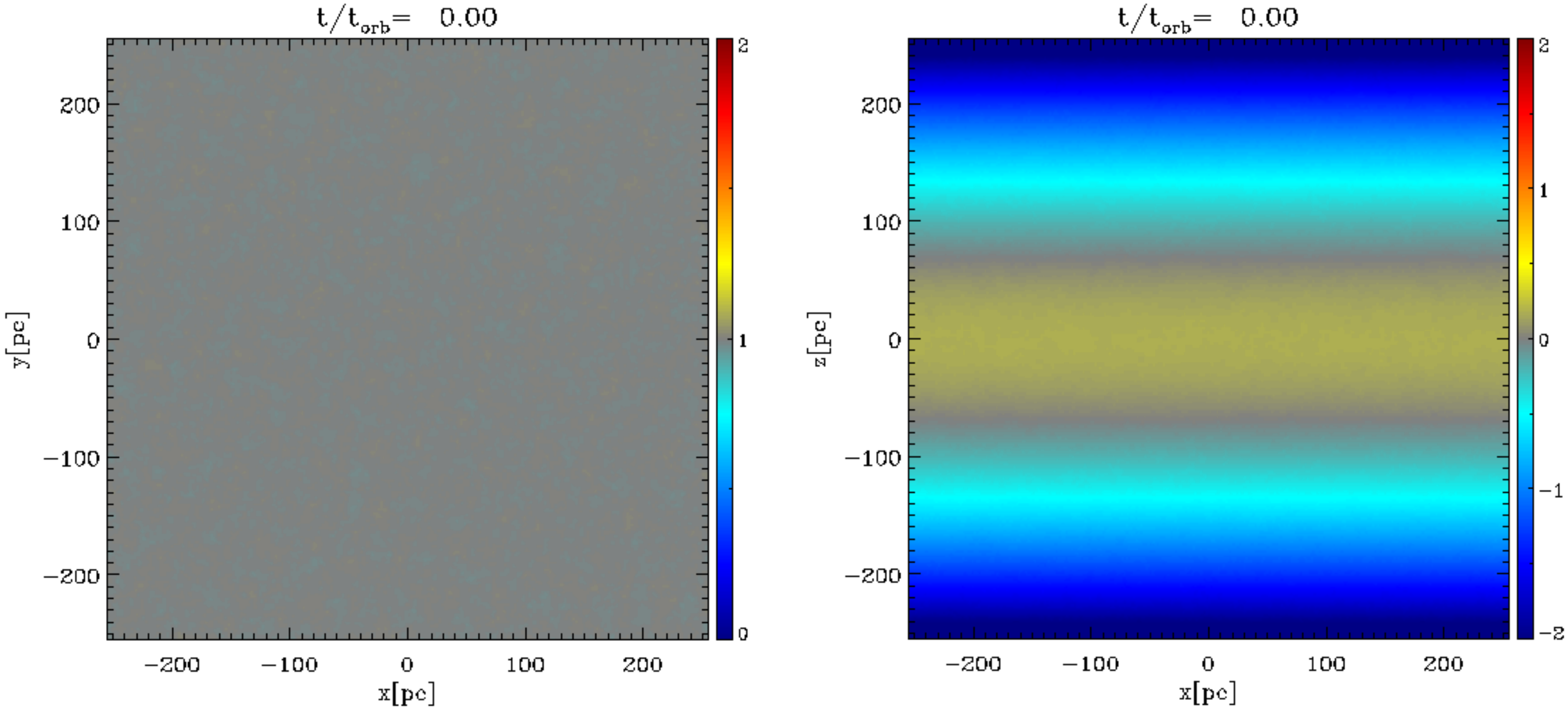




Kim & Ostriker (2015)

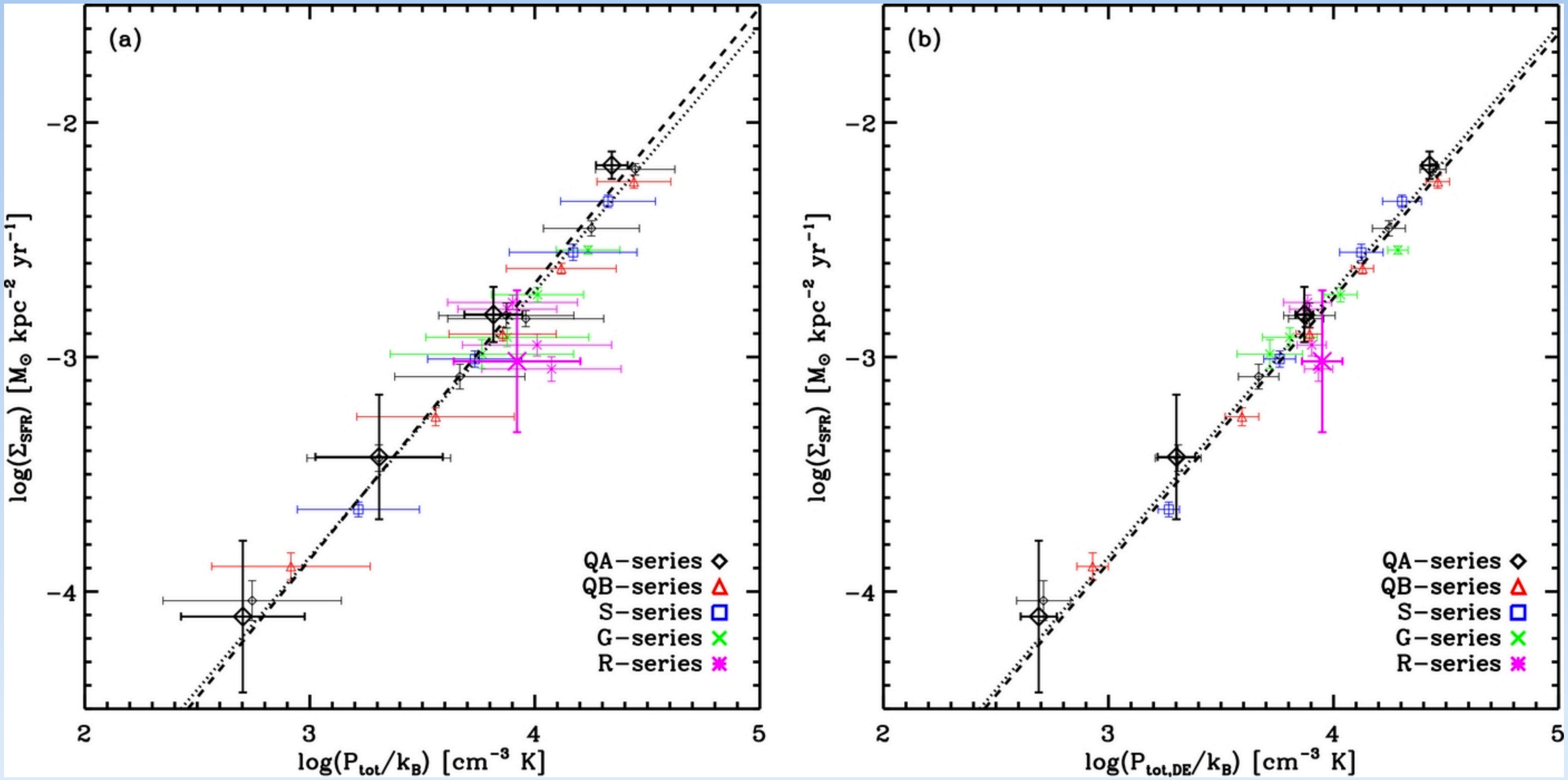
Simulations with self-consistent SN feedback and radiative heating

- Kim, Kim, & Ostriker (2011); Kim, Ostriker, & Kim (2013); Kim & Ostriker (2015b)
  - include turbulent driving from SN (momentum injection)
  - include dependence of heating rate on star formation rate
  - Include vertical gravity of stellar disk



Σ_{SFR} vs. total pressure

$$P_{tot} = P_{th} + P_{turb}; P_{tot,DE} = \frac{\Sigma g_z}{2} \approx \frac{\pi G \Sigma^2}{2} + \Sigma(2G\rho_*)^{1/2}\sigma_z$$



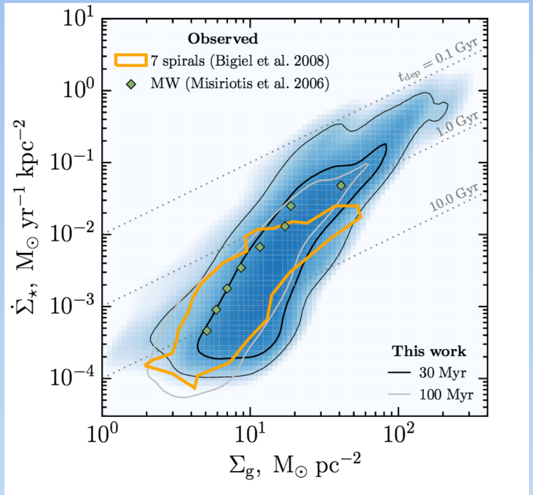
Kim, Ostriker, & Kim (2013)

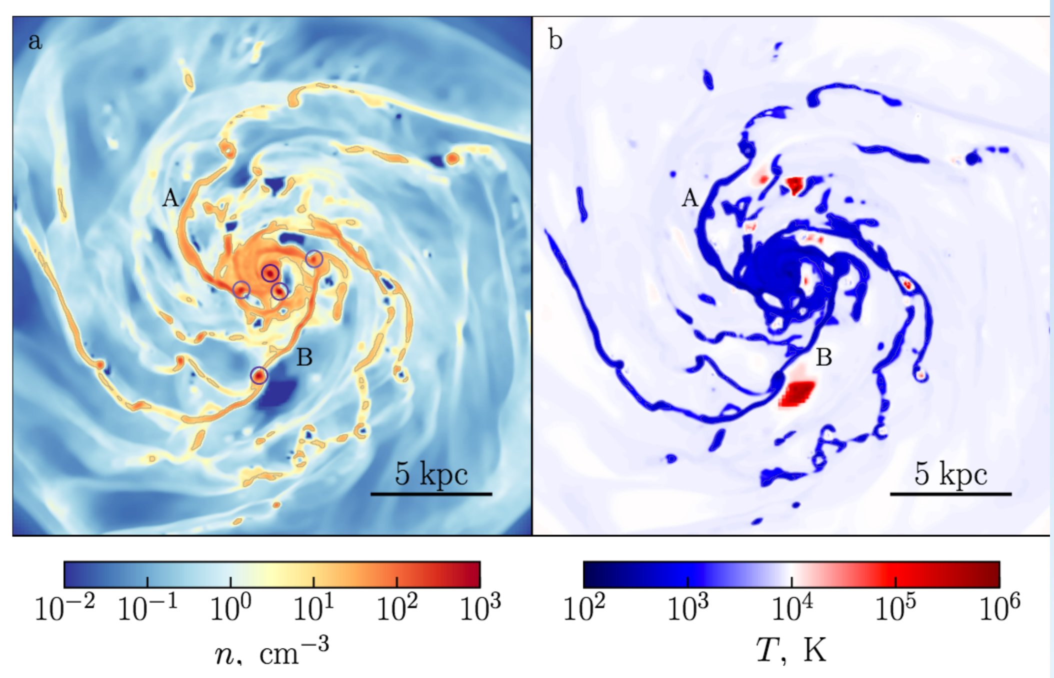
$$\Sigma_{\mathrm{SFR}} \approx 2 \times 10^{-3} \mathrm{M_\odot kpc^{-2} yr^{-1}} \left(\frac{P_{\mathrm{tot}}/k_B}{10^4 \mathrm{cm^{-3}\ K}} \right)^{1.1}$$

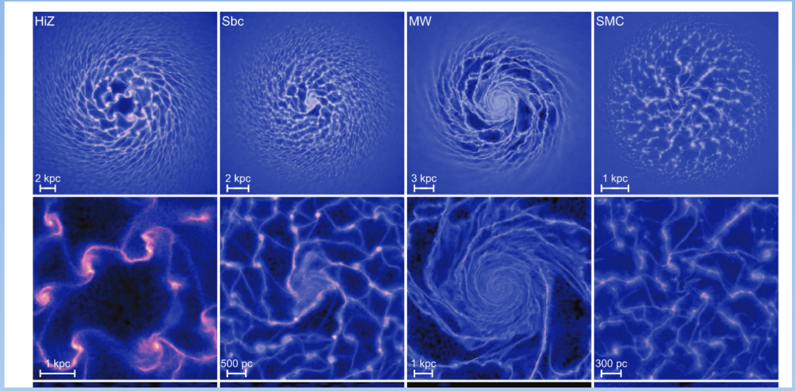
Global galaxy simulations with feedback

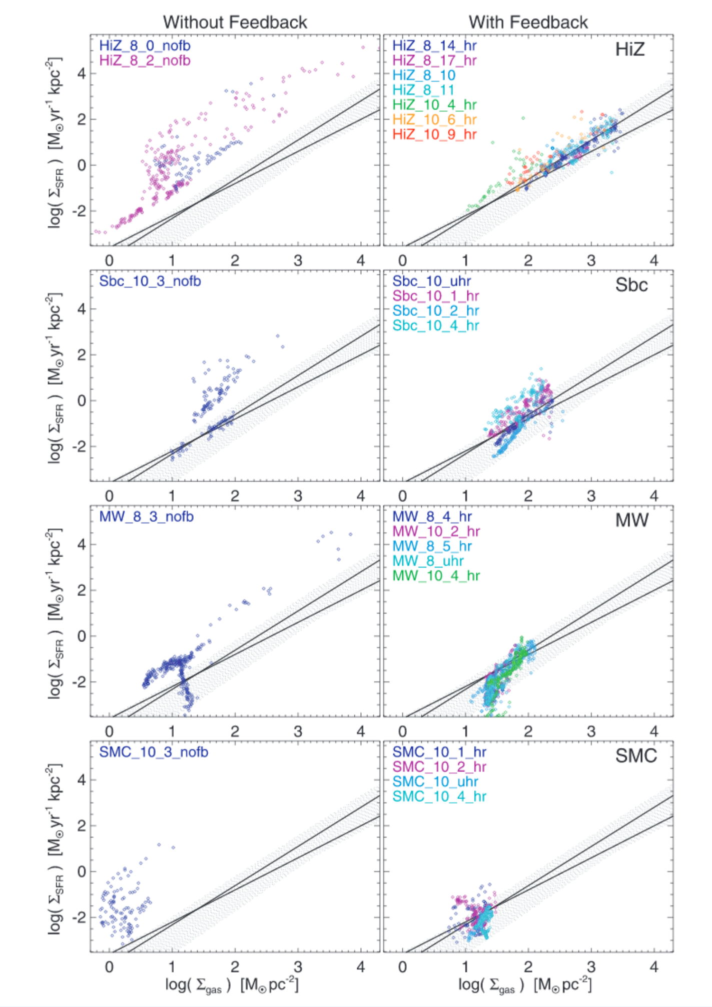
- Without feedback, SFR much higher than observed
- With feedback, comparable to observations

Semenov, Kravtsov, & Gnedin (2016)









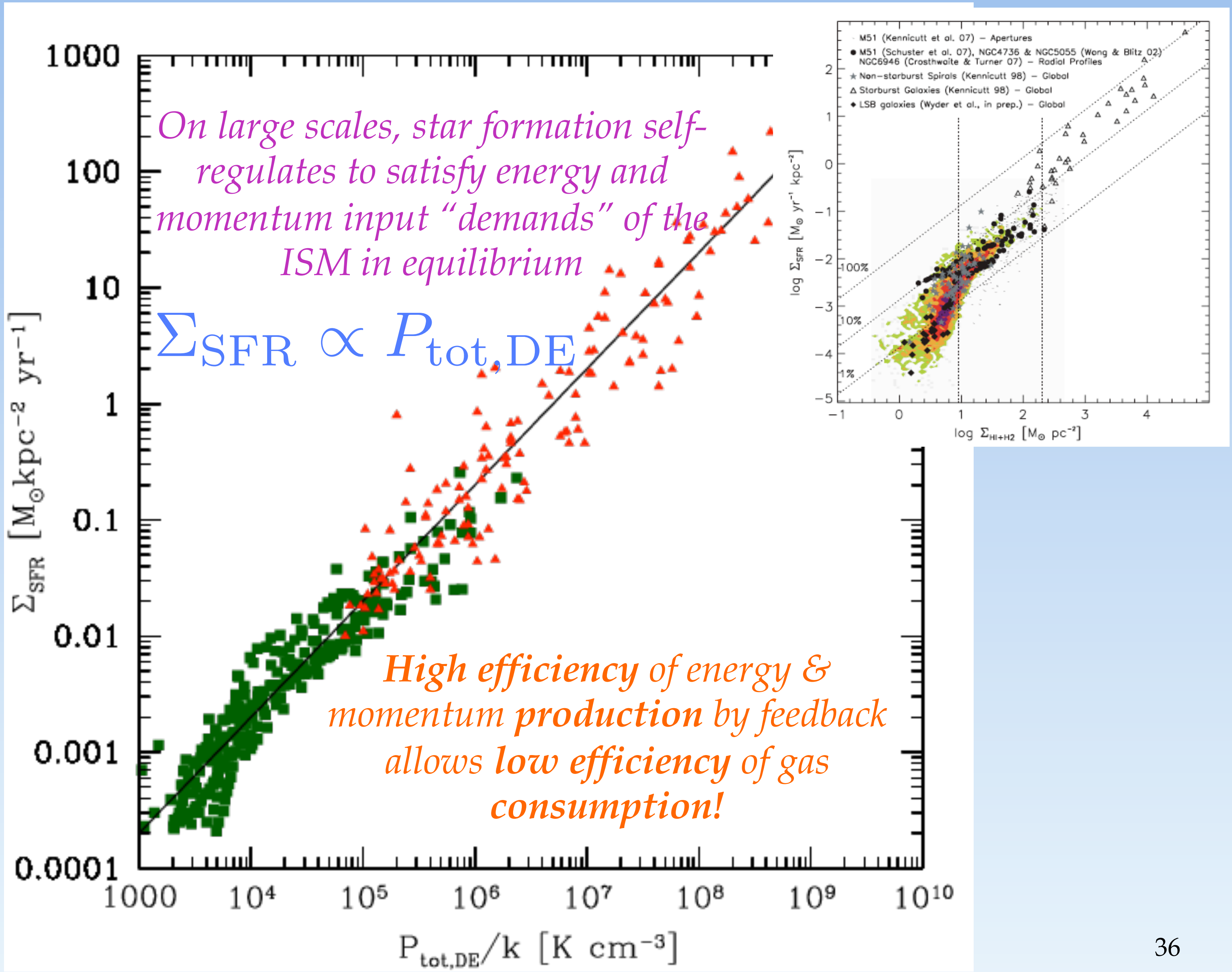
Hopkins, Quataert, & Murray (2011)

Questions for theory

- Why is SF correlated with molecular gas?
- Why is ε_{ff} so small and $t_{dep,mol}$ so large?
- Why do inner galaxies/high-Σ_{*} /high P regions have higher efficiency/lower $t_{dep,mol}$?
- What is responsible for the scaling $\Sigma_{SFR} \propto \Sigma_{mol}^{2}$ in starburst regions?
- Is star formation as "inefficient" as it seems?

No!

$\Sigma_{\rm SFR}$ vs. equilibrium pressure



On large scales, star formation self-regulates to satisfy energy and momentum input "demands" of the ISM in equilibrium

$$\Sigma_{\rm SFR} \propto P_{\rm tot,DE}$$

High efficiency** of energy & momentum **production** by feedback allows **low efficiency** of gas **consumption!

What next?

- Time-dependent MHD+chemistry (& shielding) to follow creation/evolution/destruction of molecular clouds, relation to star forming clouds
- Critical assessment of X_{CO}, other molecular tracers in varying galactic environments
- Quantify impact of feedback effects (protostellar jets/ outflows, ionizing & non-ionizing radiation and winds from OB stars, individual and correlated SNe) at varying scales in ISM, cloud evolution stages
- Measure dependence of SFE on MC properties (size, mass) and environment
- Connect galactic-scale SF to galactic-scale winds to understand cosmic-scale SF evolution

Summary

- *Resolved* galactic observations + multiwavelength coverage have quantified & clarified:
  - *Variation of SF timescales* in different galactic regimes/ environments
  - Dependence of SFR on parameters *other than molecular (CO) content*
- Consideration of *ISM/SF lifecycle* in theory & simulations has:
  - turned focus to role of *feedback and SF self-regulation*
  - led to *quantitative agreement* with large-scale SF observations
- *Next steps*: moving to integrate cloud-scale with larger-scale picture (dynamics + chemistry)