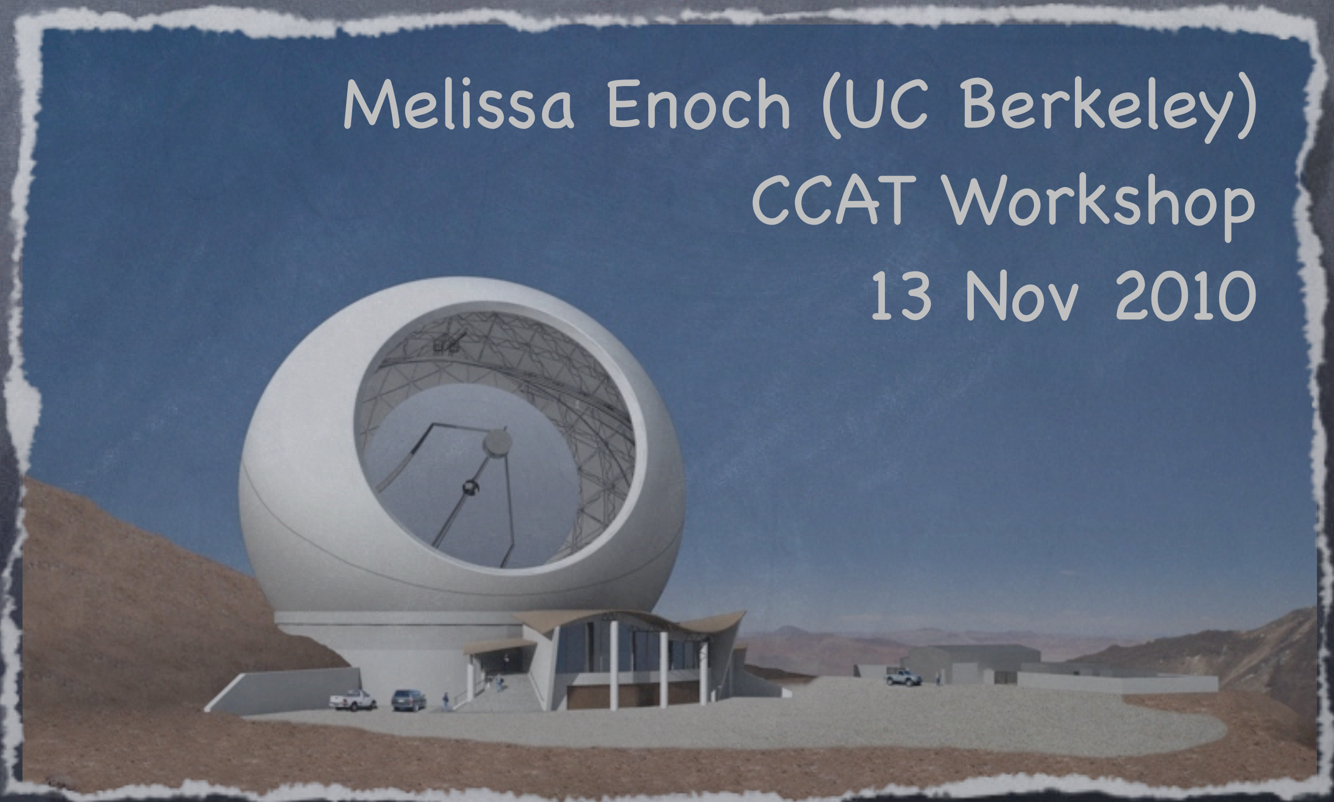
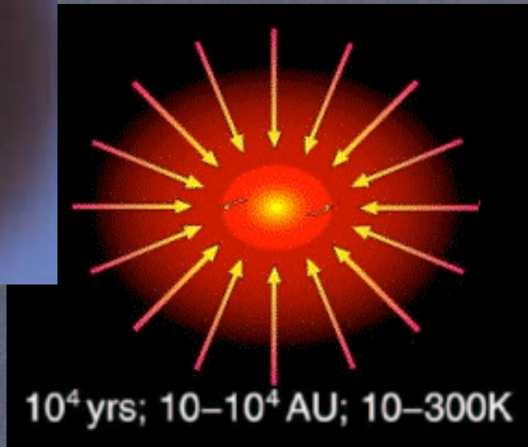
Characterizing the earliest phases of star formation with submm (continuum) surveys



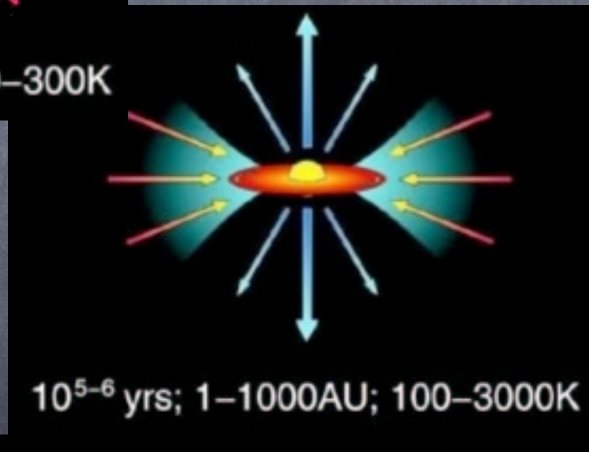
Formation of a low-mass star

Physical Stage

– Prestellar core (gravitationally bound)



– Stage 0 protostar
$M_{env} > M_{star}$



– Stage I protostar
$M_{env} < M_{star}$;
$M_{env} > 0.1\ M_{\odot}$

– Stage II star+disk;
$M_{env} < 0.1\ M_{\odot}$

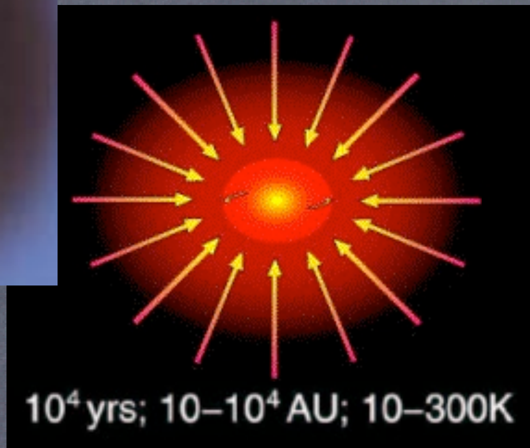
(Shu et al. 1987; Robitaille et al. 2006; Crapsi et al. 2008)

fig: McCaughrean

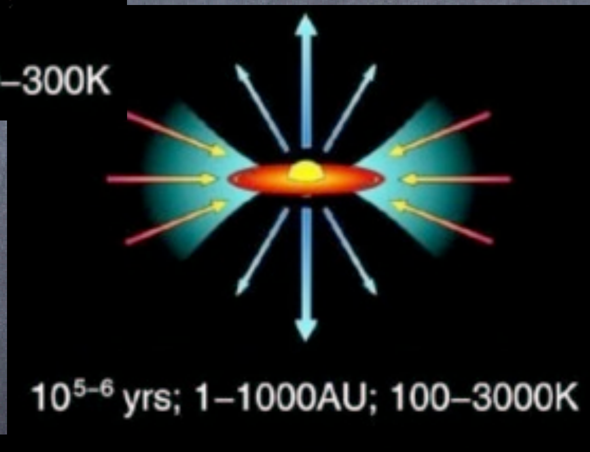
- Physical Stage
- SED Class

Formation of a low mass star

- Prestellar core
- Starless core



- Stage 0 protostar
  $M_{env} > M_{star}$
- Class 0: $T_{bol}<70$ K



- Stage I protostar
  $M_{env} < M_{star}$;
  $M_{env} > 0.1\ M_{\odot}$
- Class I:
  $70<T_{bol}<650$ K

- Stage II star+disk; $M_{env}<0.1\ M_{\odot}$
- Class II $650<T_{bol}<2800$ K

(Shu et al. 1987; Robitaille et al. 2006)

(Myers & Ladd 1993)

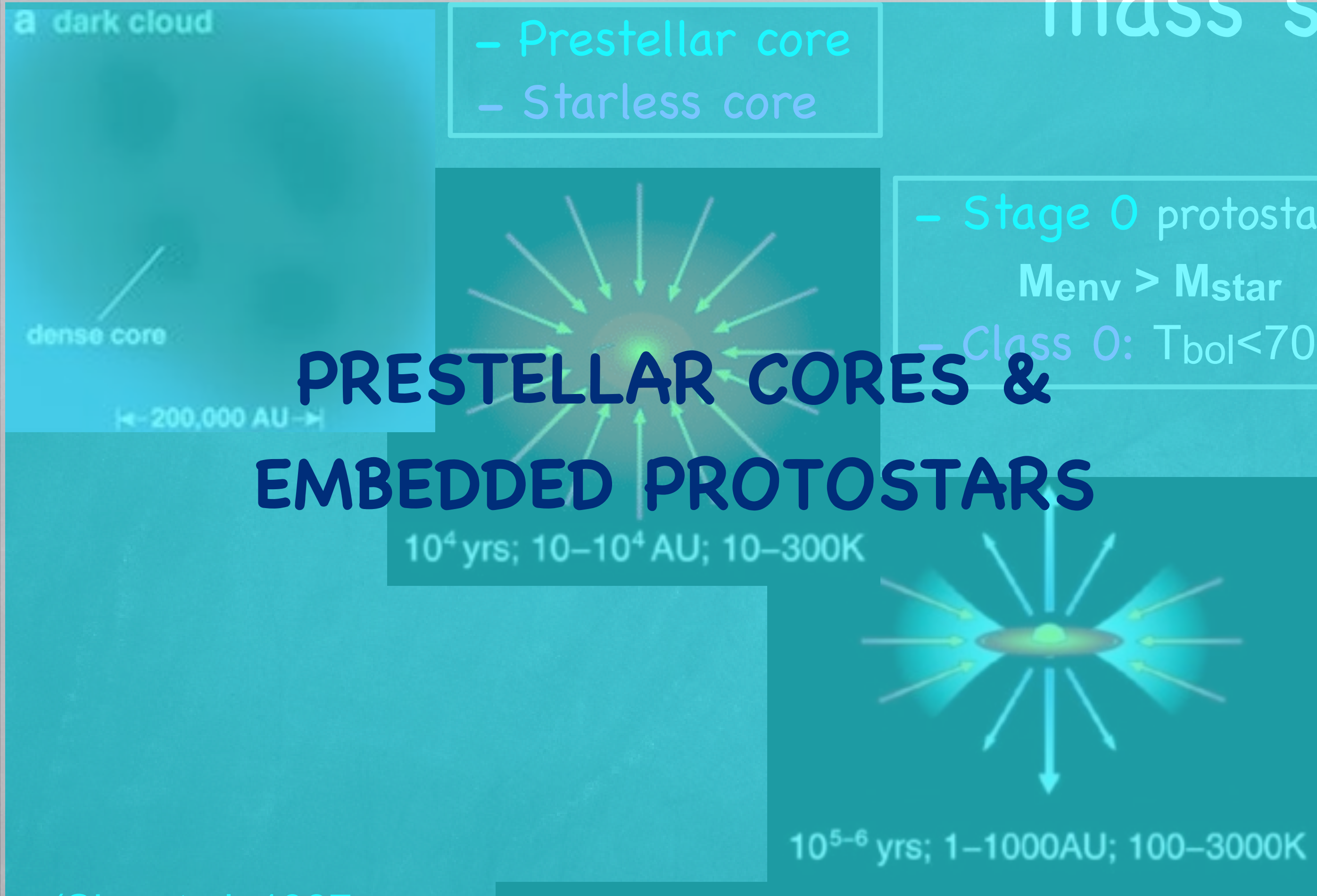
fig: McCaughrean

Formation of a low mass star

- Physical Stage
- SED Class

- Prestellar core
- Starless core

- Stage 0 protostar
  $M_{env} > M_{star}$
- Class 0: T_{bol}<70 K



- Stage I protostar
  $M_{env} < M_{star}$;
  $M_{env} > 0.1\ M_{\odot}$
- Class I:
  70<T_{bol}<650 K

(Shu et al. 1987; Robitaille et al. 2006)

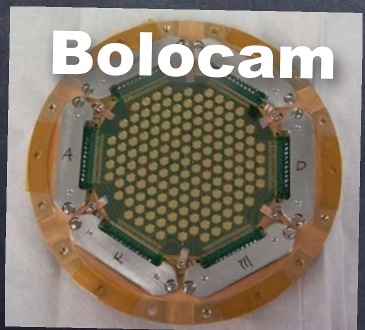
(Myers & Ladd 1993)

fig: McCaughrean

- Stage II star+disk; M_{env}<0.1 $M_{\odot}$
- Class II 650<T_{bol}<2800 K

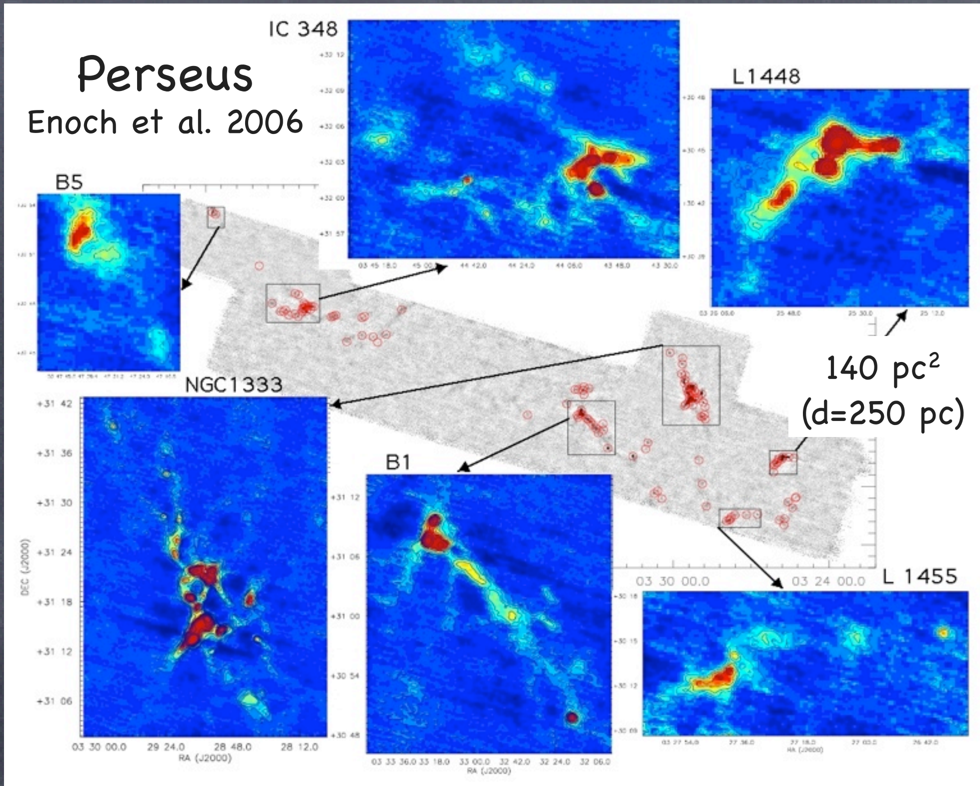
(Sub)millimeter surveys are critical for:

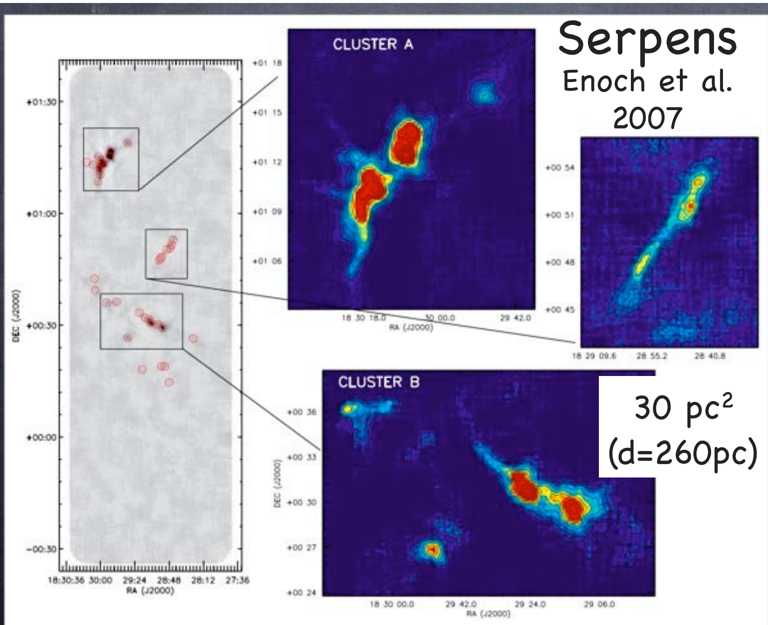
1. Prestellar core mass distribution (CMD)
   - Relationship between cores & star properties
   - Test of core formation models
2. Timescales for star formation
   - Physics of core formation & support
   - Average accretion rates
3. Characterizing embedded sources
   - Evolutionary state, luminosity, envelope mass
   - Evolution of accretion rates & envelope mass with time

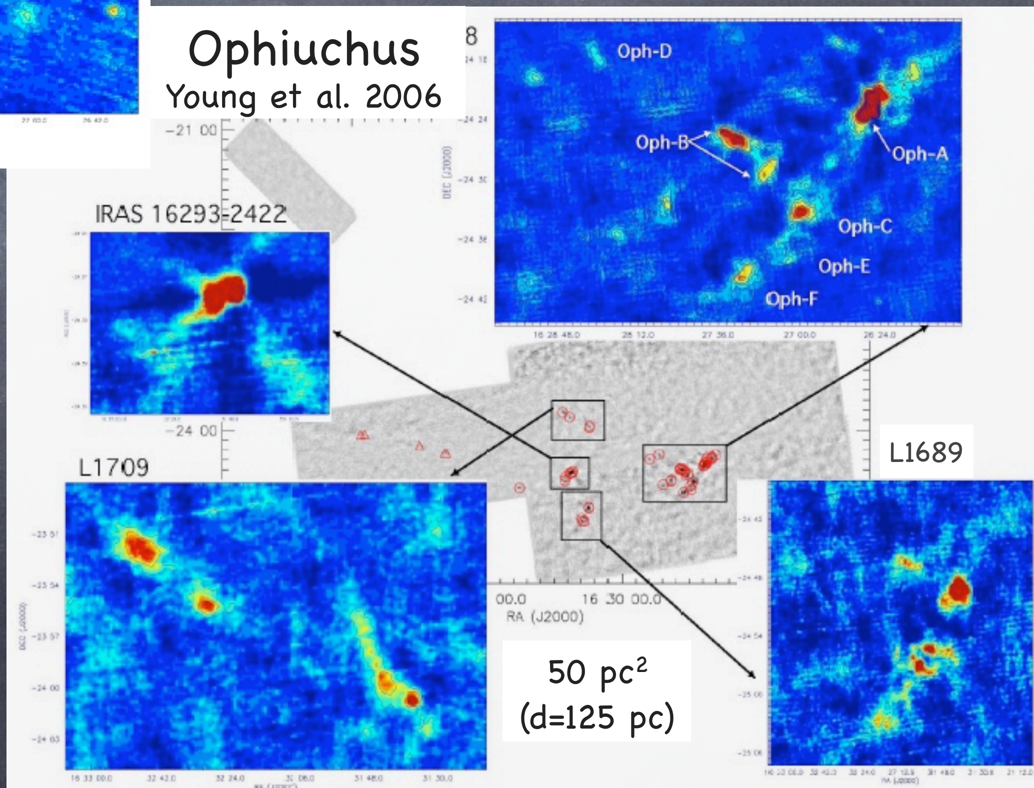


Bolocam c2d Survey

- 20 deg^2, λ=1mm, 31″ res
- >200 cores and protostars
- Mass limit ~0.1 Msun

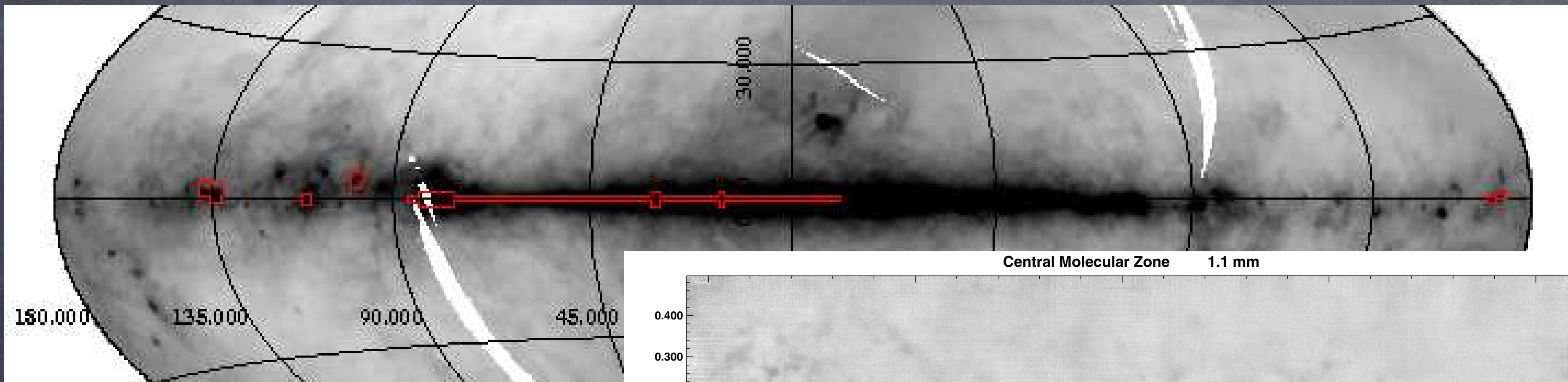


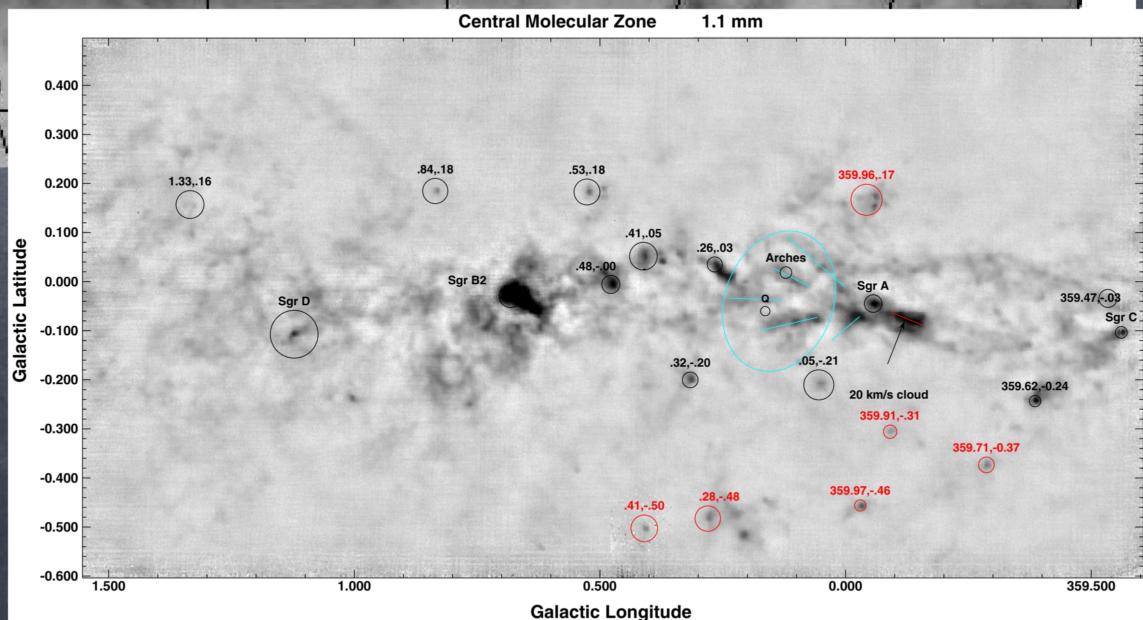




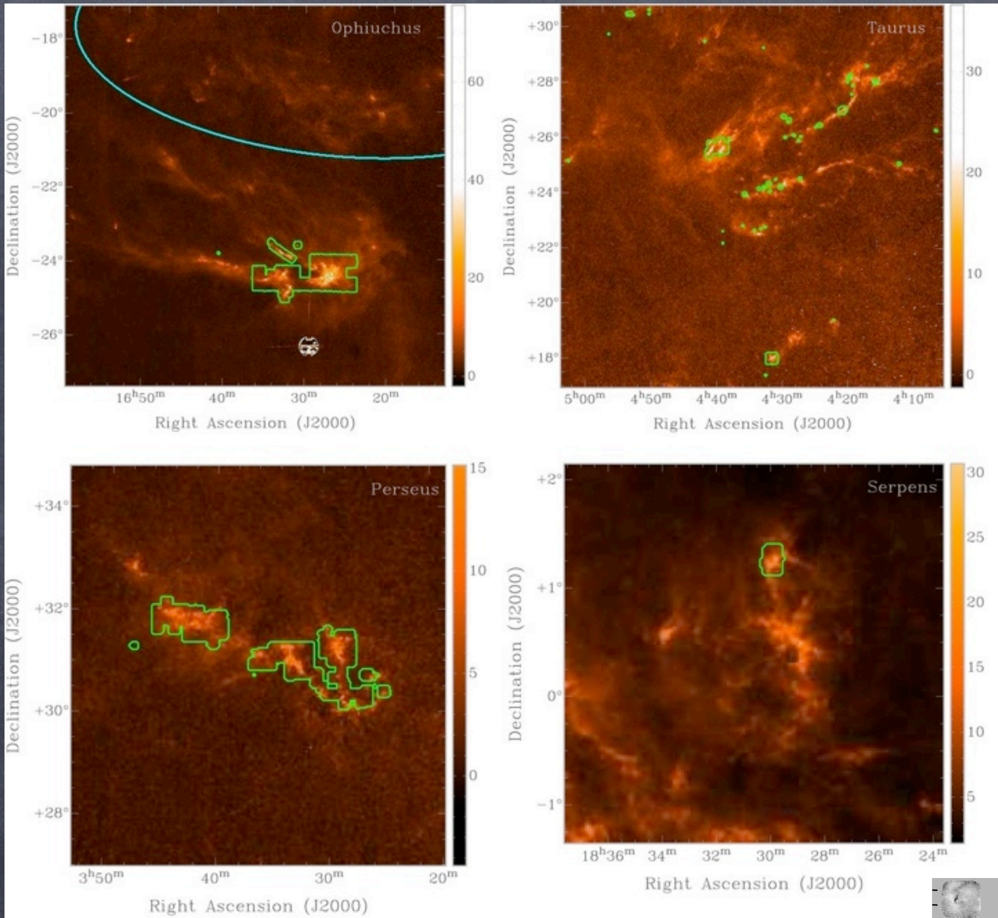
Bolocam Galactic Plane Survey

- 150 deg^2, λ=1mm, 31″ res
- 8000 star forming clumps
- 98% complete at 0.4 Jy (clumps >10 Msun)



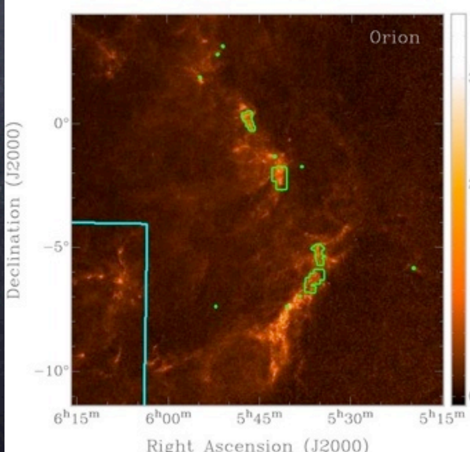


Aguirre et al. 2010;
Rosolowsky et al. 2010;
Bally et al. 2010

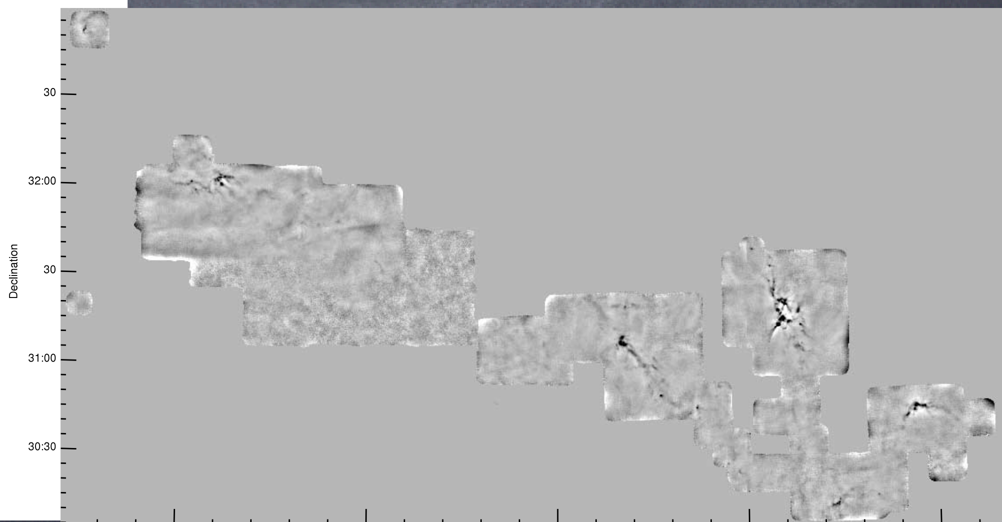


SCUBA Gould Belt

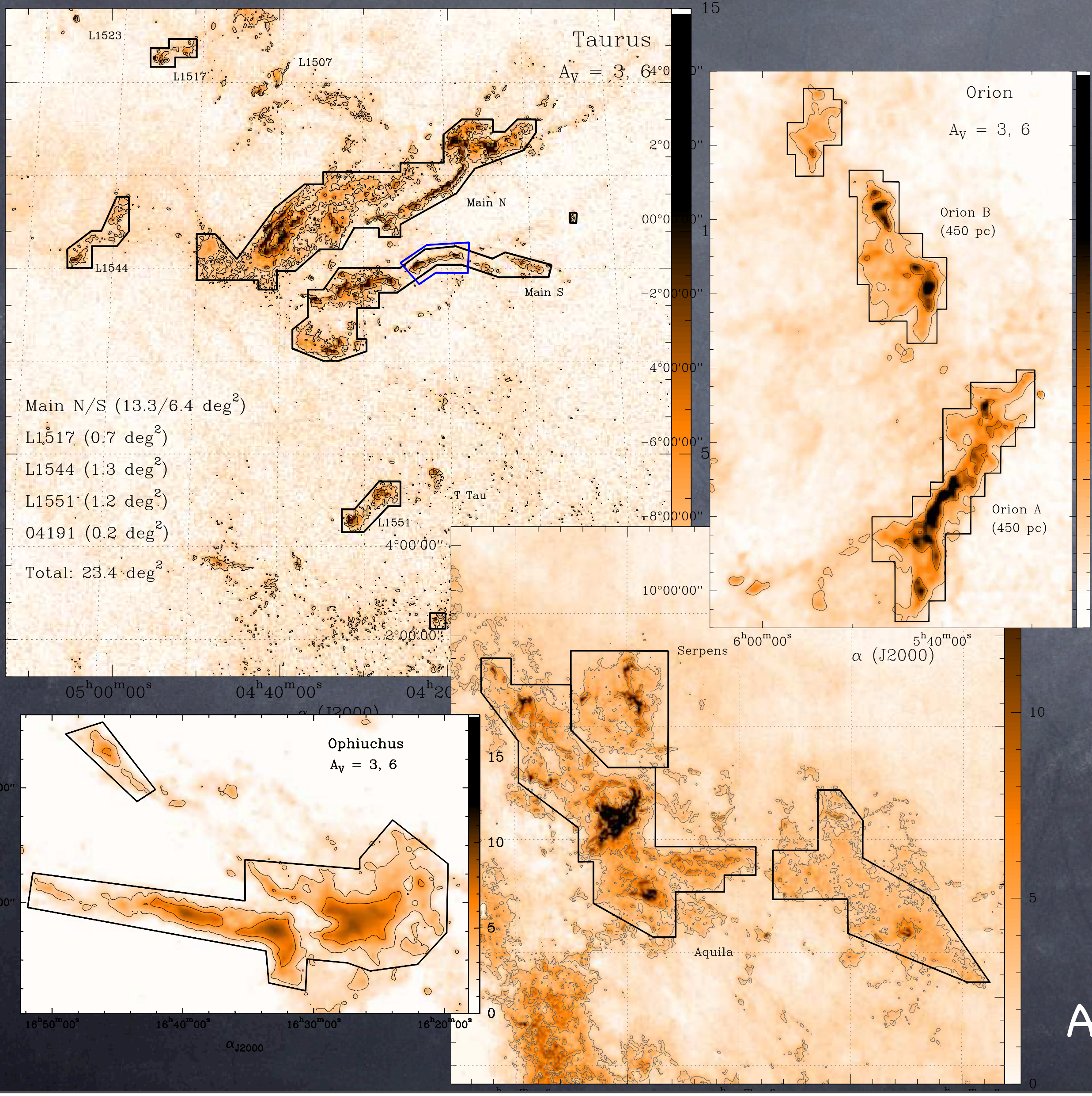
- Archival; limited covg
- 7.5 deg^2, λ=850μm, 15″ res
- 750 cores
- Mass limit = 0.3-3 Msun



Sadavoy et al. 2010;
Kirk et al. 2006;
Hatchell et al. 2005



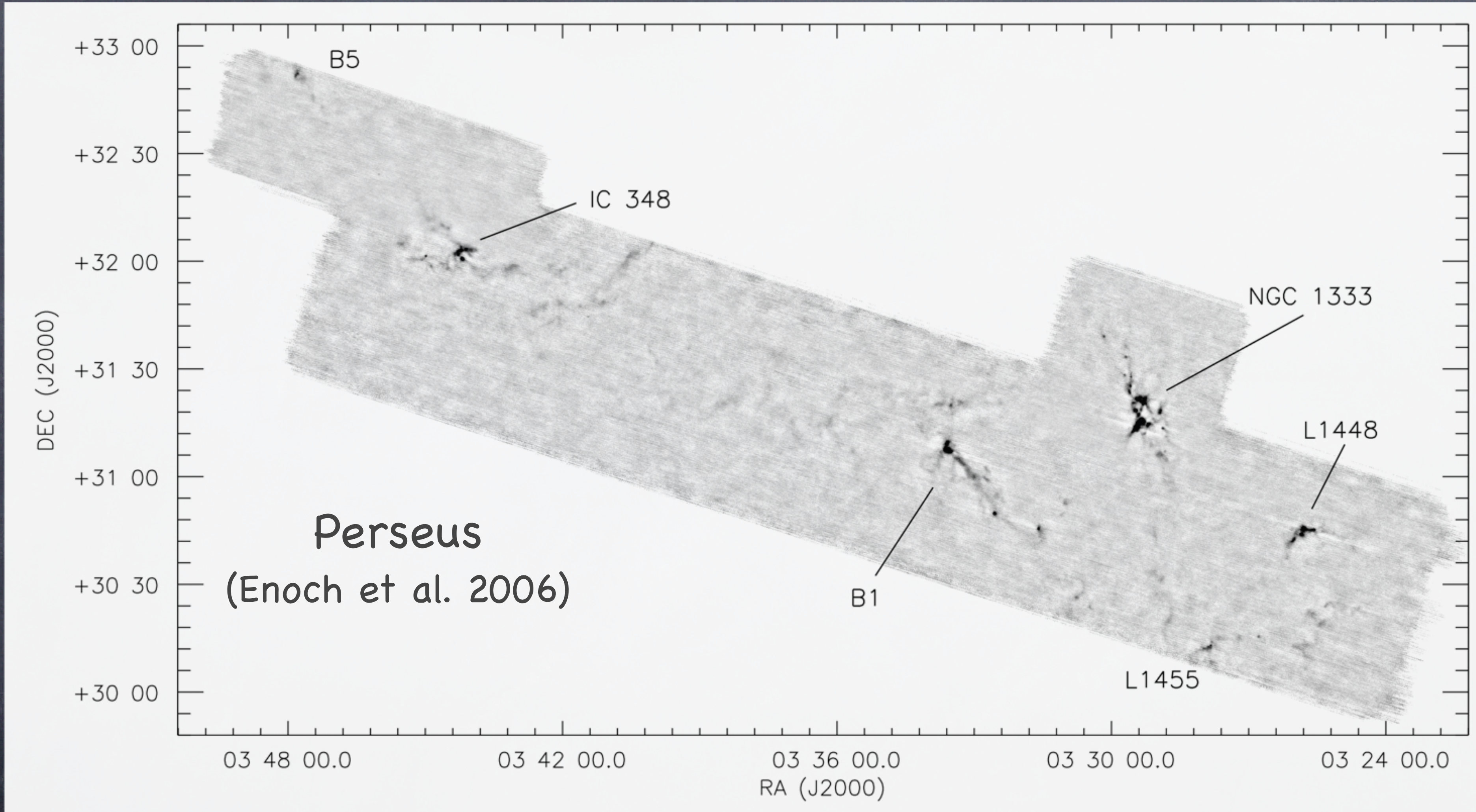
Herschel Gould Belt



- In progress
- 160 deg^2
- λ=100-500μm, ~15″ res
- Mass limit <0.3 Msun

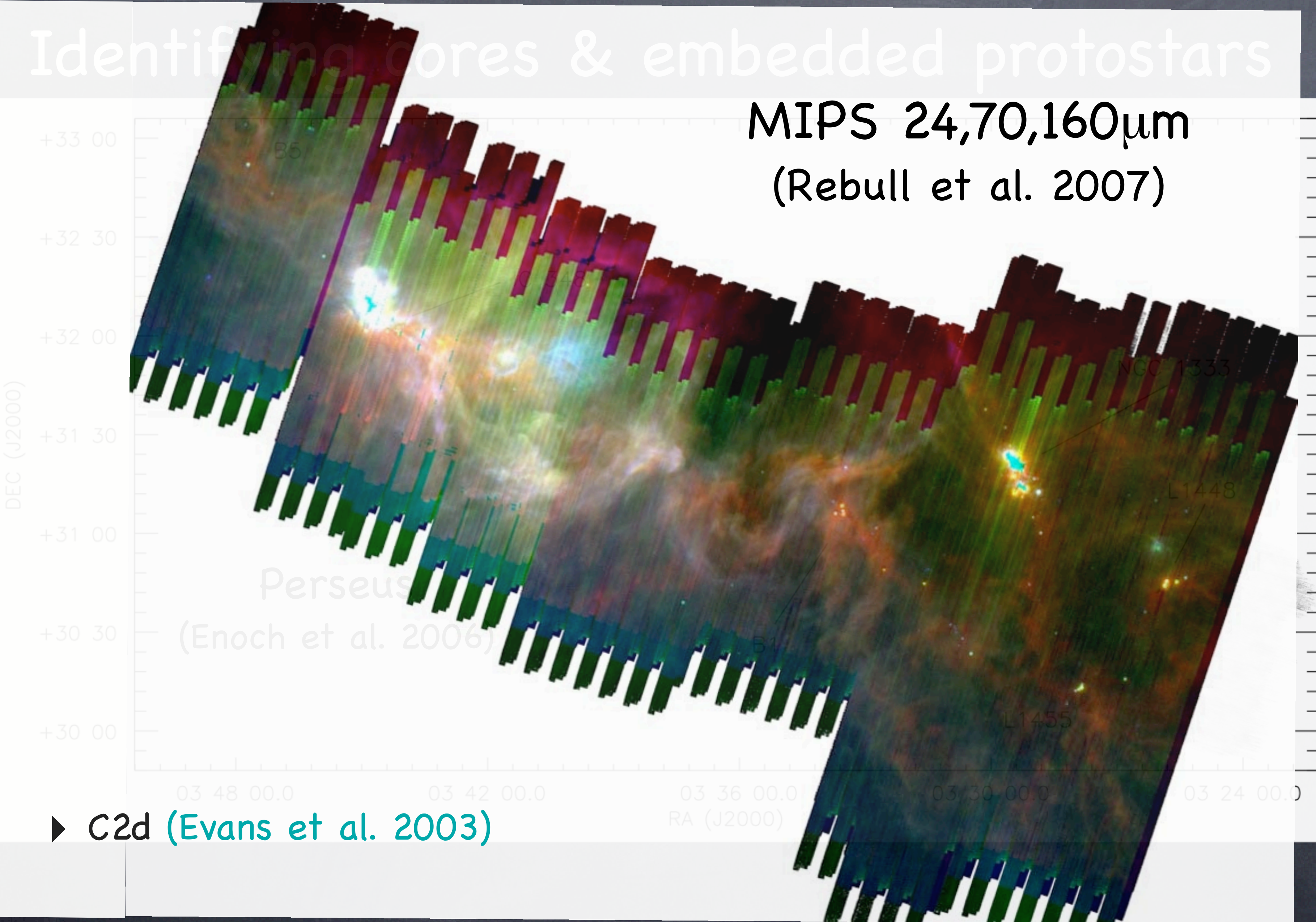
Andre et al. 2005, 2010

Identifying cores & embedded protostars



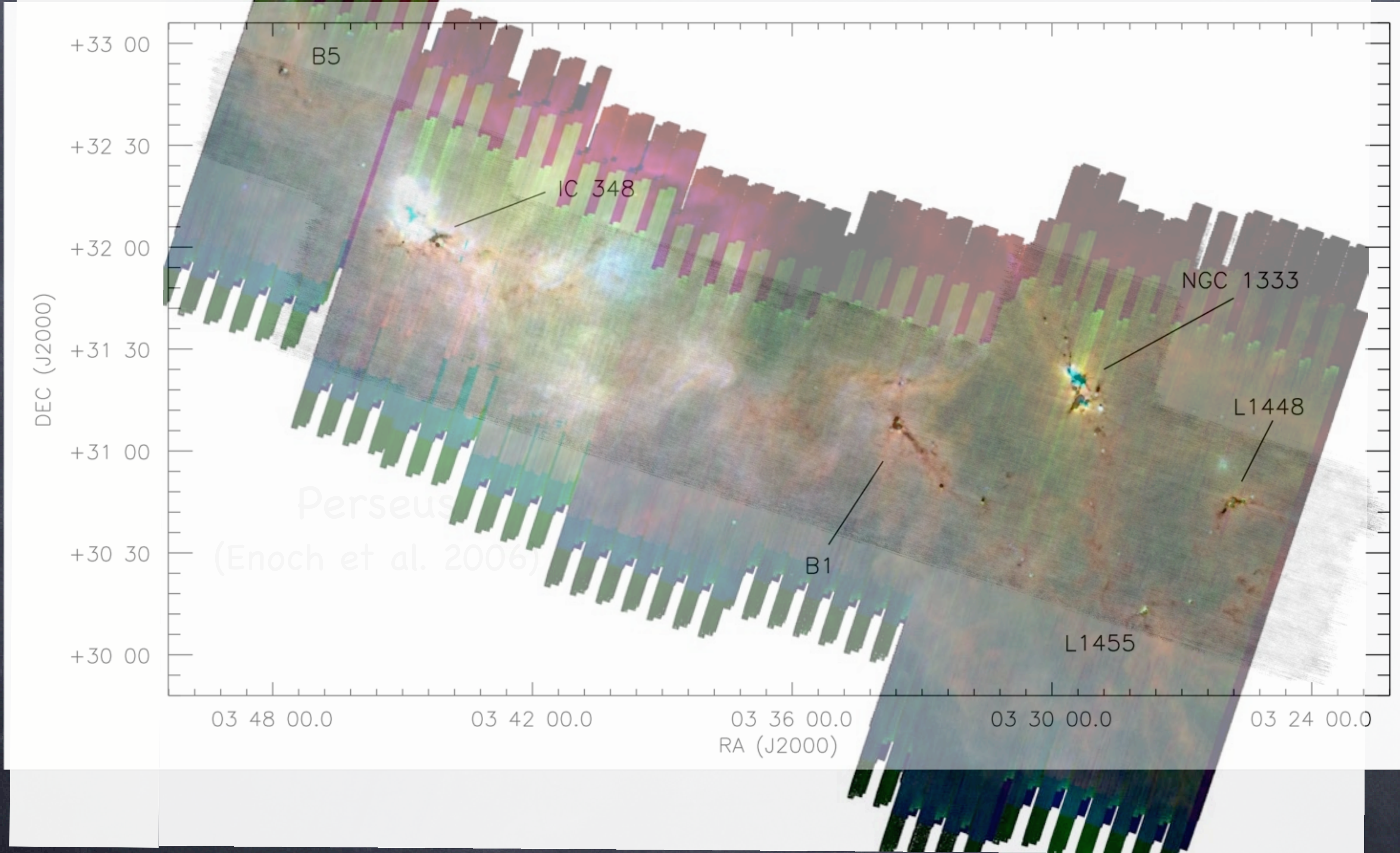
- Bolocam 1.1mm continuum surveys
  - Enoch et al. 2006; Young et al. 2006; Enoch et al. 2007

Identifying cores & embedded protostars



- C2d (Evans et al. 2003)
  - Jorgensen et al. 2006; Rebull et al. 2007; Harvey et al. 2007a, 2007b; Padgett et al. 2008

Identifying cores & embedded protostars



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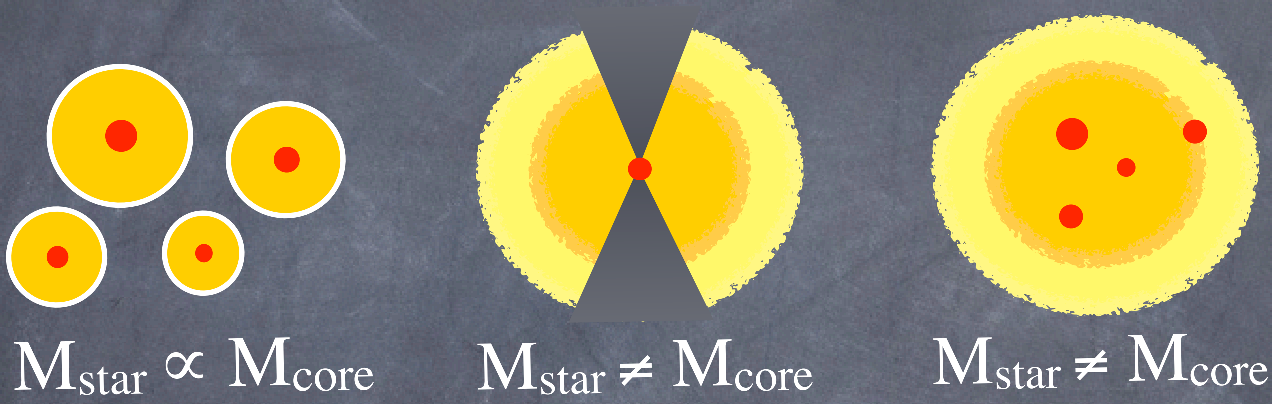
1. Prestellar core mass distribution

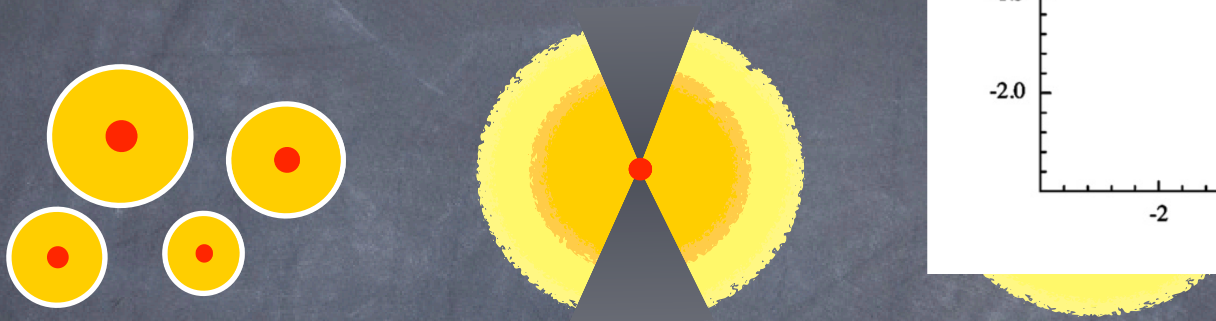
- Clues to the origin of stellar masses (core, feedback, competitive accretion)



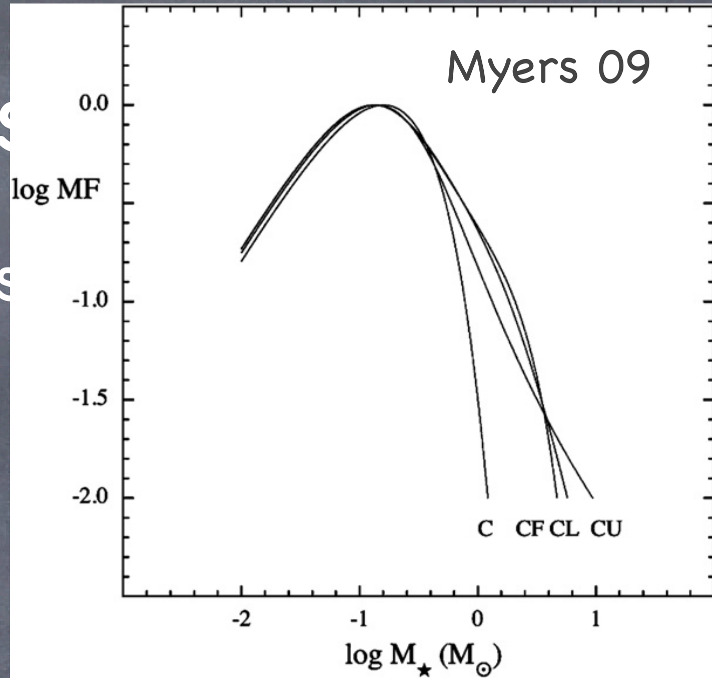
- Initial conditions for star formation
- Core formation physics
- Mass from (sub)mm flux (if dust temp & opacity known)
  - $M_{env} = d^2 S_\nu / B_\nu(T_D) \kappa_\nu$

1. Prestellar core mass

- Clues to the origin of stellar mass
competitive accretion)



$M_{star} \propto M_{core}$ $\quad$ $M_{star} \neq M_{core}$ $\quad$ $M_{star} \neq M_{core}$



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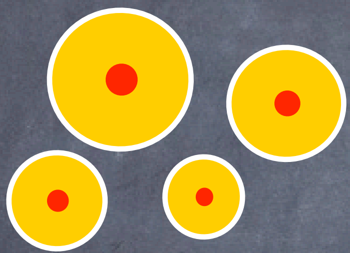

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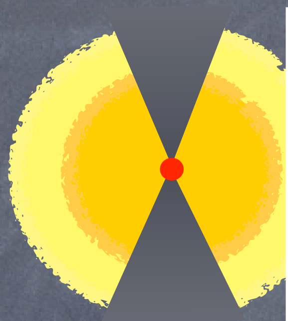
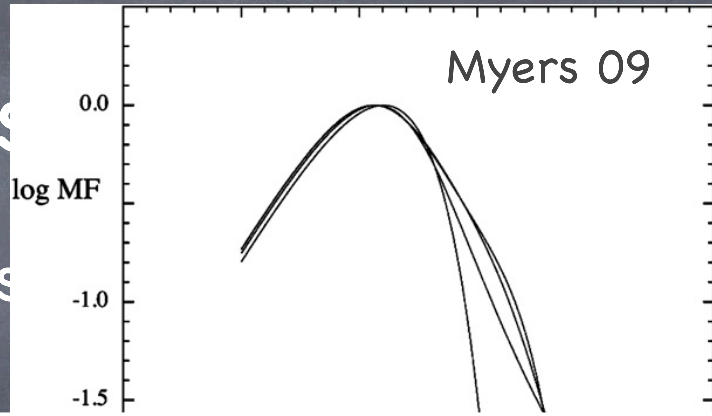
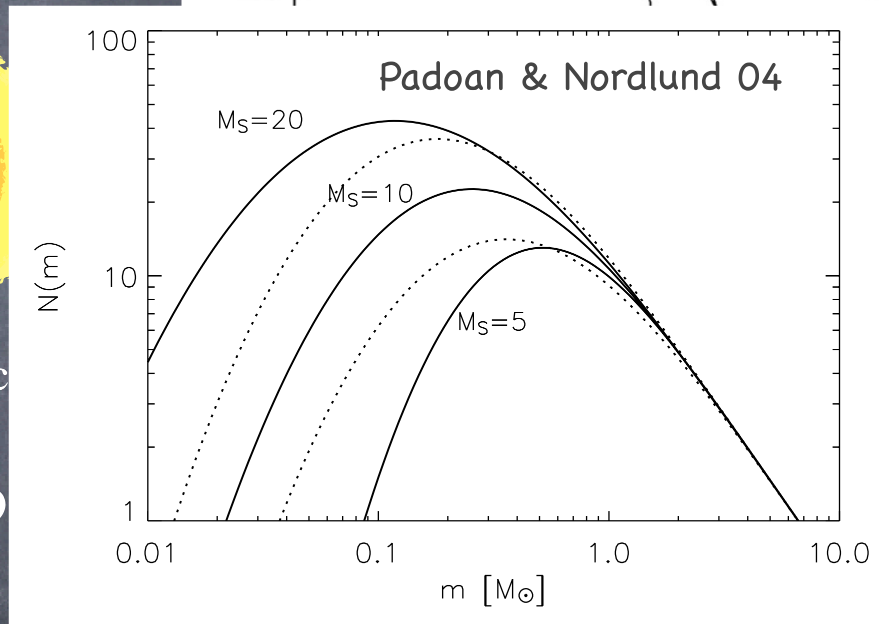


$M_{star} \neq M_{c}$





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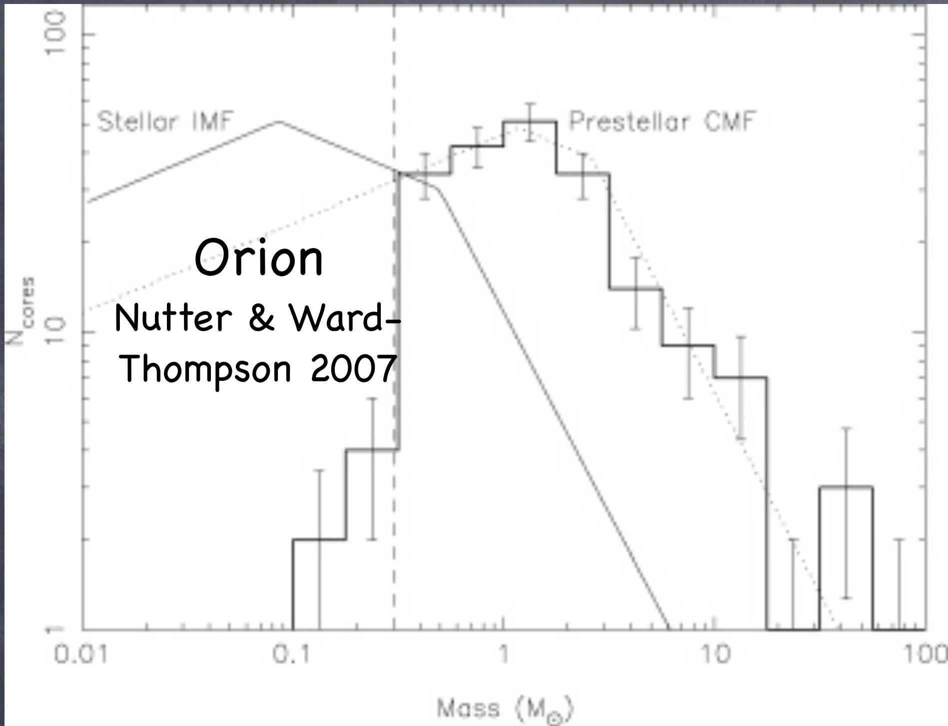

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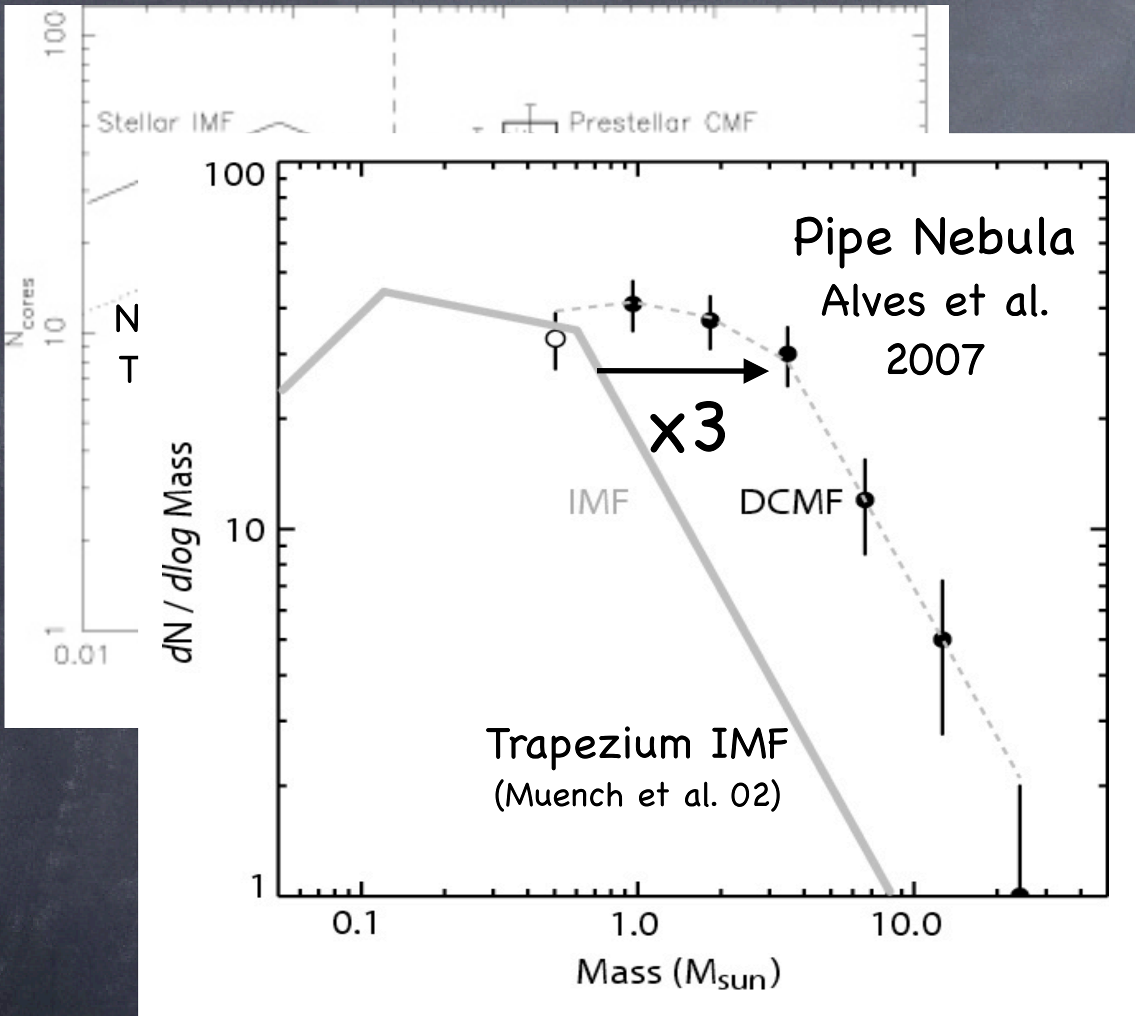

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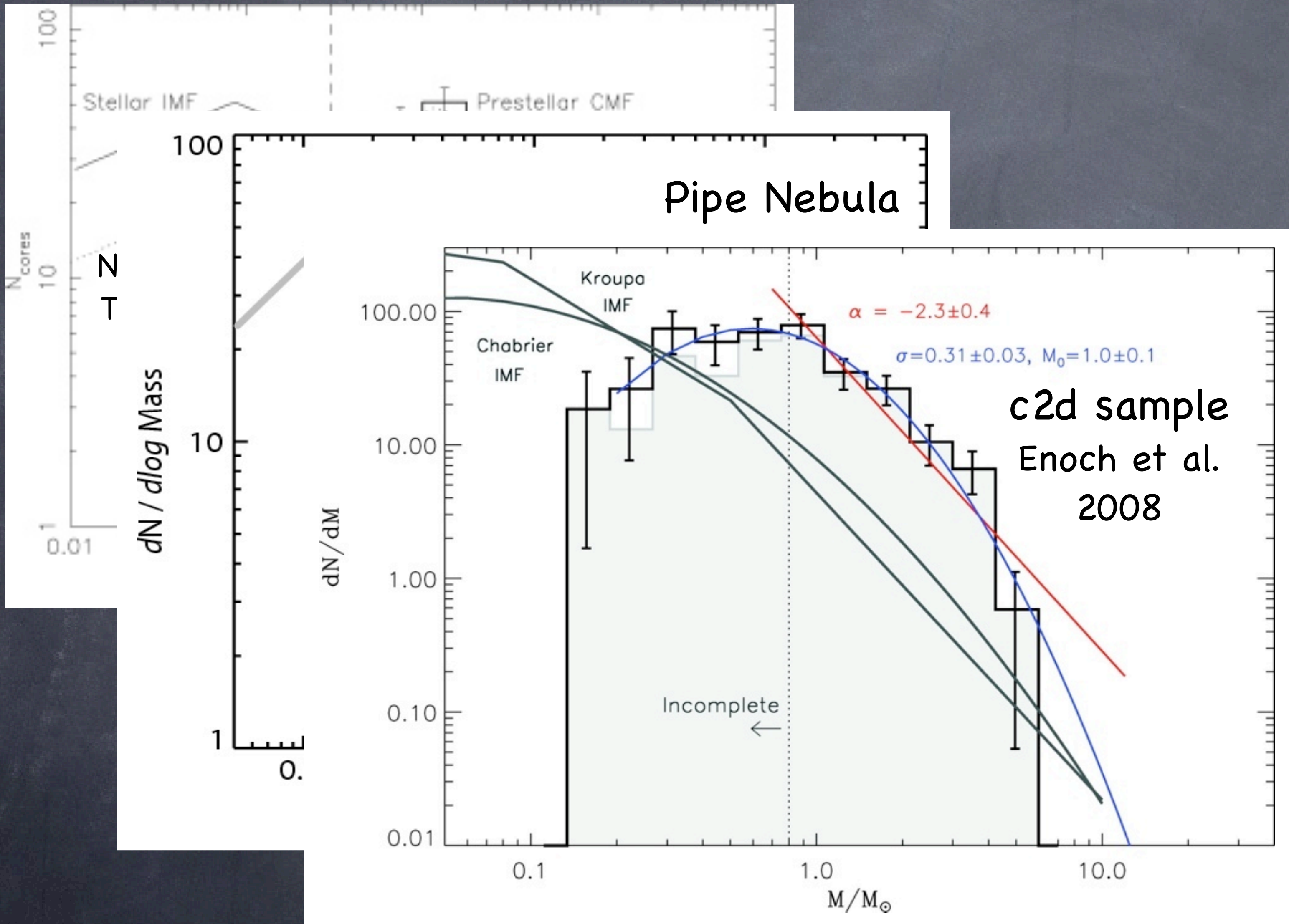

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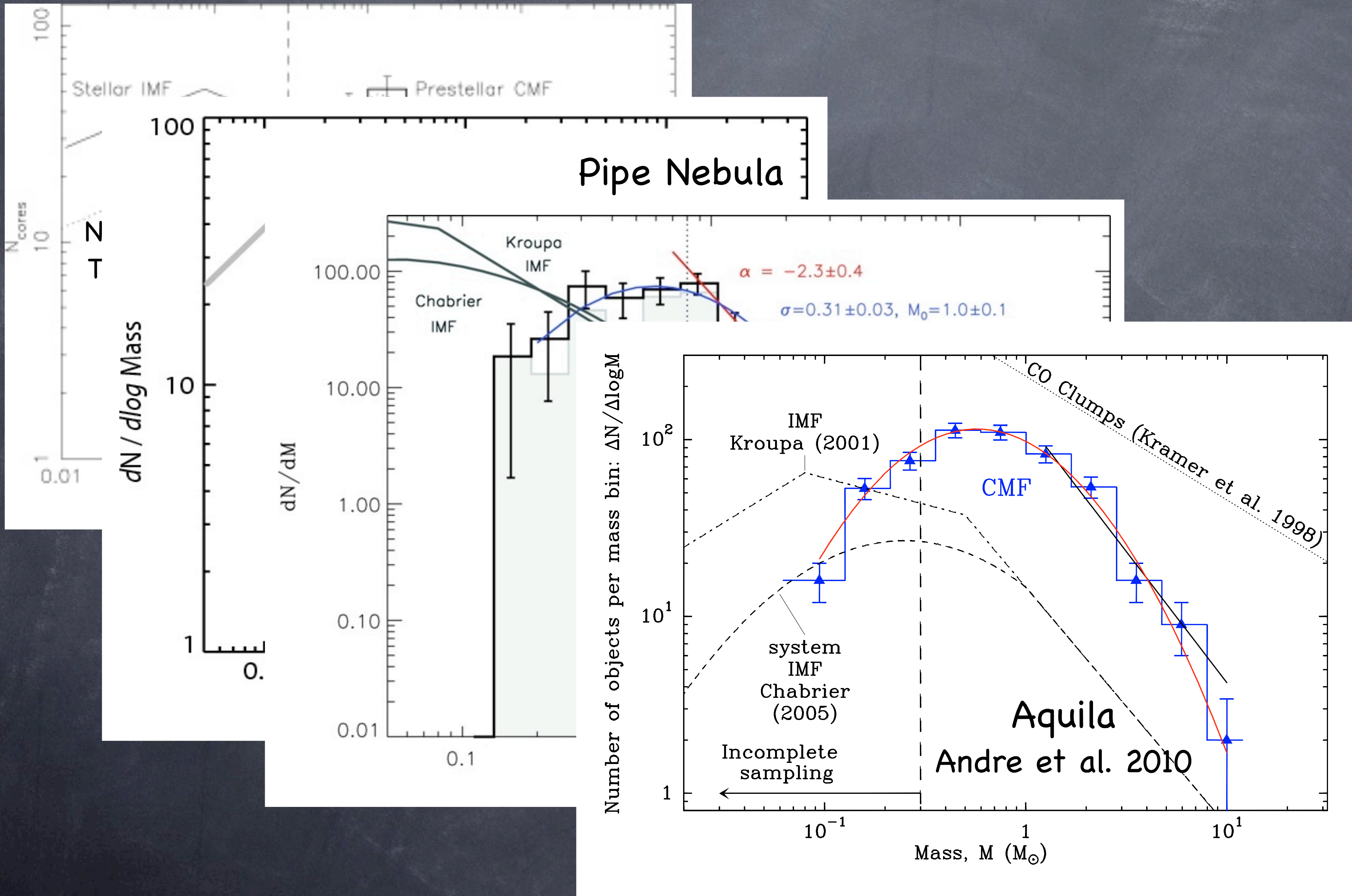

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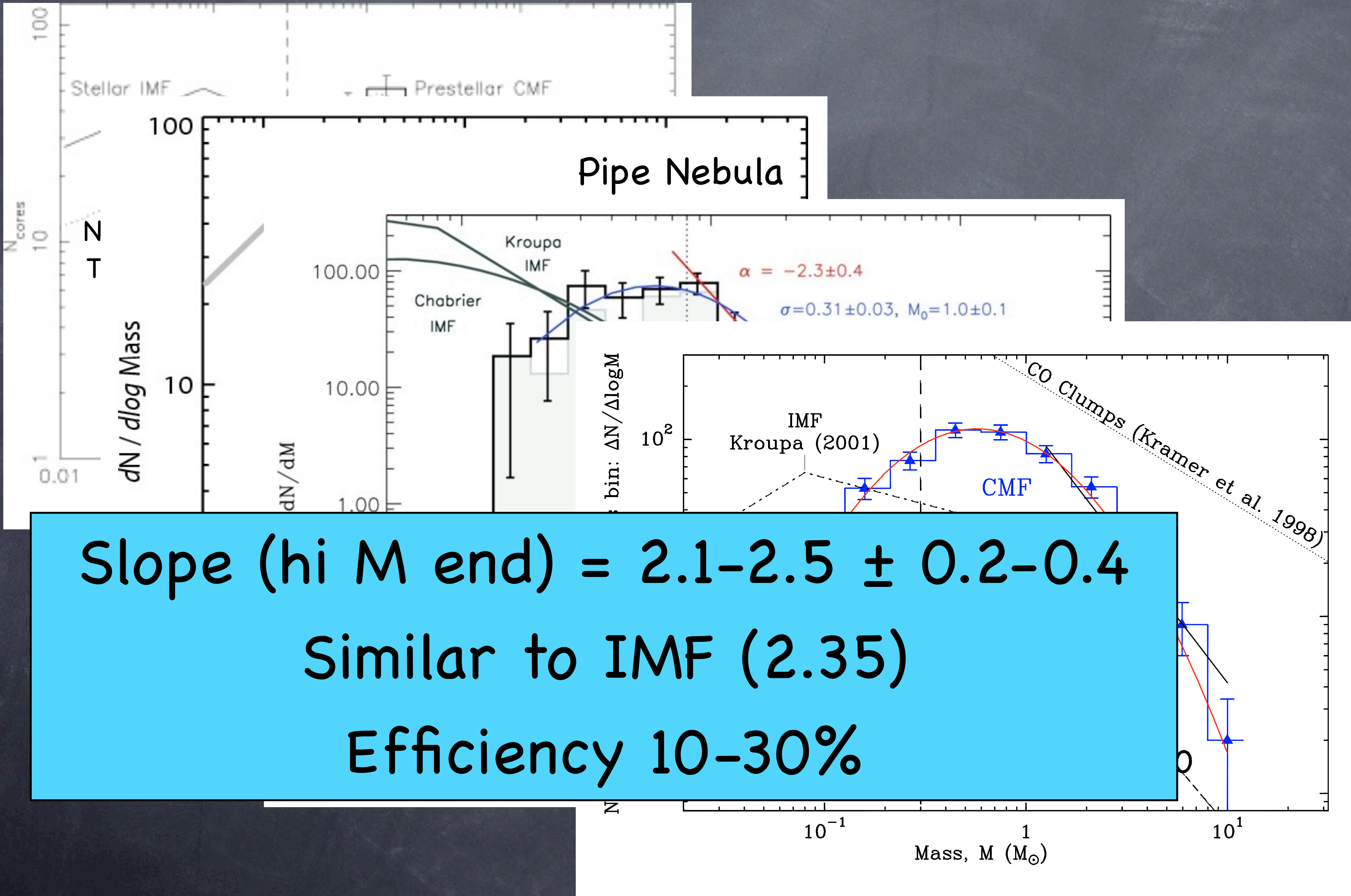
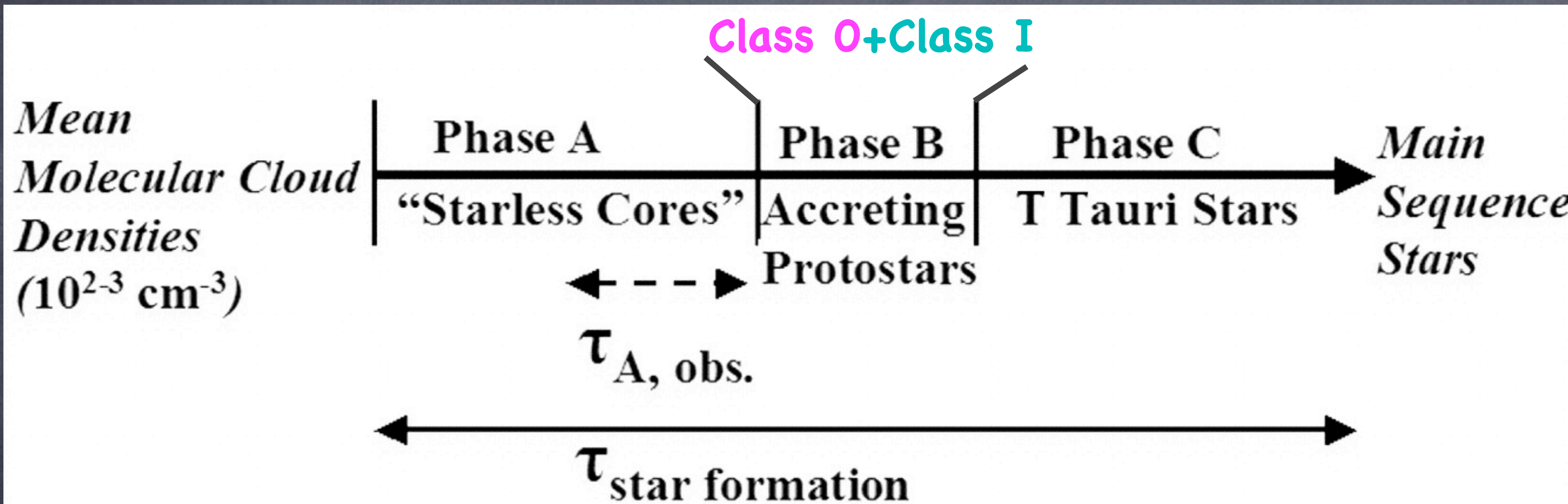


Slope (hi M end) = 2.1-2.5 ± 0.2-0.4

Similar to IMF (2.35)

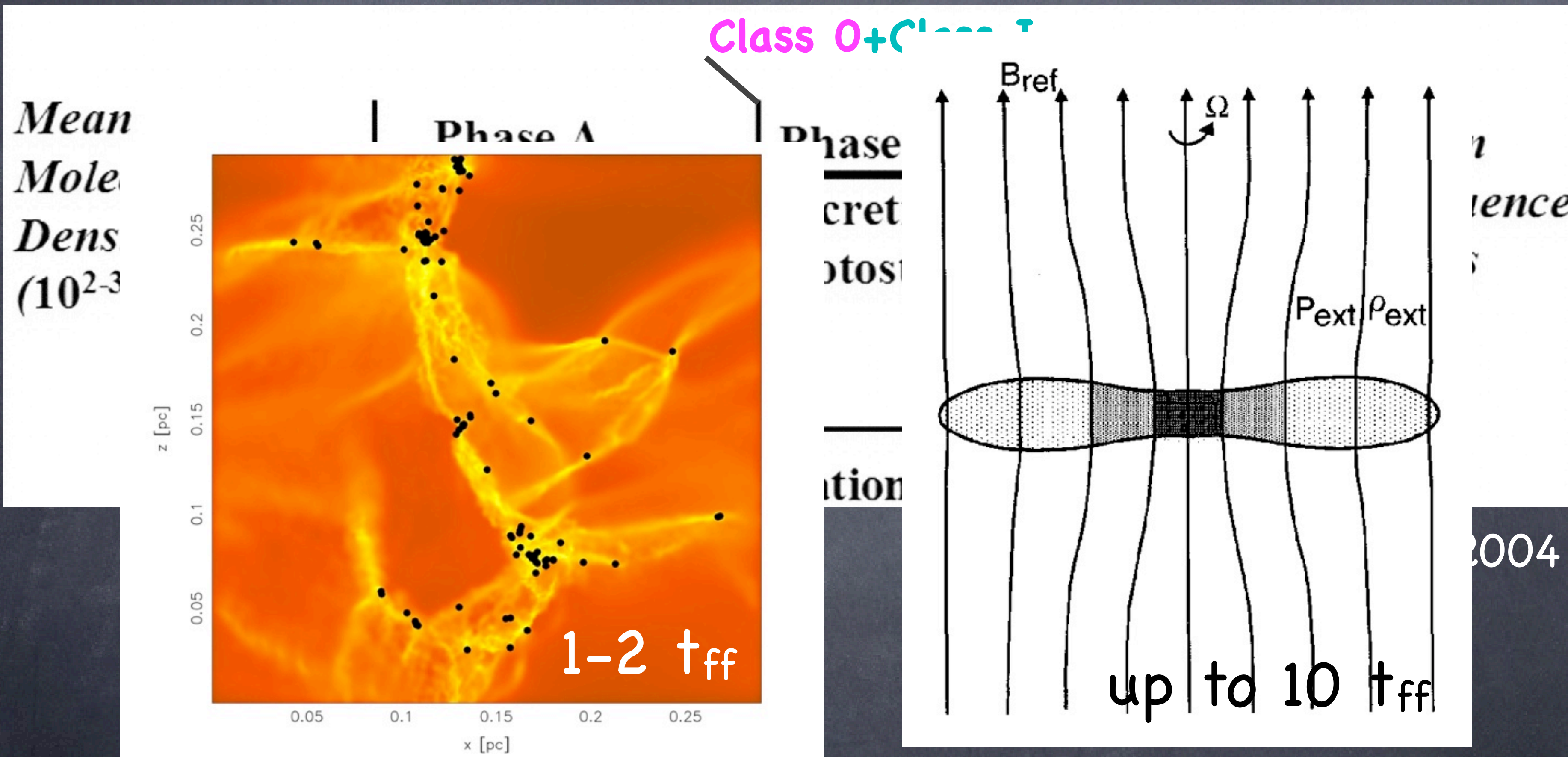
Efficiency 10-30%

2. Timescales for star formation



Tassis & Mouschovias 2004

2. Timescales for star formation



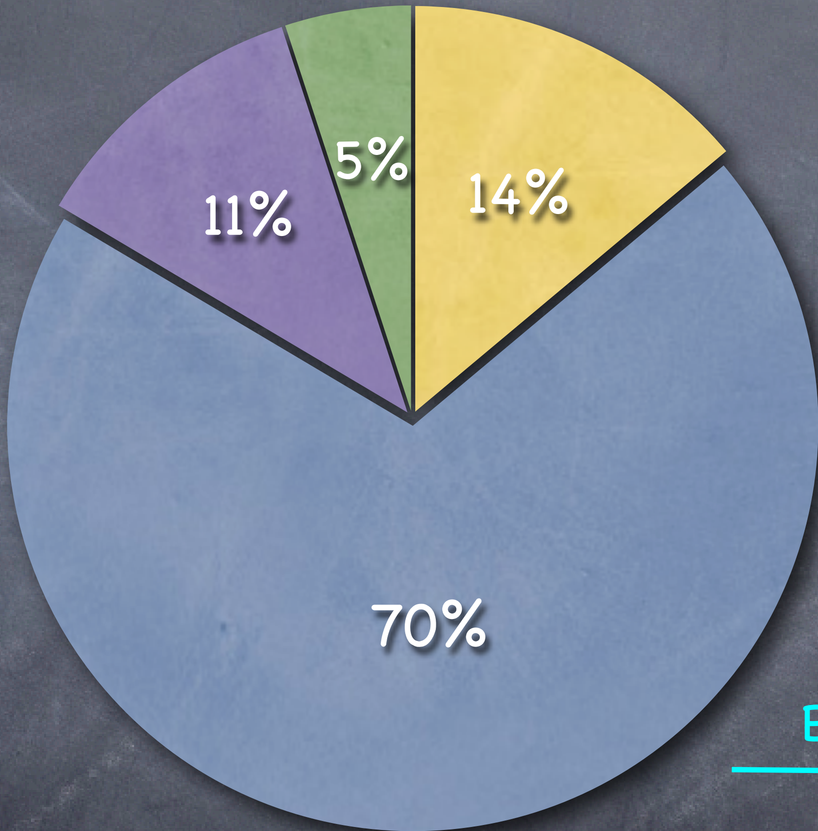
Gravo-turbulent fragmentation
(e.g. Mac Low & Klessen 2004)

Ambipolar diffusion
(e.g. Shu et al. 1987)

2. Timescales for star formation

NEED SUBMM!

- Starless
- Class 0
- Class I
- Class II

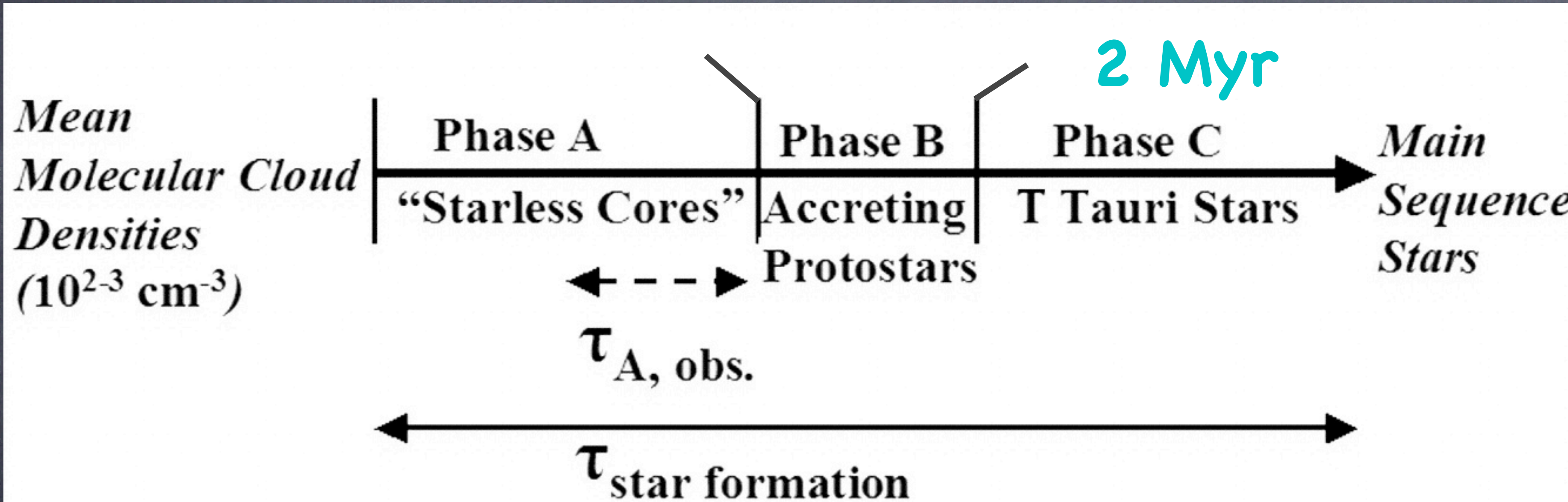


- Serpens
- Perseus
- Ophiuchus

Evans et al. 2009
Enoch et al. 08, 09

- IF steady SF AND no mass dependence AND evolutionary sequence, then t1/t2 = N1/N2. For t(Class II) = 2 Myr,
- t(Class I) = 0.38 Myr, t(Class 0) = 0.16 Myr, t(SL) = 0.45 Myr

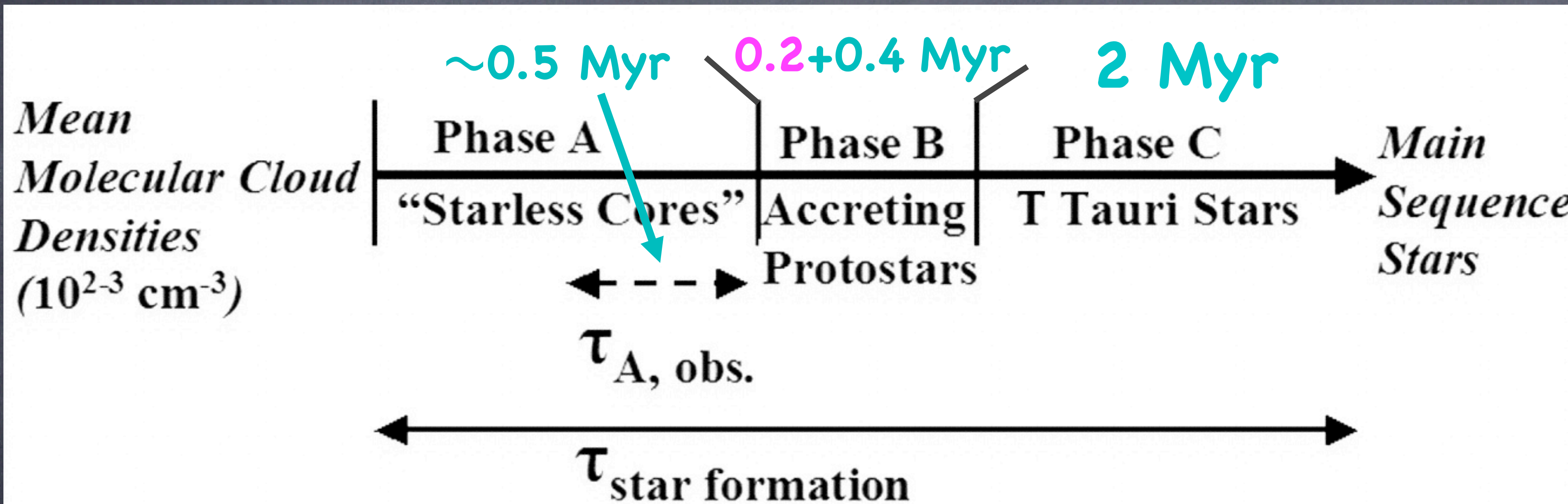
2. Timescales for star formation



Tassis & Mouschovias 2004

Kenyon et al. 1990; Cieza et al. 2007;
Spezzi et al. 2008

2. Timescales for star formation



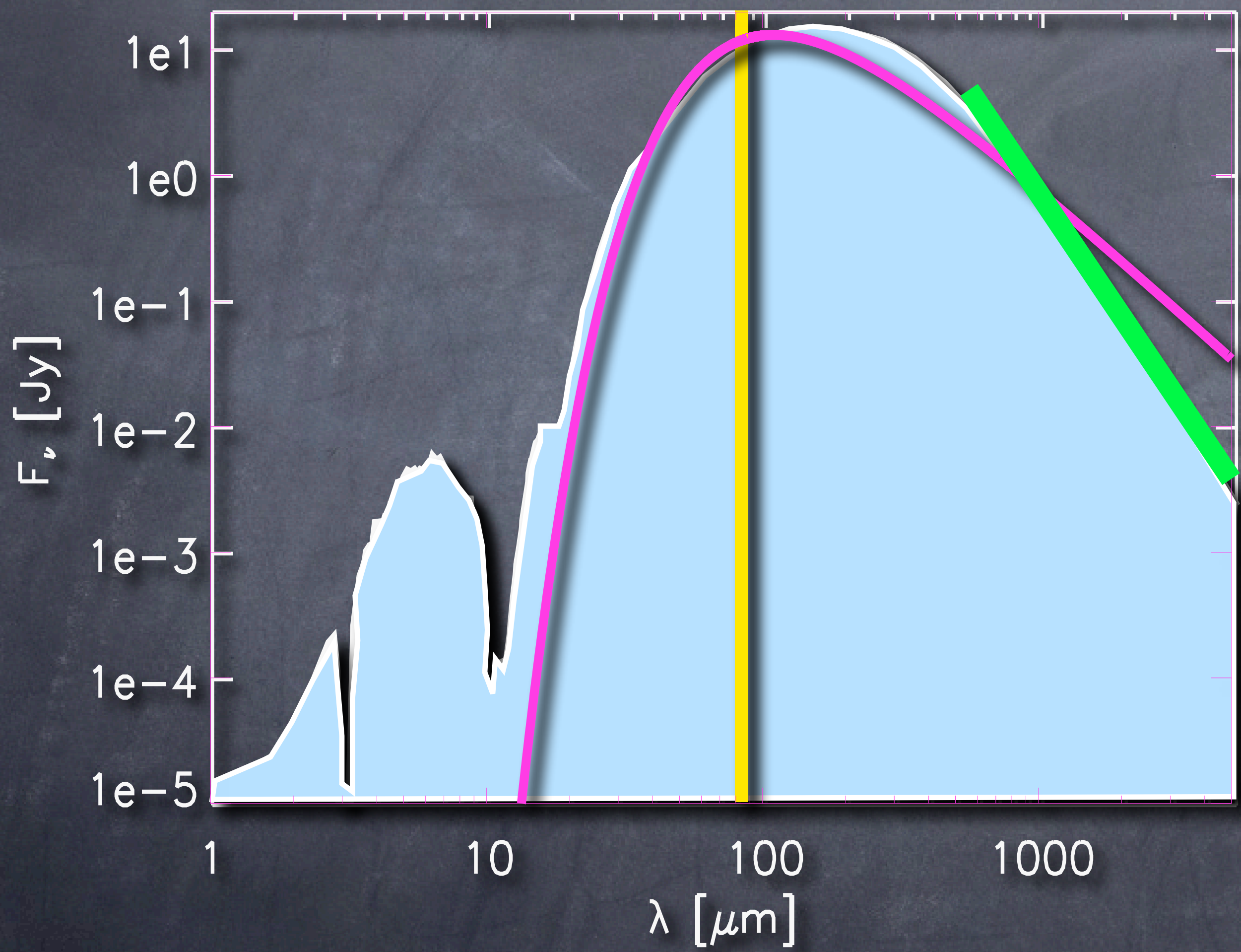
Tassis & Mouschovias 2004

Enoch et al. 2008; Jørgensen et al. 2007; Hatchell et al. 2008

Enoch et al. 2009; Hatchell et al. 2007

Evans et al. 2009

3. Characterizing embedded sources



$$L_{bol} = 4\pi d^2 \int F_\nu \, d\nu$$

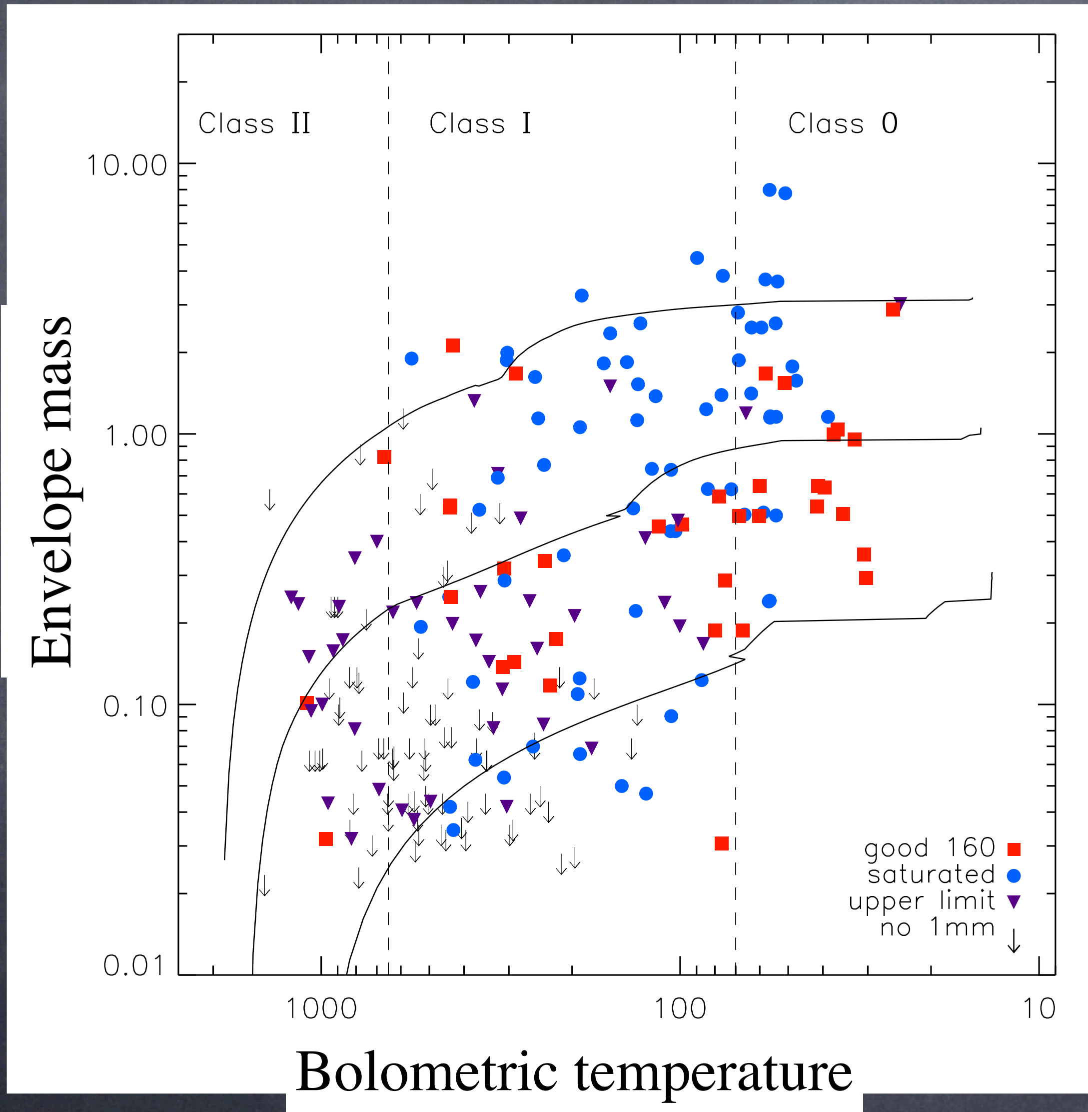
$$\bar{\nu} = \frac{\int \nu F_\nu \, d\nu}{\int F_\nu \, d\nu}$$

$$T_{bol} = 1.3\times10^{-11}\,\bar{\nu}\ \mathrm{K}$$
$$= 46.5\ \mathrm{K}$$

$$M_{env} = \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_D)}$$

SED → luminosity, envelope mass, evolutionary state (T_{bol})

Envelope mass evolution

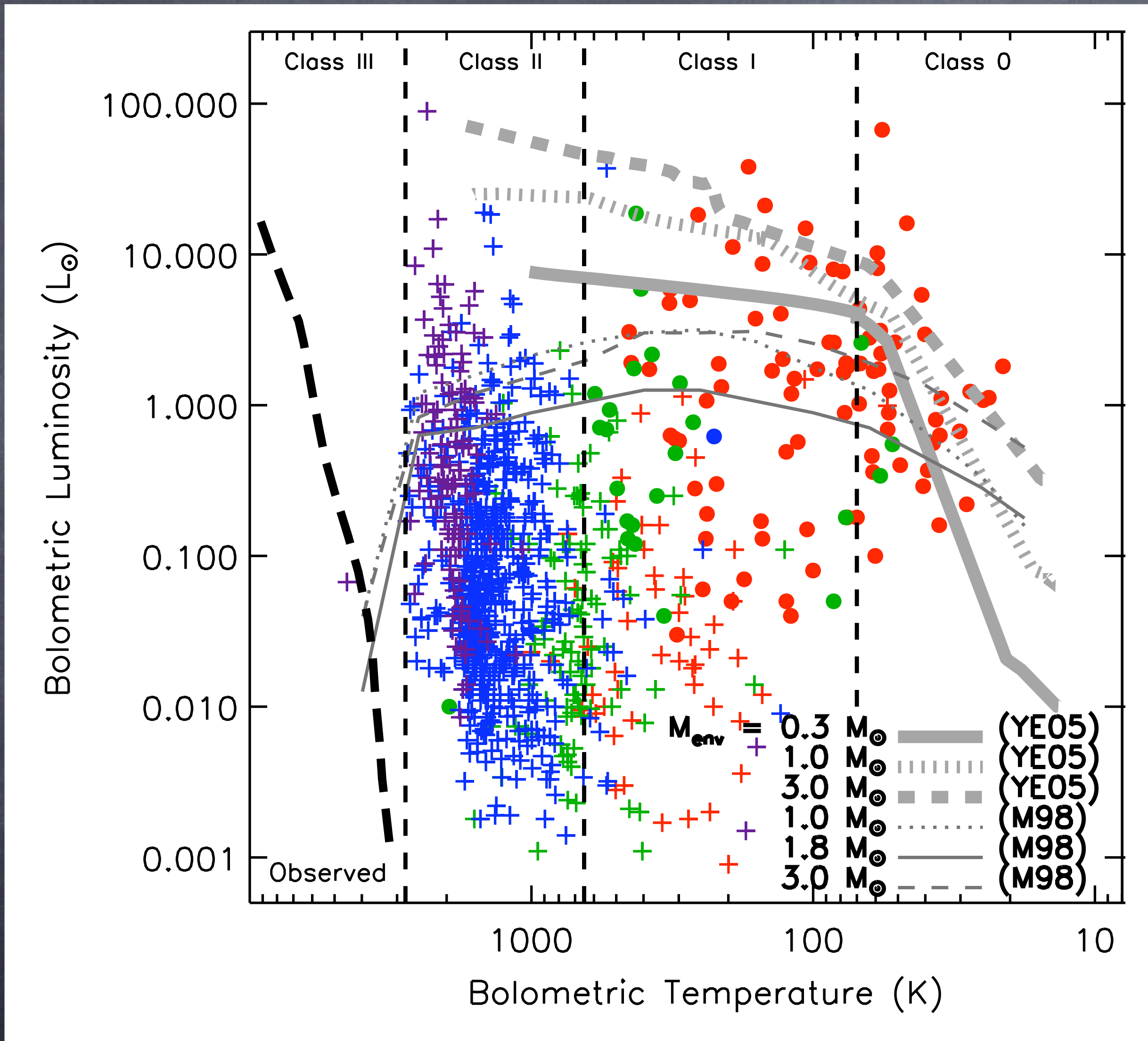


- Evolutionary tracks
  - Constant infall models from Young & Evans 2005 (0.3,1.0,3.0 $M_\odot$)

Enoch et al. 2009

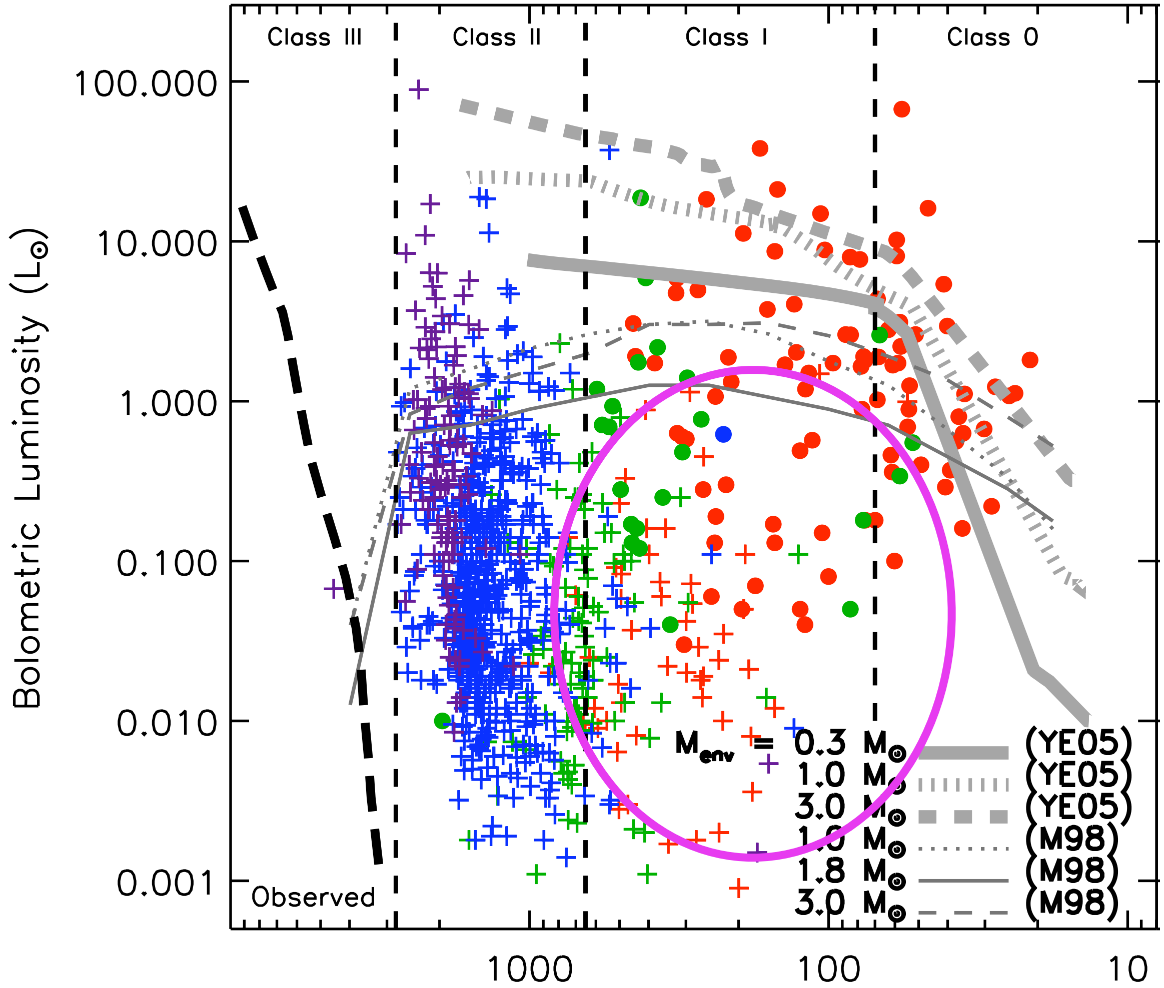
→ Infall from envelope to disk is nearly constant w/ time

Luminosity evolution



Evans et al. 2009; Dunham et al. 2010

Luminosity evolution



Evans et al. 2009;
Dunham et al. 2010

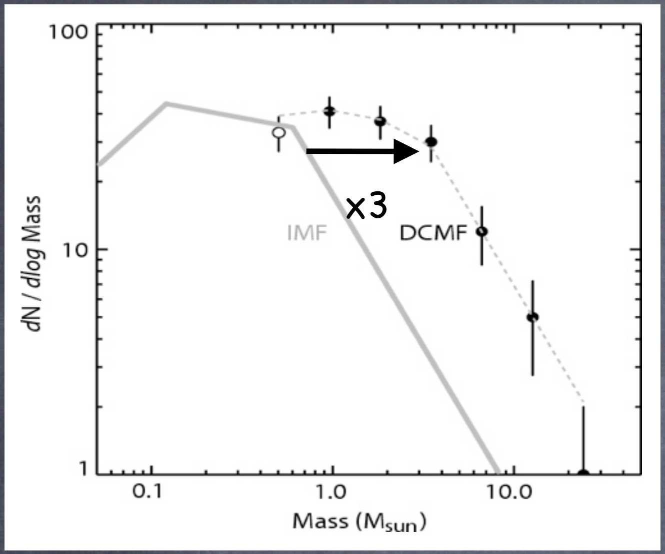
→ **EPISODIC ACCRETION (onto protostar)**

(e.g. Kenyon et al. 1990; Vorobyov & Basu 2006)

What we've learned with (sub)mm surveys

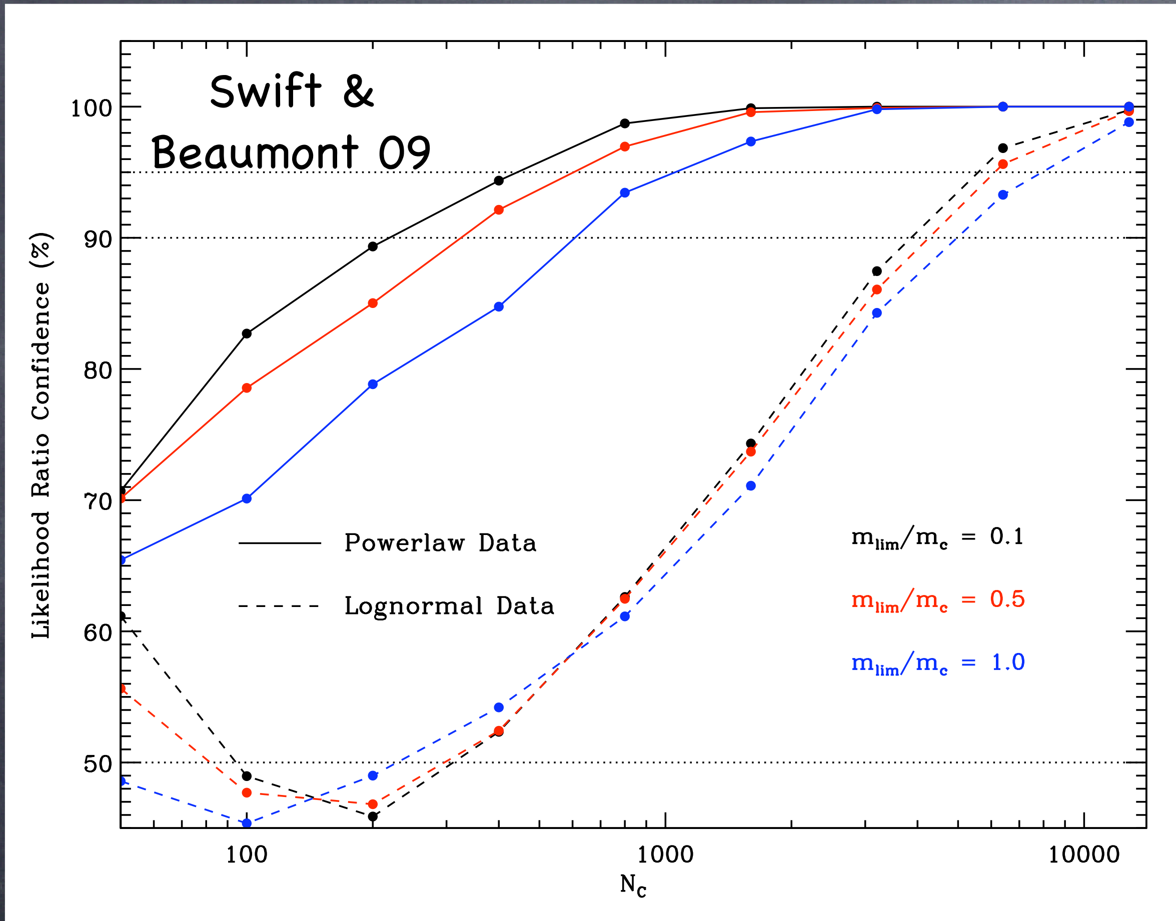
- CMD (still) looks like IMF, within (large) error bars
  - Stellar masses determined at the core formation stage?
  - Likely 10-30% efficiency
- Starless core lifetime a few free-fall times; Class 0 timescale similar to Class I
  - Dense cores not dominated by magnetic fields
  - Approximately constant average accretion rates throughout embedded protostar phase
- Large luminosity spread in embedded protostars
  - Suggests episodic accretion is the "standard" accretion mode

But....



- CMD has large errors, haven't seen turnover

But....



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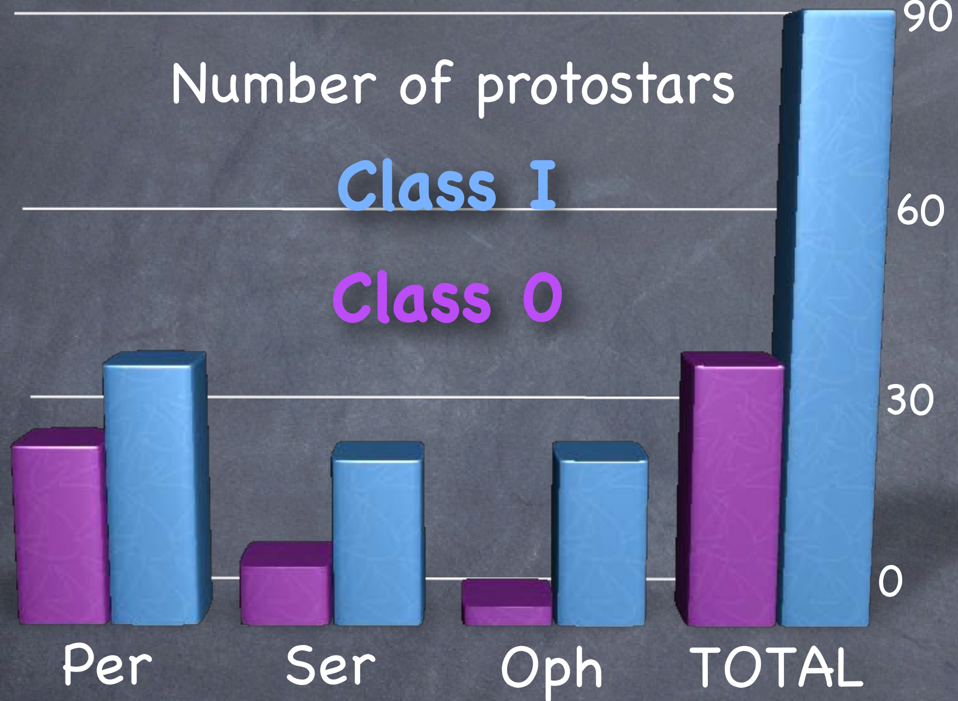


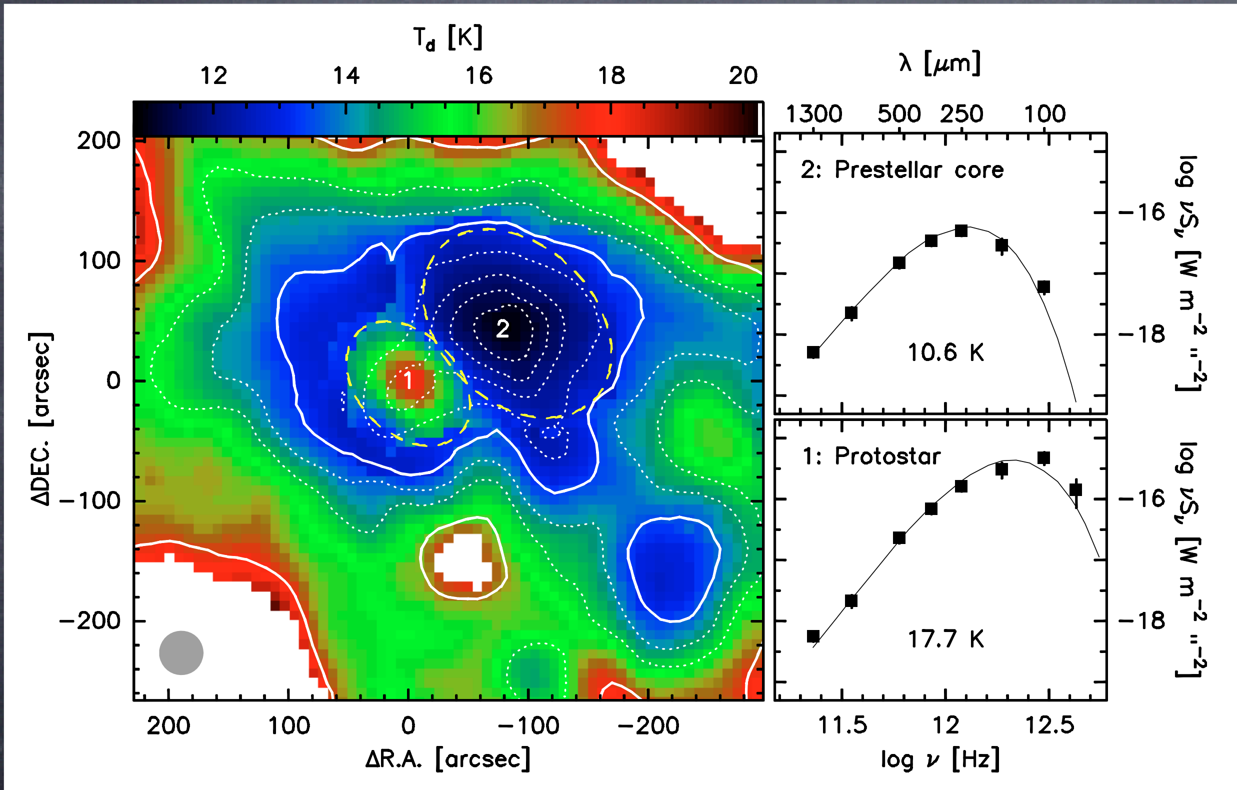
Enoch et al. 09

Also, prestellar core lifetime

(Hatchell et al. 2008; Netterfield et al. 2008)

- CMD has large errors, haven't seen turnover
- Timescales vary with environment?

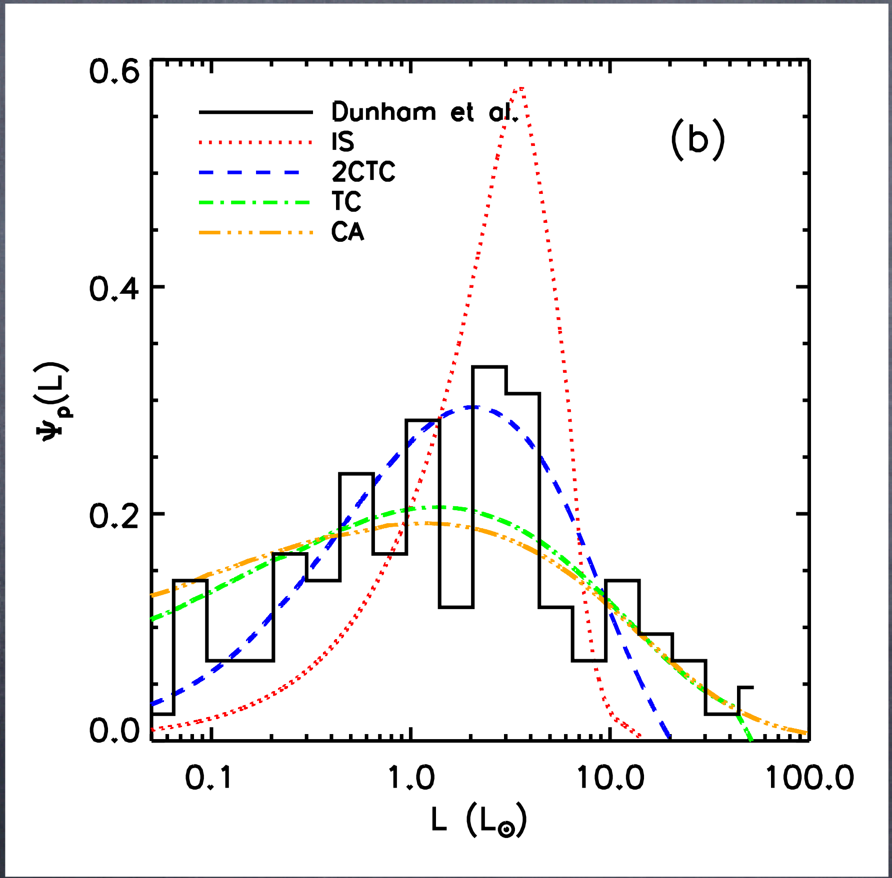
But....



Stutz et al. 2010

- CMD has large errors, haven't seen turnover
- Timescales vary with environment?
- Masses rely on assumed dust temperature

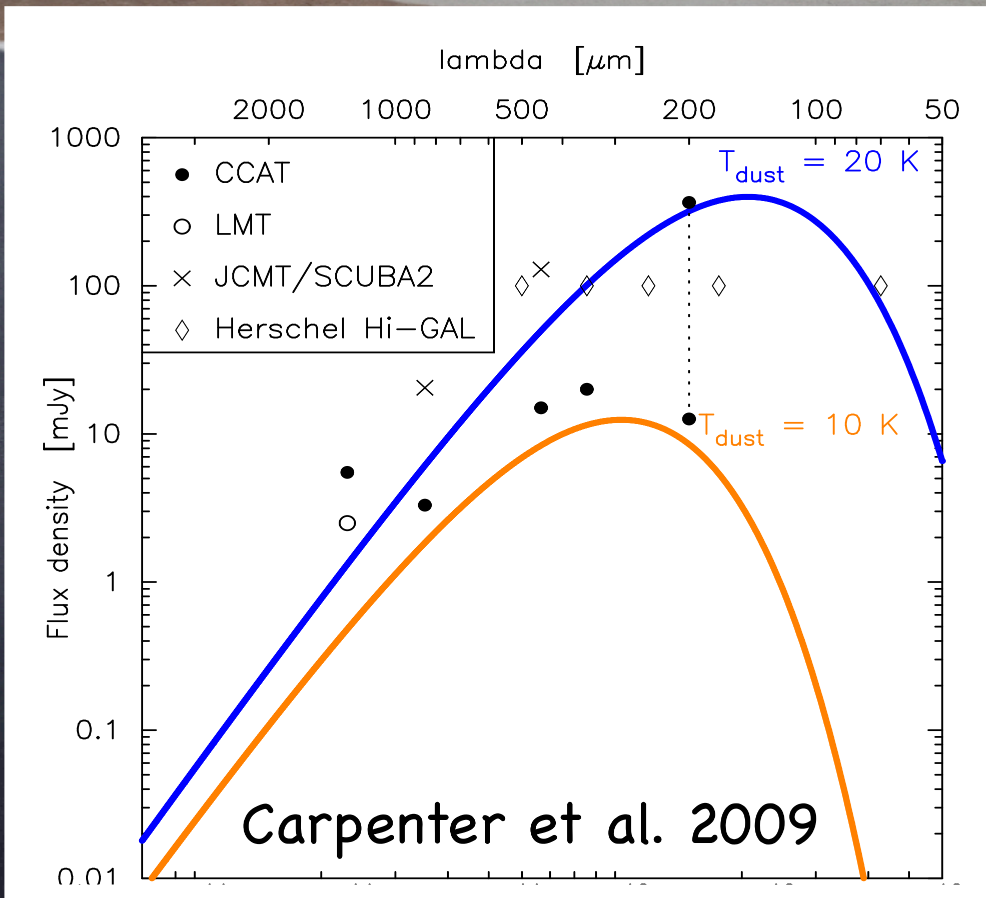
But....



McKee & Offner 2010

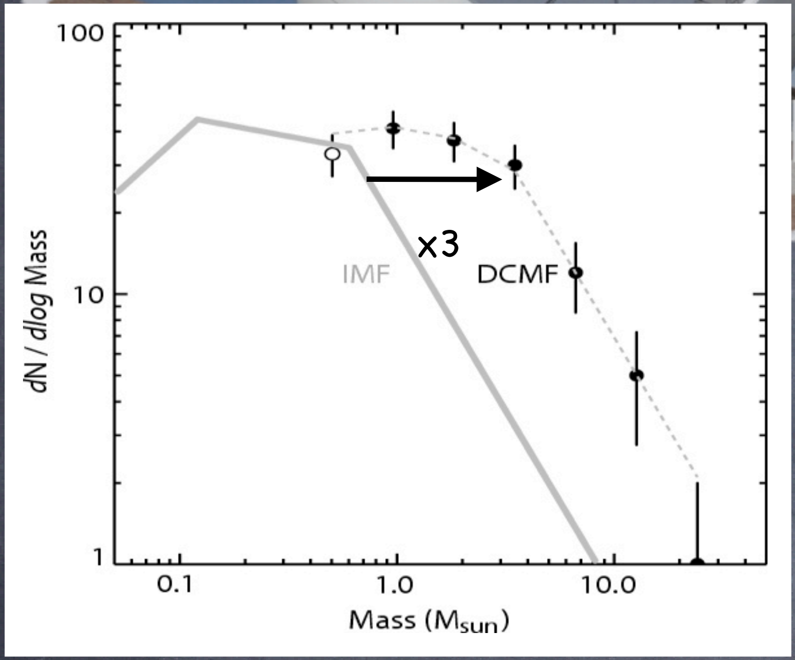
- CMD has large errors, haven't seen turnover
- Timescales vary with environment?
- Masses rely on assumed dust temperature
- Need larger protostar sample to test accretion models

CCAT Opportunities



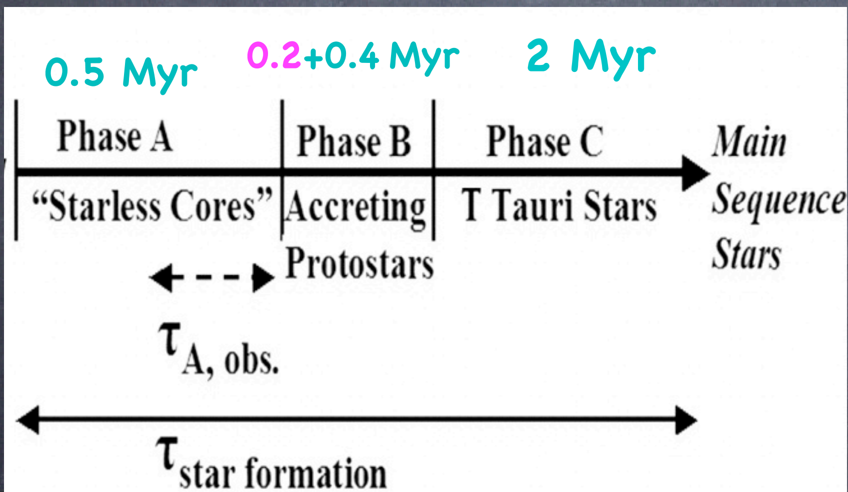
- Much improved sensitivity
- Wide field mapping for large samples
- Better resolution to minimize blending
- Multiple λs to constrain temp, improve mass estimates

CCAT Opportunities



- Observe CMD turnover (if present), reduce errors in slope, test "universality"
- Better statistics for timescales, test dependence on mass, density, environment
- Refine luminosity distributions to directly test accretion models, push to proto-substellar objects

CCAT Opportunities



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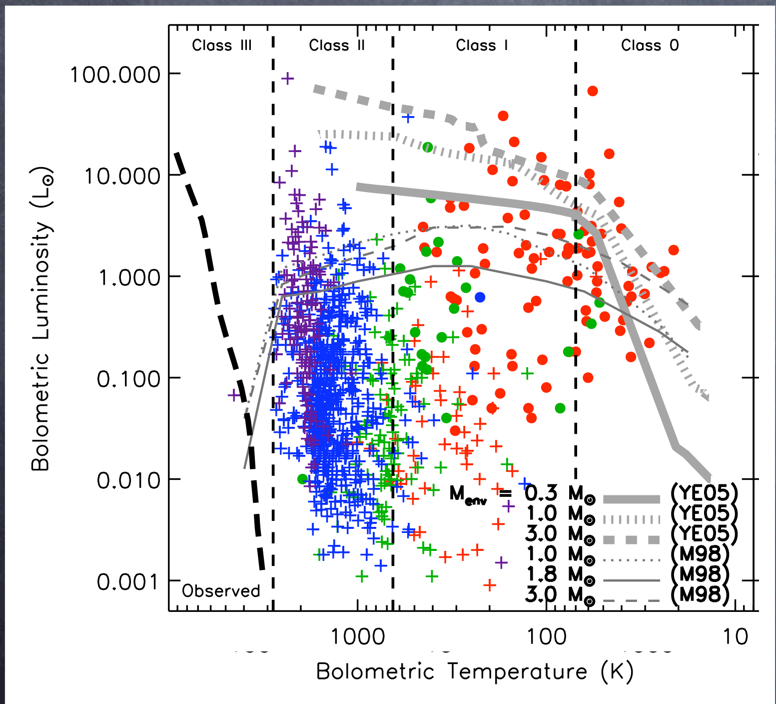

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