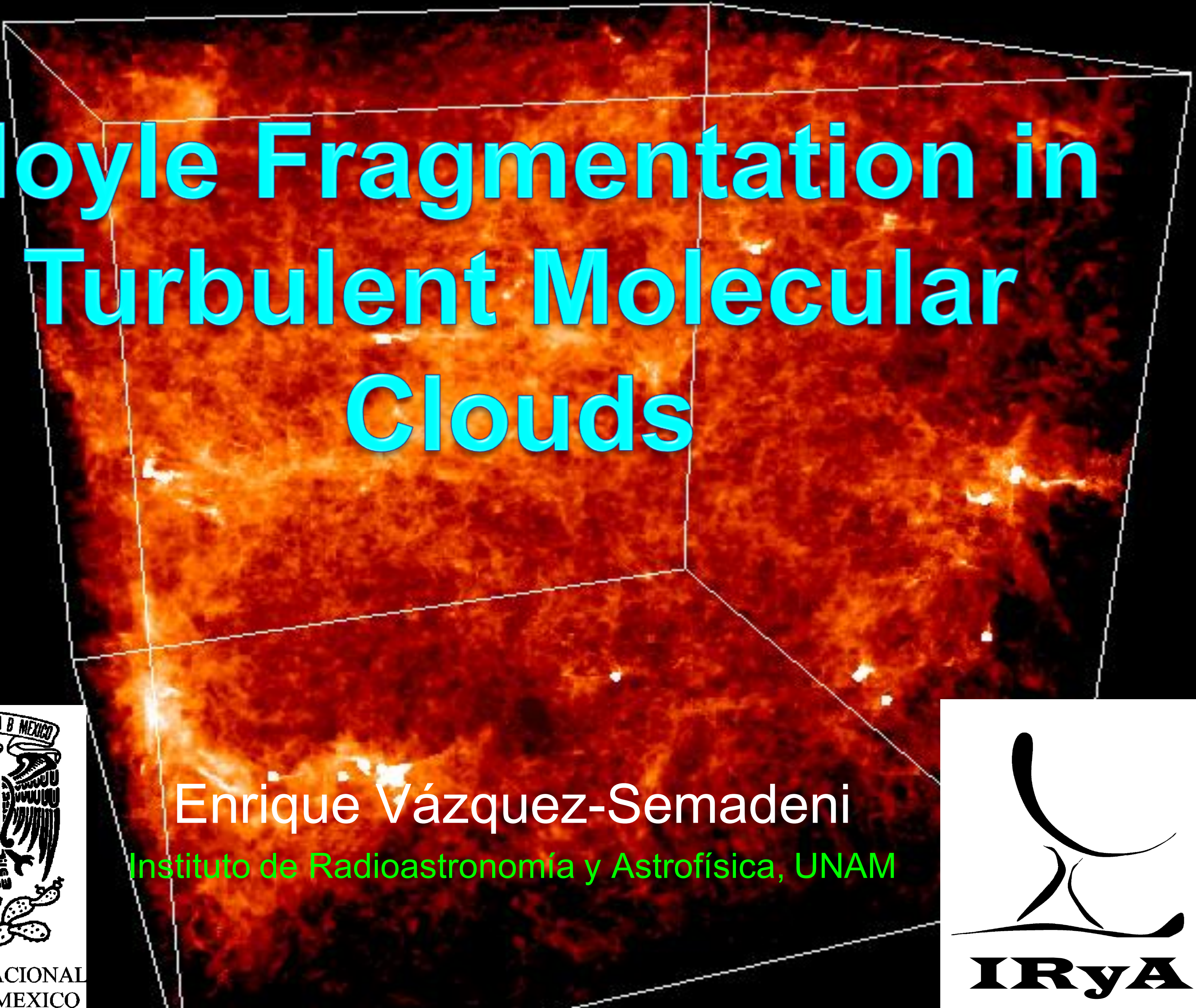


Hoyle Fragmentation in Turbulent Molecular Clouds

Enrique Vázquez-Semadeni

Instituto de Radioastronomía y Astrofísica, UNAM

UNIVERSIDAD NACIONAL
AUTONOMA DE MEXICO

IRyA

Collaborators:

Javier Ballesteros-Paredes.
Pedro Colín
Gilberto Gómez

Postdocs:
Alejandro González-Samaniego
Manuel Zamora-Avilés

- Outline:
  - The Hierarchical Gravitational Contraction (HGC) paradigm for star-forming GMCs.
  - Hoyle fragmentation revisited.
    - Overcoming old objections.
    - Approximate timescales for collapse of density fluctuations.
    - Implications.

I. The Hierarchical Gravitational Contraction Paradigm

- Mounting observational evidence that MCs are collapsing globally and on multiple scales (0.01 – several pc), *along* filaments.

The Astrophysical Journal, 706:1036–1053, 2009 December 1
doi:10.1088/0004-637X/706/2/1036

FORMATION OF AN O-STAR CLUSTER BY HIERARCHICAL ACCRETION IN G20.08–0.14 N

Roberto Galván-Madrid[1,2,3], Eric Keto[1], Qizhou Zhang[1], Stan Kurtz[2], Luis F. Rodríguez[2], and Paul T. P. Ho[1,3]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; rgalvan@cfa.harvard.edu
[2] Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia 58090, Mexico
[3] Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan
Received 2009 June 11; accepted 2009 October 14; published 2009 November 9

A&A 602, L2 (2017)
DOI: 10.1051/0004-6361/201730732

Astronomy & Astrophysics

Letter to the Editor

Gravitational collapse of the OMC-1 region★

A. Hacar[1,2], J. Alves[1], M. Tafalla[3], and J. R. Goicoechea[4]

A&A 520, A49 (2010)
DOI: 10.1051/0004-6361/201014481

Astronomy & Astrophysics

Dynamic star formation in the massive DR21 filament

N. Schneider[1], T. Csengeri[1], S. Bontemps[2], F. Motte[1], R. Sim
, C. Federrath[5], and R. Klessen[5,6]

The Astrophysical Journal, 766:115 (14pp), 2013 April 1
doi:10.1088/0004-637X/766/2/115

FILAMENTARY ACCRETION FLOWS IN THE EMBEDDED SERPENS SOUTH PROTOCLUSTER

Helen Kirk[1,4], Philip C. Myers[1], Tyler L. Bourke[1], Robert A. Gutermuth[2], Abigail Hedden[3], and Grant W. Wilson[2]
[1] Radio and Geoastronomy Division, Harvard Smithsonian Center for Astrophysics, MS-42, Cambridge, MA, 02138, USA; kirkh@mcmaster.ca
[2] Department of Astronomy, University of Massachusetts Amherst, Amherst, MA 01003, USA
[3] Army Research Labs, Adelphi, MD 20783, USA
Received 2012 November 7; accepted 2013 January 24; published 2013 March 15

A&A 555, A112 (2013)
DOI: 10.1051/0004-6361/201321318

Astronomy & Astrophysics

Global collapse of molecular clouds as a formation mechanism for the most massive stars

N. Peretto[1,2], G. A. Fuller[3,4], A. Duarte-Cabral[5,6], A. Avison[3,4], P. Hennebelle[1], J. E. Pineda[3,4,7], Ph. André[1], S. Bontemps[5,6], F. Motte[1], N. Schneider[5,6], and S. Molinari[8]

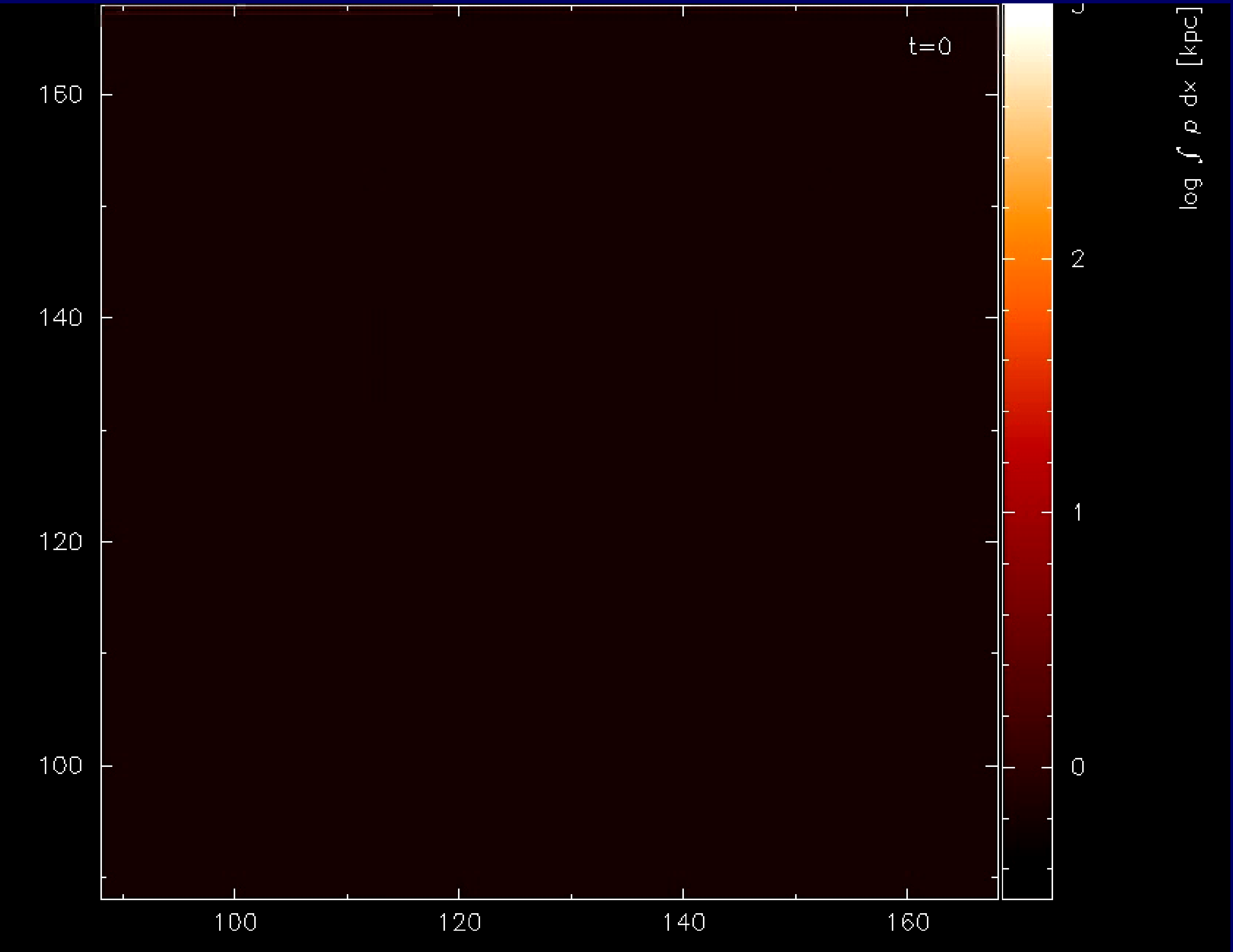
A&A 561, A83 (2014)
DOI: 10.1051/0004-6361/201322172

Astronomy & Astrophysics

SDC13 infrared dark clouds: Longitudinally collapsing filaments?★,★★,★★★

N. Peretto[1,2], G. A. Fuller[3], Ph. André[2], D. Arzoumanian[4], V. M. Rivilla[5], S. Bardeau[6], S. Duarte Puertas[7], J. P. Guzman Fernandez[7], C. Lenfestey[3], G.-X. Li[8], F. A. Olguin[9,10], B. R. Röck[11,12], H. de Villiers[13], and J. Williams[3]

Colliding-flow MC formation simulation (Gómez & VS 2014, ApJ, 791, 124; Iwasaki san’s talk)



SPH, with 26 million particles.

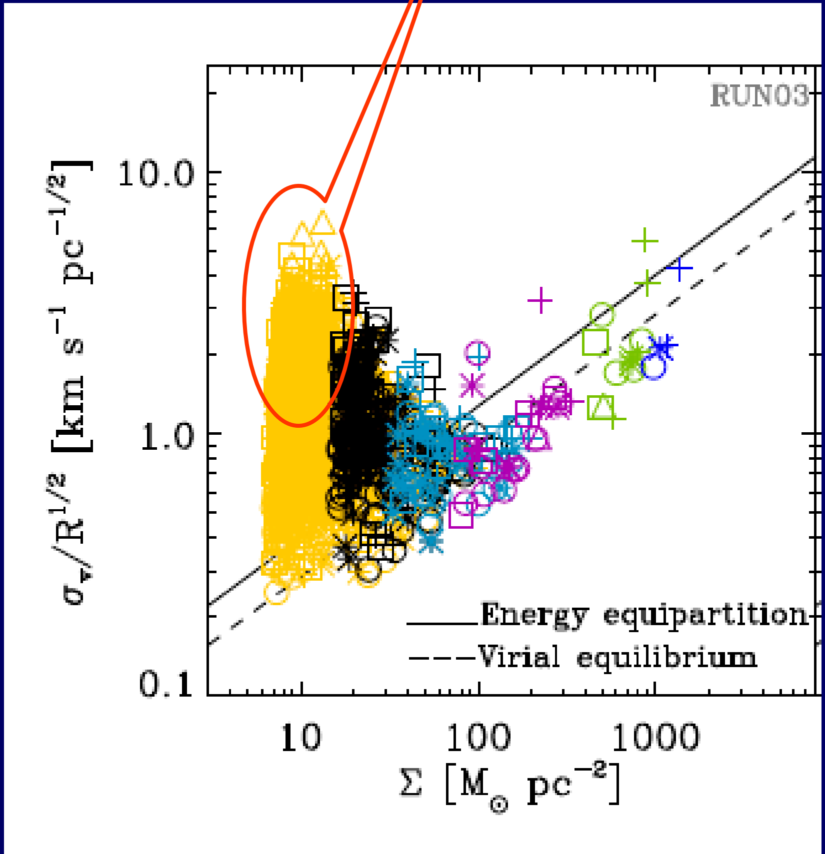
WNM at $n=1\ \mathrm{cm}^{-3}$.

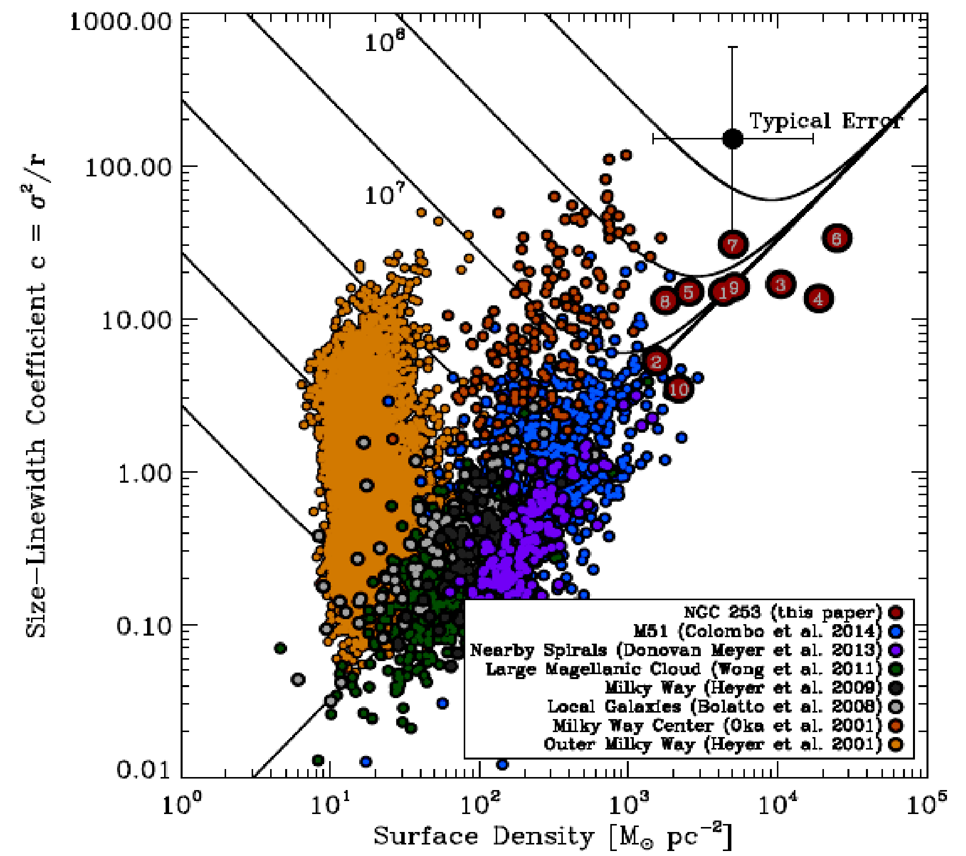
No stellar feedback.

- Dispelling the notion that MCs are “unbound”. A study of clump energy budget in simulation of turbulent assembly of MCs (Camacho+16, ApJ, 833, 113):
    - At low Σ, inertial motions dominate, but in ~1/2 of the cases, they are *assembling* the clumps (measured by <div v> in the clumps).

Camacho+16, ApJ, 833, 113

Compare to Leroy+15





- Turbulent velocities are largest at the largest scales.

  ➔ Don’t act as isotropic pressure, but as ***streams*** (pistons, shear).

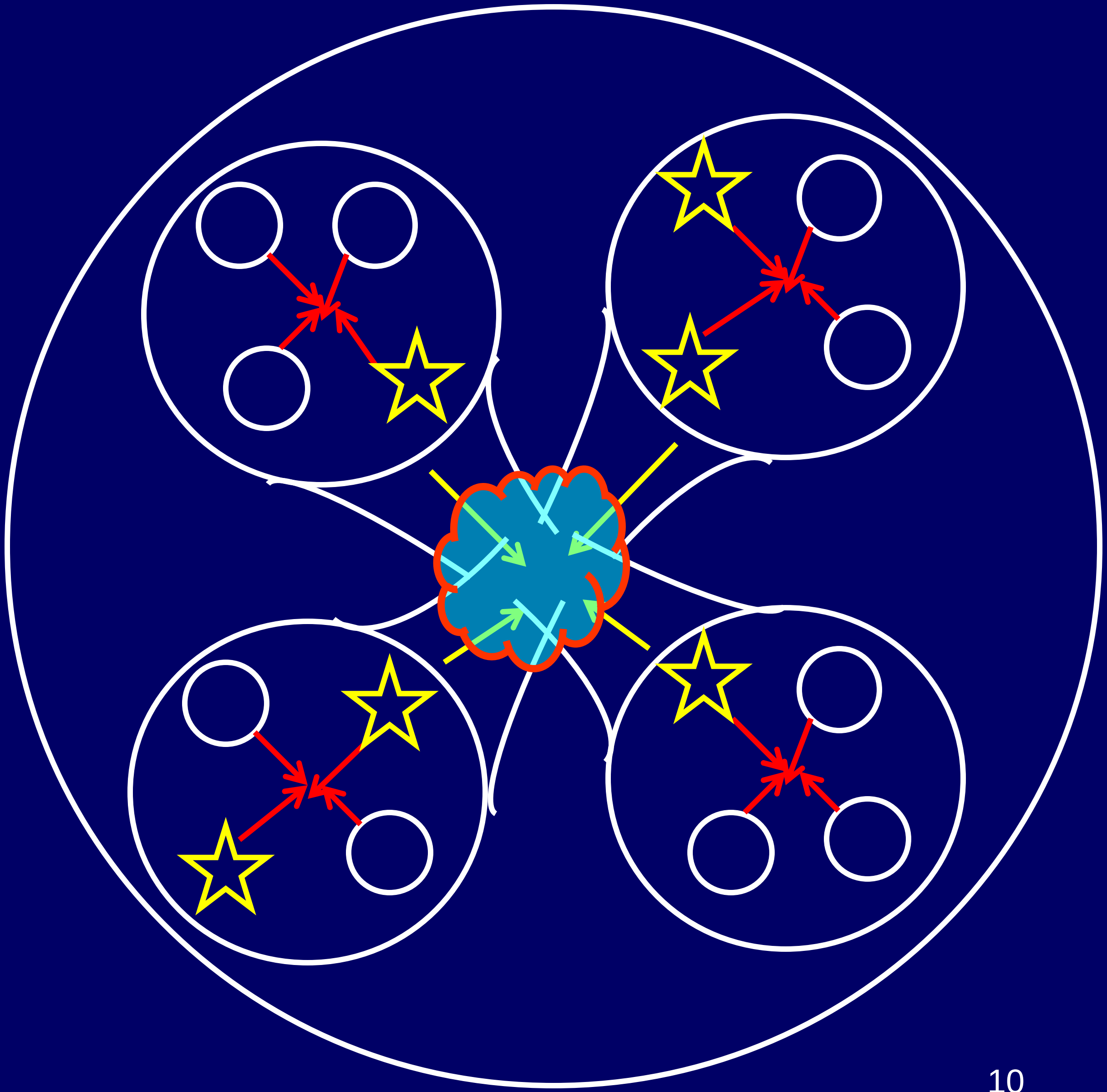
  - Tidal stretching looks like local expansion!

- Inward motions may come from gravitational instability at a larger scale (i.e., spiral arms).

- So, need to take into account weight of the CNM and CO-dark gas to determine binding.

- The HGC scenario:
  - Arose from the observed evolution of simulations of MC formation with self-gravity (VS+07, ApJ, 657, 870).
  - Solar-neighborhood-type clouds form by compression-triggered phase transition WNM → CNM (Hennebelle & Perault 99; Koyama & Inutsuka 02; Heitsch+05; VS+06).
    - (Converging flows, NOT cloud-cloud collisions. Cloud “boundaries” are fake, due to tracers (Sarah’s talk).)
  - Jeans mass drops precipitously ($\times 10^4$) by cooling/compression and cloud begins to collapse (VS+07; Gómez & VS 14).
    - Turbulence is only moderately supersonic. Not enough to prevent collapse, just a population of moderate fluctuations.
    - Clouds quickly acquire many Jeans masses.
  - Collapse is *multi-scale*: small-scale collapses within and falling into larger-scale ones (VS+09, ApJ, 707, 1023).
  - Massive star-forming regions consist of mergers of low-mass regions occurring at late evolutionary stages.

Gravitational contraction starts at the largest scales.



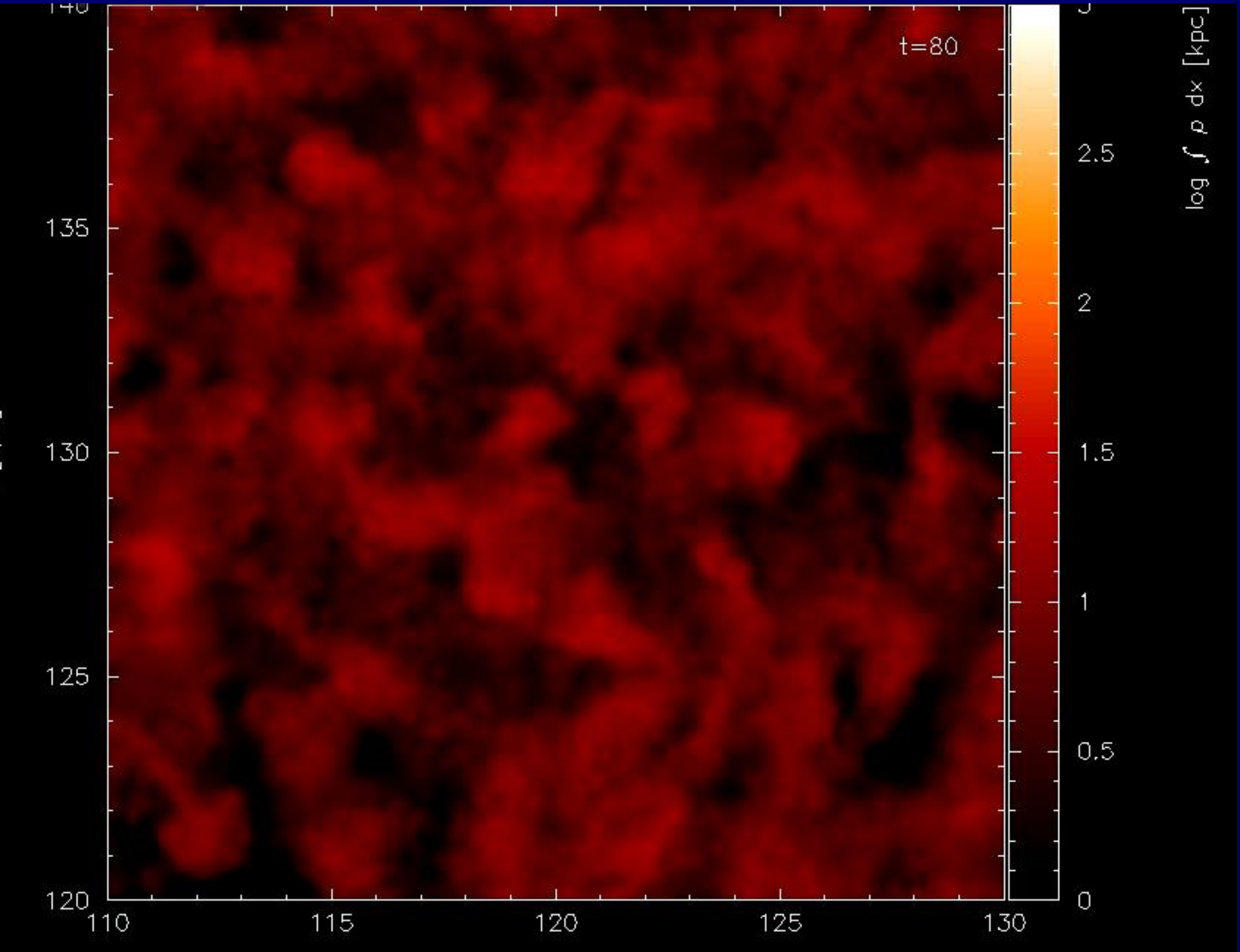
Small-scale collapses within large-scale ones develop sequentially.

Small-scale objects terminate their collapse first because of their shorter free-fall times.

Similar to Hoyle’s (1953) fragmentation, but with nonlinear fluctuations and filament formation.

- Filaments form spontaneoulsy (Gómez & VS 14, ApJ, 791, 124):
  - Because the clouds contain many Jeans masses...
  - ... the collapse is nearly pressureless...
  - ... and proceeds first along shortest scales (Lin+65):

volume → sheet → filament → core



SPH simulation with no feedback (GV14).

Fragmentation occurs along filaments as they feed central objects.

III. Hoyle Fragmentation Revisited

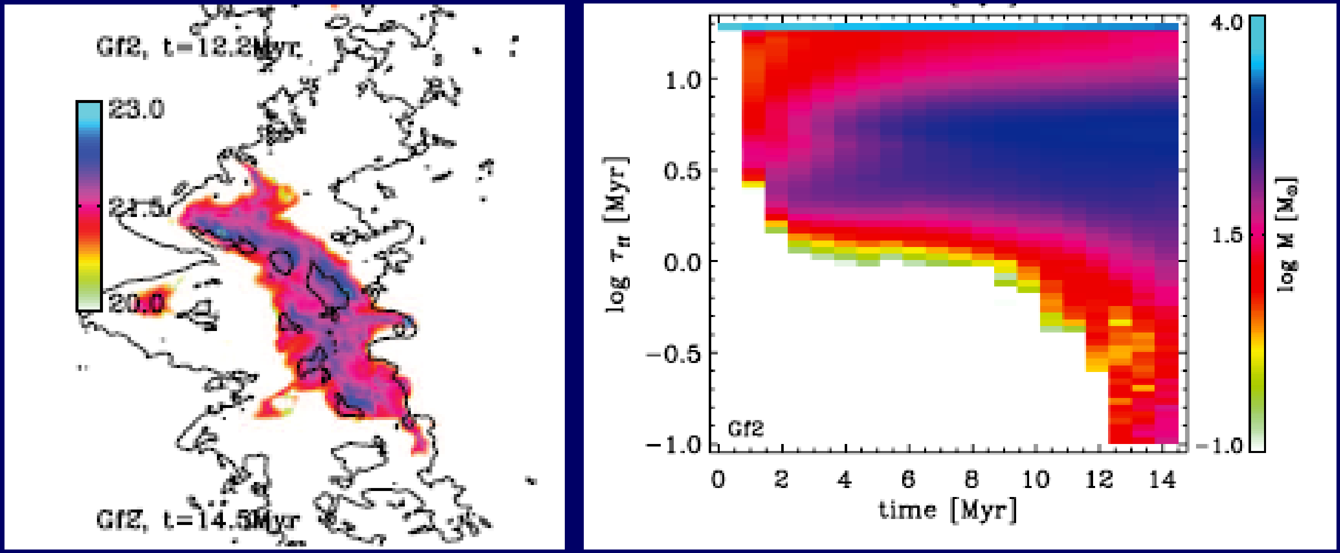
(VS+18, in prep.)

- Hoyle fragmentation (Hoyle, 1953, ApJ, 118, 513):
  - Jeans mass scales as

$$M_J \sim T^{3/2}\,\rho^{-1/2}$$

  - In particular, for isothermal flows, M_J decreases with increasing density.
    - ➔ As an isothermal cloud contracts gravitationally, it contains ever more Jeans masses → *fragmentation*.
  - The mechanism was criticized by Tohline (1980):
    - For spherical clouds just over the Jeans mass with linear fluctuations, the fastest-growing modes are the largest scales.
      - ➔ Large-scale collapse should overwhelm small-scale one.
      - ➔ No fragmentation

- Hoyle fragmentation in realistic MCs (VS+18, in prep.):
  - Actual MCs:
    - Are not spherical. Likely sheet-like, because their formation ***requires*** collisions of streams (Bally+87; Heiles & Troland 03; VS+06, ApJ, 643, 245).
    - Contain many Jeans masses.
      - Guszejnov+18: Number of Jeans masses determines fragmentation, not turbulent Mach number.
    - Contain ***nonlinear***, turbulent density fluctuations.
      - Distribution of density fluctuations ➔ distribution of free-fall times.



Projected cloud shape and distribution of free-fall times in a colliding-stream simulation of MC formation (Heitsch & Hartmann 2008).

- As the MC contracts, the ***average*** Jeans mass within it decreases.
    - However, must consider the Jeans mass at the density of the ***typical*** (rms) turbulent fluctuation, of amplitude $\rho_{rms}/\rho_0 \sim M_s^2$.

- Can estimate the evolution of the Jeans mass at the density of the typical density fluctuation in spherical geometry:
    - The evolution of the radius of a uniform-density collapsing sphere can be approximated by (Girichidis+14)

$$R(\tau) = R_0(1 - \tau^2)^{a/3}$$

where $\tau = t/t_{ff}(\rho_0)$, and a = 1.8614 is a parameter for which the fit remains within 0.5% of the actual free-fall solution.

- From here, assuming constant mass, the mean density and the mean Jeans mass in the MC are respectively given by

$$\rho(\tau) = \rho_0(1-\tau^2)^{-a}$$

and

$$M_{\rm J}(\tau) = M_{\rm J}(\rho_0)(1-\tau^2)^{a/2}$$

- The Jeans mass at the density of the typical fluctuation therefore evolves as

$$M_{\rm J,rms}(\tau) \approx \frac{M_{\rm J}(\rho_0)}{\mathcal{M}_{\rm s}}\left(1-\tau^2\right)^{a/2}$$

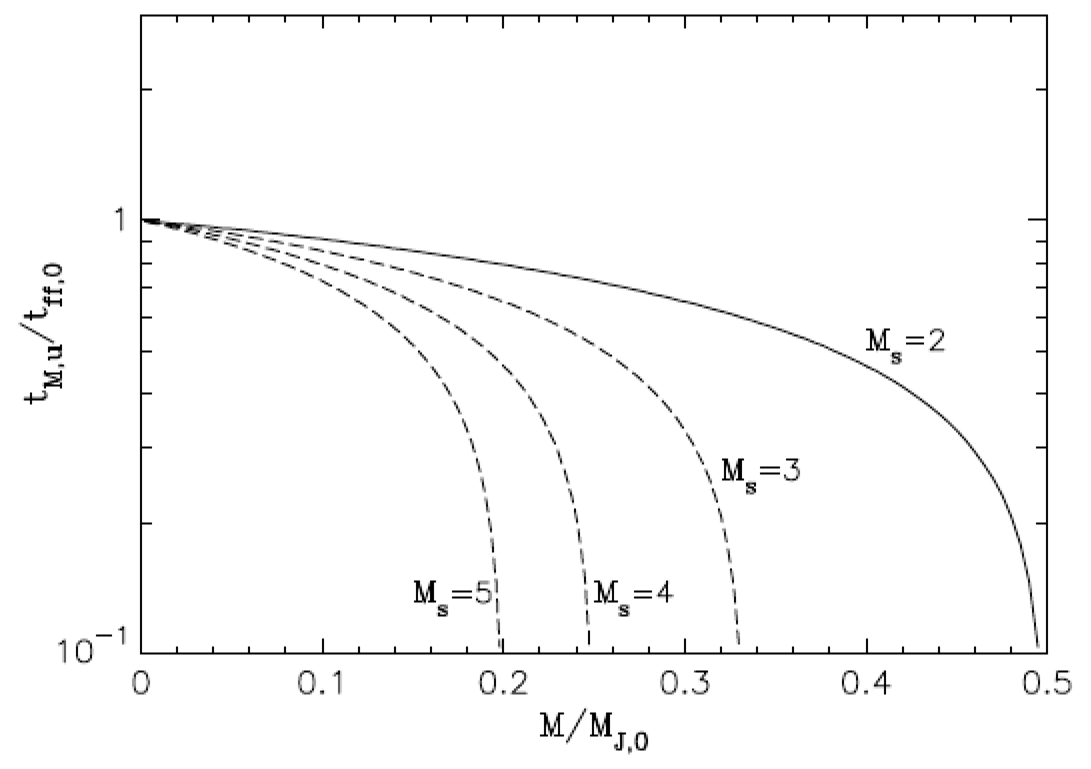
where M_s is the sonic Mach number of the turbulence.

- Inverting this expression, we obtain the time for mass M at the density of the rms fluctuation to become equal to $M_{J,rms}(\tau)$:

$$\tau_{\rm M,u} \equiv \frac{t_{\rm M,u}}{t_{\rm ff,0}} \approx \left[1-\mu^{2/a}\right]^{1/2}$$

where $\mu \equiv \mathcal{M}_{\rm s} M / M_{\rm J}(\rho_0)$ is the fluctuation's mass normalized to the initial Jeans mass in the cloud.

- Thus, the time for mass scale M at the density of the rms turbulent fluctuation to go unstable, for various M_s, is

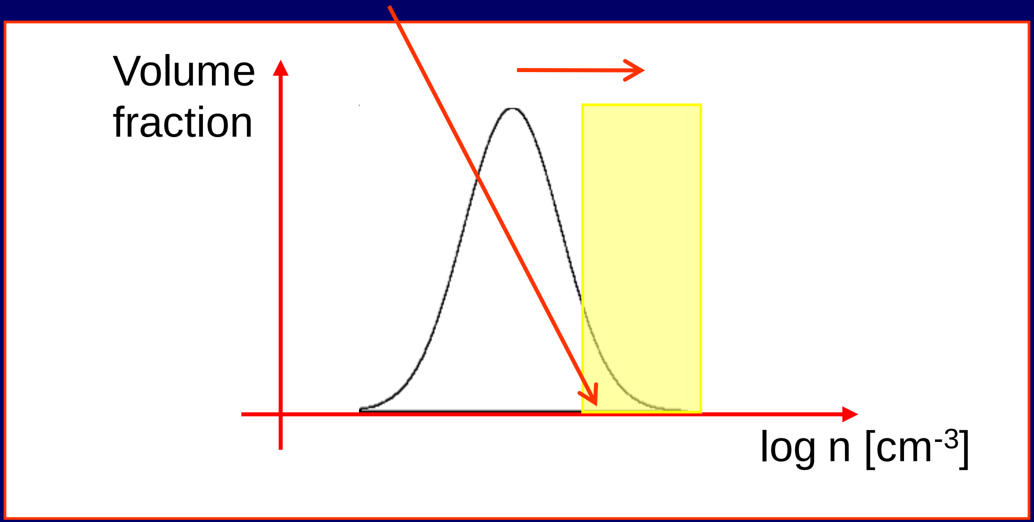


VS+18, in prep.

- Thus, sequentially smaller masses become unstable as time proceeds.

- Can also estimate the time at which the ***first-ever*** fragment collapses occur.
  - Now, consider the most extreme fluctuations, with t_{ff} so small that they can be assumed to form stars instantaneously.
  - The first collapses occur when the mass above this density (given by the density PDF) equals the local Jeans mass:

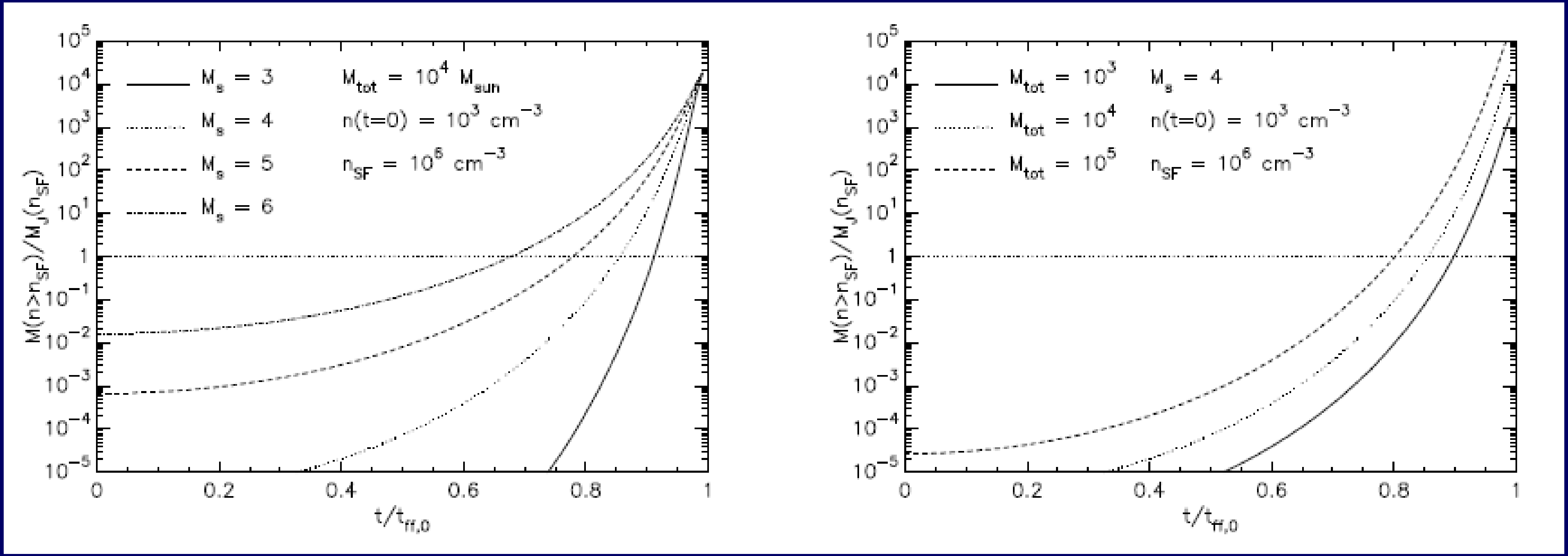
$$M(\rho \geq \rho_{SF}) = M_J(\rho_{SF})$$



Lognormal PDF (VS94).

- As cloud collapses, mass fraction above n_{SF} increases.

- Thus, the time for the first collapses to occur, for various M_s and various cloud masses M_{tot}, is



- For reasonable parameters, the first collapses typically occur between 0.7 and 0.9 $t_{ff,0}$.
  - Qualitatively consistent with simulations.

VS+18, in prep.

- Implications:
  - HGC is an *evolutionary* scenario for MCs and their SFR.
    - Contrary to stationary models for the SFR (Krumholz & McKee 05; Padoan & Nordlund 11; Hennebelle & Chabrier 11; Hopkins 12; Federrath & Klessen 12).
  - Collapse starts at the large scales.
    - Smaller-scales are the “tips of the iceberg” of the large scales.
  - ***SF accelerates*** (Zamora-Avilés+12, ApJ, 751, 77; Matt’s talk)…
  - … until feedback destroys the region (Colín+13, MNRAS 435, 1701; VS+17, MNRAS, 467, 1313).
  - Nonlinear turbulent fluctuations allow Hoyle-like fragmentation.
    - Sequential destabilization of progressively smaller mass scales.

- Caveats:
  - Calculations are highly idealized:
    - Based on spherical geometry.
      - Actual timescales (for sheets and filaments) are longer (Toalá+12; Pon+12).
    - Ignored accretion.
  - However, illustrate time-dependence of collapse at different mass scales.

THE END