Overview of KS-Law: Interpretations, Cloud and Star Formation Structures

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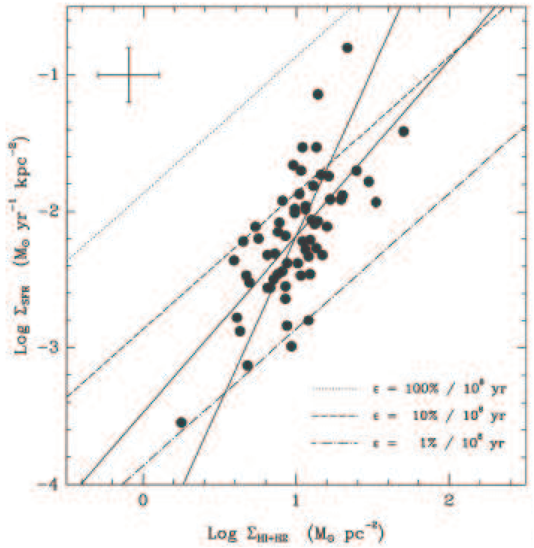
1. Observations
2. Theory
3. Reflections

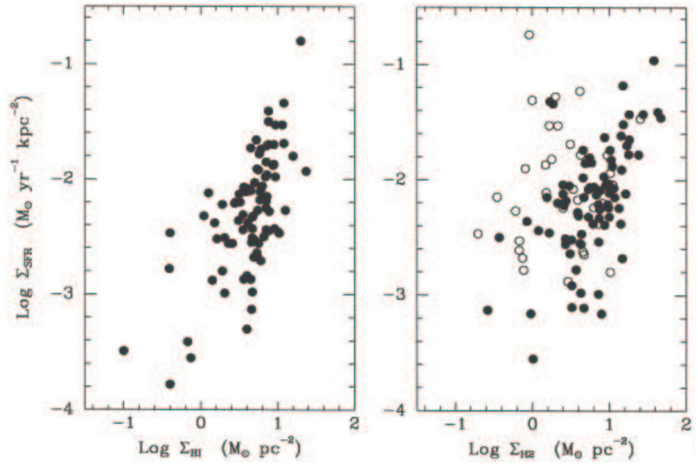
The Schmidt (1959) paper

- Derived SFR over history of galaxy
  - assuming a constant initial luminosity function $\Psi(M_v)$
  - a lifetime function $T(M_v)$, and gas return/star of M-0.7
  - a rate f(t) that scales with a power of gas mass $M_G(t)$
    - $\boxed{f(t)\,\Sigma_{Mv}\,\Psi(M_v) = C\,[M_G(t)]^n}$
  - gave analytical solutions for $n=0,1,2$
  - used scale height for HI of 144 pc, scale height for Cepheids of 80 pc, and for clusters of 58 pc to give $n=2$ to 3.
    - whitedwarf count: $n>2$, He abundance: $n=2$, uniform HI: $n\geq 2$, cluster MF: $n=1\text{-}2$
  - noted that $n=2$ suggests dense galaxies (ellipticals) should now have less gas than low-density galaxies (LMC)
- final comment: “It is hoped to study the evolution of galaxies in more detail in the future”

The Kennicutt 1998 result, normal gal.



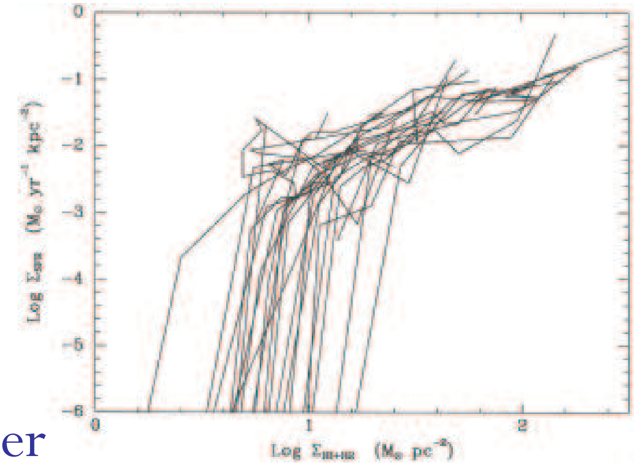
Hα SFR vs
HI+H2,
n=1.29,2.47



Hα SFR vs HI and H_2

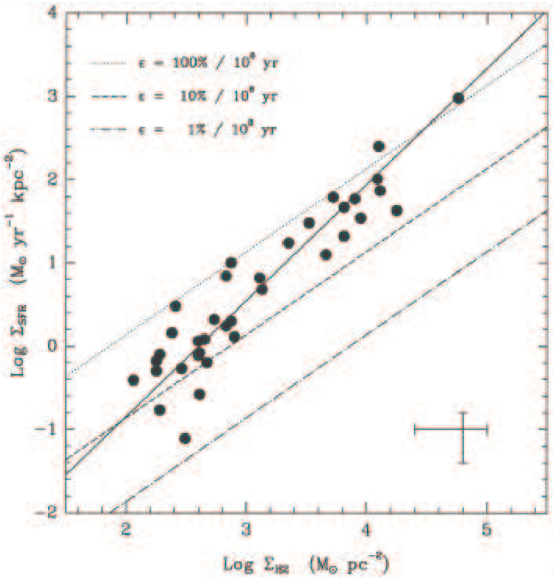
Assumptions:

1. 61 $i<75^{o}$ galaxies with CO,HI,Hα
2. constant extinction correction & H_2/CO
3. Salpeter IMF, 0.1-100 M_O
4. Radial size from RC2



local Hα SFR vs HI+H_2
with gal. radius a parameter

The Kennicutt 1998 result, starburst gal



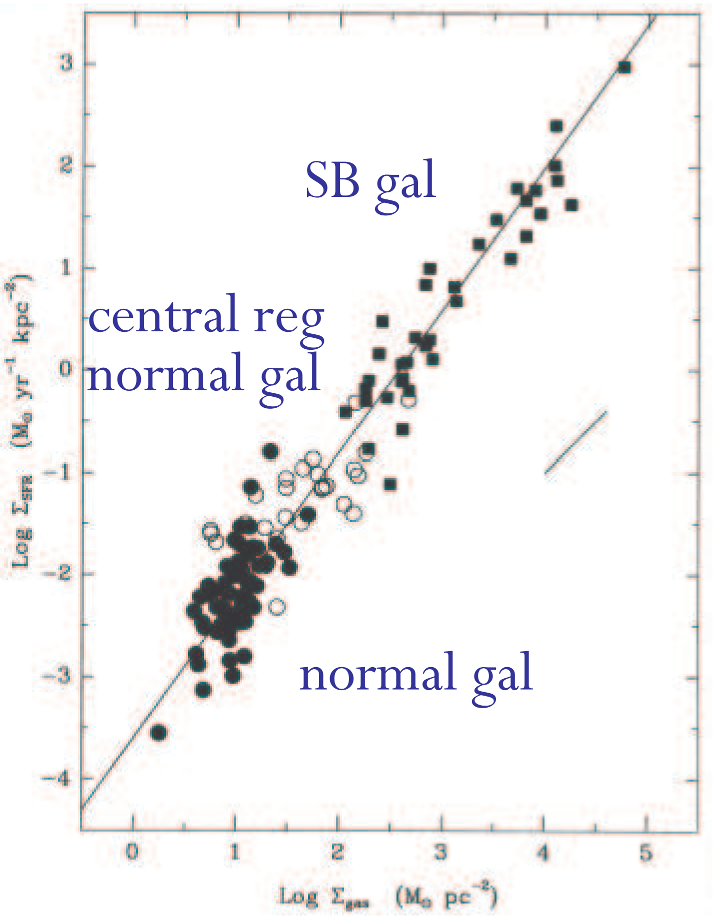
FIR SFR

vs H_2

n=1.28,1.4

Assumptions:

1. 36 galaxies with high-res CO, FIR (ignore HI)
2. constant H_2/CO
3. 10-100 My continuous bursts (Leitherer et al)
4. Radial size from burst region (CO or IR)

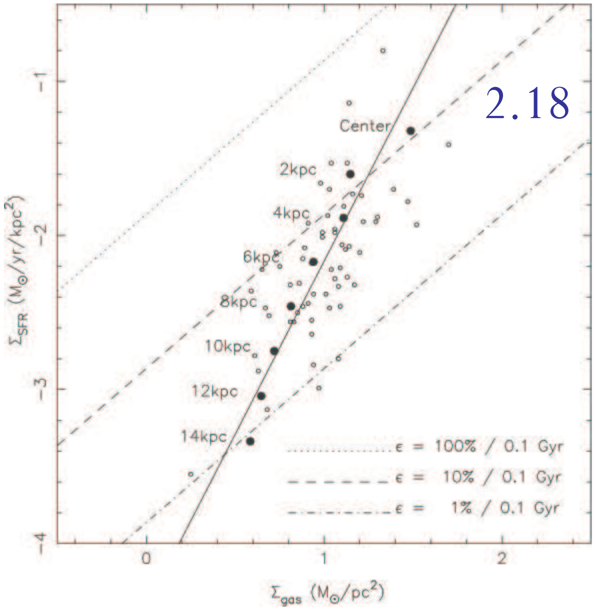


combined: normal& SB

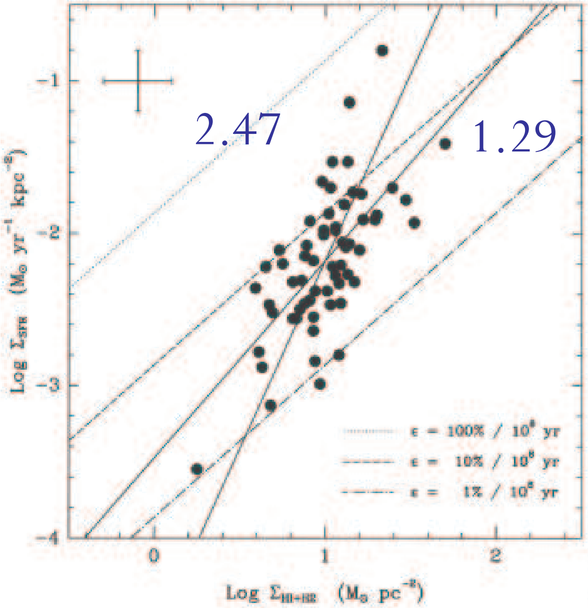
n=1.40pm0.05

K-S Law in the Milky Way

- Misiriotis et al. 06 use COBE/DIRBE to get both the gas/dust distribution and SFR distribution
  - find K-S slope of 2.18pm0.20
  - claim similar to Kennicutt '98 n=2.47 (from bivariate fit)

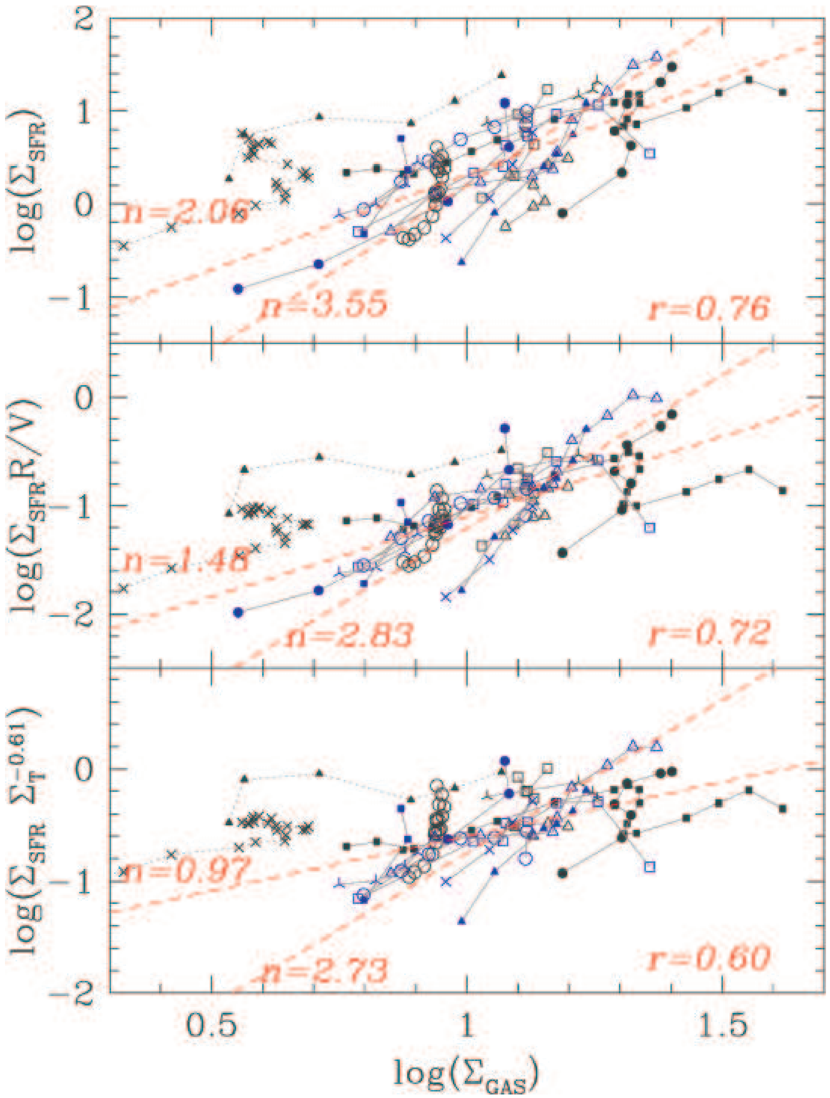


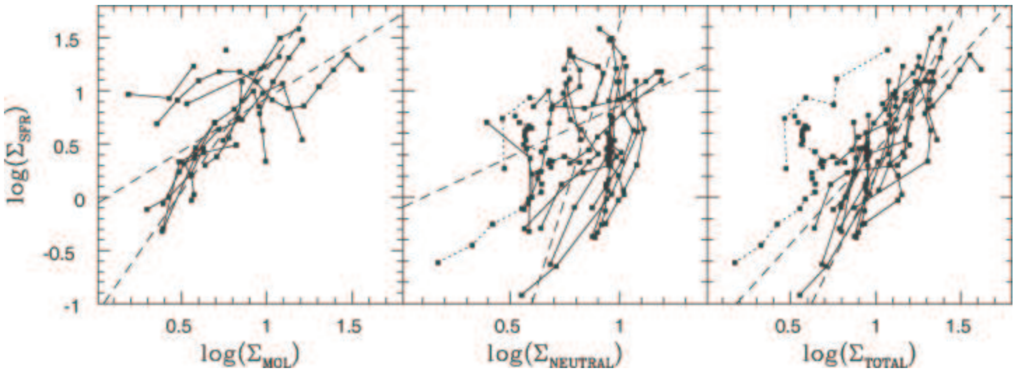
(Kennicutt 98)



K-S law variations

- Boissier et al. 03 compared SFR vs radius in 16 galaxies with three expressions, best fits:
    - Kennicutt/Schmidt: $\Sigma gas^{2.06}$
    - Boissier & Prantzos '99: $\Sigma gas^{1.48} V/R$
    - Dopita & Ryder '94: $\Sigma_{gas}^{0.97}/\Sigma_{tot}^{0.61}$
  - assumed H_2/CO varied with radius as the metallicity (Boselli et al 02)
- concl: 3 laws are equally good; K-S n>1.4

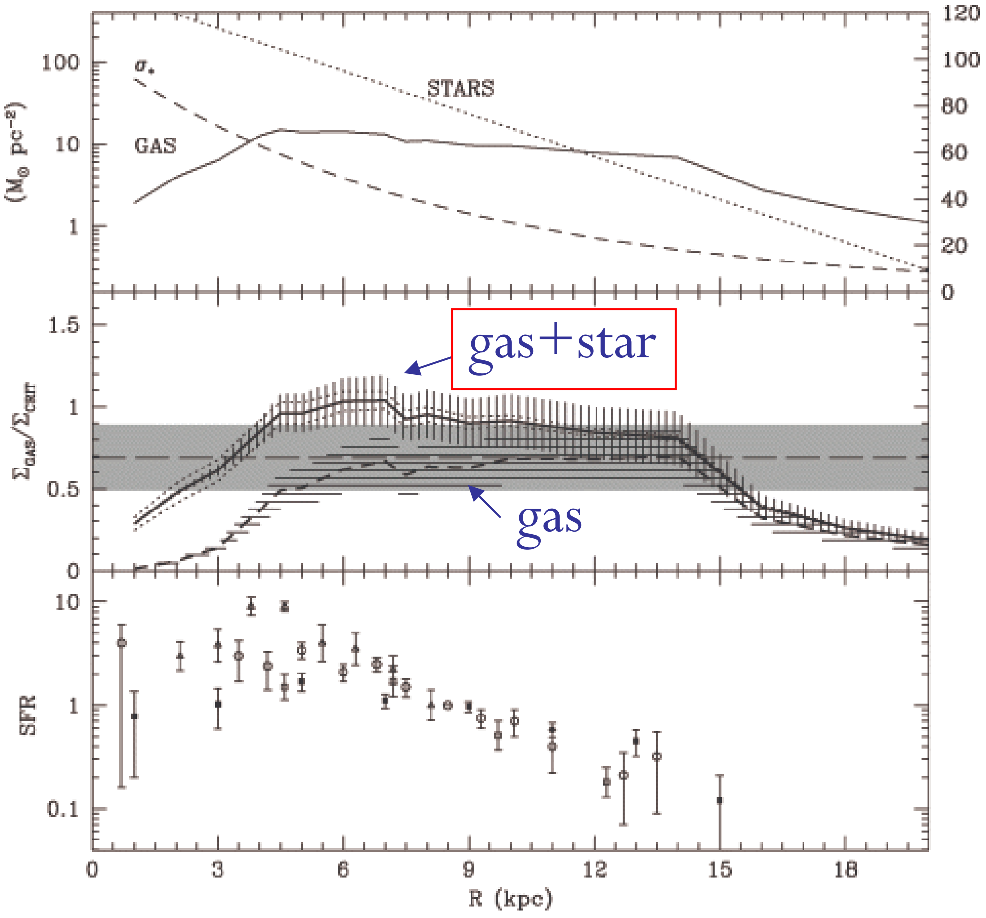




molecular, atomic, total gas comparison

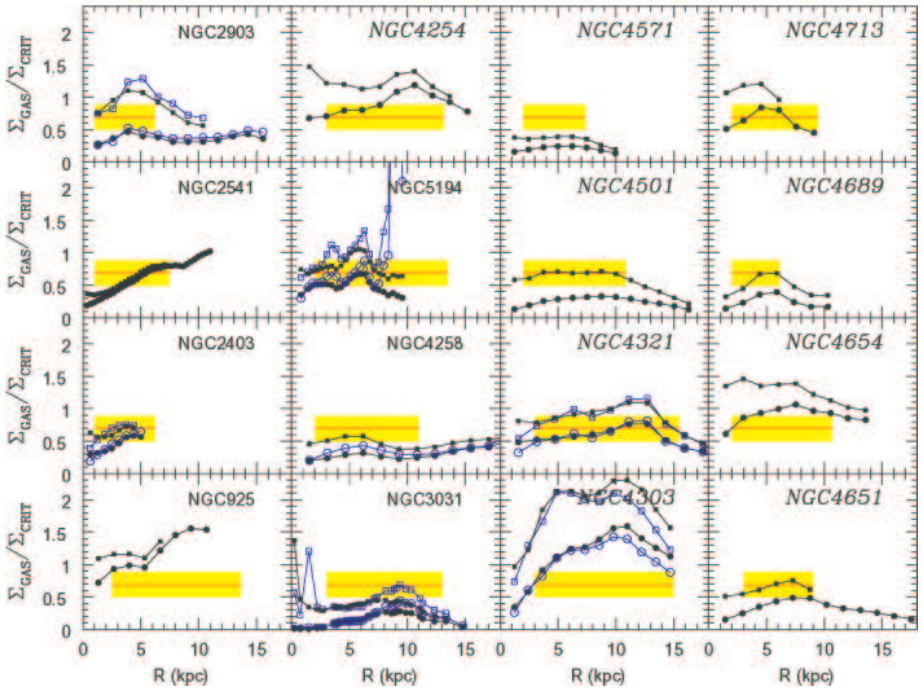
K-T Threshold in the Milky Way

- Boissier et al. 03 determined Σ/Σ_{crit} in the MW using pure-gas Σ_{crit} or gas+star Σ_{crit} (Wang&Silk94)
  - gas+star gives best threshold



K-T Threshold Variations

- Boissier et al. 03 also determined Σ/Σ_{crit} (R) for 16 galaxies
  - assumed H_2/CO varies radially
  - for pure-gas Σ_{crit}, 8/16 of disks are subcritical
  - for gas+star Σ_{crit}, 2/16 subcritical
  - biggest difference: M&K get higher H_2 density using constant H_2/CO



filled circles: gas only

filled squares: gas+stars

open symbols: high-res RC

$\Sigma_{GAS}/\Sigma_{crit}$ versus Radius
(yellow – Martin & Kennicutt '01)

Threshold determines gas fraction

Zasov & Smirnova 06:

All galaxies have Σ(HI) at critical Σ_c

$\Sigma_c = \alpha\kappa c/\pi G \sim V/R$ from κ

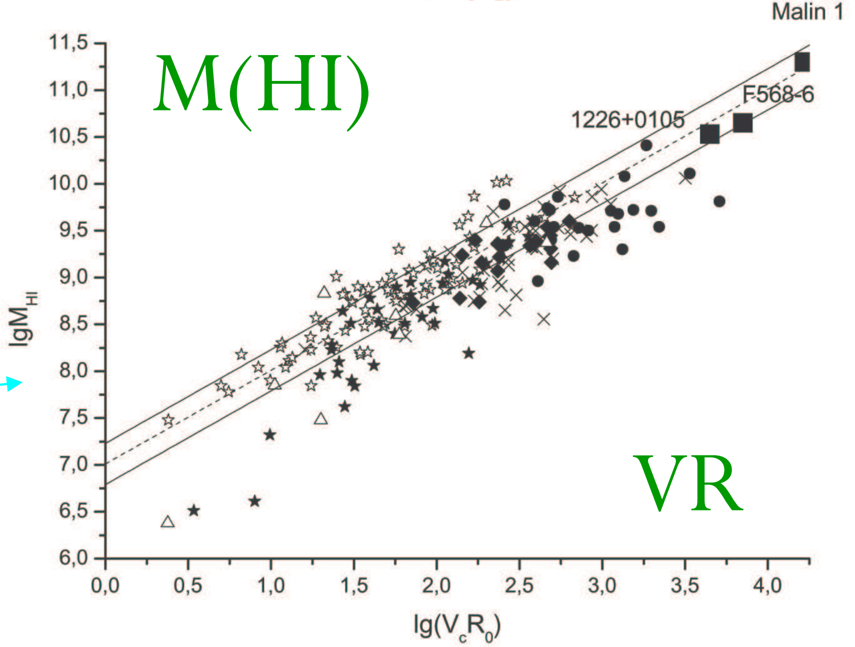
so $M_{gas} = \mathrm{Int}^R\ 2\pi R\Sigma_c dR \sim VR$

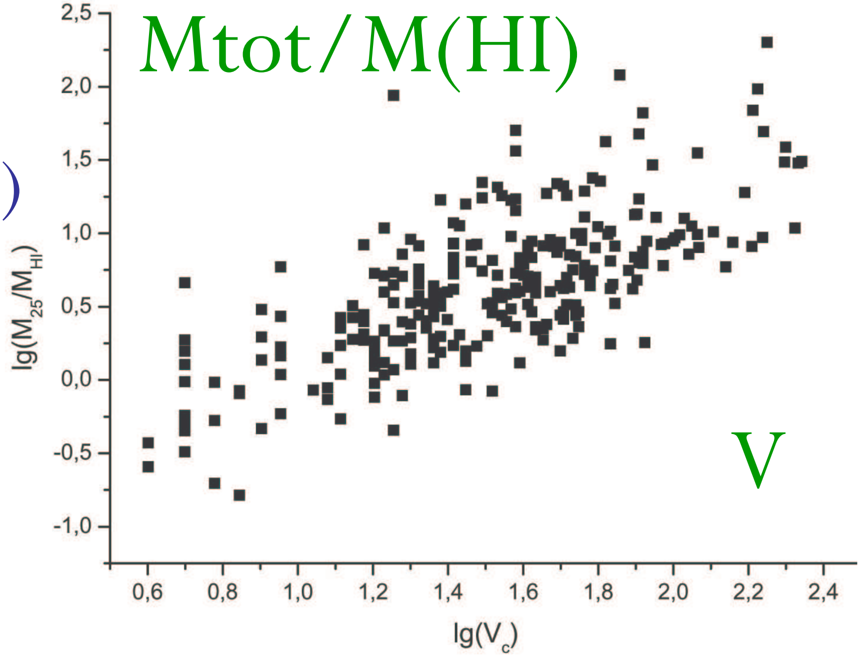
but $M_{tot} \sim V^2R$

so $M_{tot}/M_{gas} \sim V$

-small galaxies are more gas-rich

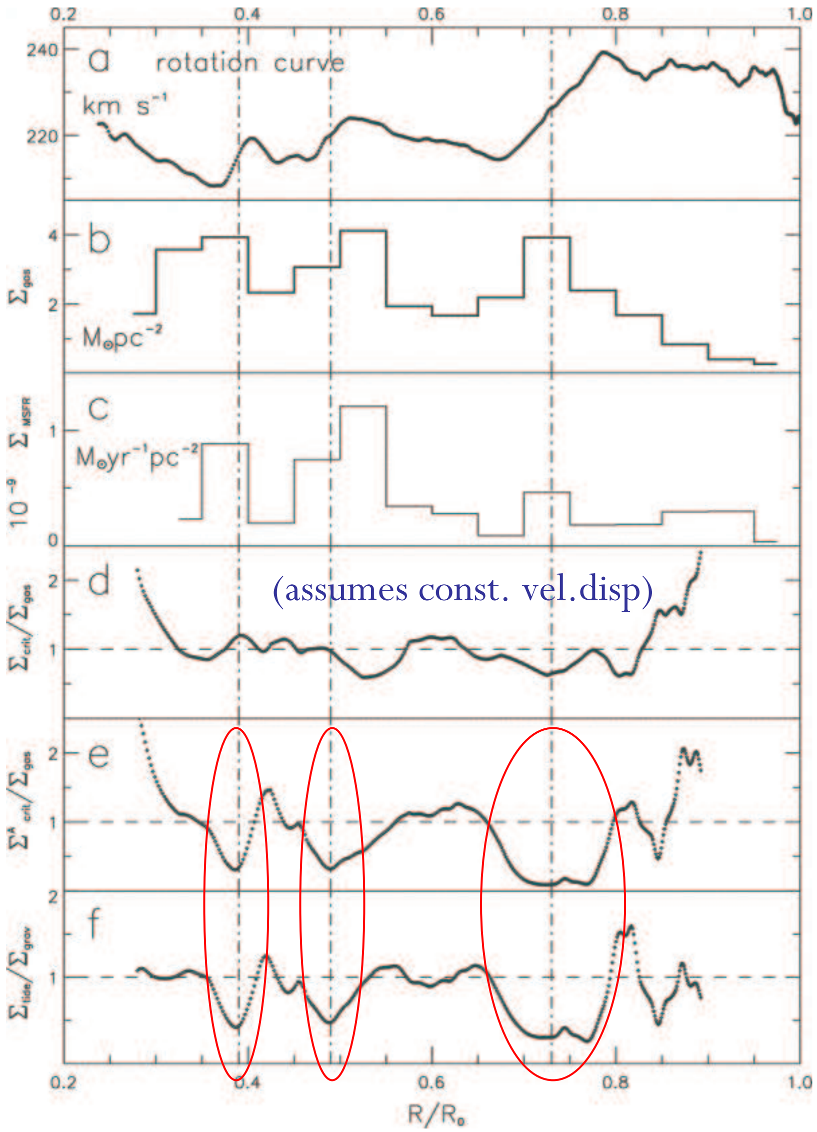
because $\Sigma \sim \Sigma_c$ (not n>2 ala Schmidt)





A Shear Dependence?

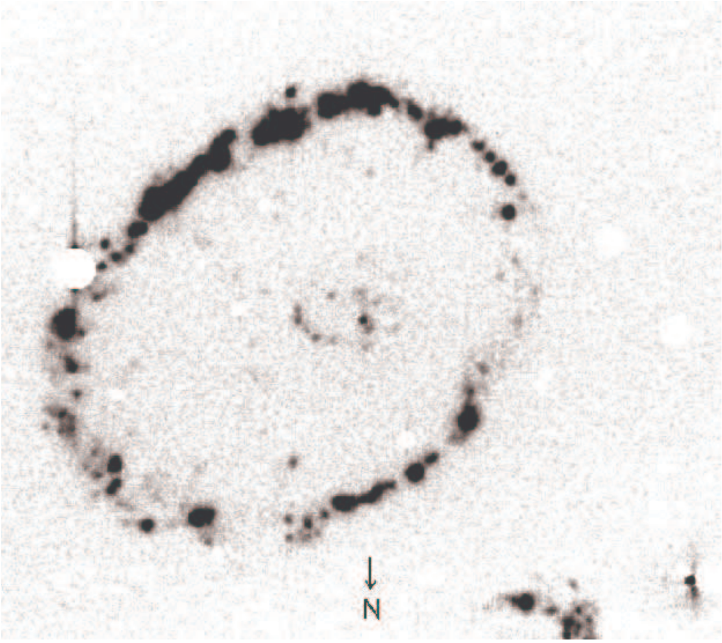
- Luna et al. 06: MW SF from IRAS point sources, CO from new southern survey (const. H_2/CO)
  - finds massive SF in low-shear spiral arms, and overall, SFR~$\Sigma_{gas}^{1.2pm0.2}$.

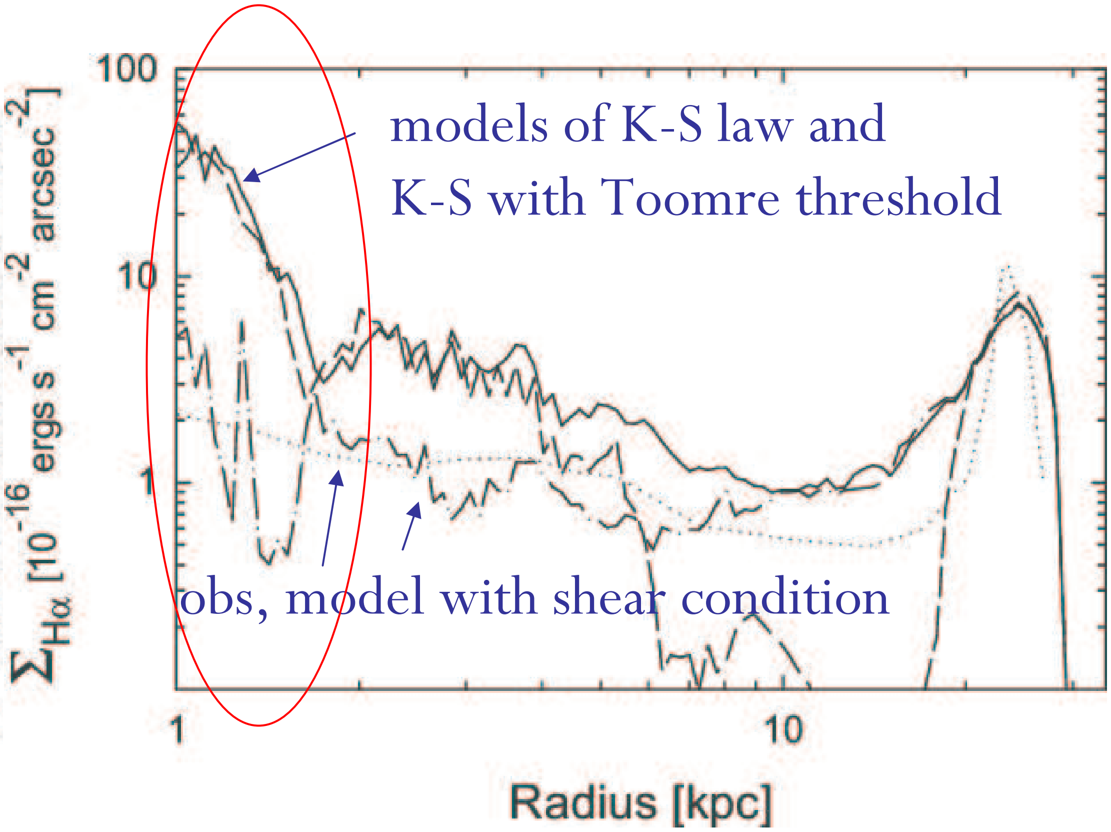


(assumes const. vel.disp)

Another Shear Dependence

- Vorobyov 03: Cartwheel galaxy inner ring too faint for pure K-S law, <u>need high shear to limit SF</u> there.





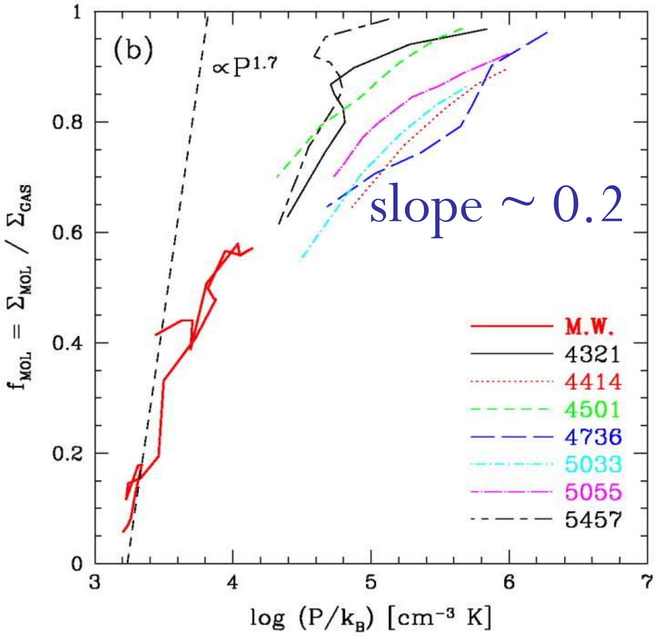
models of K-S law and
K-S with Toomre threshold

obs, model with shear condition

The Molecular Cloud Connection

- Wong & Blitz 02: find SFR in direct proportion to molecular cloud density (n=1), and suggest K-S law from changing f_{mol}
  - assumed H_2/CO const.
  - combined index $n=n_{mol}(1+d\ln f_{mol}/d\ln\Sigma_{gas})$
  - where $n_{mol}=1$ (e.g., Rownd & Young 99) and f_{mol} increases with P

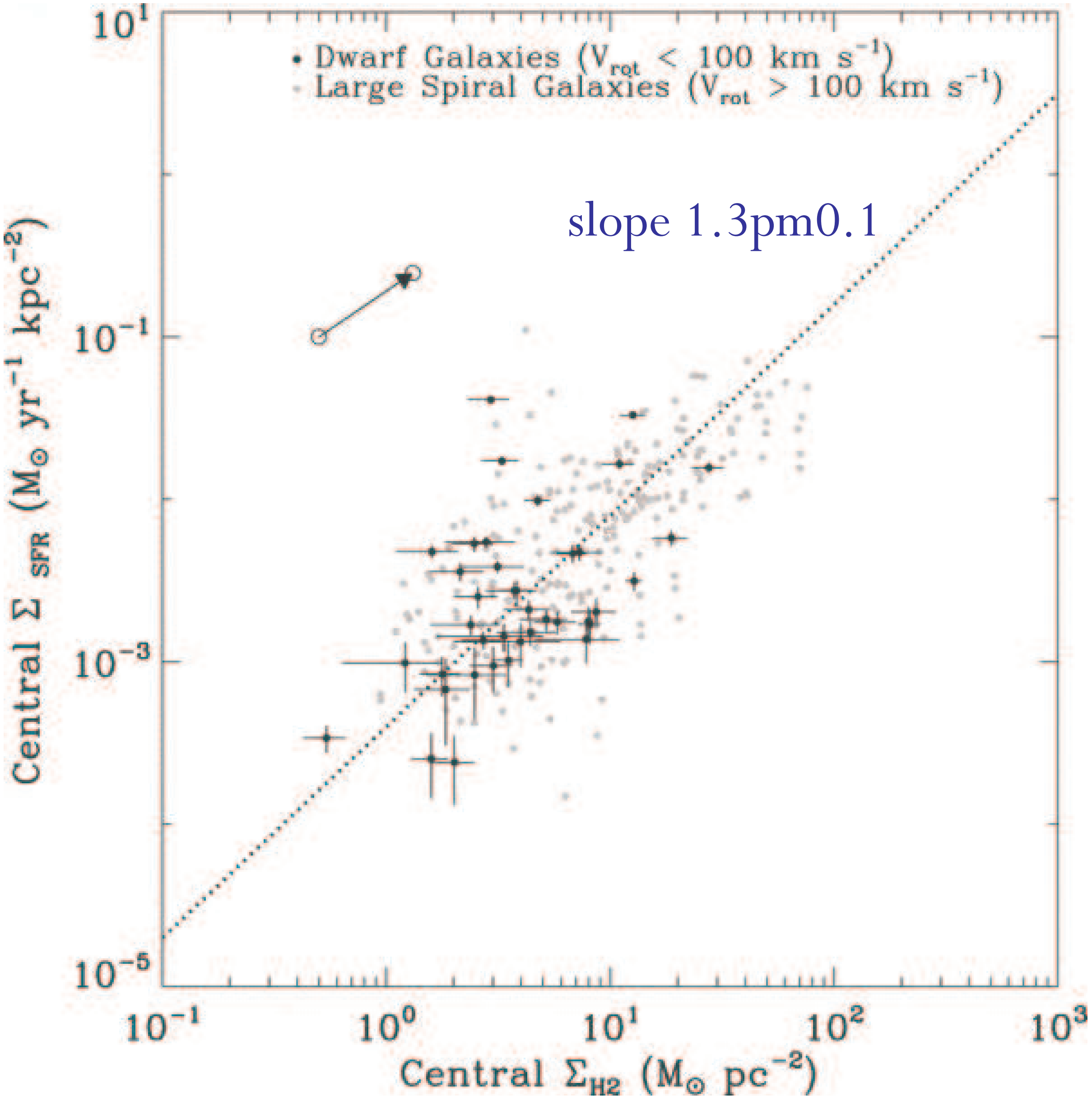
measure $d\ln f_{mol}/d\ln P \sim 0.2$
and if $P \sim \Sigma_{gas}^{2}$
then $d\ln f_{mol}/d\ln\Sigma_{gas} \sim 0.4$ ☺



slope ~ 0.2

Suggest Q not a good measure of SFR, but a better measure of gas fraction (high Q corresponds with low $\Sigma_{gas}/\Sigma_{tot}$)

Dwarf galaxies continue the correlation of spirals

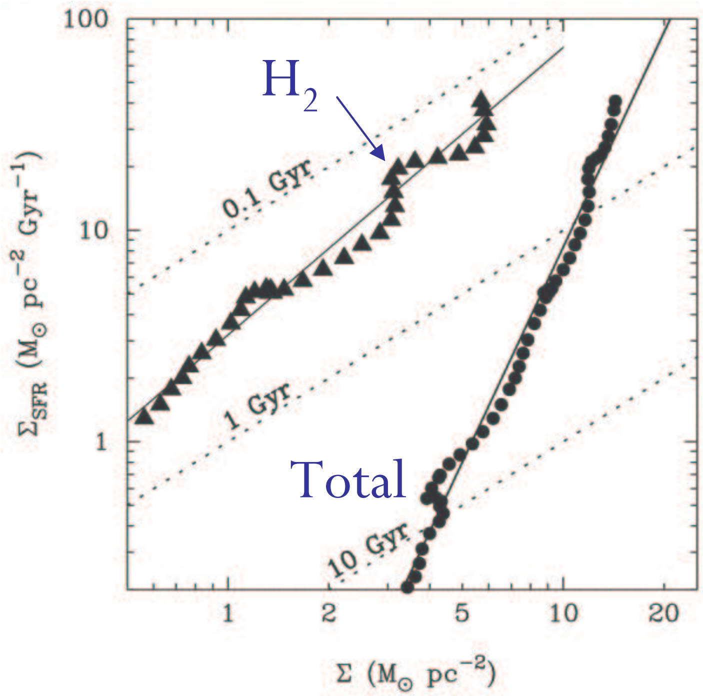


slope 1.3pm0.1

Leroy et al. 05

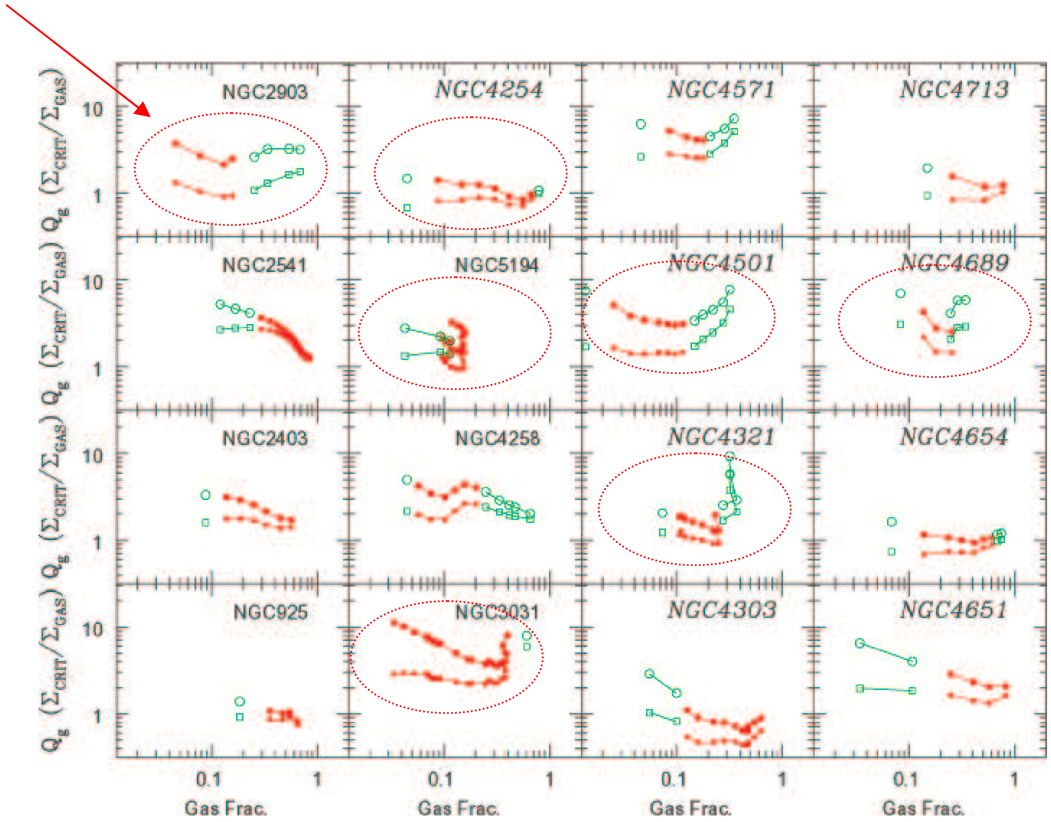
M33 Molecular K-S law

- Heyer et al. 04 found n=1.36 for $\Sigma(H_2)$
  - In M33, f_{mol} is small, P small



A Molecular Cloud Connection?

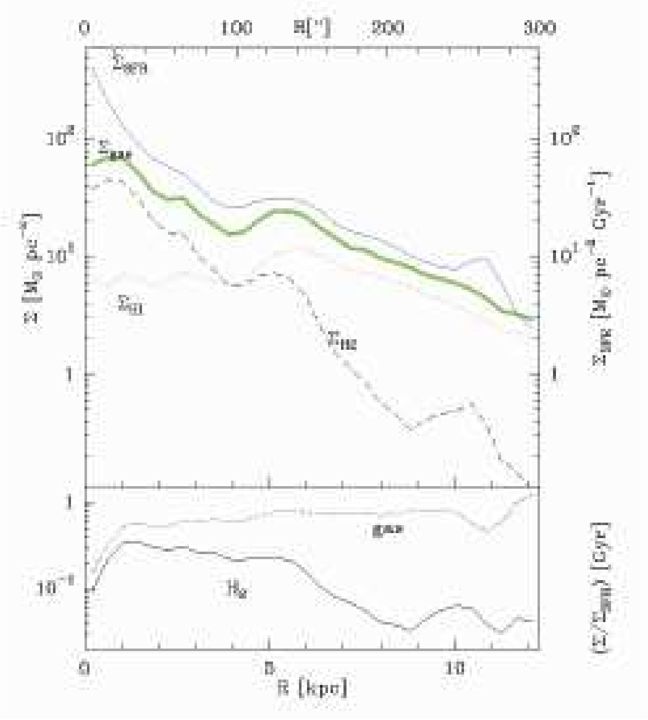
- Boissier et al. 03 found no anticorrelation between f_{gas} & Q
    - – assumed variable H_2/CO
- 7/16 low Q & low f_{gas}

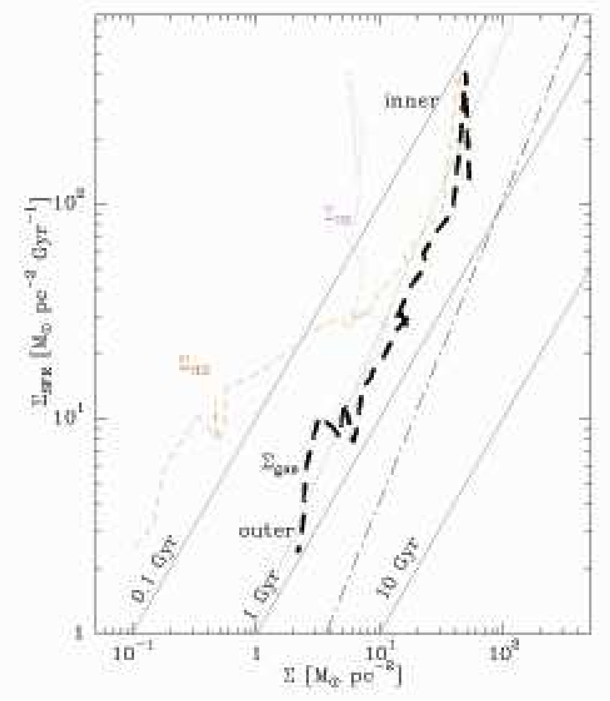


gas only = circles
gas+stars = squares
red symbols = active SF

No Molecular K-S Law in M51?

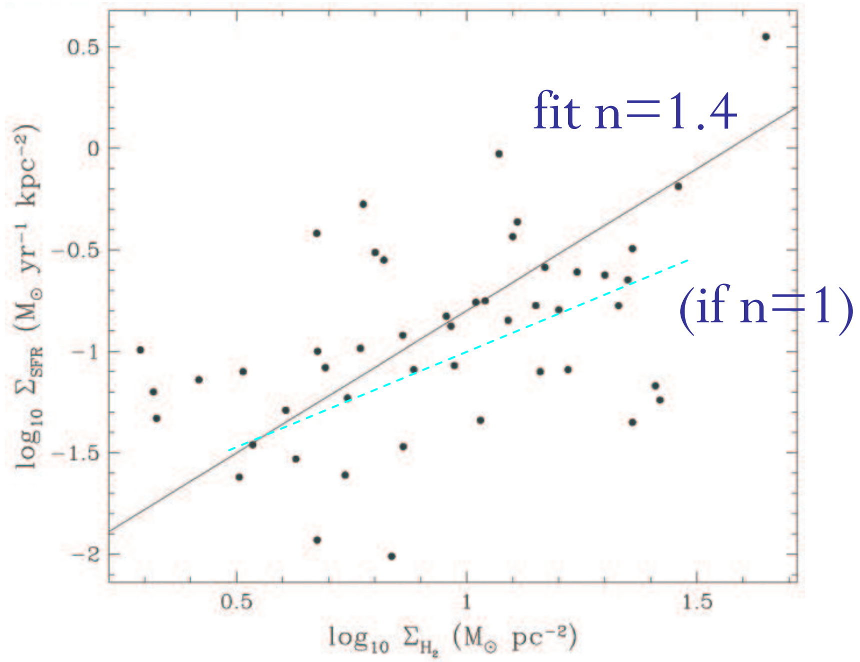
- Schuster et al. 06 use IRAM 30-m map of CO(2-1), VLA of 21 cm, and SFR from VLA 20 cm continuum; resolution 450 pc.
  - – assume constant H_2/CO
  - – find total gas n=1.4pm0.6, poor correlation with H_2





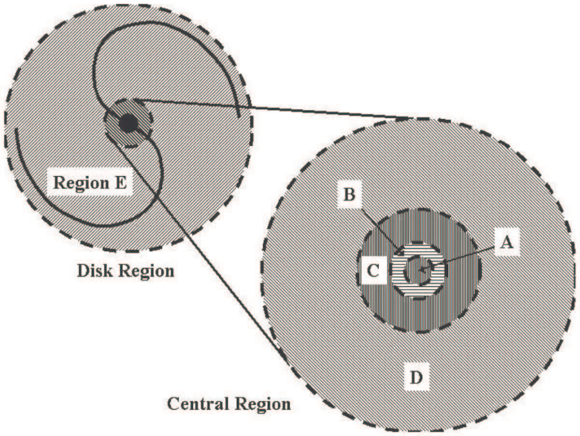
K-S Law at High Molecular Densities

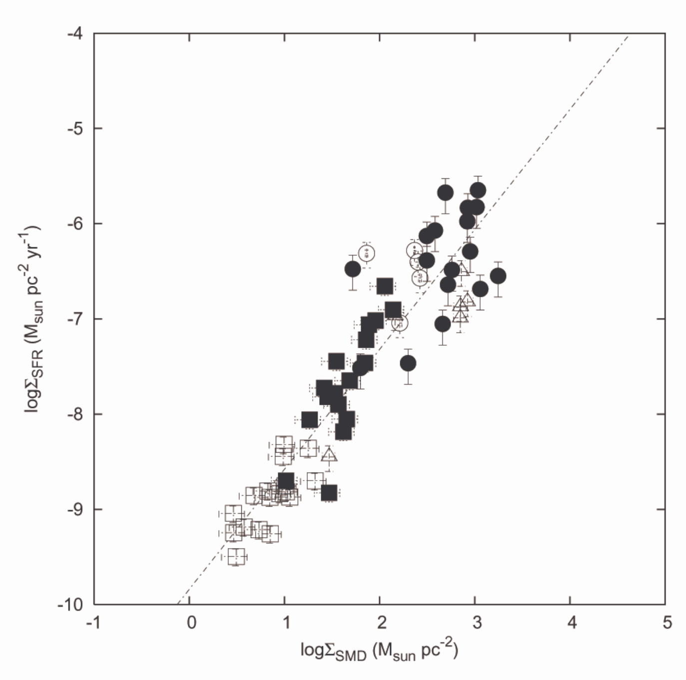
- Yao et al. 03 measure CO in SCUBA IR luminous galaxies. SFR from FIR. H_2/CO constant.
  - find $\boxed{n=1.4pm0.3}$
- These are highly molecular galaxies; should be no variation in f_{mol}



K-S Law at High Molecular Densities

- Komugi et al. 06 obs CO with 5 beam sizes in 17 best-case galaxies.
  - SFR from Hα (extinction corr.,), assumed constant H_2/CO
  - finds K-S relation, n=1.33pm0.08, radial dependence
  - K-S valid from 1 to 1000 $M_{O}pc^{-2}$ (using a single tracer)
- Their result (with Yao et al's) suggests that n=1.4 is not from variations in the molecular fraction but is intrinsic to the total gas.





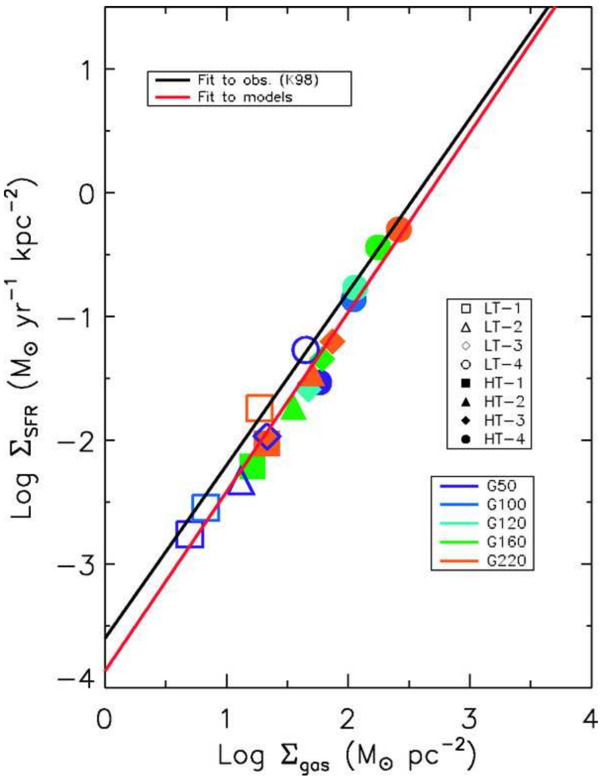
Observations Summary

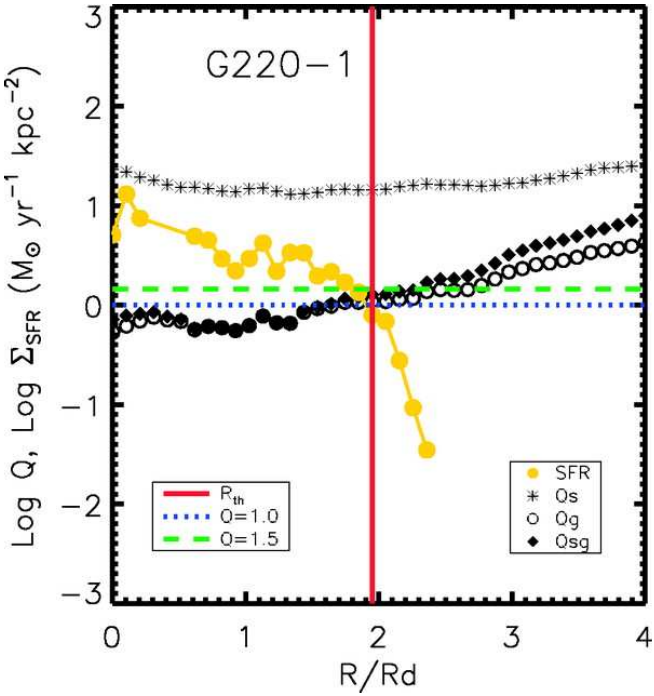
- K-S slope depends on assumptions (variable H_2/CO, extinction, …) and varies from 1.2 to 3 in different studies
- K-T threshold may require stars+gas, and sometimes shows shear sensitivity
- molecular K-S law still debated
  - it may be independent of SF that $f_{mol} \sim \Sigma_{gas}^{0.4}$ at low f_{mol}

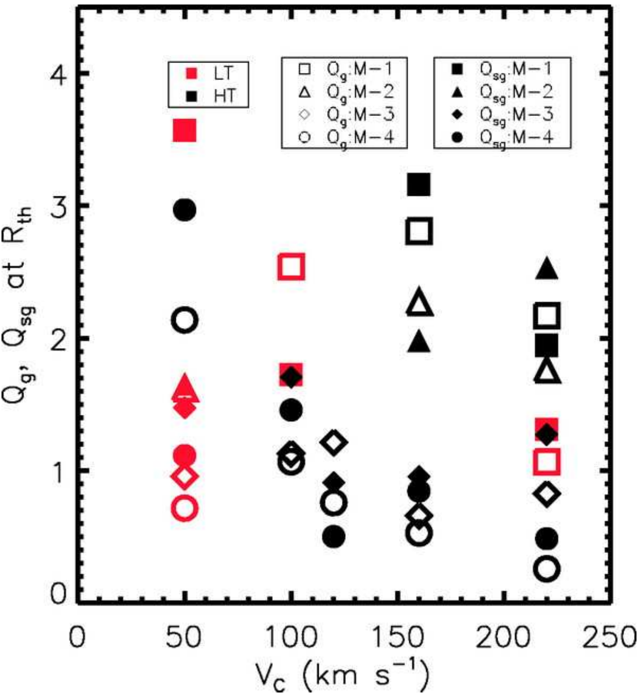
Theory

K-S Law by Gravitational Instability

- Li, Mac Low & Klessen 05: SPH of galaxy disk with self-gravity forming sink particles at $n > 10^3$ cm^{-3}

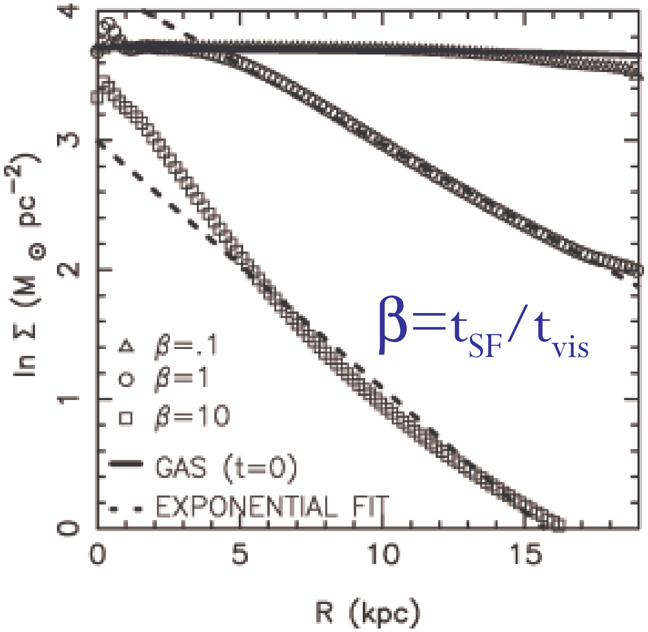




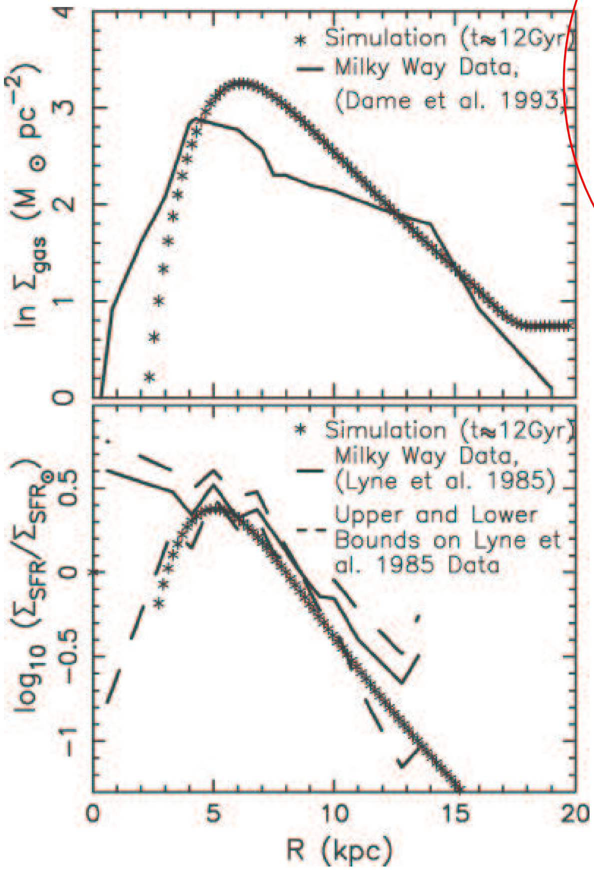


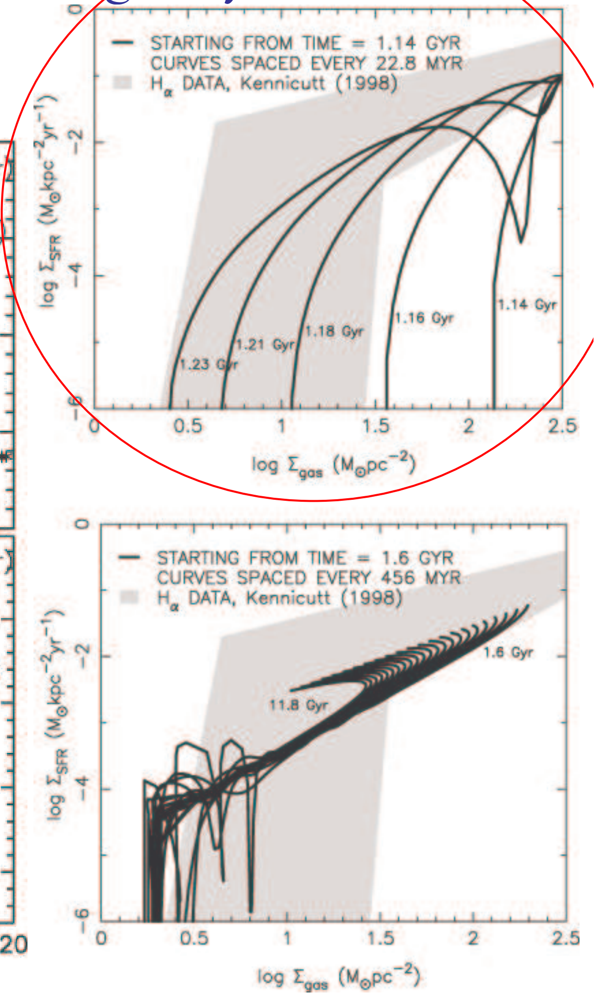
Viscous Disk Evolution

- Slyz et al. 02 model disk evolution with:
  - SFR ~ Σ/t where t = viscous time, large in outer galaxy



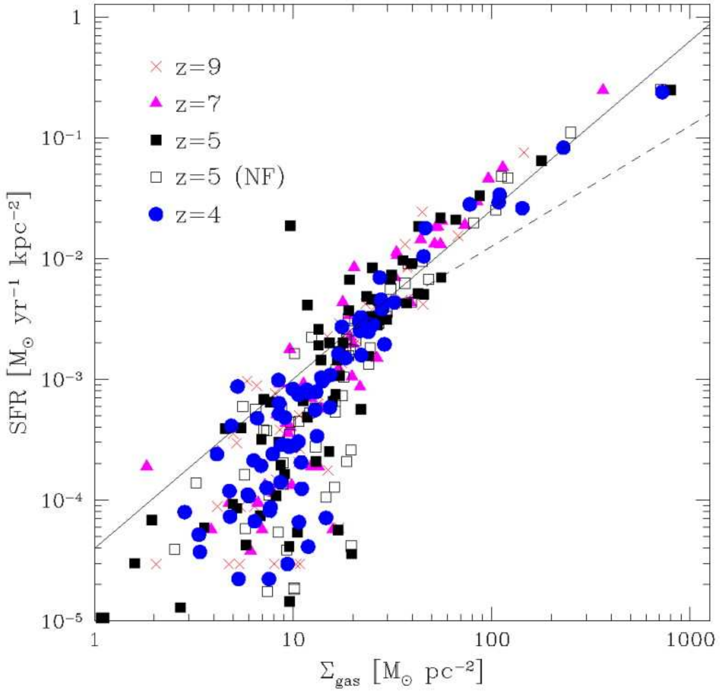
$\beta = t_{SF}/t_{vis}$





K-S from Tail of Density pdf

- Kravtsov 03: cosmol. simulations, N-body in Eulerian adaptive mesh.
  - assume constant efficiency at high gas density
  - and SF only in dense regions (n>50 cm^{-3} – resol. limit)
  - SF in tail of density pdf (cf. Krumholz & McKee 05)

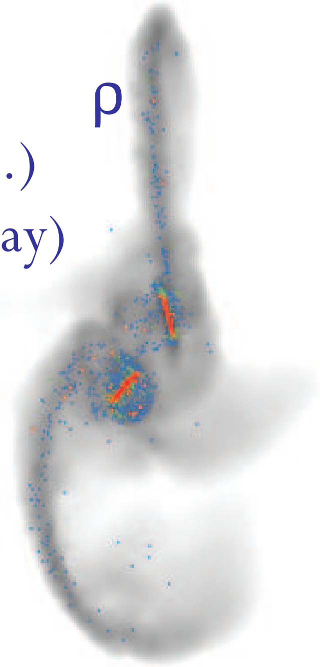


A SFR dependent on shocks, not ρ

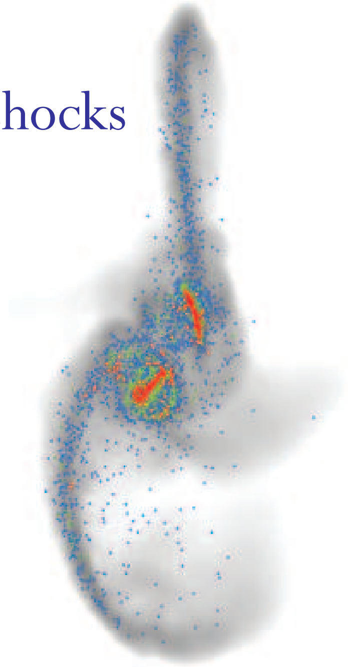
- Barnes 04 modeled the interacting pair “Mice” with SPH, replacing the ρ dependence with a dependence only on dU/dt from PdV work in shocks. $SFR \sim \rho^n (dU/dt)^m$
- The result was better with shocks (n=1, m>0)
  - earlier SF, more dispersed SF, as observed

stars (con.)
& gas (gray)

ρ

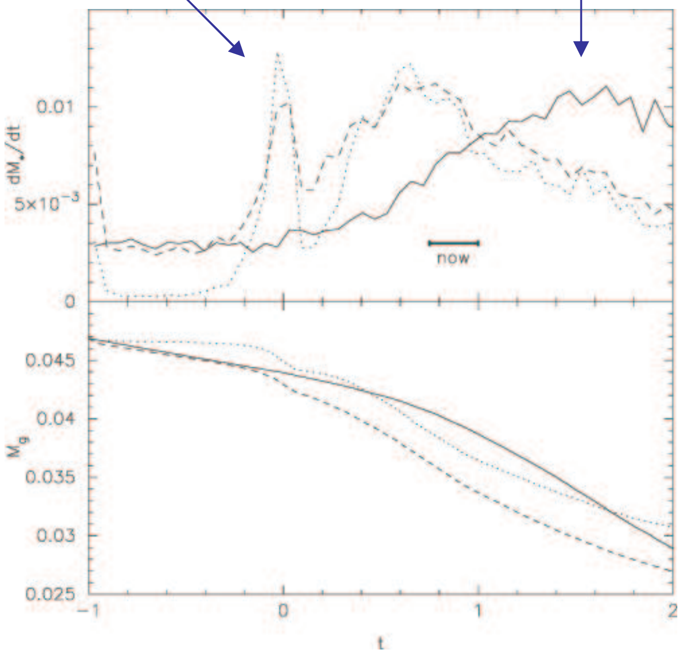


shocks



n=1.5,m=0

n=1, m=0.5,1



K-S from cloud collisions

- Tan 00 suggested all SF from colliding clouds and derived
  - SFR $\sim 1.5\varepsilon\, \Sigma f_{SF} f_G \Omega(1-0.7\beta)/Q$ $\boxed{\sim \Sigma\Omega/Q}$
    - ε = fraction of cloud turned into stars
    - f_{SF} = fraction of collisions which form stars
    - f_G = collision probability (~0.5)
    - β = power in power law rotation curve
    - Ω = rotation rate

Theory Summary

- GI, pdf tails, shocks, cloud collisions all similar in a Q~1 ISM
  - different ways of identifying the dense gas
  - origin of the dense gas the same:
    - gravity + turbulence (+ stellar compressions)
- Viscous model OK too for K-S-T, but seems to fail in dwarf galaxies, which have little shear and still have exponential disks

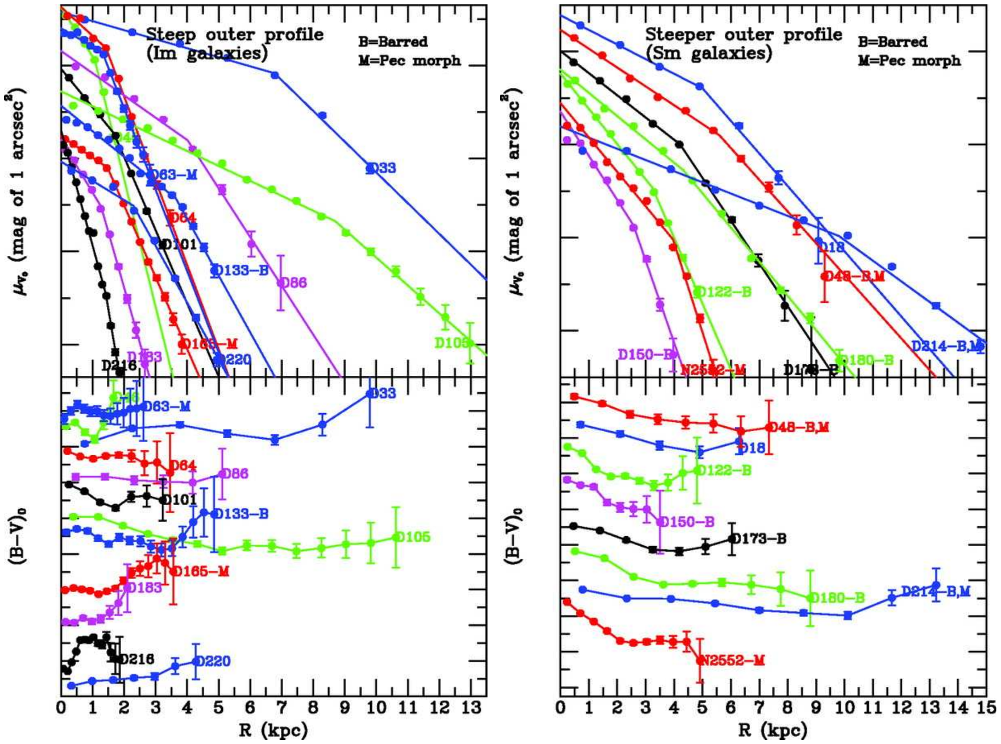
Reflections

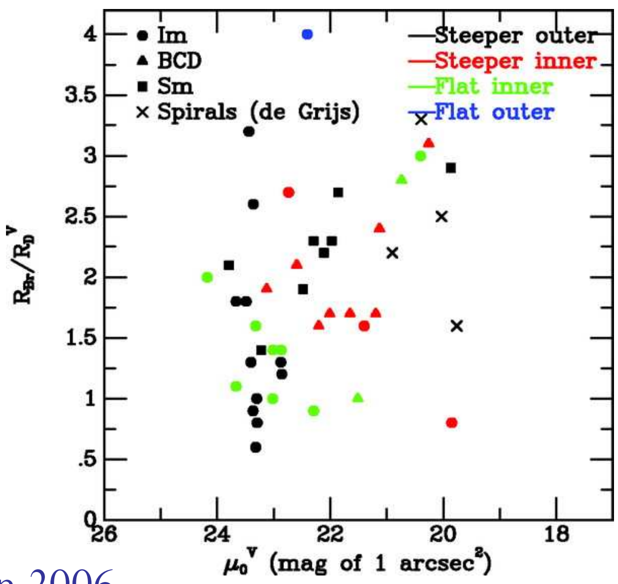
The Threshold:

- Smooth, not sharp (Hα edge sharper than V-band)
- Three main SF processes all have a Q threshold
  - gravitational instability, shell collapse, turbulence
- No normal thresholds with B or viscosity
  - shear limits time for gas condensations
- Islands of high Σ unstable when average Σ is stable
- Threshold also from cool/warm phase transition

Smooth, not Sharp

- There is rarely a sharp outer cutoff in galaxy disks
  - second exponential or slow taper is more common (Naslund & Jorsater 1997; de Grijs, Kregel, & Wesson 2001; Pohlen et al. 2002; Hunter et al. 2006)
  - $R_{break}/R_{innerdisk}$ ~4 for spirals, ~2 for dwarfs

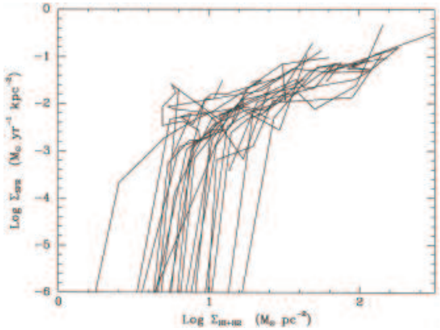




Hunter & Elmegreen 2006

Expect Hα edge sharper than V or uv

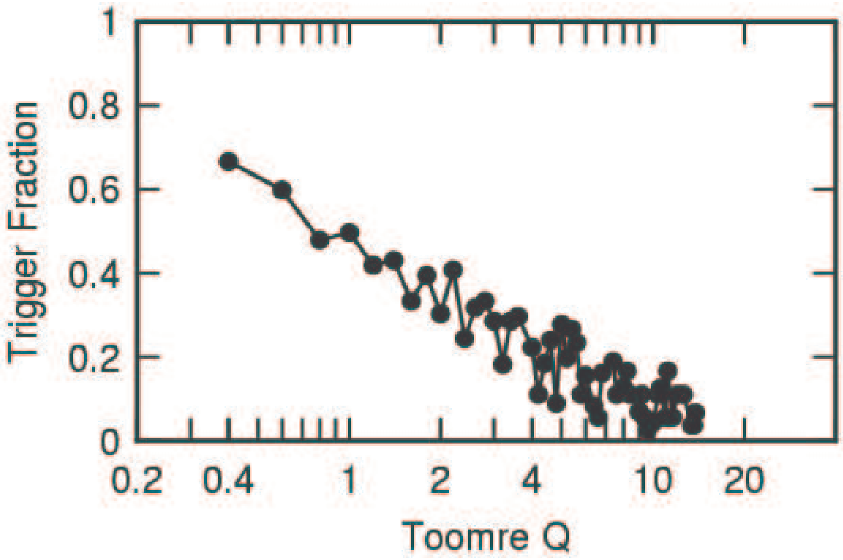
- Hα emission measure for a fixed Lyman continuum luminosity varies as $n^{4/3}$
  - For constant scale height, EM is 200 times fainter at 4 scale lengths than in inner disk ($=e^{-16/3}$)
- If the disk flares, the EM drops even faster:
  - for a self-grav disk at constant vel. disp., $n \sim \Sigma^2$ and EM drops by a factor of 4×10^4 in 4 scale lengths ($=e^{-32/3}$)
- Galaxy edges look sharper in Hα than they are in total SFR
  - e.g., Thilker et al. 2005 GALAX observations



Q threshold for Sequential Triggering

- Shells expand and go unstable when accumulated gas is cold and massive enough, & induced rotation (κ) is small enough

  $Q = \kappa c / \pi G \Sigma$ <u>important</u>



Elmegreen, Palous & Ehlerova 02

Also,

$$t_{frag} \sim \left(\frac{c_{sh}/[GL]^{0.2}}{2\pi G\rho} \right)^{0.5} \quad \sim 0.3\ t_{dynamical}$$

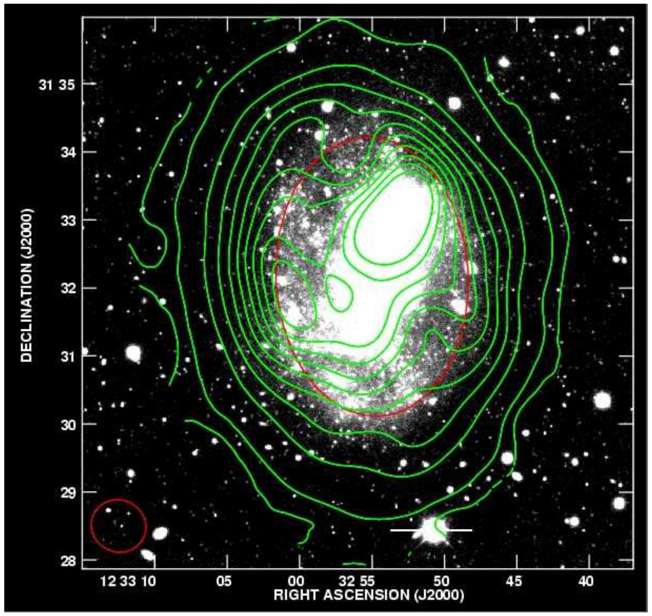
(Numerator~0.1 for c_{sh}~1 km/s and $L=10^4\ L_{O)}$

Q Threshold for Turbulence Triggering

- Isothermal compression has to include the ambient M_{Jeans} to trigger instabilities
- Turbulent outer scale comparable to L_{Jeans}, which is ~scale height
- But if compress distance > epicyclic length, Coriolis forces spin up compression, leading to centrifugal force resistance.
- so need $L_{Jeans} < R_{epicycle}$, which means $Q<1$
  - $L_{Jeans} \sim H \sim a^2/\pi G\Sigma$, $R_{epic} \sim a/\kappa$, so $L_{Jeans}/R_{epi} = Q$

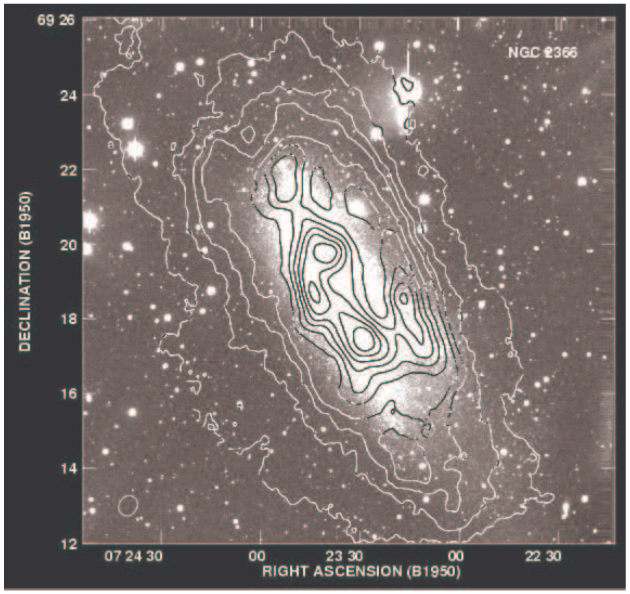
GI with B or viscosity

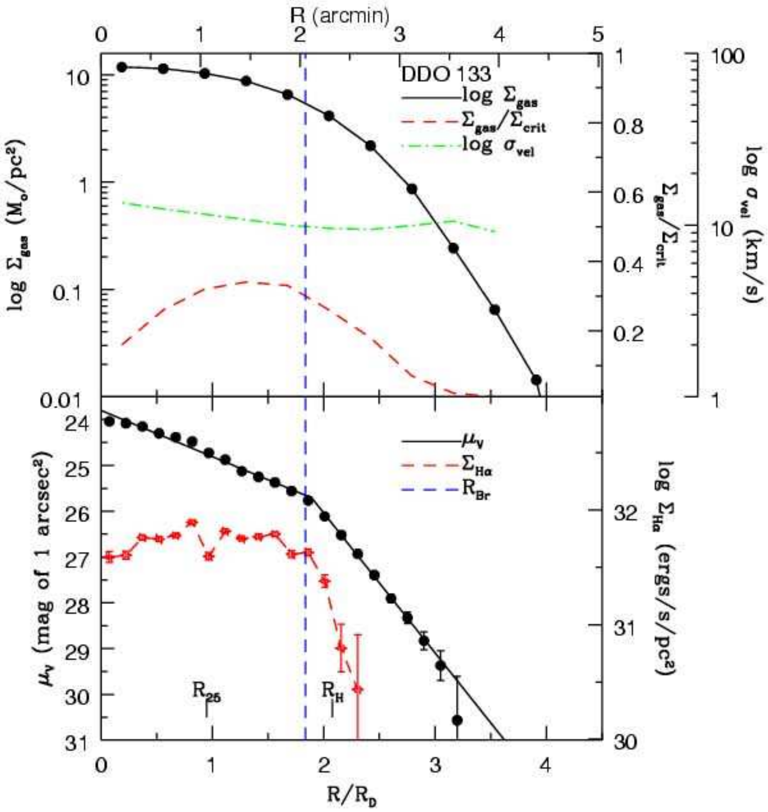
- Q: centrifugal force (from Coriolis spin-up) balances self-gravitational force over a Jeans length.
- If angular momentum is not conserved then the disk can be always unstable
  - B and viscosity strip angular momentum, removing threshold
  - Magneto-Jeans instability can dominate in low-shear environments like spiral arms and some inner disks
    - Elmegreen 87, 91,94; Kim & Ostriker 01.02

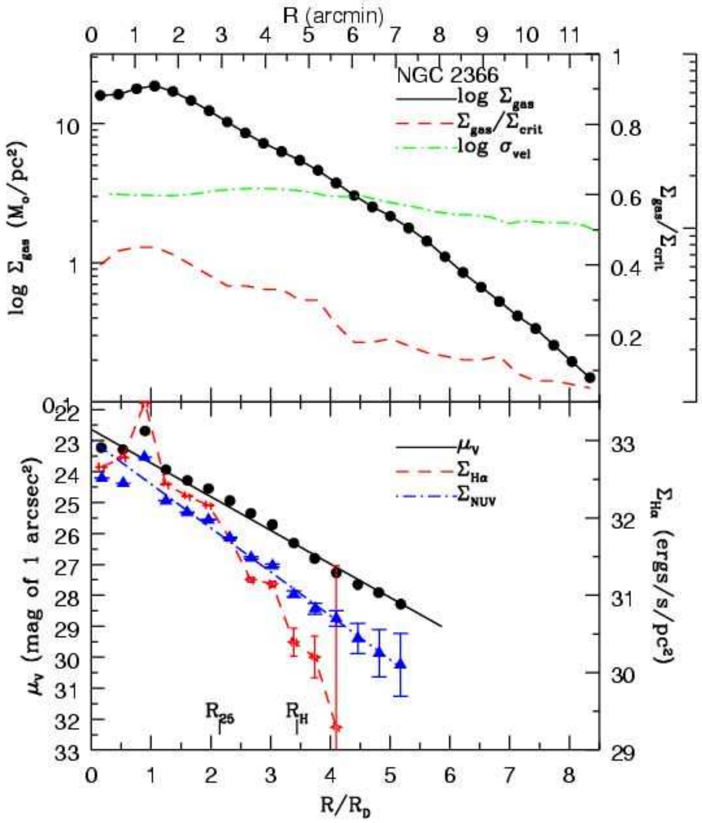


Hunter et al 06

- -double exponentials
- -very stable outer disks
- -sudden drop in Hα
- -SF in “islands”





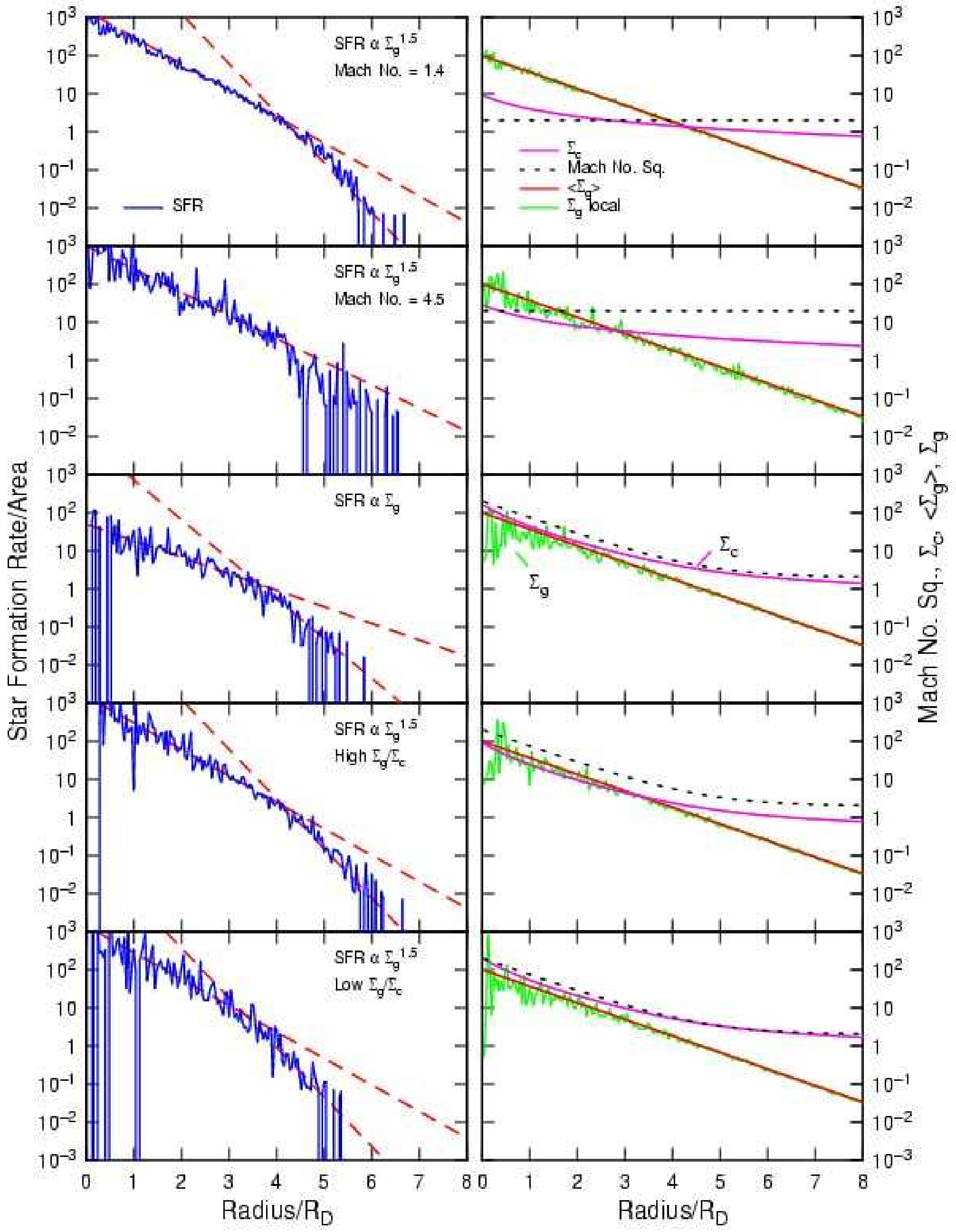


Inner/Outer disk transition:

1. exponential gas disk
2. turbulent Mach, M(R)
3. Σ distribution log-normal
4. SF locally where Σ>Σc
5. rising and then flat RC
6. SFR ~ Σ^1 or $\Sigma^{1.5}$

SF saturated in the inner disk

Continues in the Σ peaks in the outer disk because of turbulence (M~1) even though average Σ<Σc . Outer profile is steeper exp.



Elmegreen & Hunter 06

Threshold from a warm/cool phase transition: outer disks, dwarfs, LSB gal

- SF needs a cool phase; a cool phase needs moderate P
  - Elmegreen & Parravano 94; Gerritsen & Icke 97; Hunter et al. 98, 01; Billett et al. 02; Wolfire et al. 03
  - Observe outer disk high warm fraction (Braun 97) and high warm fraction in dw Irr (Young & Lo 96,97; de Blok & Walter 06)
  - P high (cool gas possible) in self-gravitating “island” clouds, spirals, cloud collision shocks, turbulence-compressed regions, …
- Schaye 04: modeled the SF threshold, considering where the cold phase becomes important.

The Power Law

- Three models: GI, shocks, pdf tail, are all similar
- SF is from a combination of processes (sequential triggering, GI, turbulence compression, SDW compression, …) so the power law is probably from a combination of processes too.
  - there is no single "theory of the K-S law"

Summary

- Significant variations from galaxy to galaxy, within a galaxy, and from observer to observer in the form of the SFR-Σ law
- There is a threshold for SF
  - from disk gravity, cooling limitations, shear, …
- The power law has several explanations, most related to a ~sqrt dependence of dynamical rate on column density, or a sqrt dependence of the relevant column density (molecular, shocked, pdf tail, etc) on the total density for a fixed rate inside that relevant column density.