Star Formation and "Feedback"

Eve Ostriker
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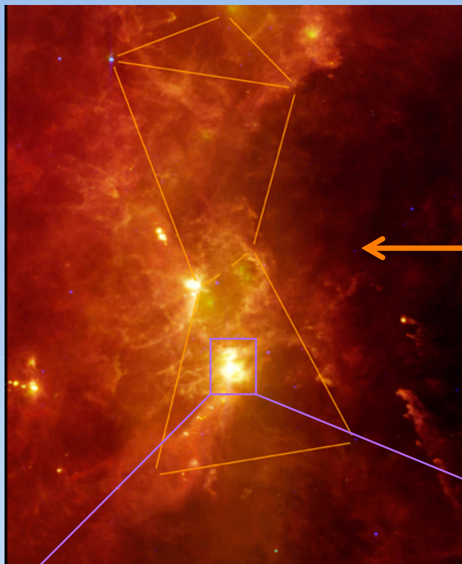
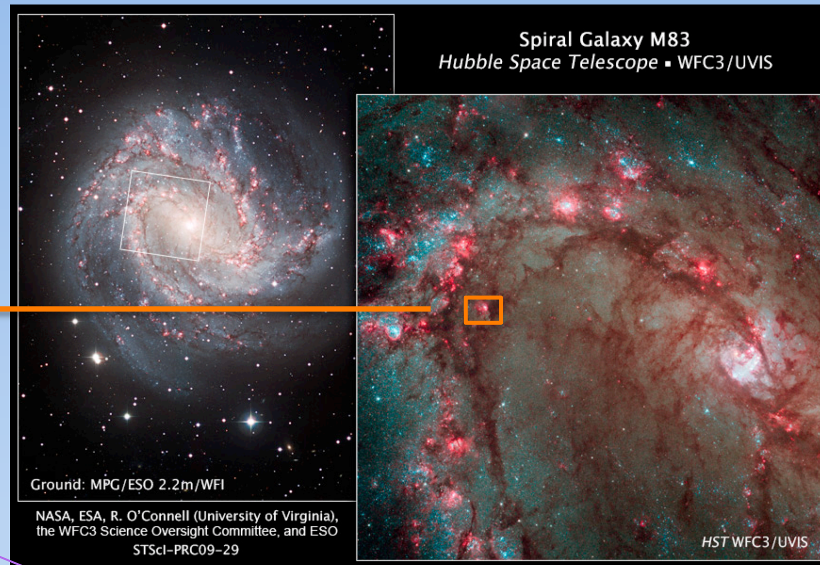
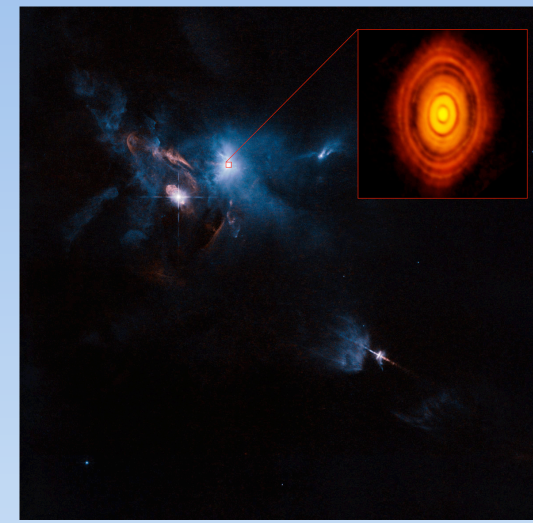
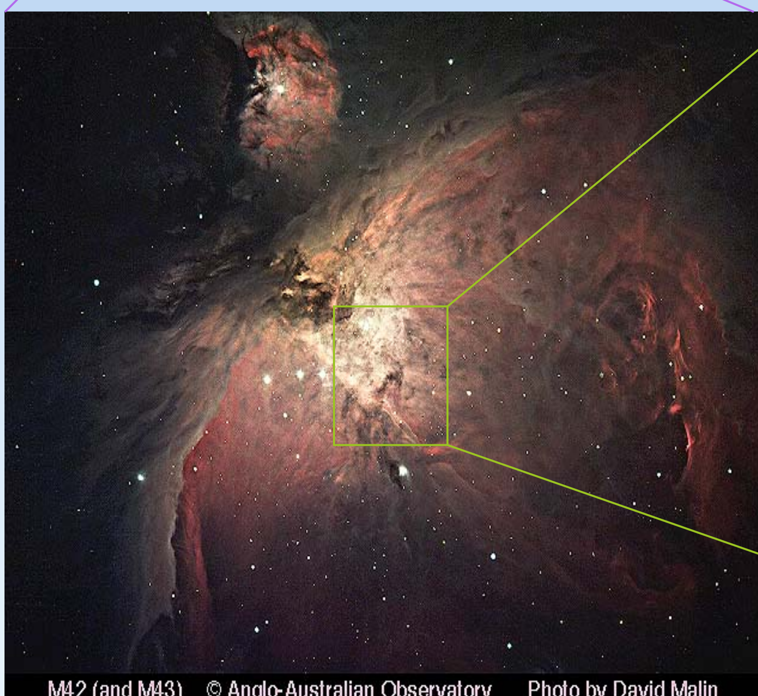
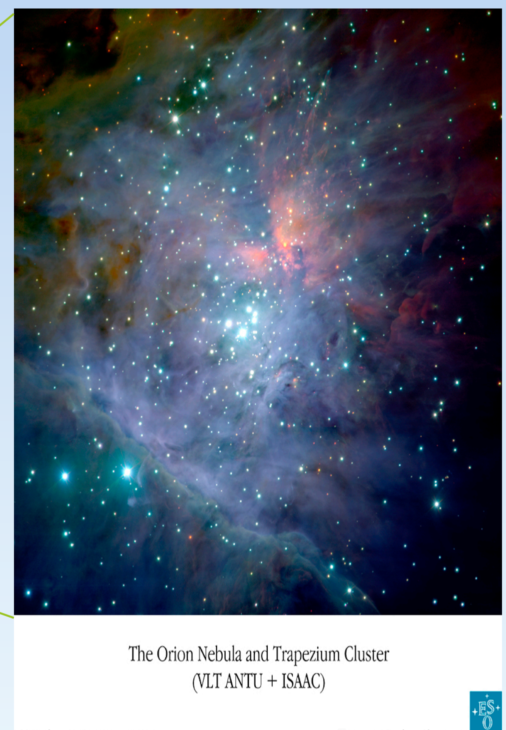


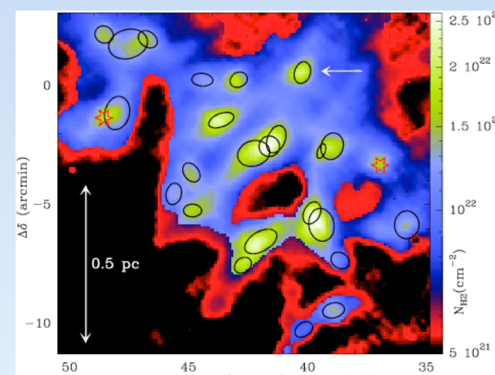




HL Tauri (ALMA/HST)







Könyves et al (2010)

Star formation and the life-cycle of the interstellar medium

- Star formation begins with the condensation of diffuse, turbulent interstellar gas ($\langle n \rangle \sim 1$ cm^{-3}) into giant molecular clouds

  GMC: M~10^4-10^6 $M_\odot$, $\langle n \rangle \sim 100$ cm^{-3}, T ~ 10K

- Supersonic turbulent motions within GMCs create shocks that drives gas to higher density
- Densest regions within filaments in GMCs contract gravitationally to make **prestellar cores**

  core: M~0.1-10 $M_\odot$, n ~ 10^4-10^6 cm^{-3}

Star formation and the life-cycle of the interstellar medium

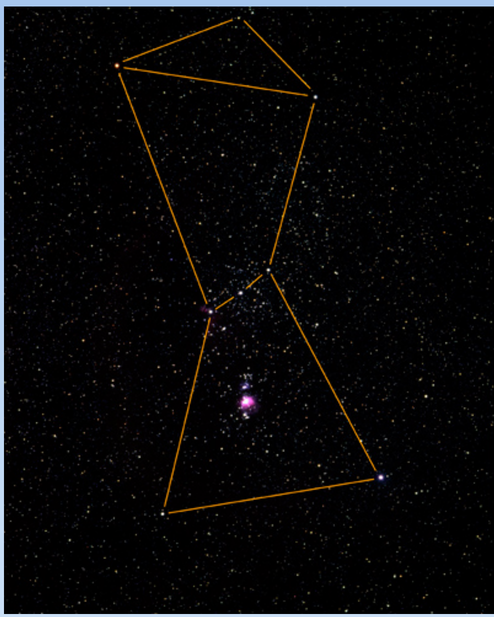
- Prestellar cores collapse to make star ($n \sim 10^{24}$ cm^{-3})/disk system; disks evolve into planets
- Massive stars emit copious radiation (luminosity $L \propto M^{3.5}$), including UV that ionizes and strongly heats ($T \sim 10^4$ K) the near environment
- High-pressure ionized gas rapidly expands
- Momentum carried by stellar FUV radiation directly pushes on the surrounding dusty gas
- Stars with $M > 8M_{\odot}$ end as supernovae; blast wave created by explosion expands into ISM

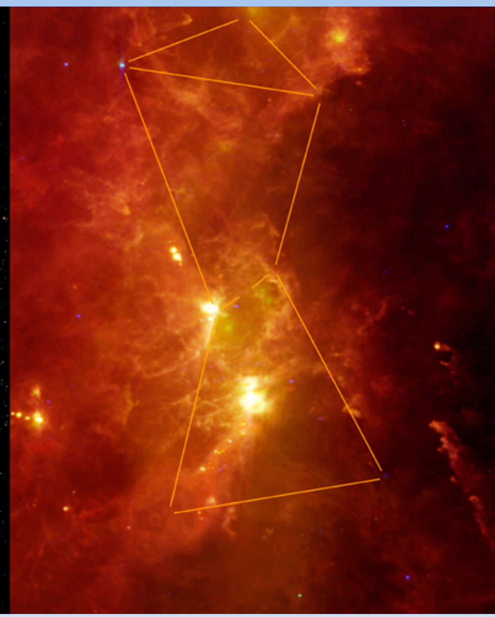
Star formation and the life-cycle of the interstellar medium

- The momentum and energy injected by massive stars disperses GMCs
- "Feedback" from massive stars also heats and stirs up turbulence in the diffuse ISM
- When gravitational energy exceeds kinetic energy locally in the ISM, a new cycle of GMC formation and then star formation begins

1. Formation of stars
   – Roles of turbulence, thermal pressure, magnetic fields
2. Quantifying “feedback”
   – Radiation
   – Supernovae
3. Self-regulated star formation

Orion: optical, IR, radio





GMC Turbulence

- On large scales, GMCs are self-gravitating and have $E_g \sim E_k$

  $GM^2/R \sim M\,\delta v^2$

  $G\Sigma_{gas}^2 \sim \rho\,\delta v^2 >> P_{\text{diffuse ISM}}$
- $\delta v(s) \propto s^{1/2}$ linewidth-size relation inside GMCs is consistent with Burgers spectrum
- Cloud scale:

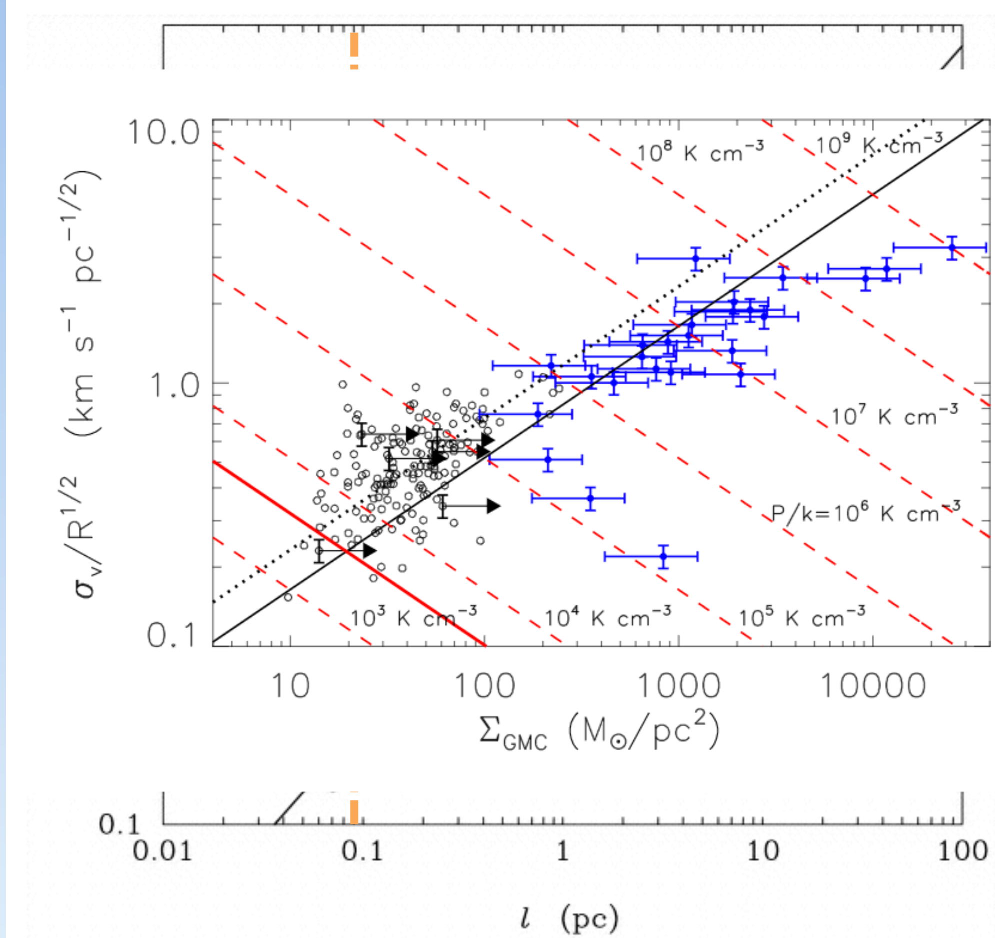
$\delta v^2(R) \sim GM/R \sim G(\Sigma R^2)/R \sim G\Sigma R$

  sub-cloud scales:

  $\delta v(s) \sim (G\Sigma R)^{1/2}(s/R)^{1/2}$
- Sonic scale, where

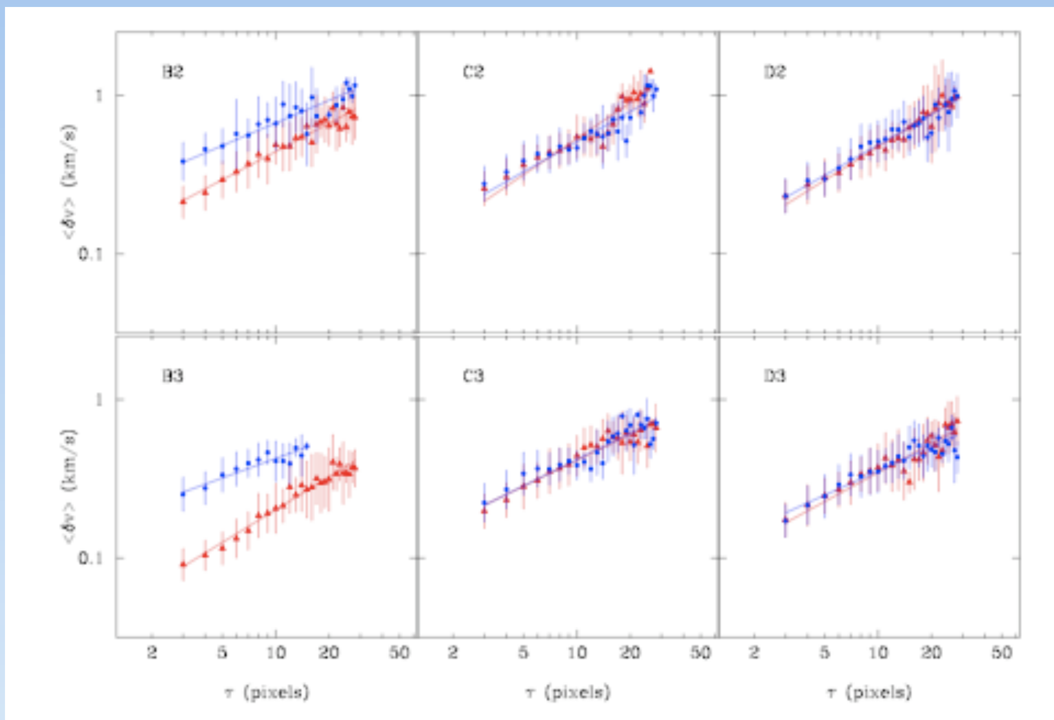
  $\delta v(L_{sonic}) = c_s = 0.2$ km s^{-1}

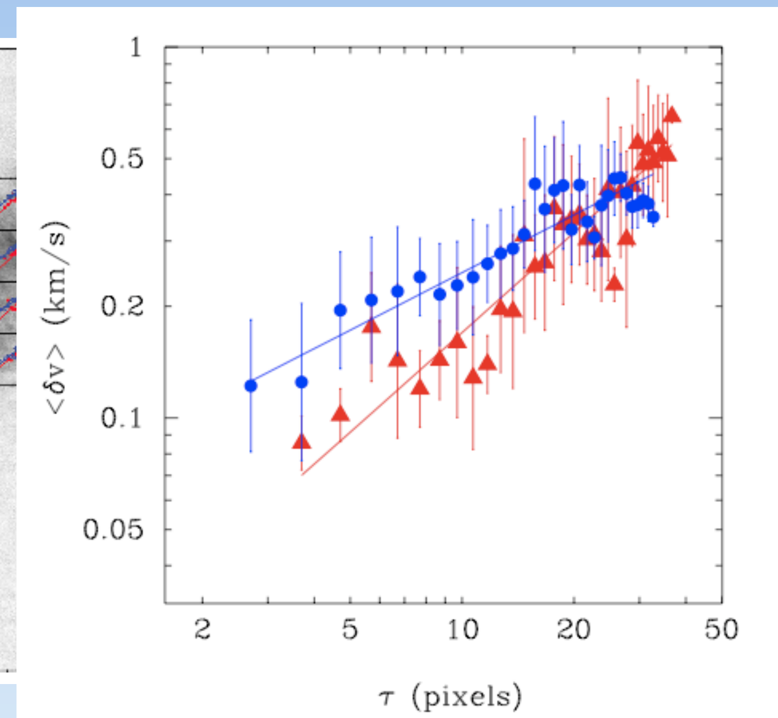
  is $L_{sonic} \sim 0.1$ pc
- Simulations reproduce observed velocity scalings, anisotropy



Heyer & Brunt (2004)

$$\sigma_v = 0.7(\Sigma_{GMC}/100 M_\odot\,\text{pc}^{-2})^{1/2}(\text{R}/1\,\text{pc})^{1/2}\,\text{km s}^{-1}$$





Velocity vs. size scale (synthetic CO observation based on simulations)

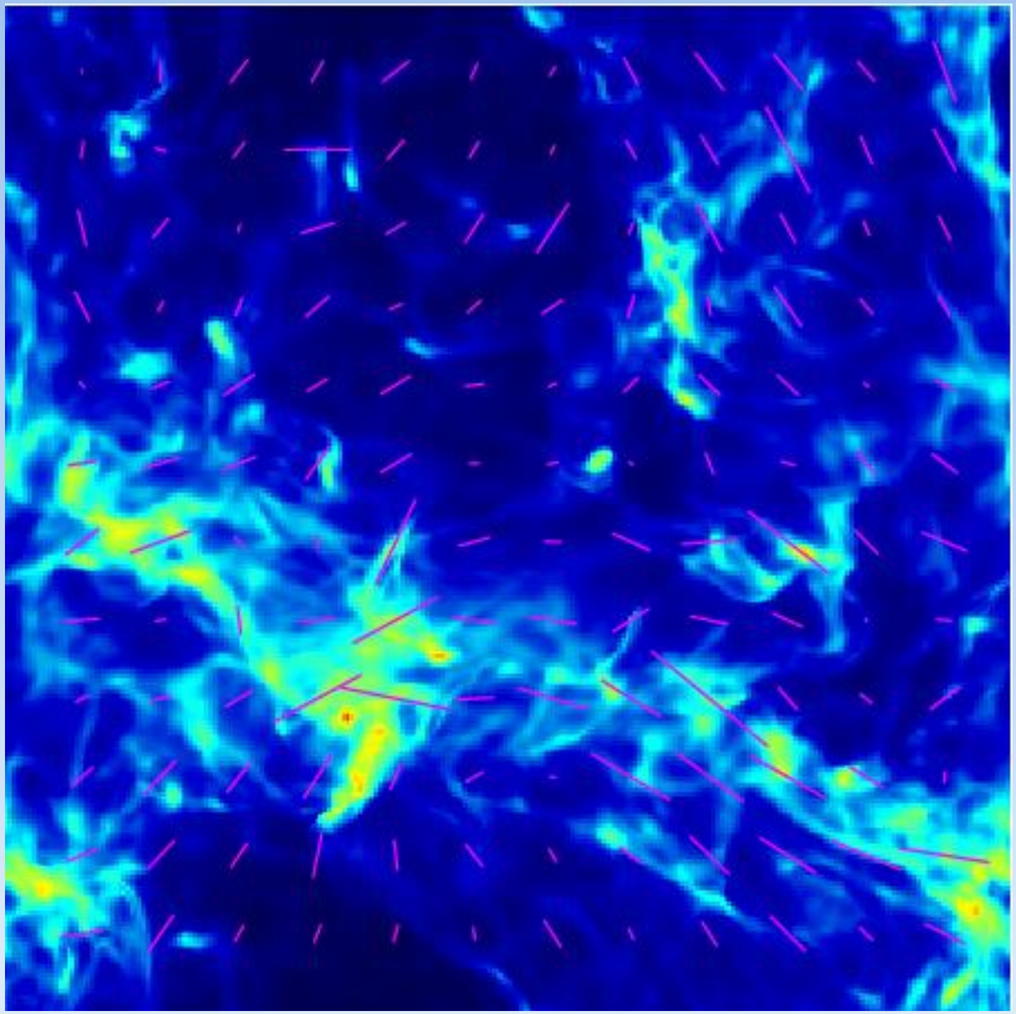
Velocity vs. size scale (CO observation in Taurus)

Heyer et al (2008); Heyer & Brunt (2012)

Turbulence and density structure

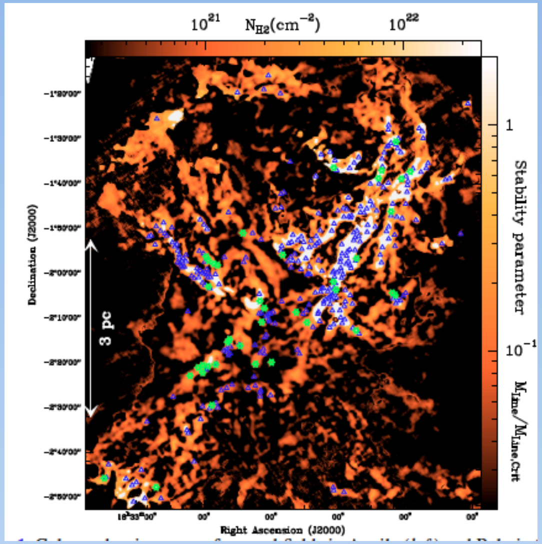
- Because compression is due to turbulence, and largest-scale velocities dominate the turbulence

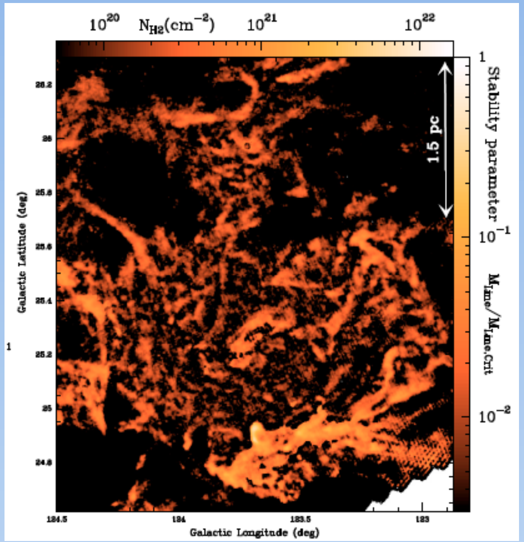
  ⇒ the largest scales also dominate the density structure
- This has important consequence that star formation lies along **filaments** and is **clustered**



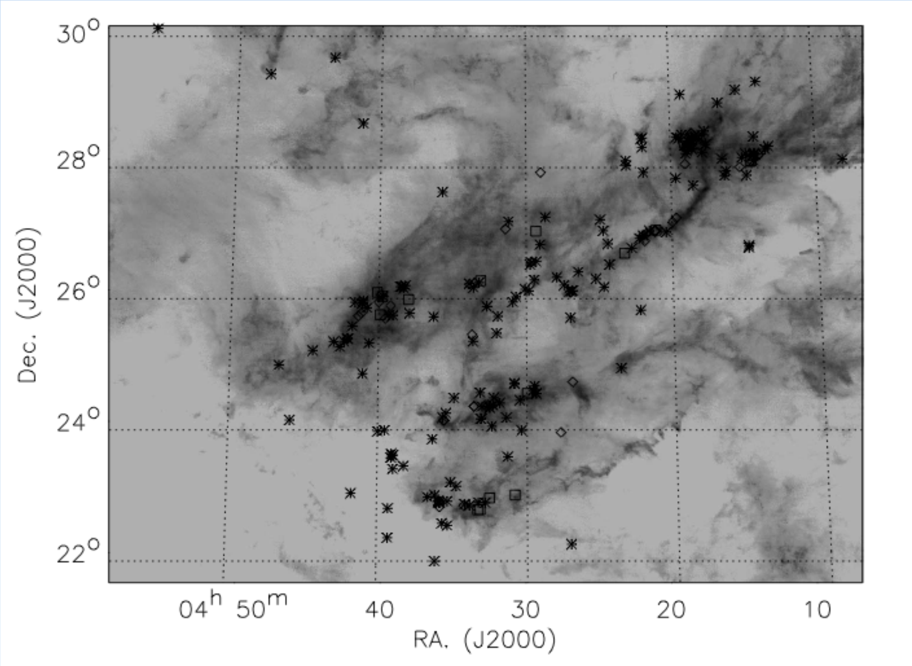
Ostriker, Stone & Gammie (2001)

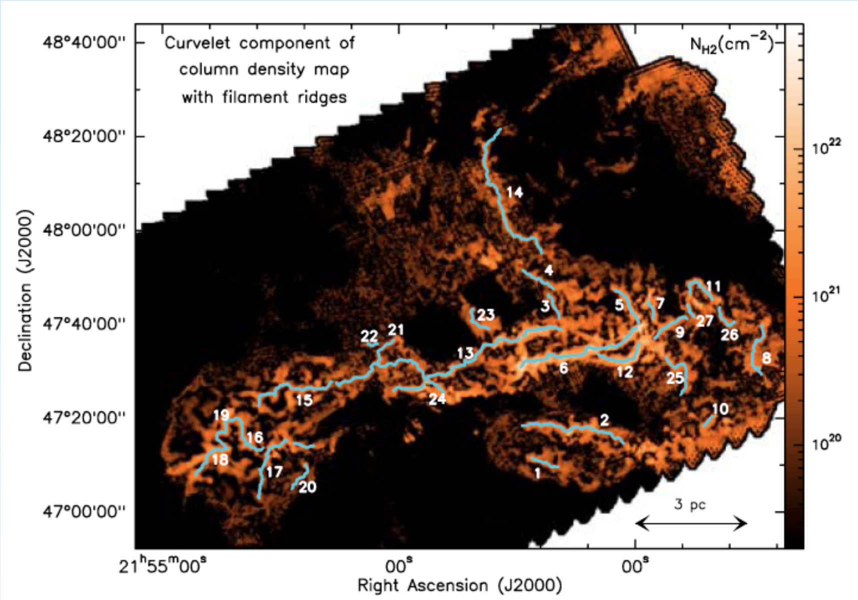
Filaments in molecular clouds





Herschel: Aquila; Polaris Flare (Andre et al 2010)

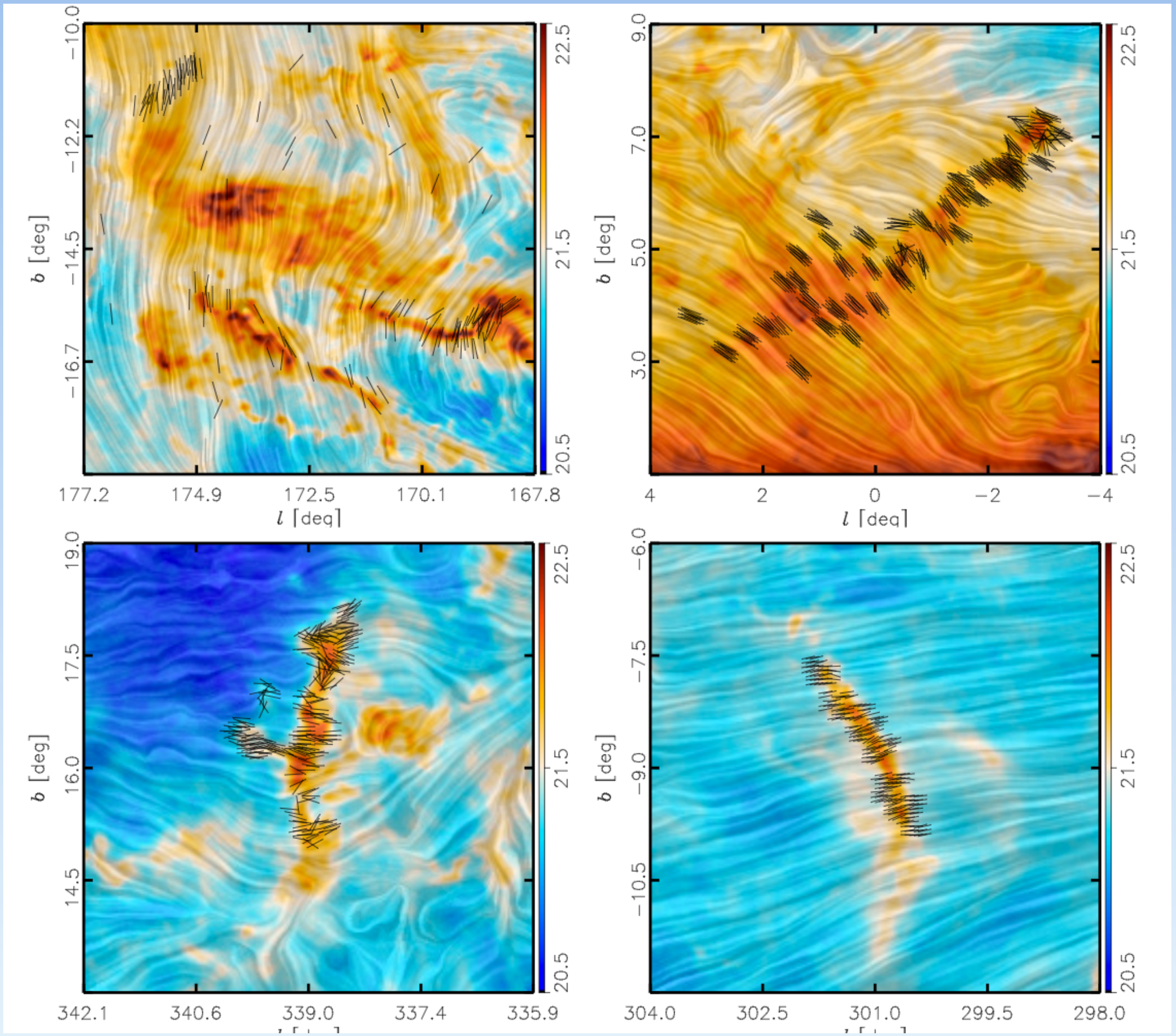




Herschel: IC 5146 (Arzoumanian et at 2011)

CO: Taurus cloud (Goldsmith et al 2008)

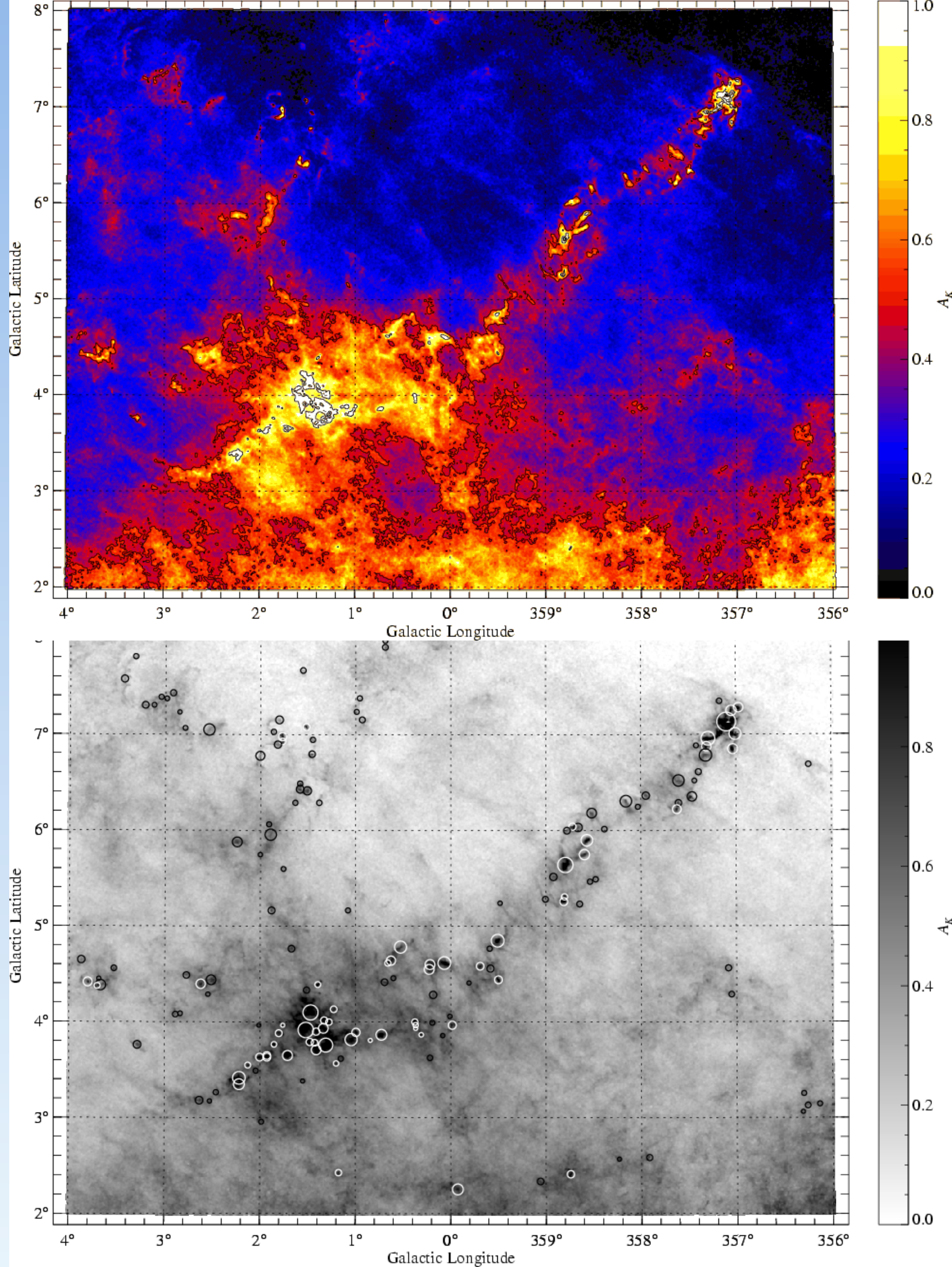
Magnetic Field from Polarization



Soler et al (2016)

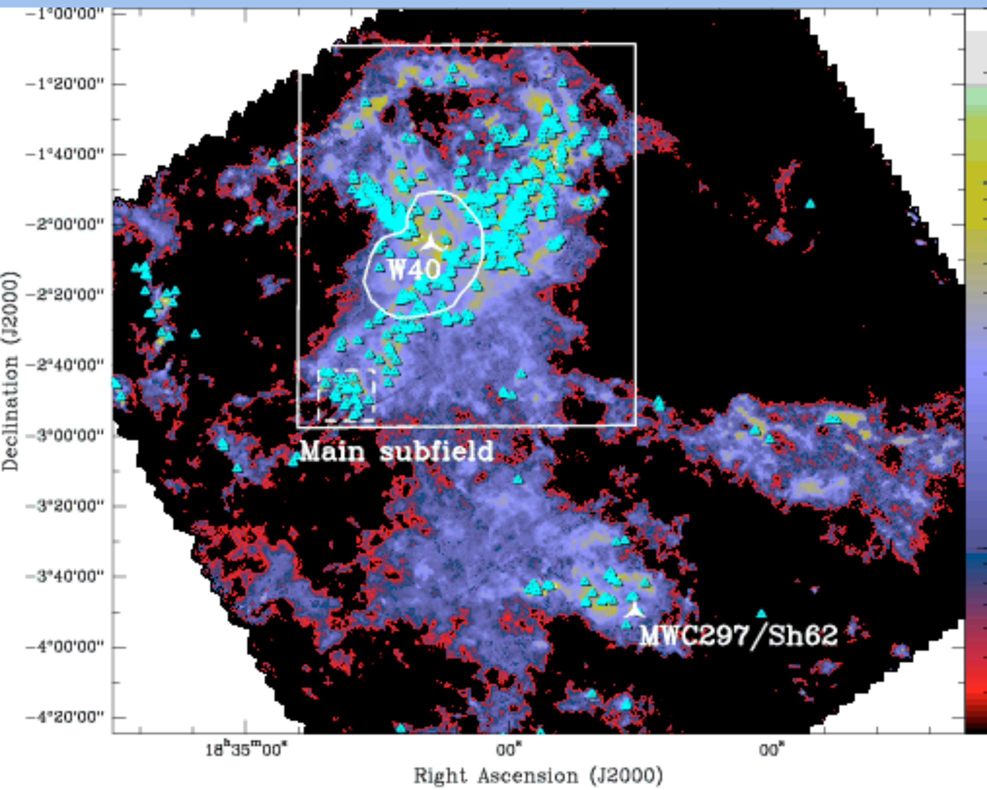
Molecular cores

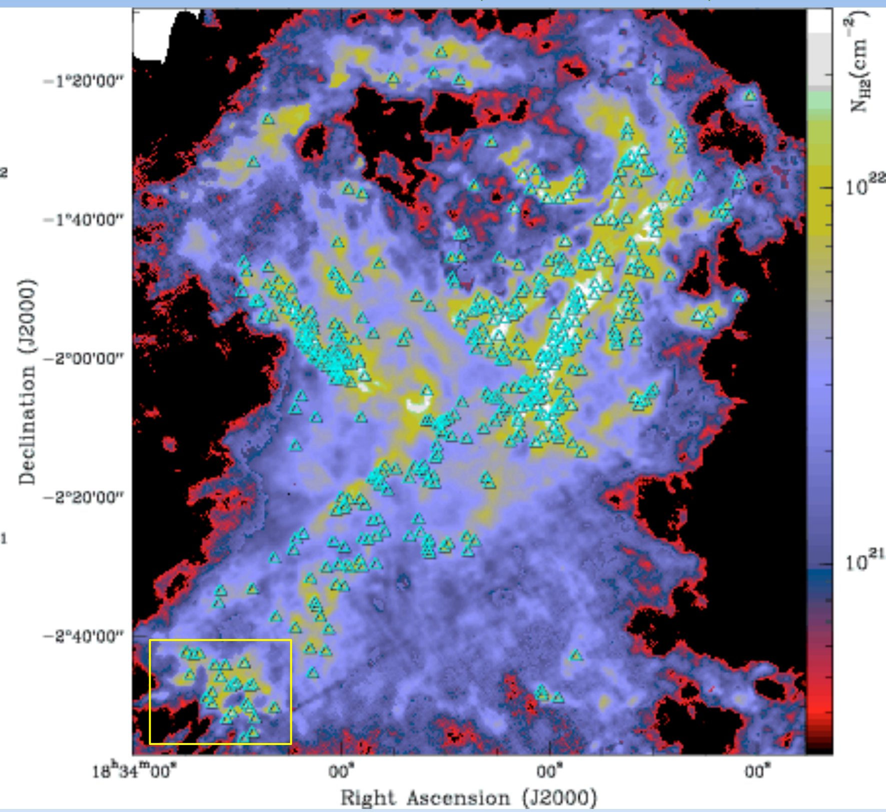
- Molecular cores ($n>10^4$ cm^{-3}) are identified and observed using dense molecular tracers (NH_3, CS, $C^{18}O$, etc), mm, sub-mm, far-IR continuum, and extinction mapping



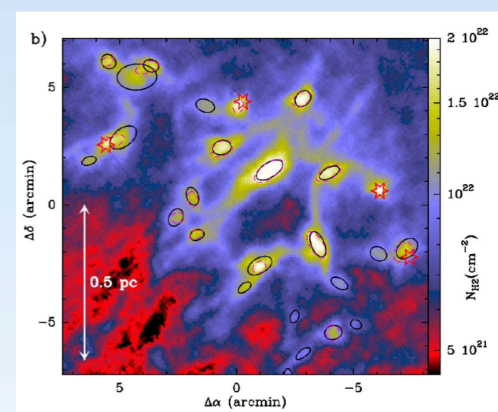
Pipe nebula extinction map and cores (Alves et al 2007)

Prestellar Core Mass Function (CMF)

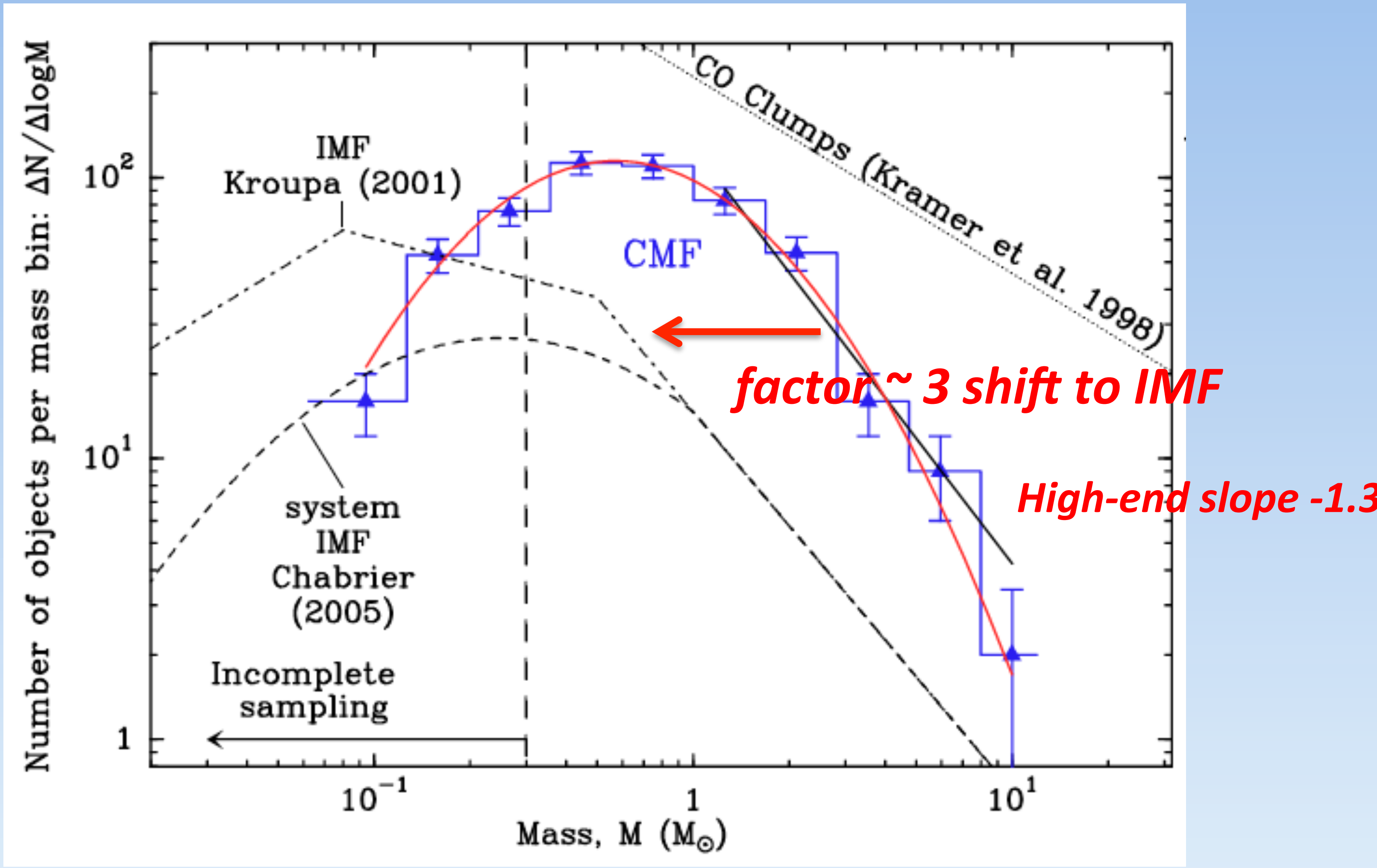




Konyves et al (2010): Aquila cloud map with core positions from *Herschel* Gould Belt survey



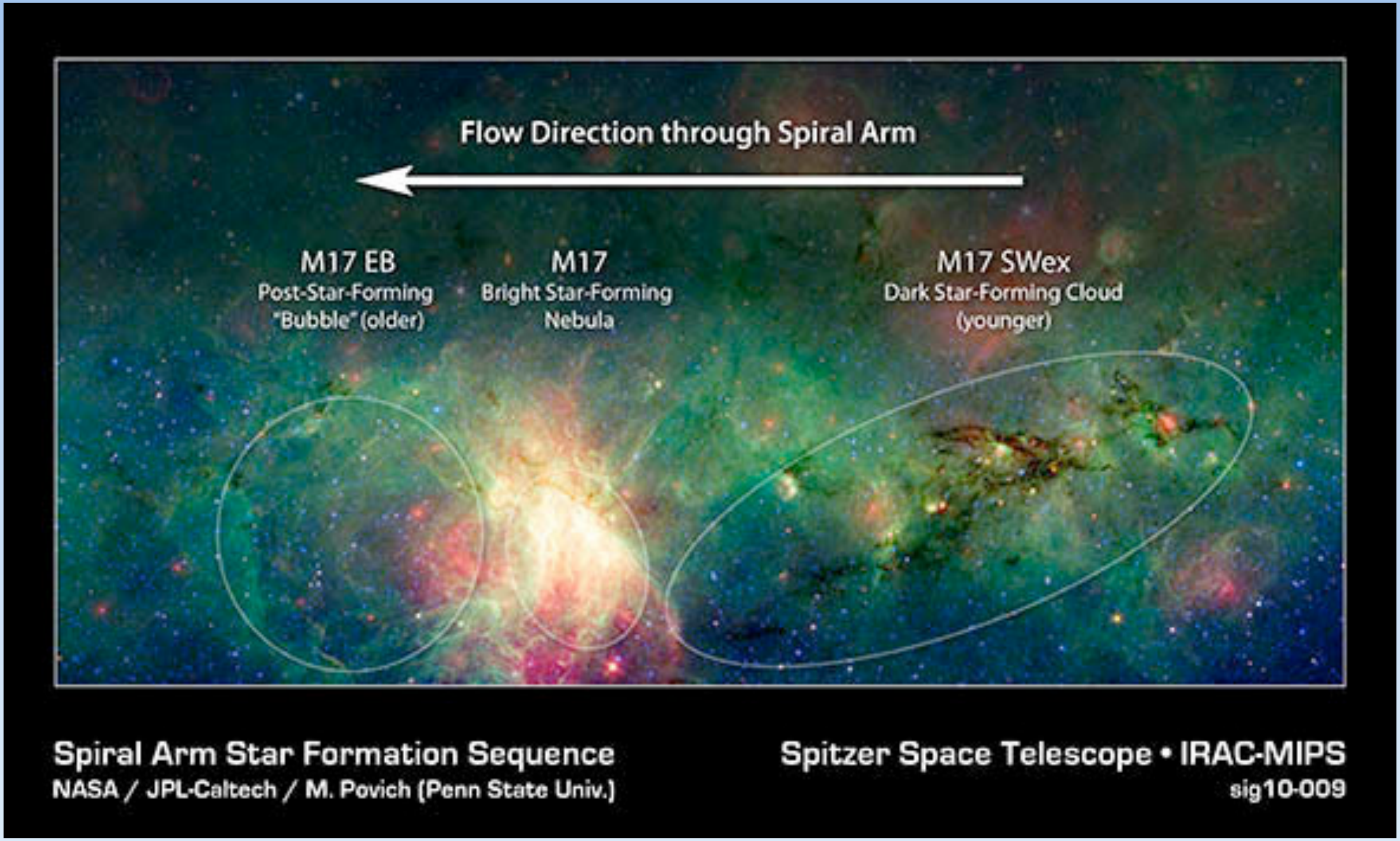
Prestellar Core Mass Function (CMF)

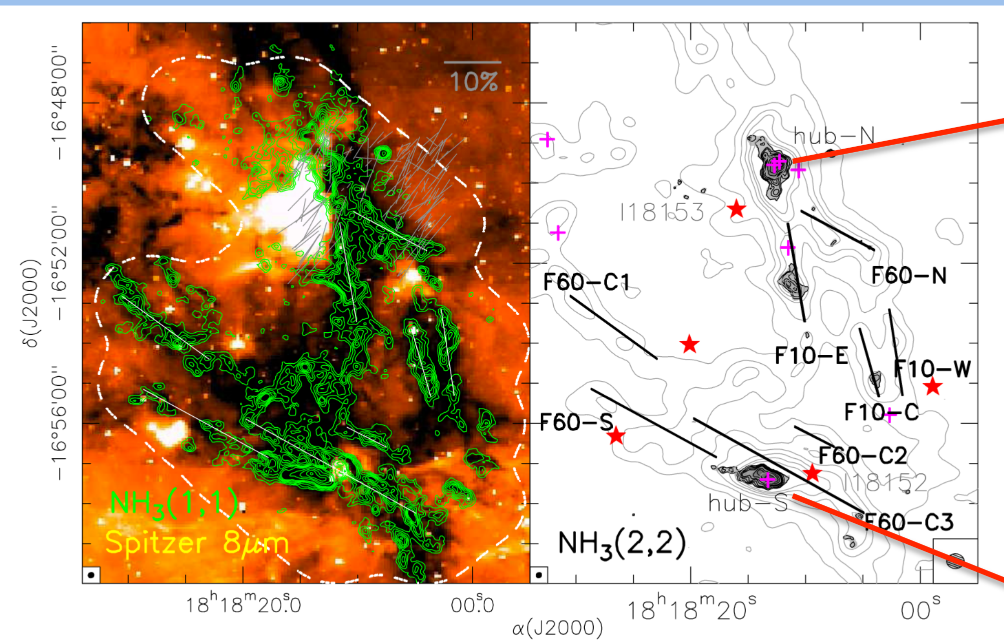


Konyves et al (2010): CMF in Aquila from *Herschel*

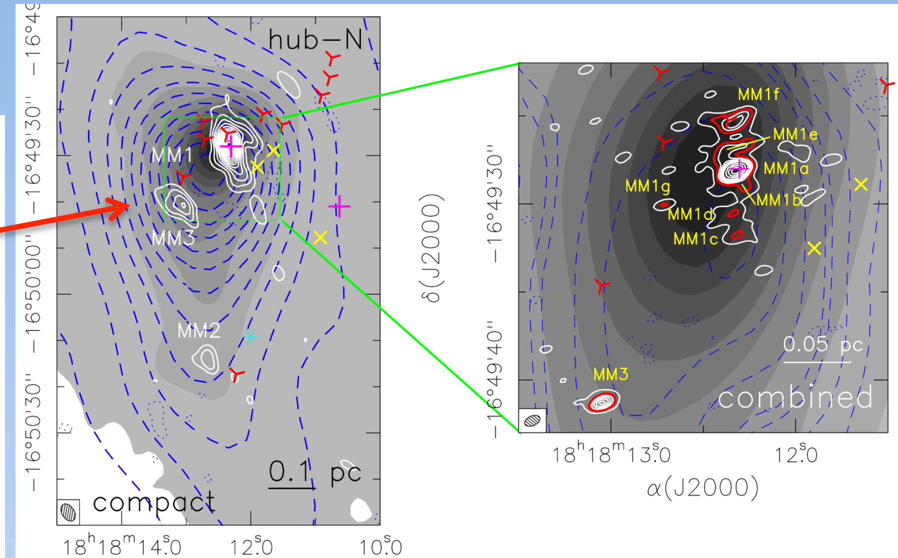
See also.: Motte et al (1998), Testi & Sargent (1998), Johnstone et al (2000), Onishi et al (2002), Enoch et al (2006), Alves et al (2007), Nutter & Ward-Thompson (2007)

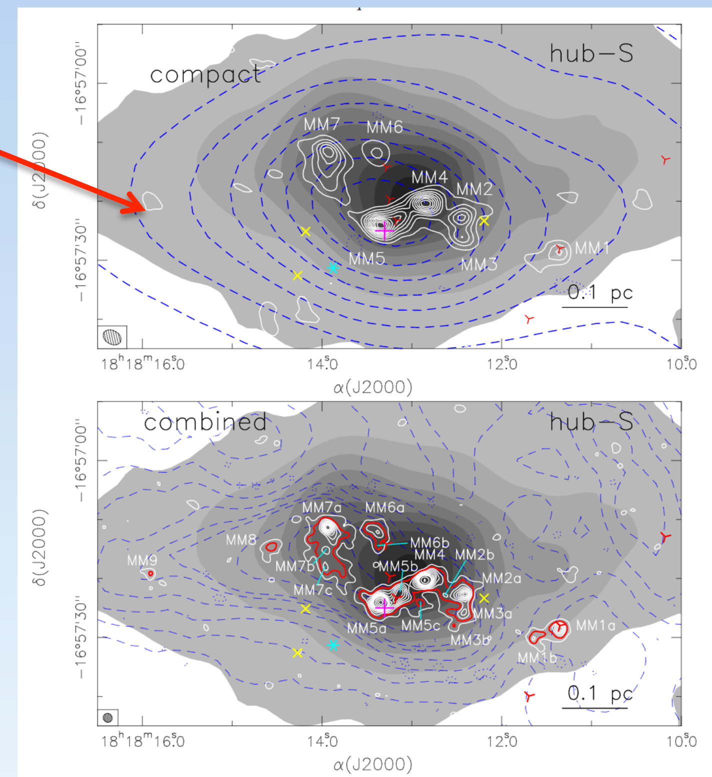
IRDCs


Flow Direction through Spiral Arm
M17 EB
Post-Star-Forming
"Bubble" (older)
M17
Bright Star-Forming
Nebula
M17 SWex
Dark Star-Forming Cloud
(younger)
Spiral Arm Star Formation Sequence
NASA / JPL-Caltech / M. Povich (Penn State Univ.)
Spitzer Space Telescope • IRAC-MIPS
sig10-009



Busquet et al (2013)





- “Hubs” at high resolution break into cores with M ~ M_J

Busquet et al (2016)

Prestellar core properties

- High density: $n \gtrsim 10^4$ cm^{-3}
- Centrally concentrated; consistent with isothermal equilibrium "Bonnor Ebert" sphere

  (Ward-Thompson et al 1994, Evans et al 2001, Caselli et al 2002, Lada et al 2003, Tafalla et al 2004, Kirk et al 2005, Kandori et al 2005)

- Subsonic internal turbulent velocity

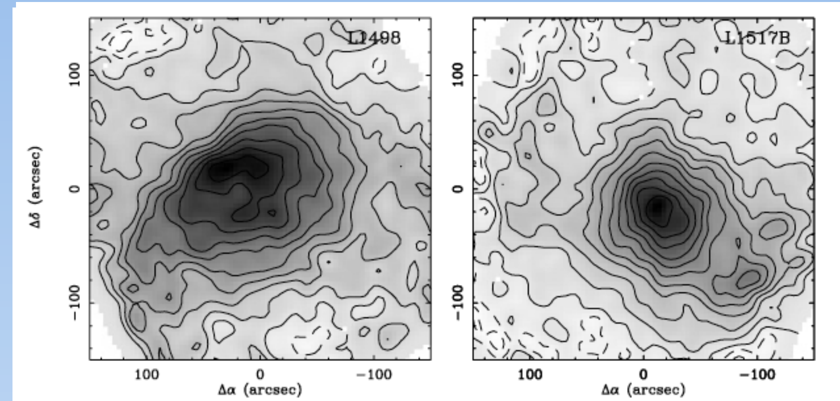
  (Myers 1983; Goodman et al. 1998; Kirk et al.2007; Andre et al 2007; Lada et al. 2008)

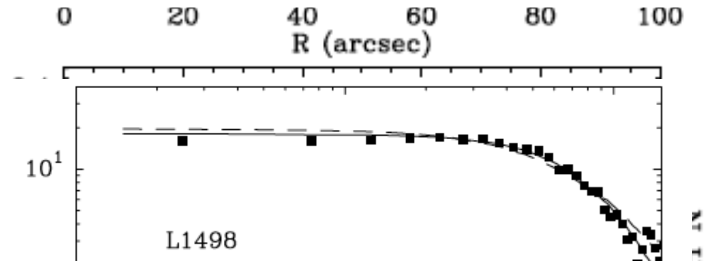
- Duration of prestellar phase
  ~ few× gravitational free-fall time

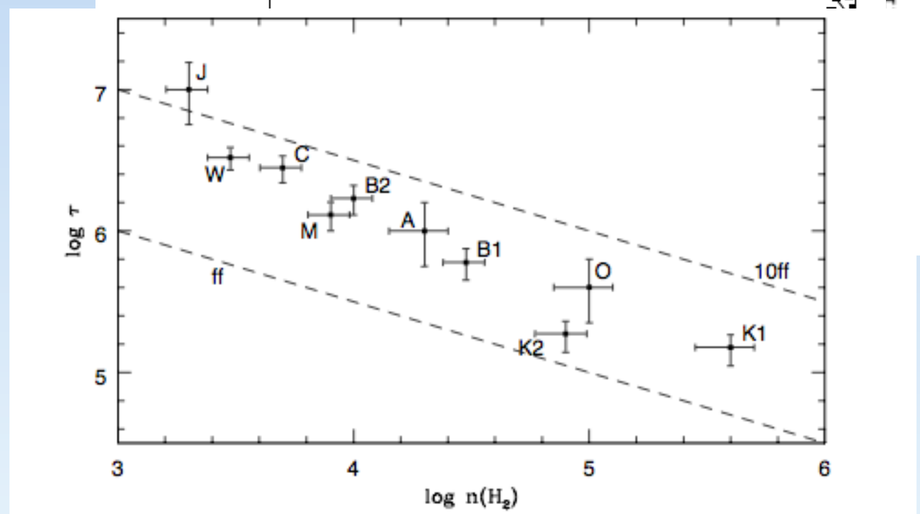
$$t_{ff} \equiv \left(\frac{3\pi}{32G\rho}\right)^{1/2} = 1.4 \times 10^5 \mathrm{yr} \left(\frac{n_H}{10^5 \mathrm{cm}^{-3}}\right)^{-1/2}$$

~ embedded protostellar lifetime

(Hatchell et al 2007, Ward-Thompson et al 2007, Enoch et al 2008, Evans et al 2009)







Ward-Thompson et al (2007)

Classical theory: isothermal spheres

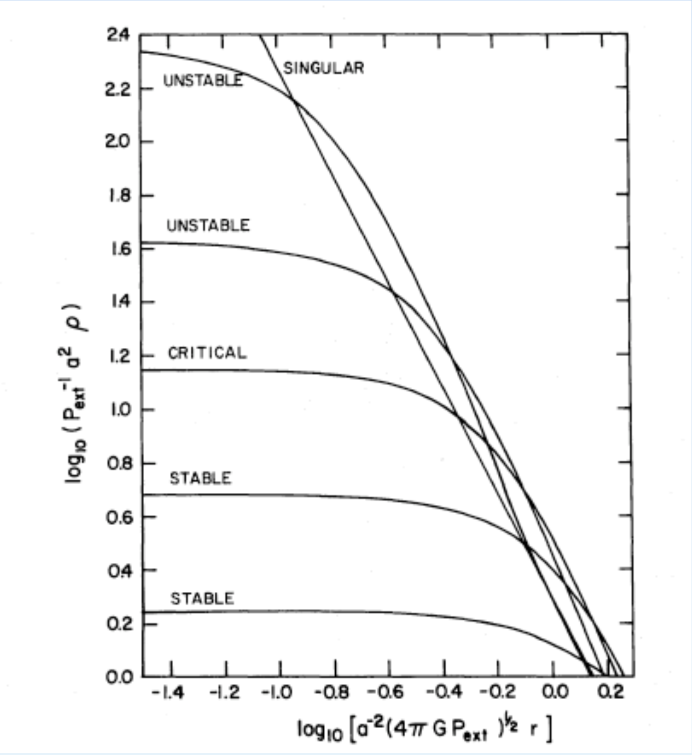
- Maximum spherical mass that can be supported by thermal pressure at a given temperature and external pressure is the critical Bonnor-Ebert mass (Bonnor 1956, Ebert 1955):

$$M_{BE} = 1.2\frac{\mathrm{v}_{\mathrm{th}}^4}{\left(G^3 P_{edge}\right)^{1/2}} = 1.2\frac{\mathrm{v}_{\mathrm{th}}^3}{\left(G^3 \rho_{edge}\right)^{1/2}} = 1.5 M_\odot \frac{\left(T/10K\right)^{3/2}}{\left(n_{edge}/10^4\,cm^{-3}\right)^{1/2}}$$

- More centrally-concentrated spheres are unstable, less concentrated spheres are stable

For critical BE sphere

- $\rho_c = 14\rho_{edge}$
- $\langle\rho\rangle = 2.5\rho_{edge}$
- $R = 0.4\ GM/\mathrm{v}_{\mathrm{th}}^2$



Shu (1977)

Critical BE mass =

- 1/4.7 × Jeans mass at edge P and T
- 1/3 × Jeans mass at average P and T

Exercise

- Integrate ODE to obtain solution to

$$\frac{1}{\xi^2} d_\xi [\xi^2 d_\xi \ln(\rho/\rho_0)] = -\frac{\rho}{\rho_0}$$

where $\xi = r\,(4\pi G\rho_0)^{1/2}/v_{th}$ for ρ_0 the central density of isothermal sphere with pressure $P(r) = v_{th}^2\,\rho(r)$.

- Each ξ corresponds to a ratio $\rho(\xi)/\rho_0 = P_{edge}/P_0$
- Mass within ξ is

$$M(\xi) = \frac{4\pi v_{th}^4}{(4\pi G)^{3/2} P_{\rm edge}^{1/2}} \left(\frac{\rho(\xi)}{\rho_0}\right)^{1/2} \int^{\xi} d\xi' \xi'^2 \rho(\xi')/\rho_0$$

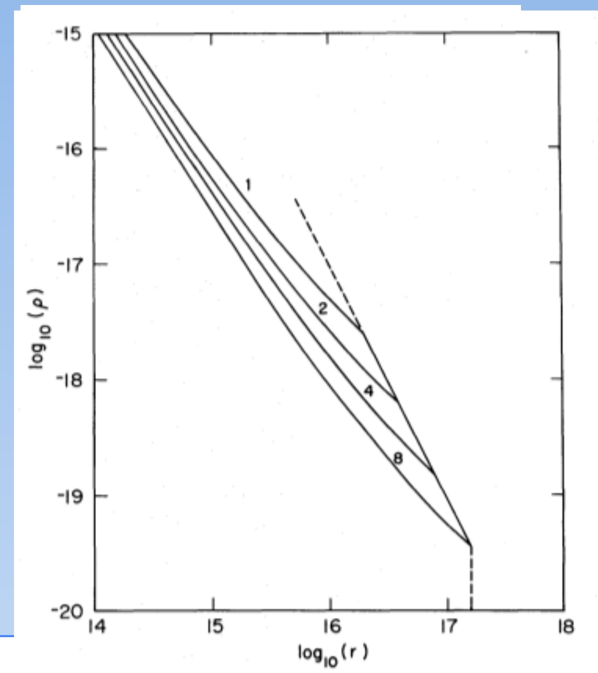
- Show that $\xi = 6.5$, $\rho(\xi)/\rho_0 = 14$ yields the maximum mass for a given external pressure P_{edge}. Show that this $M(\xi) = M_{BE,crit}$.

Core collapse

- Collapse of initial unstable static core is "outside-in" (Larson 1969, Penston 1969) followed by "inside-out" (Shu 1977, Hunter 1977)
- Inside initially has low velocity; wave of collapse starts in outer core and redistributes mass to attain singular profile:

$$\rho_{\rm LP} = 8.9 \frac{c_s^4}{4\pi G r^2}$$

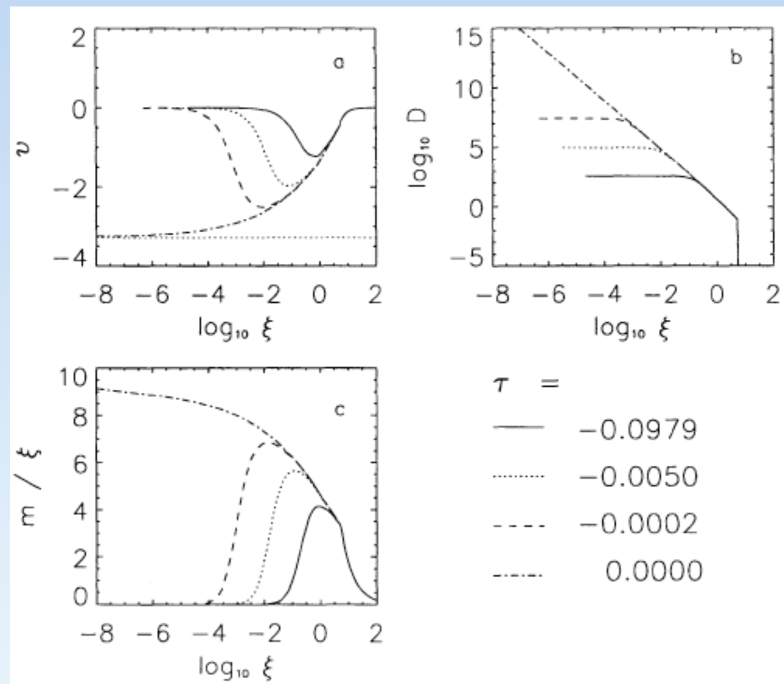
- After central density $\rightarrow\infty$, rarefaction starts to propagate outward from the center as gas accretes onto the protostar: $t_{\rm infall}(r) \propto \rho^{-1/2} \propto r$
- In infalling region, $v \propto r^{-1/2}$, $\rho \propto r^{-3/2}$



Shu (1977): self-similar expanding rarefaction wave

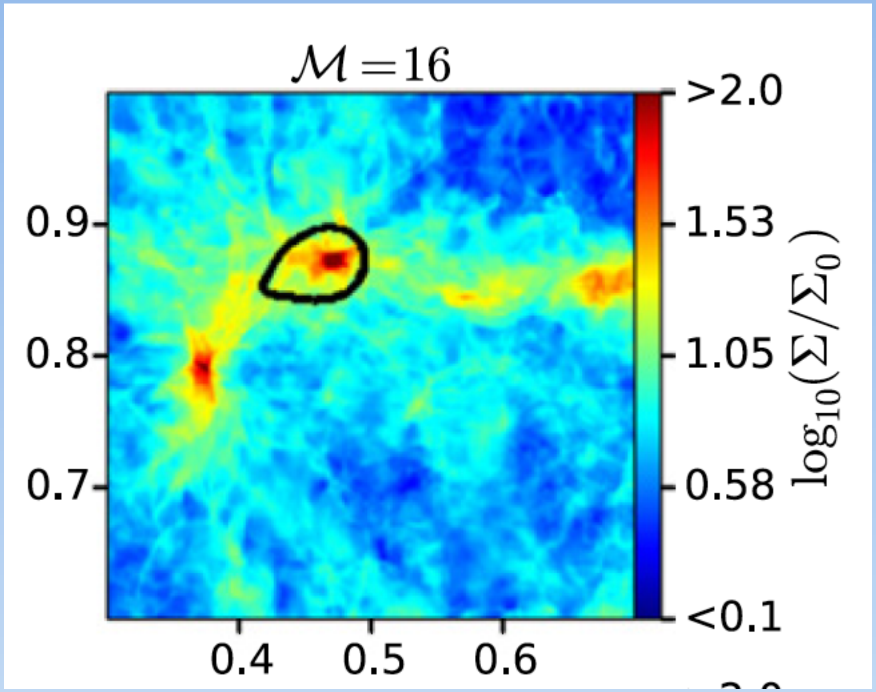
son (1969):
form initial
ere; approaches
f-similar sol'n

$$\eta = 8{\cdot}86x^{-2}.$$

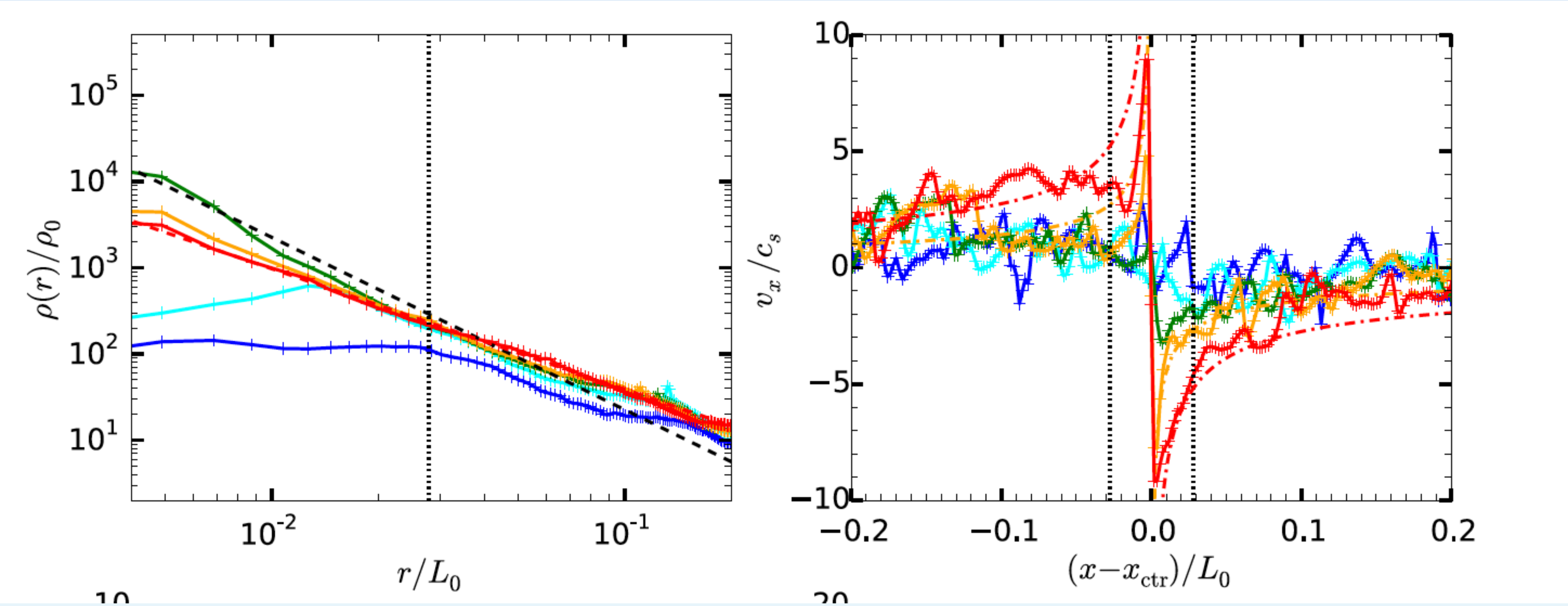


Foster & Chevalier (1993): near-critical initial sphere

Core collapse in simulations



Gong & Ostriker (2015)



Gravitational collapse: sink particle

- Singular density profile implies collapse become *unresolved*
- Numerical approach: introduce a "sink particle"
- Various different criteria and implementations

Bate et al 1995, Krumholz et al 2004, Federrath et al 2010, Wang et al 2010, Teyssier et al 2011, Gong & Ostriker 2013

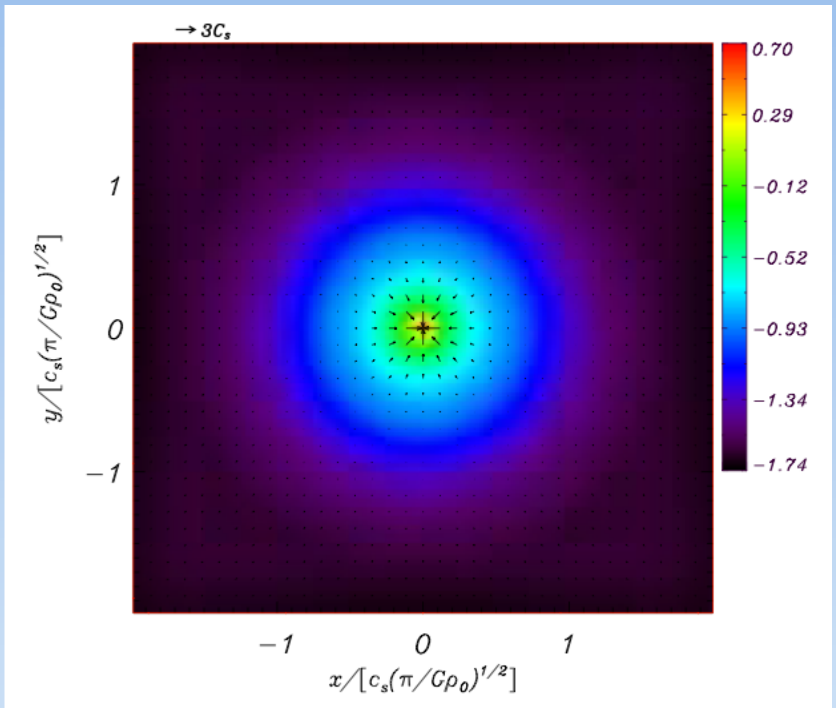
EG: density threshold

Truelove (1997): $\rho_{Tr} = \frac{\pi}{16} \frac{c_s^2}{G \Delta x^2}$ GO13: $\rho_{LP} = \frac{8.86}{\pi} \frac{c_s^2}{G \Delta x^2}$

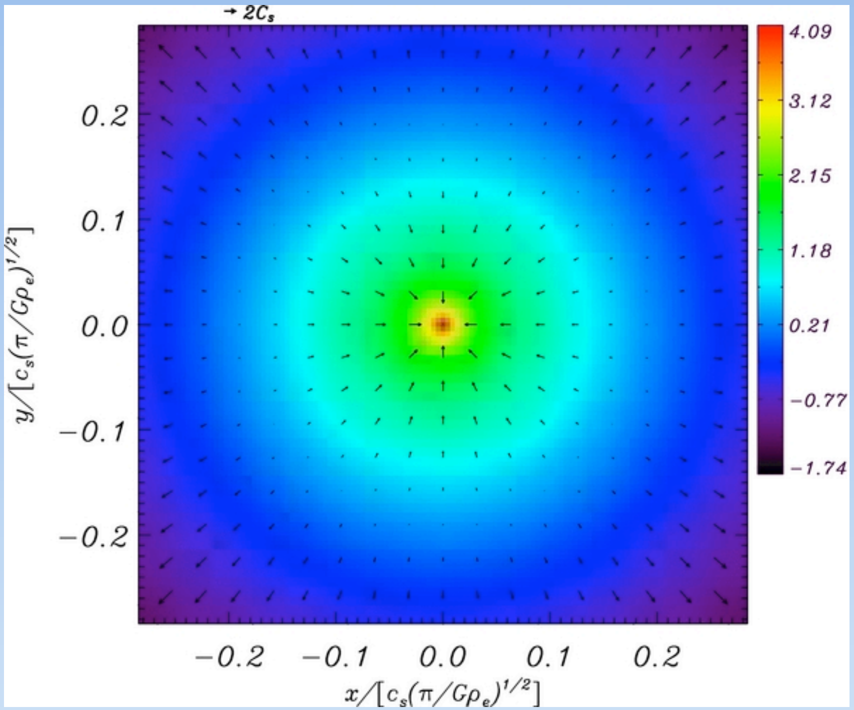
+ potential minimum, + converging flow

- Sink **x**(t), **v**(t) integrated as particle under gravity; mass grows by accretion
- Resolution must be high enough that inflow is *supersonic*
- Useful code test: Shu (1977) expansion wave sol'n

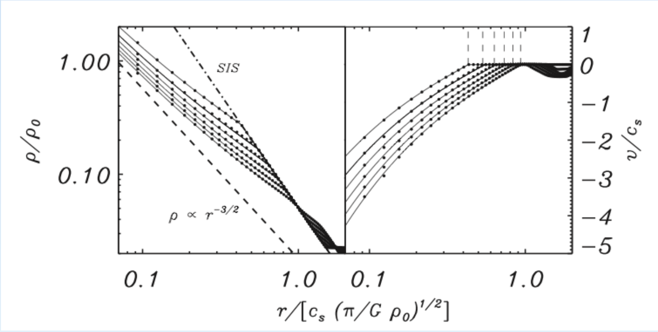
Sink particles in *Athena*

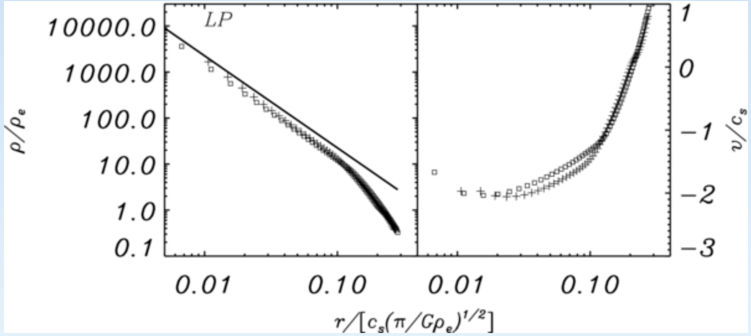


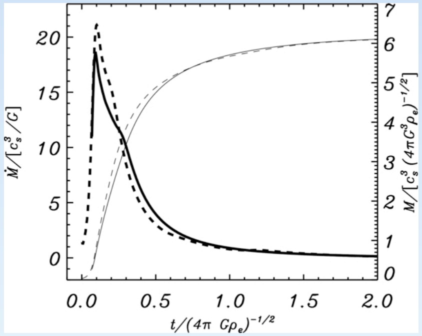
Collapse of singular isothermal sphere



Collapse of unstable BE sphere

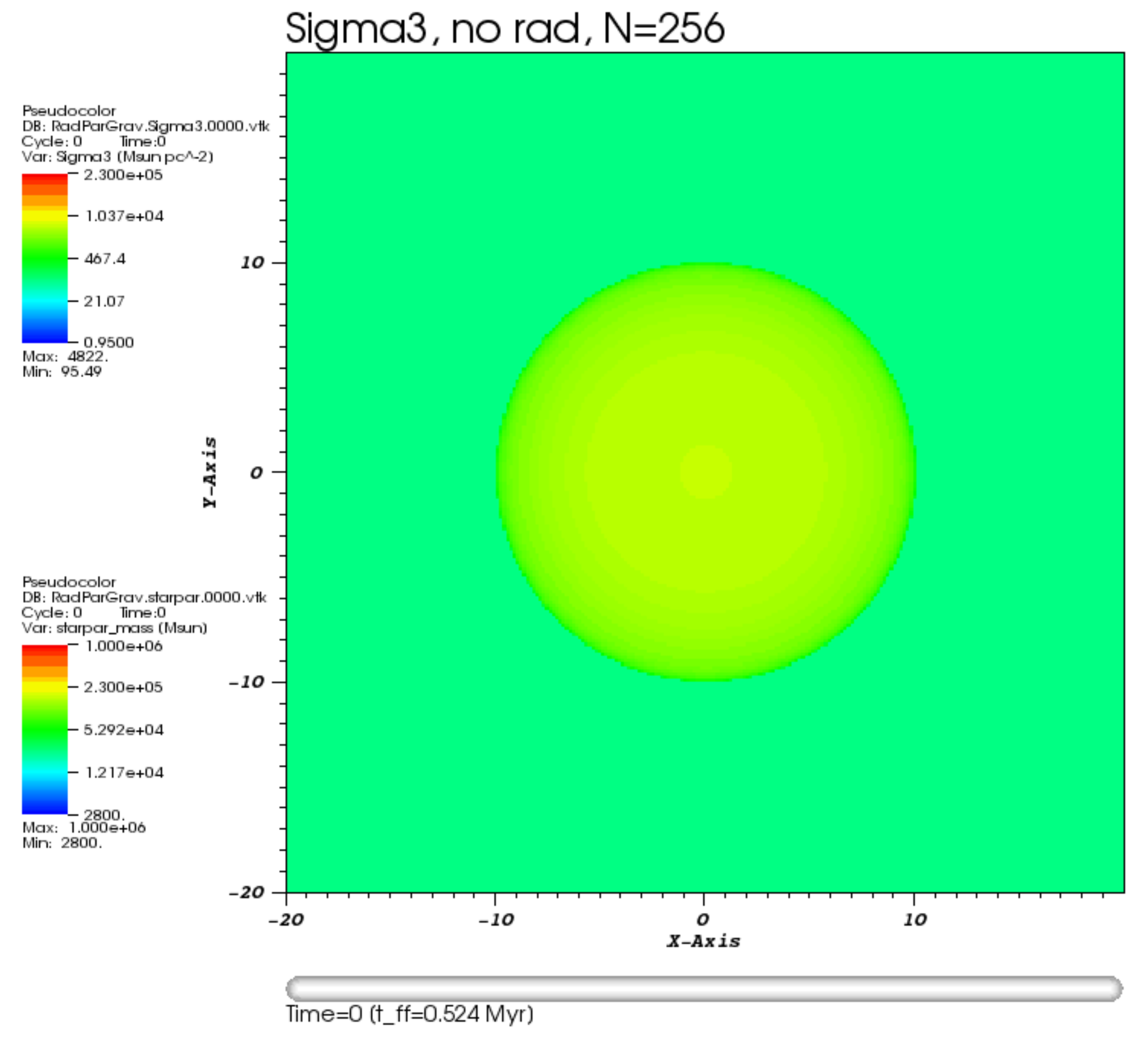






Gong & Ostriker (2013)

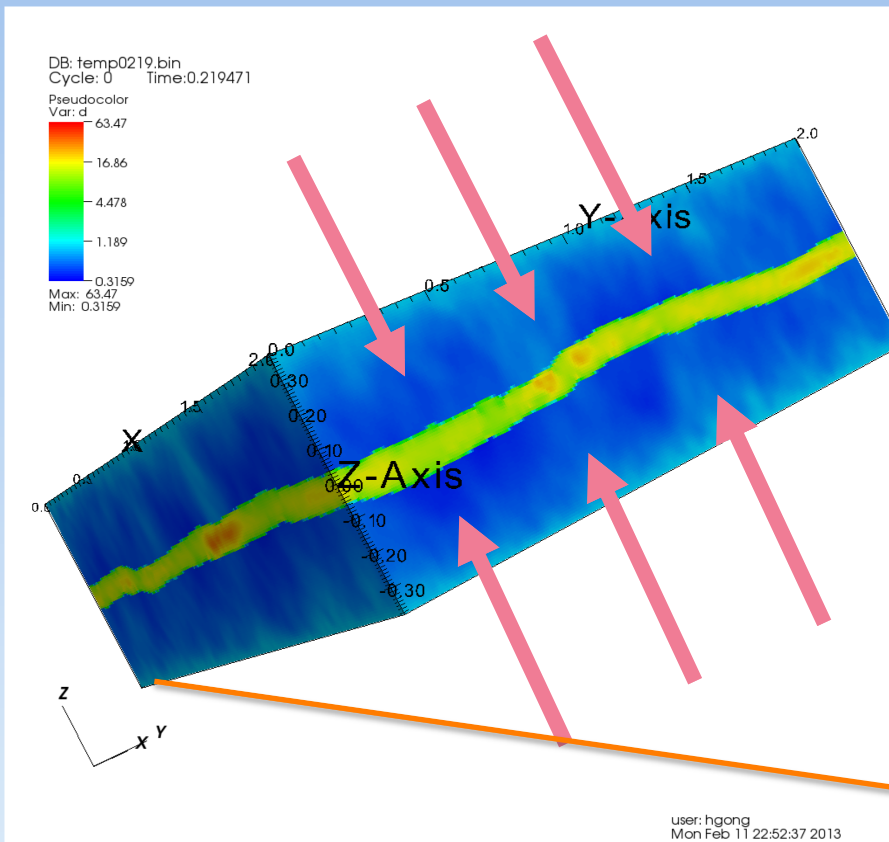
Global cloud with sinks



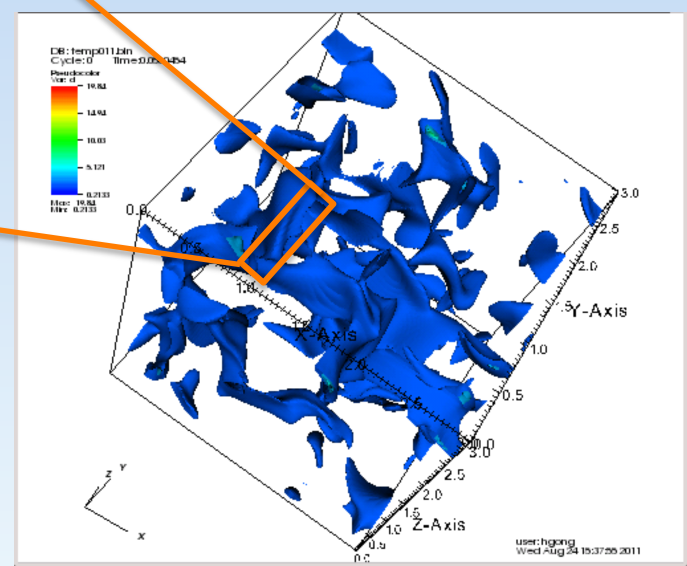
Skinner & Ostriker (2015)

$10^6 M_\odot$ initial cloud

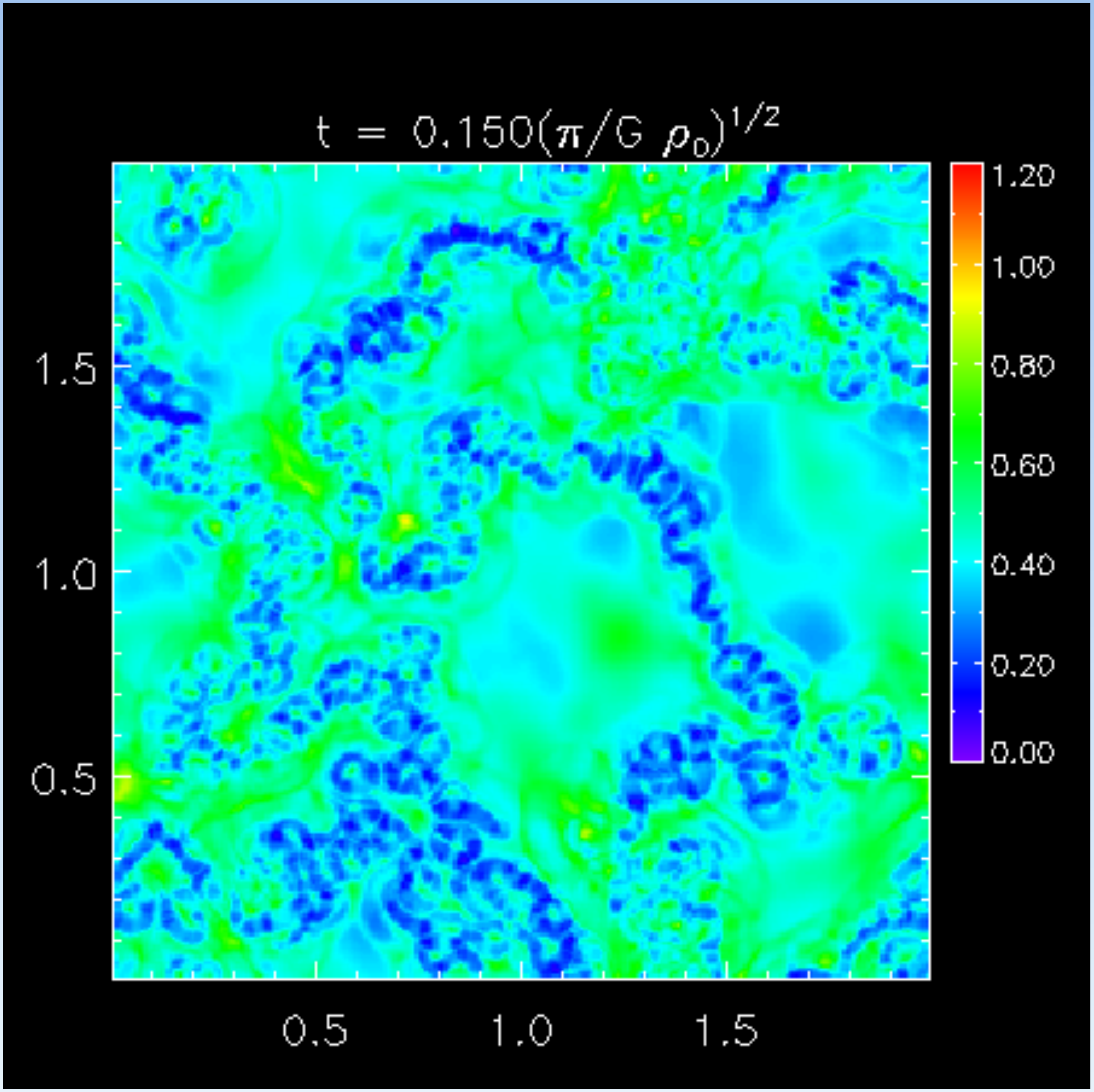
Planar converging flow within a turbulent cloud



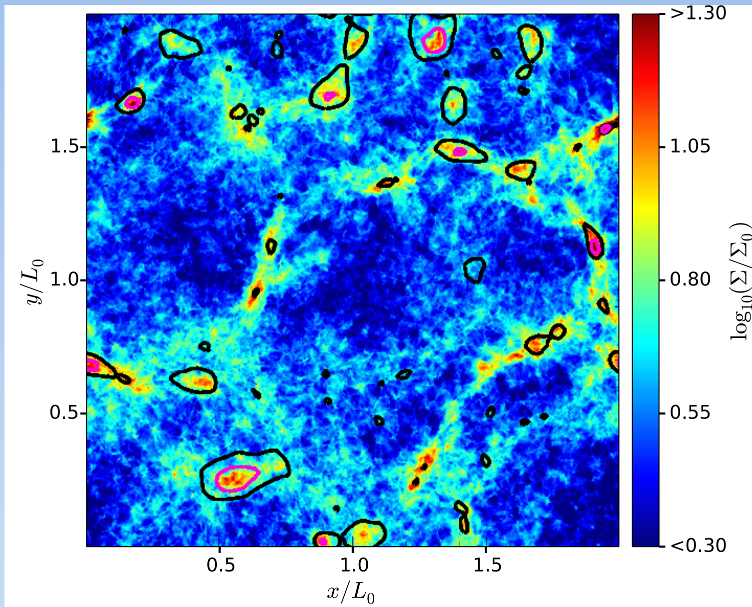
- Focus on local shocked region in a large cloud
- Range of inflow Mach numbers (v_{in}/c_s)
- Additional turbulence included



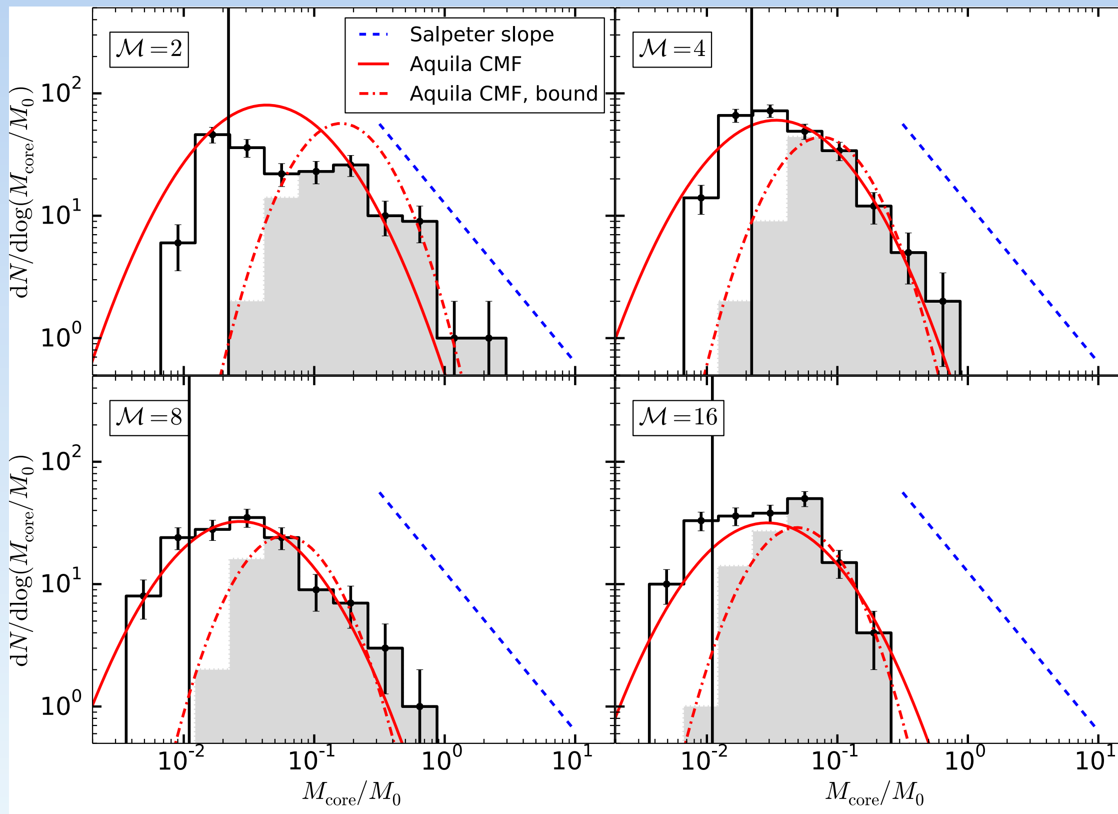
Star formation in filaments



Comparison to observed CMF

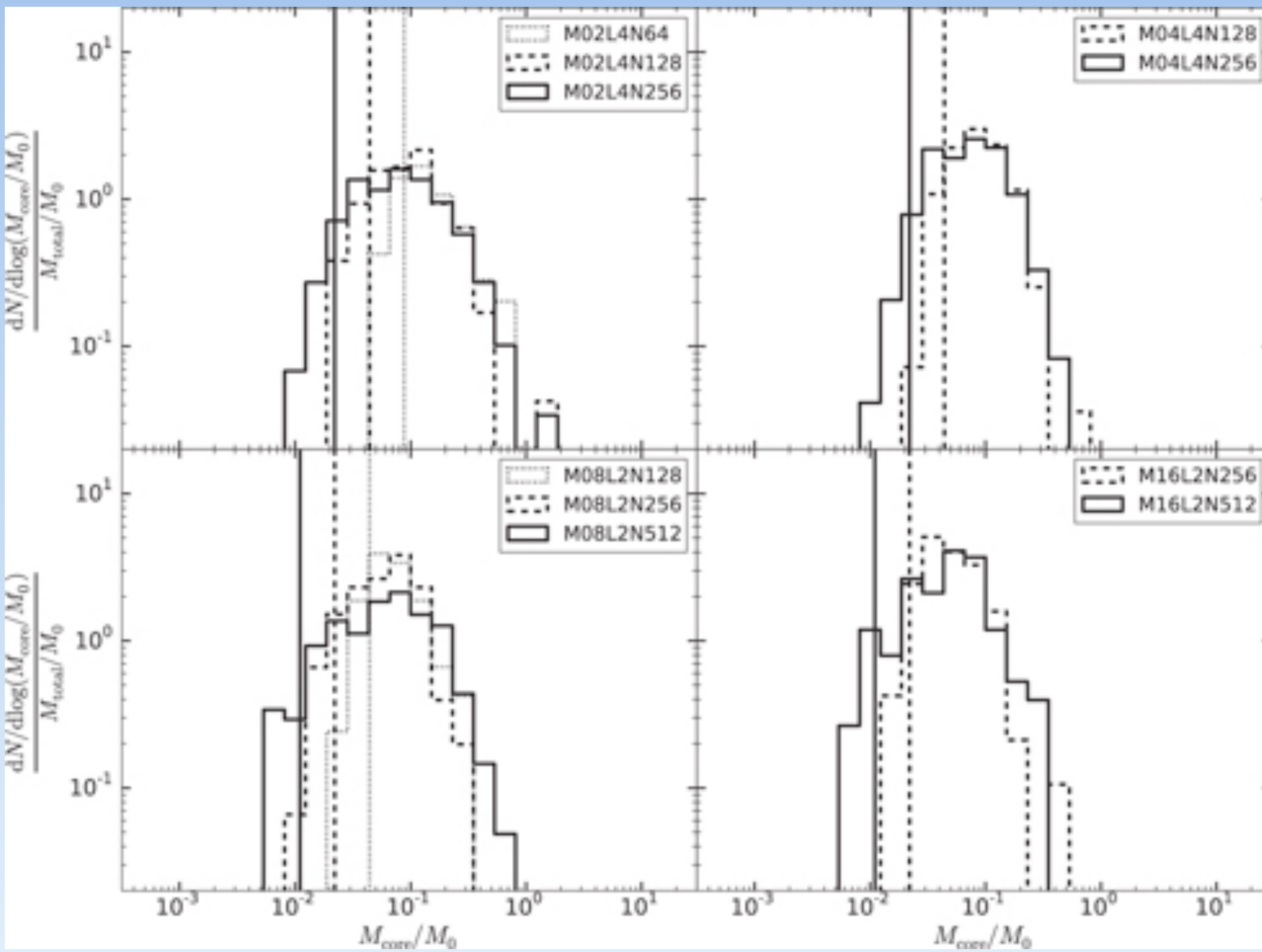


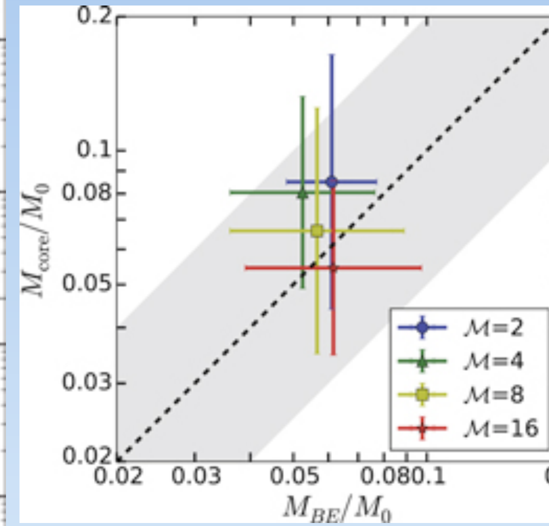
Gong & Ostriker (2015)



- Full CMF is similar to Aquila cores (Konyves 2010, from *Herschel)*
- CMF of bound cores also similar to Aquila bound cores
- High mass cores are lacking compared to IMF

Convergence study: CMF





- Median M ~ M_{BE} @ t_{coll}
- *Infall continues after initial core accretes*

Gong & Ostriker (2015)

Magnetic critical mass

- Mestel & Spitzer (1956): For object to contract gravitationally, must have: $E_G \sim G M^2/R > E_B \sim (B^2/8\pi)(4\pi R^3/3)$

  i.e. $\frac{M}{\Phi} > \frac{1}{\pi\sqrt{6G}}$ *Note: conserved from flux freezing (Kunz lecture)*

- More exact solution for sphere: $\frac{M}{\Phi} > \frac{0.13}{\sqrt{G}}$

  (Mouschovias & Spitzer 1976)

- Cold cloud or sheet: $\frac{M}{\Phi} = \frac{\Sigma}{B} > \frac{0.17}{\sqrt{G}} \approx \frac{1}{2\pi\sqrt{G}}$

  (Nakano & Nakamura 1978)

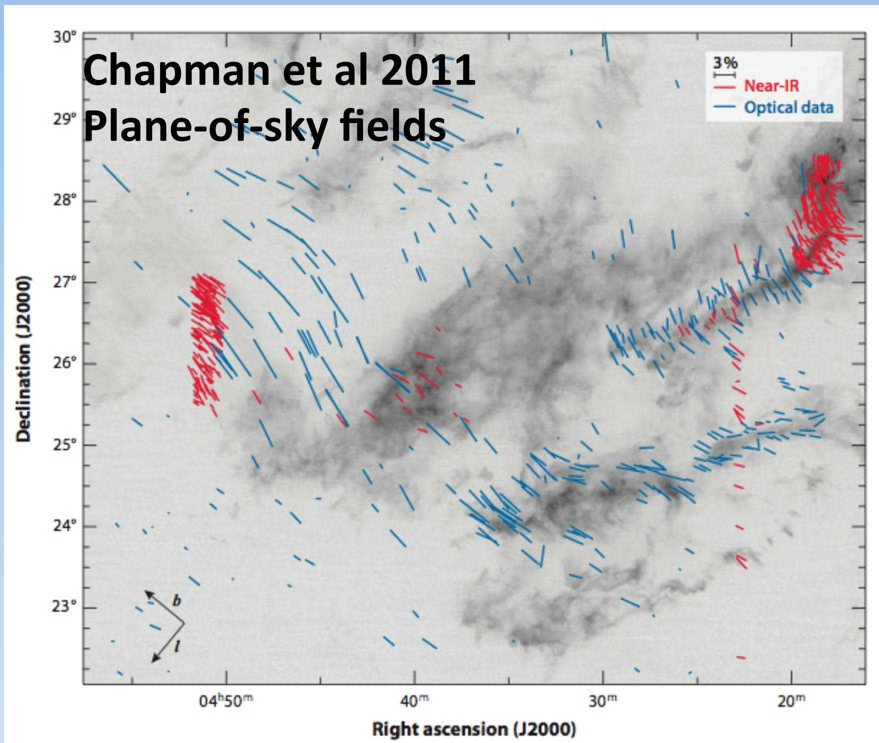
- Corresponds to minimum "gathering scale" along the magnetic field:

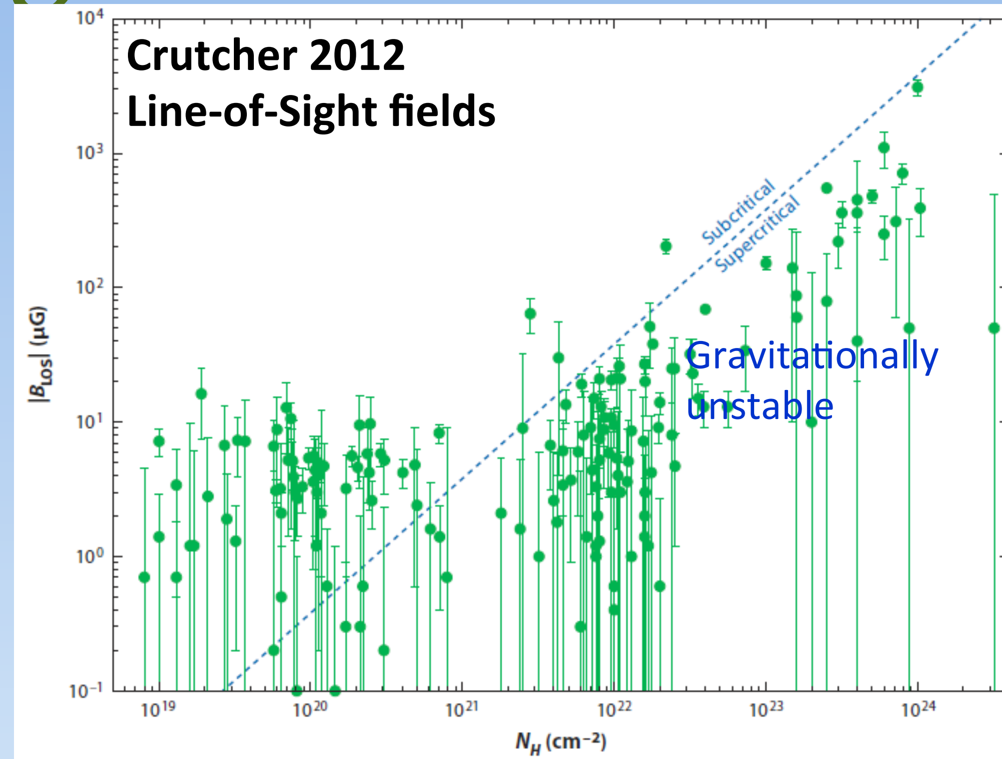
$$L_{crit} = \frac{B}{2\pi\sqrt{G}\rho} = 0.9\text{pc}\left(\frac{B}{10\mu\text{G}}\right)\left(\frac{n}{10^3\text{cm}^{-3}}\right)^{-1}$$

- For spherical core,

$$M_{crit,sph} = \frac{9B^3}{128\pi^2 G^{3/2}\rho^2} = 38M_\odot\left(\frac{B}{10\mu\text{G}}\right)^3\left(\frac{n}{10^3\text{cm}^{-3}}\right)^{-2}$$

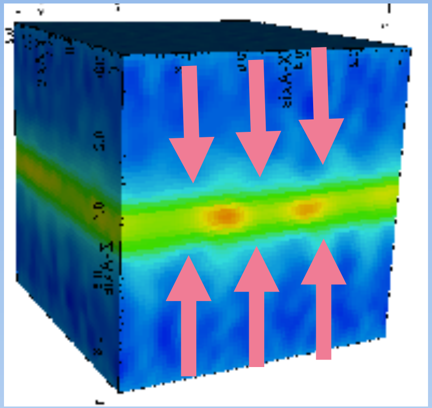
Role of magnetic Fields



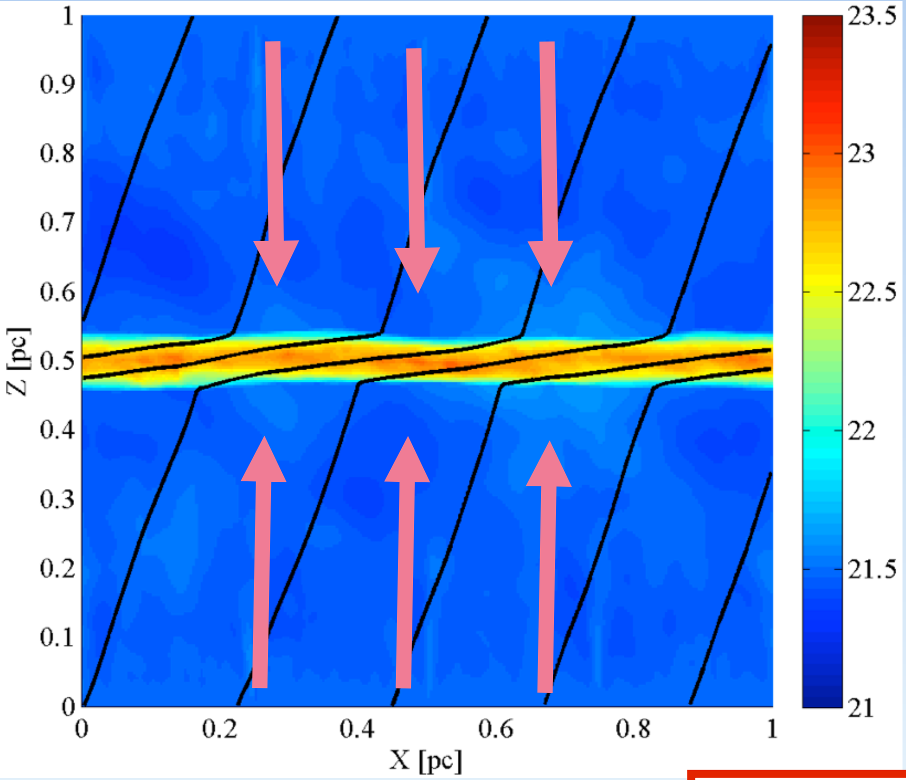


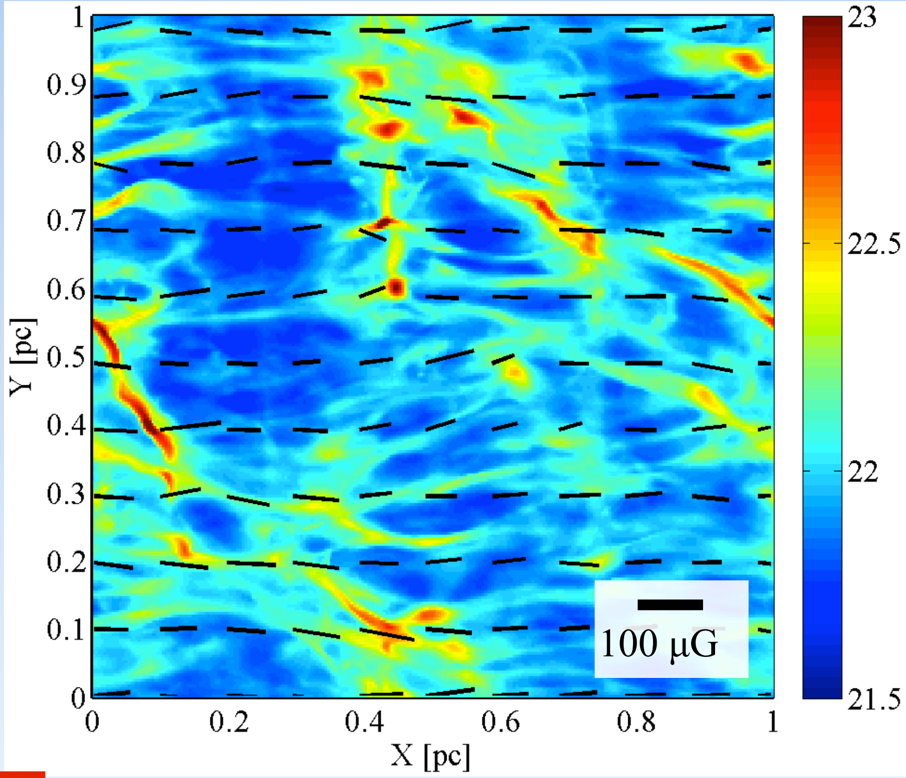
- Observed dense cores have $M/\Phi \sim$ 2-3 $\times$critical value
- But: $M_{crit,sphere} = 0.007\ B^3/(G^{3/2}\rho^2)$ for "pre-core" gas is typically tens of $M_\odot$ - much larger than observed cores
- Ambipolar diffusion in low-mass cores could reduce M/Φ as neutrals drift inward relative to ions and the magnetic field (Mestel & Spitzer 1956)
- But: $t_{AD} \sim 10\ t_{dyn}$ for initially critical core (Mouschovias 1987) is longer than observed core lifetimes

Post-shock layer for magnetized model



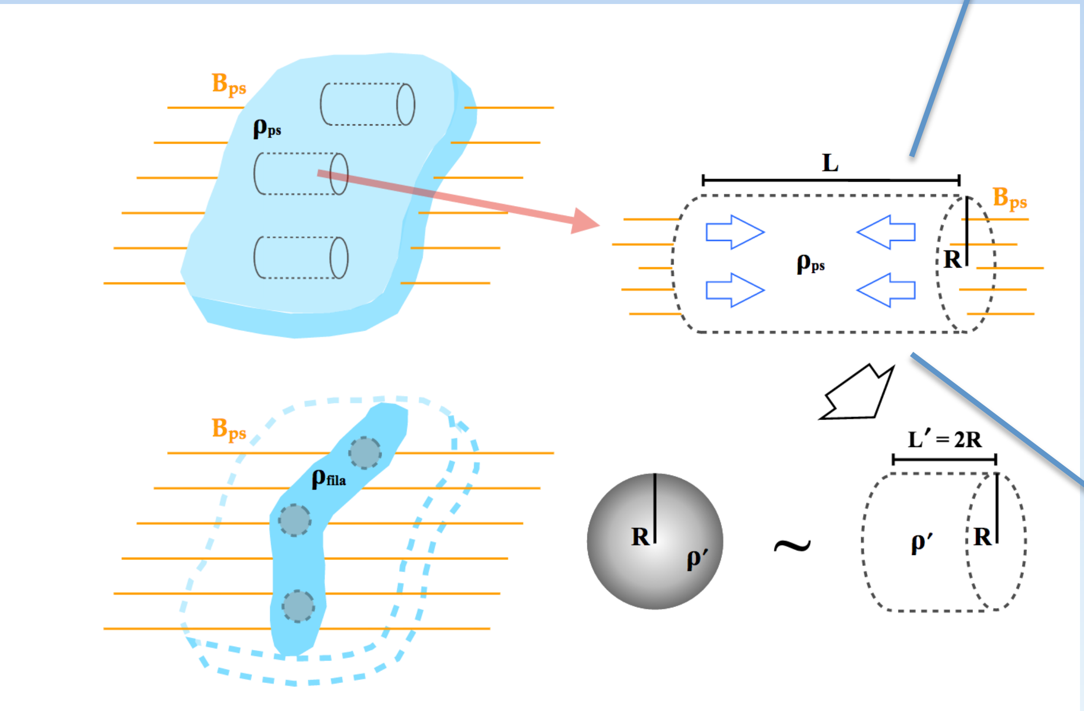
(Chen & Ostriker 2014)

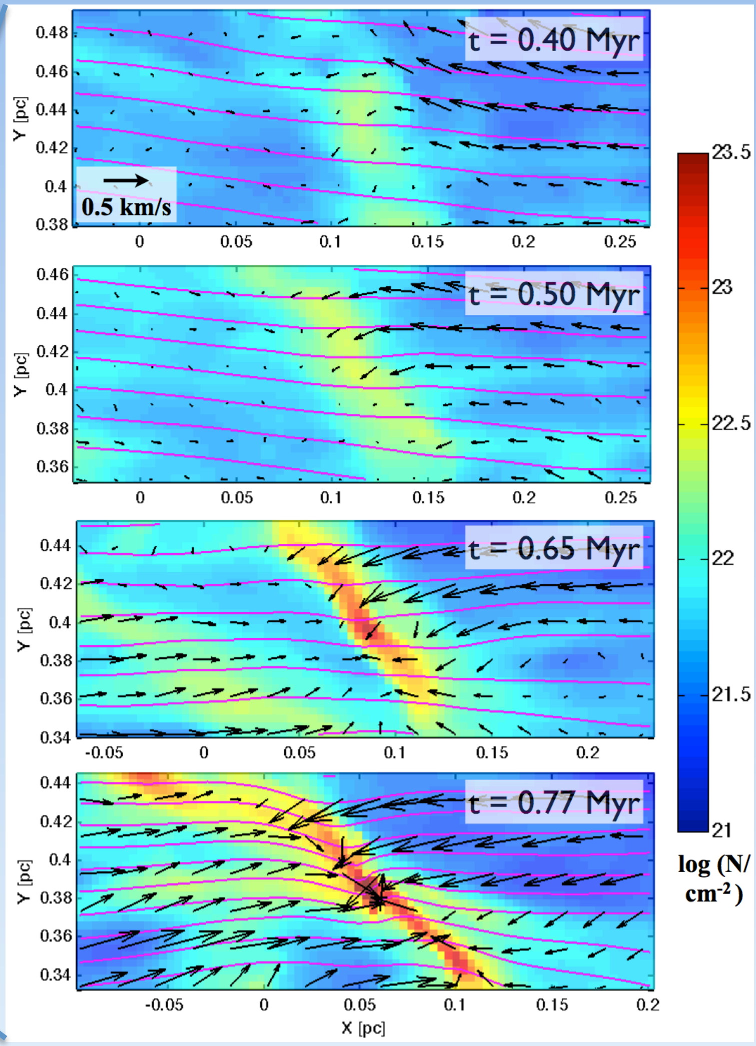




$B_{ps}^2/8\pi \sim \rho_0 v_0^2$

B-aligned flow for filament/core formation





Exercise

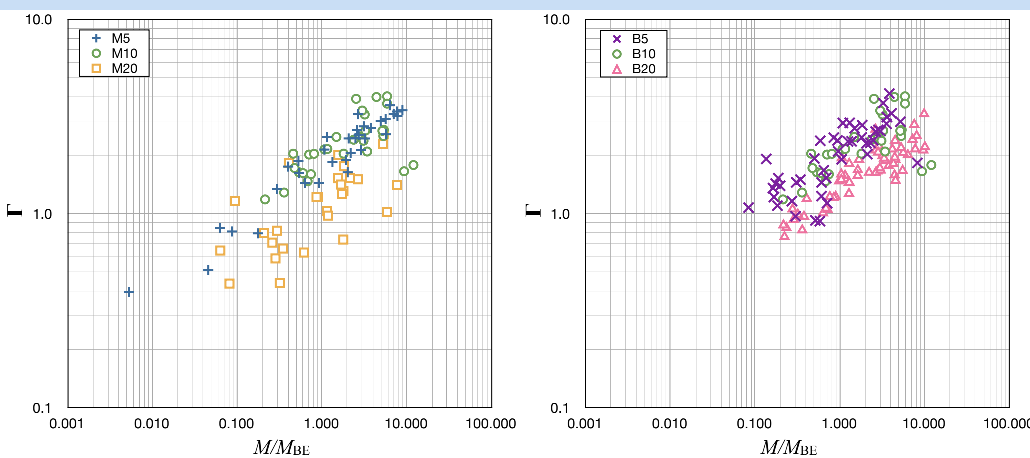
- Consider post-shock layer with $B_{ps}^2/8\pi \approx \rho_0\, v_0^2$
- Magnetic critical length along field has $\rho_{ps}L_{crit}=B_{ps}/(2\pi G^{1/2})$
- Gas contracts along flux tube maintaining $\rho L=\rho_{ps}L_{crit}$
- When $L=R_{BE}=0.8\, v_{th}/(G\rho)^{1/2}$ a core that is both magnetically and thermally unstable can contract
- Show that this condition yields:

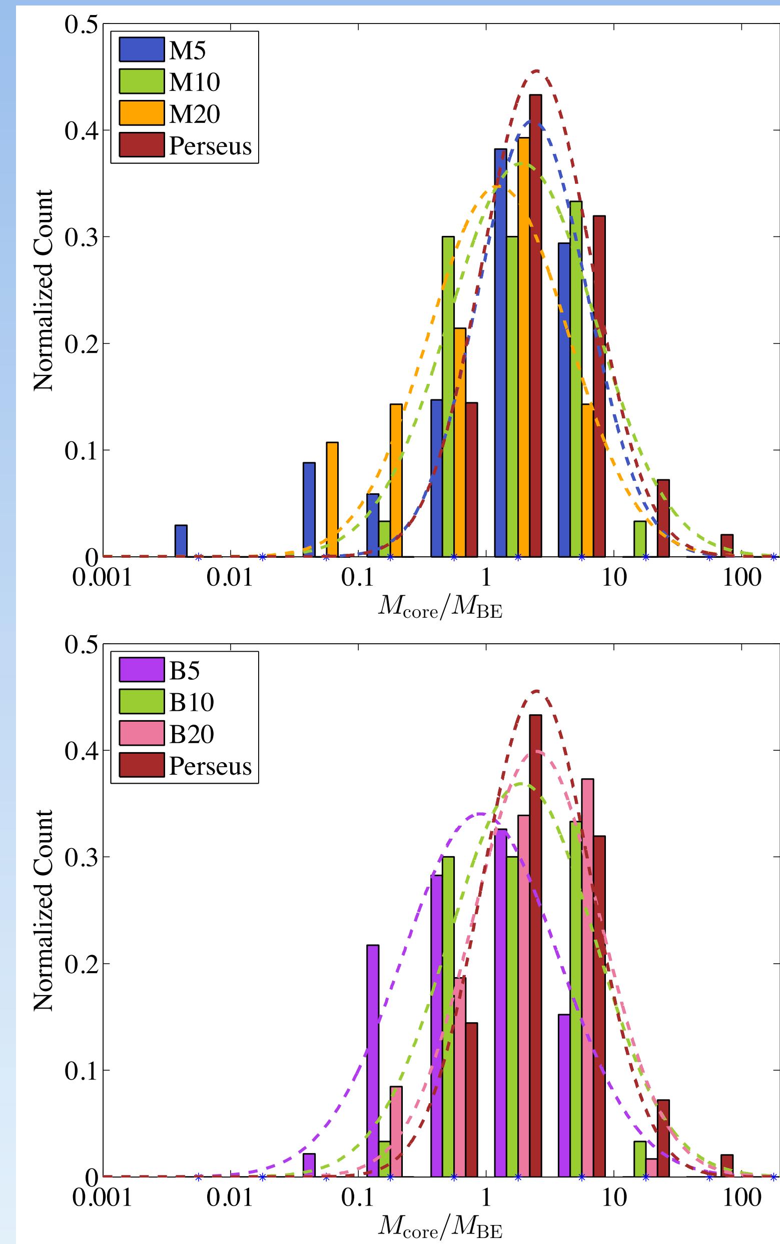
$$M=(4\pi/3)\, R_{BE}^3\rho \approx 2v_{th}^4/(G^{3/2}\, \rho_0^{1/2}v_0),$$

i.e. characteristic core mass is comparable to critical M_{BE} using $P_{edge}=\rho_0\, v_0^2$

M/M_{BE} & M/Φ

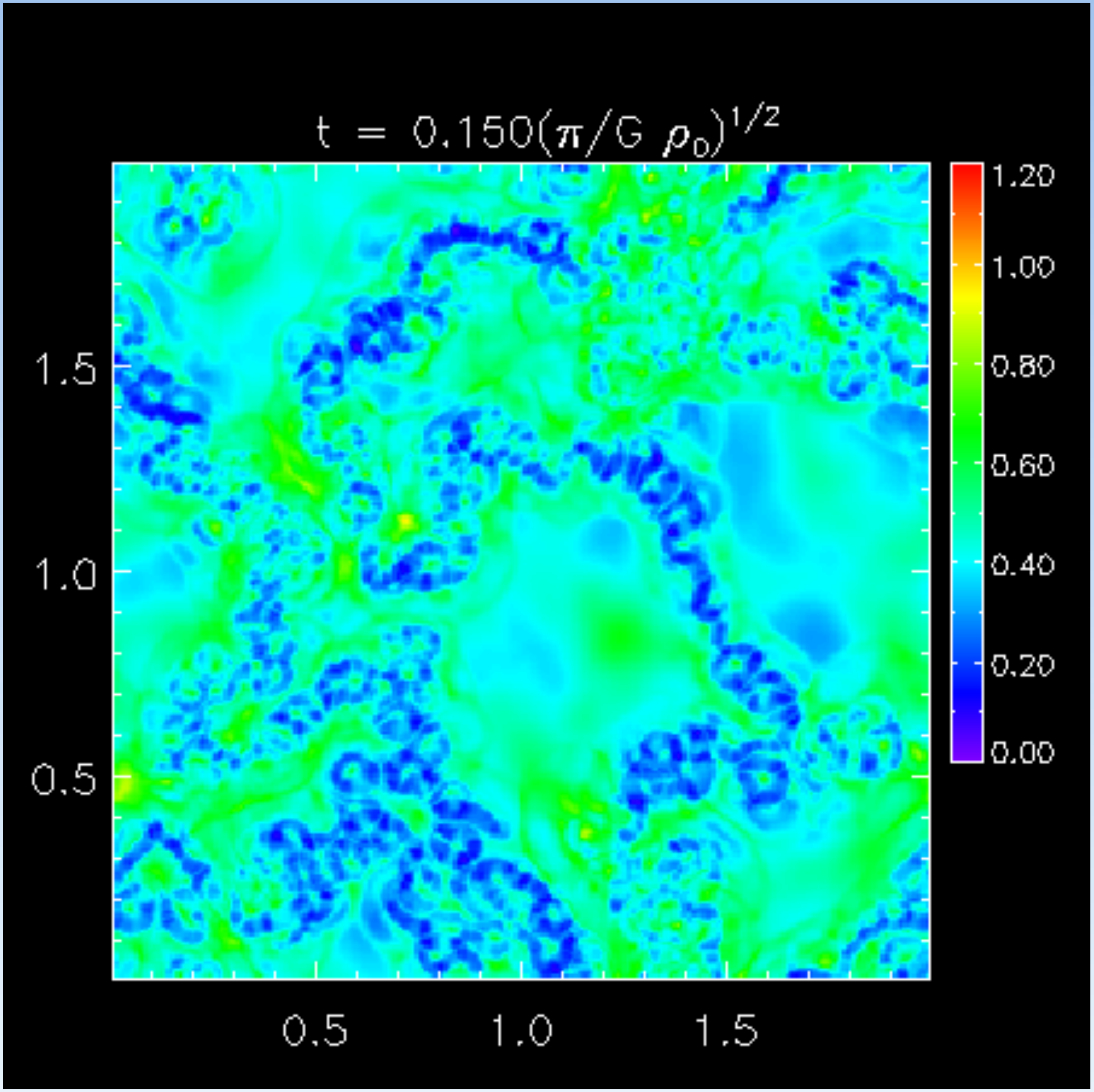
- Distribution of mass relative to BE mass is similar to observed cores
- Cores with M/M_{BE} >1 in simulations are also magnetically supercritical, Γ>1





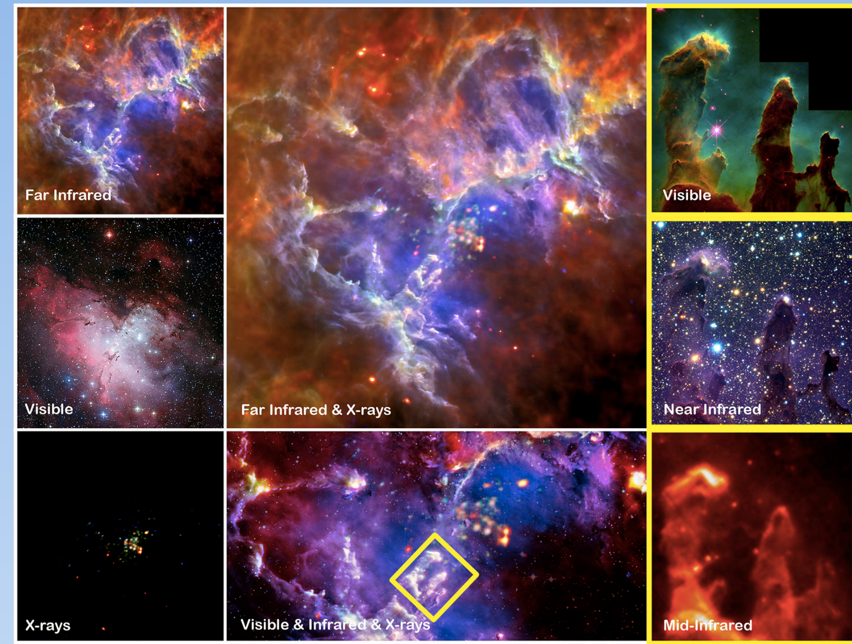
Chen & Ostriker (2015)

Star formation runaway!

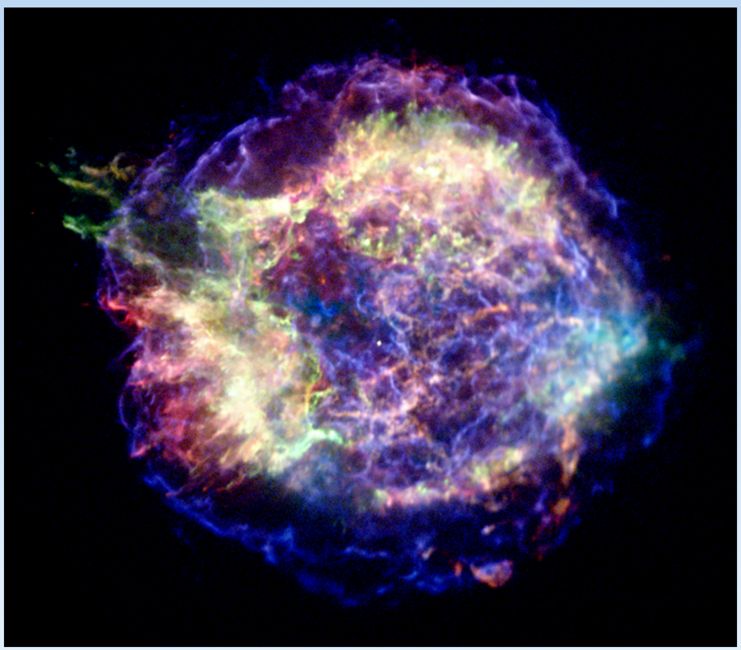


The need for feedback

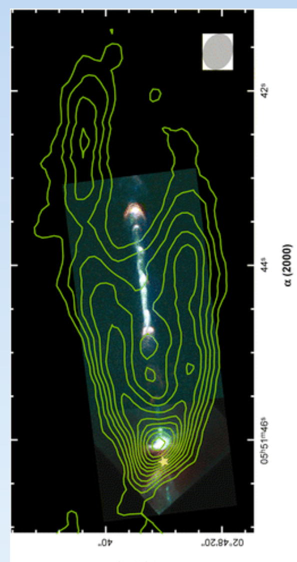
- **Without feedback, all the mass in a cloud would end up in stars**
- Can be halted/turned around by:
  - Protostellar outflows
  - HII regions (photoionization, winds)
  - Radiation pressure
  - Supernova blasts



Eagle nebula/M16 cluster



Cas A supernova remnant



HH 111 jet and outflow

Herschel: Carina nebula

Why feedback?

By allowing a small part of the gas to collapse…

- new stars are born
- high mass stars energize their surroundings

…collapse of the majority of gas is prevented

Enables star formation to be self-regulated by feedback:

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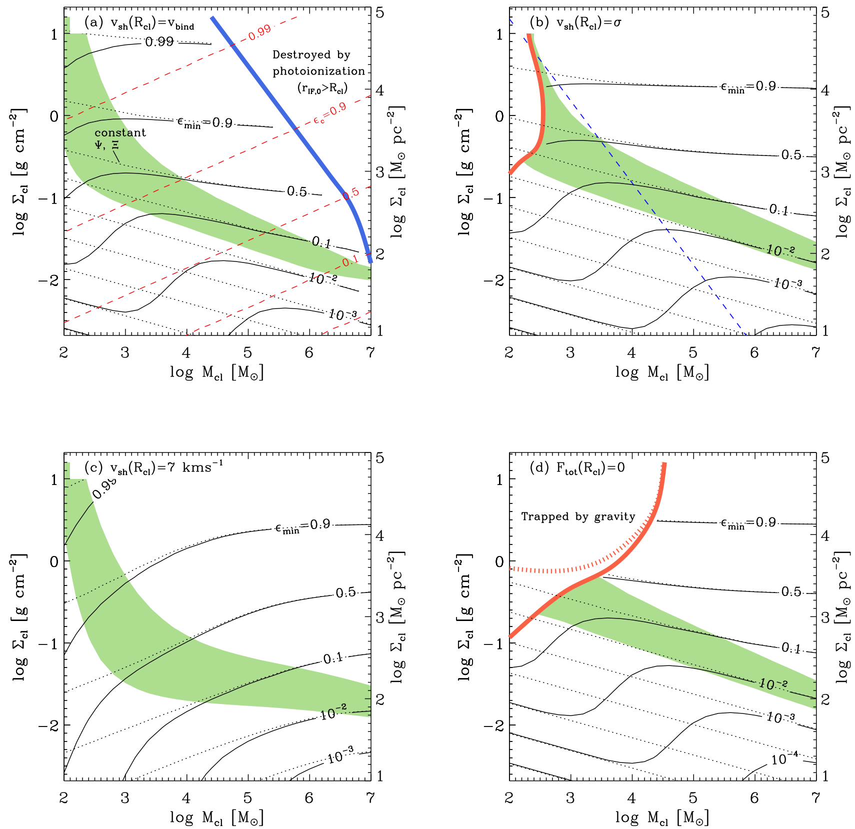
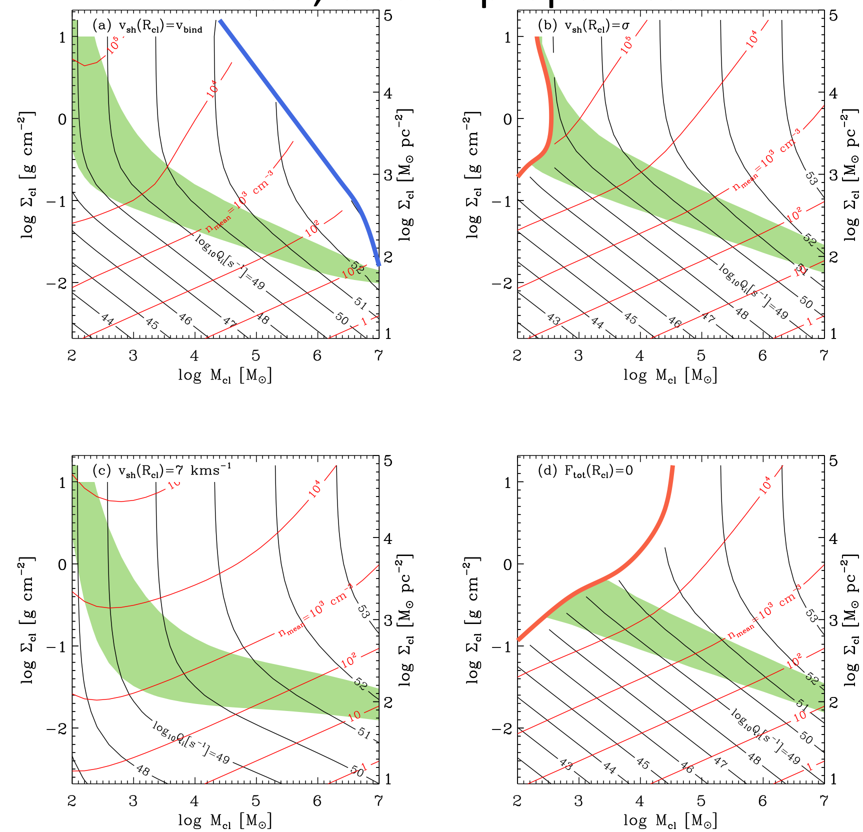
Spherical cloud: ionizing + non-ionizing radiation

Minimum SFE



Cloud, cluster properties



J.-G. Kim, W.-T. Kim, & Ostriker (2016)

Effects of non-ionizing radiation

- Photon momentum = photon energy/c
- Maximum force from direct radiation (UV) of star or cluster with luminosity L is L/c
- UV radiation is absorbed by dust and re-emitted as infrared (IR)
- Reprocessed photons give multiple "kicks" to gas if the cloud IR optical depth $\tau=\kappa\rho R$ is large
- We follow gas + radiation interaction using *radiation hydrodynamics* (RHD) computational models
  - Follow evolution of turbulent cloud with gravity
  - Collapsing gas is replaced by "star particles" (representing clusters) with luminosity $L_*=\Psi M_*$

Skinner & Ostriker (2015), Raskutti, Ostriker, & Skinner (2015)

RHD with RSL

- Basic equations (Skinner & Ostriker 2013, 2015; Raskutti et al 2016)

IR: radiative equilibrium

UV: absorption only

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

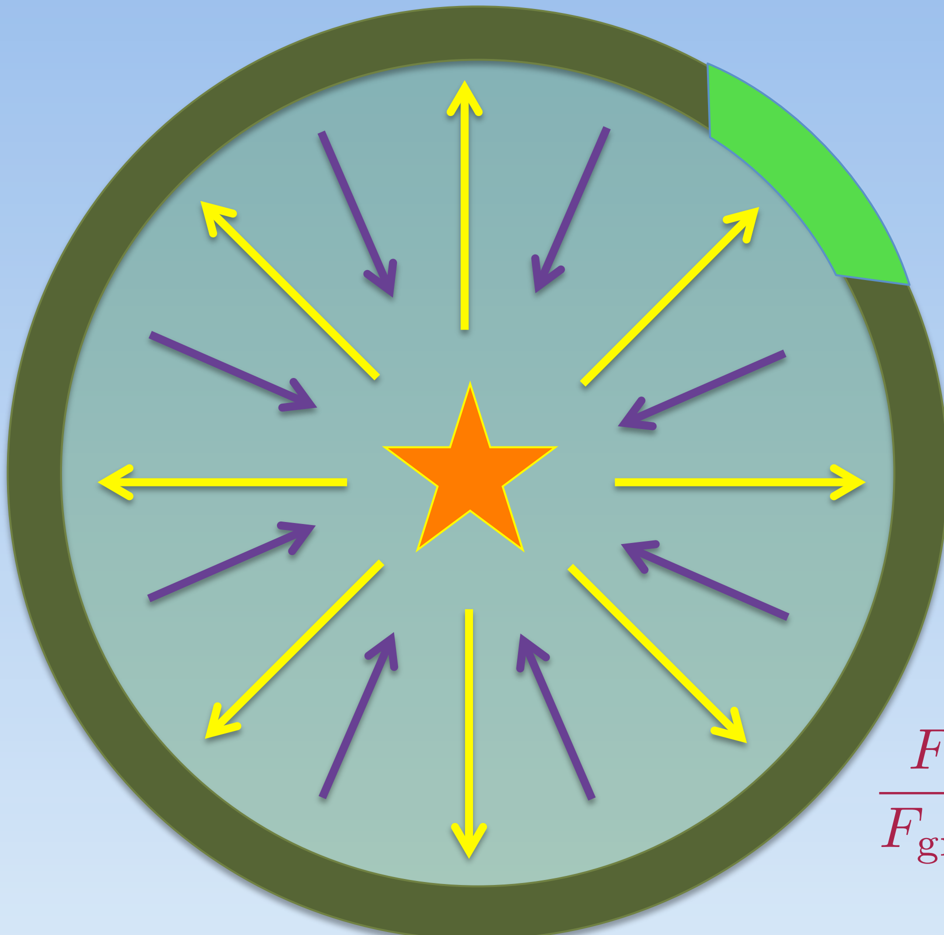
$$\partial_t (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + P\mathbb{I}) = -\rho \nabla \Phi + \rho \kappa \frac{\mathbf{F}}{c}, \quad (2)$$

$$\frac{1}{\hat{c}} \partial_t \mathcal{E} + \nabla \cdot \left(\frac{\mathbf{F}}{c} \right) = -\rho \kappa \mathcal{E} + \mathbb{S}, \quad (3)$$

$$\frac{1}{\hat{c}} \partial_t \left(\frac{\mathbf{F}}{c} \right) + \nabla \cdot \mathbb{P} = -\rho \kappa \frac{\mathbf{F}}{c}, \quad (4)$$

- RSL signal speed $\hat{c} \gg v_{max} \times \tau$ (diffusion) or 1 (absorption only)
- Finite volume scheme with HLL-type solvers, piecewise linear
- Operator-split radiation (substepped) from gas
- Adopt M1 closure (Levermore & Pomraning 1981) for radiation pressure tensor in terms of $\mathcal{E}$ and $\boldsymbol{F}$
- Sink particles are also radiation sources with luminosity $L_* = \Psi M_*$

Effect of UV radiation feedback



$\tau_{shell} = \kappa M_{shell}/(4\pi R^2)$

$\mathcal{L}_* = \Psi M_*$ $\Psi \sim 1000\ L_\odot/M_\odot$

$F_{rad} = \mathcal{L}_*(1-\exp(-\tau_{shell}))/c$
$= \Psi M_*(1-\exp(-\tau_{shell}))/c$

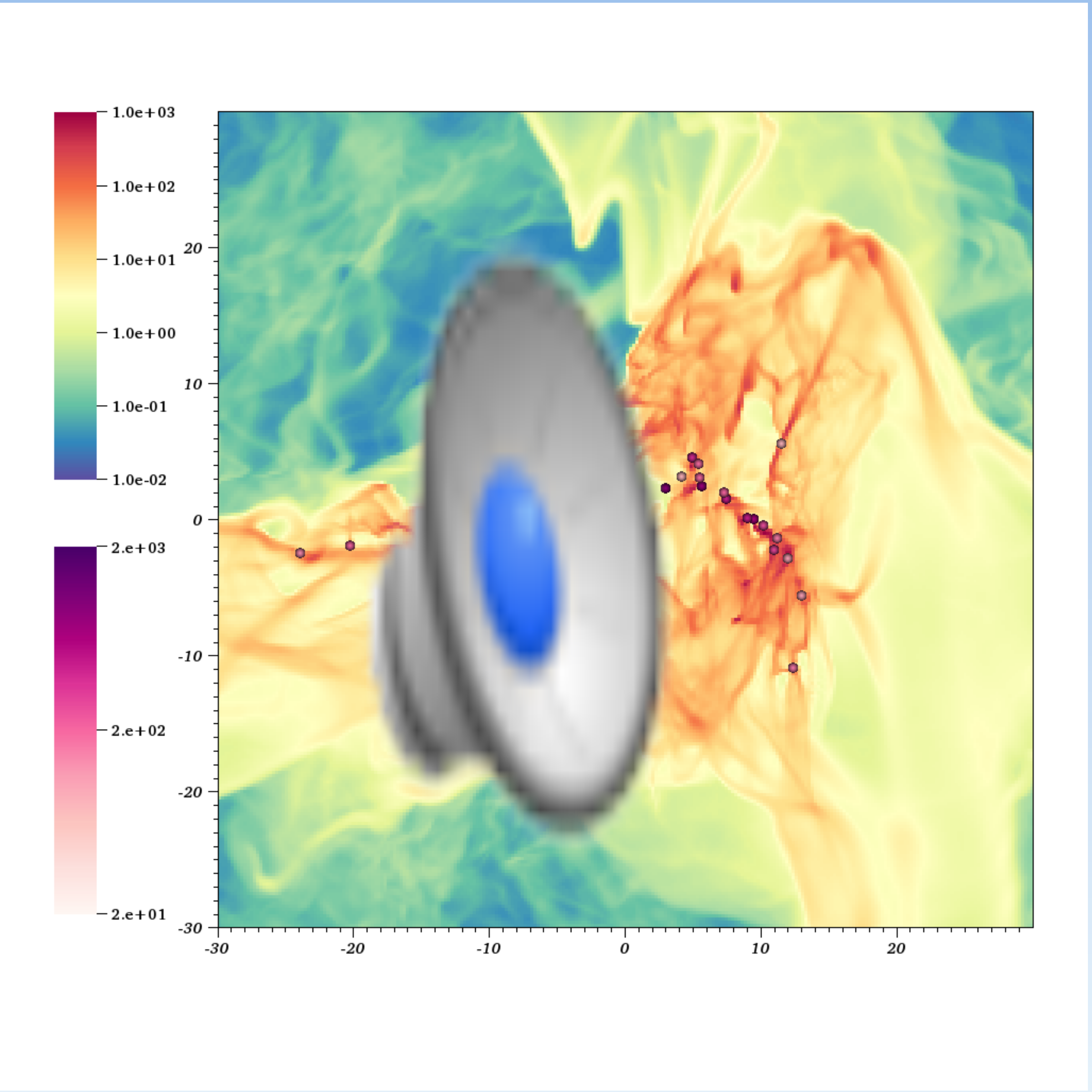
$F_{grav,*} = G M_* M_{shell}/r^2$
$= G M_* \Sigma_{shell}\, 4\pi$

$$\frac{F_{rad}}{F_{grav,*}} = \frac{\Psi/(4\pi c G)}{\Sigma_{shell}}[1 - \exp(-\tau_{shell})]$$

$$= \frac{380 M_\odot \mathrm{pc}^{-2}}{\Sigma_{shell}}[1 - \exp(-\tau_{shell})]$$

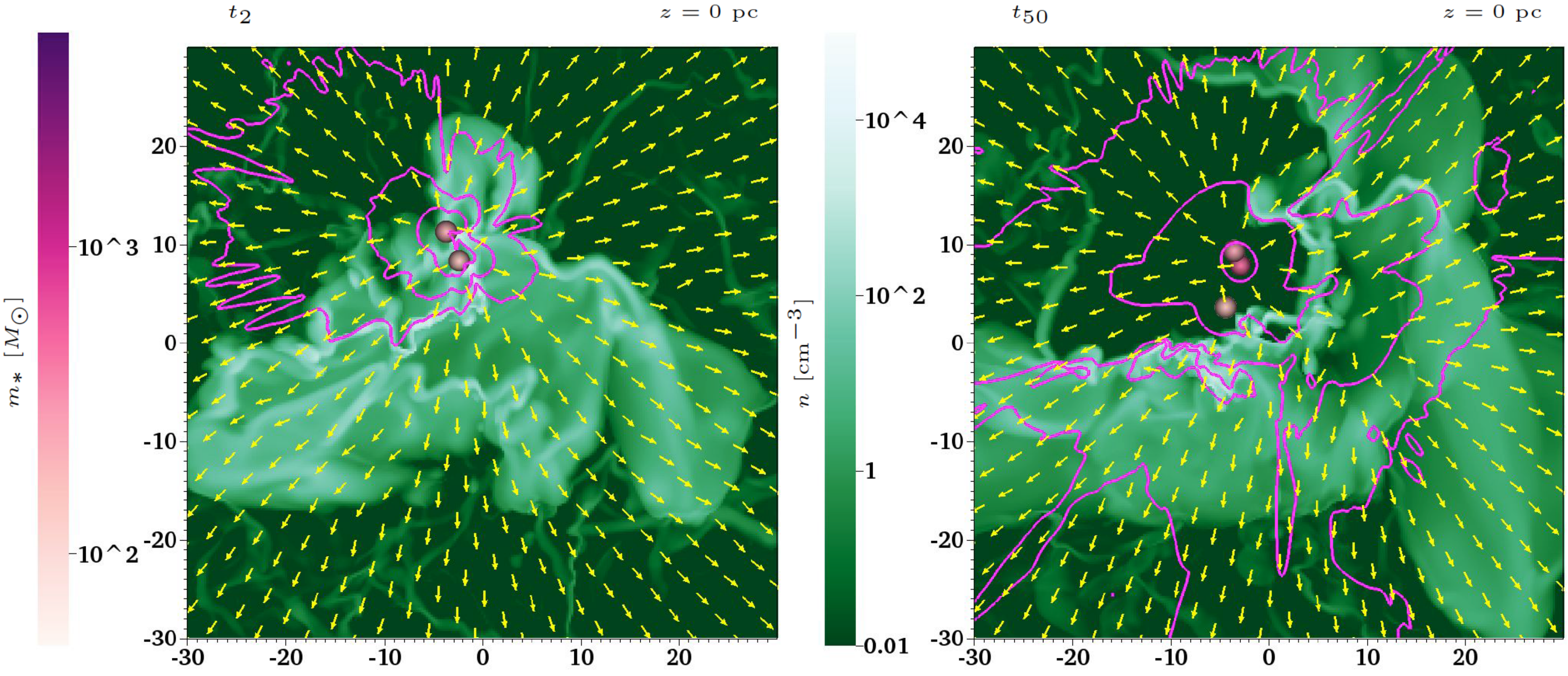
- Maximum $f_{Edd,*} = \Psi \kappa_{UV}/(4\pi c G) = 80$ for $\tau_{shell} \lesssim 1$, $\Sigma_{shell} \lesssim 5\ M_\odot/\mathrm{pc}^2$
- $f_{Edd,*} < 1$ for $\Sigma_{shell} > 380\ M_\odot/\mathrm{pc}^2$

Cloud evolution with direct (UV) radiation



Raskutti, Ostriker, & Skinner (2016)

$5 \times 10^4 M_\odot$ r=15pc initial cloud with sink particles to represent cluster, and RHD for non-ionizing UV radiation


t_2
$z = 0$ pc
t_{50}
$z = 0$ pc
m_* [$M_\odot$]
10^3
10^2
n [cm^{-3}]
10^4
10^2
1
0.01
20
10
0
-10
-20
-30
-30
-20
-10
0
10
20

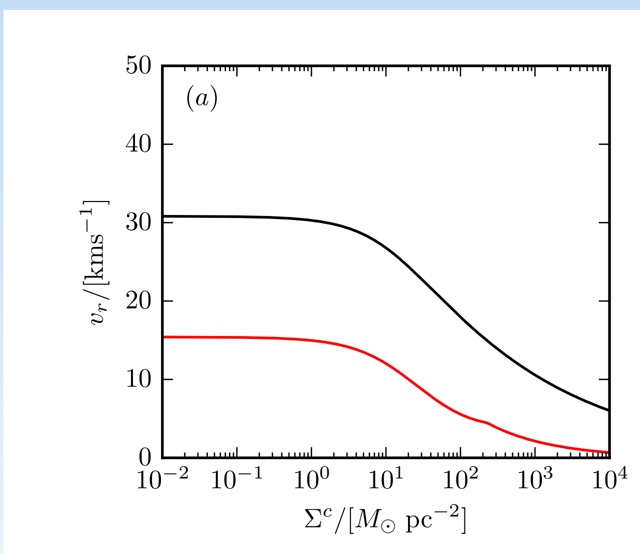
UV radiation driven outflows

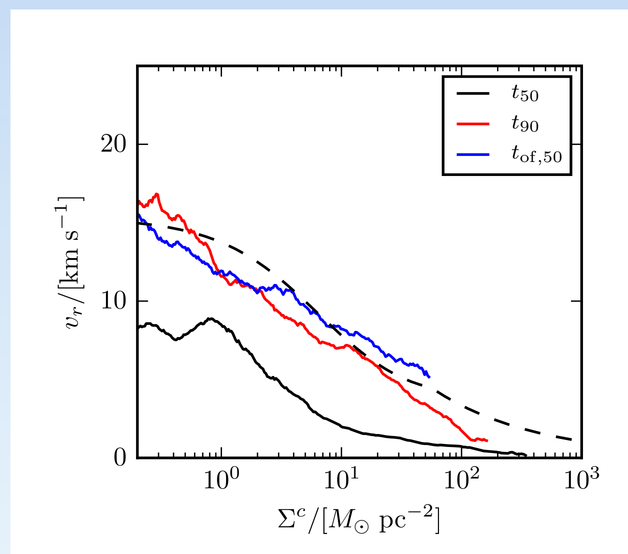
- At r≫r$_0$, shell with initial surface density $\Sigma_0 < \Sigma_E$ reaches:

$$v^2 \to \frac{2GM_*}{r_0}\frac{\Psi/(4\pi cG)}{\Sigma_0}\left[\sqrt{\pi\tau_0}\,\mathrm{erf}(\sqrt{\tau_0}) + \exp(-\tau_0) - 1\right]$$

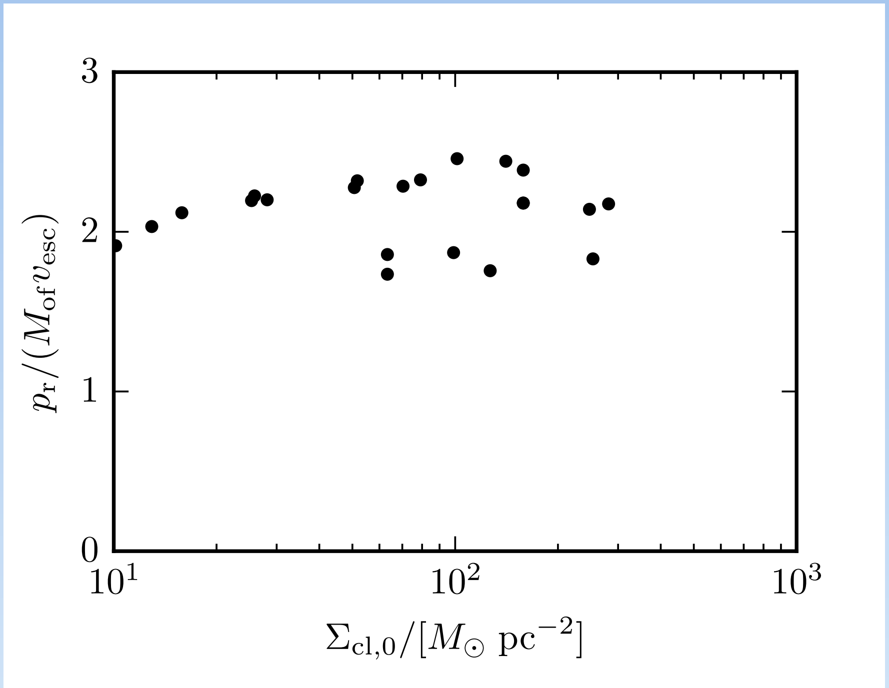
- Optically thin (UV): $$v^2 \to \frac{2GM_*}{r_0}\frac{\Psi\kappa}{4\pi cG} \approx 80 v_{\mathrm{esc}}^2(r_0)$$

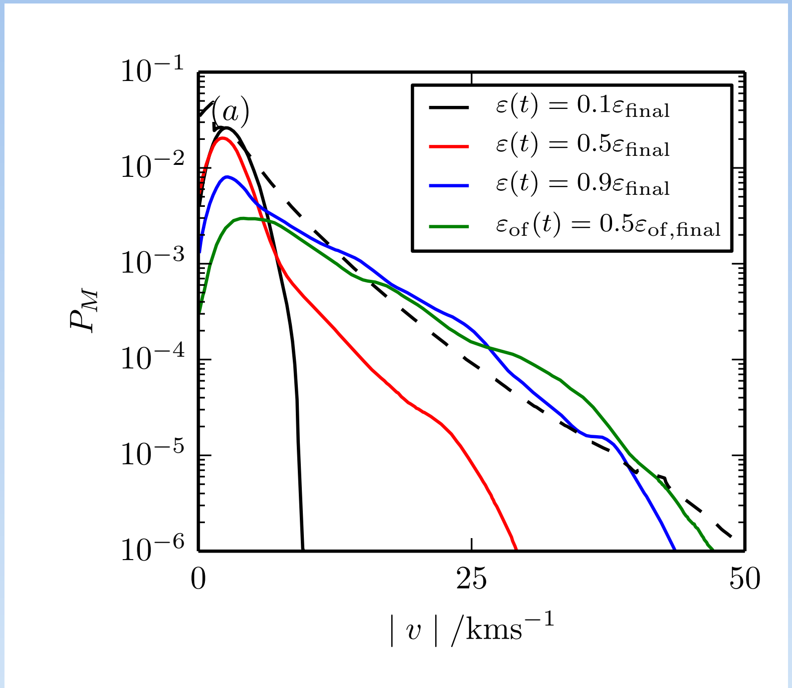
- Optically thick (UV): $$v^2 \to \frac{2GM_*}{r_0}\frac{\Psi\kappa}{4\pi cG}\left(\frac{\pi}{\tau_0}\right)^{1/2} = v_{\mathrm{thin}}^2\left(\frac{\pi}{\tau_0}\right)^{1/2}$$





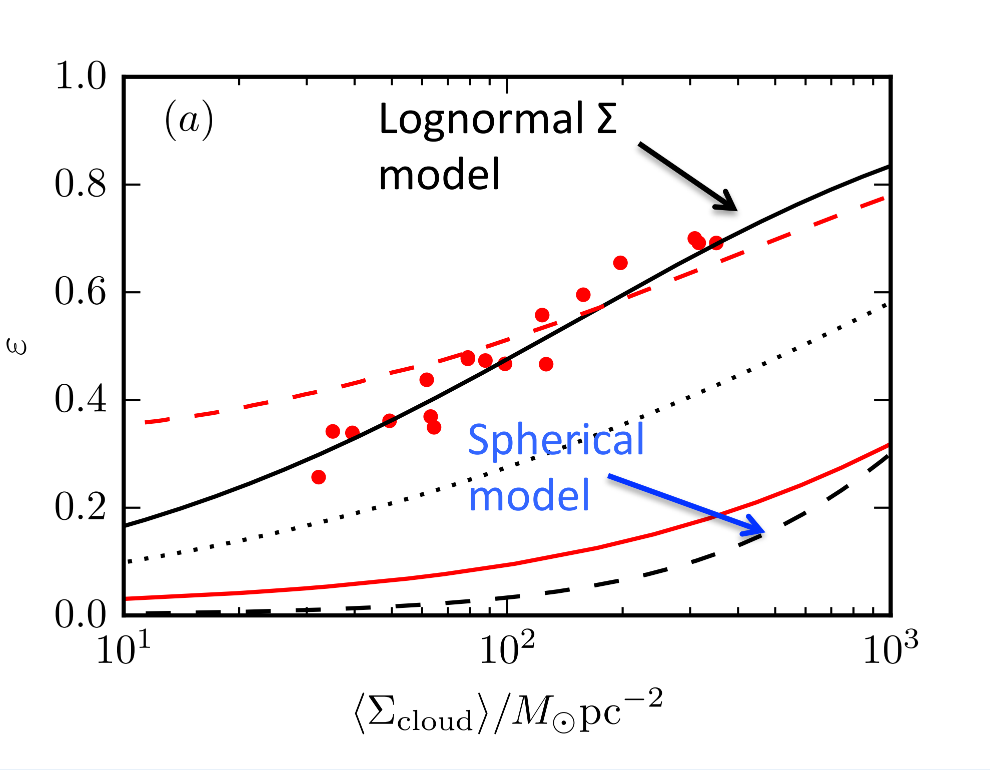
$M(v)$ distribution





- Mean velocity of outflowing gas is ~2 $v_{esc}(r_{cloud})$
- But: extends to ~15 $v_{esc}(r_{cloud})$ due to range of r_0
- Consistent with convolution of $v(r_0, \Sigma)$ with $f_m(\Sigma)$ for $r_0 < r_{cloud}$

Lifetime star formation efficiency of GMC

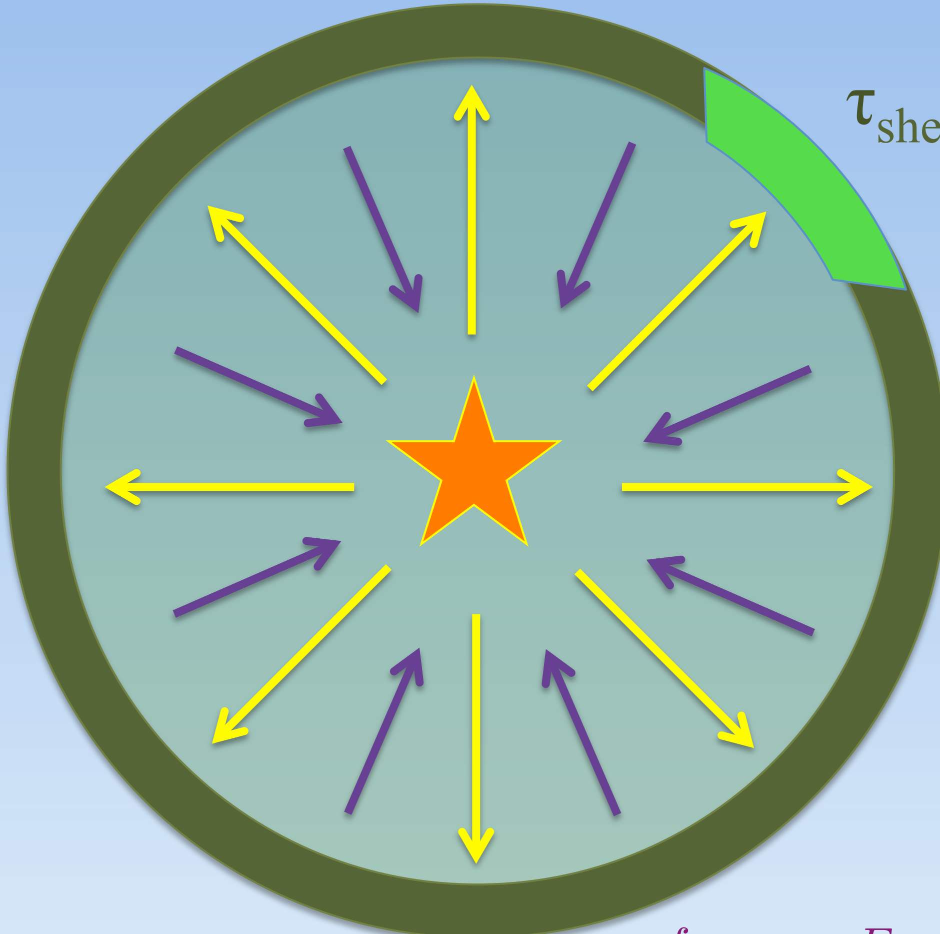


Raskutti, Ostriker, & Skinner (2016)

$$\Sigma_E = \frac{2\varepsilon}{\varepsilon+1}\frac{\Psi}{4\pi c G} = 380 M_\odot {\rm pc}^{-2}\frac{2\varepsilon}{\varepsilon+1}\frac{\Psi}{2000\,{\rm erg\ s^{-1}\ g^{-1}}}$$

- Radiation force/area $\sim L/(c4\pi r^2) \propto M_*/r^2$ must exceed gravity force/area $\sim G(M_* + M_{gas}/2)\Sigma/r^2$ to expel structure:
  require $\Sigma < \Sigma_E$
- *Non-spherical, turbulent*:
  - Lognormal Σ distribution
  - Gas structures of increasingly high Σ are driven out as ε and L_* of cluster increases.
- Final SFE much higher than for simple spherical model (uniform Σ) because turbulence increases $\langle\Sigma\rangle_M$

Effect of IR radiation feedback



$\tau_{shell} = \kappa M_{shell}/(4\pi R^2)$
$= \kappa \Sigma_{shell}$

$\mathcal{L}_* = \Psi M_*$

$\Psi \sim 1000\ L_\odot/M_\odot$

$F_{rad} = \mathcal{L}_* \tau_{shell}/c = \Psi M_* \kappa_{IR} \Sigma_{shell}/c$

$F_{grav,*} = G M_* M_{shell}/R^2 = G M_* \Sigma_{shell} 4\pi$

$$f_{Edd,*} \equiv F_{\rm rad}/F_{\rm grav} = \frac{\Psi \kappa_{IR}}{4\pi G c}$$

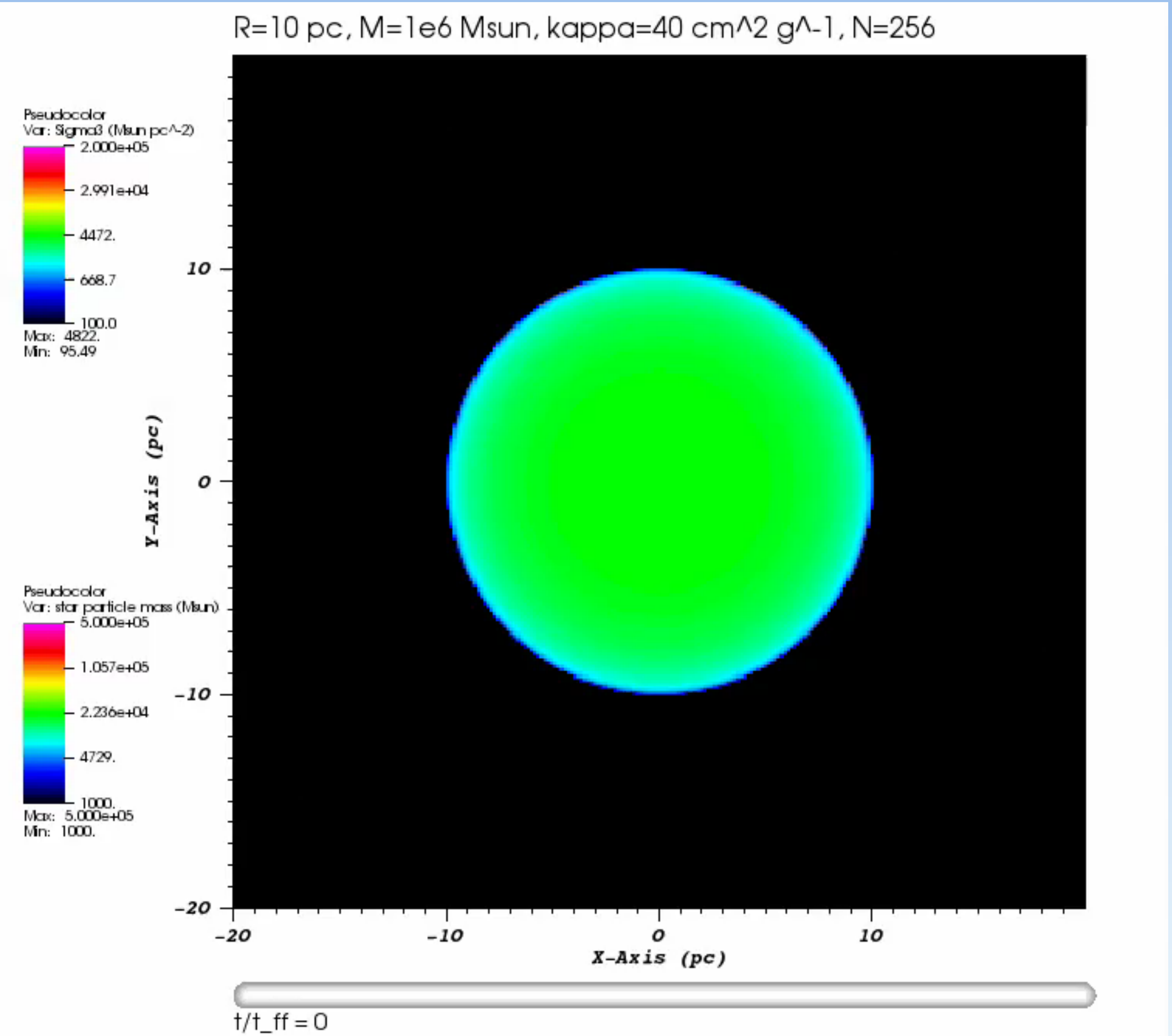
$\to 0.7$ for $\kappa = 10$ (*bound*)

$\to 1$ for $\kappa = 15$ (*CRITICAL*)

$\to 1.4$ for $\kappa = 20$ (*unbound*)

$\to 2.4$ for $\kappa = 40$ (*unbound*)

Star-forming cloud with IR RHD



Skinner & Ostriker (2015)

$10^6\,M_\odot$ initial cloud with sink particles and RHD

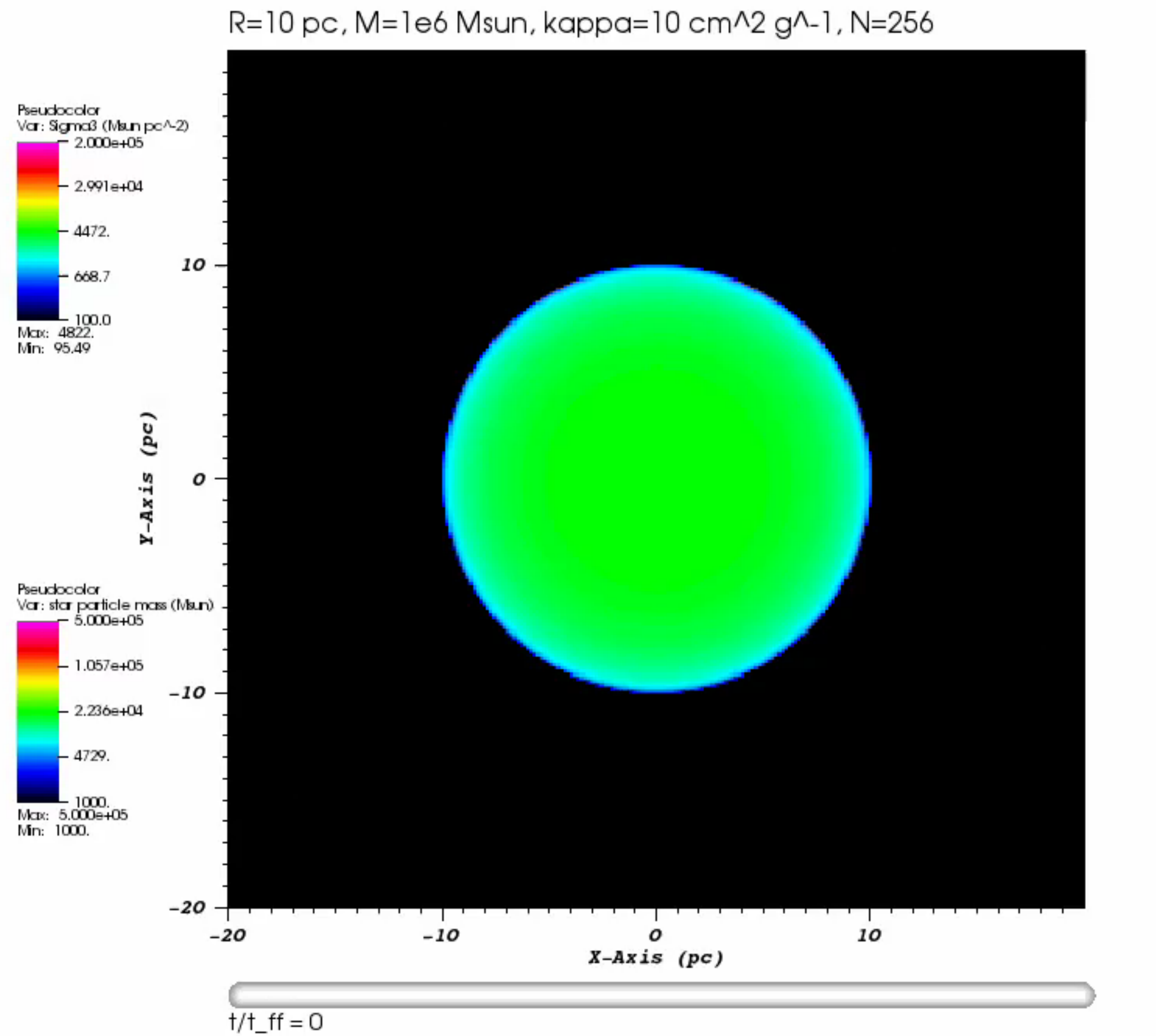
$\kappa = 40\ \mathrm{cm}^2/\mathrm{g}$

$L_* = \Psi M_*$ for subclusters; $\Psi = 1700$ erg/s/g

$t_{ff} = 0.52$ Myr

Star-forming cloud with IR RHD

Skinner & Ostriker (2015)



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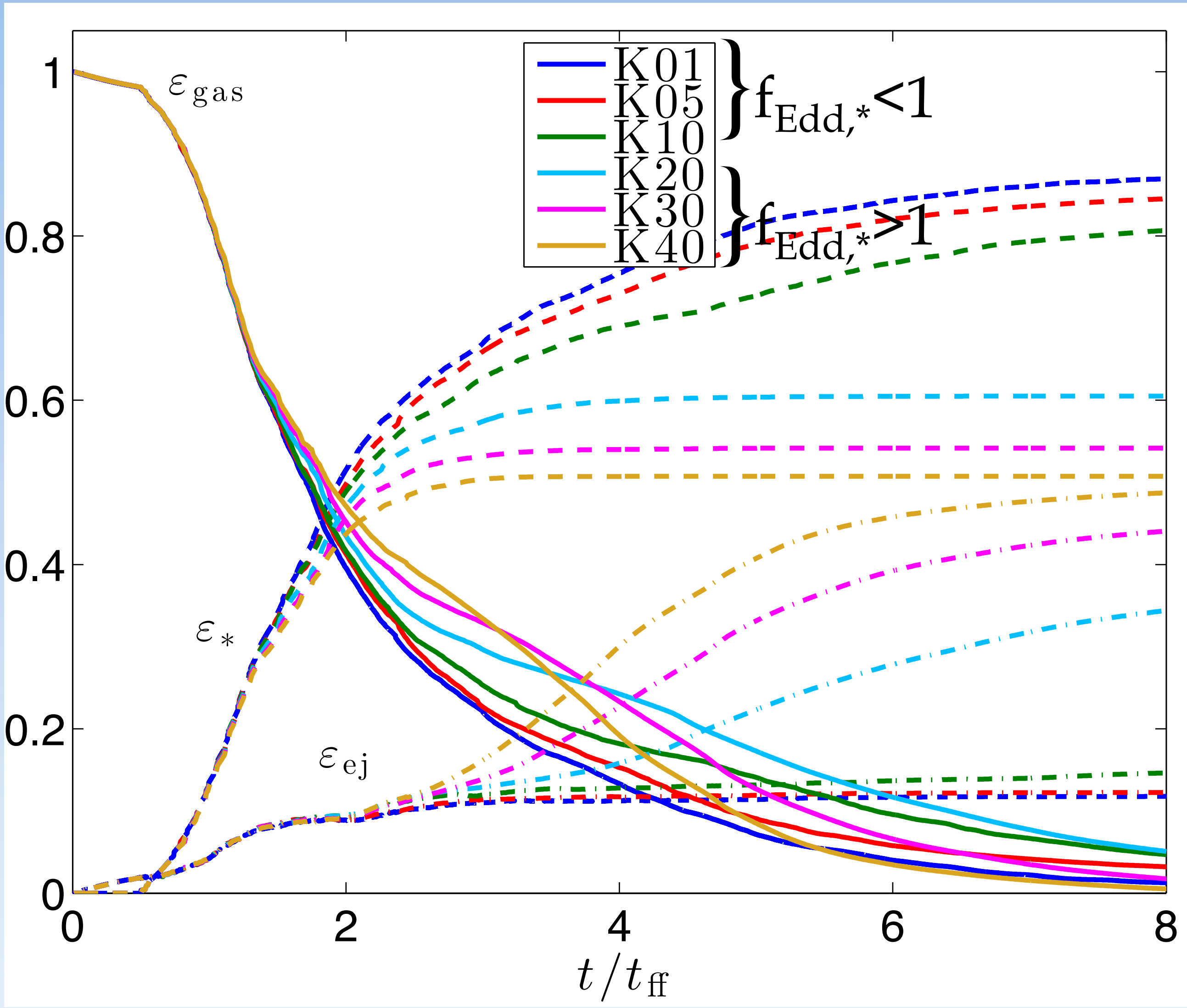
SF efficiency for varying IR opacity



Skinner & Ostriker (2015)

$f_{Edd,*}=F_{rad,*}/F_{grav,*}$
$=\Psi\kappa/(4\pi Gc)$

κ_{IR}=1, 5, 10, 20, 30, 40 g/cm^2

Fractional mass loss and net SF efficiency depends strongly on IR opacity

$10^6\,M_\odot$, 10 pc initial cloud; t_{ff}=0.52 Myr

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Feedback by SNe

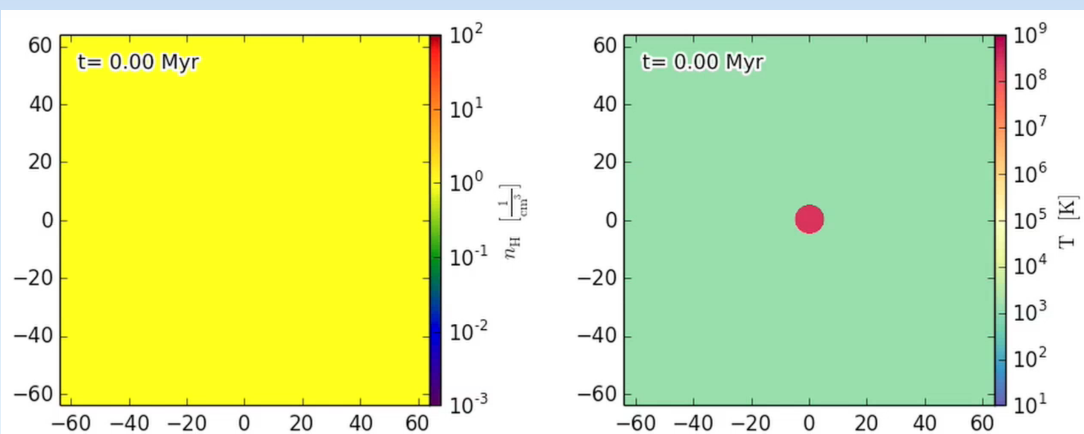
- Supernovae drive blast waves into surrounding interstellar medium
- Blast shocks and sweeps up ambient medium
  - Initially adiabatic
  - Shell cools and expansion slows when shock drops to ~ 200 km/s
- Classical evolution stages :
  - Free expansion, Sedov-Taylor, Pressure-Driven Snowplow, Momentum-Conserving Snowplow

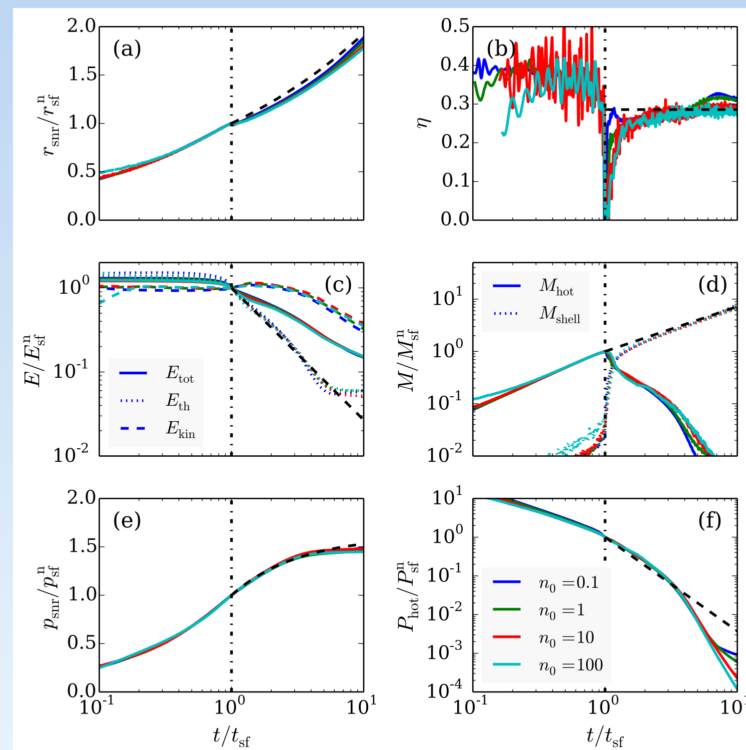
  Spherical simulations: Cioffi et al 1988, Blondin et al 1998, Thornton et al 1998
- Key feedback parameter is the net (spherical) momentum injection p_* to surroundings

Supernova remnant momentum

- Uniform medium: "congruent" evolution depending on t/t_{sf}
- Momentum increases ~ 50% after shell formation
- Maximum hot gas mass ~$1000 M_\odot$
- **Real ISM: inhomogenous medium**

$$t_{sf} = 40\,\mathrm{kyr}\,n_0^{-0.6}$$
$$r_{sf} = 22\,\mathrm{pc}\,n_0^{-0.4}$$
$$v_{sf} = 210\mathrm{km/s}\,n_0^{0.1}$$
$$M_{sf} = 1550\mathrm{M}_\odot\,n_0^{-0.3}$$
$$p_{sf} = 2\times 10^5\,\mathrm{M}_\odot\,\mathrm{km/s}\,n_0^{-0.15}$$



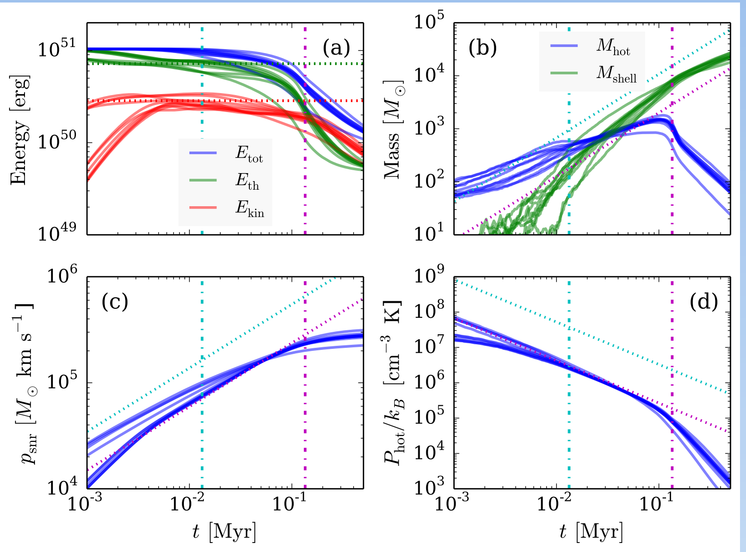


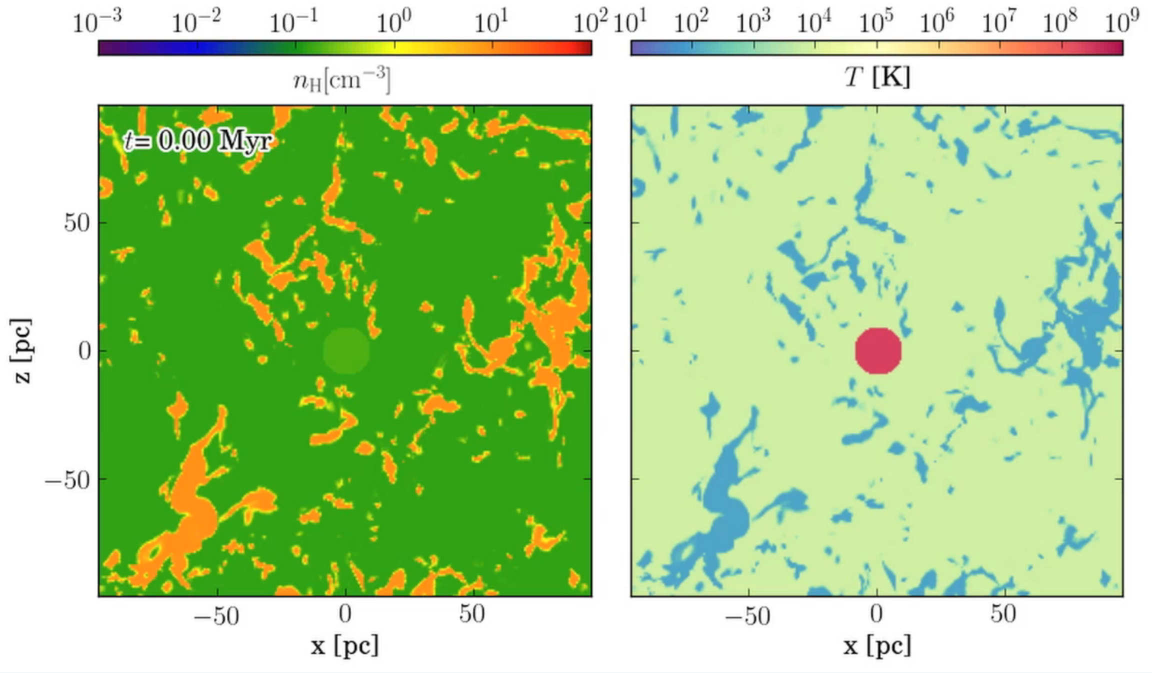
Kim & Ostriker (2015a)

Cloudy ambient medium: SNR

- Cloudy-ISM models with mean density $\langle n_0 \rangle$ from 0.1 to 100 cm^{-3}
- Intercloud density sets maximum radius before onset of strong cooling
- Final SNR momentum is ~10 × initial momenta of SN ejecta

Kim & Ostriker (2015), , Iffrig & Hennebelle (2015), Martizzi et al (2015), Walch & Naab (2015)





$$p_{final} = 2.8\times10^5\ M_\odot km/s\ \langle n_0 \rangle^{-0.17}$$

Comparable momentum to single-phase prediction using average ambient density

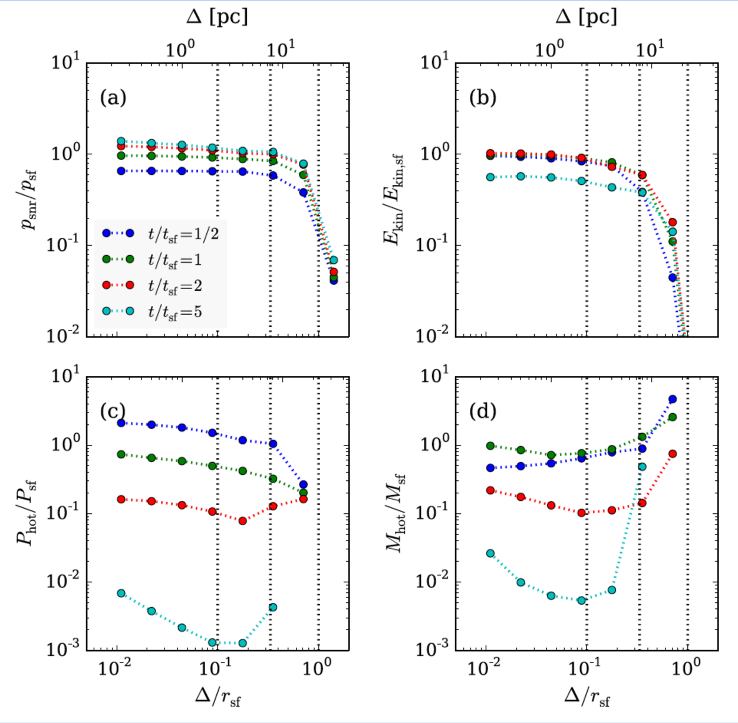
Kim & Ostriker (2015a)

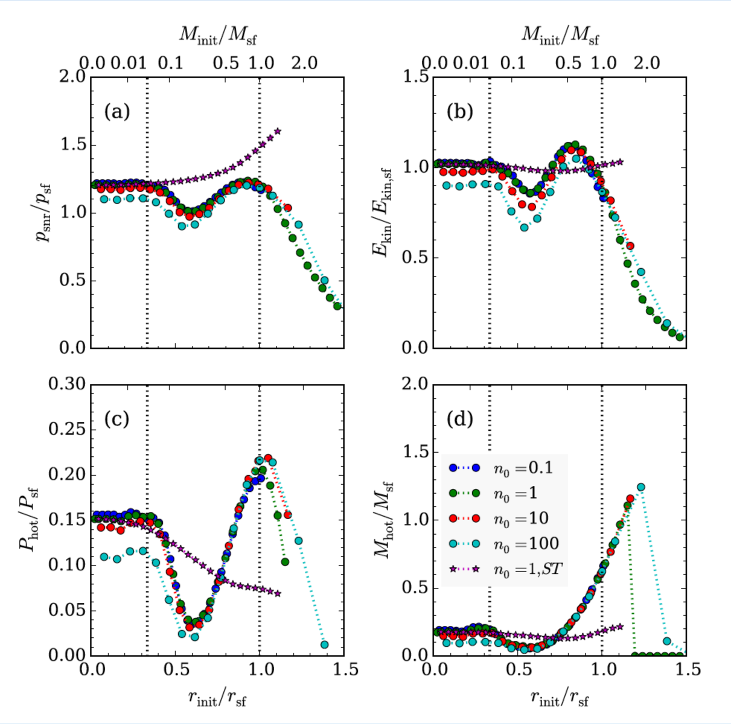
Numerical resolution requirements

- To resolve the ST stage and obtain the correct mass of hot gas and total momentum injected, must have:

  $r_{init}/r_{sf} < 1/3$ and $\Delta/r_{sf} < 1/10$

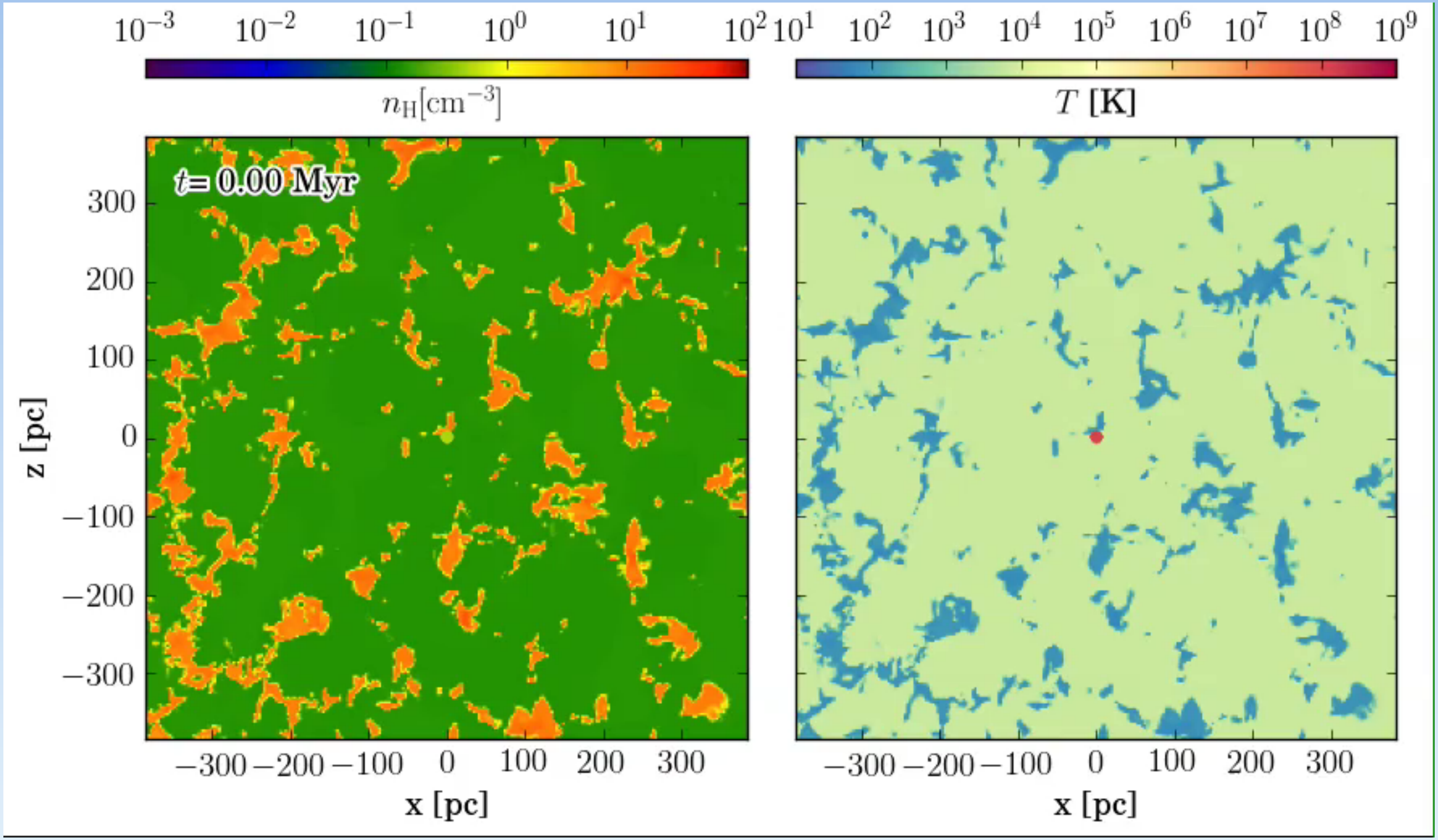
- "Overcooling" problem of SN feedback in many galaxy formation simulations is due to insufficient numerical resolution





Kim & Ostriker (2015)

Superbubbles in two-phase ISM



SB & galactic wind loading

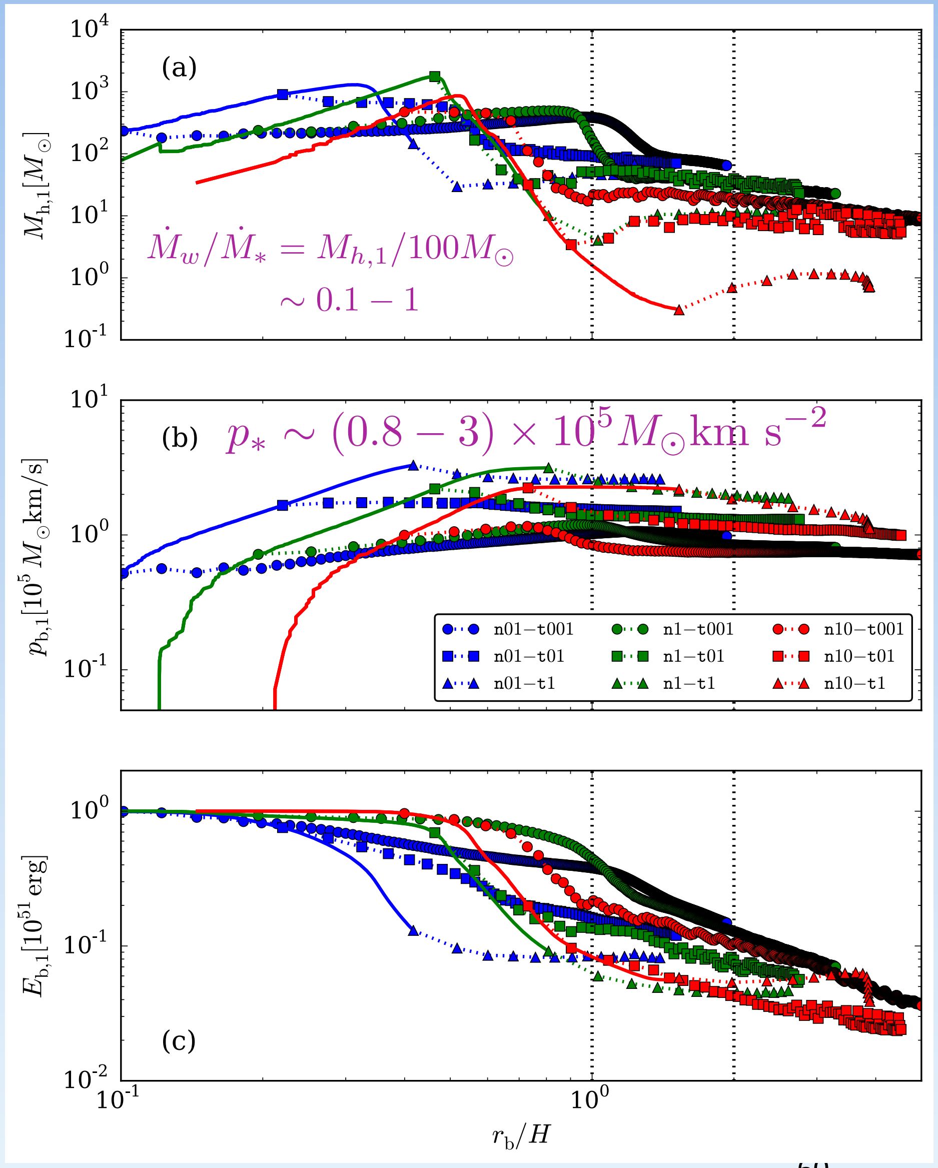
- For high enough Σ_{SFR}, superbubble breaks out before shell formation:

(SB mass)/(star cluster mass) ~10

- Lower Σ_{SFR} :

(hot gas mass)/(cluster mass) ~0.1 -1

  – Wind mass loading is higher at lower density and for shorter Δt_{SN}



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Self-regulation concept

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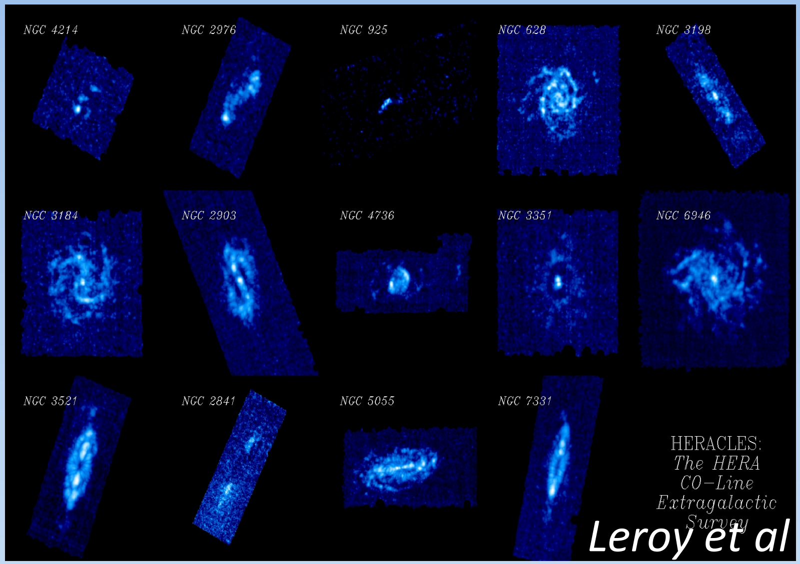
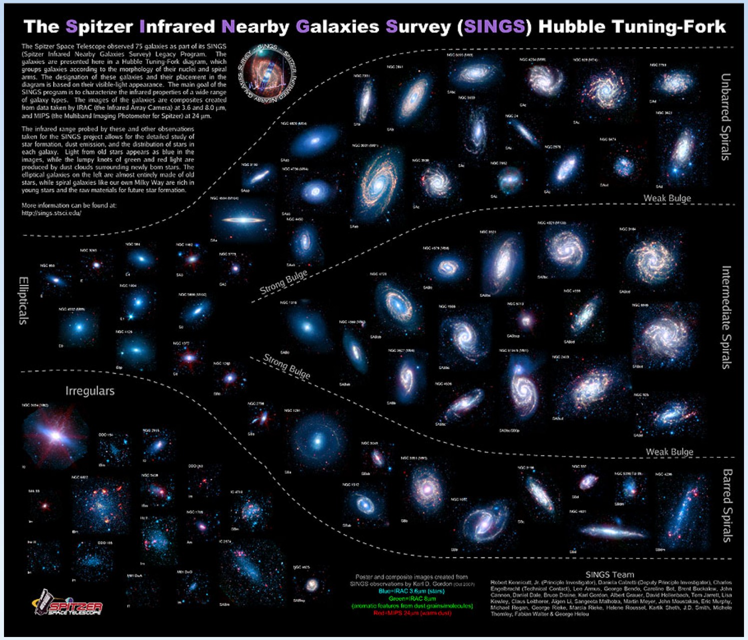
…collapse of the majority of gas is prevented

Star formation rates and efficiencies can be predicted from energy and momentum requirements to maintain ***ISM equilibrium*** *on scales ~H^3 in galactic disk*

Large-scale gas and SFR



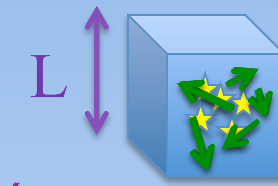


kpc-scale surveys

ISM energetics and feedback

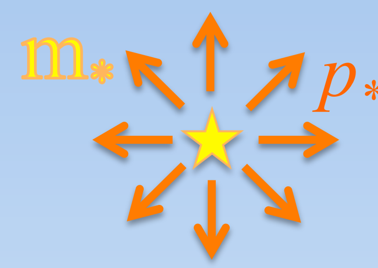
- Timescales for cooling and turbulent dissipation in the diffuse ISM are short
- To maintain equilibrium, radiated energy must be replenished
- Energy input is from high-mass stars
- Midplane pressure $\propto$ energy density must support weight of diffuse ISM
  - weight depends on gravity of gas, stars, dark matter
- *ISM equilibrium **demands** a certain level of feedback*

Quantifying self-regulation



Gas mass M, size L^3, turbulence v, SFR $\dot{M}_*$

- Assume SF feedback momentum/mass is p_*/m_*



- Momentum input rate is

$$\dot{p}_{driv} = \frac{p_*}{m_*}\dot{M}_*$$

- Momentum dissipation rate is

$$\dot{p}_{diss} \sim \frac{vM}{t_{dyn}} \sim \frac{v^2 M}{L}$$

- Balancing, $\dot{M}_* \sim \frac{v^2 M}{L p_*/m_*}$

- For system in dynamical equilibrium $v^2 \sim GM_{tot}/L$

(Kin. E ~ Grav. E)

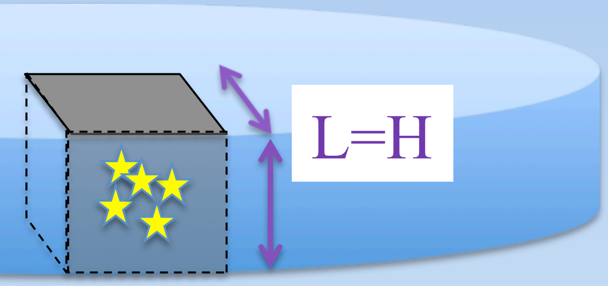
$\Rightarrow$

$$\dot{M}_* \sim \frac{G M_{tot} M}{L^2 p_*/m_*}$$

Self-regulated star formation

Gas-dominated starburst disk

$$\dot{M}_* \sim \frac{GM_{tot}M}{L^2 p_*/m_*} \longrightarrow \frac{\dot{M}_*}{L^2} \sim \frac{GM^2}{L^4(p_*/m_*)}$$



$$\dot{M}_*/H^2 \rightarrow \Sigma_{SFR}$$

$$M/H^2 \rightarrow \Sigma$$

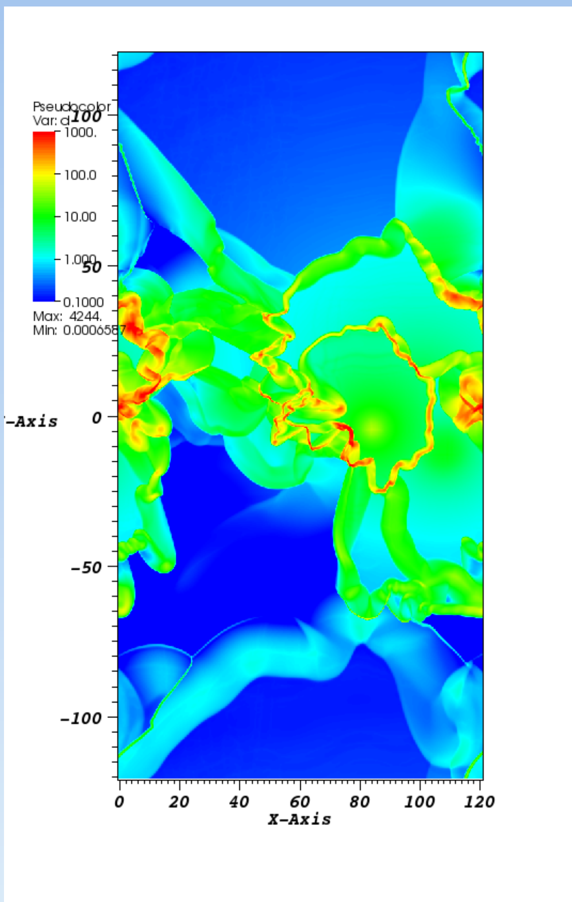
$$\Sigma_{\rm SFR} \sim \frac{G\Sigma^2}{p_*/m_*}$$

- Star formation rate per unit area in disk is
  - *independent* of details of turbulence
  - *independent* of small-scale collapse rate

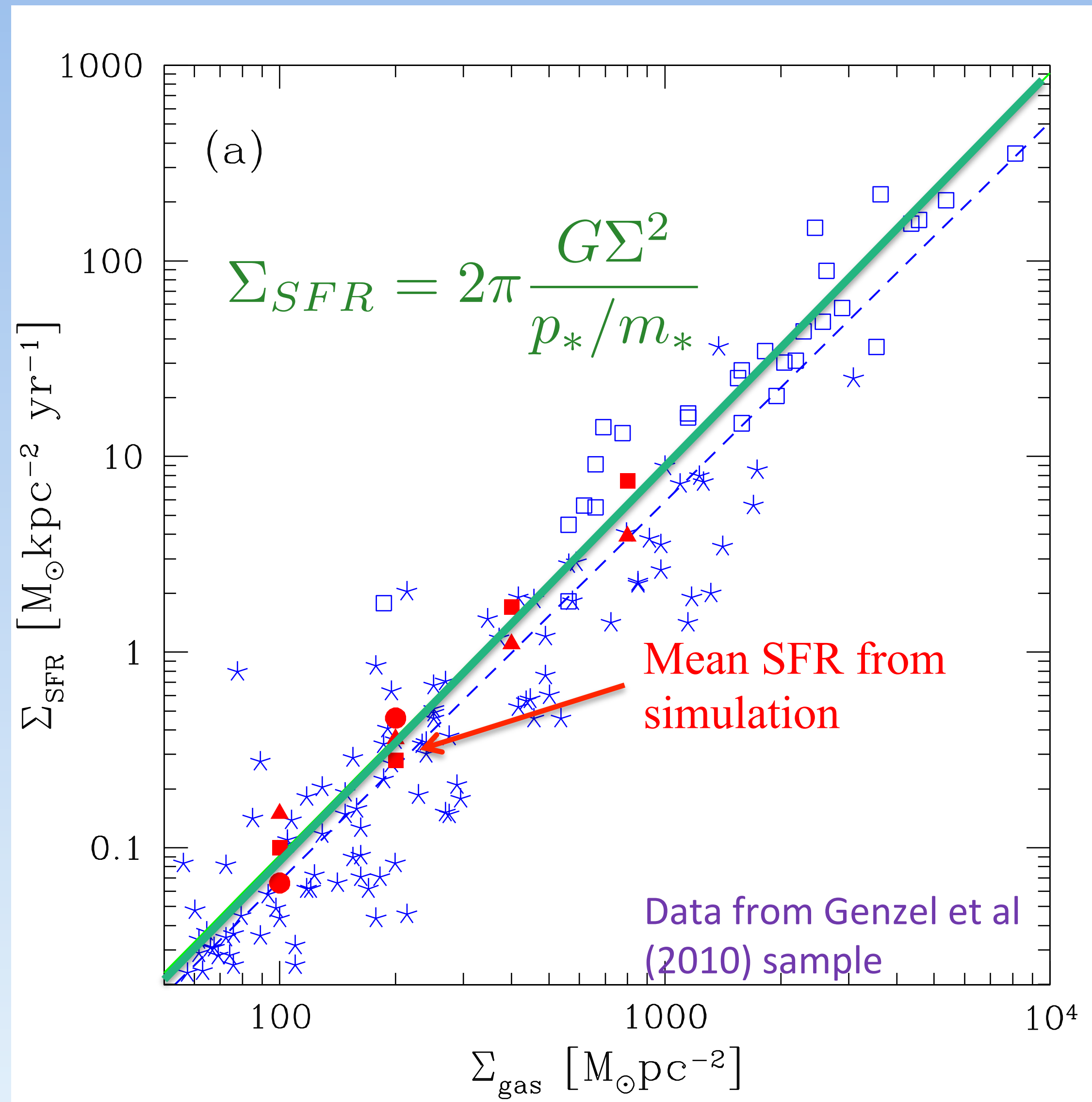
$\pi G\Sigma^2/2$ = weight of gas = Pressure

- Disk thickness and internal dynamical time must adjust until momentum feedback rate matches vertical gravitational force on ISM

Starburst regime



Ostriker & Shetty (2011)



Adopt: **p_*=300,000 km/s** for SNR with "momentum feedback," isothermal EOS

Self-regulation in outer disks

Allowing for *thermal* and *magnetic* as well as *turbulent* feedback to atomic gas, $P_{th} = \eta_{th}\,\Sigma_{SFR}$, $\delta P_{mag} = \eta_{mag}\,\Sigma_{SFR}$ and $P_{turb} = \eta_{turb}\,\Sigma_{SFR}$, leading to

$$\Sigma_{SFR} = (P_{th} + \delta P_{mag} + P_{turb})/(\eta_{th} + \eta_{mag} + \eta_{turb}) = P_{DE}/\eta_{tot}$$

for

$$P_{DE} = \frac{\Sigma}{2} g_z \approx \frac{\pi G \Sigma^2}{2} + \Sigma (2G\rho_*)^{1/2} \sigma_z$$

depending only on the total gravity and total gas surface density of the disk from vertical dynamical equilibrium

- General result is

$$\Sigma_{SFR} = 2 \times 10^{-3} M_\odot \text{ kpc}^{-2} \text{yr}^{-1} \left(\frac{P/k}{10^4 \text{cm}^{-3} \text{K}} \right)$$

and for disk regions where stellar gravity dominates:

$$\Sigma_{SFR} = 2 \times 10^{-3} M_\odot \text{kpc}^{-2} \text{yr}^{-1} \left(\frac{\Sigma}{10 M_\odot \text{pc}^{-2}} \right) \left(\frac{\rho_*}{0.1 M_\odot \text{pc}^{-3}} \right)^{1/2}$$

Ostriker, McKee, & Leroy (2010); Kim, Kim, & Ostriker (2011), Kim, Ostriker, Kim (2013), Kim & Ostriker (2015)

Exercise

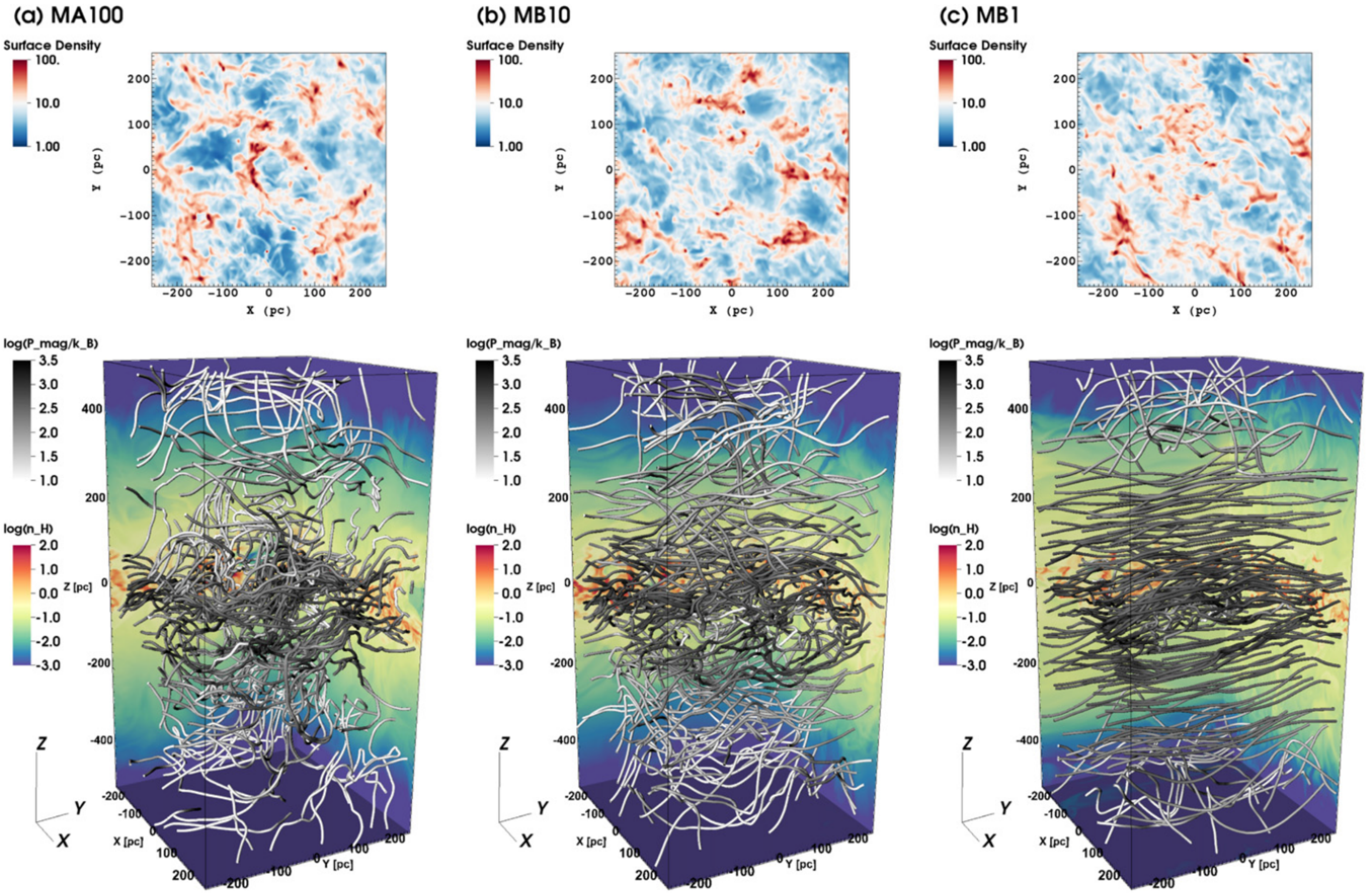
- Integrating vertical component of momentum equation

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla \cdot \left[\rho\mathbf{v}\mathbf{v} - \frac{\mathbf{B}\mathbf{B}}{4\pi} + \mathbf{I}(P + \frac{B^2}{8\pi})\right] = -\rho\nabla\Phi$$

from z to z_{max} in steady state, show:

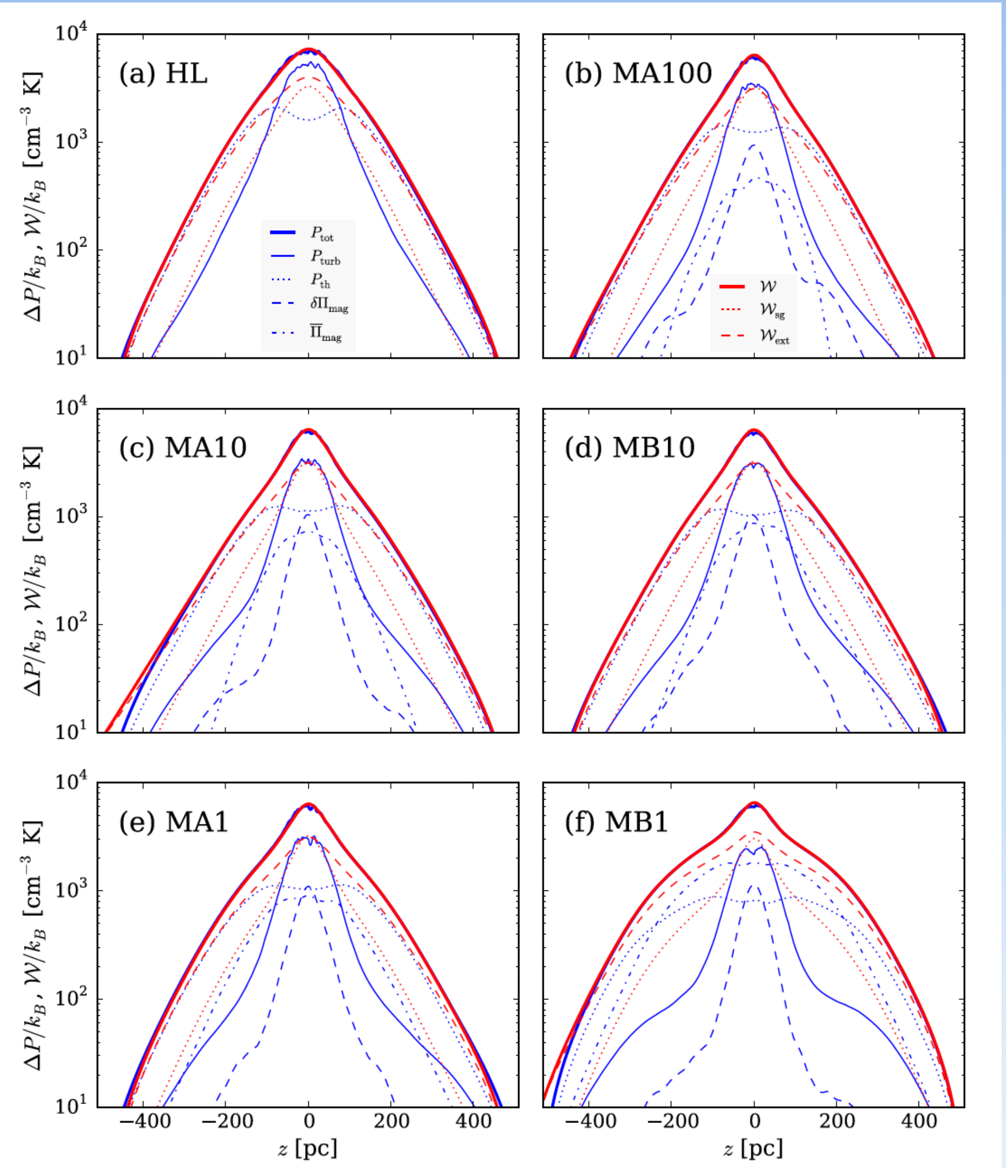
$$\langle \rho v_z^2 + P\rangle_z + \left\langle \frac{|\mathbf{B}|^2}{8\pi} - \frac{B_z^2}{4\pi}\right\rangle\Big|_z^{z_{max}} = -\int_z^{z_{max}} \rho\frac{\partial\Phi}{\partial z}dz$$

For z=0 and Φ_{gas}, show $-\int_0^{z_{max}} \rho\frac{\partial\Phi}{\partial z}dz = \frac{\pi G\Sigma^2}{2}$

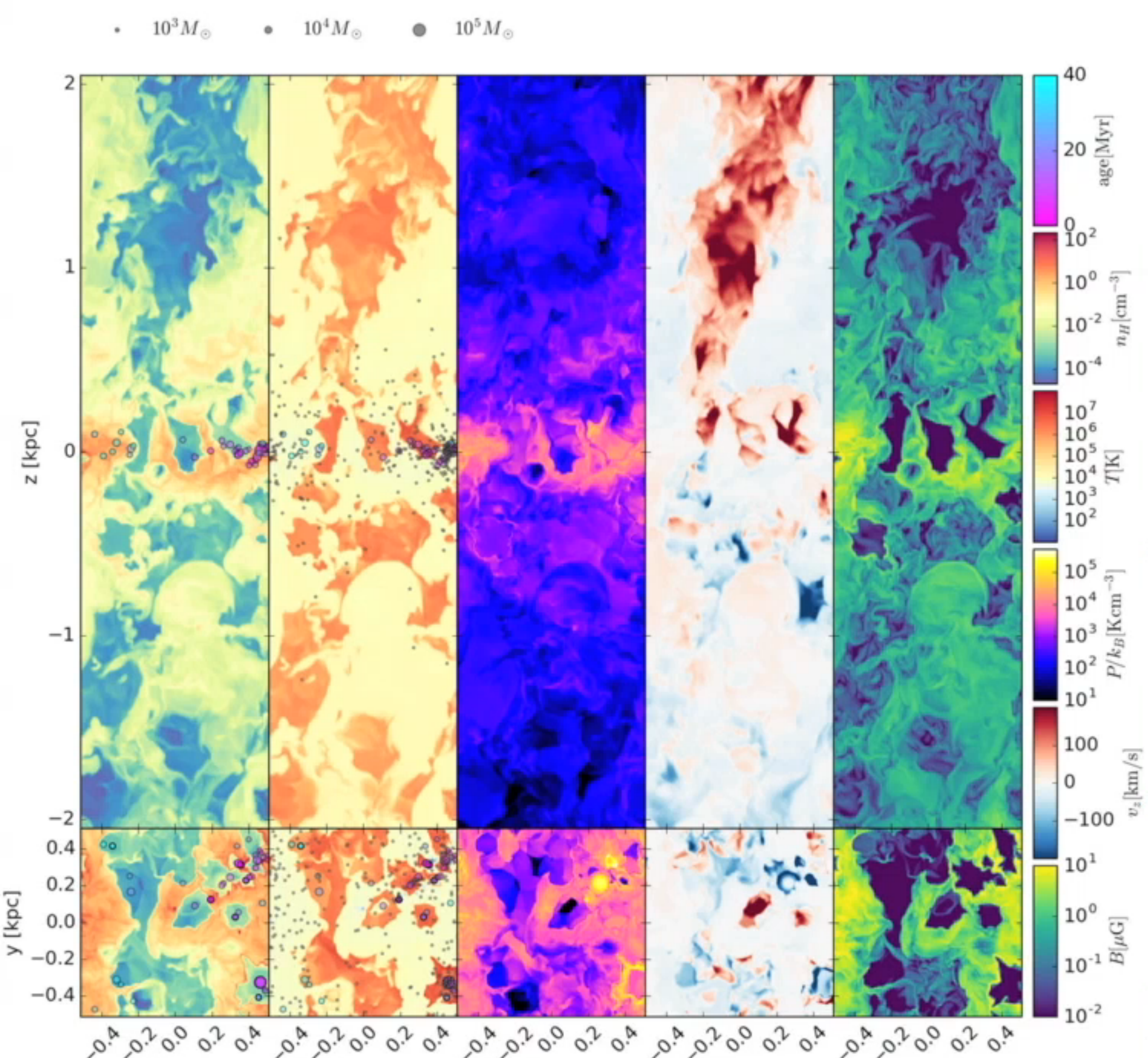


Kim & Ostriker (2015)

Vertical equilibrium



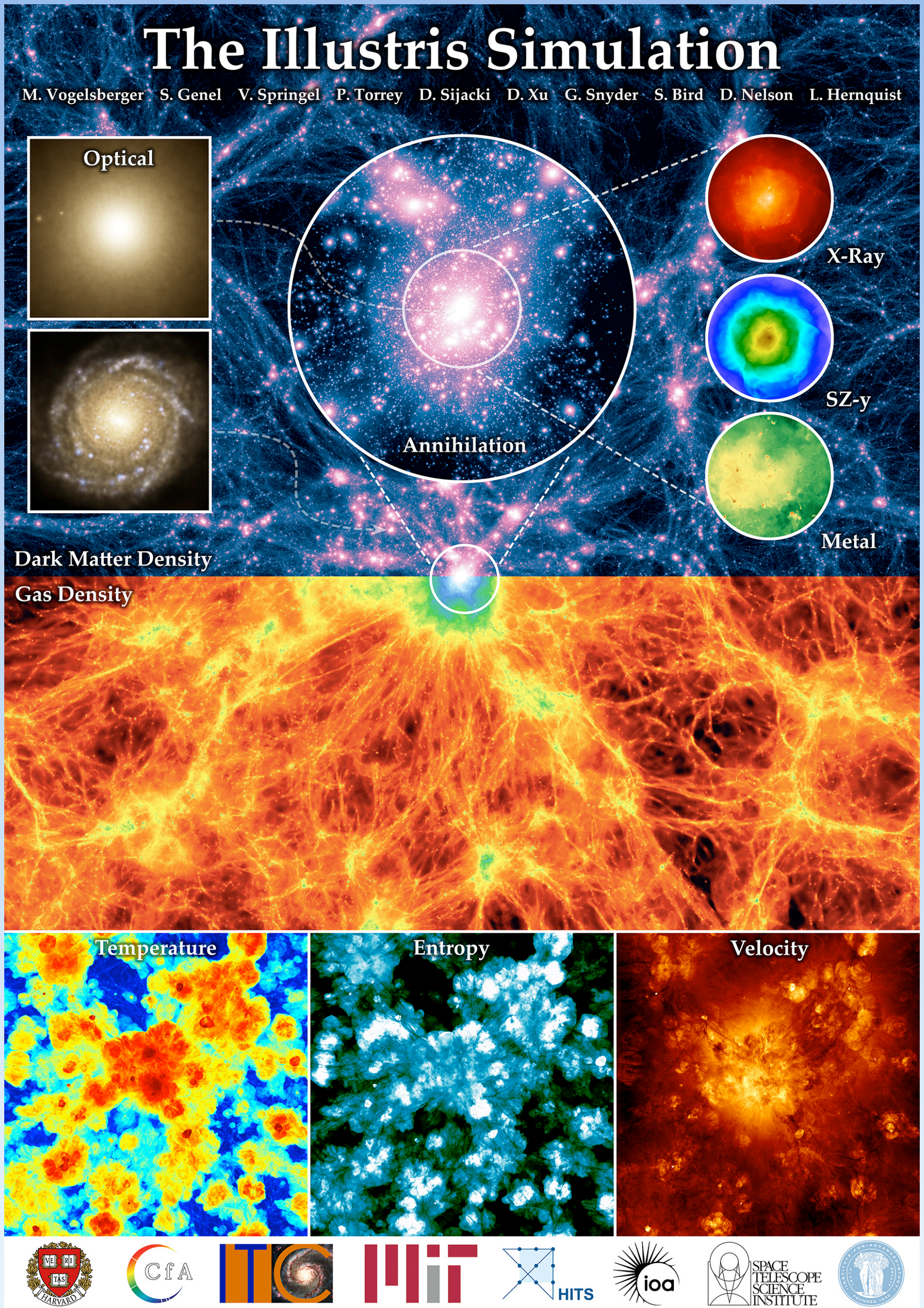
Kim & Ostriker (2015)



$10^3 M_\odot$
$10^4 M_\odot$
$10^5 M_\odot$
z [kpc]
y [kpc]
age[Myr]
$n_H[\mathrm{cm}^{-3}]$
$T[\mathrm{K}]$
$P/k_B[\mathrm{Kcm}^{-3}]$
$v_z[\mathrm{km/s}]$
$B[\mu\mathrm{G}]$

“Only connect.”

-- E.M. Forster



…and a final word

Think◆Read◆Act

Read◆Act◆Think

Act◆Think◆Read

"All this will not be finished in the first 100 days. Nor will it be finished in the first 1,000 days… But let us begin.

In your hands, my fellow citizens, more than in mine, will rest the final success or failure of our course." -- J.F. Kennedy (1961)