# Computational Astrophysics versus the Big Questions: An Assessment

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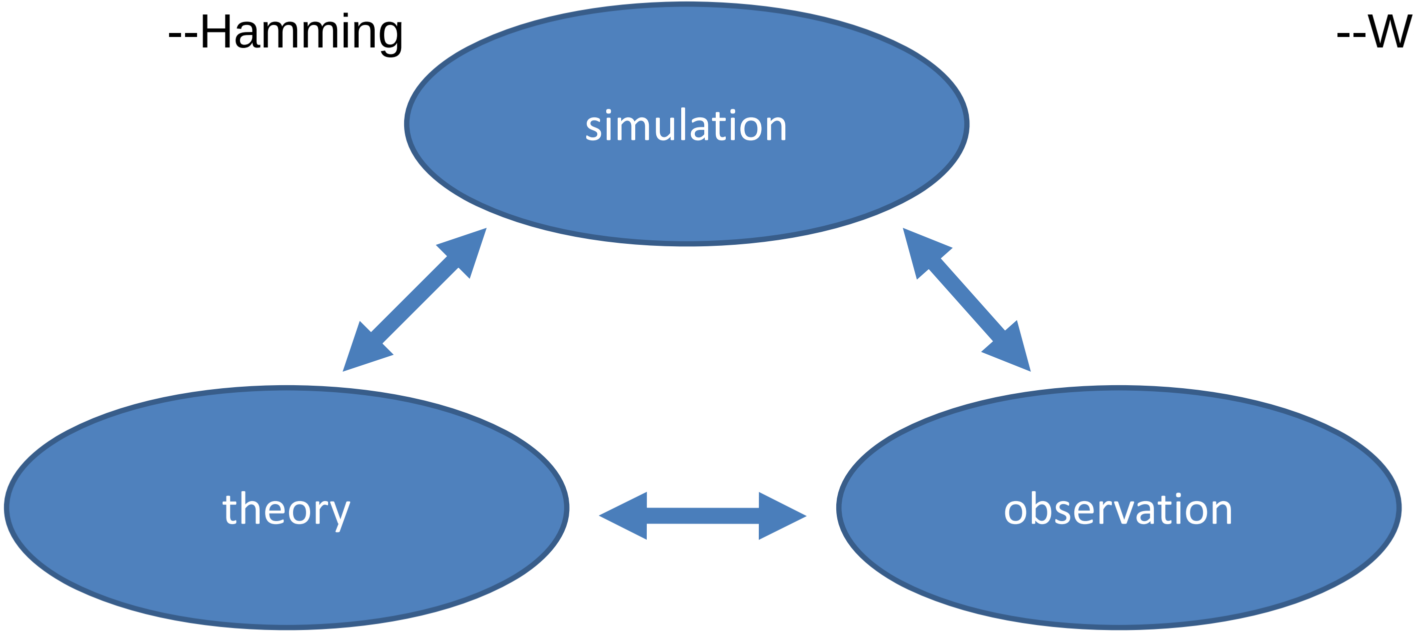
# Computational Science:
# The 3rd Pillar of Science

“The purpose of computing
is *insight*, not numbers”
--Hamming

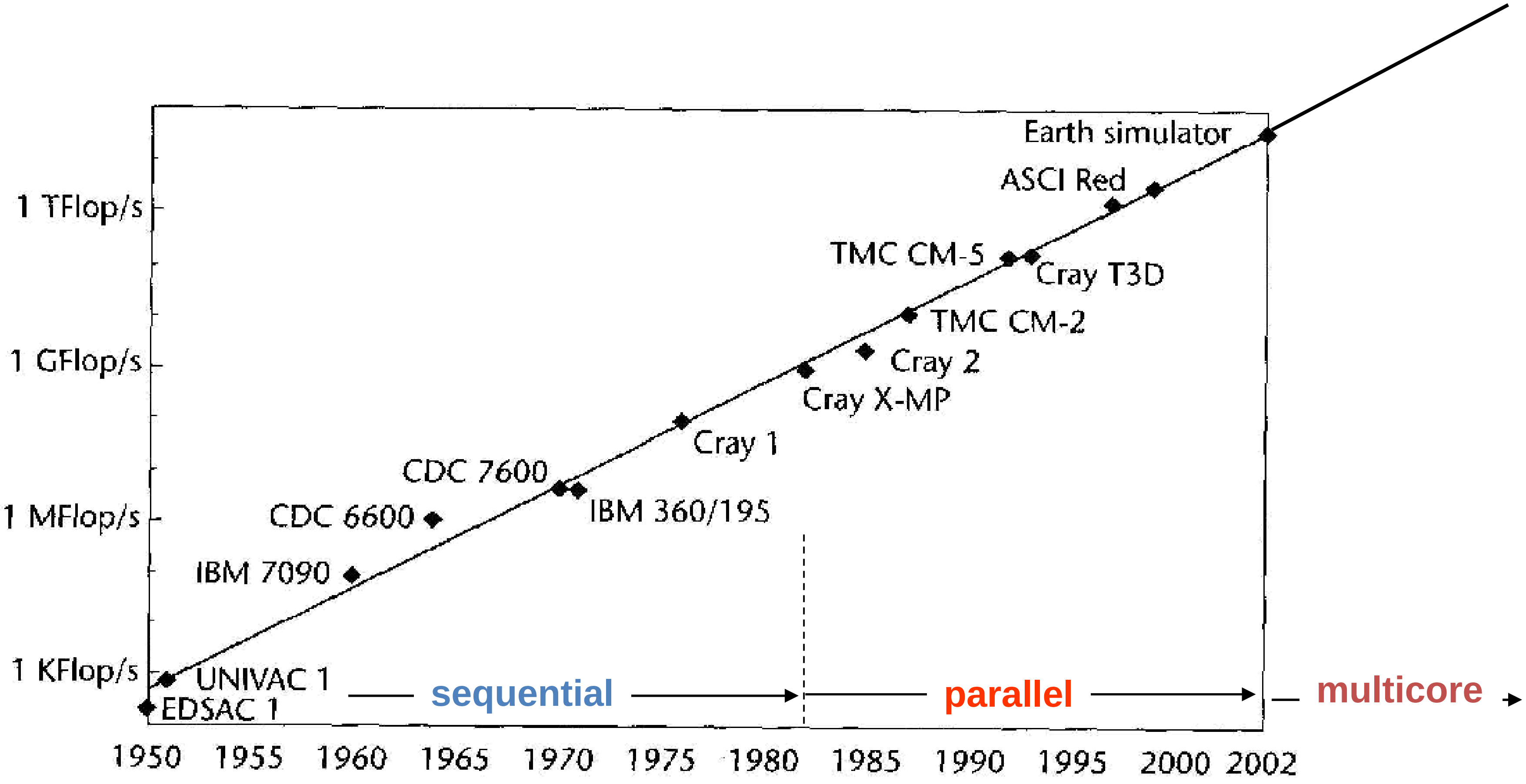
“The purpose of computing
is *prediction”*
--Worlton



“Simulation is a *bridge* between theory and observation”

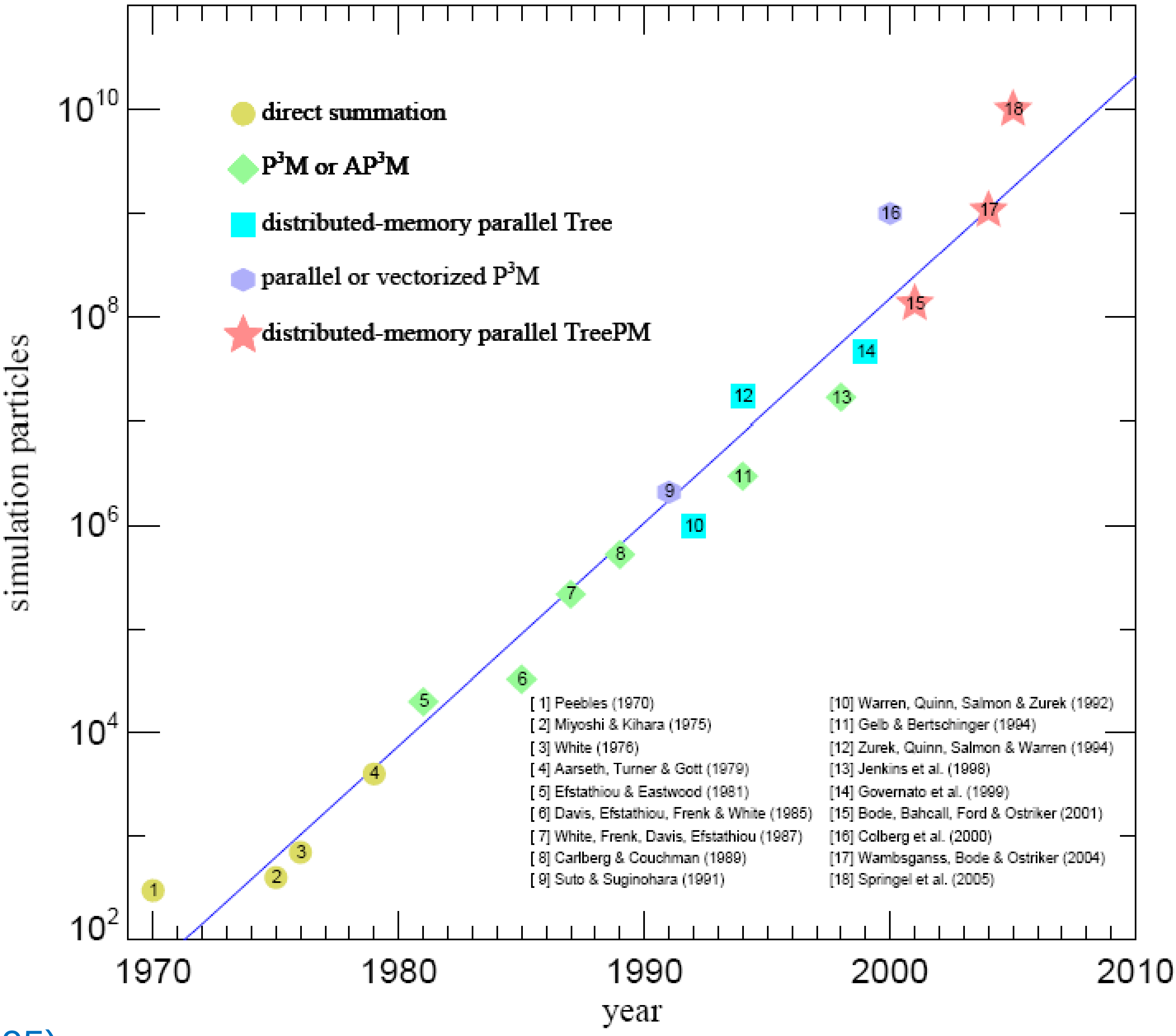
“Computer simulations are the most complete descriptions of complex phenomena we have”

# 60 years of supercomputer performance tracks Moore's law



Sourcebook, Ch. 1

# Importance of Numerical Algorithms

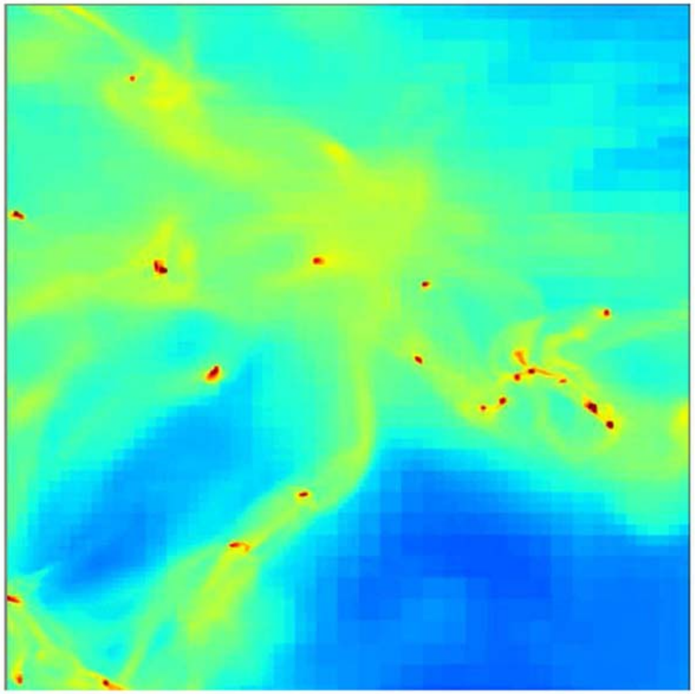


Springel et al. (2005)

# Mature Multiscale Methods

- N-body/SPH tree codes
- AMR hydro/MHD

DM substructure in Milky Way
Diemand et al. (2008)



Dense molecular cloud cores
Collins (2009)

# Where’s the Beef?

- What Grand Challenge problems has computational astrophysics solved?
  - “For every problem solved, 10 new problems are identified”
- If not solved, then what progress has been achieved, and how?
- What general lessons have we learned about what is needed for genuine progress?

# Some Grand Challenge Problems

- Formation of stars and planetary systems
- Type Ia and II supernovae mechanisms
- Formation of galaxies and large scale structure
- Formation of supermassive black holes
- Origin of cosmic magnetic fields
- Origin of highest energy cosmic rays
- Nature of the solar dynamo

# Why Grand Challenge Problems are Difficult

- Phenomena are
  - Complex
  - Dynamical
  - Multidimensional
  - Multiscale
  - Inter-related

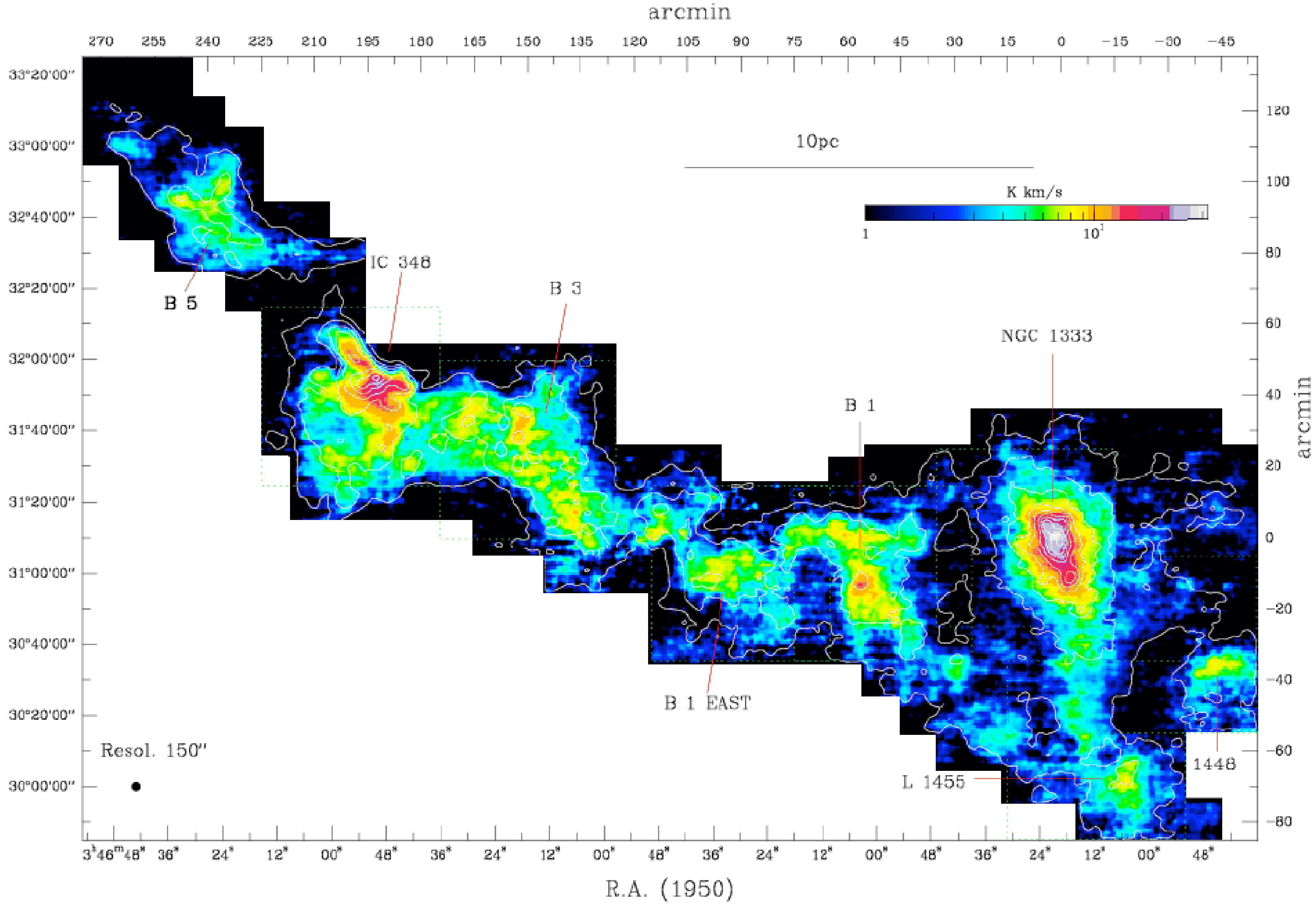
- Direct observations sometimes not possible or yield meager information (e.g, supernovae)

# Galactic Star Formation

- Driving questions
  - Origin of mass scale?
  - Origin of IMF?
  - Why star formation efficiency is so low?
  - Origin of binarity?
  - Role of feedback (outflows, radiation) in setting final mass?
  - Properties of Young Stellar Objects (YSOs)

NCG 602 in LMC

# Molecular Cloud Complex in Perseus



# Molecular Clouds, Clumps, and Cores

Highly complex structure:
Hierarchical, fractal

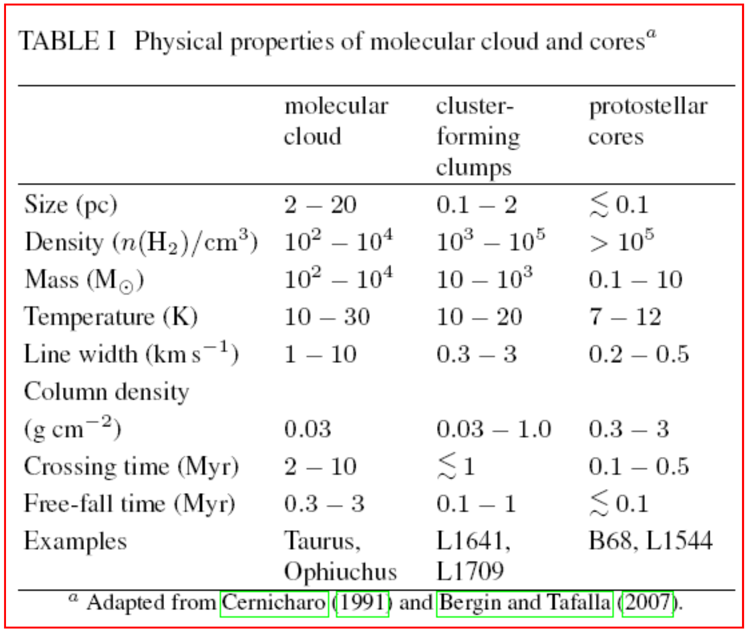


TABLE I Physical properties of molecular cloud and cores[a]

| | molecular cloud | cluster-forming clumps | protostellar cores |
|---|---|---|---|
| Size (pc) | 2 – 20 | 0.1 – 2 | $\lesssim 0.1$ |
| Density ($n(\mathrm{H}_2)/\mathrm{cm}^3$) | $10^2 - 10^4$ | $10^3 - 10^5$ | $> 10^5$ |
| Mass ($\mathrm{M}_\odot$) | $10^2 - 10^4$ | $10 - 10^3$ | 0.1 – 10 |
| Temperature (K) | 10 – 30 | 10 – 20 | 7 – 12 |
| Line width ($\mathrm{km\,s}^{-1}$) | 1 – 10 | 0.3 – 3 | 0.2 – 0.5 |
| Column density ($\mathrm{g\,cm}^{-2}$) | 0.03 | 0.03 – 1.0 | 0.3 – 3 |
| Crossing time (Myr) | 2 – 10 | $\lesssim 1$ | 0.1 – 0.5 |
| Free-fall time (Myr) | 0.3 – 3 | 0.1 – 1 | $\lesssim 0.1$ |
| Examples | Taurus, Ophiuchus | L1641, L1709 | B68, L1544 |

[a] Adapted from Cernicharo (1991) and Bergin and Tafalla (2007).

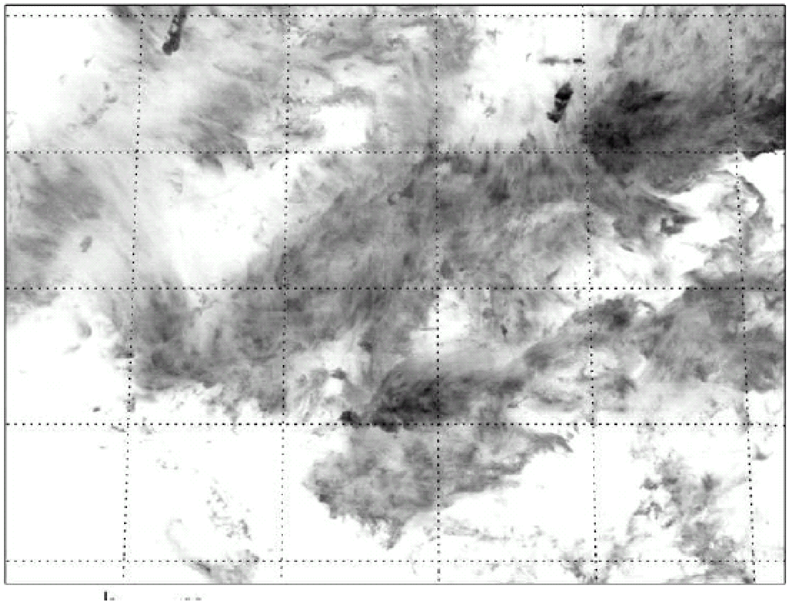
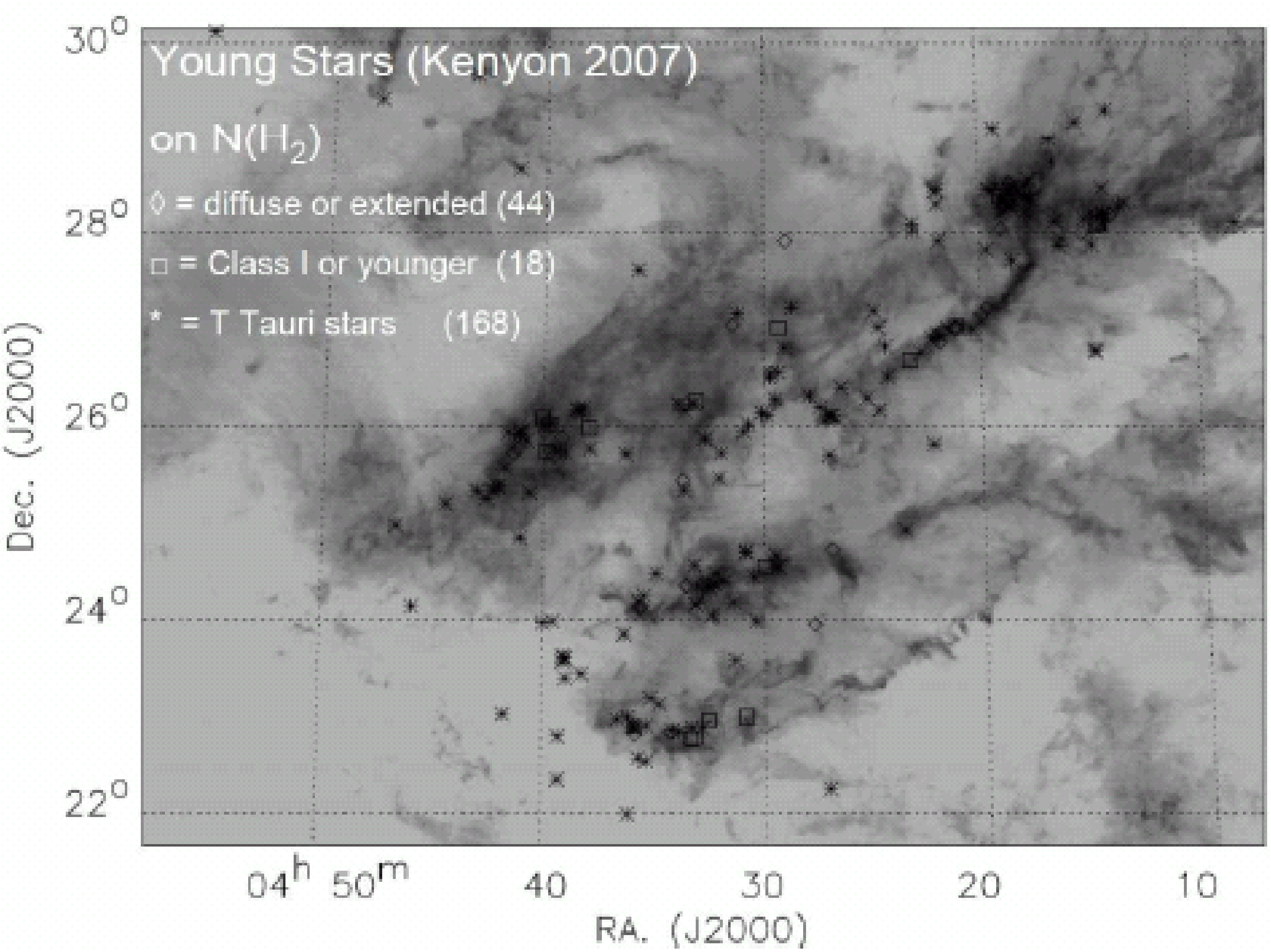


Figure 1.2: An image of the Taurus molecular cloud in $^{12}CO$, from Goldsmith et al. (2008)

# Young stars and molecular gas in Taurus



From Goldsmith et al. (2007)

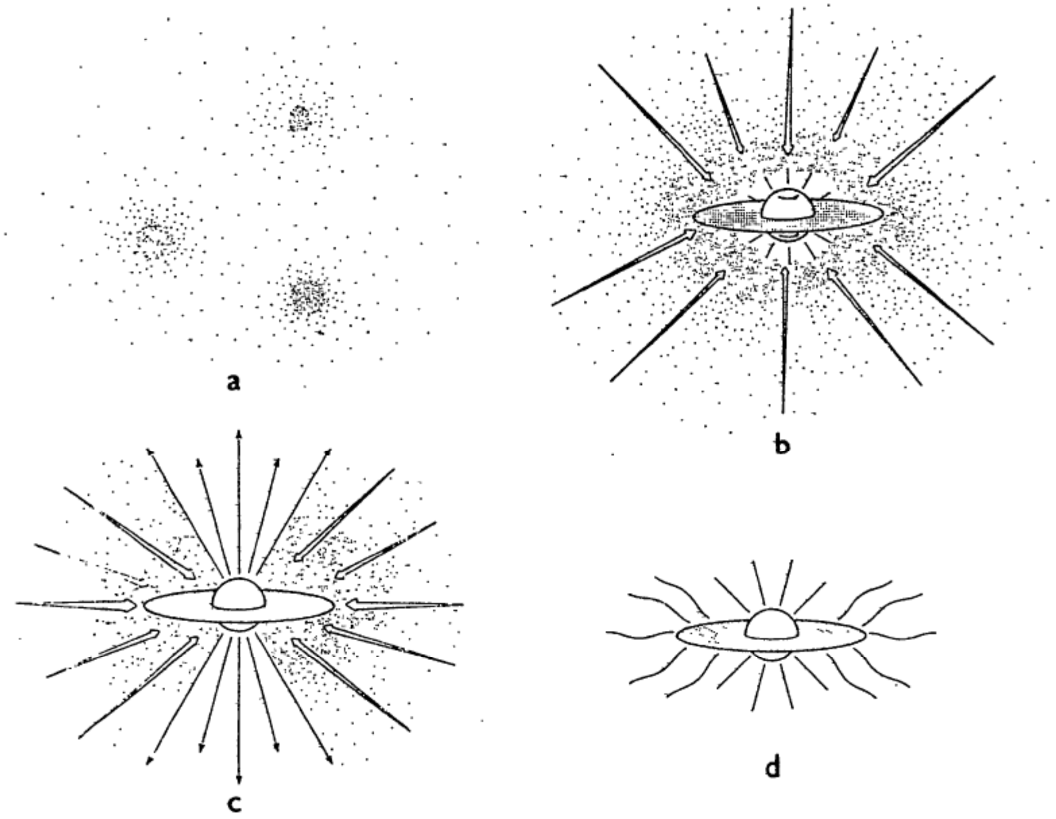
# Tale of 2 Reviews

| **Shu et al. (1987)** | **McKee & Ostriker (2007)** |
|---|---|
| FOCUS | |
| o Low mass star formation<br>o How dense cores form stars | o Stars of all masses<br>o How molecular cloud turbulence forms dense cores |
| PARADIGM | |
| o “Magnetic star formation”<br>o Ambipolar diffusion creates dense cores quasi-statically | o “Turbulent star formation”<br>o Molecular cloud turbulence dynamically compresses gas to beyond stability limit |
| MAIN PREDICTIONS | |
| o Subcritical clouds: isolated low mass stars form at low efficiency<br>o Supercritical clouds: high mass stars and clusters form at high efficiency | o Density and velocity statistics<br>o Core IMF<br>o Star formation efficiency |
| TYPICAL SIMULATIONS | |
| o 1D, 2D cloud collapse models<br>o Synthetic spectra of YSOs | o 3D turbulence in a box<br>o Synthetic molecular cloud maps |

# Formation of Low Mass Stars

Shu, Adams & Lizano (1987), ARAA 25

- Stage 1
  - Dense cores form via ambipolar diffusion
- Stage 2
  - Inside-out collapse to form protostar/disk
- Stage 3
  - Inflow + outflow triggered by deuterium burning
- Stage 4
  - Isolated star/disk system



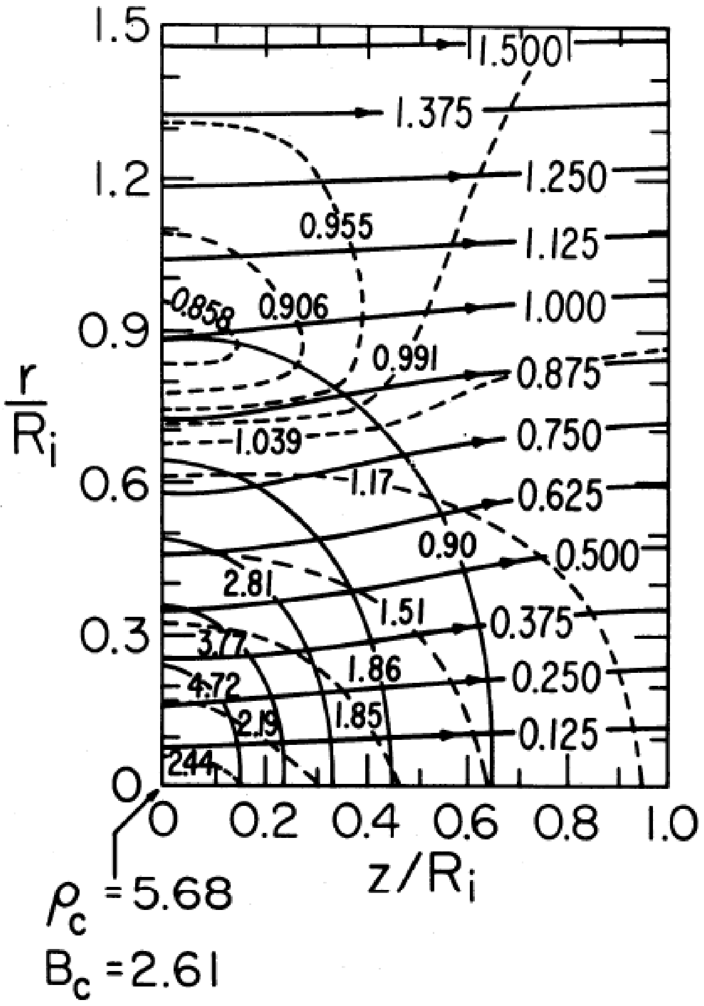
# Magnetically Supported Clouds

## Mouschovias (1976a,b)

- Jeans instability requires M > $M_{cr}$

$$M_{cr} = 0.13\frac{\Phi}{\sqrt{G}} \approx 10^3\left(\frac{B}{30\mu G}\right)\left(\frac{R}{2\,pc}\right)^2$$

  - Subcritical: M< $M_{cr}$
  - Supercritical: M> $M_{cr}$
- M/Φ increases due to ambipolar diffusion, inevitably leading to collapse



# Collapse of Singular Isothermal Sphere

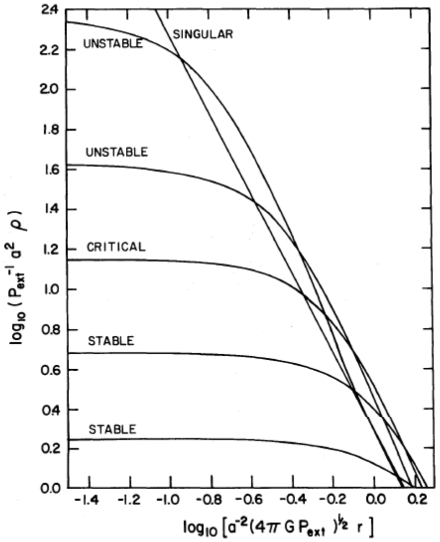
## Shu (1977)

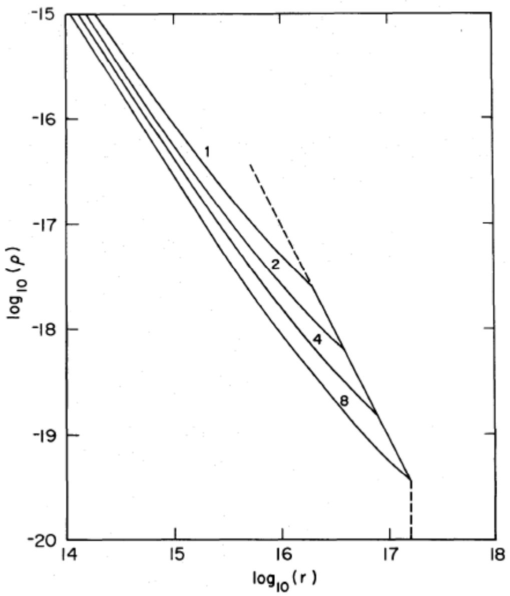
- SIS: no characteristic mass scale

$$\rho(r)=\frac{a^2}{2\pi G r^2},\quad a=\sqrt{kT/m}$$
$$r\Rightarrow 0,\ \rho(r)\Rightarrow\infty$$
$$r\Rightarrow\infty,\ M(r)\Rightarrow\infty$$

- SIS: characteristic mass accretion rate

$$\dot{m}_{SIS}=0.97\frac{a^3}{G}$$





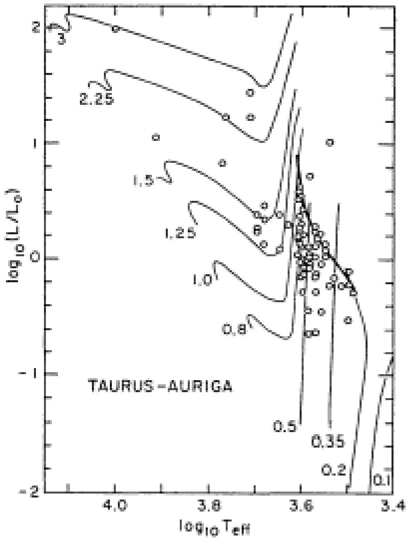
# Critique

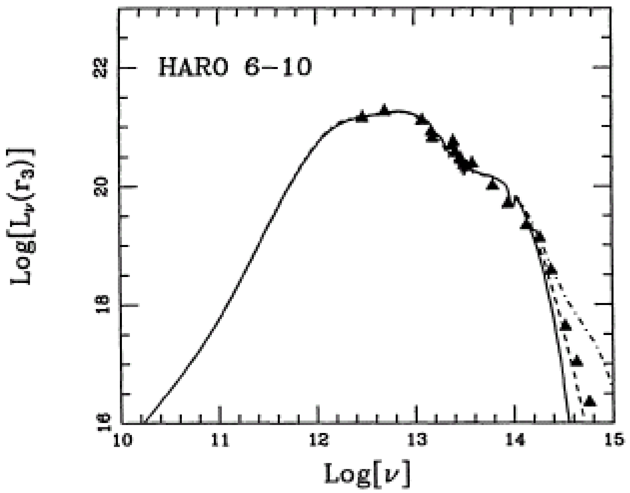
- Shu et al's 4 stages are essentially a summary of what is observed, not our theoretical understanding
- No theory for origin of core mass spectrum or IMF
- Intermediate and high mass stars not addressed
- Mass scale for low mass stars cannot fall out of SIS theory since it is scale free
    - Either mass scale is set by:
        - core mass, for which no theory was presented
        - protostellar feedback (Shu), for which no theory presented
    - Or
        - Magnetic or turbulent support of envelope
- Numerical simulations not prominently featured

# However…

- Shu et al. summarize good agreement between Phase 4 models and observations of YSOs

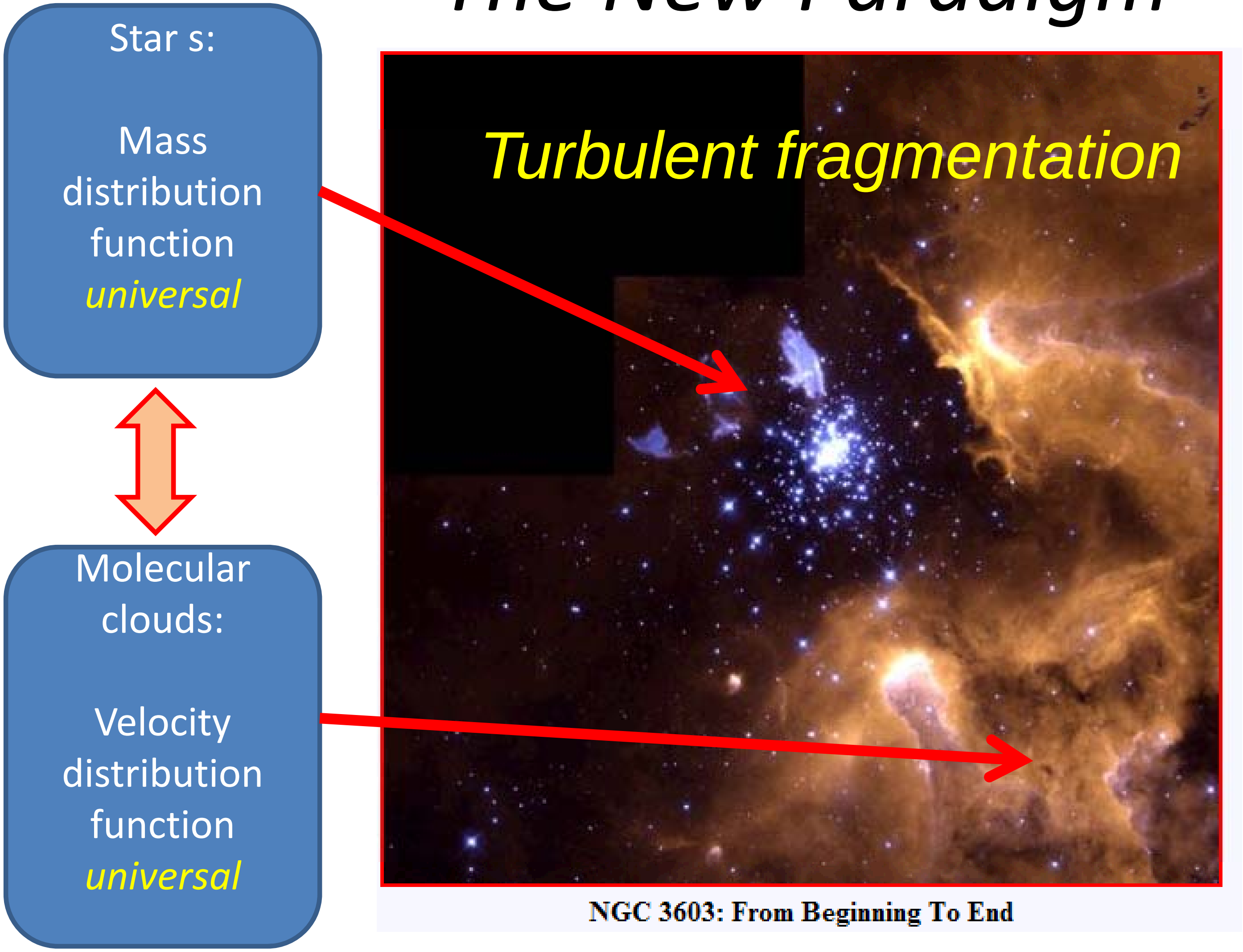
*Stellar “birthline”*





*Reprocessed radiation in Star-dusty disk system*

# Star Formation and Turbulence:
# *The New Paradigm*



Star s:

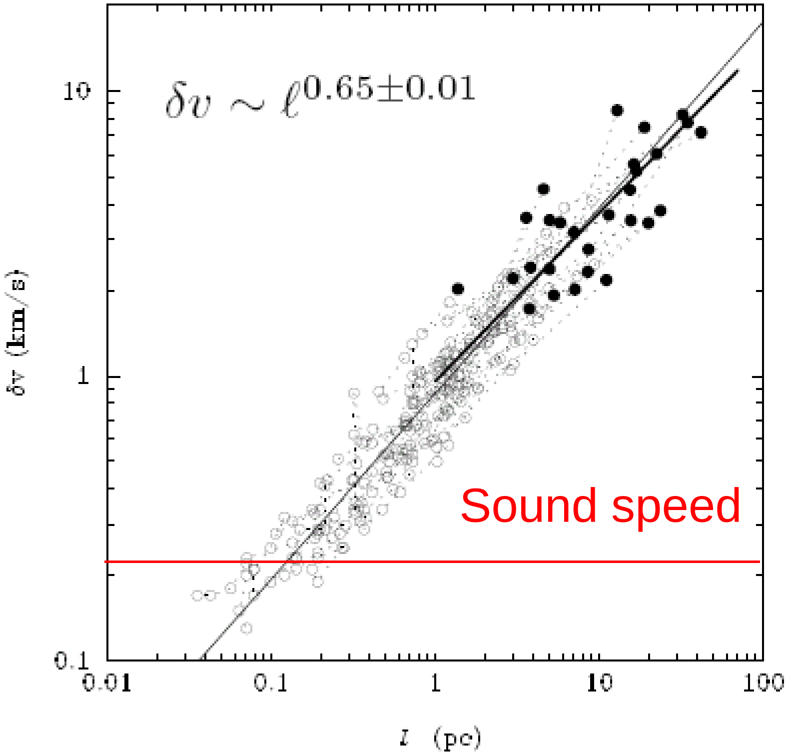
Mass distribution function *universal*

Molecular clouds:

Velocity distribution function *universal*

NGC 3603: From Beginning To End

# Universal Linewidth – Size Relation in Molecular Clouds (Larson’s Law)



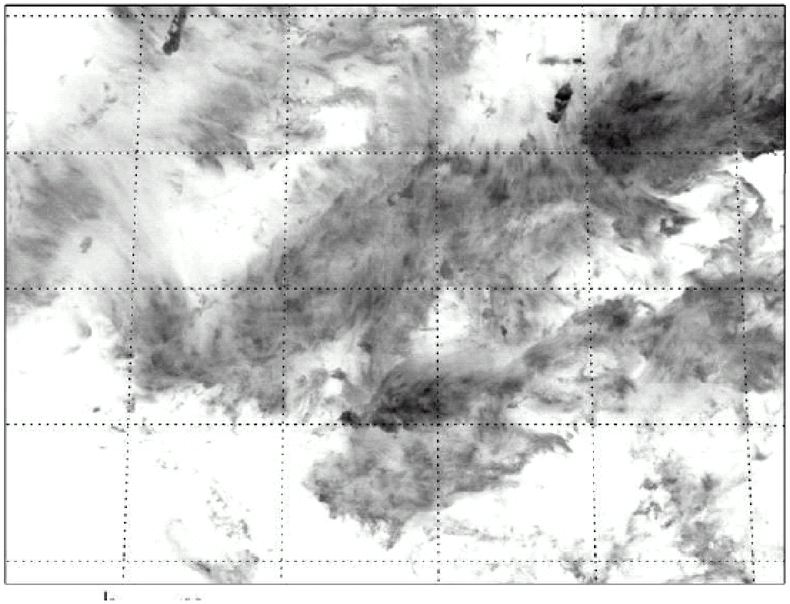


Figure 1.2: An image of the Taurus molecular cloud in $^{12}CO$, from Goldsmith et al. (2008)

*Molecular cloud turbulence is supersonic*

# Universal Stellar Mass Function

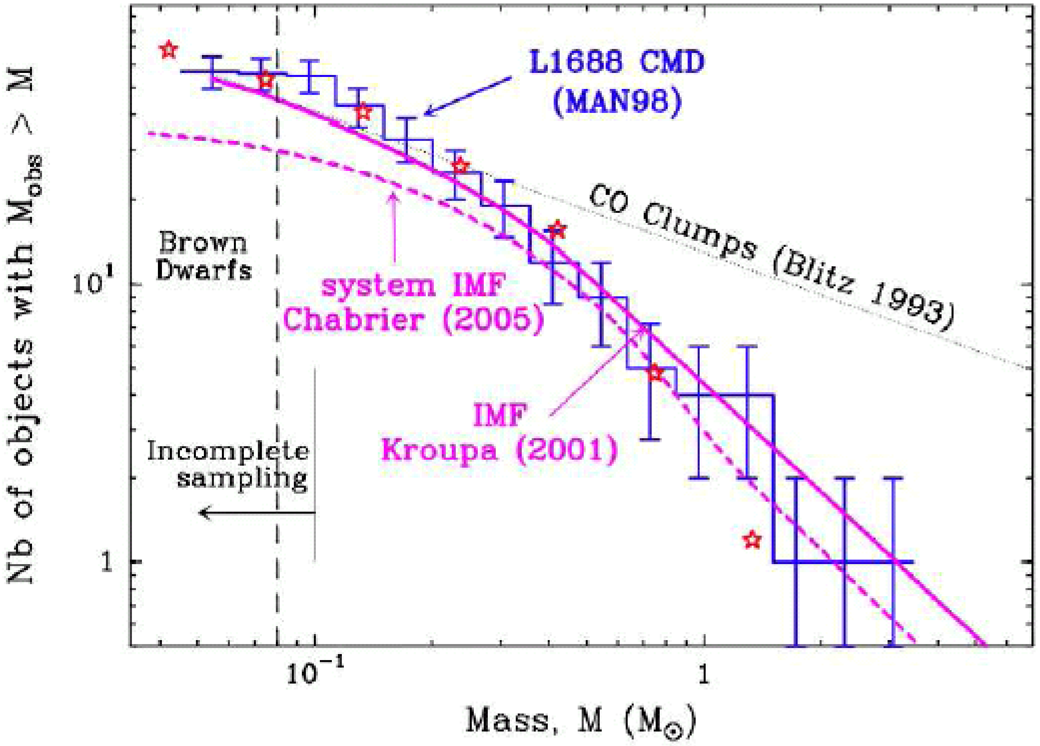
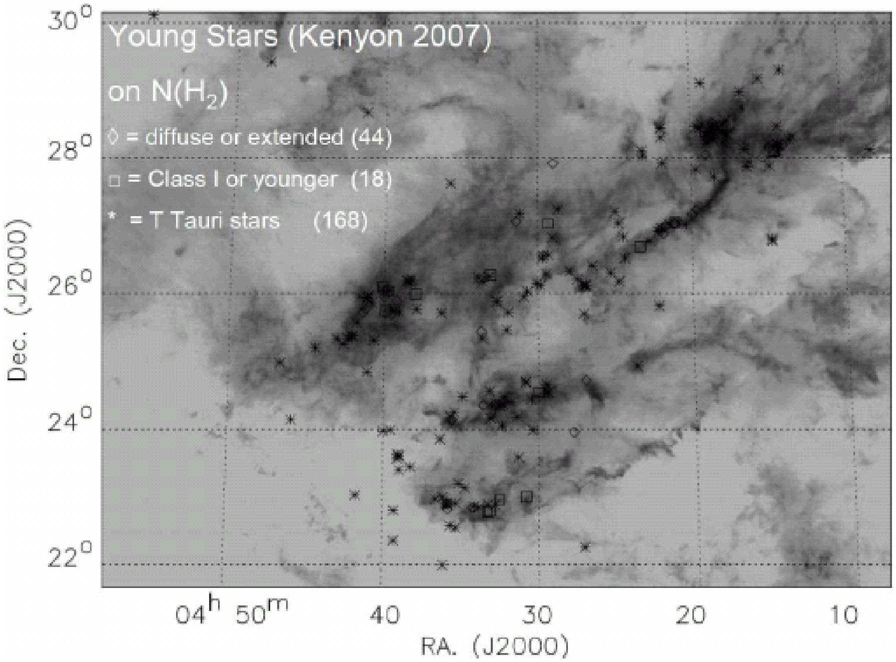


Figure 4.19: Cumulative mass distributions for stars and cores, taken from André et al. (2007). The pink curves show the stellar IMFs from Chabrier (2003) and Kroupa (2001), and the blue points show the data from Motte et al. (1998)

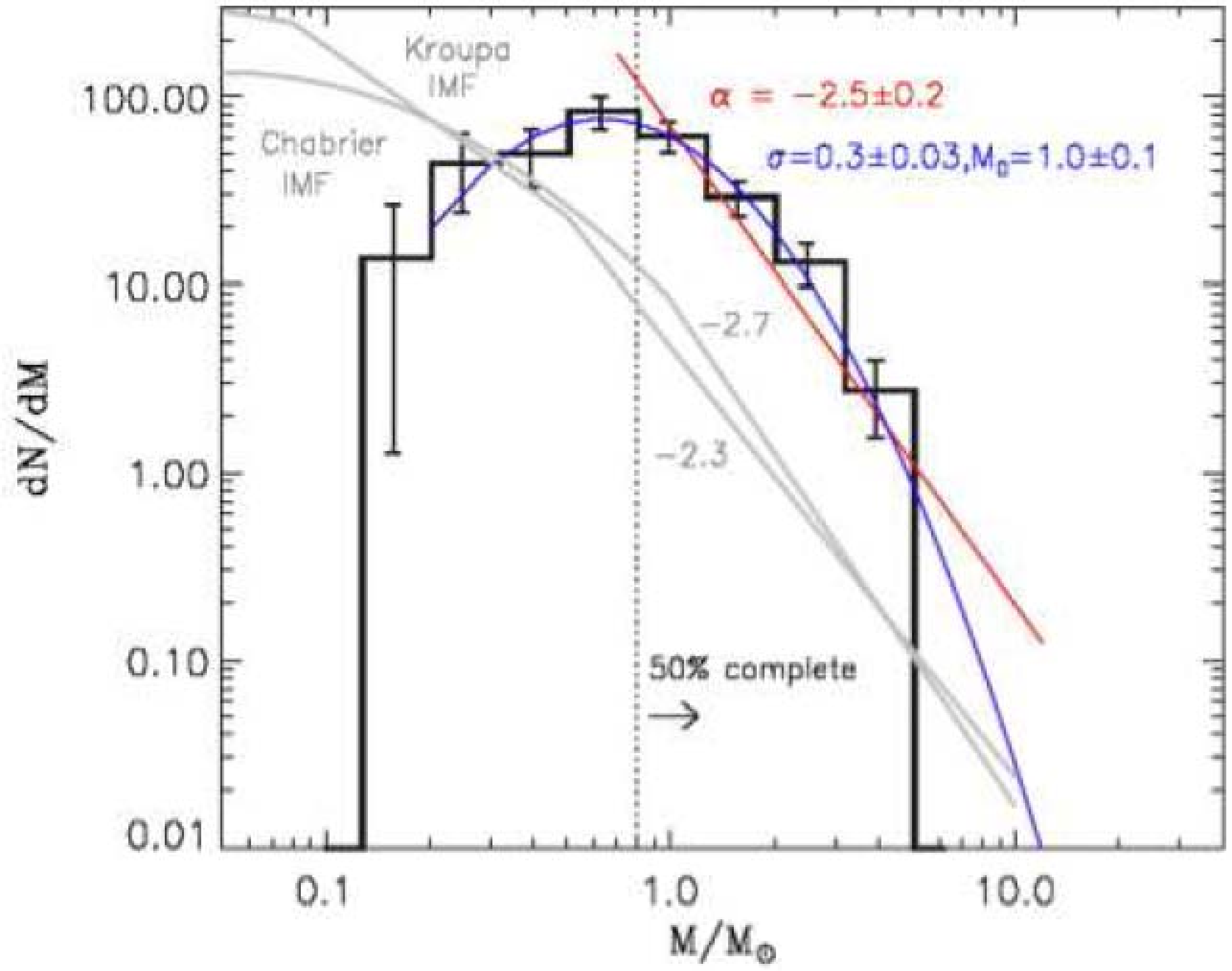
# Turbulent Fragmentation Paradigm (Padoan & Nordlund 2002)

- Supersonic turbulence induces large compressions in the gas
  - Origin of core mass function
- Regions of high density collapse to form stars
- Hypothesis: statistics of supersonic turbulence govern
  - statistics of star masses and
  - Star formation rate

- Young stars in Taurus



# Core Mass Distribution

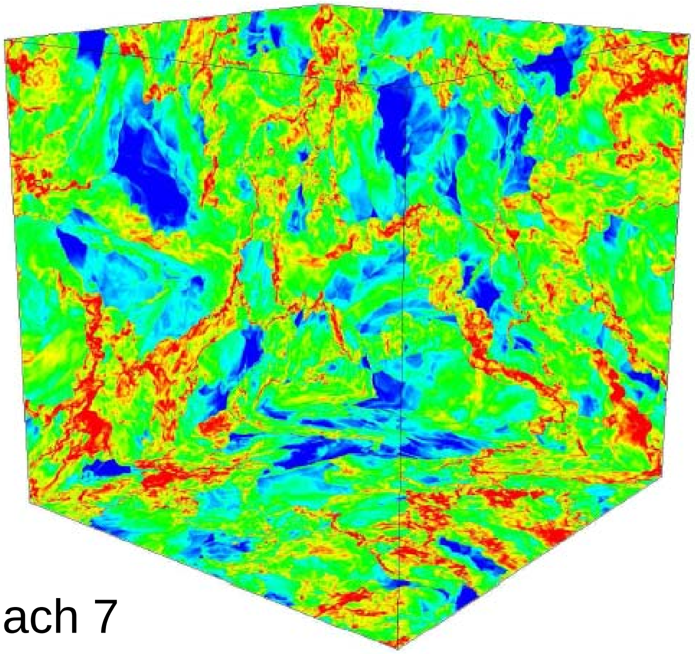


Enoch et al. (2007)

# Turbulence in a Box: Dissipation Rates

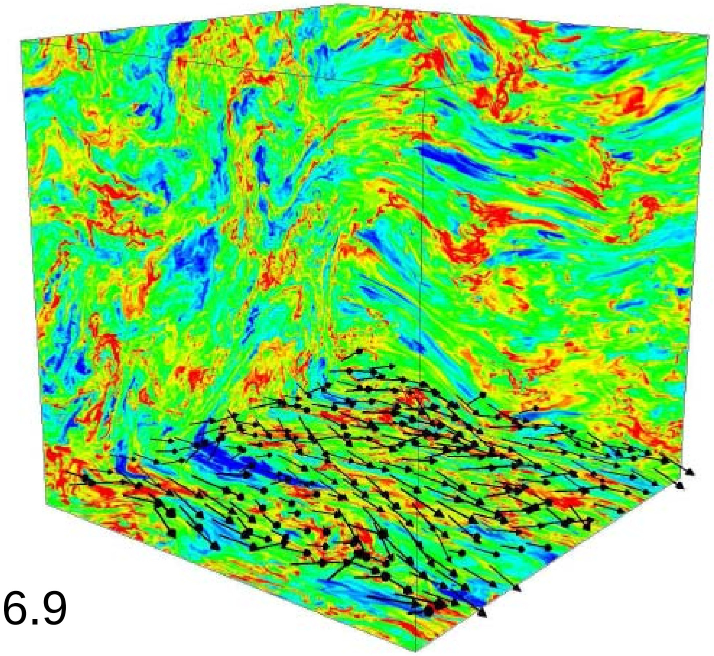
## Lemaster & Stone (2008)

$1024^3$ gas dynamics



Mach 7

$1024^3$ MHD

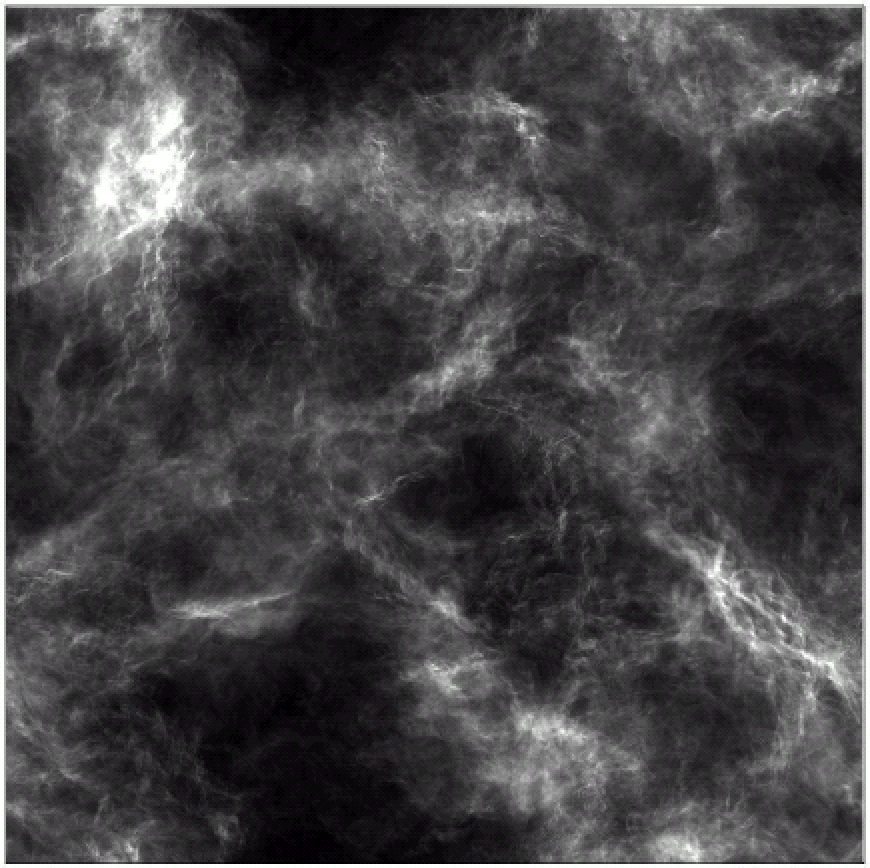


Mach 6.9

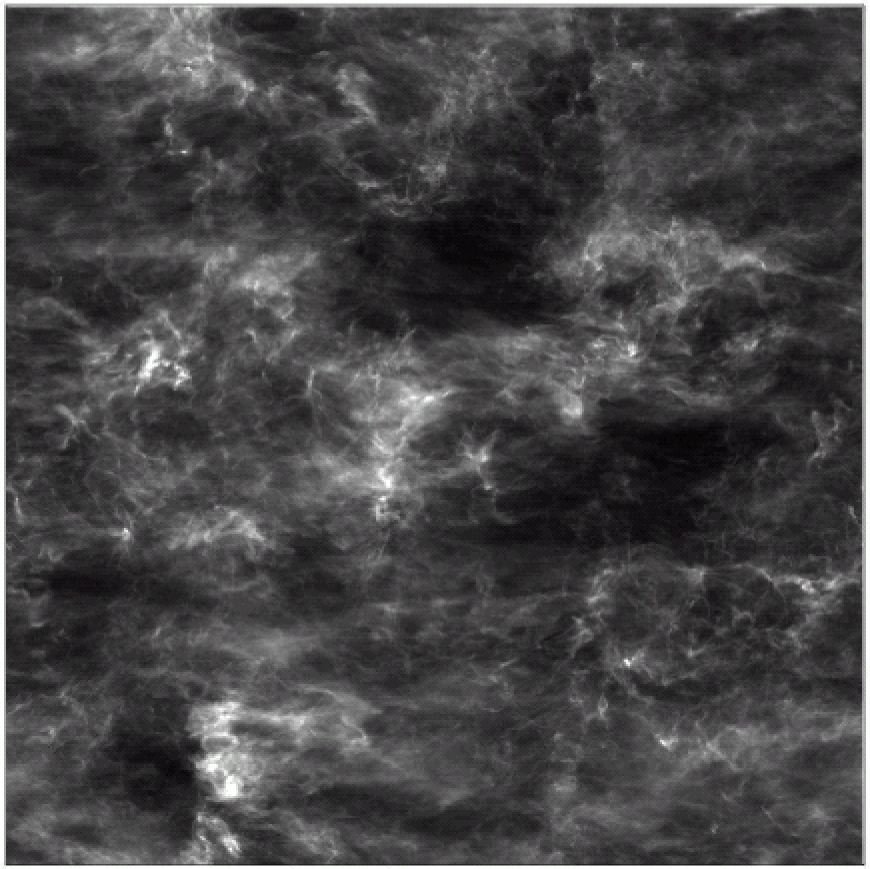
- Turbulence decays on a crossing time unless driven
- Dissipation rate converges by $64^3$ for HD, but not until $512^3$ for MHD
- Very high resolution needed to measure inertial range slopes

# Column Density Maps

## Lemaster & Stone (2008)

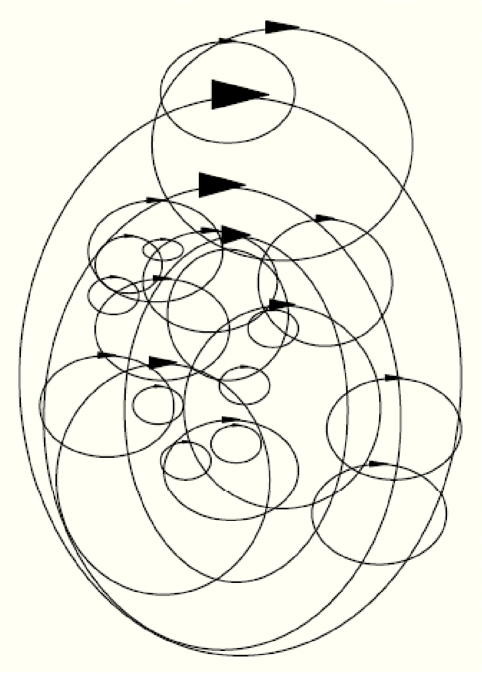


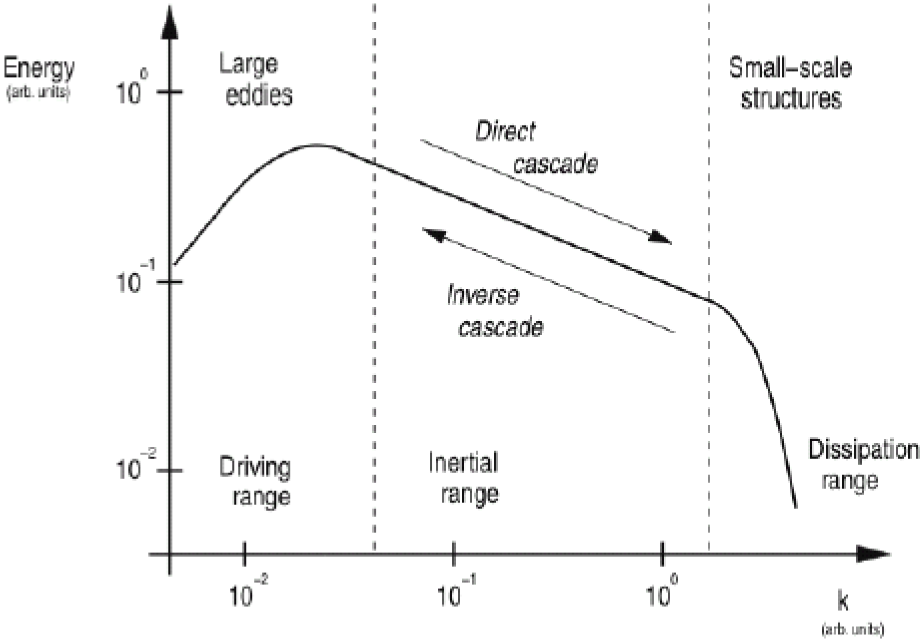
$1024^3$ gas dynamics



$1024^3$ MHD

# Turbulent Cascade a la Richardson-Kolmogorov





# Compressible cascade à la Kolmogorov-Richardson

- Simple dimensional arguments:

Energy cascade in incompressible turbulence:

$$\delta u^2 \left(\frac{\delta u}{\ell}\right) \equiv const \Rightarrow \delta u^3 \sim \ell \Rightarrow \delta u^p \sim \ell^{\frac{p}{3}}$$ [Kolmogorov 1941]

Energy cascade in supersonic turbulence:

$$\rho \delta u^2 \left(\frac{\delta u}{\ell}\right) \equiv const \text{ [Lighthill 1955] } \Rightarrow \rho \delta u^3 \sim \ell$$

$$v \equiv \rho^{\frac{1}{3}} \delta u \Rightarrow \delta v^p \sim \ell^{\frac{p}{3}}$$

The scaling laws are not exact and may require intermittency corrections.

Using $v$ instead of $u$, one properly accounts for the important density–velocity correlations in compressible flows.

- What are the scaling exponents in supersonic turbulence?

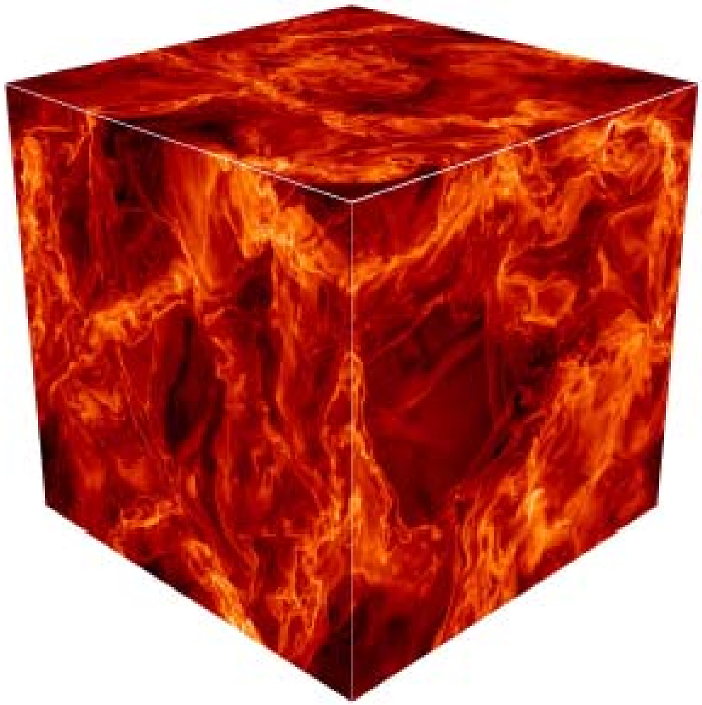
# Turbulence in a Box: Scaling Relations

Kritsuk et al. 2006, 2007, 2008, 2009

$2048^3$ gas dynamics

Supersonic - $M_s$=6

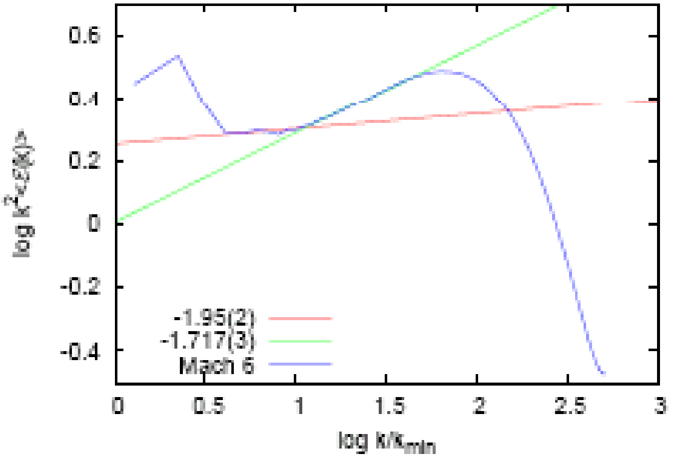
$1024^3$ MHD



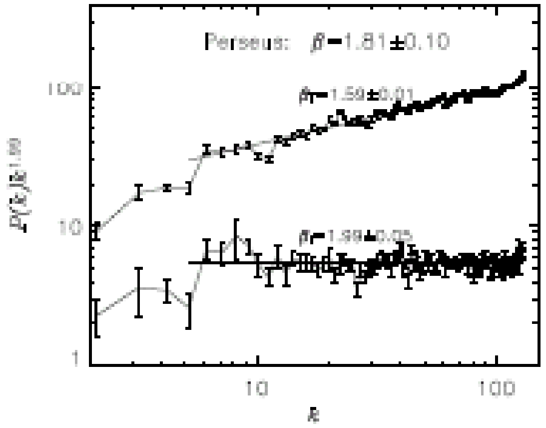
Supersonic - $M_s$=10, super-Alfvenic $M_A$=3

# Non-Kolmogorov velocity scaling

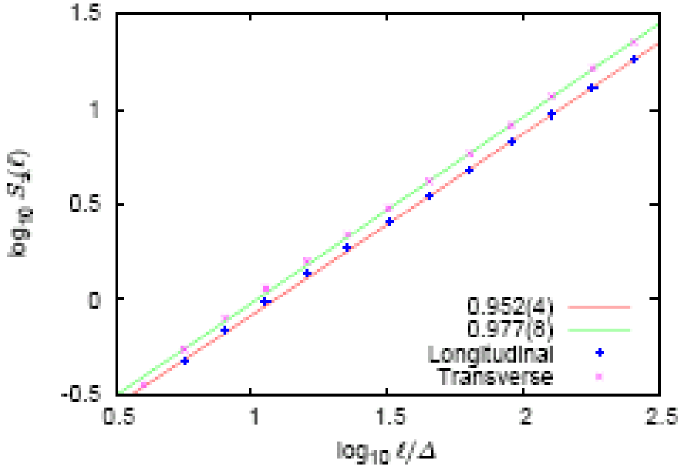
Spectrum: $\beta = 1.95\ (1024^3)$



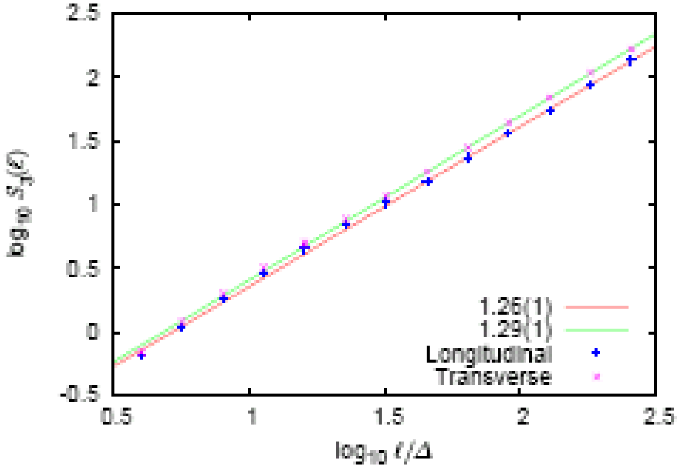
Perseus: $\beta = 1.81$ [Padoan+'06]



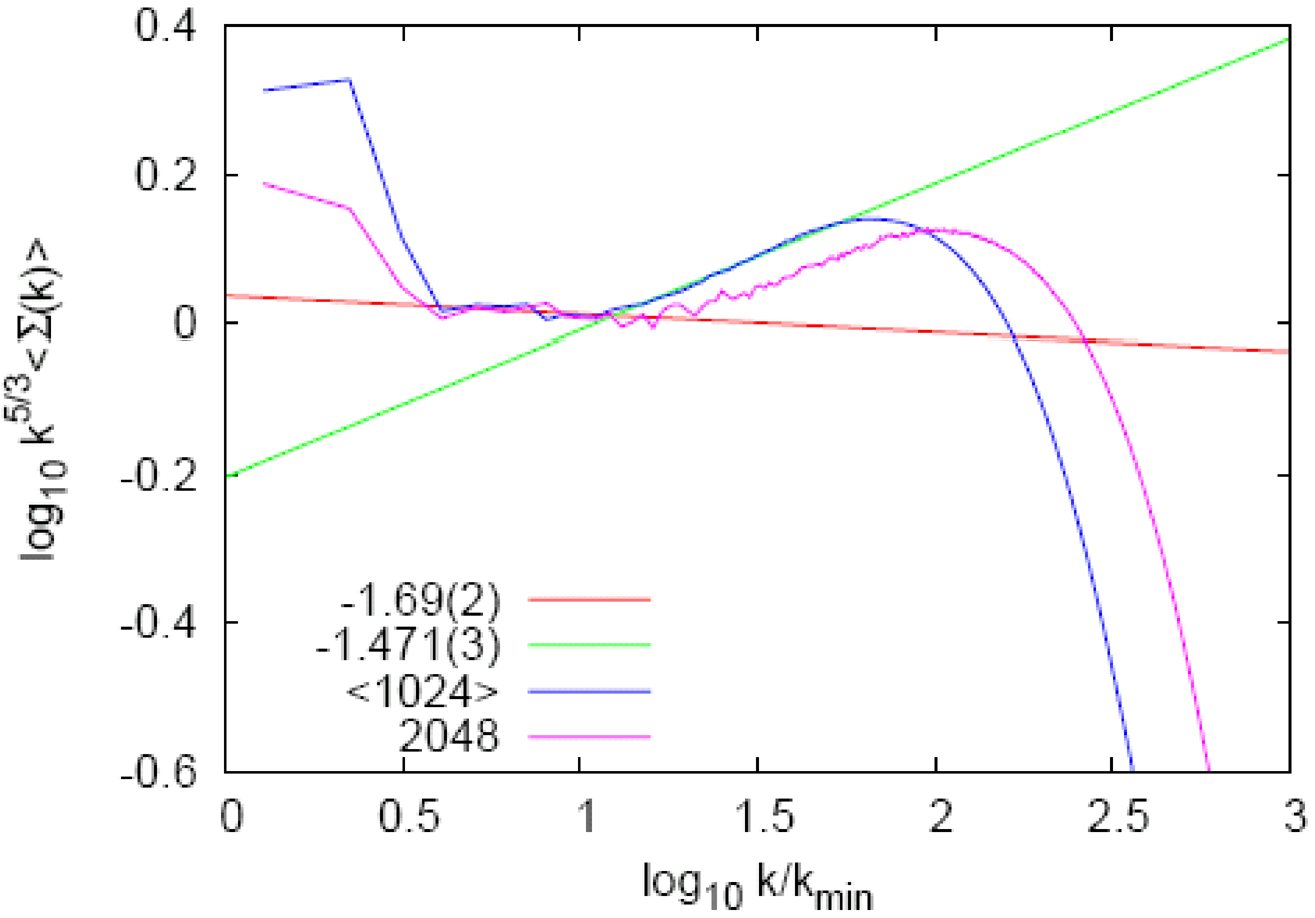
2nd order SFs: $\zeta_2^{\parallel} = 0.95,\ \zeta_2^{\perp} = 0.98$



3rd order SFs: $\zeta_3^{\parallel} = 1.26,\ \zeta_3^{\perp} = 1.29$



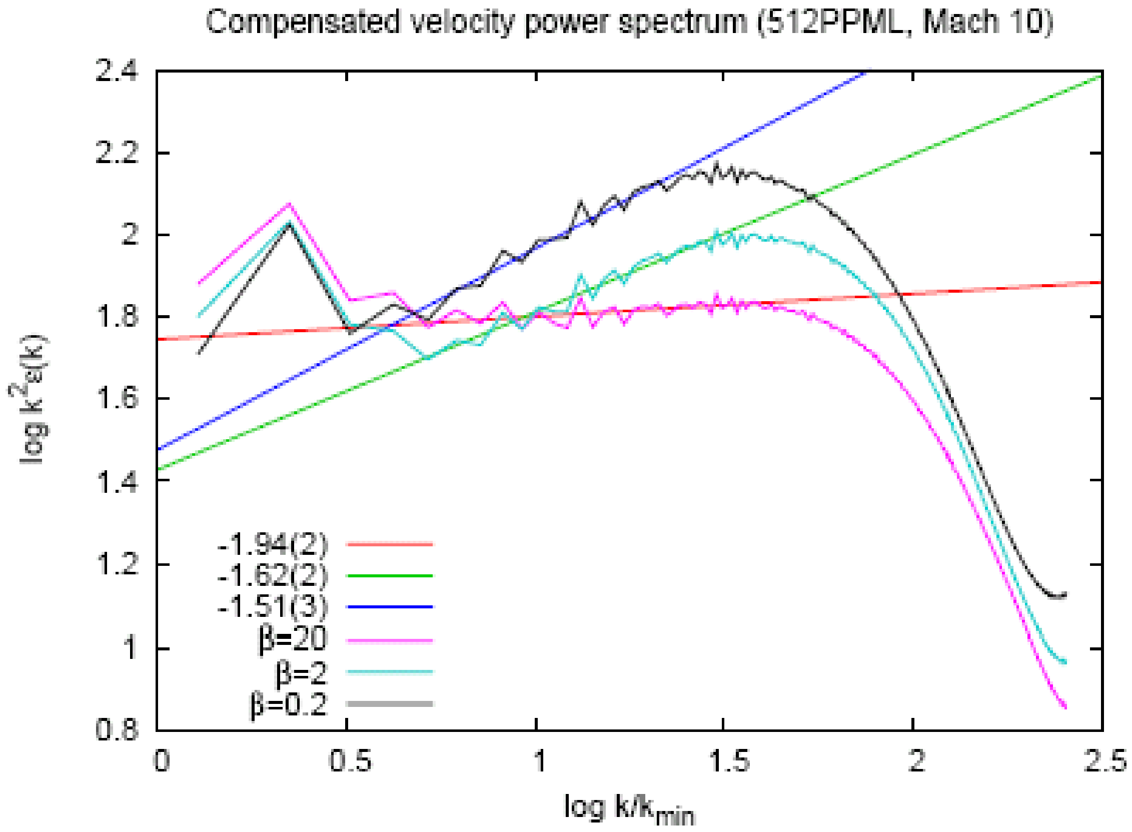
# Power spectrum of $v \equiv \rho^{1/3} u$



**Kolmogorov scaling for $\boldsymbol{v}$:** $\Sigma(k) \sim k^{-1.7}$

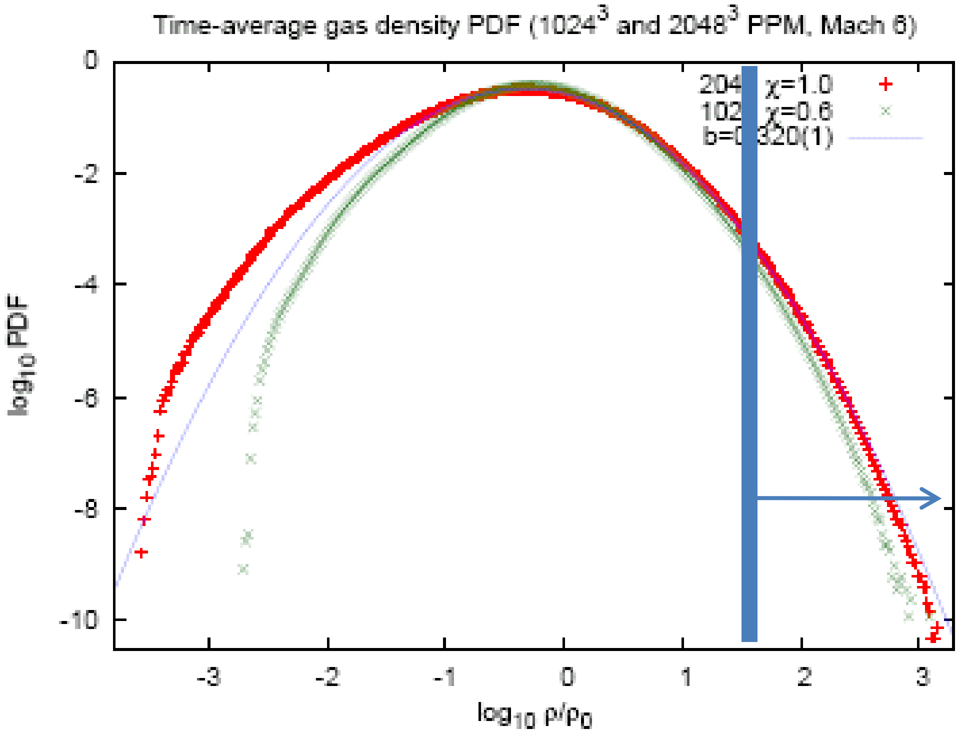
# Magnetized turbulence with PPML at $512^3$

Slopes of the velocity power spectra depend on the level of saturation of the field strength



# Lognormal PDF of density

Theory: Vazquez-Semadeni 1994; Padoan, Nordlund & Jones 1997; Passot & Vázquez-Semadeni 1998; Nordlund & Padoan 1999; Biskamp 2003

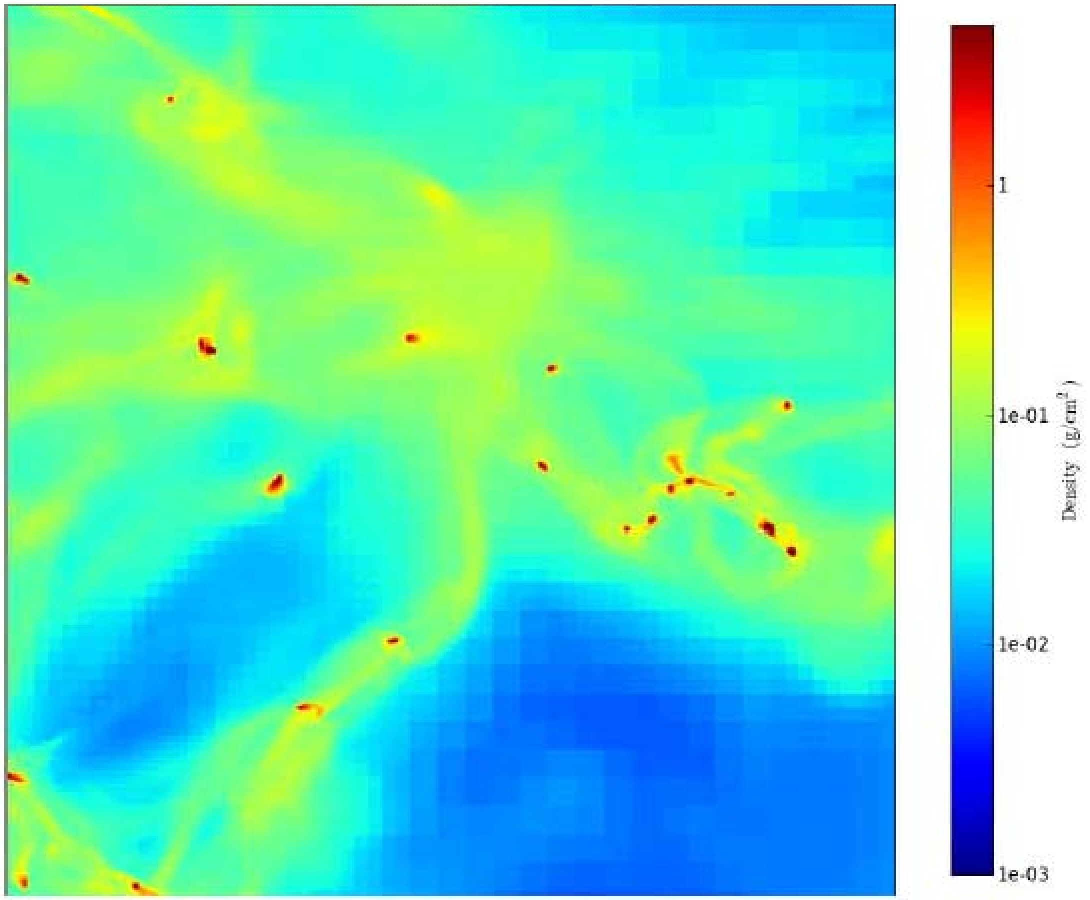


Forms stars

- Good fit quality over 8 decades in probability!
- Sample size $2 \times 10^{11}$ $(1024^3)$ and $9 \times 10^{11}$ $(2048^3)$
- The best-fit values of the width parameter are $b \approx 0.260 \pm 0.001$ and $b \approx 0.320 \pm 0.001$, respectively, for $\log_{10} \rho \in [-2, 2]$

# David Collins PhD thesis (UCSD, 2009)

## first self-gravitating AMR MHD sim of turbulent fragmentation



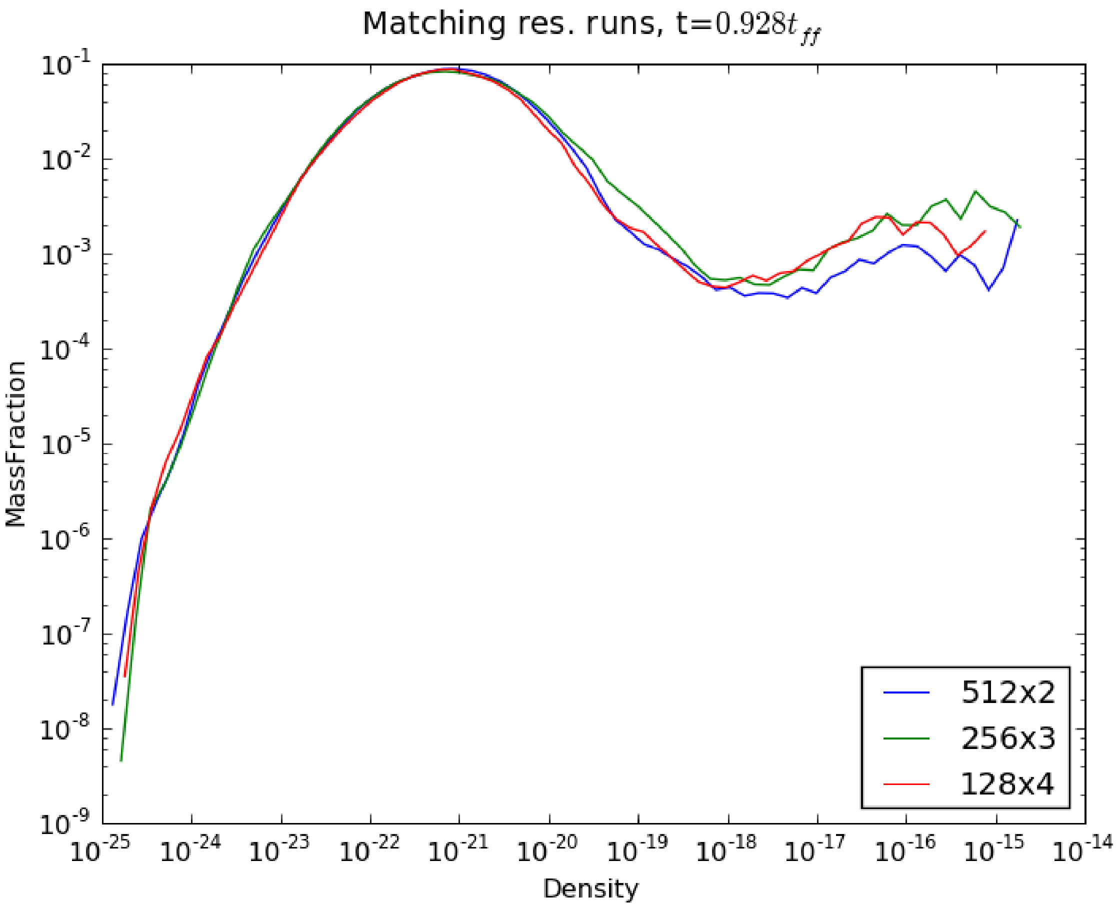
ENZO-MHD code

$128^3$ root grid
4 levels of refinement

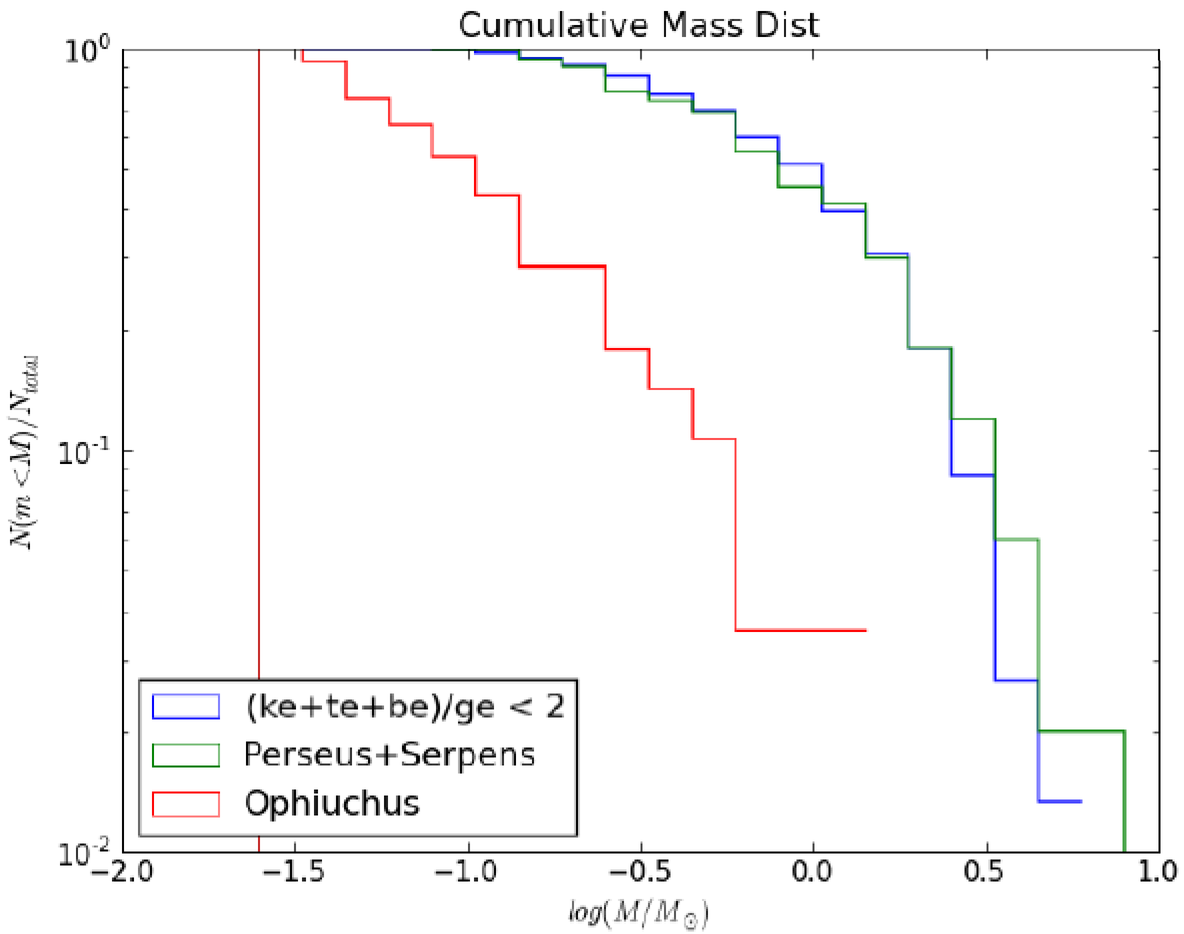
Movie without AMR grids

Movie with AMR grids

# Effect of Self-Gravity on PDF



# Core Mass Function: Comparison with Data



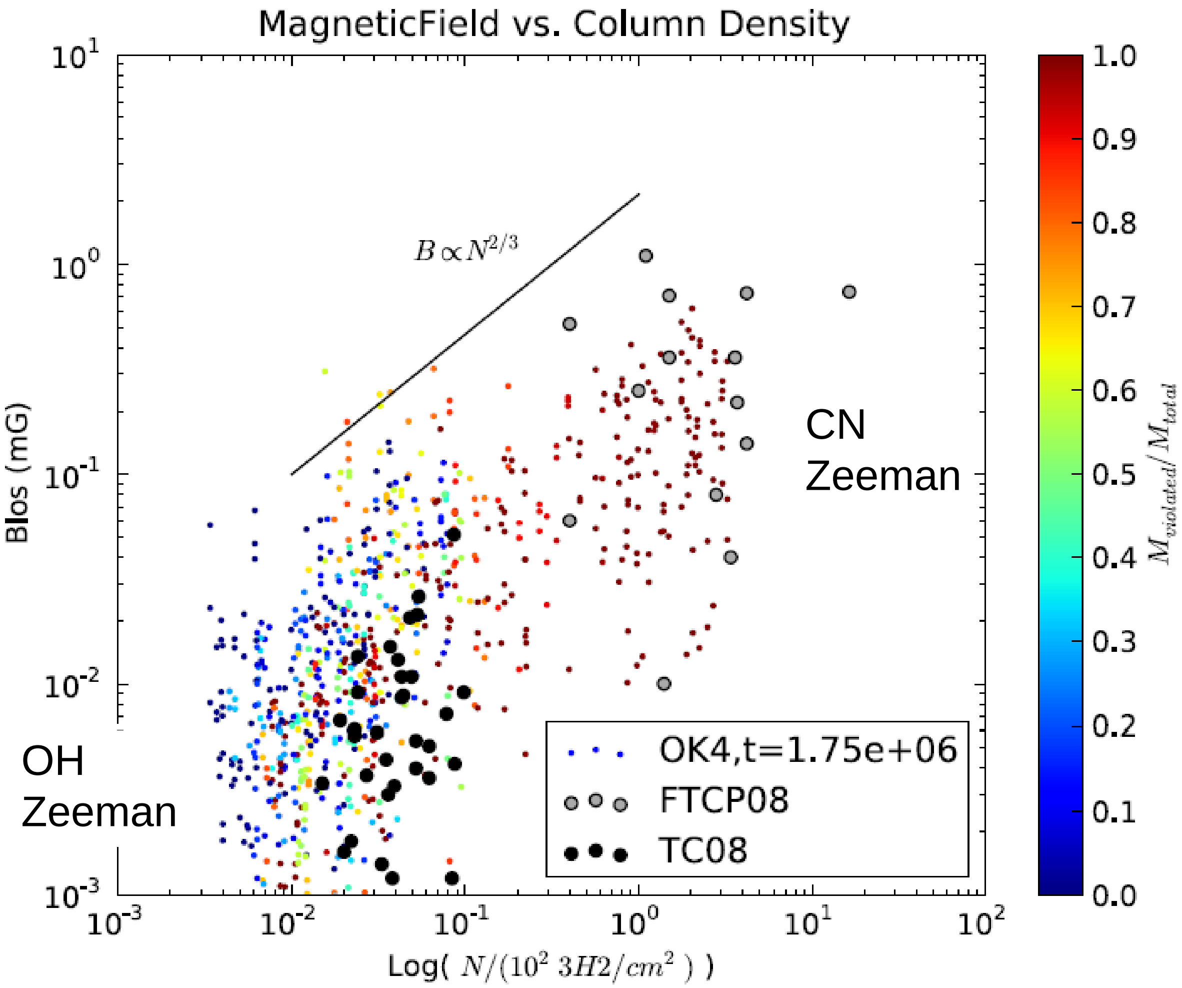


Figure 4.17: Magnetic Field vs Column Density for $\alpha_{vir} < 2$ cores in simulation $ok4$ at n=750 (colored points), data from Troland & Crutcher (2008) (black points) and Falgarone et al. (2008) (grey points). The trend for cores looks somewhat like $B_{los} \propto N^{2/3}$. Color denotes fraction of the core above the Truelove density

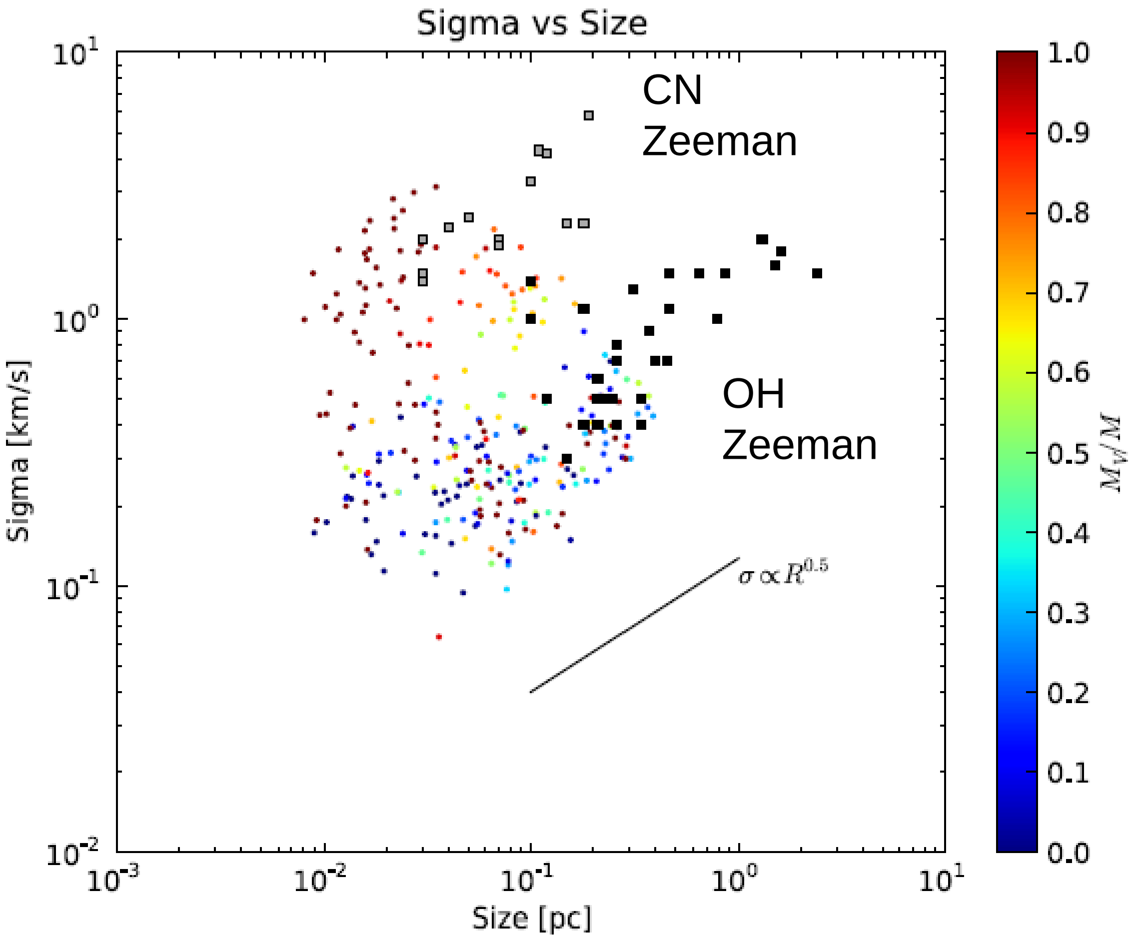
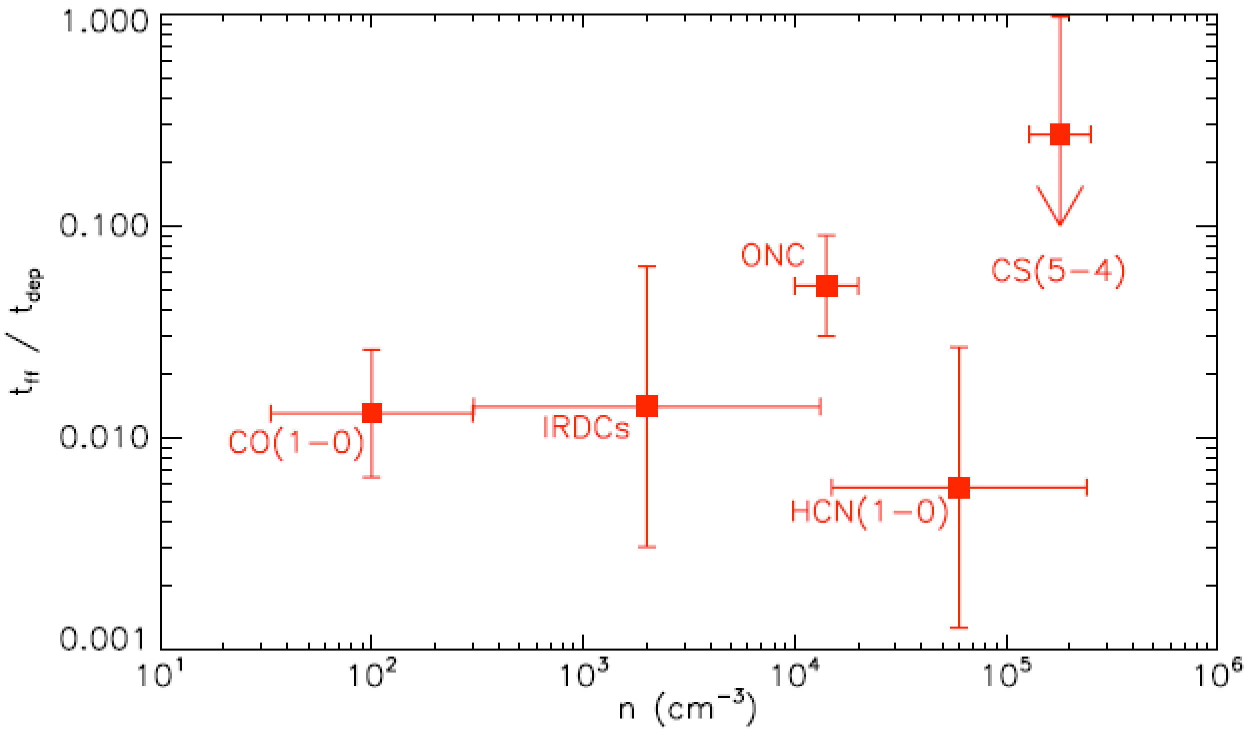


Figure 4.18: Line width Size Relation. Cores selected here are for $\alpha_{sphere} < 4$, and are from the $\alpha_{vir} = 0.52$ simulation at $t = 0.75t_{ff}$. Grey squares are from Falgarone et al. (2008) CN Zeeman measurements, and the black squares are from Troland & Crutcher (2008) OH Zeeman measurements.

# Star Formation Efficiency

*Freefall time in units of the depletion time, measured by various tracers*



Klessen, Krumholz & Heitsch (2009)

# Krumholz & McKee (2005) Theory

- Assume only gravitationally bound regions of turbulent flow collapse to form stars
- Assume turbulence obeys Larson's law
- Fraction of the cloud at or near the sonic scale will form stars

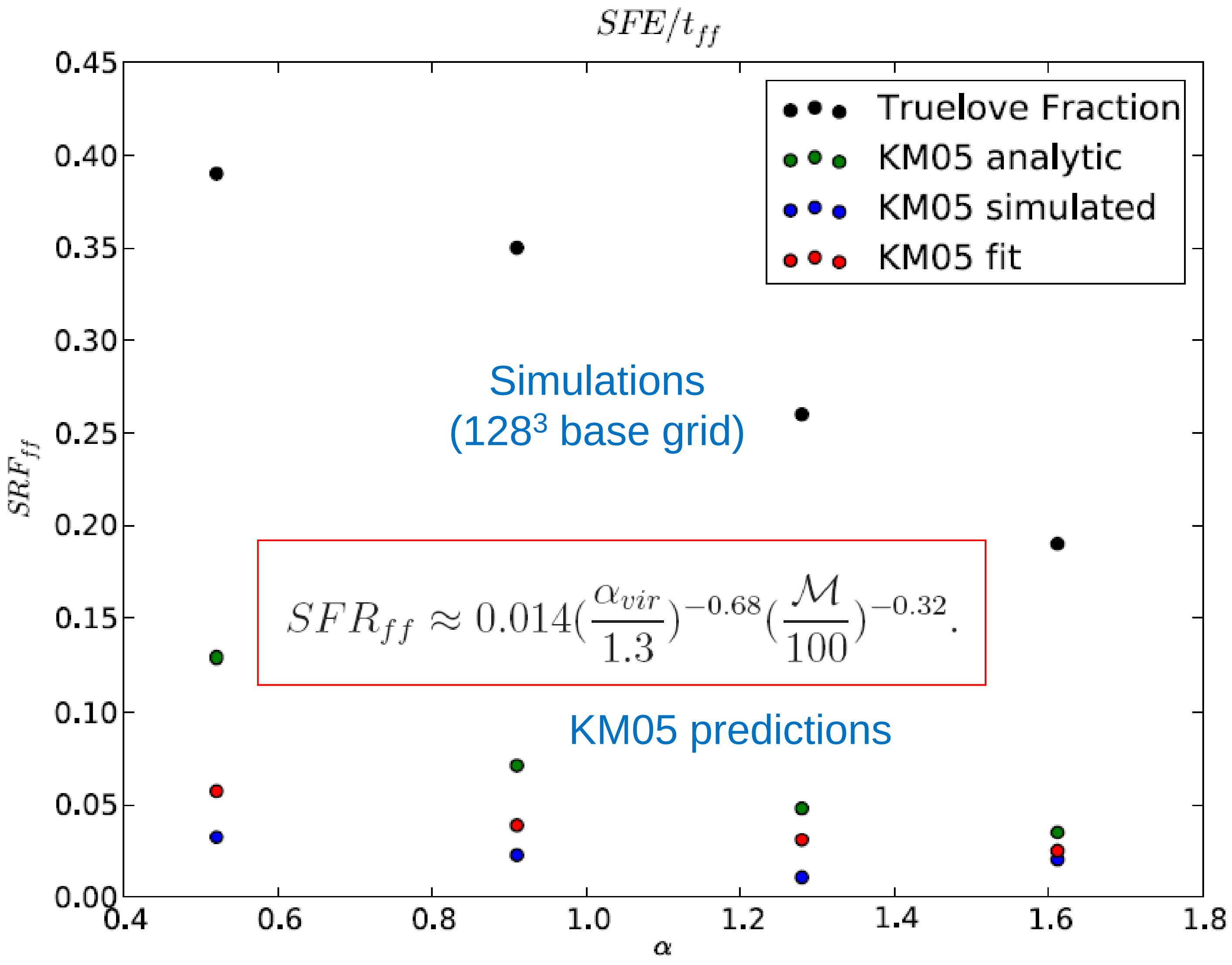
$$\alpha_{vir} = \frac{5\sigma_{1D}^2 R}{GM} < 2$$

$$\sigma_{1D} = \sigma_{3D} / \sqrt{3} \propto R^{1/2}$$

$$\therefore \alpha_{vir} \propto R^2$$

$$\Rightarrow \text{decreases with scale}$$

# Comparison with KM05



Simulations
($128^3$ base grid)

$$SFR_{ff} \approx 0.014(\frac{\alpha_{vir}}{1.3})^{-0.68}(\frac{\mathcal{M}}{100})^{-0.32}.$$

KM05 predictions

# Assessment: Galactic Star Formation

- Turbulent star formation has displaced magnetic star formation paradigm because
  - Zeeman measurements which show cores are mildly supercritical
  - Provides a natural explanation for origin of cloud cores that agrees with observations
  - Provides a natural explanation for low star formation efficiencies
- Progress simulating TSF has been paced by growth in computing power and availability of stable super-Alfvenic MHD algorithms
- Preliminary AMR results look promising, but much more work is required to critically test predictions

# Formation and Evolution of Disk Galaxies

- Stellar structure
  - Bulge, disk, halo
- Kinematics
  - stars, gas
- Tully-Fisher relation
- Gas content
- Stellar ages
- Role of mergers on disk formation and destruction

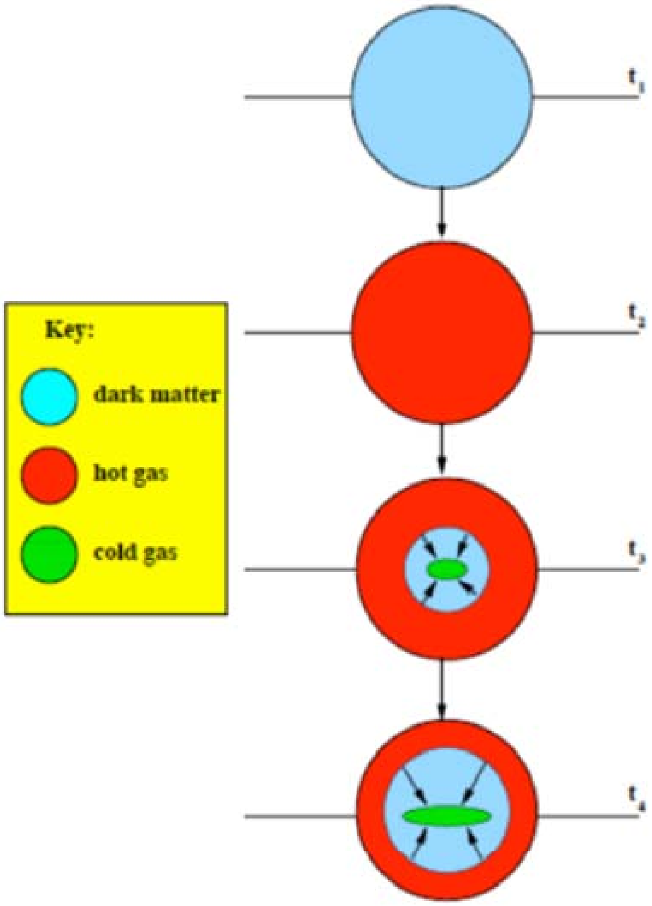
M101

# Theoretical Notions

- Bottom-up structure formation (Davis et al. 1985)
- Tidal torque origin of angular momentum (Fall & Efstathiou 1980; Fall 1983)
- Dissipational collapse of baryons and stellar disk formation via fragmentation (White and Rees 1978)
- Destruction of disks by major mergers (Toomre & Toomre 1972; Barnes & Hernquist 1996)
- Secular processes (gas accretion, galactic dynamics) reshape galaxy at late times (e.g., Valenzuela & Klypin 2003)

*Galaxy formation is continuous, ongoing process and history dependent*

# Formation of Disk Galaxies: Conventional Wisdom (White & Rees 1978)



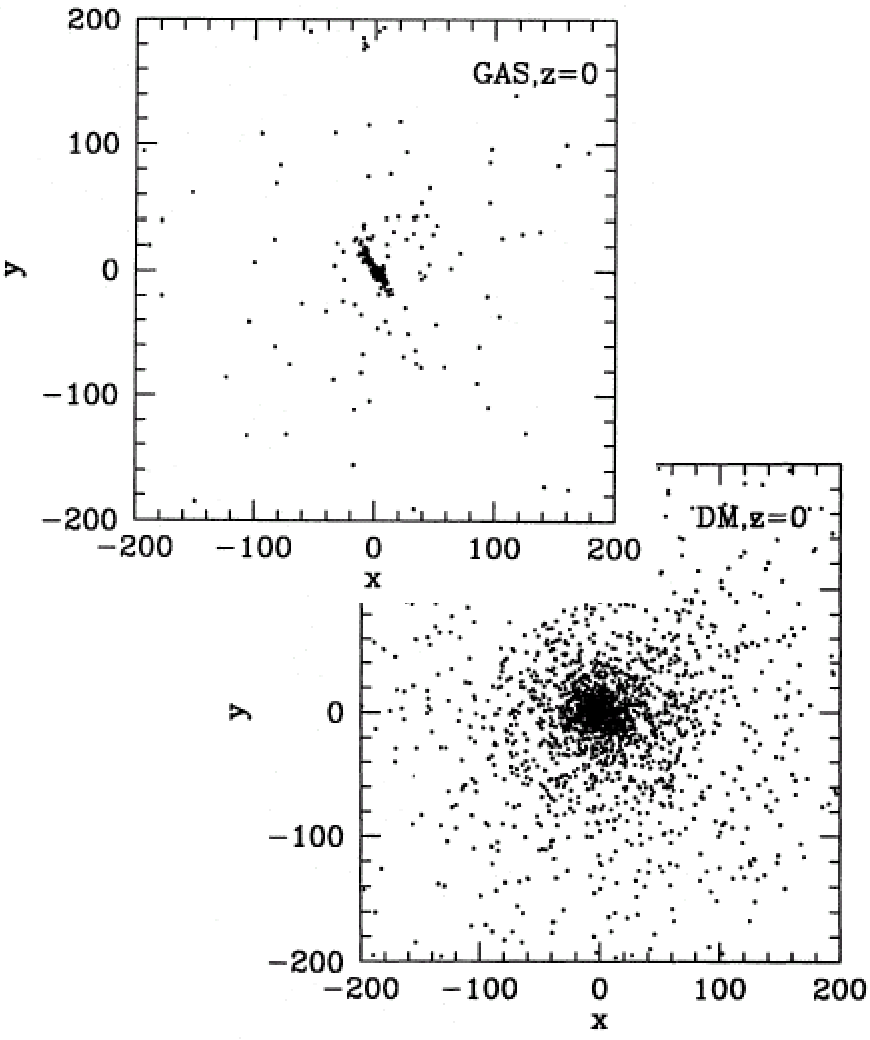
Baugh (2006)

# Early Numerical Experiments:
# Abject Failure

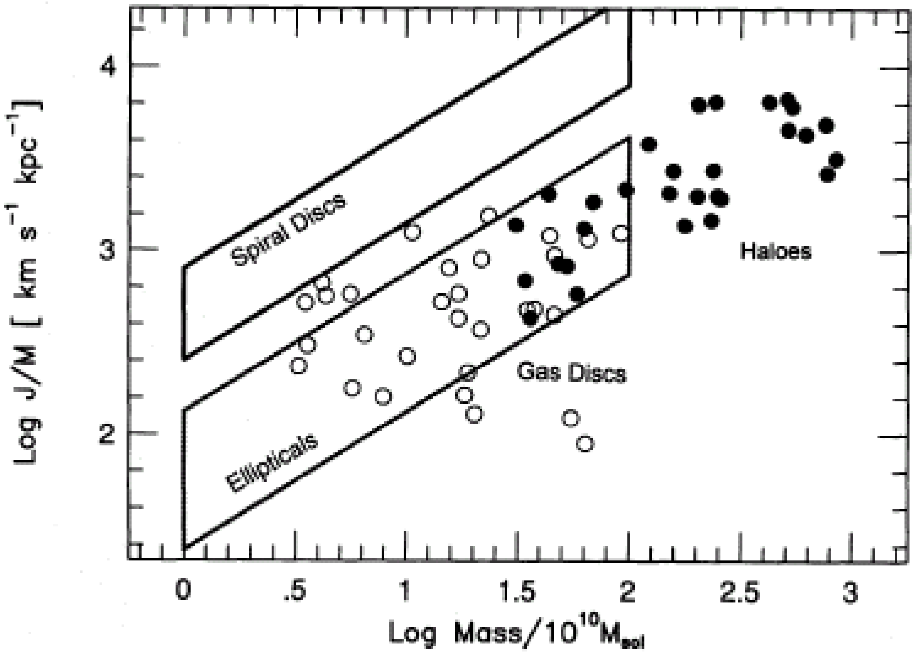
- Poor force resolution→Catastrophic loss of baryonic angular momentum→ tiny disks (Navarro & White 1994)
- Lack of SN feedback→star formation rate too high (White & Frenk 1991, Balogh et al. 2001)
- Combined effects yielded compact disk galaxies which disagreed with Tully-Fisher relation (Navarro & Steinmetz 2000; Eke et al. 2001)

# Angular Momentum Loss

## Navarro, Frenk & White (1995)



Cooling but no feedback



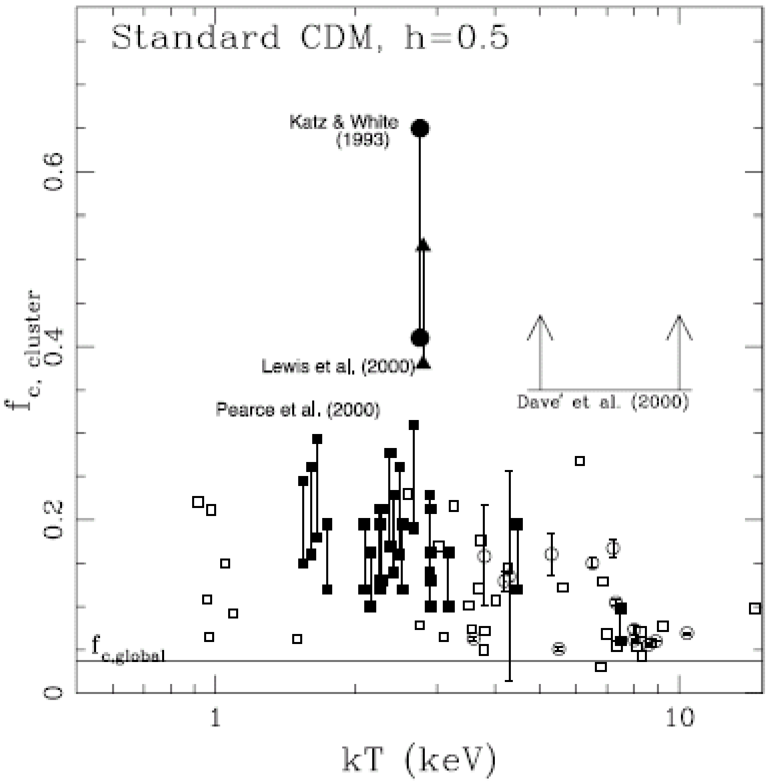
# Possible Reasons for Angular Moment Loss in Disk Galaxies

- Dynamical friction on clumpy gas distribution (Navarro & White 1996)
- Gravitational torques in gaseous spiral arms (Lynden-Bell & Kalnajs 1971)
- Artificial viscosity at hot/cold SPH interfaces (Okamoto 2006)
- Torques from “grainy” dark matter halos (Kaufmann 2007)

# The Overcooling Problem

White & Frenk 1991, Balogh et al. 2001

- Simulations with radiative cooling but no no star formation and feedback produce too much cool gas relative to observations
- This problem led to many mostly unsuccessful attempts to model SF+FB



# I-band Tully-Fisher Relation

## Navarro & Steinmetz (2000)

- N-body/SPH simulations of GF with SF/FB
  - N=32,000 particles
  - ε=1 kpc
- I-band Tully-Fisher relation slope recovered, but not normalization
- Due to excessively compact DM halos and high mass/light ratio

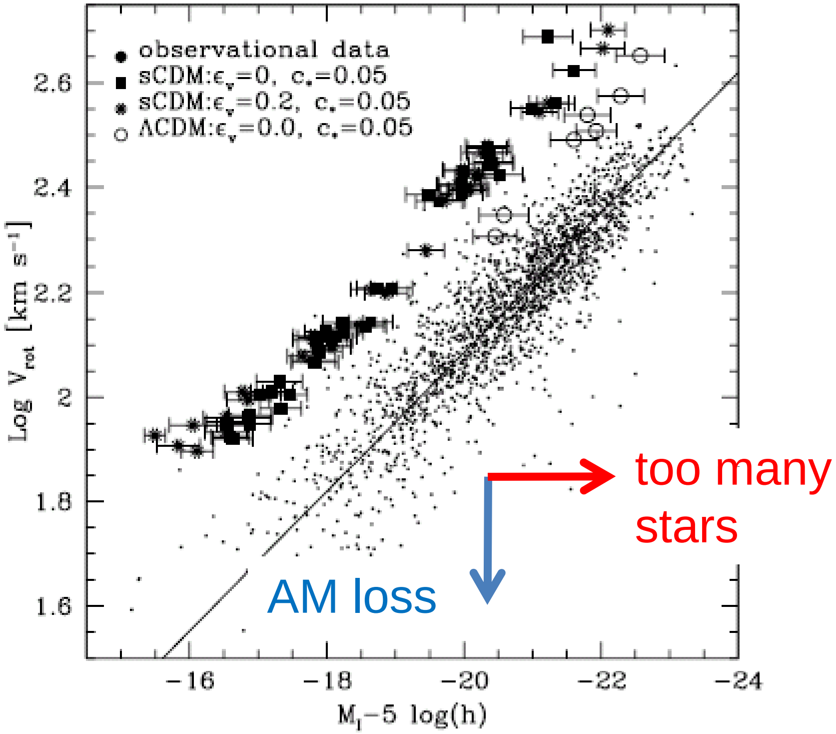
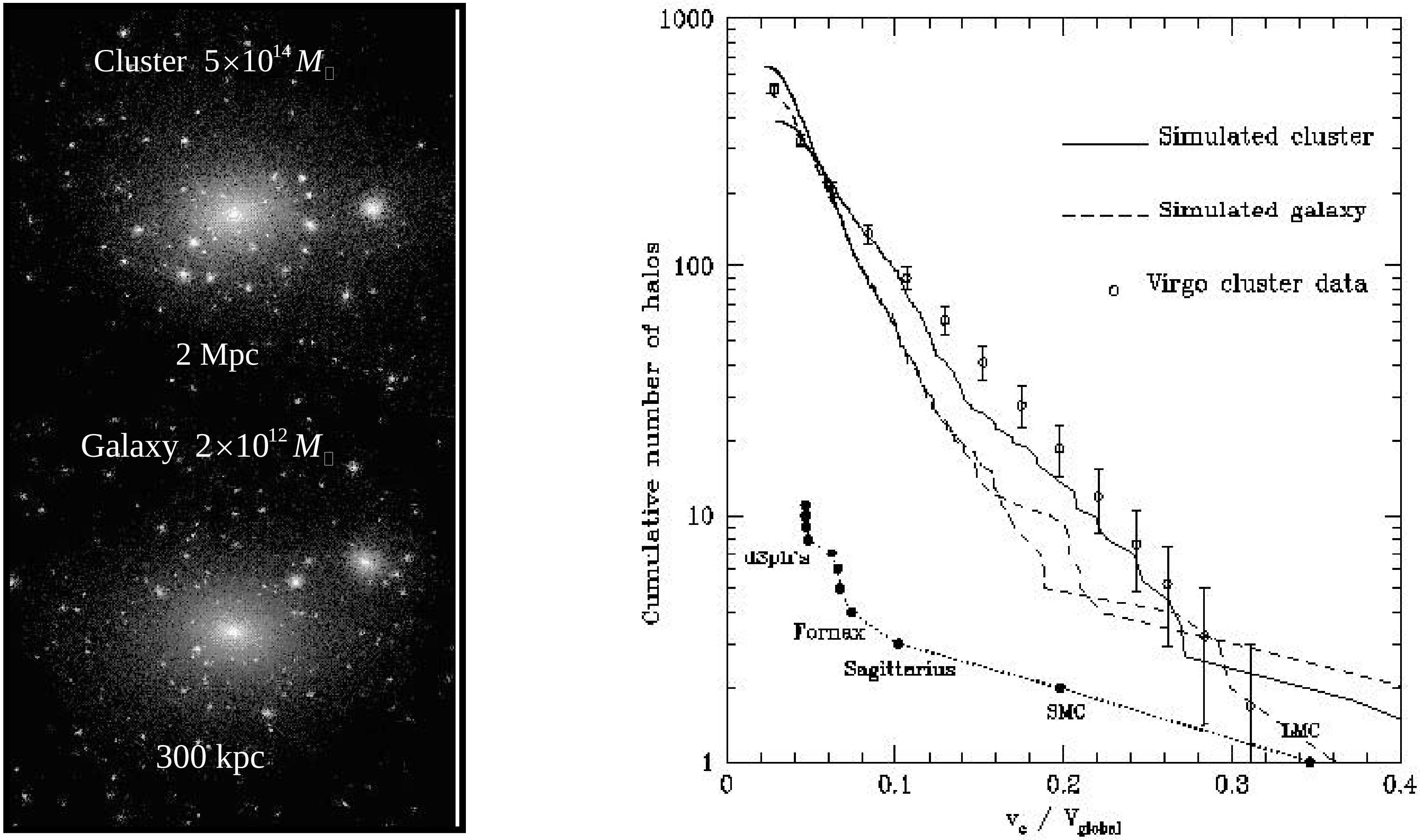


Fig. 1.—*I*-band Tully-Fisher relation compared with the results of the numerical simulations. Dots correspond to the observational samples of Mathewson, Ford, & Buchhorn (1992), Giovanelli et al. (1997), and Han & Mould (1992). Error bars in the simulated magnitudes correspond to adopting a Salpeter or a Scalo IMF.

# Other Challenges to CDM:

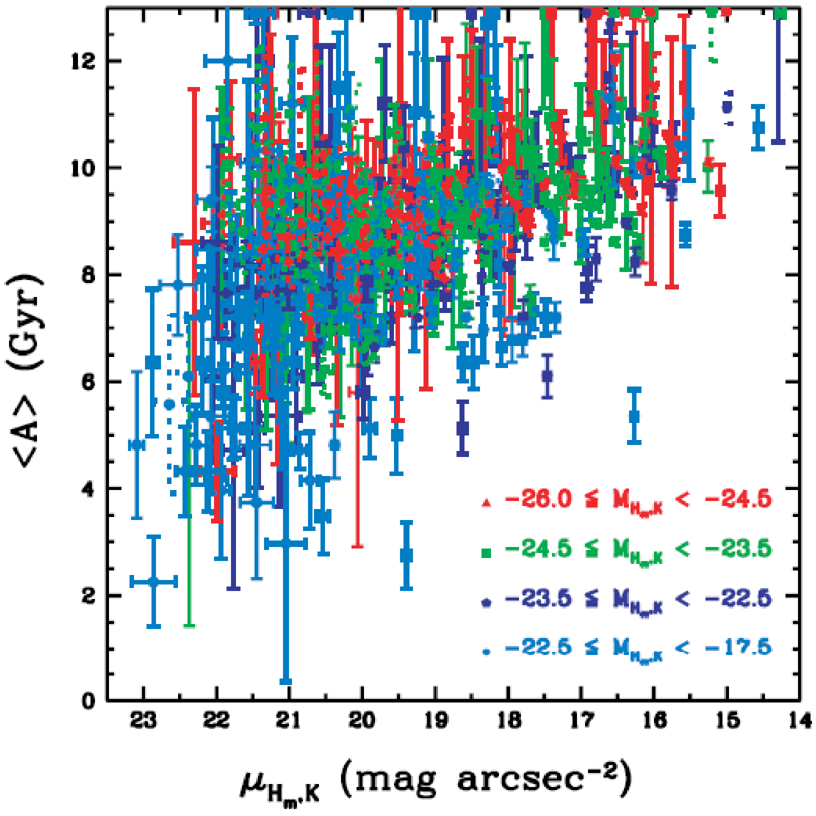
# The "Missing Satellite" Problem



B. Moore et al. (1999)

# Yet Another Challenges to CDM: “Galaxy Downsizing”

- Galaxies with less massive stellar component have younger stellar populations (Cowie et al. 1996; MacArthur et al. 2004)
- Contrary to naieve interpretation of hierarchical model

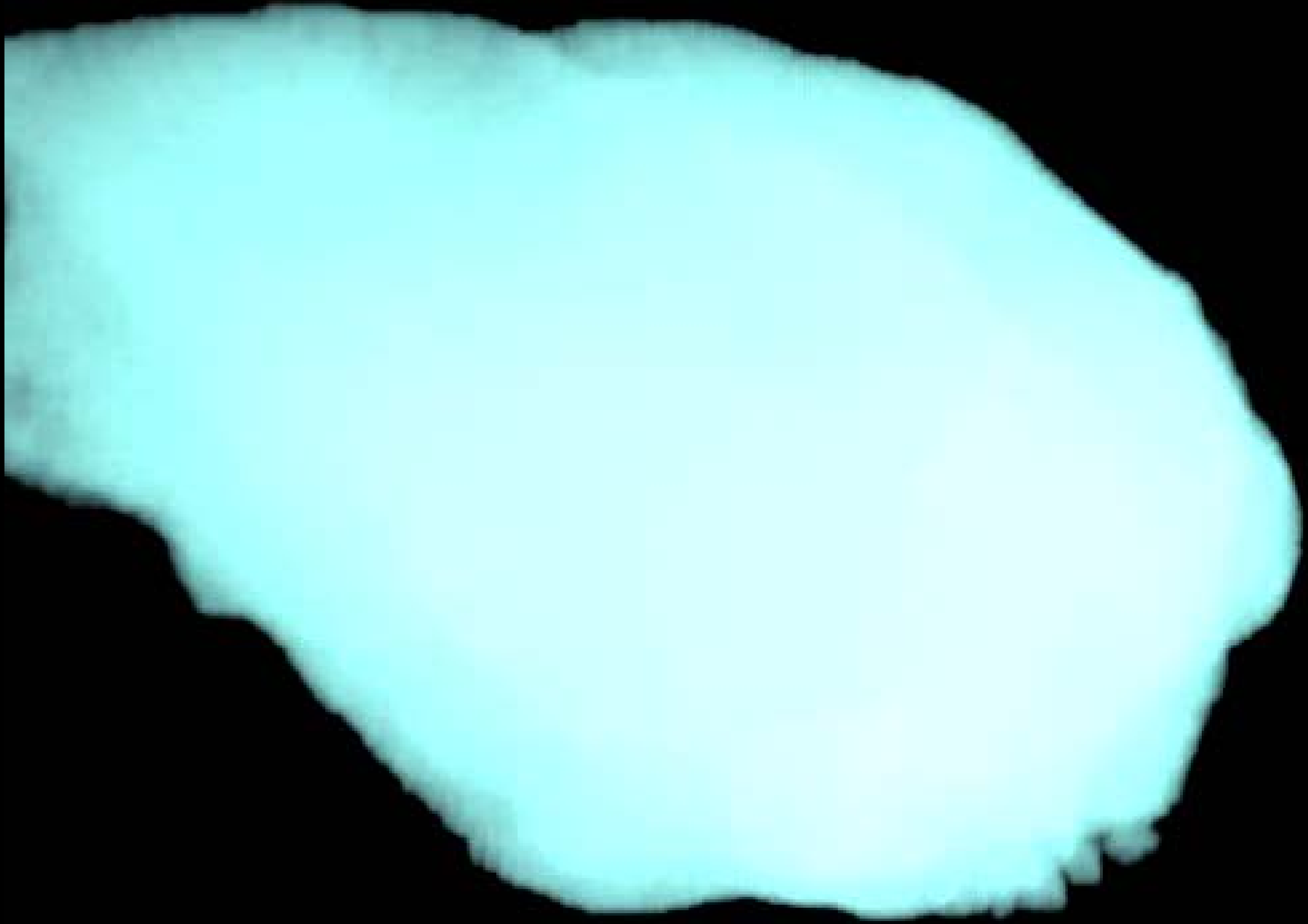


MacArthur et al. (2004)

# Cosmological hydro simulations of MW formation.

(Ngas, Ndm > $10^6$ within Rvir + BlastWave feedback model )

*(Governato, Willman, Mayer et al. 2006, 2007)*

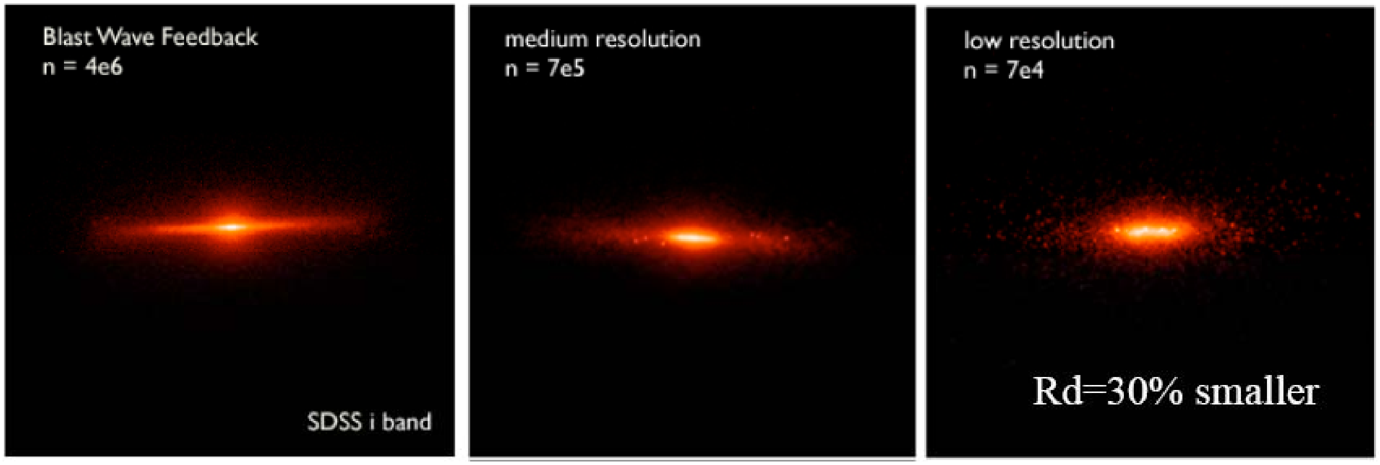


*Slide courtesy F. Governato*

# Achieving Agreement with Observations

(Governato et al. 2007, 2008; Zavala et al. 2008)

- Improved star formation + FB recipe
  - More astrophysically motivated
  - Calibrated with data
- Substantially better mass and force resolution
  - $N_{vir} > 10^6$
  - $\varepsilon_{soft} <<$ disk scale length, scale height (~300 pc)



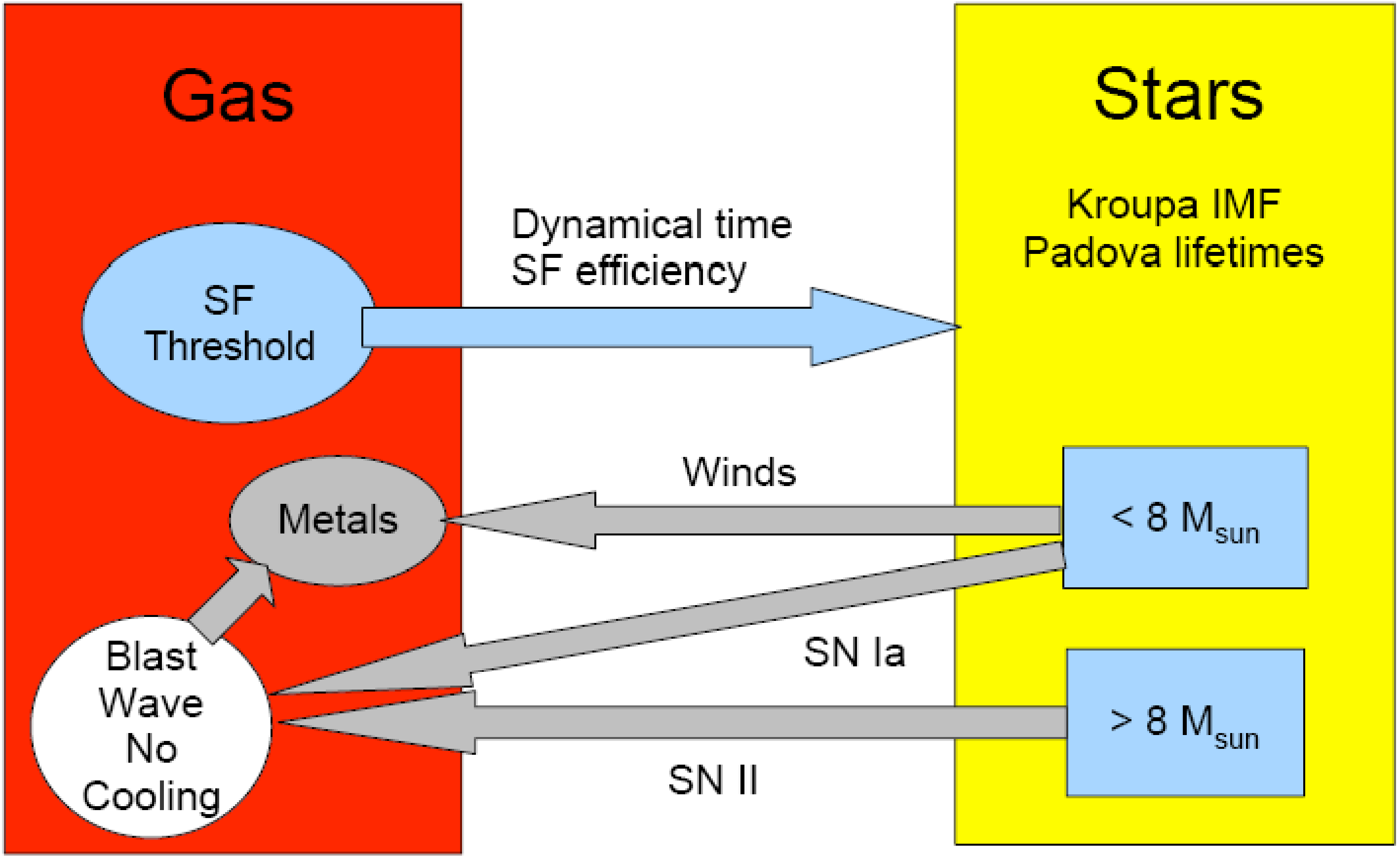
# Star formation/feedback recipes

Cen & Ostriker (1992); Katz, Weinberg, Hernquist (1996), Yepes et al. (1997), Springel & Hernquist (2003), Kravtsov (2003), Stinson et al. (2006)

```
forall (cells or SPH particles)
if {set of criteria = .true.}
then
    create_star_particle
    evolve_as_N-body
    deposit_energy $\dot{E} \propto \dot{M}_{SF} c^2$
endif
```

- *deposit_energy*
  - Locally as thermal energy ➔ radiated away
  - Locally as kinetic energy ➔ escape galaxy
  - In neighborhood region as thermal energy ➔ still radiated away
  - radiative cooling suppressed in region for some time Δt ➔ Sedov blast wave

# Star Formation/Feedback



2 free parameters: C*, eSN

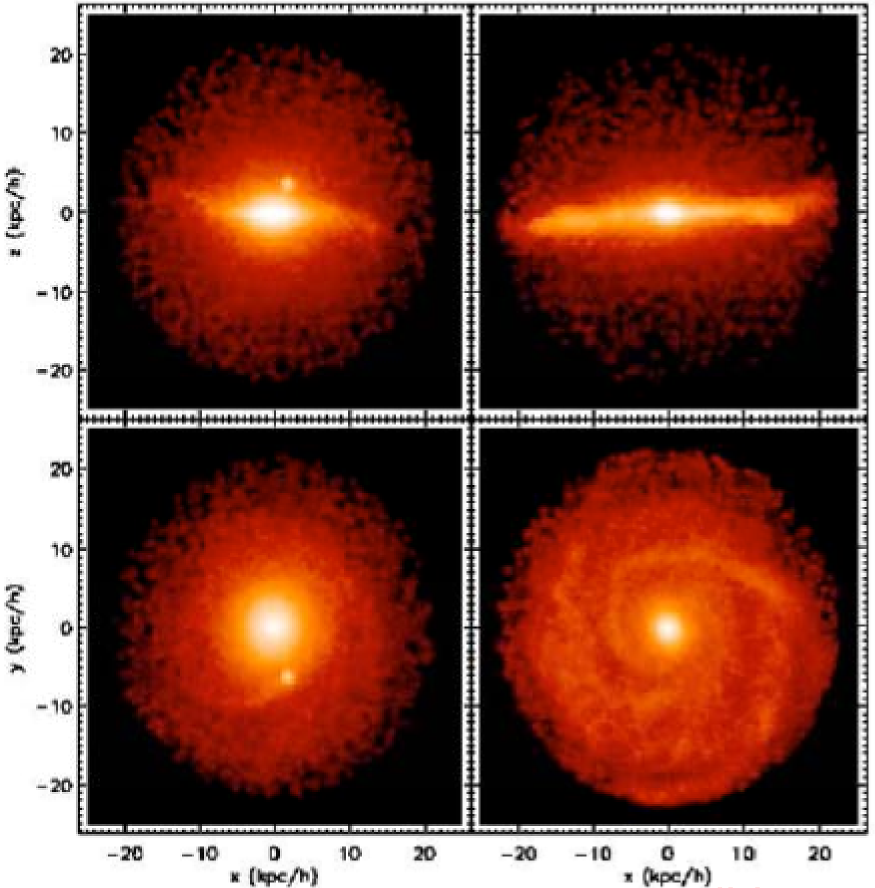
Stinson et al 2006

*Slide courtesy F. Governato*

# Effects of Feedback. Zavala et al 08

No FB

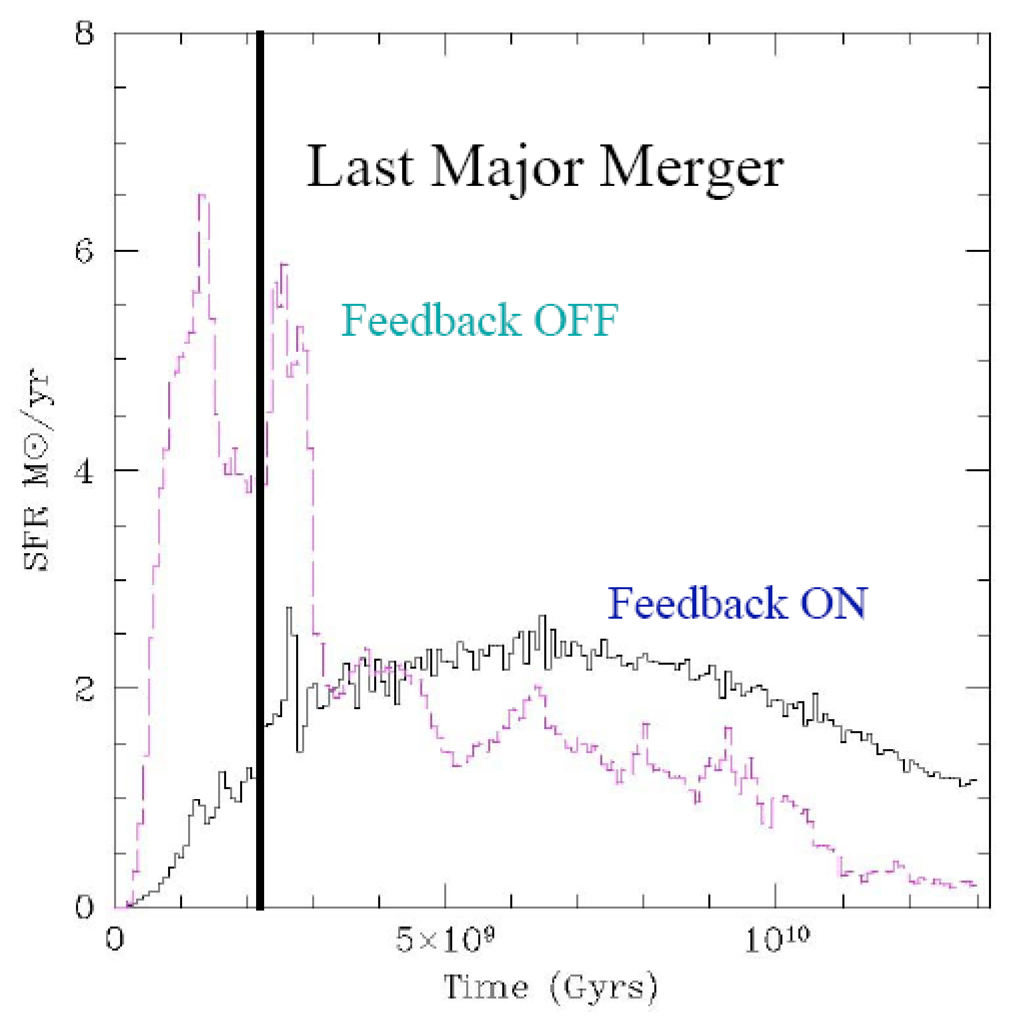
FB on.



*Slide courtesy F. Governato*

# *But Feedback crucial to regulate star formation*

Effect of blastwave feedback on SFH of galaxy with halo of $10^{11}$ Mo



If blastwave feedback is on, star formation peaks at z< 1 AFTER Last Major Merger.

Progenitors forms stars inefficiently due to feedback

SF in bulges suppressed.

*Slide courtesy F. Governato*

SFH includes all progenitors at any given time

L. Mayer, 08

# The effects of limited resolution in gaseous disks Embedded in a DM + hot gas halo.

6 *Kaufmann et al.*

Isolated disk galaxy + hot halo

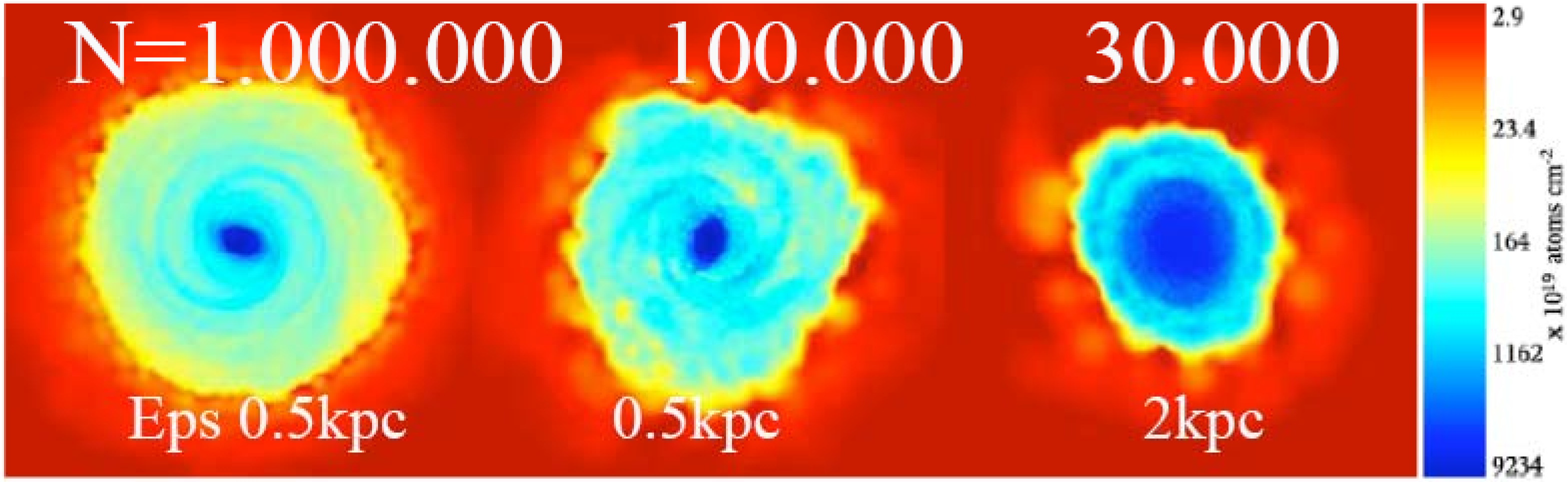


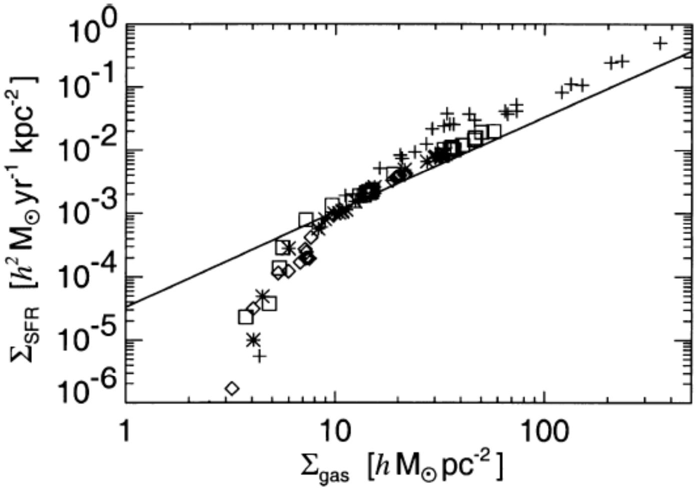
**Figure 3.** The three panels show density maps of gas in a slice through the centre of the Milky Way gas disk after 5 Gyr, from left to right: HRLS, IRLS, LRLS. Box side length 20 kpc for every panel - clearly the disk is larger for higher resolution and the bulge to disk ratio lower.

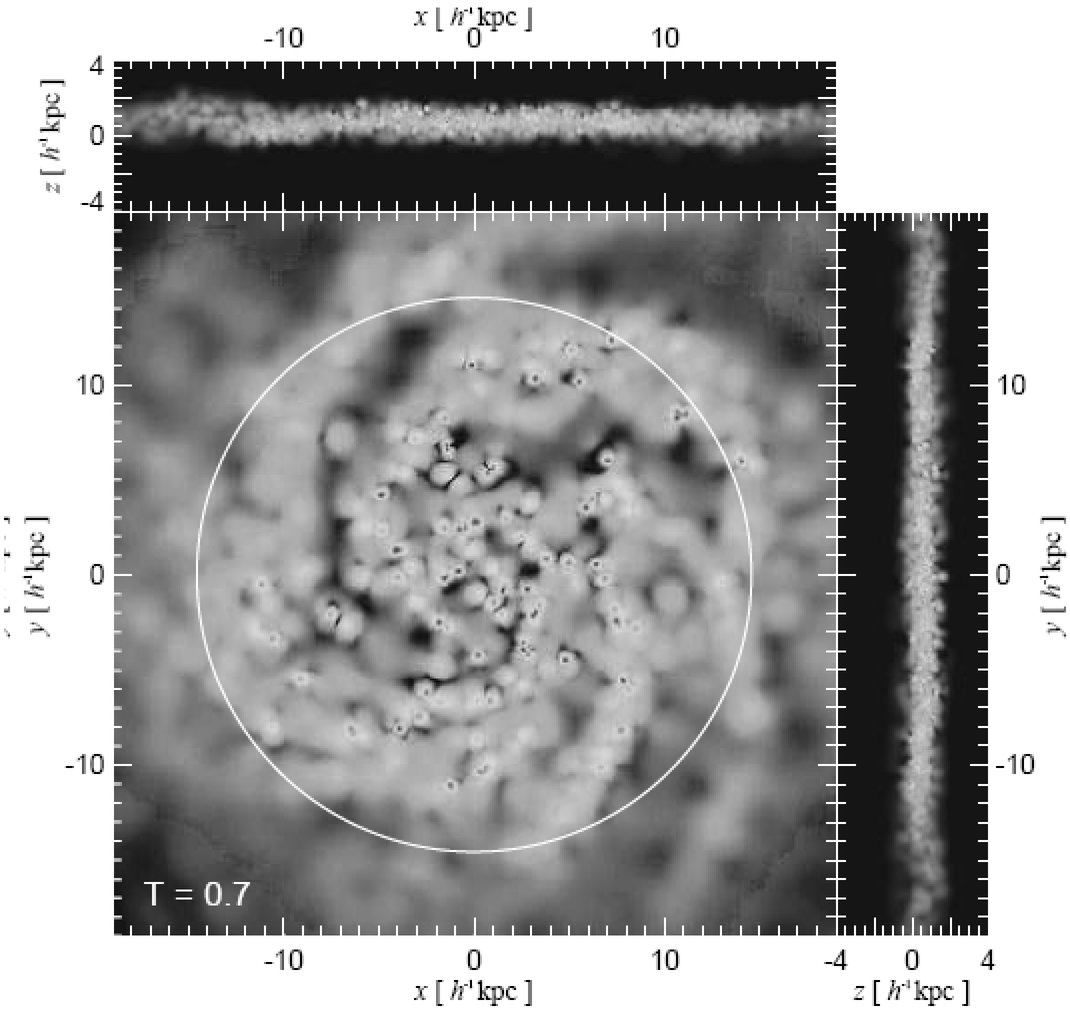
*Slide courtesy F. Governato*

# Calibrating Star Formation/Feedback Recipes

## Springel (2000)

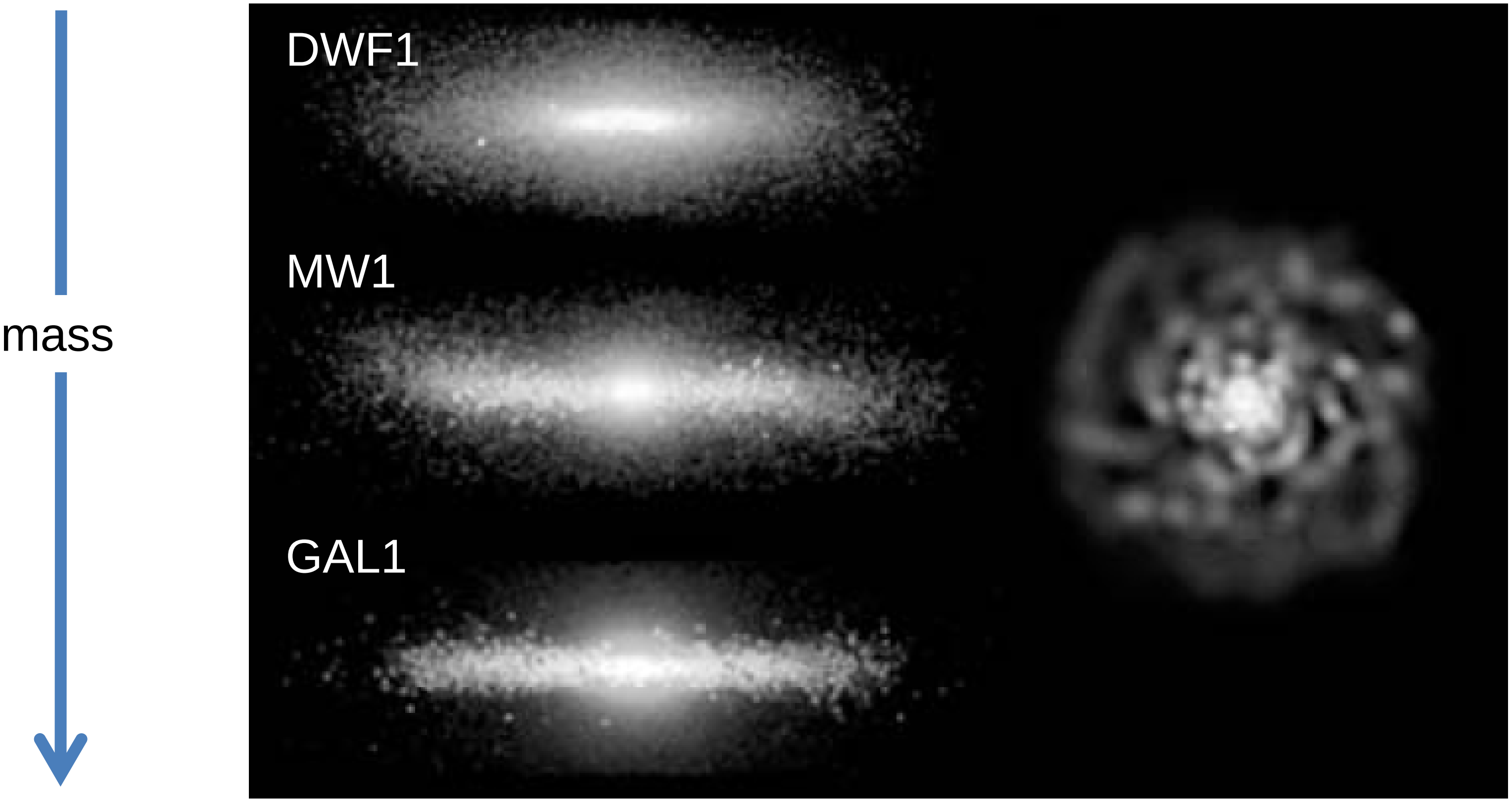
- Build isolated galaxy model matching observations (B/D/H)
- Calibrate SFE and feedback parameters to Kennicutt law



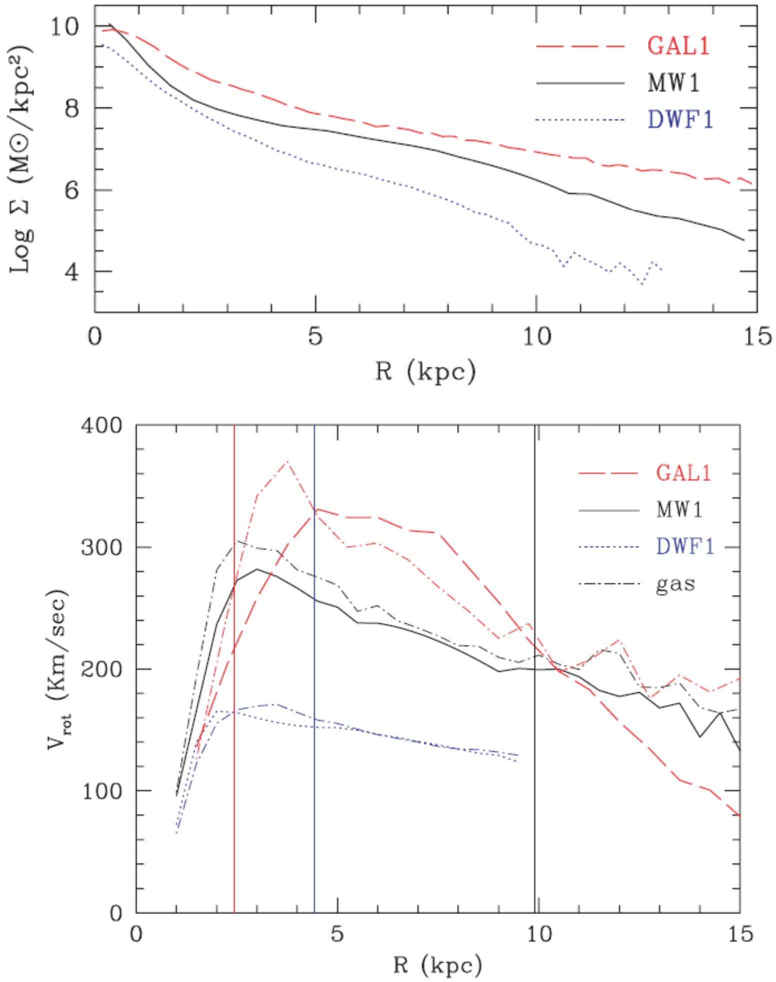


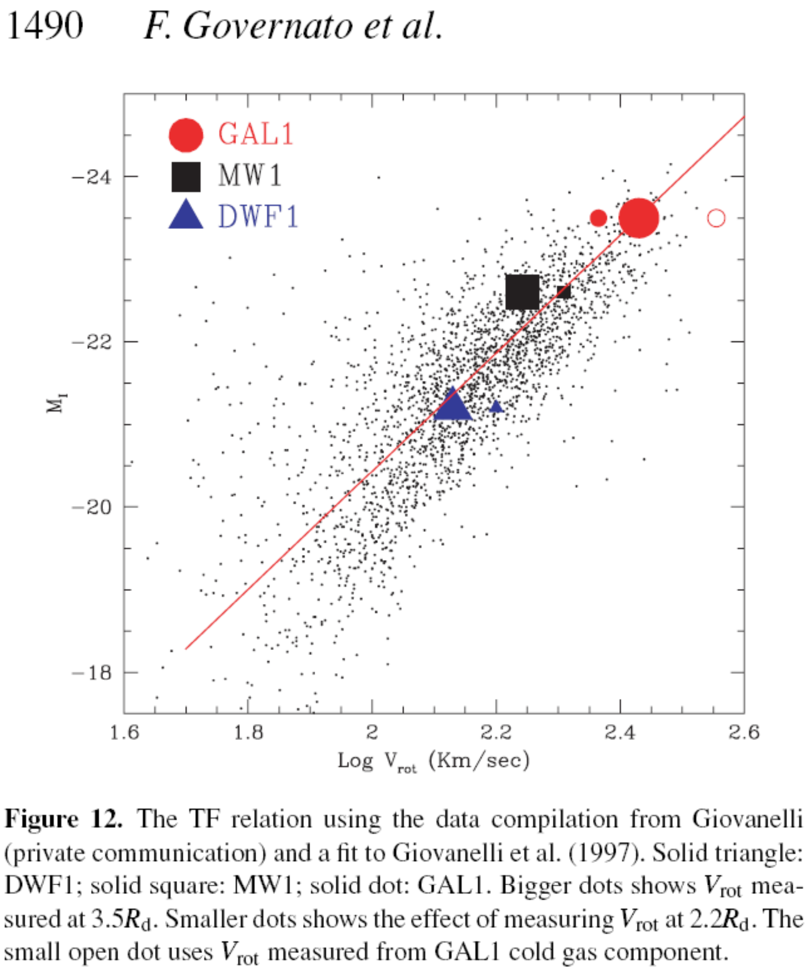
# Disk Galaxies from CosmoSims

## Governato et al. (2007)



# Observable Properties



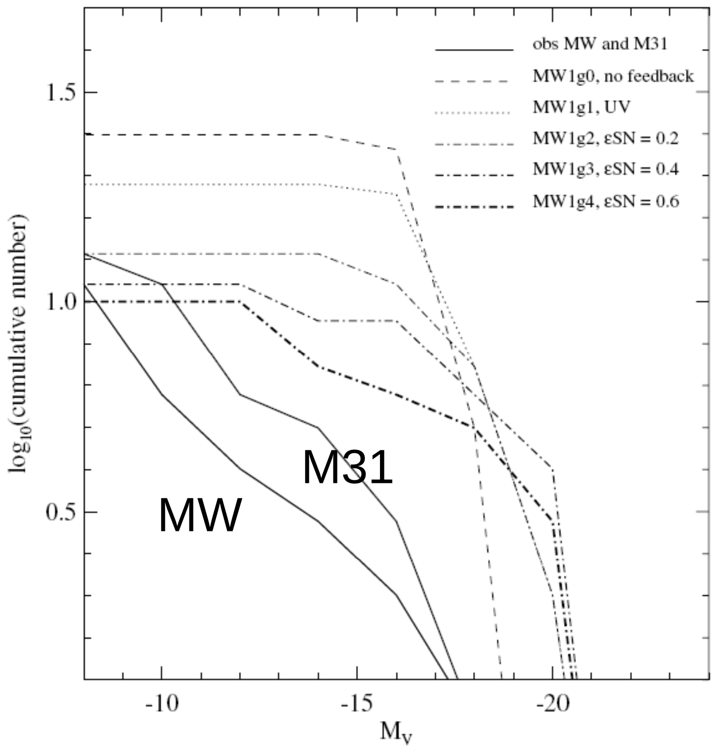


1490 *F. Governato et al.*

**Figure 12.** The TF relation using the data compilation from Giovanelli (private communication) and a fit to Giovanelli et al. (1997). Solid triangle: DWF1; solid square: MW1; solid dot: GAL1. Bigger dots shows $V_{\rm rot}$ measured at $3.5R_{\rm d}$. Smaller dots shows the effect of measuring $V_{\rm rot}$ at $2.2R_{\rm d}$. The small open dot uses $V_{\rm rot}$ measured from GAL1 cold gas component.

# Missing Satellite Problem

Effect of feedback



Effect of resolution

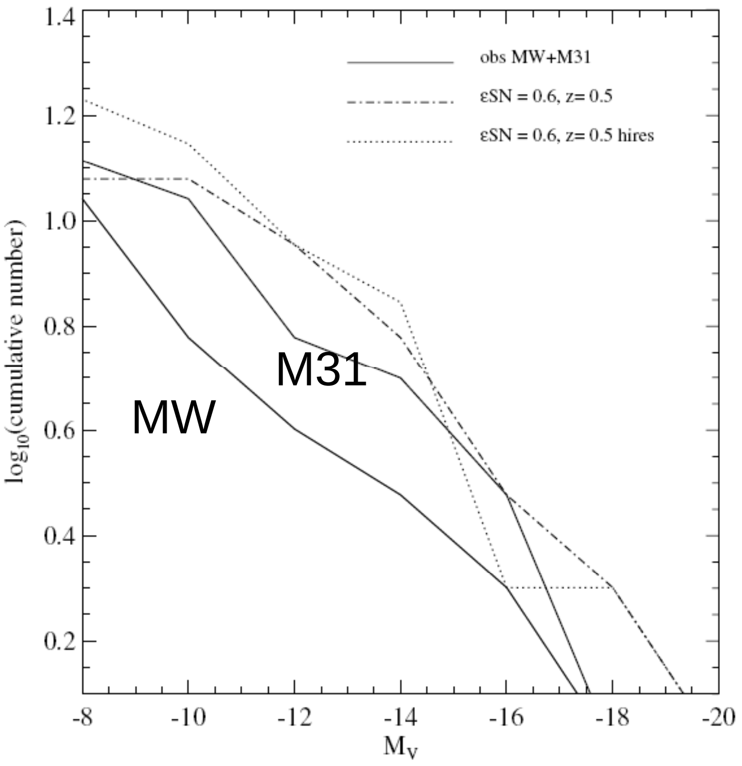
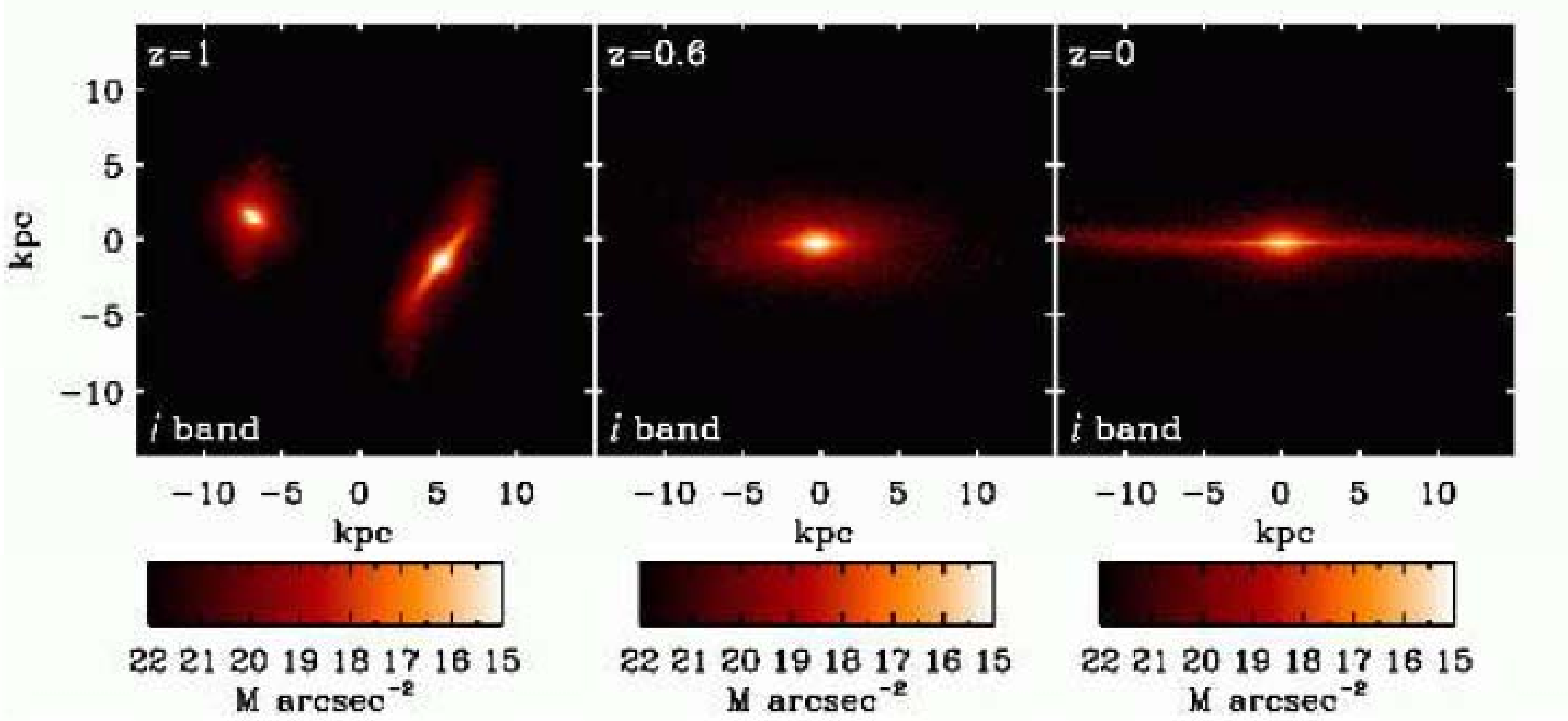


**Figure 20.** Resolution tests: the *V*-band LF of the satellites system of MW1g4 (dashed) and its high resolution version (dotted) at $z = 0.5$ compared with the MW and Andromeda (solid lines).

# Q: Do Major Mergers Destroy Galaxy Disks for All Time?

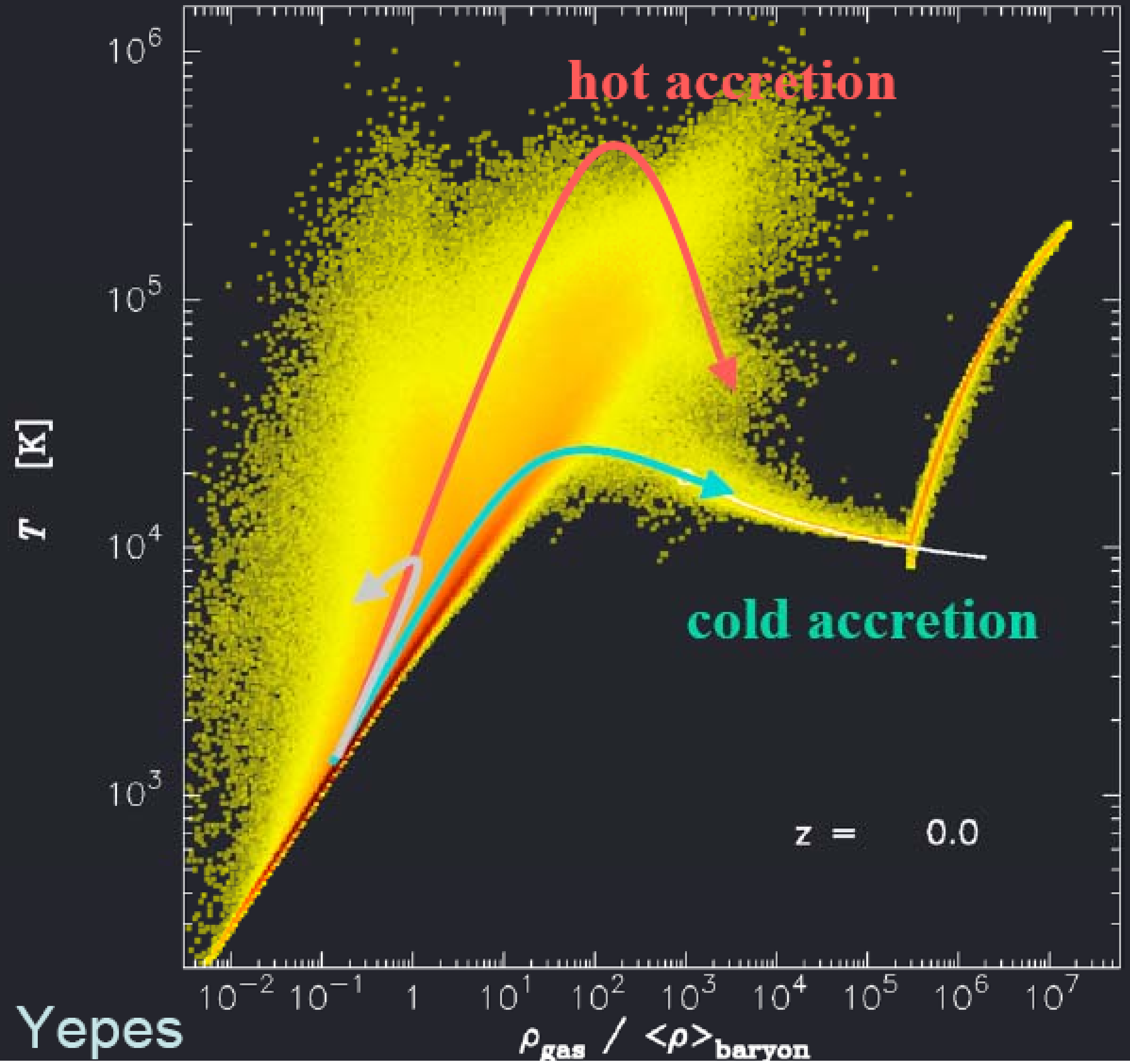
# A: Not Necessarily



Governato et al. (2008)

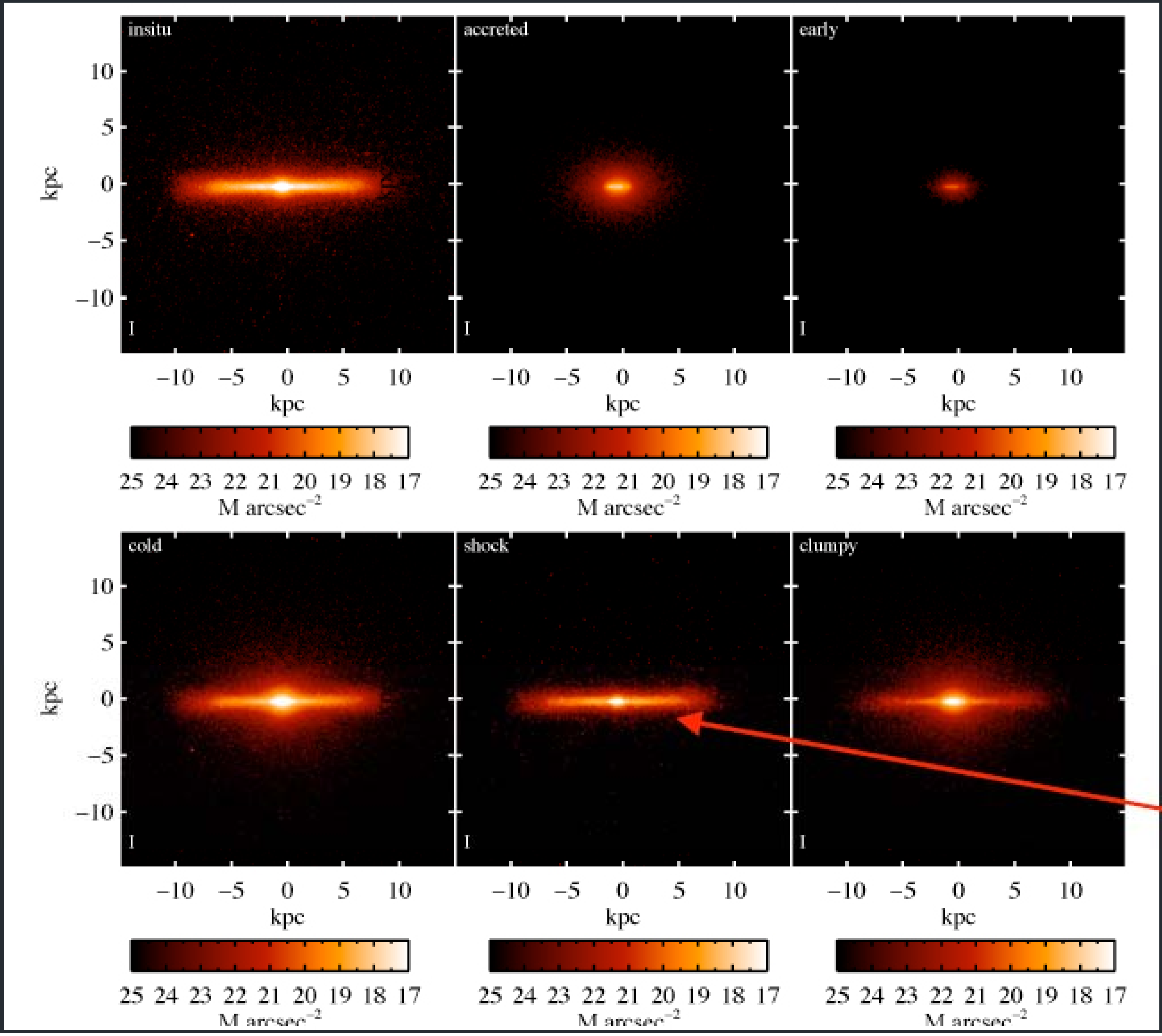
# The New Model of Gas accretion: Cold Flows

**"Cold mode" (Keres et al. 04) of galactic gas accretion: gas creeps along the equilibrium line between heating and Cooling. It never Shocks to Tvir.**



Courtesy of Hoeft & Yepes

# Accretion of different components in L* Galaxies



Stars accreted as stars form part of the bulge. (thick disk faint)

Late accretion forms disks

# Assessment: Disk Galaxy Formation

- Tremendous progress in last 5 years
- Conventional Wisdom is wrong: stellar disks form and reform even after major mergers
  - Primarily from cold flow accretion
  - Secondarily from hot flow accretion
- Models agree quite well now with observations (structure, kinematics, populations)
  - Require quite high resolution and SN feedback implemented in a way that suppresses SF for SNR cooling time
  - Missing satellite problem largely goes away

# Open Issues

- LF of satellite galaxies
- origin of Morphology-Density relation (Dressler)
- resolving bulge formation/evolution
- dynamical erasure of DM cusps

# Lessons Learned from these Two Examples

- “the role of simulation is insight, not numbers” *–Hamming*
- “there is no free lunch at the table of computational physics” *–Norman age 25*
- “…..but, with correct physics, adequate algorithms, and sufficient computer power to resolve the relevant scales, only then may we be in a position to obtain the insights we seek, and learn something new” *–Norman age 55*