The formation of high mass stars from cores

Jonathan Tan
(University of Florida)

Karl Jaehnig, Michael Butler, Audra Hernandez
Elizabeth Tasker
Peter Barnes, Elizabeth Lada, Charlie Telesco

Christopher McKee (UCB),
Mark Krumholz (UCSC)

UF Astronomy

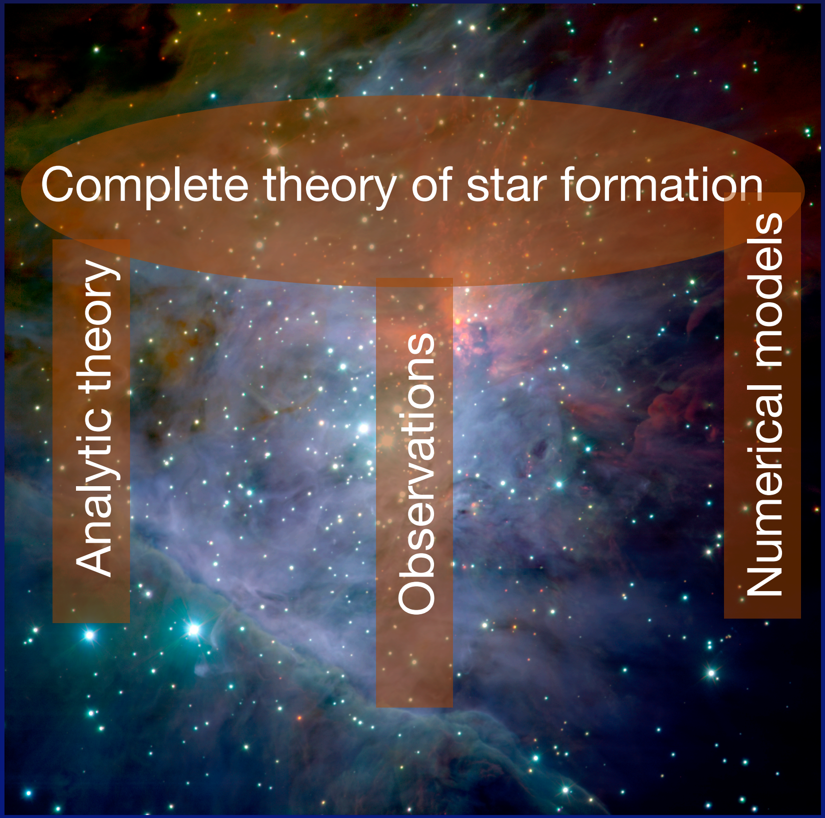
Star Formation: A complicated, nonlinear process

Physics:

Gravity vs pressure (thermal, magnetic, turbulence, radiation, cosmic rays) and shear.

Heating and cooling, generation and decay of turbulence, generation (dynamo) and diffusion of B-fields, etc.

Chemical evolution of dust and gas.



Wide range of scales (~10 dex in space, time) and multidimensional.

Uncertain/unconstrained initial conditions/boundary conditions.

Star Formation: Open Questions

- Causation: external triggering or spontaneous gravitational instability?
- Initial conditions: how close to equilibrium?
- Accretion mechanism: turbulent fragmentation vs competitive accretion
- Timescale: fast or slow?
- End result
  - Initial mass function (IMF)
  - Binary fraction and properties
  - Initial cluster mass function (ICMF)
  - Efficiency and Rate (& relation to galaxy-scale)

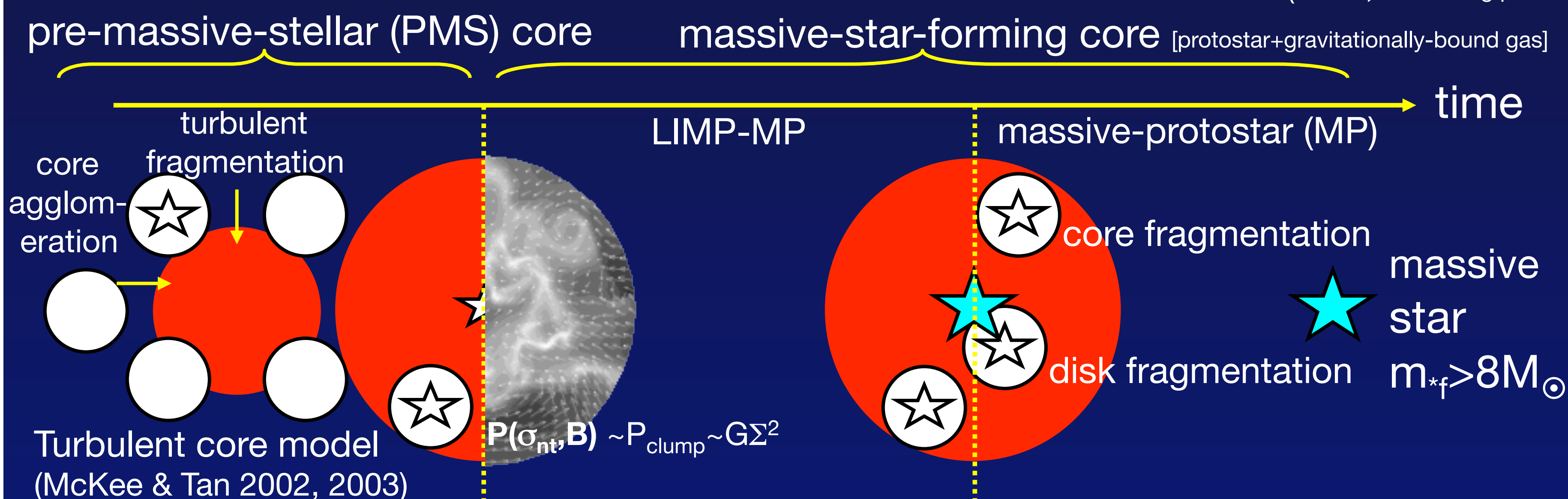
How do these properties vary with environment?

Local Massive Star and Star Cluster Formation

How do we start our theoretical models?
What are the observed initial conditions?
What is the formation mechanism for massive stars?
What is the timescale of star cluster formation?
Effect of metallicity, cluster mass, crowding, etc on IMF?

Schematic Differences Between Massive Star Formation Theories

Beuther, Churchwell, McKee, Tan (2007, PPV); Tan (2008, Heidelberg proceedings)



Criticisms: based on simulations with limitations of:

1. Isothermal EOS (Dobbs, Bonnell, Clark 2005; Urban & Evans)
2. No B-fields (Price & Bate 2008; Padoan et al.)
3. No feedback (Edgar & Clarke 2004; Krumholz, Klein, McKee 2007)
4. Global collapse of clump (Krumholz, McKee, Klein 2005)
5. Poor spatial resolution of mergers (e.g. collision radius ~2AU)

Competitive Bondi-Hoyle accretion model
(Bonnell ea. 2001; Bonnell & Bate 2006)

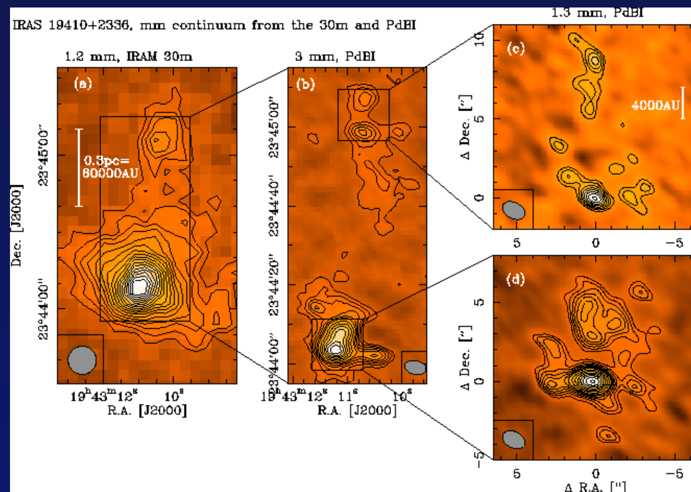
protostellar mergers?
(Bonnell et al. 1998; Clarke & Bonnell 2008)

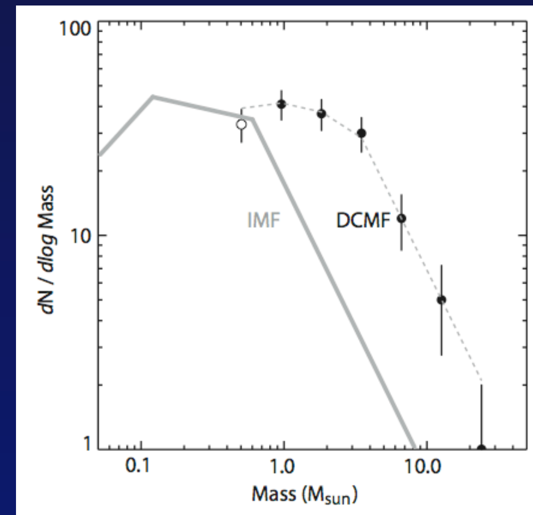
t=0
protostar
formation

$m_* = 8M_\odot$

Observed Cores:
Mass Function; Turbulent Motions; Magnetic Fields

Cores are seen, both with and without stars. Mass function of cores appears similar to stellar IMF (Testi & Sargent 1998; Motte et al. 2001; Beuther & Schilke 2004; Mike Reid & Wilson 2005; Alves et al. 2007)





No break seen in stellar IMF (Massey 1998)

Larger cores have line widths that are much broader than thermal (e.g. Caselli & Myers 1995)

Strength of B-field vs. Σ (Crutcher 2005; Falgarone et al. 2008)

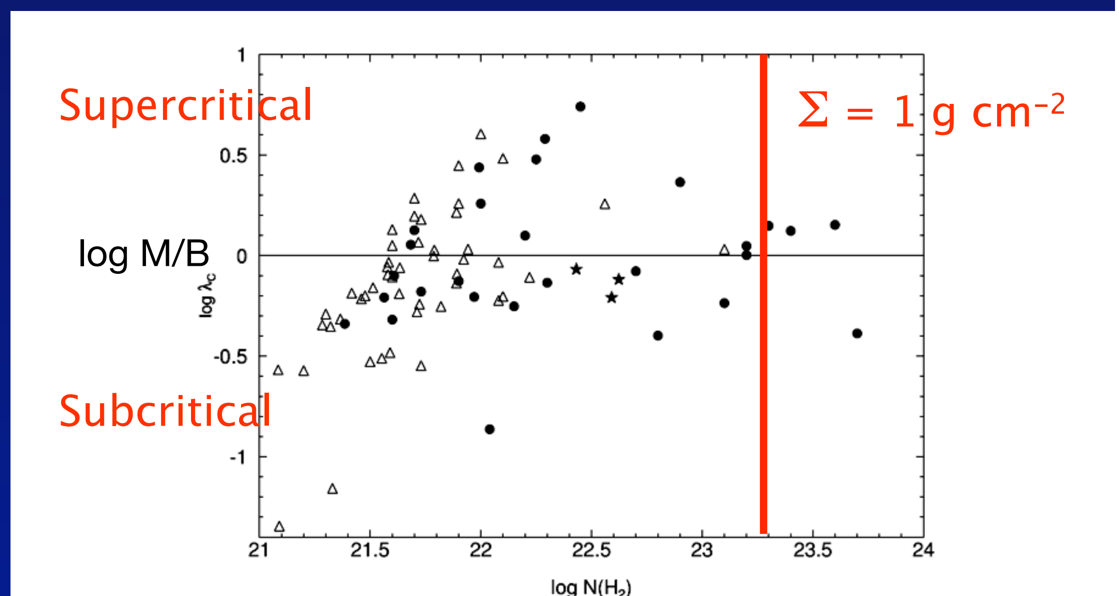
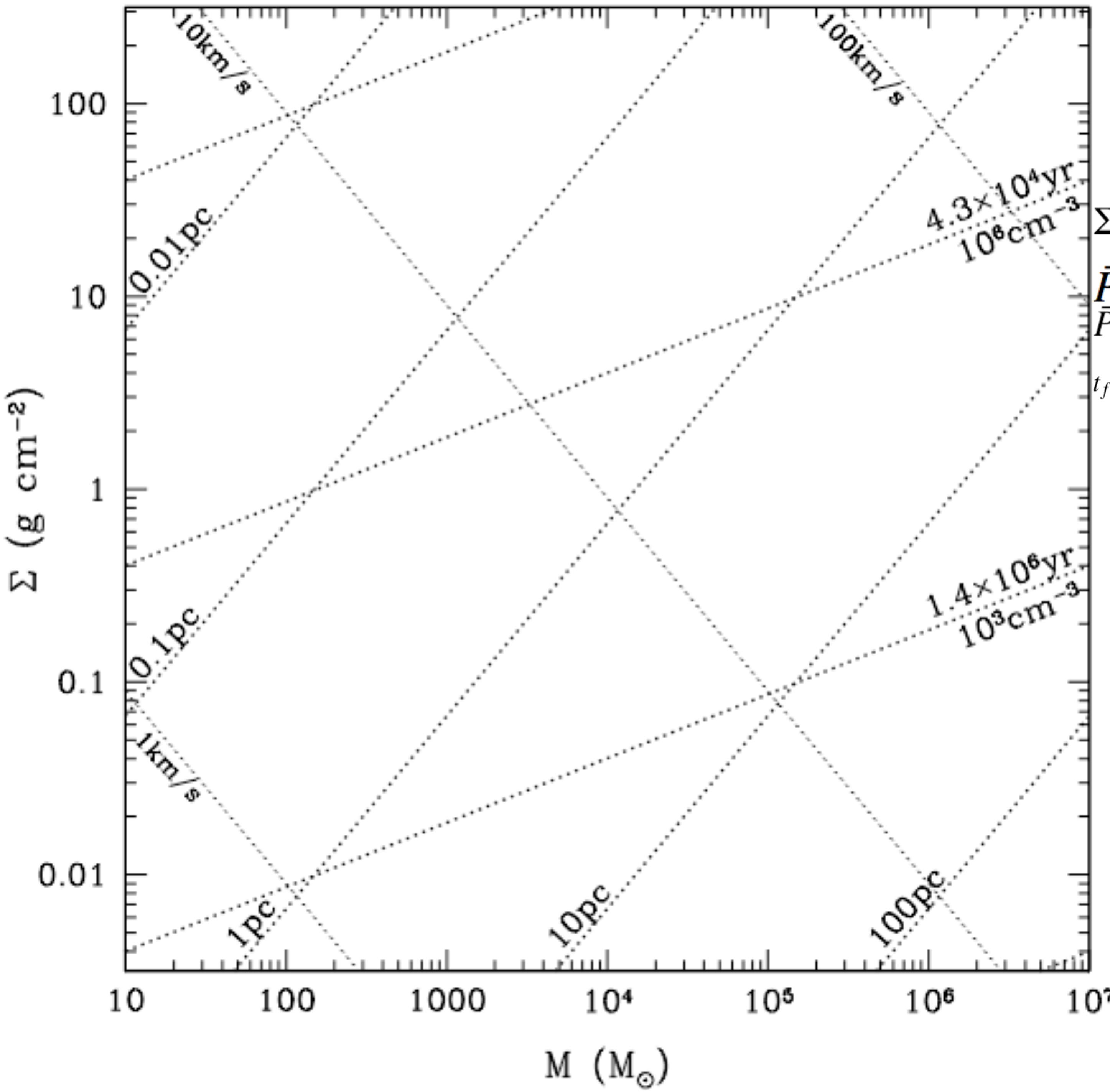


Figure 2: λ_C are the observed mass to magnetic flux ratios (eq. 3), divided by 3 to correct for projection bias (eq. 4), in units of the critical values. $\lambda_C > 1$ is supercritical, $\lambda_C < 1$

Overview of Physical Scales



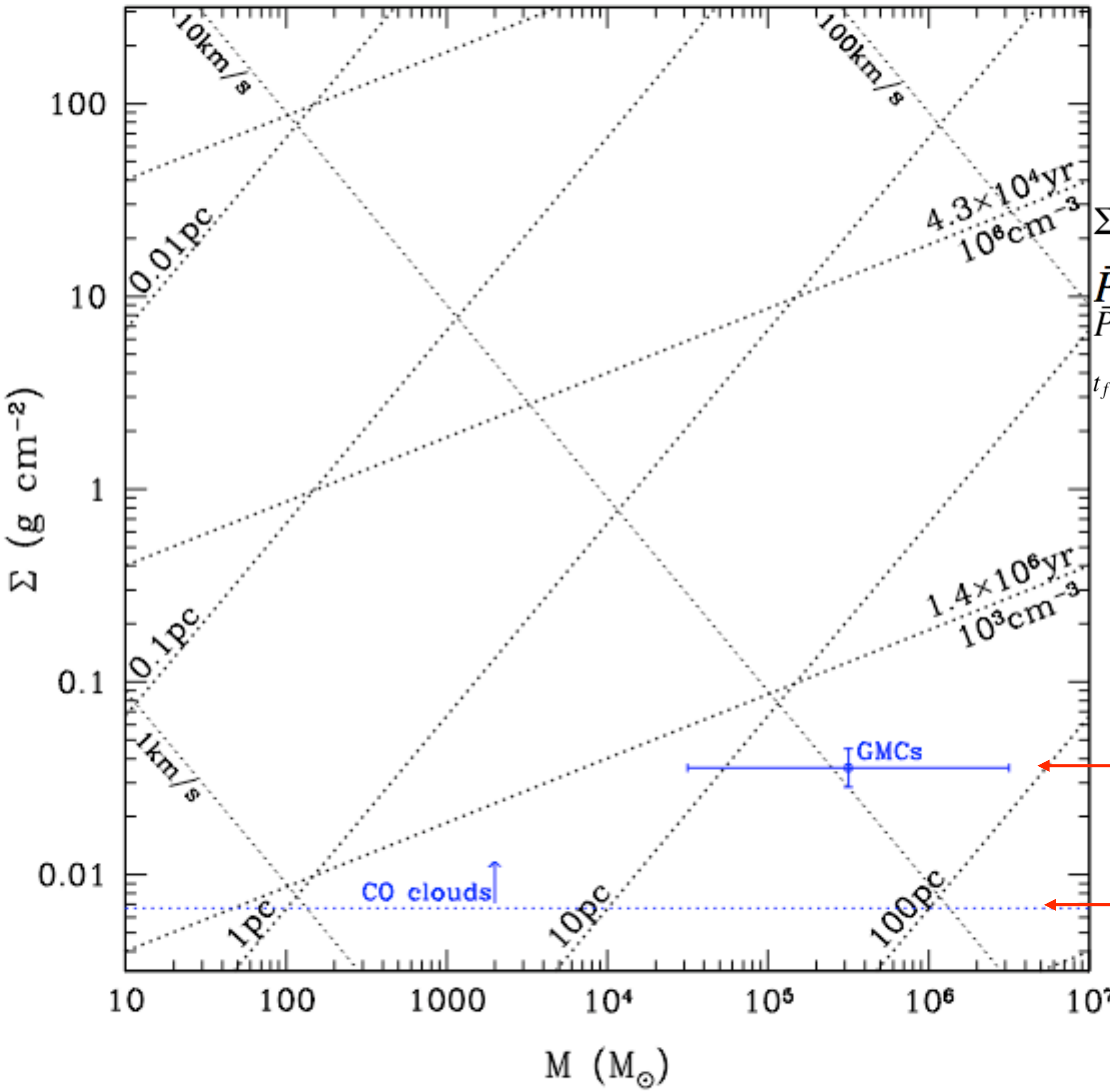
$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K \, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

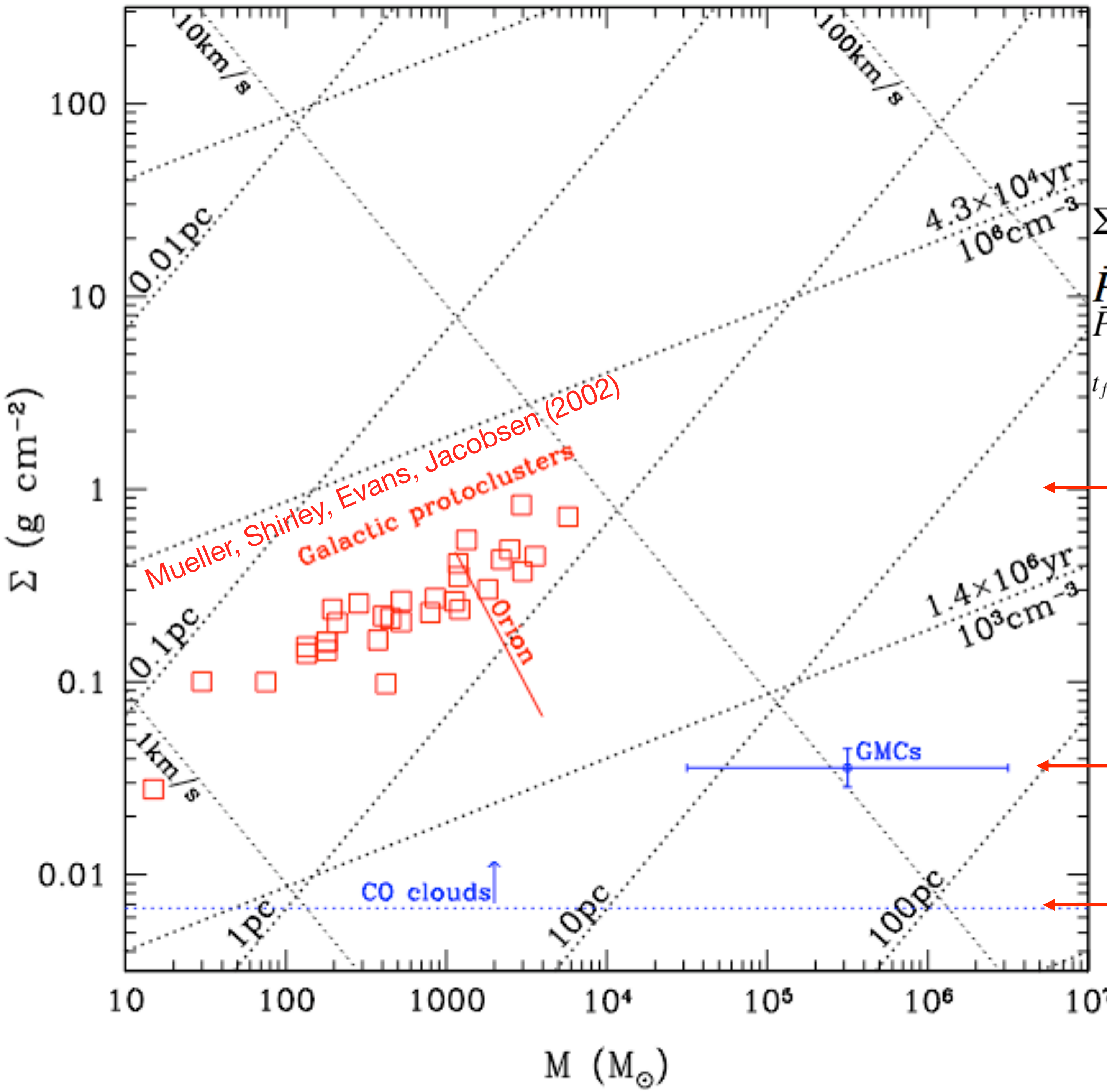
$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

$A_V=7.5$
$N_H=1.6\text{x}10^{22}\text{cm}^{-2}$
$\Sigma=180\ M_\odot\ \text{pc}^{-2}$

$A_V=1.4$
$N_H=3.0\text{x}10^{21}\text{cm}^{-2}$
$\Sigma=34\ M_\odot\ \text{pc}^{-2}$

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K \, cm^{-3}$$

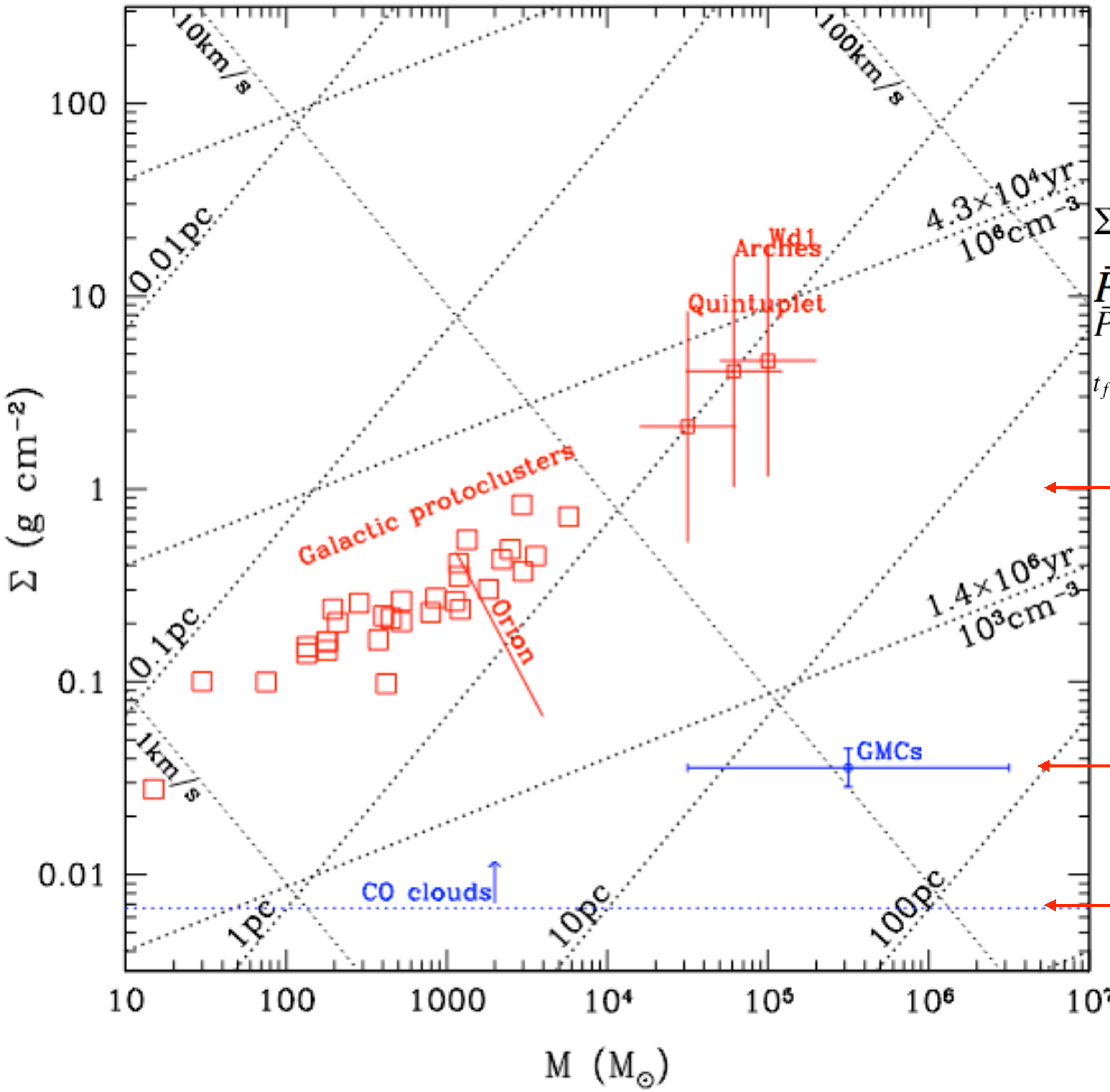
$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

$A_V=200$
$N_H=4.2\times10^{23} cm^{-2}$
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$N_H=1.6\times10^{22} cm^{-2}$
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21} cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K\, cm^{-3}$$

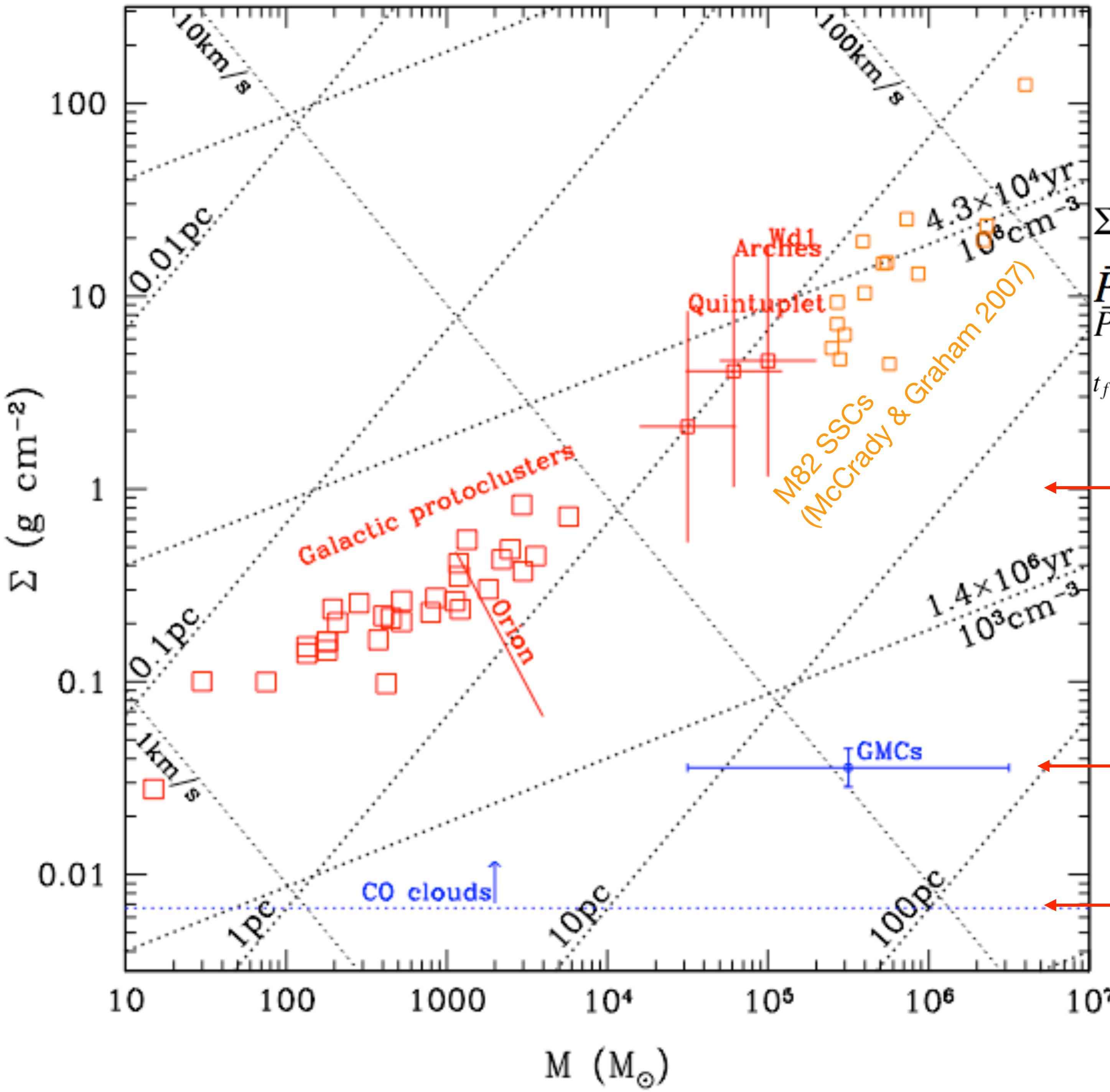
$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

A_V=200
N_H=4.2x10^{23}cm^{-2}
Σ=4800 $M_\odot$ pc^{-2}

A_V=7.5
N_H=1.6x10^{22}cm^{-2}
Σ=180 $M_\odot$ pc^{-2}

A_V=1.4
N_H=3.0x10^{21}cm^{-2}
Σ=34 $M_\odot$ pc^{-2}

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K\, cm^{-3}$$

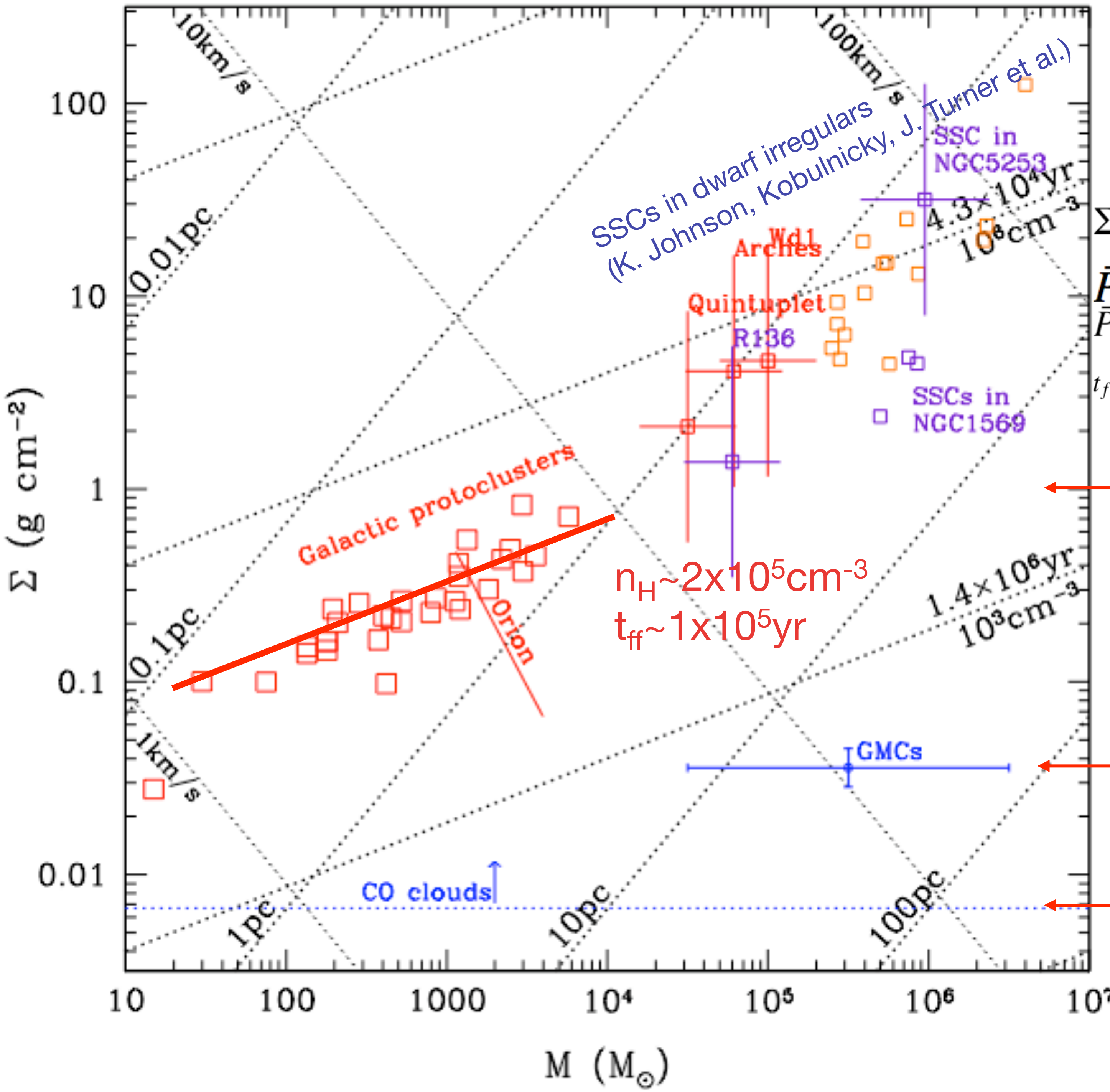
$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

A_V=200
N_H=4.2x10^{23}cm^{-2}
Σ=4800 $M_\odot$ pc^{-2}

A_V=7.5
N_H=1.6x10^{22}cm^{-2}
Σ=180 $M_\odot$ pc^{-2}

A_V=1.4
N_H=3.0x10^{21}cm^{-2}
Σ=34 $M_\odot$ pc^{-2}

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K \, cm^{-3}$$

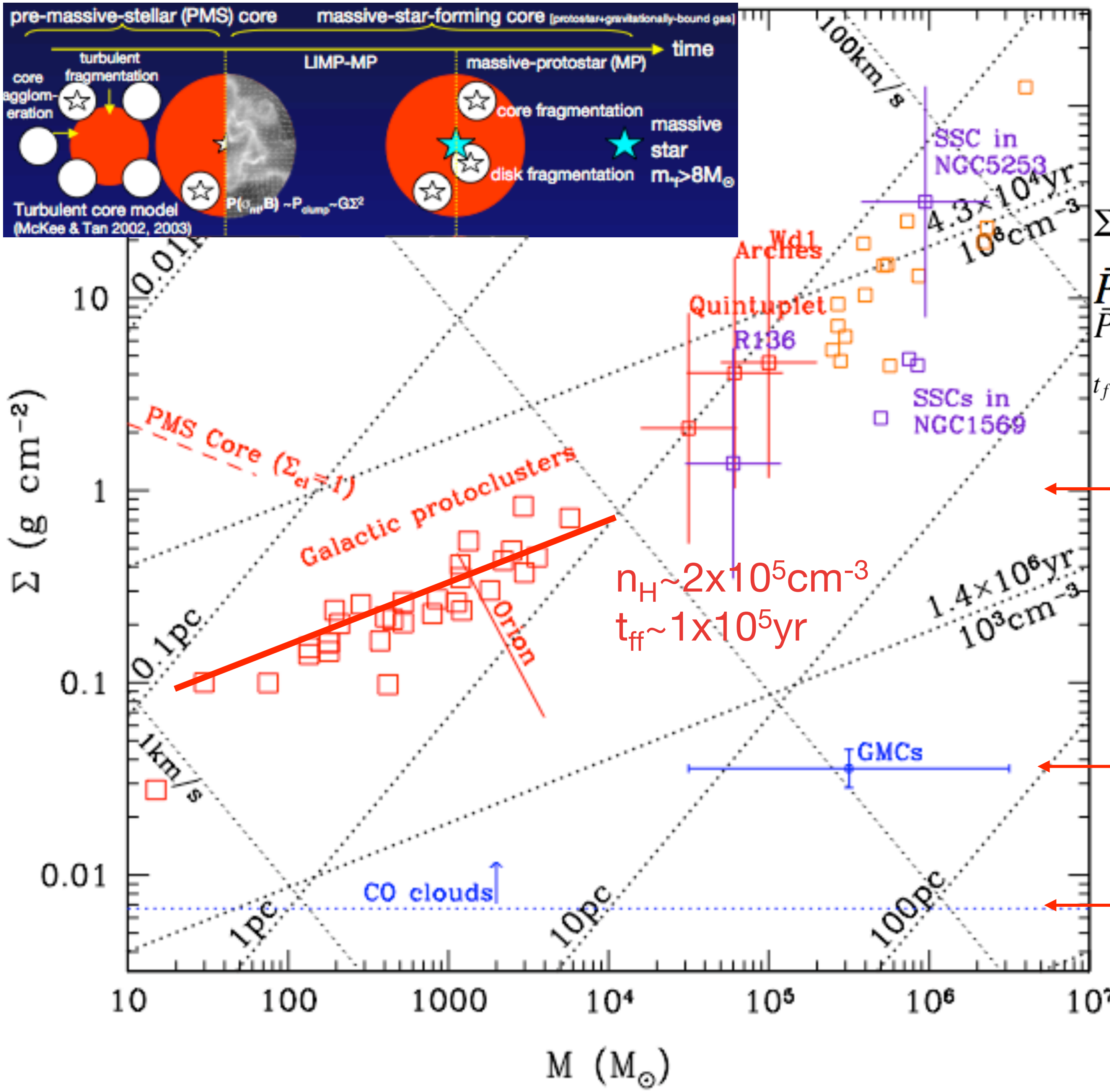
$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

$A_V=200$
$N_H=4.2\times10^{23} cm^{-2}$
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$N_H=1.6\times10^{22} cm^{-2}$
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21} cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

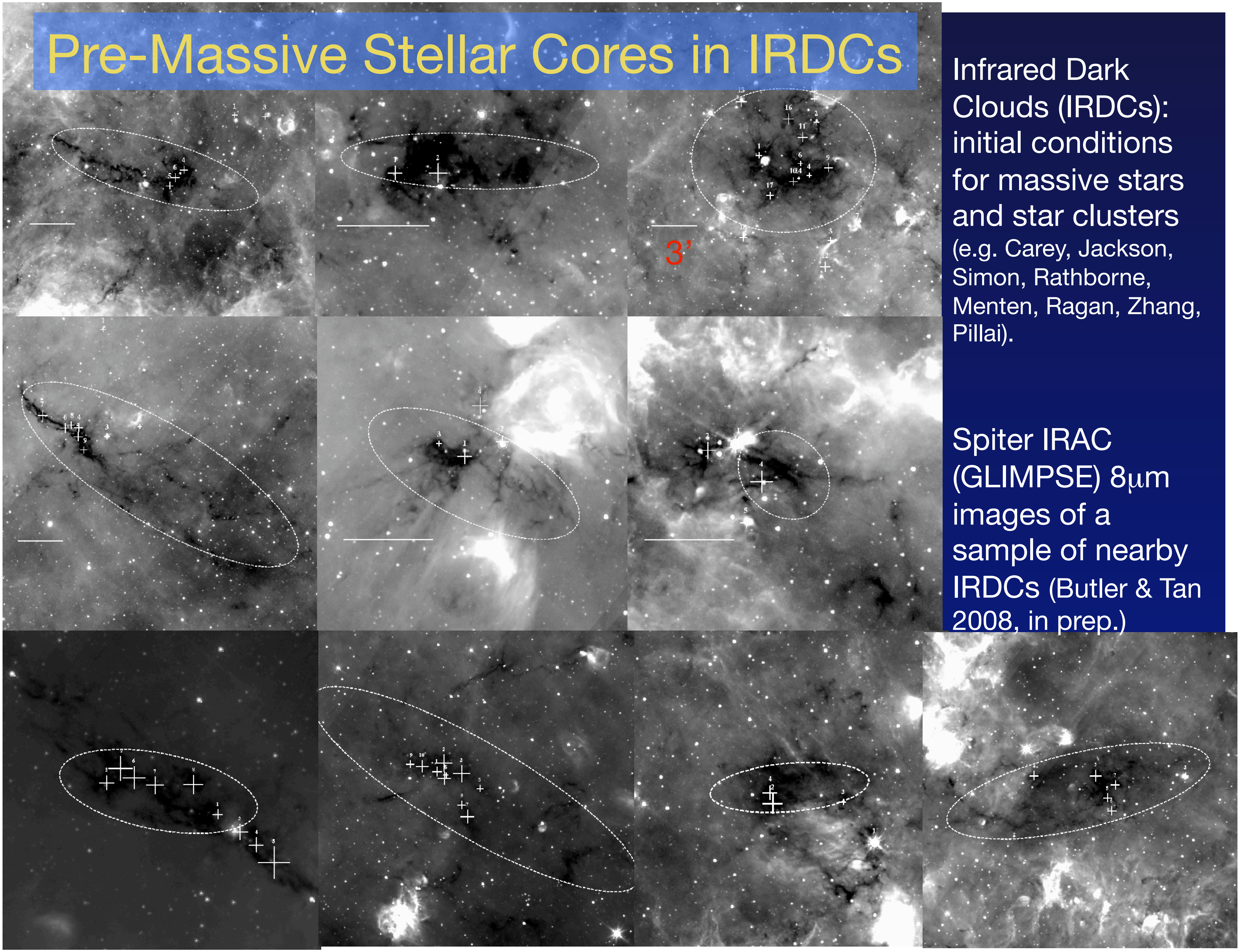
$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

$A_V=200$
$N_H=4.2\times10^{23}$cm^{-2}
$\Sigma=4800\ M_\odot$ pc^{-2}

$A_V=7.5$
$N_H=1.6\times10^{22}$cm^{-2}
$\Sigma=180\ M_\odot$ pc^{-2}

$A_V=1.4$
$N_H=3.0\times10^{21}$cm^{-2}
$\Sigma=34\ M_\odot$ pc^{-2}

Pre-Massive Stellar Cores in IRDCs

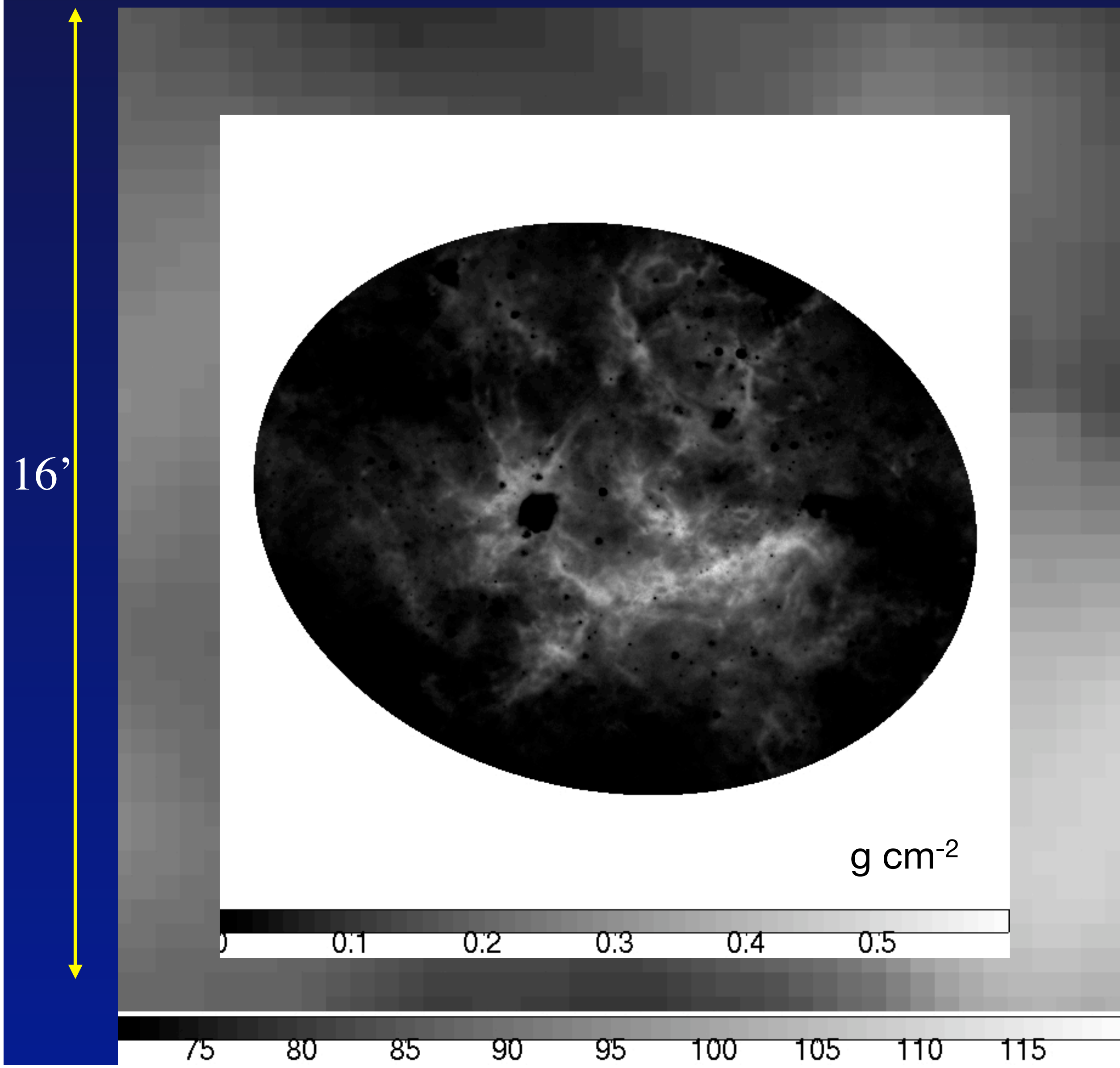


Infrared Dark Clouds (IRDCs): initial conditions for massive stars and star clusters (e.g. Carey, Jackson, Simon, Rathborne, Menten, Ragan, Zhang, Pillai).

Spiter IRAC (GLIMPSE) 8μm images of a sample of nearby IRDCs (Butler & Tan 2008, in prep.)

Extinction Mapping of Infrared Dark Clouds

Butler & Tan (2008) in prep.



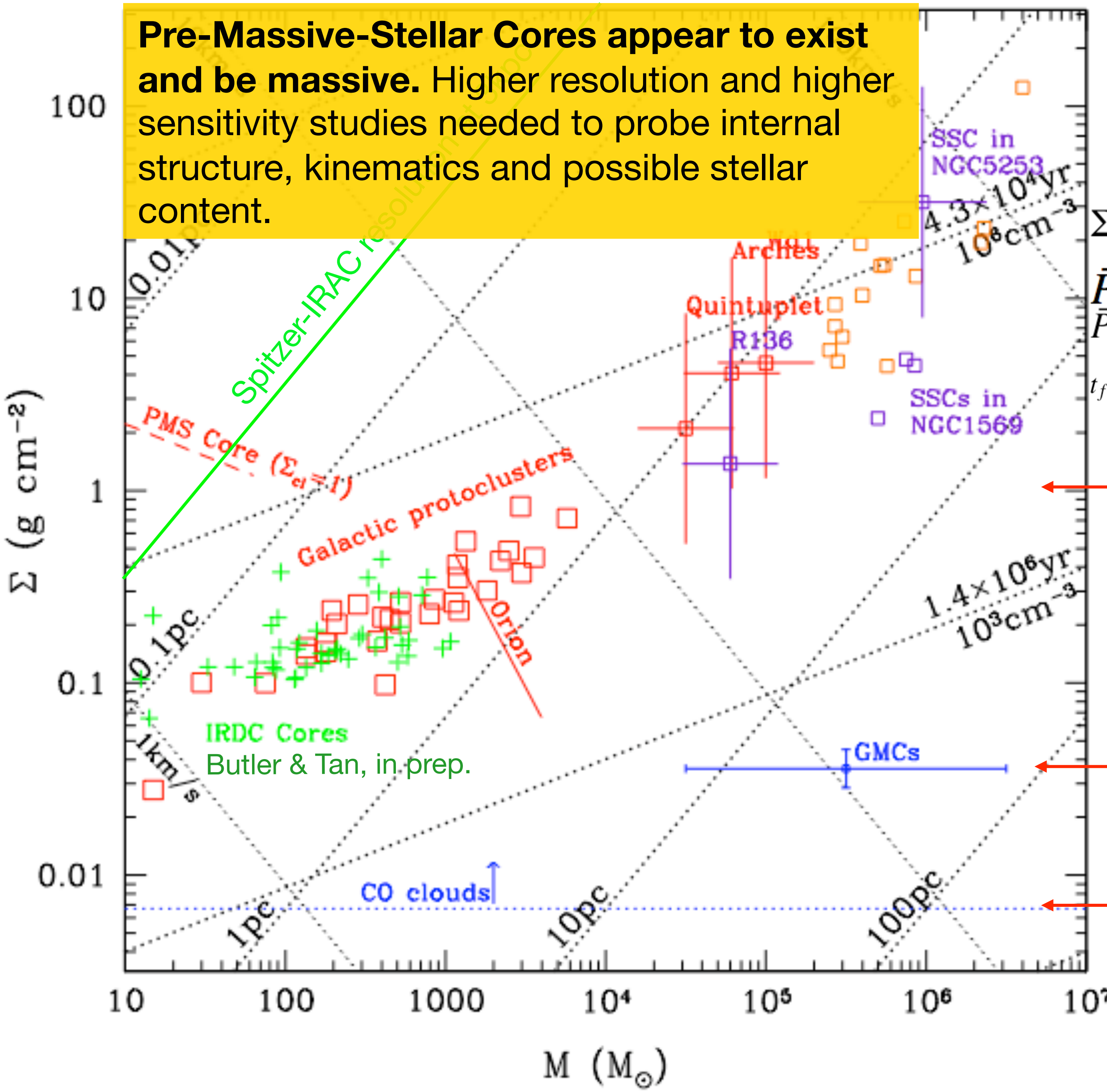
Spitzer - IRAC 8μm (GLIMPSE)

Extinction map to derive Σ

Kinematic distance (near) from molecular line velocities (GRS) -> M(Σ)

IRDC Cores

Pre-Massive-Stellar Cores appear to exist and be massive. Higher resolution and higher sensitivity studies needed to probe internal structure, kinematics and possible stellar content.



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

$A_V=200$
$N_H=4.2\times10^{23} cm^{-2}$
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$N_H=1.6\times10^{22} cm^{-2}$
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21} cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

Statistics of Pre-Massive-Stellar Cores

Number in the Galaxy: (see also Zinnecker & Yorke 2007)

If lifetime of this phase is ~ t_{*f} ~ 10^5yr,

then for a Galactic SFR of $3M_{\odot}yr^{-1}$

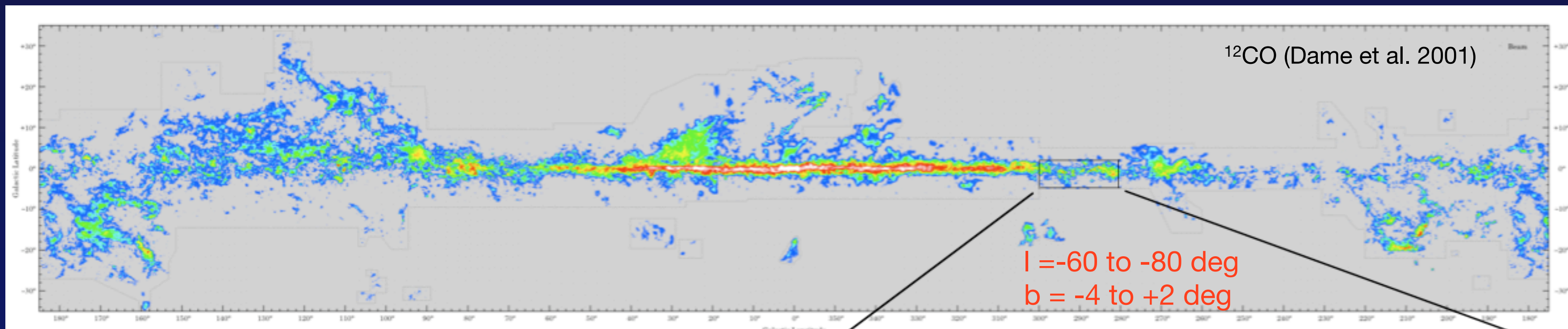
and an IMF yielding 1 massive star per 130 $M_{\odot}$ (Salpeter 0.1-120$M_{\odot}$)

and 2/3 of massive stars are forming in binaries,

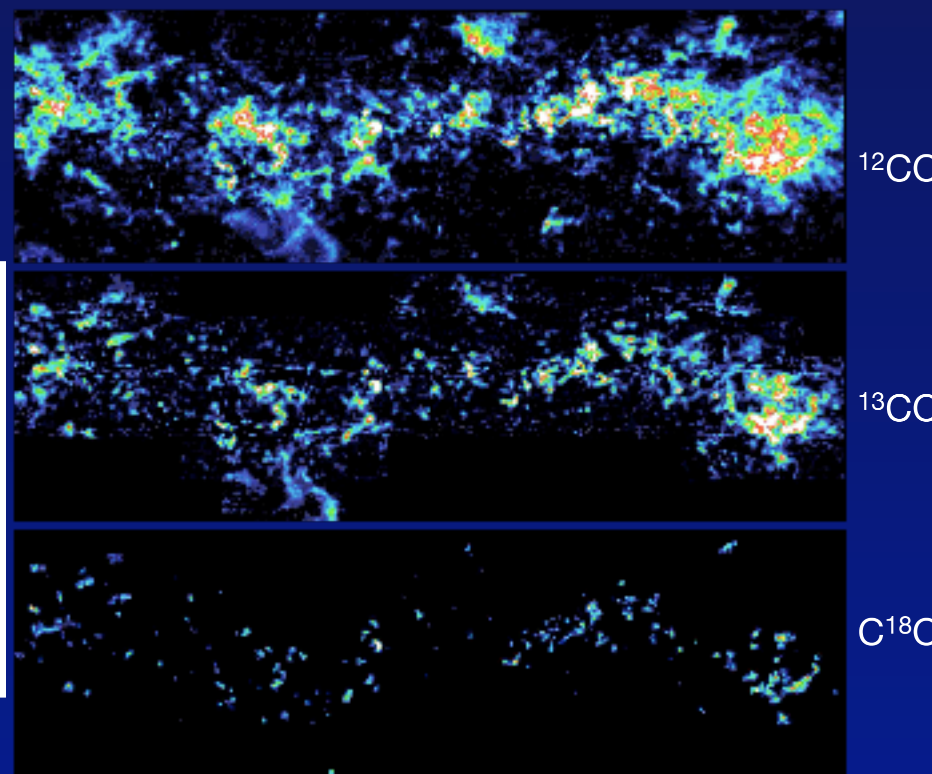
we expect 1500 PMS cores in the Galaxy.

Barnes, Yonekura, Ryder, Hopkins, Fukui, et al. (2008): see poster

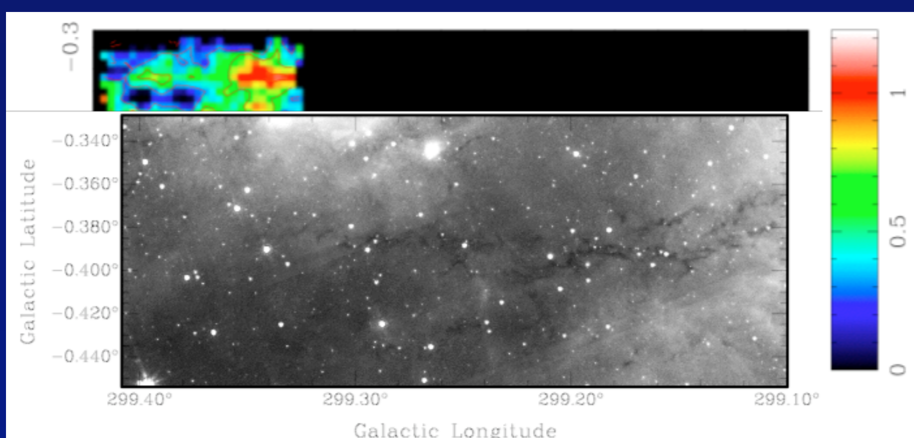
Census of High and Medium Mass Protostars (CHaMP)



MOPRA mapping survey (36", 0.1km/s) of ~200 clumps in dense gas tracers: e.g. HCO^+(1-0), N_2H^+(1-0), HCN(1-0)



Nanten CO survey



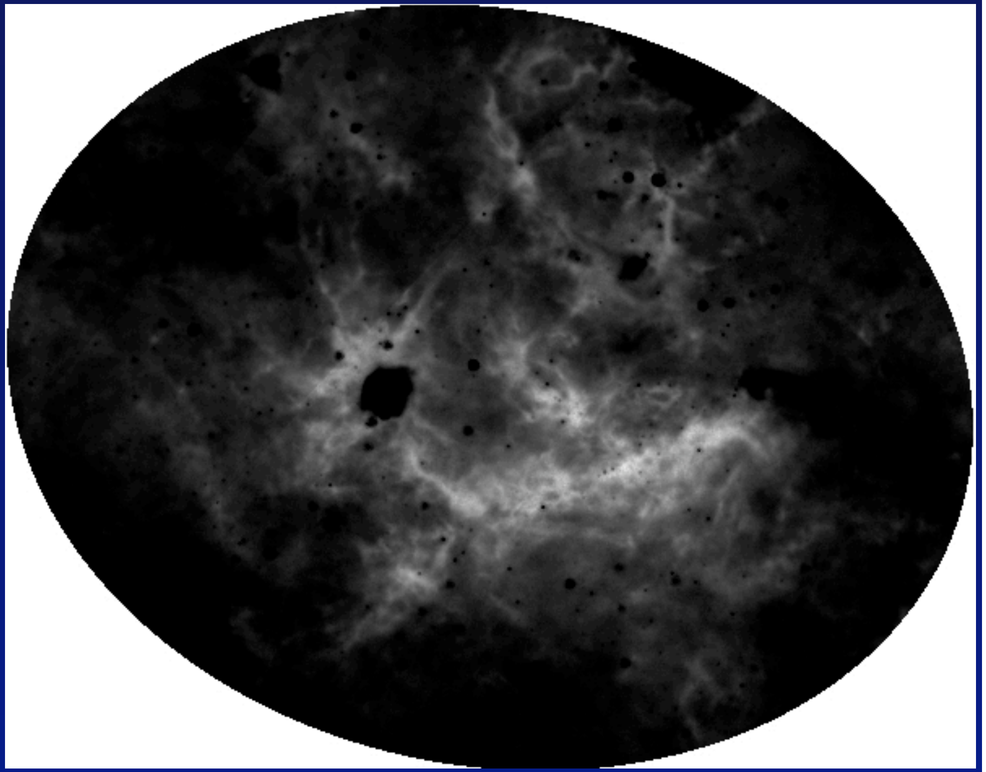
GLIMPSE 8 micron

McKee & Williams (1997) SFR(R) ->
CHaMP covers 5% of Galactic SFR -> 75 PMS cores

Physical properties of the clump gas: turbulence? virial equilibrium? infall?

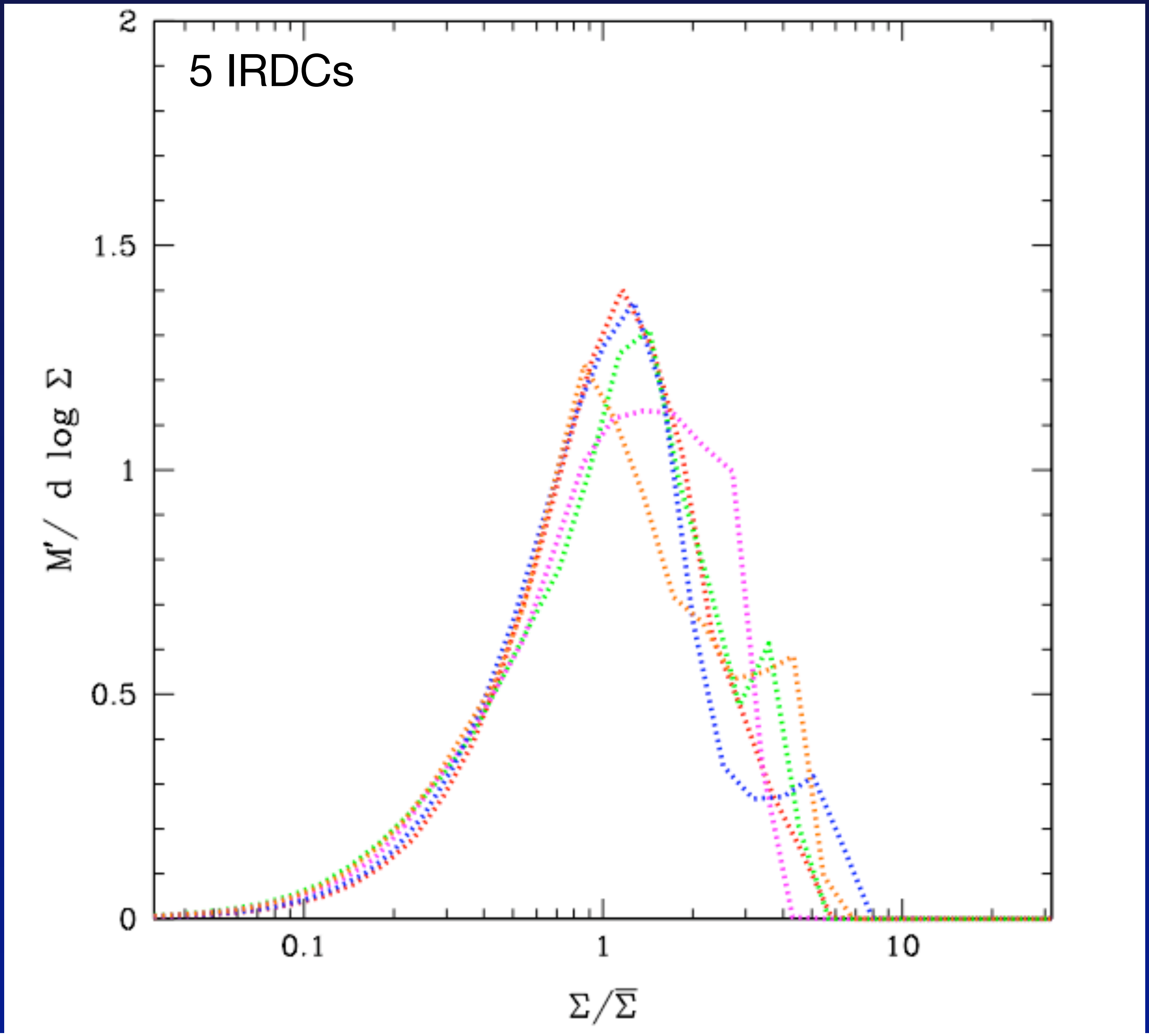
1. Comparison of IRDC extinction map structure to simulations of turbulence.

Eulerian (AMR) driven turbulence
(Offner, Krumholz, Klein, McKee)

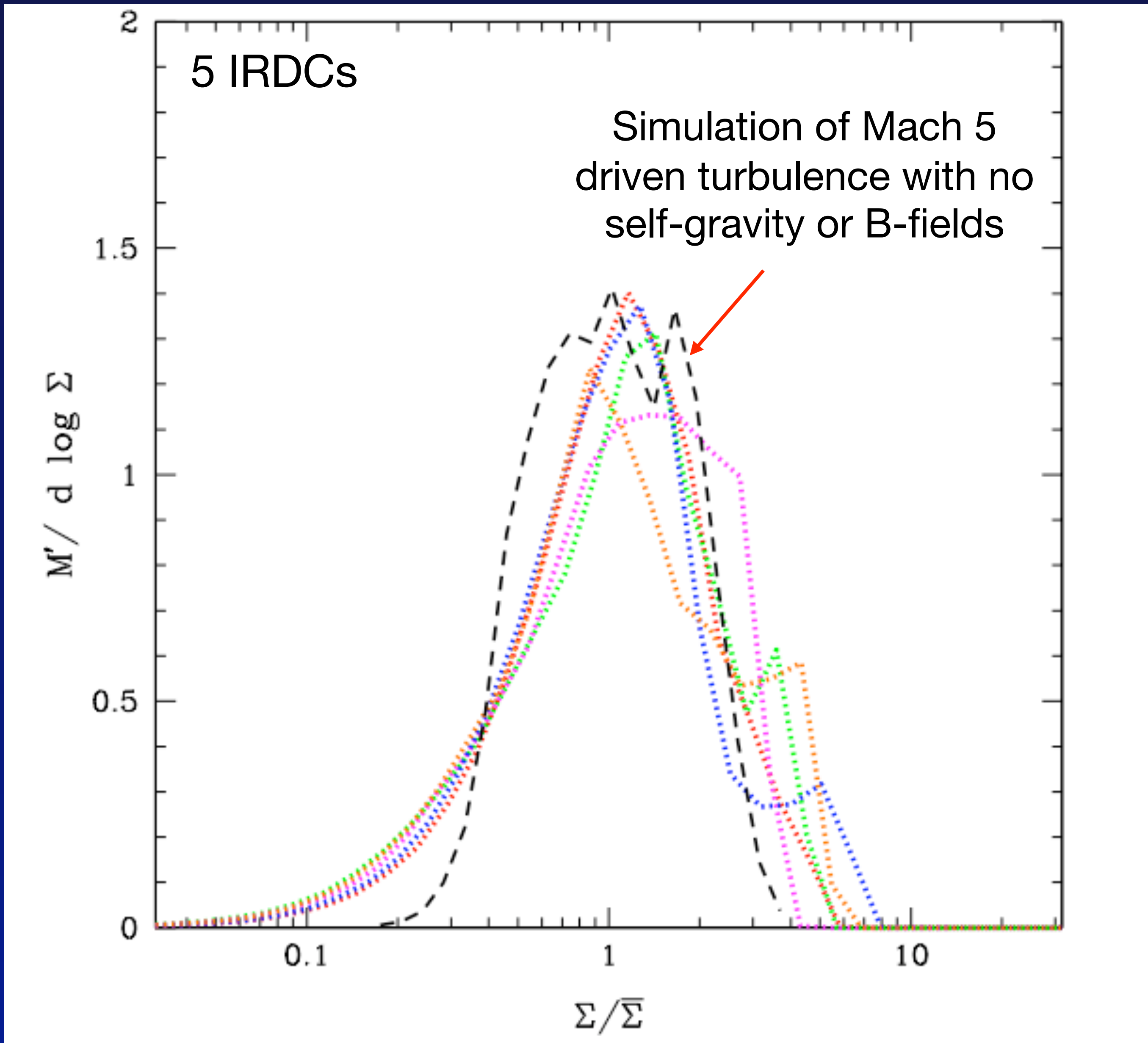


Butler & Tan, in prep

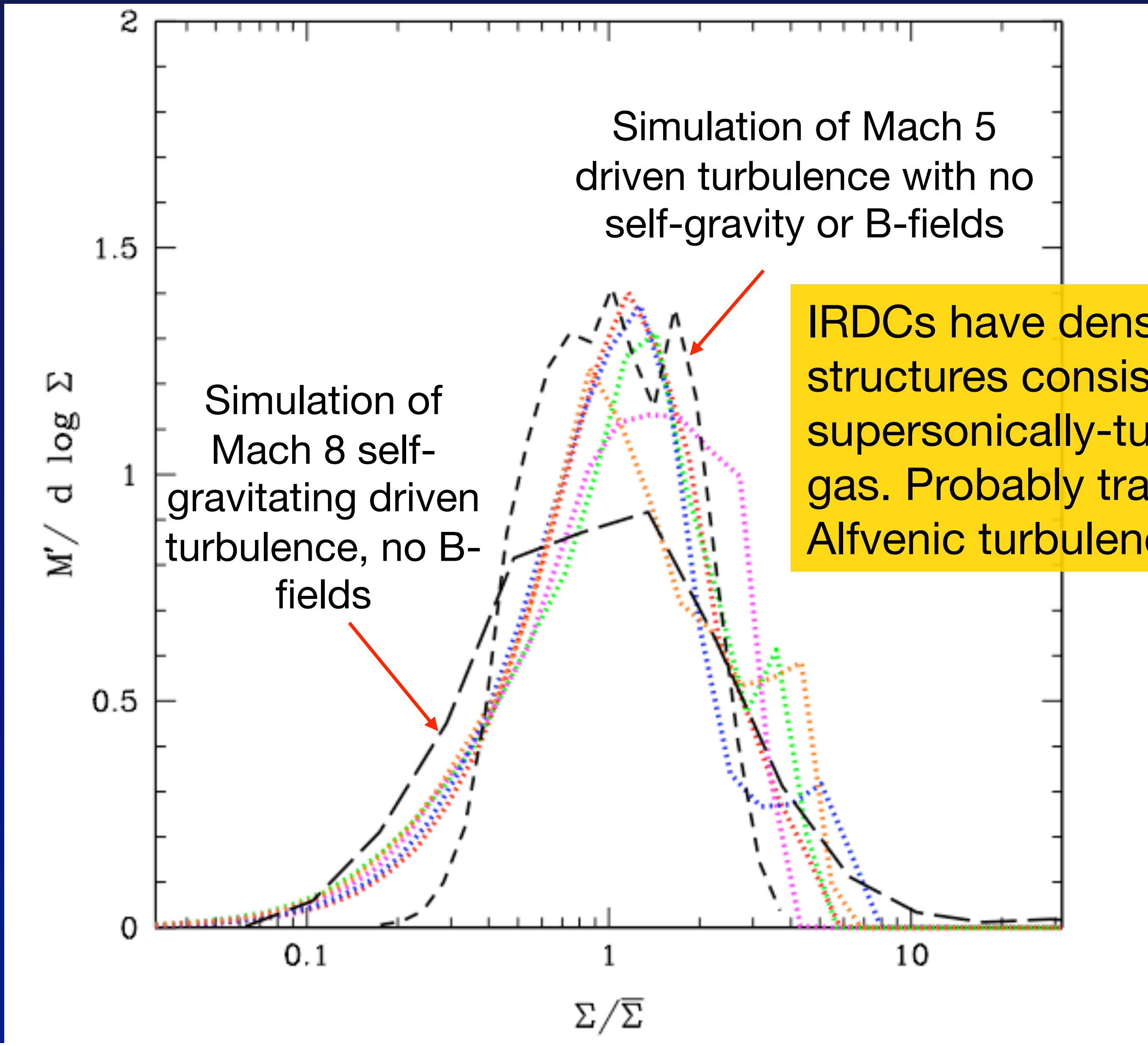
Distribution of M with Σ



Distribution of M with Σ

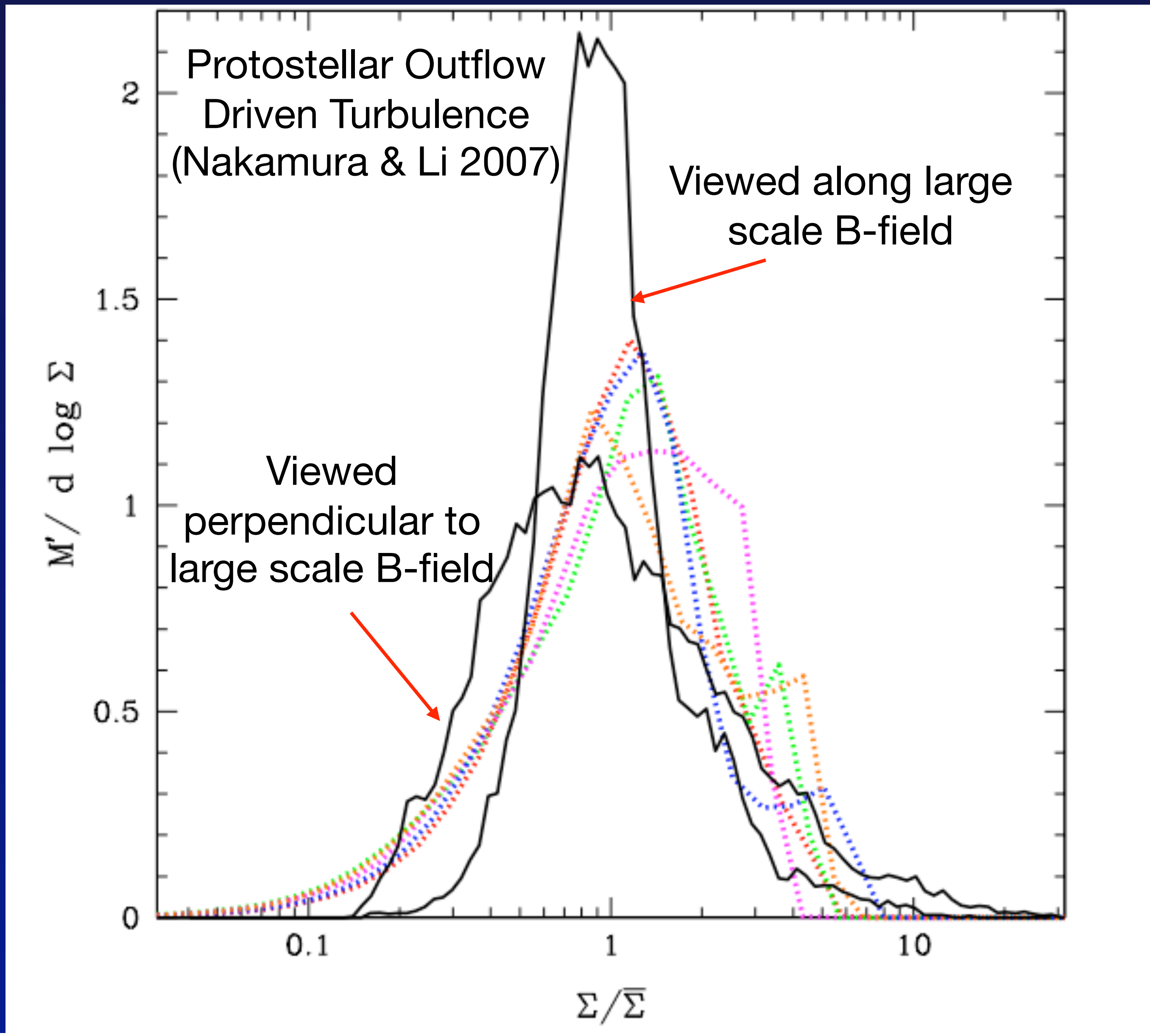


Distribution of M with Σ



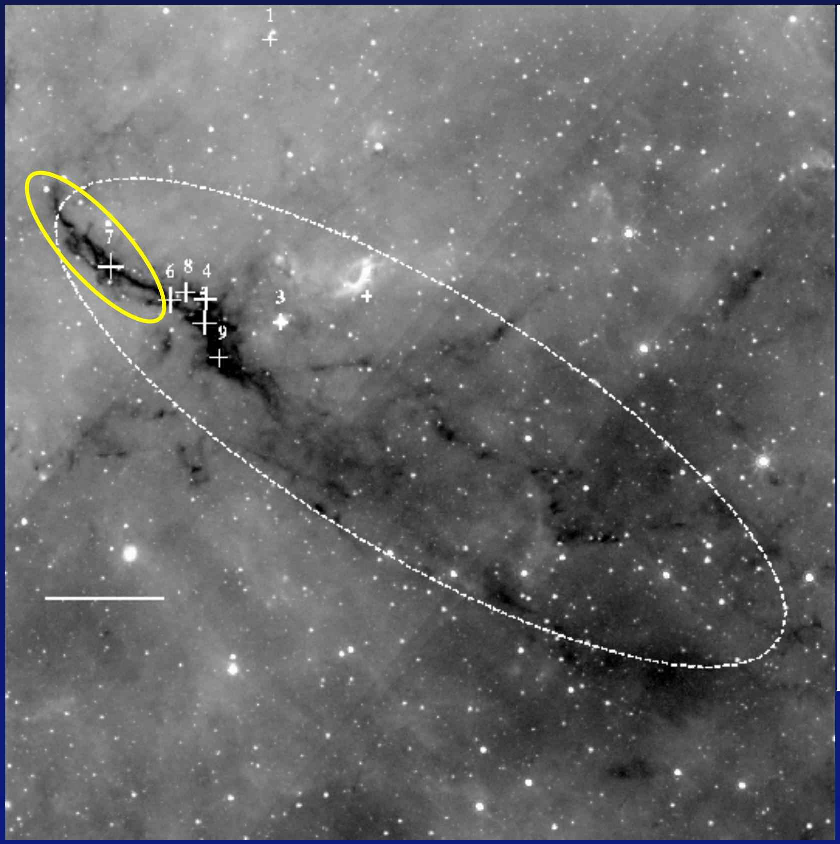
IRDCs have density structures consistent with supersonically-turbulent gas. Probably trans-Alfvenic turbulence.

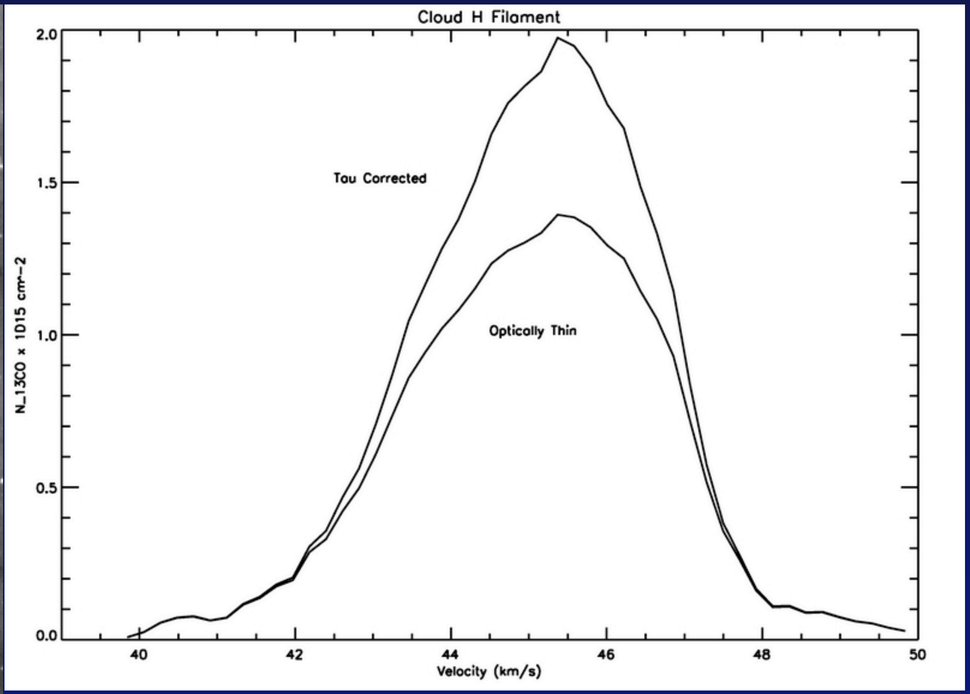
Distribution of M with Σ



Virial Analysis of IRDCs

Hernandez & Tan, in prep



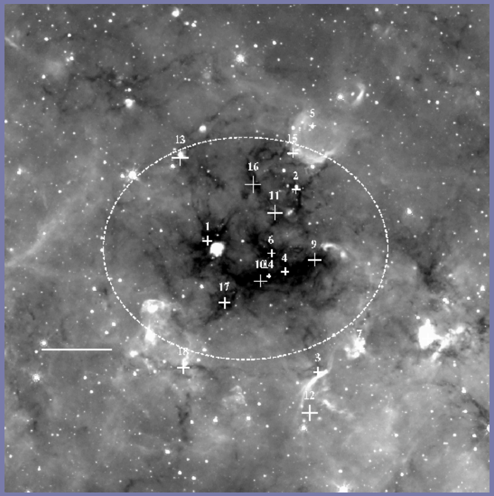


M_{vir} = 1600 $M_\odot$

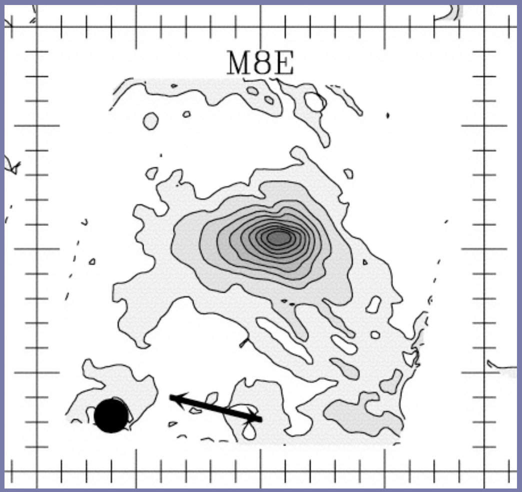
M_{13CO} = 1500, 1100, 1000 $M_\odot$
(T=10, 15, 20K)

Timescale of Star Cluster Formation: Fast ($t_{form} \sim t_{ff}$) or Slow ($t_{form} >> t_{ff}$)?

(Is there time for pressure equilibrium to be established?)



Infrared dark clouds (IRDCs)



Star-forming clumps

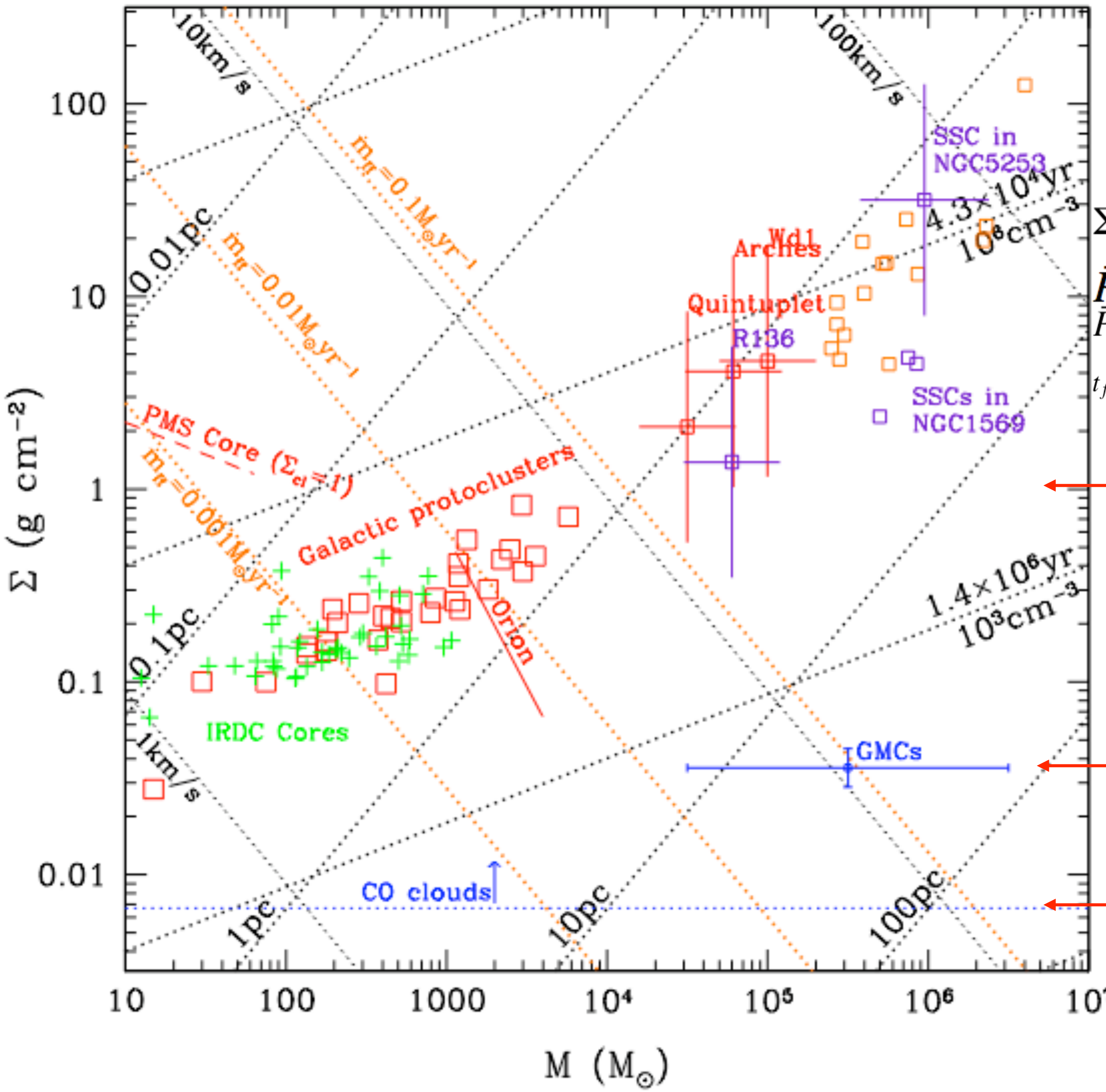
Embedded clusters

Tentatively: IRDCs appear to be reasonably close to virial equilibrium.

Equilibrium star cluster formation
(Tan, Krumholz, McKee 2006)

$n_H \sim 2.0 \times 10^5$ cm^{-3}
$t_{ff} \sim 1.0 \times 10^5$ yr

Clump mass infall rates



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

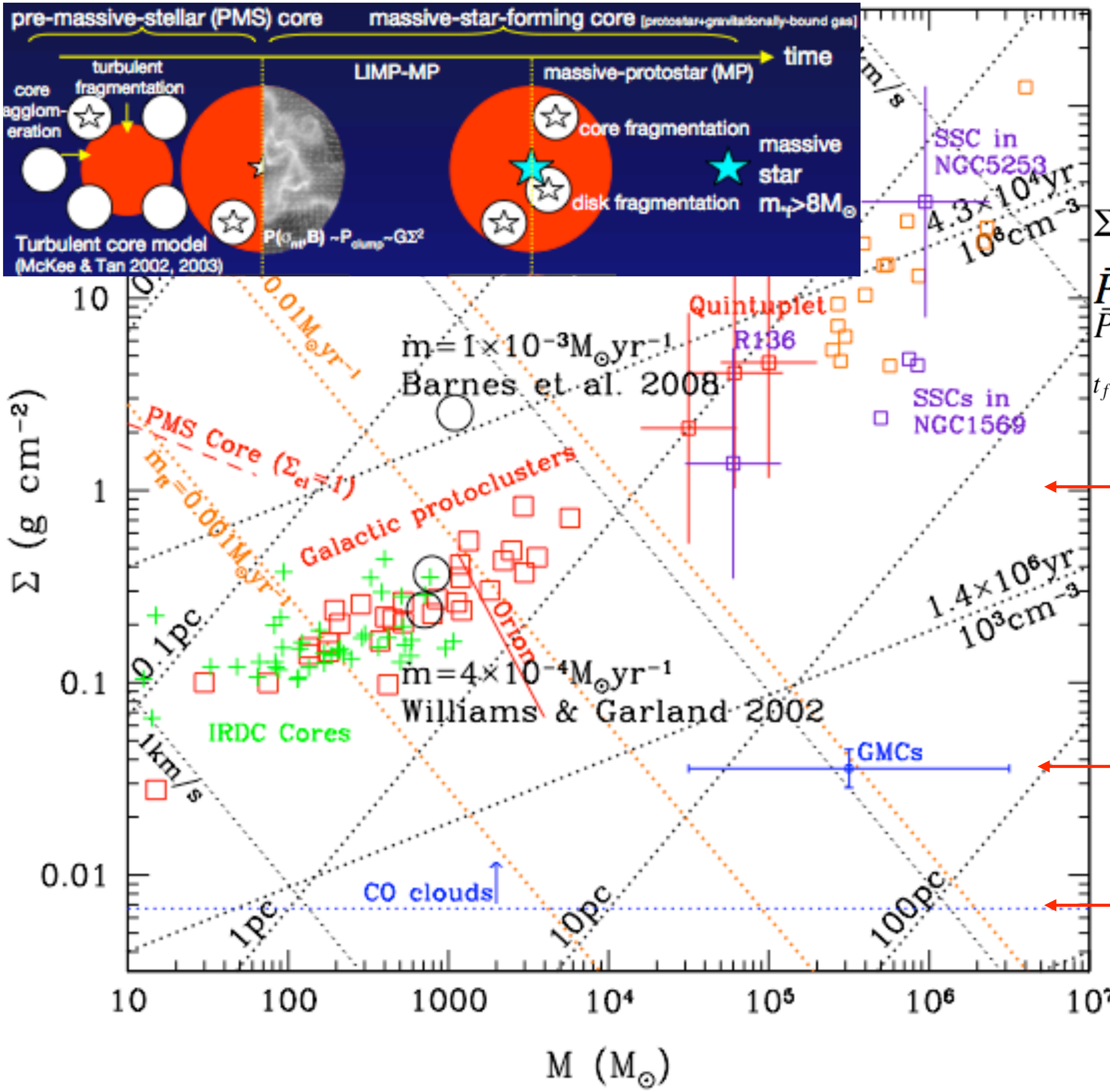
$$t_{ff} = \left(\frac{3\pi}{32 G \rho}\right)^{1/2}$$

A_V=200
N_H=4.2x10^{23}cm^{-2}
Σ=4800 M$_\odot$ pc^{-2}

A_V=7.5
N_H=1.6x10^{22}cm^{-2}
Σ=180 M$_\odot$ pc^{-2}

A_V=1.4
N_H=3.0x10^{21}cm^{-2}
Σ=34 M$_\odot$ pc^{-2}

Clump mass infall rates



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K\, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

A_V=200
N_H=4.2x10^{23}cm^{-2}
Σ=4800 M$_\odot$ pc^{-2}

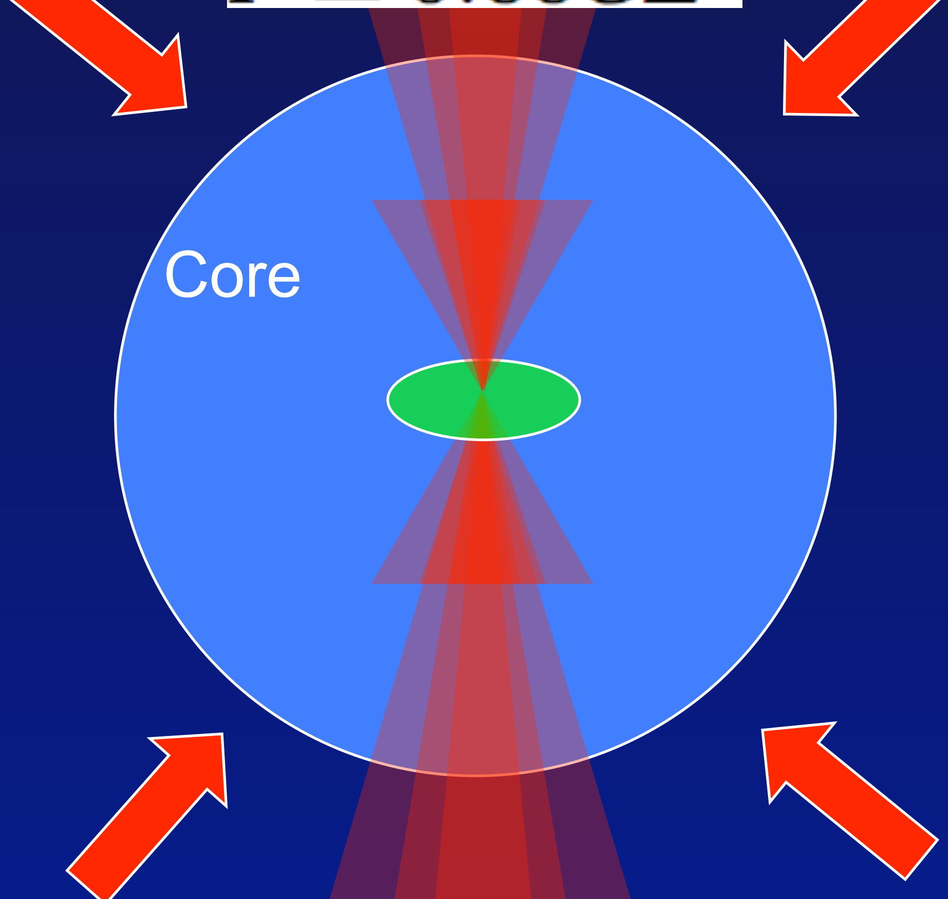
A_V=7.5
N_H=1.6x10^{22}cm^{-2}
Σ=180 M$_\odot$ pc^{-2}

A_V=1.4
N_H=3.0x10^{21}cm^{-2}
Σ=34 M$_\odot$ pc^{-2}

Massive star-forming cores

Theory: core in quasi pressure equilibrium with clump

$$\bar{P} \simeq 0.88 G\Sigma^2$$



$$r_{core} = 0.06 \left(\frac{M_{core}}{60 M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} pc$$

$$r_{disk} = 1200 \frac{\beta}{0.02} \left(\frac{M_{core}}{60 M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} AU$$

$$t_{*f} = 1.3 \times 10^5 \left(\frac{M_{core}}{60 M_\odot}\right)^{\frac{1}{4}} \Sigma^{-\frac{3}{4}} yr$$

Final mass accretion rate

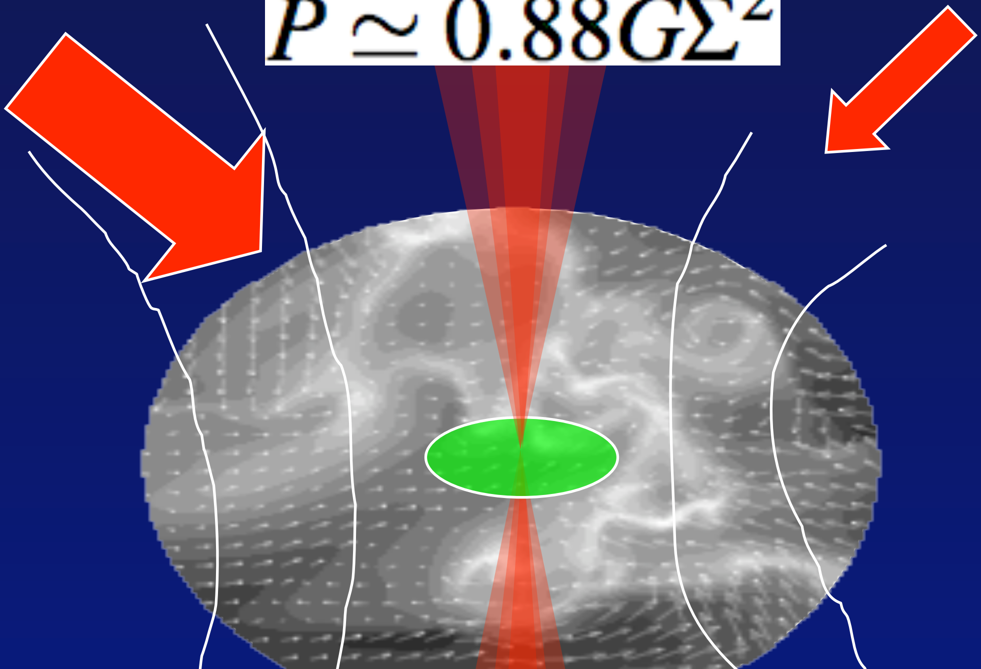
$$\dot{m}_* = 4.6 \times 10^{-4} \left(\frac{M_{core}}{60 M_\odot}\right)^{\frac{3}{4}} \Sigma^{\frac{3}{4}} M_\odot\, yr^{-1}$$

McKee & Tan (2002;2003)

Massive star-forming cores

Turbulent cores, fragmenting from a turbulent medium, reasonably close to virial, hydrostatic equilibrium

$$\bar{P} \simeq 0.88 G\Sigma^2$$



$$r_{core} = 0.06 \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} pc$$

$$r_{disk} = 1200 \frac{\beta}{0.02} \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} AU$$

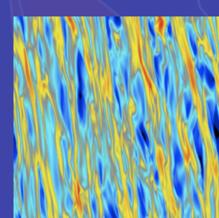
$$t_{*f} = 1.3 \times 10^5 \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{1}{4}} \Sigma^{-\frac{3}{4}} yr$$

Final mass accretion rate

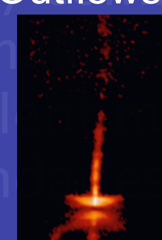
$$\dot{m}_* = 4.6 \times 10^{-4} \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{3}{4}} \Sigma^{\frac{3}{4}} M_\odot yr^{-1}$$

Protostellar evolution

Disk structure



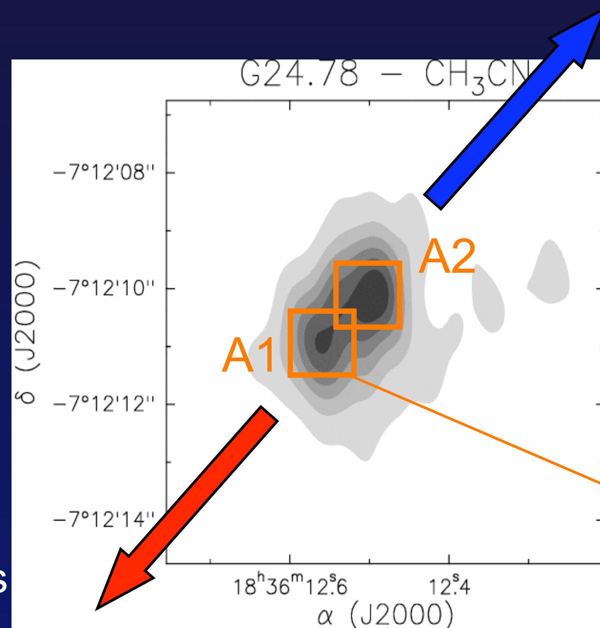
Outflows

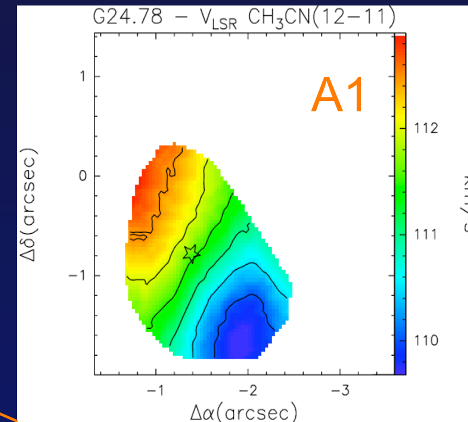


Support by combination of large & small scale B-fields, and turbulent motions. Core boundaries fluctuate.

Accretion Disks

Observational evidence for rotating toroids on scales ~1000AU, perpendicular to bipolar outflows, e.g.
G24.78+0.08 A1 Beltrán et al. (2004)

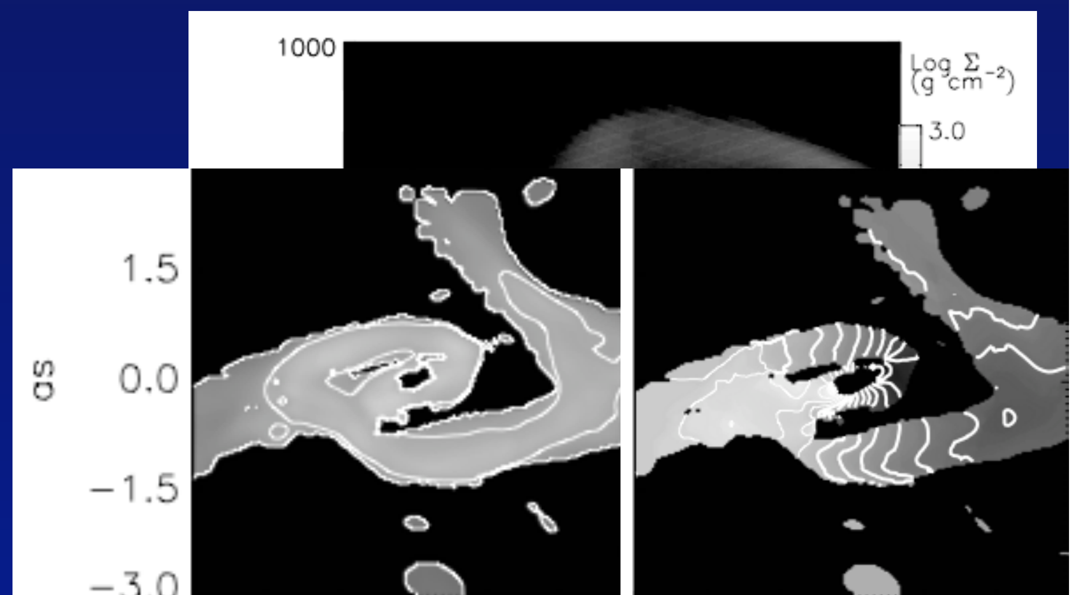




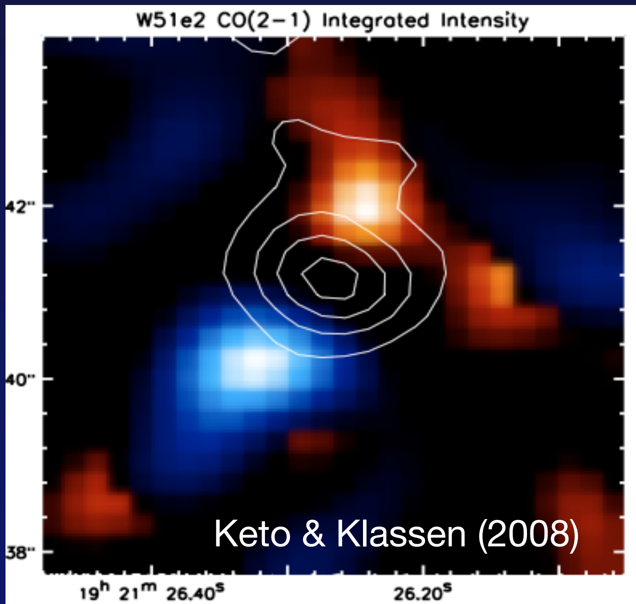
Also claims from maser observations (e.g. Wright et al. and Greenhill et al. in Orion KL)

Theory:
Analytic study of disk accretion and fragmentation
(Kratter, Matzner, Krumholz 2007)

Radiation-hydro simulation of turbulent core collapse: modest disk fragmentation.
(Krumholz, Klein, McKee 2007a).
Simulated ALMA observations
(Krumholz, Klein, McKee 2007b).



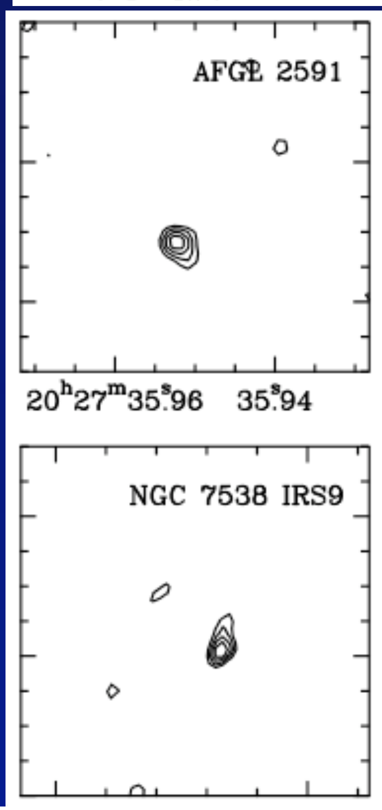
CH_3CN (12,0,0,13)->(11,0,0,12) [220GHz, 69K]



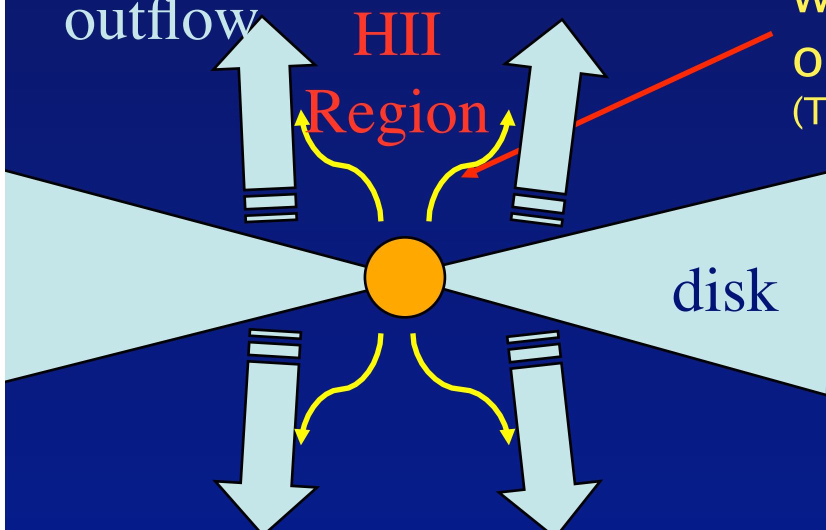
Protostellar Outflows and Outflow-Confined HII Regions

Density distributions of hydromagnetic outflows (e.g. disk wind, X-wind) approach a common form far from the star or inner disk: collimated wind (Shu et al. 1995; Ostriker 1997; Matzner & McKee 1999).

Collimated outflows observed from massive protostars (e.g. Richer et al. 2000; Shepherd et al. 2001 Beuther, Schilke et al. 2002)



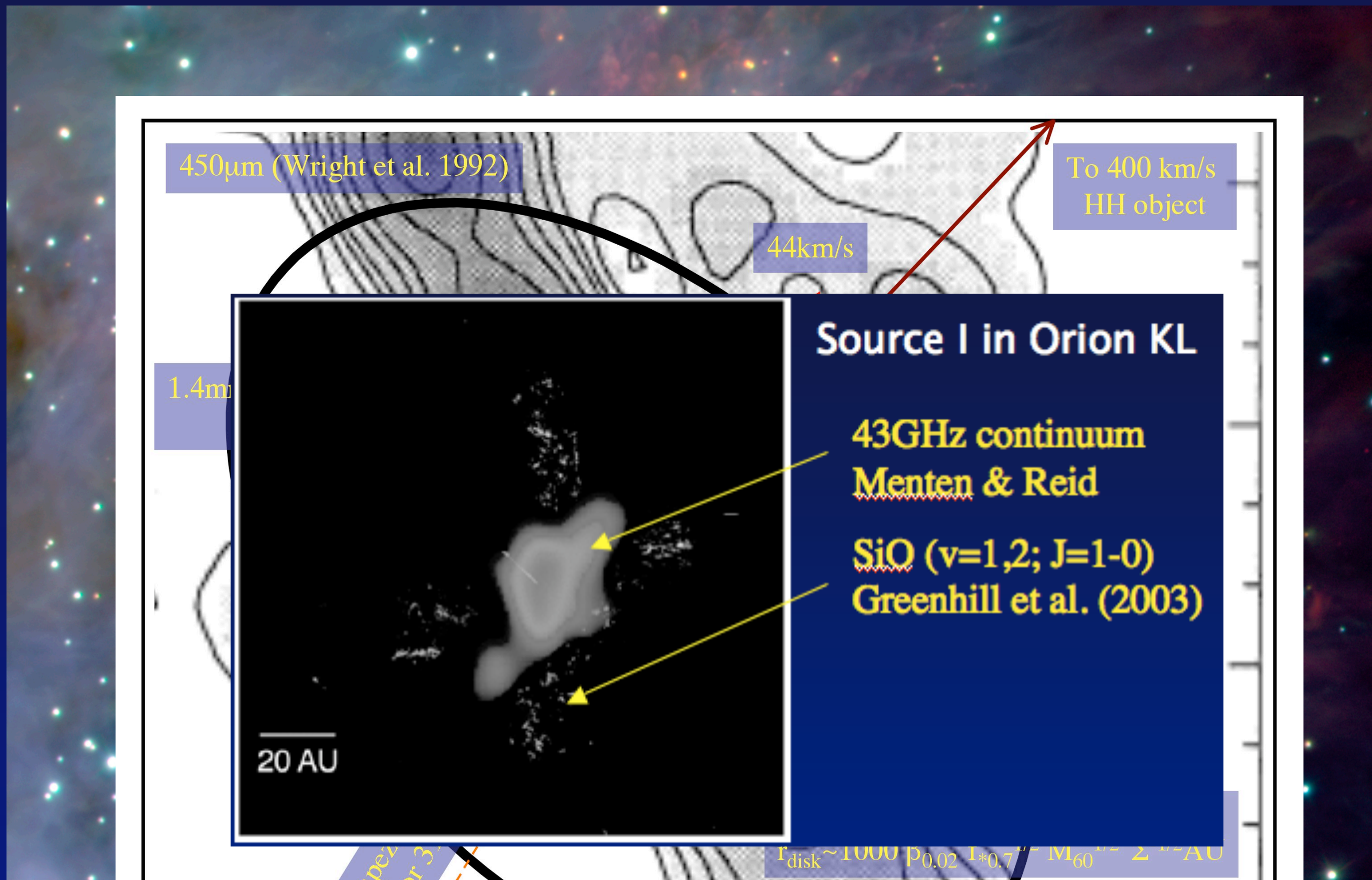
A massive hot protostar will ionize the inner part of the outflow (Tan & McKee 2003).



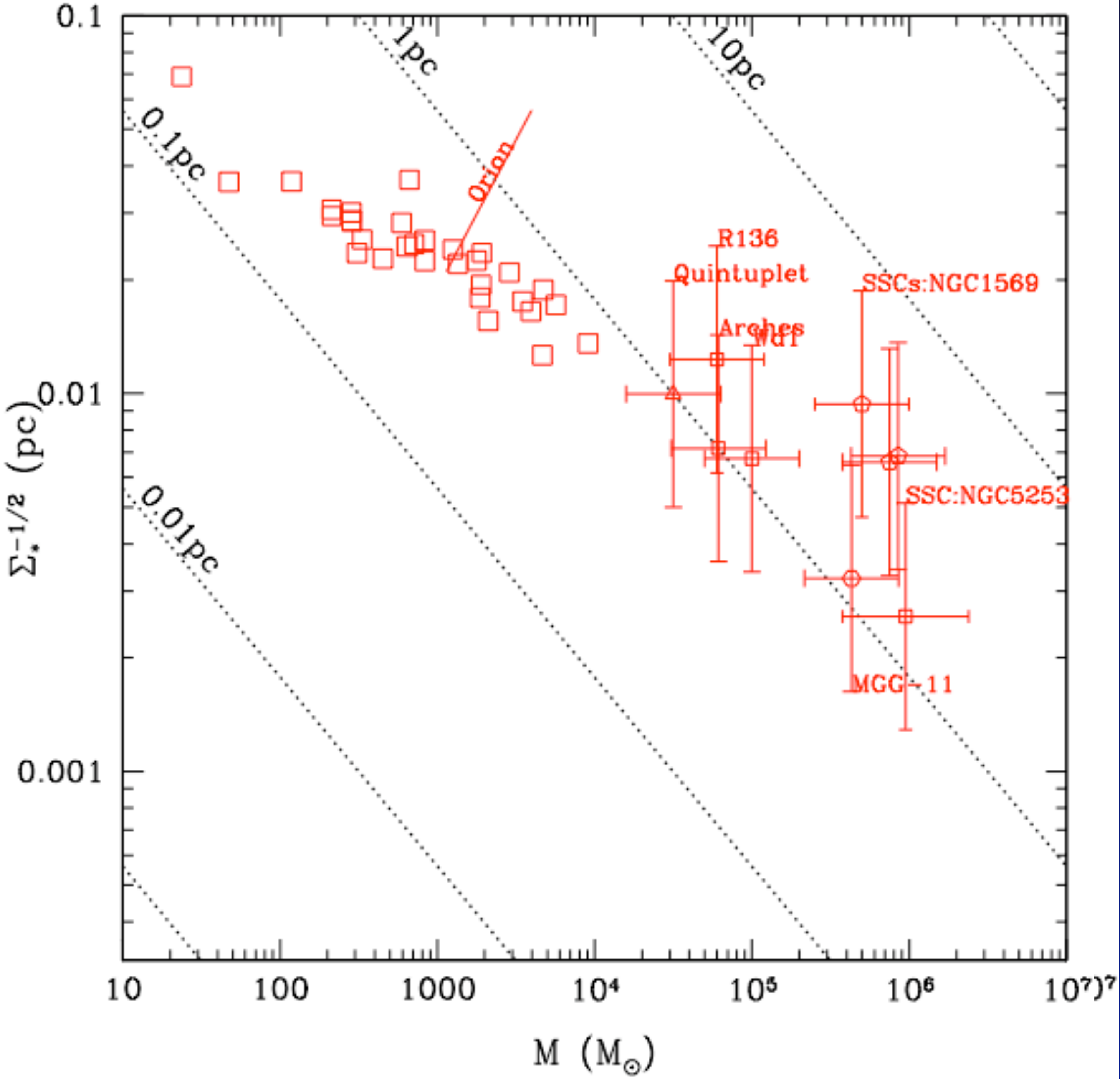
An alternative explanation is that these are ionized accretion flows (+thermally driven outflows) (Keto 2006)

A number of ionized HCHIIs seen (e.g. van der Tak & Menten 2005)

Application to Orion KL

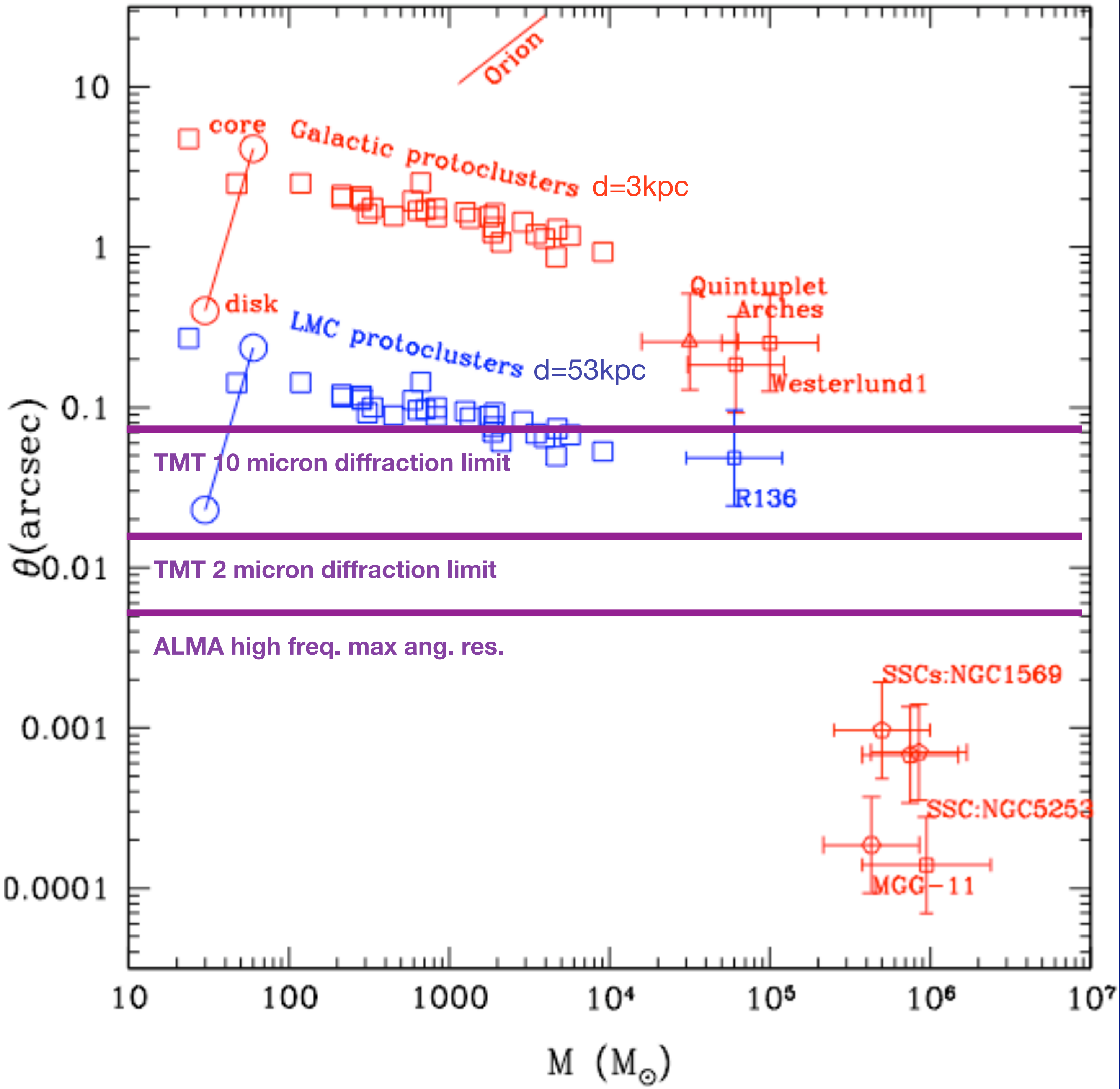


The disk has suffered a recent perturbation from the close passage of the Becklin-Neugebauer object (a runaway B star ejected from the Trapezium star θ^1Ori C) (Tan 2004; 2008; however, see: Bally & Zinnecker 2005; Gomez et al. 2008; Greenhill et al. 2003; Matthews, Goddi, Humphreys et al. 2005; see also poster by Goddi et al.: search for high velocity masers).



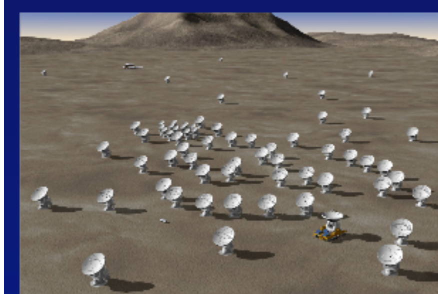
High angular resolution with ALMA

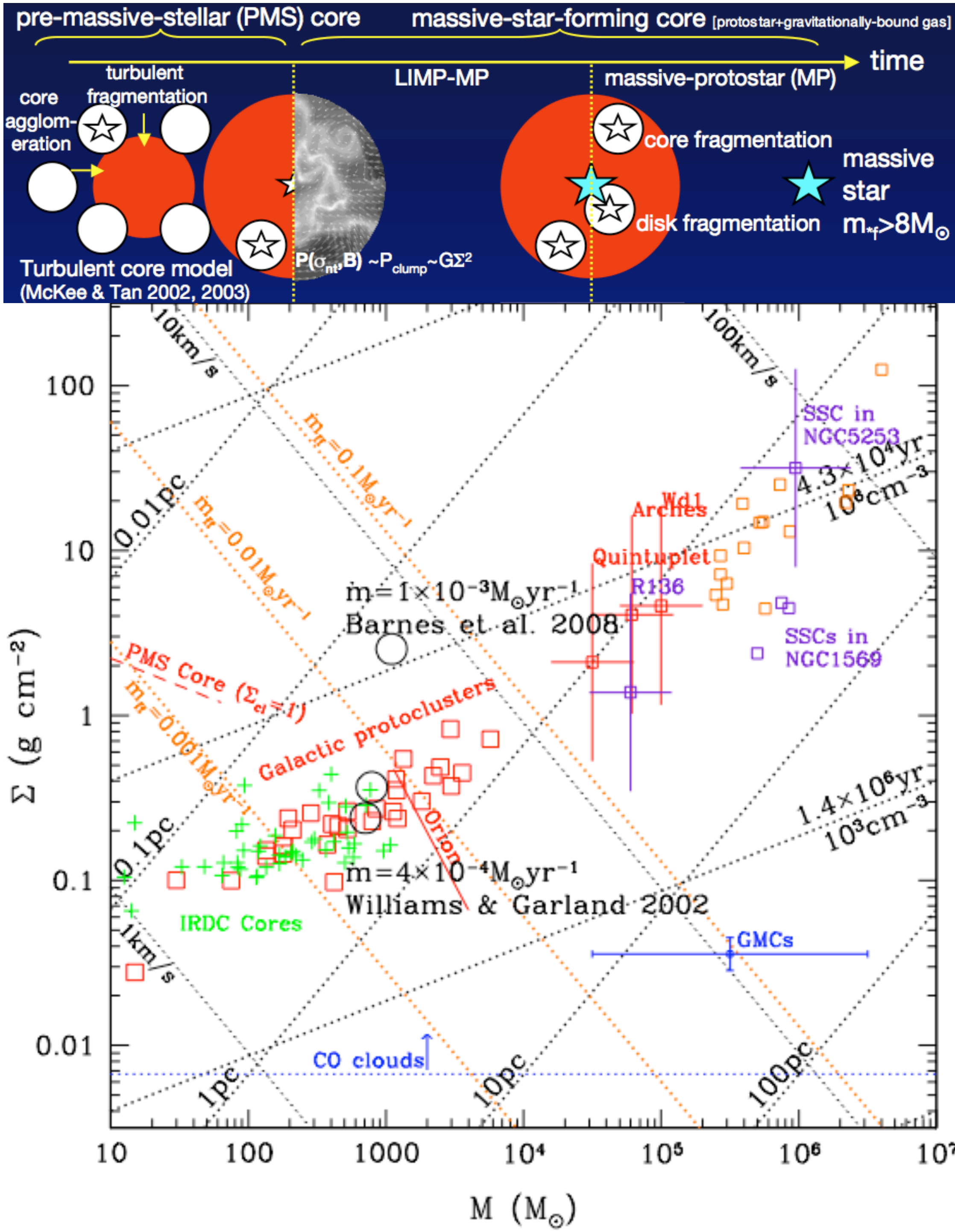
Typical stellar separations



Stellar angular separations

Core/disk angular sizes





Conclusions

1. Pre-massive-stellar cores appear to be massive, but ALMA is needed to resolve their structure, ideally from large unbiased samples (e.g. CHaMP + IR extinction map).

2. Star cluster formation times >> t_{ff} ~10^5yr, allowing approximate pressure equilibrium to be established.

3. Scaled-up disks and outflows are likely present around massive protostars. ALMA needed to resolve their structure and kinematics, though inner hot disk will be difficult.

4. Outflow-confined HII regions (appearing ~radio jets) are important diagnostics.

5. Stellar encounters can perturb core/disk, as in Orion.

Turbulent Core Model of Massive Star Formation

Basic Model: McKee & Tan (2002; 2003)

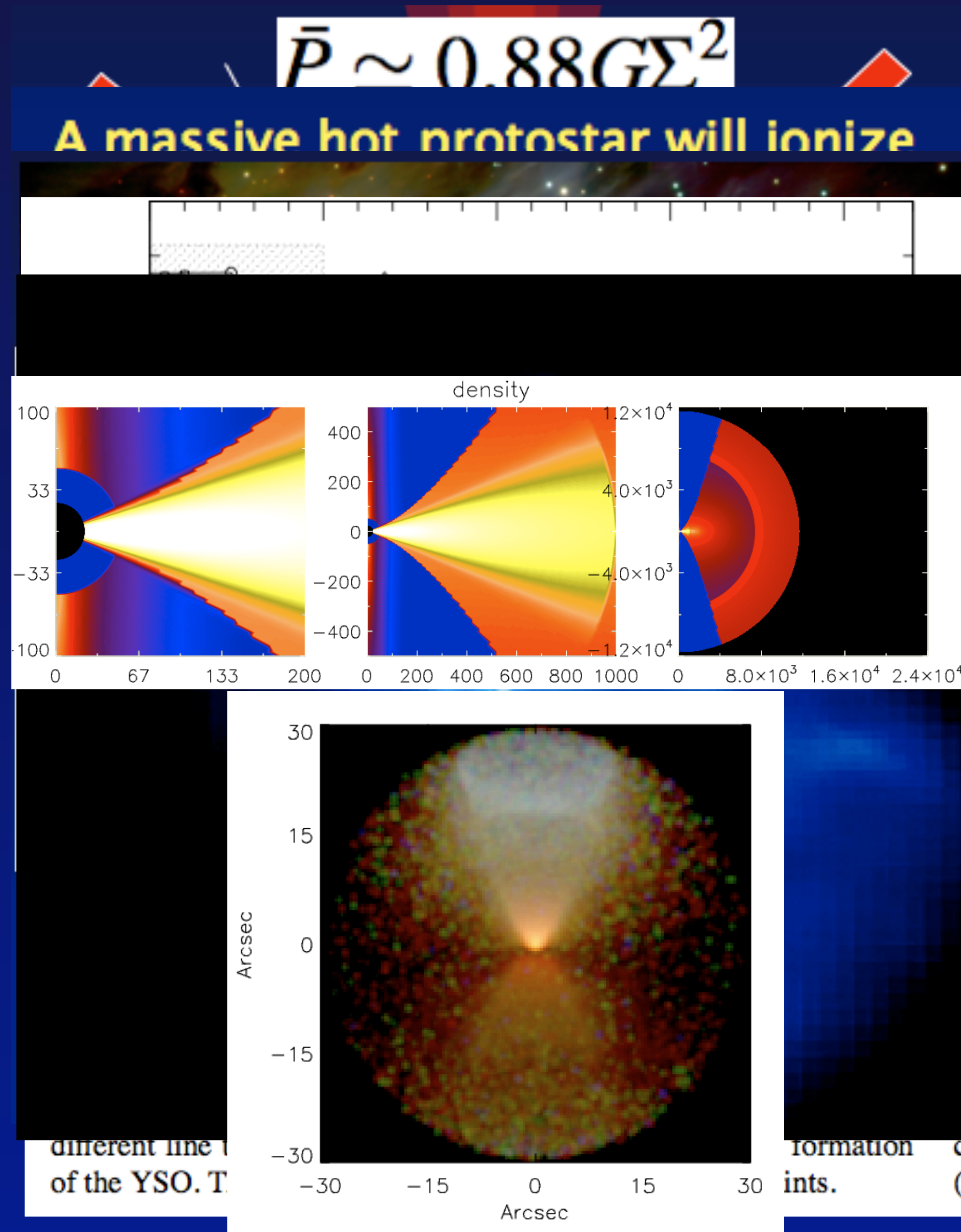
Outflows and Hypercompact HII regions: Tan & McKee (2003)

Application to Orion KL: Tan (2004)

Chemistry: Doty, van Dishoeck, Tan (2006)

Radiation-Hydro Simulation: Krumholz, Klein, McKee (2007)

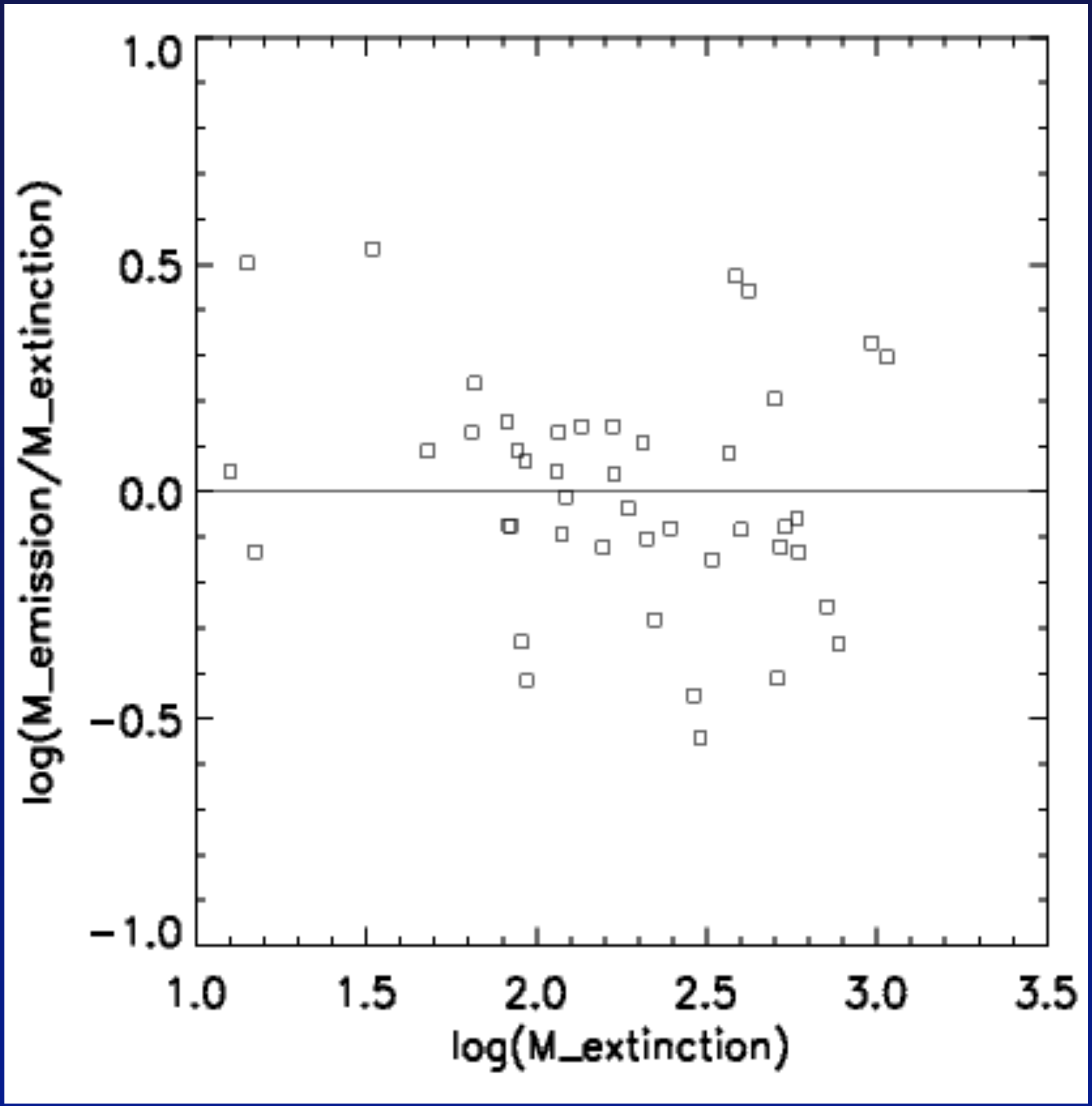
Radiative Transfer: Chakrabarti & McKee (2005); Tan, Whitney, in prep.



Comparison of dust emission masses with dust extinction masses

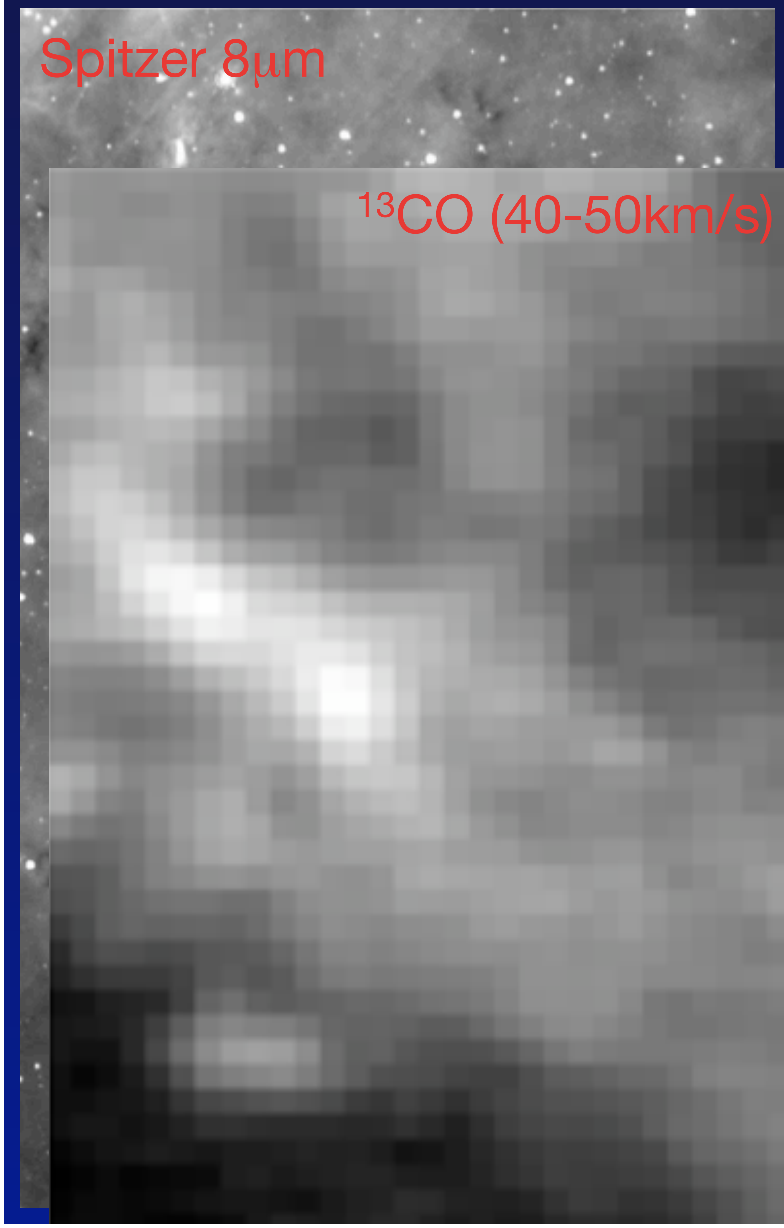
Observations of mm continuum emission from dust, tracing dense cores within IRDCs (Rathborne et al. 2006).

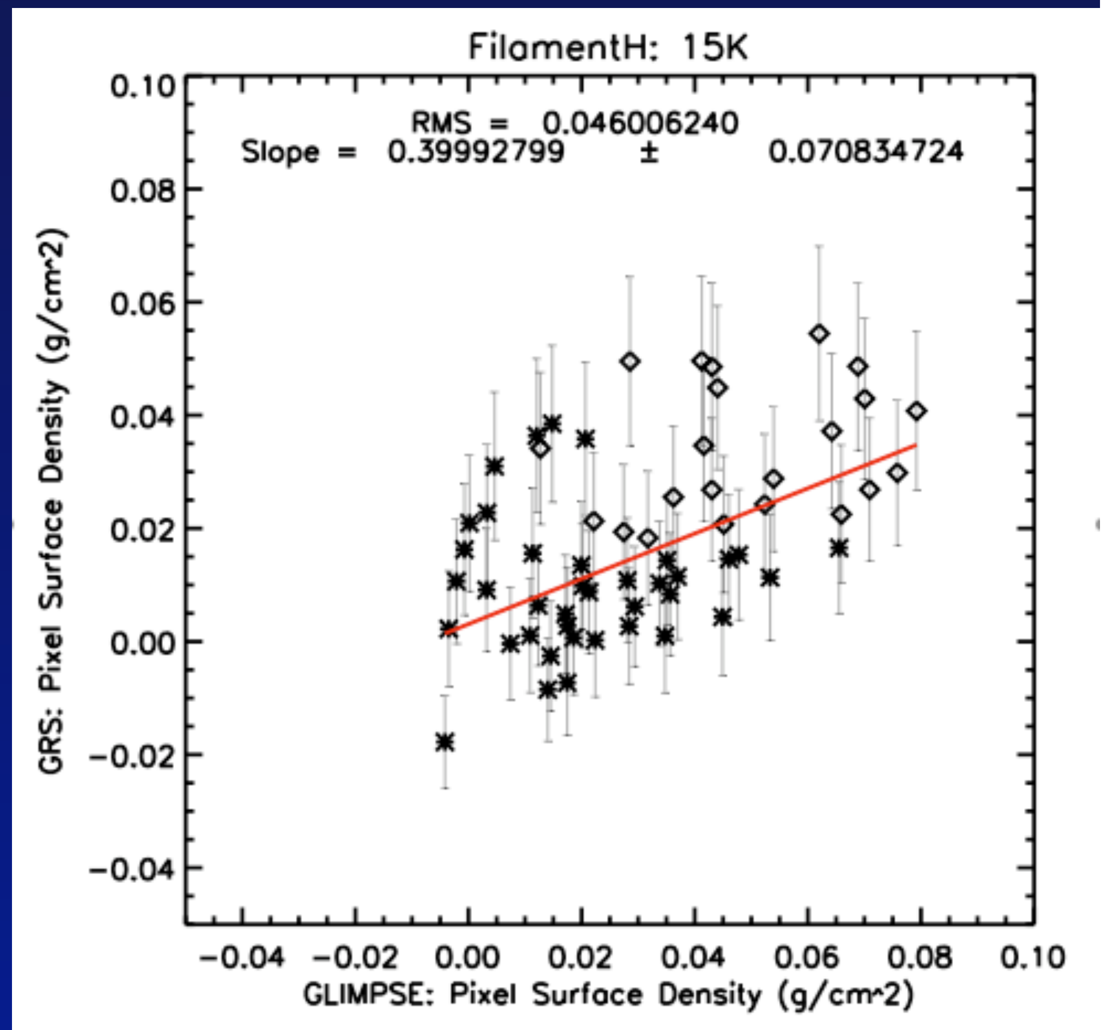
Extinction masses agree with emission masses to within a factor of 3, with very small systematic offset.



Comparison of ^{13}CO-derived mass surface densities with extinction-derived surface densities

Hernandez & Tan, in prep.





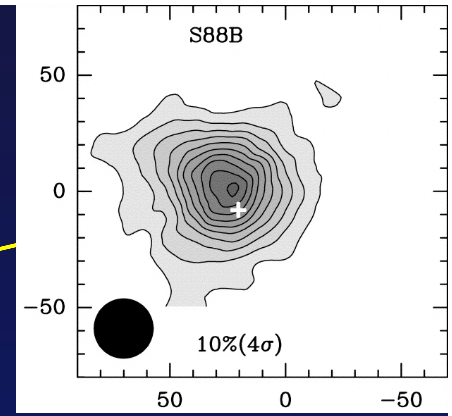
Timescale: Slow, Equilibrium Star Cluster Formation

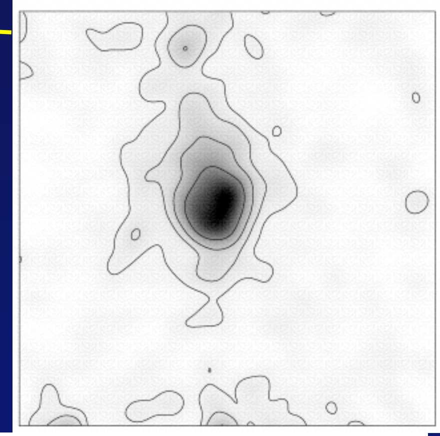
(Tan, Krumholz, McKee 2006)

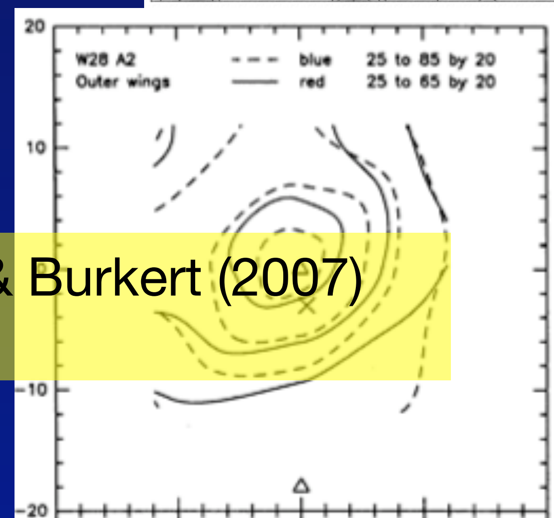
<u>Formation time long relative to free-fall time for rich (high SFE) clusters</u>

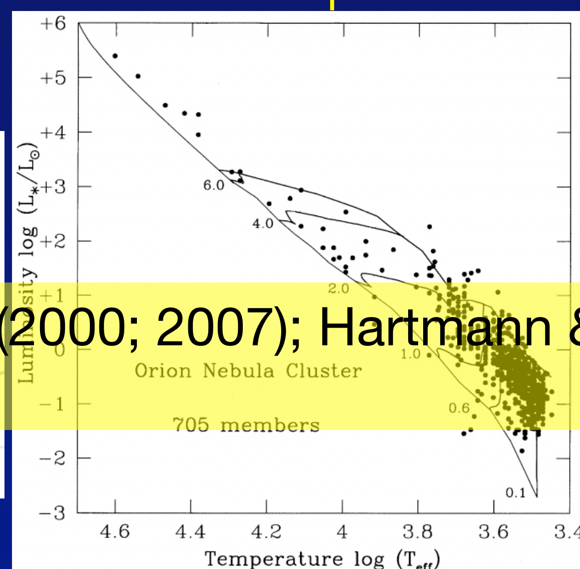
Observational evidence:

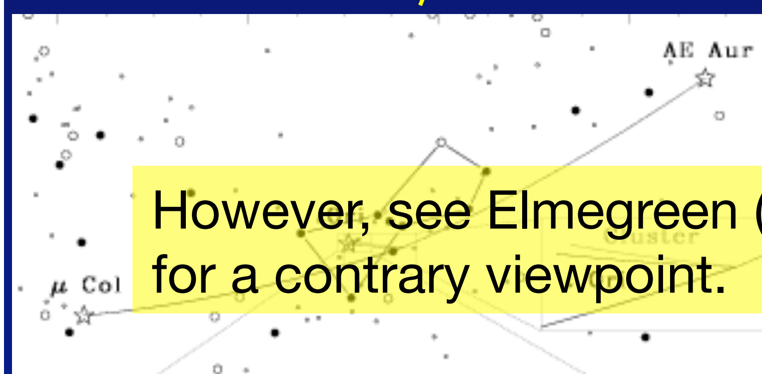
- ROUND Clump morphologies
- SMOOTH Substructure of young stars
- SMALL Momentum flux of outflows
- LARGE Age spreads of cluster stars
- OLD Age of ONC ejection event







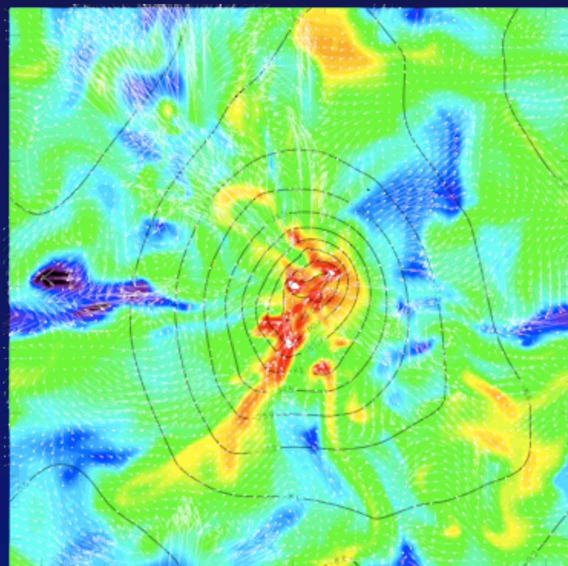




However, see Elmegreen (2000; 2007); Hartmann & Burkert (2007) for a contrary viewpoint.

If one accepts the theoretical and observational evidence for low SF efficiency per free-fall time (SFR_{ff}~0.03) time from turbulent gas, then the observed high overall SFE of rich clusters (up to ~30-50%) require long formation times.
(Krumholz & McKee 2005; Krumholz & Tan 2007, Nakamura & Li 2007).

SFR per freefall time



Shirley et al. 2003

Nakamura & Li (2007)

Implications:

1. Star formation in rich clusters is a local process regulated by turbulence rather than global collapse (turbulent fragmentation rather than competitive accretion)
2. Turbulence must be driven and maintained [probably by outflows]
3. Mass segregation of massive stars: more time available in gas rich phase

Krumholz & Tan (2007)

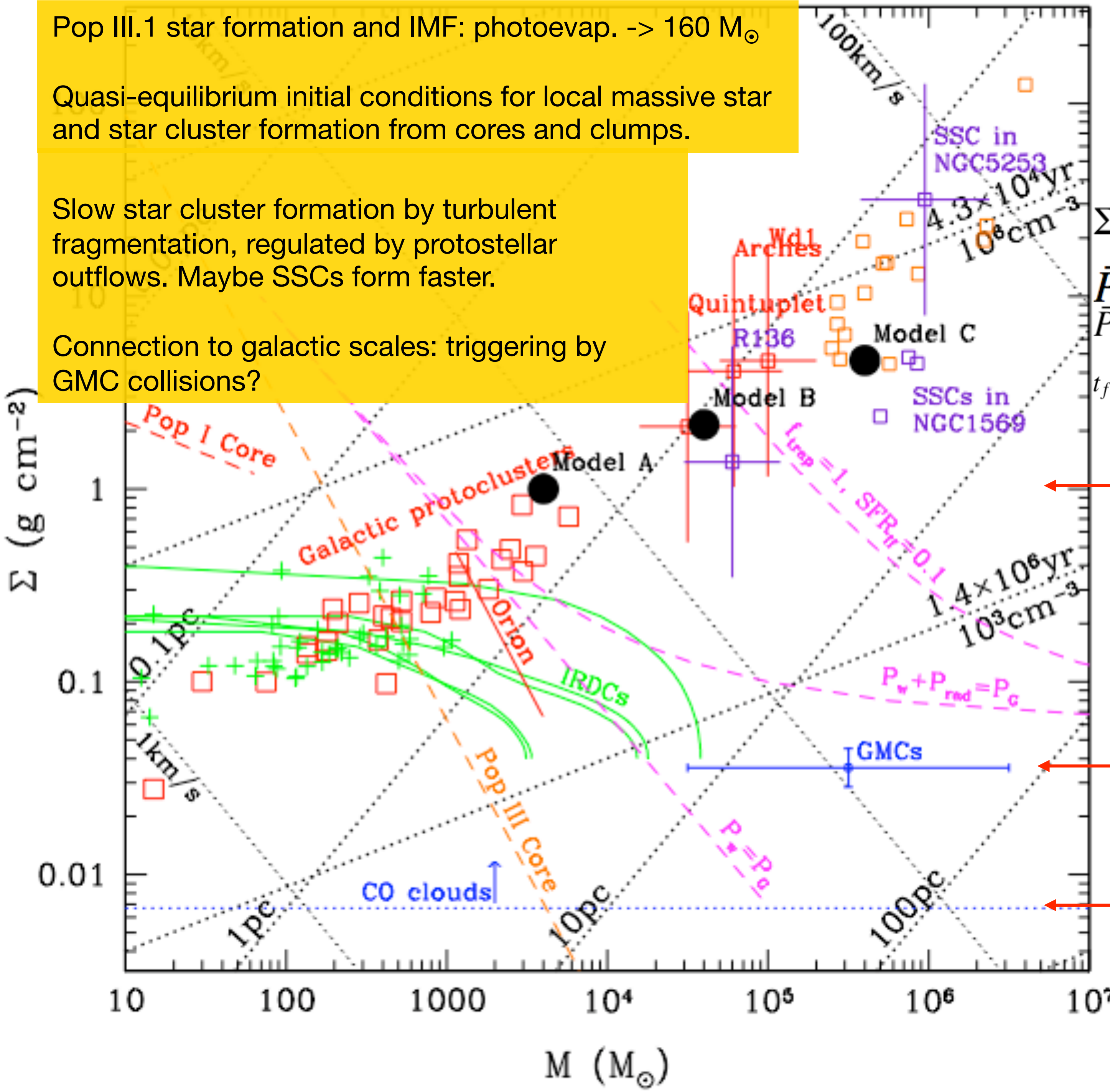
Conclusions

Pop III.1 star formation and IMF: photoevap. -> 160 $M_\odot$

Quasi-equilibrium initial conditions for local massive star and star cluster formation from cores and clumps.

Slow star cluster formation by turbulent fragmentation, regulated by protostellar outflows. Maybe SSCs form faster.

Connection to galactic scales: triggering by GMC collisions?



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

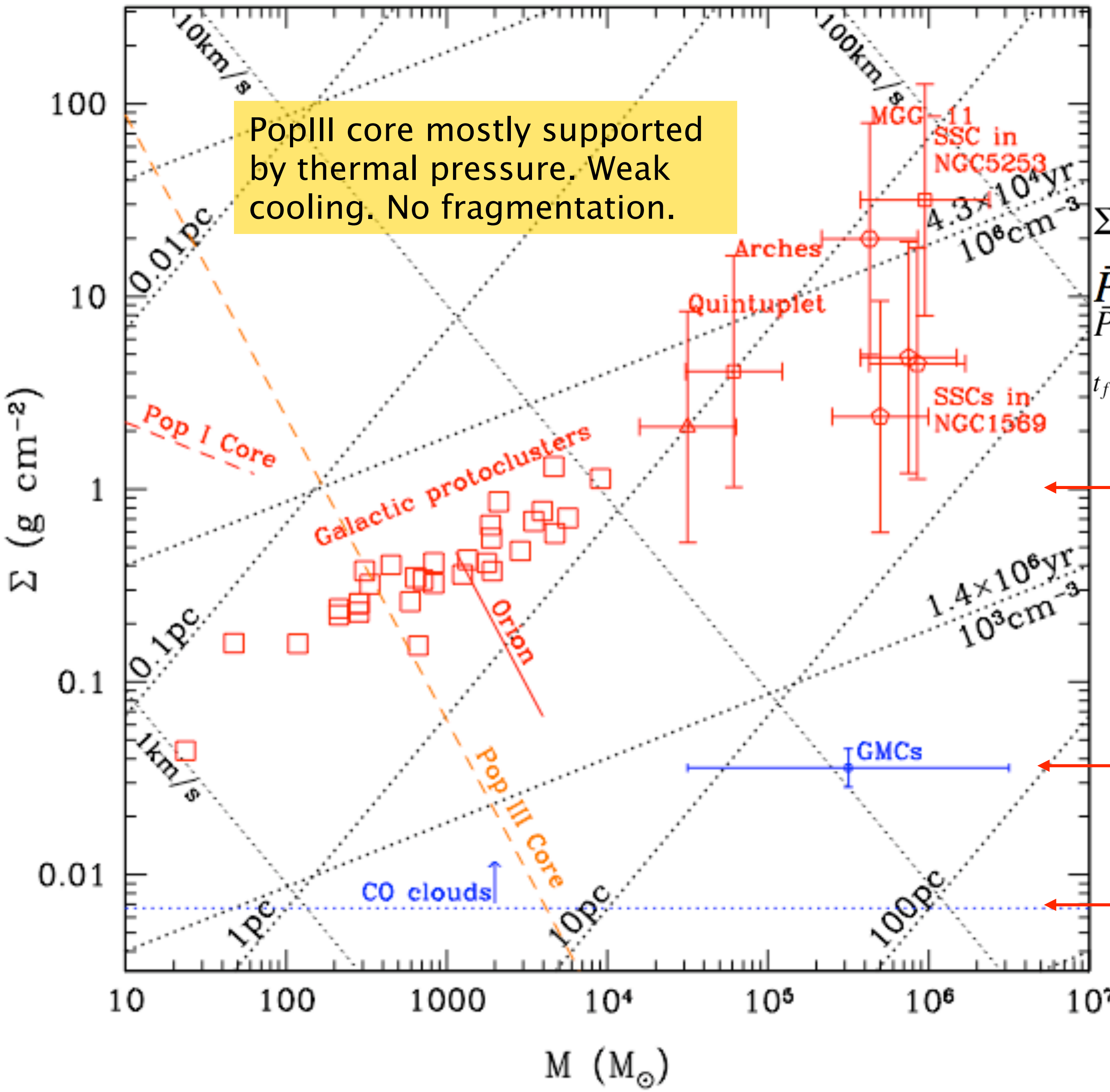
$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

$A_V=200$
$N_H=4.2\times10^{23} cm^{-2}$
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$N_H=1.6\times10^{22} cm^{-2}$
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21} cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K \, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

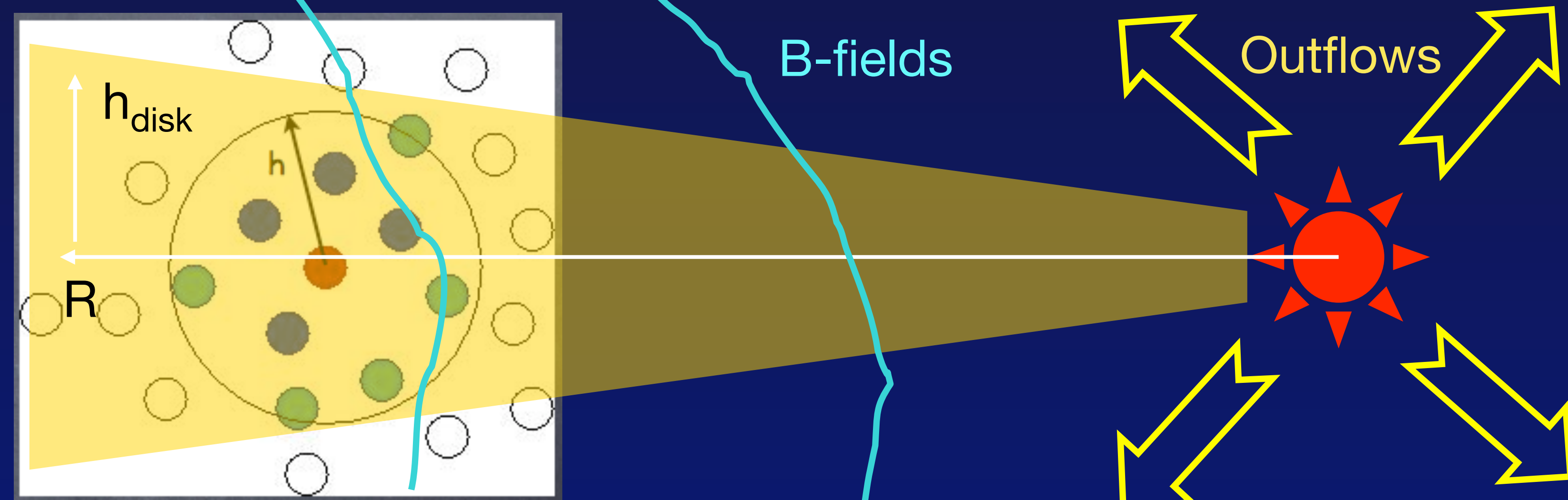
$A_V=200$
$N_H=4.2\times10^{23} cm^{-2}$
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$N_H=1.6\times10^{22} cm^{-2}$
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21} cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

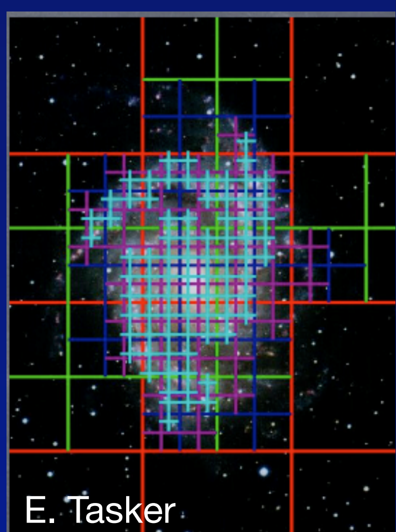
Star Formation Simulations: SPH and AMR

SPH:



# of SPH particles to resolve disk around 1 star ~$10x(10R/h_{disk})^2$~$10x100^2$~10^5!
Growth of star from disk with m_d=$0.1m_*$ -> 10^6 part. per * (cf. Inutsuka ea. 2007, PPV)

AMR:



Adaptive mesh refinement based on certain criteria, e.g. to resolve shocks, density contrasts, Jeans length.
Good at resolving shocks, multi-phase ISM, and better at including magnetic fields (although complicated).
Both SPH and AMR simulations of star formation need to include sink particles.

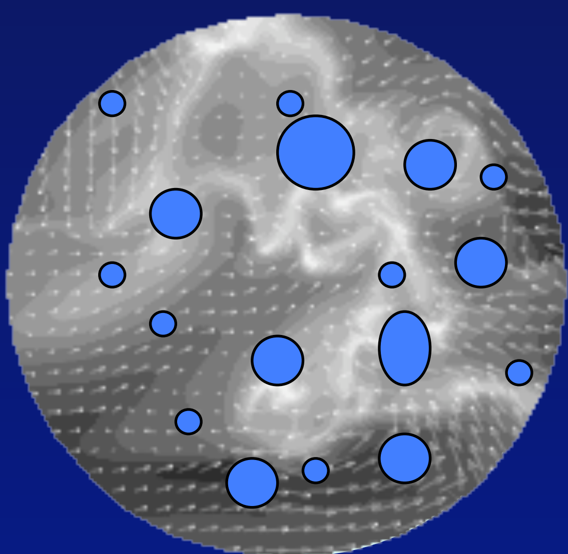
Mode of star formation in star clusters

Two different models:

<u>Turbulent Fragmentation into Cores</u>

Padoan & Nordlund (2002); McKee & Tan 2003;
Vázquez-Semadeni et al. 2004;

Stars form from "cores", $M_{core} \sim m_*$, that fragment from the clump



$$\bar{P} = \phi_P G \Sigma^2$$

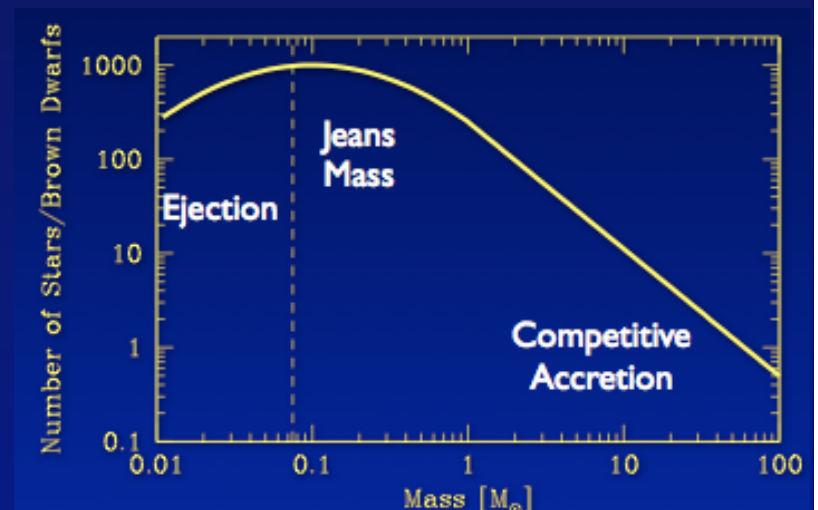
If in equilibrium, then self-gravity is balanced by internal pressure: B-field, turbulence, radiation pressure (thermal P is small)

Cores form from this turbulent medium: at any given time there is a small mass fraction in unstable cores. These cores collapse quickly to form individual stars or binaries.

<u>Competitive Accretion</u>

Bonnell, Vine, & Bate 2004
Schmeja & Klessen 2004

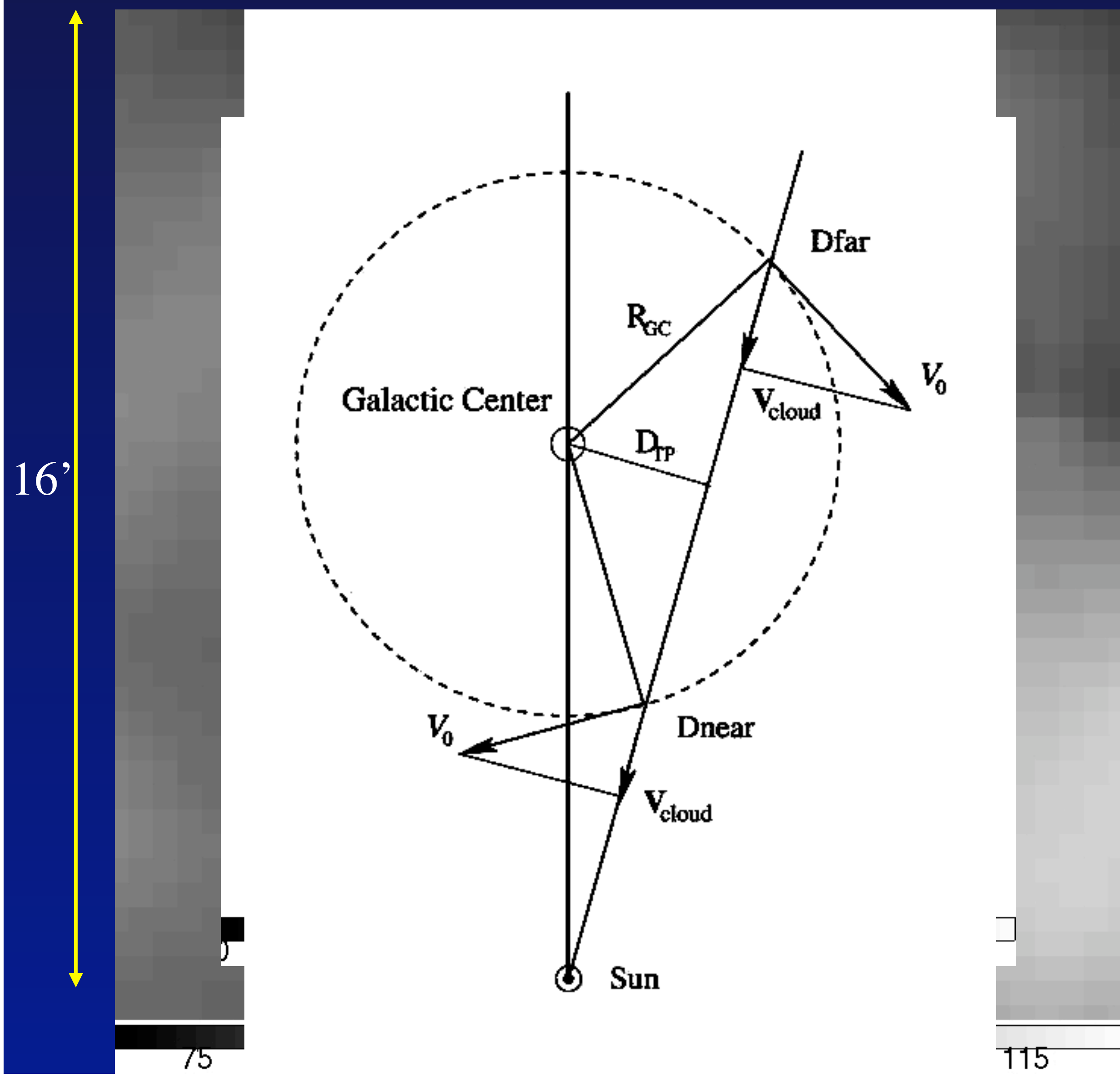
Stars gain most mass by Bondi-Hoyle accretion of ambient gas



Based on SPH simulations with sink particles

Structure of Infrared Dark Clouds

with Butler, Hernandez, Krumholz, Offner, McKee, Klein in prep.



MSX

MSX IRDC sample from Rathborne et al. (2005); Simon et al. (2006).

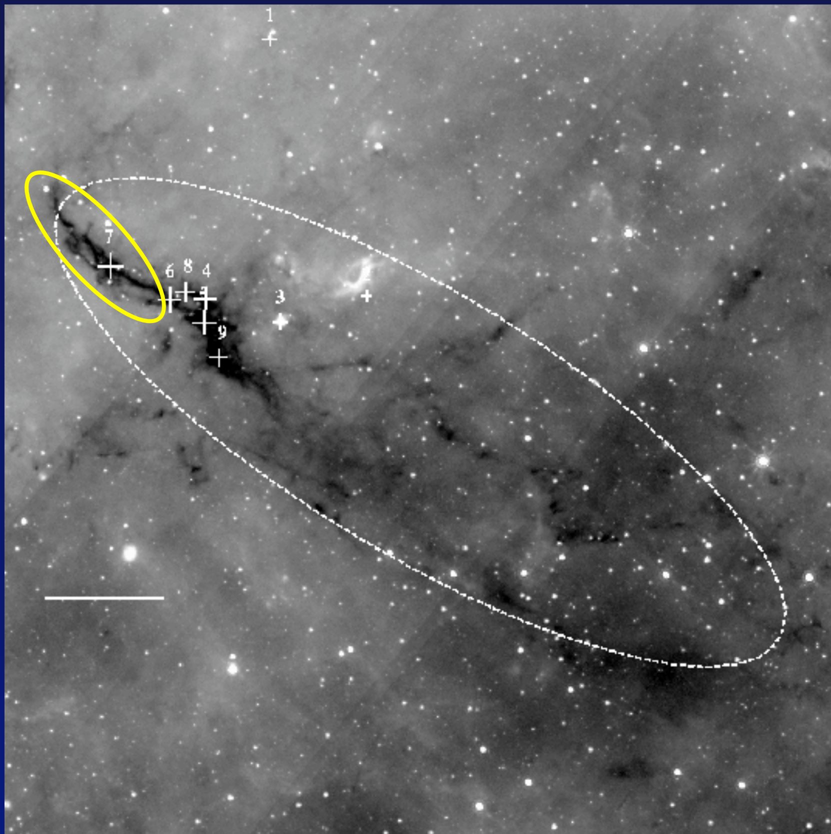
Spitzer - IRAC 8μm (GLIMPSE)

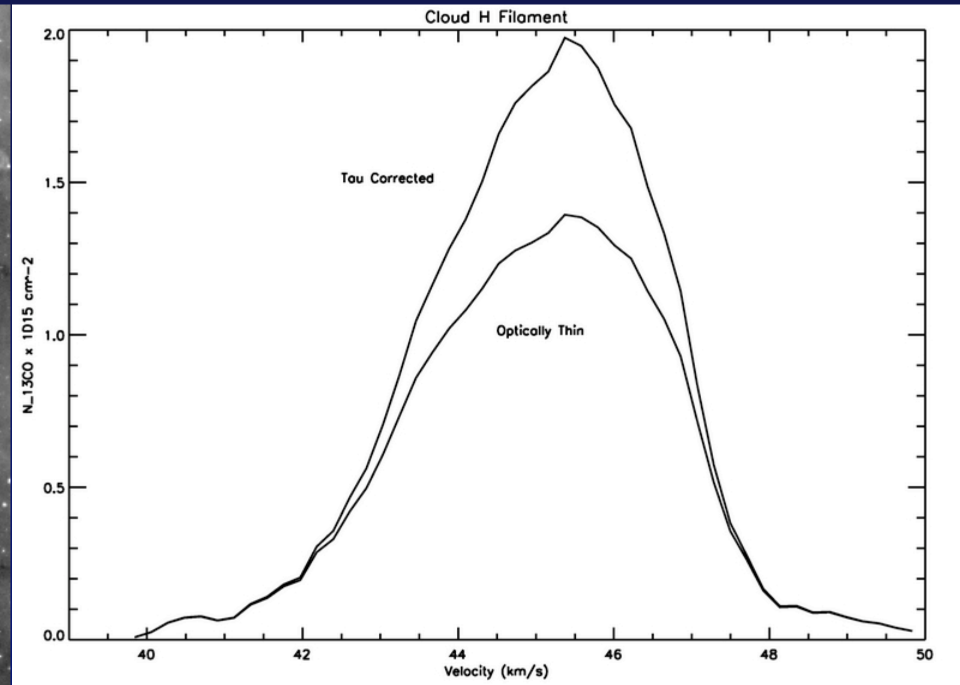
Extinction map to derive Σ

Distance from molecular line velocities (GRS) -> M(Σ)

Virial Analysis of an IRDC

Hernandez & Tan, in prep





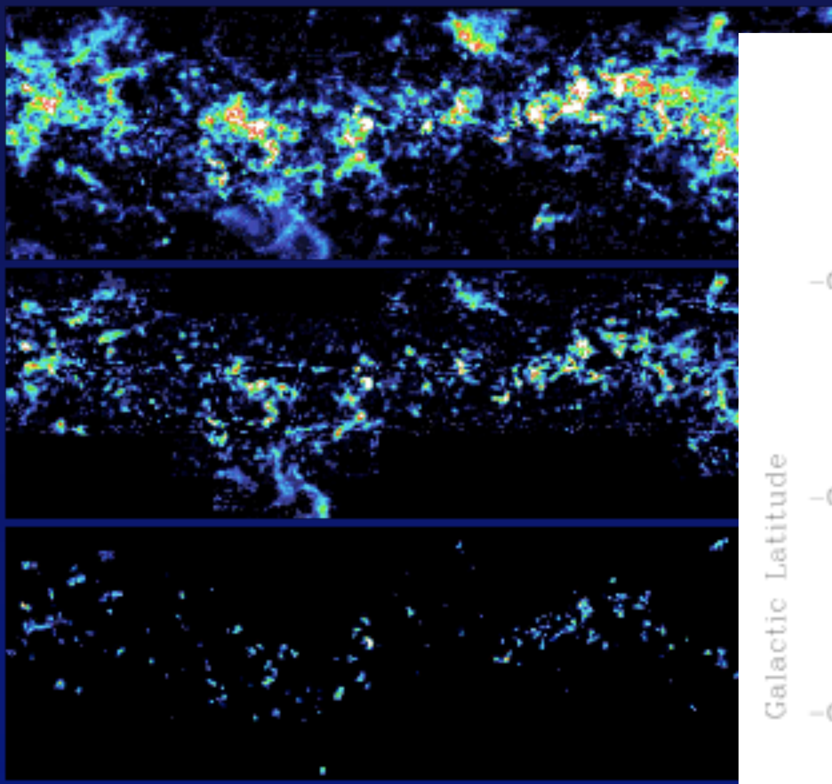
M_{vir} = 1600 $M_\odot$

M_{13CO} = 1500, 1100, 1000 $M_\odot$
(T=10, 15, 20K)

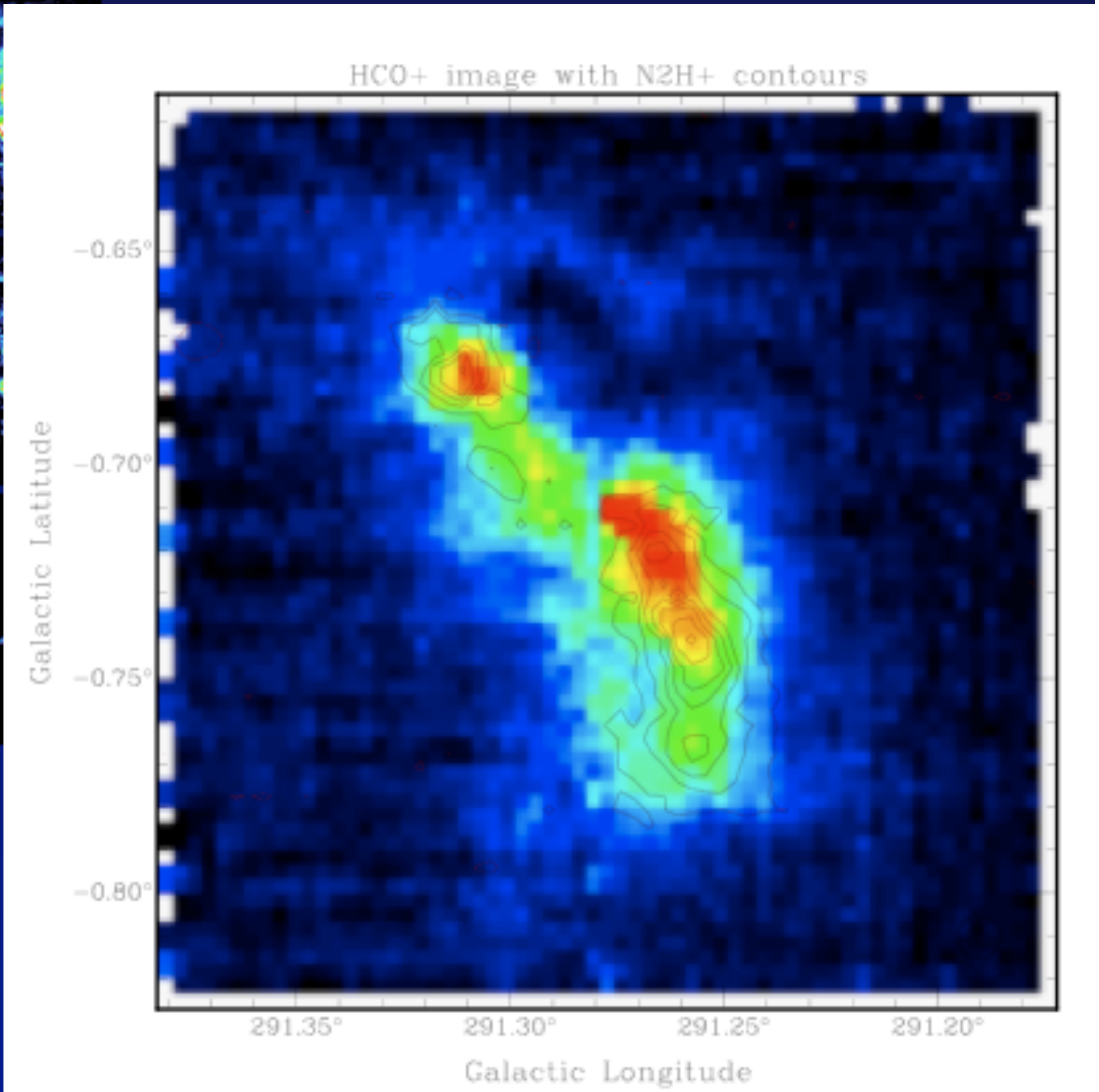
CHaMP

Barnes, Yonekura, Fukui, et al. 2008

l =-60 to -80 deg
b = -4 to +2 deg



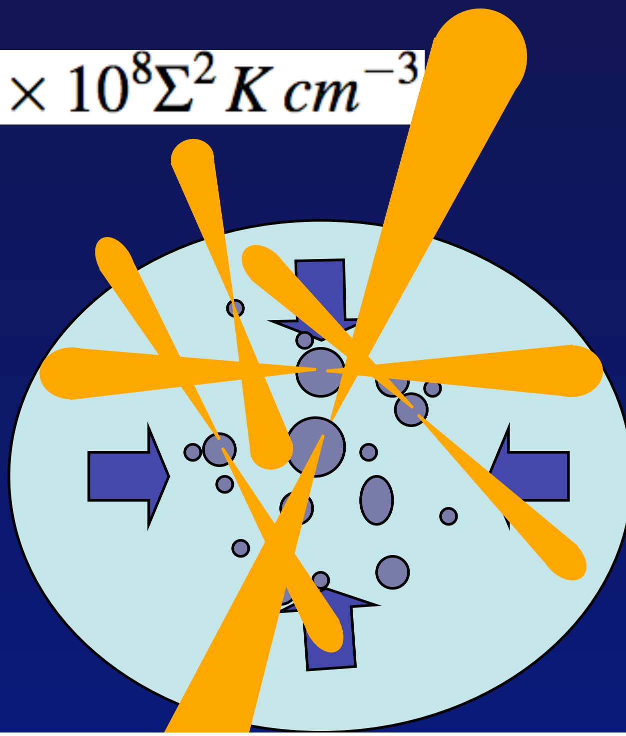
Nanten CO survey



MOPRA

Feedback: protostellar outflows

$$\bar{P}_G \simeq 0.88 G\Sigma^2 \rightarrow 4.25 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

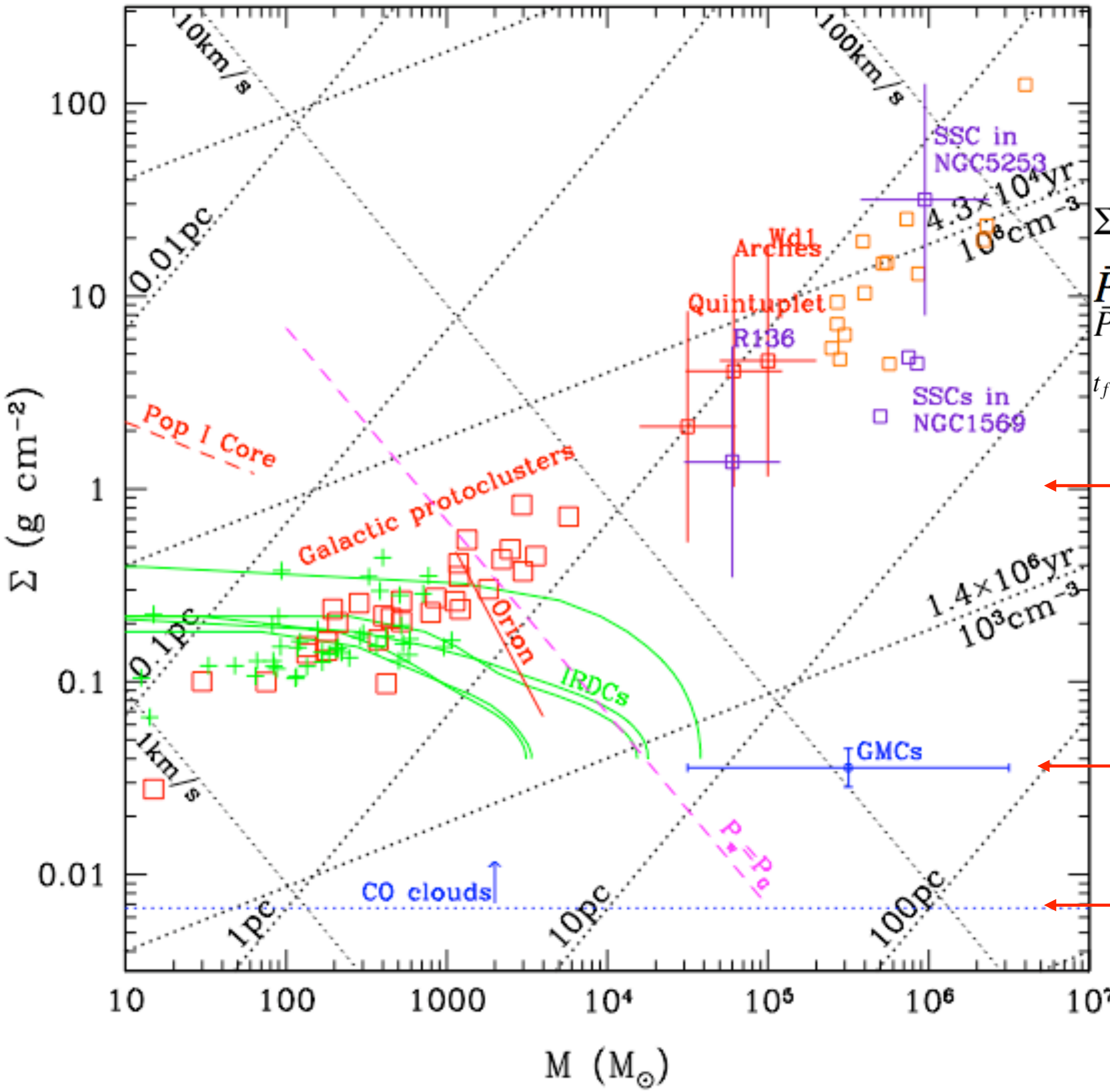


$$\bar{P}_w = \frac{f_{trap}\dot{p}_w}{4\pi(0.8R)^2}$$

$$\rightarrow = 3.87 \times 10^8 \frac{f_{trap}}{0.5}\frac{p_*}{87 km\, s^{-1}}\frac{SFR_{ff}}{0.05}\left(\frac{M}{1000 M_\odot}\right)^{-1/4} \Sigma^{7/4}\, K\, cm^{-3}$$

$$\bar{P}_w = \bar{P}_G \longrightarrow \Sigma = 0.684 \left(\frac{f_{trap}}{0.5}\frac{p_*}{87 km\, s^{-1}}\frac{SFR_{ff}}{0.05}\right)^4 \left(\frac{M}{1000 M_\odot}\right)^{-1} g\, cm^{-2}$$

Outflow Wind Feedback



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3\times10^8\Sigma^2\,K\,cm^{-3}$$

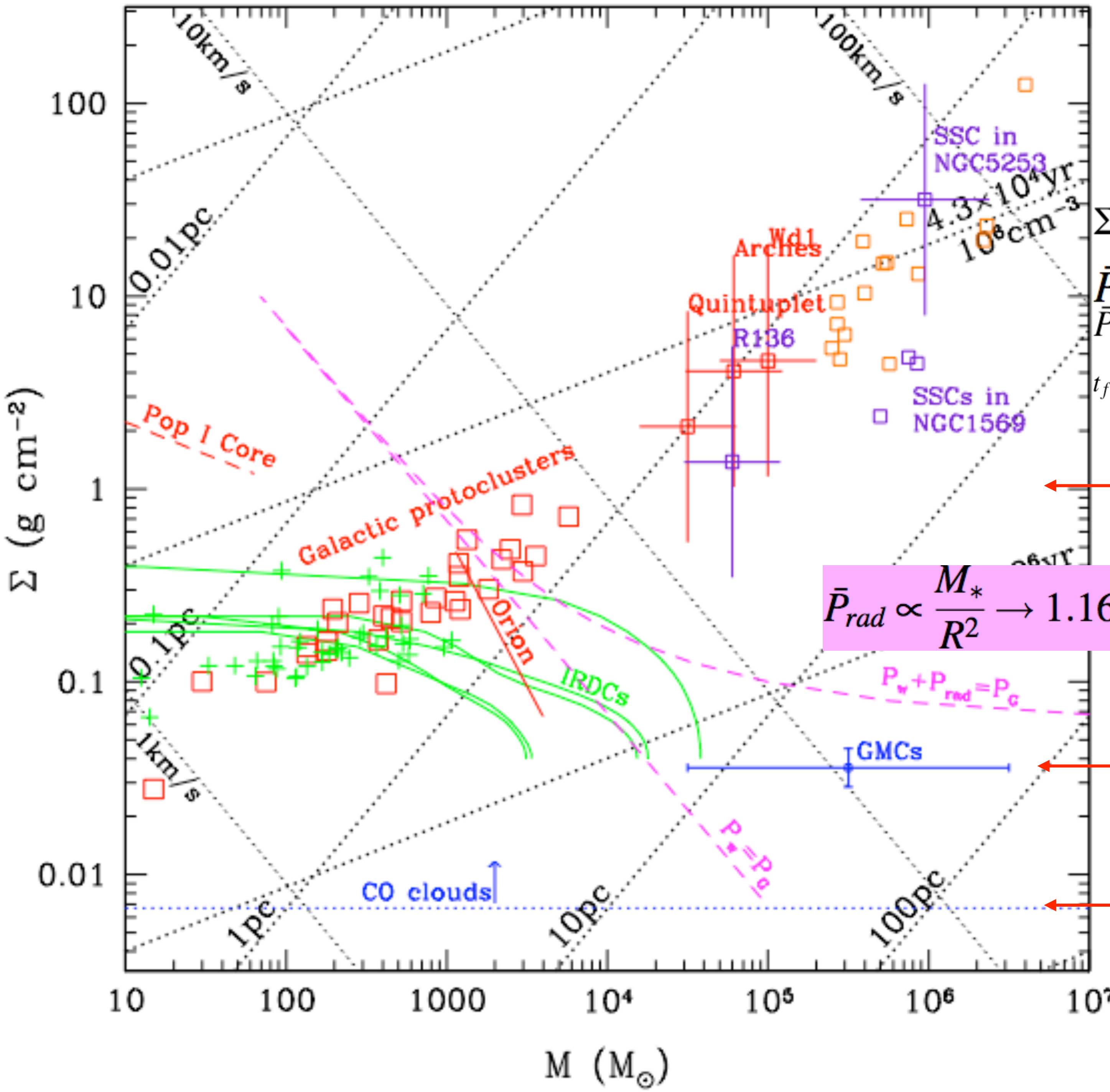
$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

A_V=200
N_H=4.2x10^{23}cm^{-2}
Σ=4800 $M_\odot$ pc^{-2}

A_V=7.5
N_H=1.6x10^{22}cm^{-2}
Σ=180 $M_\odot$ pc^{-2}

A_V=1.4
N_H=3.0x10^{21}cm^{-2}
Σ=34 $M_\odot$ pc^{-2}

Outflow Wind and Radiation Pressure Feedback



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

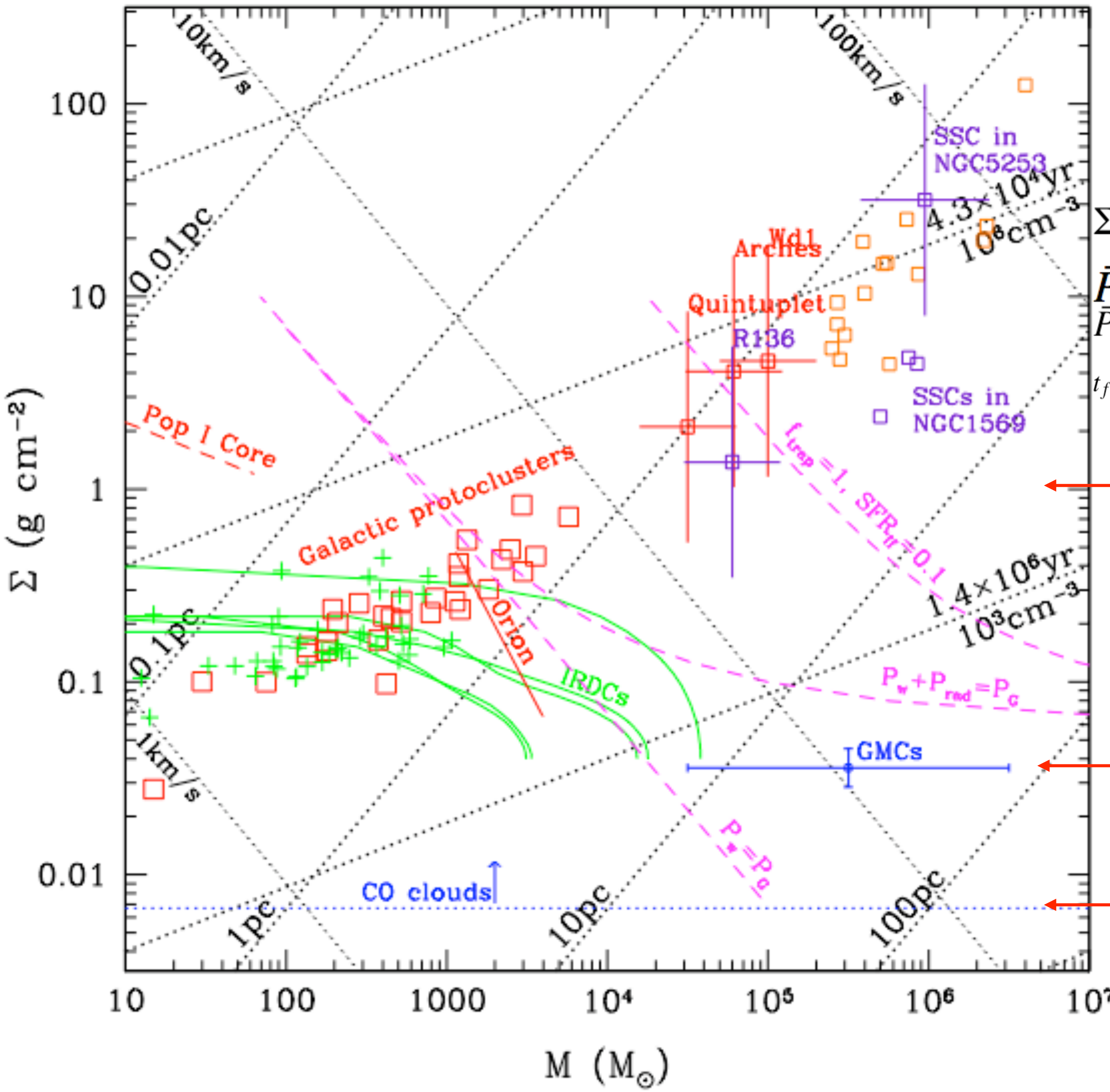
$$\bar{P}_{rad} \propto \frac{M_*}{R^2} \rightarrow 1.16 \times 10^7 \frac{\varepsilon_*}{0.33} \Sigma\, K\, cm^{-3}$$

$A_V=200$
$N_H=4.2\times10^{23} cm^{-2}$
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$N_H=1.6\times10^{22} cm^{-2}$
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21} cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

Outflow Wind and Radiation Pressure Feedback



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

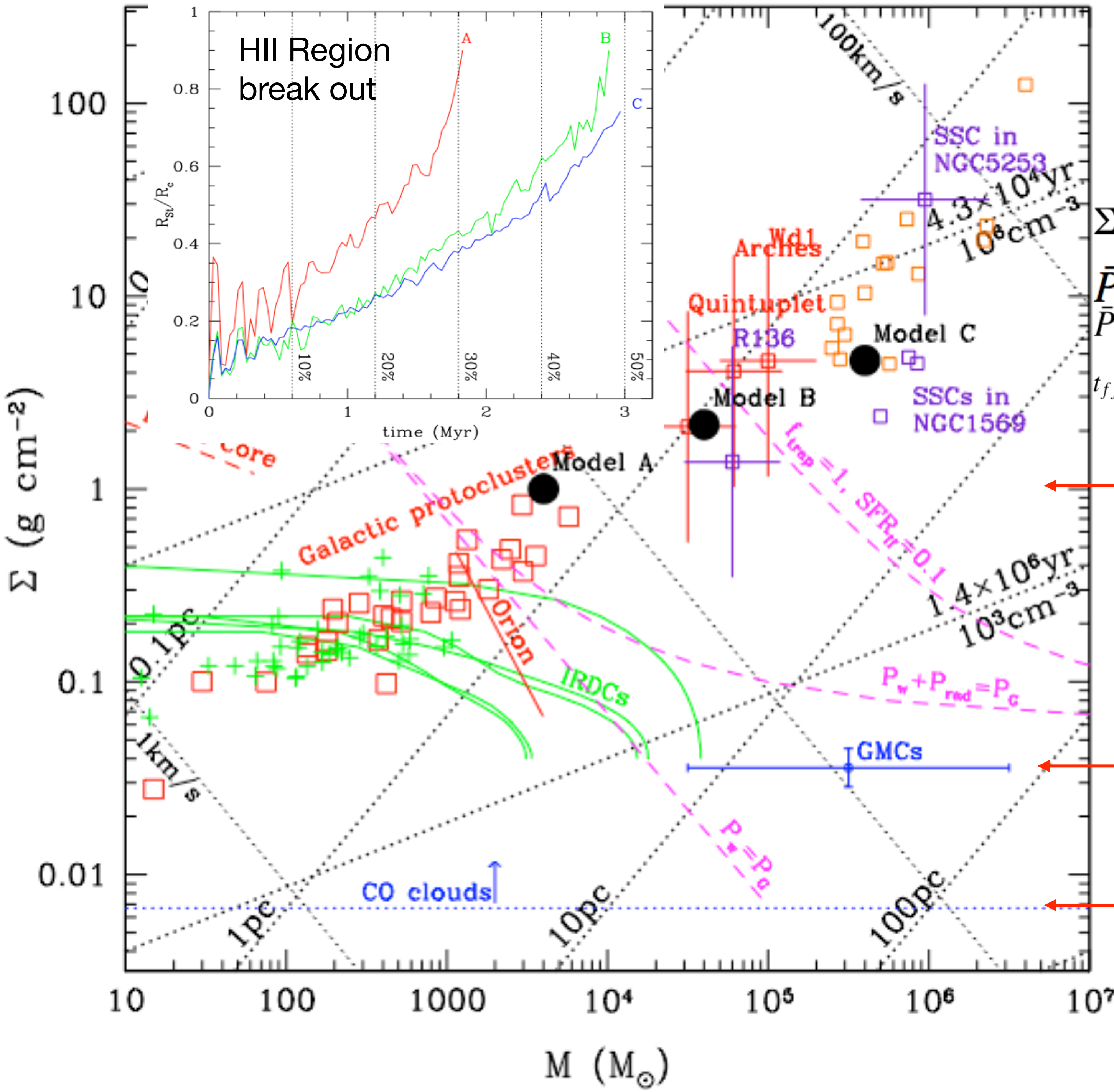
$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

$A_V=200$
$N_H=4.2\times10^{23} cm^{-2}$
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$N_H=1.6\times10^{22} cm^{-2}$
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21} cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

Ionization Feedback



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3\times10^{8}\Sigma^2\,K\,cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

$A_V=200$
$N_H=4.2\times10^{23}$cm^{-2}
$\Sigma=4800$ M$_\odot$ pc^{-2}

$A_V=7.5$
$N_H=1.6\times10^{22}$cm^{-2}
$\Sigma=180$ M$_\odot$ pc^{-2}

$A_V=1.4$
$N_H=3.0\times10^{21}$cm^{-2}
$\Sigma=34$ M$_\odot$ pc^{-2}