THE FINAL TALK

SFR @ 50

FUTURE CHALLENGES

CHRIS MCKEE

IN HONOR OF MAARTEN SCHMIDT

A radio astronomer who turned optical, as we learned last Sunday

Who established one of the pillars of star formation studies

And who then deserted the field because of some discovery he made!

WELCOME BACK, MAARTEN!

QUESTIONS ON THE STAR FORMATION RATE

1. How does the star formation rate depend on scale?

   Scale matters---Kennicutt on Monday

2. Does the star formation law evolve with redshift?

3. Does the star formation rate depend on the IMF?

4. How can theories be tested by observations?

I. HOW DOES THE STAR FORMATION RATE DEPEND ON SCALE?

The star formation rate per unit area is (Krumholz & McKee 2005)

$$d\Sigma_*/dt \equiv \varepsilon_{ff}\, f_{mol}\, \Sigma_g / t_{ff}$$

where

ε_{ff} = SFR_{ff} (in the KM05 notation) is the star formation rate per free-fall time in the molecular gas out of which stars form (Bigiel; Bolatto)

It is the fraction of the molecular mass converted into stars in one free-fall time---ie, it is a star formation efficiency.

$f_{mol}\, \Sigma_g$ is the surface density of molecular gas (in GMCs)

This is an identity that clarifies the three quantities that determine the SFR:

- the efficiency, ε_{ff}
- the surface density of molecular gas = $f_{mol}\, \Sigma_g$
- the density, $\propto t_{ff}^{-2}$

How does ε_{ff} depend on scale?

RELATION BETWEEN THE STAR FORMATION RATE PER FREE-FALL TIME, $\varepsilon_{ff} = SFR_{ff}$, AND THE GAS DEPLETION TIME

Define the depletion time as the time to convert the molecular gas into stars:

$$t_{dep} \equiv M_{mol} / (dM_*/dt) \qquad \text{(global)}$$

$$\equiv \Sigma_{mol} / (d\Sigma_*/dt) \qquad \text{(local)}$$

Then $\quad d\Sigma_*/dt \equiv \varepsilon_{ff}\ \Sigma_{mol} / t_{ff} \quad \Rightarrow \quad \varepsilon_{ff} = t_{ff} / t_{dep}$

The total gas depletion time is $t_{dep,tot} = M_{gas} / (dM_*/dt)$

The physical processes determining the depletion time and therefore ε_{ff} depend on scale

The observed values of Σ_{mol} and Σ_* depend on how they are averaged (Boissier)

PET PEEVE:

The star formation efficiency SFE is NOT the depletion rate $1/t_{dep}$

An efficiency is dimensionless, such as

$$SFE = M_* / (M_* + M_{gas})$$

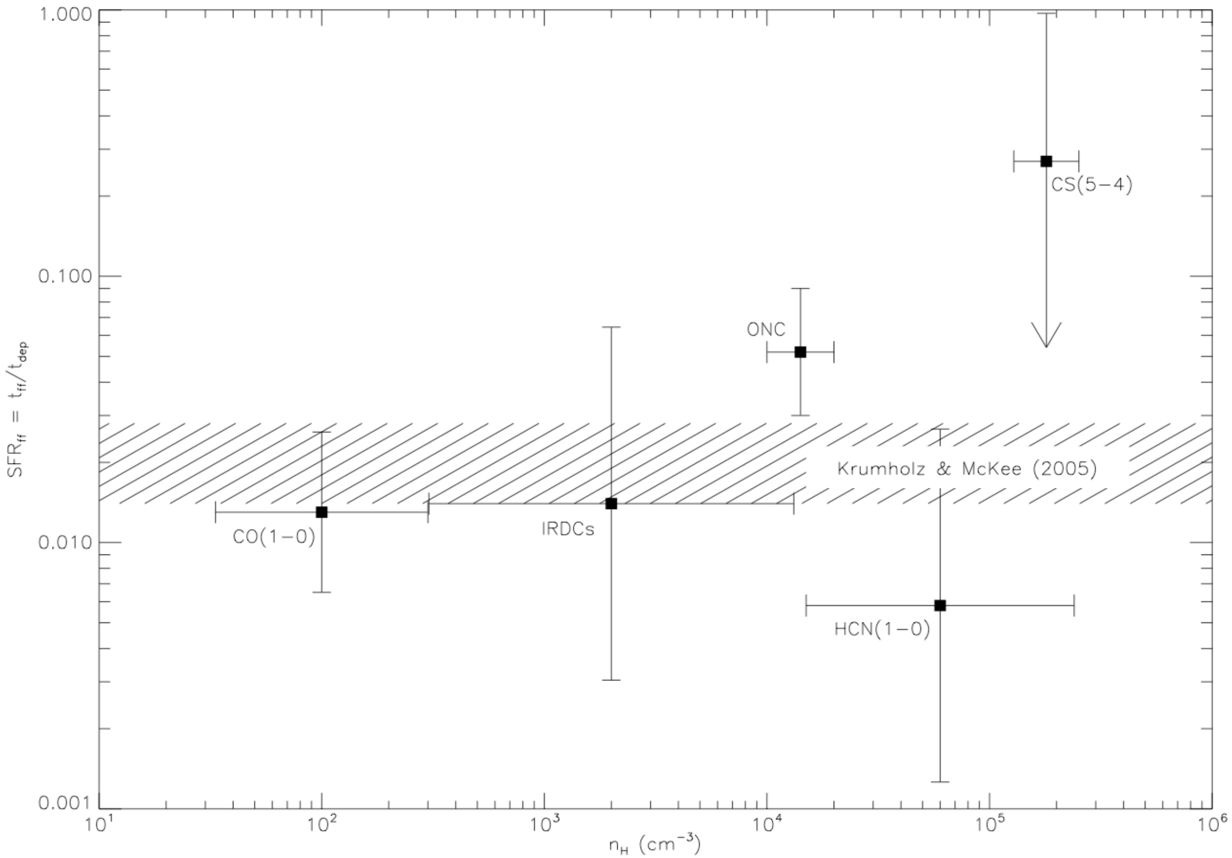
or

$$\varepsilon_{ff} = t_{ff} / t_{dep}$$

Recommend using the depletion time, which is easier to understand

The star formation efficiency ~ 1 - 2%, ~ independent of molecular density

(Krumholz & Tan 2006)



IRDCs = Infrared Dark Clouds, thought to be a very early stage of star cluster formation

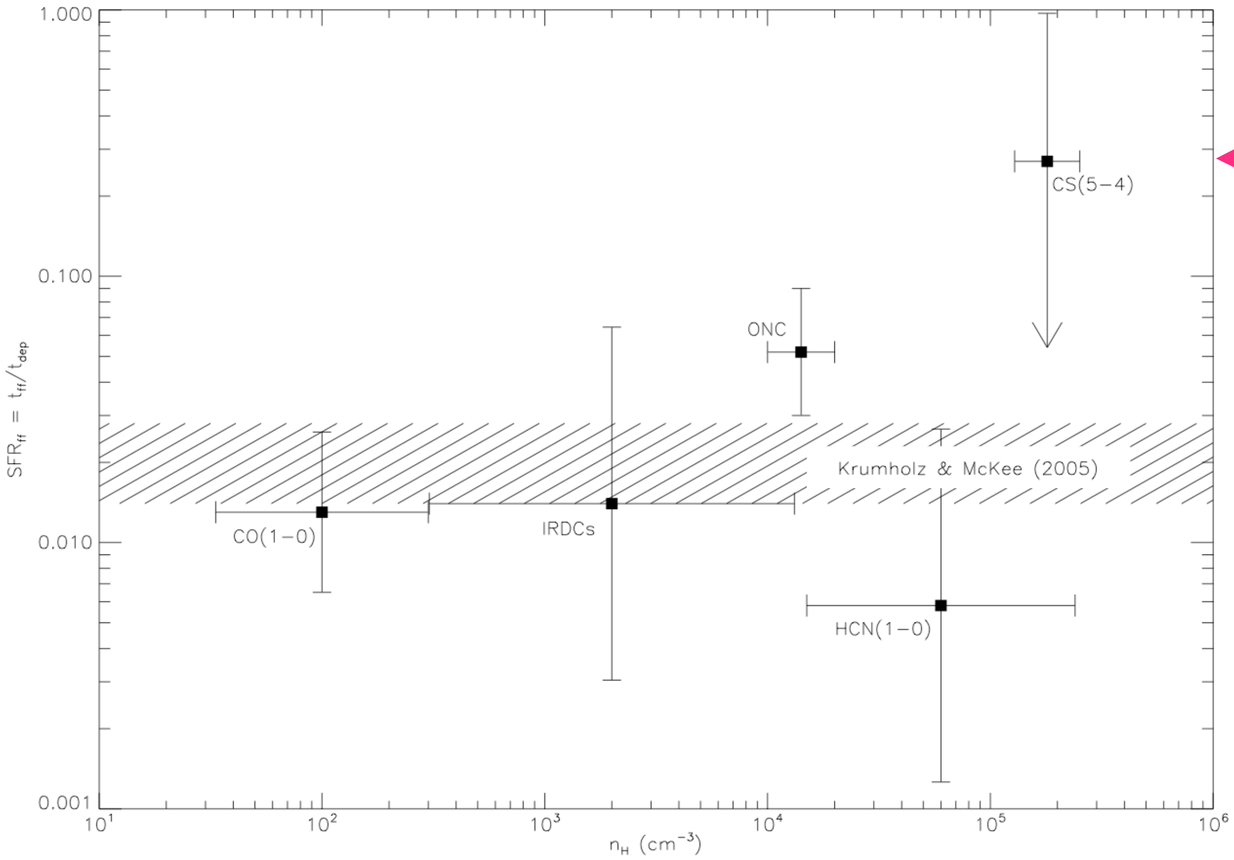
ONC = Orion Nebula Cluster

HCN observations of a wide range of galaxies (Gao & Solomon 2004)

CS observations of high-mass star-forming regions in the Galaxy

Survey incomplete => lower limit on M_{CS} => upper limit on SFR_{ff}

ε_{ff} less than unity for individual star formation



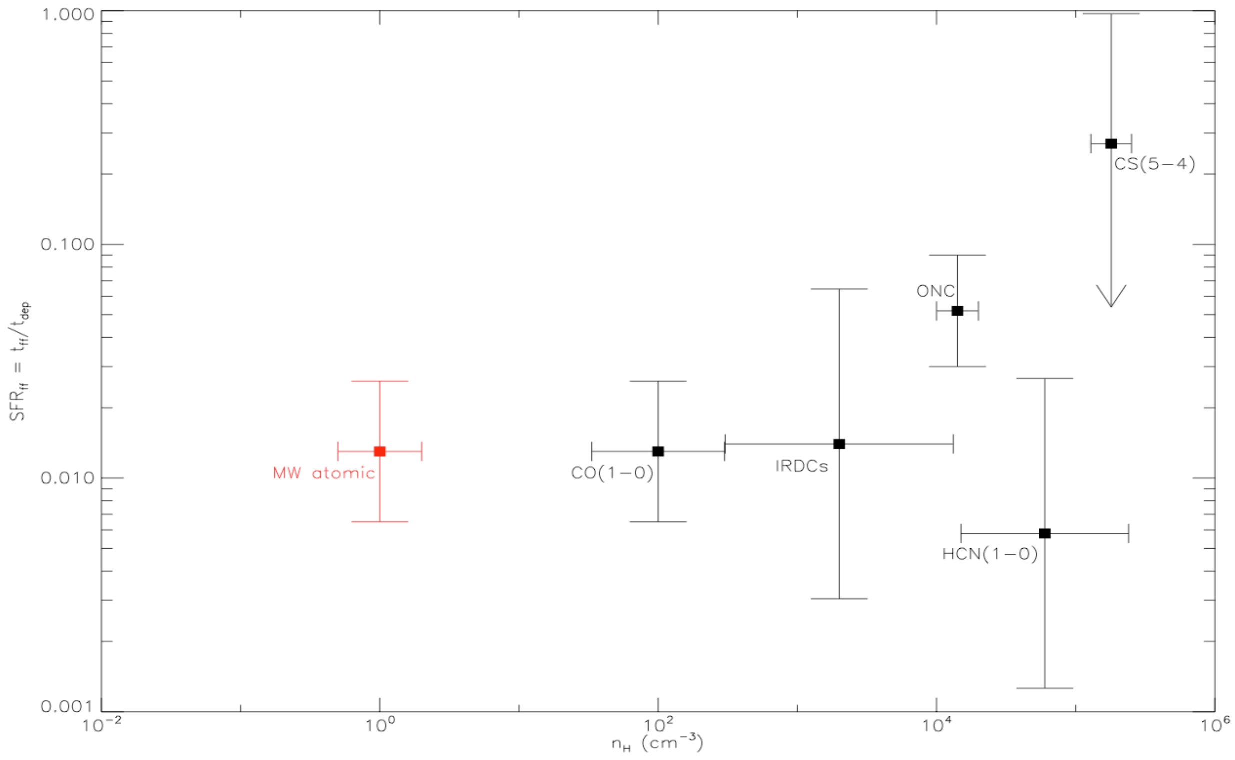
Shu accretion

mdot = c^3/G

Time for collapse of an isothermal sphere is consistent with observed formation time for low-mass stars

Corresponds to several free-fall times: $\varepsilon_{ff} = 0.27$ allowing for moderate B; protostellar outflows reduce this further

Global star formation efficiency in the Galaxy ~ 1%



The Milky Way Galaxy: SFR = $dM_*/dt \sim 1.5\ M_{sun}\ yr^{-1}$

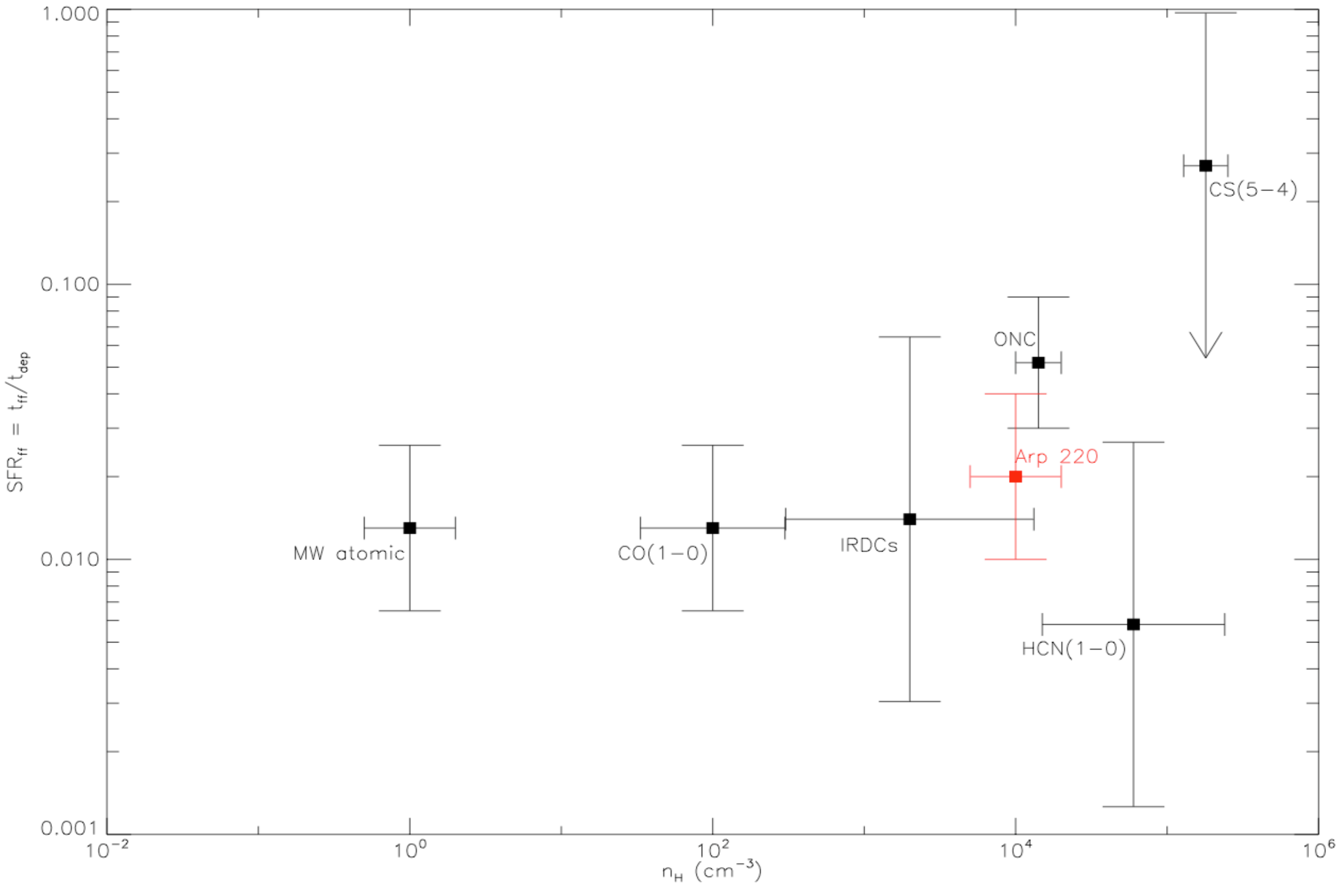
Molecular gas: $M_{mol} \sim 5\times10^8\ M_{sun}$ => $t_{dep} \sim 3 \times 10^8$ yr

GMCs: $n \sim 10^2\ cm^{-3}$ => $t_{ff} \sim 4 \times 10^6$ yr => $\varepsilon_{ff} = t_{ff} / t_{dep} \sim 0.01$

Atomic gas: $M_{at} \sim 5\times10^9\ M_{sun}$ => $t_{dep,tot} \sim 3 \times 10^9$ yr

$n \sim 1\ cm^{-3}$ => $t_{ff} \sim 4 \times 10^7$ yr => $\varepsilon_{ff} = t_{ff} / t_{dep,tot} \sim 0.01$

Star formation efficiency in Arp 220 (a starburst) ~ 2 %



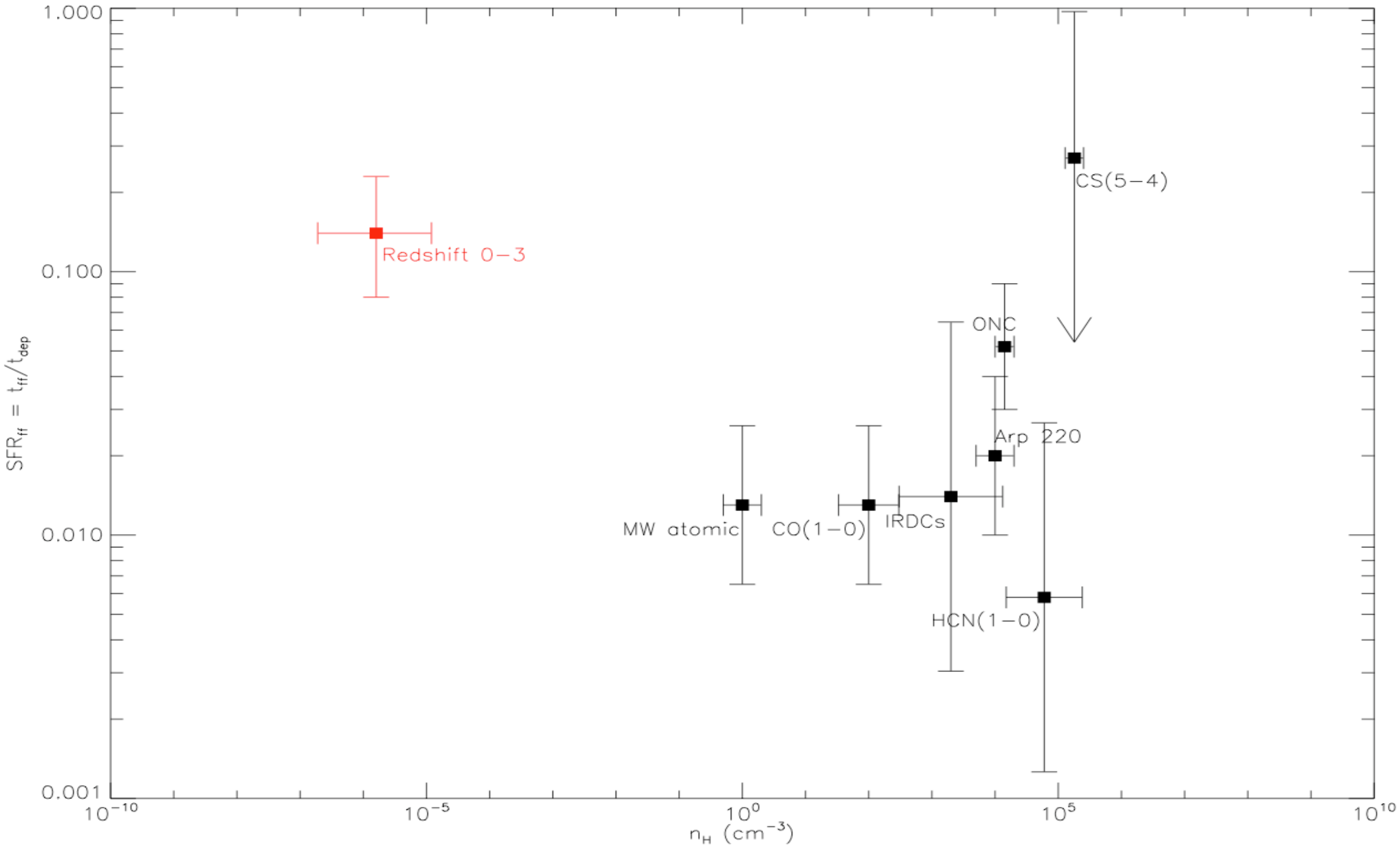
Starburst galaxy Arp 220: $M_{mol} \sim 10^9\ M_{sun}$ and $dM_*/dt \sim 50\ M_{sun}\ yr^{-1}$

$$\Rightarrow t_{dep} \sim 2 \times 10^7\ yr$$

The mean density of molecular gas is $n \sim 10^4\ cm^{-3} \Rightarrow t_{ff} \sim 4 \times 10^5\ yr$

Hence $\varepsilon_{ff} = t_{ff} / t_{dep} \sim 0.02$

Star formation efficiency in the universe is high: $\varepsilon_{ff} \sim$ 0.1 - 0.2



Star formation rate in the universe: 0.02 ($z \sim 0$) - 0.1 ($z \sim 1$-3) M_{sun}/yr Mpc^3

Pascale et al 09 (BLAST)

Free-fall time: $t_{ff} = 4.2 \times 10^{10} / (1+z)^{3/2}$ yr (including dark matter)

=> $\varepsilon_{ff} = 0.08$ (z=3), 0.13 (z=0), 0.23 (z=1)

FOUR SCALES OF STAR FORMATION

1. The universe

   -Cosmological physics (Blitz, Bouche, Prochaska)

2. Formation of individual galaxies

   -Hydrodynamics in the cosmic web of dark matter (Dekel, Kravtsov)

3. Interstellar medium of individual galaxies

   -Thermal state of atomic gas ---WNM v. CNM (Elmegreen & Parravano; Schaye)

   -Dynamics: large scale gravitational instabilities

   -Conditions for CNM to become molecular

4. Molecular medium of individual galaxies

   -Star formation in H_2, not just CO (Bolatto); why?

   -Evolution of gas to high densities and gravitational collapse

   -Hierarchical star formation: Formation of clusters from clumps in GMCs

THE CHALLENGE:

Understand the physical processes governing the rate at which baryons are incorporated into stars on all scales.

Bathtub/ swimming pool model (Bouche, Prochaska) :

In gravitational contraction, gas accumulates until there is enough to drive a process that will allow it to go to the next density

Example: in cold flow model, gas accumulates in galaxy until SFR = accretion rate - gas ejected by stellar feedback

Similar process occurs in ISM to drive gas molecular

Stellar feedback critical (Nesvadba):

-Can recycle molecular gas back to atomic

-Governs the properties of the ISM (radiative heating, photoionization, kinetic heating, momentum and kinetic energy injection, cosmic ray acceleration)

The monster in the tub/pool: responsible for the low baryon fraction in galaxies (Schaye)

II. DOES THE STAR FORMATION RATE LAW EVOLVE WITH REDSHIFT?

* Not much evolution in massive galaxies for z<3: $d\Sigma_*/dt \propto \Sigma_g^{1.4}$ (Tacconi)

* KS law steeper for typical galaxies and DLAs at high redshift (Kravtsov)

  -Consistent with local SF law of KMT09

* However, star formation often occurs in large, highly turbulent clumps,

  similar to SF in some dwarf galaxies today (D. & B. Elmegreen; Dekel)

  -Does this affect the star formation efficiency ε_{ff} ?

THE CHALLENGE :

Extend observations and theory to higher redshifts and lower metallicities

Can stars form in atomic gas? (Zinnecker)

Theoretically, yes: Primordial Population III.1 stars (those that form in the absence of feedback from previous stars) form in dark matter halos with H_2 fractions ~ 10^{-3}

(Abel + 02, Bromm + 02)

Difficult in contemporary, low Z gas:

Bolatto finds that stars form efficiently in the SMC (Z=0.2) in H_2, but not in H I

Since star formation must proceed through molecular gas, it is apparently easy to form CO in density fluctuations in H_2, but not to form both H_2 and CO in density fluctuations in H I

(Krumholz +, in prep)

Further work needed in lower Z gas (cf Jappsen et al)

3. DOES THE STAR FORMATION RATE DEPEND ON THE IMF?

Two pillars of star formation studies:

The star formation rate

The IMF

CHALLENGE: How do they interact?

Physically: IMF at high masses determines feedback, which can affect the SFR

E.g., radiation pressure feedback (Murray et al)

Observationally: Tracers sensitive only to high mass stars, must infer low-mass ones

Characteristic stellar mass: Jeans mass $\propto (T^3 / \rho)^{1/2}$

Somehow this is about constant over a wide range of conditions (Elmegreen + 08)

Change in slope of IMF can have dramatic effect, but most observations consistent with Salpeter slope

Observational effects of IMF on inferred SFR -- continued

Change in high-mass part of IMF: suppression of highest mass stars =>

Hα and FIR could underestimate SFR relative to FUV

Turbulent core model for high-mass star formation (M&Tan 02, 03):

Massive stars form from turbulent cores of mass ~ M_J(turb) >> M_J(thermal)

But such cores should fragment into many small cores (Dobbs + 05)

Thermal feedback from the initial stars suppresses fragmentation (Krumholz; Krumholz +)

Thermal feedback effective only at high surface densities, $\Sigma > 1$ g cm^{-2} (KM08)

Hence, *IF* stars formed in regions of lower surface density, then there would be a deficit of very high mass stars and Hα would underestimate the SFR

Recent Hα observations in outer disks suggest that this is not the case in most galaxies (Kennicutt +) => high Σ regions occur even in outer disks

Are low Hα/FUV ratios in dwarf galaxies due to SF history? (Calzetti)

Currently little understanding of the surface density distribution in SF regions: connection between the *macro*physics and *micro*physics of star formation

IV. HOW CAN THEORIES BE TESTED BY OBSERVATION?

Half the theories of the SFR give the right answer (Tan), most likely because the SFR is determined by simple principles (Schaye)

[Note: getting the coefficient in the KS law is not simple, and KM05 was the first to do that]

All theories of the IMF give the right answer because they are based on scale-free processes and statistics (Klessen)

Challenge:

Test SFR theories under extreme conditions: in dwarf galaxies, outer disks of galaxies, spatially resolved starbursts, high-redshift galaxies

More sophisticated tests: Star formation history, evolution of metallicity, in conjunction with models of gas supply (Kravtsov)

THANK YOU!

-TO MAARTEN FOR INSPIRING THE CONFERENCE

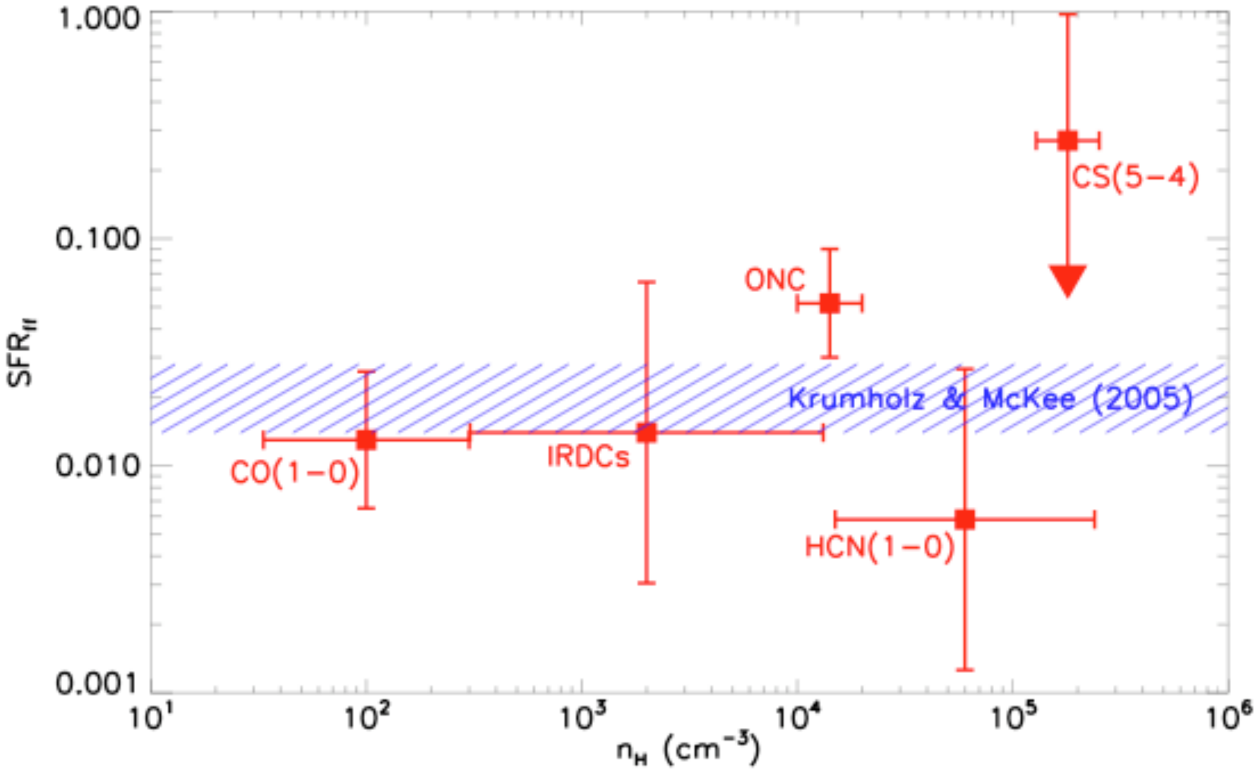
-TO EDVIGE, FRANCESCO & FILIPPO FOR ARRANGING IT

-AND TO THE ABBAZIA DI SPINETO FOR HOSTING IT

MAY WE MEET HERE AGAIN SOON!

The star formation efficiency is approximately independent of density

(Krumholz & Tan 2006)



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