Early Protostar Evolution

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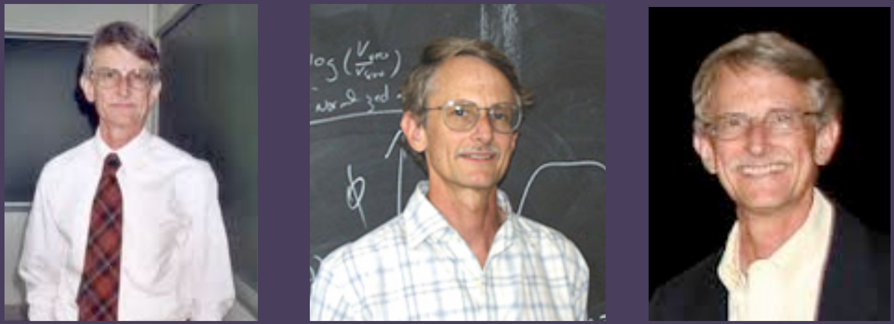
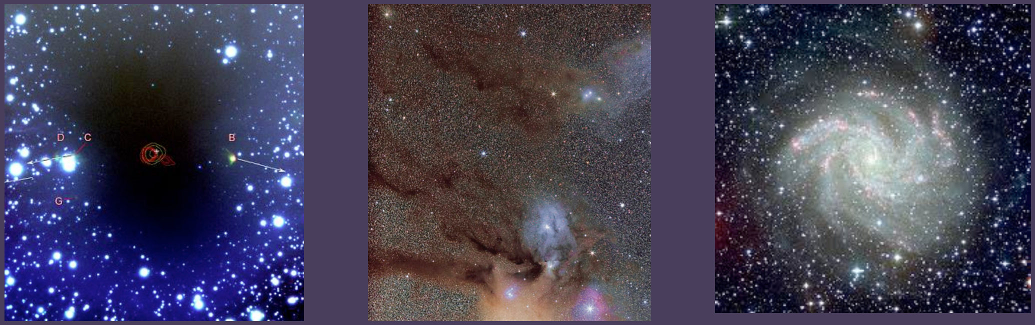
Introduction

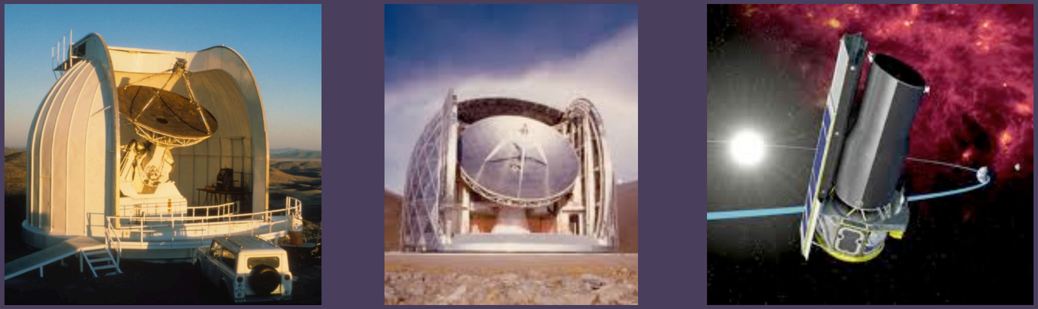
Why we are here



some of Neal’s pursuits

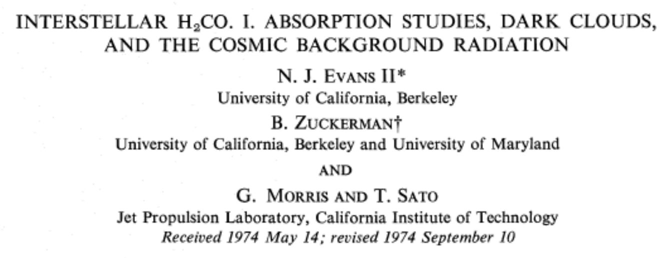


and his tools



Classic Neal papers

comprehensive studies of observations & models → conclusions



INTERSTELLAR H_2CO. I. ABSORPTION STUDIES, DARK CLOUDS, AND THE COSMIC BACKGROUND RADIATION

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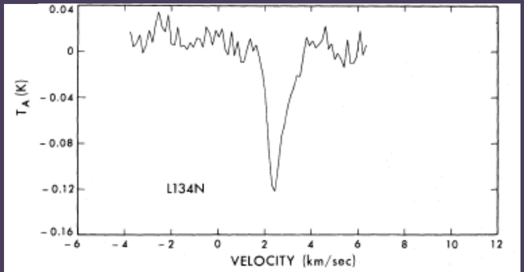
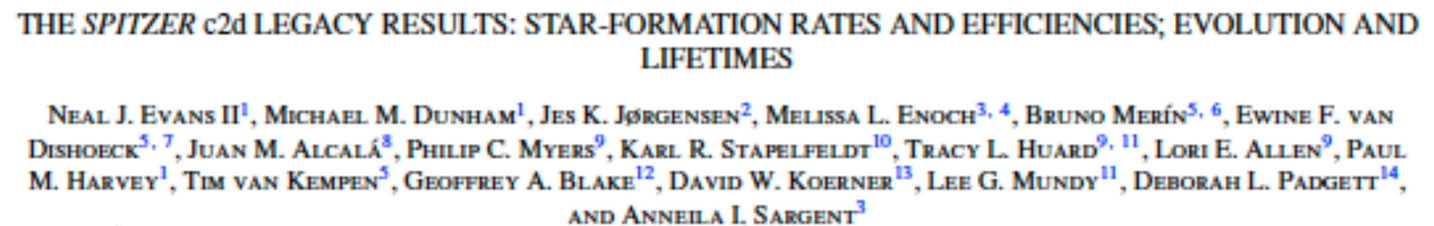
University of California, Berkeley and University of Maryland
AND
G. MORRIS AND T. SATO
Jet Propulsion Laboratory, California Institute of Technology
Received 1974 May 14; revised 1974 September 10

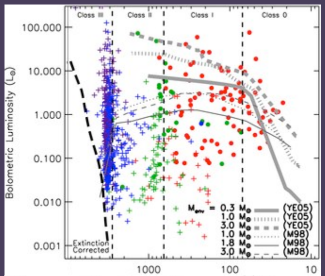


1975 4 authors 130 cites H_2CO line absorption → collisional cooling



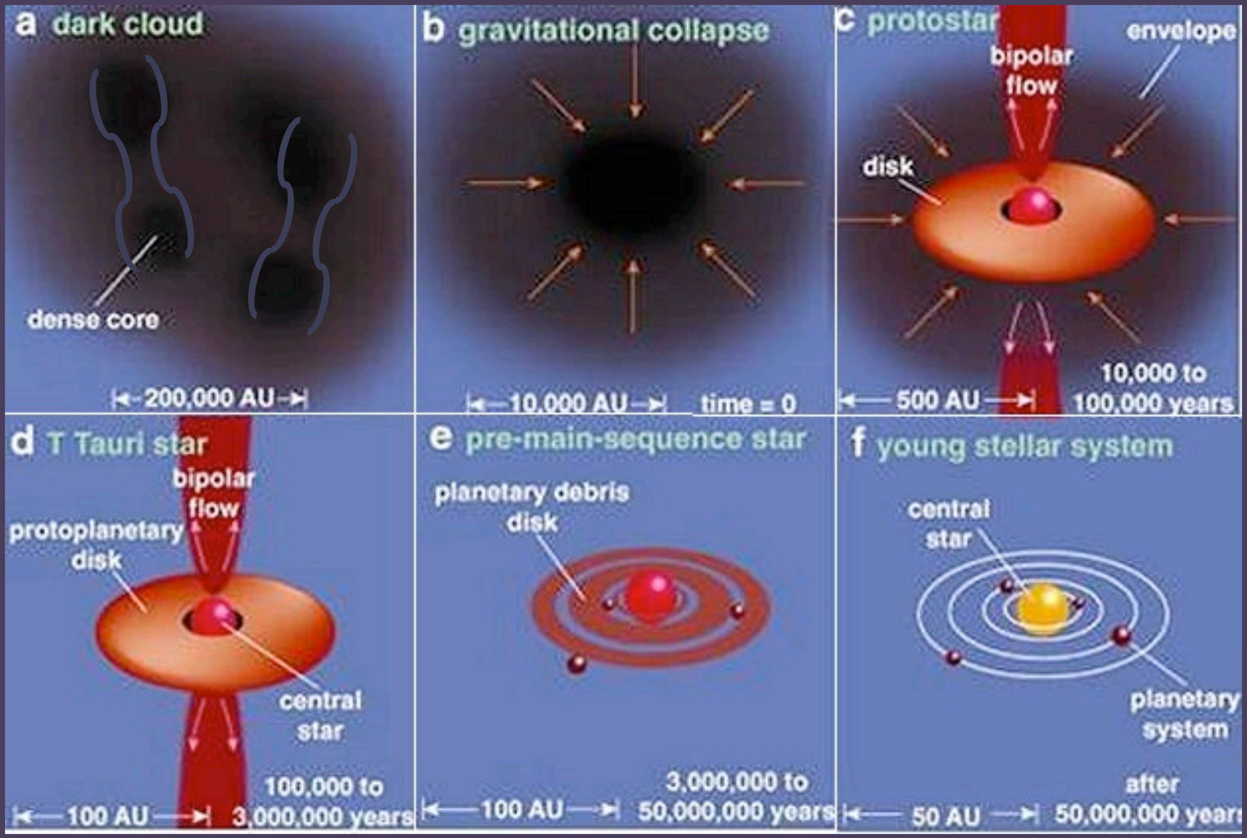
THE *SPITZER* c2d LEGACY RESULTS: STAR-FORMATION RATES AND EFFICIENCIES; EVOLUTION AND LIFETIMES

NEAL J. EVANS II[1], MICHAEL M. DUNHAM[1], JES K. JØRGENSEN[2], MELISSA L. ENOCH[3, 4], BRUNO MERÍN[5, 6], EWINE F. VAN DISHOECK[5, 7], JUAN M. ALCALÁ[8], PHILIP C. MYERS[9], KARL R. STAPELFELDT[10], TRACY L. HUARD[9, 11], LORI E. ALLEN[9], PAUL M. HARVEY[1], TIM VAN KEMPEN[5], GEOFFREY A. BLAKE[12], DAVID W. KOERNER[13], LEE G. MUNDY[11], DEBORAH L. PADGETT[14], AND ANNEILA I. SARGENT[3]



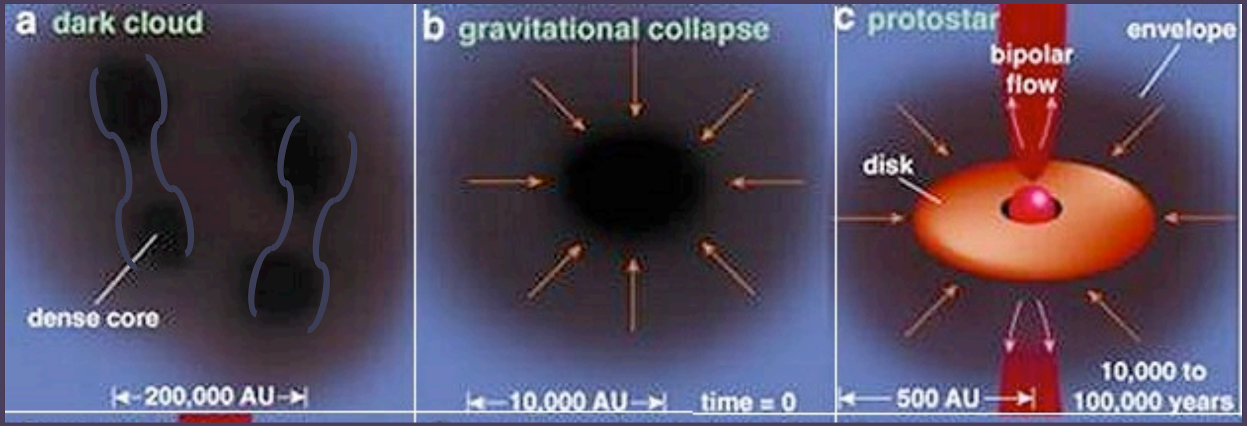
2009   18 authors   339 cites
infall rate ≈ SIS collapse rate >> typical accretion rate
→ nonsteady accretion.

Protostar evolution



Spitzer Science Center (after Shu, Adams & Lizano 1987)

Outline



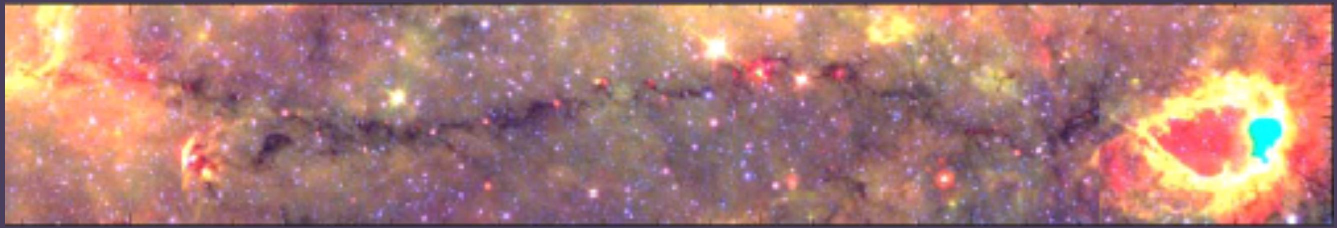
“protostar evolution” = before and after star birth

settings of star formation

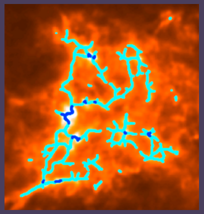
observing and simulating protostars

modeling protostars with IMF constraint

Settings: big filamentary complexes

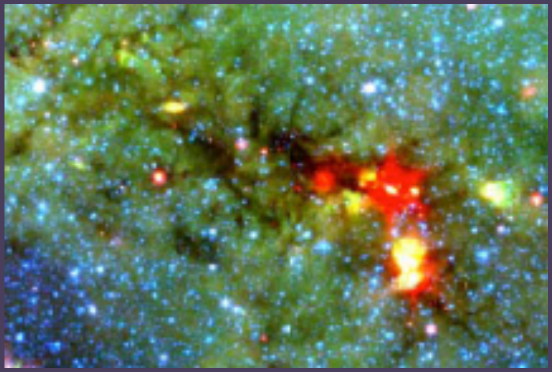


"Nessie" Jackson et al 10 ~80 pc



"South-Nest"

Vela C Hill et al 11 ~ 30 pc



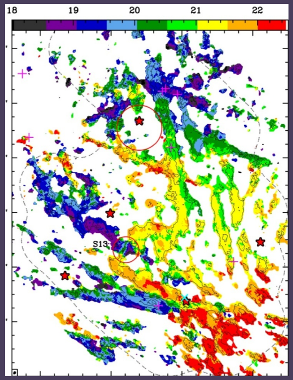
G345.00-022 ~20 pc

M09a

Oph ~20 pc

Cr Australis ~5 pc

www.panther-observatory.com



G14.2-0.5 ~ 5 pc

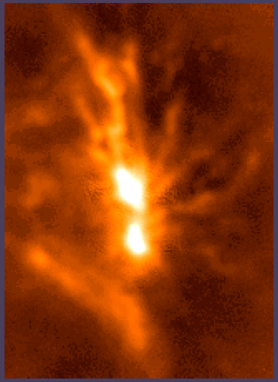
Busquet et al 11

Small filamentary complexes

Ser S ~ 2 pc

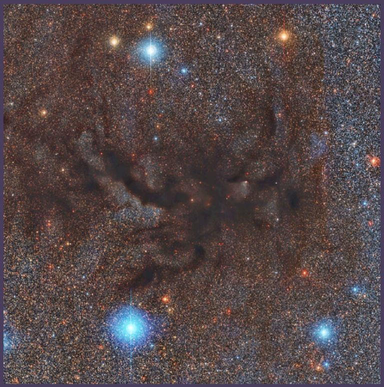
Gutermuth et al 08

Orion A ~1pc



Johnstone & Bally 99

B59 ~1 pc

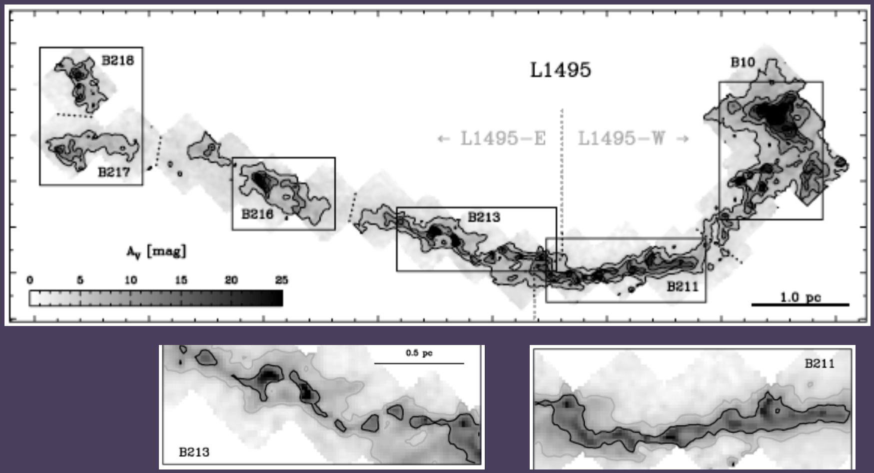


Alves et al 10

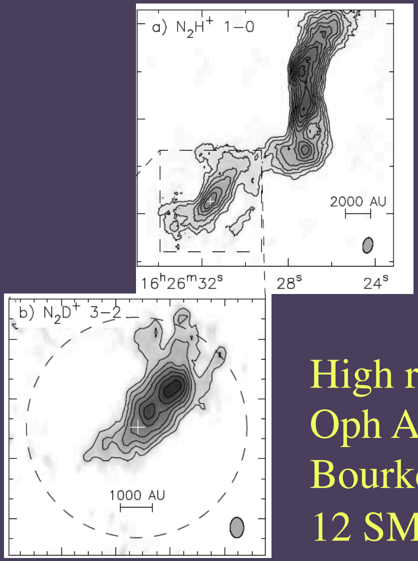
Morphological types--single filament (Nessie)
parallel filaments (G14.2-0.5)
network (Vela C South-Nest)
hub-filament (CrA). Clusters in hubs (M 09)

Cores in filaments

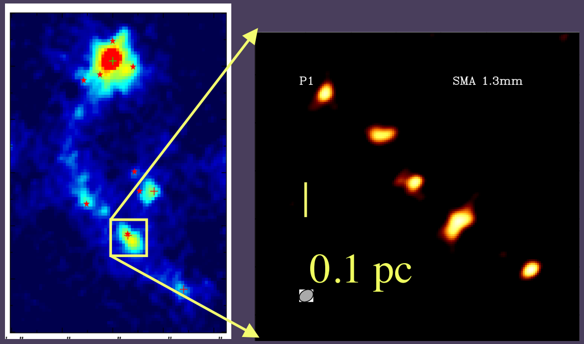
multiple cores, ~ regular spacing, many size scales, infall



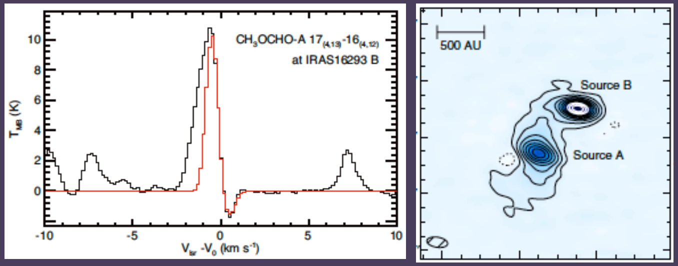
Taurus L1495 Schmalzl et al 10



High resolution
Oph A N6
Bourke et al
12 SMA



IRDC G28.34 Zhang et al 09   SMA

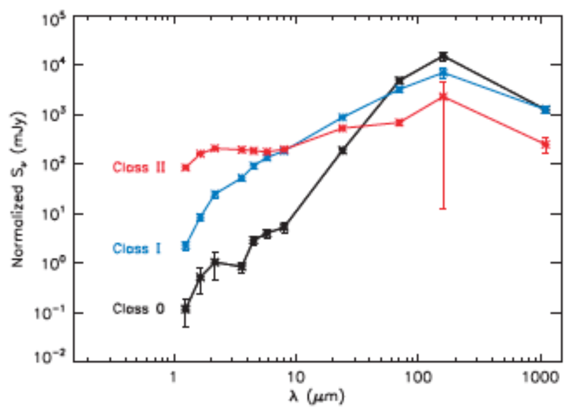


Small scale infall I16293B
Pineda et al 12 ALMA

Observing protostars

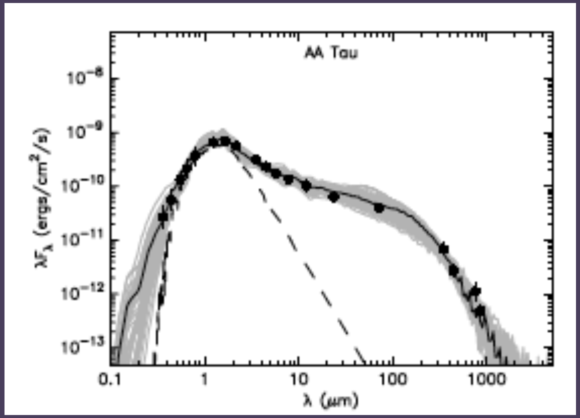
“protostar”	future star accreting gravitationally from a dense envelope
observing	2MASS, IRAS, Spitzer, Herschel, WISE...
classifying SED	by NIR slope (α), area (L_{bol}), shape (T_{bol})
fitting SED	radiative-transfer models (Robitaille et al 07)

S_ν (λ)



Enoch et al 09

λF_λ (λ)



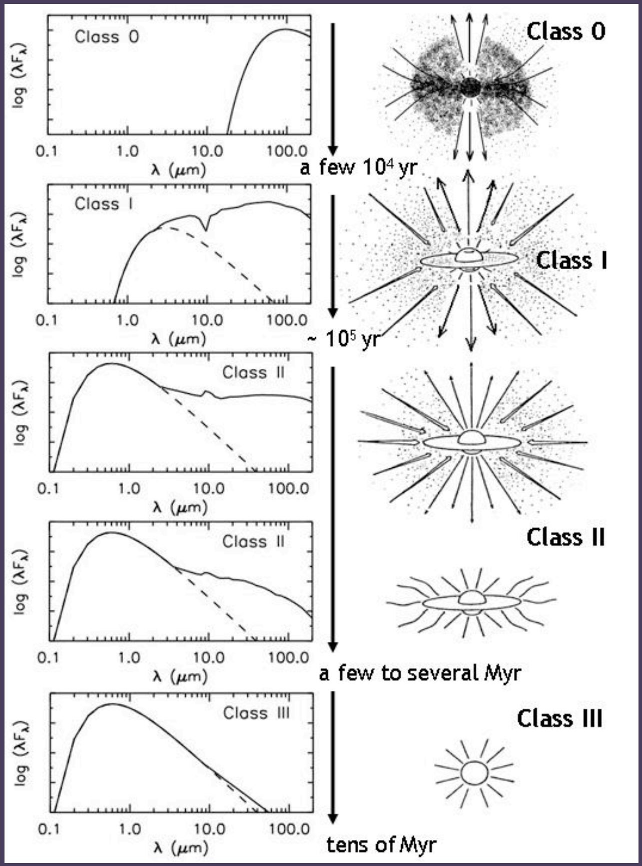
Robitaille et al 07

still missing	how fast do protostars gain mass? *(ALMA)*

Protostar evolution from population studies

Protostar spectra evolve as protostar accretes, core & disk disperse (Lada & Wilking 84, Adams et al 87)

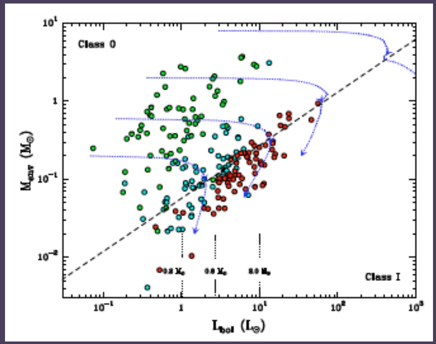
Spectral evolution



Furlan 13, Wilking 89, Shu et al 87

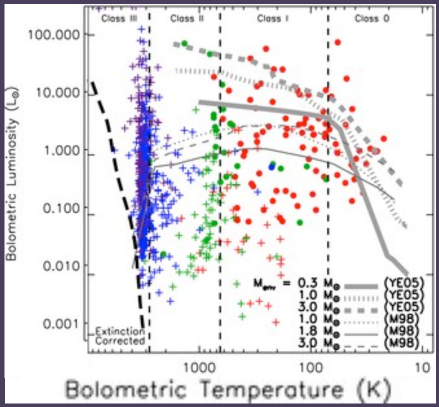
Population studies

M (L_{bol})



Aquila • Herschel • Bontemps et al 10

L_{bol} (T_{bol})

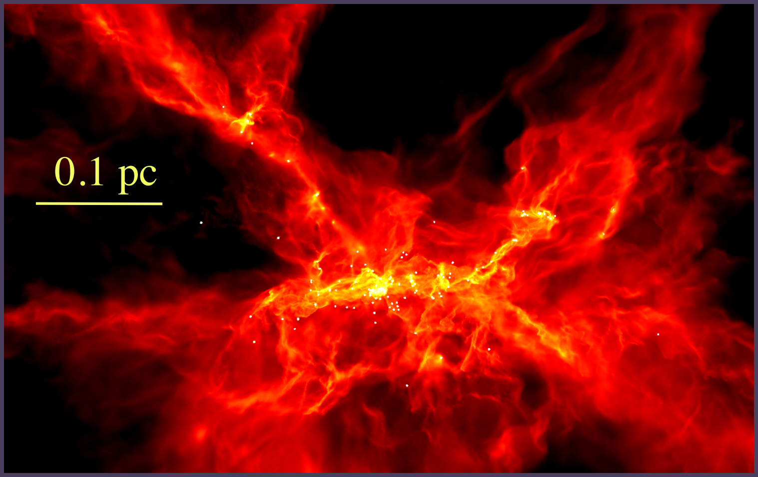


VELLOs
Dunham
et al 06

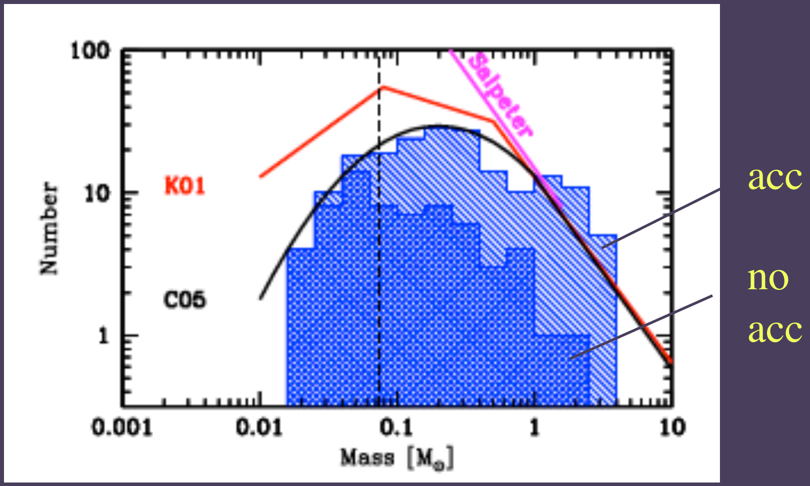
c2d • Spitzer • Evans et al 09

Simulating protostars

SPH turbulent fragmentation, 500 $M_\odot$ cloud makes 147 stars, 36 bds in 1.2 $t_{ff} = 0.23$ Myr.
Radiative heating feedback, ejection, exhaustion, no outflows, no $\boldsymbol{B}$. Bate 12



column density



mass function at $1.2t_{ff}$

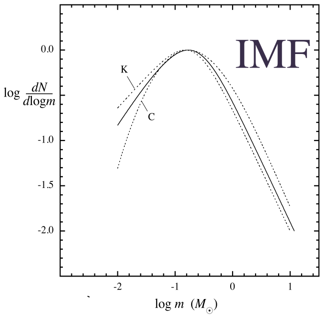
Pro – approximates cloud structure, IMF,
distribution of binaries

Con – artificial initial state, not enough
final masses, no B, no ionization,
no outflows

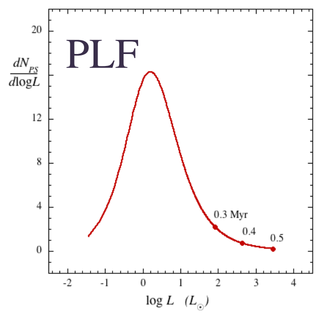
Also, Krumholz et al 12, Pudritz 10, Federrath & Klessen 12, Offner et al 09, Smith et al 09

Protostars and the IMF

As protostars approach IMF, observable PLF tests star formation models (MO 10, OM 11)



accretion model

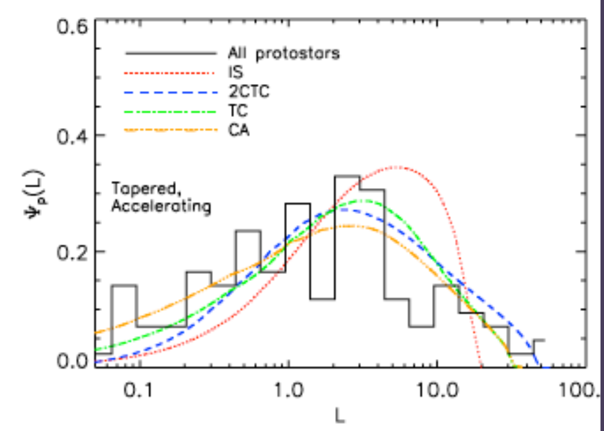


$$L = \frac{\varepsilon G m \dot{m}}{R} \qquad \dot{m} = \dot{m}(m)$$

$$\frac{dN}{d\log L} = PLF = \frac{MF}{1 + \frac{m}{\dot{m}} \frac{d\dot{m}}{dm}}$$

constant ε/R, accretion model $\dot{m}(m)$,
MF = IMF → PLF(accretion model)

dN/dlog*L*
(L)



low mass stars-- exclude IS, allow TC, CA, 2CTC, 2CCA - OM 11; Dunham & Vorobyov 12

Protostar models matching IMF

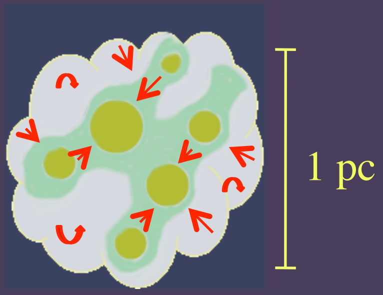
Accretion *(IMF)*	Competitive accretion	rate increases with m, competing with neighbors
	Stopped accretion	duration set by ejection, feedback, exhaustion
Fragmentation *(CMF → IMF)*	Gravo-turbulent	core formation by MHD shocks, weak B, lognormal λ_J
	Turbulent dispersion	turbulence compresses and disperses gas, Jeans collapse depends on scale

CA Zinnecker 82, Bonnell et al 01, Bate 12
GT Padoan & Nordlund 02

SA Adams & Fatuzzo 96, Basu & Jones 04, Myers 09-13
TD Jappsen et al 05, Hennebelle & Chabrier 08, Hopkins 12

Initial and final conditions model matches IMF

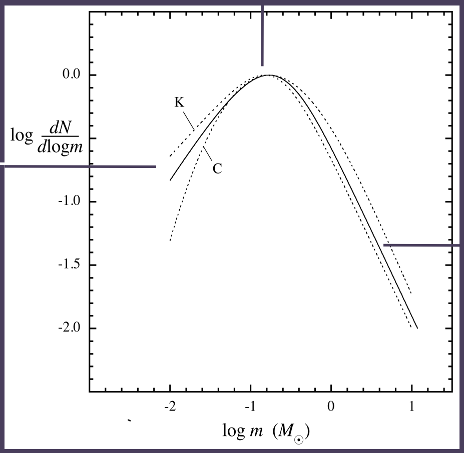
2CA accretion	thermal core in turbulent clump
equally likely stopping	ejections, stellar feedback
→ MF ≈ IMF	3 parameters initial & final conditions



$$\frac{dN}{d\log m} = \ln(10) N \Gamma (\mu/\nu)(\mu+\nu)^{-\Gamma}\ ,\quad \mu \equiv \frac{m}{m_0},\quad \nu \equiv (1+\mu^2)^{1/2},\quad \Gamma \equiv \frac{m_0}{\dot{m}_0 \tau_{stop}}$$

mass scale $m_0 \approx 0.2\ M_\odot$

slope = 1
due to
constant $\dot{m}_0$



when typical star-forming gas has $\tau_f = \tau_{stop}$

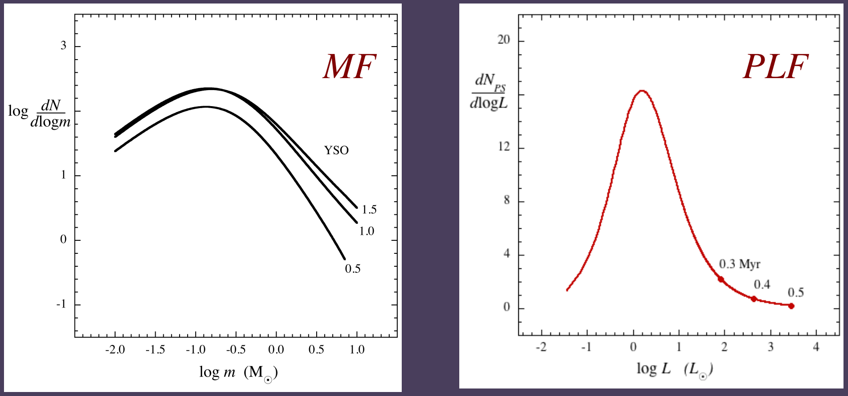
T (K)	$\bar{n}$ (10^4 cm^{-3})	ε	
10	8	1/3	nearby clouds
20	64	1/3	IRDCs

-slope $\Gamma = M(\mathrm{CIS})/M(\mathrm{SIS}) = 1.34$
$\Gamma \approx 1.35$ Salpeter slope
“universal” - independent of M, T, n

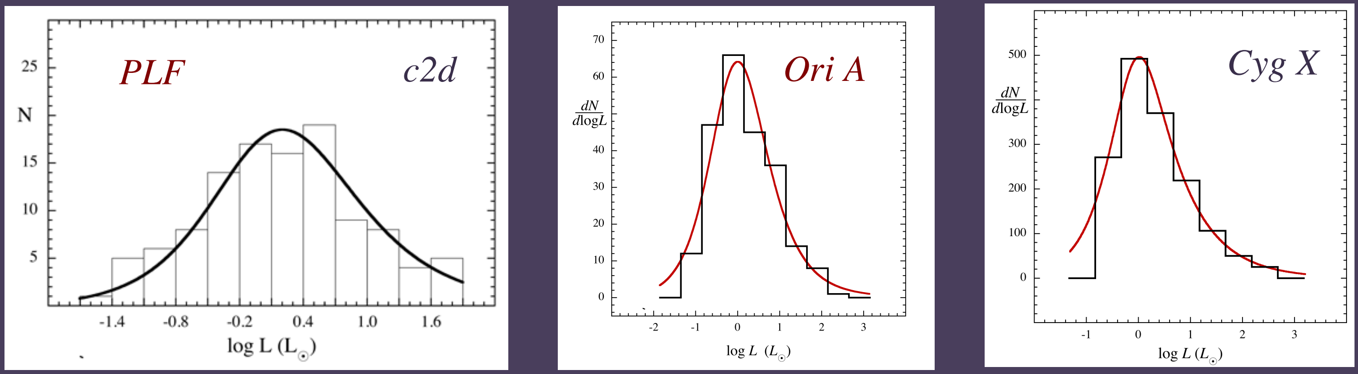
M12, 13

Initial and final conditions model matches PLFs

2CA model predicts evolution of MF, PLF *(cf.* McKee & Offner 10*)*



high-*m* and high-*L* tails grow as cluster evolves



model fits PLFs in c2d clouds, Orion A, and Cygnus X
(Evans et al 09, Dunham et al 10, Kryukova et al 12a,b; M12)

Summary

Protostars

form in cores in filamentary clouds

evolve by accreting, by dispersing core & disk

accrete at rates still to be measured (soon?)

test star formation models via their LFs

and…

Serpens South
Gutermuth et al 08

Thank you, Neal!

for your achievements, generosity, and leadership