A census of starless cores and deeply embedded protostars w/ Spitzer and Bolocam:
Perseus, Serpens, and Ophiuchus

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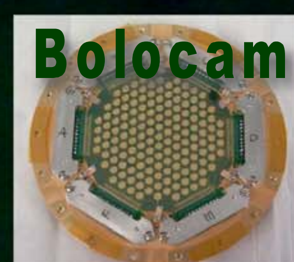


Understanding the earliest phases of star-formation

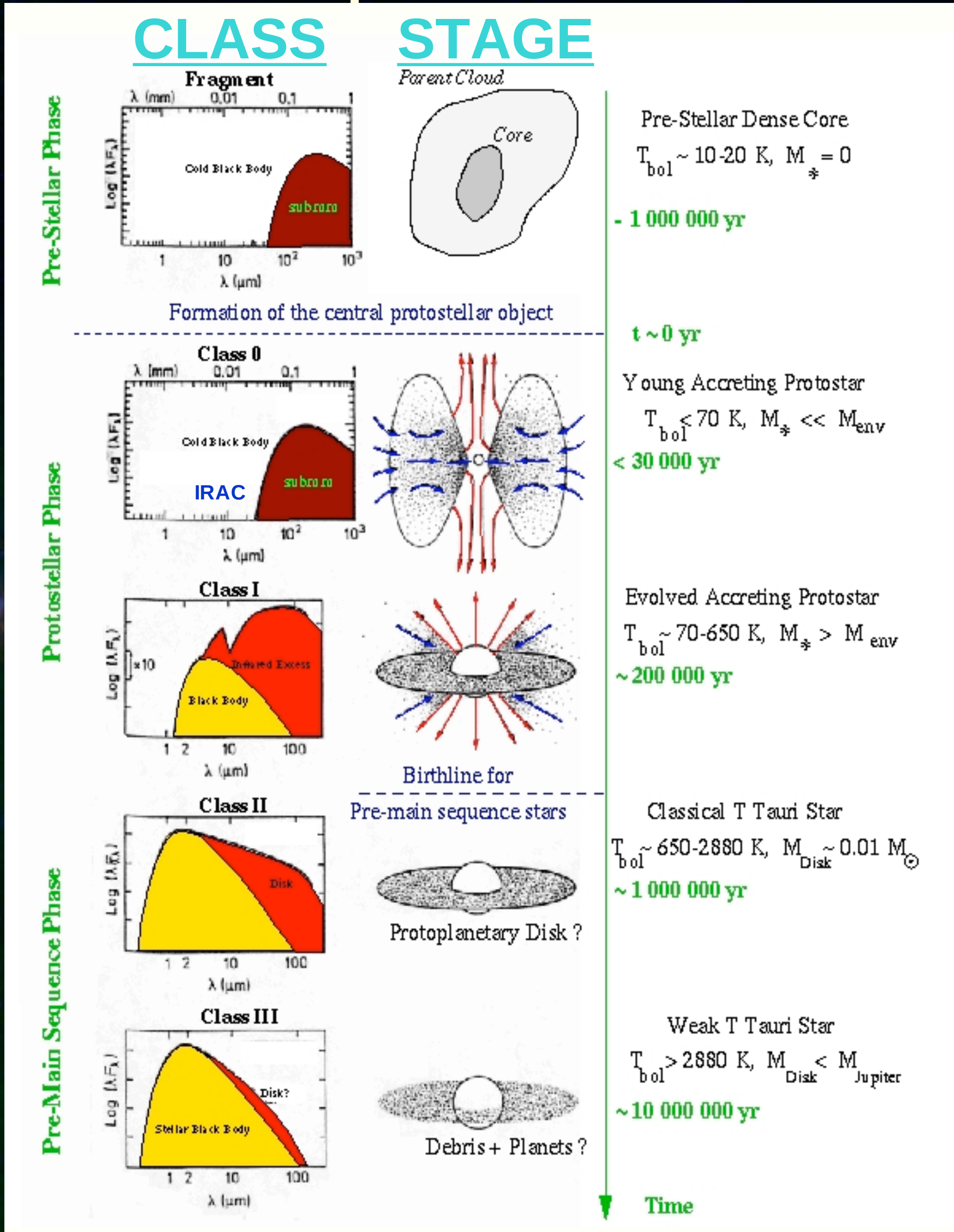
Outstanding questions

1) Global physics controlling the formation, support, and collapse of prestellar cores

2) Initial conditions of prestellar cores in molecular clouds

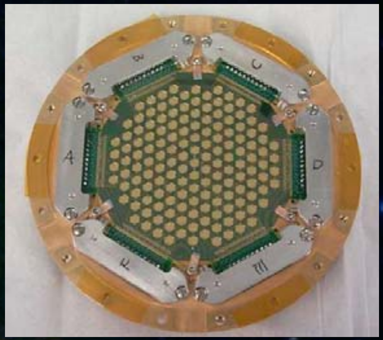
3) Protostellar evolution through the earliest phases

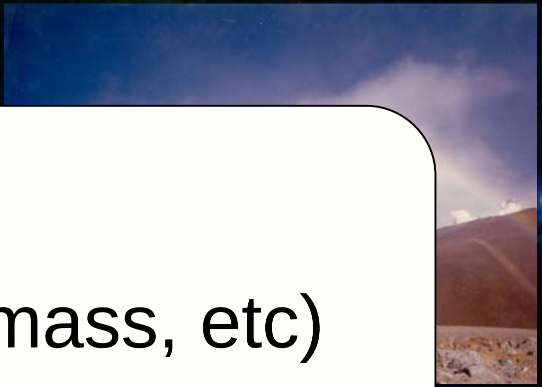
4) Variations with cloud environment



Observations

- Unbiased census of prestellar cores, young protostars
  - Large, complete surveys of molecular clouds
- Bolocam 1.1mm continuum surveys
  - FOV = 7.5', resolution = 31"
  - Unprecedented coverage: 7.5 deg^2 (Perseus), 10.8 deg^2 (Ophiuchus), 1.5 deg^2 (Serpens)
    - M_{lim} ~ 0.2 $M_\odot$ (Per), 0.15 $M_\odot$ (Oph), 0.1 $M_\odot$ (Ser)
  - NO CHOPPING, but not sensitive to > few arcmin
  - Detect prestellar cores
  - Initial conditions (core masses)





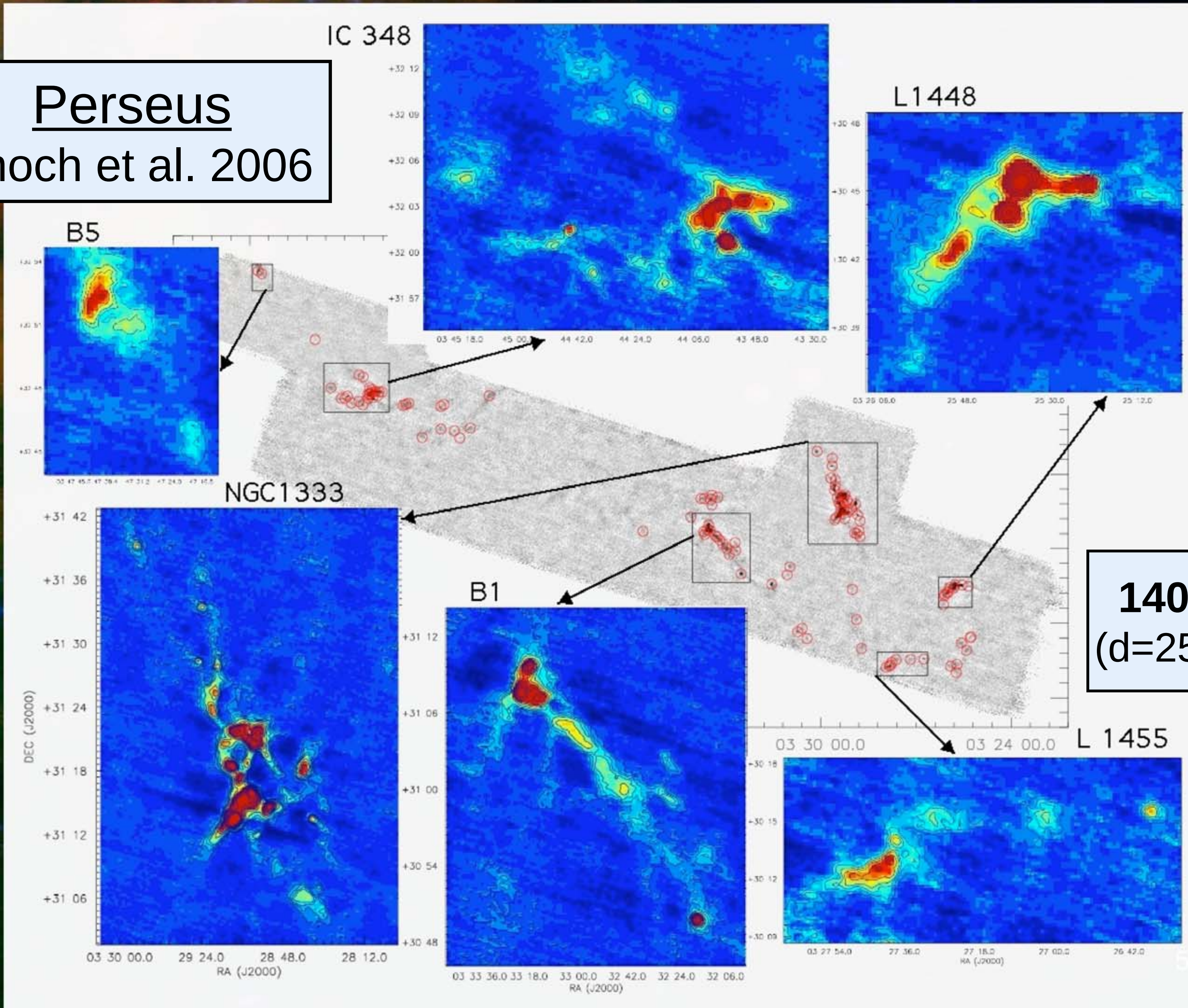
- Data (fits) available on c2d page
- Source props (flux, size, density, mass, etc) in c2d delivery

Observations

- Unbiased census of prestellar cores, young protostars
  - Large, complete surveys of molecular clouds
- "Cores to Disks" (c2d) *Spitzer* Legacy program
  - Lupus, Cham, Perseus, Serpens, Ophiuchus
  - Coverage out to A_V ~ 2–5 mag
  - λ = 3.6-160 μm (IRAC & MIPS) + 2MASS
    - Properties of embedded protostars
    - Separate prestellar cores, youngest Class 0
  - Source "classification" based on colors, mags, likelihood they are not galaxies (Harvey et al., 2007)
  - Complete to embedded protostars w/ L_{bol} > ~ 0.05 $L_{\odot}$ (Dunham et al., in prep)

Perseus

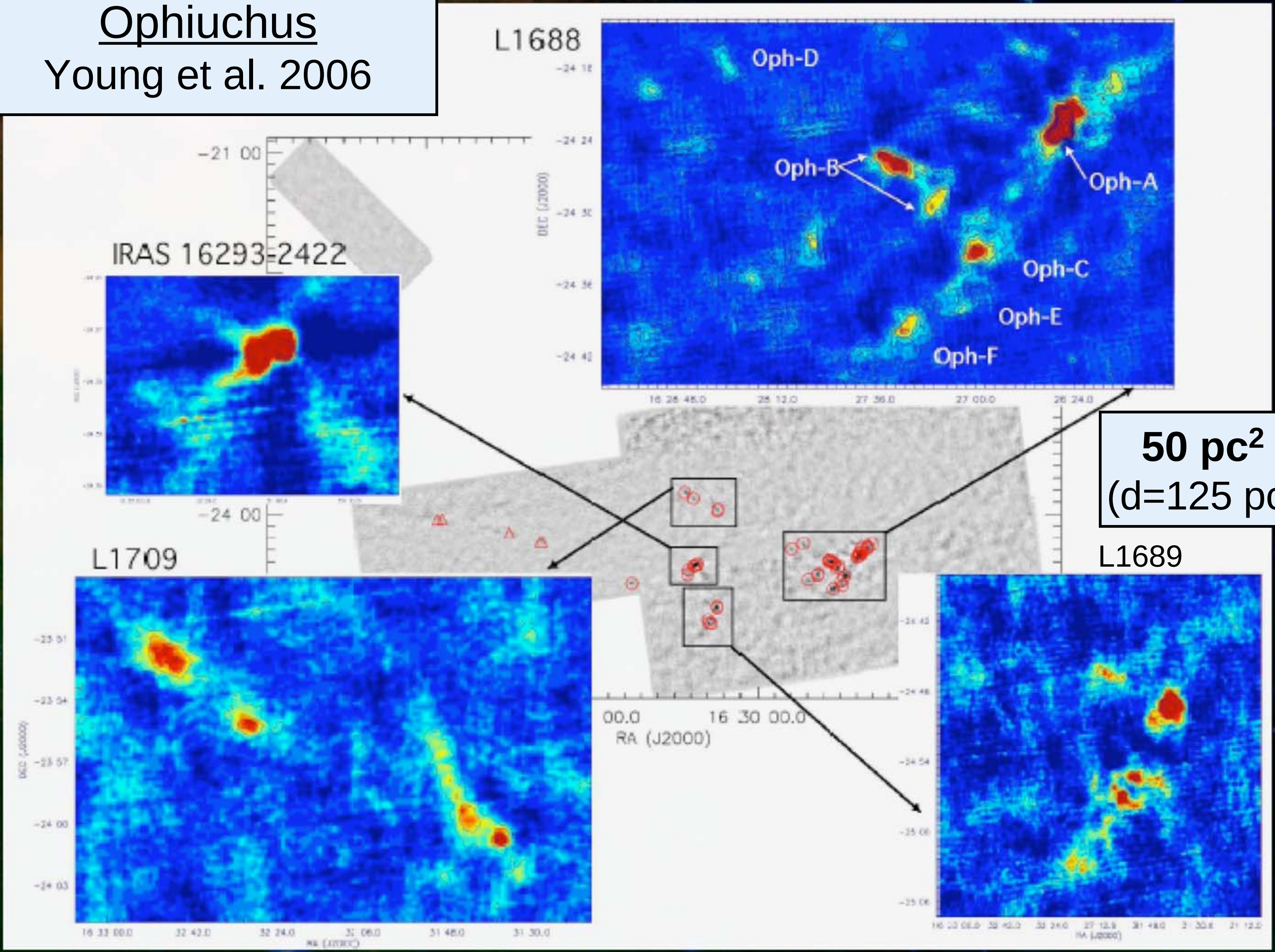
Enoch et al. 2006



140 pc^2
(d=250 pc)

Ophiuchus

Young et al. 2006

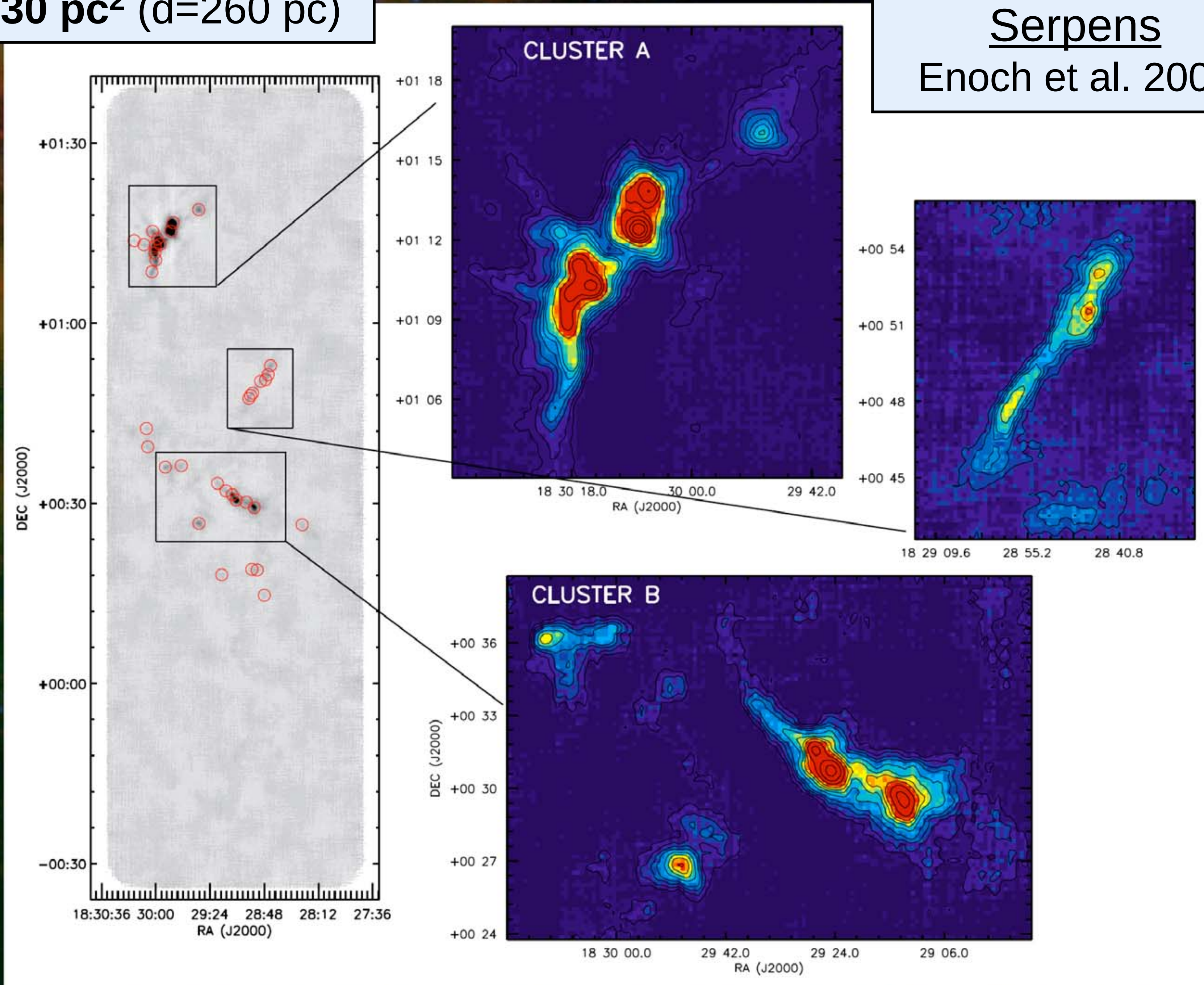


50 pc^2
(d=125 pc)

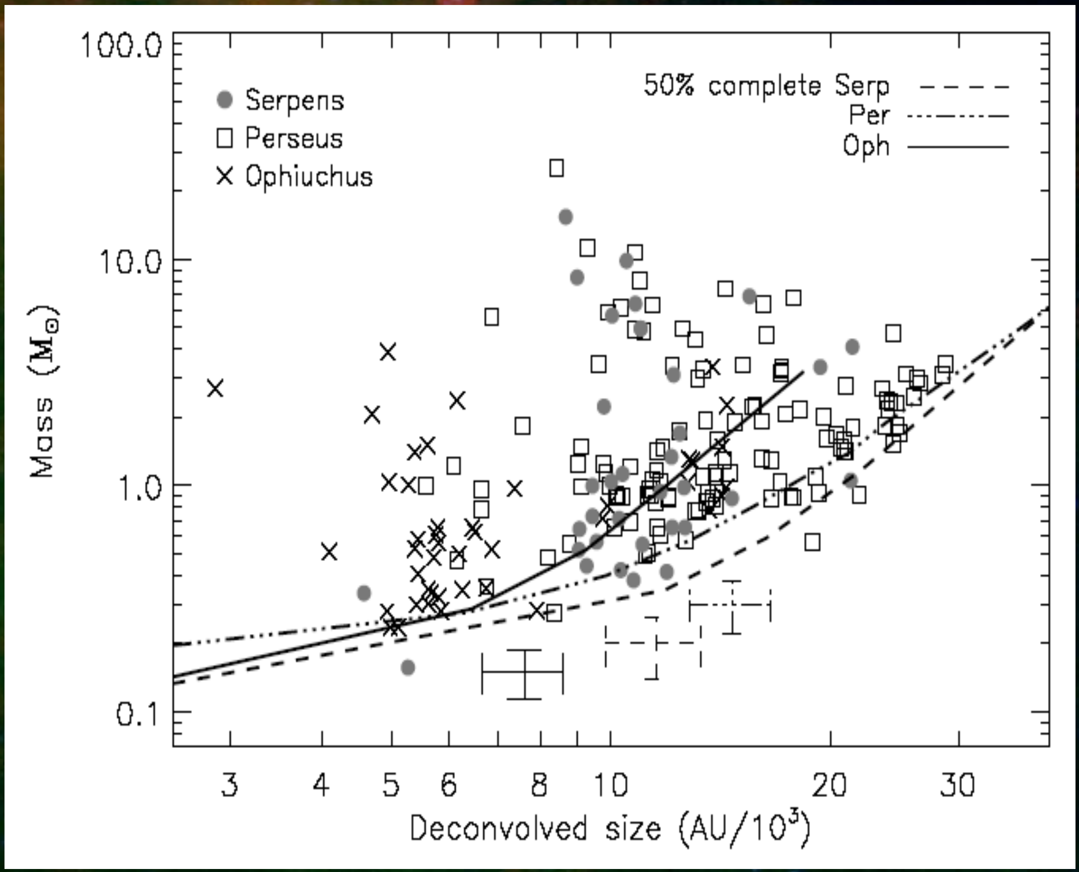
30 pc^2 (d=260 pc)

Serpens

Enoch et al. 2007

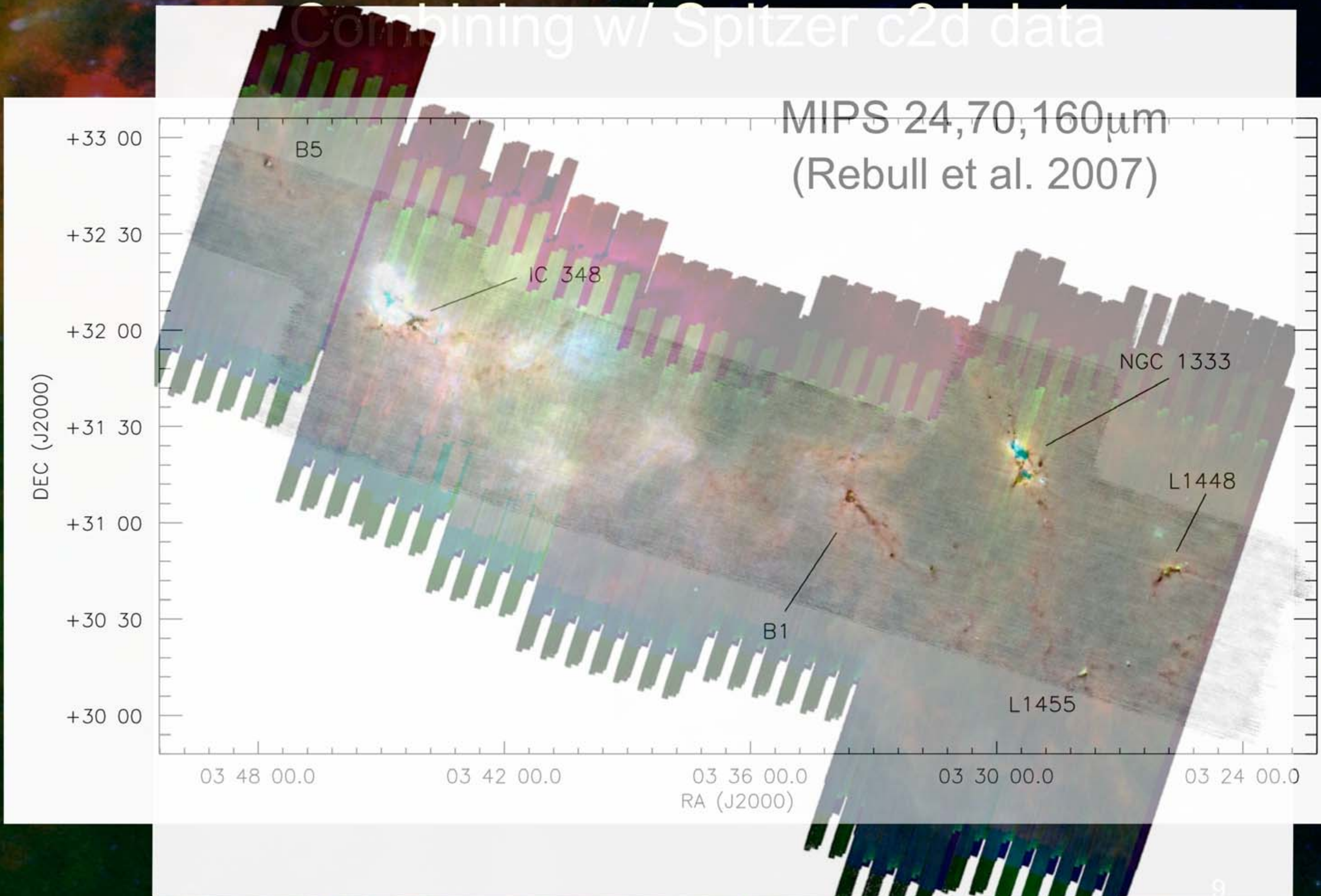


What is a core?



- Mean density required for detection
  - $n \geq$ 2-3x10^4 cm^{-3}
- Contrast to background
  - $\geq$ 30-100
  - For cloud mean density
    - 200 cm^{-3} (Per)
    - 1000 cm^{-3} (Ser)
    - 400 cm^{-3} (Oph)
- Sensitive to sizes
  - D $\leq$ 1.5-3x10^4 AU
- Total mass at 1mm (>5 σ) ~ 2 x mass in cores

Combining w/ Spitzer c2d data



Identifying embedded protostar candidates

YSO candidates from c2d catalogs

(Harvey et al. in press, c2d delivery doc)

From "YSOc"+"red" sample:

(a) $S_{24\mu m}$ > 3 mJy

(b) $S_{24\mu m}$ > $5\alpha_{IR}$+8 mJy

en

3μm

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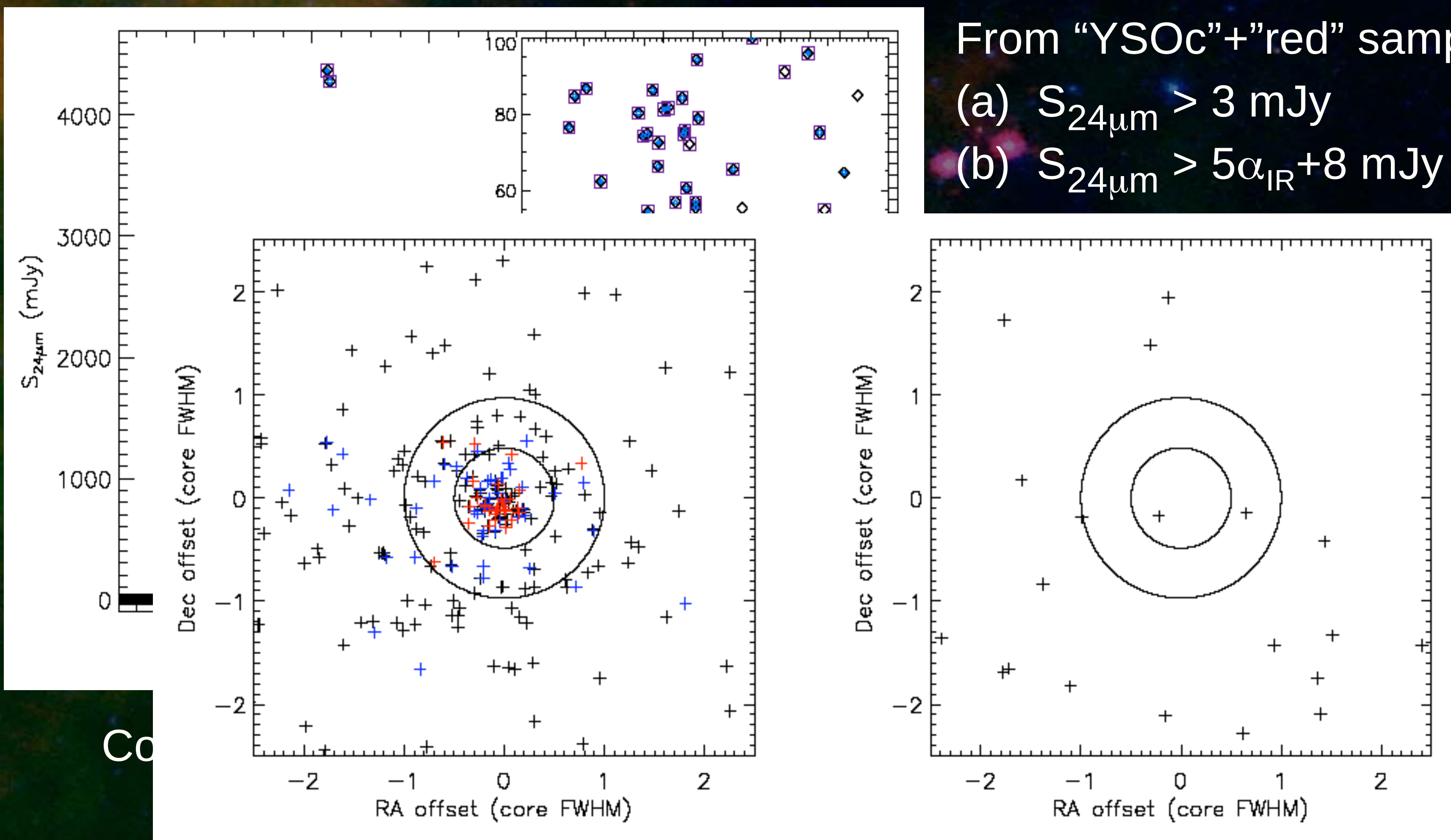
Co



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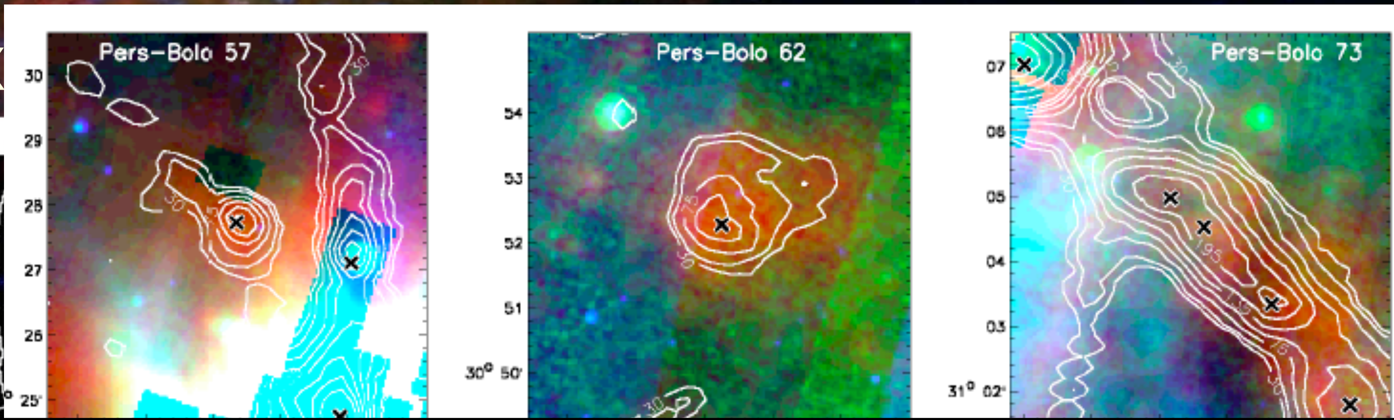
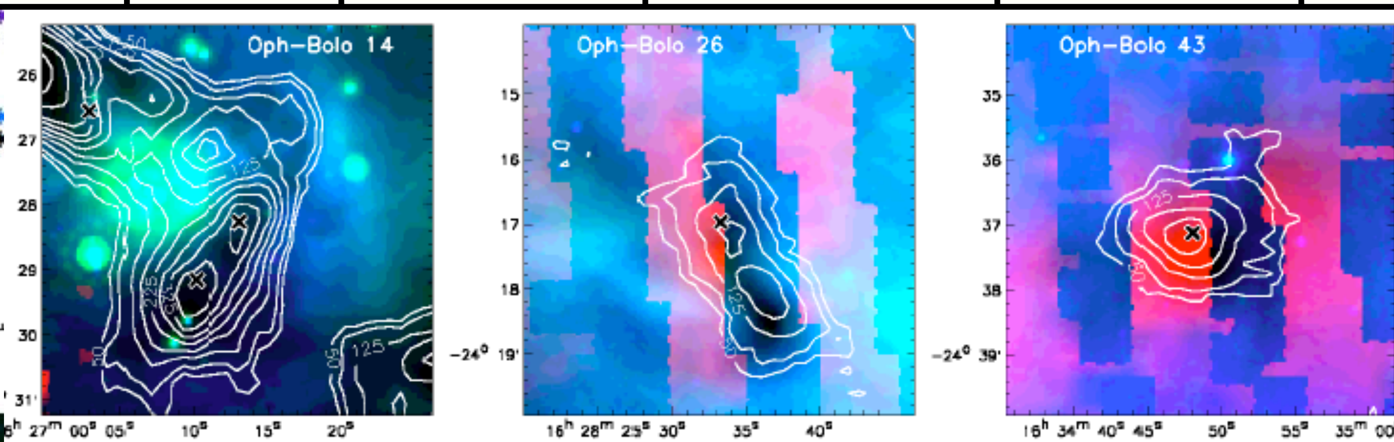


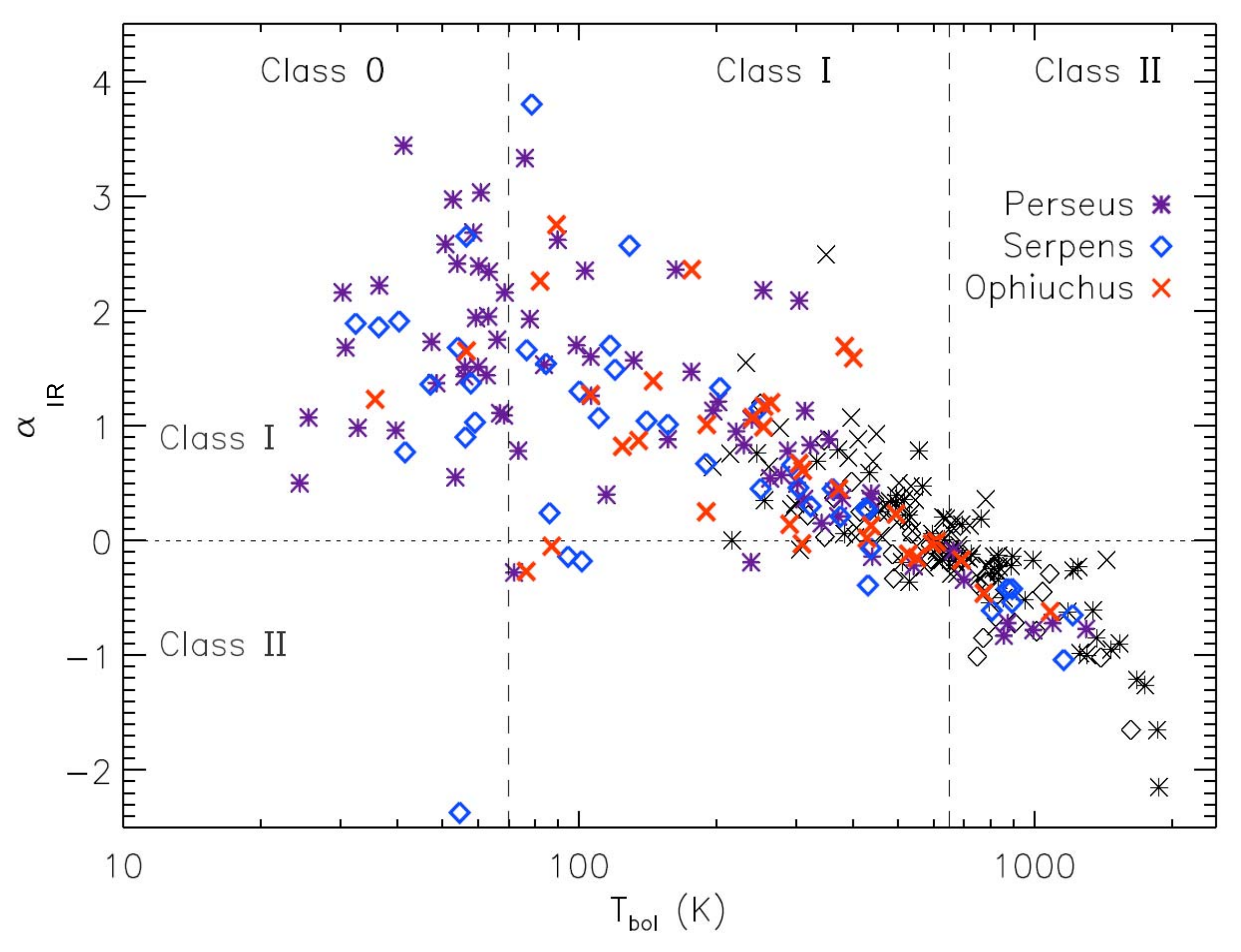
Cloud	# 1mm cores	# starless 1mm cores	# protostellar 1mm cores	starless / protostellar	# cores w/ ≥ 2 YSOs
Perseus	122	67	55	**1.2**	13
Serpens	35	15	20	**0.8**	11
Ophiuchus	44	26	18	**1.4**	3



Protostellar classification

Possible methods

- NIR-MIR spectral index (α_{IR})
  - Criteria for very embedded objects?
- T_{bol}
  - Biases?
- Overall SED shapes?



Protostellar classification

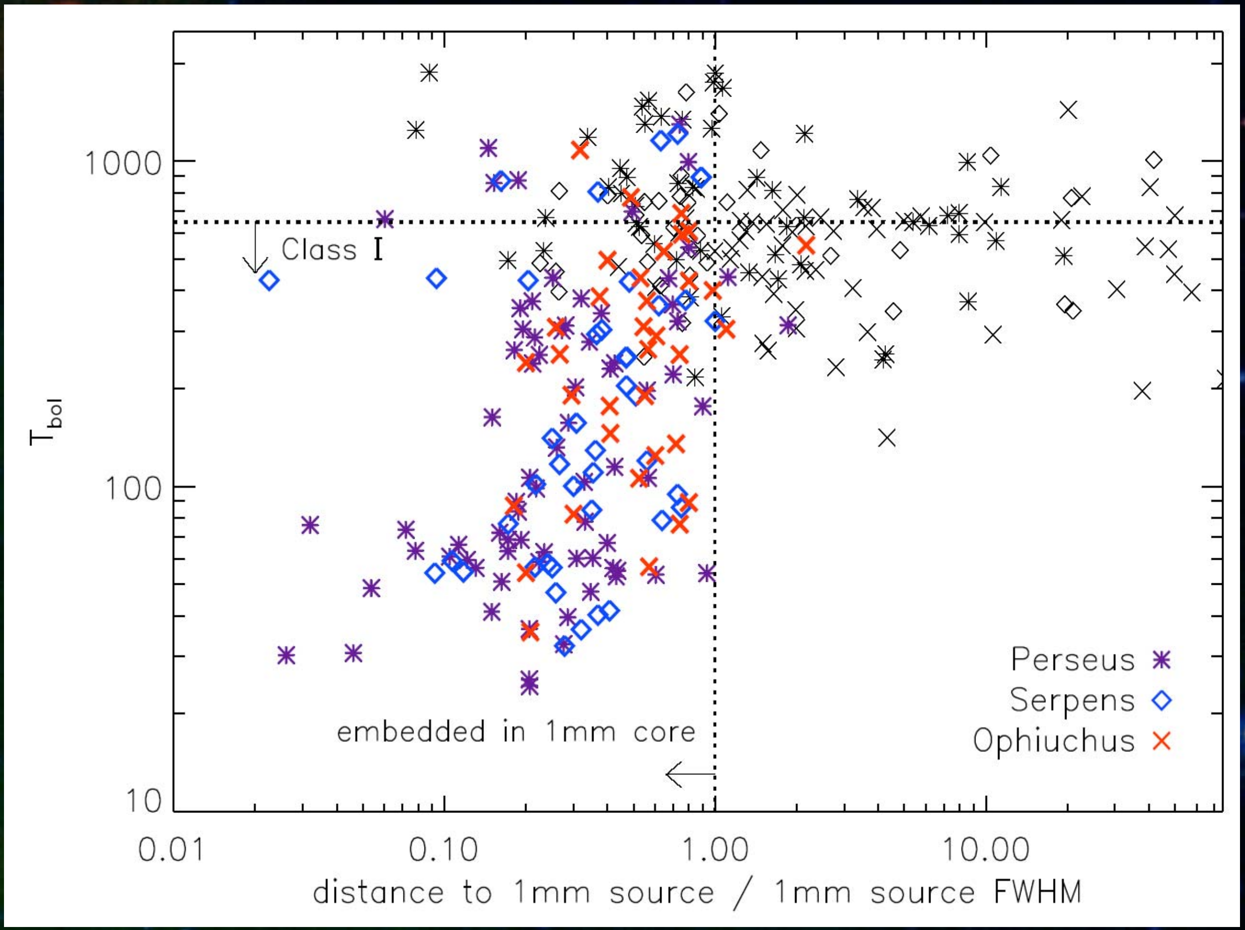
- More embedded ⇔ lower Tbol

⇒ Tbol is a good measure of evolutionary state for young sources

- Adopt class divisions from Chen et al. 1995:

T < 70 K (Class 0)
70 < T < 650 K [+ 1mm] (Class I)
T > 650 K (Class II)

Complete to $M_{env} > 0.1\ M_{\odot}$



Key results

- Spatial distribution (cores & embedded protostars)
  - Clustering, extinction threshold
- Starless (prestellar?) core mass distribution
  - Comparison to the IMF & protostellar CMD
- Lifetime of prestellar cores
- Early protostellar evolution
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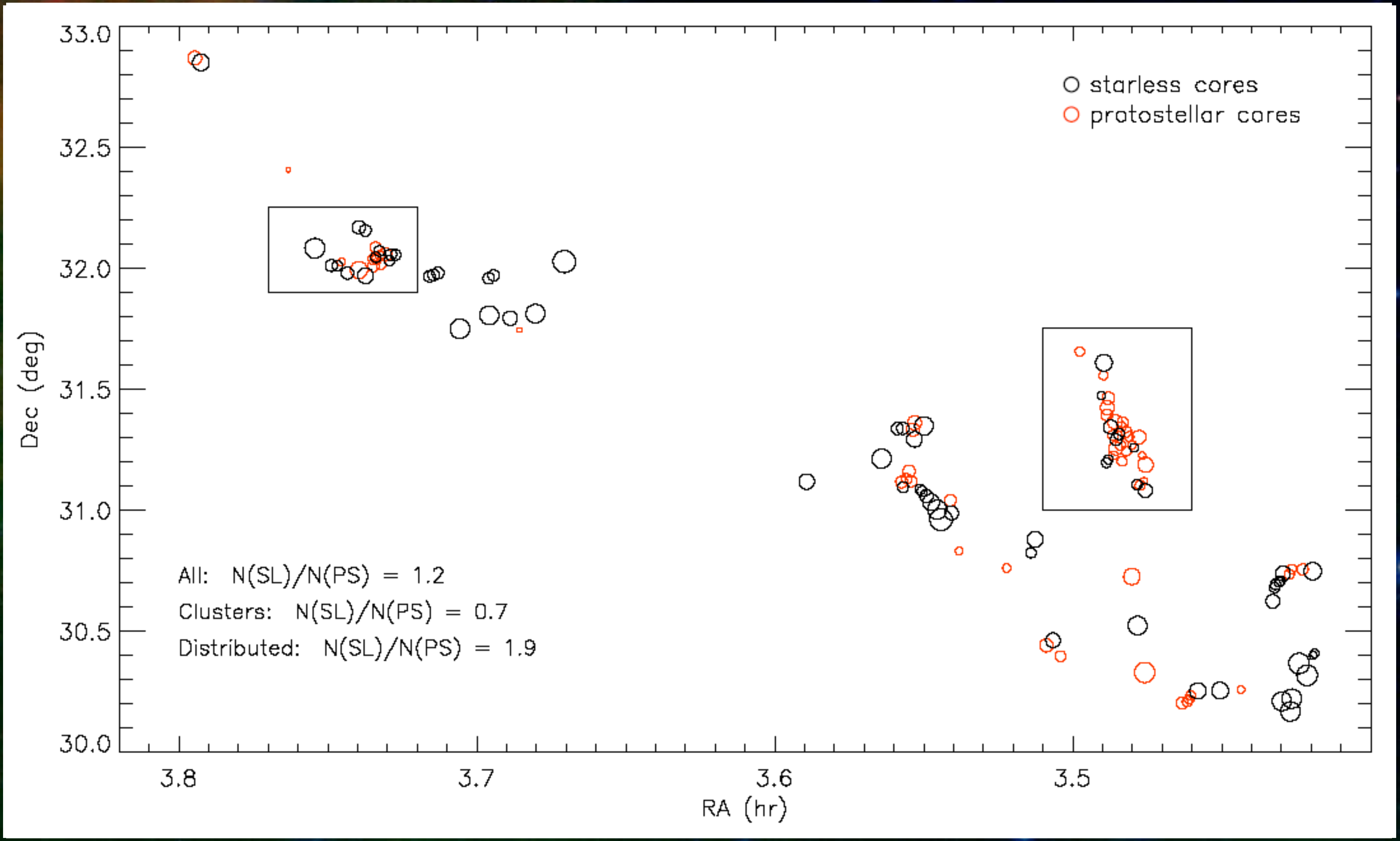
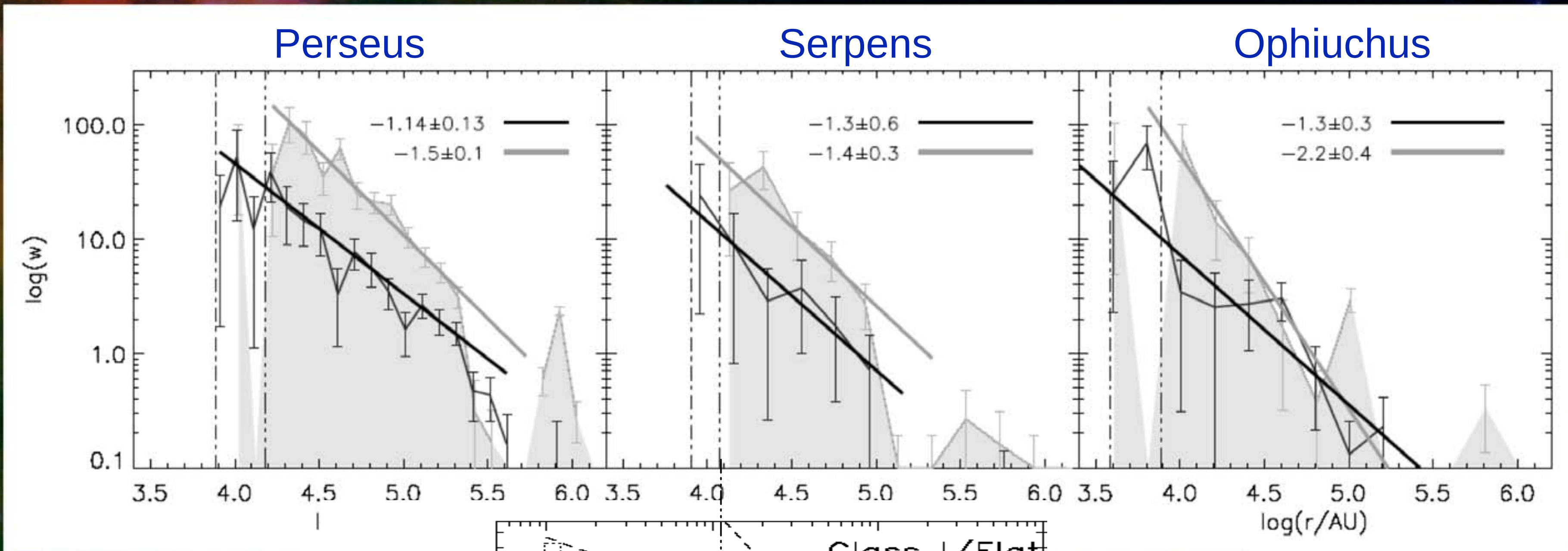
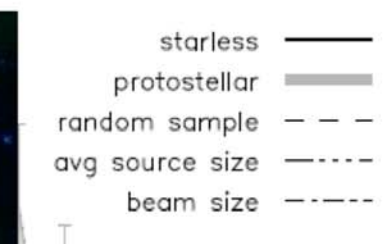
Comparing starless & protostellar cores: spatial distribution



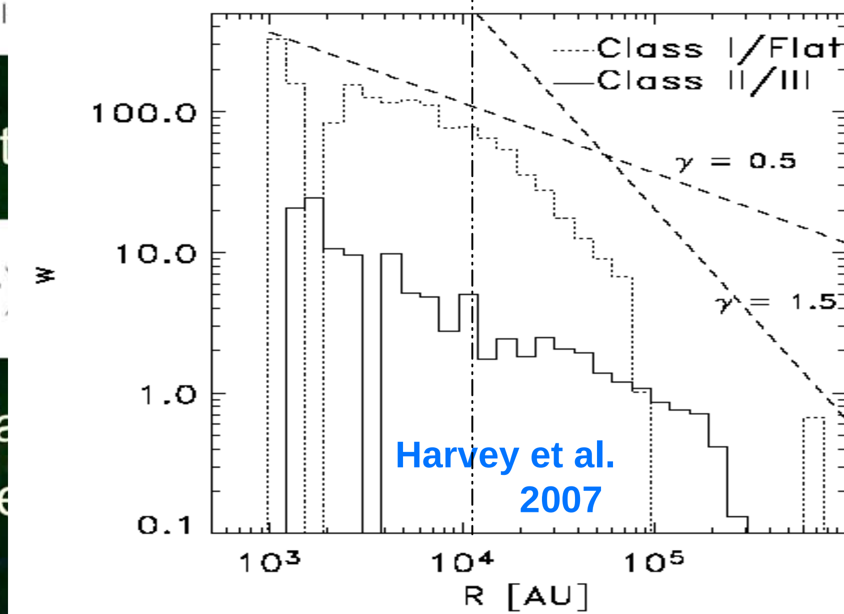
Clustering of starless & protostellar cores





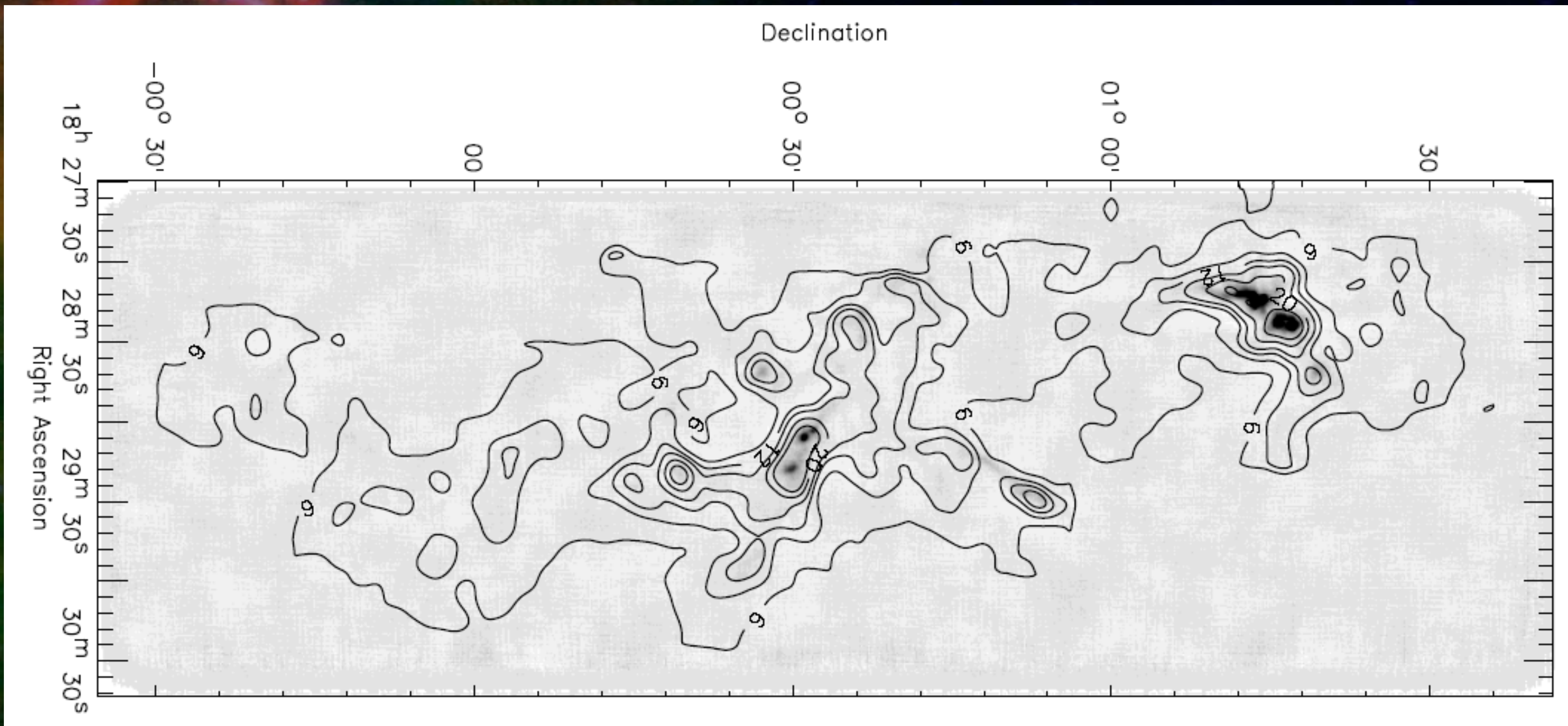
- Two-point

$w(r$



- Peak surfa ... (Ser), 12 pc^{-2} (Oph)
- Median se ... AU)

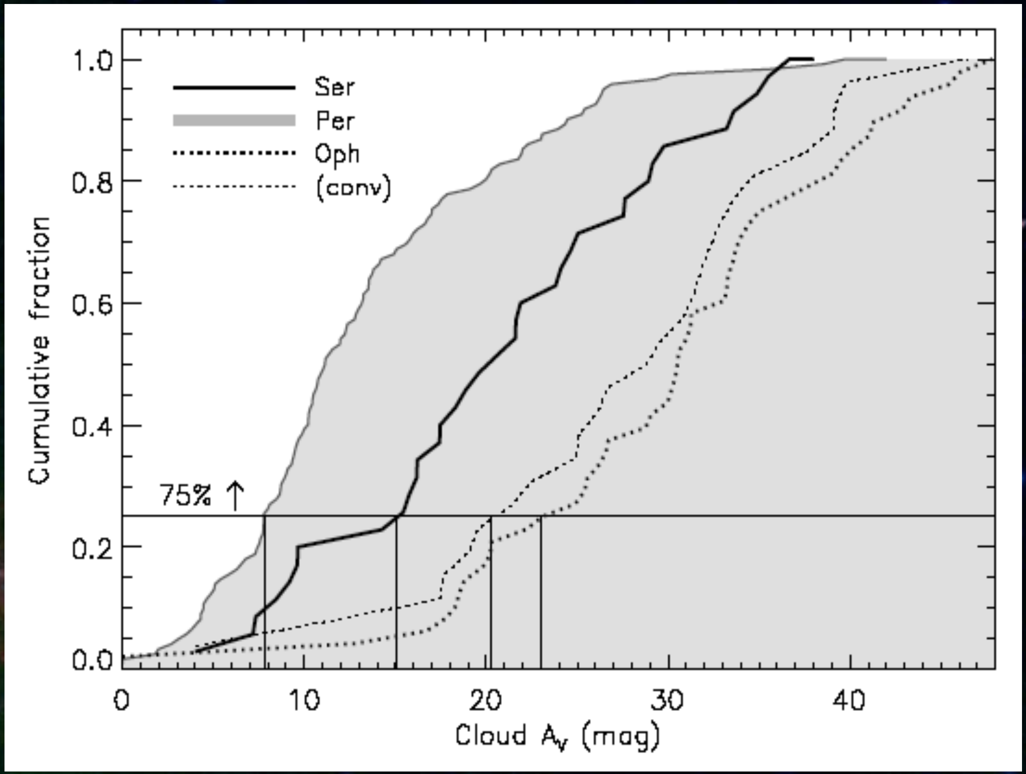
Correlation w/ visual extinction



- A_V from 2MASS + c2d IRAC maps (>90% sources are stars)
- Strong correlation between A_V and 1 mm, but not all high A_V regions have well-defined cores

Extinction threshold & core formation efficiency

- 75% of cores found above
  - A_V~8 (Per), A_V~14 (Ser), A_V~20-23 (Oph)
- Evidence for A_V thresholds:
  A_V~6 (Per, Kirk et al. 06)
  A_V~15 (Oph, Johnstone et al. 04)
- Low mass ratios ⇒ SF is inefficient on cloud scales
  - More efficient at high A_V



Cloud	A_V	Cloud mass	Core mass	Mass ratio (%)
Perseus	2 (20)	7300 (340)	278 (88)	3.8 (26)
Serpens	2 (20)	3500 (230)	92 (79)	2.7 (34)
Ophiuchus	2 (20)	3600 (560)	44 (37)	1.2 (7)

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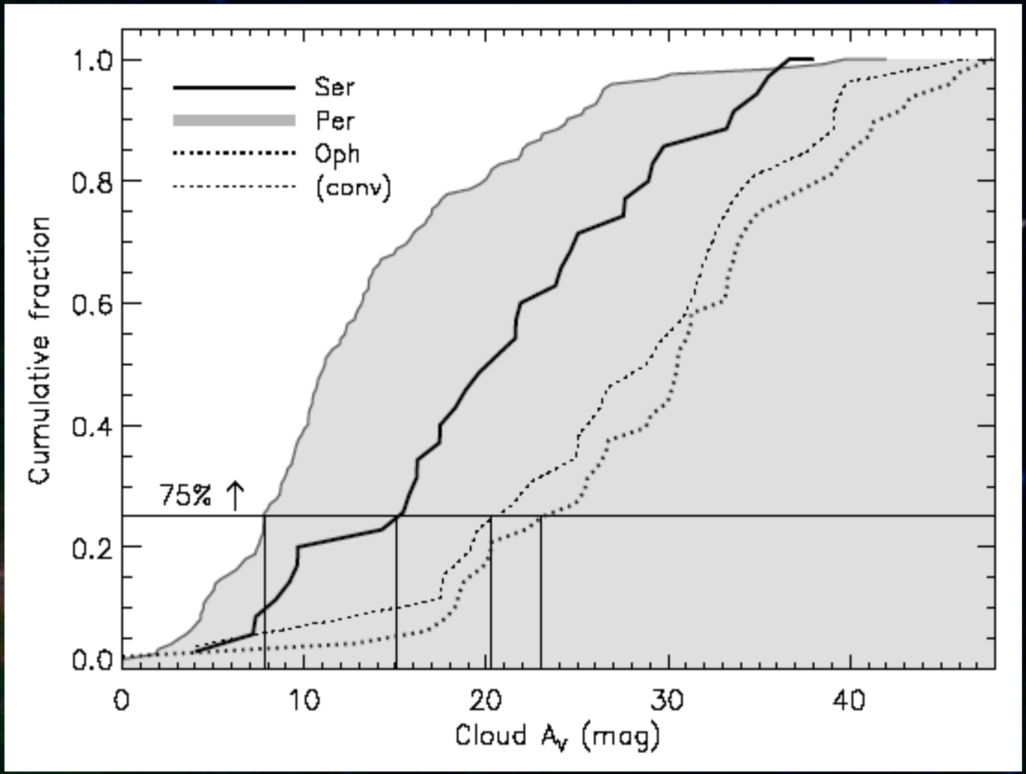

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Combined prestellar core mass distribution

- Combine starless cores from 3 clouds
  ⇒ **108 cores**

  Masses:

  T_D = 10K

  κ_ν = 0.0114 cm²/g

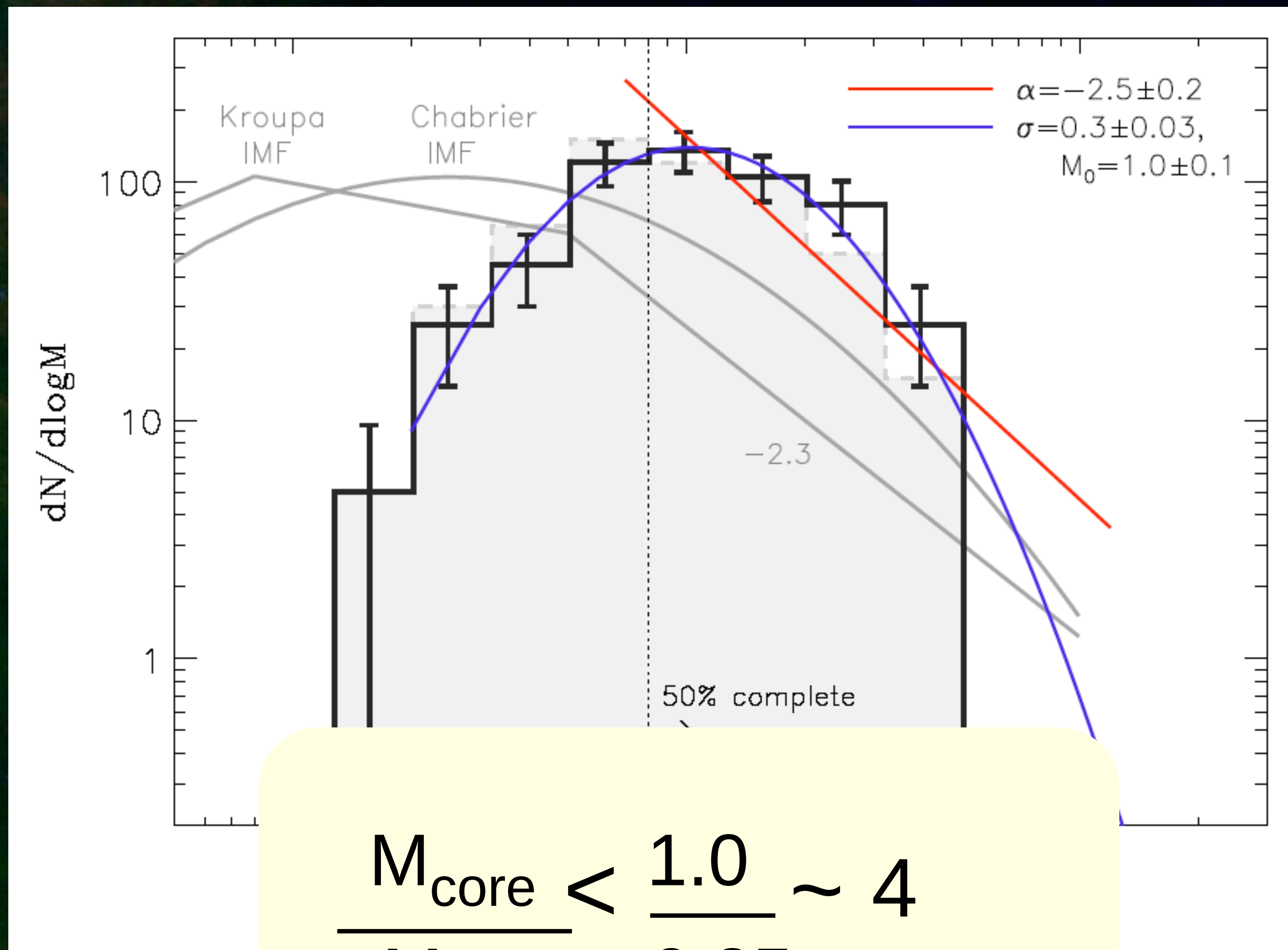
- Best fit power law: $\alpha \sim 2.5$

- IMF:

  Salpeter: (α~2.4)

  Scalo: (α~2.7)

  peak: 0.2–0.3 $M_\odot$

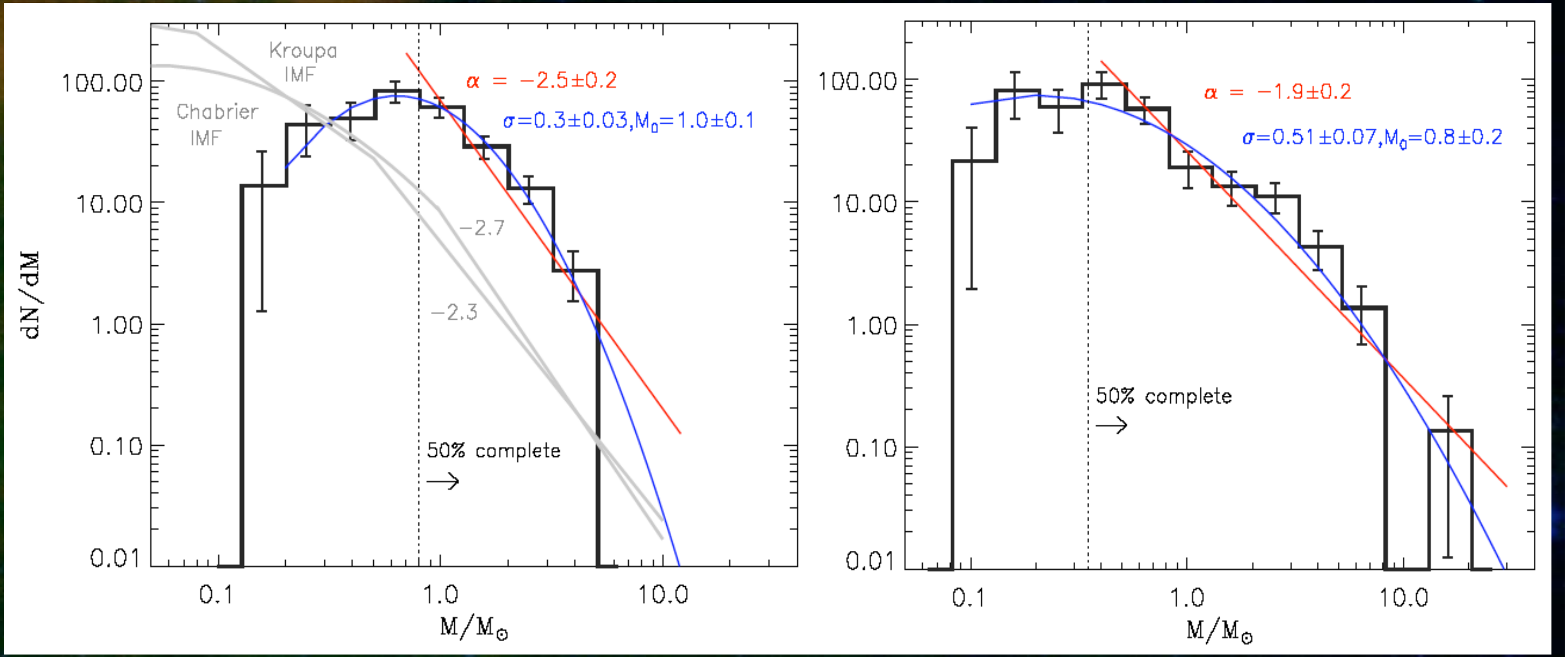


$$\frac{M_{core}}{M_{star}} < \frac{1.0}{0.25} \sim 4$$

⇒ “Not inconsistent” wit
are determined during core formation

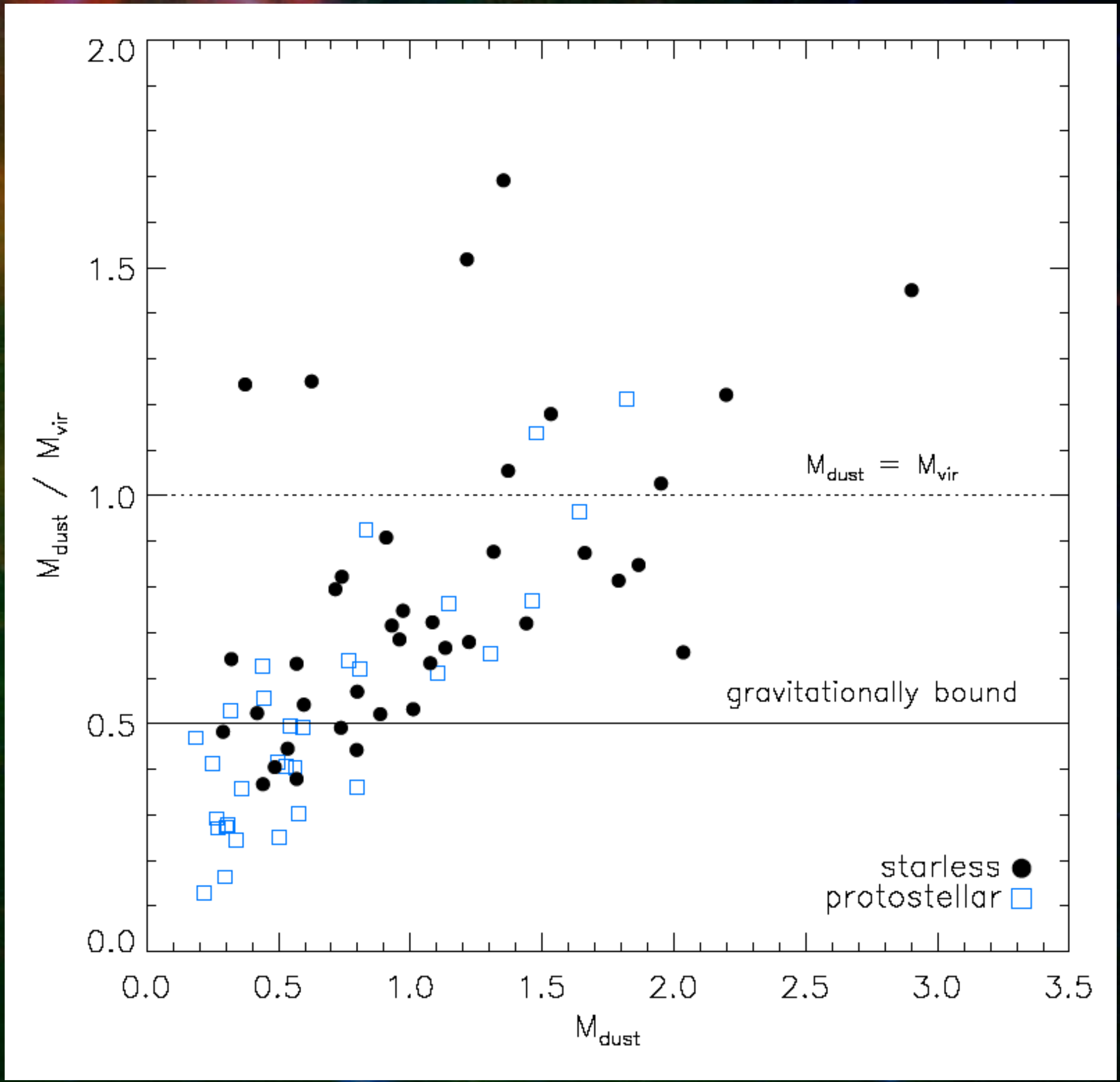
Comparing starless & protostellar cores: mass distribution

STARLESS **PROTOSTELLAR**



- Starless mass distribution is steeper (highest mass cores are protostellar) and narrower

Are the starless cores "bound"?



- GBT NH_3 survey of Bolocam cores in Perseus (Rosolowsky et al.)
- M_{vir} from NH_3 linewidth & HWHM size
- M_{dust} from 1mm flux
- Most starless cores are likely to be bound

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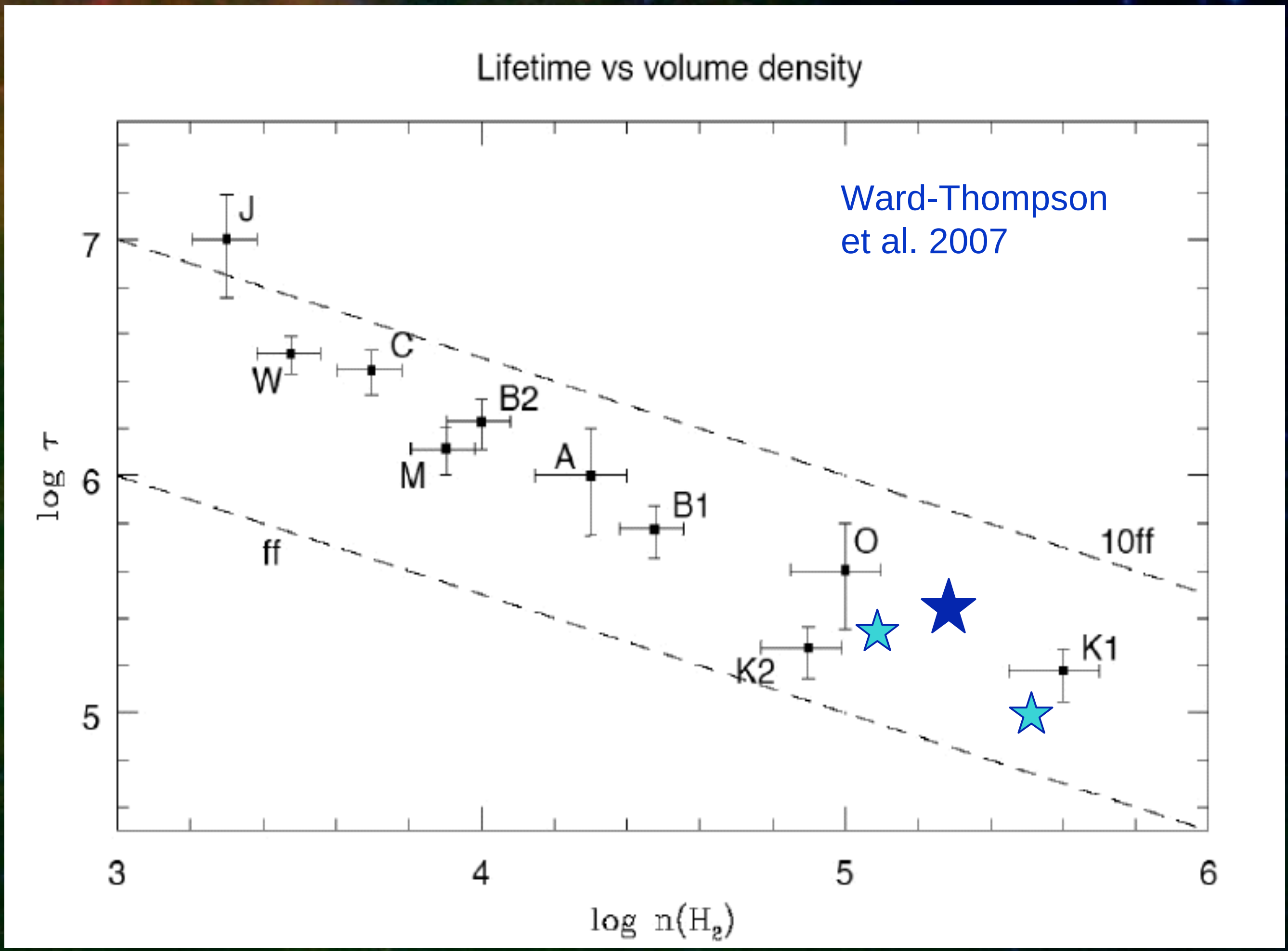
Prestellar core lifetime

Cloud	N_{SL}	N_{SL} / N_{emb}	$\langle n \rangle_{SL}$ (cm^{-3})	t_{ff} (yr)	t_{SL}/t_{ff}
Per	67	1.0	$1.4x10^5$	$9x10^4$	4.4
Ser	15	0.4	$1.2x10^5$	$10x10^4$	2.0
Oph	26	0.8	$1.7x10^5$	$9x10^4$	3.3

- Assuming continuous SF, evolutionary sequence, time is the only variable… $N_1/N_2 = t_1/t_2$
  - N_{SL}/N_{emb} and t_{emb} ~ $4x10^5$ yr $\Rightarrow$ prestellar core lifetime ~
    $4x10^5$ yr (Per); $2x10^5$ yr (Ser); $3x10^5$ yr (Oph)

    ~ few x t_{ff}, and « t_{AD} ~ 10^7 yr
- Prestellar core lifetime suggests dynamic core evolution
- Inconsistent w/ magnetically dominated paradigm?
  (for densities ≥ $2x10^4$ cm^{-3})

Prestellar core lifetime



- $n(H_2)$ measured in 10^4 AU aperture
- Estimated τ
  - ⇒ Cores not in free-fall
  - ⇒ Not highly subcritical
- Lifetime decreases at higher densities

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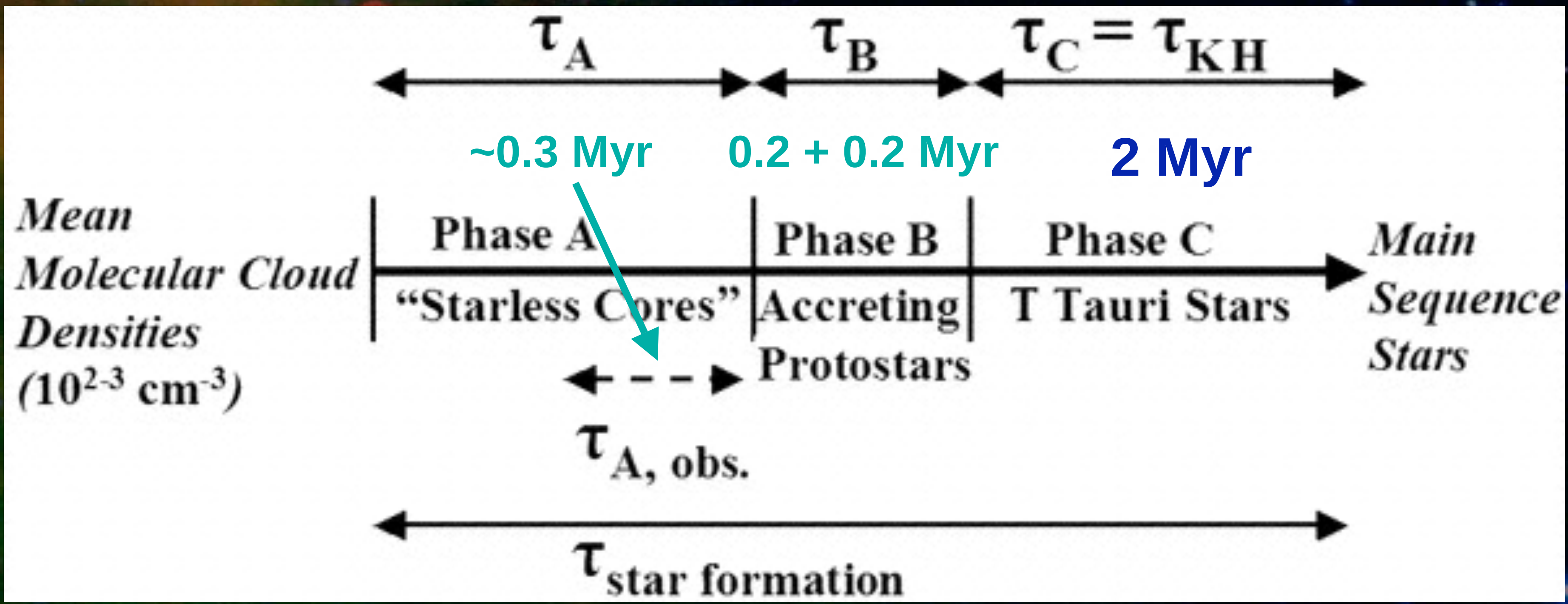
Class 0 timescale

Cloud	N_{Class0}	N_{ClassI}	N_{Class0} / N_{ClassI}	$t_{Class\ 0}$ (yr)
Per	29	39	0.7	1.7×10^5
Ser	11	26	0.4	1.2×10^5
Oph	3	29	0.1	0.4×10^5

- Assuming continuous SF, evolutionary sequence, time is the only variable… $N_1/N_2 = t_1/t_2$
  - N_{Class0}/N_{ClassI} and $t_{emb} \sim 4 \times 10^5$ yr

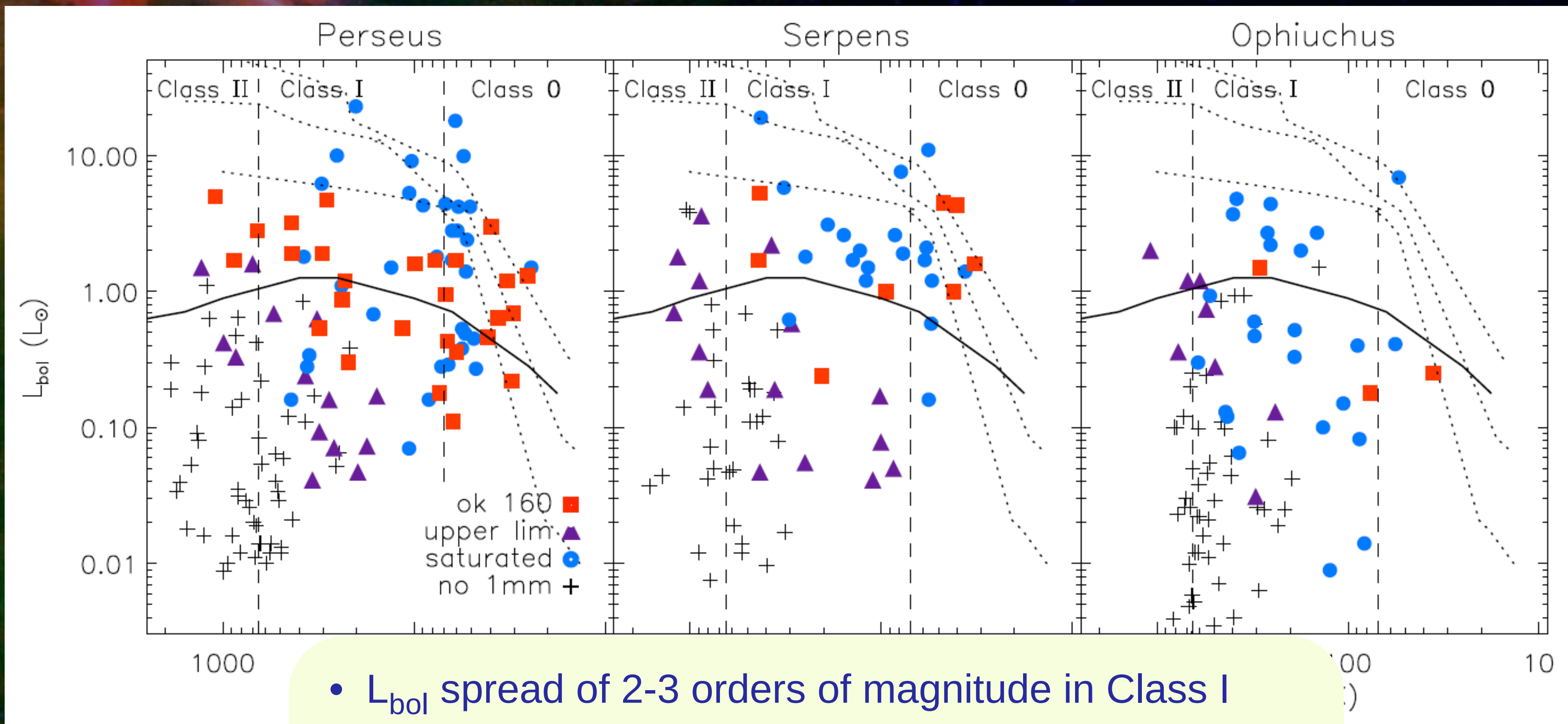
    $\Rightarrow$ Class 0 lifetime ~ 1.7×10^5 yr (Per); 1.2×10^5 yr (Ser); 0.4×10^5 yr (Oph)
- No very rapid accretion phase in Perseus and Serpens
  - As was suggested based on $t_{Class\ 0} \sim 10^4$ yr (Andre & Montmerle 94, Froebrich et al. 06)
- Class 0 timescale is significantly different in Ophiuchus

Timescales for star formation



Tassis & Mouschovias 2004

Protostellar evolution: L_{bol}-T_{bol} diagram



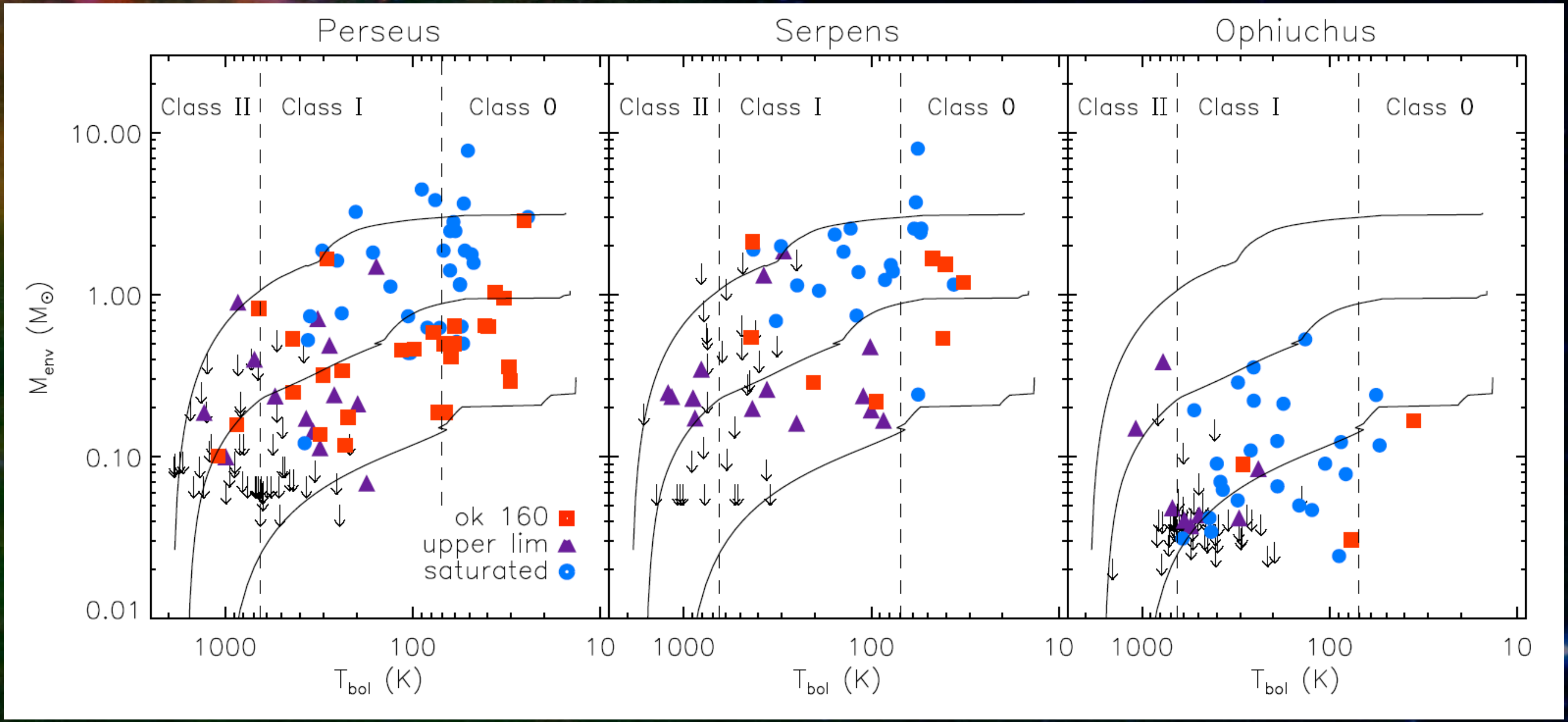
- Evolut … 0 $M_\odot$)

  a

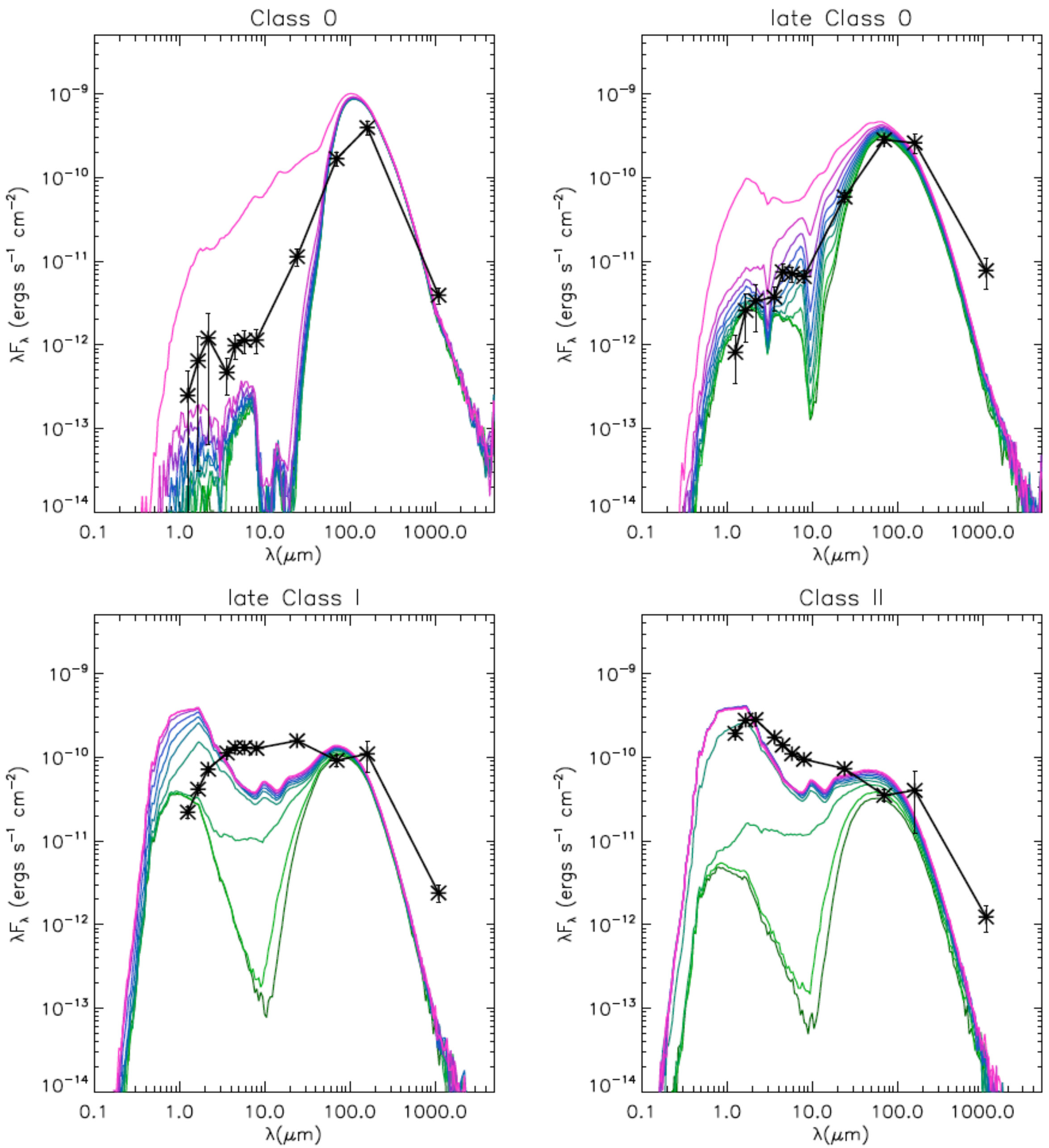
- L_{bol} spread of 2-3 orders of magnitude in Class I
- Mean L_{bol} = 2.4 (Class 0), 1.9 (Class I)
- ~ 25% have L_{bol} < 0.1 $L_\odot$

$\Rightarrow$ Strong evidence for episodic accretion in Class I, ~25% in quiescent state

Protostellar evolution: M_{env} vs T_{bol}



- M_{env} correlated with T_{bol}, as expected
- Constant dM/dt tracks fit well
  - ⇒ Masses of ~ 0.3-4 $M_\odot$ for Per & Ser, < 1 $M_\odot$ for Oph



Whitney et al., 2003
i = 0-90°

- underestimate 1mm flux, late Class 0 on
- too much NIR, too little MIR in Class I
- need to compare to grid!

Summary (so far…)

- Largest millimeter surveys to date in 3 molecular clouds: 20 deg^2, 200 cores
- Compared w/ *Spitzer* surveys ⇒ complete, unbiased sample:

  108 prestellar cores, 43 Class 0, and 94 Class I protostars

1. Physics controlling the formation, support, and collapse of cores
   - Prestellar core lifetime ~ 2–4x10^5 yr

     ⇒ dynamic, turbulent formation process
   - But, disagreements w/ simulations, B fields may also be important?
2. Initial conditions of prestellar cores
   - Starless cores strongly clustered, comparable to embedded protostars
   - Presteller CMD similar to IMF

     ⇒ Further evidence that stellar masses determined by core fragmentation
3. Early protostellar evolution
   - Class 0 lifetime 1–2x10^5 yr (Per, Ser)

     ⇒ No very rapid early accretion phase, dM/dt ~ constant
   - Evidence for episodic accretion during Class I, 25% quiescent
4. Variations with environment
   - Early accretion or SF history very different in Oph