Formation of Molecular Clouds and Global Conditions for Star Formation

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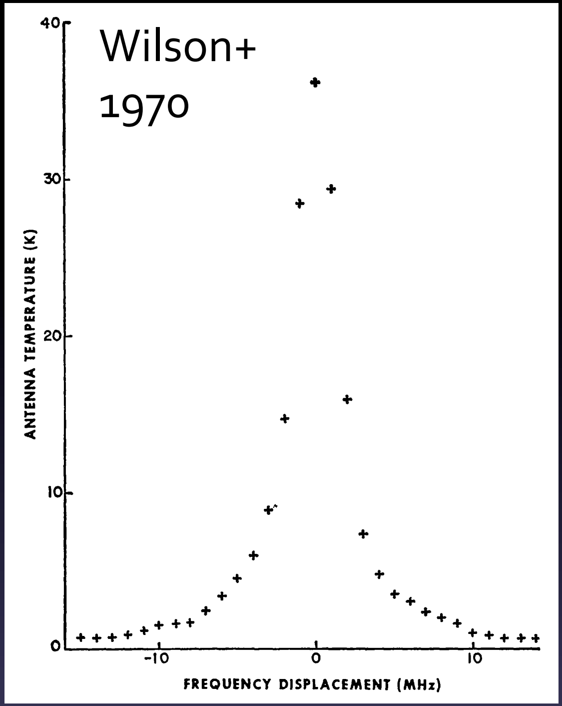
The Four Questions

- What do observations tell us?
- How do molecular clouds form?
- What processes control molecular cloud structure, evolution, and dissolution?
- What regulates star formation in molecular clouds?

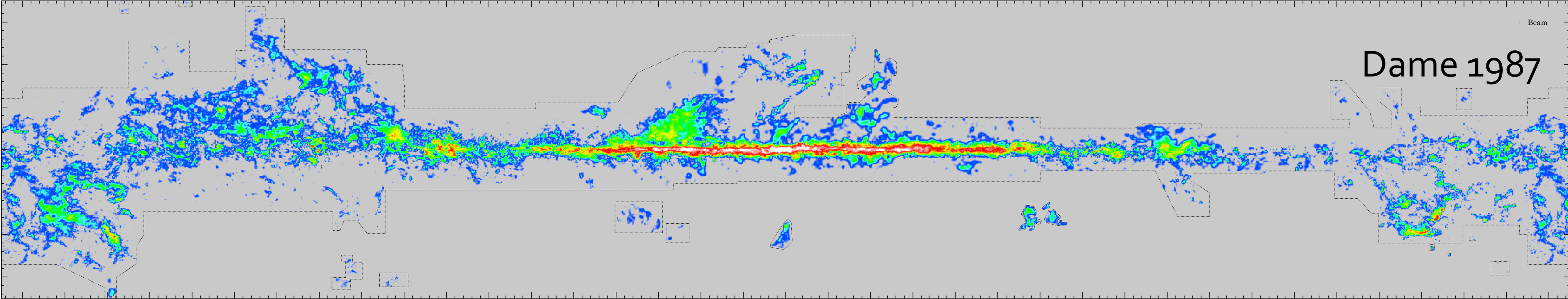
Question 1:

WHAT DO OBSERVATIONS TELL US?

In the beginning...

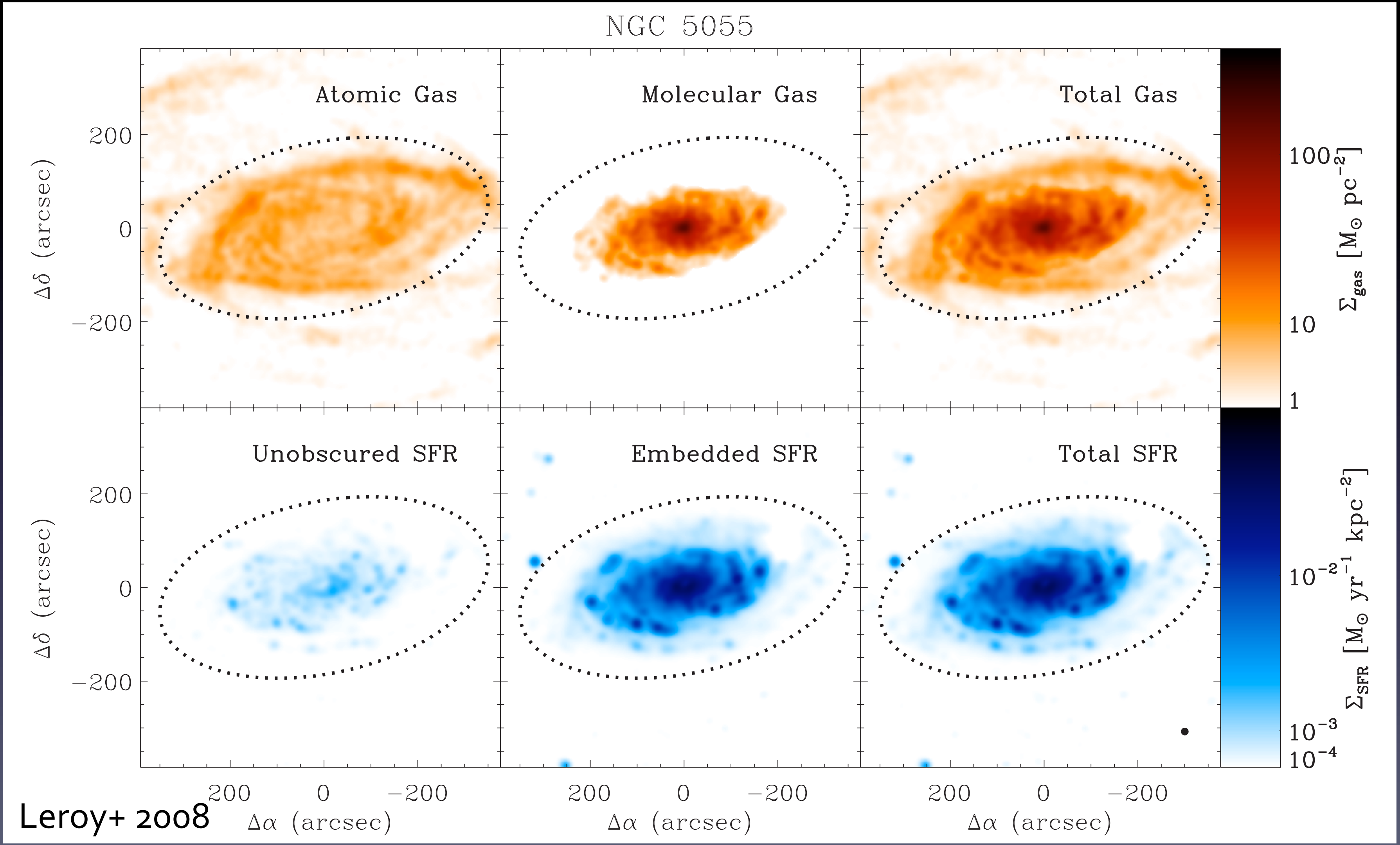


- 1930s: molecules in optical absorption
- 1960s: molecules in radio emission
- 1970: H_2 (Carruthers 1970), CO (Wilson+ 1970)
- 1980s: all-Galaxy CO maps (Dame 1987), cloud catalogs (Solomon+ 1987, Scoville+ 1987), high density tracers: NH_3, HCN, CS (Myers 1983; Snell+ 1984)
- 1990s: extragalactic GMCs, interferometer maps, sub-mm dust



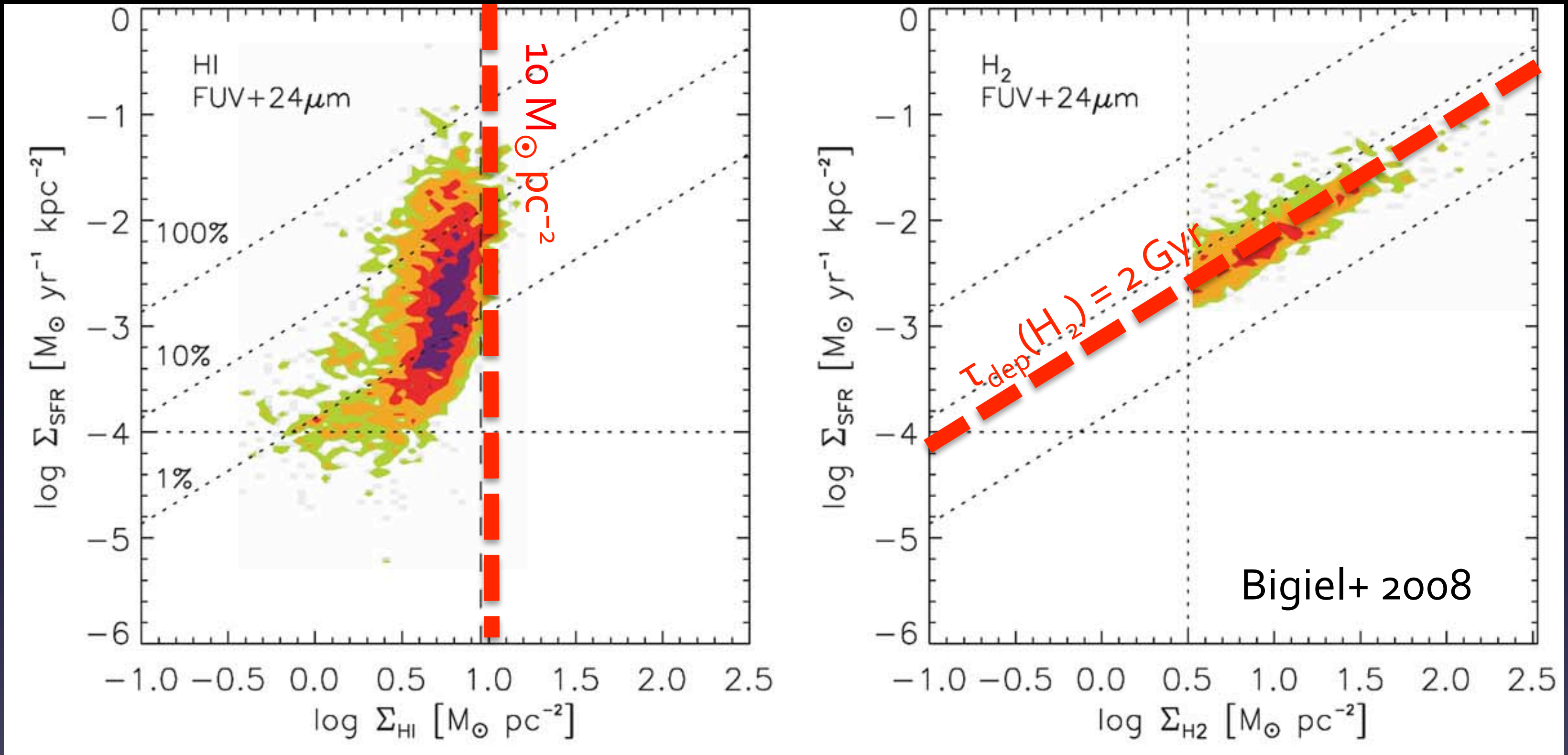
Top: Wilson et al., 1970,ApJL, 161, L43 ; Bottom: Dame et al., 1987, ApJ, 322, 706

Stars form in molecular clouds



Leroy et al., 2008, AJ, 136, 2782

Quantitative correlations

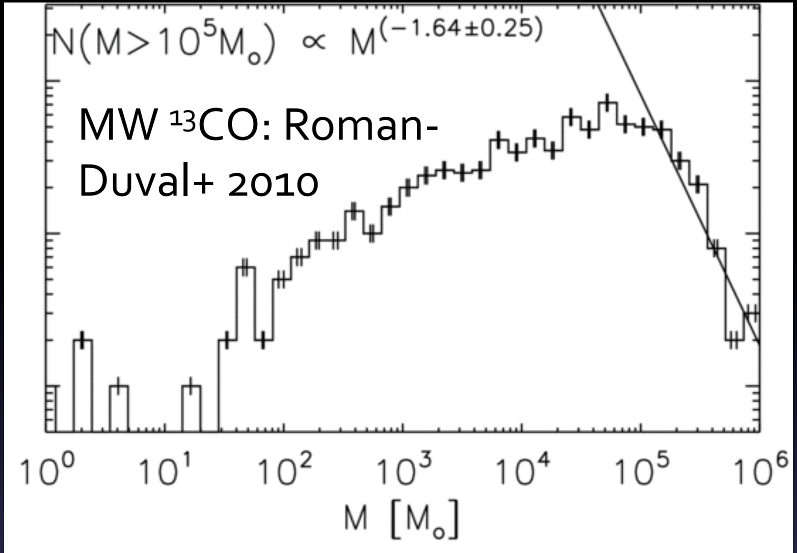


Bigiel+ 2008

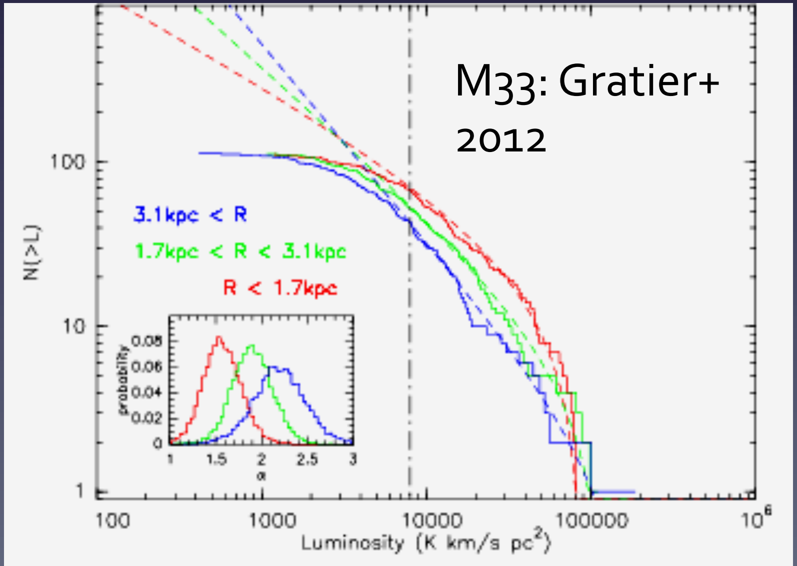
- SFR-HI correlation poor
- SFR-H_2 correlated, index ~1, $\tau_{dep}(H_2) = M_{H2}/SFR \sim 2$ Gyr
- Caveats: CO-H_2 and light-SFR conversion; correlation fails on small scales

Bigiel et al., 2008, AJ, 136, 2846

MC masses



MW ^{13}CO: Roman-Duval+ 2010

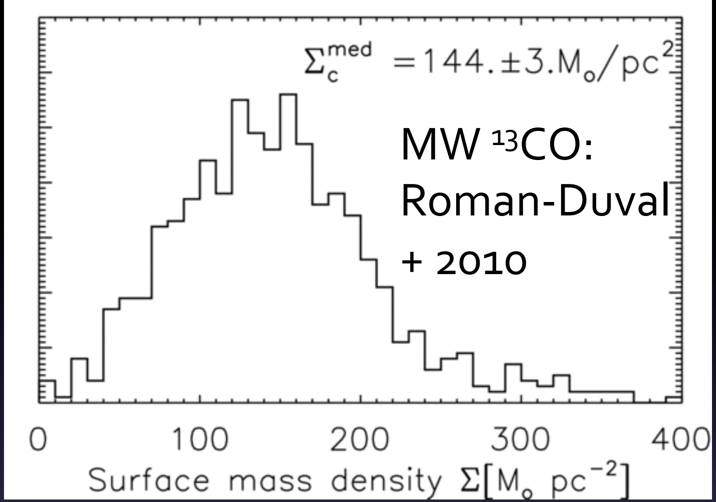


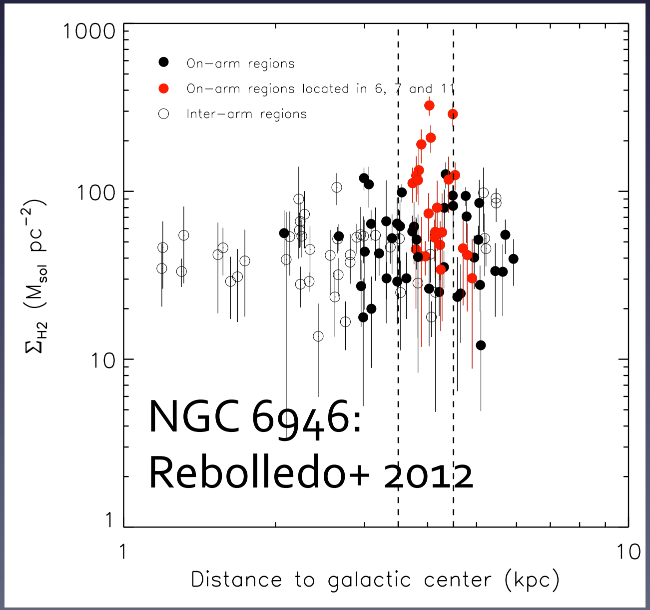
M33: Gratier+ 2012

- Mass range ~ $10^2 - 10^7\ M_\odot$
- Mass spectrum is a powerlaw dN / dM ~ M^γ, possibly with an upper cutoff
- γ ~ −2 to −1.5 in H_2-rich regions (inner MW and M33)
- γ ~ −2.5 to −2 in H_2-poor regions (outer MW and M33, LMC, SMC)
- NB: $\gamma > -2$ means most gas in big clouds

Top: Roman-Duval et al., 2010, ApJ, 723, 492
Bottom: Gratier et al., 2012, A&A, 542, A108

MC surface densities





- MC surface densities ~100 $M_\odot$ pc^{-2}, no systematic variation with mass or Milky Way galactocentric radius
- Possible weak dependence on environment in other galaxies: lower in low Σ regions, higher in high Σ regions
- PDF of Σ within GMCs roughly lognormal w/powerlaw tail
- Caveat: sensitivity bias

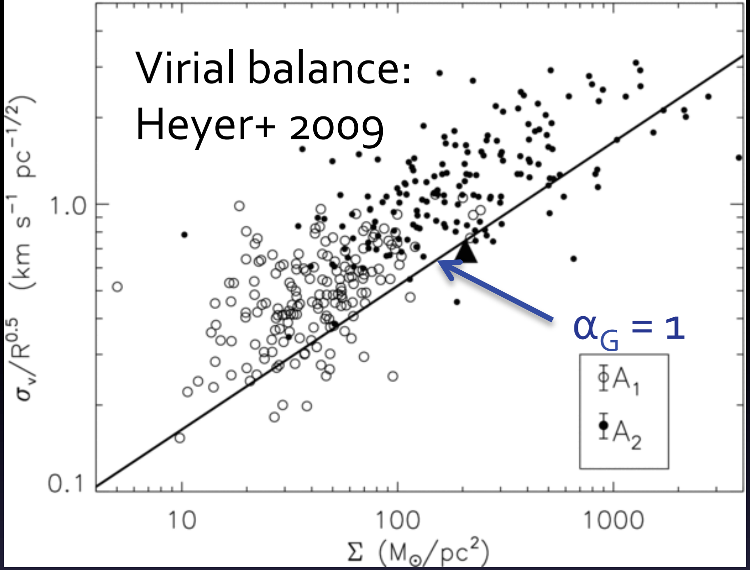
Top: Roman-Duval et al., 2010, ApJ, 723, 492
Bottom: Rebolledo et al., 2012, ApJ, 757, 155

MC velocity dispersions

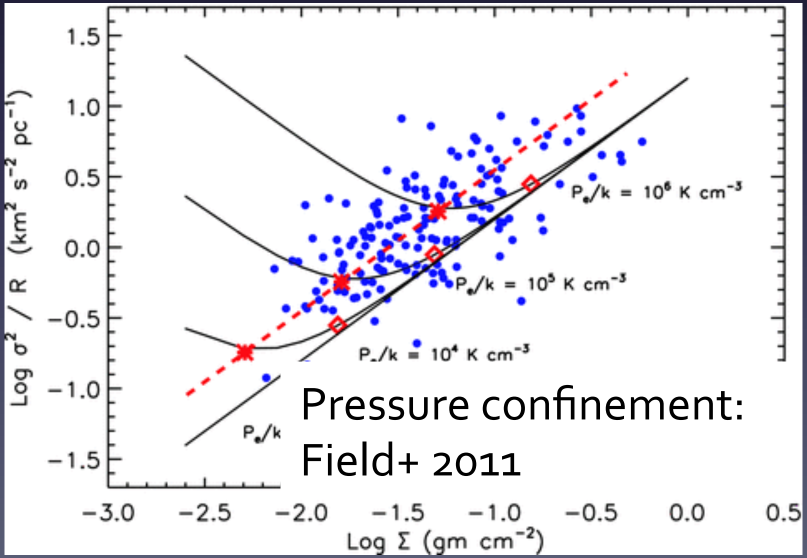
- Velocity dispersion obeys

  $\sigma_v = (\alpha_G \pi G \Sigma R/5)^{1/2}$

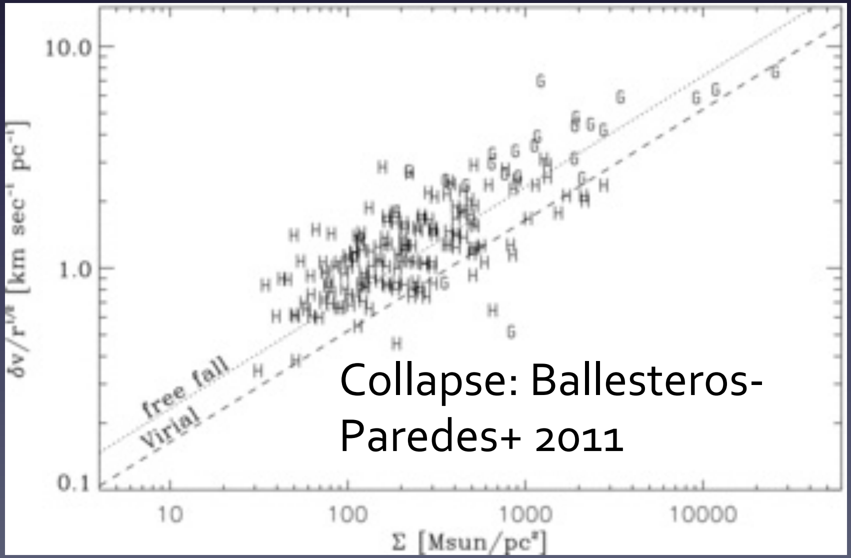
  with $\alpha_G \approx 1$ (Heyer+ 2009)
- Could be virialization, pressure confinement, free-fall collapse
- Most power on large scales



Virial balance: Heyer+ 2009



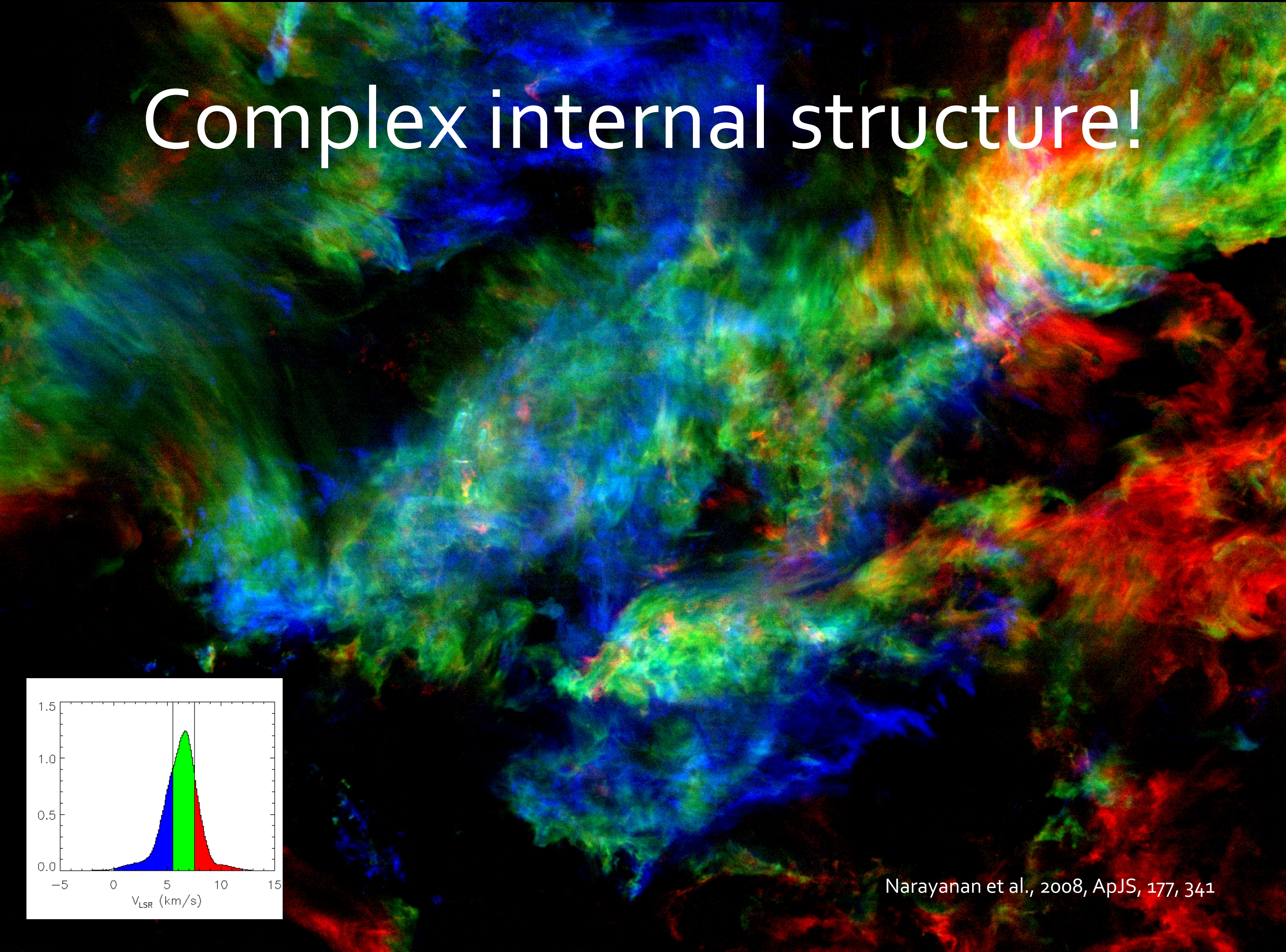
Pressure confinement: Field+ 2011



Collapse: Ballesteros-Paredes+ 2011

Top: Heyer et al., 2009, ApJ, 699, 1092; Bottom left: Field et al., 2011, MNRAS, 416, 710;
Bottom right: Ballesteros-Paredes et al., 2011, MNRAS, 43, 123

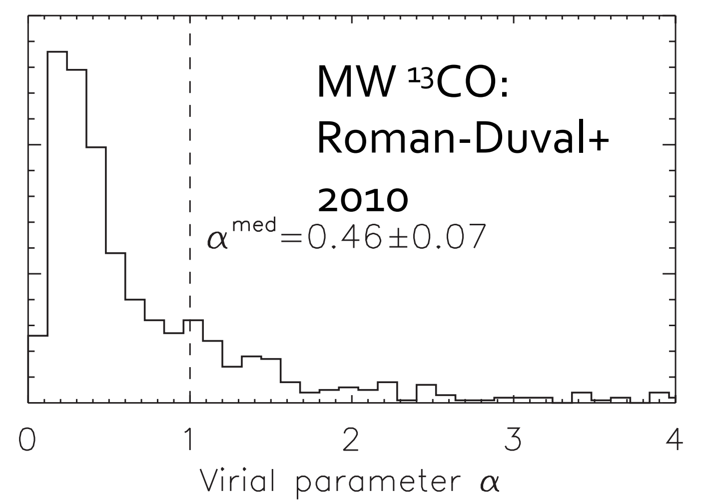
Complex internal structure!

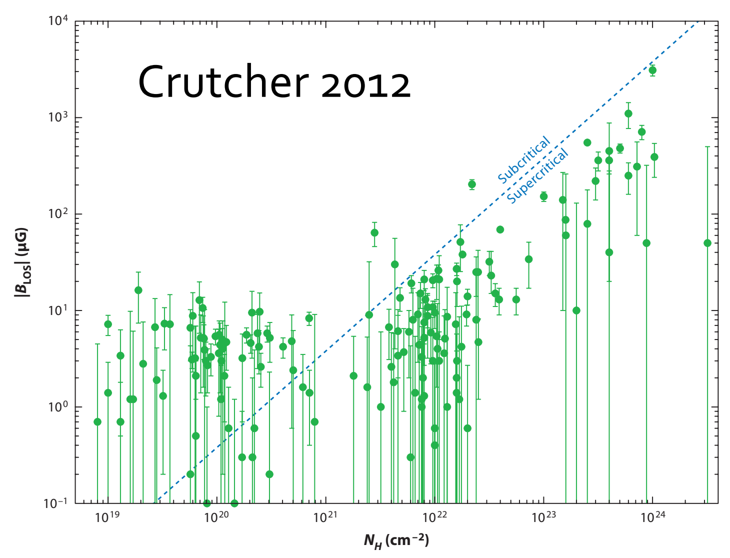


Narayanan et al., 2008, ApJS, 177, 341

Dimensionless numbers!

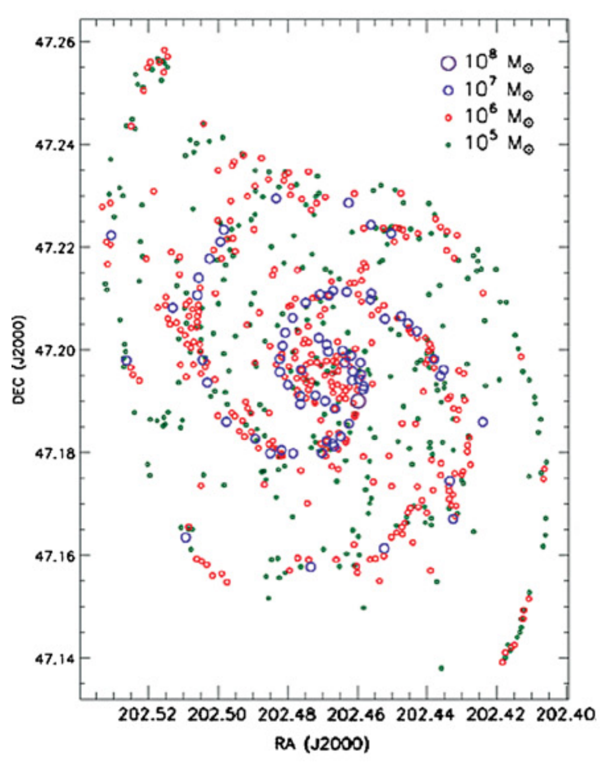
- Virial theorem describes large-scale dynamics of GMCs; ratio of terms says what forces are important
- $\alpha_G = -2\,T\,/\,W \approx 1$: gravity and large-scale motions comparable
- $M\,/\,M_{crit} = M\,/\,[\Phi/(4\pi G)^{1/2}] \approx 2$: magnetic fields not negligible, but not strong enough to offset gravity



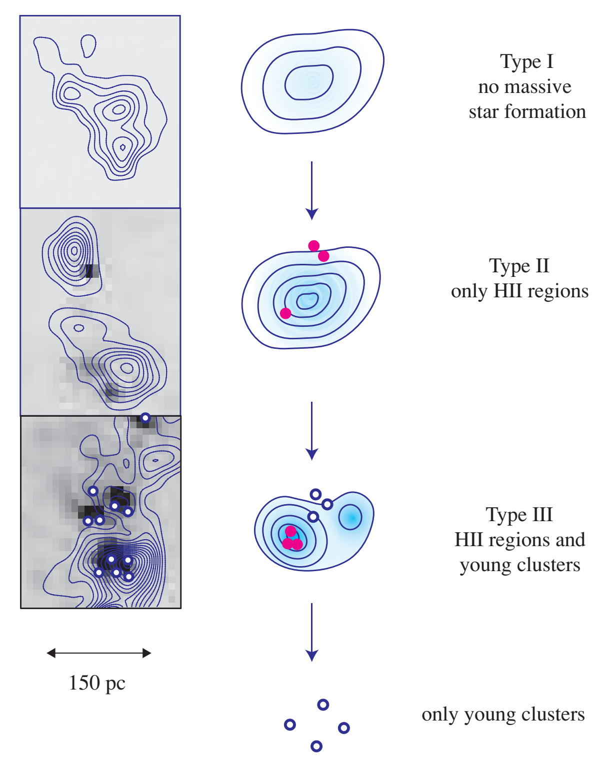


Top: Roman-Duval et al., 2010, ApJ, 723, 492
Bottom: Crutcher, 2012, ARA&A, 50, 29

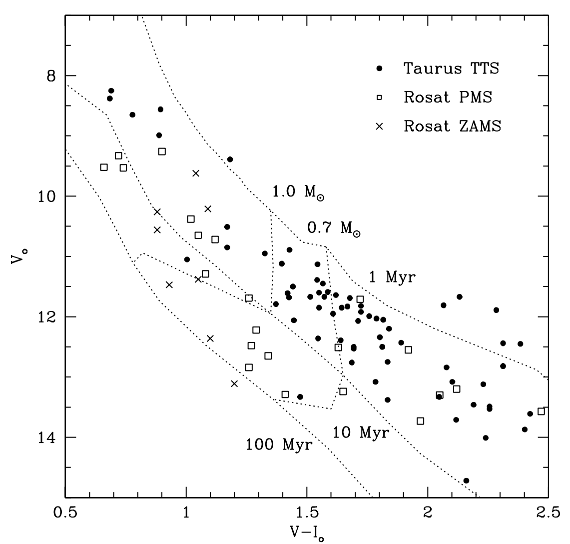
GMC lifetimes



M51: lots of inter-arm clouds, lifetime ~100 Myr (Koda+ 2009)



LMC: lifetime from number counts + cluster ages ~30 Myr (Kawamura+ 2009)

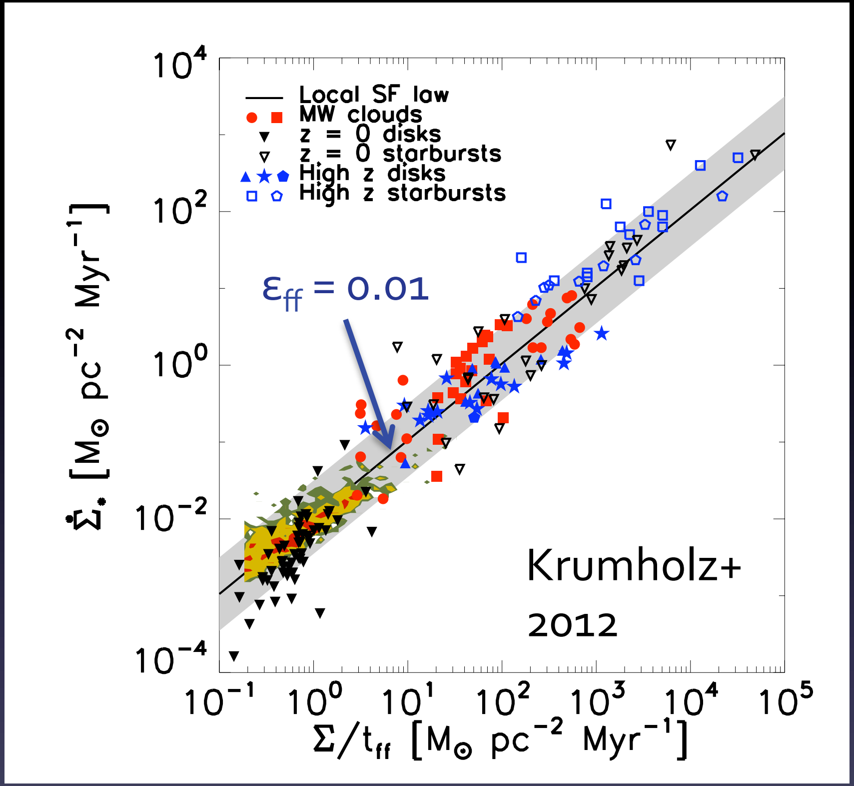


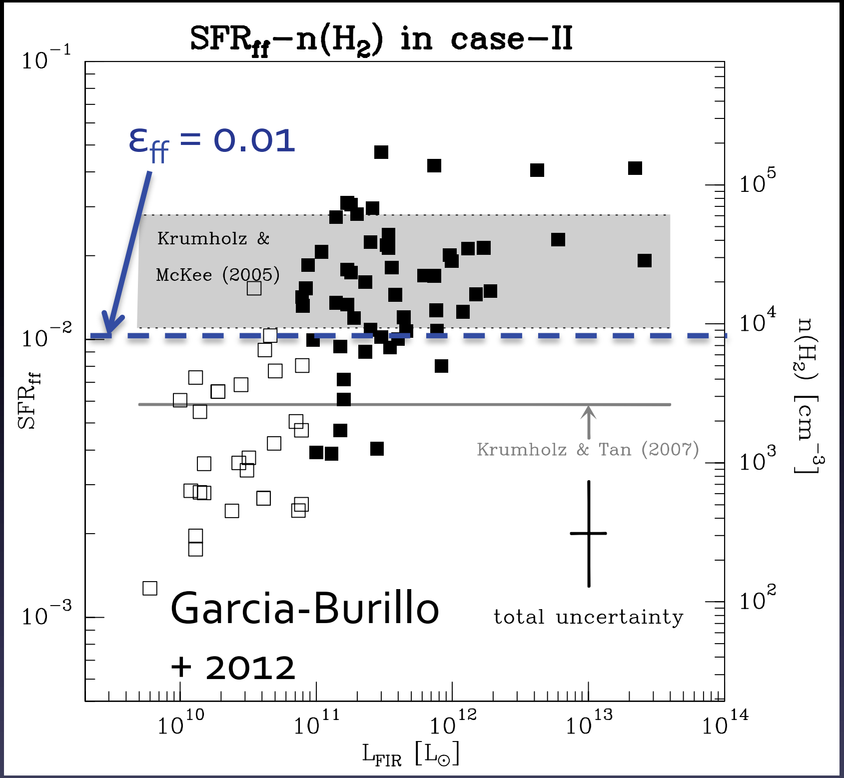
Solar neighborhood: no post-T Tauri stars in nearby clouds, ~ 3 Myr (Hartmann+ 2001)

- For comparison, free-fall time $t_{ff} = (3\pi/32G\rho)^{1/2} \approx 1 - 5$ Myr
- Local vs. M51, LMC lifetime difference may be selection effect

Left: Koda et al., 2009, ApJ, 700, L13; middle: Kawamura et al., 2009, ApJS, 184, 1; Right: Hartmann et al., 2001, ApJ, 562, 852

Star formation: low efficiency



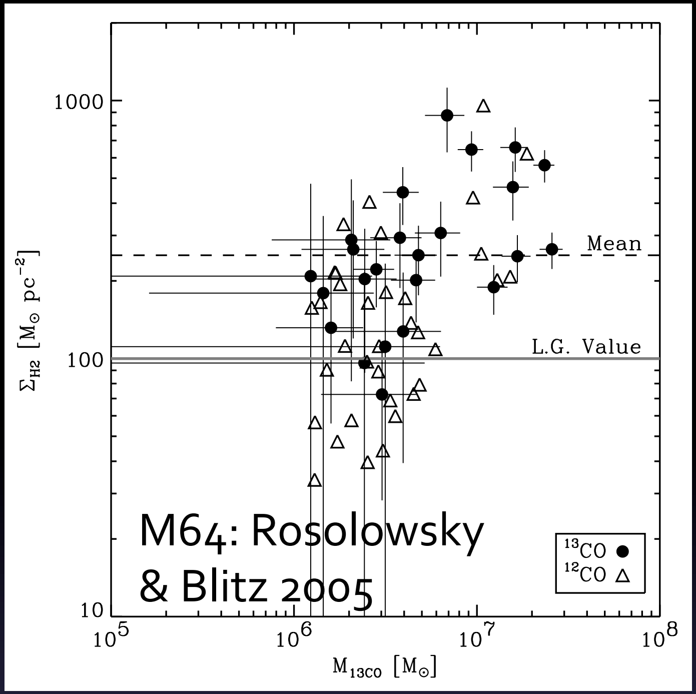


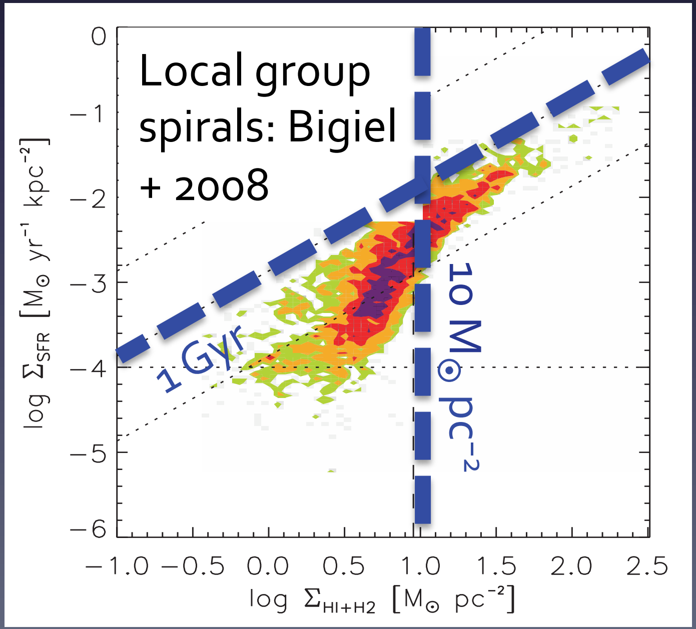
- SFR per free-fall time ϵ_{ff} = SFR / (M_{gas}/t_{ff}) ~ 0.01 (factor of ~3 spread) over broad range of densities, environments
- $t_{life} < 100\ t_{ff}$, so GMCs disrupted at low overall SFE

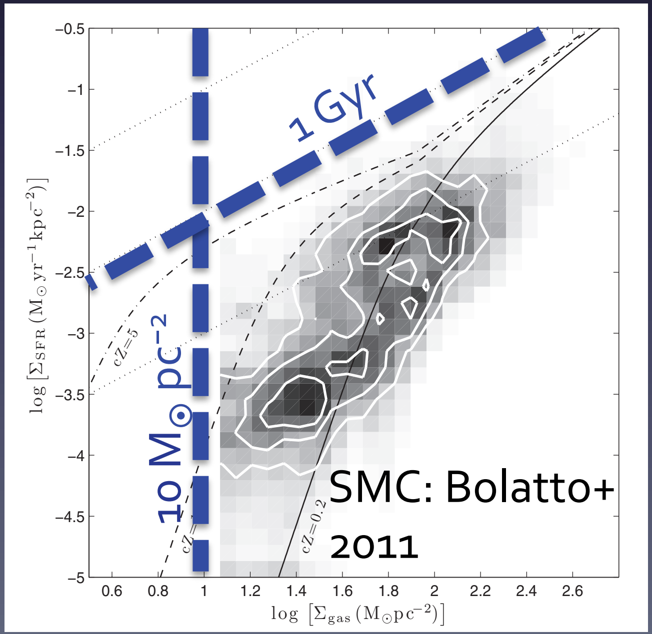
Left: Krumholz et al., 2012, ApJ, 745, 69; Right: Garcia-Burillo et al., 2012, A&A, 539, A8

GMCs in extreme environments

Physical and star formation properties vary near galactic centers, in starburst galaxies, and at low metallicity







Top: Rosolowsky & Blitz, 2005, ApJ, 623, 826

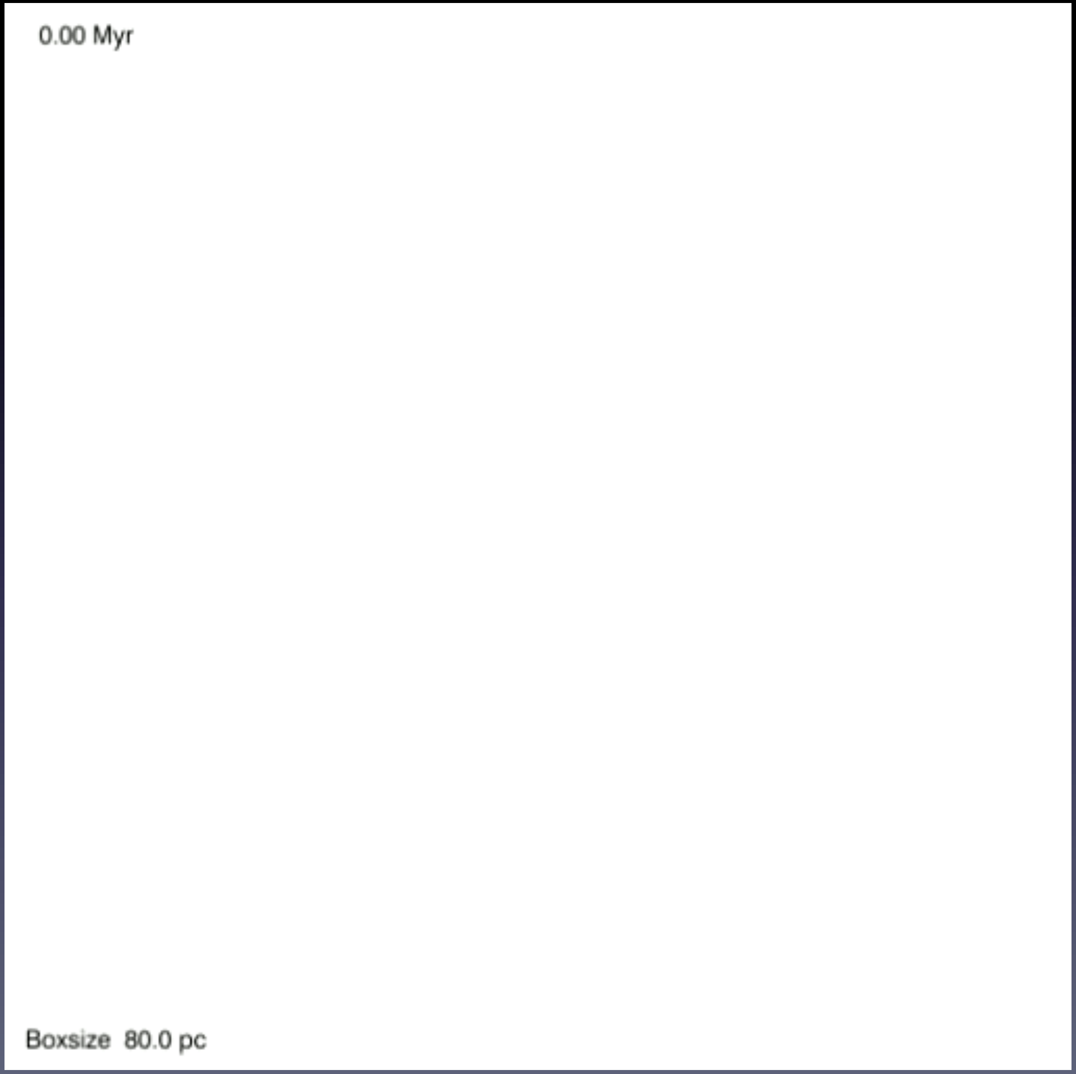
Bottom left: Bigiel et al., 2008, AJ, 136, 2846

Bottom right: Bolatto et al., 2011, ApJ, 741, 12

Question 2:

HOW DO MOLECULAR CLOUDS FORM?

Local converging flows I



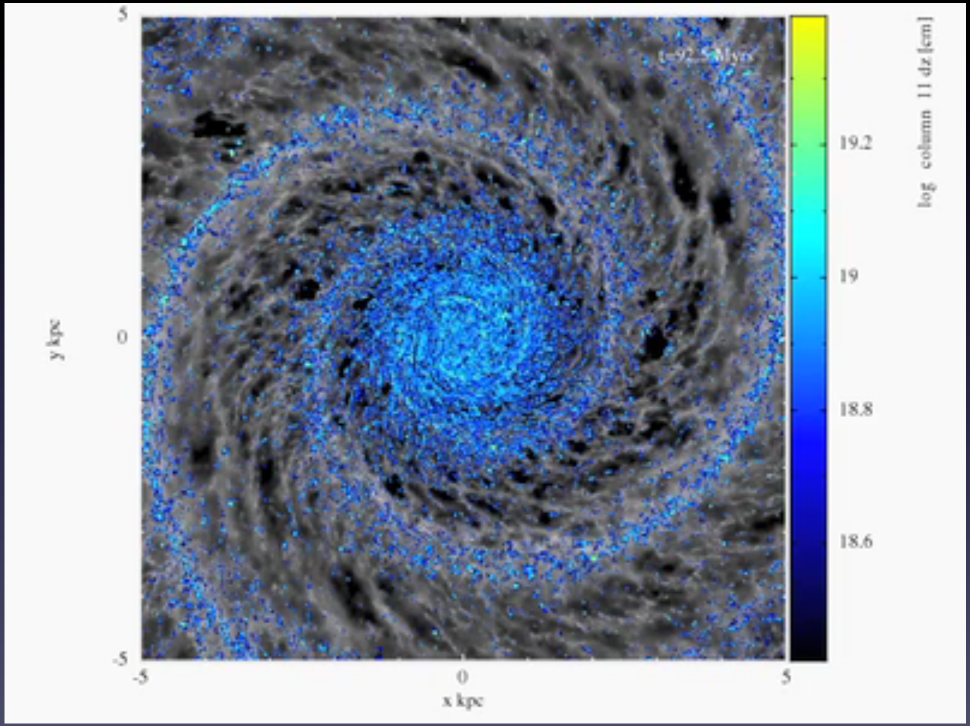
Vazquez-Semadeni+ 2011

Vazquez-Semadeni et al., 2011, MNRAS, 414, 2511

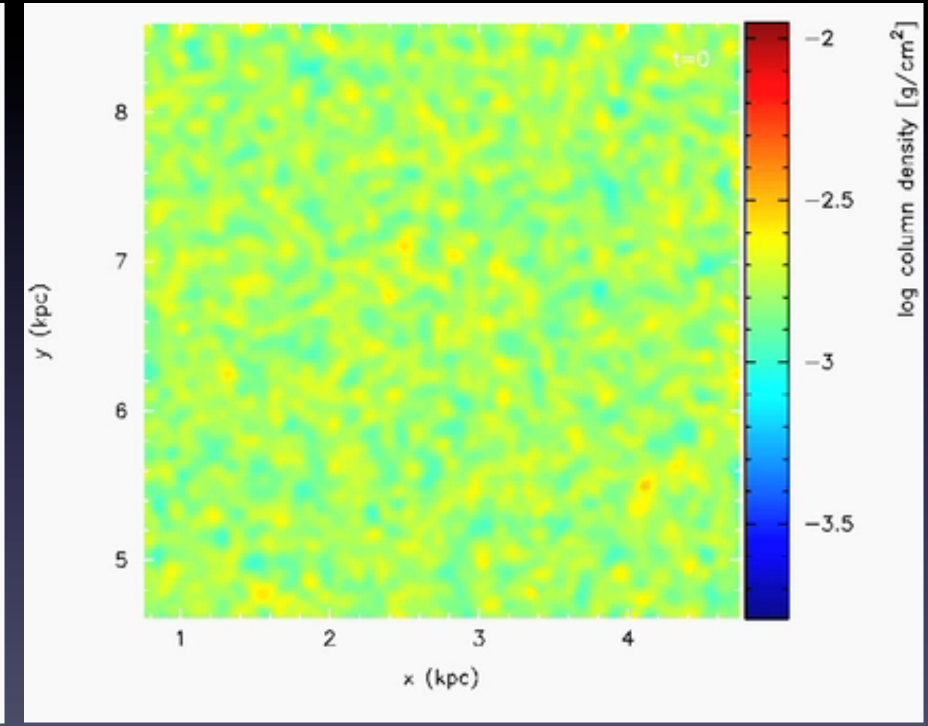
Local converging flows II

- Local turbulence or feedback (e.g. SN blast wave) triggers collision of warm HI streams
- Density rise triggers transition to cold HI, then H_2 once column exceeds $\sim 10^{21}$ cm^{-2}; H_2 formation and star formation simultaneous
- Maximum mass ~ mean ISM surface density x $H^2 \sim 10^4$ $M_\odot$; can't produce the big GMCs that contain most of the mass

Cloud collisions in spiral arms I



Dobbs & Pringle 2013



Dobbs+ 2012

Left: Dobbs & Pringle, 2013, MNRAS, 432, 653; right: Dobbs et al., 2012, MNRAS, 425, 2157

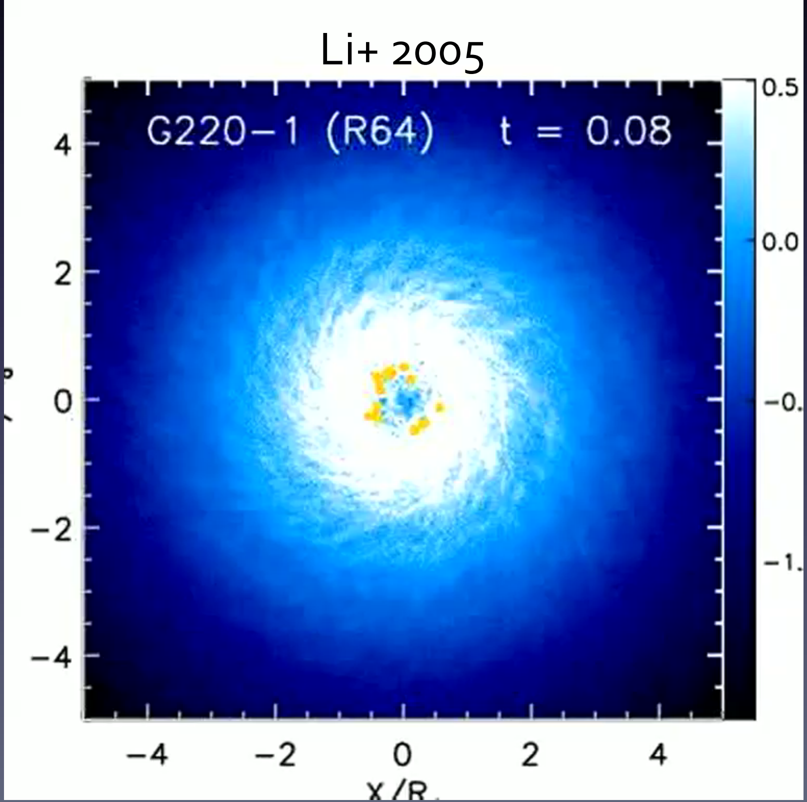
Cloud collisions in spiral arms II

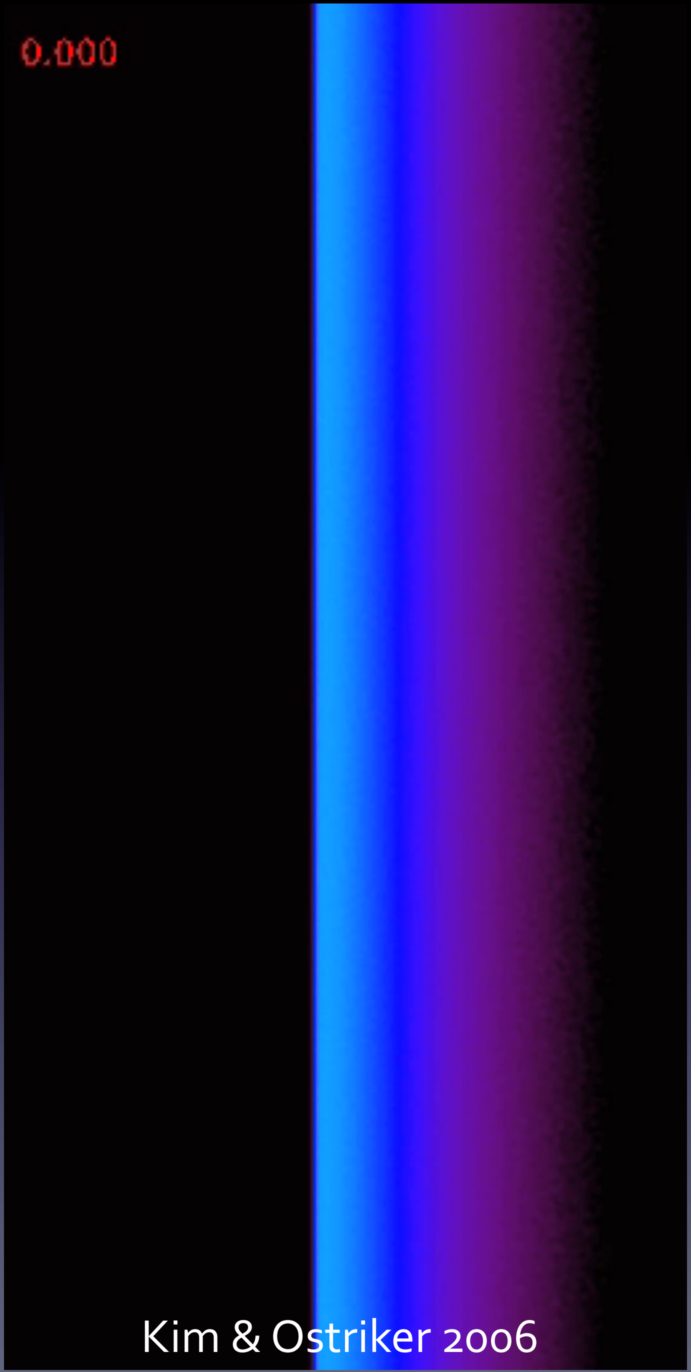
- Collisions slow except in spiral arms, where rate is enhanced by orbit crowding
- Can build > 10^6 $M_\odot$ clouds in such regions
- Explains why many GMCs are counter-rotating relative to galaxy
- Produces right cloud mass spectrum
- Operation unclear in flocculent galaxies without big stellar spiral potential

Gravitational and magneto-Jeans instability I

Left: Li et al., 2005, ApJ, 626, 823

Right: Kim & Ostriker, 2006, ApJ, 646, 212


Li+ 2005

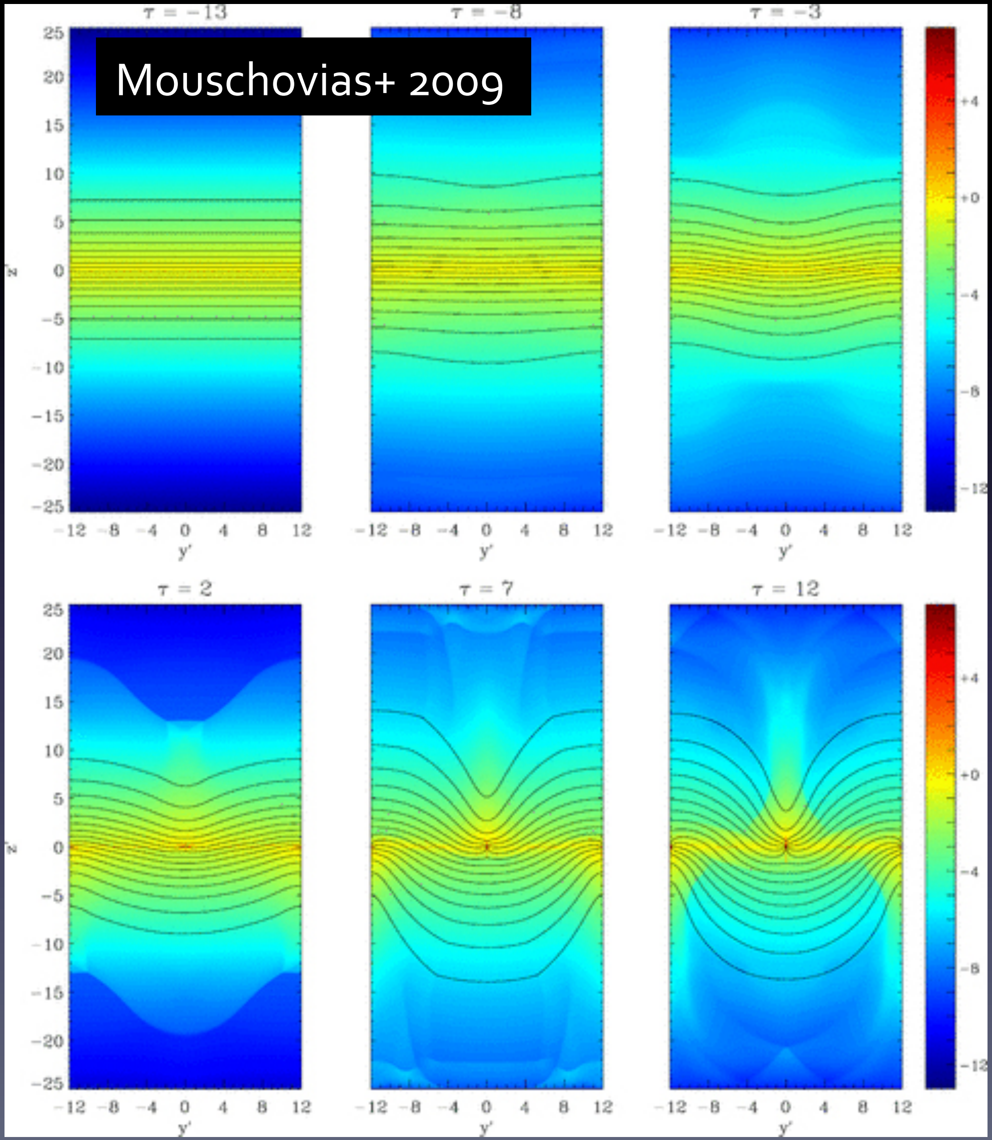


Kim & Ostriker 2006

GI and MJI II

- Non-axisymmetric instability occurs when $Q = \kappa c_{eff}/\pi G\Sigma <\sim 1.5$
- GI makes ~10^{7-8} $M_\odot$ clouds without spiral structure; smaller clouds from fragmentation
- MJI: works in arms w/low shear, B fields counter Coriolis; high Σ allows ~10^6 $M_\odot$ clouds
- Naturally explains spurs, "beads on a string" HII regions, low GMC spins (magnetic braking)
- Full cloud mass spectrum not yet determined

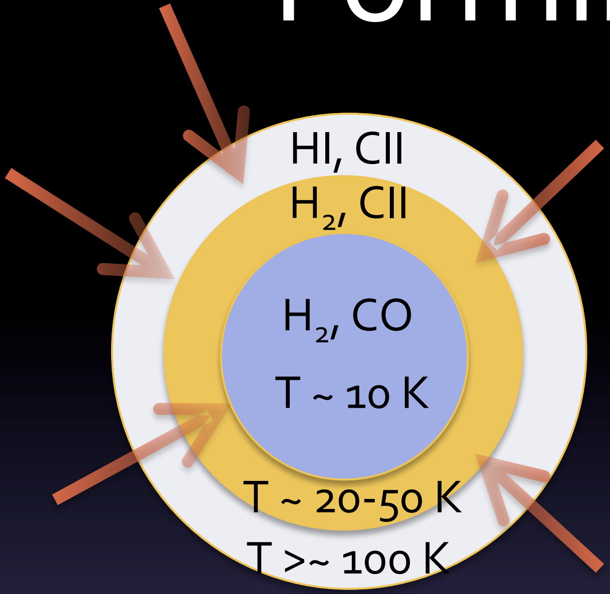
Parker + thermal instability



- Buoyancy makes B field lines rise out of plane, gas collects in valleys
- For isothermal medium density enhancement only factor of a few
- TI allows runaway cooling (cf. colliding flows)
- Makes ~10^5 $M_\odot$ clouds
- May not work in turbulent or multiphase medium

Mouschovias et al., 2009, MNRAS, 397, 14

Forming H_2 and CO



HI, CII

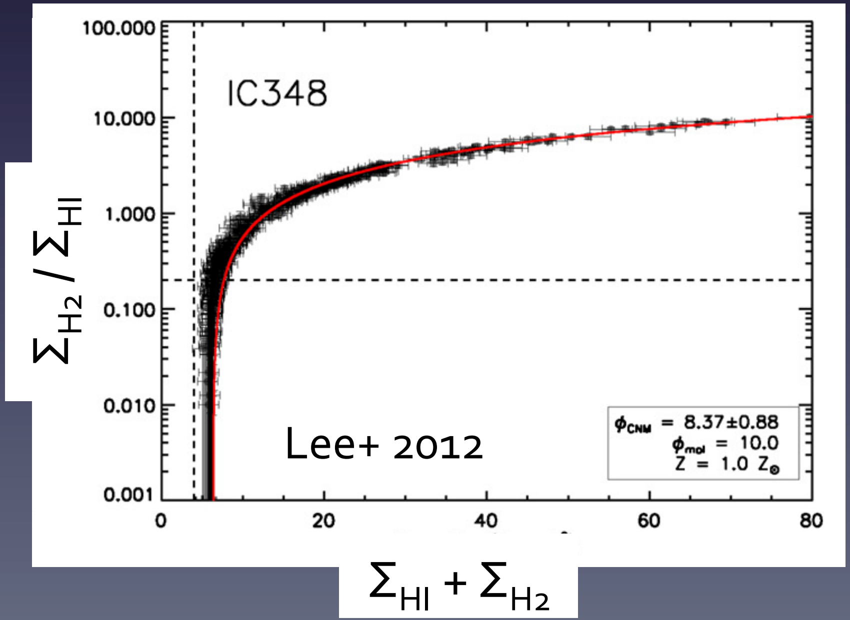
H_2, CII

H_2, CO

T ~ 10 K

T ~ 20-50 K

T >~ 100 K

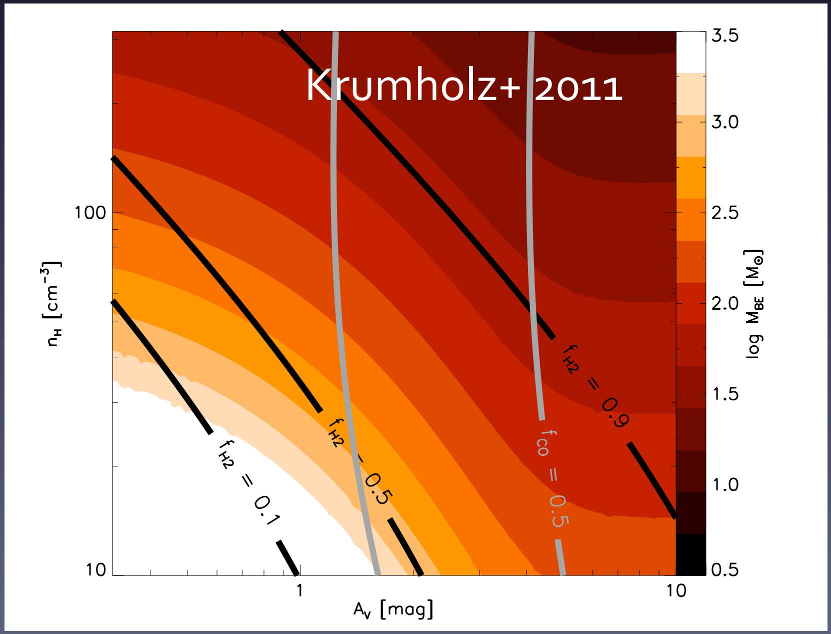


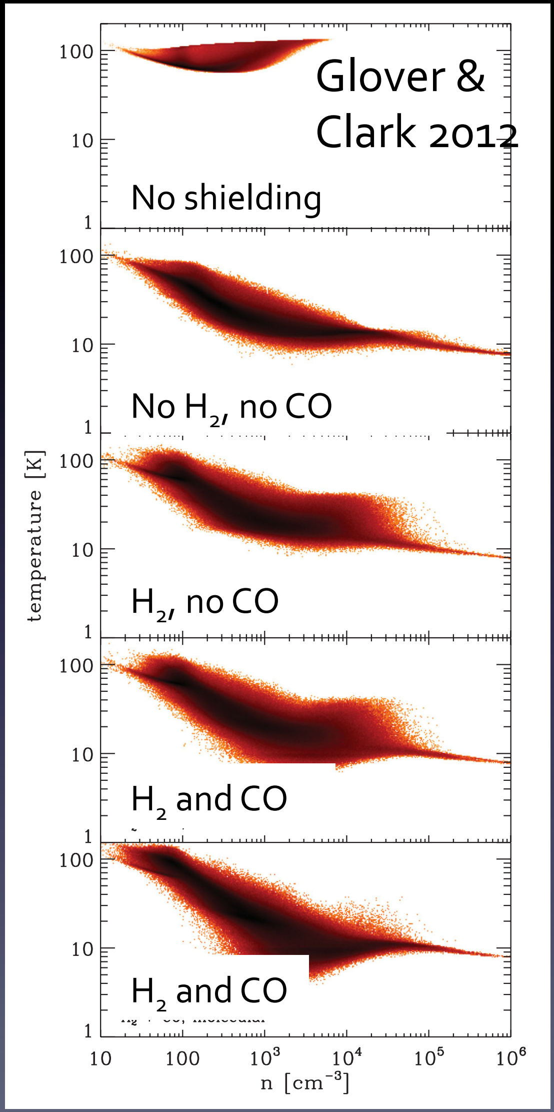
- H_2 forms on dust grains, dissociated by FUV; dominates only in dense, shielded regions
- CO forms in gas, requires H_2, also FUV dissociated
- Layered structure: HI + CII with column $\Sigma \sim 10/Z\ M_\odot\ pc^{-2}$, then H_2 + CII, then H_2 + CO
- Dust abundance matters a lot
- Unclear whether / when non-equilibrium chemistry important

Lee et al., 2012, ApJ, 745, 75

Do H_2, CO matter for SF?

- CO: no! CO-SF correlation fails at low Z, CO forms rapidly, not needed for cooling
- H_2 : ? H_2-SF still correlated at low Z, but probably because shielding matters for both H_2 and SF





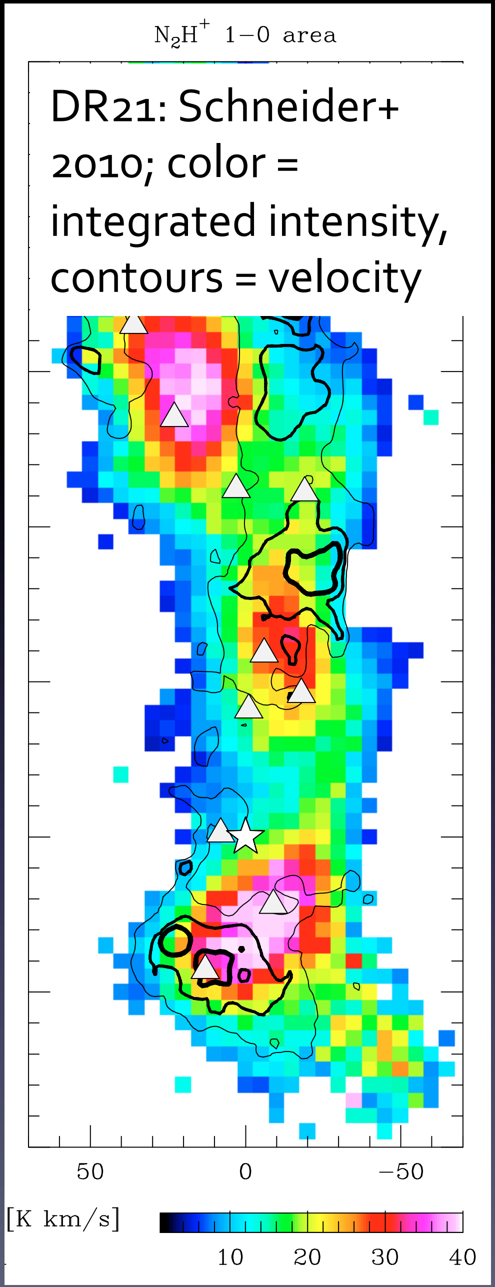
Left: Krumholz et al., 2011, ApJ, 731, 25

Right: Glover & Clark, 2012, MNRAS, 421, 9

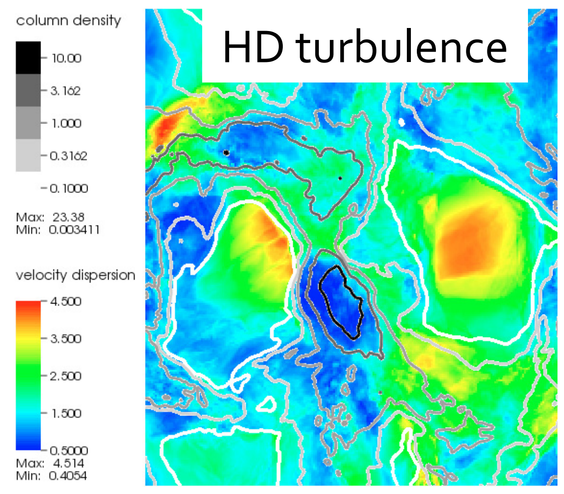
Question 3:

WHAT PROCESSES CONTROL GMC STRUCTURE, EVOLUTION, AND DISSOLUTION?

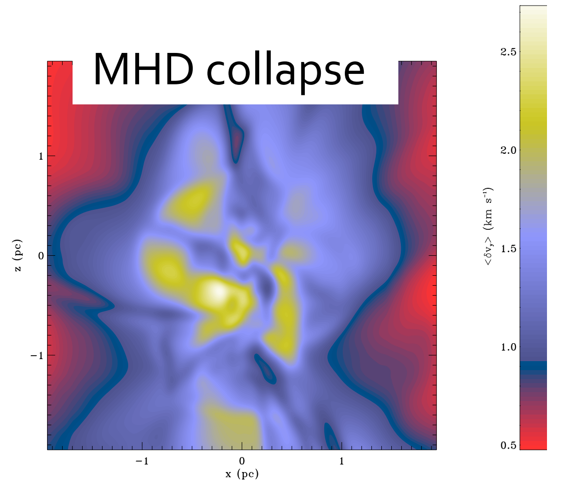
Morphological evidence



DR21: Schneider+ 2010; color = integrated intensity, contours = velocity



HD turbulence



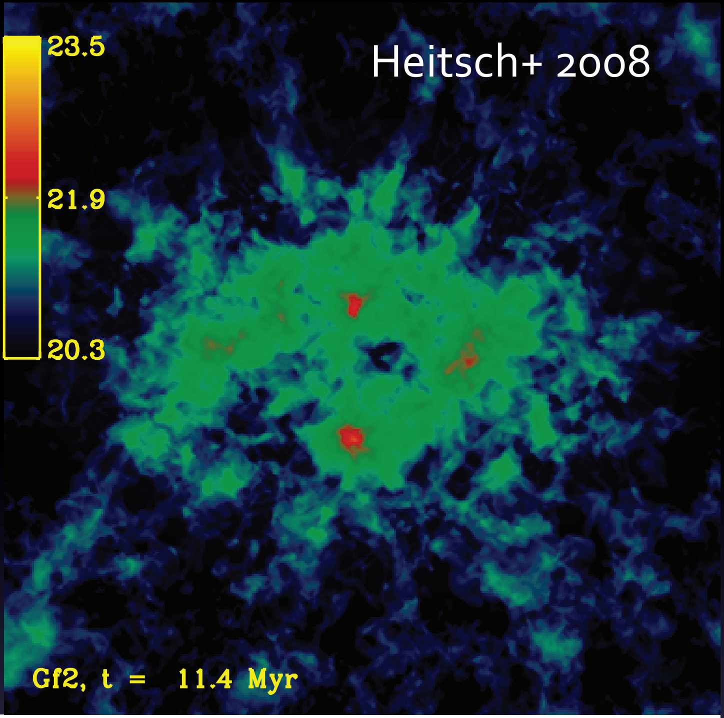
MHD collapse

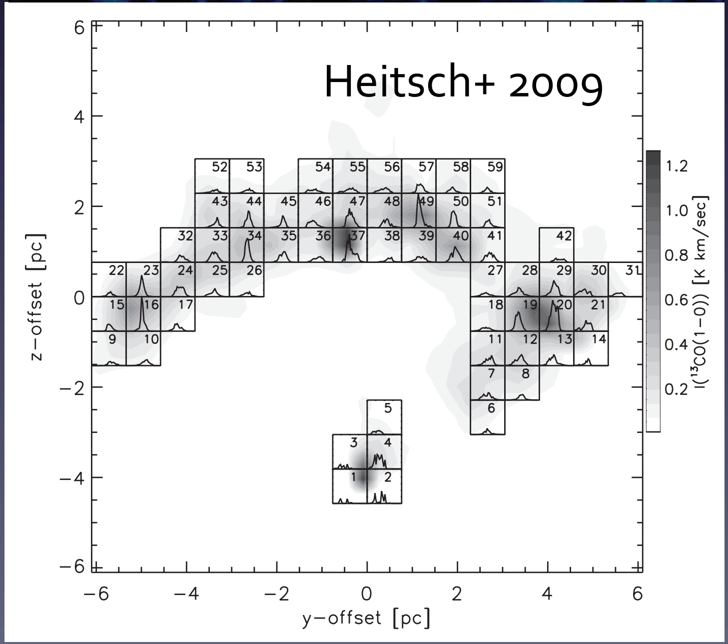
- Filaments with converging flows toward / along them
- Offset maxima of velocity, col. density
- Origin unclear: HD turbulence w / no self-gravity and free-fall magnetized collapse both fit!
- Need statistical measures

All figures: Schneider et al., 2010, A&A, 520, A49

Non-thermal motions

- $\sigma \sim 1 - 10$ km s^{-1} on $L \sim 10$ pc scales
- Viscosity $\upsilon \sim 10^{16}$ cm^2 s^{-1}, so $Re \sim LV / \upsilon \sim 10^9$: flow inevitably turbulent
- Turbulence decays, so why is σ so large?
- Possibilities:
  - – Global gravitational collapse
  - – External driving (e.g., accretion, collisions)
  - – Internal energy injection from SF feedback



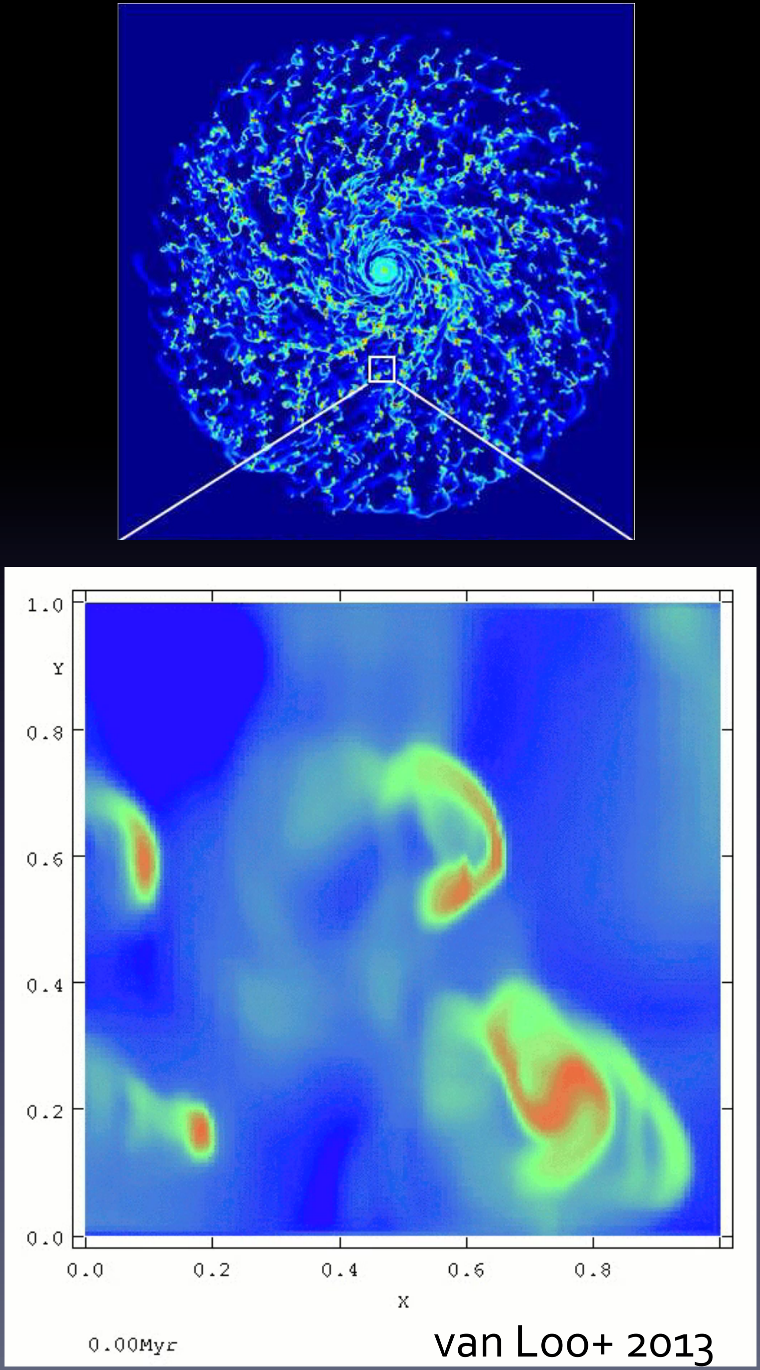


Global collapse

- Colliding flows of warm gas drive turbulence via NLTSI
- Gravity takes over, chaotic collapse follows
- Linewidths reflect collapse
- Easily explains linewidths
- Getting right ε_{ff} depends on details of feedback

Top: Heitsch et al., 2008, ApJ, 674, 316
Bottom: Heitsch et al., 2009, ApJ, 704, 1735

External driving

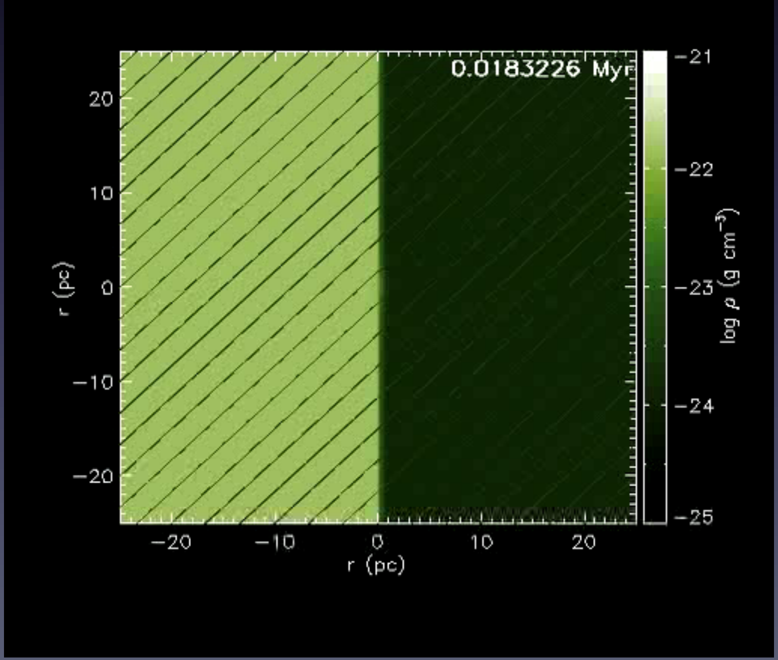


van Loo+ 2013

- Accretion onto cloud as it forms drives turbulence
- For big clouds, large-scale shear flows and turbulent cascade from rest of galaxy
- Seems able to explain both linewidths and lifetimes
- Needs feedback to get right ε_{ff}

Top and bottom: van Loo et al., 2013, ApJ, 764, 36

Internal driving



- Protostellar jets too weak on GMC scales
- Radiation pressure, main sequence winds: couple too weakly
- HII regions may work
- Gets ϵ_{ff} right
- Challenge: drive without disruption
- B fields may be important

Top: Gritschneder et al., 2009, ApJ, 694, L26; Bottom: Gendelev & Krumholz, 2012, ApJ, 745, 159

GMC disruption

- Except perhaps in M51, $\tau_{life} << \tau_{dep}$, so disruption mechanism required
- In global collapse, need disruption time <~ τ_{ff}; can be 1 – 10 τ_{ff} for external or internal driving
- Same candidate mechanisms as for internal driving: HII regions, Sne
- FEW FIRST-PRINCIPLES SIMULATIONS, mostly simulations with subgrid feedback recipes, and (semi-)analytic models

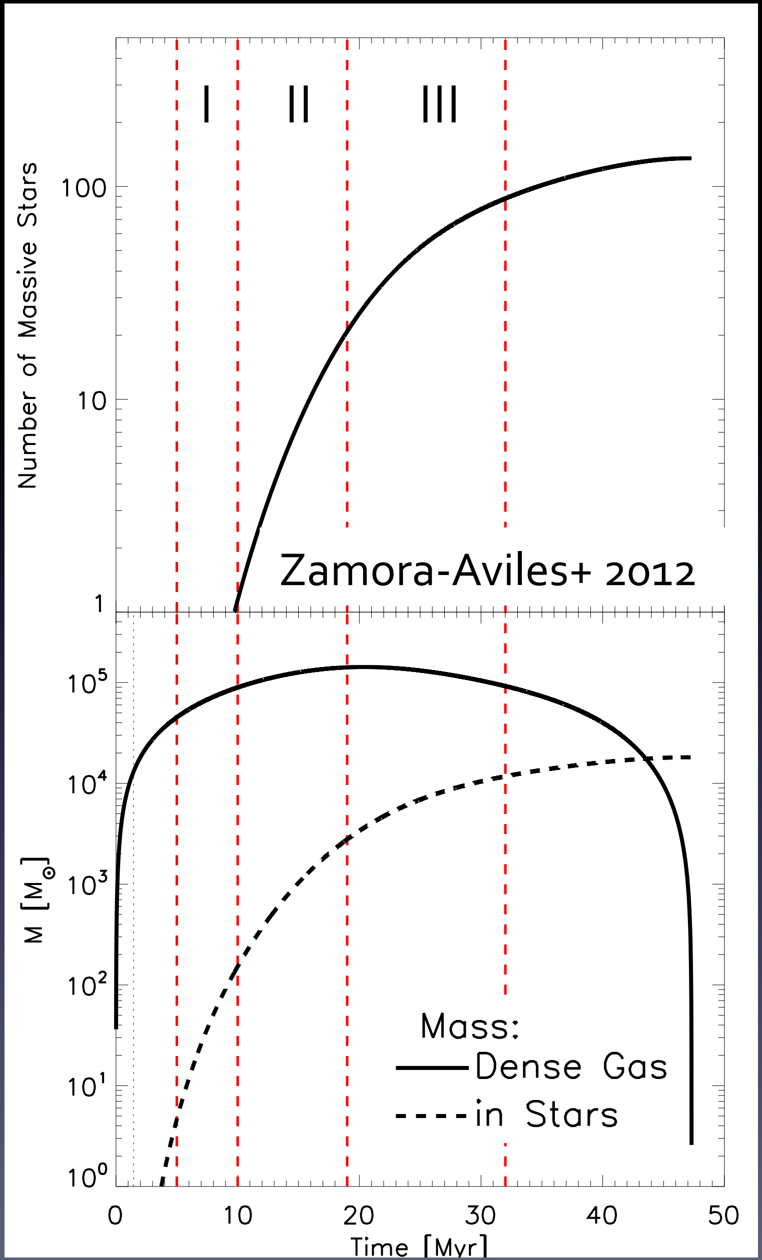
Question 4:

WHAT REGULATES STAR FORMATION IN GMCS?

The problem in a nutshell

- For uninhibited collapse, $\varepsilon_{ff} \sim 1$, but observed value is $\varepsilon_{ff} << 1$
- In MW, $\varepsilon_{ff} \sim 1$ gives SFR ~ 100 $M_\odot$ yr^{-1}; observed SFR ~1 $M_\odot$ yr^{-1}
- Classical explanation is B fields, but observed field strengths too small
- Remaining contenders: collapse + rapid disruption by feedback, and turbulence

Collapse + disruption

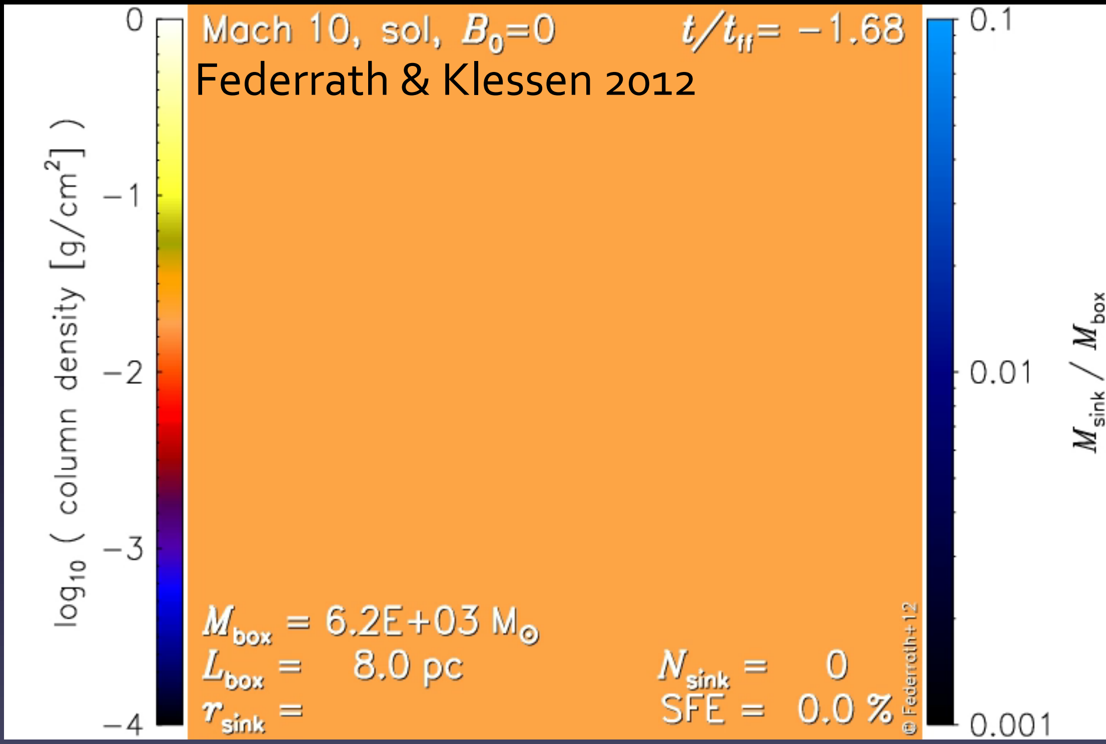


- Can keep ϵ_{ff} low if clouds disrupted by feedback in <~ 1 t_{ff}, before much SF
- Disruption by ionization possible up to ~ 10^5 $M_\odot$ clouds, but depends on subgrid model
- Not clear if large clouds can be disrupted rapidly

Zamora-Aviles et al., 2012, ApJ, 751, 77

Turbulence-regulated SF

- Turbulence supports against collapse on large-scales, allows it on small scales
- Many models for ϵ_{ff} (α_G, $\mathcal{M}$, β); all give $\epsilon_{ff} \sim 0.01 - 0.1$ for GMCs

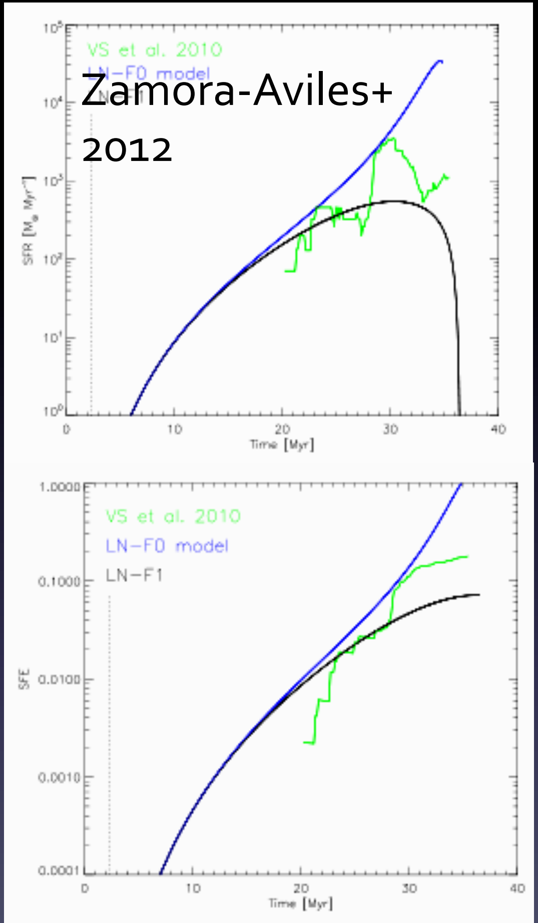


Federrath & Klessen 2012

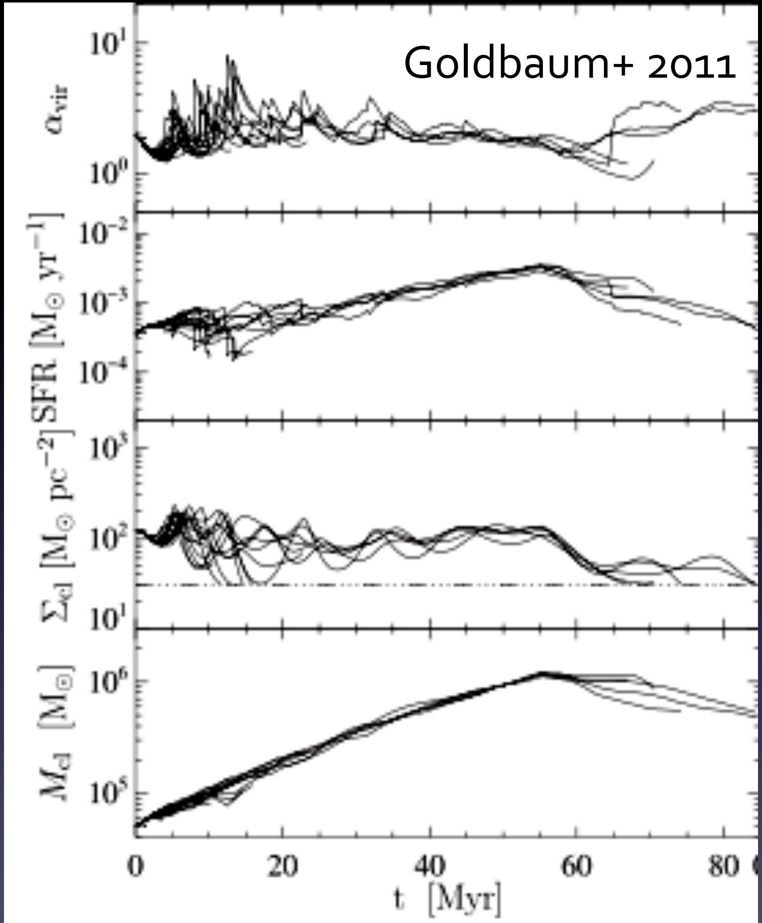
Federrath & Klessen, 2012, ApJ, 761, 156

- Turbulence must be maintained by external driving and/or feedback

Combination models



Zamora-Aviles+
2012



Goldbaum+ 2011

Reality likely between pure collapse and turbulence models: SF regulated by turbulence, but cloud properties evolve with time

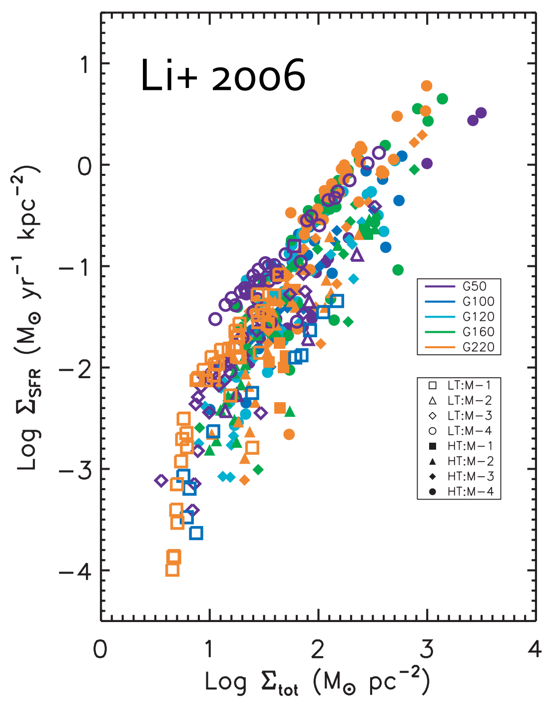
Left: Zamora-Aviles et al., 2012, ApJ, 751, 77; right: Goldbaum et al., 2011, ApJ, 738, 101

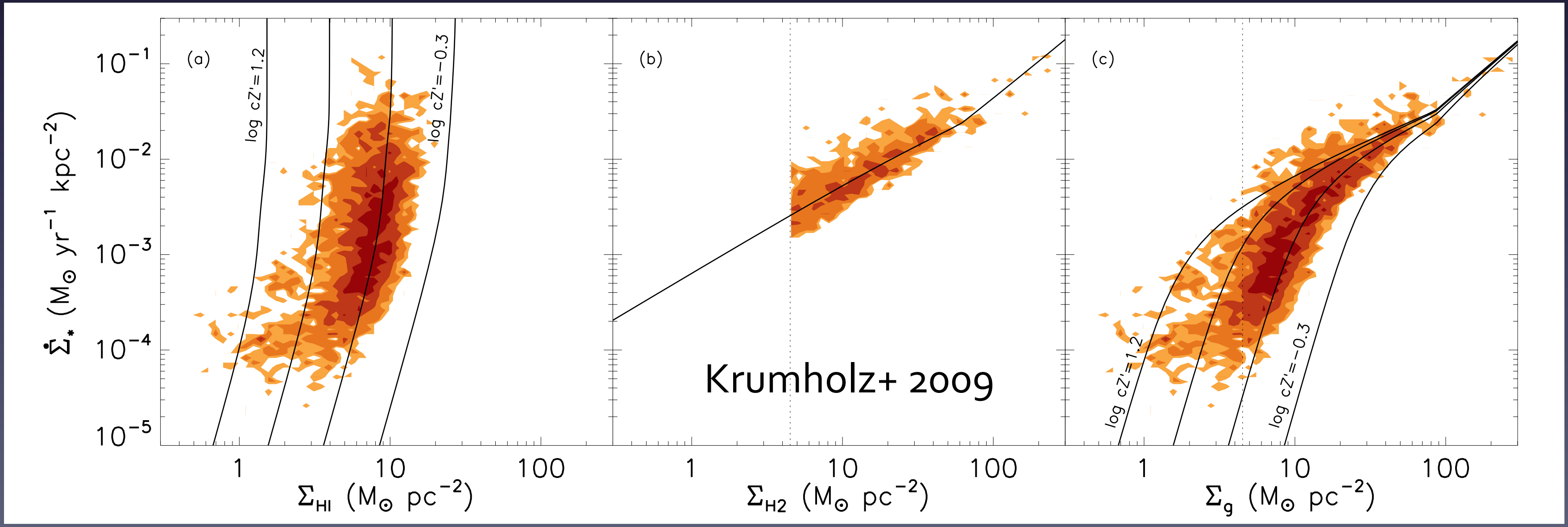
Connection to galactic scale

- What sets Σ_{SFR} at galactic scales?
- $\Sigma \sim 10 - 100\ M_\odot\ pc^{-2}$: $\Sigma_{SFR} \sim \Sigma_g^N$ with $N \sim 1$: probably just cloud-counting, all clouds are (on average) the same
- $\Sigma > 100\ M_\odot\ pc^{-2}$: $N > 1$, probably because GMCs are getting denser
- $\Sigma < 10\ M_\odot\ pc^{-2}$: $N > 1$, and third parameters (e.g. metallicity, mass of old stellar population) seem to matter

Three possibilities

- GI dies out at low Σ_g, so Σ_{SFR} declines non-linearly
- ISM at low Σ_g is HI-dominated, only H_2 phase forms stars; metallicity matters for this reason

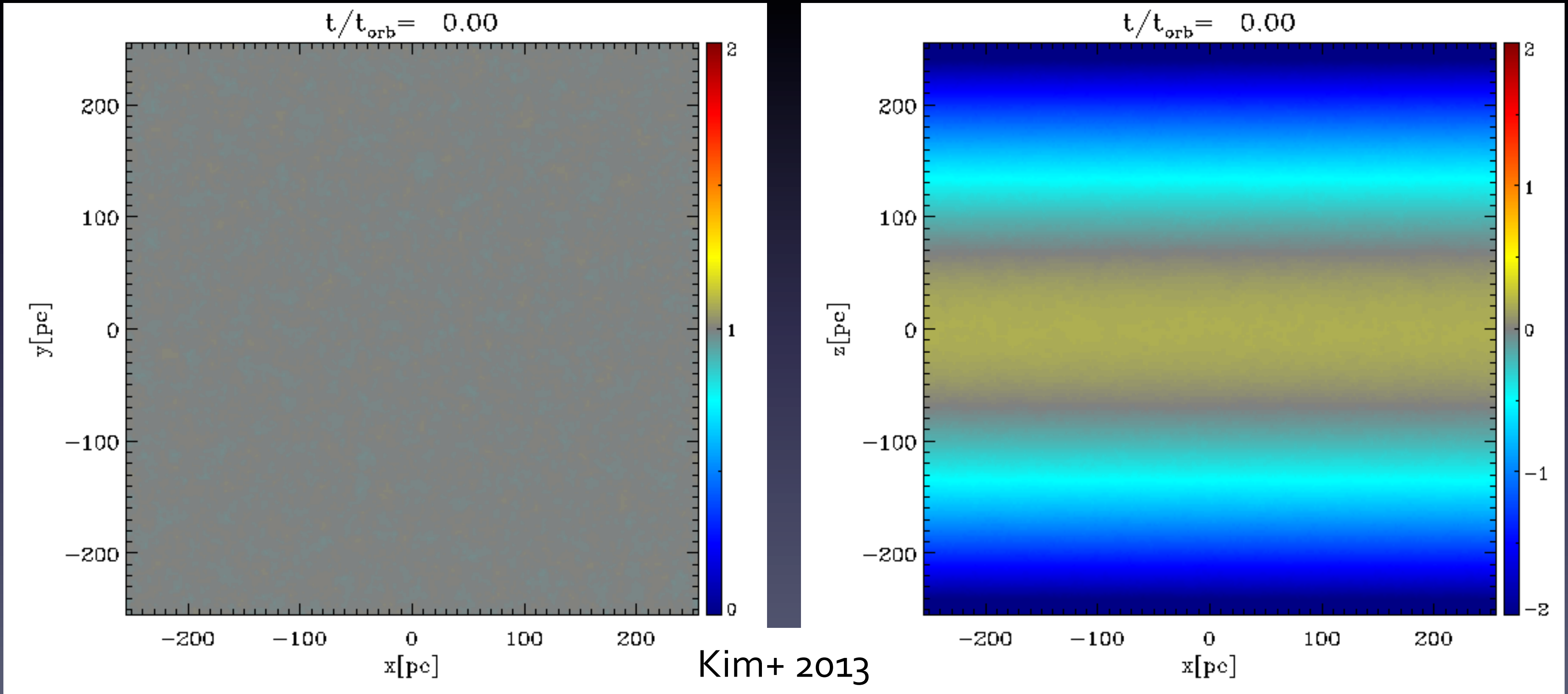




Top: Li et al., 2006, ApJ, 639, 879; bottom: Krumholz et al., 2009, ApJ, 699, 850

Three possibilities ctd.

- Balance between feedback-driven turbulence and gravity is key, with vertical g_z dominated by stars at large radii



Kim+ 2013

Kim, Ostriker, & Kim, 2013, ApJ, submitted

Things will be better in…

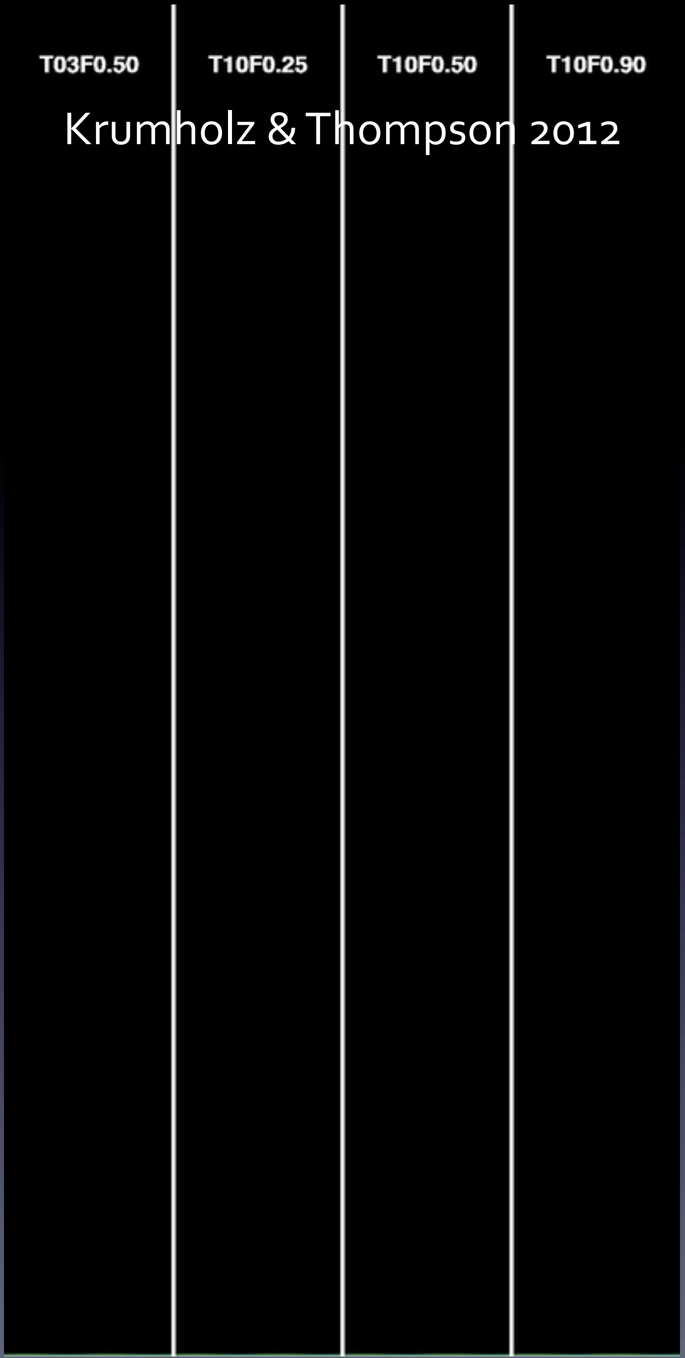
THE FUTURE

Observations

Refrained from adding ALMA photo here – it's not like there won't be enough of them at this meeting

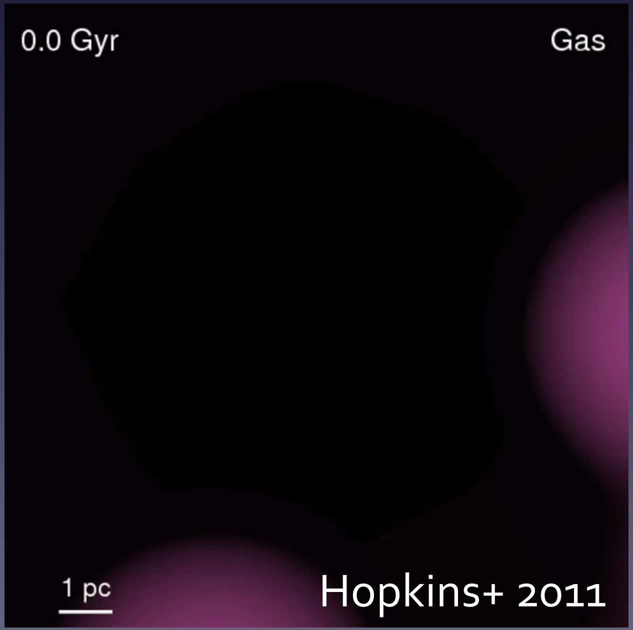
- ALMA and NOEMA: sensitivity to measure internal GMC structure in extragalactic sources
- IRAM 30m, NRO 45m, LMT 50m, NANTEN2, CCAT: large-area mapping
- CARMA, SMA: big surveys of GMCs in MW

Theory



Krumholz & Thompson 2012

- Combine galactic-scale codes w/small-scale ones
- Idea: get both environment and feedback right – needs physics beyond hydro + gravity



Hopkins+ 2011

Left: Krumholz & Thompson, 2012, ApJ, 760, 155
Right: Hopkins et al., 2011, MNRAS, 417, 950