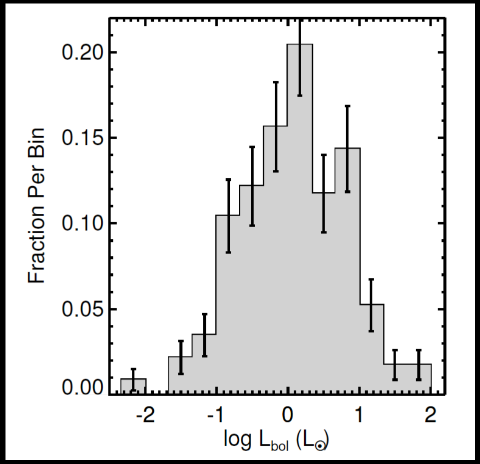
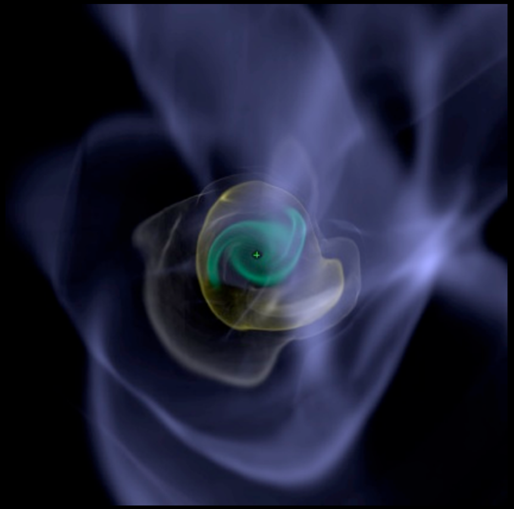
Early Protostellar Evolution

Challenges for star formation observations & theory



Mike Dunham

&



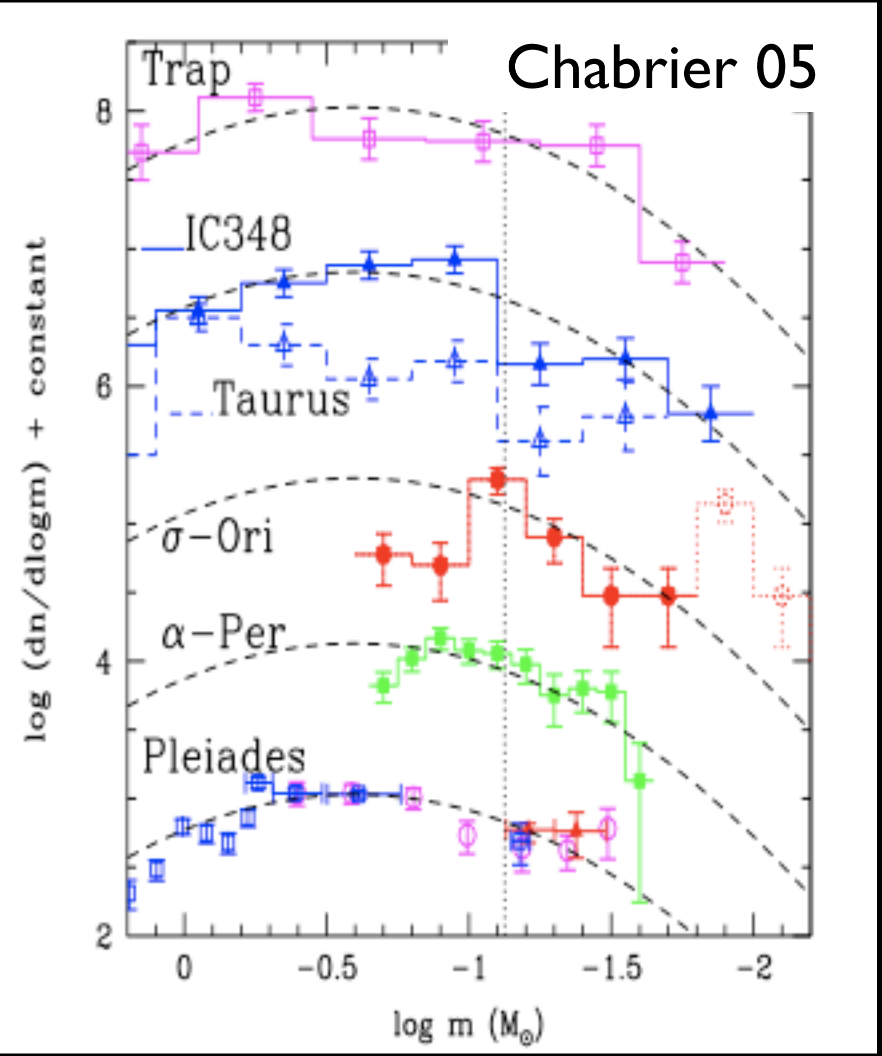
Stella Offner
Hubble Fellow

Yale University

Frontiers in Star Formation, Oct 27, 2012

Motivation

The IMF is universal



Solution: to understand early protostellar evolution study a different observational metric:

protostellar luminosities are a window to instantaneous star formation processes (accretion, masses, time-dependence, duration, big picture)

Luminosity Problem

- Protostars are dimmer than star formation models predict (Kenyon et al. 1990)

- $<L>_{obs} \cong 2$ Lsun for Class 0,1 (Enoch et al. 2009)

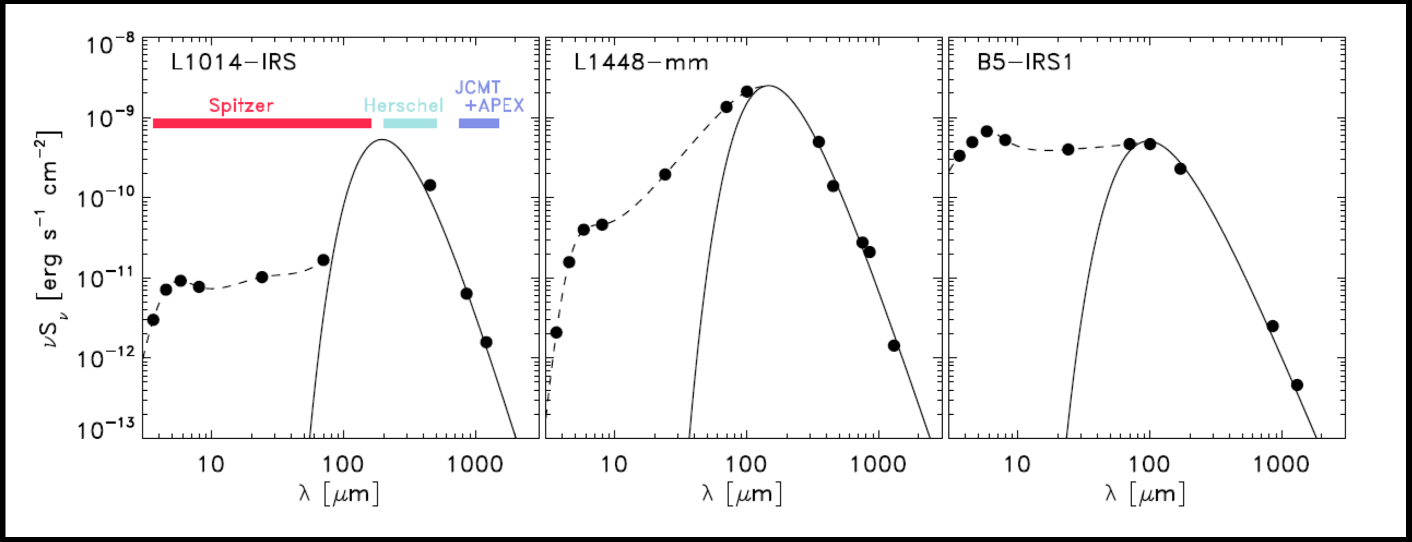
- Considering only accretion:

$$< L_{\rm acc} >= f_{\rm acc} \left(\frac{G m \dot{m}}{r} \right)$$

$$\simeq \frac{0.75 \times G \times 0.25 \mathrm{M}_{\odot} \times 2.5 \times 10^{-6} \mathrm{M}_{\odot}/\mathrm{yr}}{2.5 \mathrm{R}_{\odot}} = 5.9 \mathrm{L}_{\odot}$$

Observational Challenges

- Identify protostars
- SEDs show great diversity
- Obtain >3 order of mag. wavelength coverage
- Extinction Corrections
- What is Lbol?

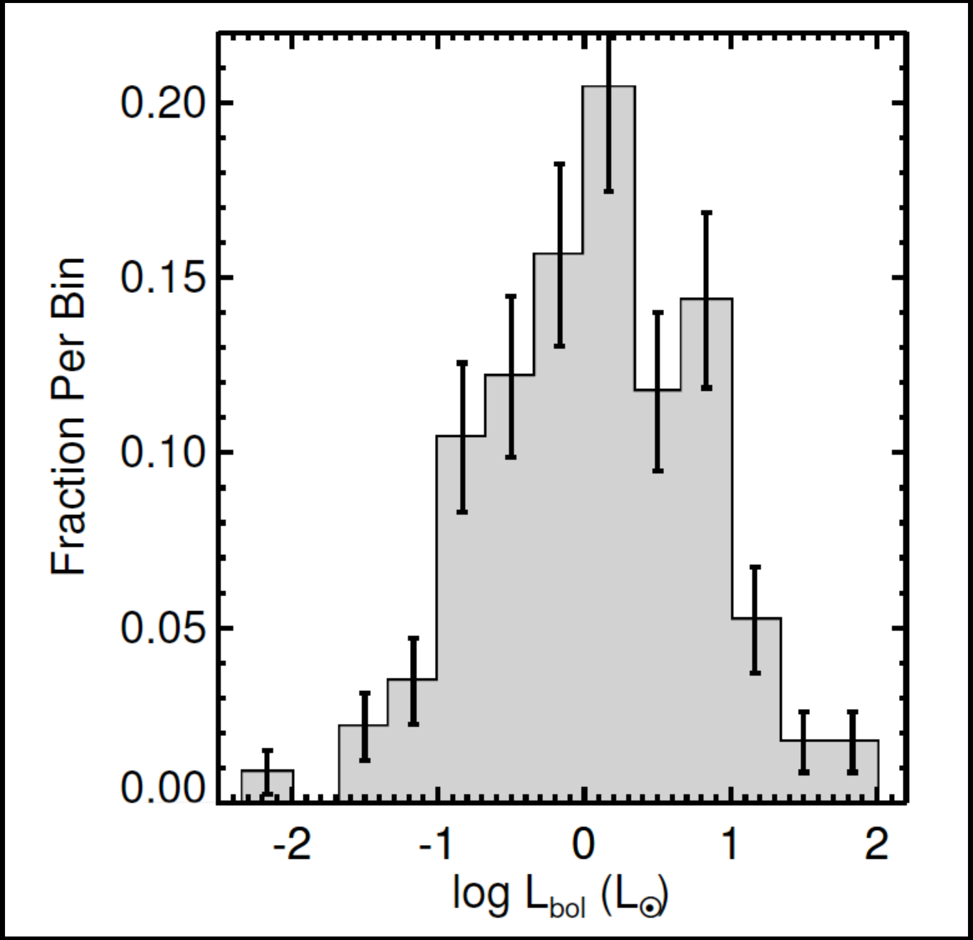


Jorgensen et al.

What are the key observations?

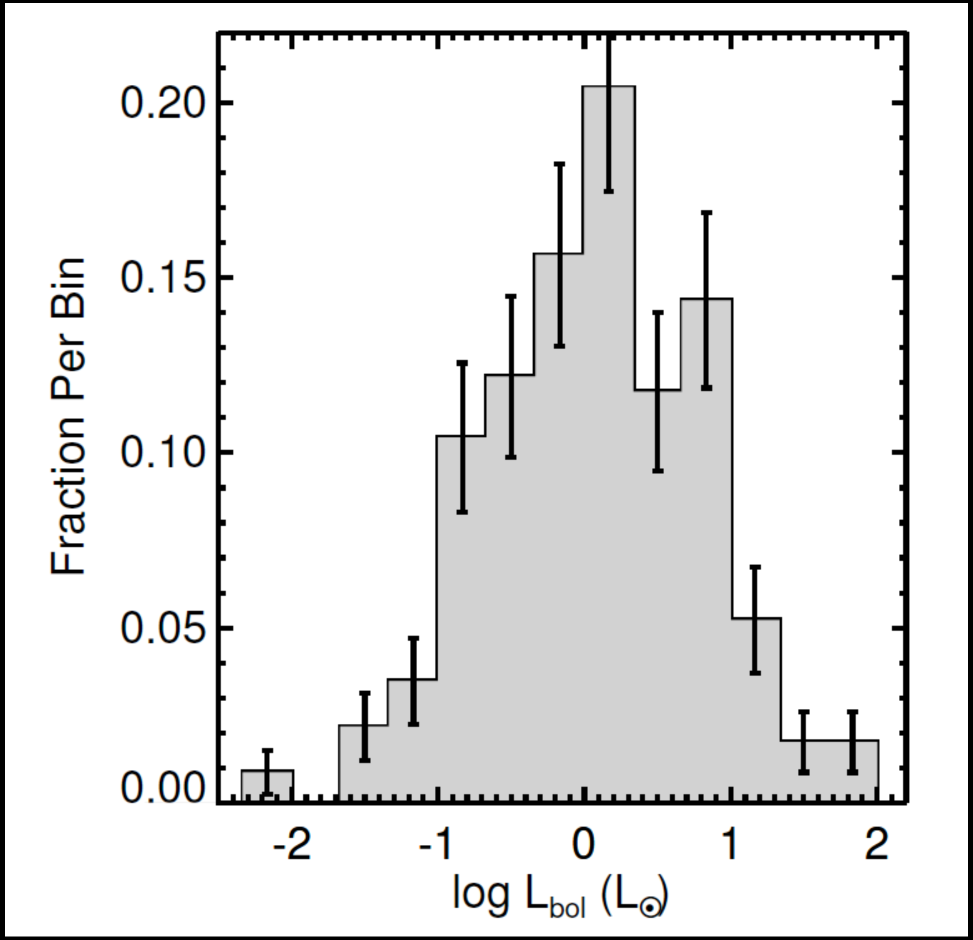
- What are the mean and median luminosities?
- What is the total range of luminosities?
- How are Class 0/1 luminosities different? (Or are they?)
- How low do they go?

Mean and Median Luminosities



- Mean:
  L_{bol} = 4.3 L_{sun} (5.8 L_{sun})
  (c2d+GB; Dunham et al. 2012)
- Median:
  L_{bol} = 1.3 L_{sun} (1.8 L_{sun})
  (c2d+GB; Dunham et al. 2012)

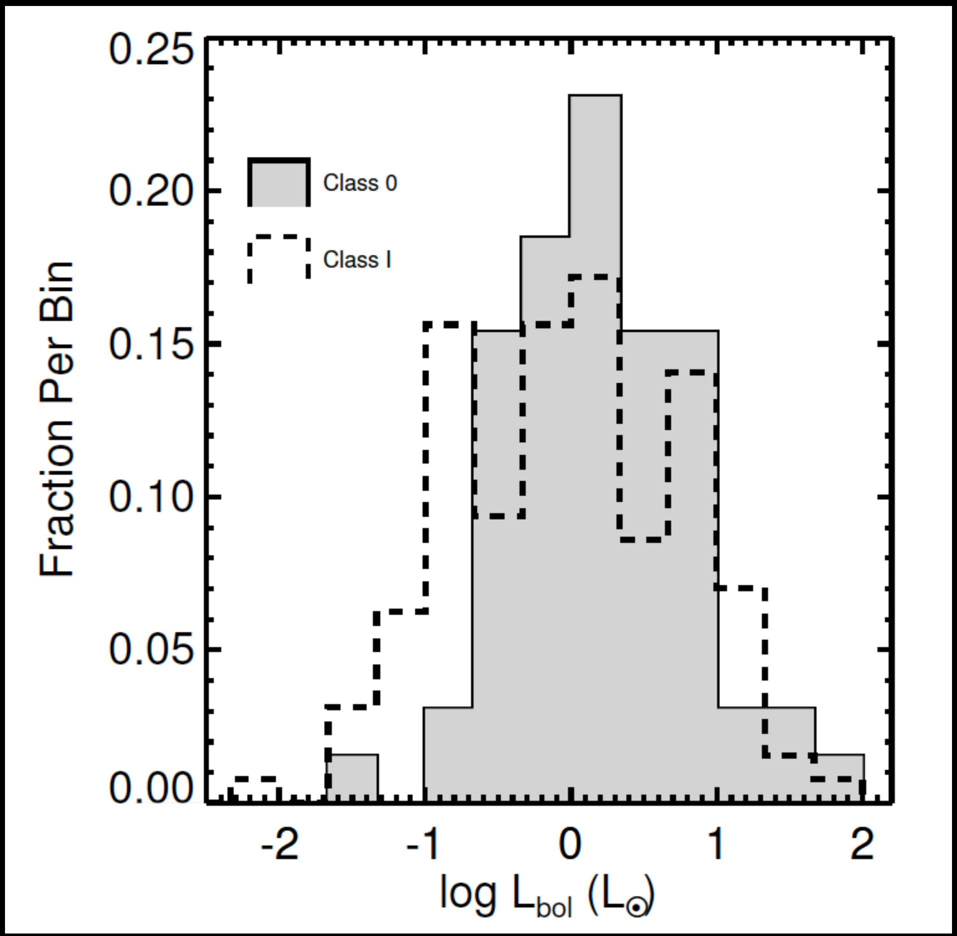
Range of Luminosities



- 0.01 - 69 Lsun
- >3 orders of magnitude (3.8 dex)

Dunham et al. (2012)

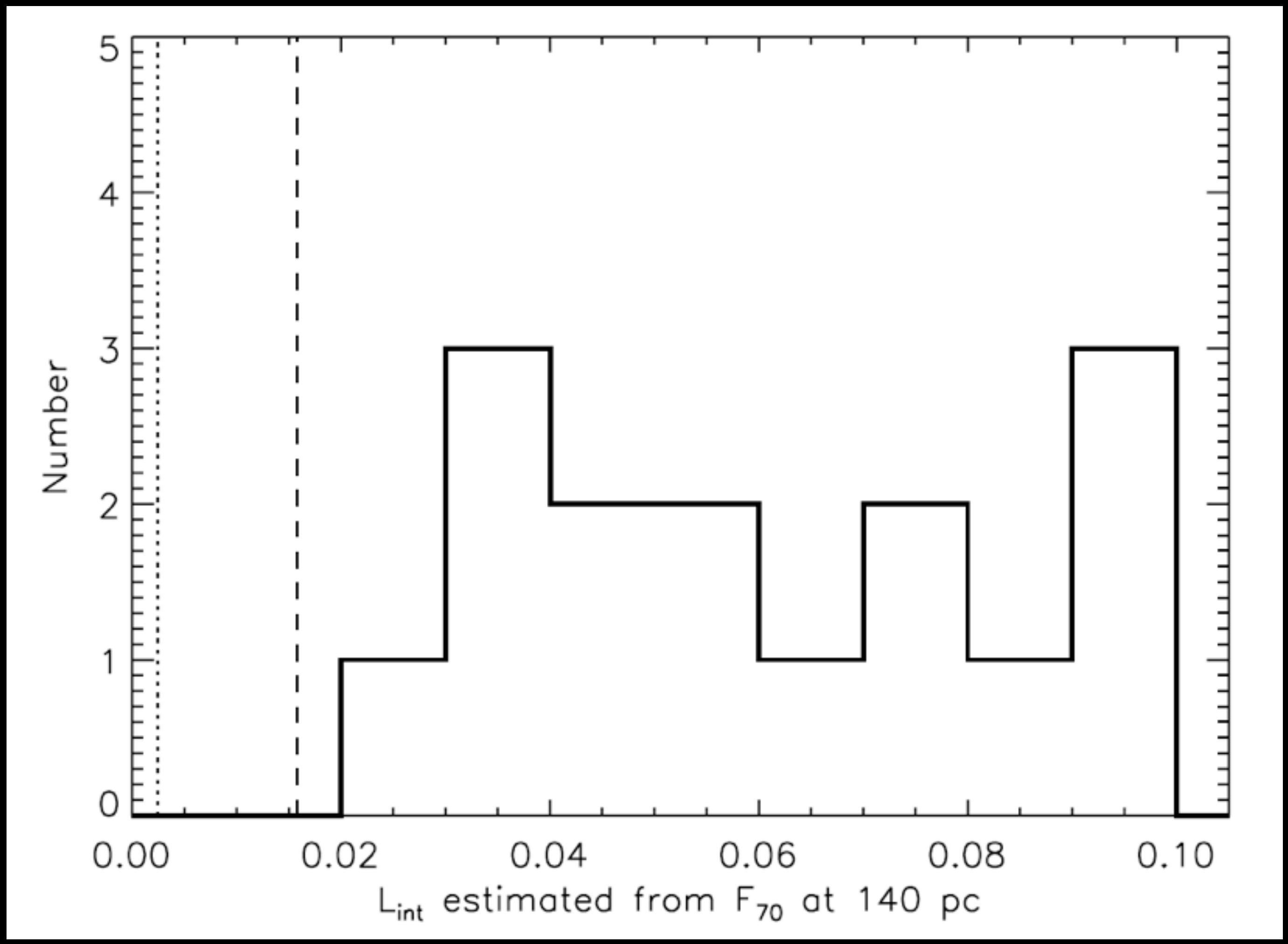
Class 0 vs. Class I



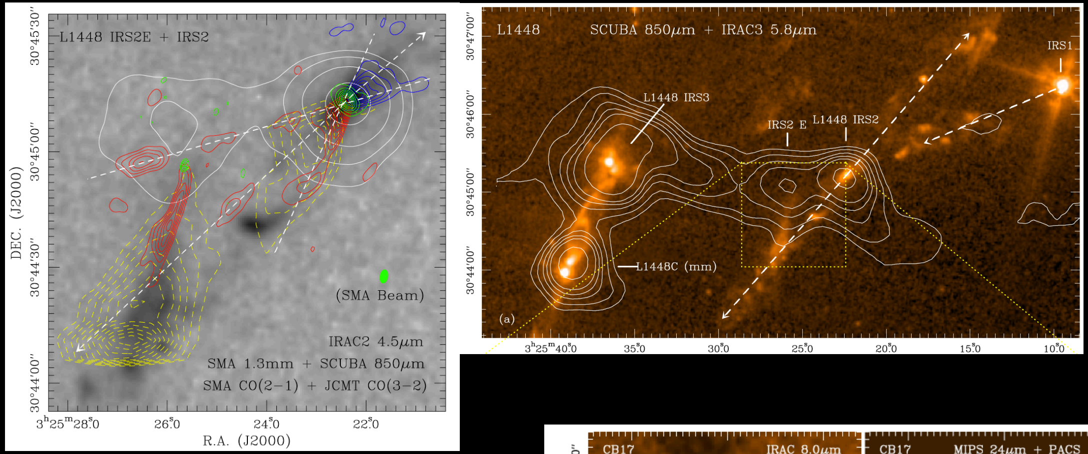
- **Mean:**
  4.5 Lsun (Class 0)
  3.8 Lsun (Class I)
- **Median:**
  1.4 Lsun (Class 0)
  1.0 Lsun (Class I)
- **Lbol < 0.5 Lsun:**
  20% (Class 0)
  36% (Class I)
- **K-S test:** 0.04

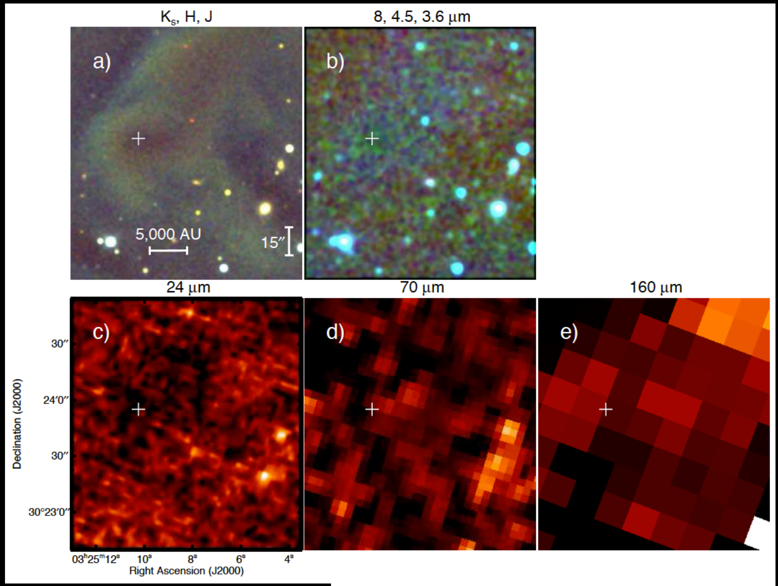
Dunham et al. (2012)

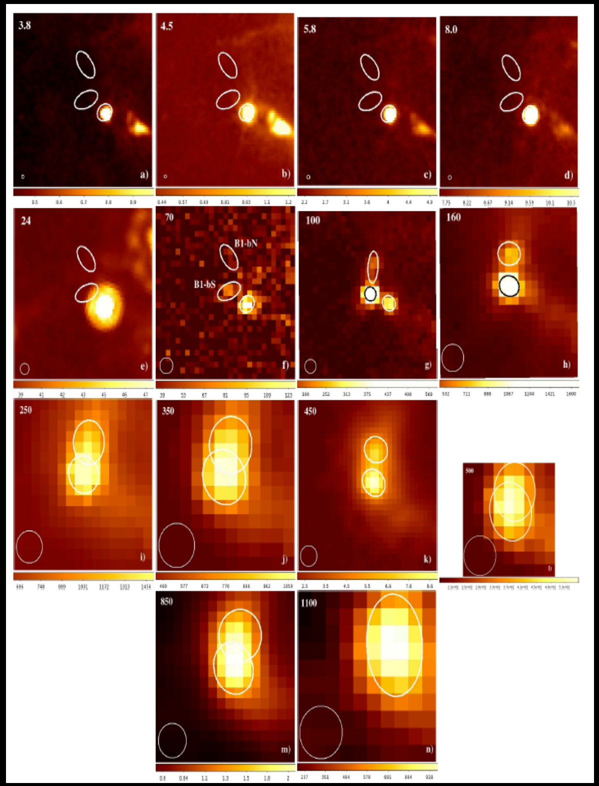
How low do they go?

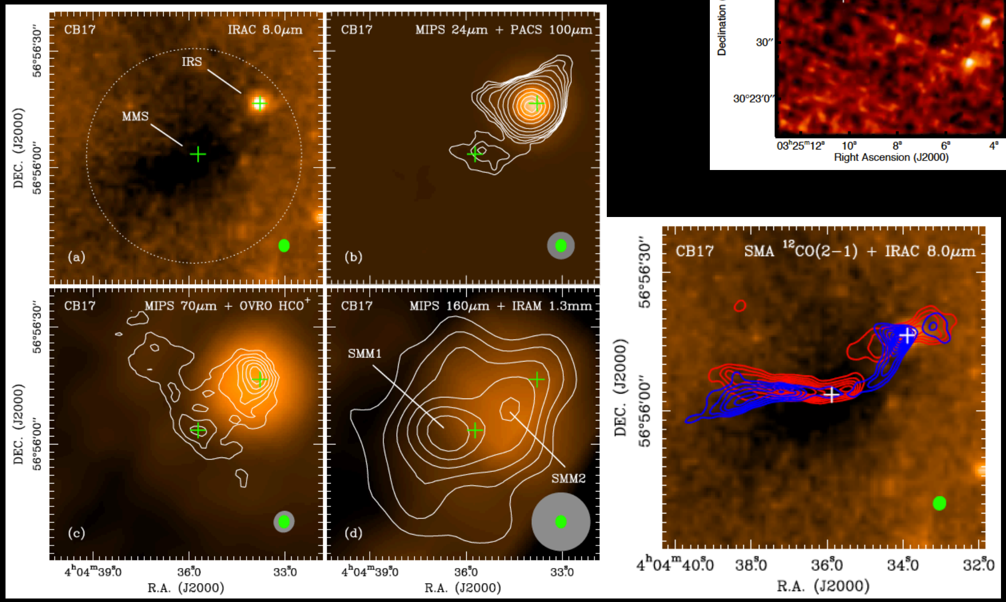


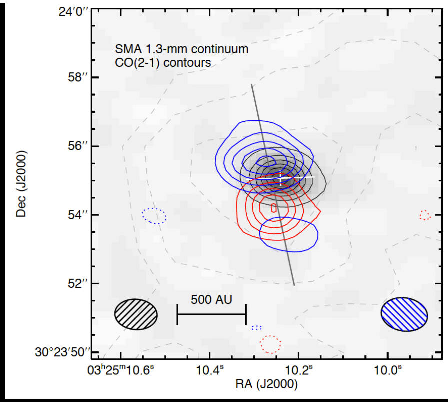
Dunham et al. (2008)

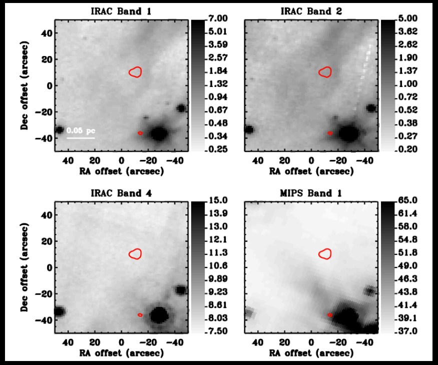


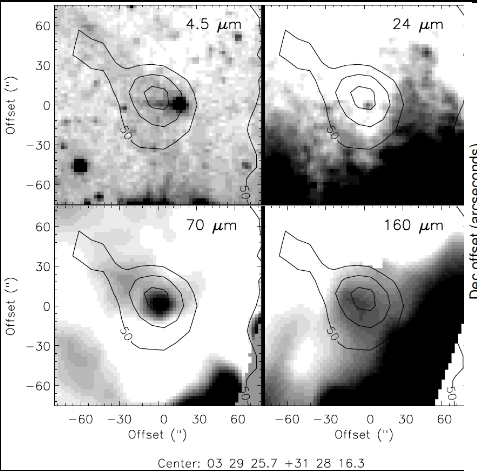


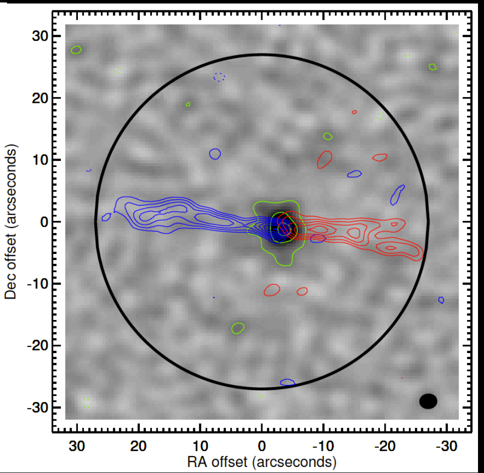








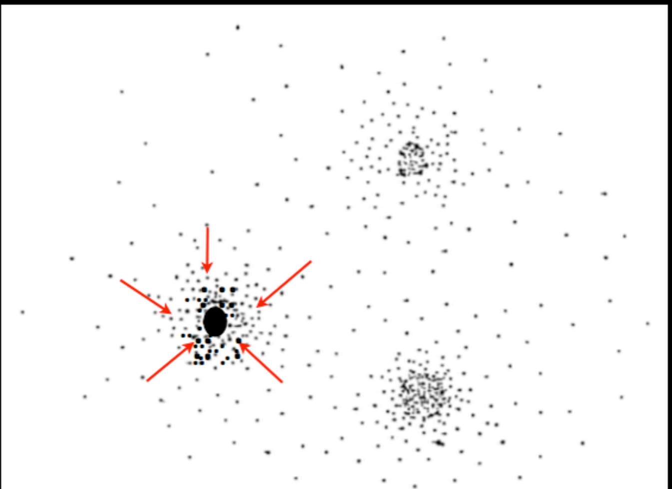


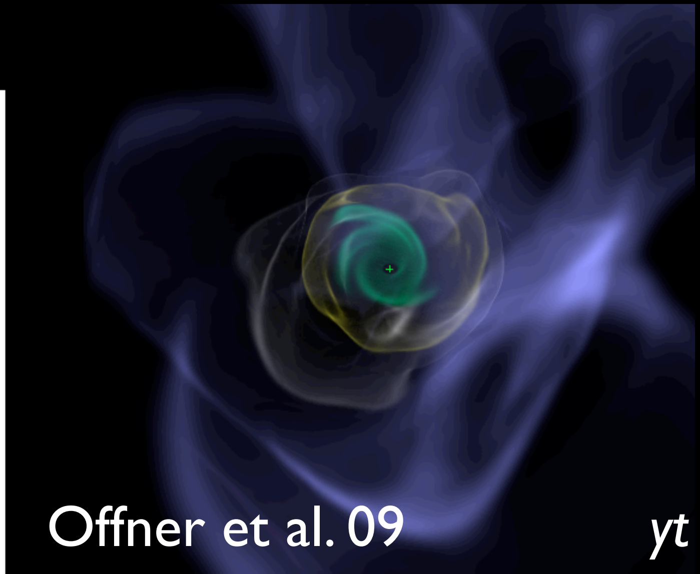


Chen et al. (2010)
Enoch et al. (2010)
Pineda et al. (2011)
Dunham et al. (2011)
Schnee et al. (2012)
Chen et al. (2012)
Pezzuto et al. (2012)

What does it all imply?

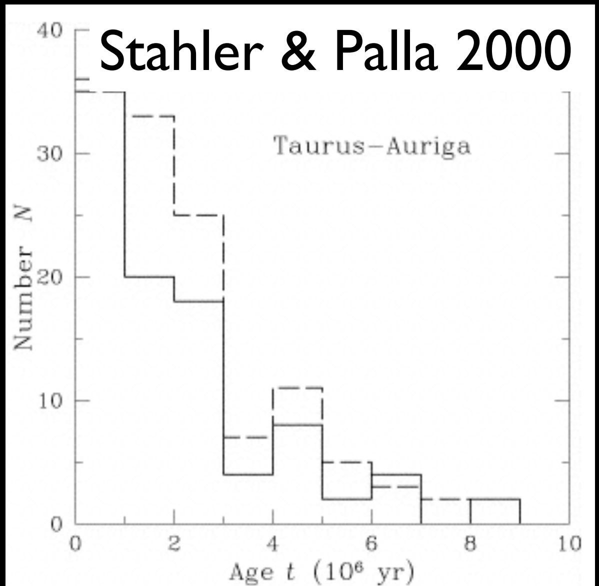
- What is the underlying star formation theory (e.g. Turbulent Core, Competitive Accretion)?
- What is the role of episodic accretion (i.e. importance of disks)?
- How does (de)accelerating star formation or early/delayed high-mass star formation fit in?





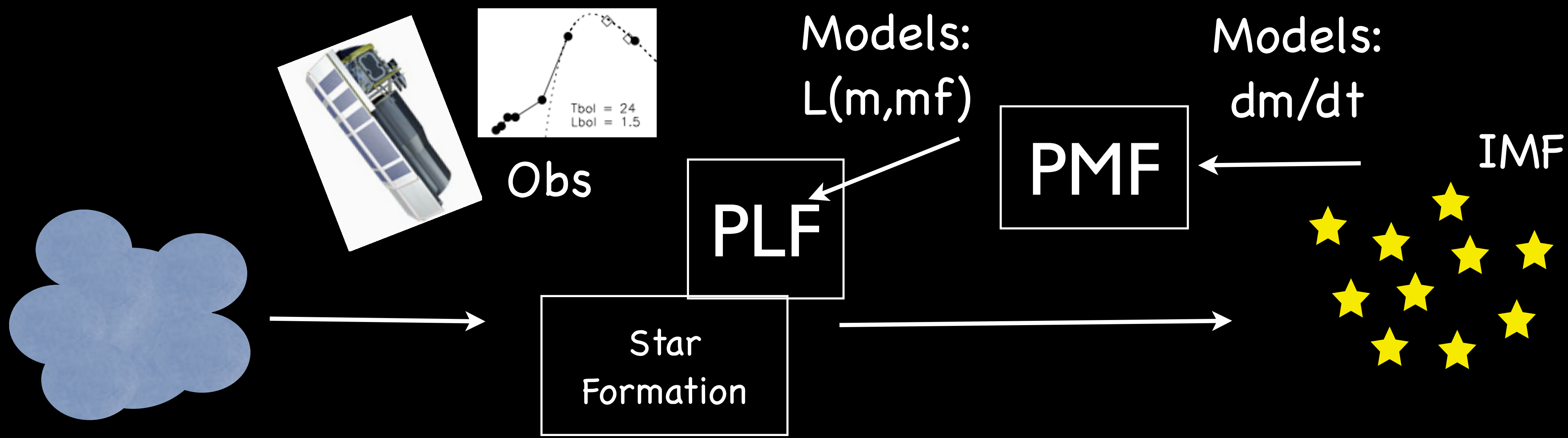
Offner et al. 09

yt



Stahler & Palla 2000

Protostellar Mass & Luminosity Functions (PMF, PLF)

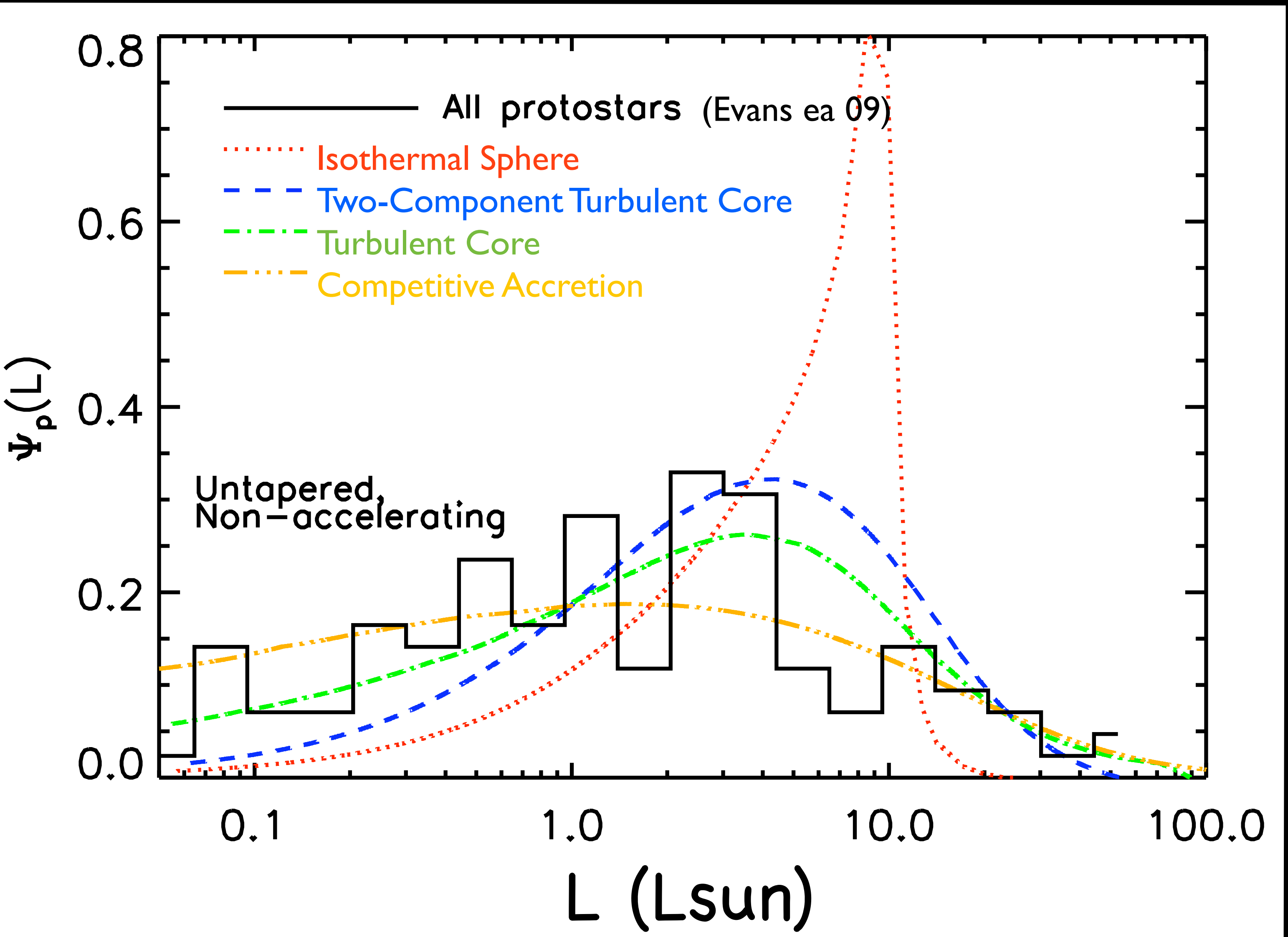


- Isothermal Sphere (IS), Shu 77
- Turbulent Core (TC), McKee & Tan 03
- Competitive Accretion (CA), Bonnell et al. 97
- 2-Component Models (IS+TC, IS+CA)

Offner & McKee (2011)
McKee & Offner (2010)

Star Formation Models

Protostellar Luminosity Function (PLF)

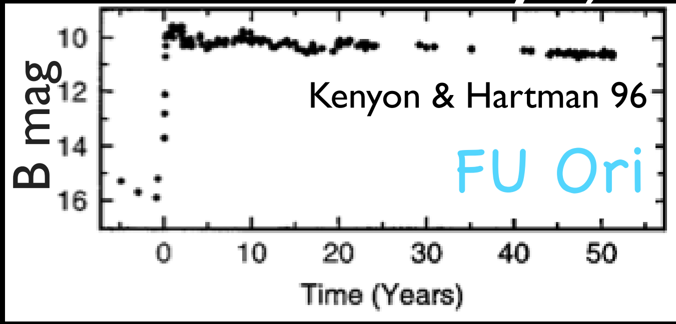


TC, CA are better models: constant star formation times (i.e. accretion increases with final mass)

Offner & McKee 2011

Estimating Episodic Accretion

- N_p = # of bursting sources = 20 (observed in last 70 yr)
- N_* = Star Formation Rate = 0.016*/yr
- $<m_f>$ = 0.5 Msun



$$\Delta t_{\rm high} = \frac{N_p}{\dot{N}_*} = \frac{20}{0.016 * /\mathrm{yr}} \simeq 1200 \ \mathrm{yr}$$

0.1–1% of acc. time

$$f_{\rm epi} = \frac{\dot{m}_{\rm high}\Delta t_{\rm high}}{< m_f >} = \frac{10^{-4} M_\odot/\mathrm{yr} \ 120}{0.5 M_\odot}$$

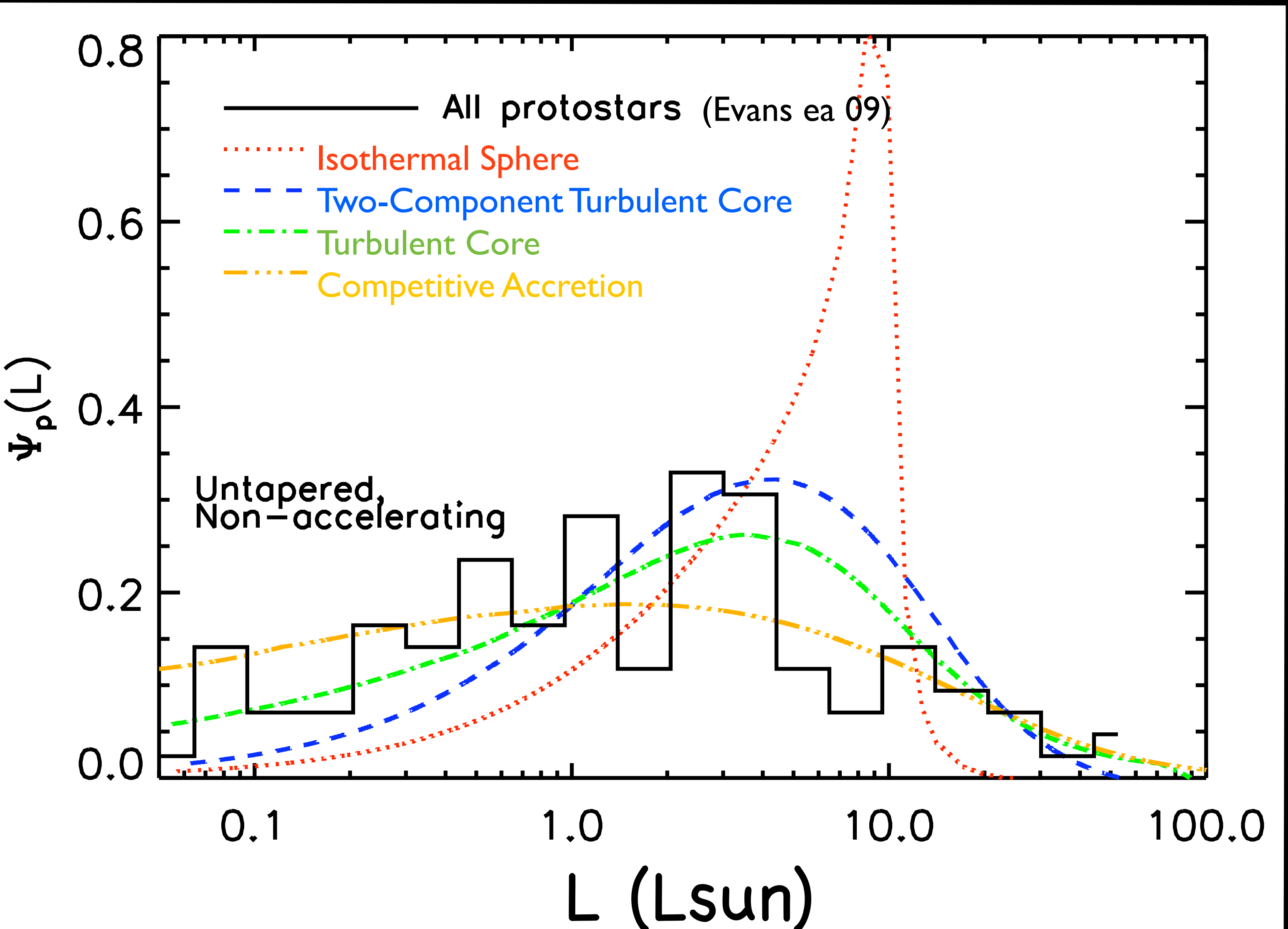
1/4 of Mass

$$N_{b*} = \frac{0.2 \ \mathrm{bursts/yr}}{0.016 * /\mathrm{yr}} \simeq 10 \ \mathrm{bursts} \quad t_{b*} = \frac{1200 \ \mathrm{yr}}{10 \ \mathrm{bursts}} \simeq 100 \ \mathrm{yr}$$

Offner & McKee 2011

Star Formation Models

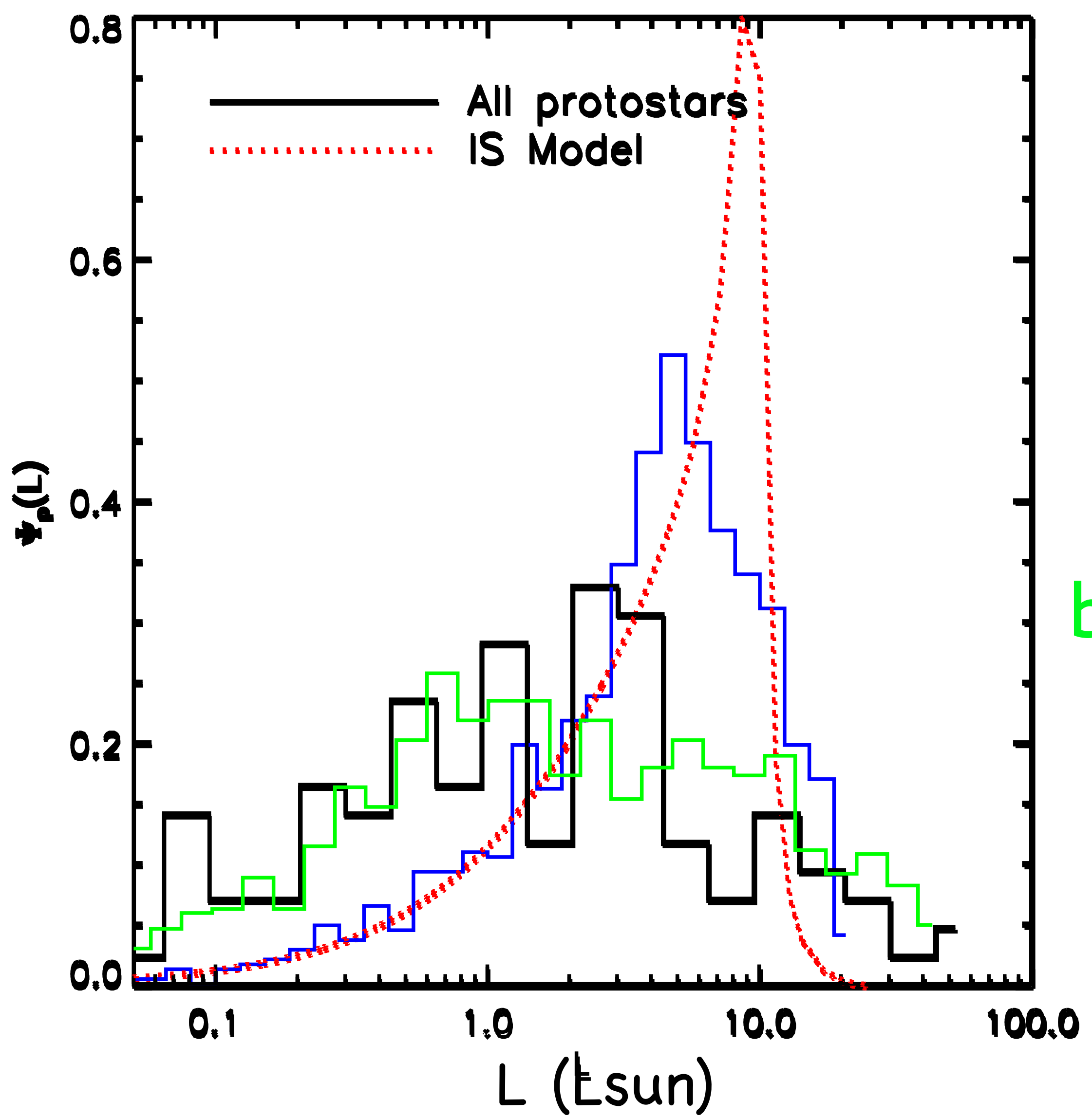
Protostellar Luminosity Function (PLF)



TC, CA are better models: constant star formation times (i.e. accretion increases with final mass)

Offner & McKee 2011

“Episodic” vs. Variable Accretion



Add random variations on top of accretion IS trend:

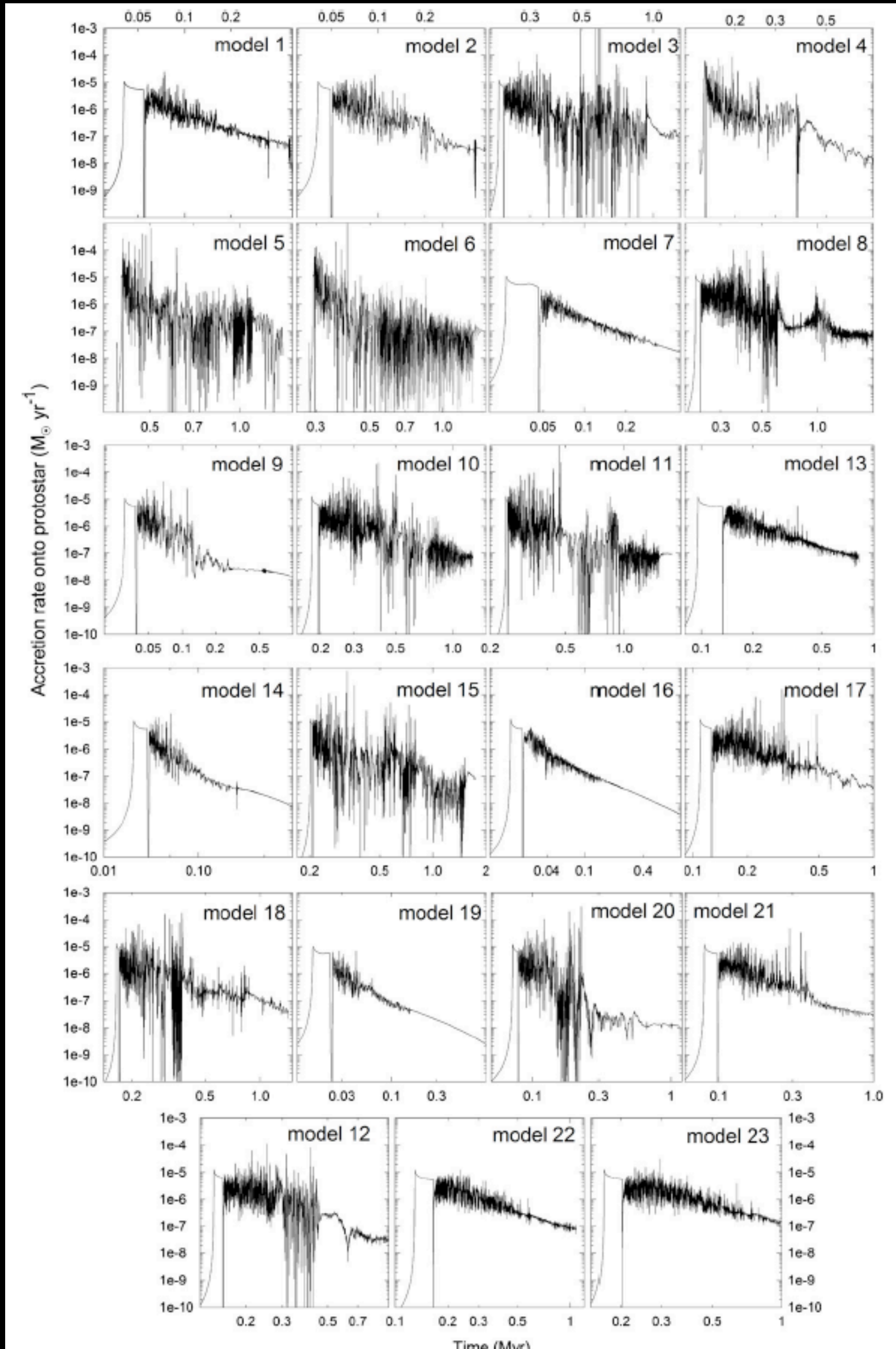
dm/dt can vary by a factor of 2

by a factor of 10

Question:
How much time variability occurs?

Offner & McKee in prep.

Second Approach: Modeling Individual Cores



Vorobyov & Basu (2005, 2006, 2010)

- Hydro simulations of collapsing cores
- Resolve disk physics
  (but not inner disk < 6 AU)
- Variable, episodic accretion dependent on initial conditions

Assemble models over range of IC

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Post-process with continuum rad. trans.

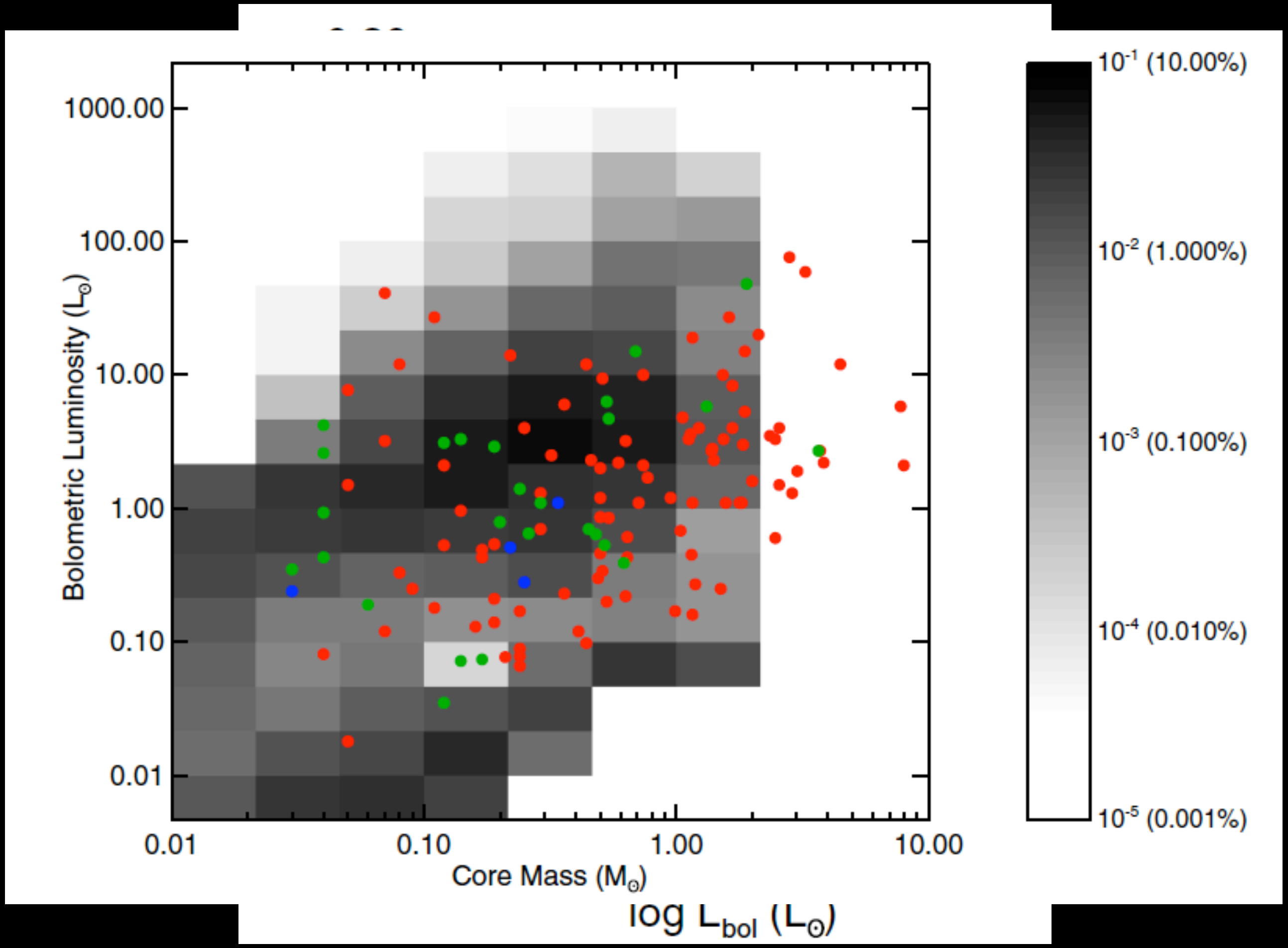
↓

Generate synthetic obs., measure L_{bol}

↓

Weight over inclinations, IMF

Second Approach:
Modeling Individual Cores



Dunham & Vorobyov (2012)

Conclusions

- Protostars in local regions have a mean luminosity of ~4.3 Lsun and extend over 3 order of magnitude
- Class 0 & Class 1s have similar luminosities but there are more low luminosity Class 1s
- Many candidate first cores exist but require confirmation
- Episodic accretion could account for ~1/4 of a star's mass but probably <1% of accretion time.
- Observations can be explained by some combination of longer accretion, episodic/variable accretion, and mass-dependent accretion