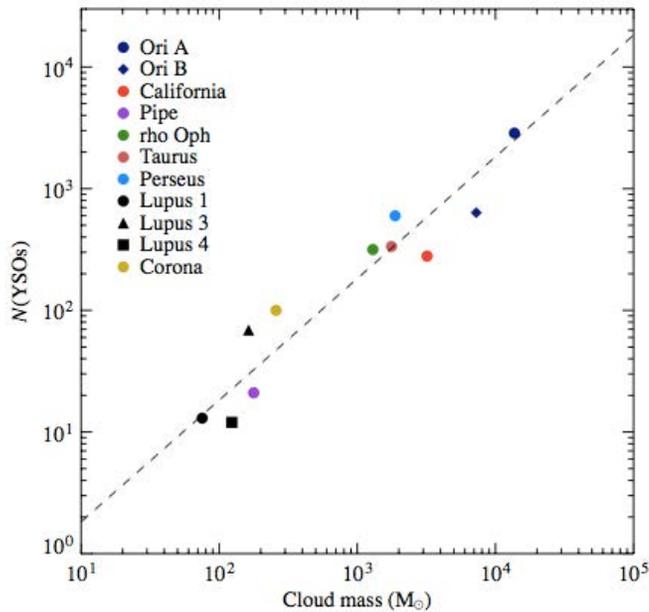


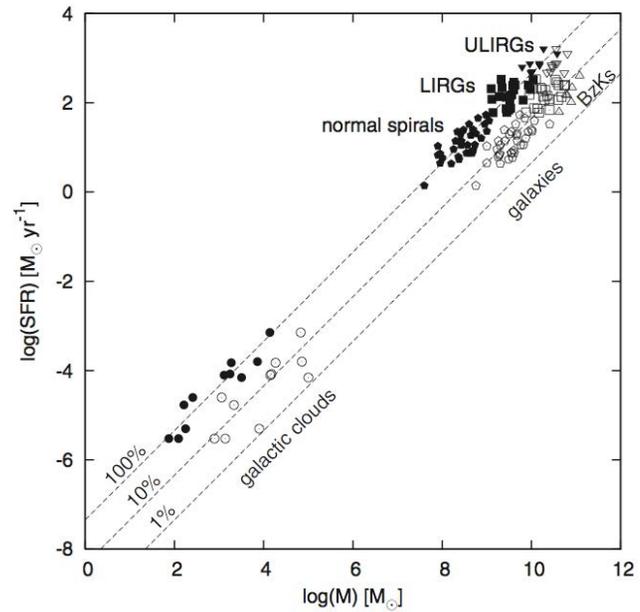
Star formation laws and the local environment in
nearby starbursts and our own Galactic center

Eric Keto

SFR linear with gas mass. Constant SF efficiency and rate.



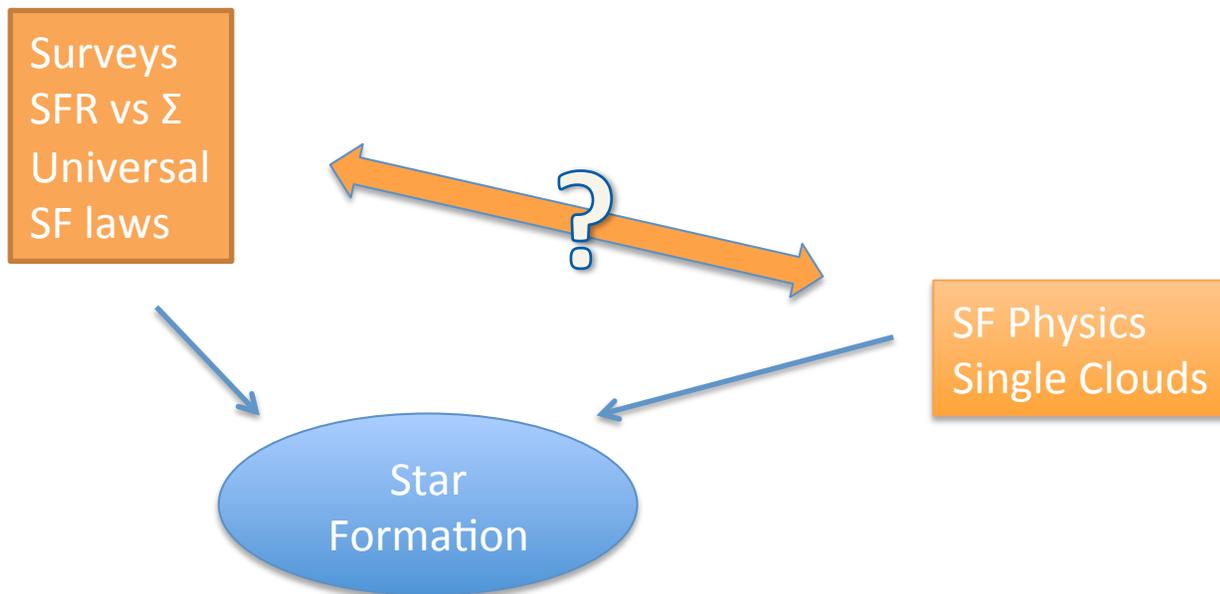
Dust mass vs N(YSO)
(Lada 2010)



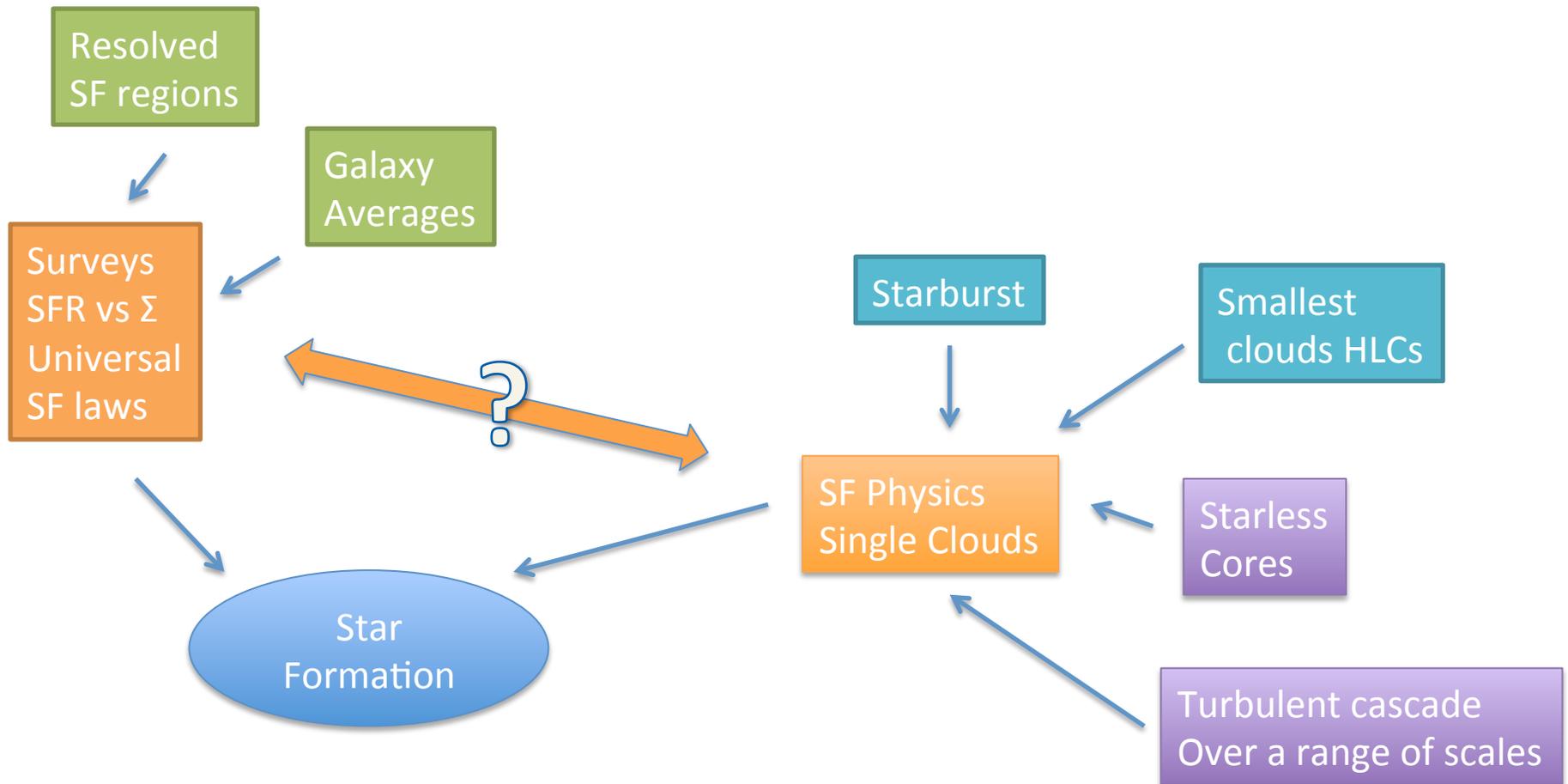
CO+HCN vs IR
(Lada 2012)

SFR vs mass
not
SFR vs density

How do we understand universal laws in terms of local star formation physics derived from observations of single clouds?

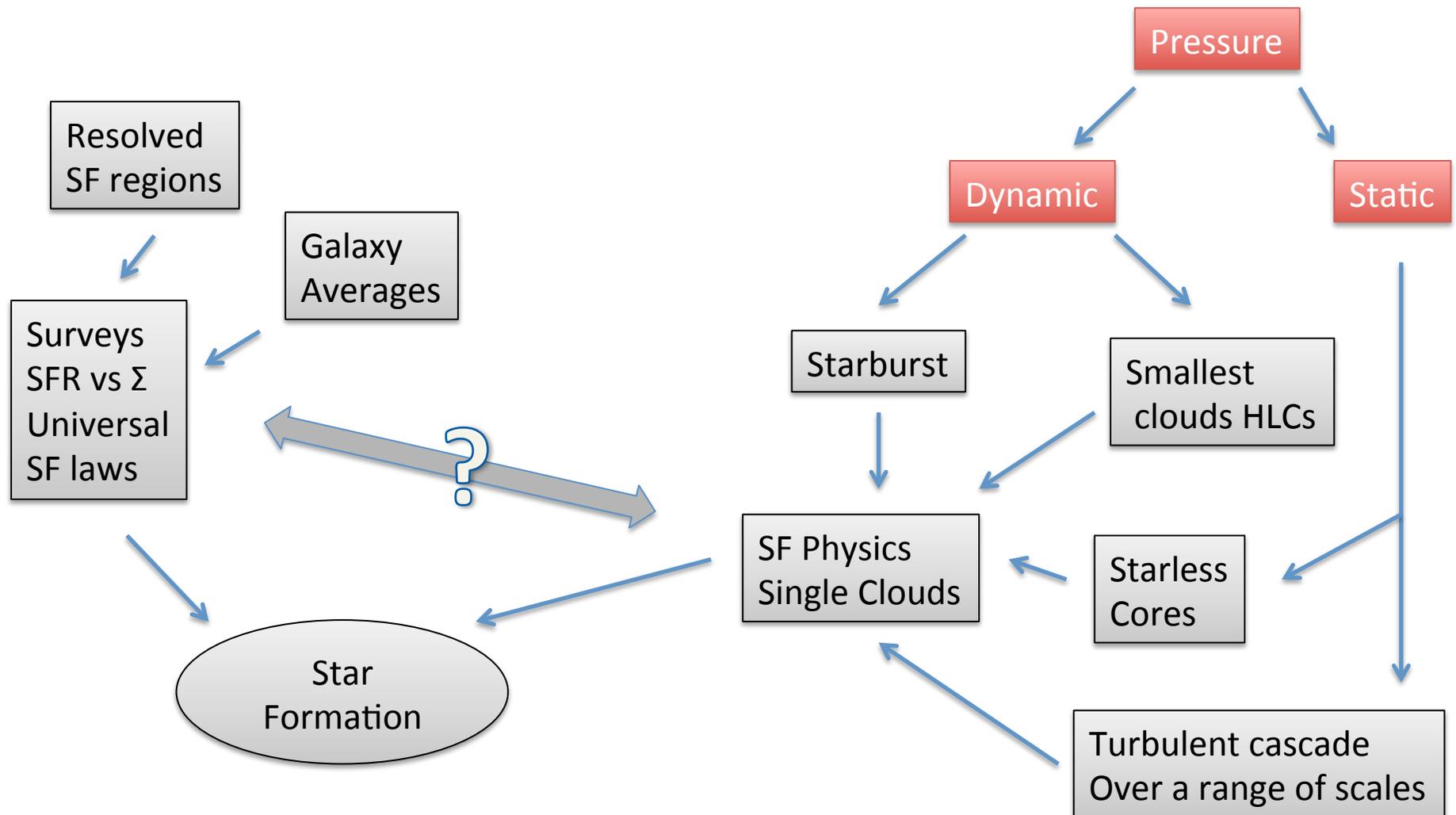


Observations

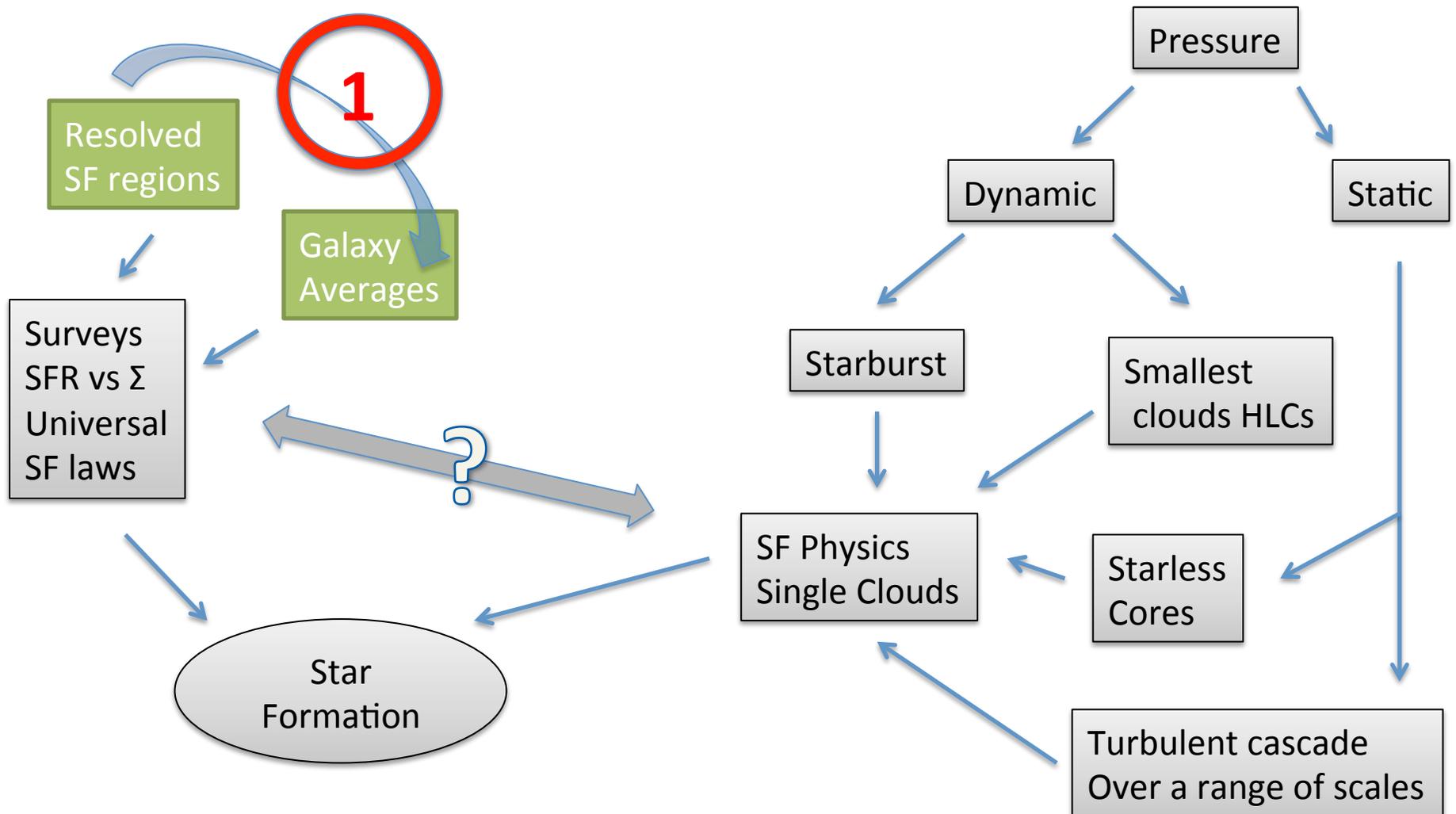


Concepts

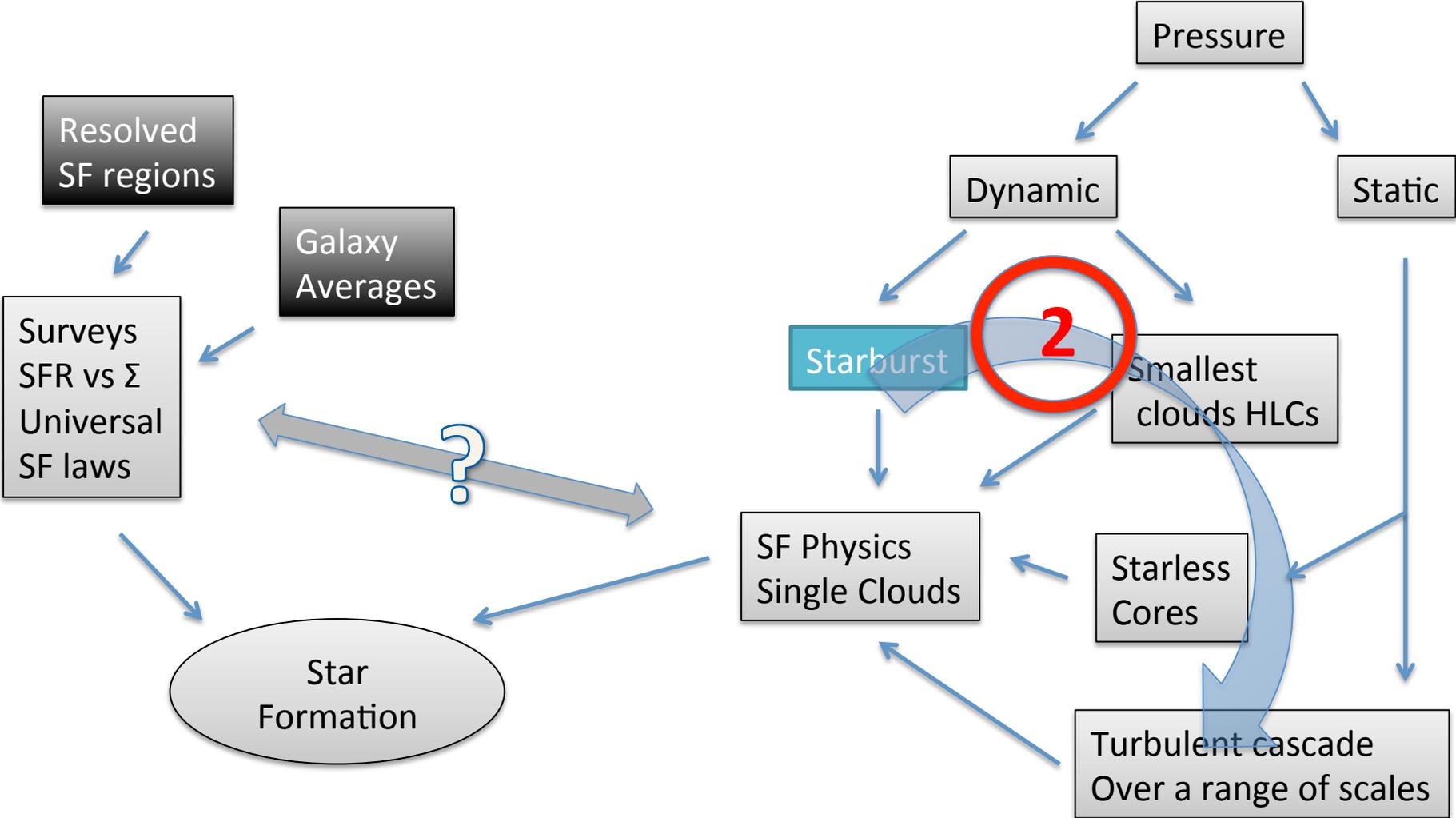
The virial equation for understanding SF
Pressure as the often missing element



The observed universal star formation laws



Cloud-scale observations of starbursts



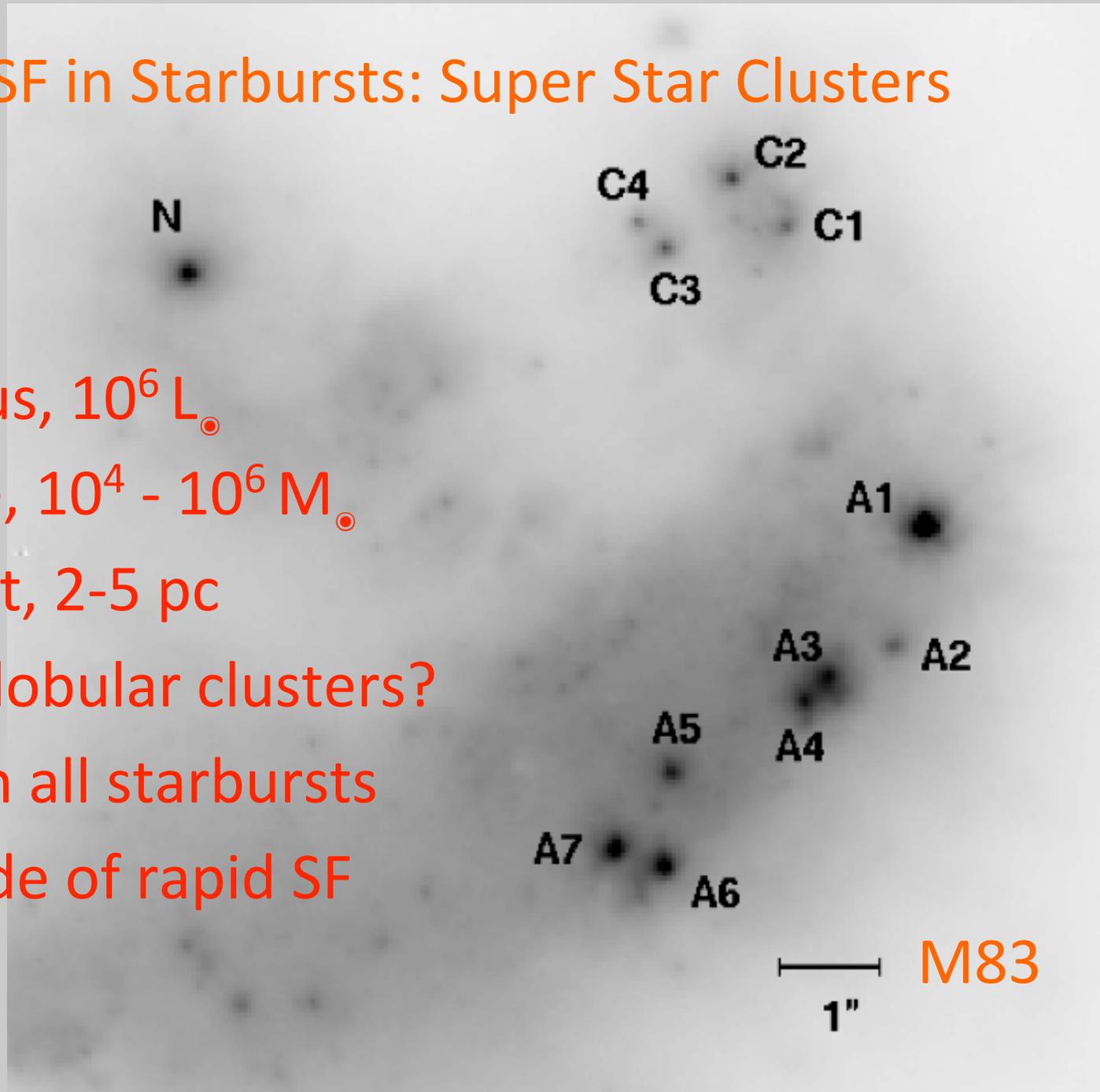
SF in starbursts is not normal

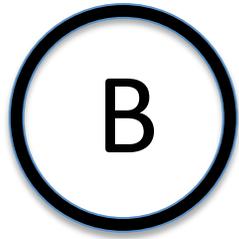
- A. In starbursts, SF takes in super-star clusters. There are no SSCs in our Galaxy.
- B. Gravitationally bound SSCs imply higher efficiency of star formation.
- C. SF tracers in 2 local starbursts are correlated with velocity gradients inside molecular clouds rather than with density or mass.

A

SF in Starbursts: Super Star Clusters

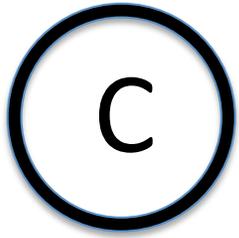
- luminous, $10^6 L_{\odot}$
- massive, $10^4 - 10^6 M_{\odot}$
- compact, 2-5 pc
- proto-globular clusters?
- found in all starbursts
- the mode of rapid SF





Do SSCs require higher efficiency than in normal star formation?

- Convert most of the gas mass into stars
- Otherwise
 - Gas (most of the mass) will disperse
 - Because the stars inherit the KE of the gas
 - Cluster will be unbound (not an SSC or globular)



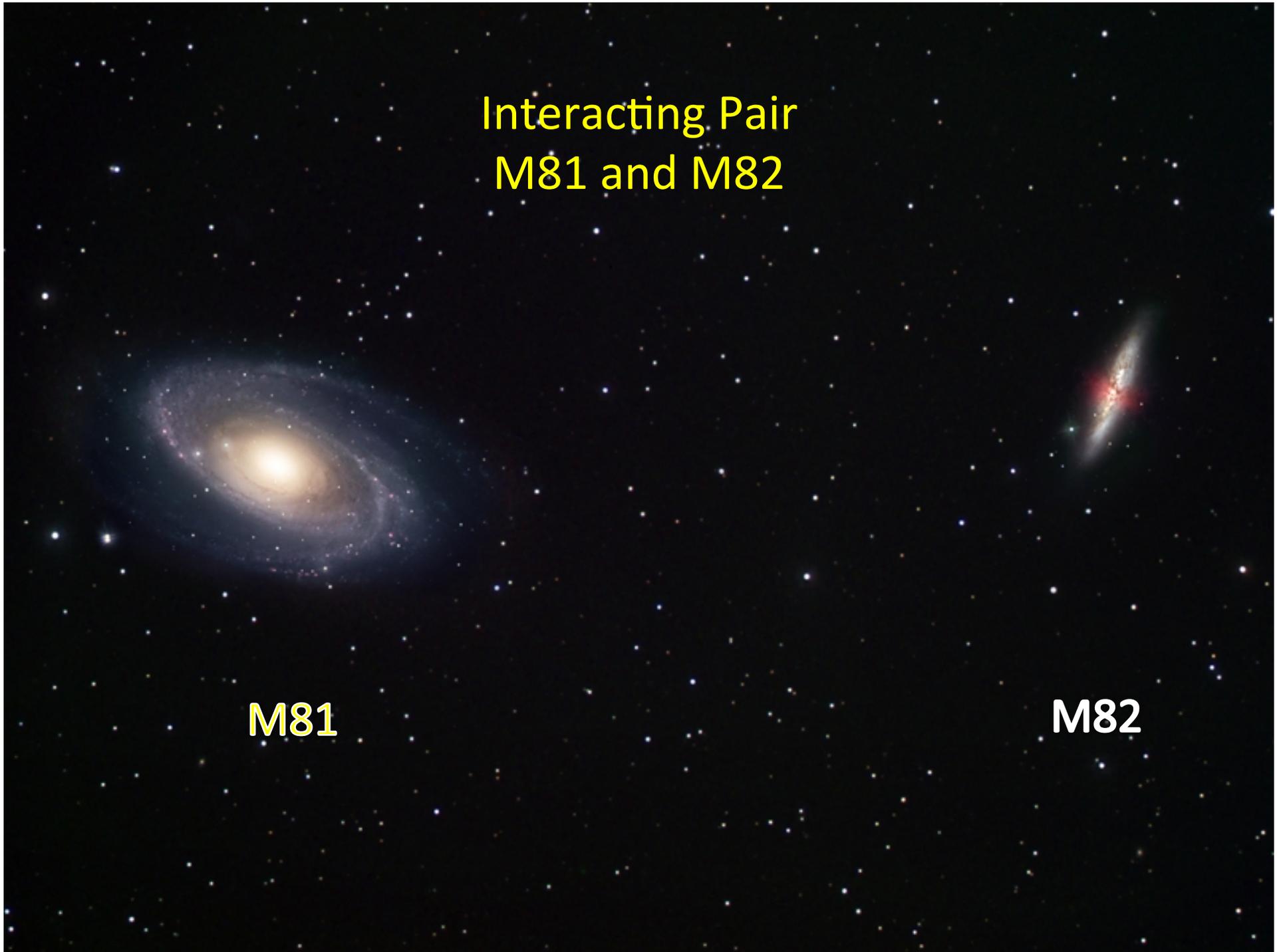
SF in starbursts is observed to be correlated with velocity rather than density or mass

- High angular resolution molecular line data in two starbursts
- A gravitational interaction: M82
- A major merger: The Antennae

Interacting Pair
M81 and M82

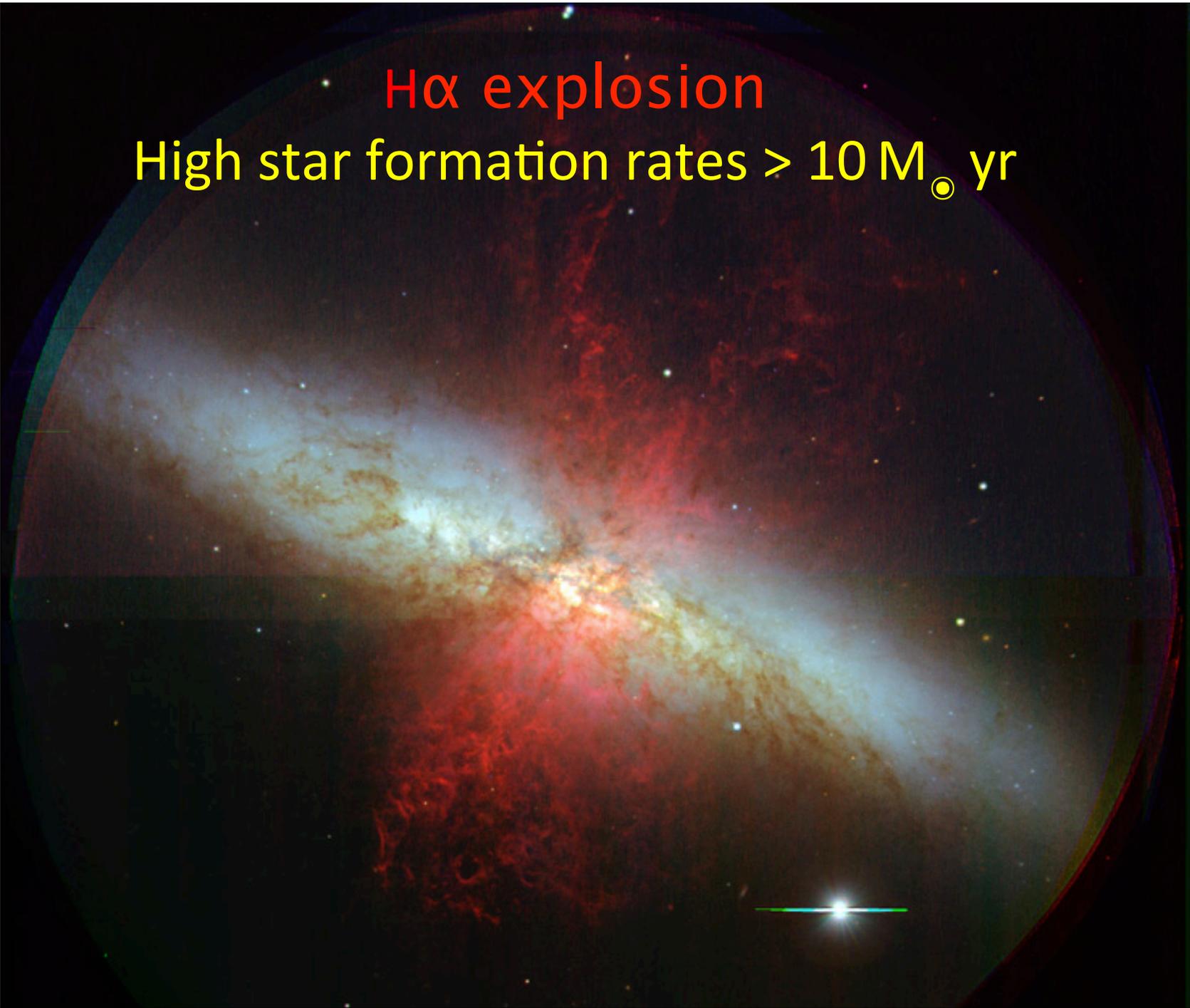
M81

M82



H α explosion

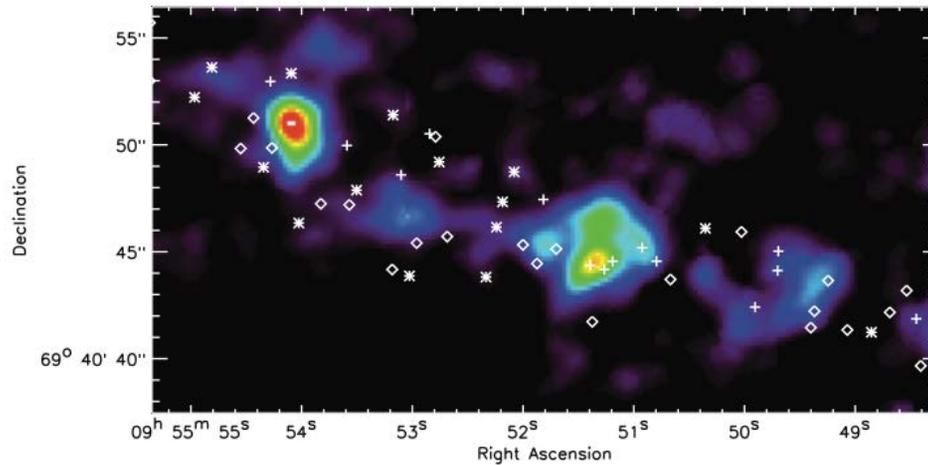
High star formation rates $> 10 M_{\odot} \text{ yr}$



Most of the luminosity is in the IR

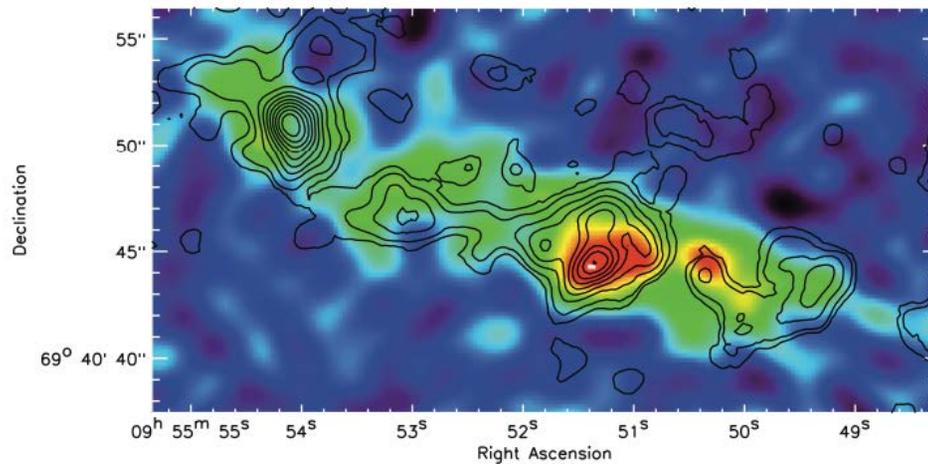
M82 seen by Spitzer ST

M82 CO intensity is not correlated with SF tracers



CO(2-1)
OVRO
1'' = 17 pc

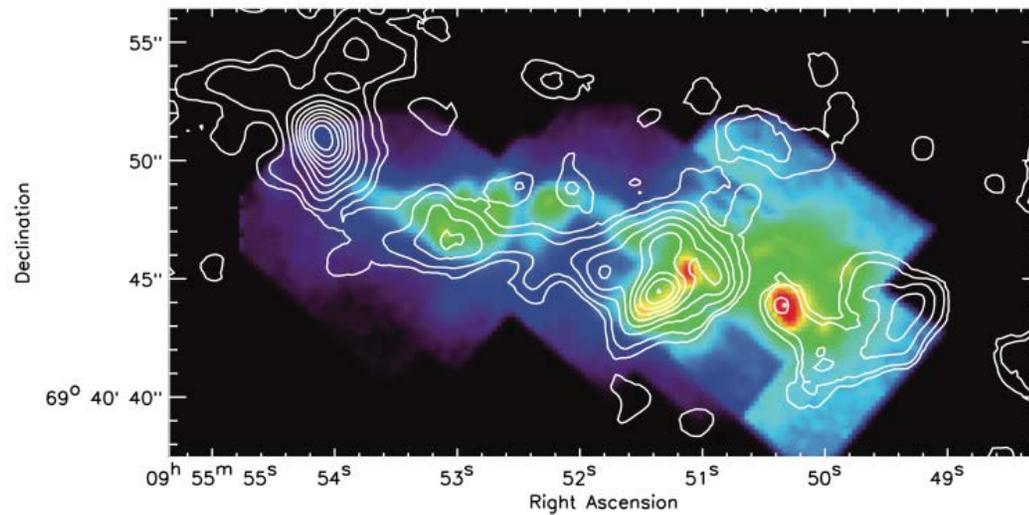
CO intensity in color
RRL (HII regions) as symbols



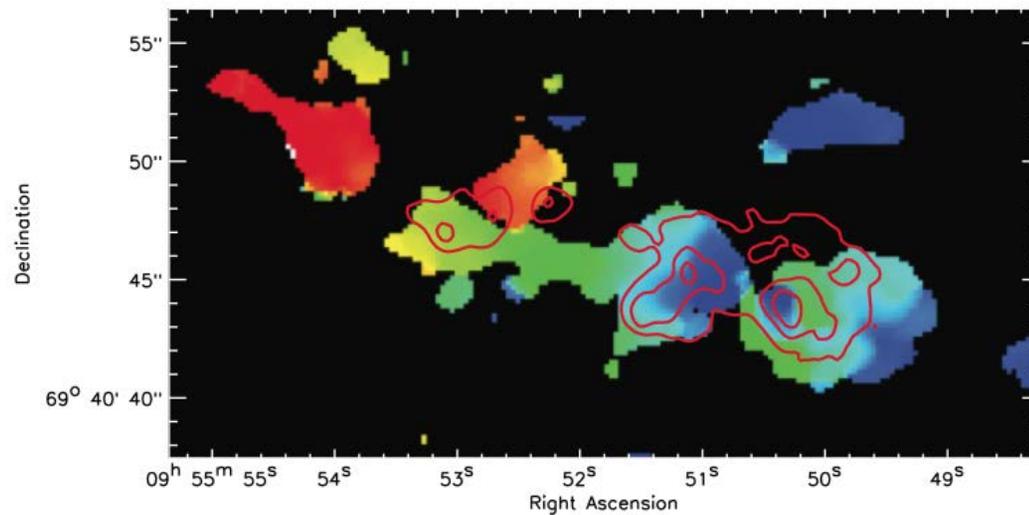
CO intensity in contour
Radio continuum in color

Keto, Ho, Lo 2005

SF (mid-IR) correlated with velocity gradient



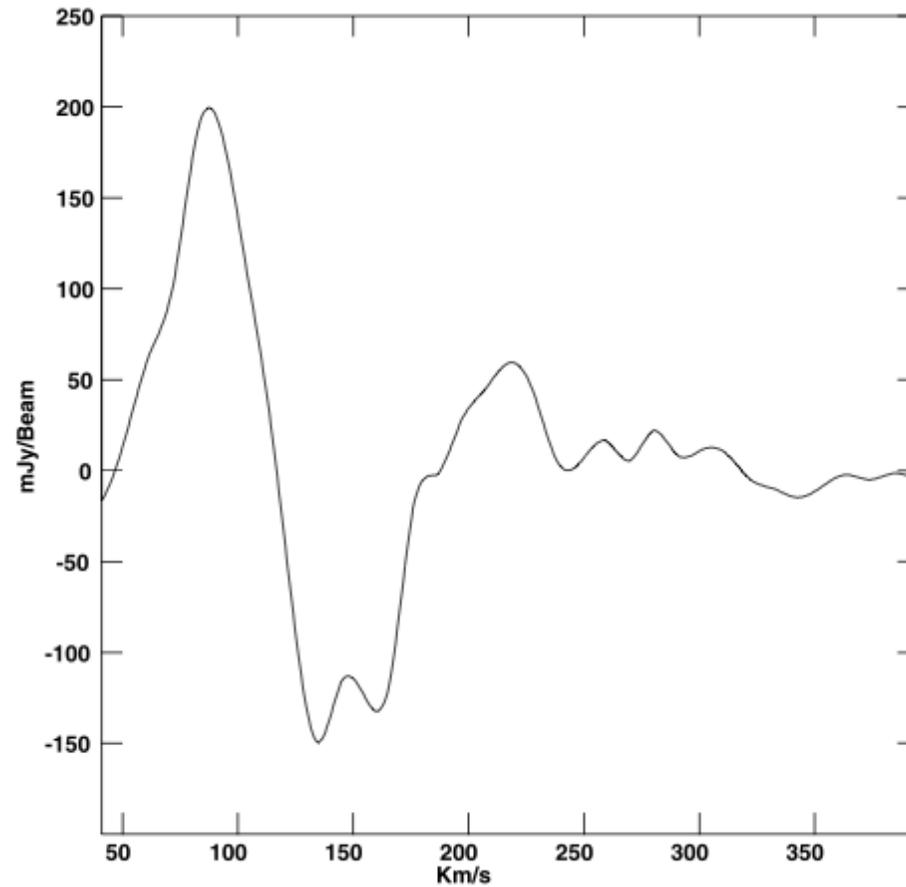
CO intensity in contour
Mid-IR in color



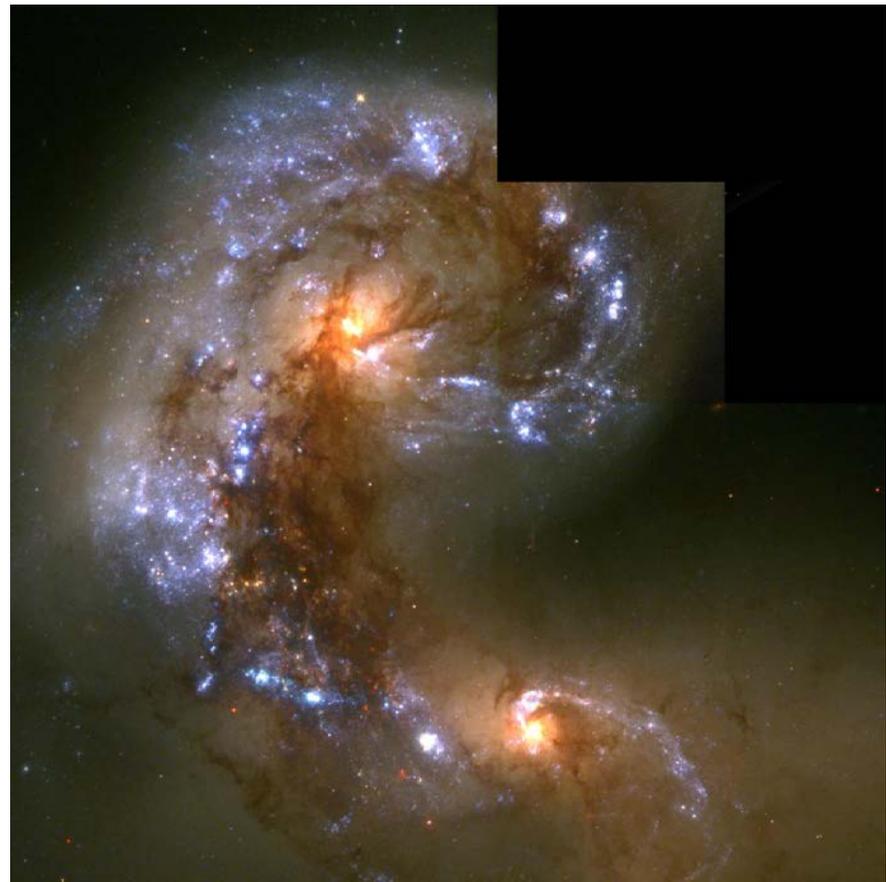
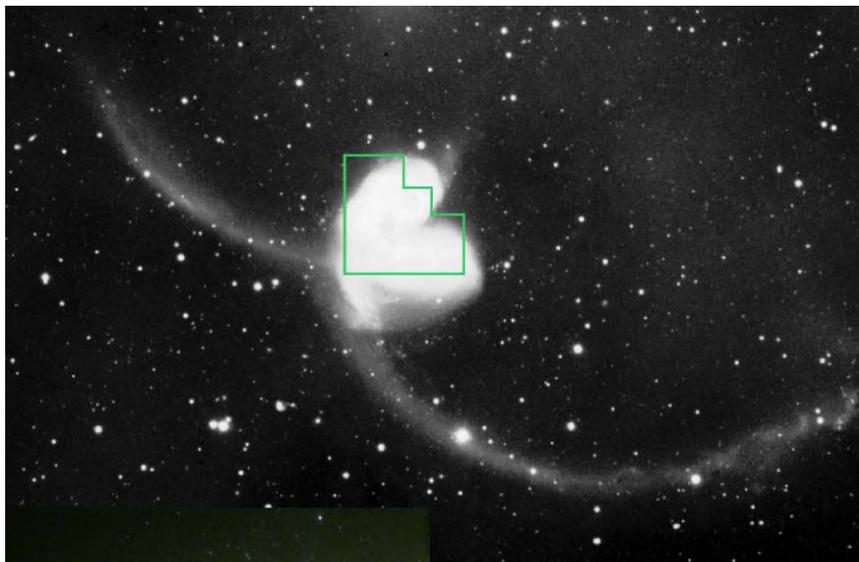
Mid-IR in contour
CO velocity in color

Keto, Ho, Lo 2005

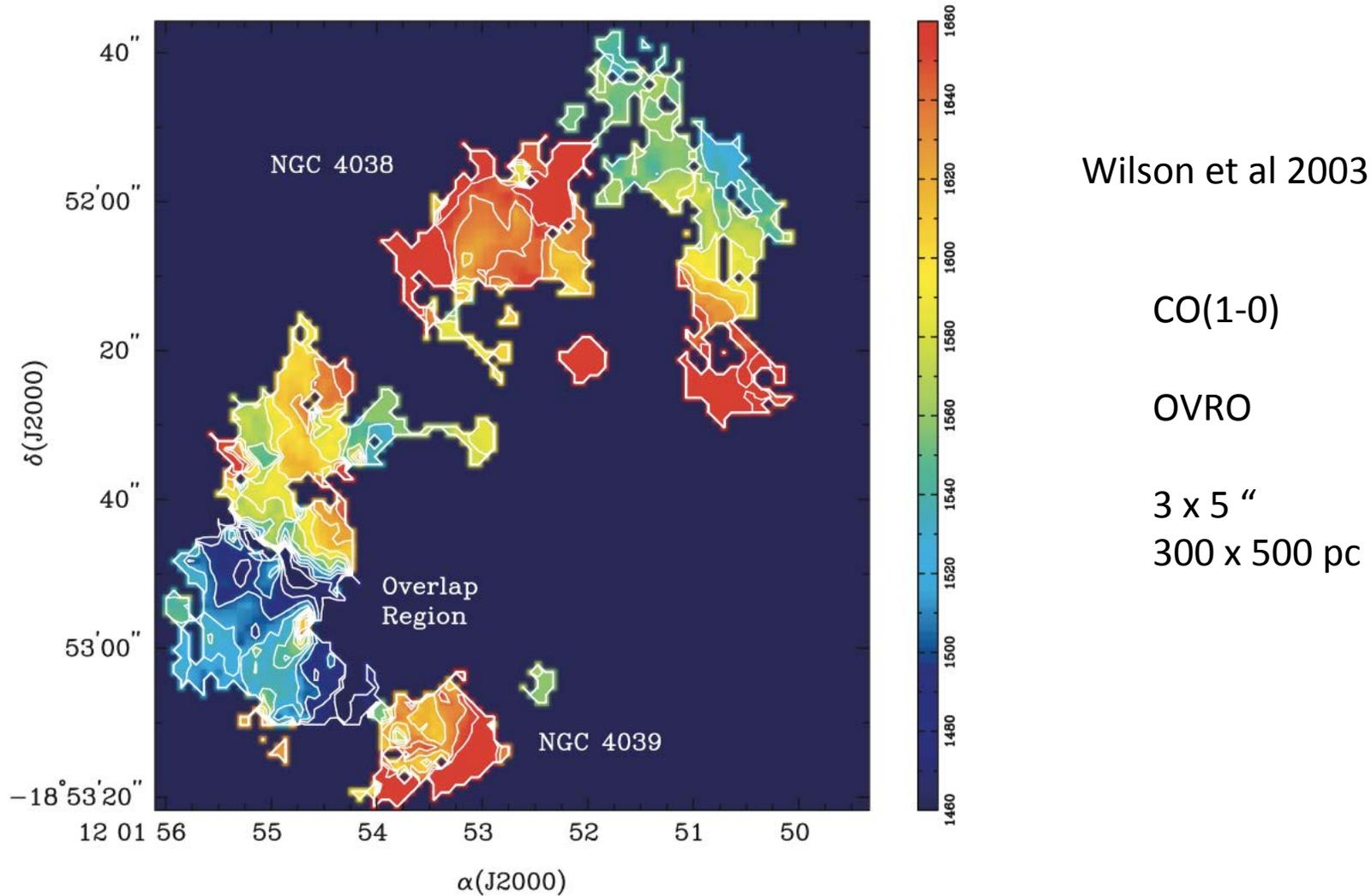
CO spectra of SF clouds show compression in inverse P-Cygni profile



Merging pair NGC 4038/39 Antennae galaxies



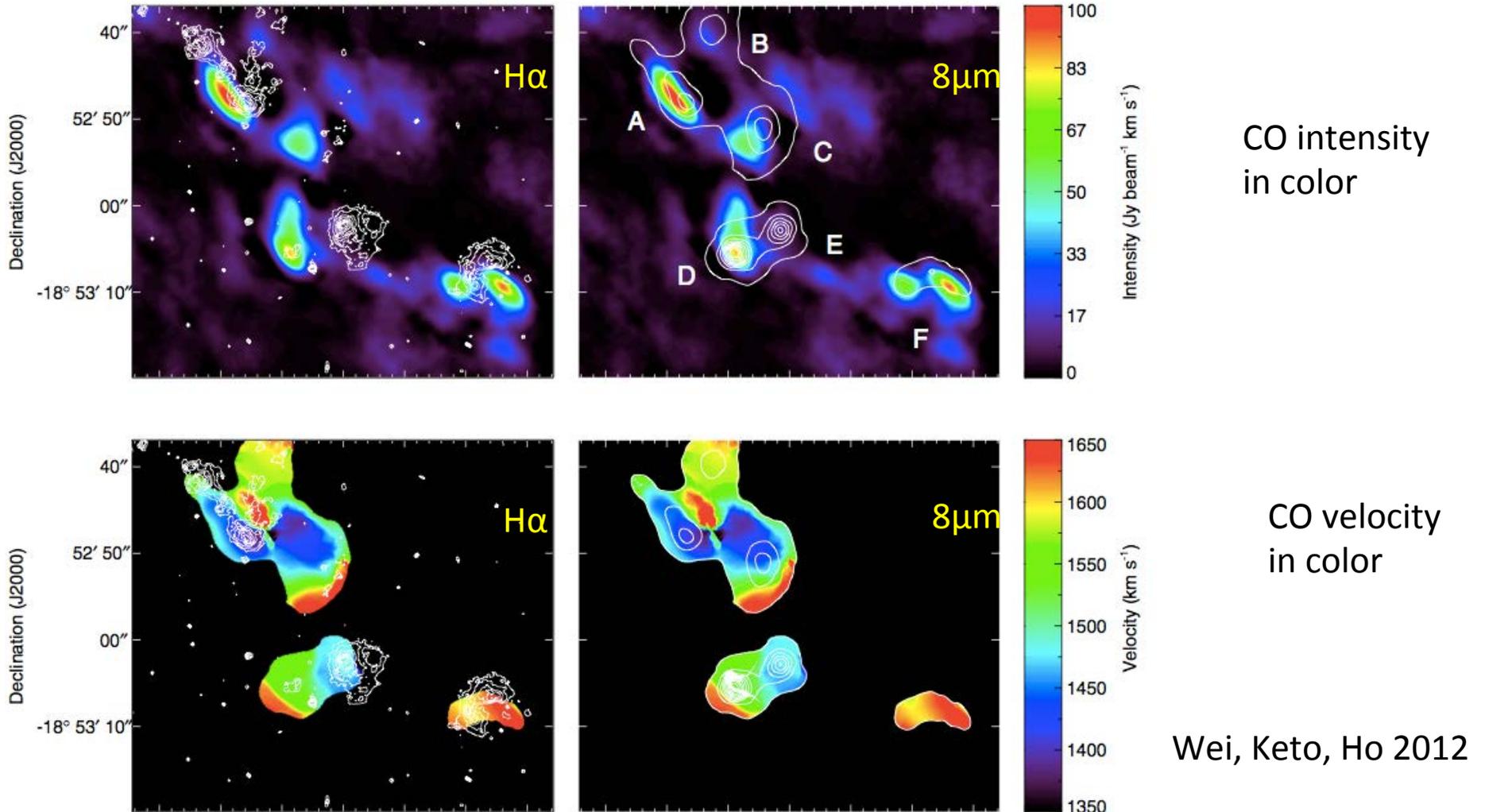
Compression in overlap region seen in CO velocities



Target the overlap region with the PdBI and
SMA



SF ($H\alpha$ and $8\mu\text{m}$) better correlated with V than I

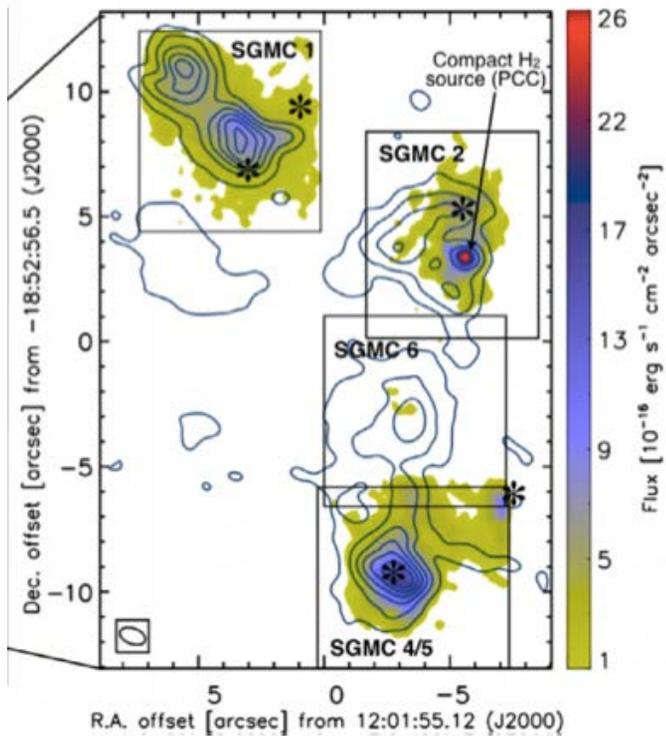


H₂ S(1) and CO(3-2)

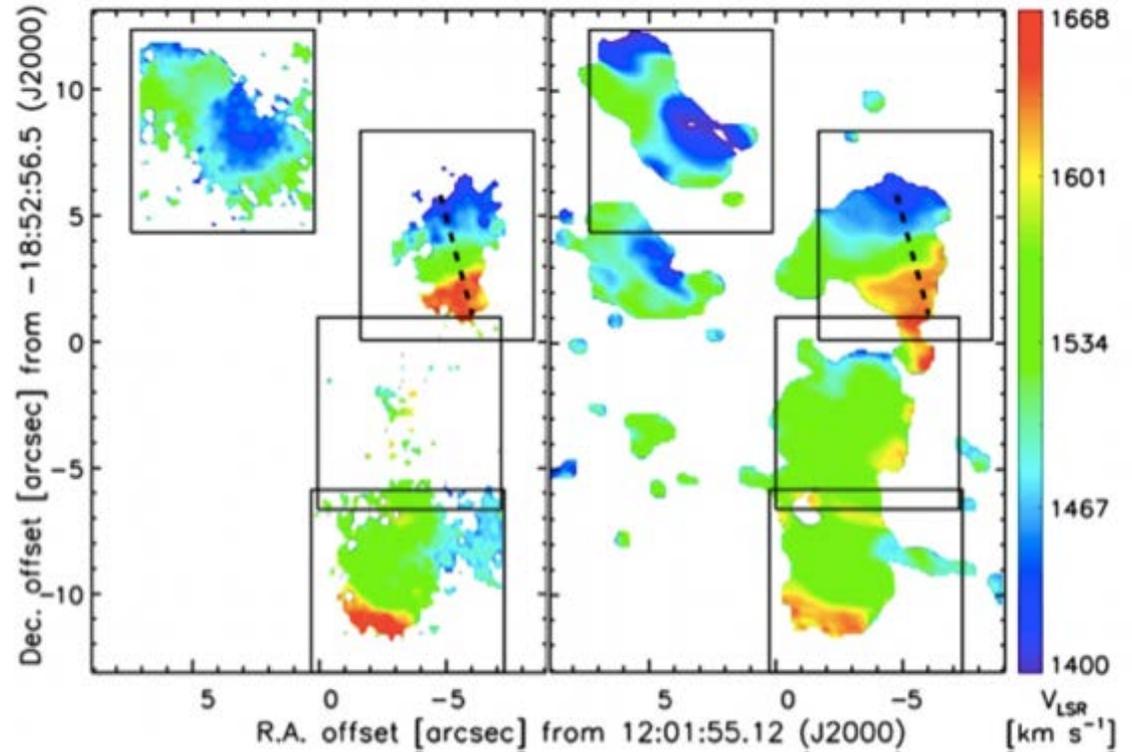
Cinthyra Herrera's poster #81

Intensities

Velocities



Herrera 2010



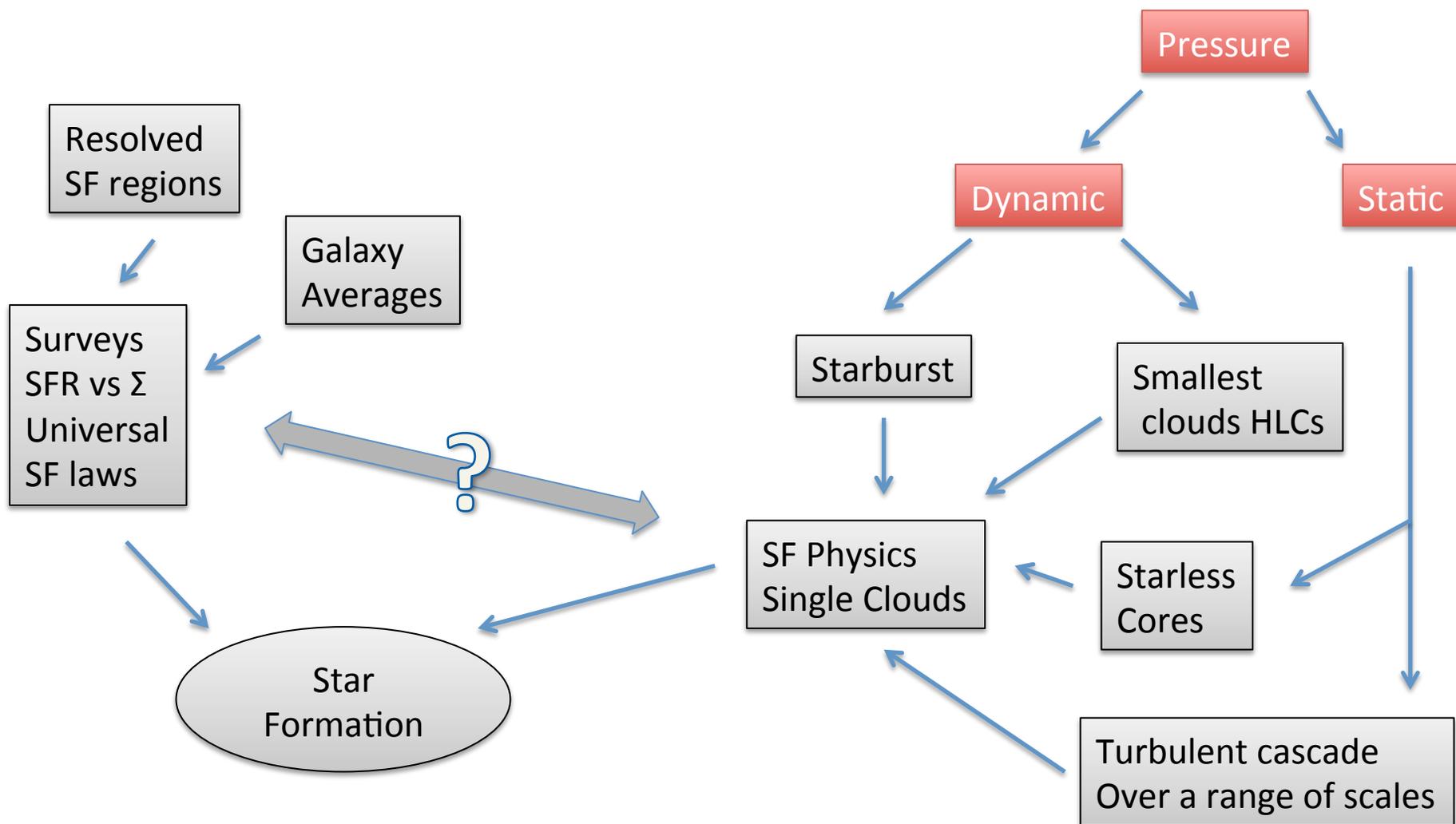
H₂ S(1)

CO(3-2) from ALMA

Hypothesis for Starbursts

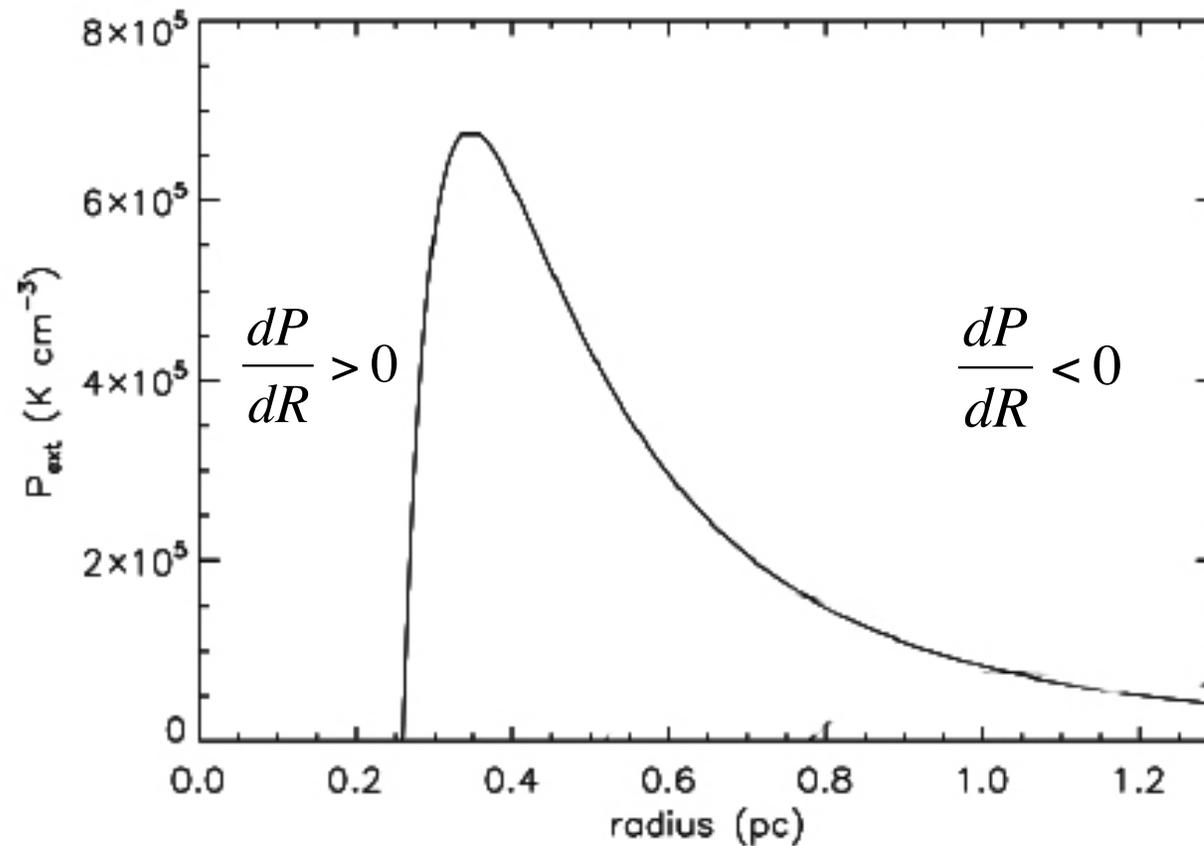
- Velocity gradients within star-forming GMCs indicate compression rather than shear.
- Increased dynamic pressure results in rapid star formation and starbursts
- Question: How is pressure implicated in SF?
 - Commonly “virial parameter” = Kinetic / Gravitational
 - Galactic clouds are better described when the external pressure is included.

Pressure



Pressure, stability, and collapse

$$3M\sigma^2 - \frac{\Gamma GM^2}{R} - 4\pi P_e R^3 = 0$$

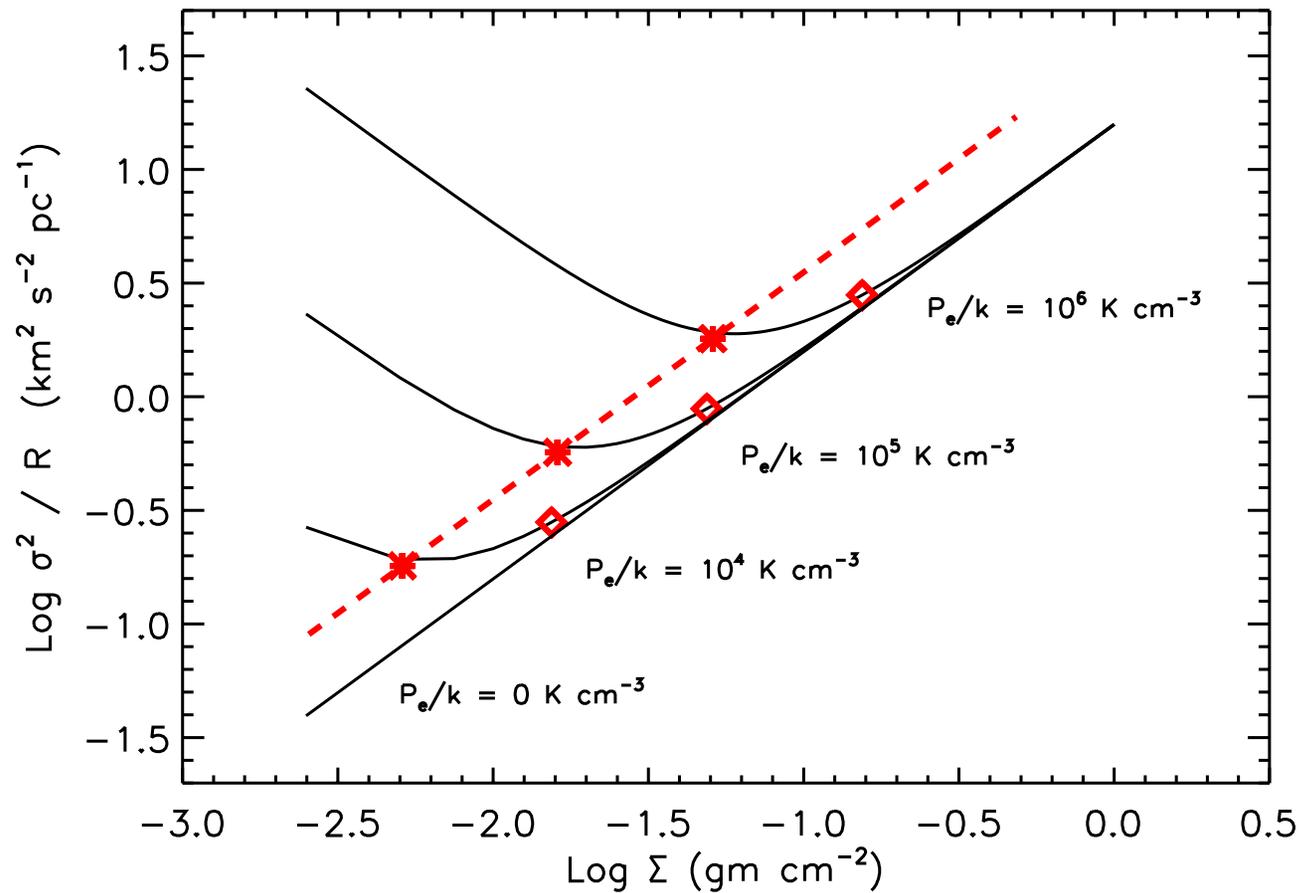


Virial equation
with external pressure

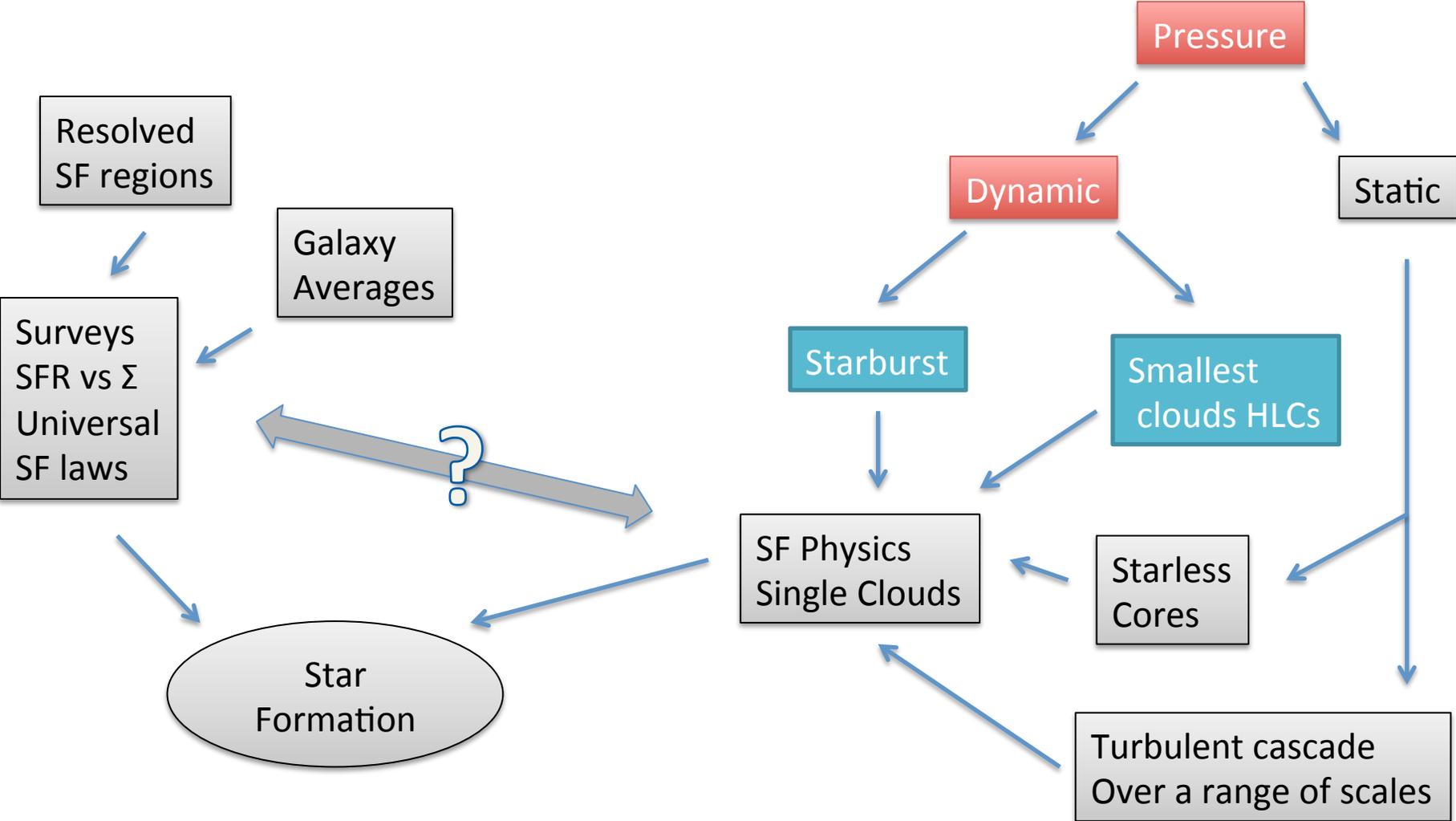
$$3M\sigma^2 - \frac{\Gamma GM^2}{R} - 4\pi P_e R^3 = 0$$

$$\frac{3\sigma^2}{R} = \Gamma GN + \frac{4\pi P_e}{N}$$

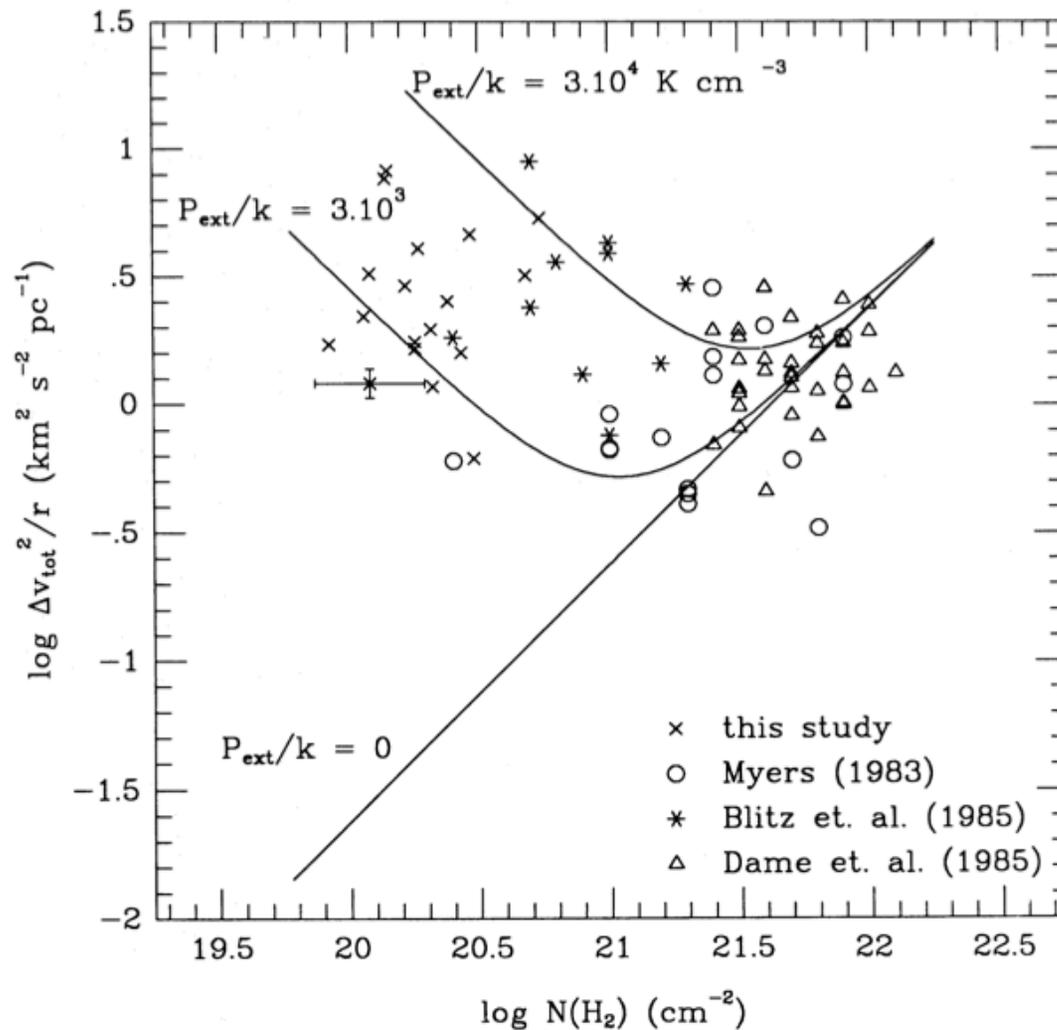
The star formation threshold



Dynamic pressure controls the largest clouds in starbursts and the smallest clouds in our Galaxy



High Latitude Clouds



Very low density clouds discovered as “IR cirrus” by IRAS satellite.

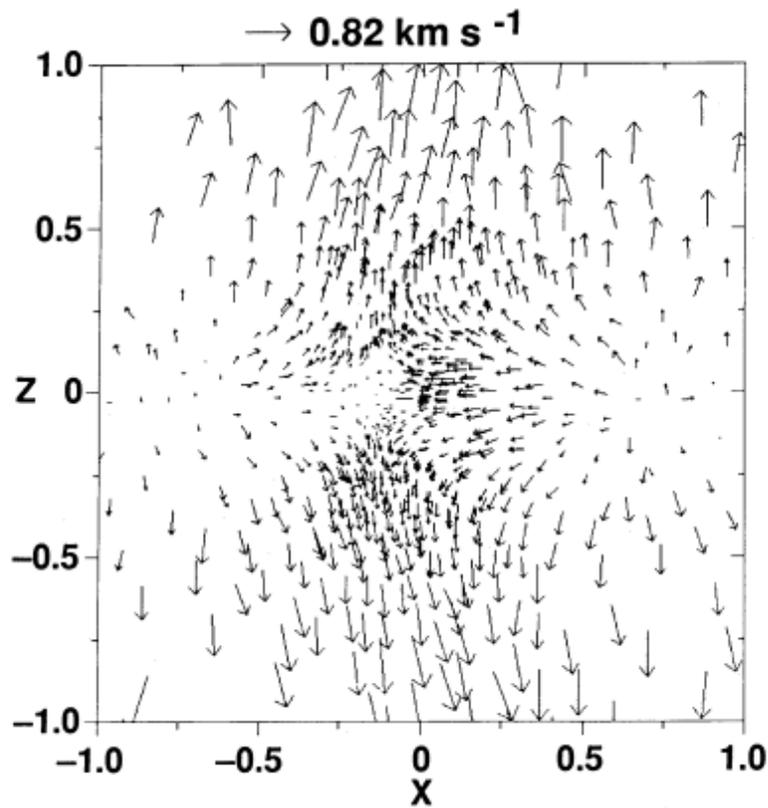
They exist in the turbulent atomic HI.

Too little mass to be gravitationally bound.

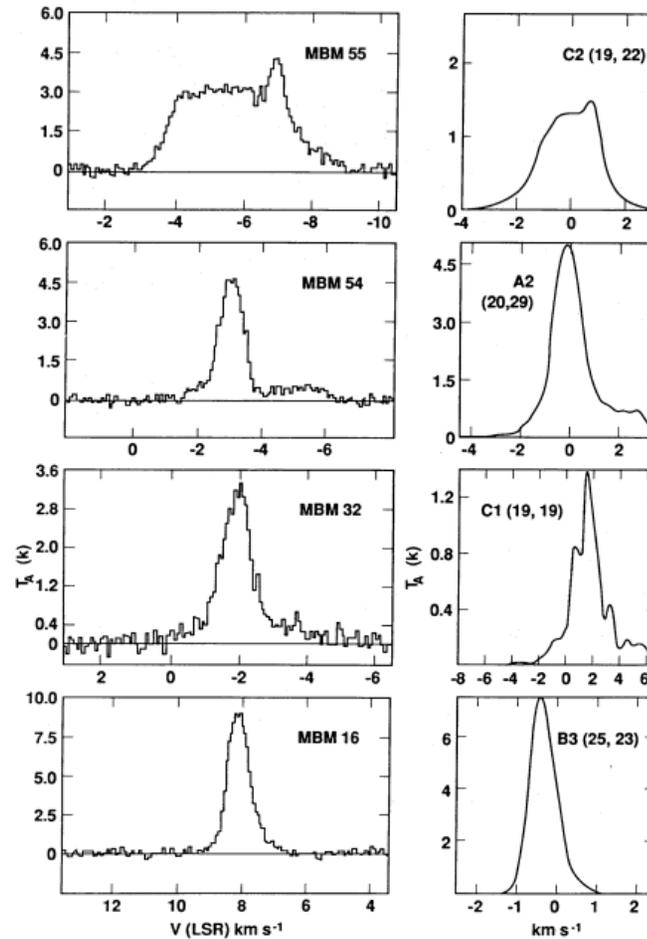
Why do they exist at all?

Keto & Myers 1986

HLCs as converging flows

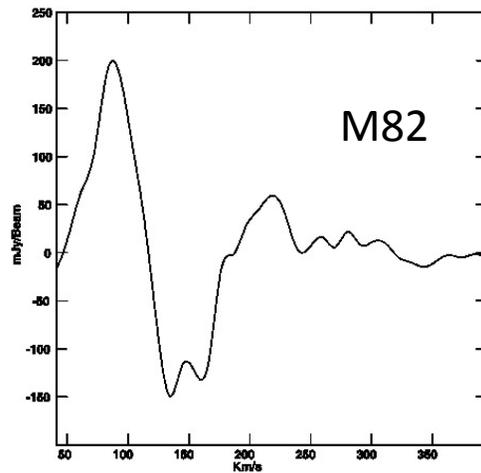
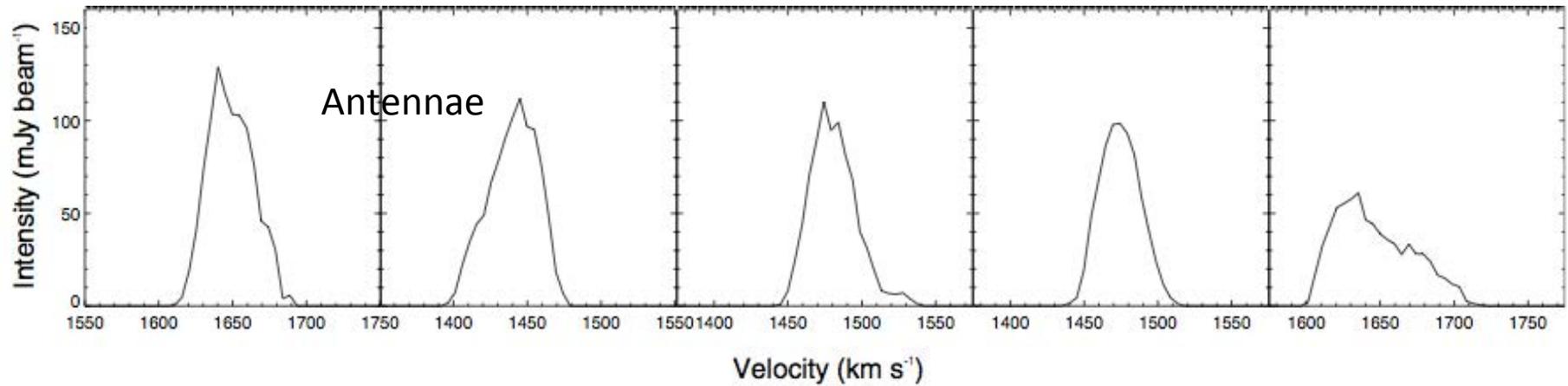


Keto & Lattanzio 1989



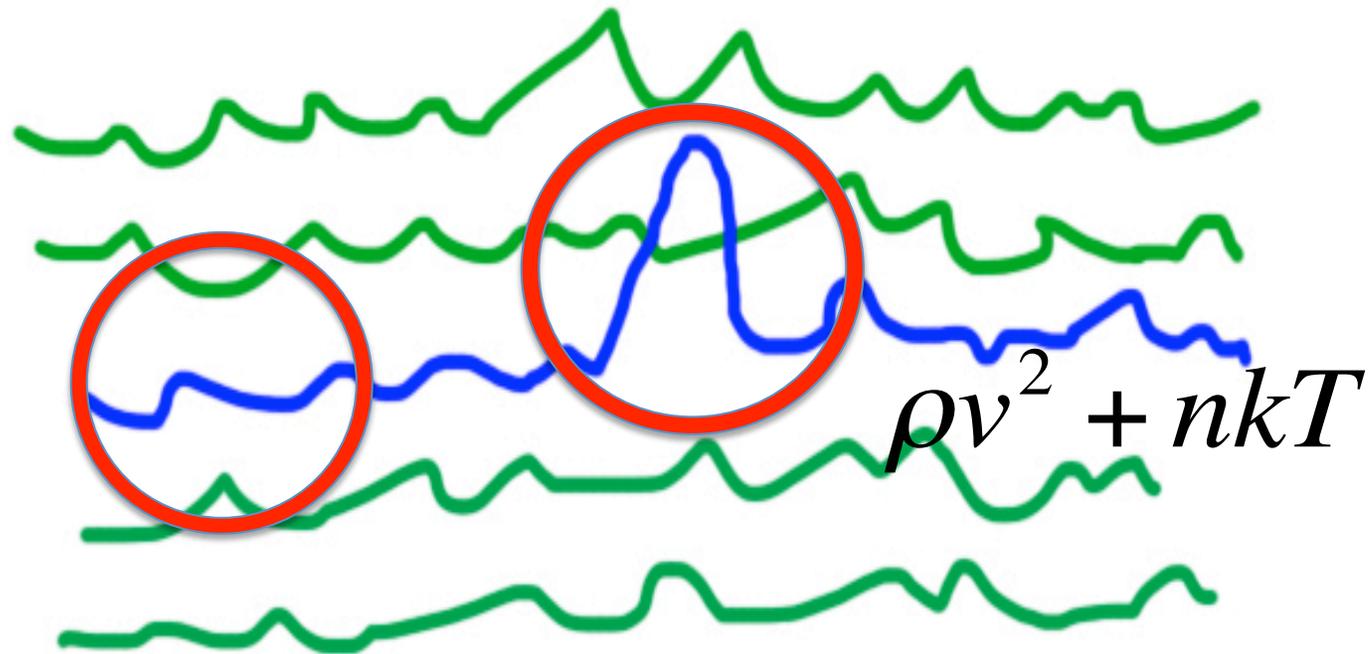
Mollie
25 yrs

Starburst clouds have line widths $\sim 100 \text{ km s}^{-1}$
requiring external origin for the velocities



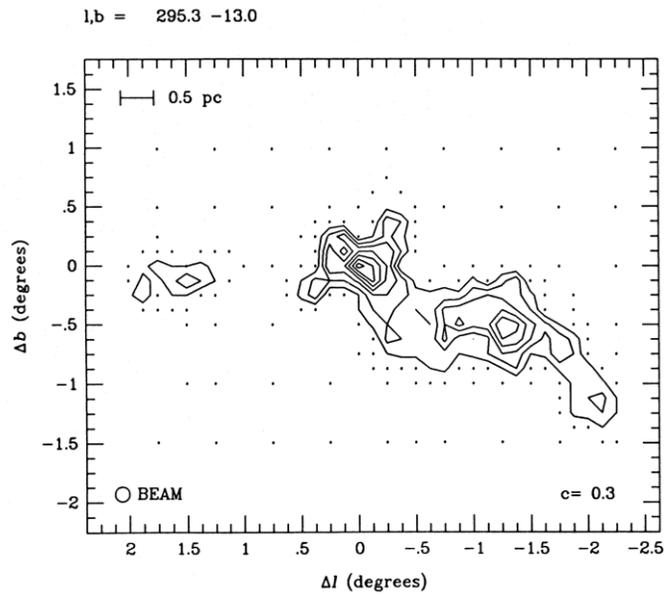
Keto, Ho, Lo 2005
Wei, Keto, Ho 2012

The virial equation applied to non-equilibrium indicates a distribution or virialization of energy

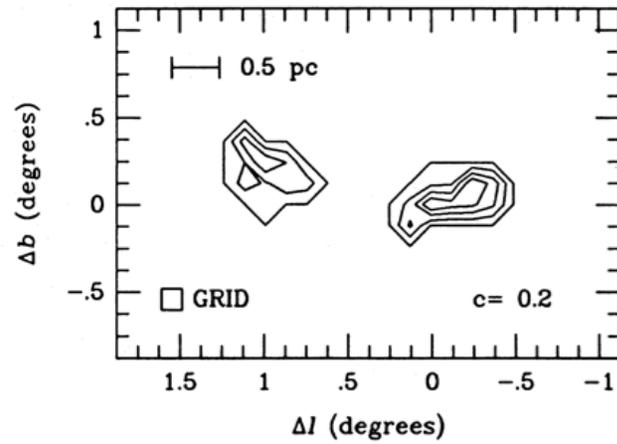


$$P = \text{energy} / \text{volume}$$

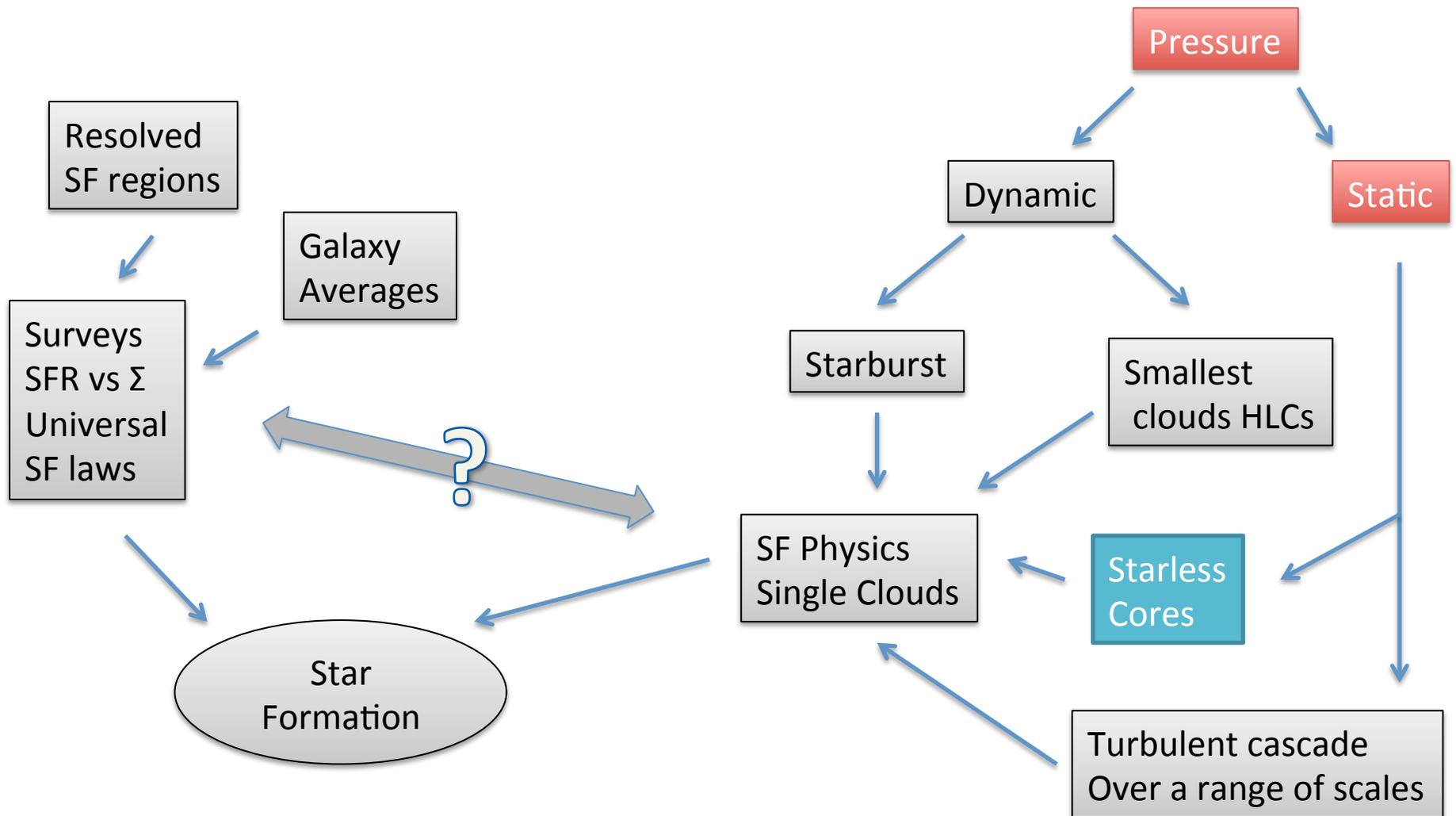
Recognizable clouds within turbulence



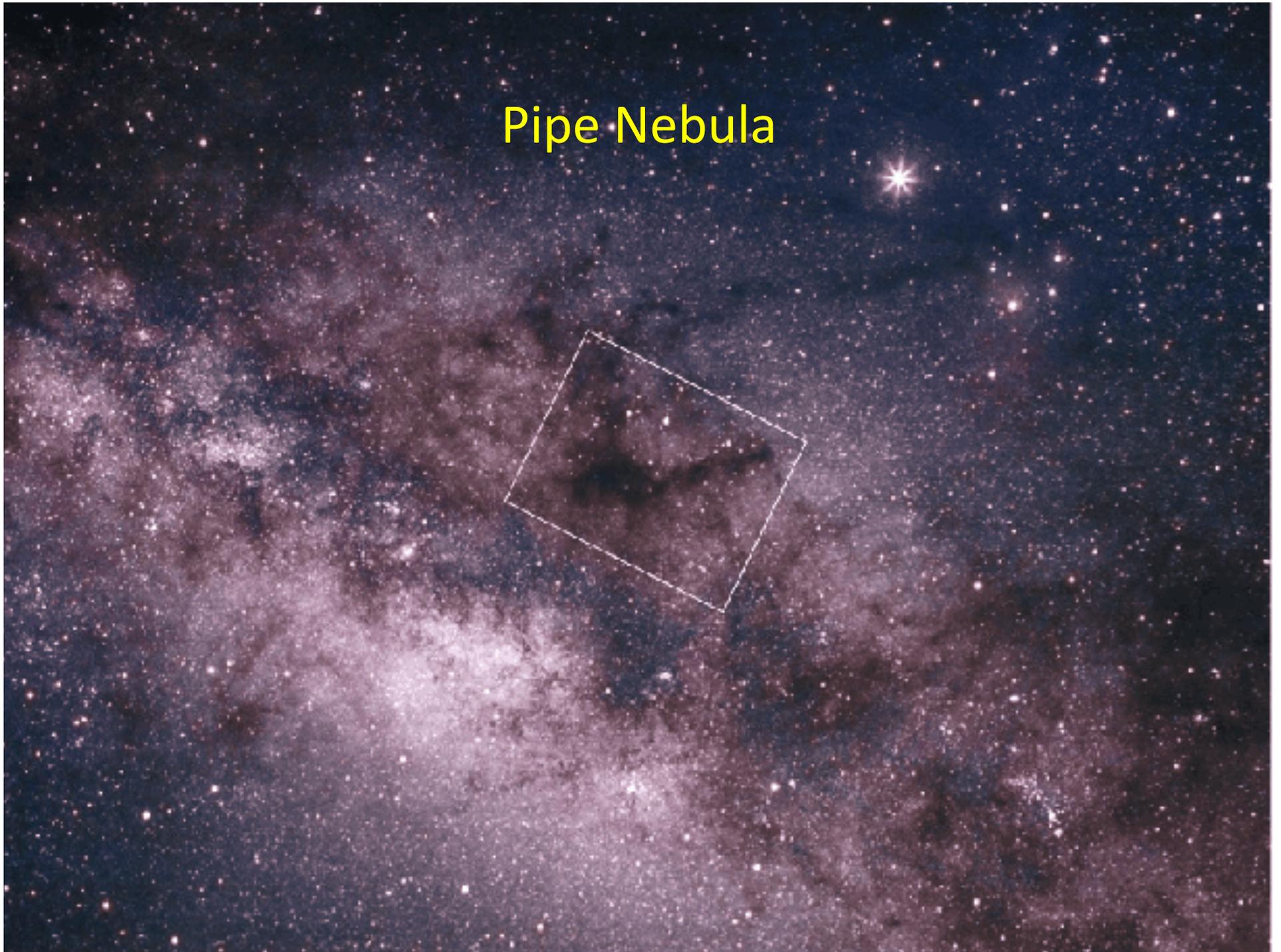
Keto & Myers 1986



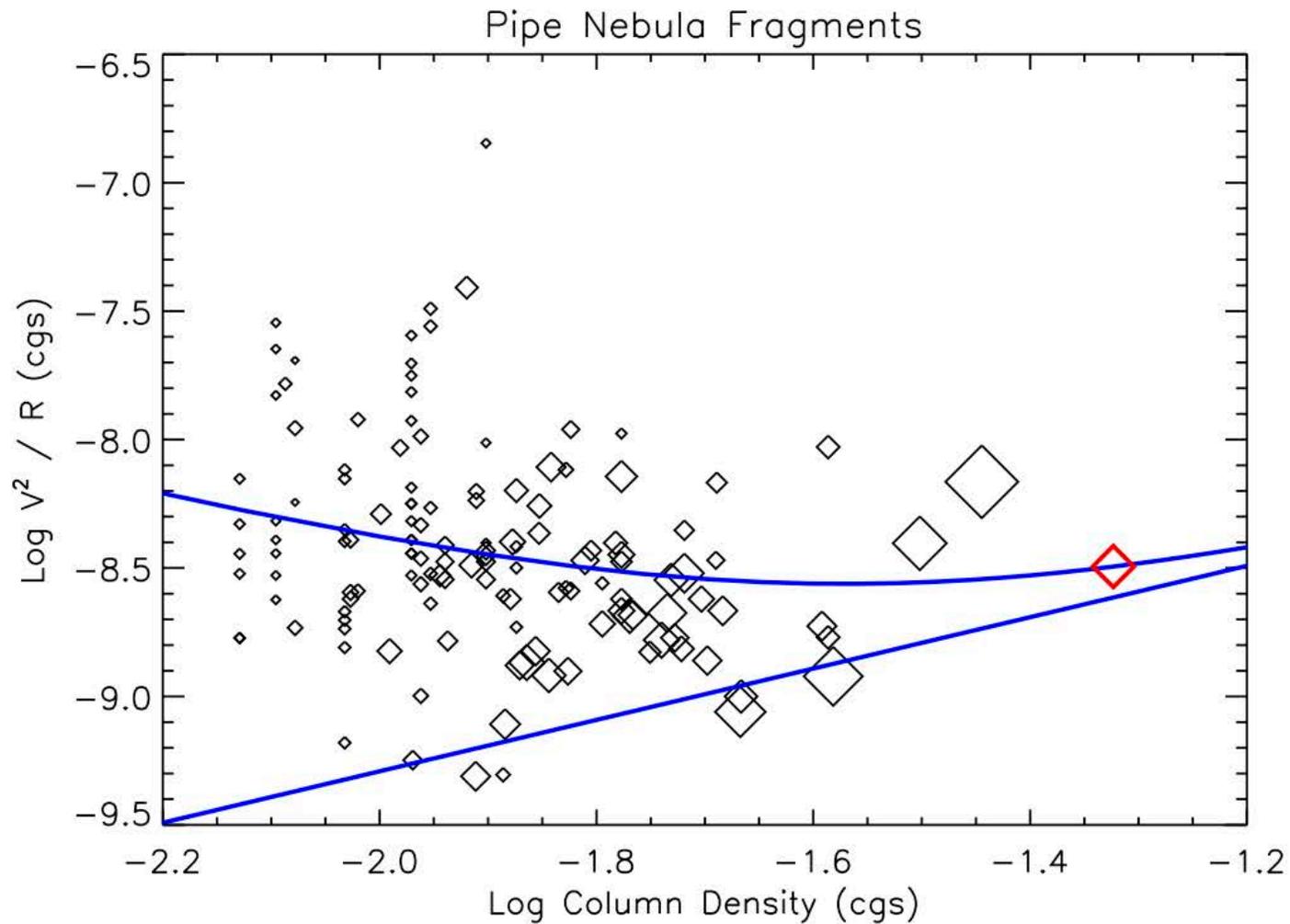
The starless cores exist within a static pressure



Pipe Nebula

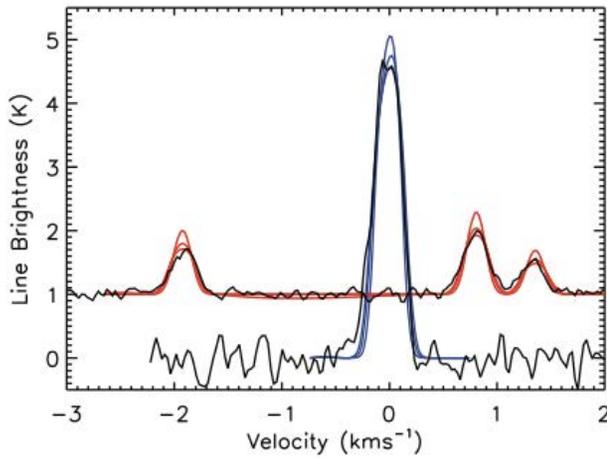


Small starless cores in Pipe



Data from Jill Rathborne, Charlie Lada, Jan Forbrich

Starless cores have sonic line widths

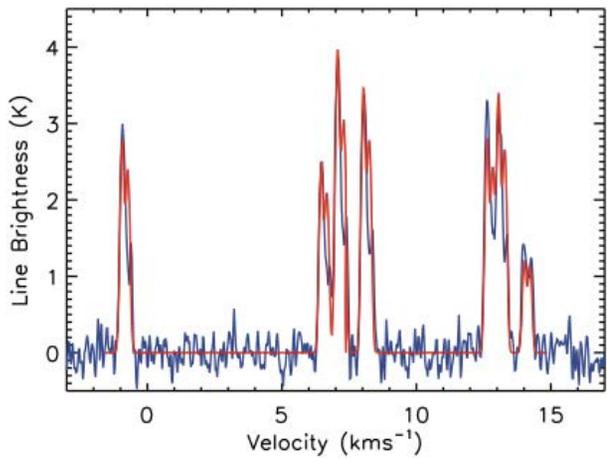


C¹⁸O

L1544

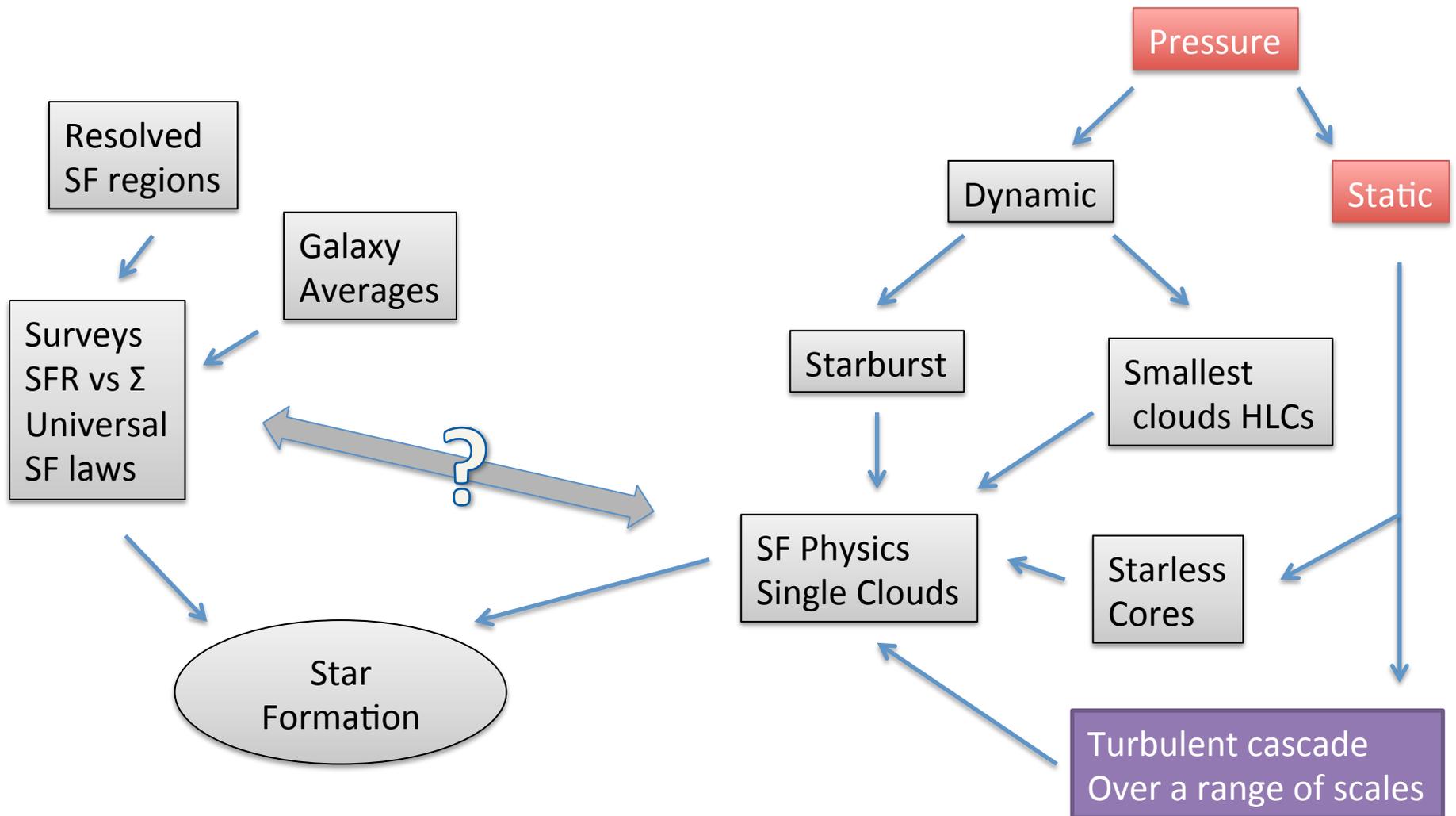
C¹⁷O

Keto & Caselli 2010

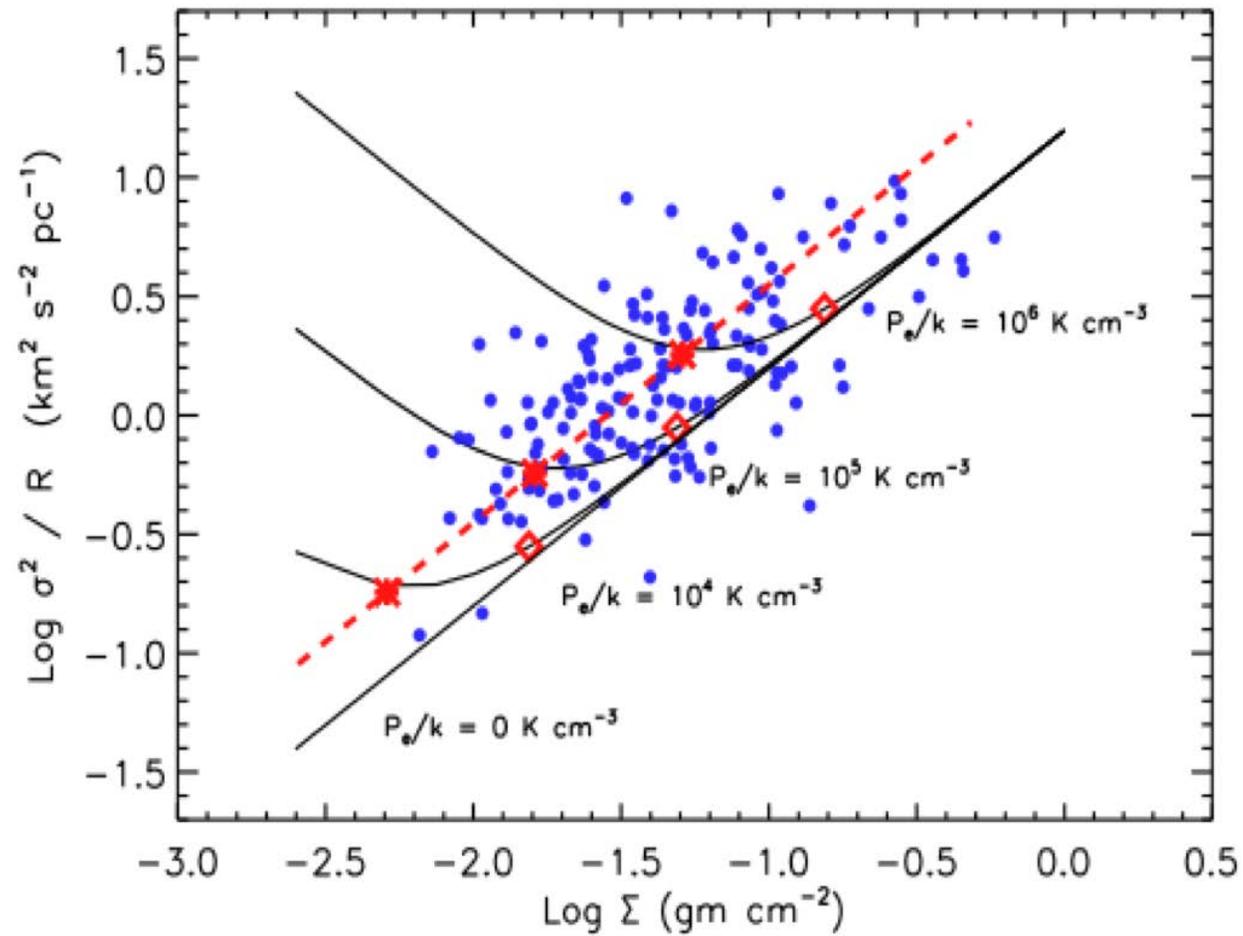


N₂H⁺

Galactic molecular clouds $10 - 10^6 M_{\odot}$ in the supersonic turbulent cascade

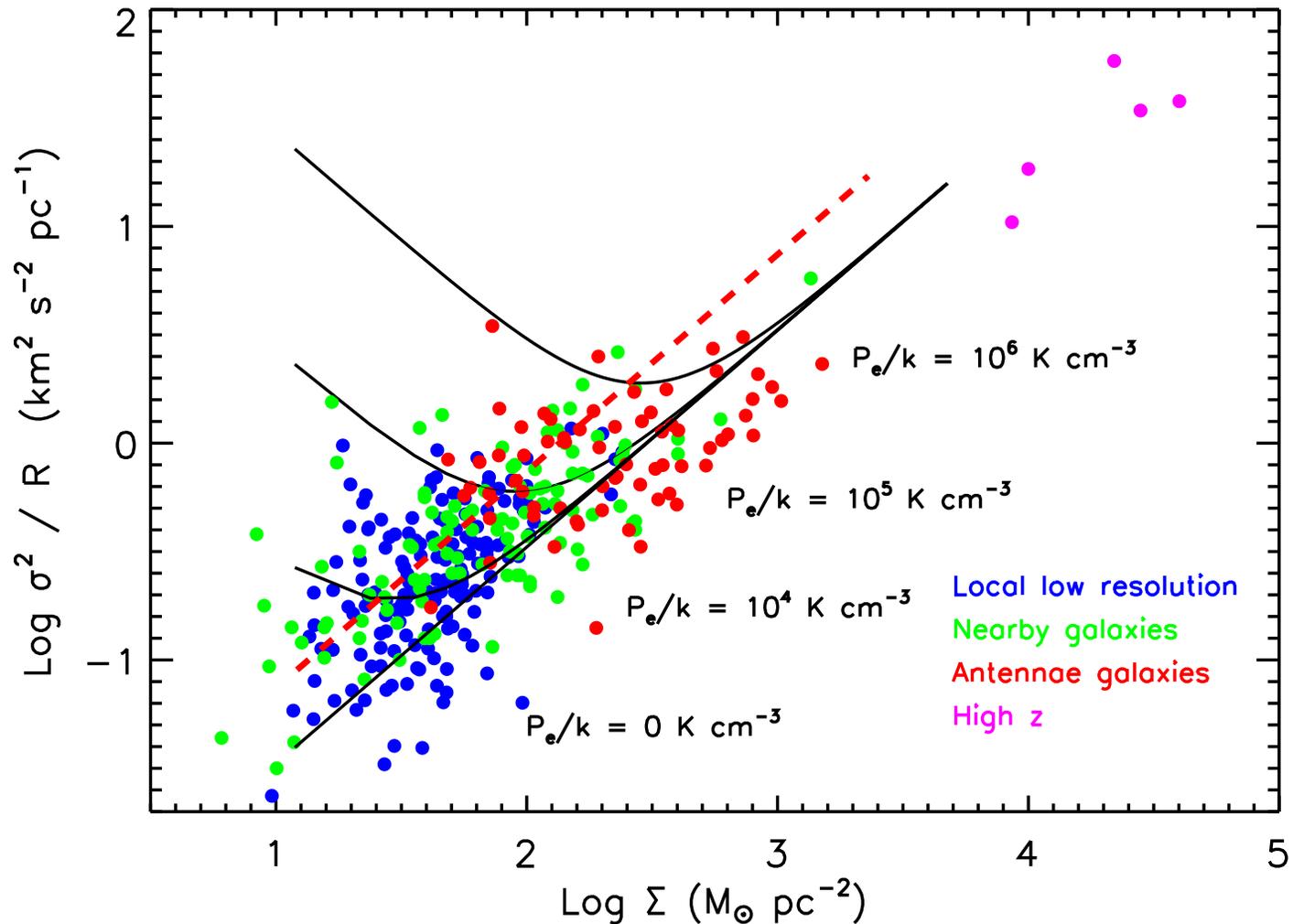


Galactic clouds



Field, Blackman & Keto 2011
data from Heyer (2009)

Higher pressure-density in starbursts

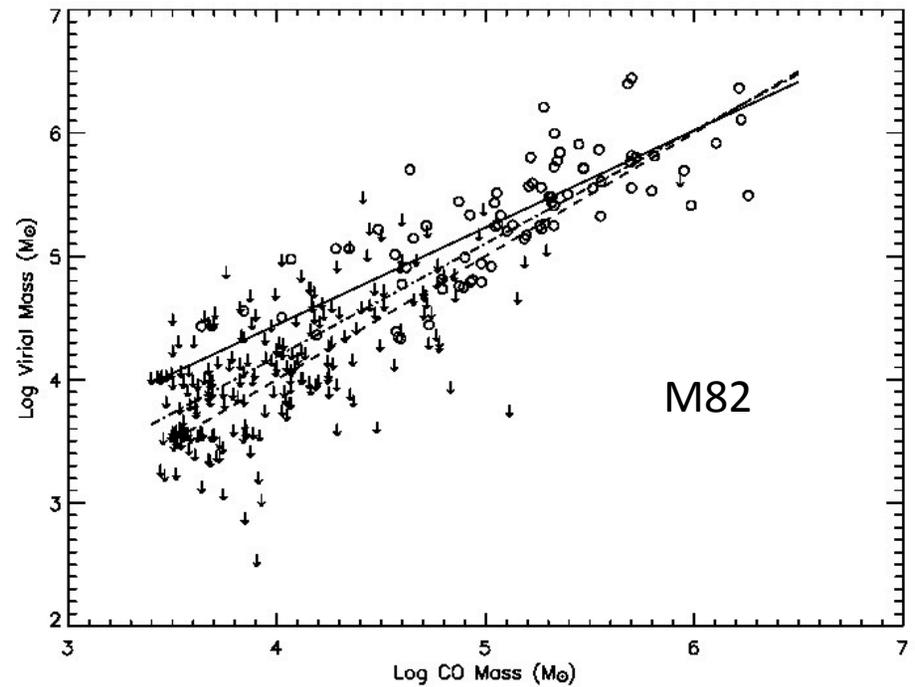
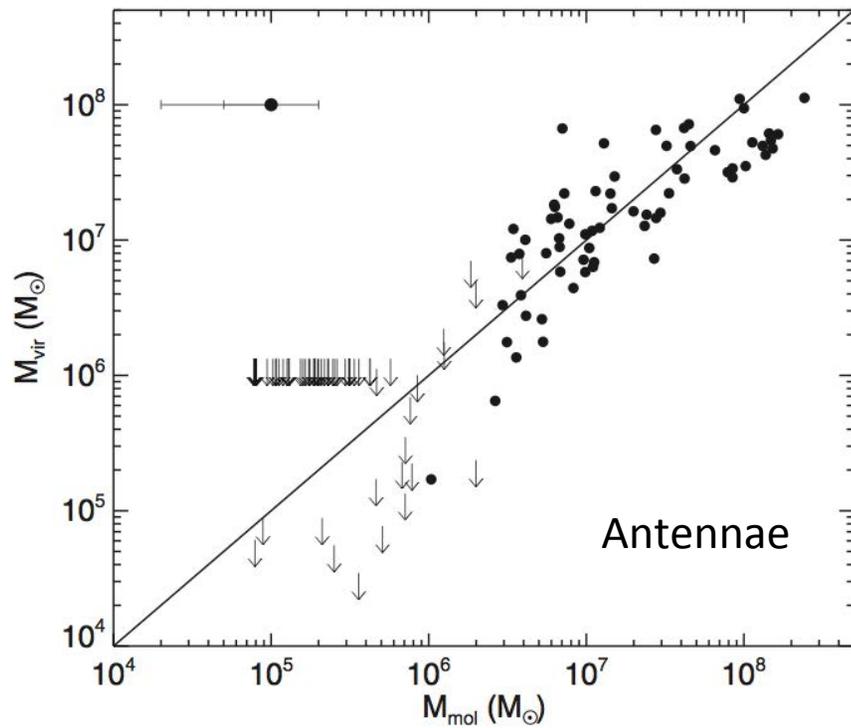


- Data from Longmore & Kruijssen 2013; Heyer 2009; Bolatto et al 2008; Wei, Keto, Ho 2011

Time scale for star formation

- Now that we have assembled the clouds, we need to form the stars.
- Two possible time scales:
 - Turbulent dissipation => crossing time
 - Free fall time
- If the clouds are virialized, these time scales are the same by definition.

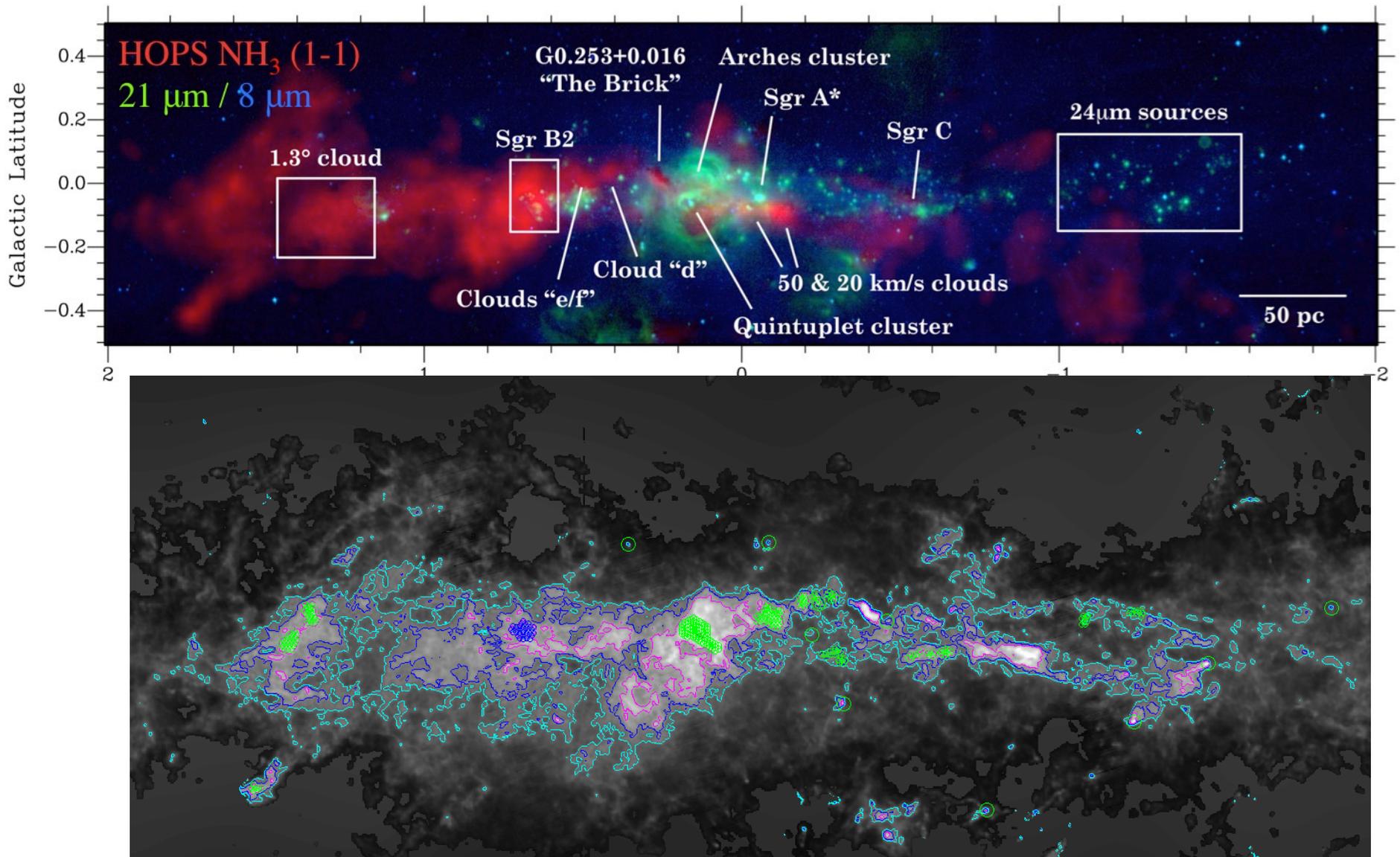
Approximate virialization in observations with cloud scale angular resolution



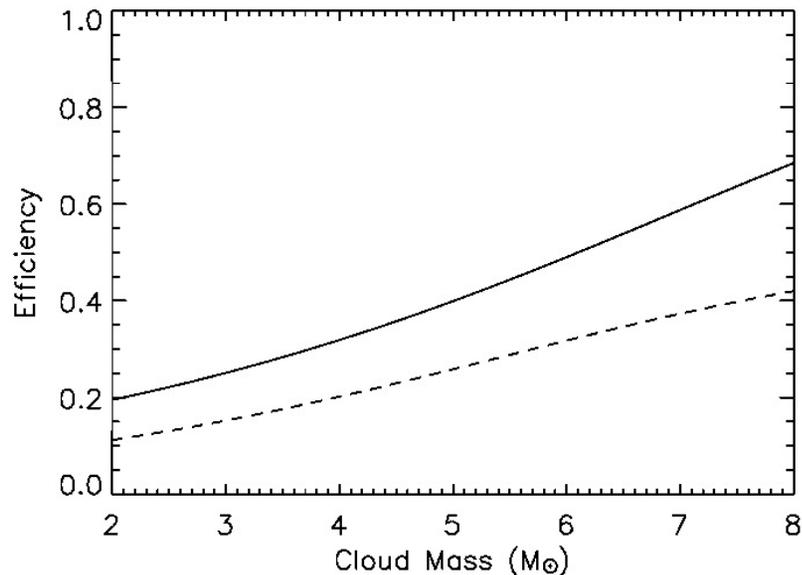
Conclusions (Hypothesis)

- 1) Universal star formation laws attempt to unify the SF process on all scales.
- 2) SF processes in Galactic clouds and in Starbursts are very different.
- 3) The concept of virialization including external pressure describes clouds across a range of scales from 1 to $10^8 M_{\odot}$.
- 4) Star formation takes place in a crossing time.
- 5) Universal star formation laws are universal to the extent that the environmental conditions are universal.

SMA CMZ survey



High efficiency to prevent cluster dispersal by stellar feedback



Already at 160 x Galactic pressure

gas depletion

SFR

dispersal

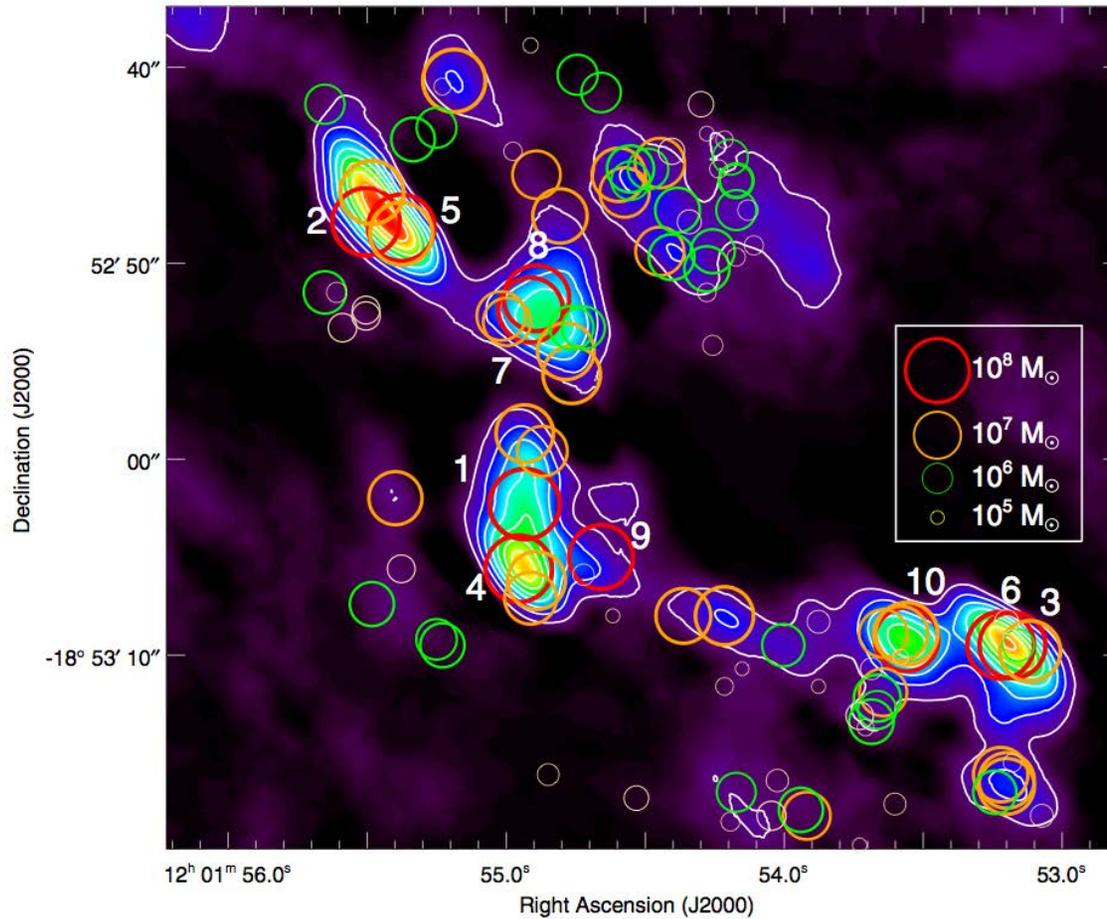
$$\frac{dM_c}{dt} = - \frac{dM_s}{dt} - \beta \frac{L}{a^2}$$

$$\frac{dM_s}{dt} \propto \rho^{1.5}$$

Schmidt law
SFR

Keto, Ho, Lo 2005

Molecular Clouds in CO(2-1)



CO(2-1)

PdBI + SMA

1.5 x 3 "

150 x 300 pc