Star formation and GMCs

- properties of H_2 and GMCs
  - internal structure and intuition
  - GMCs ⇔ Gal. environment
  - lifetimes ?
- measuring SF
  - correlation of SF with GMC properties : mass & density

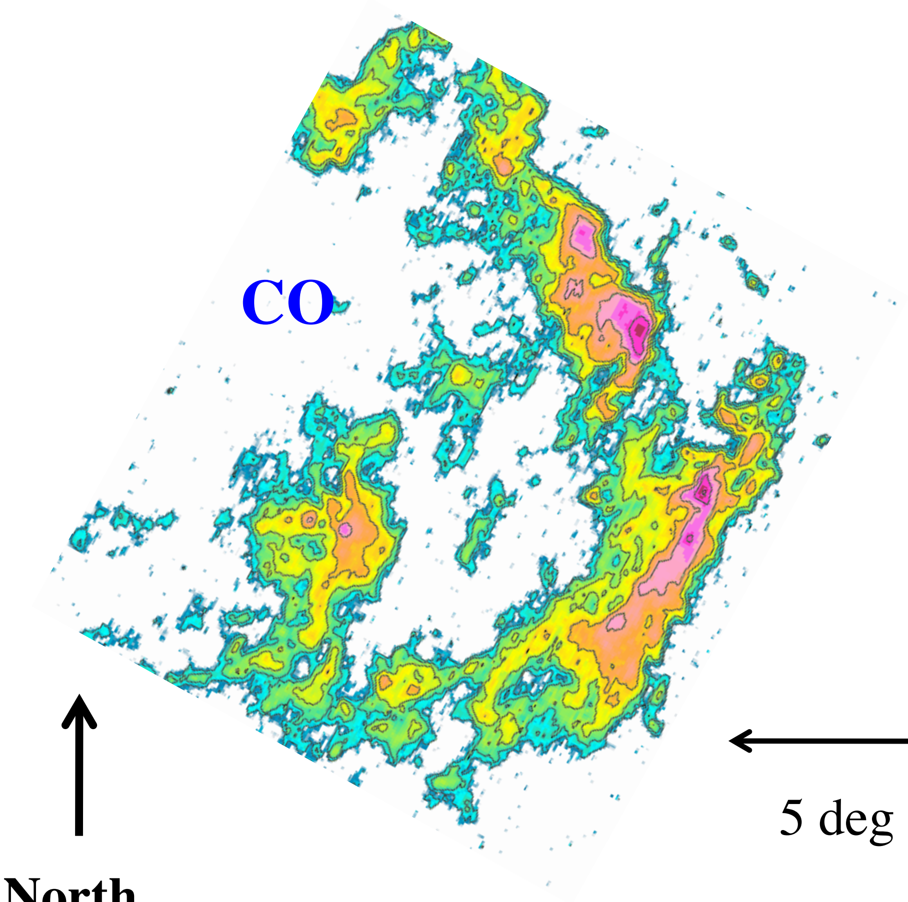
cloud densities and masses :

- virial
- extinction
- molecular column densities and excitation densities
- long wavelength RJ dust emission

star formation tracers :

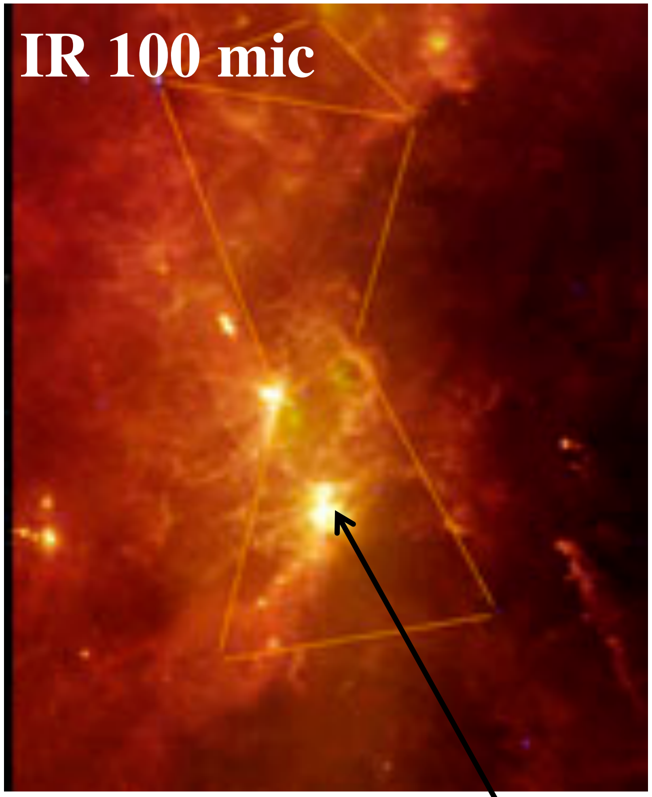
- Hα & emission lines in mid IR
- UV continuum, radio free-free , radio non-thermal
- young star counts
- IR luminosity ➔ dust obscured SF

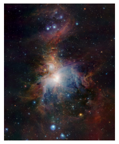
Orion GMCs :
~40 pc extent, 2-4x10^5 $M_\odot$



North

5 deg

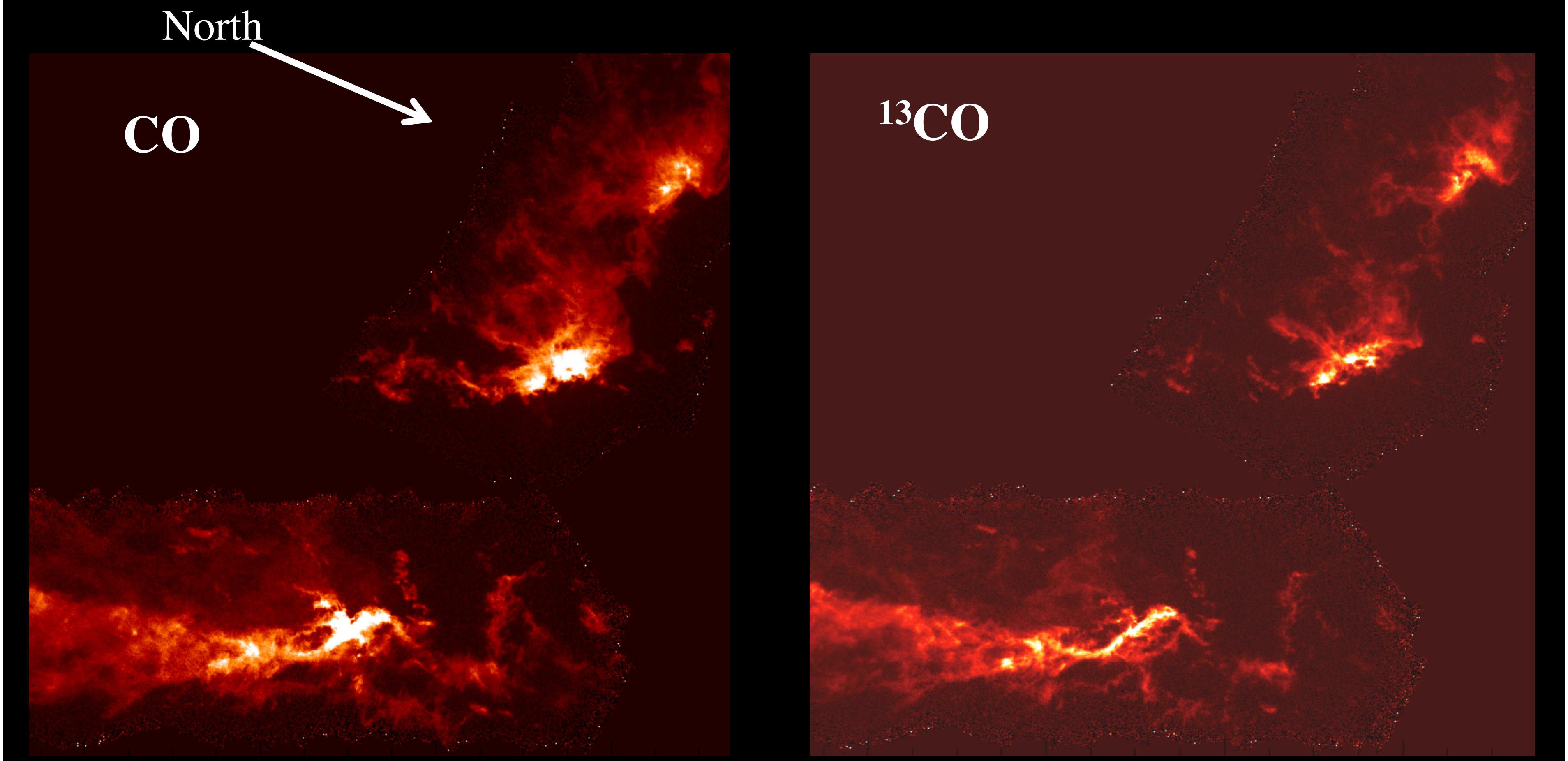




M42 optical nebula
few arcmin.

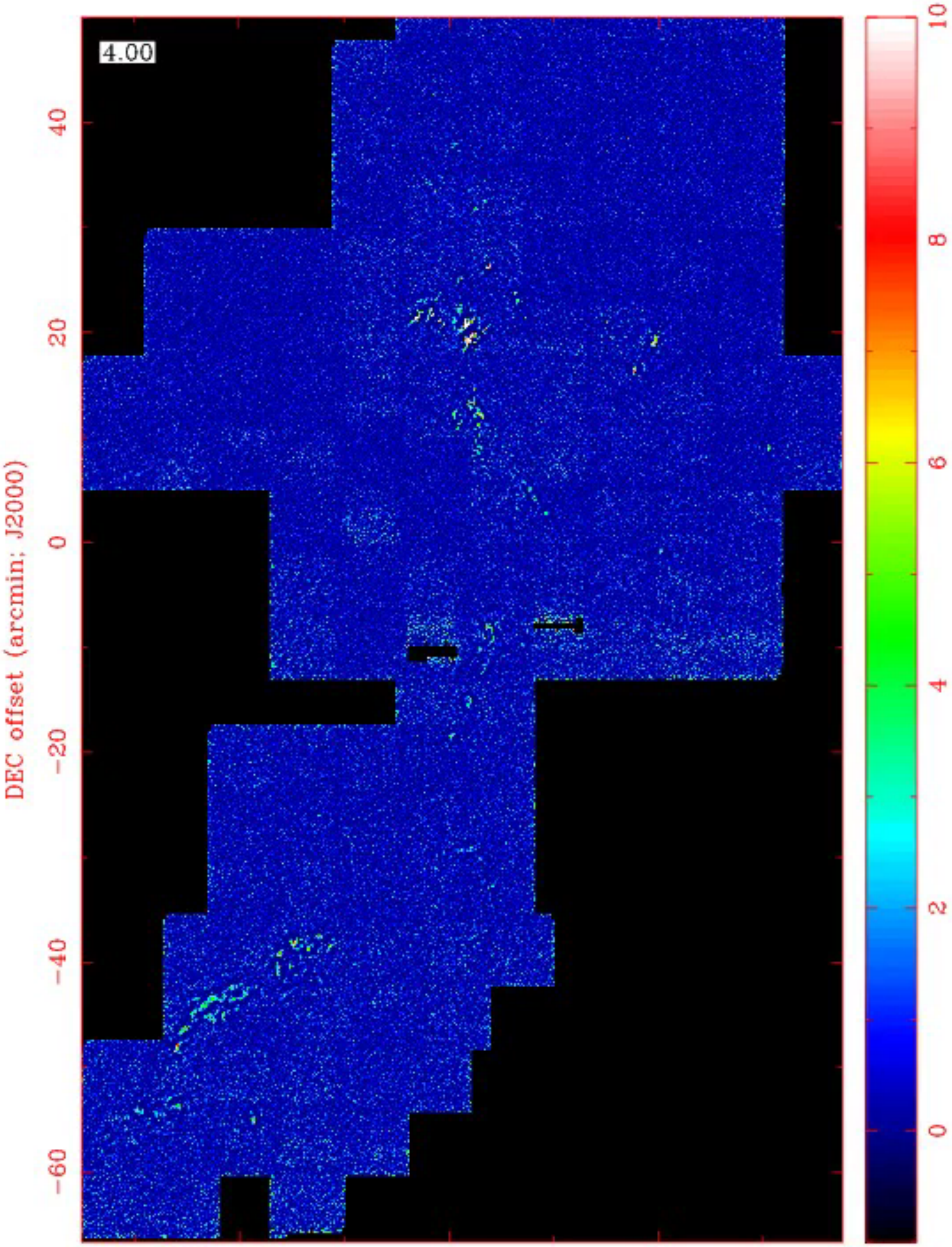
Orion

Ripple, Heyer, Gutermuth,, and Snell 2012



CARMA
^{12}CO Orion

John Carpenter
Chihomi Hara etal



Taurus – closest molecular cloud ~ 150 pc distance

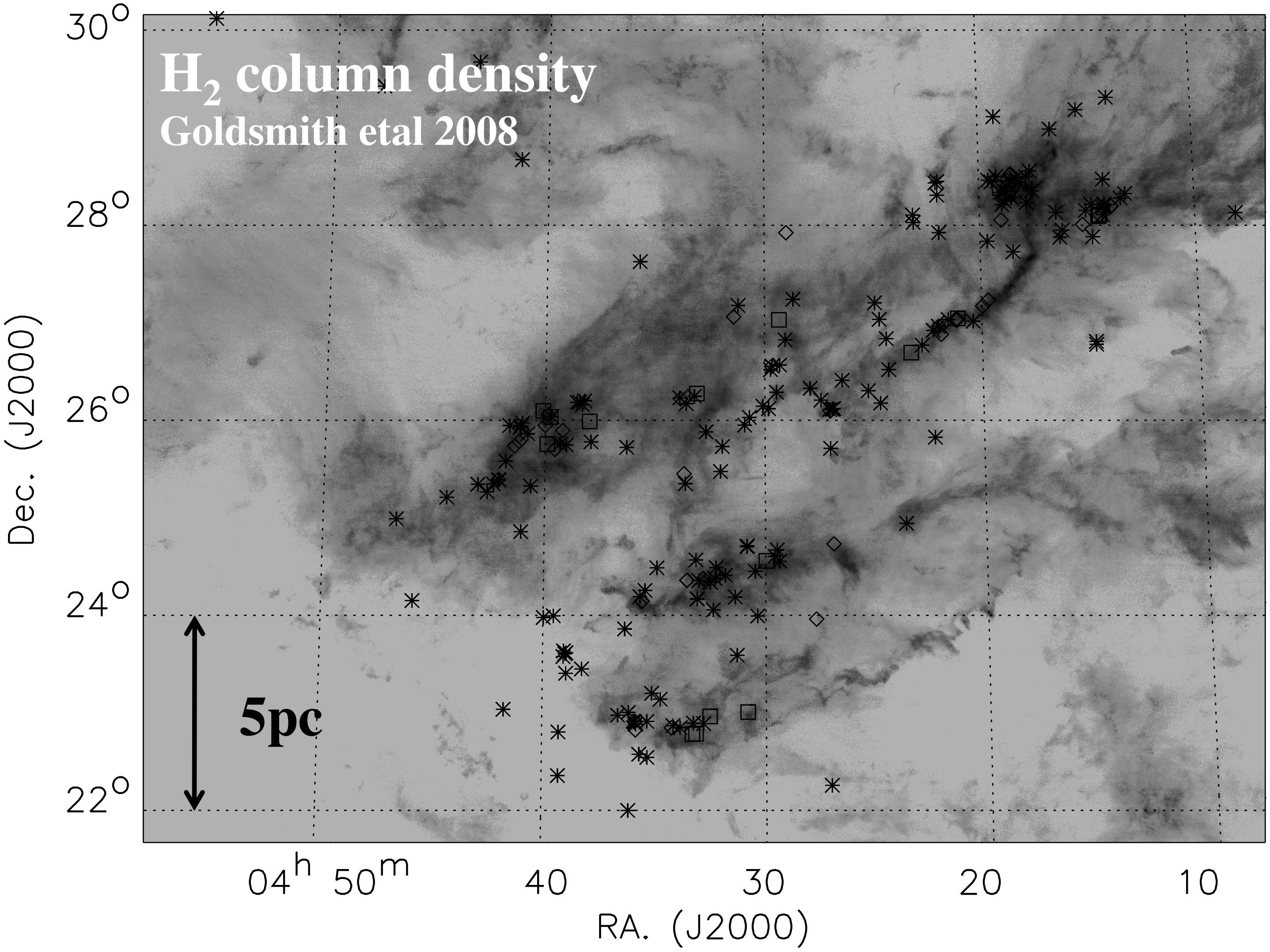
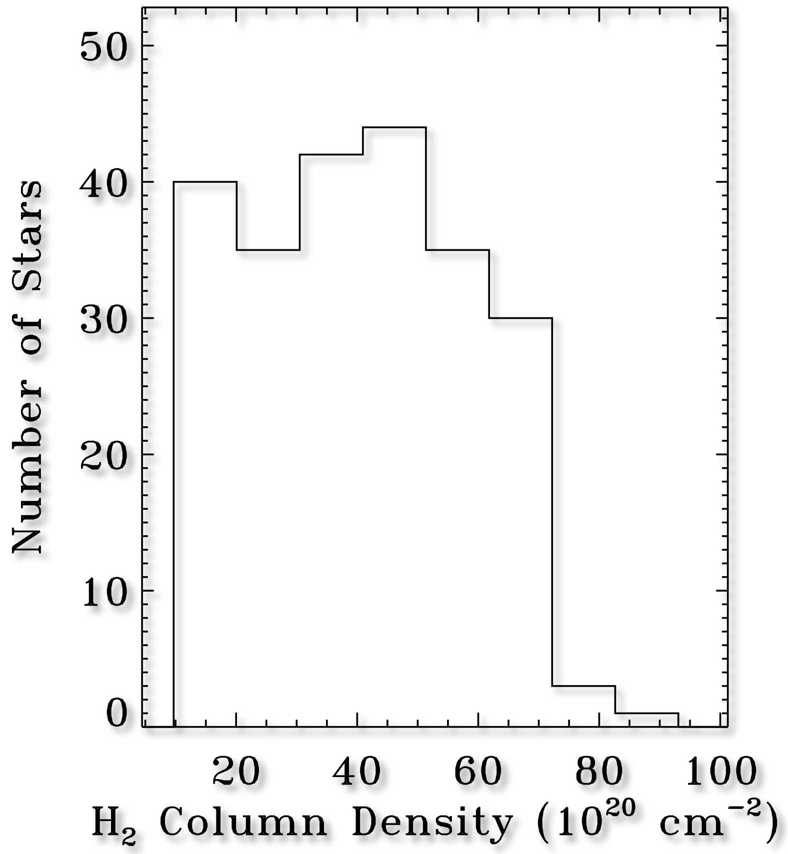
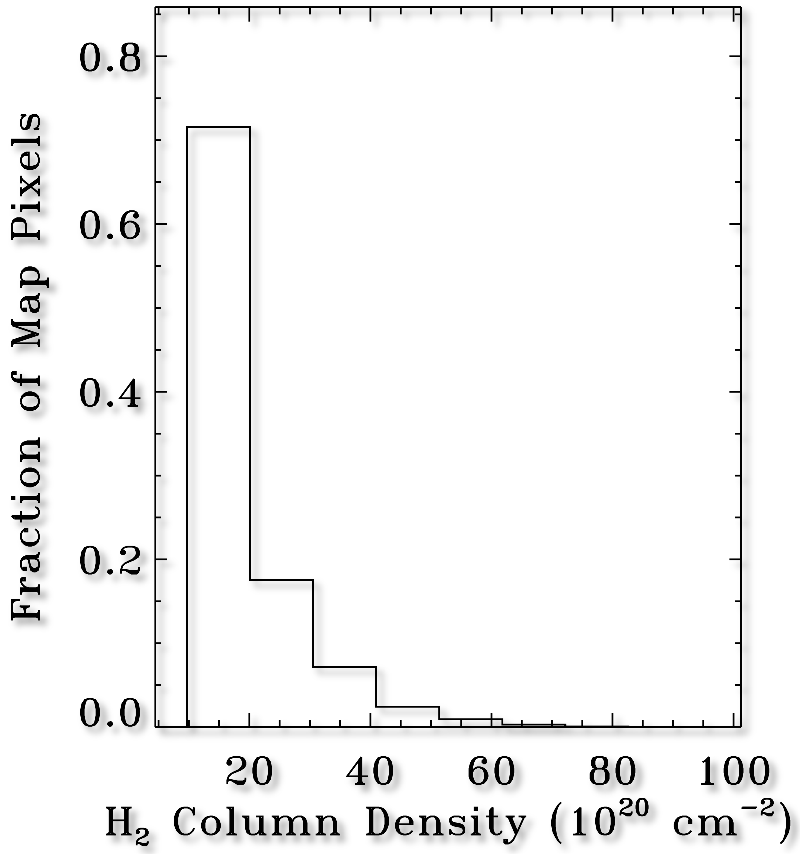


Fig. 14.— Locations of young stars in Taurus superimposed on map of the H_2 column density. The stellar positions are from Kenyon (2007). The diamonds indicate diffuse or

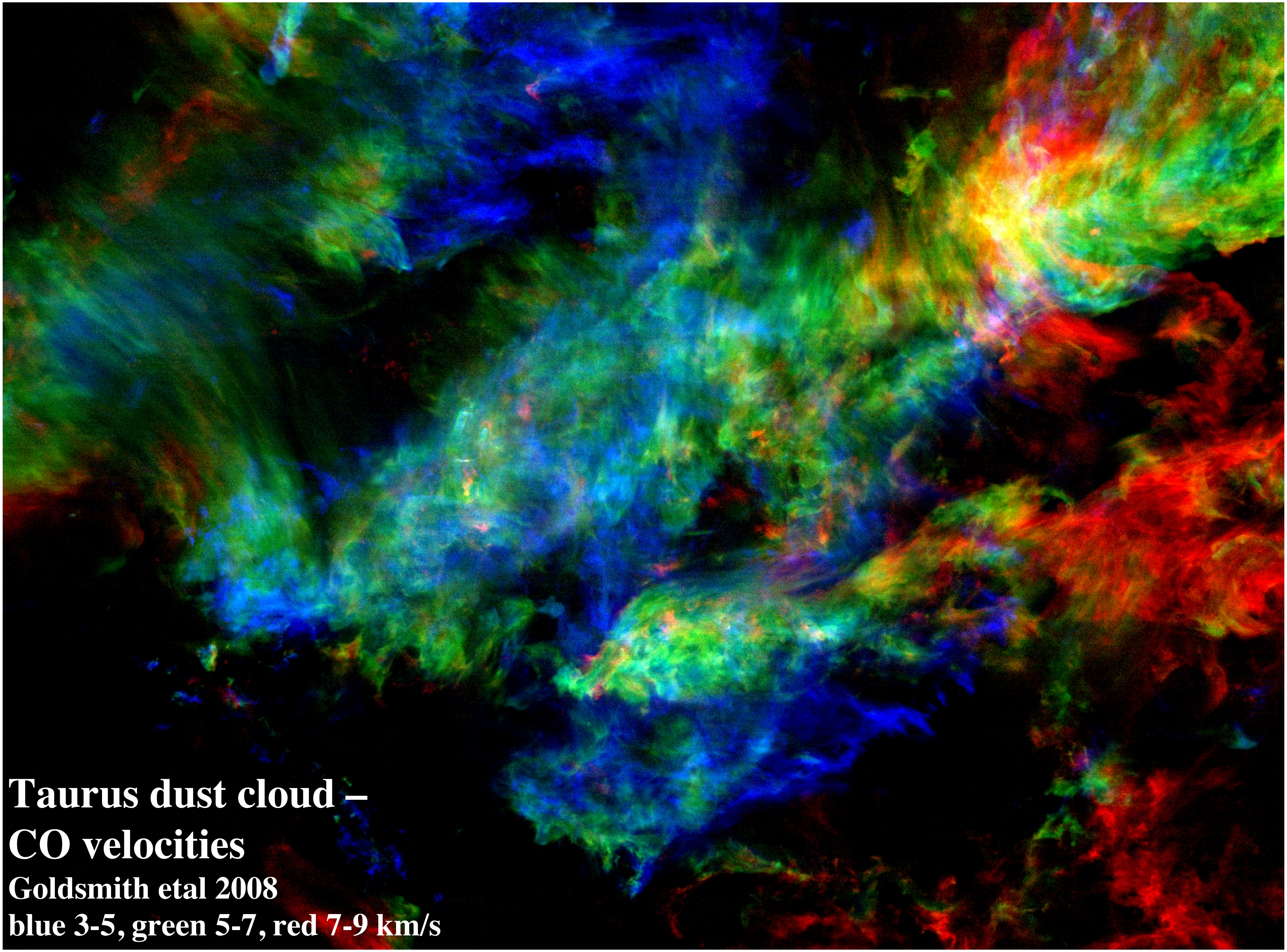
distribution of gas vs young stars





young stars
in highest density regions

typical N_{H2}~10^{21-22} cm^{-2}



Taurus dust cloud – CO velocities

Goldsmith etal 2008

blue 3-5, green 5-7, red 7-9 km/s

Galactic H_2 from CO surveys :

~3000 GMCs (compared w/ ~200 HII region > M42)
total $H_2 \sim 2\mathrm{x}10^9\ M_\odot$

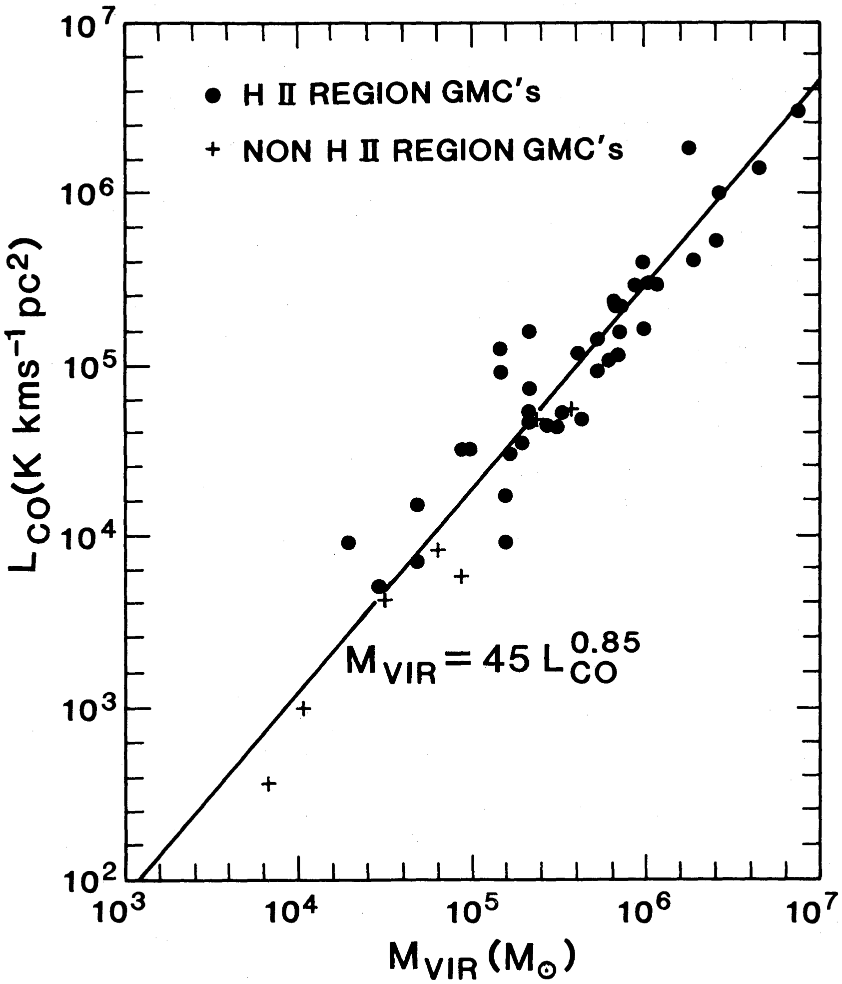
GMCs :
$n(M)\ \alpha\ M^{-1.6}$
$\langle M\rangle \sim 2\mathrm{x}10^5\ M_\odot$ (50% mass above, 50% below)
$\langle D\rangle \sim 40$ pc
$\langle n_{H2}\rangle = 180\ (D/40\mathrm{pc})^{-0.9}\ \mathrm{cm}^{-3}$
➔ $\Sigma_{H2} \sim \mathrm{constant} = 2\mathrm{x}10^{22}\ \mathrm{cm}^{-2}$ ➔ $A_V \sim 20$ mag , $A_K \sim 2$ mag

large CO linewidths ~ 10 x thermal at 10-20 K
self-gravitating , not confined by external pressure

how are these measured ?

estimating H2 masses –

for resolved clouds M_{vir} correlated with L_{CO} (= area $T_{CO}\,\Delta v$)



Scoville & Good '89

How can an optically thick CO line measure mass ??

How can an optically thick CO line measure mass ??

$$L_{CO} = \text{area} \times T_{CO} \Delta V \ \left(\text{K km/s pc}^2\right)$$

$$= \pi R^2 T_k \Delta V \ \text{-- for virial eq. , } \Delta V = \sqrt{GM/R}$$

$$= \left(\frac{3\pi G}{4\rho}\right)^{1/2} T_k M_{GMC}$$

$$\text{i.e. } L_{CO} \propto \left(\frac{T_k}{\rho^{1/2}}\right) M_{GMC}$$

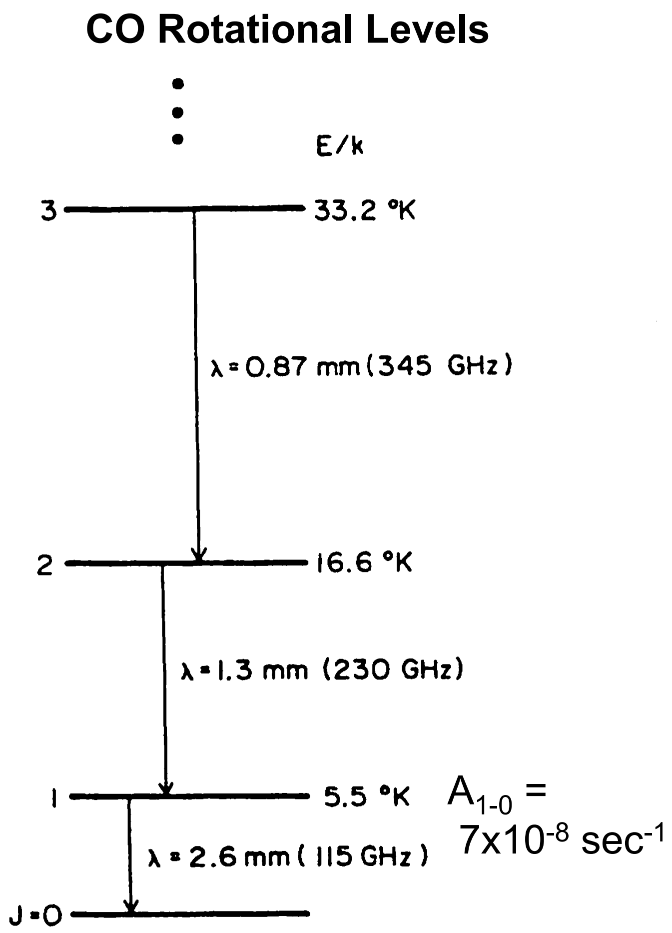
➔ if T & ϱ ~ constant , M_{GMC} = constant x L_{CO}

as you add mass, size and linewidth increase ➔ increases L_{CO}

constant ~ 4 - 5 $M_{\odot}$ / K km/s pc^2

molecular excitation :

collisional excitation by H_2
radiative excitation



collisions :

excitation of J=1 requires ?

1) kT >~ 5K (easy)

2) collision rate similar to A_{1-0}

critical $n_{H2} > A/<\sigma v>$ ➔ T_x ➔ T_k

$n_{H2\ crit} \sim 3000\ cm^{-3}$ for CO ($A=7x10^{-8}\ sec^{-1}$)
$\sim 10^{4-5}$ for HCN, CS ...

radiative transitions ...

line photon trapping for for $\tau > 1$

A ➔ $A\,\beta_{escape} \sim A/\tau$

➔ $n_{H2\ crit} > A\beta/\langle\sigma v\rangle$ ➔ reduced by τ

➔ $n_{H2\ crit}$ indep. of A !!

if $\tau \sim 10$, CO critical density ~ 300 cm^{-3}

➔ CO thermalized even in low density clouds

can show : T_x varies as $(n_m\, n_{H2})^{1/3}$

➔ T_x depends on mol. abundance ! (not A-coef.)

^{13}CO vs CO -- lower intensity since T_x lower, not $\tau < 1$!

T_x varies as (abundance)$^{1/3}$ => varies slowly w/ metal (z) in summary

star forming GMCs :

< diameter > ~ 40 pc , 200-300 H_2 cm^{-3} , <M> ~ $2x10^5$ $M_\odot$

clouds are self-gravitating but not-spherical

high internal P_{turb} >> P_{th} , $P_{diffuse\ ISM}$

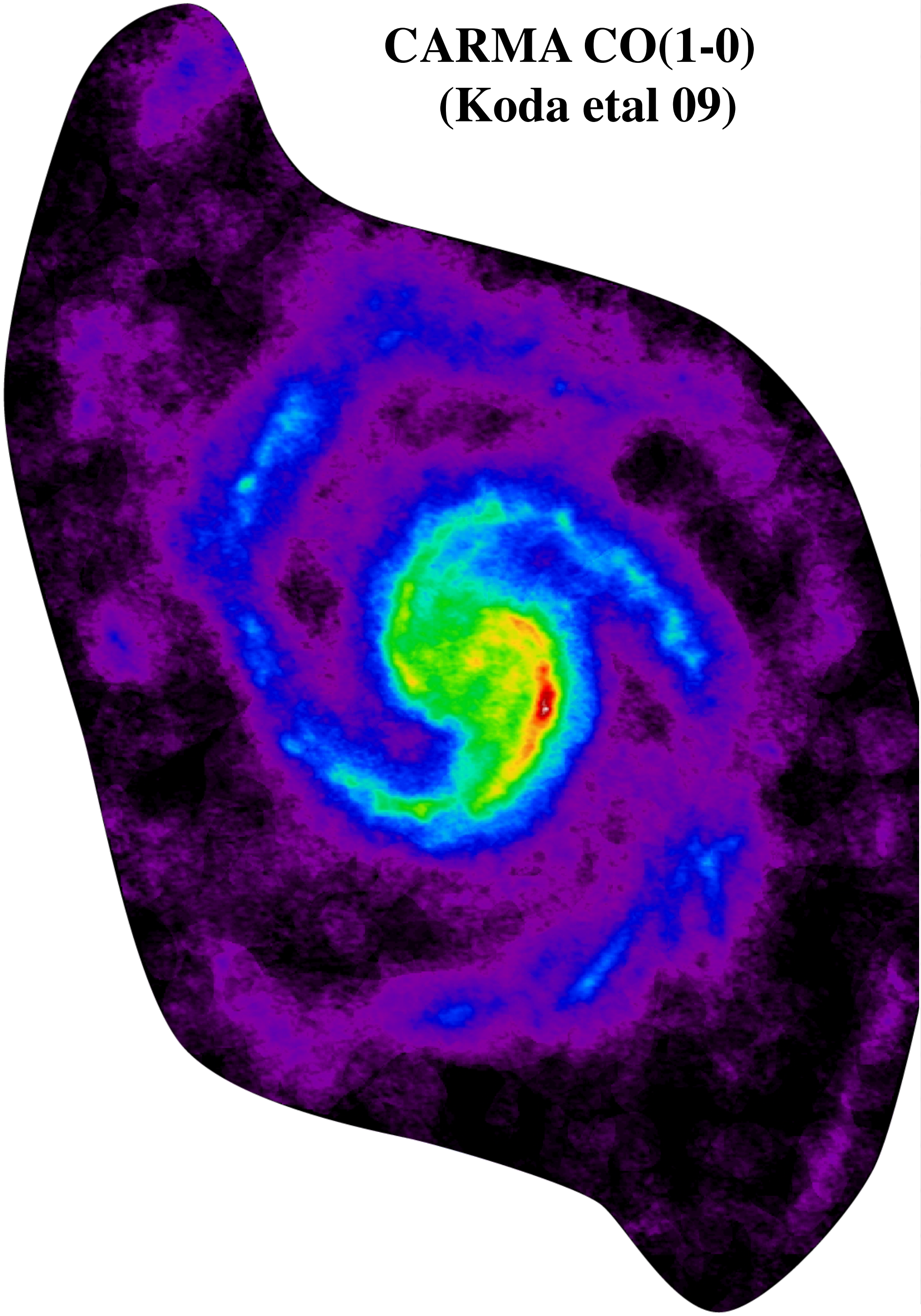
intuition : internal state of GMC not affected by external disturbances in diffuse ISM

once formed , very hard to disrupt GMC

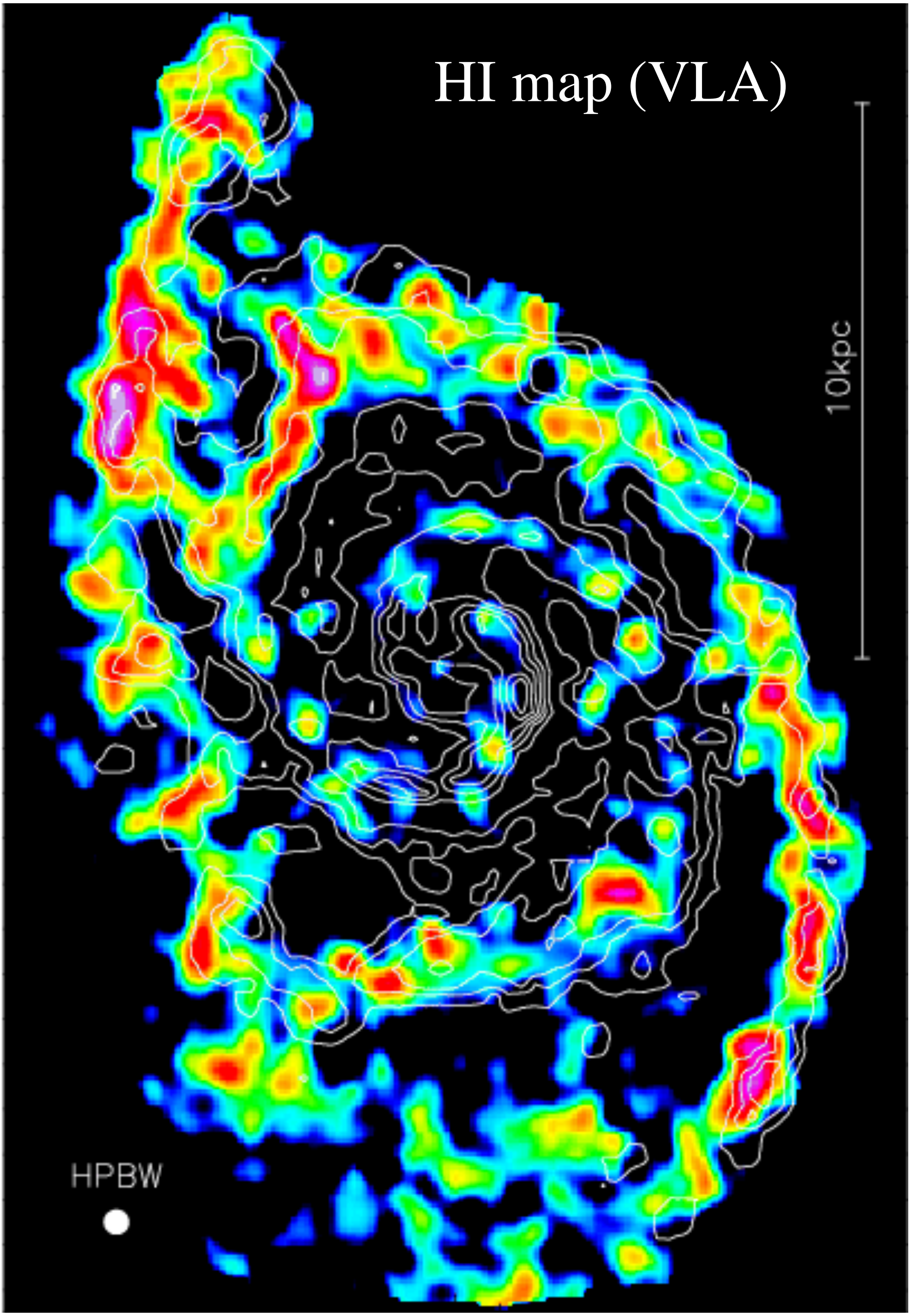
i.e. GMCs have large 'inertia'

internal SF ~ constant

how long do the GMCs last ??



CARMA CO(1-0)
(Koda etal 09)



HI map (VLA)

gas fraction ~80% molecular

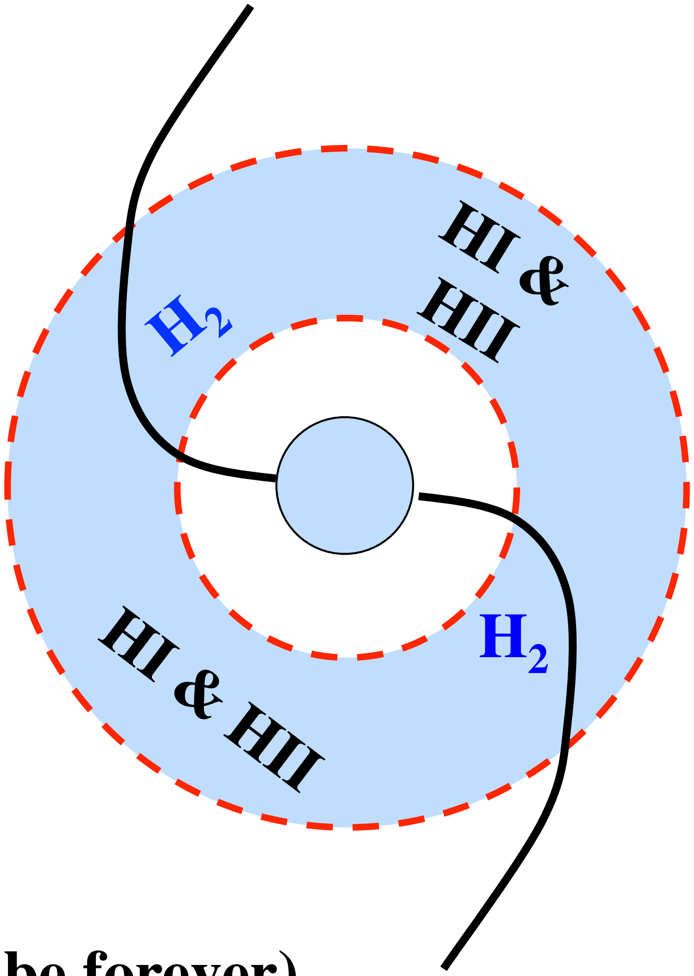
➔ H_2 can't be confined to arms

continuity (mass cons.) :

$M_{H2} / \tau_{H2} = (M_{HI} + M_{HII}) / \tau_{HI\text{-}HII}$

M : total mass of phase w/i ring

τ : lifetime of H in phase



inner disks, $M_{H2} \sim 4 (M_{HI}+M_{HII})$

➔ $\tau_{H2} \sim 4 \tau_{HI\text{-}HII}$

where $\tau_{HI\text{-}HII} \sim 5 \times 10^7$ -- 10^8 yrs

➔ typical H_2 lifetime >> 10^8 yrs !! (could be forever)

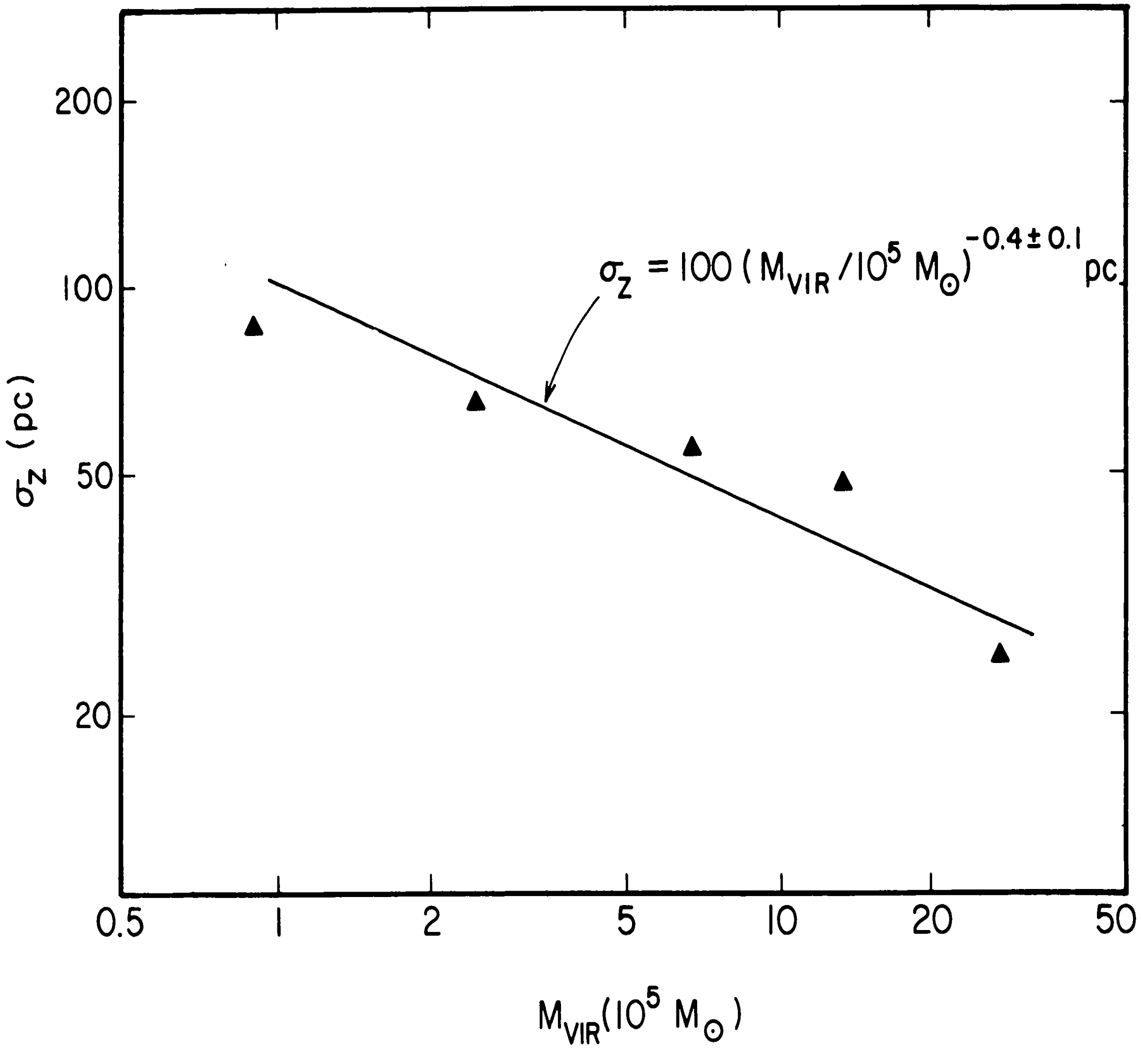
(lifetime of H_2, not necessarily GMC)

Scoville & Hersh '79
Koda etal ('09)

additional evidence ...

equipartition of cloud KE

massive clouds have lowest σ_v !!



requires clouds last
several GMC-GMC
collision times

$\tau_{GMC\text{-}GMC} > \sim 10^8$ yrs

If H_2 clouds exist in both arms and interarm regions,

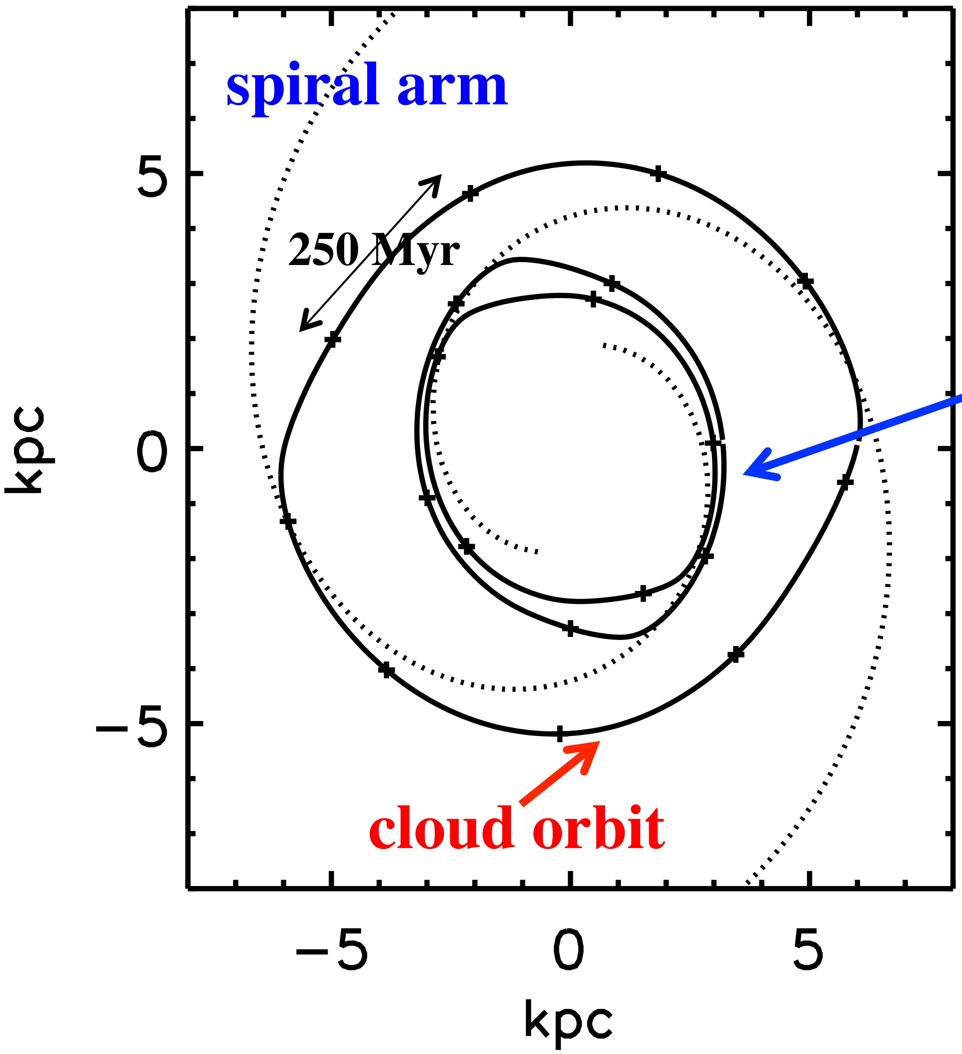
why is OB star formation in the arms ???

GMC internal turb. press. ~ 100 times external P_{ISM} !!

forming massive clusters requires a major and sudden change in a cloud

what could cause this ??

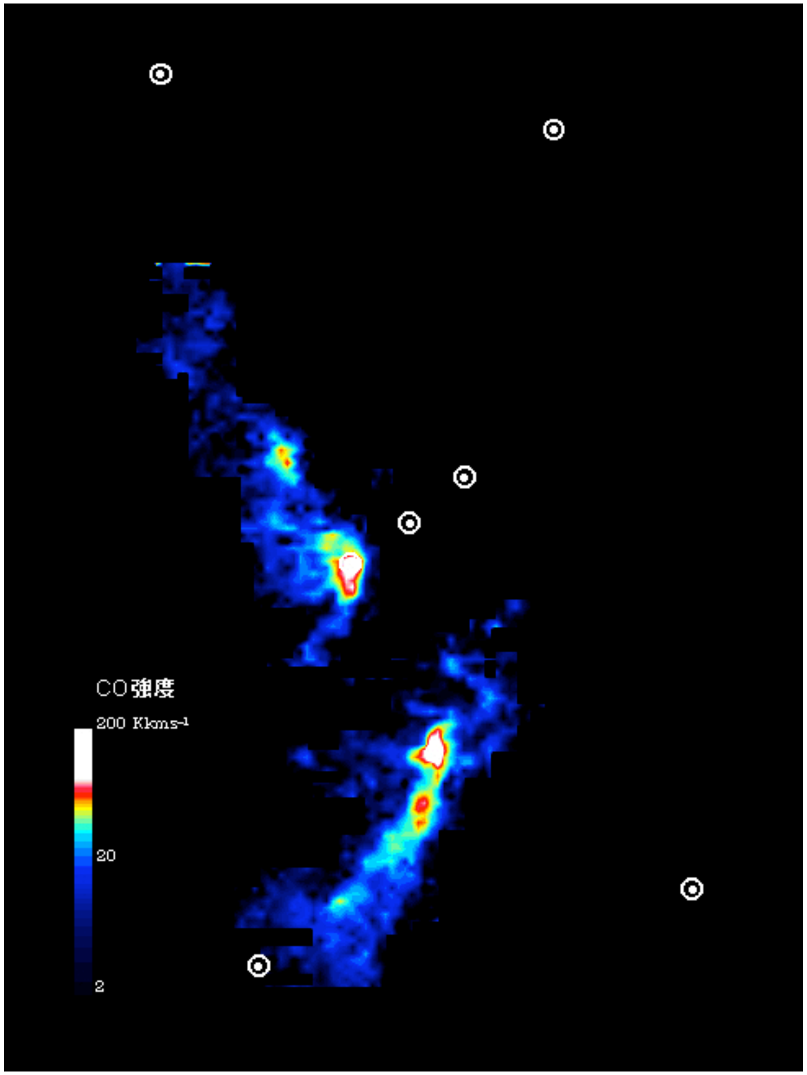
one possibility – **on the arms, clouds collide more often**
collisions can overpressure and compress GMC



orbit crowding w/i spiral arm
➔
cloud-cloud collisions

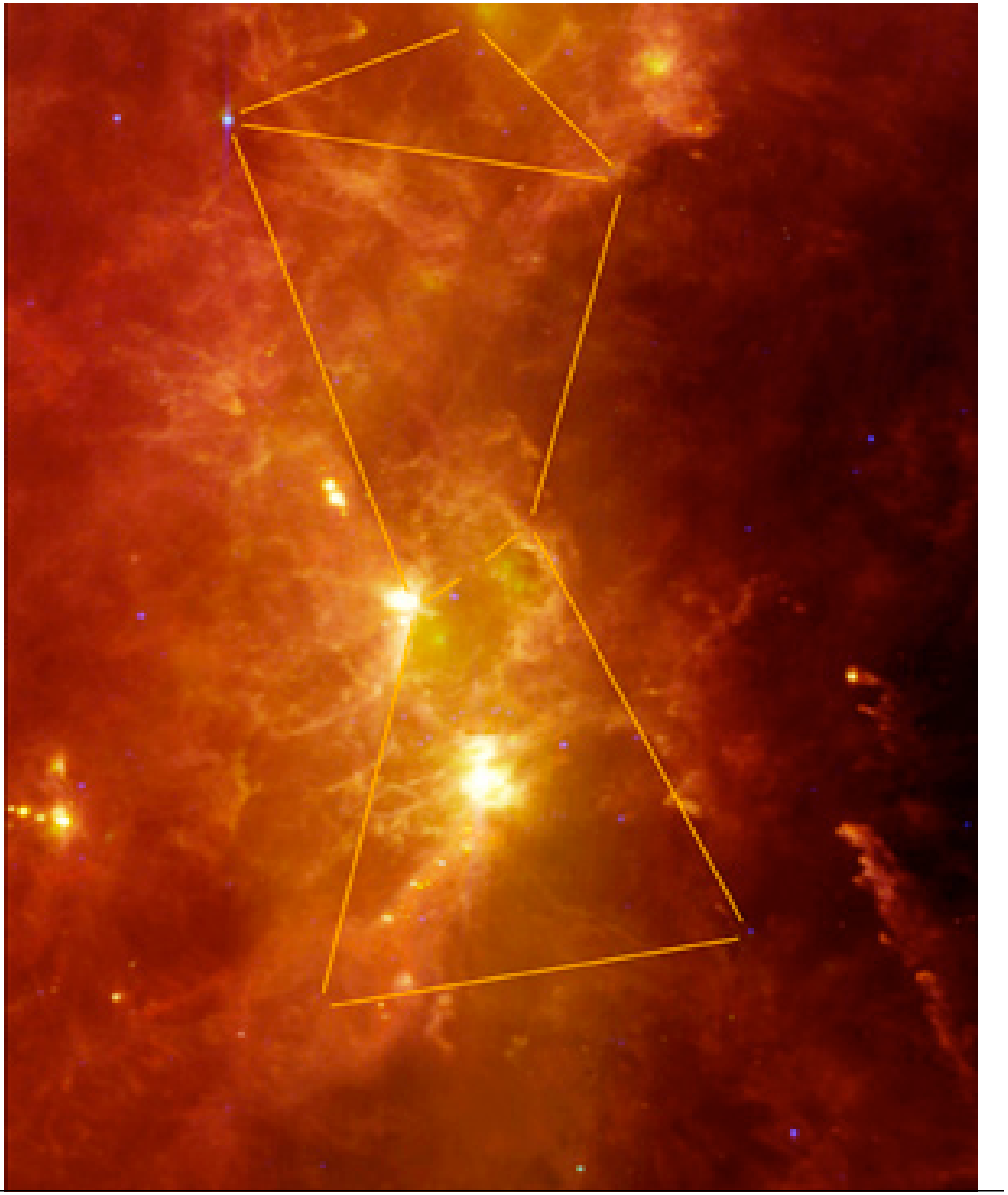
Orion GMCs – possible collision ?

CO



Courtesy of Seiichi Sakamoto (60cm telescope at U.Tokyo)

Infrared



Star Formation tracers

Hα & emission lines
UV continuum

high res. and sensitivity but obscuration ?
obscuration huge in starbursts !
e.g. ULIRG Arp220 : $L_{IR} / L_{opt} \sim 80$
radio free-free, submm recomb. lines
radio non-thermal
YSO star counts

IR luminosity → dust obscured SF

will spend some time on :
how does this work
how to interpret IR SEDs

SFR from counting YSOs :

Goldsmith 07, Heiderman 2010

Lada etal 2010

Gutermuth etal 2011

Masses and YSO Contents of Local Molecular Clouds **Lada etal 2010**

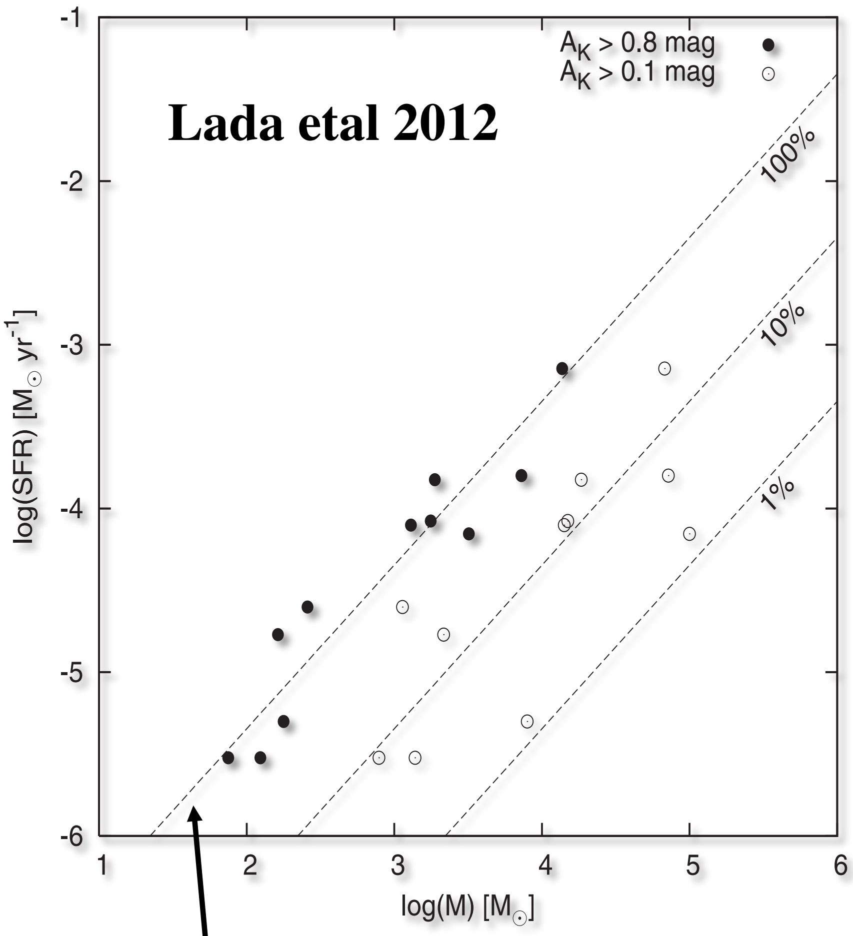
Cloud	Mass ($M_\odot$)[a]	Mass ($M_\odot$)[b]	No. of YSOs	References	SFR ($10^{-6} M_\odot$ yr^{-1})
Orion A	67,714	13, 721	2862	1, 2, 3	715
Orion B	71,828	7261	635	4, 5	159
California	99,930	3199	279	6, 7	70
Perseus	18,438	1880	598	8, 9, 10	150
Taurus	14,964	1766	335	11	84
Ophiuchus	14,165	1296	316	12	79
RCrA	1,137	258	100	13, 14, 15	25
Pipe	7,937[c]	178	21	16	5
Lupus 3	2,157	163	69	17, 18	17
Lupus 4	1,379	124	12	17, 18	3
Lupus 1	787	75	13	17, 18	3

$A_K > 0.1$

$A_K > 0.8$

problems :

- **YSO not well-defined (~0.5 $M_\odot$)**
- **small numbers**
- **extinction corrections**
- **completeness varies w/ cloud (dist. & extinction)**



Lada etal 2012

fit of dense gas mass vs SFR
➔ τ = 30 Myr

claim : SF better correlated w/ dense gas

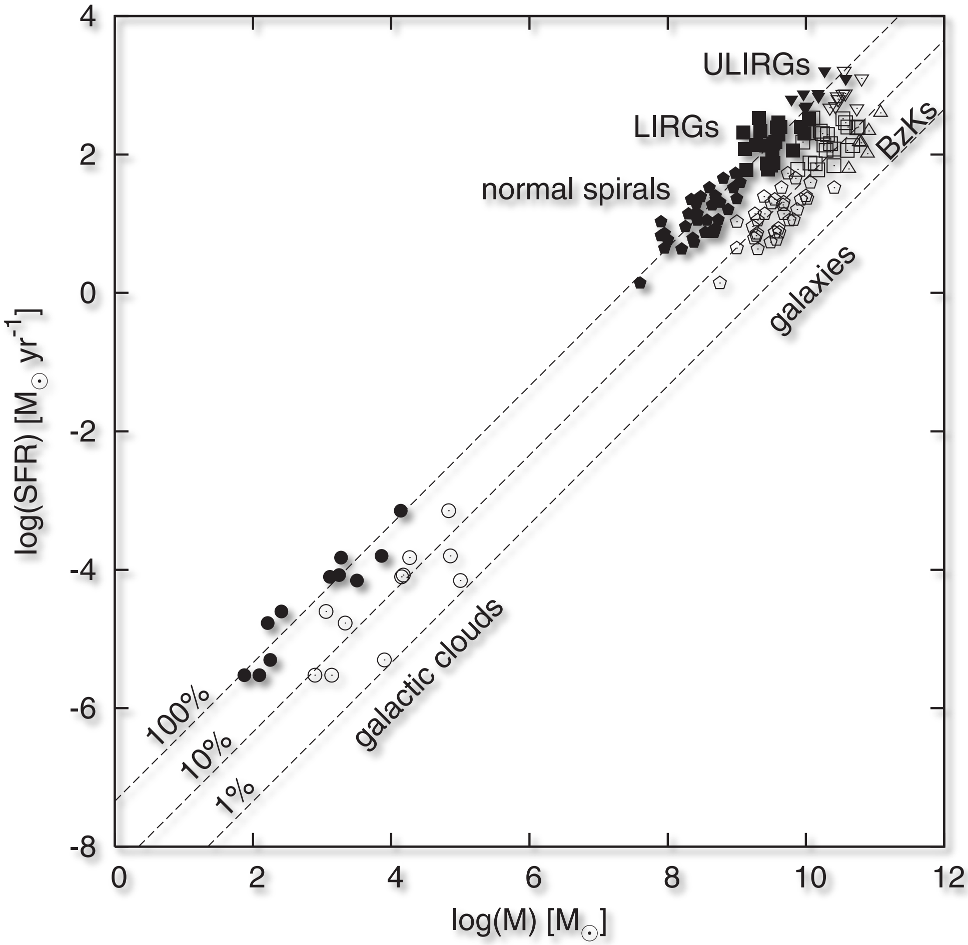


Figure 2. SFR–molecular-mass diagram for local molecular clouds and galaxies from the Gao & Solomon (2004a) sample. The solid symbols correspond to measurements of dense cloud masses either from extinction observations of the galactic clouds or HCN observations of the galaxies. The open symbols correspond to measurements of total cloud masses of the same clouds and galaxies, either from extinction measurements for the galactic clouds or CO observations for the galaxies. For the galaxies, pentagons represent the locations of normal spirals, while the positions of starburst galaxies are represented by squares (LIRGs) and inverted triangles (ULIRGs). Triangles represent high-*z* BzK galaxies. The star formation rates for the Gao and Solomon galaxies have been adjusted upward by a factor of 2.7 to match those of galactic clouds when extrapolated to local cloud masses (see the text).

SFR from L_{IR}

assume all L from young *'s absorbed

➔ $L_{IR} = L_{young\,*}$

how much L per M_* ?

2 approaches:

1) OBA *'s gen. L, via CNO cycle

13% of M_* processed on main seq.

➔ $0.13\,\dot{M}_{OBA*}\,\varepsilon_{CNO}$ ➔ L_{OBA} (Scoville & Young 83)

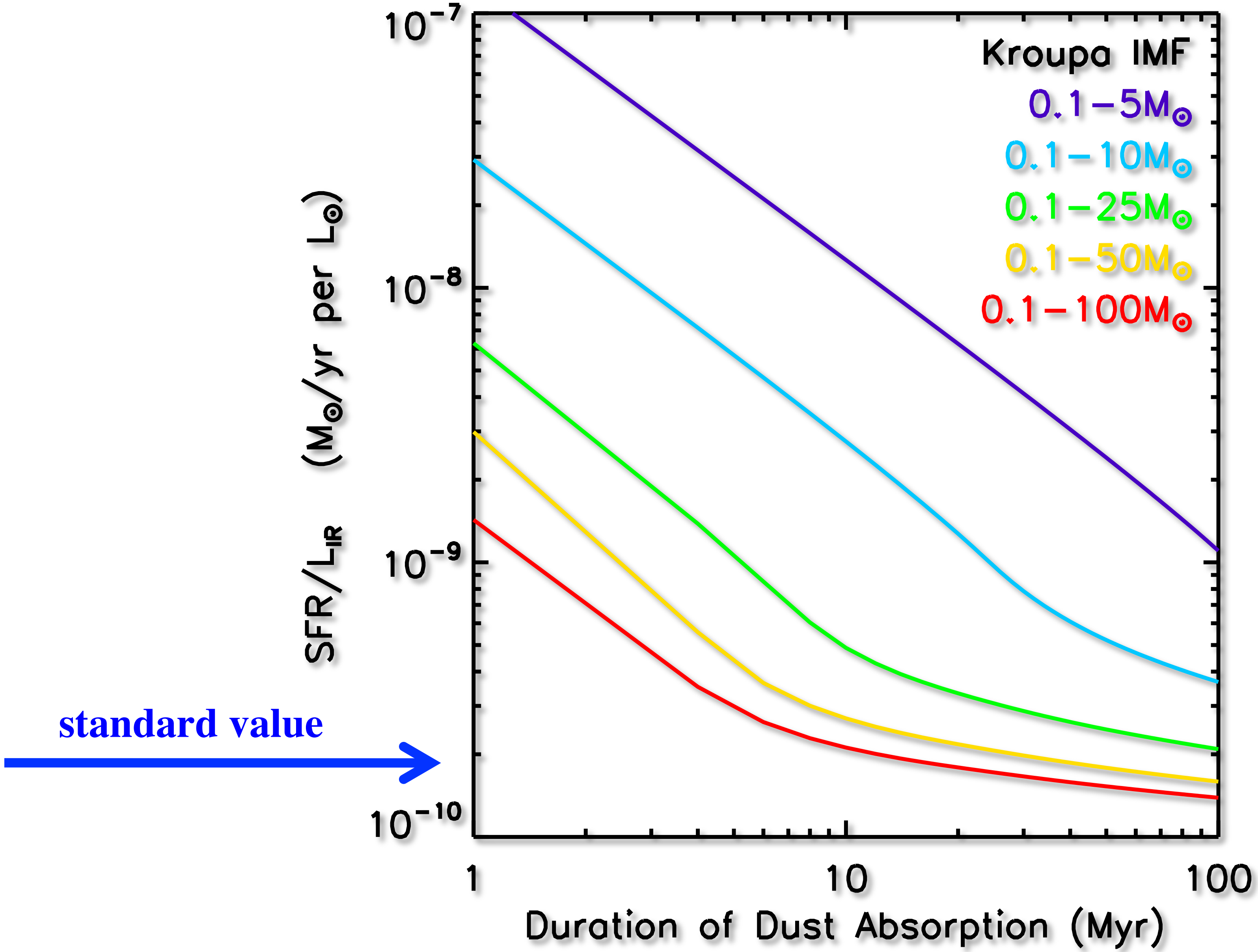
2) use SB99, to estimate L/M

➔ SFR ($M_\odot$ /yr)= 1.2 – 2×10^{-10} (L_{IR} / $L_\odot$)

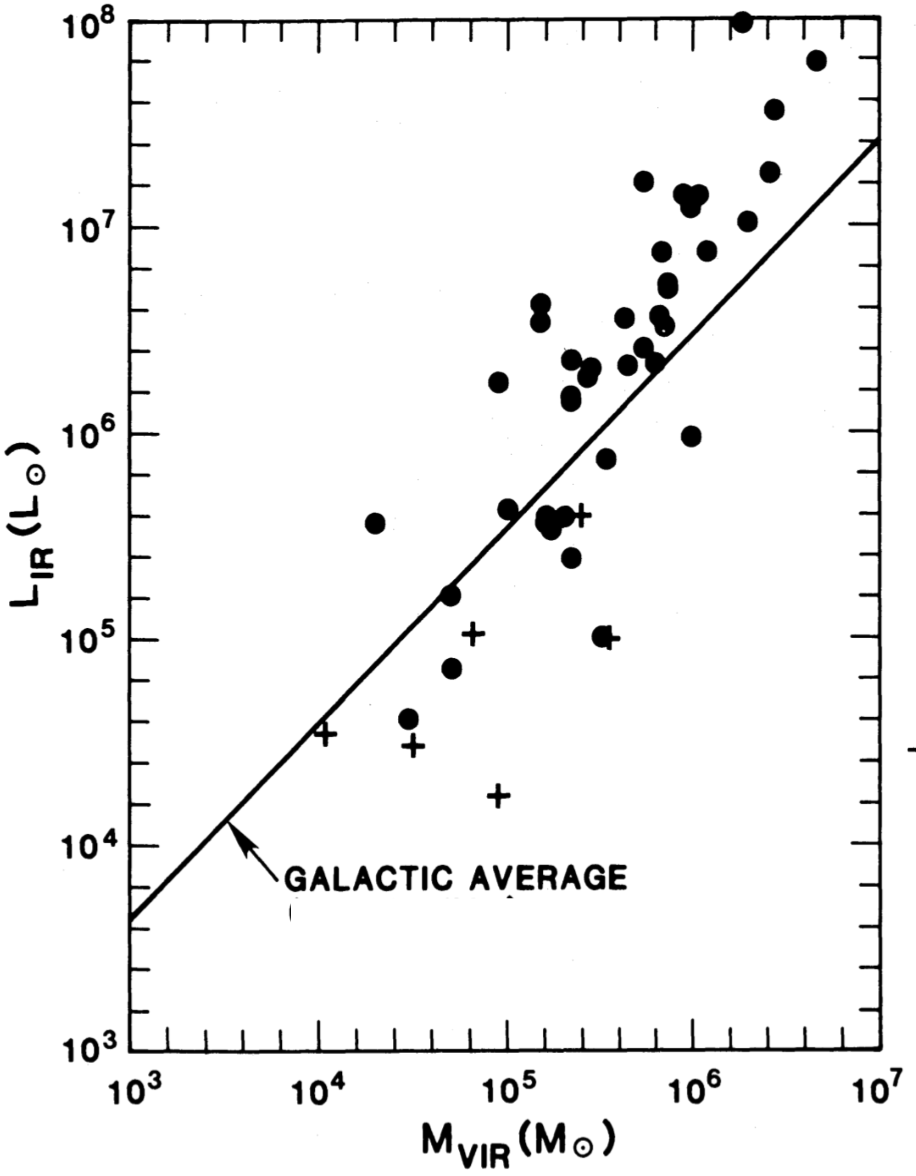
issues/caveats ...

1) how long *s' stay w/i GMC : 10^7 yrs normal SF, 10^8 yrs SB

2) m_{upper} of IMF


standard value

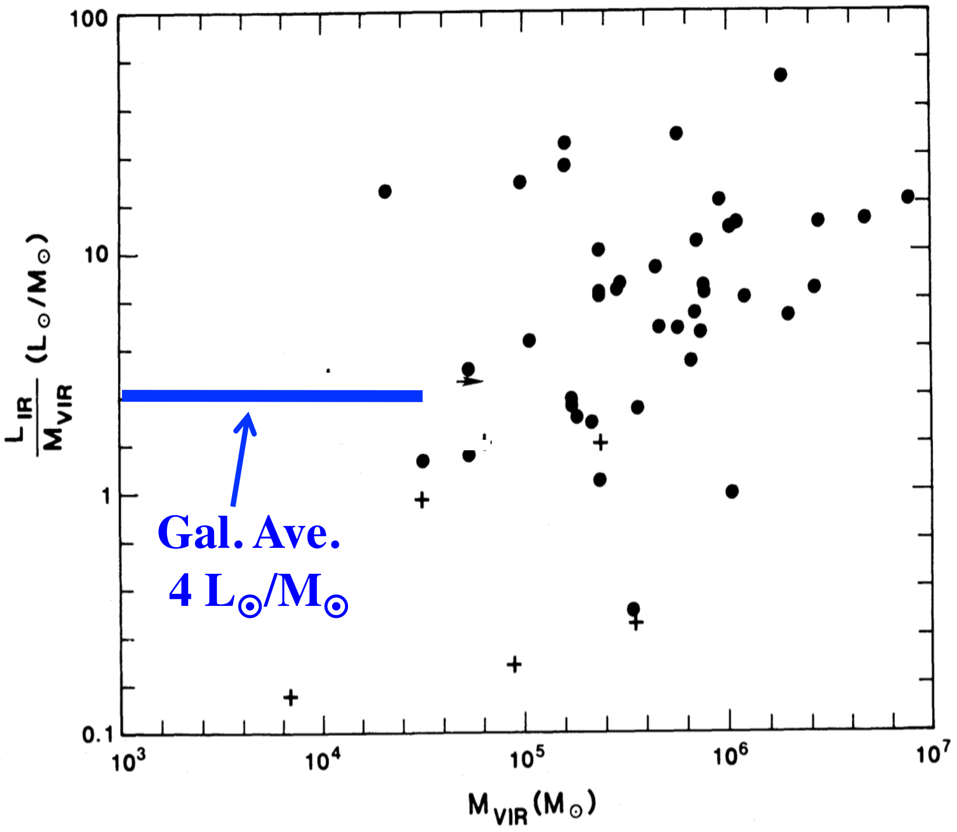
Galactic GMCs : SF vs M_{H2}



Gal. Ave. 4 $L_\odot/M_\odot$

➔ $\tau_{ism \rightarrow *} \sim 10^9$ yrs

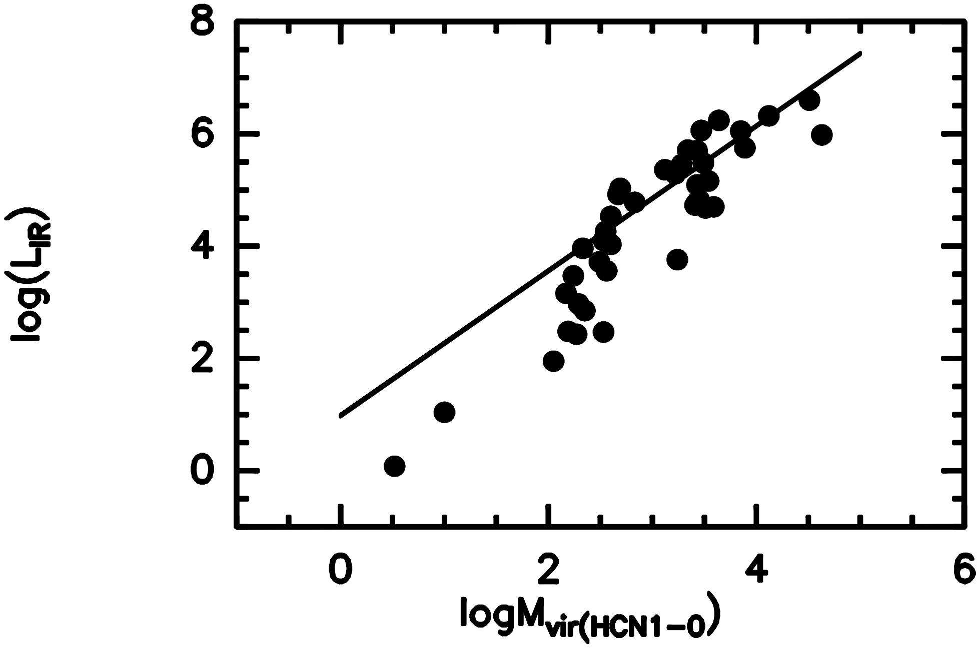
L_{IR} ~ indep. of cloud mass



Gal. Ave.
4 $L_\odot/M_\odot$

Scoville & Good 89

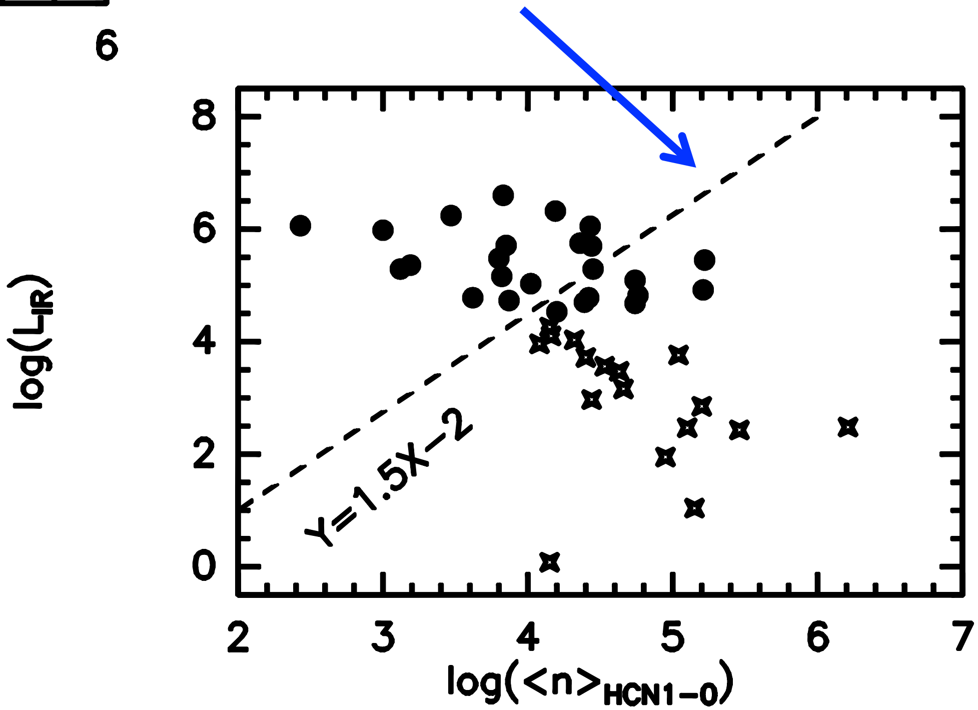
Dense gas -- HCN in MW GMCs **Wu etal 2010**



➔ correlation above $L_{IR} = 10^4$

Krumholtz & McKee

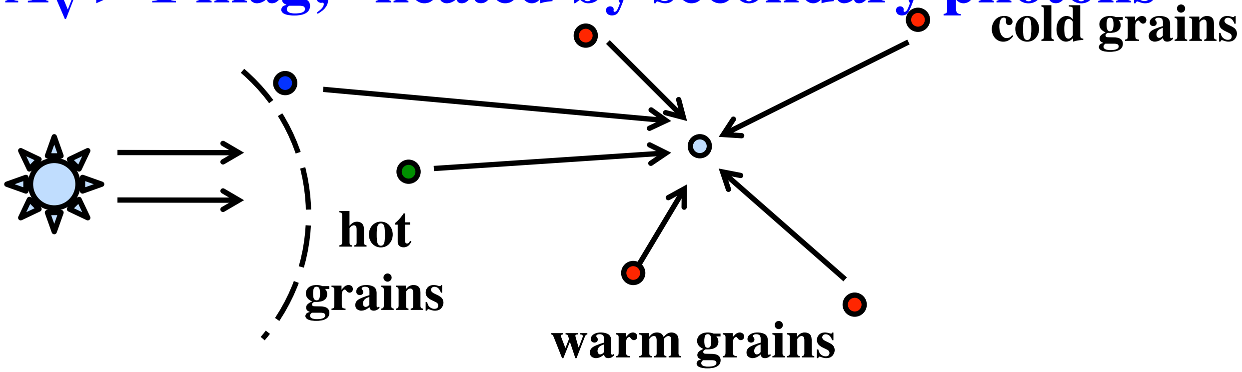
SFR α $<n_{H2}>$ /τ_{ff}



the physics of the IR emission :
modeling optically thick dust cloud

at $A_V < 1$ mag, heated by primary photons

at $A_V > 1$ mag, heated by secondary photons



secondary photons attenuated
by dust w/i cloud

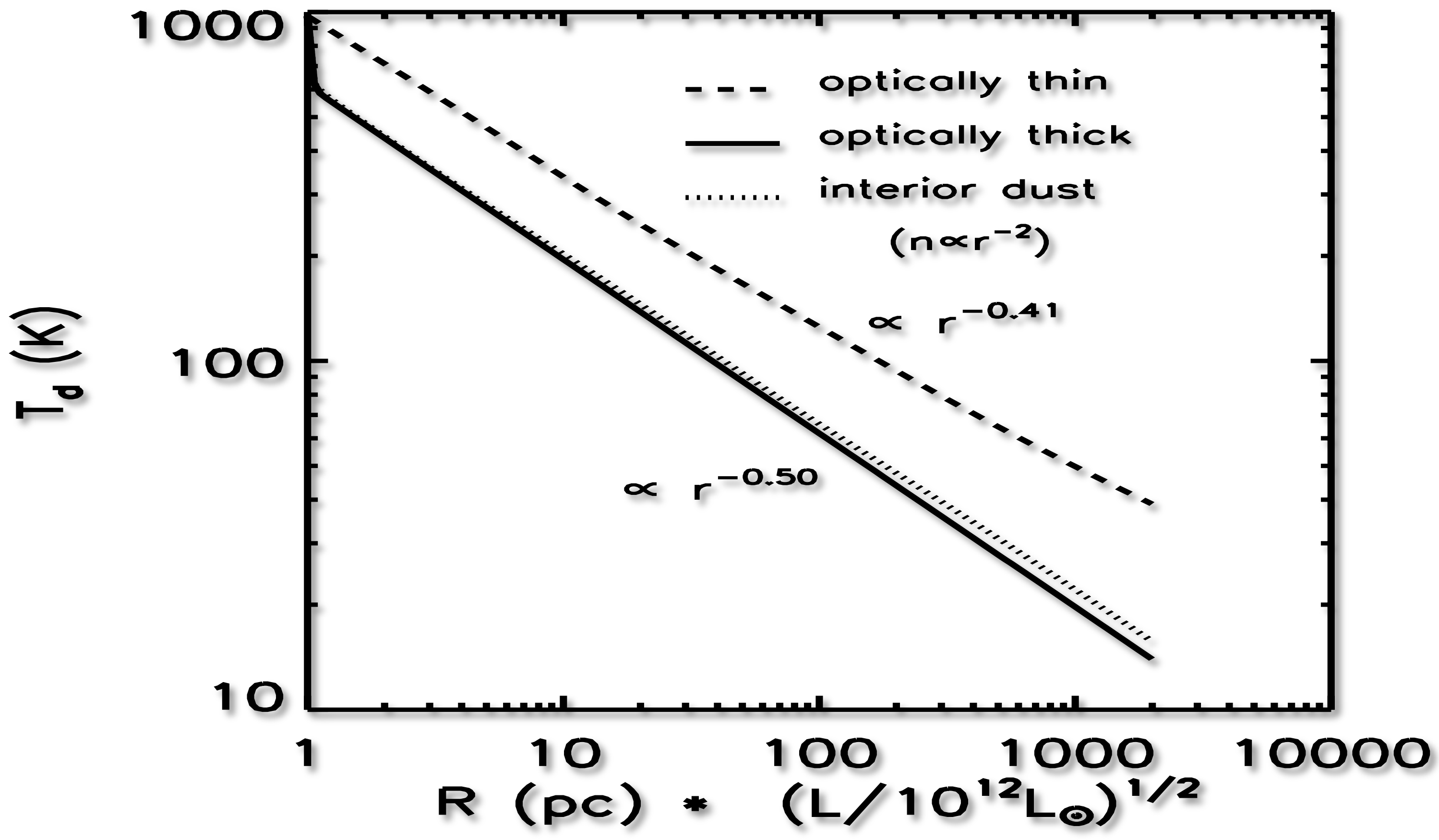
does one really need to do
full radiative transfer ?

no ...

can calculate T_{gr}

starting from inside going out

innermost grains at R s.t. $T < T_{sublimation} \sim 1500K$



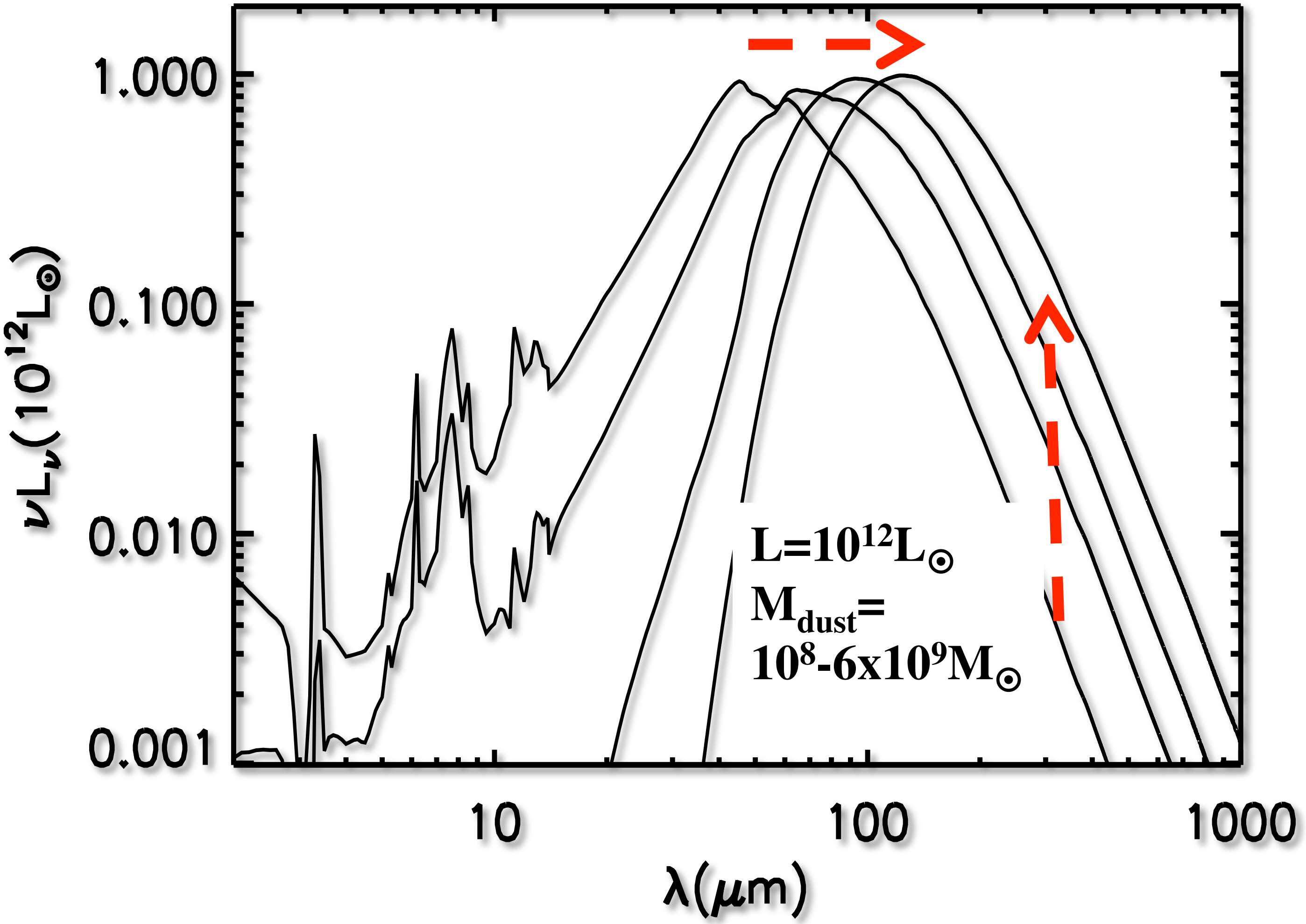
NB : radial lengths scale as $L^{1/2}$ ➔

therefore can use for higher or lower L

Scoville 2012

~1 parameter : L / M_{dust}

emitted SED as function of dust mass



increasing opacity or M_{dust}

- peak shifts to longer λ for increased τ (or dust mass)
- flux on long λ tail scales linearly with M_{dust}

R-J tail is optically thin,
therefore

$F_\nu = \varkappa_\nu T_{dust} \nu^2 M_{dust} (1+z) / (4\pi d_L{}^2)$

T_{dust} = 20-25K in Gal. SF

= 30-50K in SB regions ➔ little uncertainty due to T_{dust}

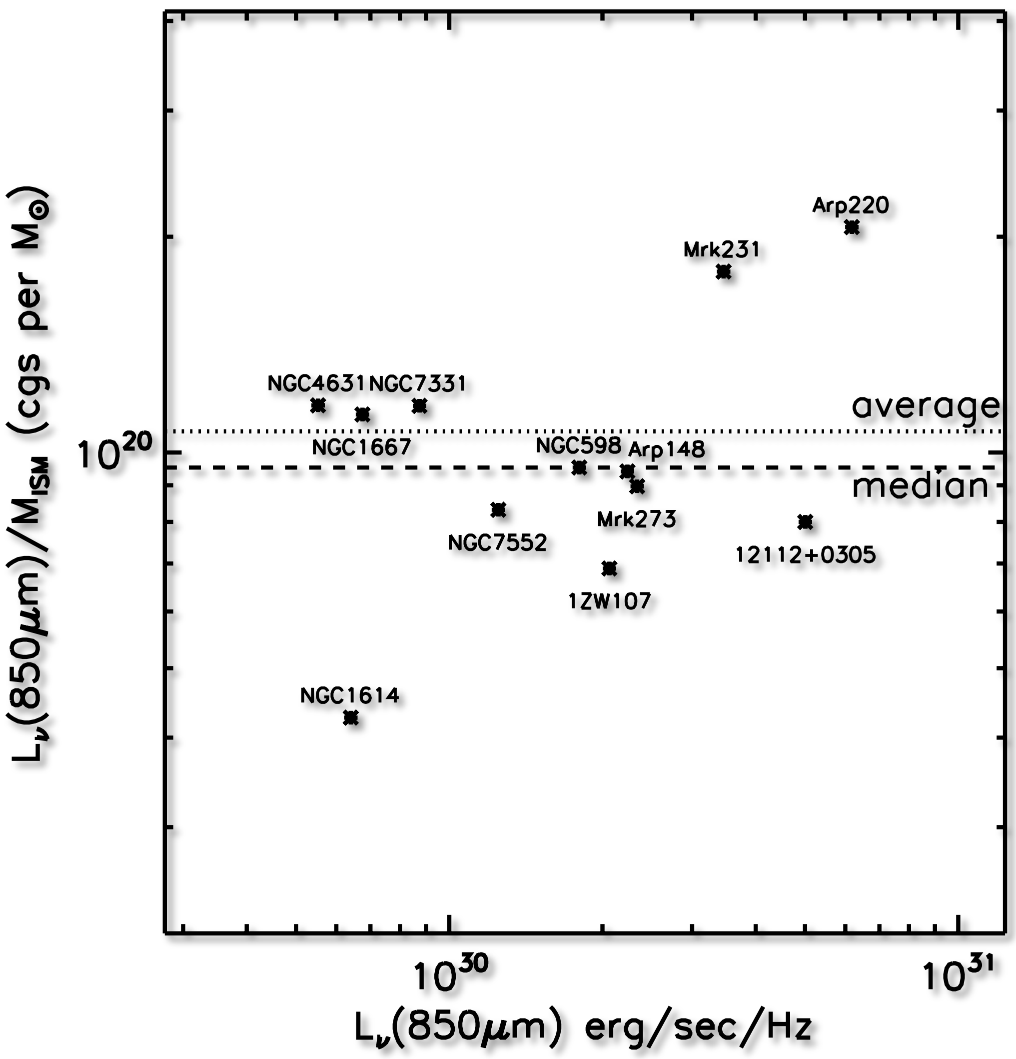
use obs. of nearby gal. with submm dust and ISM masses
to calibrate : $\varkappa_\nu$ M_{ISM} / M_{dust}

use ALMA to measure F_ν in high z galaxies
avoid CO-to-H_2 conversion & high J excitation issues

local galaxies with total 850µm & ISM mass measures

(850µm from Dale '05, Clements '09, Dunne & Eales '09)

see Scoville etal 2014



1×10^{20} erg/s/Hz/$M_\odot$

agrees also with :
Planck MW
high z SMGs

Arp 220 nucleus
α_{CO} only 2x diff.

GMCs ~ indestructable

lifetime > 10^8 yrs

internal supersonic turbulence
maintained probably by external force gradients

SF – obviously occurs in densest gas

2 modes : quiescent , dynamically triggered bursts

GMC disruption by HII region (by ionization)

$\tau_{rec} = 1/\ n_e\alpha \sim 640$ yrs ($n \sim 200$)

at 10 km/s , 20 pc takes 2 Myr ➔ > 3000 recombs per n

for $2x10^5\ M_\odot$ ➔ $2.5x10^{62}$ H x 3000 ➔ $7.5x10^{65}$ Ly c photons

for O4 * , $Q \sim 5x10^{49}$ Ly c sec^{-1} x $3x10^6$ yrs = $4.5x10^{63}$ Ly c

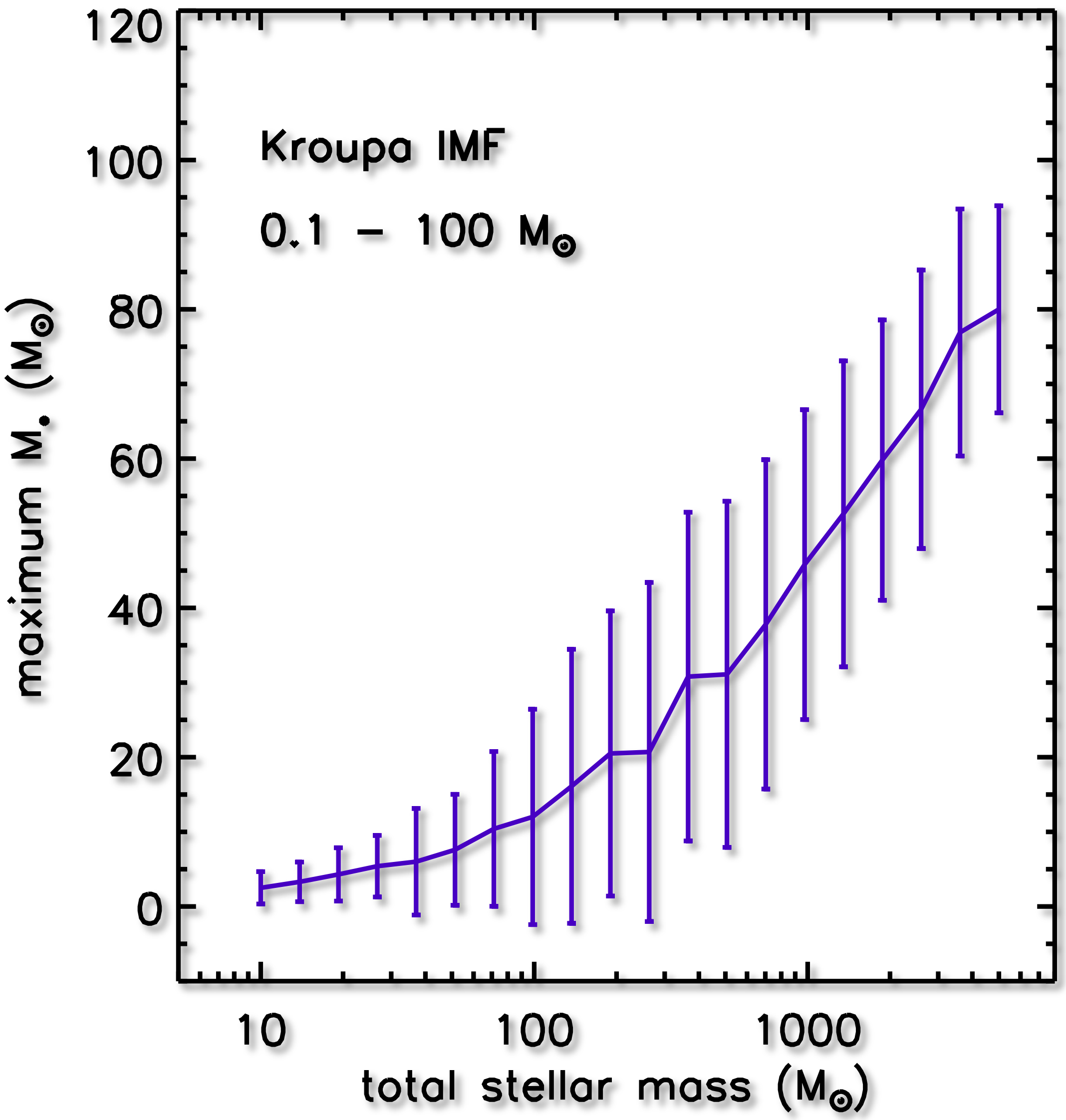
➔ need ~100 O4 *'s or $10^{4-5}\ M_\odot$ of stars being formed !!

seems unlikely !!

how much stellar mass need to form to get an O4 *

maximum stellar mass as a function of total stellar mass

➔ need ~ 300 – 1000 $M_\odot$ for significant ioniz.



O4
48000 K

B0
30000 K

GMCs ~ indestructable

lifetime > 10^8 yrs

internal supersonic turbulence
self-gravitating, but <u>not spherical</u>
maintained probably by external force gradients

SF – obviously occurs in densest gas

2 modes : quiescent , dynamically triggered bursts

how to make progress
RJ continuum ➔ mass estimates
SFR from IR but make sure they are luminous enough
maybe best to use whole galaxies
ALMA will radically advance the field !!