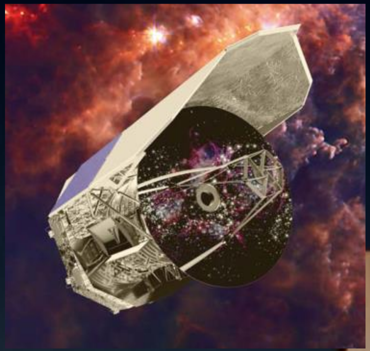

The Evolution of Star Forming Galactic Disks

from the observational perspective

Reinhard Genzel

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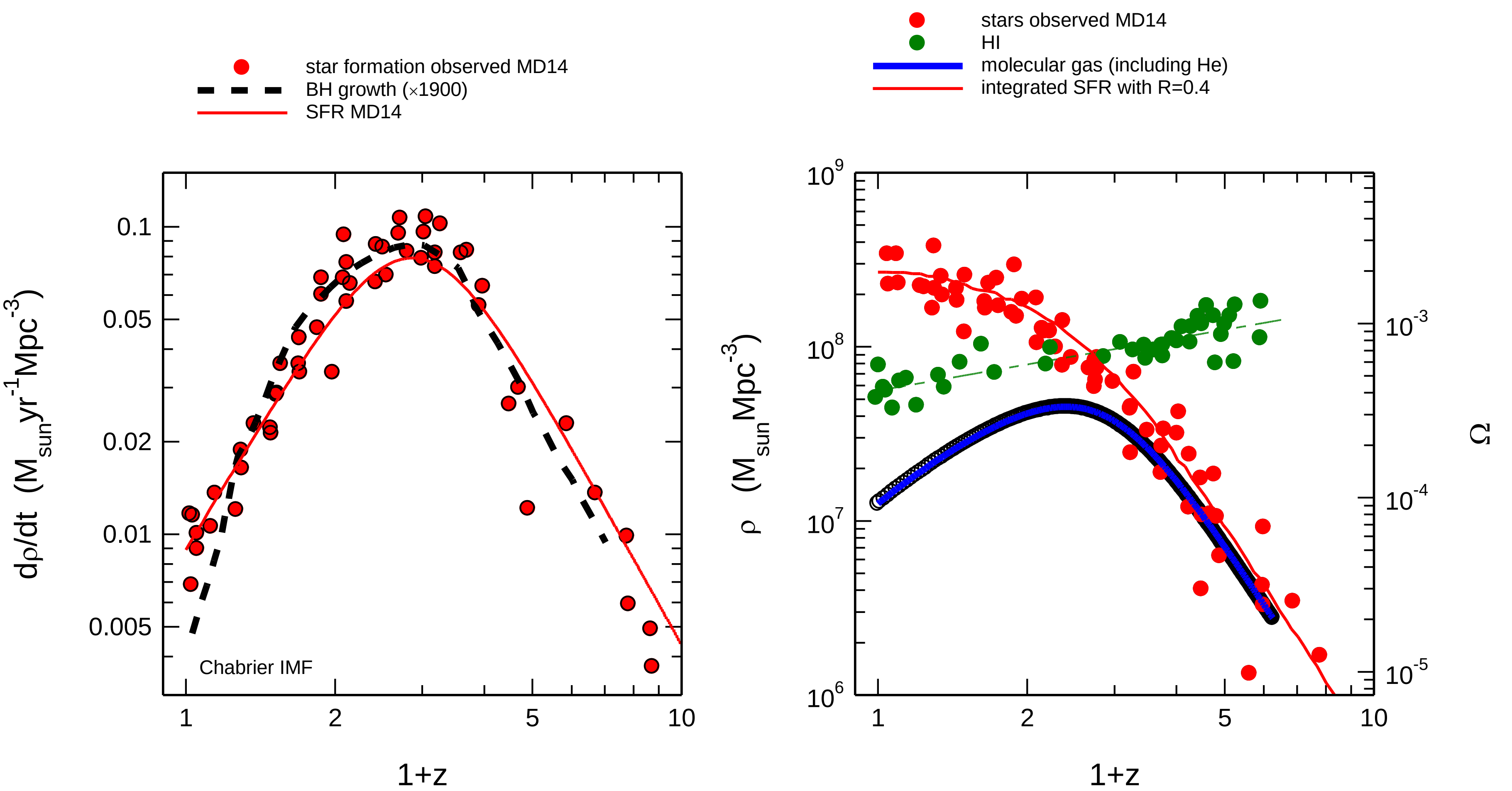
& Departments of Physics & Astronomy, UC Berkeley

and the KMOS^{3D}, SINS/zC-SINF, 3D-HST, PHIBSS Teams

Cosmic Co-evolution: Stars, Gas, BHs



molecular gas: CO, dust-FIR, dust-1mm

Madau & Dickinson 2014, Tacconi, Genzel & Sternberg 2020

The “Main Sequence” of Star-Forming Galaxies

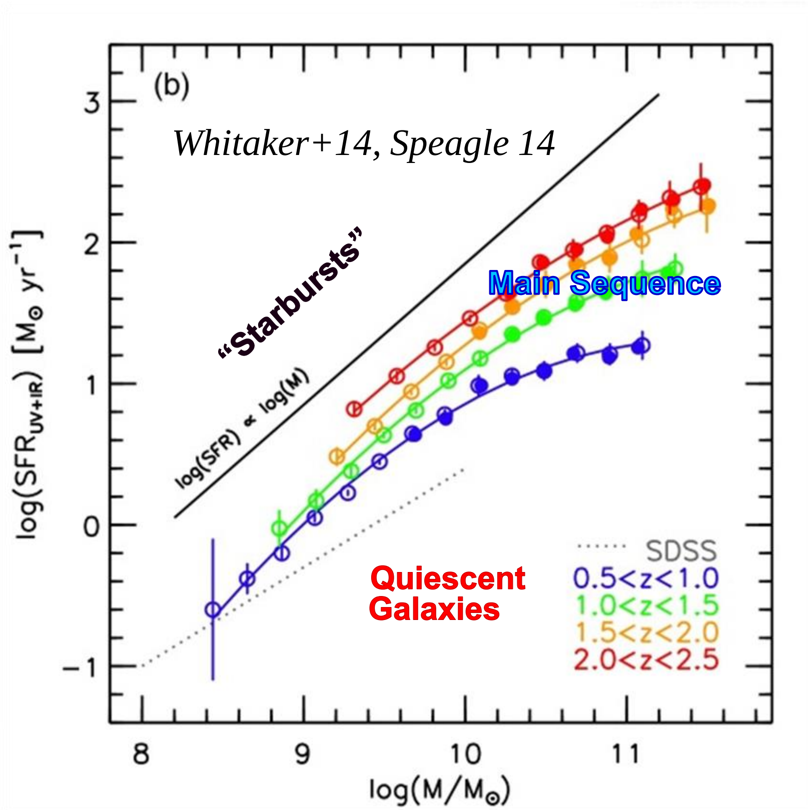
(z)-COSMOS

VVDS NEWFIRM

CANDELS

3D HST

SDSS



SFR ∝ M_* on MS
MS SFGs have high duty cycles ~ 30%-70%
~ 90% of the cosmic SFR occurs on the MS
Efficient SF quenching $M_{Schechter}$

Rudnick+03,06, Adelberger+04, Brinchmann +04, Noeske+07, Schiminovich+07, Elbaz+07, Daddi+07, Marchesini+09, Shankar+09, Ilbert+10,13, Peng+10, Brammer+11, Rodighiero+11,14, Caputi+11, Gonzalez+11, Karim+11, Magnelli+11,13, Wuyts+11, Whitaker+12,14, Muzzin+13, Stark+13, Speagle +14, Renzini&Peng15, Schreiber +16

The "Main Sequence" of Star-Forming Galaxies

(z)-COSMOS

VVDS

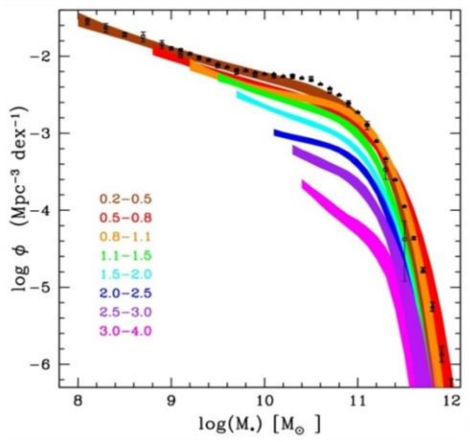
NEWFIRM

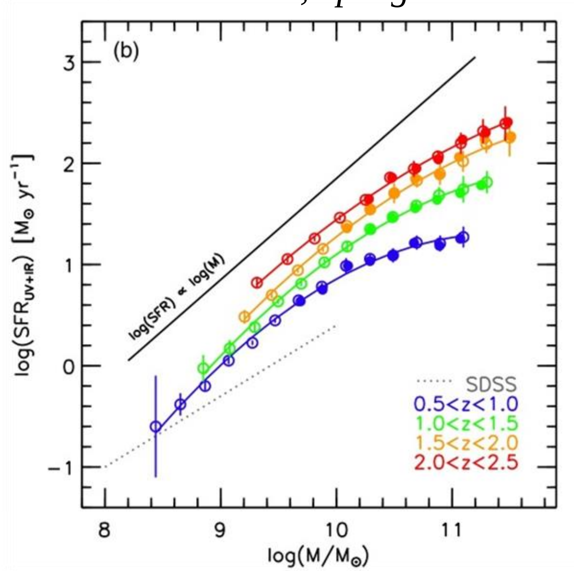
CANDELS

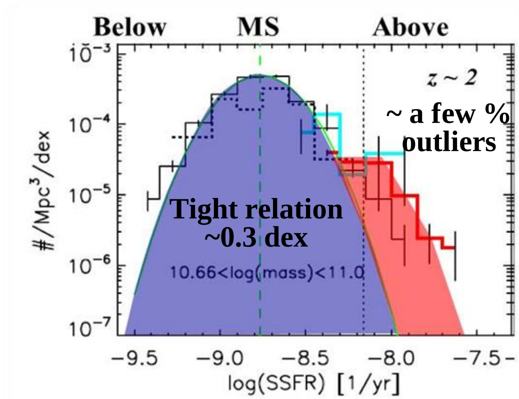
3D HST

SDSS

Whitaker+14, Speagle 14



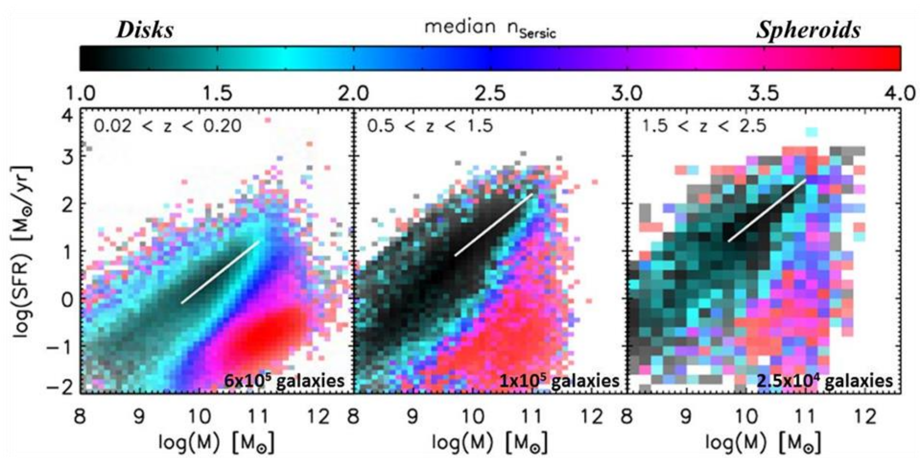




Rodighiero +11
Schreiber +16

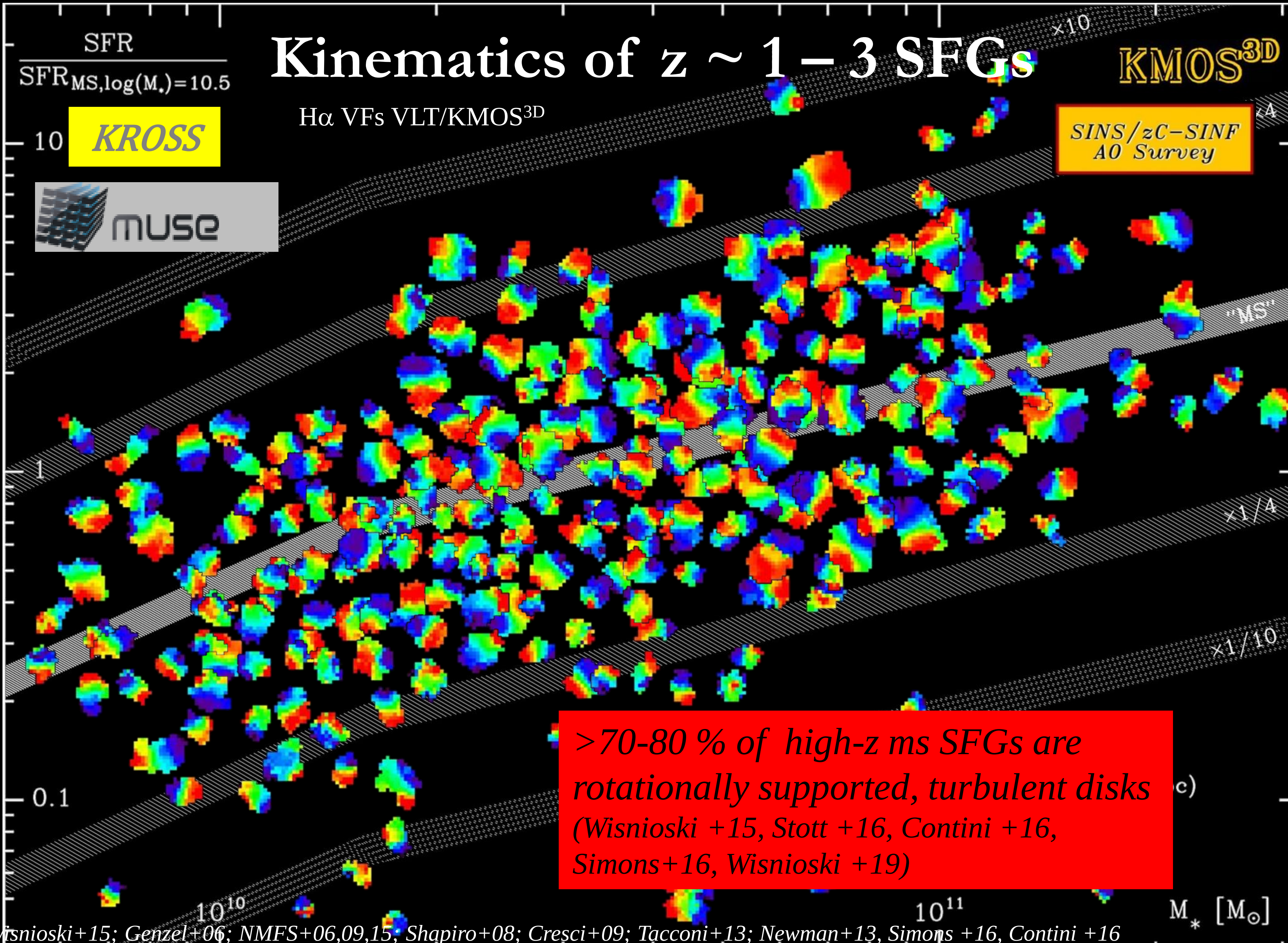
M_S~const(z)

Muzzin +13
Ilbert +10,13



Franx +08, Wuyts+11

Kinematics of z ~ 1 – 3 SFGs



>70-80 % of high-z ms SFGs are rotationally supported, turbulent disks (Wisnioski +15, Stott +16, Contini +16, Simons+16, Wisnioski +19)

Wisnioski+15; Genzel+06; NMFS+06,09,15; Shapiro+08; Cresci+09; Tacconi+13; Newman+13, Simons +16, Contini +16

Law+09,12;Epinat+09-12;Jones+10;Green+10; Wisnioski+11,12; Yuan+11,12;Kassin+12;Jones +12, Sobral+13;Stott+14; Livermore+15;

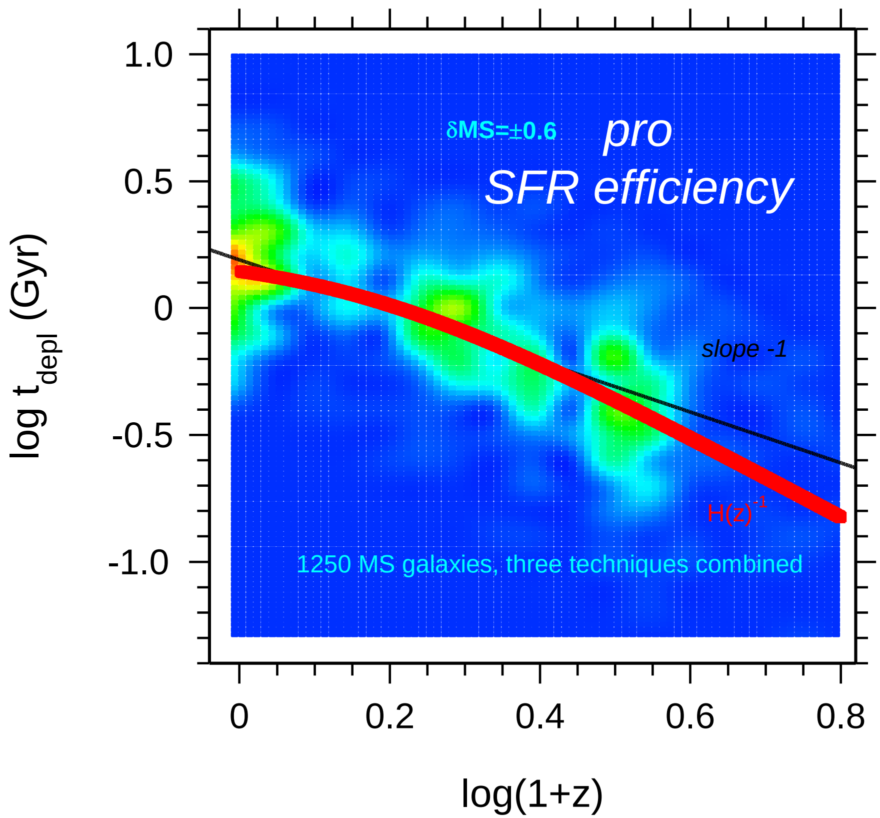
COLDGASS & PHIBSS

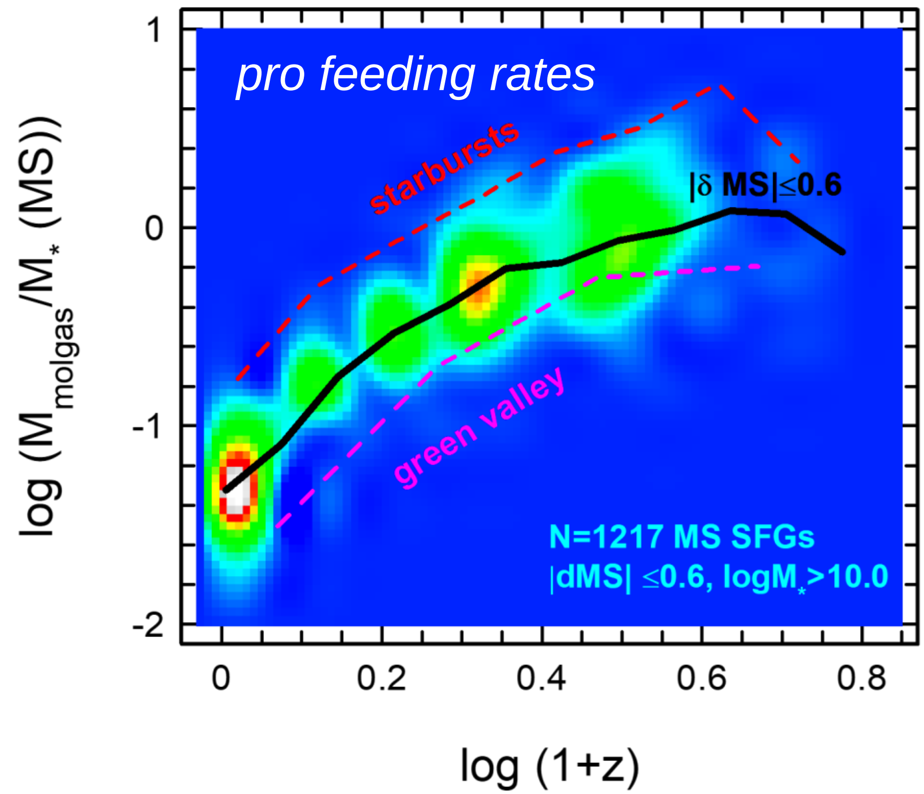
PEP@Herschel

NOEMA

ALMA

What causes the z~1-2 Cosmic SFR Peak: SFR Efficiency or Feeding Rates?





$$t_{depl} \overset{\Omega_T}{=} t_{dyn} \times Q / \varepsilon_T \overset{MMW98}{=}$$

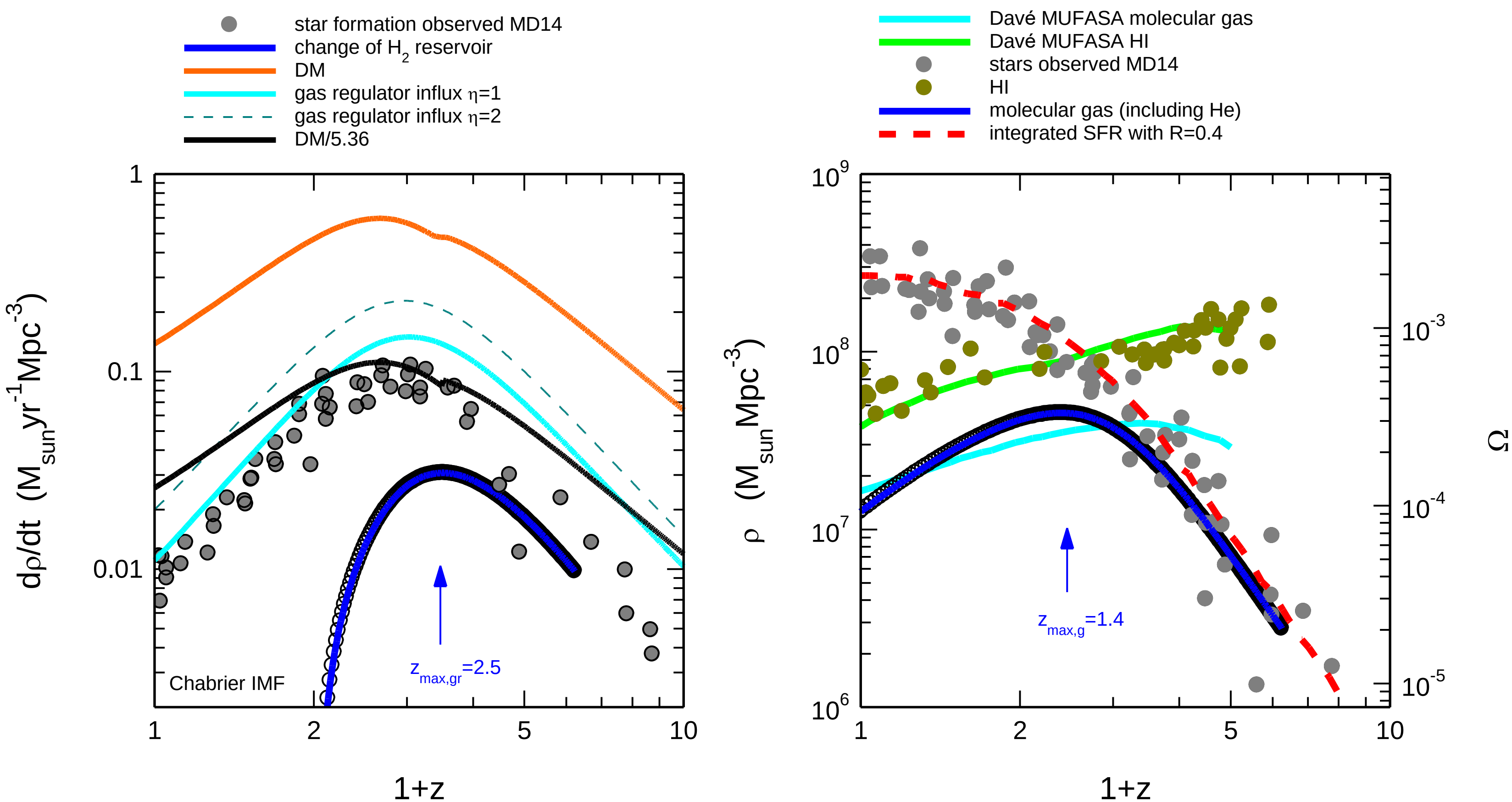
Mo, Mao & White 1998, Tacconi, Genzel & Sternberg 2020
Burkert et al. 2020

$$1.3\times10^{8} \times \frac{\lambda_{0.037}}{\varepsilon_T} \times \left(\frac{j_{baryon}}{j_{DM}}\right) \times \left(\frac{f_h\, f_{ac}}{1.5}\right) \times \left(\frac{H(z)}{H_0}\right)^{-1} \times \left(\left\{ {}^{v_c}\!/_{\sigma_0} \right\} \times \mu_{molgas}\right)^{-1} \quad (\text{yr})$$

The baryon cycle – gas regulator

$$\dot{\Phi} = (1 - R + \eta) \times SFR + \dot{M}_{molgas}$$

$$\dot{\Phi}_{gal,baryon} = f_{gh} \times f_{baryon} \times \dot{\Phi}_{h,DM} = 6.3 \times f_{gh} \times \left(\frac{f_{baryon}}{0.18}\right) \times \left(\frac{M_h}{10^{12} M_\odot}\right)^{1.15} \times (1+z)^{2.35} \quad M_\odot yr^{-1} \quad (8),$$



Madau & Dickinson 2014, Tacconi, Genzel & Sternberg 2020 Bouche et al. 2010, Obreschkow et al. 2009, Fu et al. 2010, Lagos et al 2010, 2015, Lilly et al. 2013, Peng & Maiolino 2014, Popping et al. 2014, 2019, Dave et al. 2011, 2012, 1017, Dekel & Mandelker 2014, Somerville & Dave 2015

Angular Momentum Distribution

KMOS3D, muse, KROSS, MOSDEF, SINS/zC-SINF AO Survey, CANDELS 3D-HST

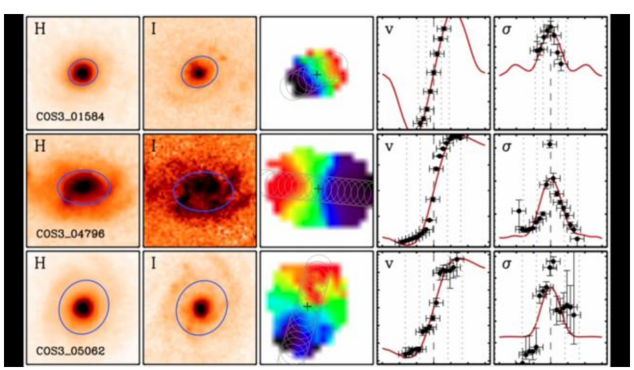
$$\lambda_{DM} \times \left(\frac{j_{baryon}}{j_{DM}} \right) \sim 0.037$$

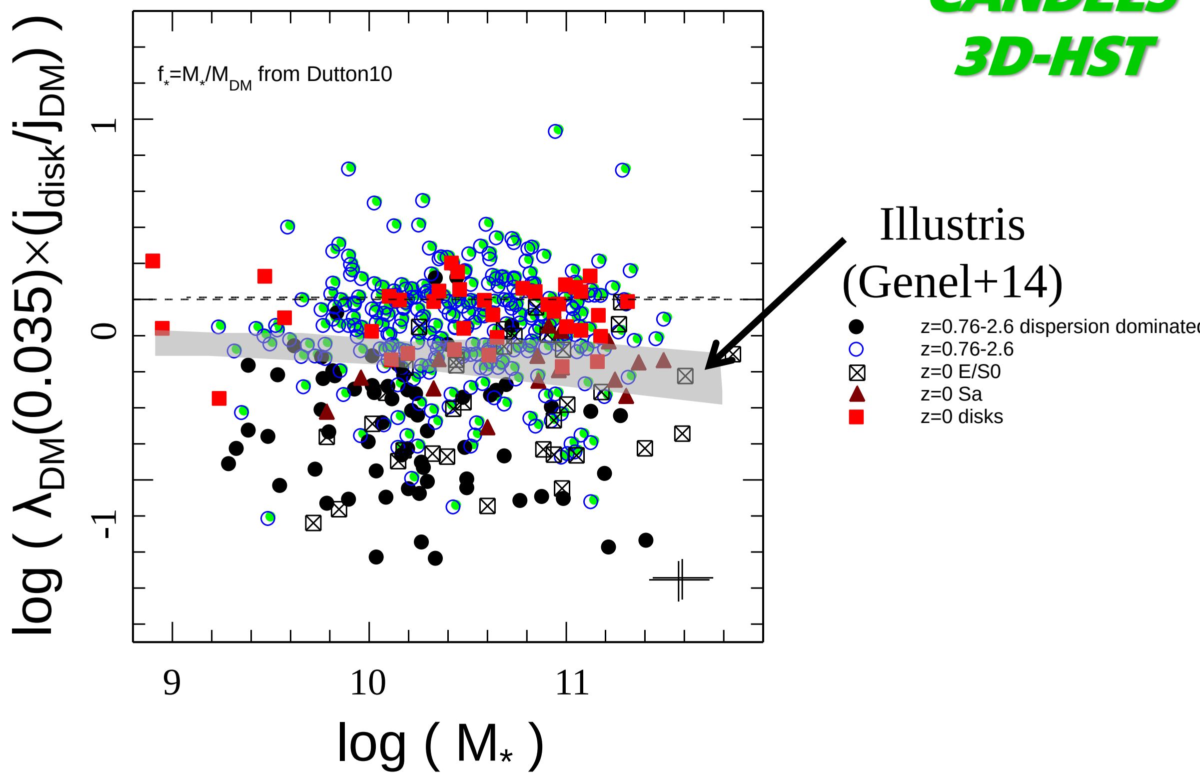
$$\rightarrow \left(\frac{j_{baryon}\,|_{0.05R_{virial}}}{j_{DM}\,|_{R_{virial}}} \right) \sim 0.9$$

not a trivial result

409 $\log(M_*) > 9.7$,
$0.76 < z < 2.6$ SFGs

Wisnioski +15





Fall & Efstathiou 1980, Danovich et al. 2015, Burkert, Förster Schreiber, Genzel +16, Fall & Romanowsky +13, Danovich +15, Übler +15, Contini +16, Tiley +16, Price +16, KMOS3D

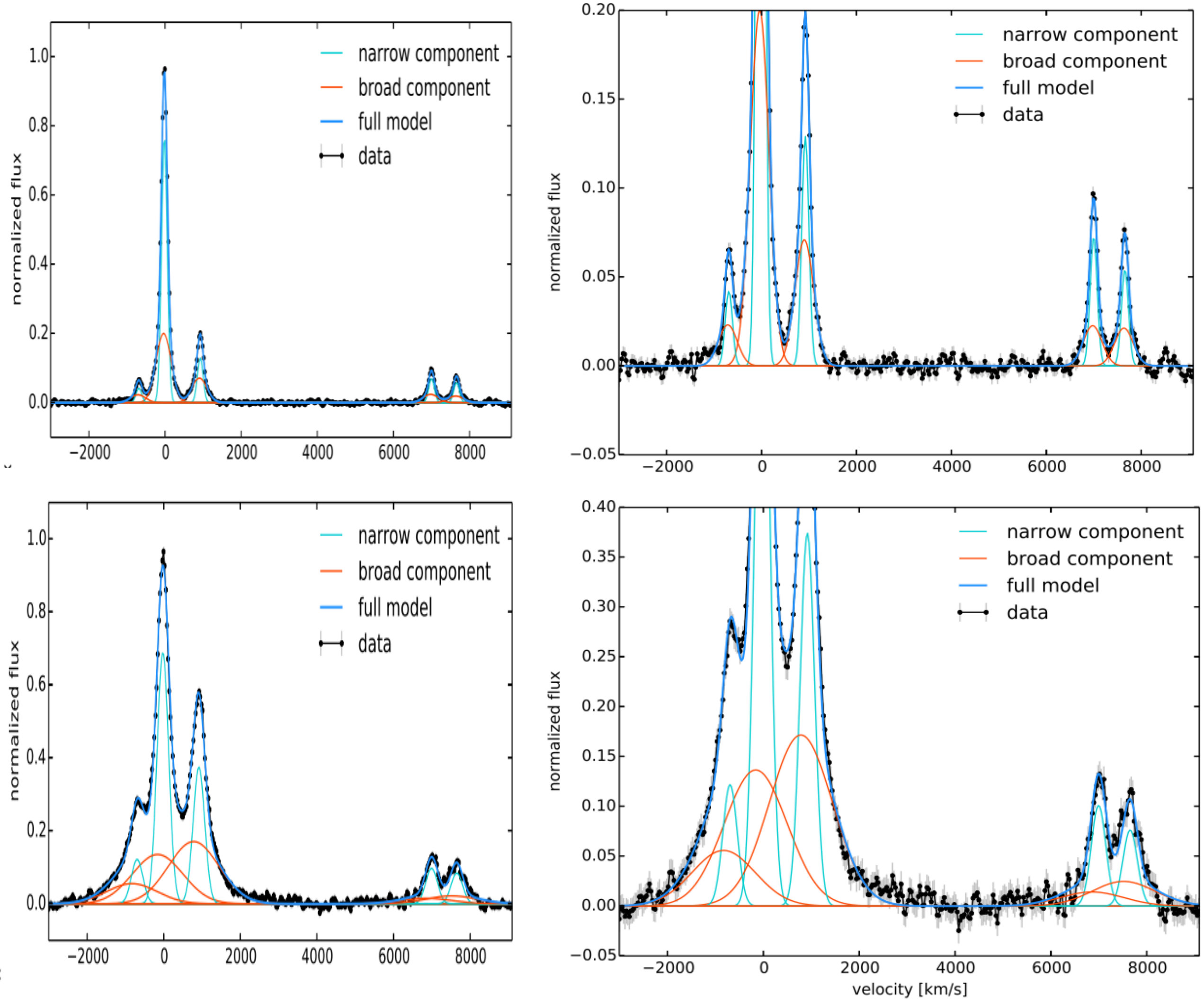
Stellar & AGN Feedback

KROSS

MOSDEF

10^4 K ionized gas

Förster Schreiber +19: 600 MS SFGs z=0.67-2.6, logM$_*$=9.2-11.5



no X-ray AGN
[NII]/Hα_{narrow}<0.45
→ stellar feedback
v_{out}~400 km/s
[NII]/Hα_{broad}~[NII]/Hα_{narrow}

Förster Schreiber +18

X-ray AGN
[NII]/Hα_{narrow}~0.5-5
→ AGN feedback
v_{out}~1000-2000 km/s
[NII]/Hα_{broad}>1
note: most of these are Eddington ratio <<10%

Also, e.g., Shapiro+09; Harrison+14,16; Maiolino+12; Cano Diaz+12; Fabian12; Newman +12, Mullaney+13; Genzel +14, Förster Schreiber +14, Brusa+15a; Perna+15a,15b;Carniani+15,16; Kakkad +16, Swinbank +19, Freeman +19

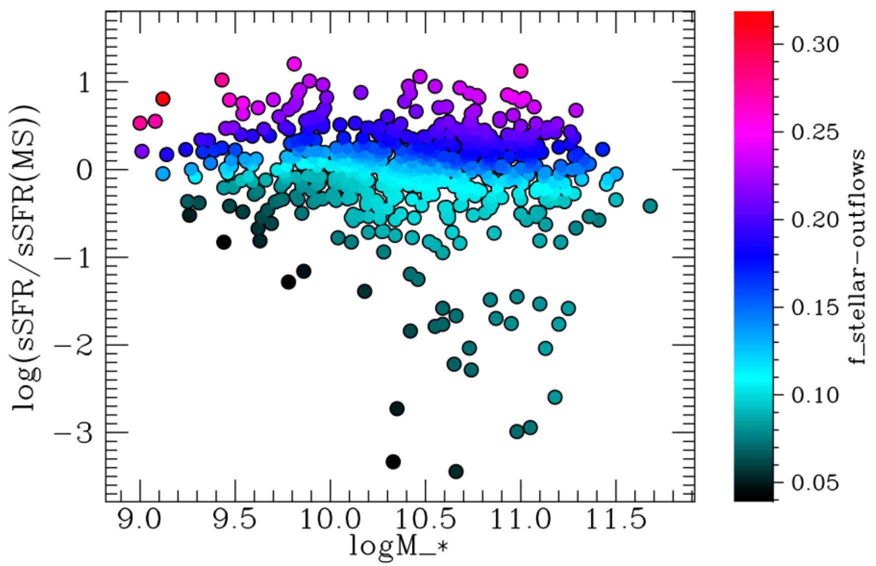
KMOS^{3D}

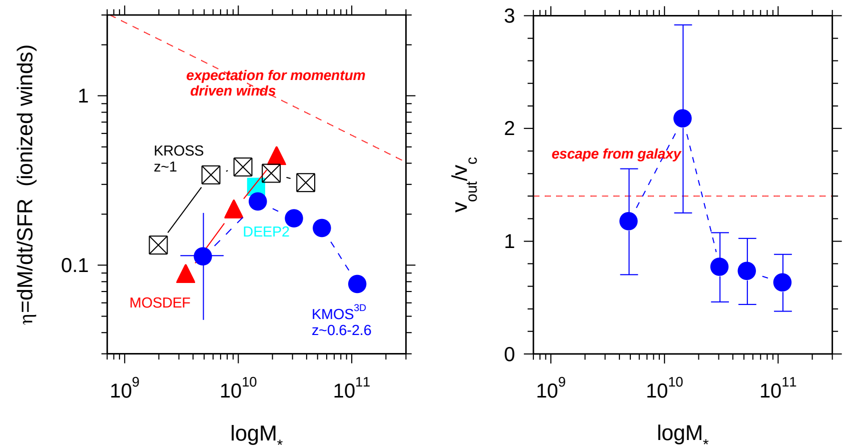
KROSS

Demographic Trends: Stellar Feedback

KMOS/MOSDEF surveys: ~2000 MS SFGs z~0.6-2.6 mass-SFR selected

incidence & strength of outflow scales with sSFR, Σ_{SFR}, δMS, low mass loading, for massive SFGs v_{out}<v_{escape}





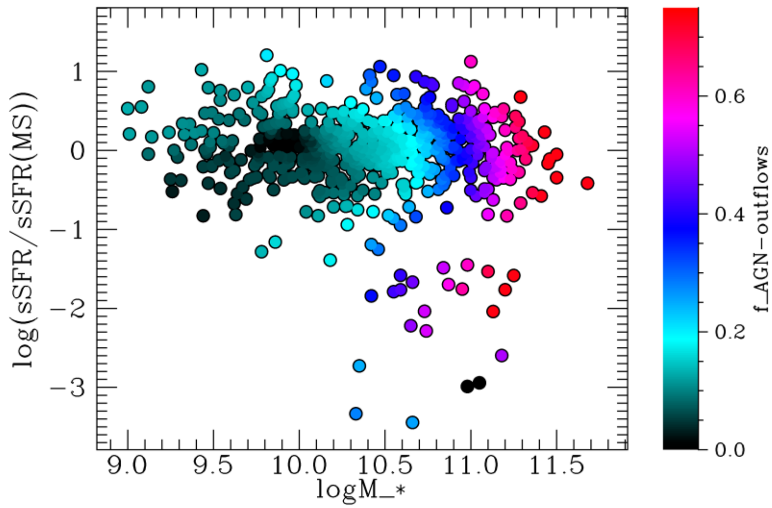
$$\eta = \dot{M}_{out}/SFR \sim 0.2 - 0.4 << 1$$

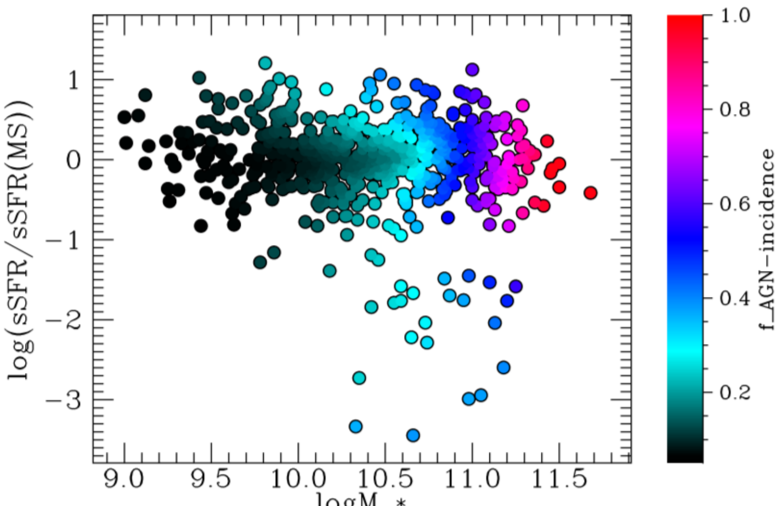
Förster Schreiber +19
Swinbank +19

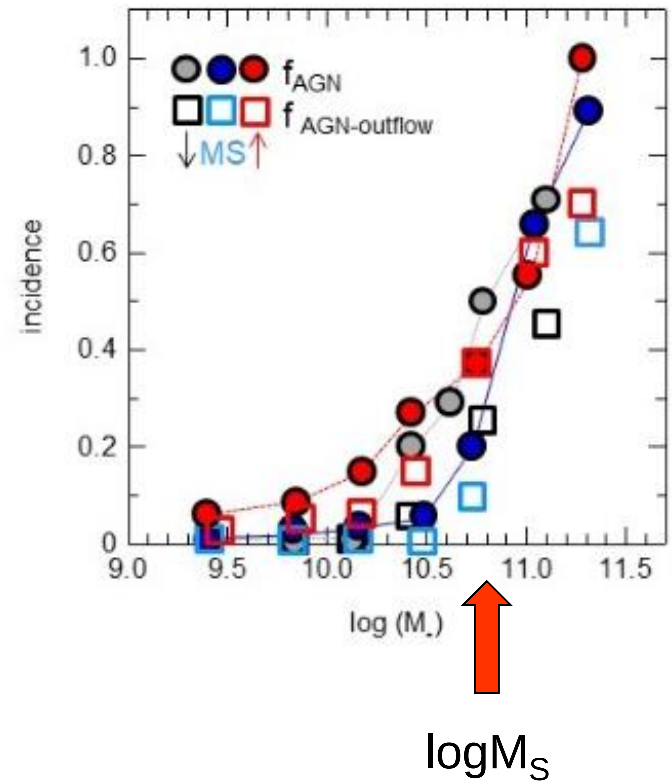
Also, e.g., Steidel +10, Coil +8, Weiner +09, Shapiro+09; Harrison+14,16; Maiolino+12; Cano Diaz+12; Fabian12; Newman +12, Mullaney+13; Genzel +14, Förster Schreiber +14, Brusa+15a; Perna+15a,15b;Carniani+15,16; Kakkad +16, Martin +12, Freeman +19

Demographic Trends: AGN Feedback

incidence & strength of outflow scales mainly with M_*







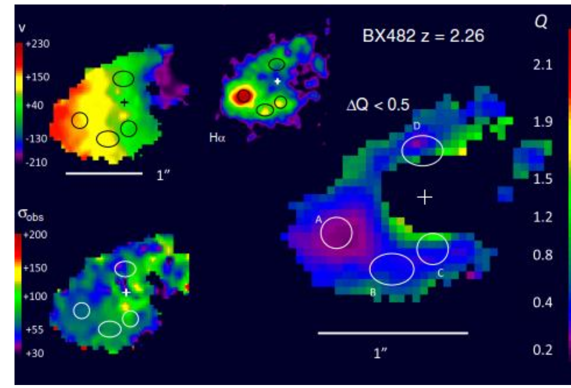
Förster Schreiber +19

secular evolution of gas rich disks, global gravitational instability, galactic turbulence and radial mass transport

$$\omega^2 = 4\left(\frac{v_{rot}}{R}\right)^2 - 2\pi G\Sigma k + k^2 c_s^2 < 0 \text{ for global instability}$$

instable cascade with smallest scale Jeans length $\lambda_J = \frac{c_s^2}{G\Sigma}$

and largest length $\lambda_T = Q \times \pi^2 G\Sigma \times \left(\frac{v_{rot}}{R}\right)^{-2}$



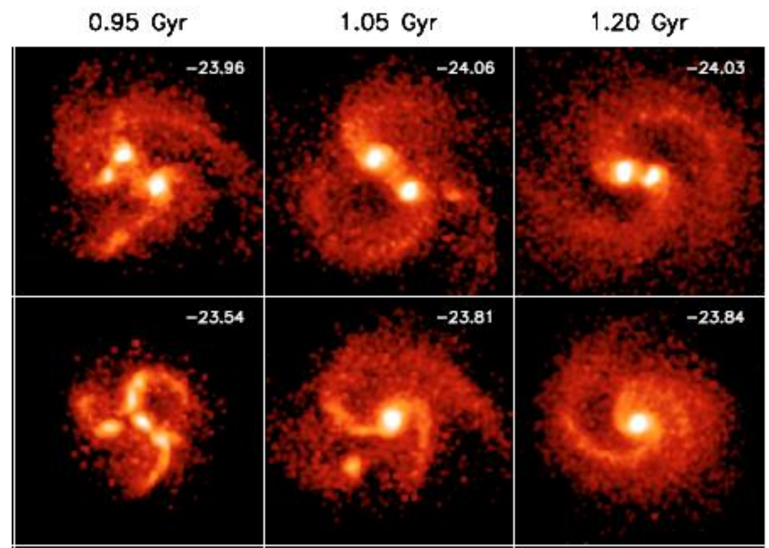
Genzel+11

$$\left(\frac{\sigma}{\mathrm{v_d}}\right) = \left(\frac{h_z}{R_{disk}}\right) \underset{Q\sim1}{=} \frac{Qf_{gas}}{\sqrt{2..3}}$$

$$L_{Toomre} \sim f_{gas} R_{disk} \sim 1 \text{ kpc}$$

$$M_{Toomre} \sim f_{gas}^2 M_{disk} \sim 10^9 \text{ M}_\odot$$

Noguchi99
Immeli+03
Bournaud+07



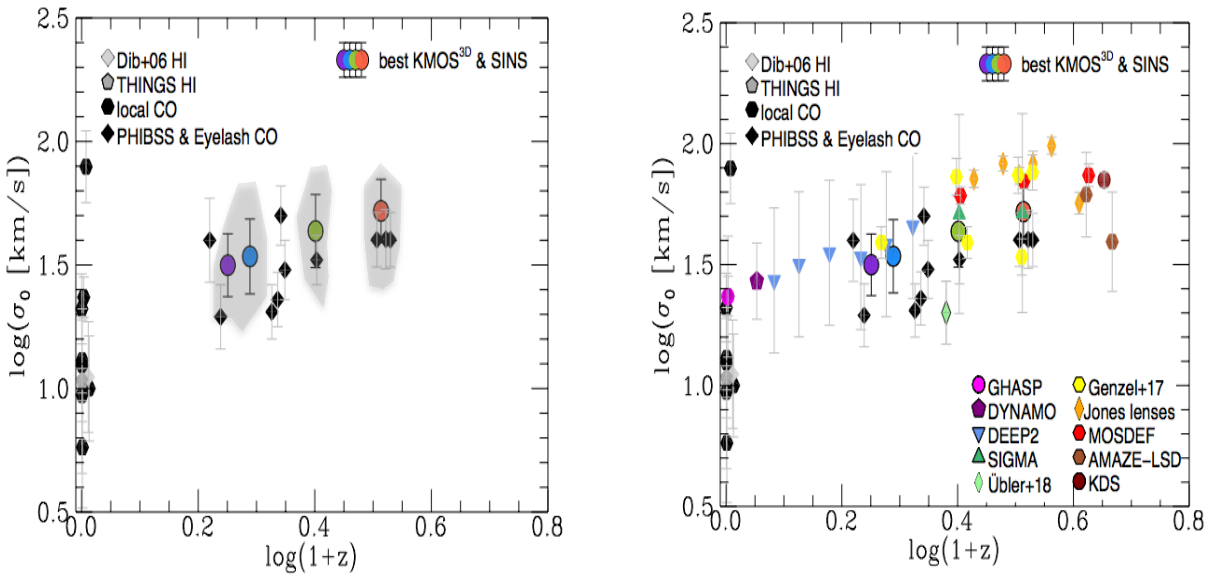
$$t_{vis} \sim t_{df} = \beta\left(\frac{R}{\lambda_{Jeans}}\right)^2 t_{dyn}(R) = \beta\left(\frac{v_d}{\sigma_0}\right)^2 t_{dyn}(\mathrm{R})$$

Lin & Pringle 87, Noguchi 1999, Immeli et al. 2003, Bournaud et al. 2007, 2014, Elmegreen +07, +09, Elmegreen & Scalo 04, Förster Schreiber +06, +09, Escala & Larson 2008, Dekel +09, 13, Elmegreen & Burkert 10, Krumholz & Burkert 10, Genzel +11, Ceverino +11, Glazebrook 13, Krumholz & Burkhart 16, Di Teodoro, Fraternali & Miller 2016, Gilmore & Reid 1983, Bovy & Rix 2012, 2015 , Madelker +15, Mayer+15, Tomburello +16, Oklopcic +15, Burkert +16

KROSS NOEMA ALMA KMOS3D

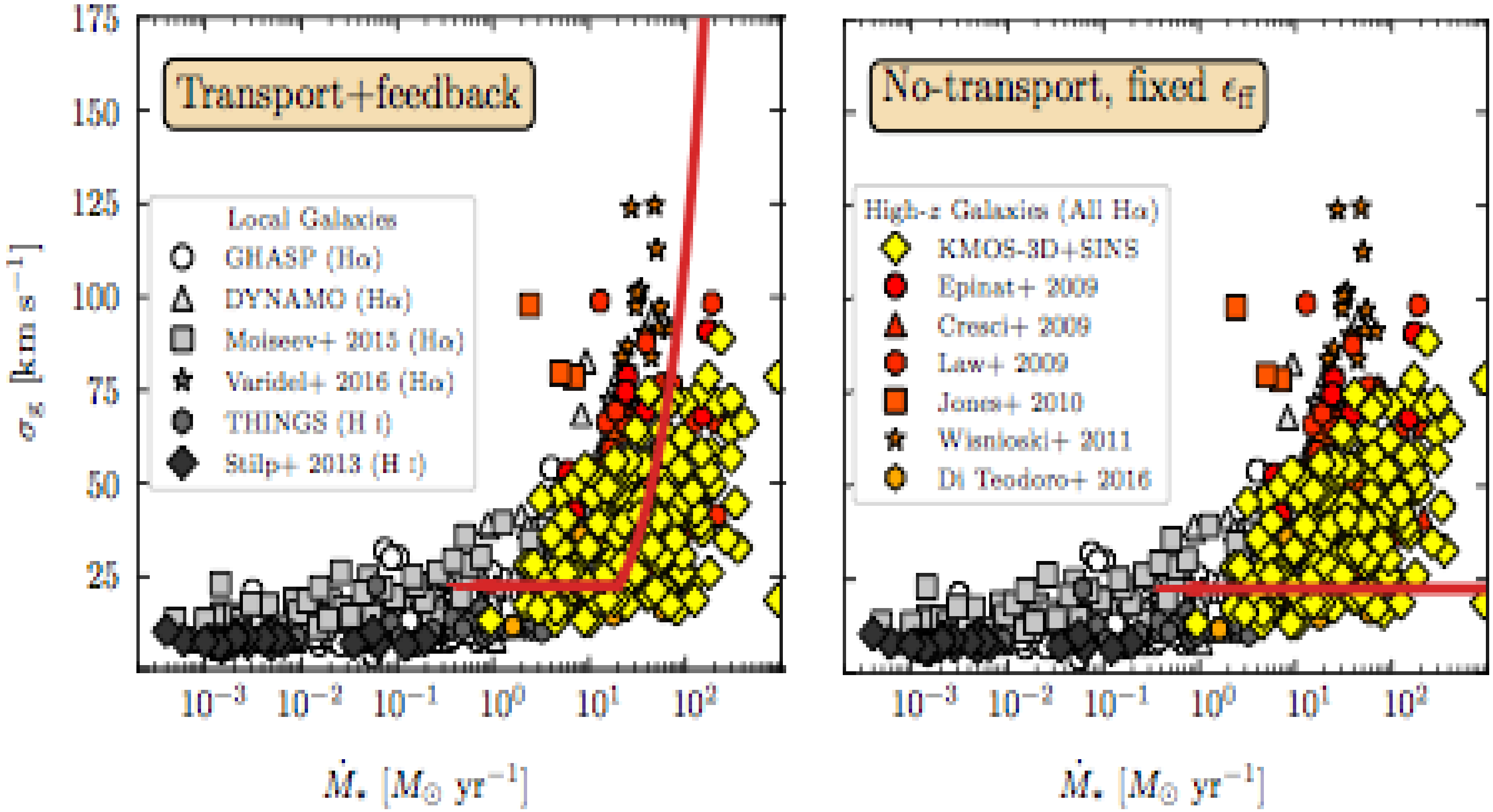
Galaxy-wide velocity dispersions increase with redshift for ionized as well as molecular gas

muse SINS/zC-SINF AO Survey

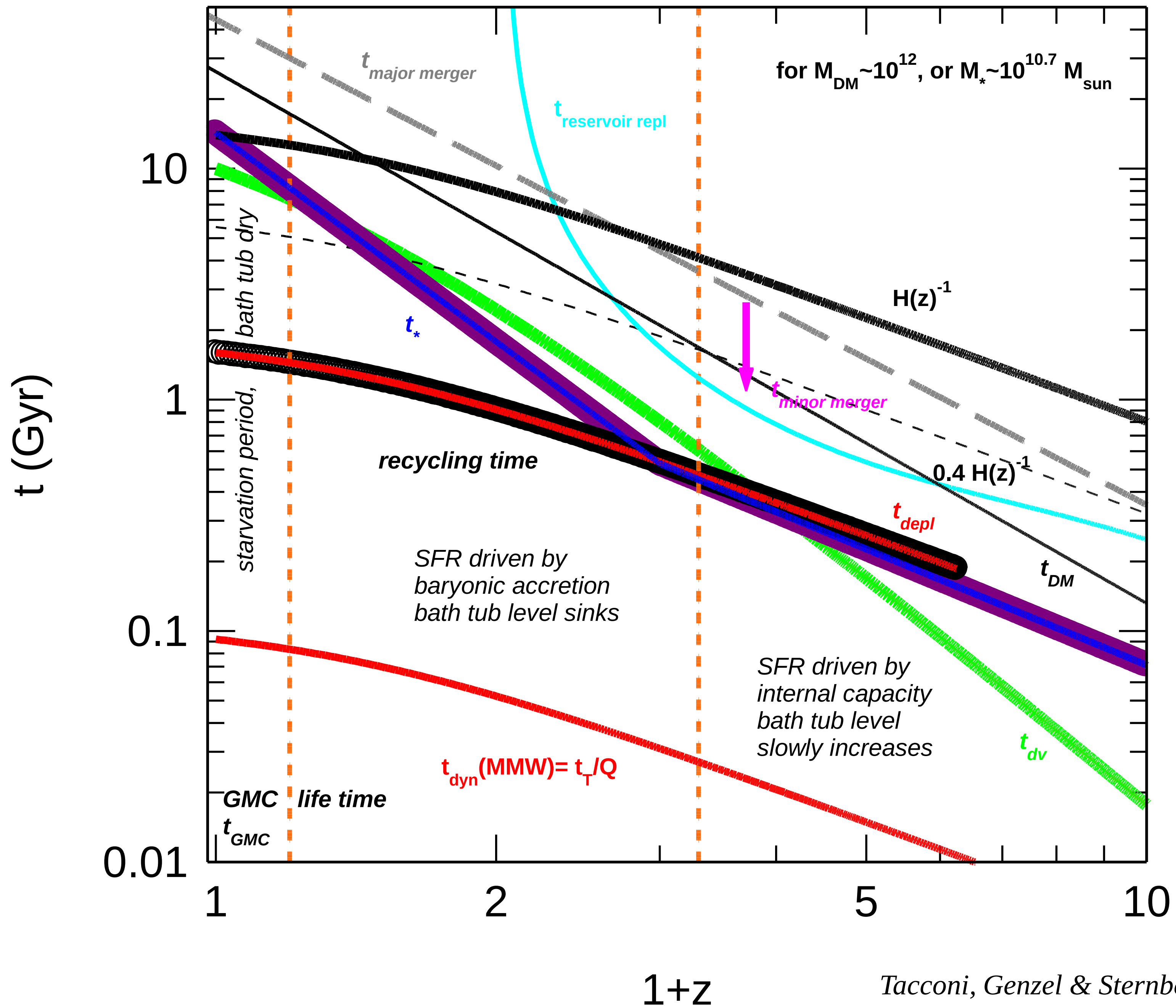


Shen+95; Elmegreen+04,10; Rosolowsky+05; Dib+06; Förster Schreiber+06,09,18; Genzel+06,08,11,17; Wright+07,09; Bournaud+08,09; van Starkenburg+08; Epinat+08,09,12; Leroy+08,09; Puech+08; Law+09; Cresci+09; Hitschfeld+09; Lemoine-Busserolle+10; Tacconi+10,13,18; Saintonge+11a,b; Wisnioski+11,15; Contini+12; Vergani+12; Kassin+12; Jones+10,12; Gnerucci+11; Swinbank+11; Tamburro+11; Glazebrook13 +refs; Meyer+13; Green+14; Colombo+14; Leroy+14; Di Teodoro+16; Price+16; Stott+16; Simons+16,17; Wuyts+16; Mieda+16; Turner+17; Johnson+17; Scoville+17; Übler+18

Stellar feedback alone is not sufficient to drive the observed high turbulences



Krumholz+2018, Übler +19



Tacconi, Genzel & Sternberg 2020