Molecular Clouds: a Collapsing Paradigm

star-forming

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IRyA

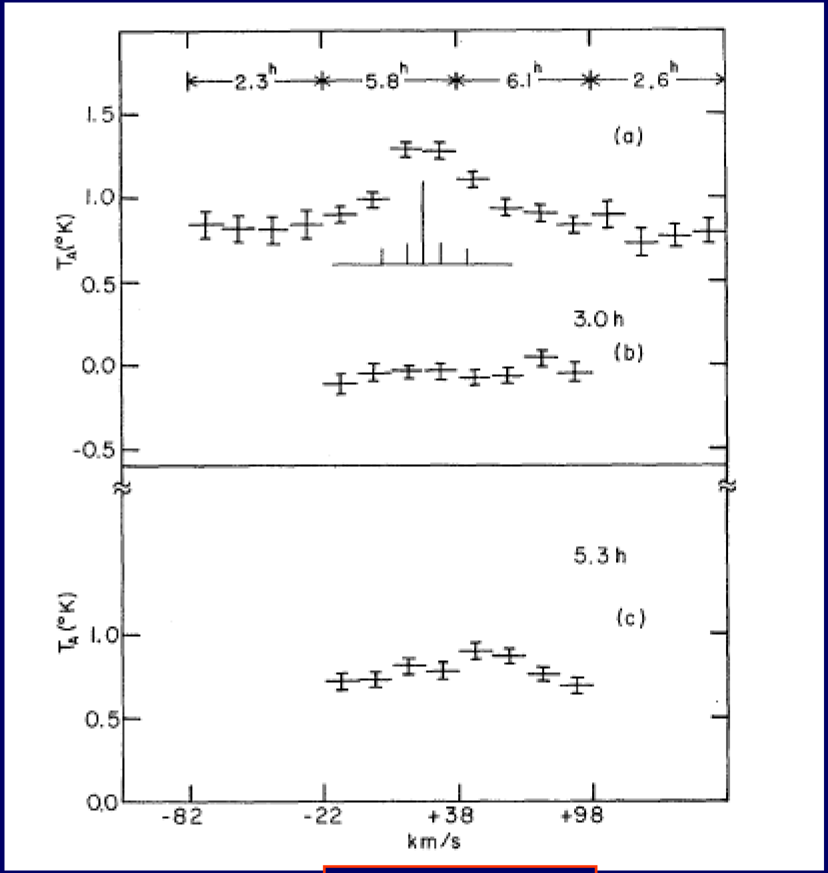
- Outline:
  - Discovery of molecular lines and early ideas.
  - The magnetic support paradigm.
    - Motivation
    - Basic principles
    - Control of star formation
  - The turbulent support paradigm.
    - Motivation
    - Basic principles
    - Control of star formation
  - The collapsing paradigm.
    - Motivation
    - Basic principles
    - Control of star formation

I. A BIT OF HISTORY…

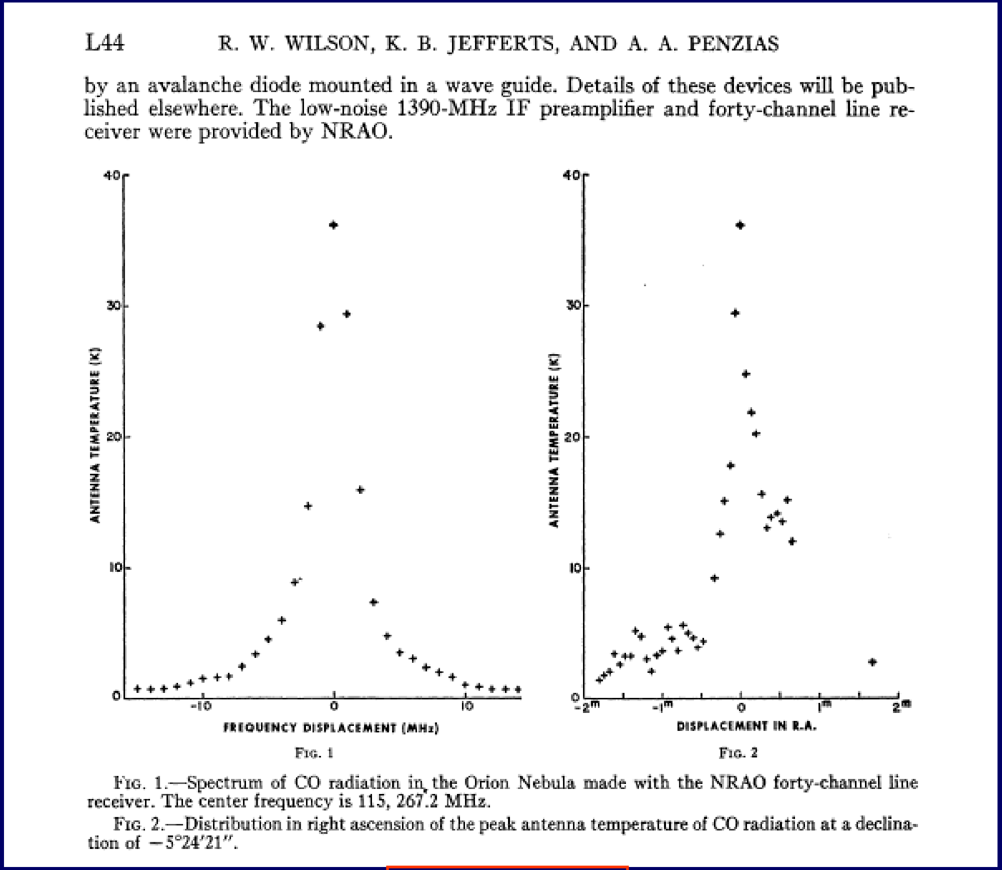
- First molecular line detections ca. 1970

NH$_3$

^{12}CO



Cheung+68



L44 R. W. WILSON, K. B. JEFFERTS, AND A. A. PENZIAS

by an avalanche diode mounted in a wave guide. Details of these devices will be published elsewhere. The low-noise 1390-MHz IF preamplifier and forty-channel line receiver were provided by NRAO.

Fig. 1

Fig. 2

Fig. 1.—Spectrum of CO radiation in the Orion Nebula made with the NRAO forty-channel line receiver. The center frequency is 115, 267.2 MHz.

Fig. 2.—Distribution in right ascension of the peak antenna temperature of CO radiation at a declination of −5°24′21″.

Wilson+70

- Supersonic linewidths.

- The debate begins:
  - “Molecular clouds are undergoing large(cloud)-scale radial motions” (possibly gravitational collapse):
    - Liszt+74:
      - Peaks of ^{12}CO emission in molecular clouds (MCs) often coincide with HII regions and IR objects (YSOs).
      - ^{12}CO lines are not self-reversed
      - Explainable if ^{12}CO allows viewing all the way through clouds, column density traces volume density, and MCs are undergoing systematic radial motions $v \sim r$ (to avoid self-absorption).
    - Goldreich & Kwan 74:
      - Turbulence dissipates quickly ➔ loss of support.
      - MC masses much larger than the Jeans mass

        ➔ collapse.

- “Molecular clouds CAN’T be dominated by large(cloud)-scale radial motions” (including gravitational collapse):
  - Zuckerman & Palmer 74:
    - If they were, the SFR would be much larger than observed:
      - Free-fall estimate of SFR:

$$\mathrm{SFR}_{\mathrm{col}} \sim \frac{M_{\mathrm{mol}}}{\tau_{\mathrm{ff}}} \sim \frac{10^9\ M_{\mathrm{sun}}}{3\ \mathrm{Myr}} = 300\ M_{\mathrm{sun}}\,\mathrm{yr}^{-1}$$

Observed rate is $\mathrm{SFR}_{\mathrm{obs}} \sim 2$—3 $\mathrm{M}_{\mathrm{sun}}\ \mathrm{yr}^{-1}$; i.e., ~100x lower.

  - Zuckerman & Evans 74:
    - If clouds were undergoing radial contraction, should observe systematic shifts between emission lines from central HII regions and absorption lines from the outer envelopes. Not observed.

      ➔Proposed that supersonic linewidths come from ***small-scale*** turbulent motions, rather than large-scale radial motions.
    - Collapse of MCs was dismissed.

- Next, came Larson's (1981) relations:

But see Kegel 1989, Scalo 1990 for criticisms (and sec. IV below)

h-size

^{28}

m s^{-1}

Density-size

$$\langle n \rangle \approx 3400 \left(\frac{L}{\text{pc}} \right)^{-1.1} \text{cm}^{-3}$$

➔Σ ~ nL = cst.

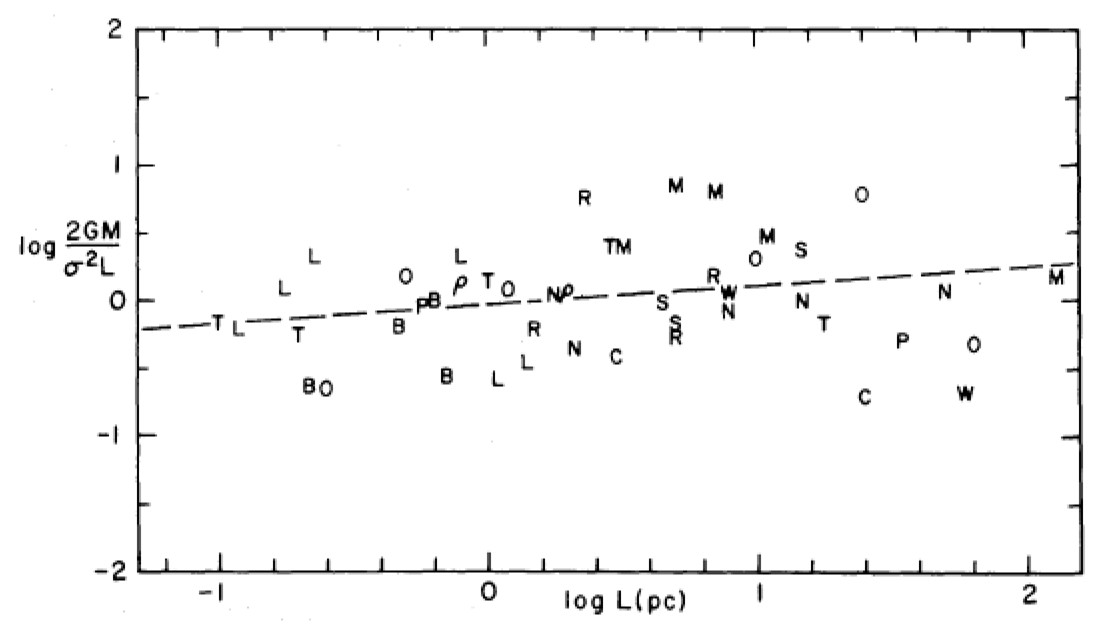
Larson 1981

- Which, together, imply approximate virial equilibrium:

$$2E_k = |E_g|$$

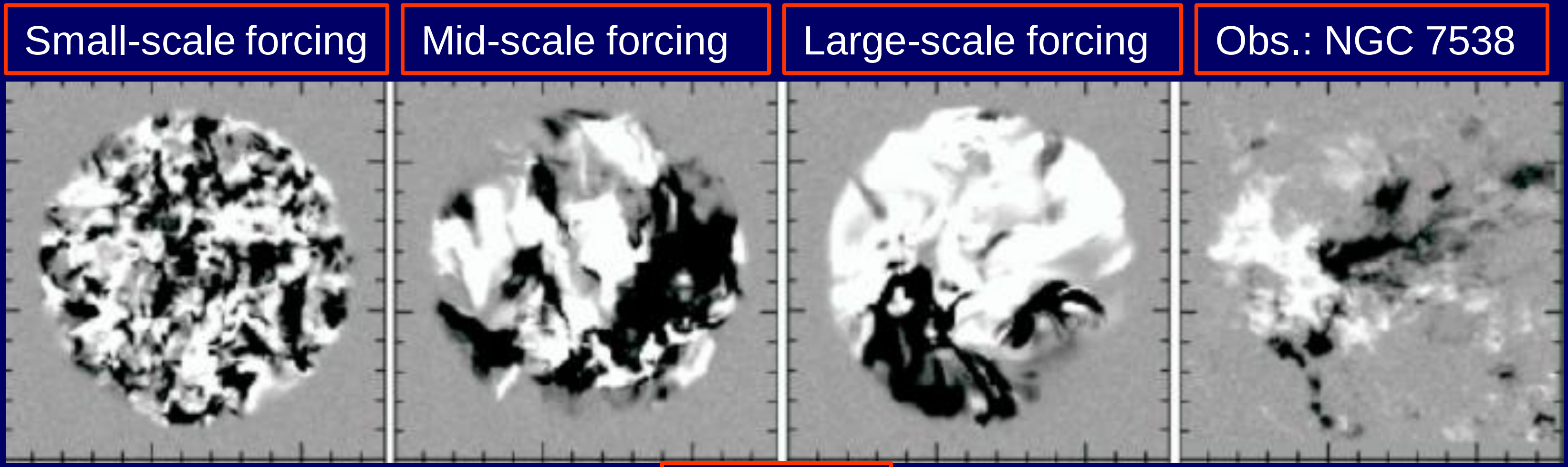
$$\Rightarrow \quad \sigma_v^2 \approx \frac{GM}{R}$$

$$\Rightarrow \quad \frac{GM}{\sigma_v^2 R} = \text{cst.}$$



Larson 1981

- Since then, the paradigm has been that MCs are in approximate virial equilibrium between their nonthermal motions and their self-gravity.
  - However, not often realized that the paradigm required small-scale (compared to cloud scale) turbulent motions.
    - Contrary to present-day understanding of MC turbulence: largest velocities at largest scales.



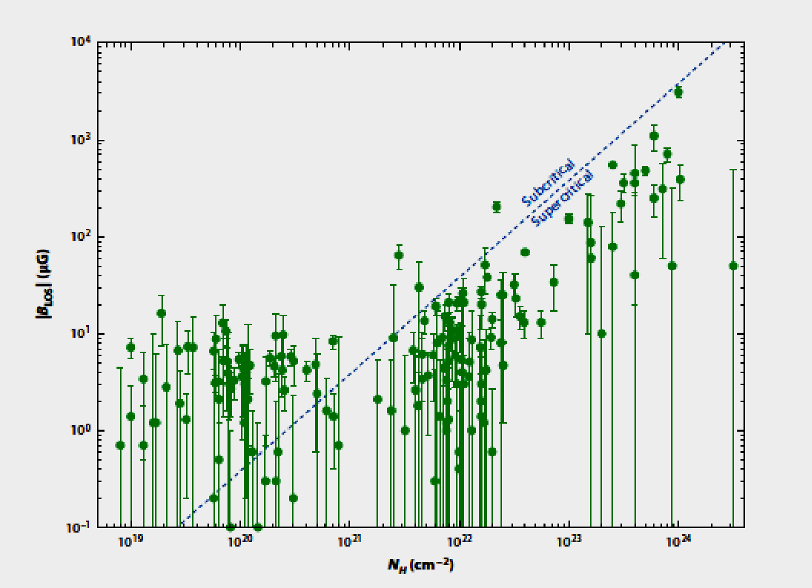
Brunt+09

II. THE MAGNETIC SUPPORT PARADIGM

- The magnetic-support paradigm.
  - In the 1980s and 90s, the nonthermal motions were interpreted mainly as MHD waves (Shu+87; Mouschovias 91):
    - Thought to be less dissipative (especially Alfvén waves) than hydrodynamic supersonic turbulence (which causes shocks).
    - The mean magnetic field could support the clouds if the latter are generally magnetically subcritical.
    - In subcritical MCs, collapse thought to occur on long timescales (~ 10 t_{ff}) through ambipolar diffusion (AD).

- The magnetic-support paradigm (cont'd).
  - Early Zeeman measurements of B field suggested approximate magnetic and gravitational energy equipartition (Myers & Goodman 88; Crutcher 99).
  - A bimodal scenario of SF (Shu+87):
    - Subcritical clouds <--> low-mass SF (most frequent mode)
      - Global (cloud-scale) magnetic support, low-mass (core-scale) "percolation" through AD.
    - Supercritical clouds <--> high-mass SF (scarce)
      - Global collapse, with slight retardation by magnetic forces.

- The magnetic-support view (cont’d).
  - However, in the late 90s and early 00s evidence began to suggest a departure (see detailed account by Mac Low & Klessen 04):
    - B nondetections as common as detections (Crutcher 99).
    - Detections often indicated that MCs were magnetically supercritical (Bourke+01, Crutcher+10).



A signature of gas accumulation along field lines? (Hartmann+01, Vázquez-Semadeni+11 [but see also Heitsch+04; Lazarian14).

Crutcher 12

- The magnetic-support view (cont’d).
  - However, in the late 90s and early 00s evidence began to suggest a departure (see detailed account by Mac Low & Klessen 04):
    - B nondetections as common as detections (Crutcher 99).
    - Detections often indicated that MCs were magnetically supercritical (Bourke+01, Crutcher+10).
    - Most low-mass stars form in high-mass SF (i.e., magnetically supercritical) environments anyway (Lada & Lada 03).
    - Supersonic MHD turbulence decays just as fast as non-magnetic turbulence, in roughly 1 crossing time (Stone+98; MacLow+98; Padoan+99).

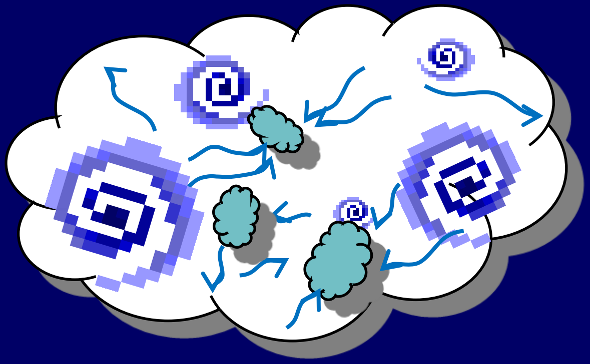
➔ No advantage of MHD to avoid dissipation (driving needed).

III. THE TURBULENT SUPPORT PARADIGM

- The turbulent-support paradigm.
  - Also in the late 90s and early 00s, supersonic turbulence became a plausible alternative again:
    - "Turbulent pressure" ($\rho \upsilon_{turb}^2$) was considered as a source of support against the global collapse of MCs.
      - Since turbulence is characterized by an energy spectrum, $E(k)$, the characteristic "turbulent velocity difference" depends on scale, $\upsilon = \upsilon(\ell)$.
        - Kolmogorov (incompressible) turbulence: $\upsilon \sim \ell^{1/3}$
        - Burgers (highly compressible) turbulence: $\upsilon \sim \ell^{1/2}$
          - (Note similarity to Larson's scaling.)
        - Studies considering:
          - No scale dependence: Chandrasekhar 51
          - Velocity scale dependence: Bonazzola+87
          - Velocity and density scale dependence: Vázquez-Semadeni & Gazol 95.

- The turbulent-support paradigm (cont’d).
  - Simultaneously, shocks should produce an ensemble of local density fluctuations within the medium (Sasao 73; Elmegreen 93).
    - With a lognormal distribution (Vázquez-Semadeni 94).

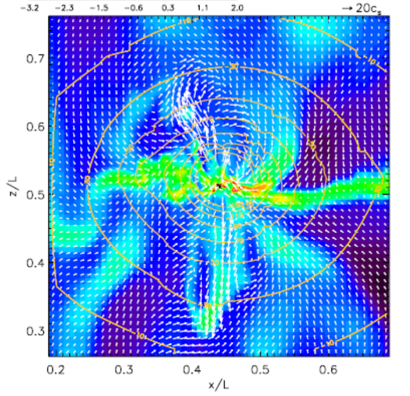
- The turbulent-support paradigm (cont'd).
  - Thus, a "dual role" of supersonic turbulence was envisioned (Vázquez-Semadeni+00, 03; Mac Low & Klessen 04 ; Ballesteros-Paredes+07):
    - Large-scale support for cloud as a whole.
    - Small-scale local density enhancements ("cores") that can collapse, if they exceed the local Jeans mass.



  - Larson's linewidth-size relation $\sigma \sim L^{1/2}$ interpreted as the manifestation of strongly supersonic (near-Burgers) turbulence.

- The turbulent-support paradigm (cont’d).
    - – Turbulence driving (for MCs, not general ISM):
        - Necessary, given the rapid dissipation (in 1 crossing time) for both HD and MHD turbulence.
        - Mechanisms (reviews: Mac Low & Klessen 04; VS 11, IAUS 270):
            - – From within:
                - Outflows (Quillen+05; de Colle & Raga 05; Cunningham+06, 09; Li+Nakamura 06, 07; Banerjee+07, Wang+10).
                    - – Efficiency unclear.
                - SNE (Iffrig & Hennebelle 15; Walch & Naab 15; Körtgen+16).
                - HII regions (VS+10; Colín+13; Dale+12,13).
            - – From the outside:
                - Propagating MHD waves.
                - Accretion (Vishniac 94; Koyama & Inutsuka 02; Heitsch+05; VS+06, Klessen & Hennebelle 10).
                - SNE (Iffrig & Hennebelle 15; Padoan+15; Ibáñez-Mejía & Mac Low 16).

Wang+10

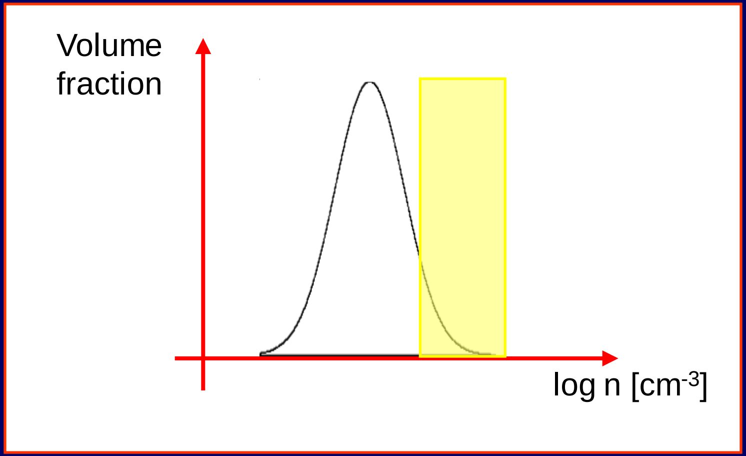


- The turbulent-support paradigm (cont'd).
  - Control of the SFR (Vázquez-Semadeni 03, 05a,b; Krumholz & McKee 05; Padoan & Nordlund 11, Hennebelle & Chabrier 11; unification by Federrath & Klessen 12; Eve's talk):
    - Assumptions:
      - Cloud globally stabilized by turbulent pressure.
      - Turbulence produces density fluctuations with a (lognormal; VS 94) distribution.
      - Turbulent density fluctuations collapse if local Jeans mass $M_J < M$ (Padoan & Nordlund 02; Vázquez-Semadeni 03; Krumholz & McKee 05).

- The turbulent-support paradigm (cont'd).
  - SFR given by

$$\mathrm{SFR} = \frac{\text{Mass of collapsing fragments}}{\text{Characteristic timescale}}$$

  - Mass of collapsing fragments given by integration of high-density tail of density PDF:



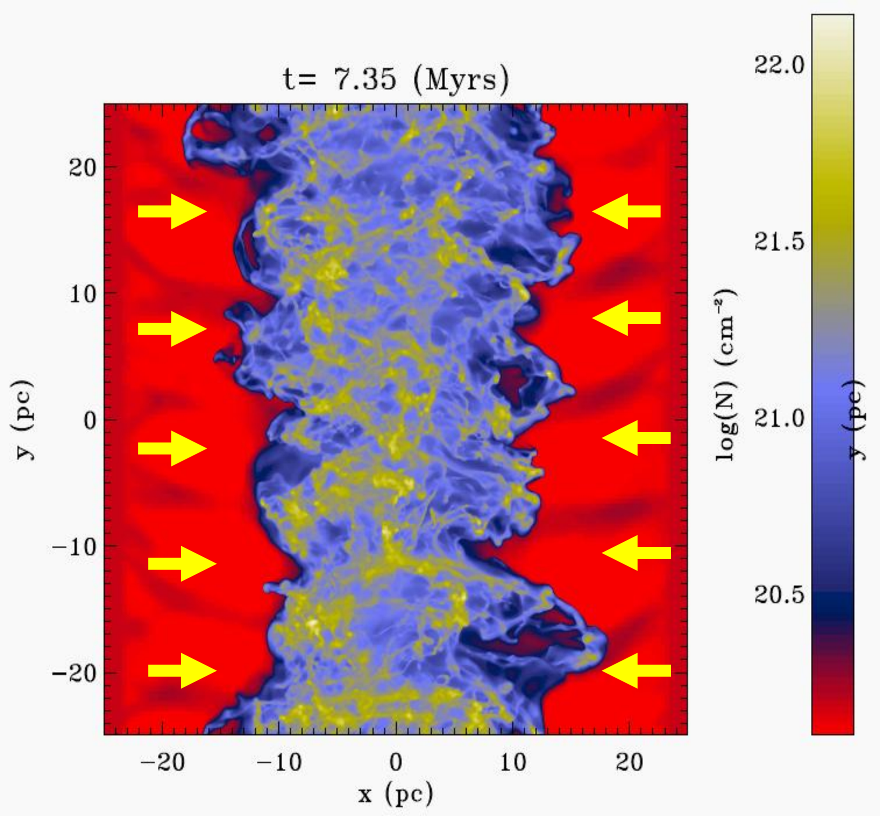
  - Timescale typically a variation of t_{ff} in high-density range (see summary by Federrath & Klessen 12).

- The turbulent-support paradigm (cont'd).
  - SFR models are in general stationary (but see Hennebelle & Chabrier 13 for a variation):
    - They give the SF efficiency per free-fall time, $\varepsilon_{\mathrm{ff}}$.
    - They consider closed systems of fixed mass.
  - $\varepsilon_{\mathrm{ff}}$ depends on gravo-turbulent parameters (Federrath & Klessen 12):
    - Sonic Mach number $\mathcal{M}_{\mathrm{s}}$.
    - Alfvénic Mach number $\mathcal{M}_{\mathrm{A}}$.
    - Virial parameter $\alpha = E_{\mathrm{turb}}/|E_{\mathrm{grav}}|$.
    - Fraction of E_{turb} in compressible modes.

IV. THE COLLAPSING PARADIGM

- The collapsing paradigm.
  - In the late 00s and 10s, evidence has again begun to suggest a departure from the turbulent paradigm (see review by Vázquez-Semadeni 2015, ASSL, 407, 401):
    - Clouds with no obvious stellar turbulence driving sources (e.g., “Maddalena’s cloud”) exhibit no significantly different nonthermal velocity dispersion compared to clouds with them (e.g., Williams+94).
    - Turbulence has the opposite effect on SFE if it is decaying than if it is driven:
      - Larger $\mathcal{M}_s$
        - Enhances SFE if decaying (Nakamura & Li 2005)
        - Reduces SFE if driven (Klessen+00; Heitsch+01; Vázquez-Semadeni+03, 05a,b)

- The collapsing paradigm (cont'd).
  - Prompted investigations of cloud formation and evolution with self-gravity to clarify nature of turbulence (Vázquez-Semadeni 07, Heitsch & Hartmann 08).
    - Colliding flows generate turbulence through NTSI (Hunter+86; Vishniac 94, Walder & Folini 00; Heitsch+05, VS+06).

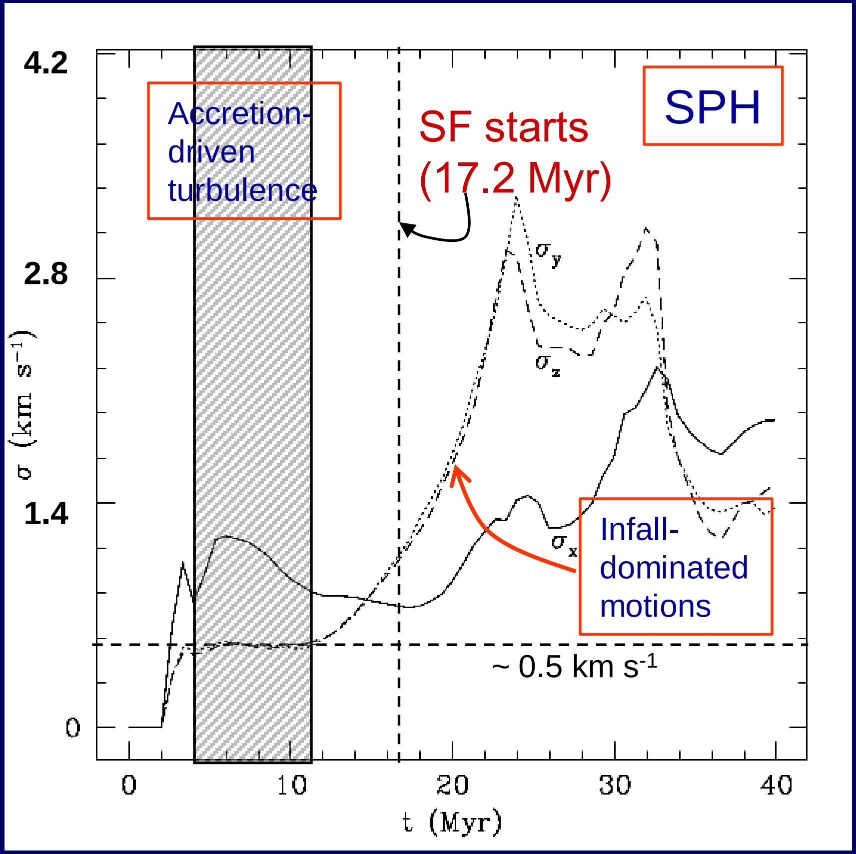


Potential to explain turbulence in clouds with no obvious driving sources.

... albeit only moderately supersonic ($\mathcal{M}_s$ ~ 3, not 10-30) (Koyama & Inutsuka 02; Heitsch+05).

Hennebelle, Banerjee, Vázquez-Semadeni+08, A&A, 486, L43

- However, strongly supersonic velocities typical of GMCs appear *later*, and are dominated by gravitational contraction.
  - SF appears even later.



SPH

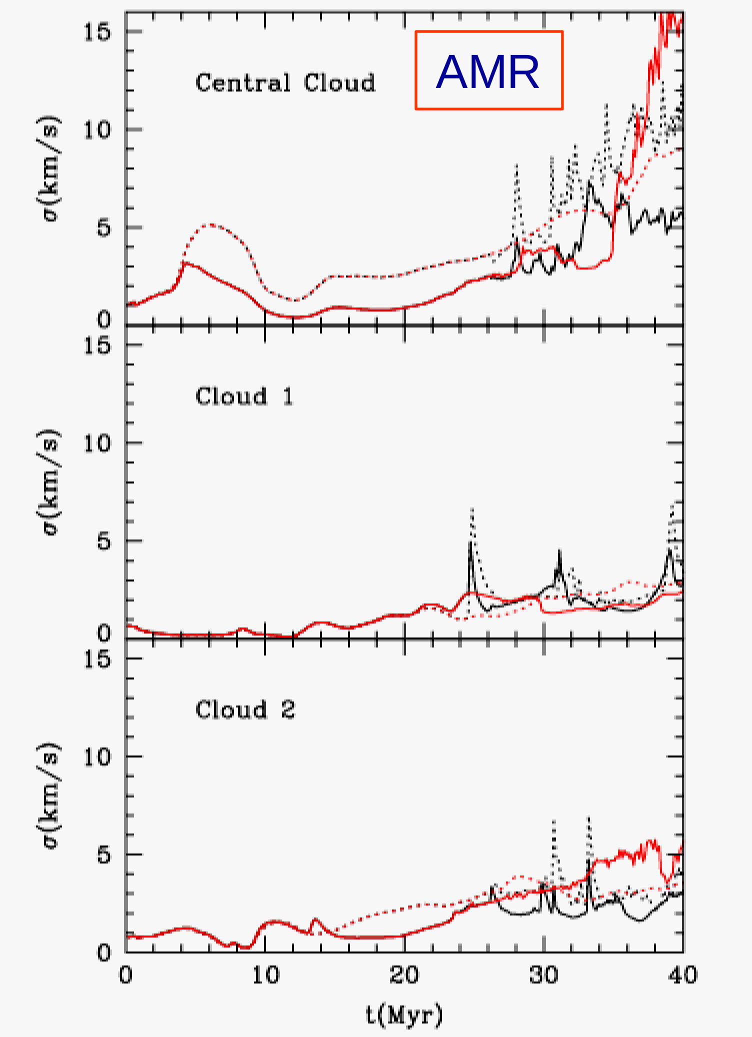
Accretion-driven turbulence

SF starts (17.2 Myr)

Infall-dominated motions

~ 0.5 km s^{-1}

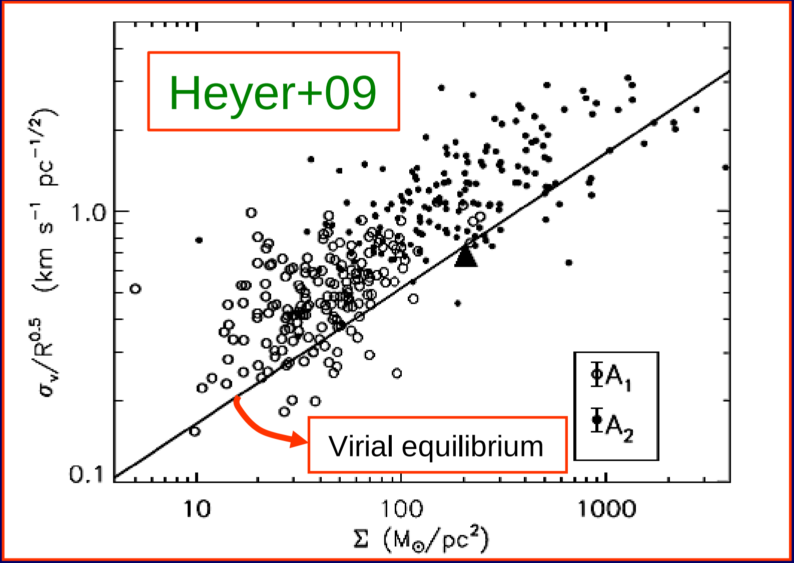
(Vázquez-Semadeni+07, ApJ, 657, 870. See also Koyama & Inutsuka 2002; Heitsch+05)



AMR

(Vázquez-Semadeni+10, ApJ, 715, 1302)

- The collapsing paradigm.
  - On the observational side, Larson’s relations shown to be particular cases of a generalized relation:



Heyer+09

Virial equilibrium

$$\Rightarrow \frac{\sigma_v^2}{R} \approx G\Sigma$$

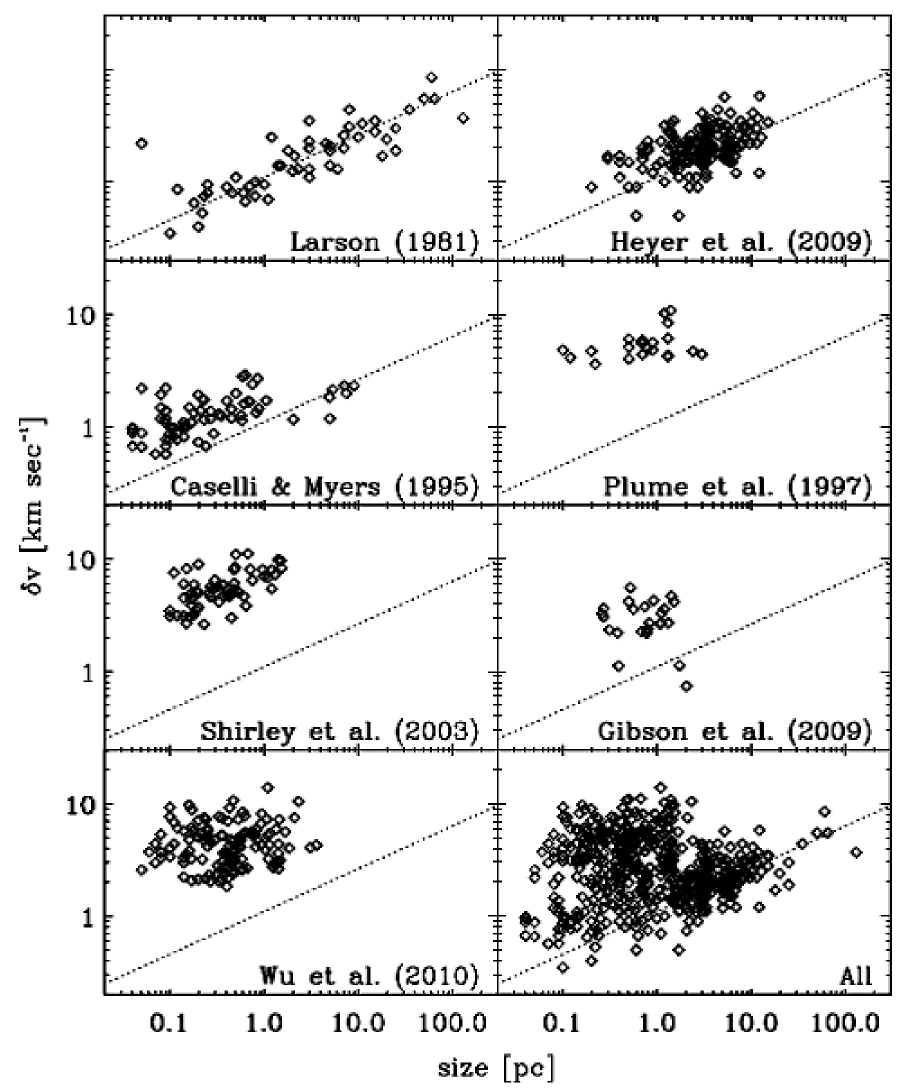
is the generalization of Larson’s linewidth-size relation for Σ not constant.

$$2E_k = |E_g| \quad \Rightarrow \quad \sigma_v^2 \approx \frac{GM}{R}$$

$$\Rightarrow \quad \frac{\sigma_v^2}{R} \approx G\Sigma$$

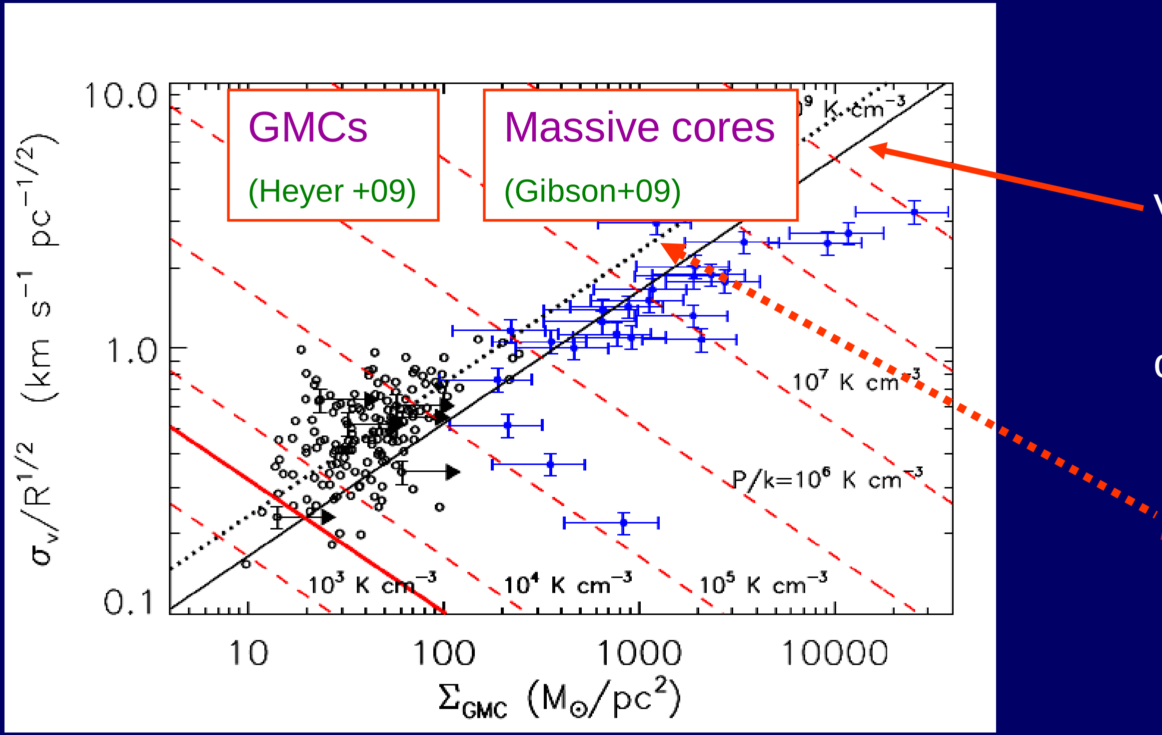
NOTICE: Σ not constant ⟹ density-size relation not valid in general.

- Moreover, massive clumps do not follow Larson’s (1981) linewidth-size relation:



Ballesteros-Paredes+11, MNRAS, 411, 65

- ... yet they do follow the same trend as GMCs in the generalization of Larson’s (1981) linewidth-size diagram for Σ ***not*** constant (Keto & Myers 86; Heyer+09):
  - Indicative of gravitationally-generated velocities.



Virial equilibrium (α=1)

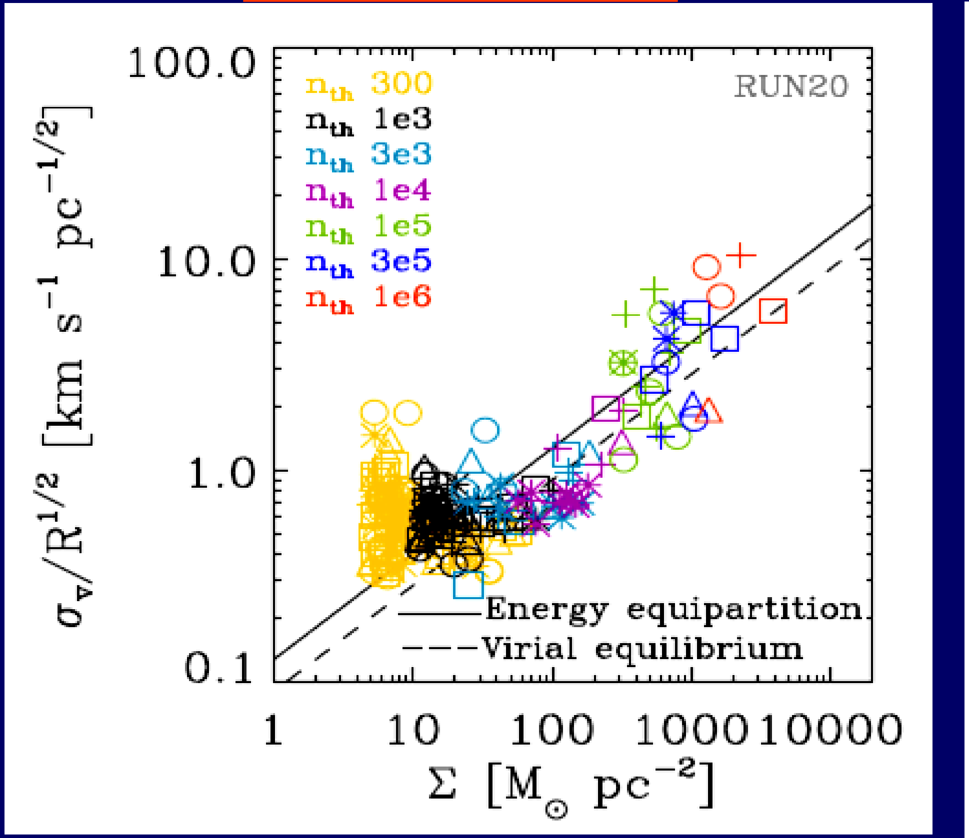
or...

Free-fall??

Dobbs+14 (PPVI), extended
from Ballesteros-Paredes+11

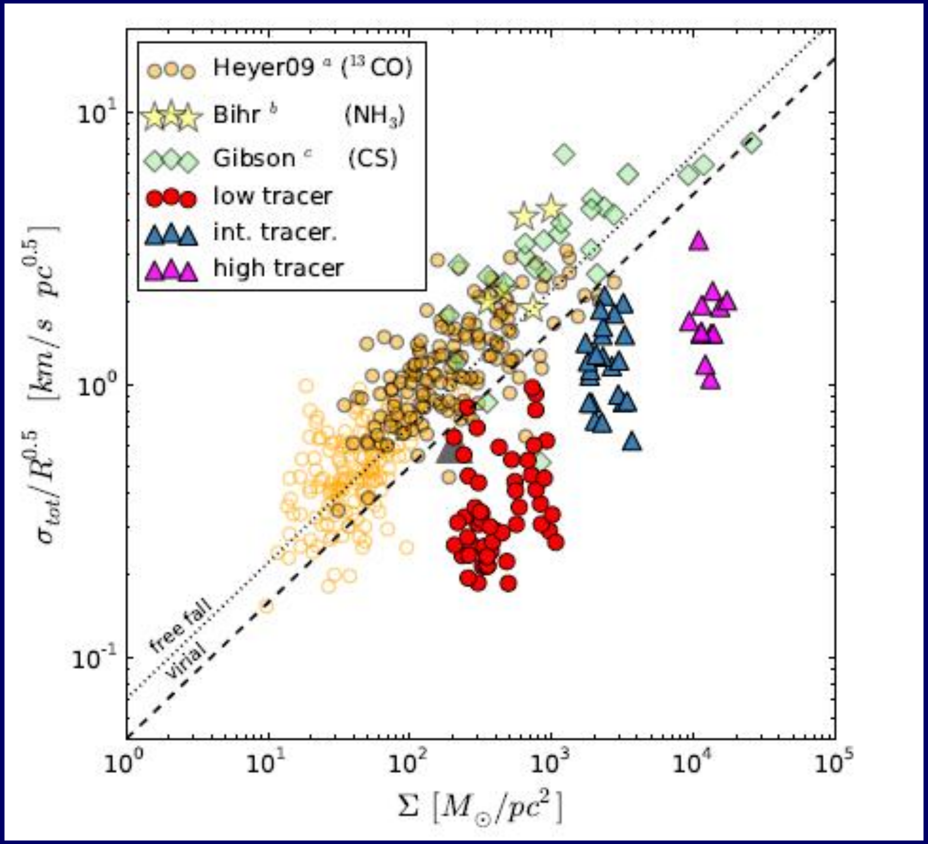
- Also observed in clumps forming in numerical simulations of cloud formation and evolution:

Converging flows



Camacho, Vázquez-Semadeni+16, submitted.

SN-driven ISM



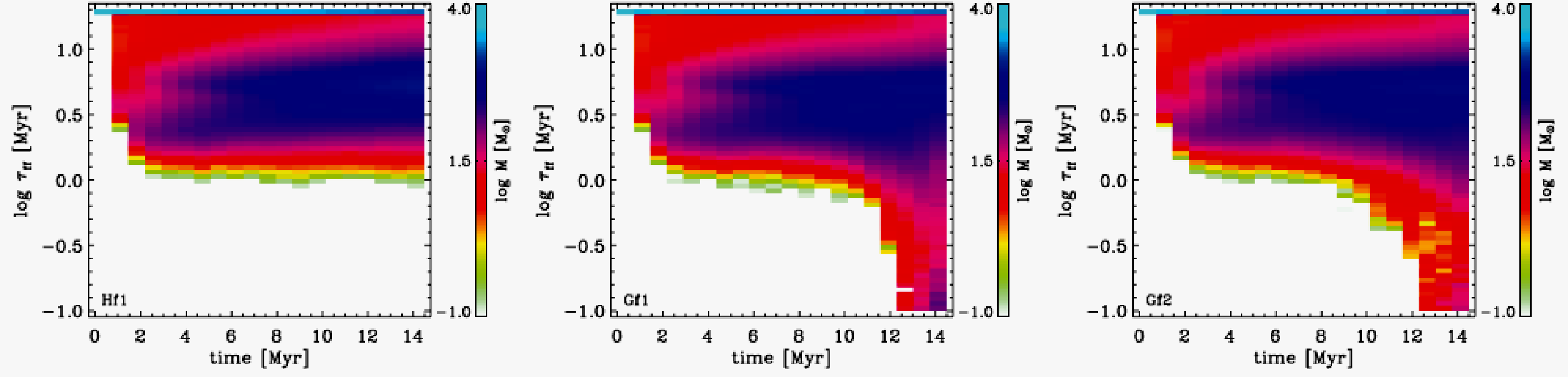
Ibáñez-Mejía+16

- Why global collapse?
  - Because, if MCs form out of a phase transition from the ***warm/diffuse*** to the ***cold/dense*** atomic phase, they quickly become strongly Jeans-unstable (Gómez & VS 14, ApJ 791, 124):

$\rho \rightarrow 10^2 \rho, \quad T \rightarrow 10^{-2}\, T$

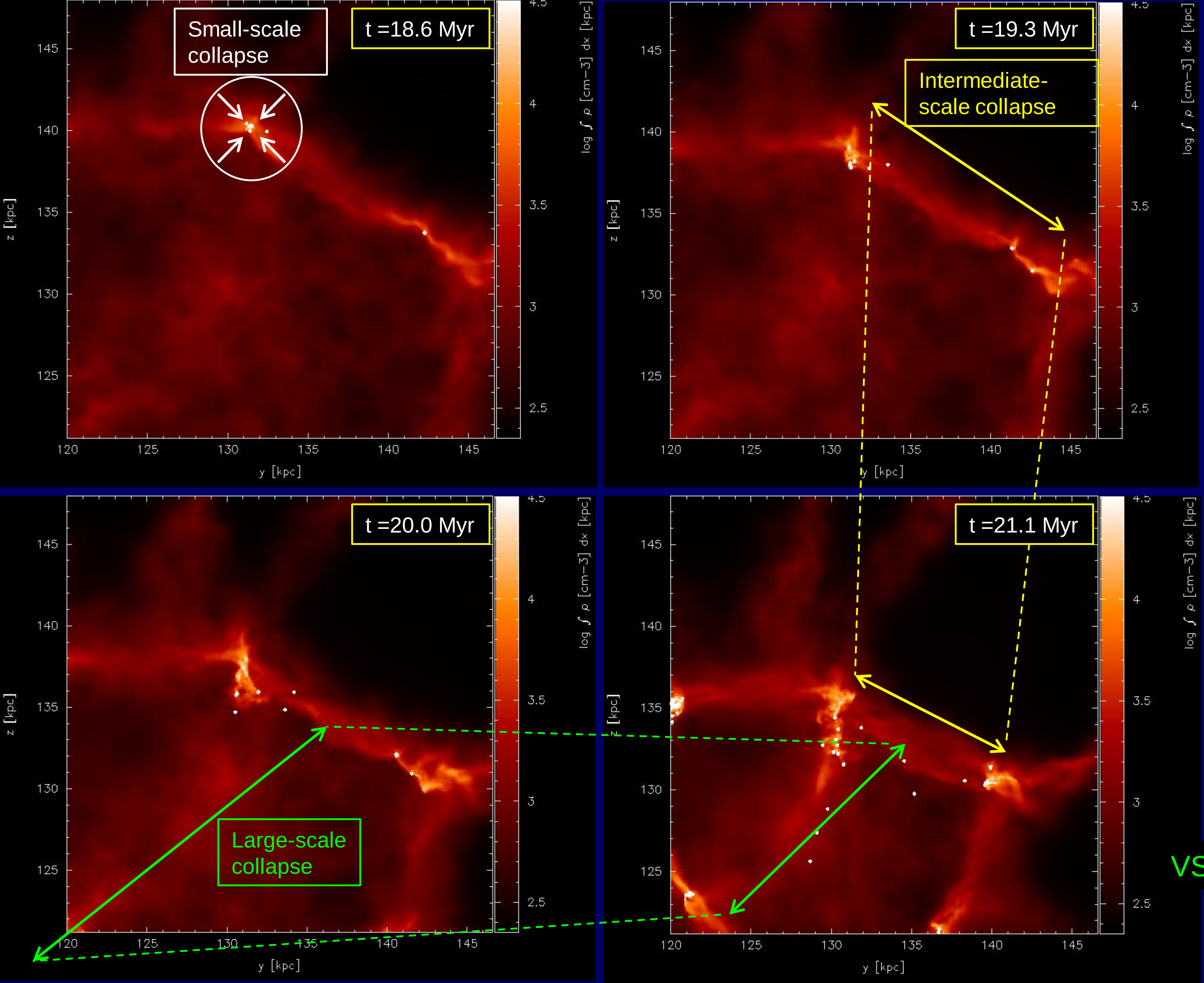
➔ Jeans mass, $M_J \sim \rho^{-1/2}\, T^{3/2}$, decreases by ~ 10^4 upon warm-cold transition.

- Global collapse of turbulent, non-spherical medium is *hierarchical...* (Vázquez-Semadeni+09, ApJ, 707, 1023).
  - Turbulence produces a distribution of (nonlinear) density fluctuations of various sizes and amplitudes.
    - Implies a distribution of free-fall times. Small-scale, high-density fluctuations have shorter free-fall times (Heitsch & Hartmann 08) than the large-scale, low-density fluctuations that contain them.



Heitsch & Hartmann 08

  - Mass of clouds and clumps evolves (generally growing) as they accrete from larger scales.


Small-scale collapse

t =18.6 Myr

t =19.3 Myr

Intermediate-scale collapse

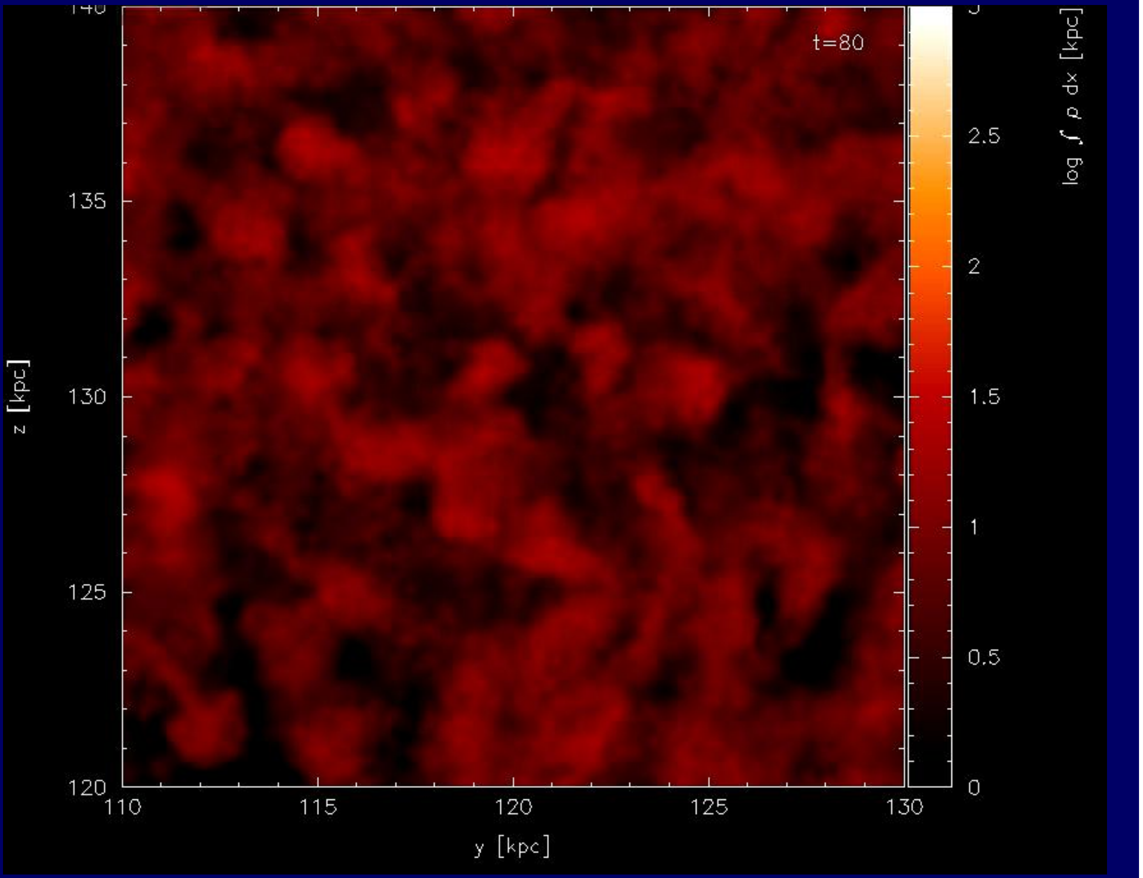
t =20.0 Myr

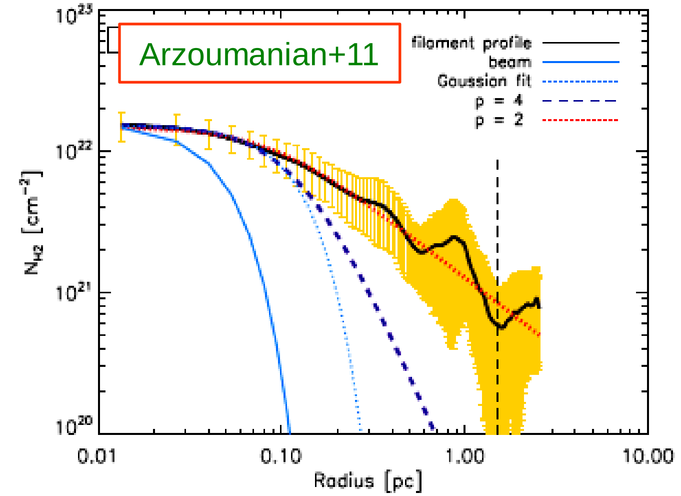
Large-scale collapse

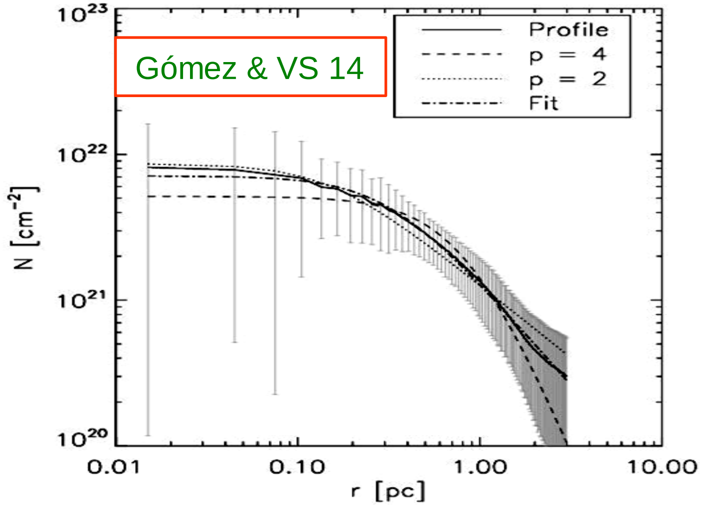
t =21.1 Myr

VS+09

- The collapsing paradigm (cont’d).
  - Bonus:
    - Naturally forms realistic filaments (Gómez & Vázquez-Semadeni 14; Gong & Ostriker 15; Rowan’s talk):
      - Pressureless collapse amplifies anisotropies (Lin+65).
      - Filaments funnel material from clouds to cores.




Arzoumanian+11

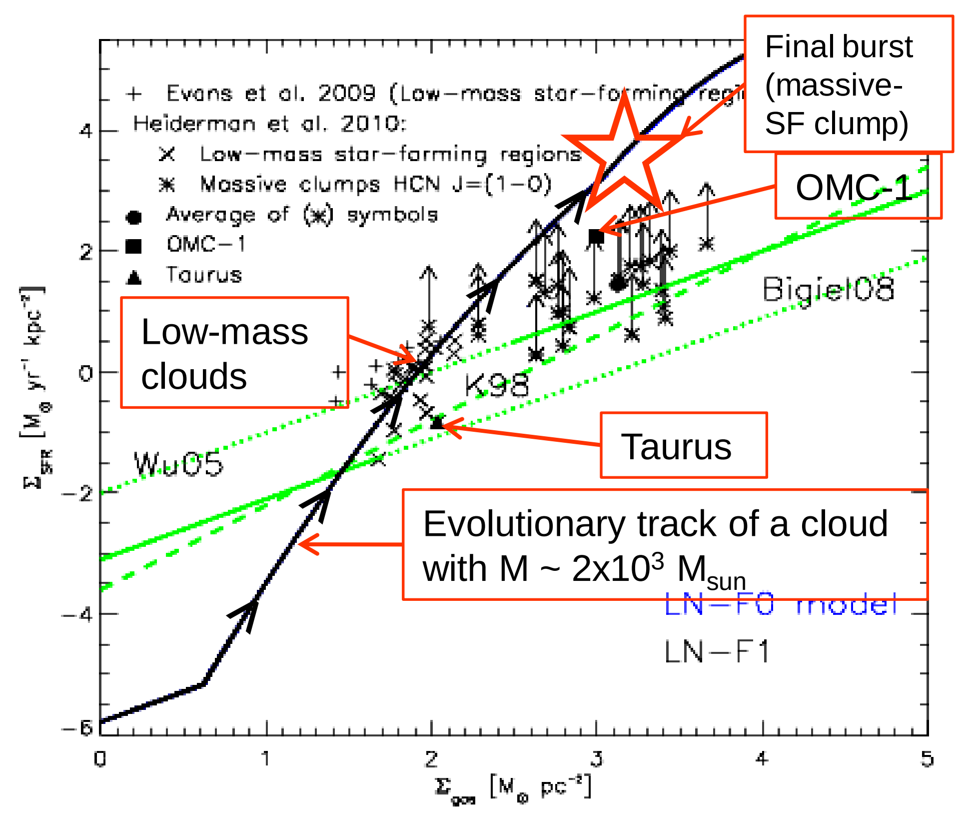

Gómez & VS 14

- The collapsing paradigm (cont’d).
  - Control of the SFR (Zamora-Avilés+2012, ApJ, 751, 77):
    - SFR increases as cloud contracts and mean density increases.
      - Mass under high-density tail of PDF increases with time.
    - Low-mass star-forming regions need no regulation mechanism: SFR is still low.
    - High-mass regions occur at culmination of global collapse. Low-mass regions fall into them (VS+16, IAUS 316).
    - High-SFR samples high-mass end of IMF, massive stars destroy local SF sites, by time when SFE ~ a few x 10%.

➔ Keep global SFE low.

Allows an evolutionary description of the collapsing clouds and their SFR:

Predicts increase of SFR that generates a realistic stellar age distribution.



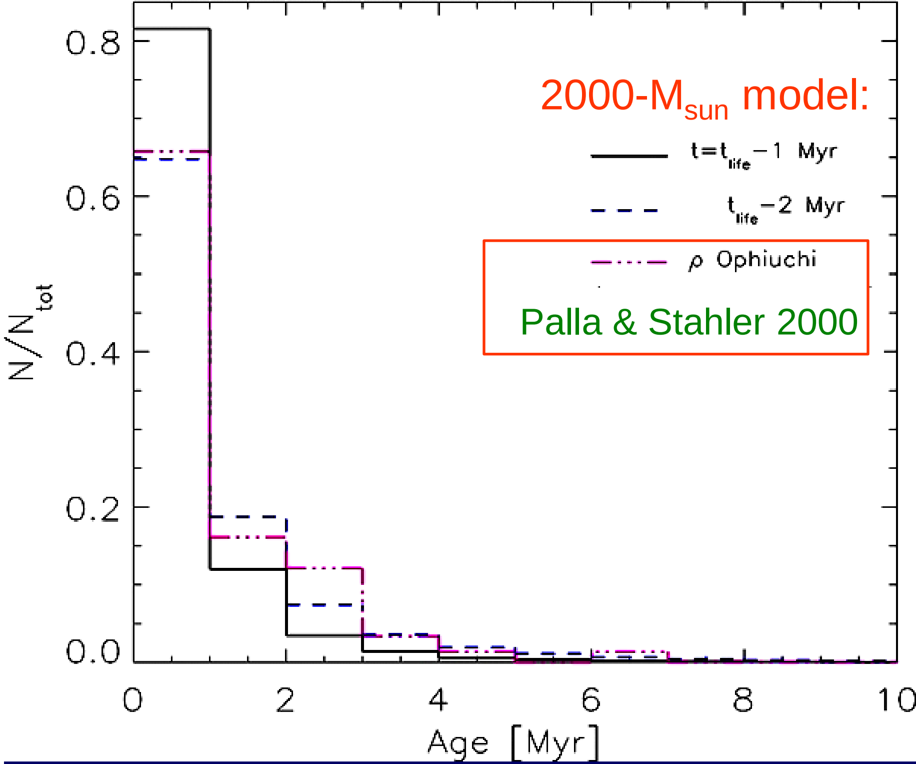
Final burst (massive-SF clump)

OMC-1

Low-mass clouds

Taurus

Evolutionary track of a cloud with M ~ 2x10^3 M_{sun}

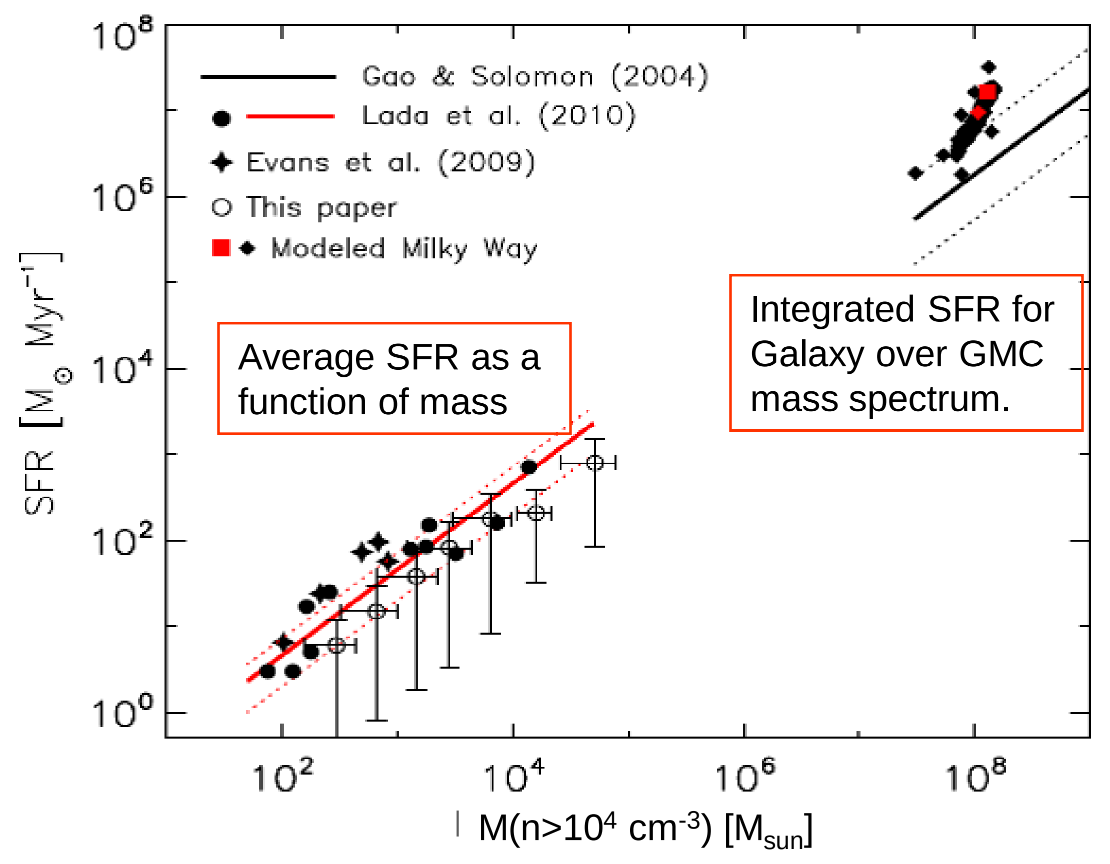


2000-M_{sun} model:

Palla & Stahler 2000

Zamora-Avilés+2012, ApJ, 751, 77

Suitable averaging produces realistic dependence of SFR vs. dense gas mass during observable stages



Average SFR as a function of mass

Integrated SFR for Galaxy over GMC mass spectrum.

$M(n>10^4\ \mathrm{cm}^{-3})\ [M_{sun}]$

Stationary values of the SFR (e.g., ε_{ff}) are meaningful only as averages over cloud ensembles.

Zamora-Avilés & VS 2014, ApJ, 793, 84

- The global, hierarchical collapse paradigm summarized:
  - MCs are born strongly Jeans unstable.
  - Turbulence from formation process insufficient to support MCs, but useful for producing distribution of density fluctuations (and free-fall times).
    - Observed velocity dispersion reflecting infall speeds, not turbulence.
  - SF (culmination of local collapses) begins several Myr after onset of global collapse, at low rates.
  - SFR increases as cloud contracts and mean density increases.
  - Accretion at all scales.
  - Final SF burst disrupts local complexes.
    - Feedback disrupts clouds, not keep them in equilibrium.

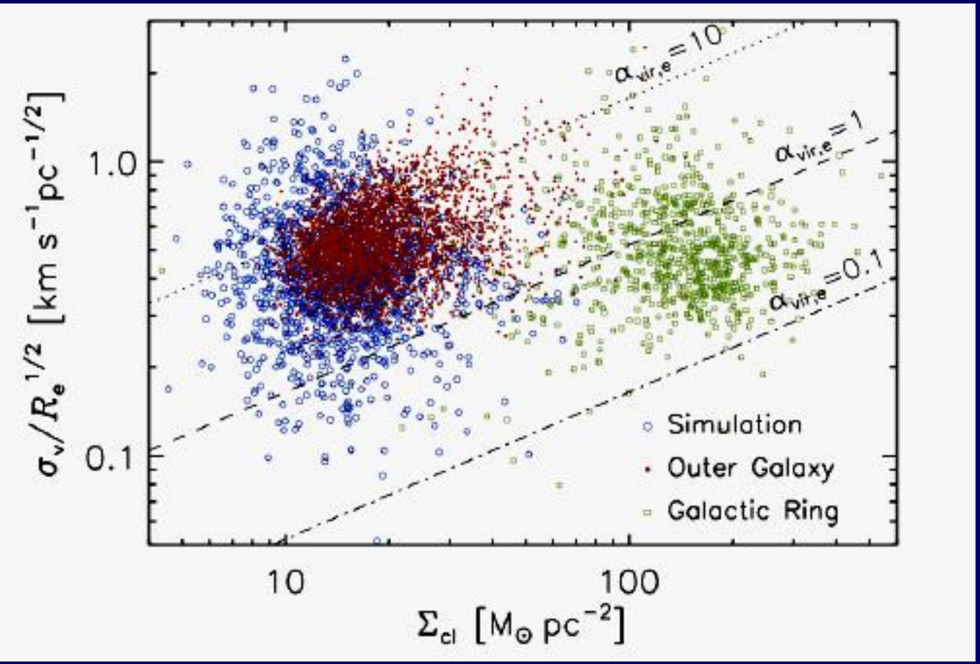
  - ZP74 and ZE74's criticisms avoided by:
    - SFR problem avoided by early cloud destruction.
    - Absence of line shifts avoided by highly non-spherical collapse.

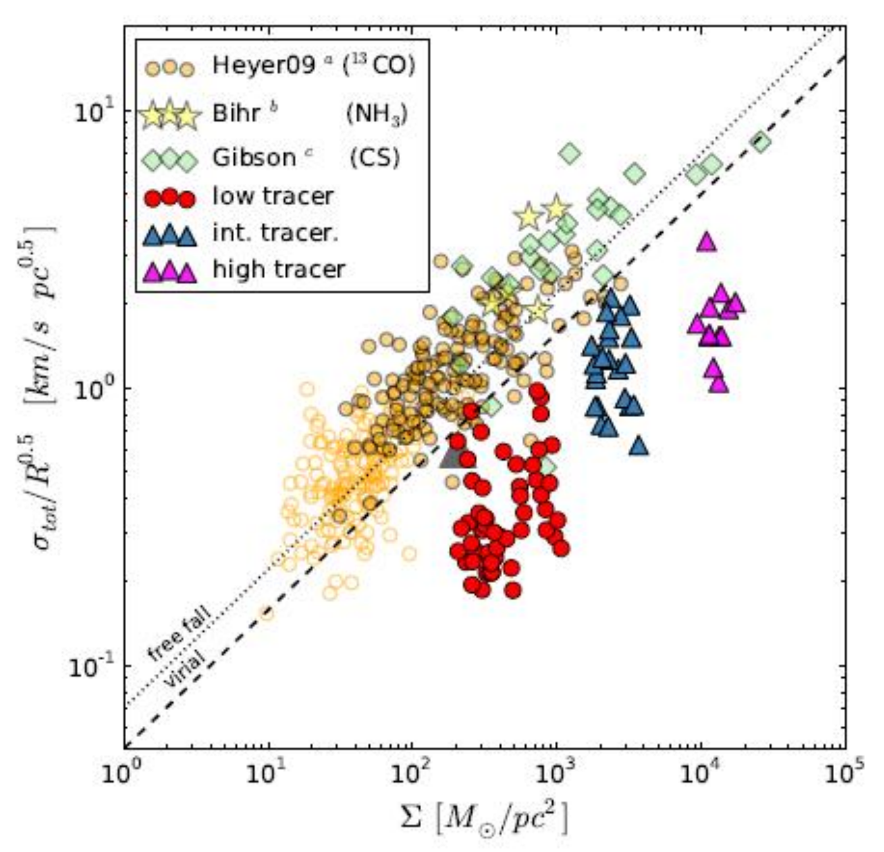
PENDING ISSUES

- Efficiency of turbulence injection by SNe being debated:
  - SN-driving simulations:

Padoan+15: SN driving keeps MCs from collapsing. No Heyer+09 scaling.

Ibáñez-Mejía+16: SN driving unable to drive realistic MC turbulence (also Iffrig & Hennebelle 15). Yes Heyer+09 scaling.



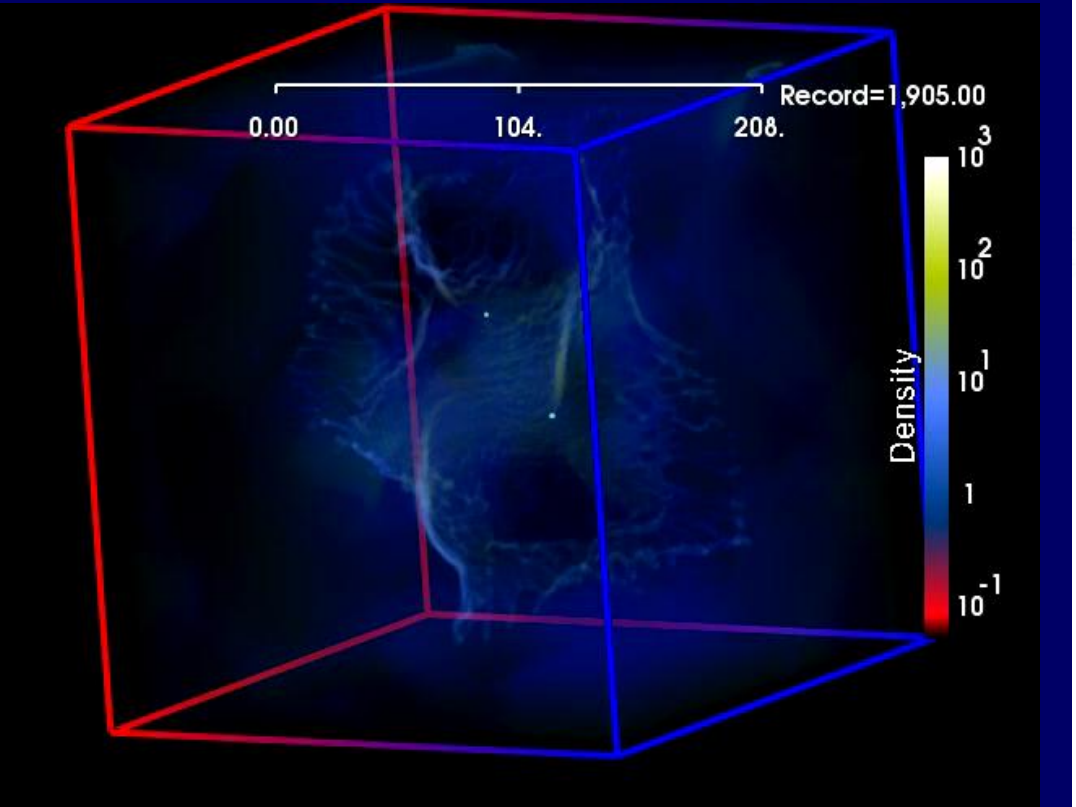


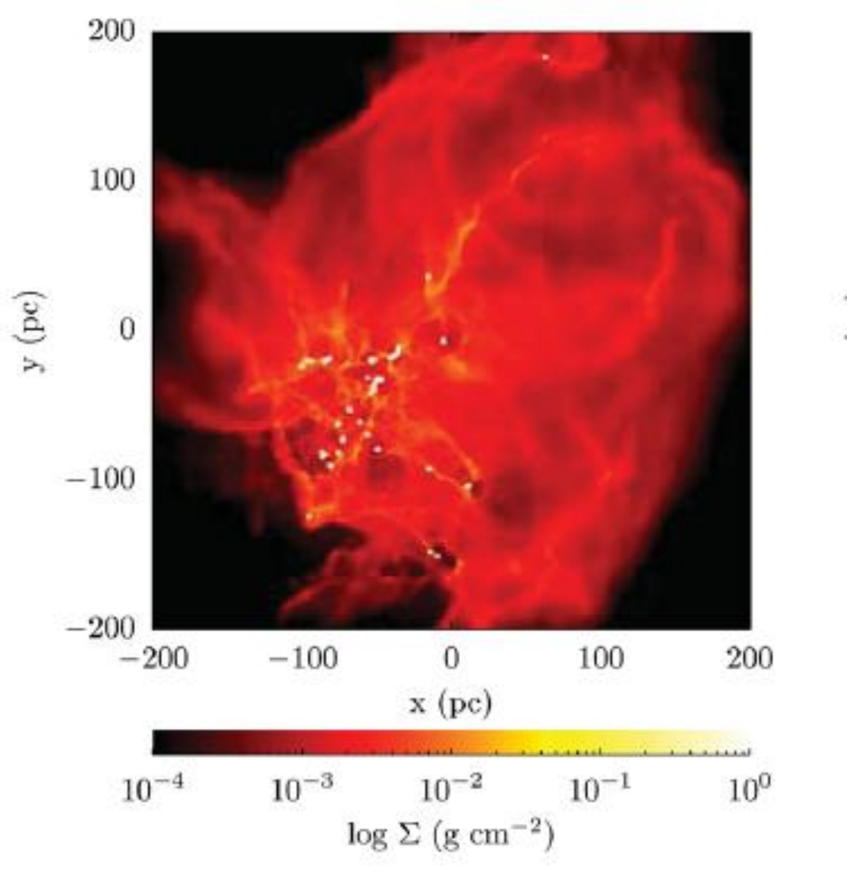
Padoan+15: Insufficiently large simulation box [(250 pc)^3]?

- Cloud destruction difficult to accomplish:

Colín, VS+2013, MNRAS, 435, 1701: easy destruction of flattened, filamentary clouds by ionization feedback. SN explosions inside clouds also disrupt them (Iffrig & Hennebelle 15).

However, massive clouds hard to destroy (Dale+12). Perhaps because of spherical rather than flattened initial conditions?





MULTI-SCALE STAR FORMATION

Morelia.Michoacán.México

April 3-7.2017

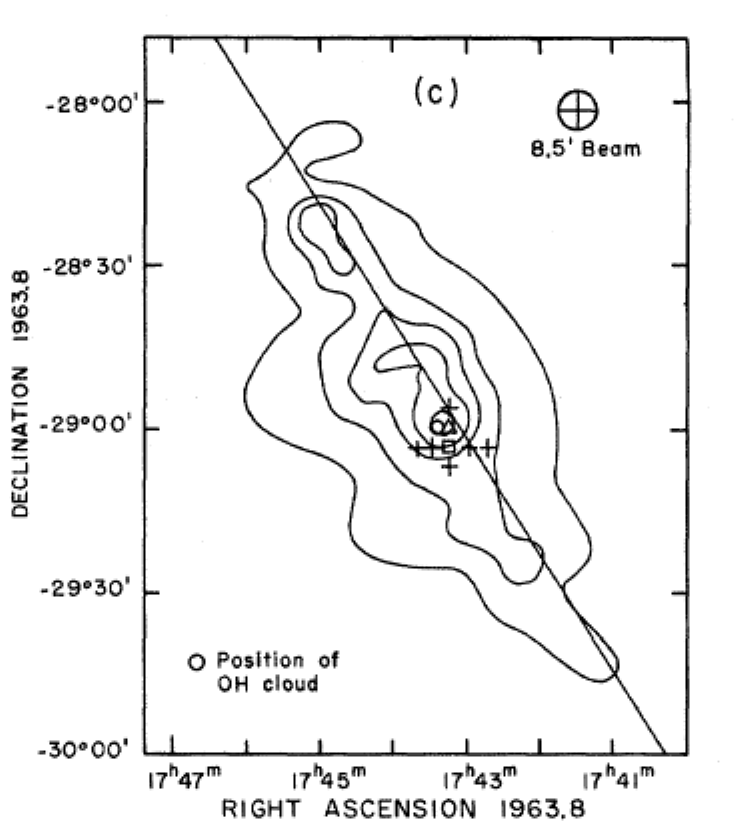
SOC MEMBERS:

Gustavo Bruzual . Daniela Calzetti
Francoise Combes . Bruce Elmegreen
Neal Evans . Lee Hartmann
Melvin Hoare . Susana Lizano
Mordecai Mac Low . Frederique Motte
Luis Felipe Rodríguez . Enrique Vázquez Semadeni
Qizhou Zhang

THE END

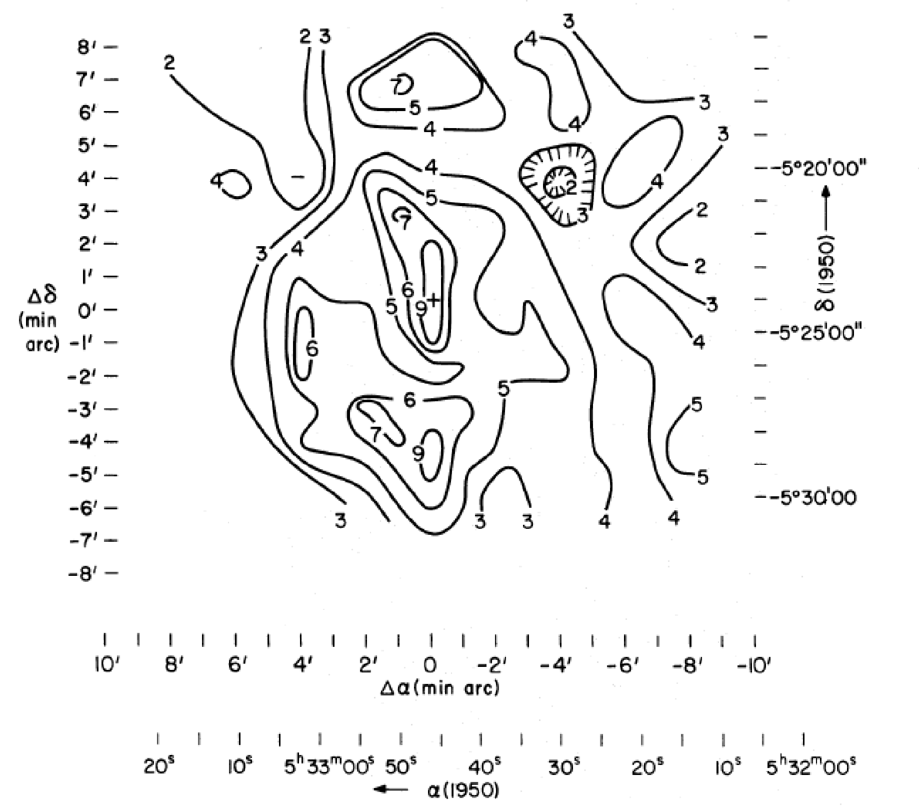
- First maps:

NH_3



Galactic center
Cheung+68

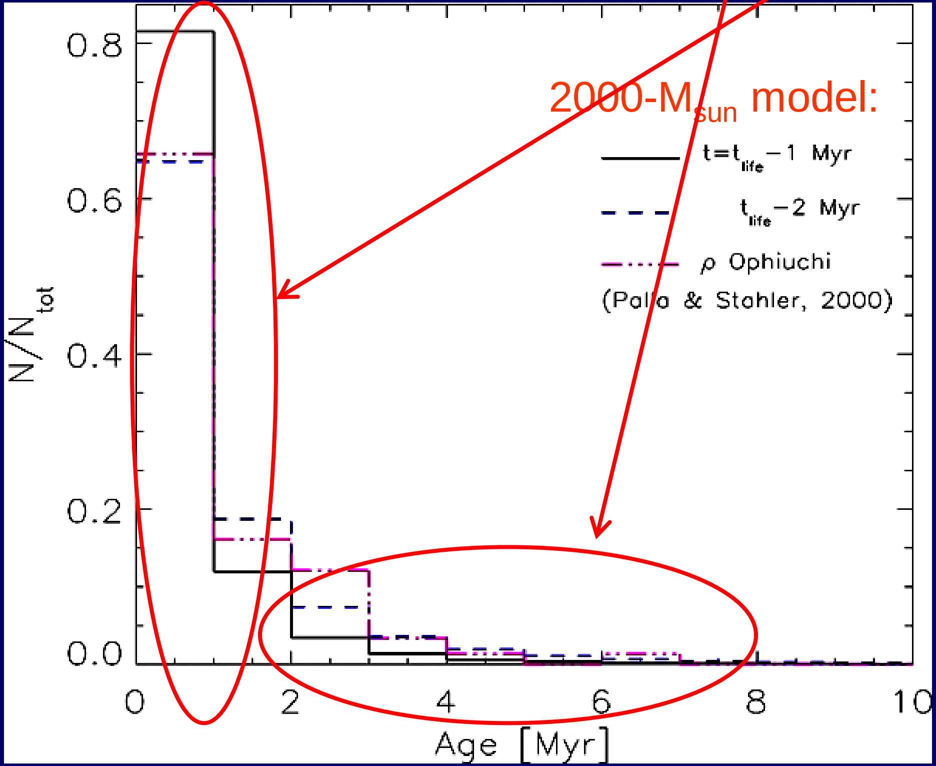
^{13}CO



Orion
Liszt+74

Implications for cluster formation

- Stellar population of an evolved star-forming region consists of:
  - Slightly older, scarce component formed by early, low-mass, low-SFR, and
  - Younger, more abundant component formed at later, massive, high-SFR burst.

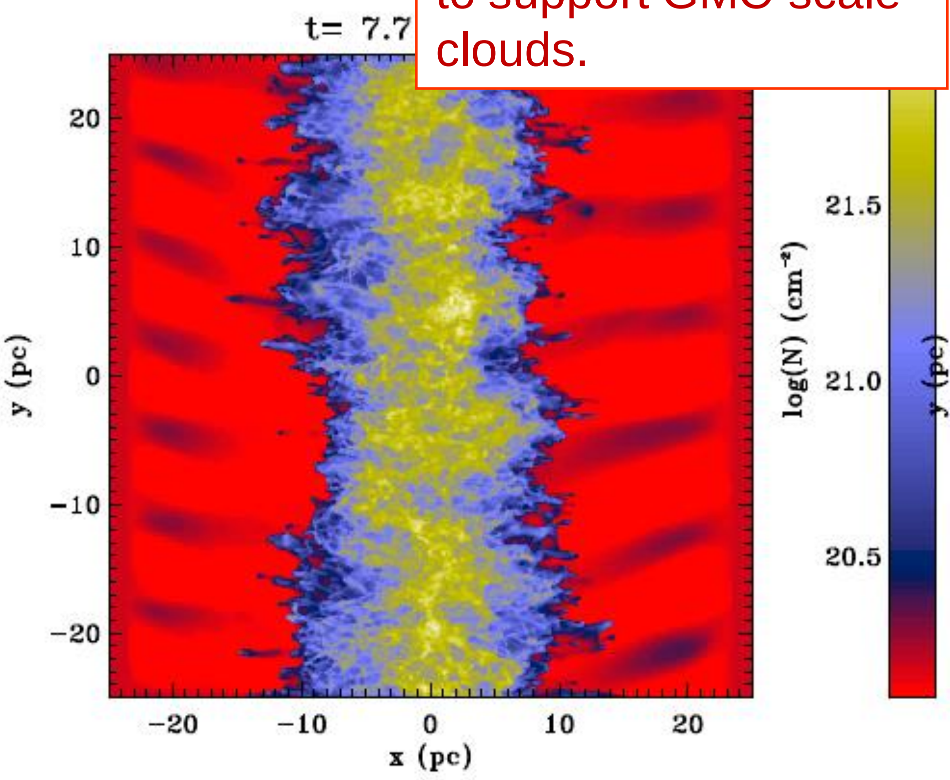


Consistent with YSO age histograms in embedded clusters by Palla & Stahler 1999, 2000.

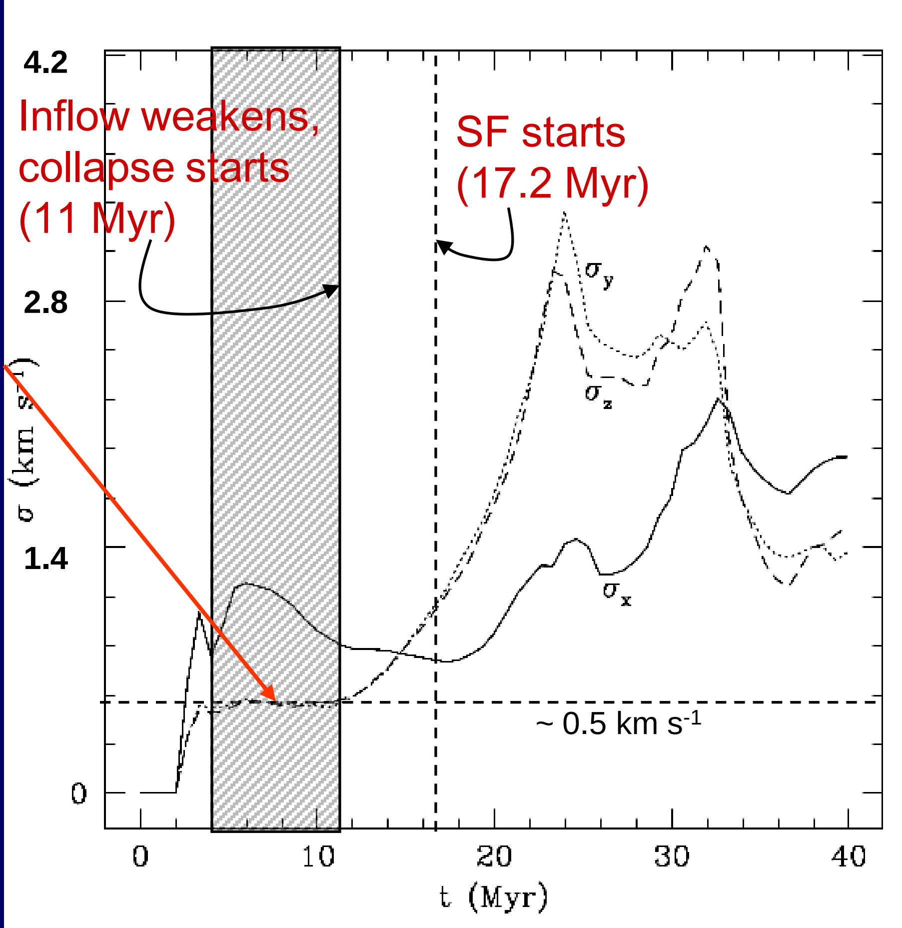
Analytical model by Zamora-Avilés+12, ApJ, 751, 77

- Flow collision produces turbulence (Vishniac 94; Walder & Folini 00; Koyama & Inutsuka 02; Heitsch+05; VS+06; Klessen & Hennebelle 10)
  - ... but not enough to support a GMC (VS+07, +10).

Hennebelle, Banerjee, Vázquez-Semadeni+08, A&A, 486, L43



➔ Accretion-driven turbulence insufficient to support GMC-scale clouds.



Inflow weakens, collapse starts (11 Myr)

SF starts (17.2 Myr)

~ 0.5 km s^{-1}

(Vázquez-Semadeni et al. 2007, ApJ, 657, 870.
See also Koyama & Inutsuka 2002; Heitsch+05)

NOTE:

- Non-thermal motions are considered infall, not turbulence.
  ➔ No turbulent support assumed.

- Main controlling parameter is ***total cloud mass***
  - ***(not turbulent Mach number nor virial parameter).***

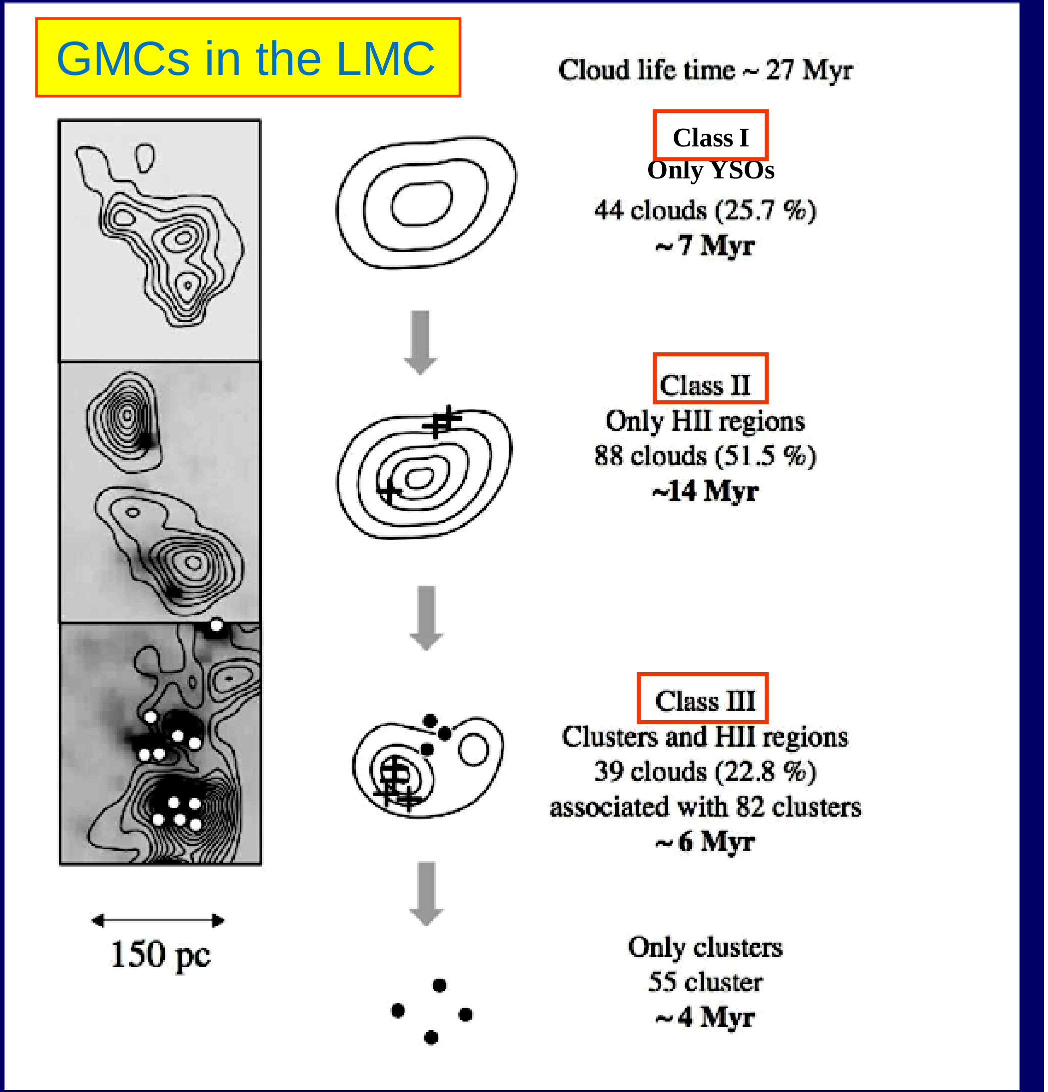
- Model is intrinsically ***evolutionary***.

- Implications and predictions:

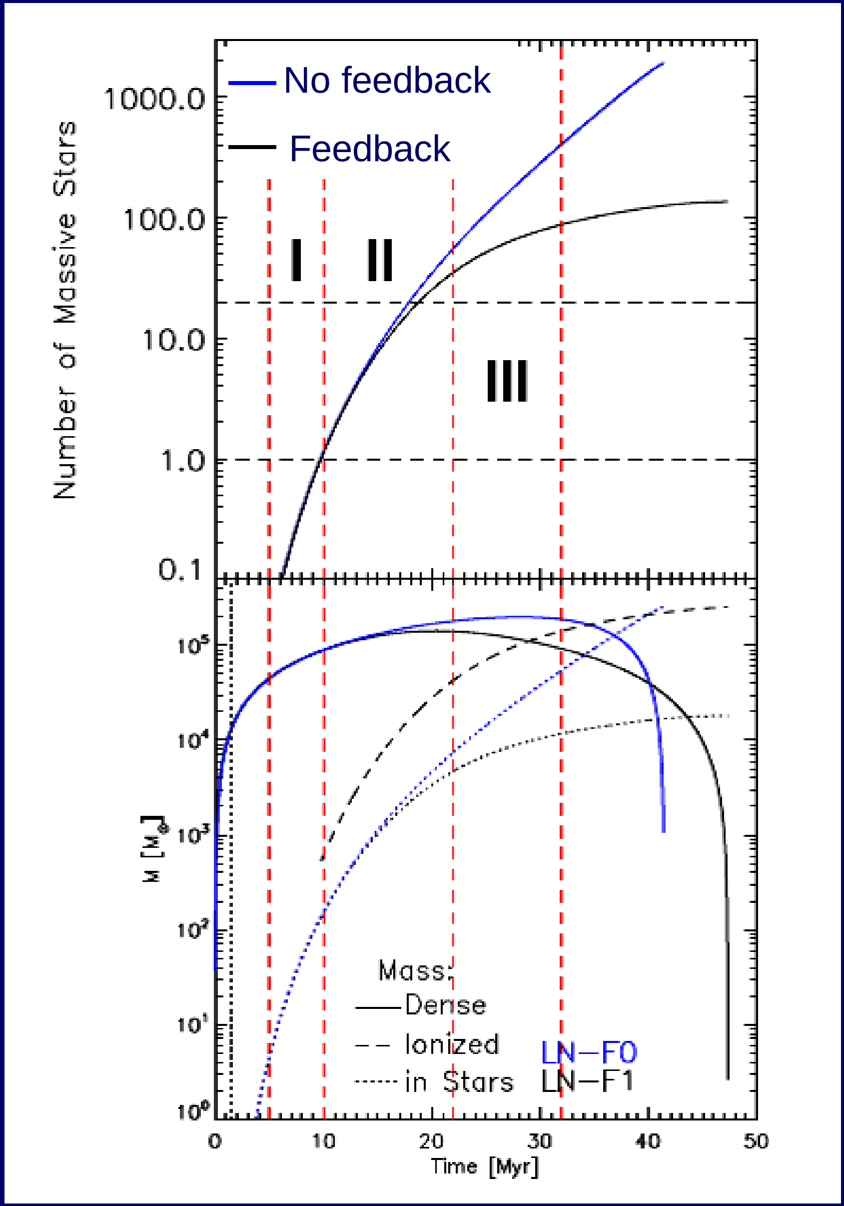
– Evolution of GMCs' stellar population ($M \sim 10^5\ M_{sun}$):

Model

GMCs in the LMC



Kawamura+2009



Zamora-Avilés+2012