Gould's Belt

Low-Mass Star Formation

Neal J. Evans II

with credit to

Mike Dunham, Lori Allen, Hyo Jeong Kim,
Amy Stutz

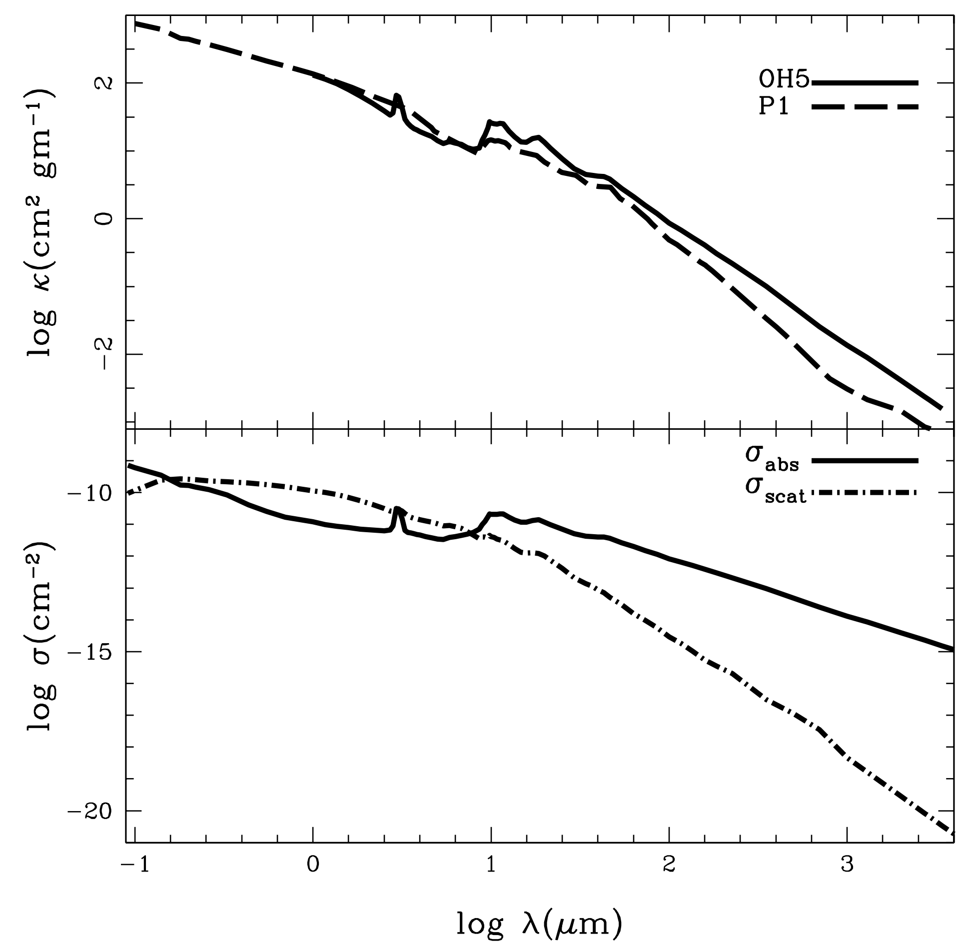
Star Formation Questions

- What determines the IMF?
- How long do various stages of the process take?
- Have we found the missing link?
- Do any theories explain the data?
- How are the star and disk built over time?
- What chemical changes accompany star formation?

What We Need

- The key is to have a large, uniform sample
- “Blind” surveys at range of wavelengths
- Complete coverage of the SED
    - Millimeter wave (mass and structure)
    - Far-infrared (energy for embedded stages)
    - Mid-infrared (disks)
    - Near-infrared (inner disk and star)
    - Visible, UV, X-ray (star and accretion)
- Spectroscopic diagnostics to follow up

Dust Controls Radiative Energy Flow



Dust opacity changes by orders of magnitude from uv-visible (stellar input) to FIR-SMM (where radiation escapes from dense regions). Scattering much less than absorption for λ> 10 microns. Energy is transferred by shifting to longer wavelengths.

Some Star Formation Surveys for Low-mass Stars

- Taurus Legacy project
  - Nearly complete survey of Taurus
- Cores to Disks (c2d) Legacy Project
  - Surveys of 7 nearby “large” clouds and many small ones
  - Complementary molecular line and dust continuum maps
- Gould Belt Legacy Project
  - Surveys of 13 nearby “large” clouds to complete census
- Herschel Surveys (partially analyzed)
  - Gould Belt Herschel Survey
  - Herschel Orion Protostar Survey (HOPS)
  - Dust, Ice, and Gas In Time (DIGIT)
  - Water In Star-forming regions with Herschel (WISH)
- JCMT Gould Belt survey (SCUBA2, lines; in progress)
- WISE data base

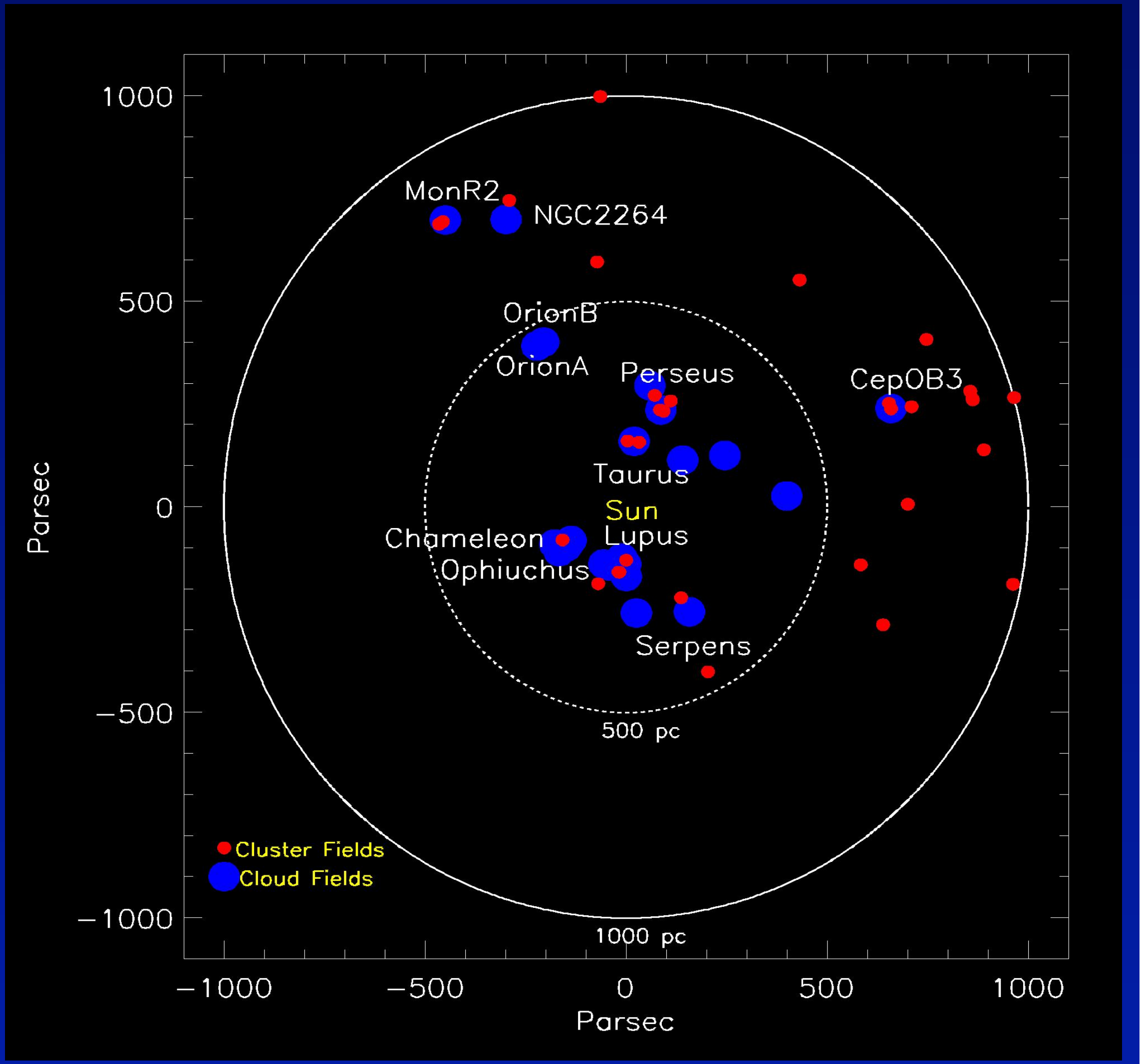
Surveys of Nearby Clouds and Clusters

20 nearby molecular clouds (blue circles)

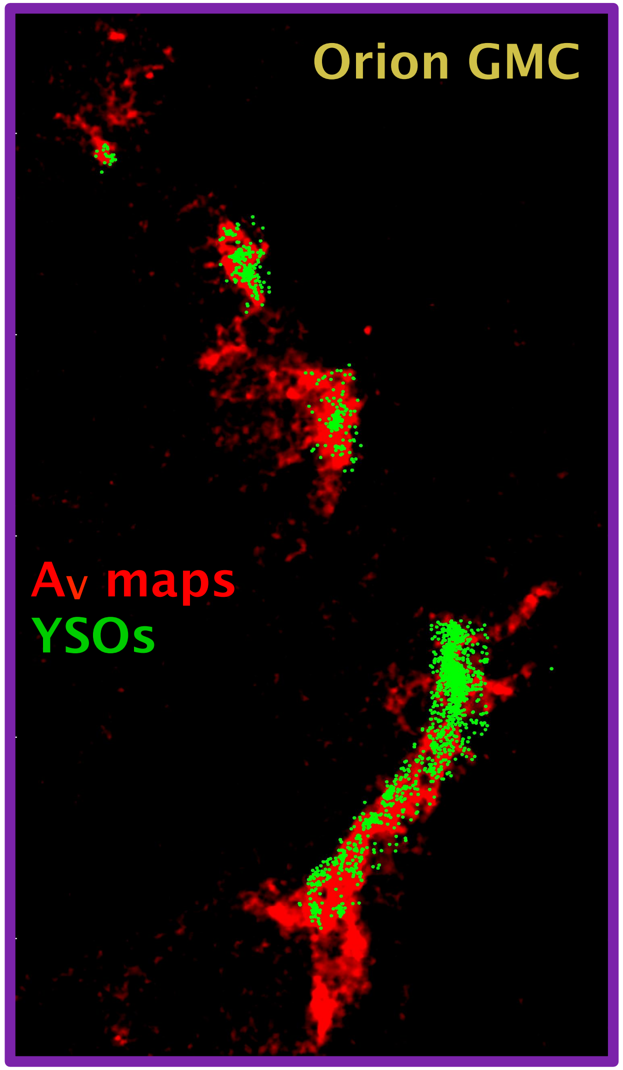
35 young stellar clusters (red circles)

90% of known stellar groups and clusters *within 1 kpc* (complete to ~ 0.1 M_{Sun})

+ Several massive sf complexes at 2-3 kpc (complete to ~1.0 M_{Sun})

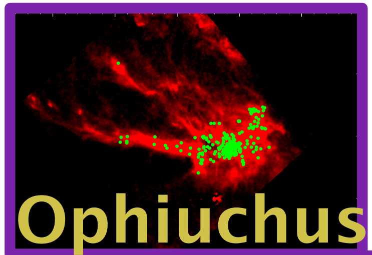


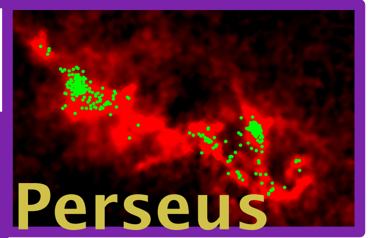
Infrared surveys (I):
The c2d, Gould Belt, Taurus, and Orion surveys

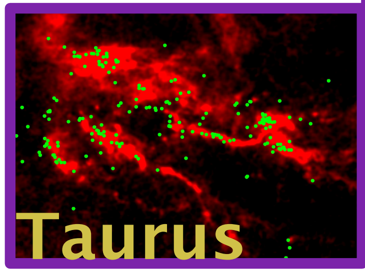


Figures from S.T. Megeath, unpublished

- From Molecular Cores to Planet-Forming Disks (**c2d**):
  7 clouds
  Evans et al. (2009)
- *Spitzer* Gould Belt (**GB**):
  11 additional clouds
  Dunham et al. (2013)
- *Spitzer* Taurus Survey:
  Rebull et al. (2010)
- *Spitzer* Orion Survey:
  Megeath et al. (2012)
- *Herschel* Orion Protostar Survey (**HOPS**):
  Fischer et al. (2013); Manoj et al. (2013);
  Stutz et al. (2013); PACS imaging at 70 and 160 μm of 300+ protostars and PACS spectroscopy of 33 targets







Figures from S.T. Megeath, unpublished

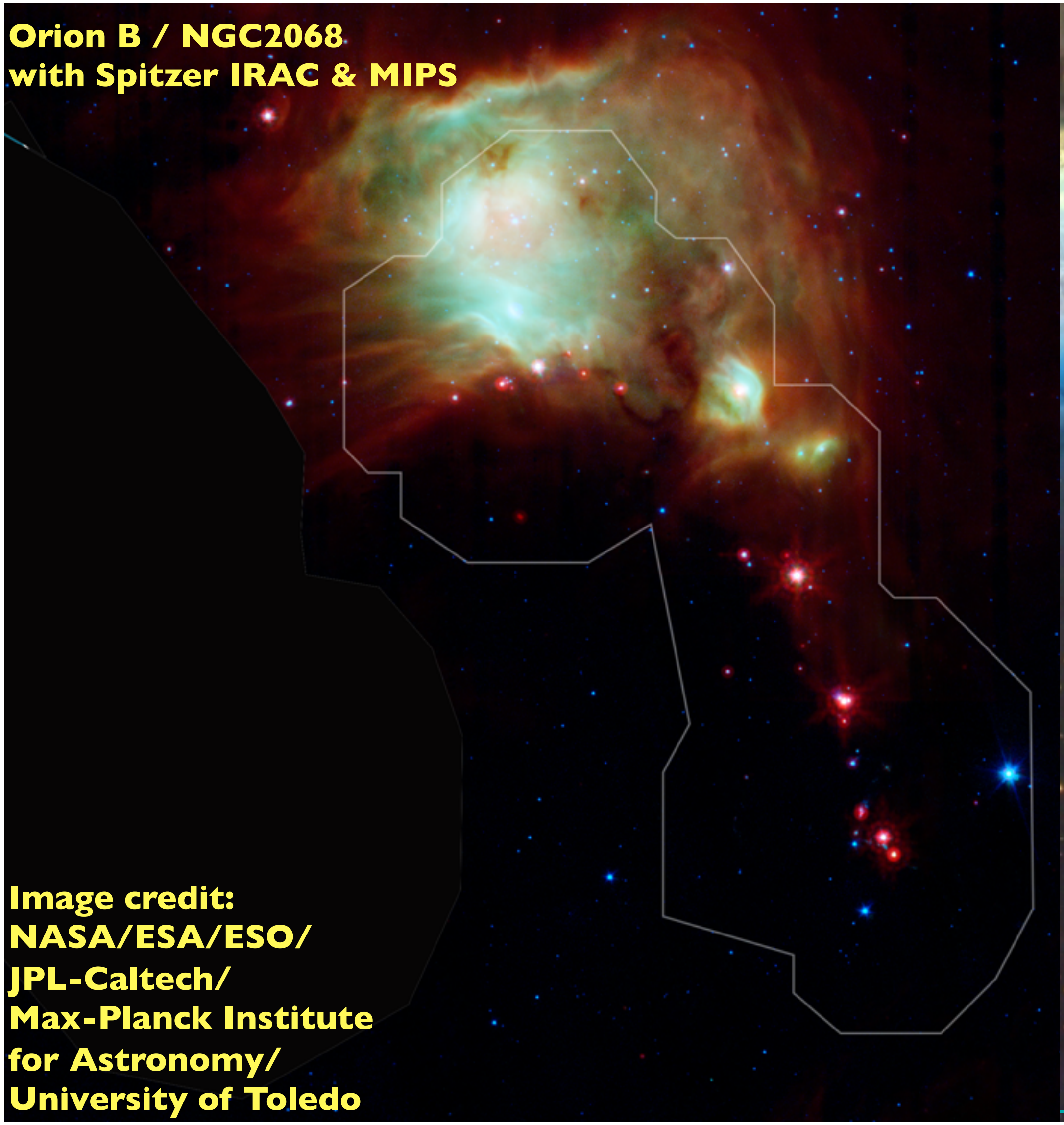
More than 6000 YSOs in total
More than 586 Protostars in total

All slides like this from Stutz, PPVI

Protostars revealed by infrared surveys

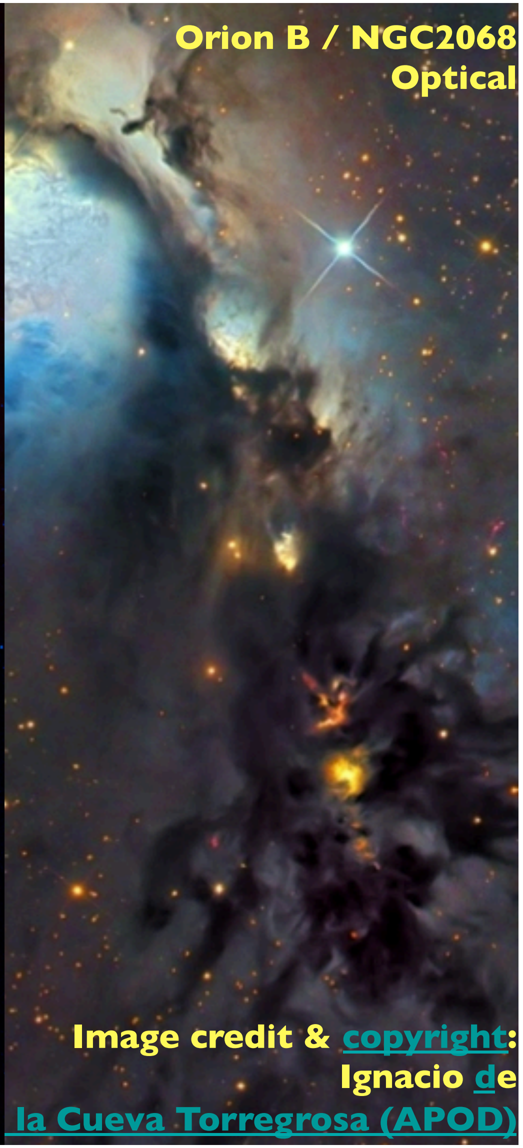
Image credit & copyright: Ignacio de la Cueva Torregrosa (APOD)

Protostars revealed by infrared surveys



Orion B / NGC2068
with Spitzer IRAC & MIPS

Image credit:
NASA/ESA/ESO/
JPL-Caltech/
Max-Planck Institute
for Astronomy/
University of Toledo



Orion B / NGC2068
Optical

Image credit & copyright:
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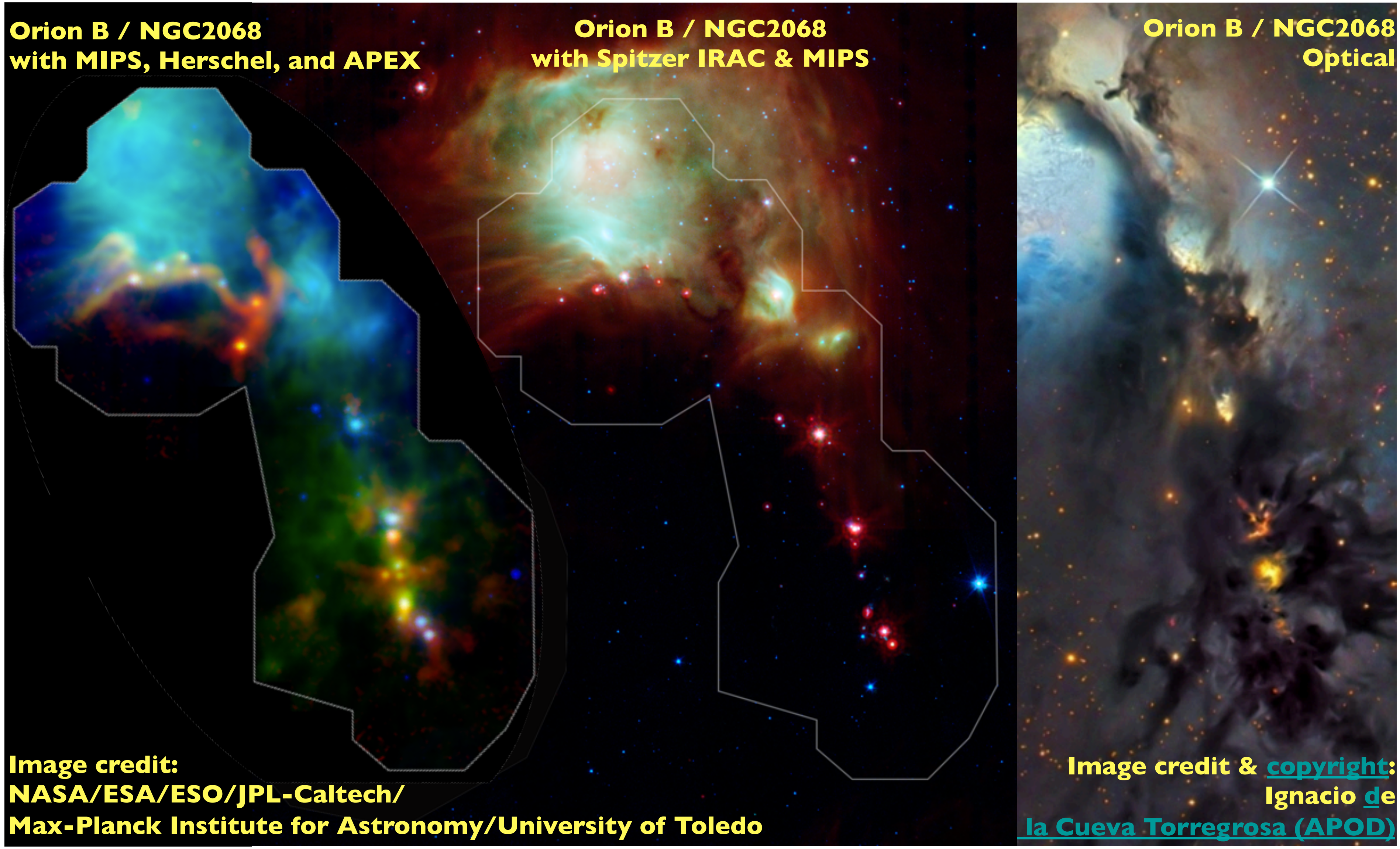
Protostars revealed by infrared surveys



Orion B / NGC2068
with MIPS, Herschel, and APEX

Orion B / NGC2068
with Spitzer IRAC & MIPS

Orion B / NGC2068
Optical

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NASA/ESA/ESO/JPL-Caltech/
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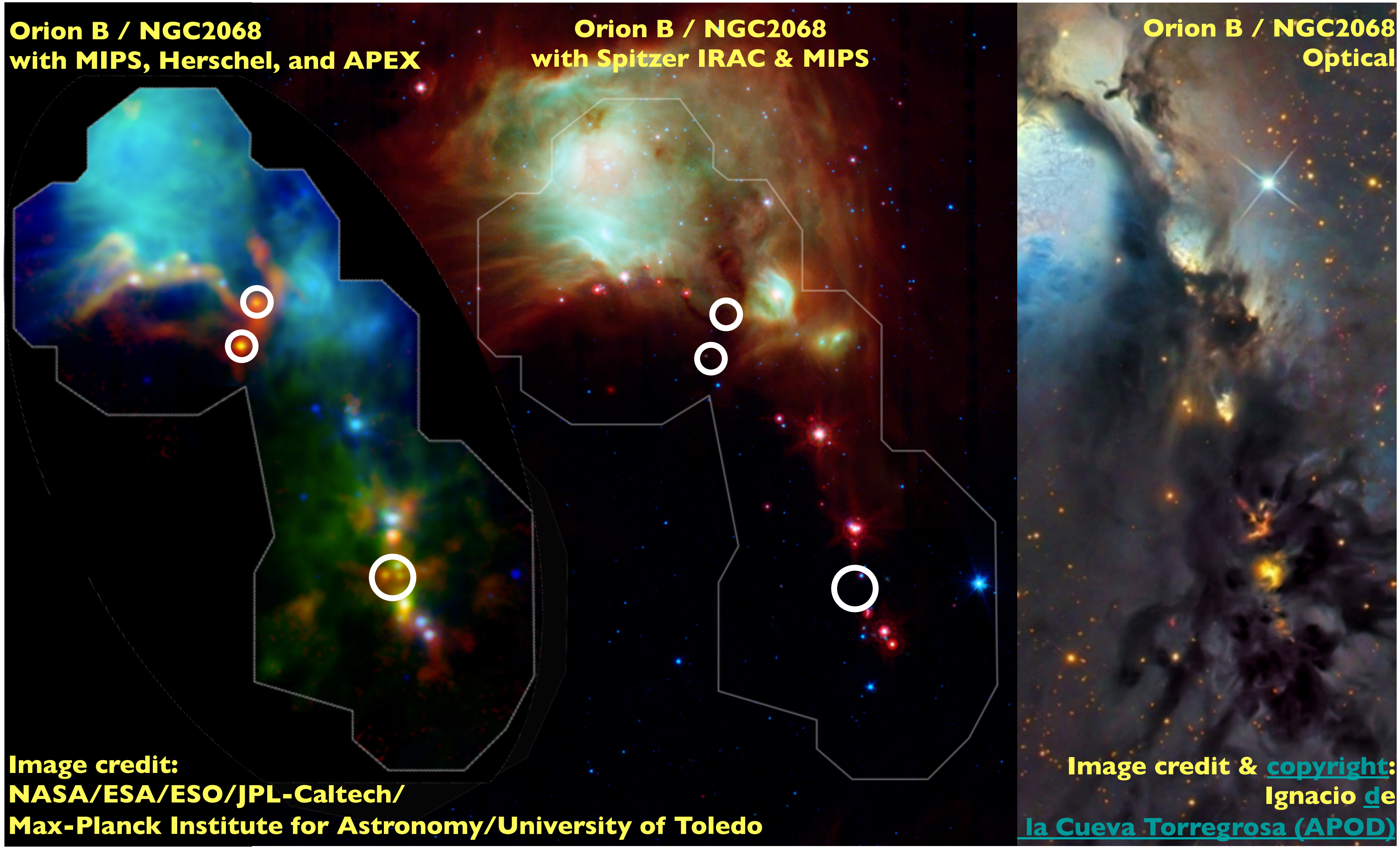

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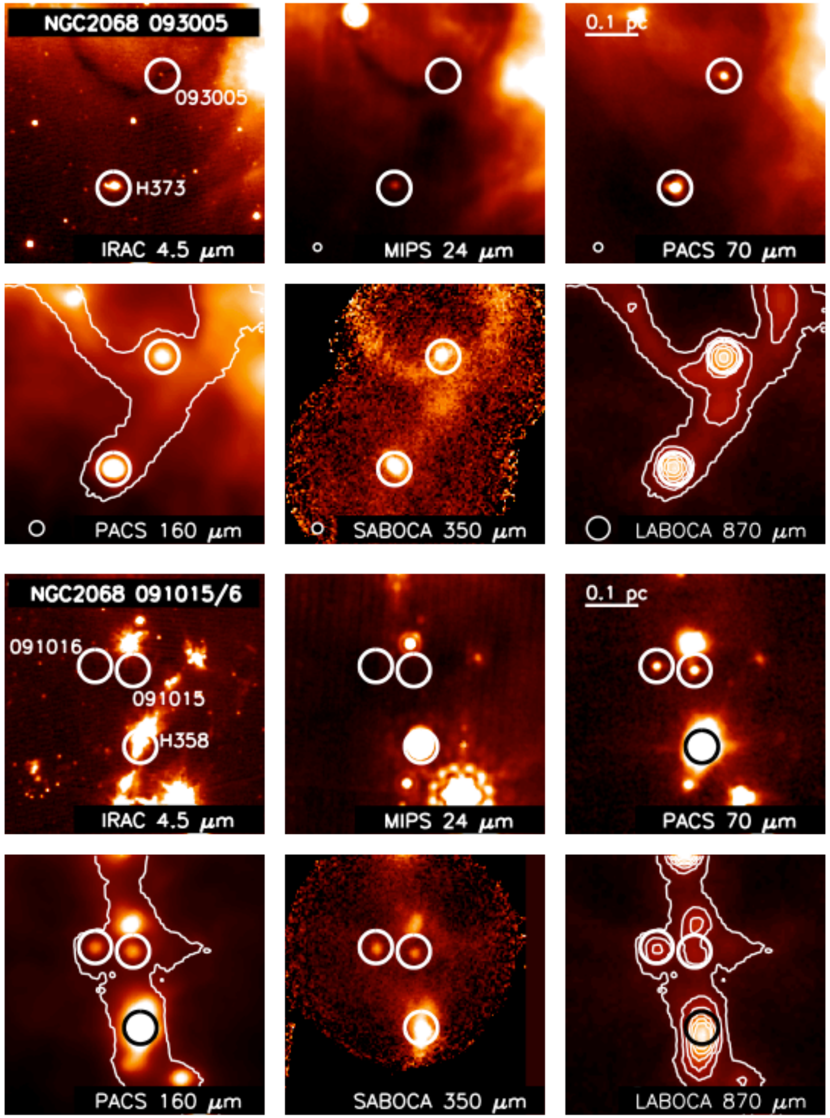
HERSCHEL ORION PROTOSTAR SURVEY

PACS Bright Red Sources *(PBRS)*

Pacs Bright Red SOURCES

Observationally selected sample of 18 reddest sources in Orion, 15 discovered by *Herschel* (Stutz et al., 2013).

Adds about 5% to the count of protostars, but some of the most embedded



See also Ragan et al. (2012) for "MIPS dark" sources in IRDCs.

Figures from Stutz et al., 2013, ApJ, 767, 36

Some Nomenclature

- Core
    - Birthplace of star, binary, multiple
    - Dense, “round”, centrally condensed
- Clump
    - Birthplace of group, cluster of stars
    - Filamentary, structured, maybe centrally condensed
- Cloud
    - Defined by contour of extinction or molecular line
    - Windswept, “cirrus-like”
    - May contain multiple clumps

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The Initial Mass Function

- **Distribution of Stars over mass**
  - **The “Initial Mass Function” (IMF)**
  - **For high masses, $dN/dM \sim M^{-2.4}$**
  - **Flattens below 1 M_{sun} and rolls over below 0.2 M_{sun}**
- **We can constrain Core Mass Function**
  - **3 Clouds with Bolocam maps**
  - **Starless cores only**
  - **Masses from 1 mm dust**
  - **Absolute uncertainties substantial**
  - **But shape is not as sensitive**

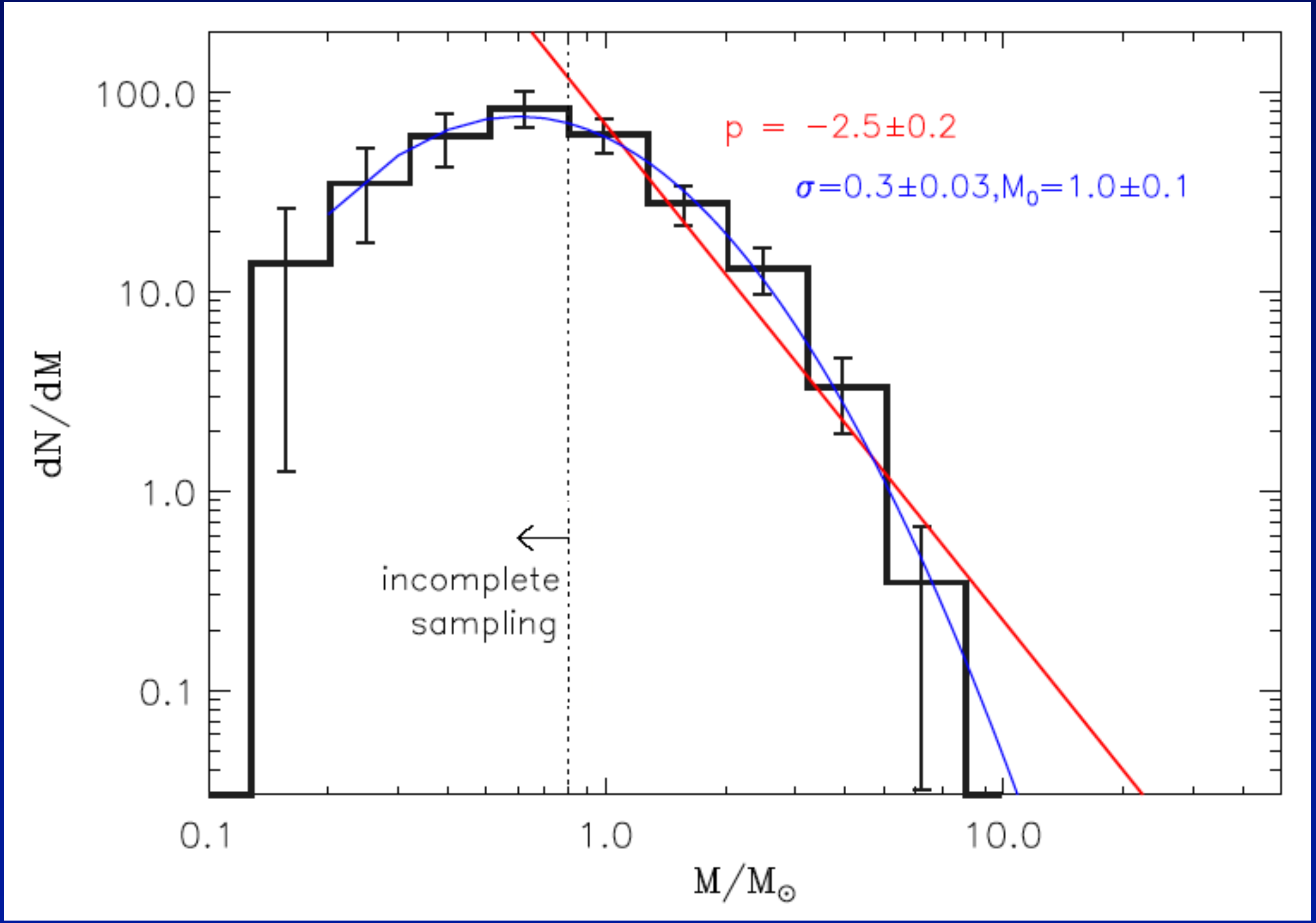
Combined starless core mass distribution

Masses:

$T_D = 10K$

$\kappa_\nu = 0.0114\ cm^2/g$

- Best fit power law: p ~ 2.5 or Lognormal
- IMF:
  Salpeter (p~2.4)
  Chabrier 03
  (p~2.7 M>1M$_\odot$)



⇒ “Not inconsistent” with a scenario in which stellar masses are determined during core formation. If so, >25% goes into star.

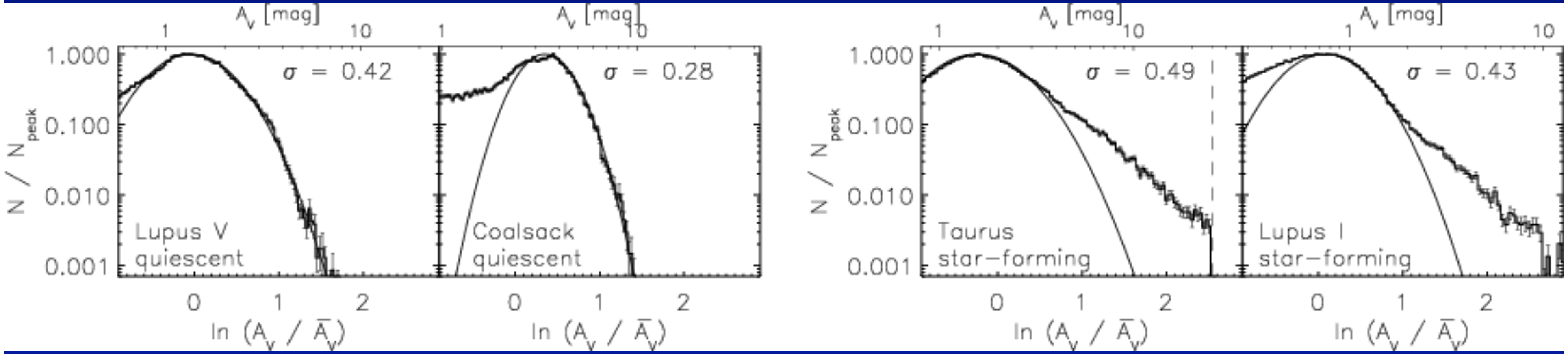
Enoch et al. 2008

Related Work

- Motte et al. 1998 pioneering study
- Alves et al. 2007
  - Turn-over at mass ~3 x turnover in IMF
- Sadavoy et al. 2010 more clouds
  - Found slopes consistent with Salpeter, but some possible differences
- Expect major progress from Herschel
  - Papers on individual sources, but no summary yet
- Caveats
  - Further fragmentation, timescales(M), …

Relation to PDF?

- Observations probe column density PDF
- Lognormal only at low extinctions
- Clouds forming stars deviate from lognormal



Not forming stars

Forming stars

Kainulainen et al. 2009

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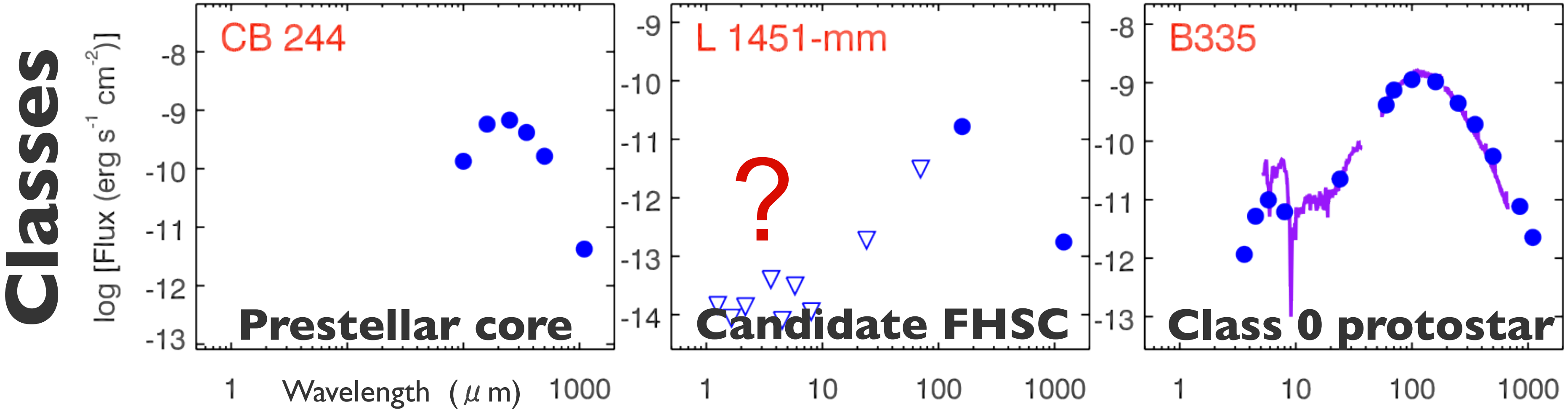
Evolution

- Various Stages in the evolution
  - Associated with Classes based on SED
- Durations in Classes inferred from numbers
- Previous studies based on small numbers
  - Typically 50 to 100 objects
  - Fewer in early classes
  - Estimates of durations differed by large factors

All SEDs from
Dunham et al. (2013),
PPVI review chapter

Standard evolutionary scenario

single isolated low-mass star



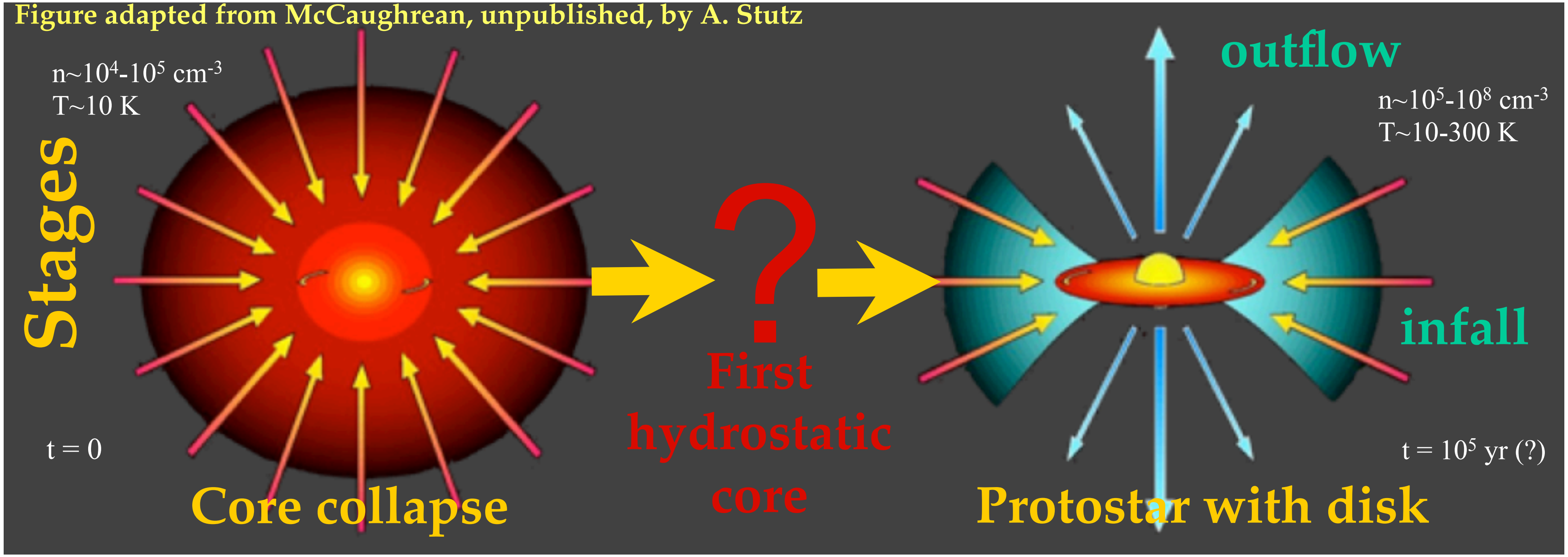


Figure adapted from McCaughrean, unpublished, by A. Stutz

SEDs from
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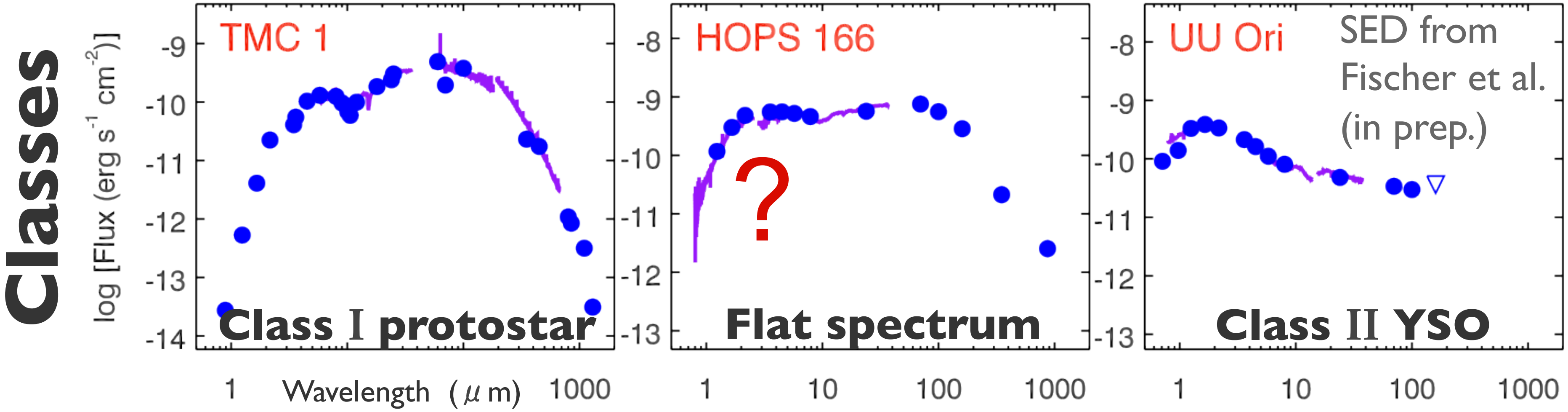

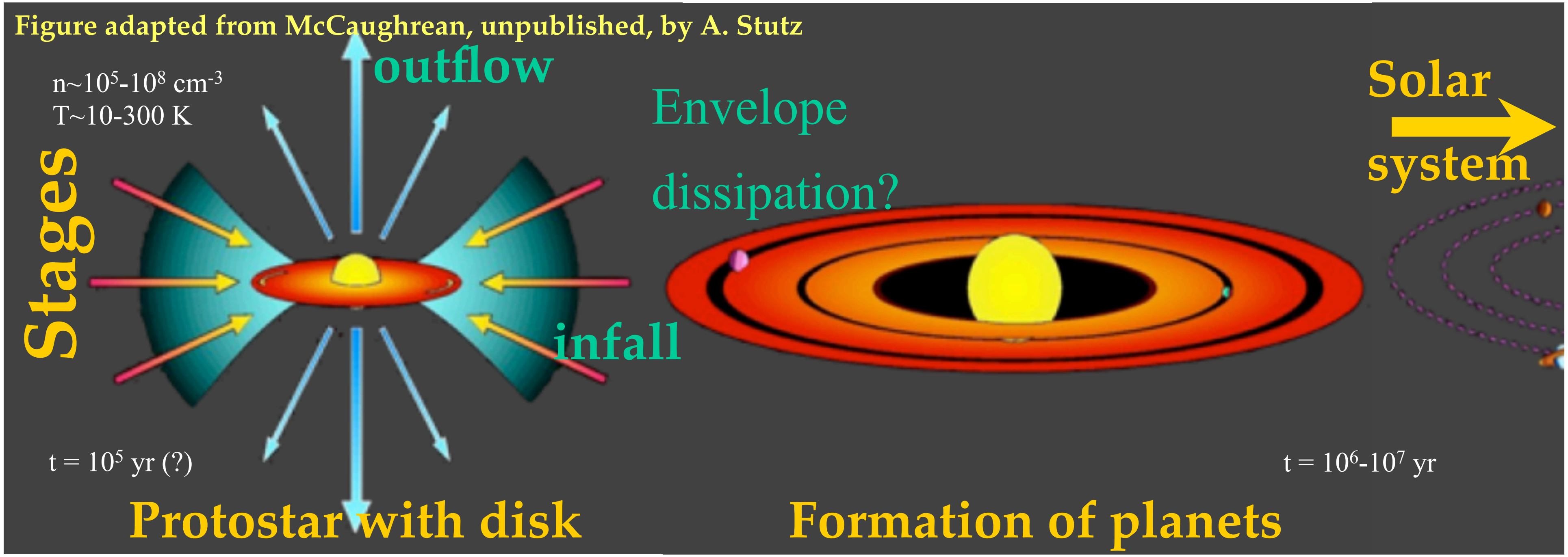
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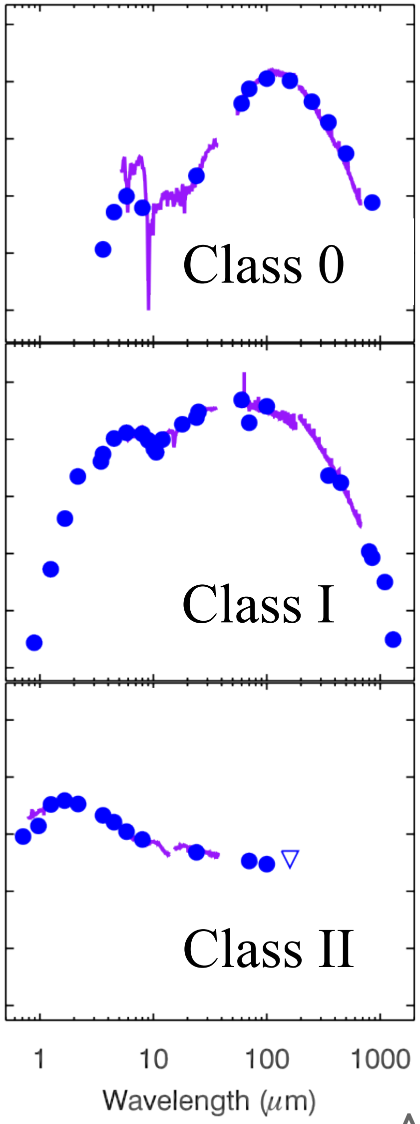
How do we classify protostars?

Based on the shape of the observed SED



$$\alpha = \frac{d\log(\lambda S_\lambda)}{d\log\lambda}$$

Class 0
$L_{SMM}/L_{BOL} > 0.5\%$
$T_{BOL} \leq 70$ K

Class I
$\alpha \geq 0.3$
70 K < $T_{BOL} \leq 670$ K

Flat
$-0.3 \leq \alpha < 0.3$

Class II
$-1.6 \leq \alpha < -0.3$
670 K < $T_{BOL} \leq 2800$K

Class III
$\alpha < -1.6$
$T_{BOL} > 2800$ K

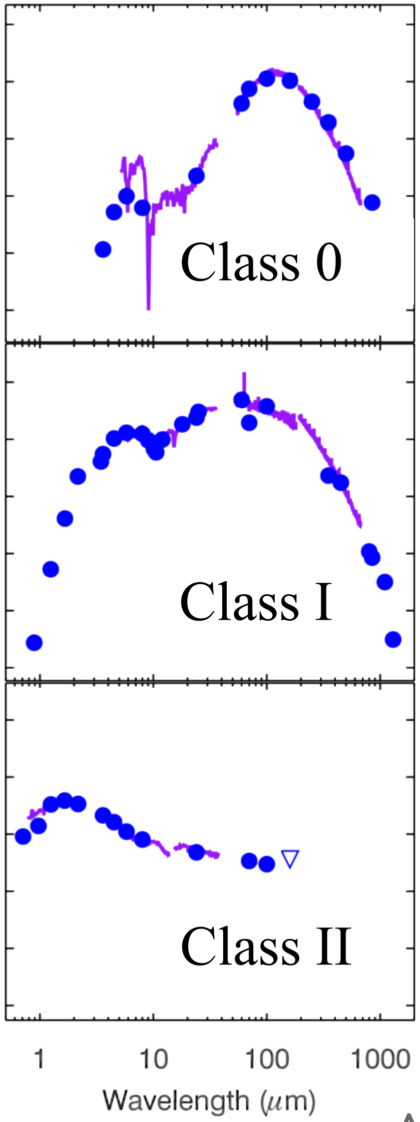
★SED slope (α method): original criteria for Classes (Lada 1987; Greene et al., 1994)

★L_{SMM}/L_{BOL}: added later to identify Class 0 (Andre et al., 1993, also Maury et al., 2011)

★ Bolometric temperature (Myers & Ladd, 1993): the temperature of a black body with the same flux weighted mean frequency as the observed SED (see also Greene et al., 1994).

All SEDs from Dunham et al. (2013), PPVI review chapter

How do we think they evolve?



ENVELOPE EVOLUTION?

Class 0
$L_{SMM}/L_{BOL} > 0.5\%$
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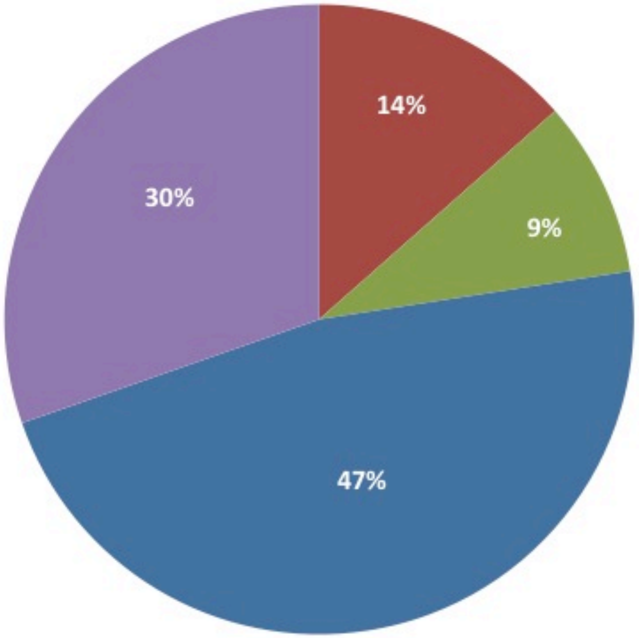
All SEDs from Dunham et al. (2013), PPVI review chapter

Timescales for Classes



I: $\alpha \geq 0.3$

Flat: $-0.3 \leq \alpha < 0.3$

II: $-1.6 \leq \alpha < -0.3$

III: $\alpha < -1.6$

IF time is the only variable
AND
IF star formation continuous
for t > t(II)
THEN

t(Class) = t(II)*N(class)/N(II)

Caveats:

Class III census incomplete

Class III not included in timescale

Depends on how α is calculated

Class 0 mixed with Class I

t(II) may be longer; this was based on half life of IR excess in clusters, but stellar ages may be longer (PPVI)

Numbers of YSOs and lifetimes

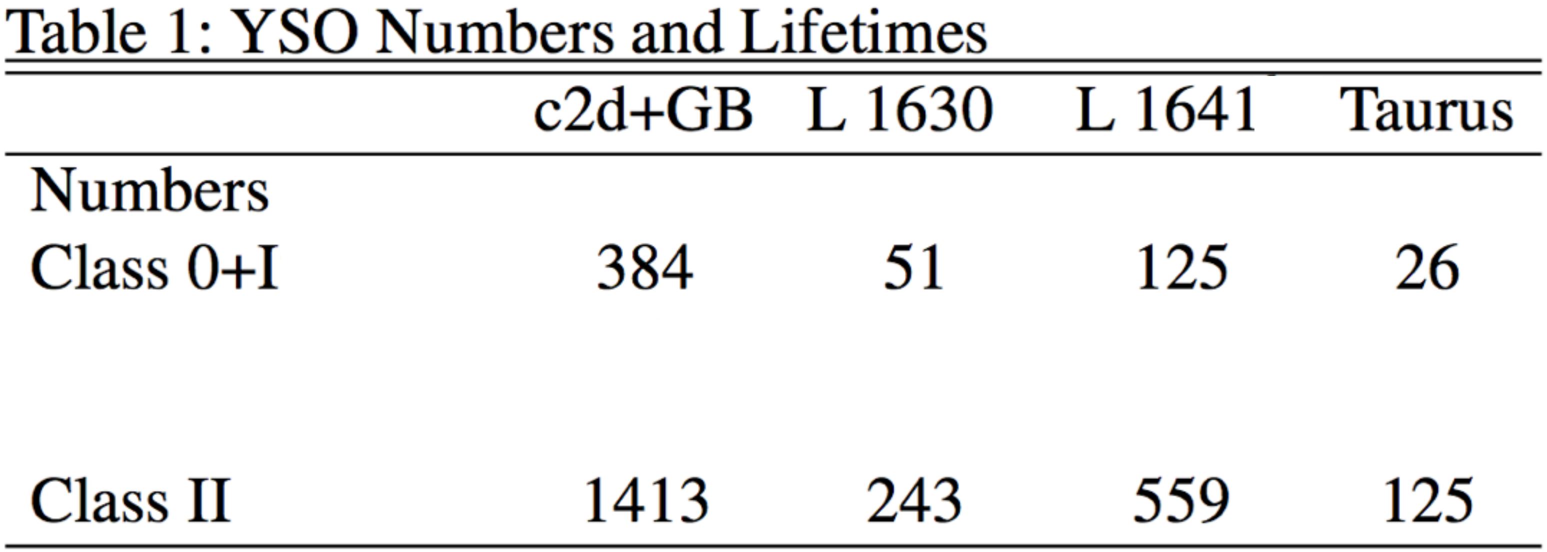


Table 1: YSO Numbers and Lifetimes

	c2d+GB	L 1630	L 1641	Taurus
Numbers				
Class 0+I	384	51	125	26
Class II	1413	243	559	125

Average half-life of Class 0+I: 0.42 to 0.54 Myr

assuming a 2 Myr Class II half-life

Table from Dunham et al., 2013, PPVI review chapter

Separating Class 0 from I

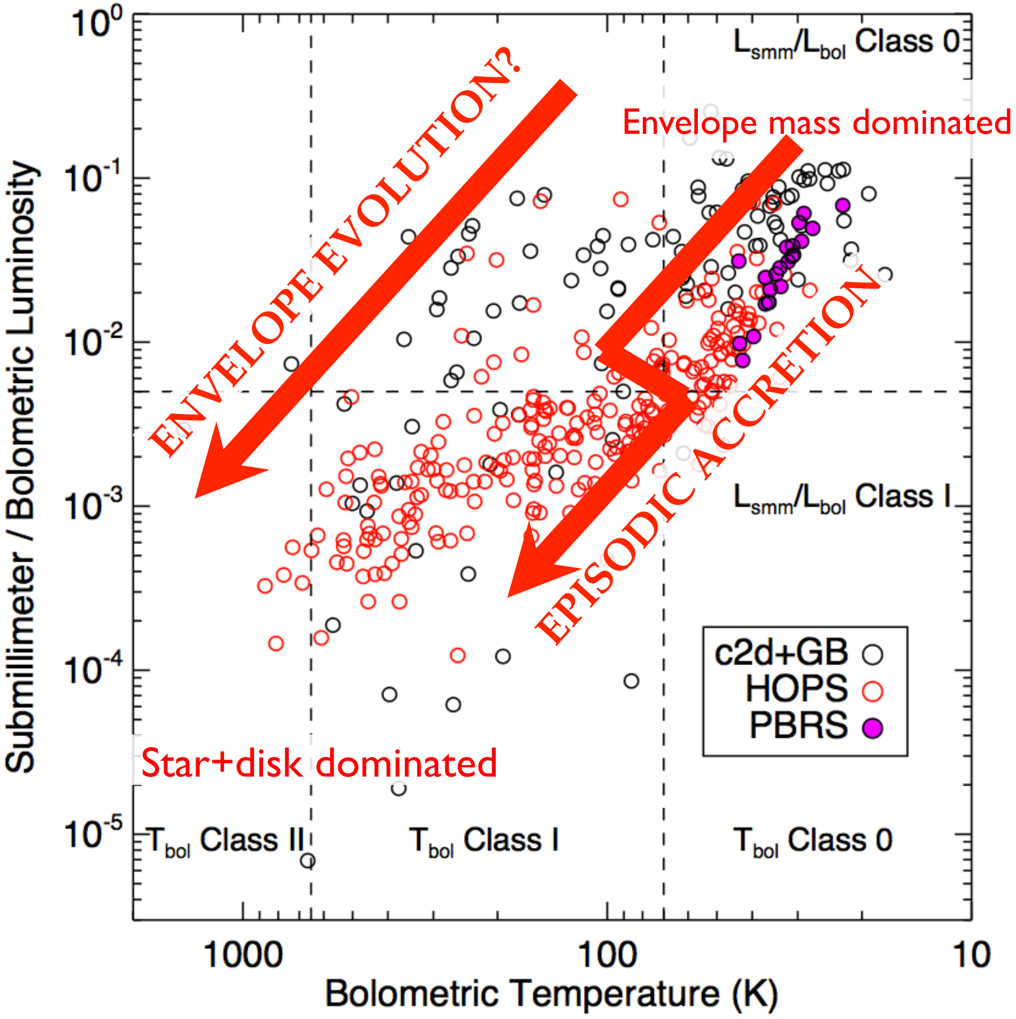


Figure from Dunham et al. (2013), PPVI review chapter

Both T_{BOL} and the ratio of the sub-millimeter (L_{SMM} ≥350 μm) to bolometric luminosity *should* trace envelope evolution in protostars.

L_{SMM}/L_{BOL} and T_{BOL} agree in ~ 84% of the cases.

T_{BOL} is subject to major geometry (including inclination) degeneracies.

Models suggest L_{SMM}/L_{BOL} is a better evolutionary tracer than T_{BOL} (Young and Evans, 2005; Dunham et al., 2010)

Caveat: episodic accretion may lead to non-monotonic evolution

Splitting Class 0 and Class I

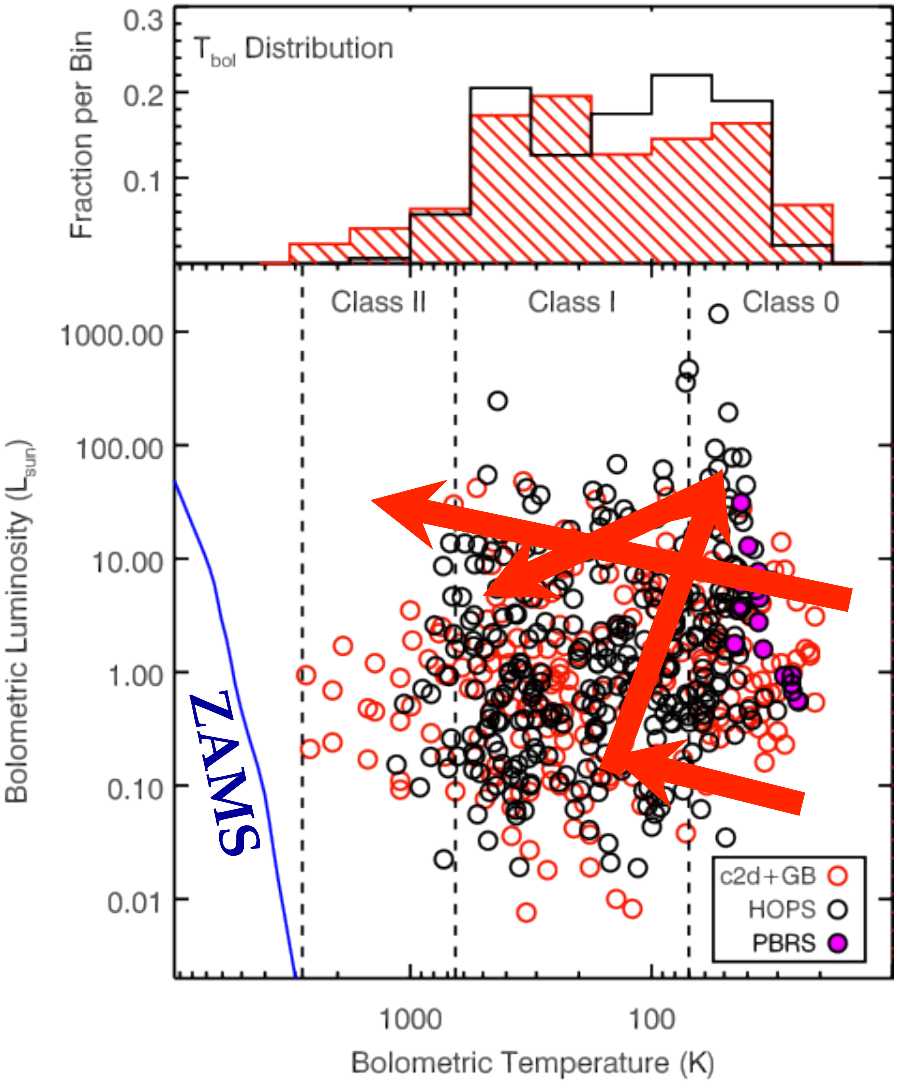


Figure from Dunham et al. (2013), PPVI review chapter

Class 0 fraction: 30%
Class 0 lifetime: 0.15 Myr
relative to the Class 0+I
lifetime of 0.5 Myr

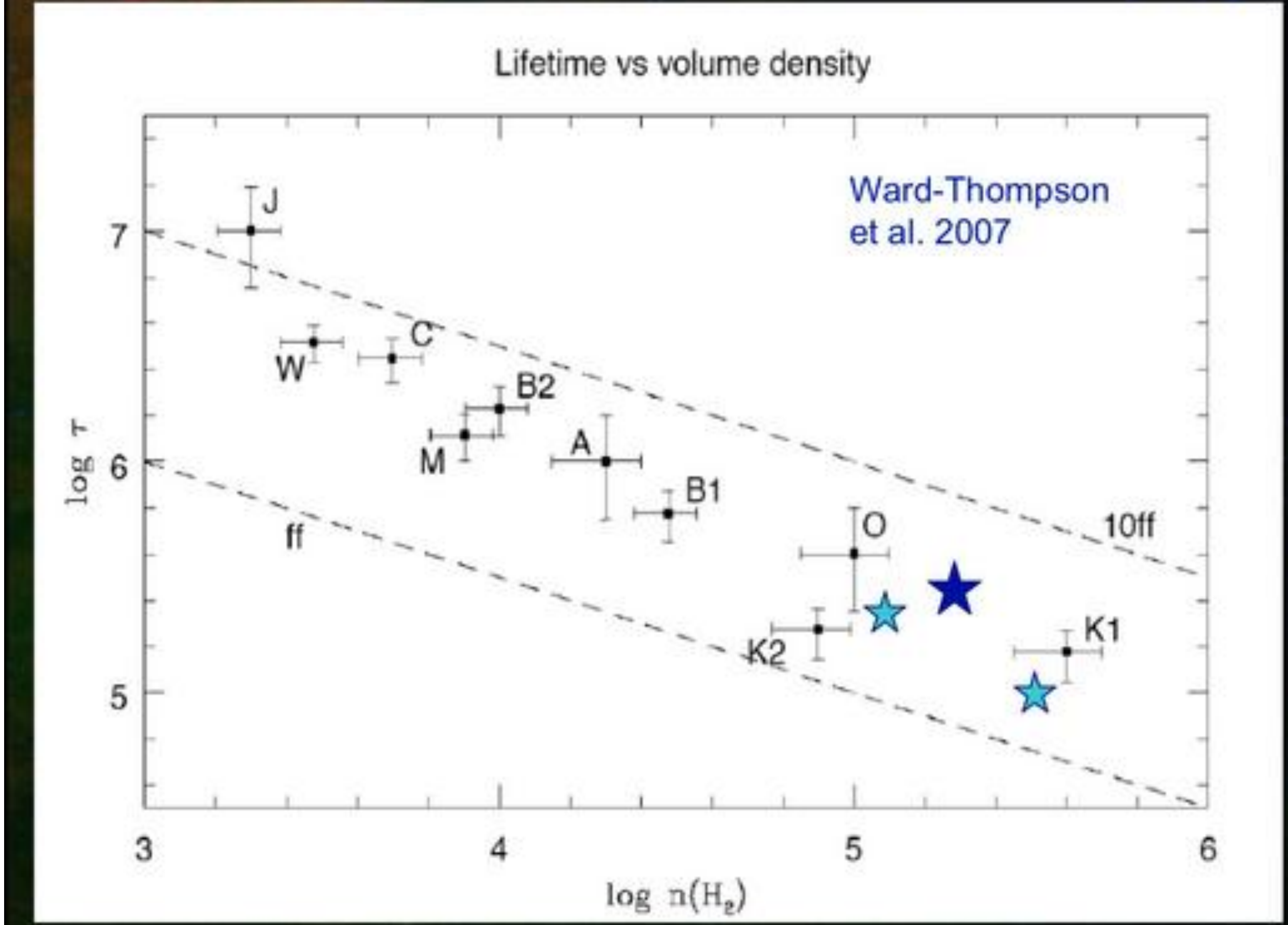
Using T_{bol} definition; would be longer if use L_{smm}/L_{bol}

If Class 0 ~ Stage 0 ($M_{env} > M_{star}+M_{disk}$) argues for decreasing mean accretion rate.

Timescales for Prestellar stages

- N(PS) = 0.8 N(0+I), so t(PS) ~ 0.43 Myr
  - After <n> > 2 x 10^4 cm^{-3}
  - t(PS) ~ 3 t_{ff}; between predictions of fast and slow
  - Enoch et al. 2008

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

Enoch et al. 2008

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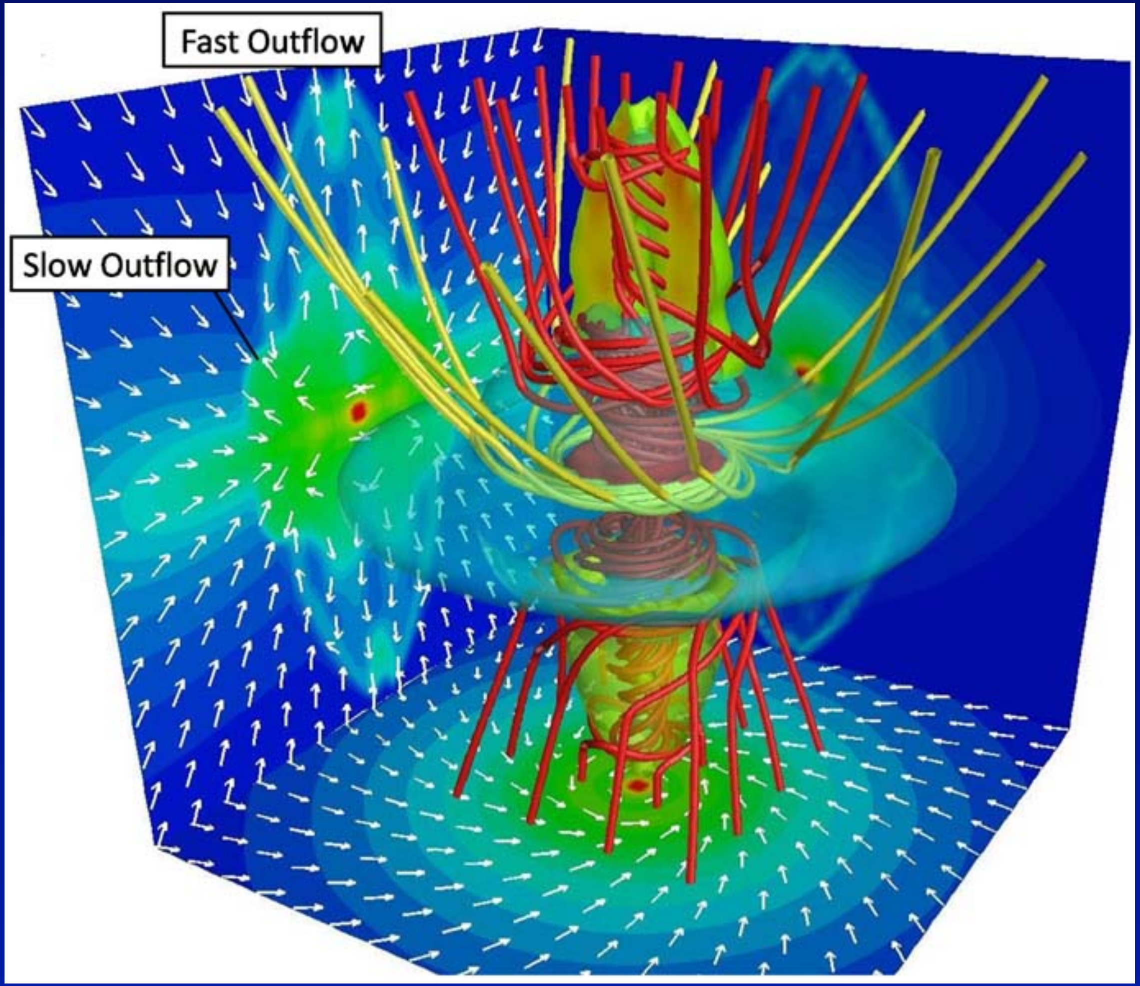
The First Hydrostatic Core (Stage -1?)

- Long predicted phase of star formation
  - Larson (1969)
- The FHSC is an H_2 core
  - Contracts slowly until H_2 dissociates (2000K)
  - Then the second (protostellar) core forms
- Had never been seen
- Short duration, very low luminosity

First Core in Theory



First Core 500 yr after formation.
“Fast flow” (2km/s) driven by magnetic pressure (weak fields)
“Slow flow” driven by magneto-centrifugal force (strong fields) carries 10x more mass and ang. mom.

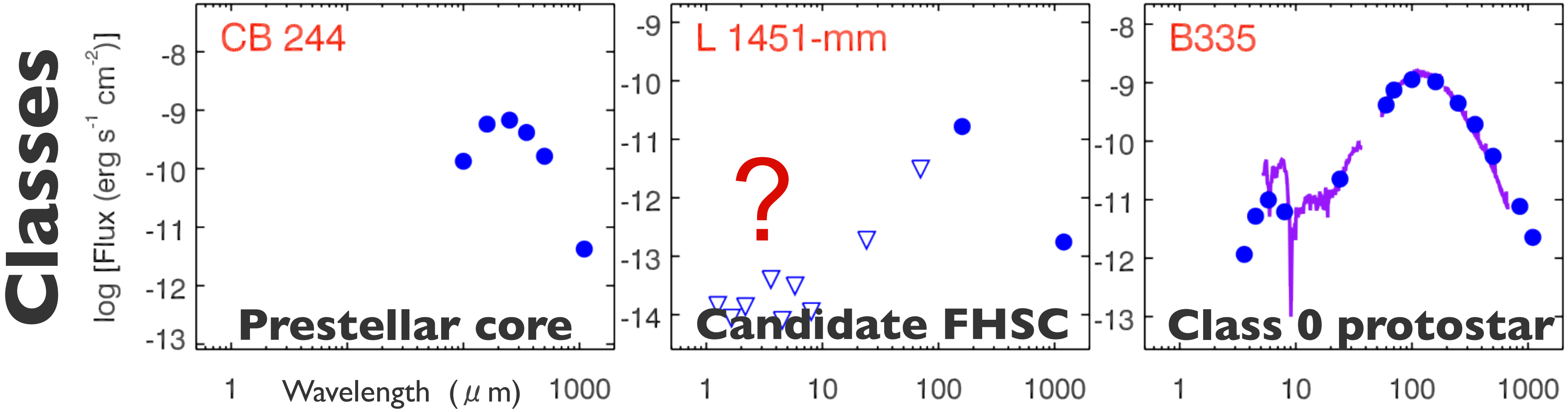
Tomida et al. 2010

Predictions of Observables

- Boss and Yorke (1995) predicted SED
  - Distinguished from prestellar core by slight excess in FIR ($L < 0.1\ L_{sun}$)
- Omukai (2007) lifetime is short (but uncertain)
  - 10^3 to 3×10^4 yr
  - Expect one per 540 to one per 18 Class 0/I
  - Zero to 8 in c2d sample, Zero to 23 in GB

All SEDs from
Dunham et al. (2013),
PPVI review chapter

Standard evolutionary scenario
single isolated low-mass star



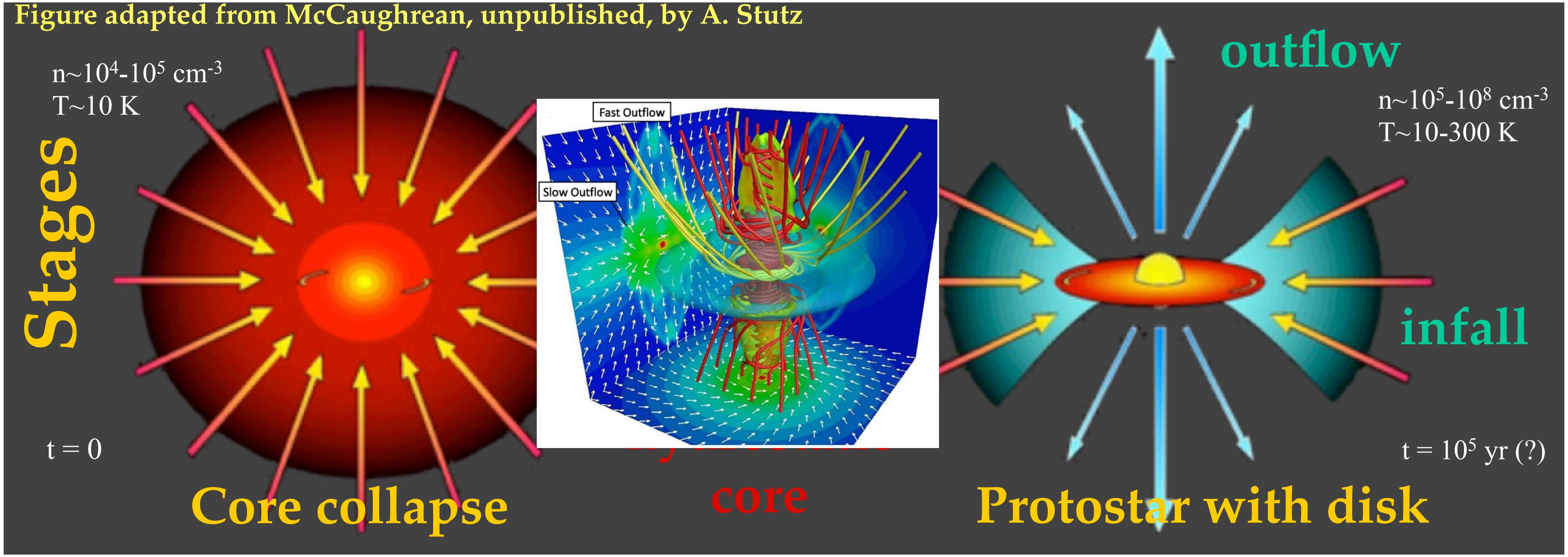
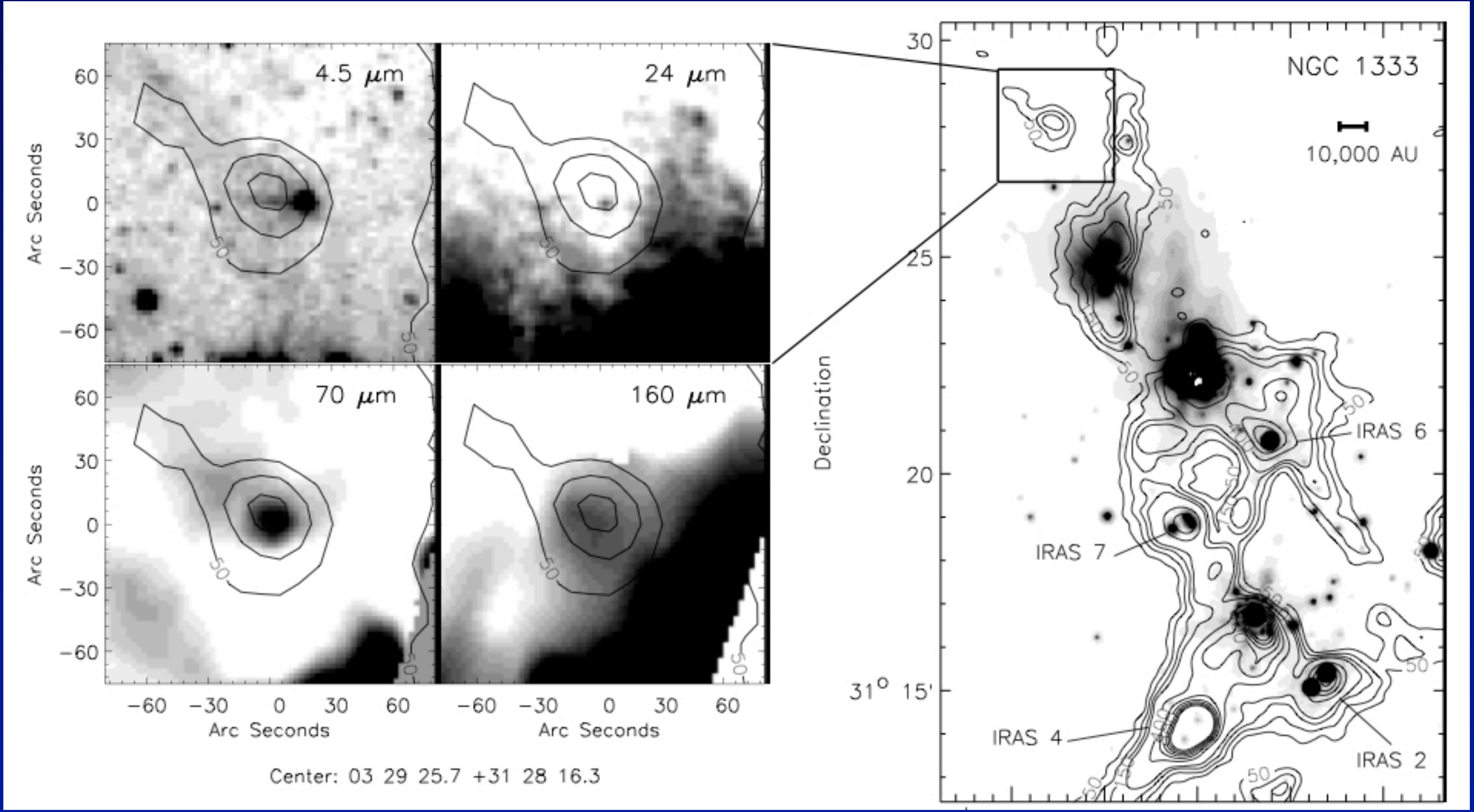


Figure adapted from McCaughrean, unpublished, by A. Stutz

Candidates

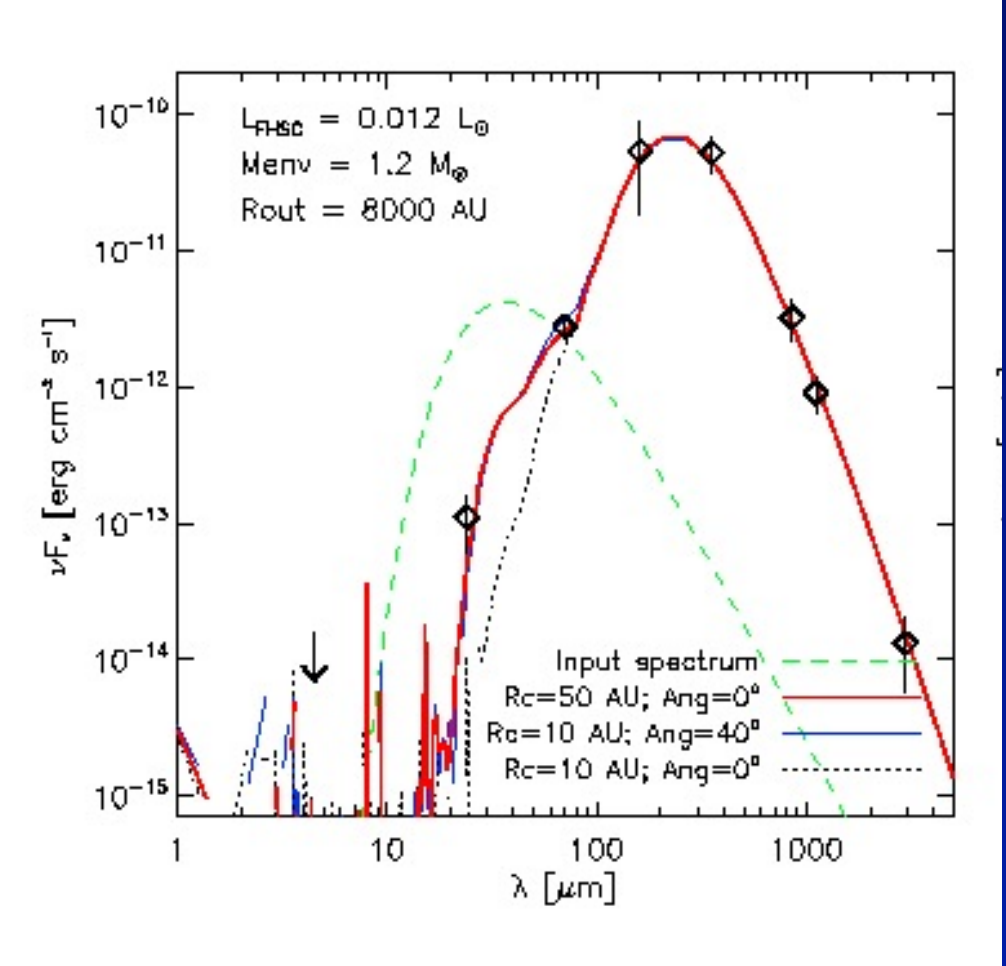
- Chen et al. (2010)
    - L1448 IRS2E
- Enoch et al. (2010)
    - Per-Bolo 58, NE of NGC1333
- Pineda et al. (2011)
    - L1451-mm
- All in Perseus (suggest duration > 2×10^4 yr)
- A few others now, maybe too many!

Per Bolo-58



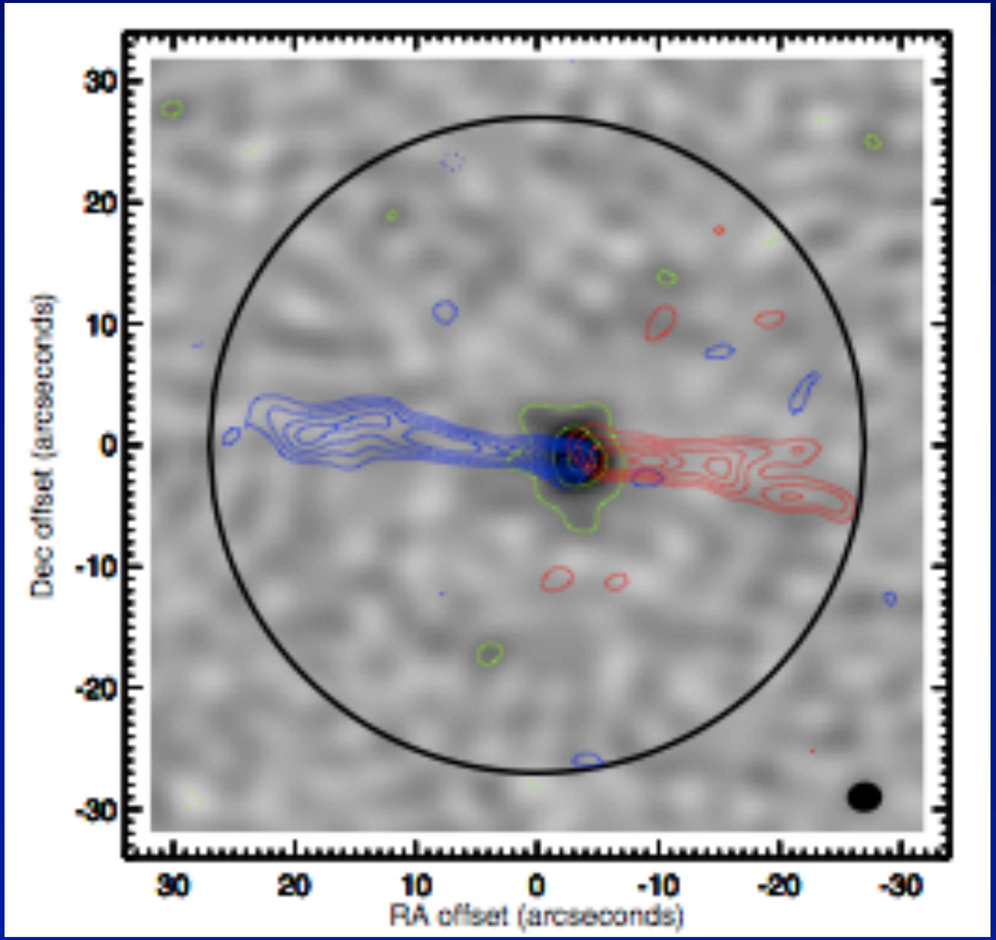
Enoch et al. (2010)

The SED fits



Enoch et al. 2010

And a slow, bipolar outflow



Per Bolo-58
Slow flow (2.9 km/s) fits theory, but more collimated than predictions

Dunham et al. 2011

Are All/Any of these FHSCs?

- The picture is currently unclear
- But at least we have some plausible candidates
- Primary need is for theory to converge on properties, lifetimes

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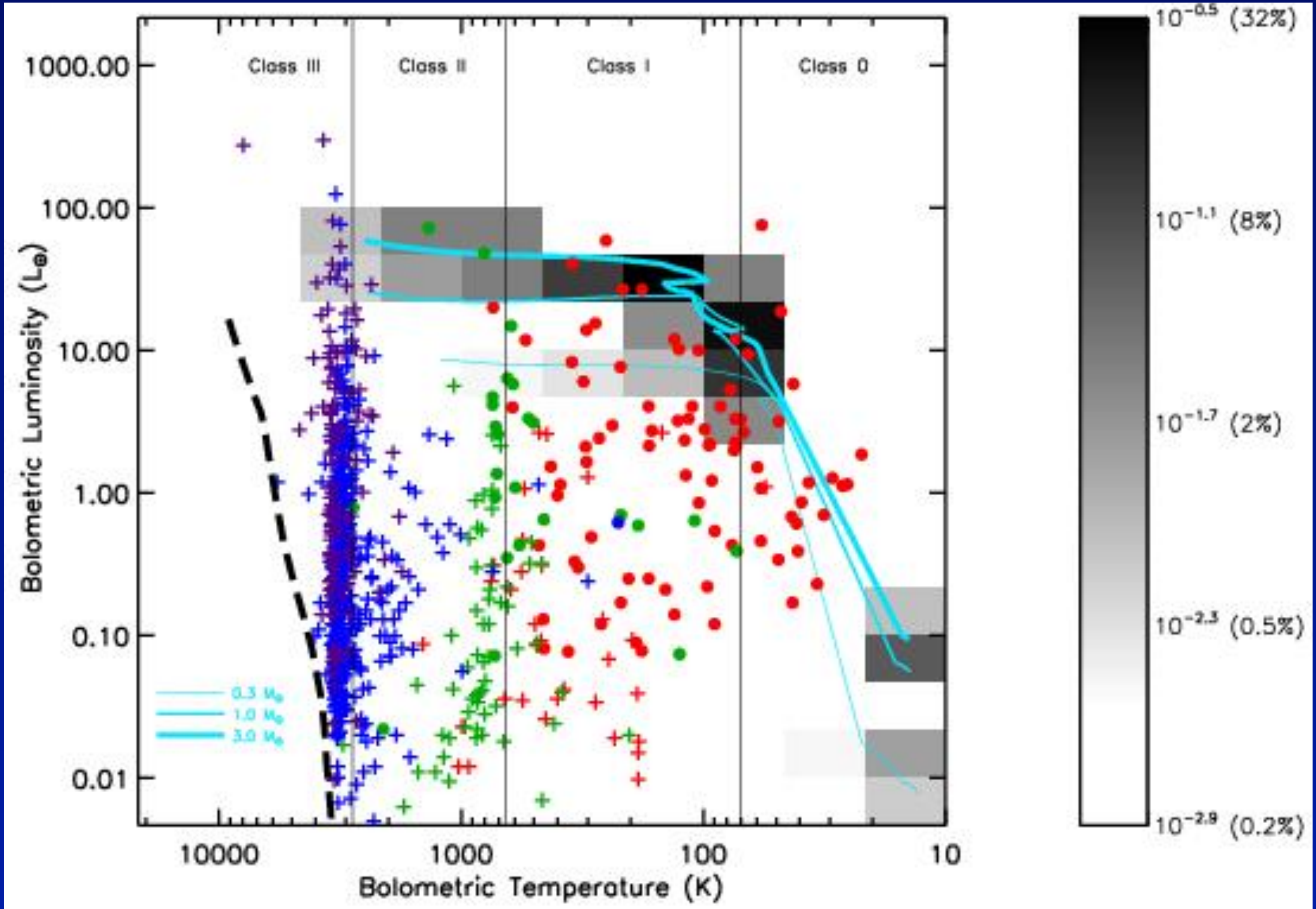
Comparison to Shu model

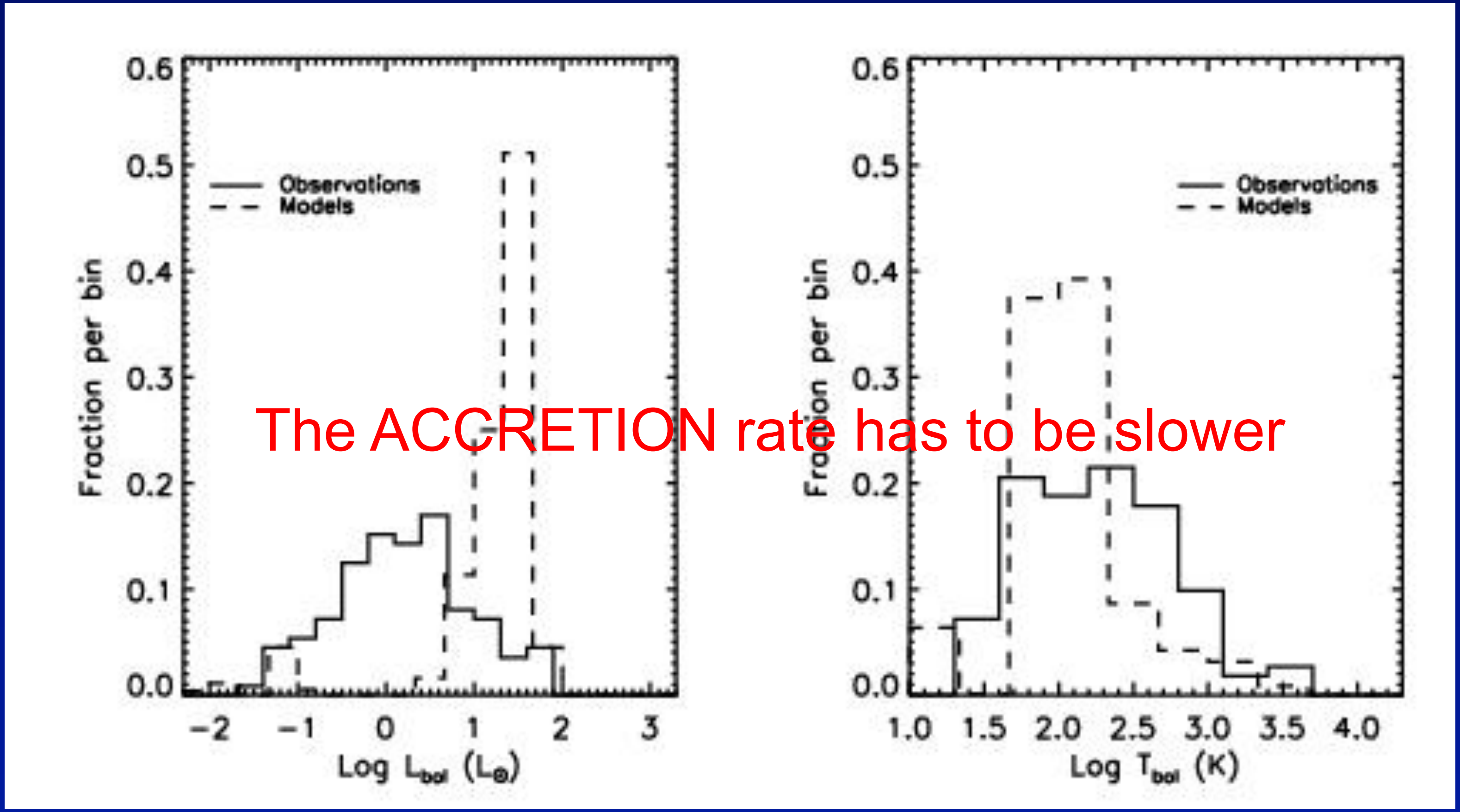
- Assume inside-out collapse at 0.19 km/s
  - Sound speed at 10 K
- In 0.54/2 Myr, $r_{inf} = 0.054$ pc
  - Consistent with some sizes
  - Mean separation in clusters 0.072 pc (Gutermuth)
- At $dM/dt = 1.6 \times 10^{-6}\ M_{sun}/yr$, $M_* \sim f\ 0.86\ M_{sun}$
  - If f ~ 0.3, get 0.26 M_{sun} ~ modal mass
  - Infall rate is right to build star in allowed time
- Consistent with assumptions, most data
- Picture holds together, except…

The Luminosity Problem!



M. M. Dunham et al. 2010

Many are under-luminous



The ACCRETION rate has to be slower

Predicted L = GM(dM/dt)/R= 1.6 L_{sun} for standard (Shu) accretion onto M = 0.08 M_{sun}, R = 3 R_{sun}. Most (59%) are below this. M. M. Dunham et al. 2010

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Episodic Accretion

- Infall rate like Shu, but accretion rate highly variable
  - Kenyon and Hartmann (1995) suggested this to solve luminosity problem (IRAS)
  - Exacerbated by Spitzer data
- Simulations show it (Vorobyov and Basu 2005, 2006)
  - Infall from envelope to disk is not obviously synchronized with accretion from disk to star

Direct Evidence for Episodic Accretion

- Luminosity Variations (e.g., FU Orionis)
- VeLLOs ($L<0.1\ L_{sun}$), much less than prediction for standard accretion onto BD/star
- Outflow morphologies suggesting multiple ejection events (e.g., HH 211)
- Comparison of L(now) with <L(t)>
  - Outflows trace history of ejection, hence accretion
  - Careful analysis of several sources gives strong evidence for L(now) < <L(t)>
    - Dunham et al. 2006, 2010

Luminosity bursts:
direct evidence for a change in mass accretion rate

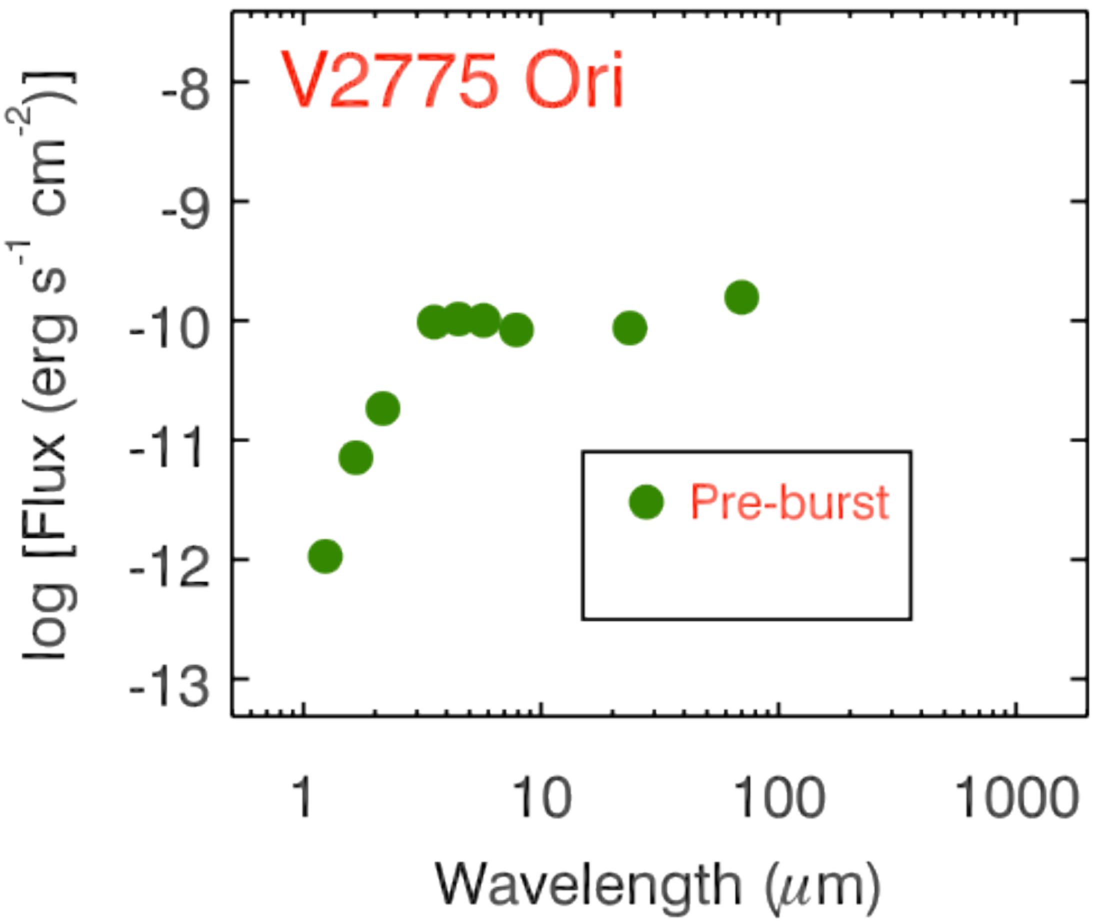

Figure adapted from Fischer et al., 2012, ApJ, 756, 99

> 50% of protostars exhibit variability

V2775 Ori = HOPS223
factor of ~10 rise in luminosity, with a post outburst luminosity of 28 L_{SUN}

Least luminous FU Ori outburster protostar

Low-luminosity outbursts consistent with a range of episodic accretion phenomena

But how common and how frequent are bursts?

Luminosity bursts:
direct evidence for a change in mass accretion rate

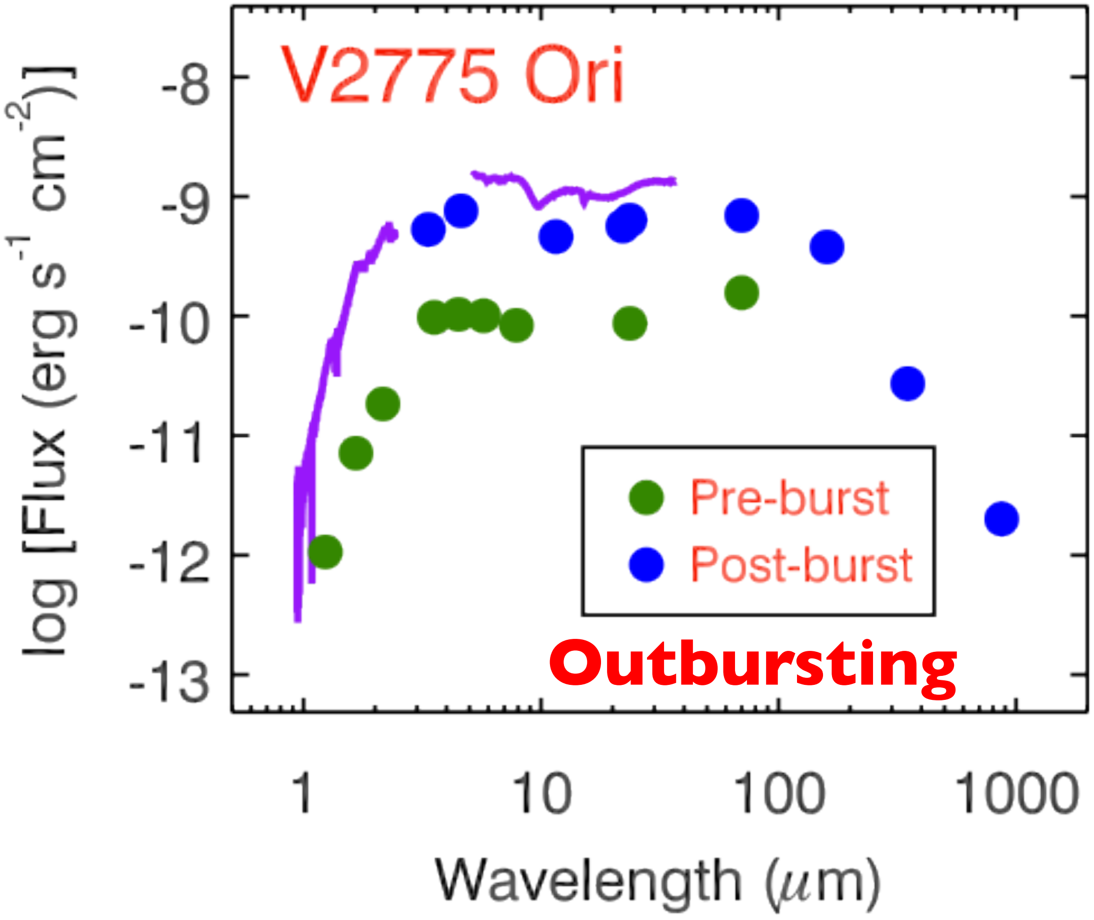

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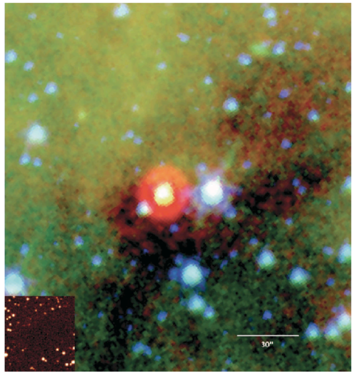
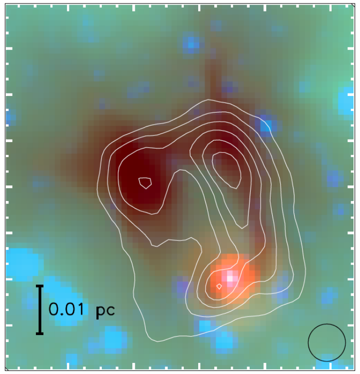
Figure adapted from Fischer et al., 2012, ApJ, 756, 99

Very Low Luminosity Objects
(VeLLOs)

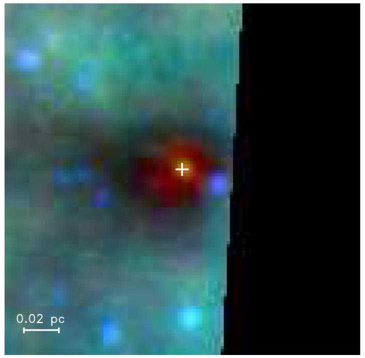
L1014
$L_{int} \sim 0.09\ L_{SUN}$
Young et al., 2004,
ApJS, 154, 386



L328
$L_{int} \sim 0.04 - 0.06\ L_{SUN}$
Lee et al., 2009,
ApJ, 693, 1290



L673-7
$L_{int} \sim 0.04\ L_{SUN}$
Dunham et al., 2010,
ApJ, 721, 995



Observationally selected: low luminosity objects, with $L_{int} < 0.1\ L_{SUN}$ (Di Francesco et al., 2007); 15 VeLLOs have been identified in c2d regions (Dunham et al., 2008)

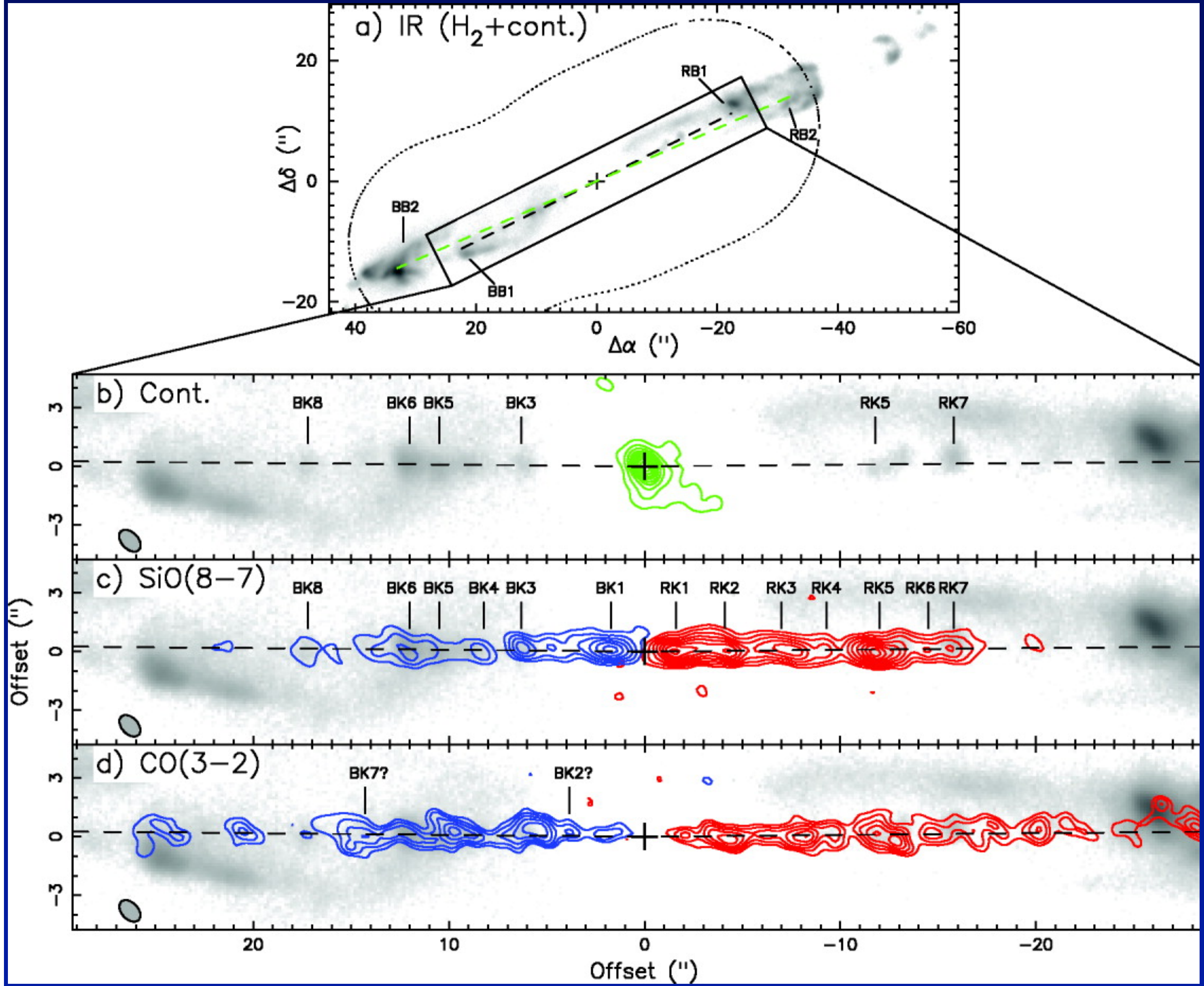
Low luminosities require low protostellar masses and/or low accretion rates.

Proposed explanations for VeLLOs:
(1) Extremely young low-mass protostars
(2) Older protostars in low-accretion phase
(3) Proto-brown dwarfs

Outflow properties vary greatly

Results suggest that as a class, the VeLLOs do not correspond to a single evolutionary Stage.

Episodic Jets



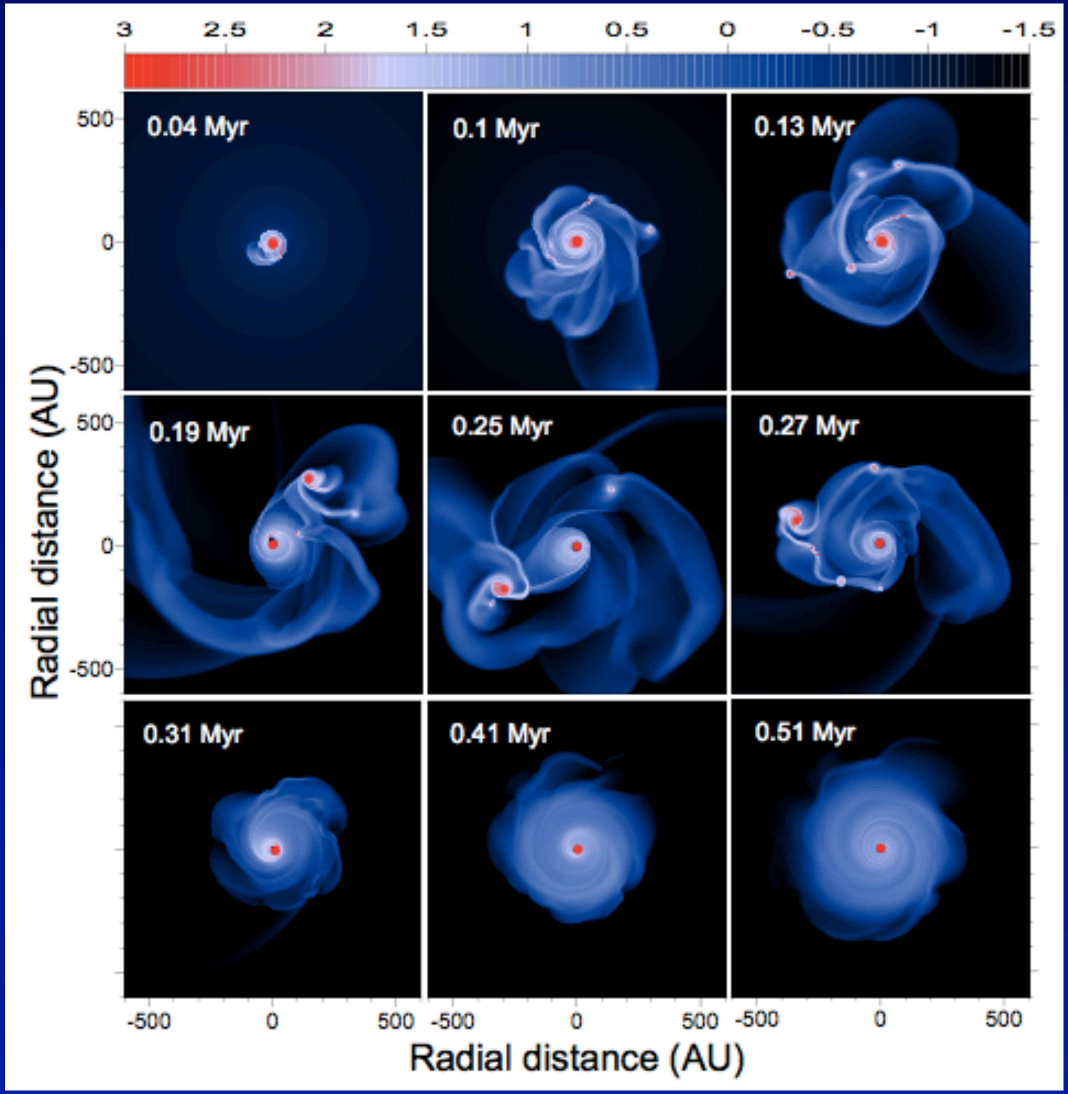
HH 211 Jet shows series of bow shocks. Time between estimated at 15-44 yr

Lee et al. 2007

Models

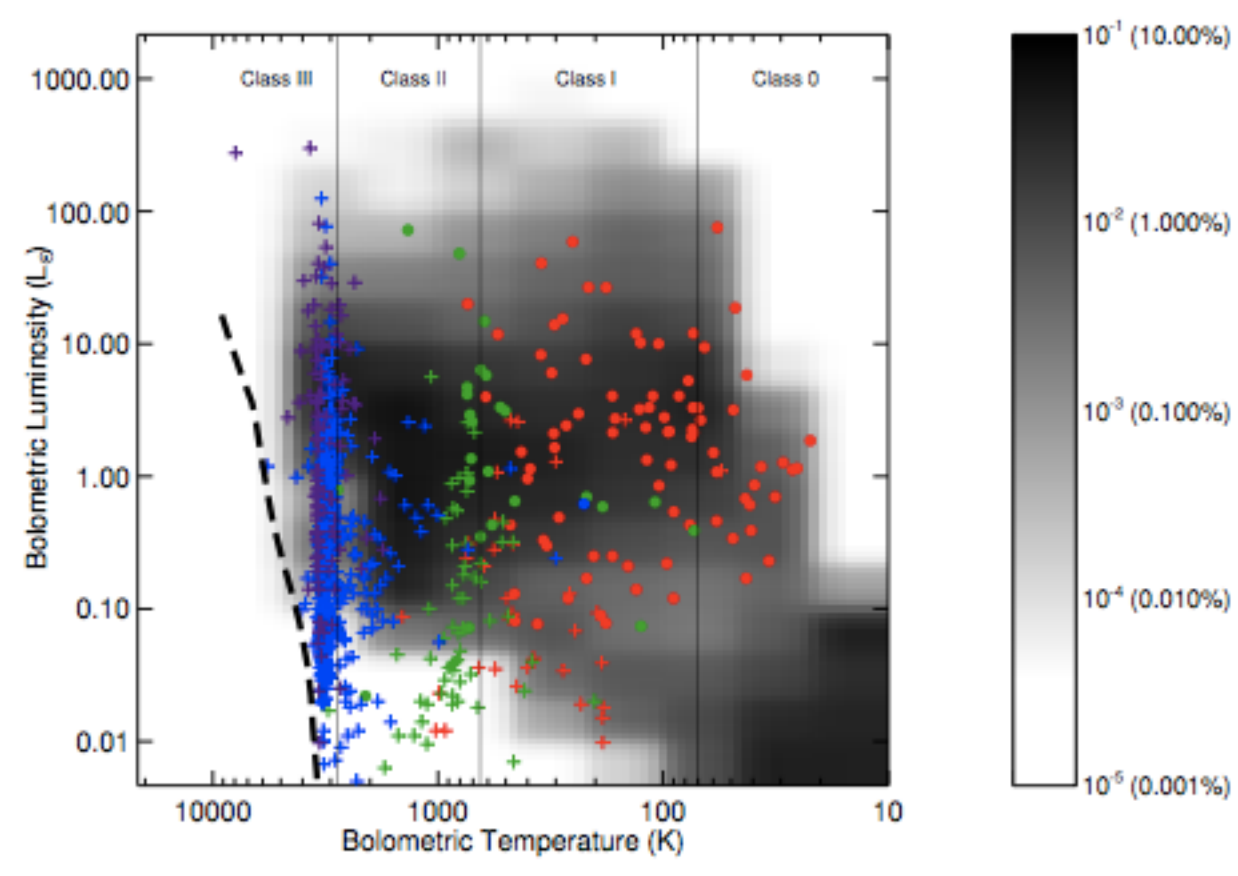
- Couple Hydro simulations to simulation of observations
    - Dunham and Vorobyov, 2011
    - Vorobyov hydro with disk instabilities
    - Follow L_{acc} through time
    - Feed into models of envelope evolution
    - Calculate $T_d(r, t)$ and SED
    - Simulate actual observations

Instability of Disk during Infall



Dunham & Vorobyov 2011

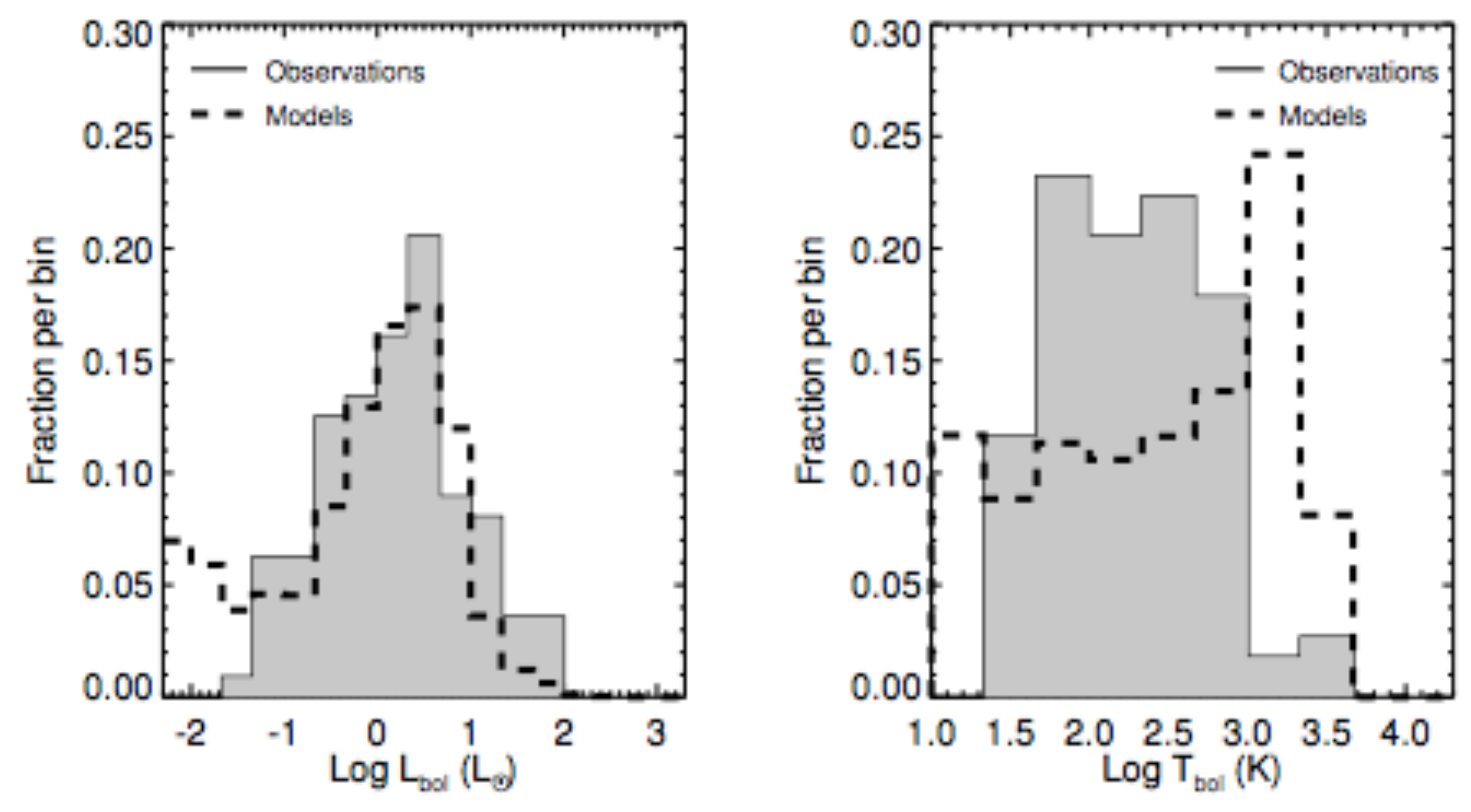
Improved fit to BLT Data



Shading indicates time spent in that cell of BLT diagram in (more sophisticated) episodic models

Dunham & Vorobyov 2012

And 1D Distributions

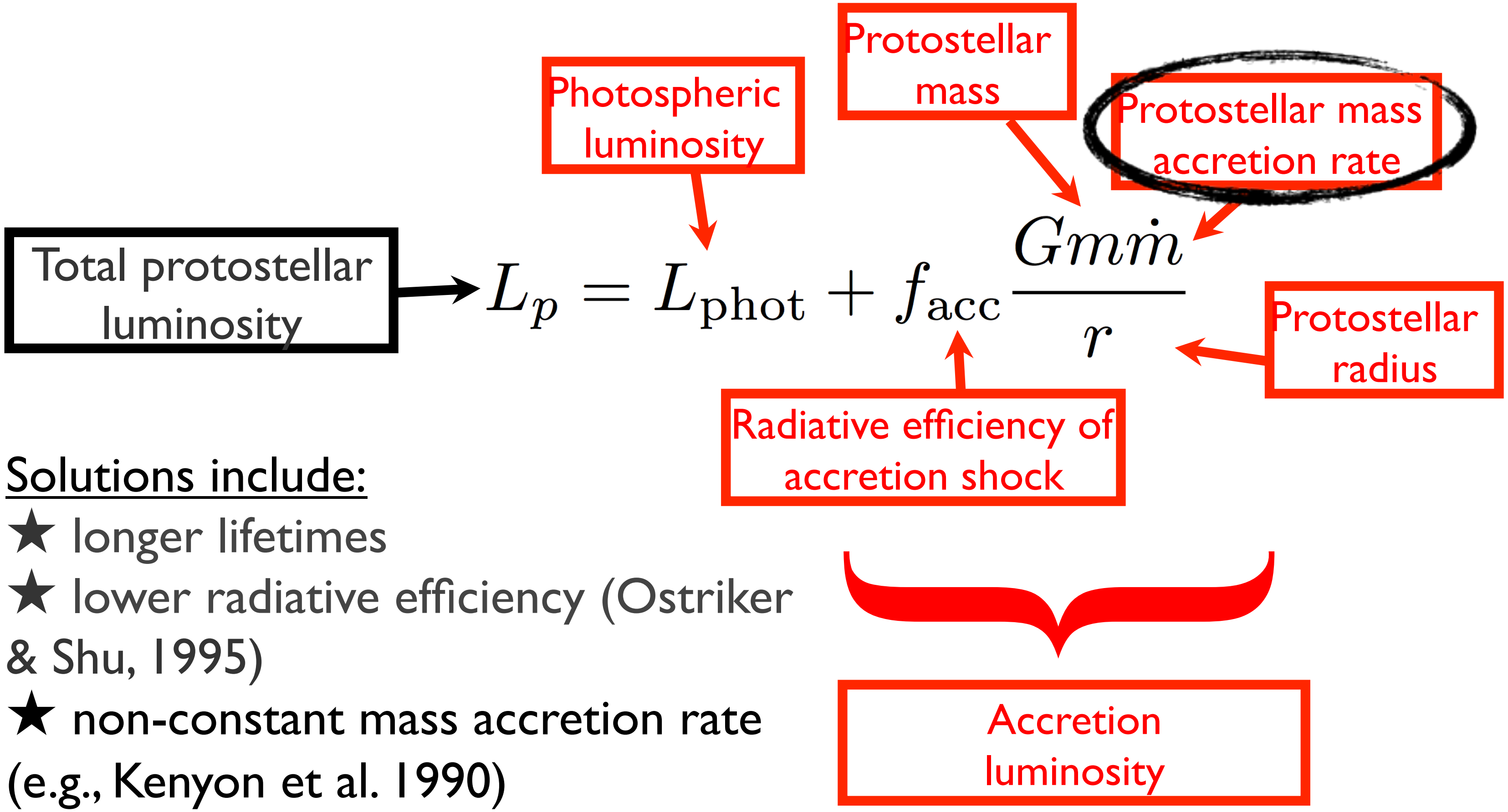


Dunham & Vorobyov 2012

Consequences of Episodicity

- The connection between Classes and Stages becomes tenuous
- The luminosity is not an indicator of stellar mass until nuclear burning dominates
    - ($L_{acc} \sim M_* dM_{acc}/dt$)
- Stellar ages from tracks may be way off (Baraffe et al. 2009)
- The initial conditions for planet formation may be determined by time since last episode of disk instability

Other Solutions?



Total protostellar luminosity

Photospheric luminosity

Protostellar mass

Protostellar mass accretion rate

Protostellar radius

Radiative efficiency of accretion shock

$$L_p = L_{\rm phot} + \underbrace{f_{\rm acc}\frac{Gm\dot{m}}{r}}_{\text{Accretion luminosity}}$$

Solutions include:

★ longer lifetimes

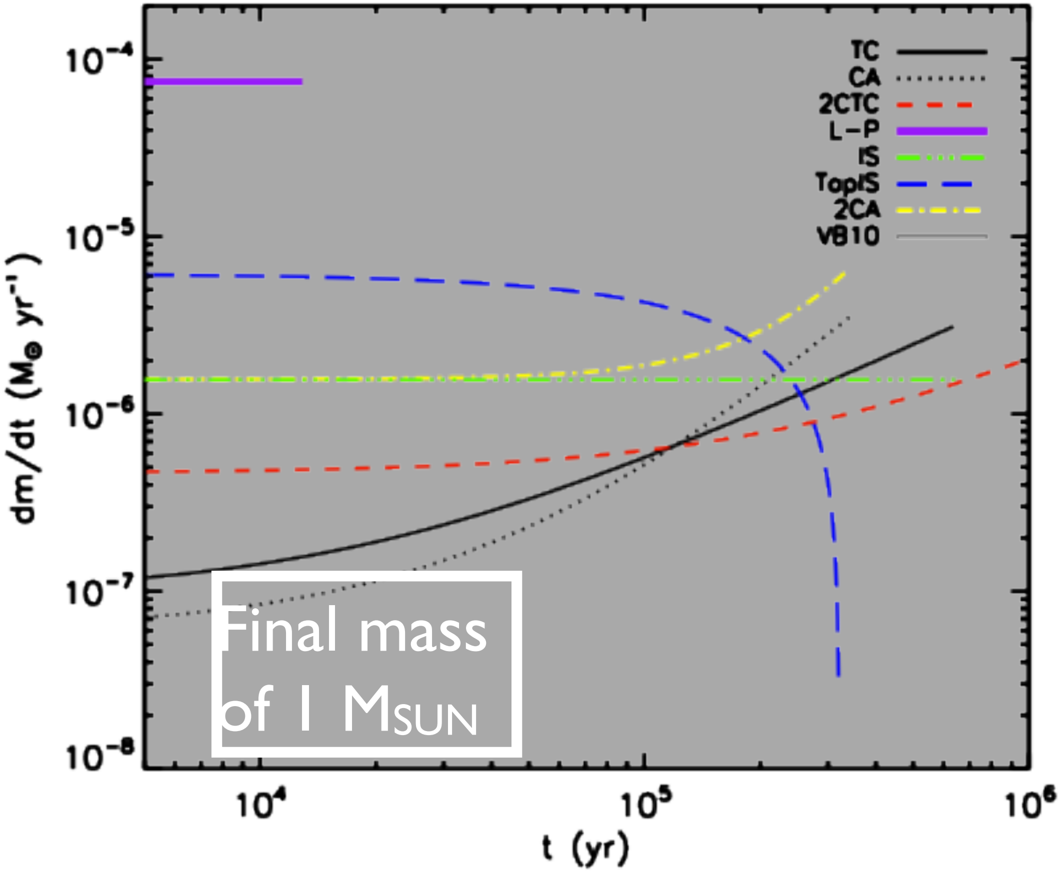
★ lower radiative efficiency (Ostriker & Shu, 1995)

★ non-constant mass accretion rate (e.g., Kenyon et al. 1990)

How do stars get their mass?

Core regulated versus disk regulated accretion

Figure from Dunham et al. (2013), PPVI review chapter



Final mass of 1 MSUN

TC = Turbulent core (McKee & Tan, 2003)

CA = Competitive accretion (Bonnell et al., 2001)

2CTC = 2-component TC (McKee & Offner, 2010)

L-P = Larson-Penston (Larson, 1969; Penson 1969

IS = Isothermal sphere (Shu 1977)

TapIS = TaperedIS (McKee & Offner, 2011)

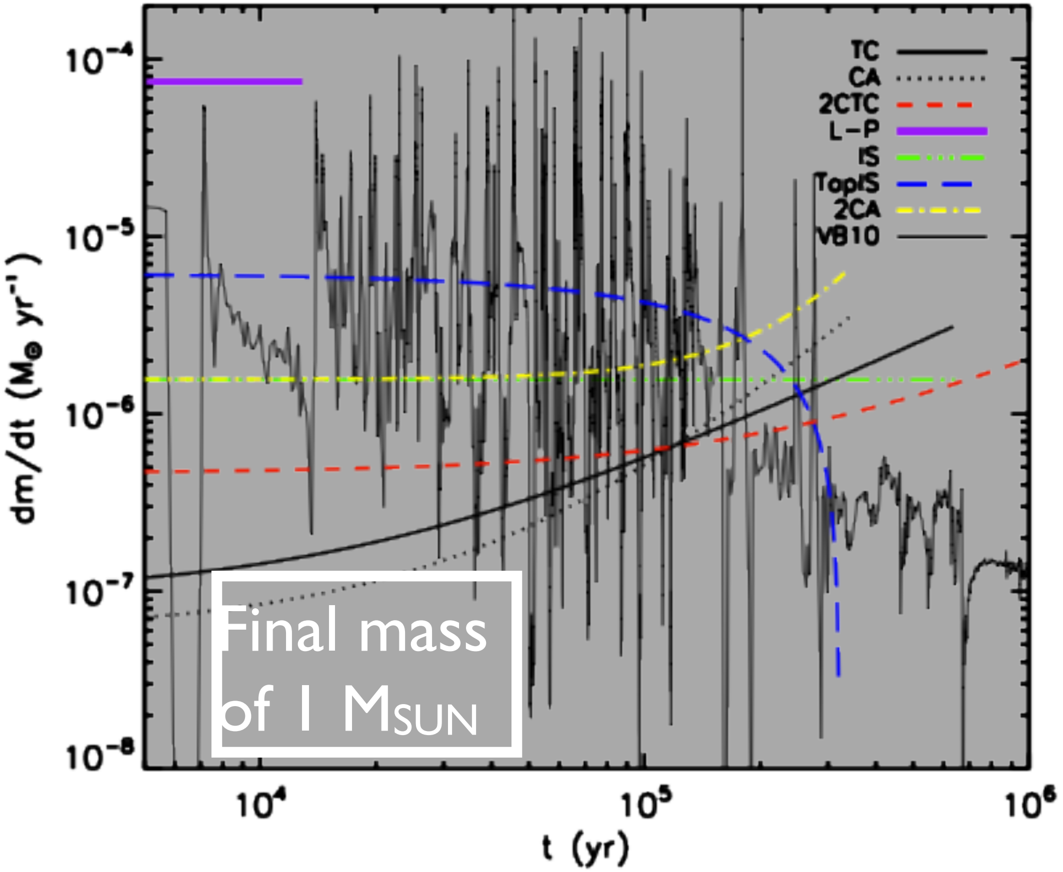
2CA = 2-component accretion, from Myers (2010)

Core-Regulated Accretion: all models fall between the limits of constant accretion rate and constant star formation time

How do stars get their mass?

Core regulated versus disk regulated accretion

Figure from Dunham et al. (2013), PPVI review chapter



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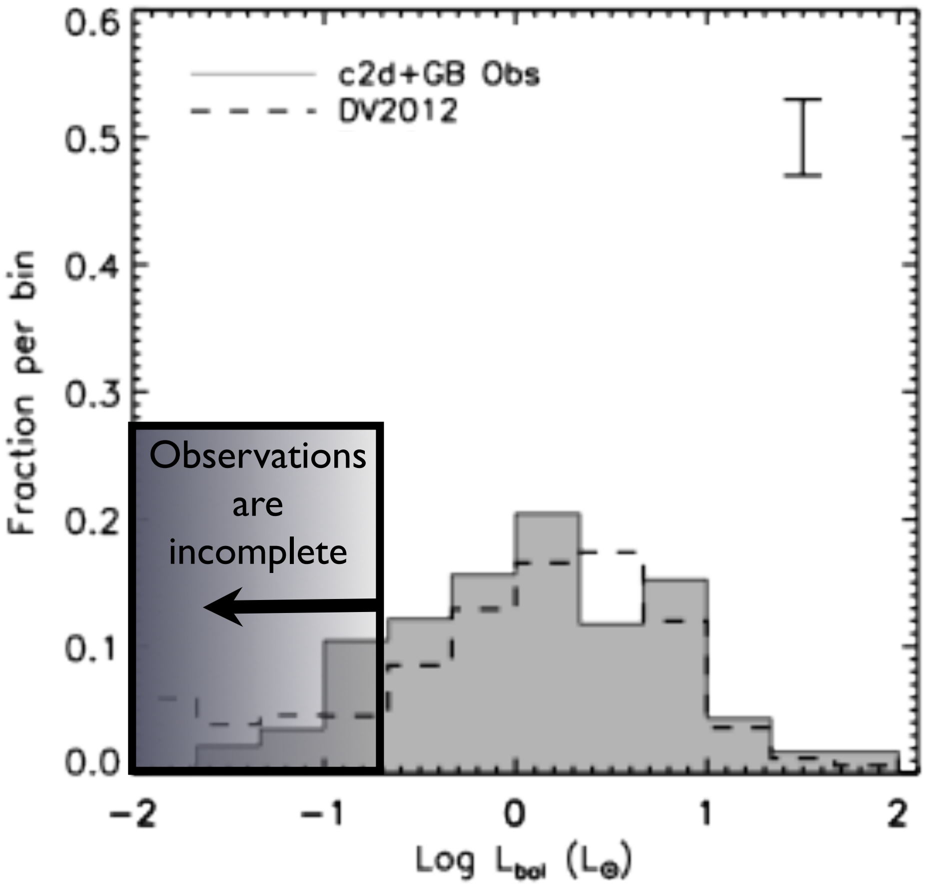
VB10 = Variable accretion, from Vorobyov & Basu, 2010, ApJ, 719, 1896

Disk-Regulated Accretion: disk accretion is intrinsically variable; fragmentation is one of many mechanisms that can generate luminosity and accretion bursts (see PPVI chapter by Audard et al.)

How do stars get their mass?

Core regulated versus disk regulated accretion

Figure from Dunham et al. (2013), PPVI review chapter



Observations

DV2012 = disk simulations; Dunham & Vorobyov (2012)

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Models with and without episodic accretion are capable of reproducing the observed protostellar luminosity distribution.

How do stars get their mass?
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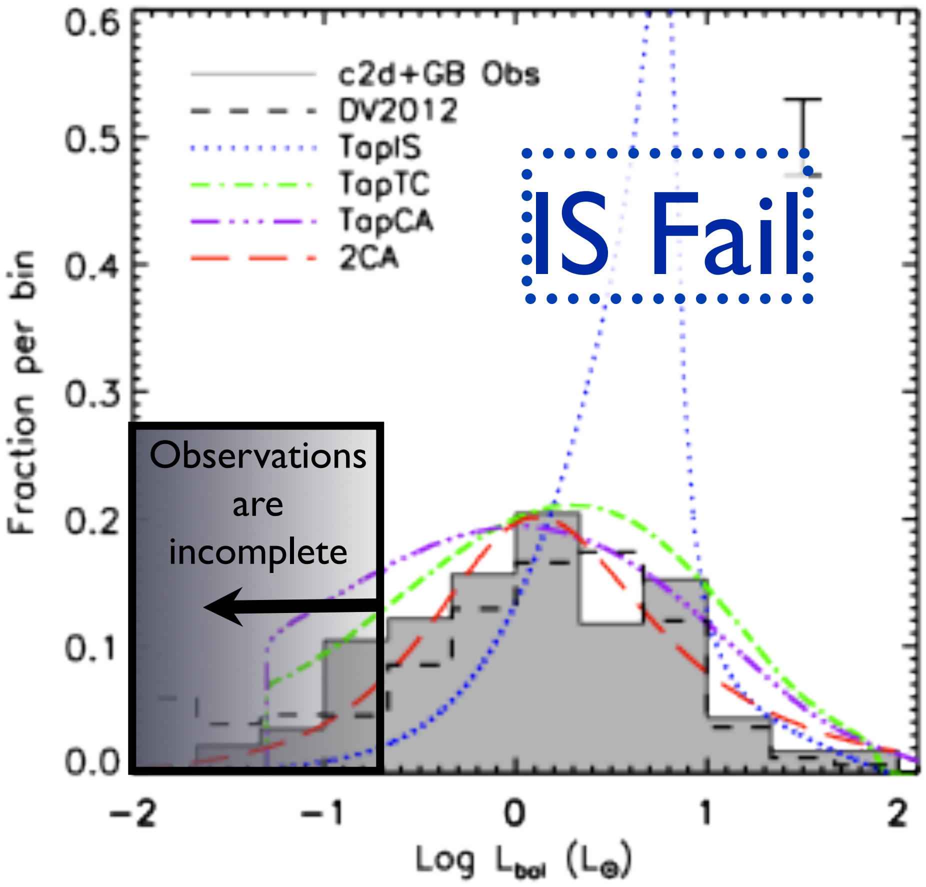

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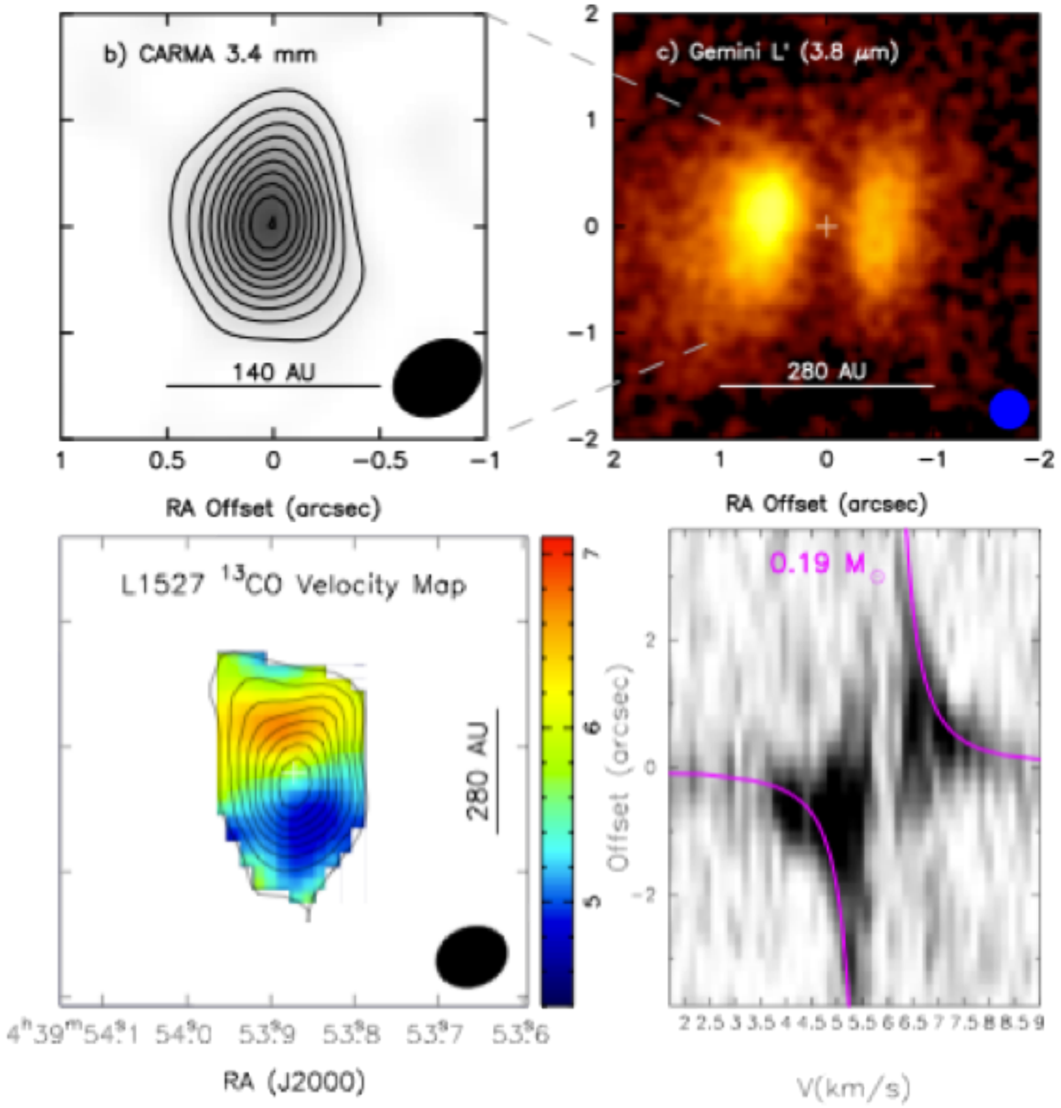
Models with and without episodic accretion are capable of reproducing the observed protostellar luminosity distribution

Star formation is “slow” per t_{ff}, even on scale of core

Do Protostars Have Disks?
(Despite theoretical difficulties…)



L1527 in Taurus:
Edge-on disk in a Class 0 source

Disk rotation allows the only direct means of measuring protostar masses.

^{13}CO velocity map consistent with Keplerian rotation, implying a protostellar mass of ~ 0.2 M_{SUN}

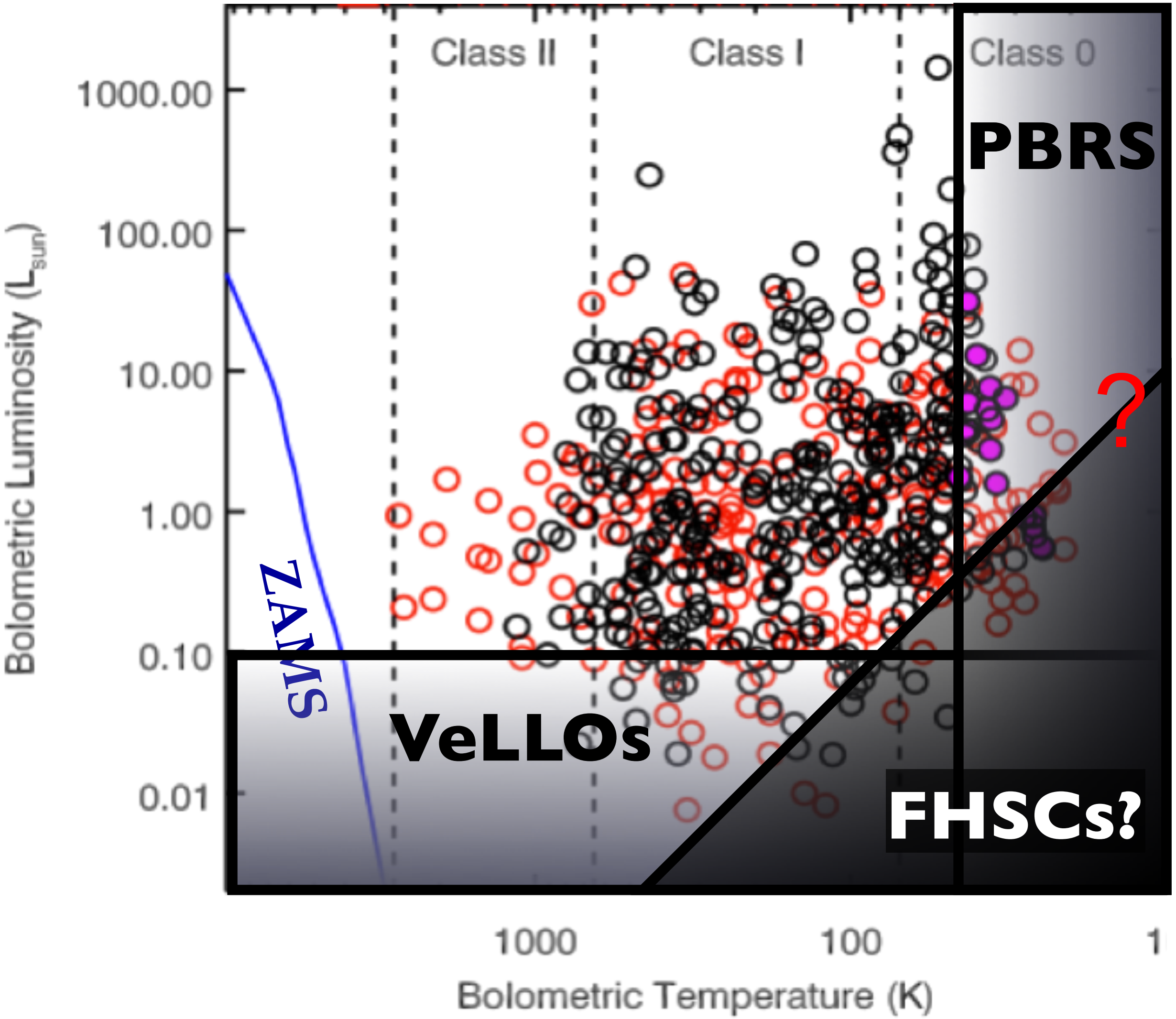
R_{DISK} = 70 - 125 AU
M_{DISK} ~ 0.007 M_{SUN}
(Tobin et al., 2012, 2013)

ALMA will do more

Figures from Tobin et al., 2012, Nature, 492, 83 and Dunham et al., 2013, PPVI Review Chapter

Where do all these new things fit?

Figure from Dunham et al. (2013), PPVI review chapter

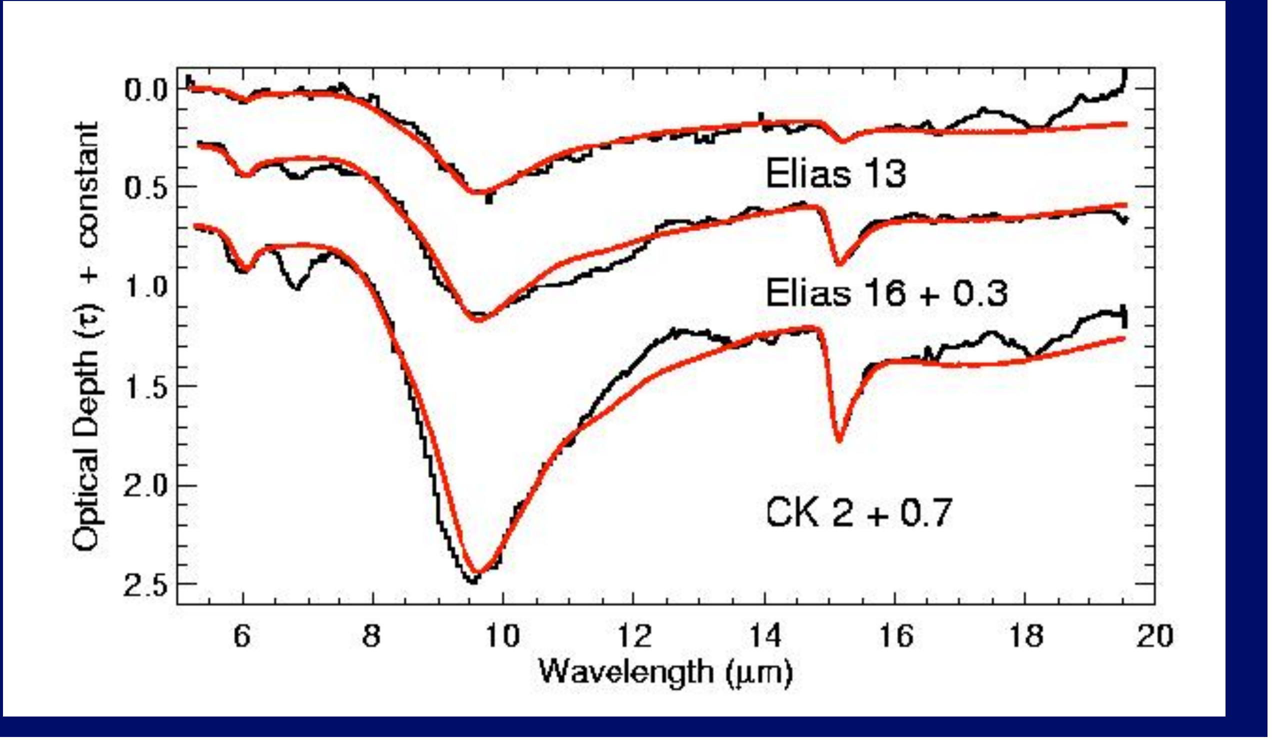


Star Formation Questions

- What determines the IMF?
- How long do various stages of the process take?
- Have we found the missing link?
- Do any theories explain the data?
- How are the star and disk built over time?
- What chemical changes accompany star formation?

Molecules Freeze out in Cloud

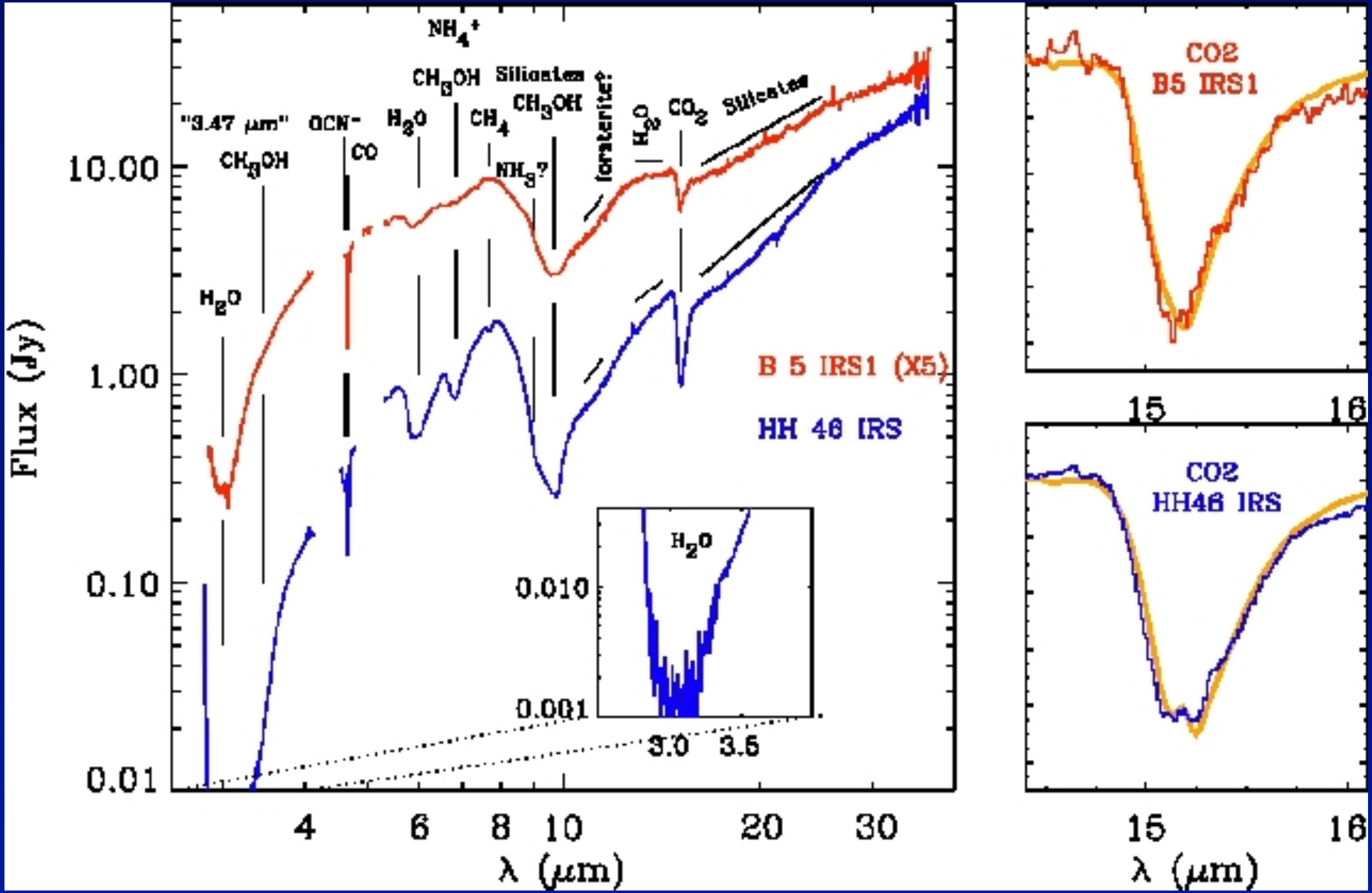
- Molecules should freeze on dust at T ~ 10 K.
- Except H_2, He
- And they do…

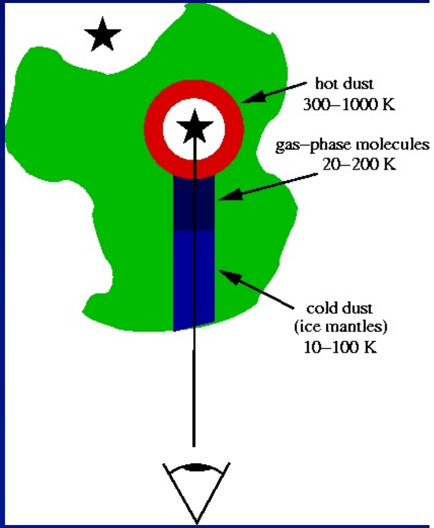


Ices seen toward background stars: H_2O, CO_2
Knez et al. (2005)

Even More as Core/protostar form

Ice inventory





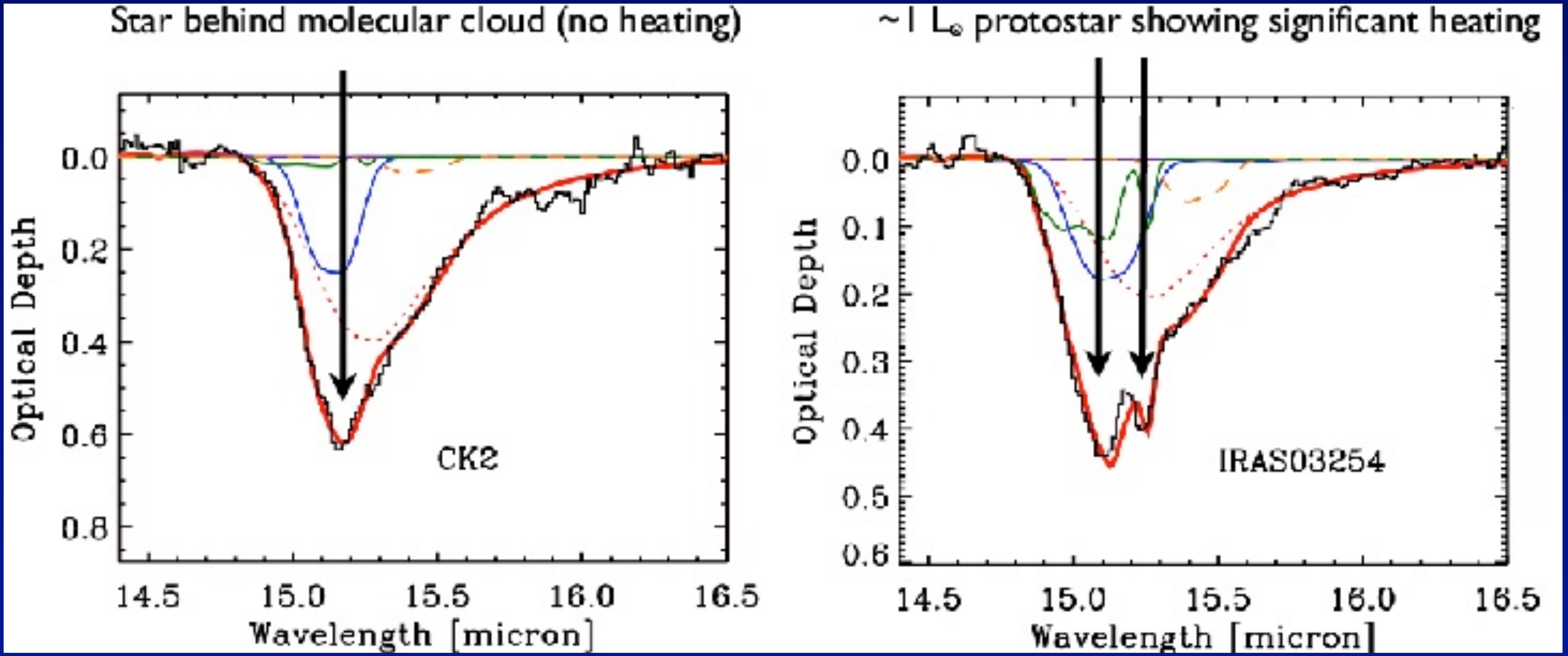
Boogert et al. 2004, 2007 Oberg 2011

- Abundances of some species similar within factor of 2 (e.g., CO_2)
- Significant variations (>10) for other species (e.g., CH_3OH, NH_3, OCN^-)
- Evidence for NH_3 with high abundances (>10%) in some objects
- First detection of CH_4 ice toward low-mass YSO's

Chemical Memory

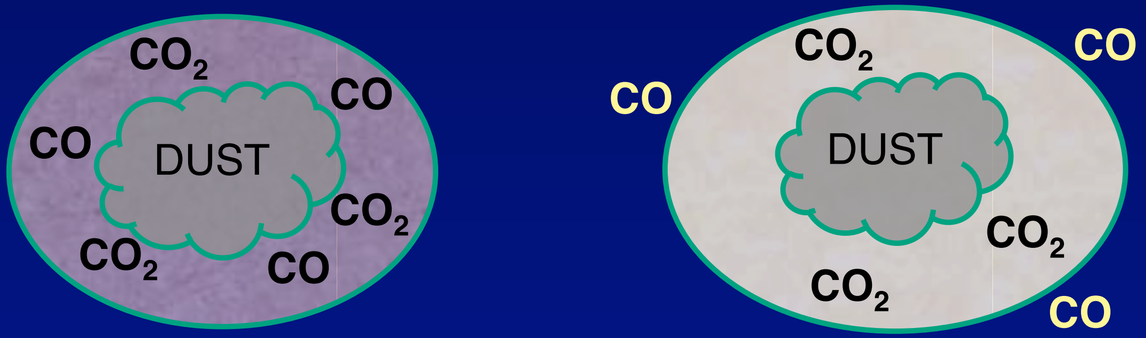
- Chemical timescales differ from dynamical timescales
- Desorption of ices, photodissociation, … essentially instantaneous
- Freeze-out, some chemical reactions depend on density, can be long
- Irreversible Reactions
- Chemistry may trace history

Irreversible Reactions

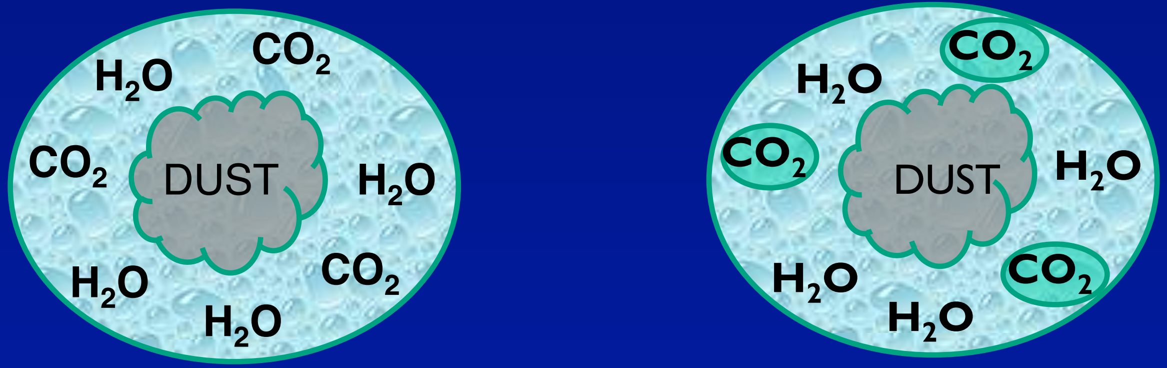


CO freezes out, some is converted to CO_2. Upon warm-up, the CO evaporates, leaving pure CO_2 behind. The shape of the absorption feature changes to reflect this.

Pure CO_2 ice formation



- Distillation (requires 20-30K)

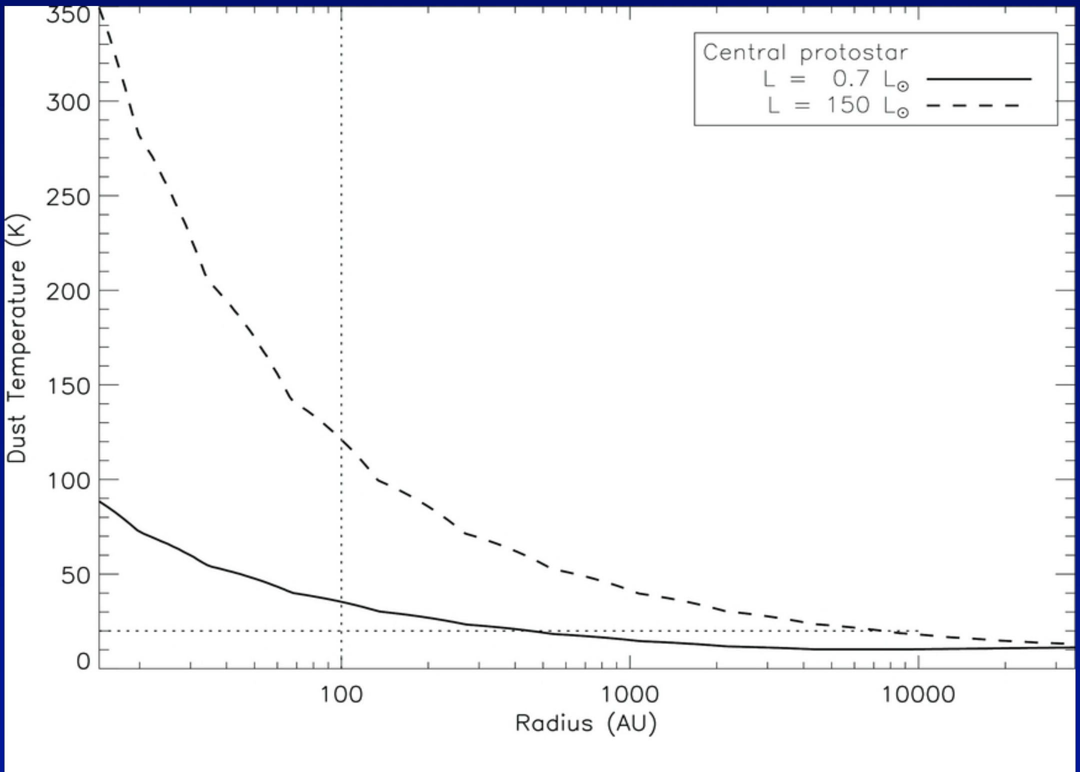


- **Segregation (requires 50-80K)**

Using Chemistry to study L(t)

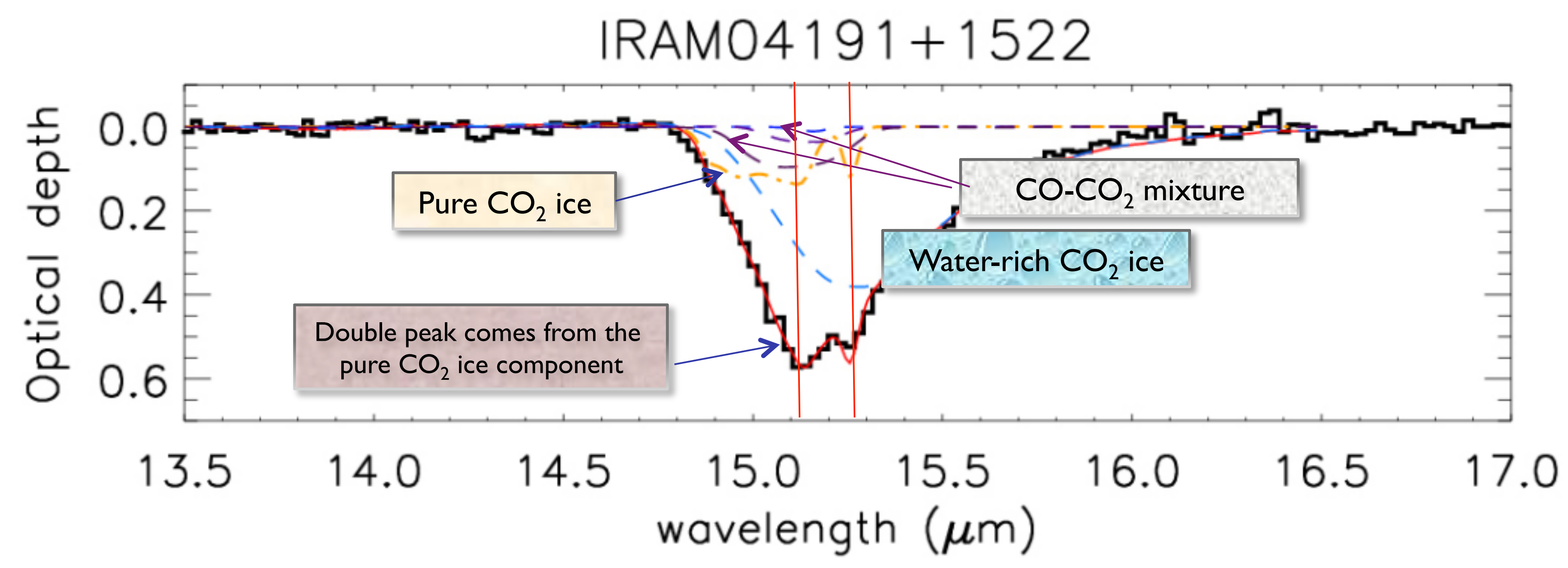
- See pure CO_2 ice toward low luminosity sources?
  - Currently too cold to distill pure CO_2
  - Would imply more luminous in the past
  - Evidence for episodic accretion

Dust Temperature around Low Luminosity Protostars



- If we can find pure CO_2 ice around low luminosity protostars, they must have had higher accretion rates in the past!

Pure CO_2 In a Low-L Source



Pure CO_2 ice

CO-CO_2 mixture

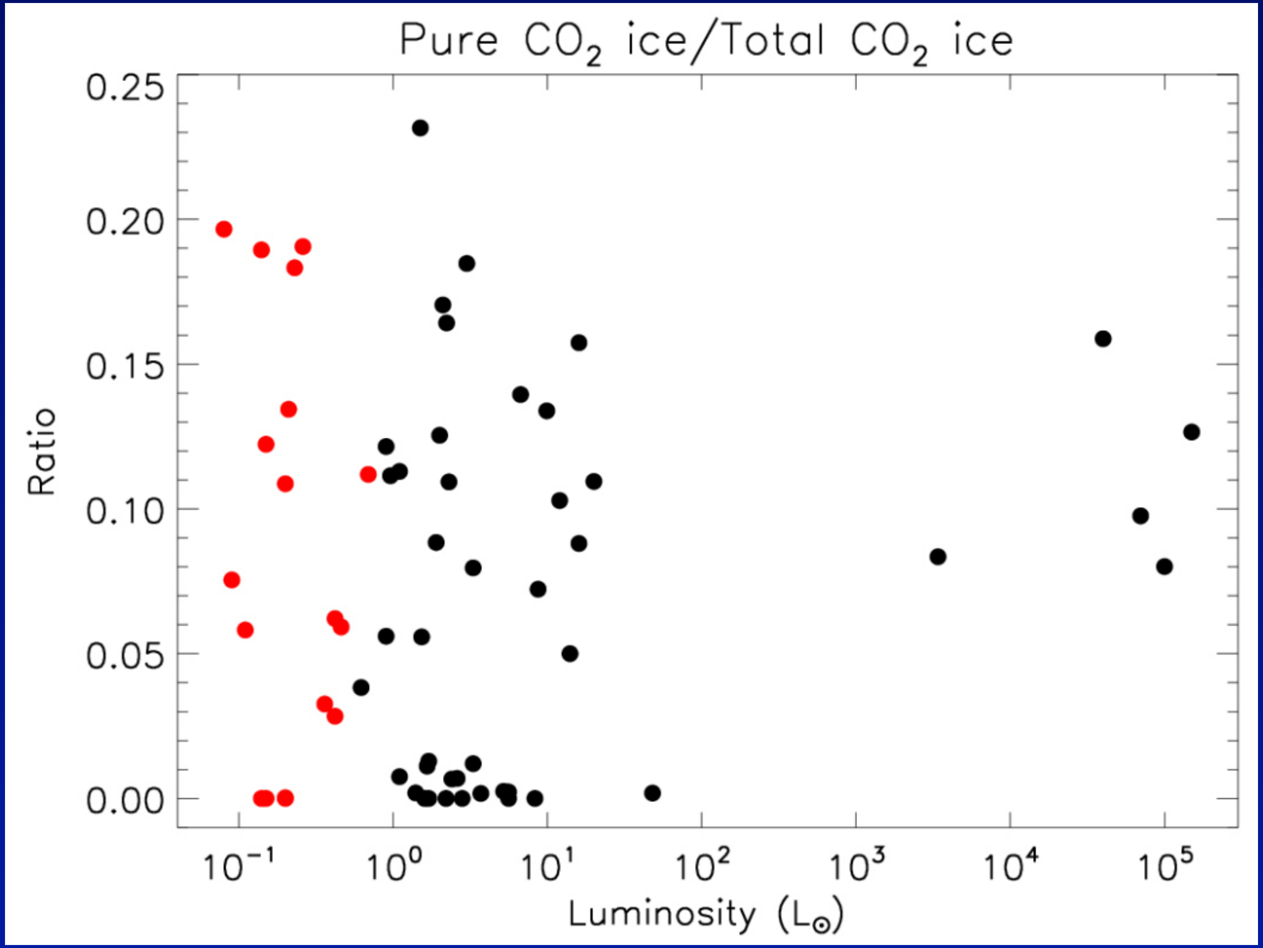
Water-rich CO_2 ice

Double peak comes from the pure CO_2 ice component

The internal luminosity of IRAM 04191+1522 is 0.23 $\mathbf{L}_\odot$, but it has pure CO_2 ice component. The source had higher temperature than the dust temperature of currently existing envelope.

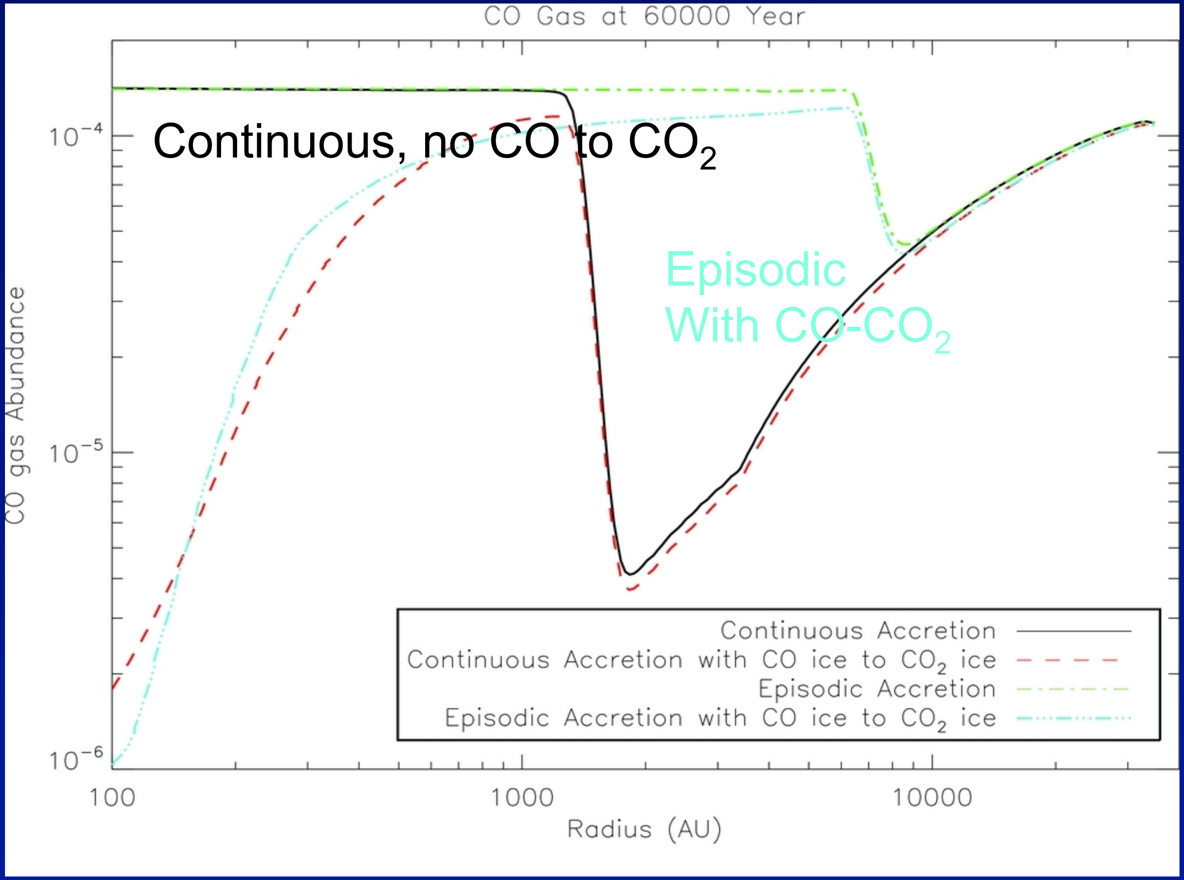
Kim et al. 2012

Pure CO_2 Ice is Common



Red: low L sample, Black: high L sample (Pontoppidan 2008)
Pure/total CO_2 similar in both samples. (Kim et al. 2012)

Effects on Gas



Continuous, no CO to CO_2

Episodic With CO-CO_2

Gas Phase CO

Radius

With episodic accretion and CO to CO_2 ice conversion, the abundance profile of CO gas is very different. This is at 60,000 yr during a burst. Observations matched better.

Kim et al. (2012)

Summary

- Core mass function may trace IMF of stars
- Timescales for Class 0+I about 0.5 Myr
    - But connection to Stages is less clear
- Candidates for FHSC have been found
- Shu inside-out collapse consistent, except
    - Luminosities are too low
    - Accretion is likely episodic and/or infall is slow
- Disks are seen in some protostars, expect more
- Complex chemical changes throughout
    - Chemistry can constrain history
    - Consistent with episodic accretion
- Implications of episodic accretion are wide-ranging