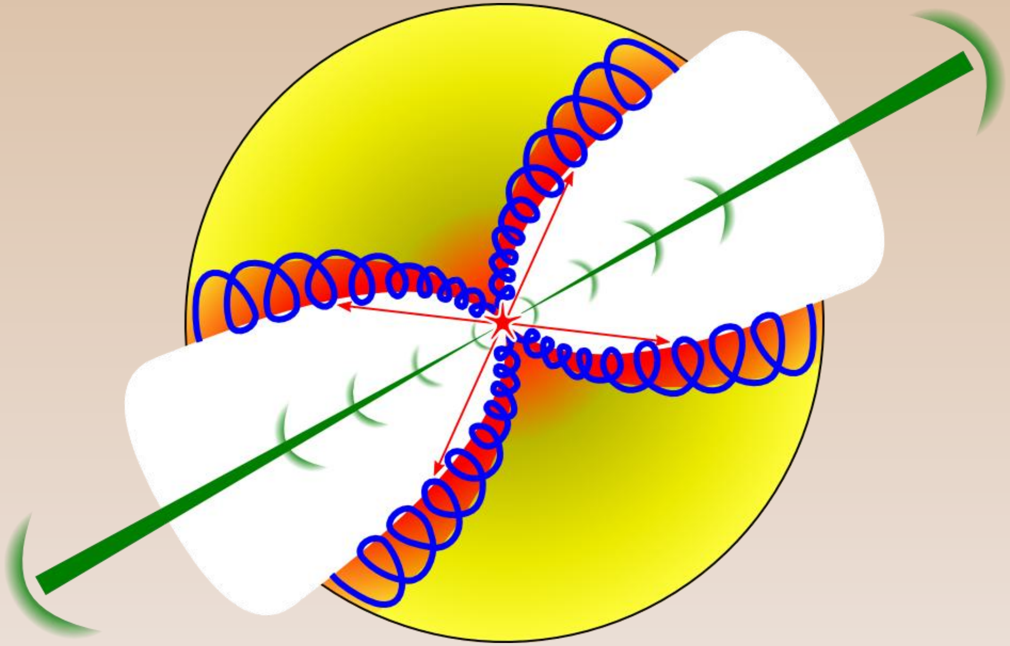

Protostars: Theory and Models

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University of Michigan

March 21, 2012

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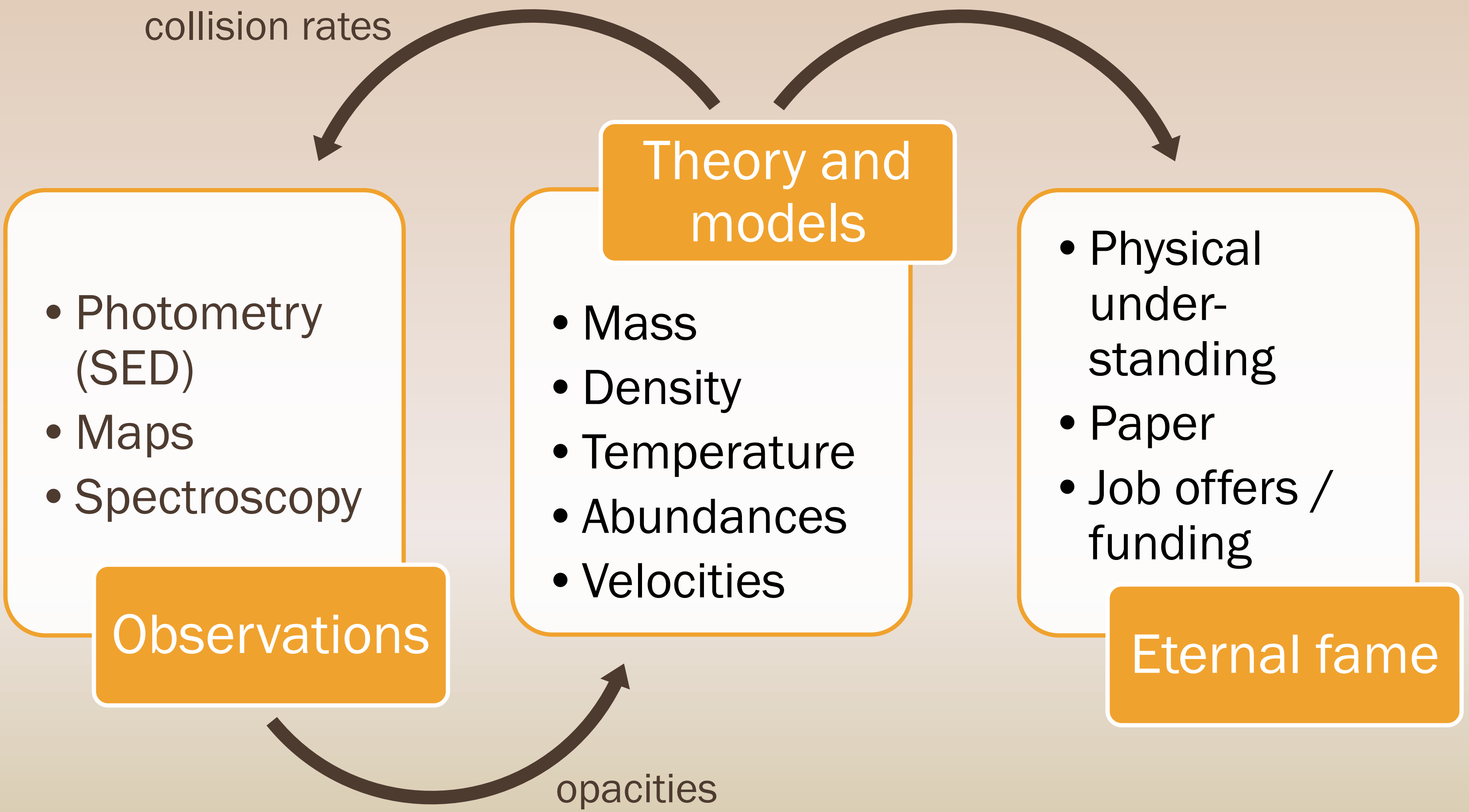
A TYPICAL PROJECT



Protostars: theory & models in four steps

1. Physical structure
2. Energetic feedback
3. Episodic accretion
4. Chemistry

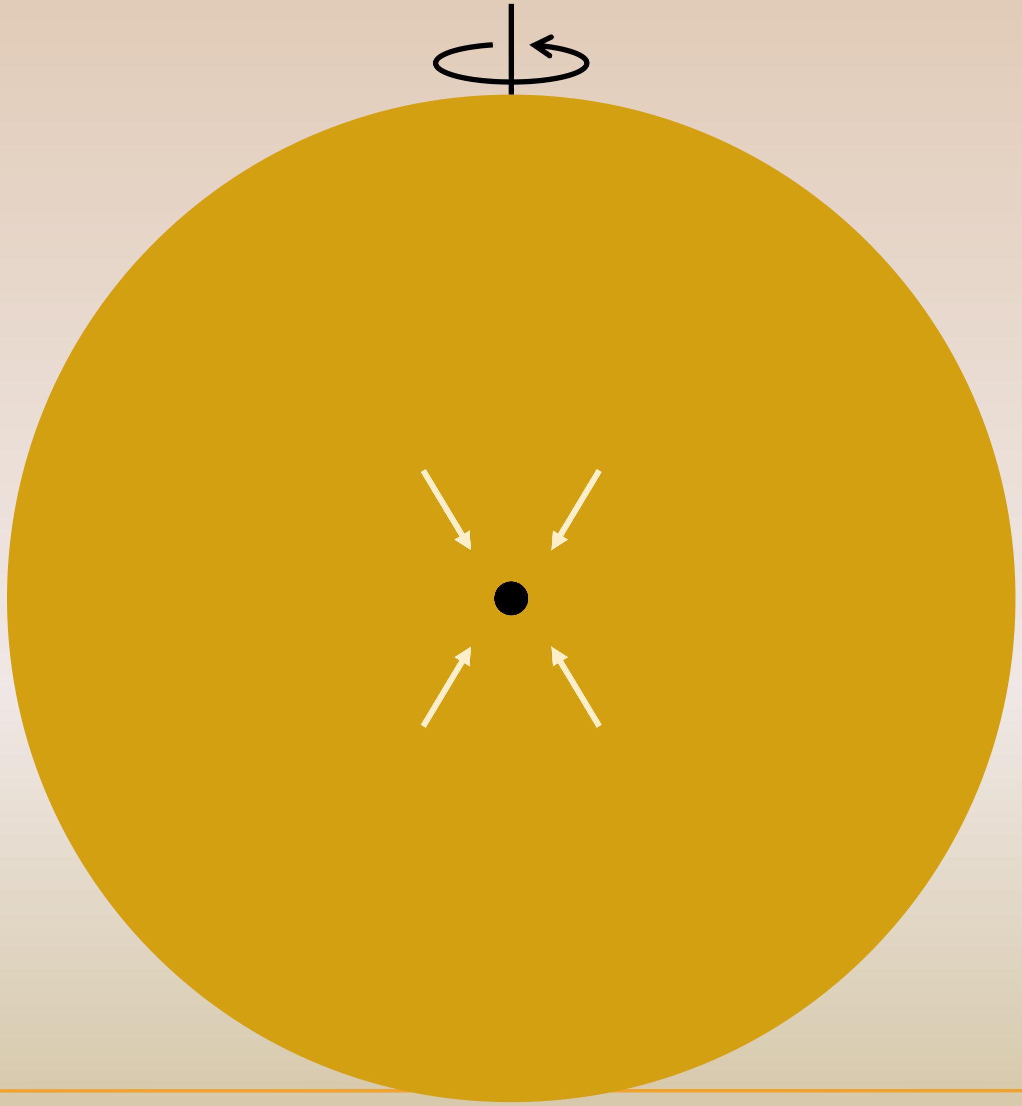
1. Physical Structure

Inside-out collapse

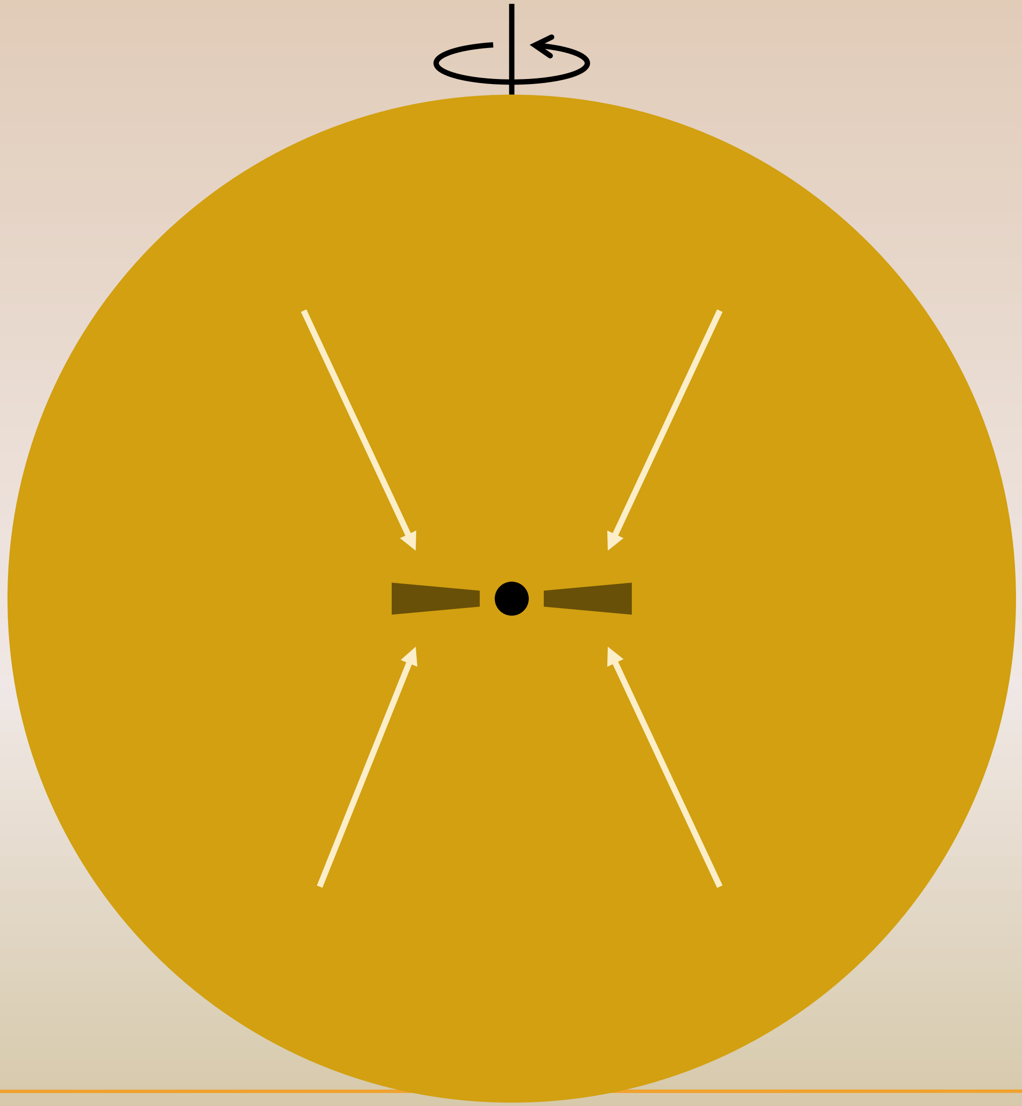
- Analytical solution of fluid equations
- $n \propto R^{-2}$ outside collapse front, tends to $R^{-1.5}$ inside
- Rotation or magnetic field breaks spherical symmetry, forms disk
- Realistic initial conditions?

Shu (1977), Terebey, Shu & Cassen (1984), Galli & Shu (1993a,b)

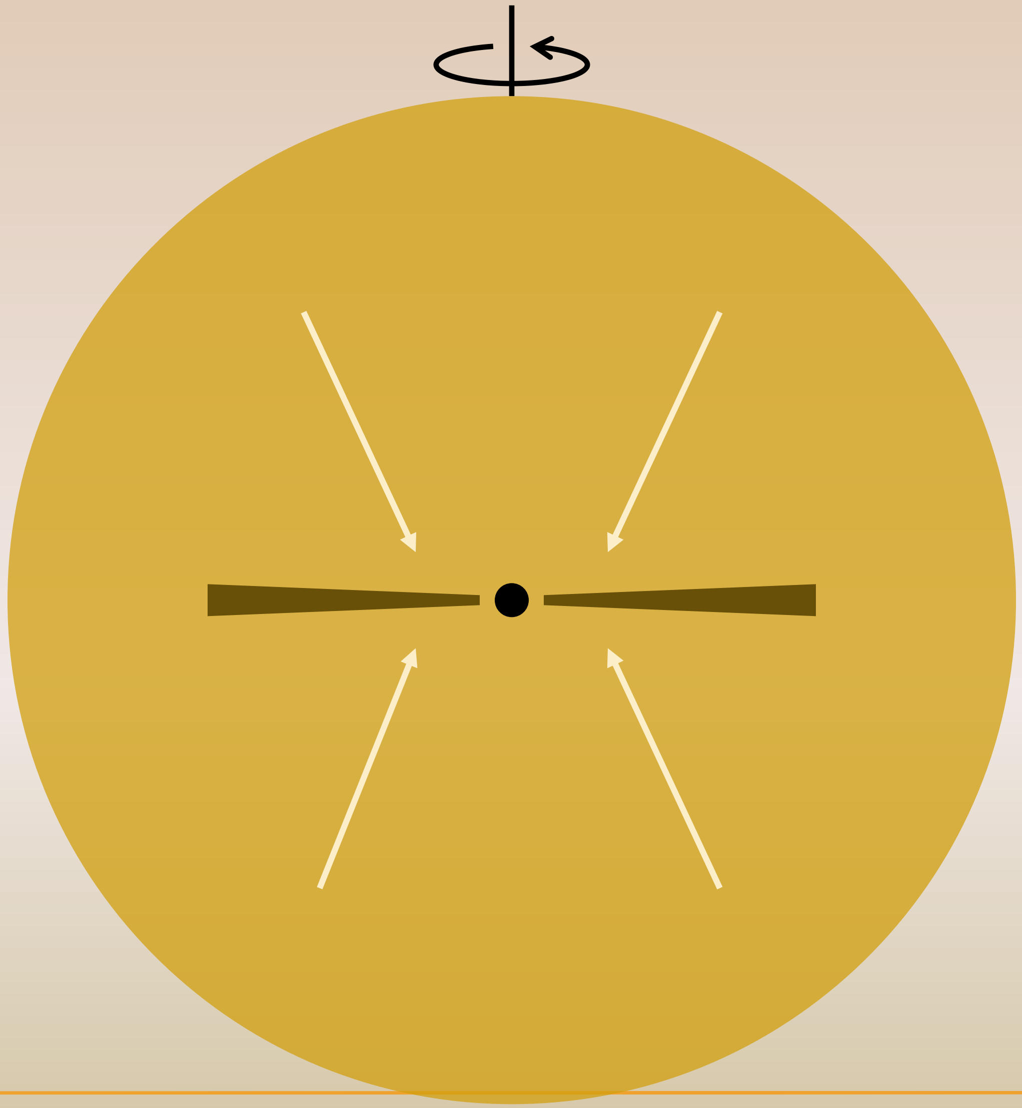
Disk formation and spreading



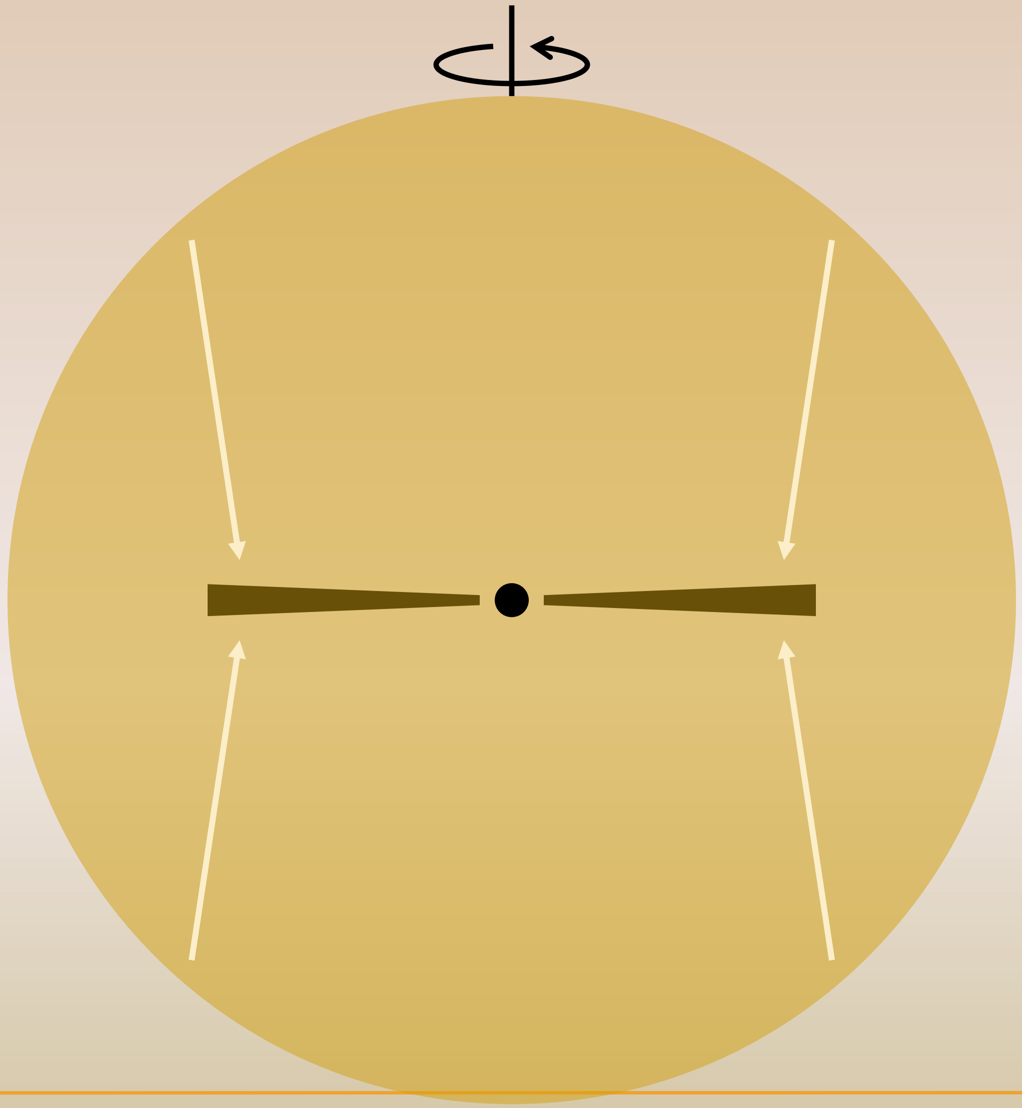
Disk formation and spreading



Disk formation and spreading



Disk formation and spreading



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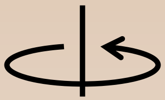
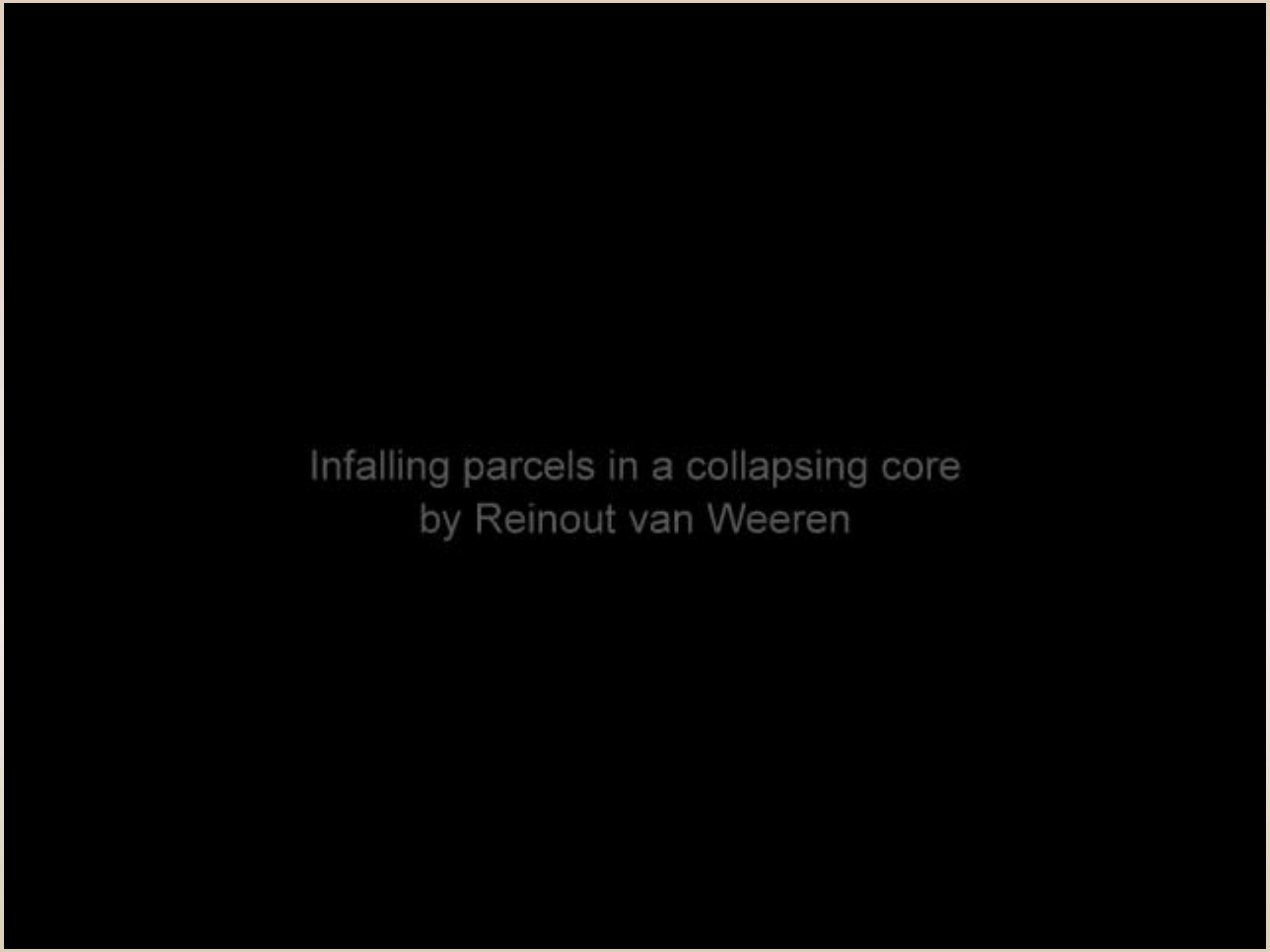
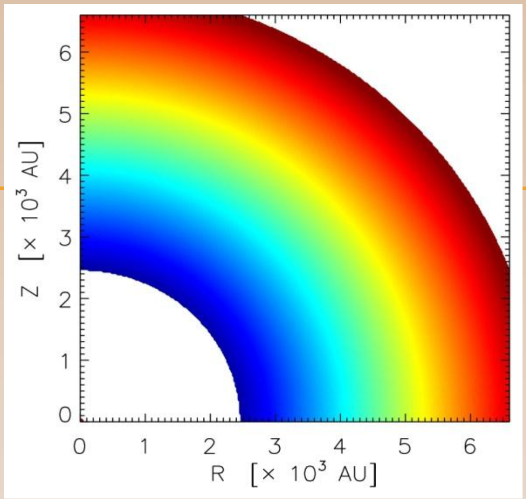


Flow of matter



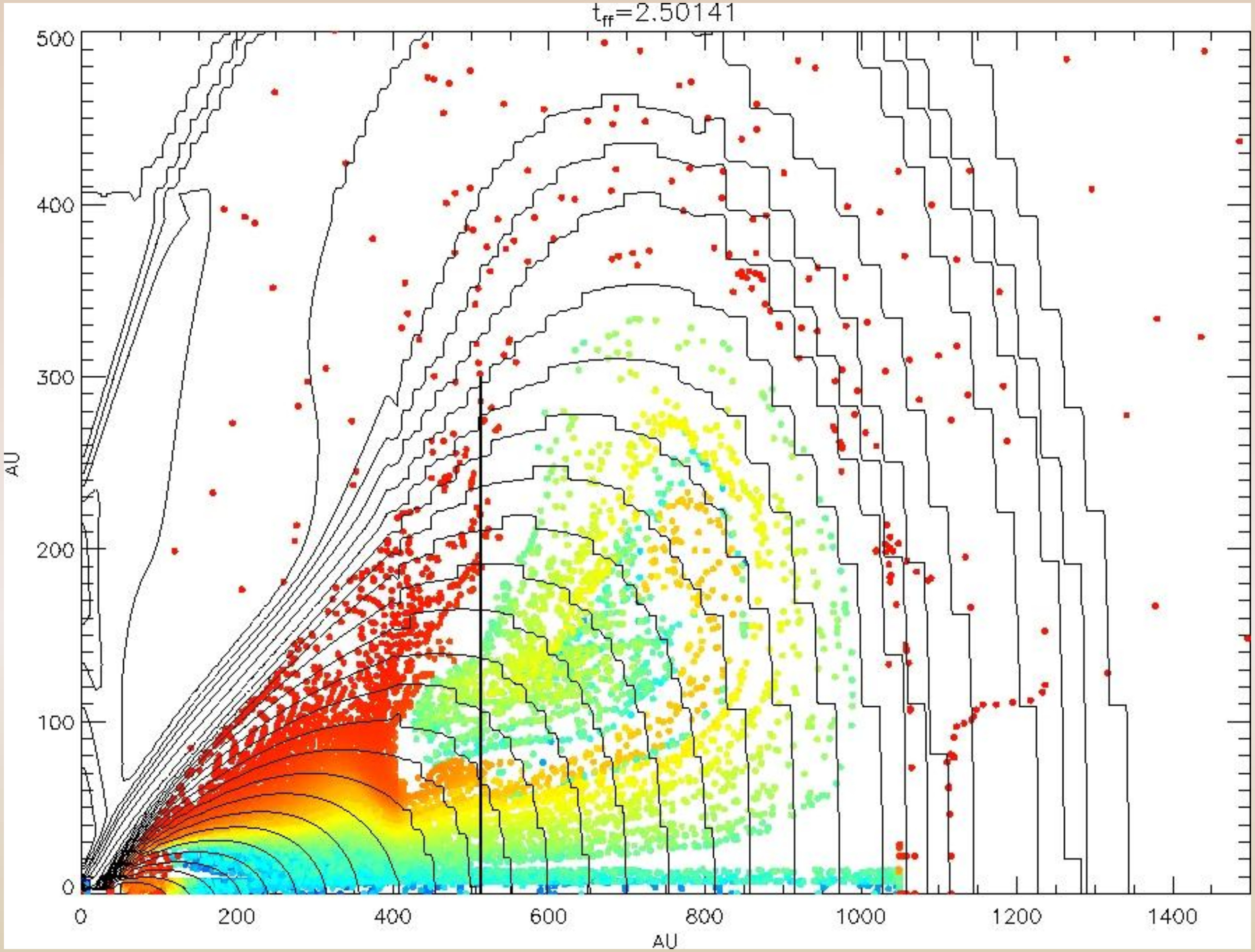


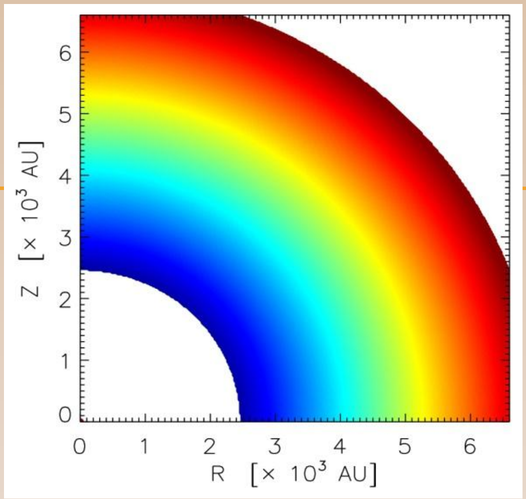
Note:

- Spreading of disk
- Accretion on top and at outer edge
- Inner envelope ends up at midplane
- Outer envelope ends up at surface

Yorke & Bodenheimer (1999), Brinch et al. (2008a,b), van Weeren et al. (2009)

Flow of matter





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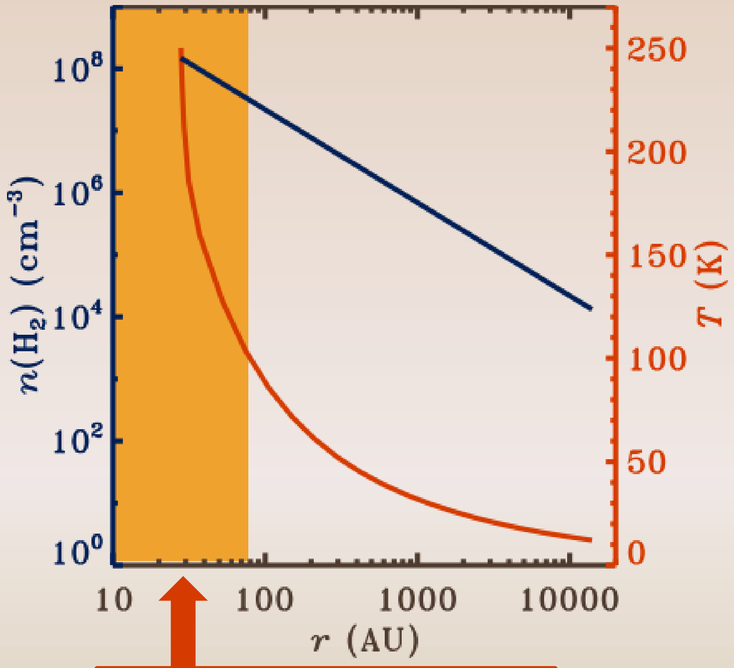
How to apply this to observations?

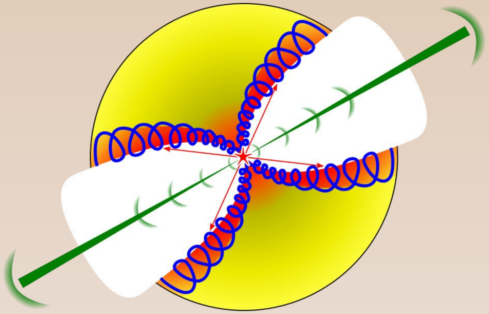
- Assume spherical power-law density: $n(H_2) \propto r^{-p}$
- DUSTY: 1d continuum RT (Ivezić & Elitzur 1997)
- Free parameters: p, r_{out}, τ_{100}, (r_{in}, L_*, T_*)
- Beware: protostars not spherical on 100 AU scales



Hot core/corino is poorly constrained

Schöier et al. (2002), Jørgensen et al. (2002), Crimier et al. (2010), Kristensen et al. (2012)

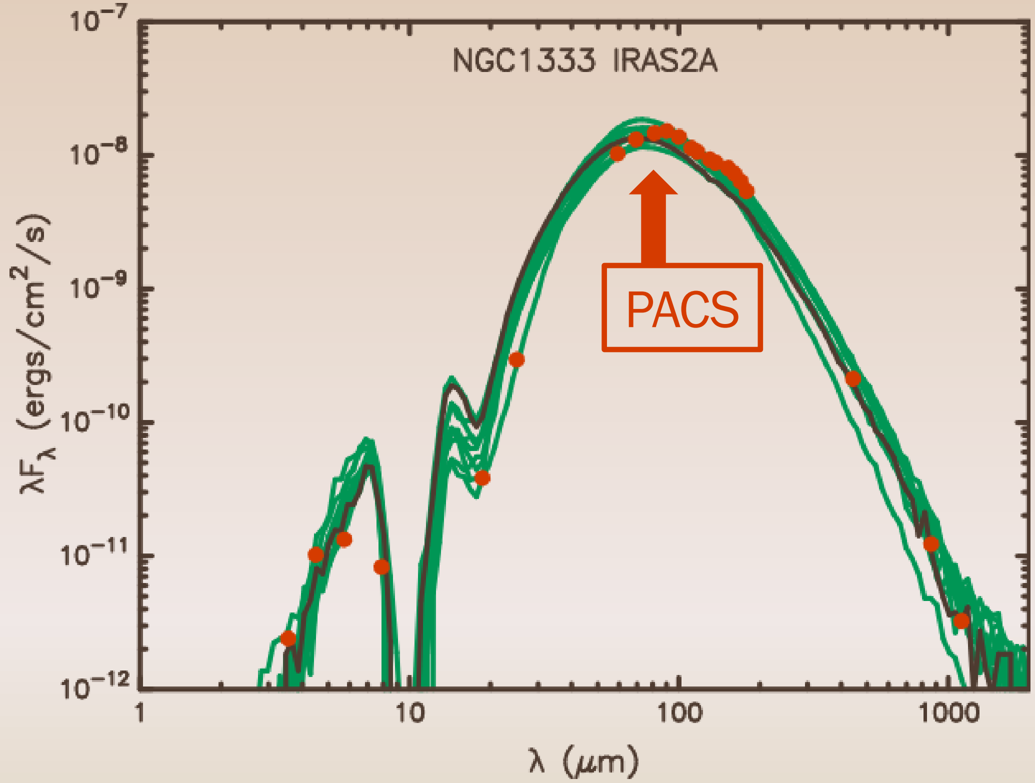
Beyond spherical power-law models



- Three physical components
  - Rotating collapsing envelope (Ulrich 1976, Terebey, Shu & Cassen 1984)
  - Bipolar outflow cavity (Whitney et al. 2003)
  - Flared disk (Chiang & Goldreich 1997)
- More model parameters (!)
  - Fix some, vary the rest (Whitney et al. 2003ab, Crapsi et al. 2008, Tobin et al. 2008, Fischer et al. 2010)
  - Explore everything (Robitaille et al. 2006)

A GRID OF 200,000 SEDS

- 15 free parameters
- Online SED fitter: www.astro.wisc.edu/ protostars
- Beware: solutions are degenerate



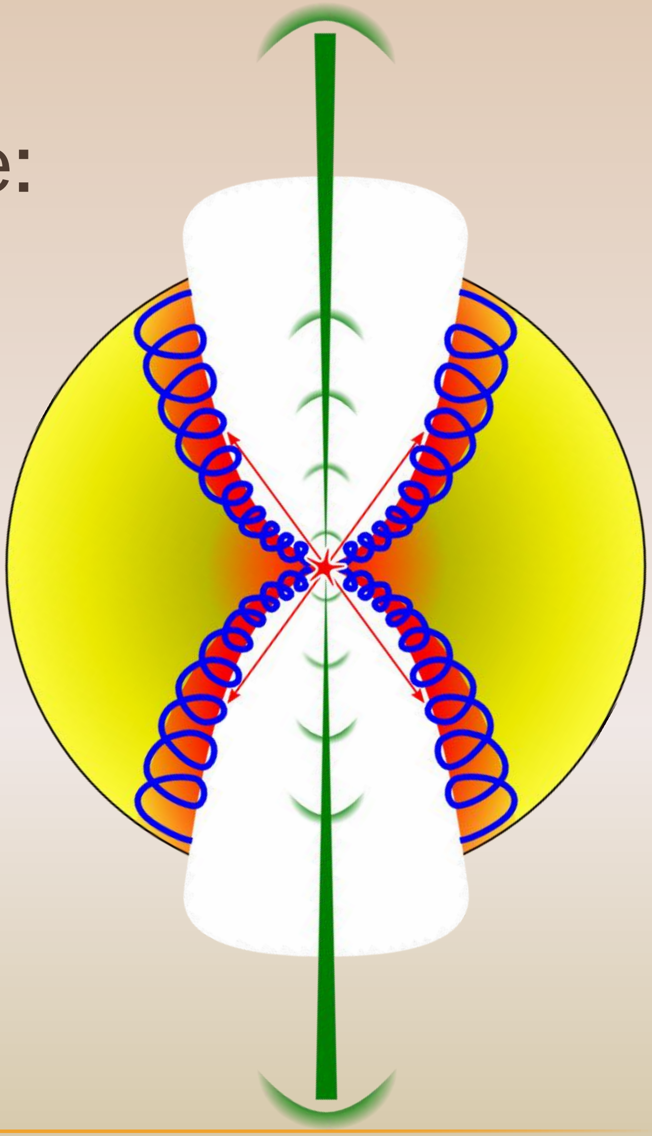
Herschel covers peak of SED:
key to constraining masses, temperatures

Robitaille et al. (2006); photometry from Froebrich (2005), Kristensen et al. (2012)

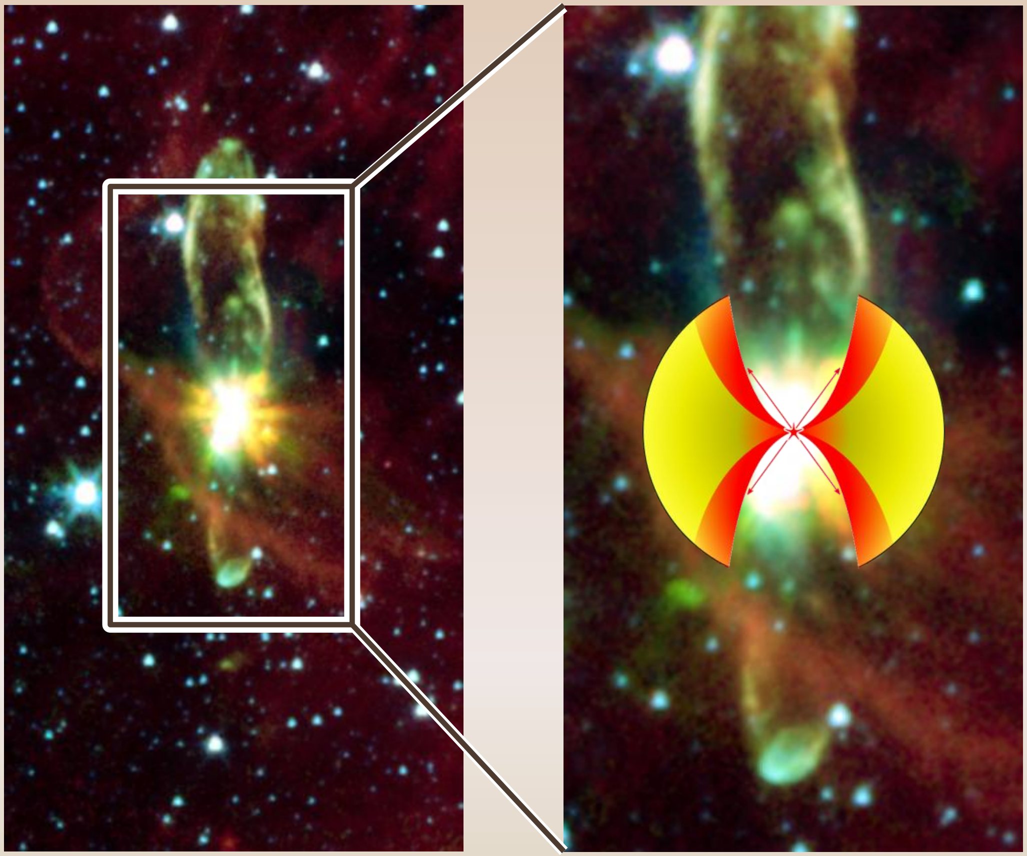
2. Energetic Feedback

Energetic feedback

- Components to characterize:
  - Jets, winds, shocks
  - UV
  - X-rays
- Questions:
  - Relative energy inputs
  - Spatial distribution
  - Effect on chemistry



How to quantify heating by UV and shocks?



HH46: Class I protostar (L_{bol} = 26 $L_{\odot}$)
Spitzer image from Velusamy et al. (2007)

Source structure

- $n(H_2)$, T_{dust} from SED
- Cavity shape from *Spitzer*

UV heating

- $T_{gas} = f(n_H, F_{UV}, A_V)$
- Problem: factor 10 spread in T_{gas} in literature

Shock heating

- T_{gas} from 1D shock models
- Uncertainties unknown

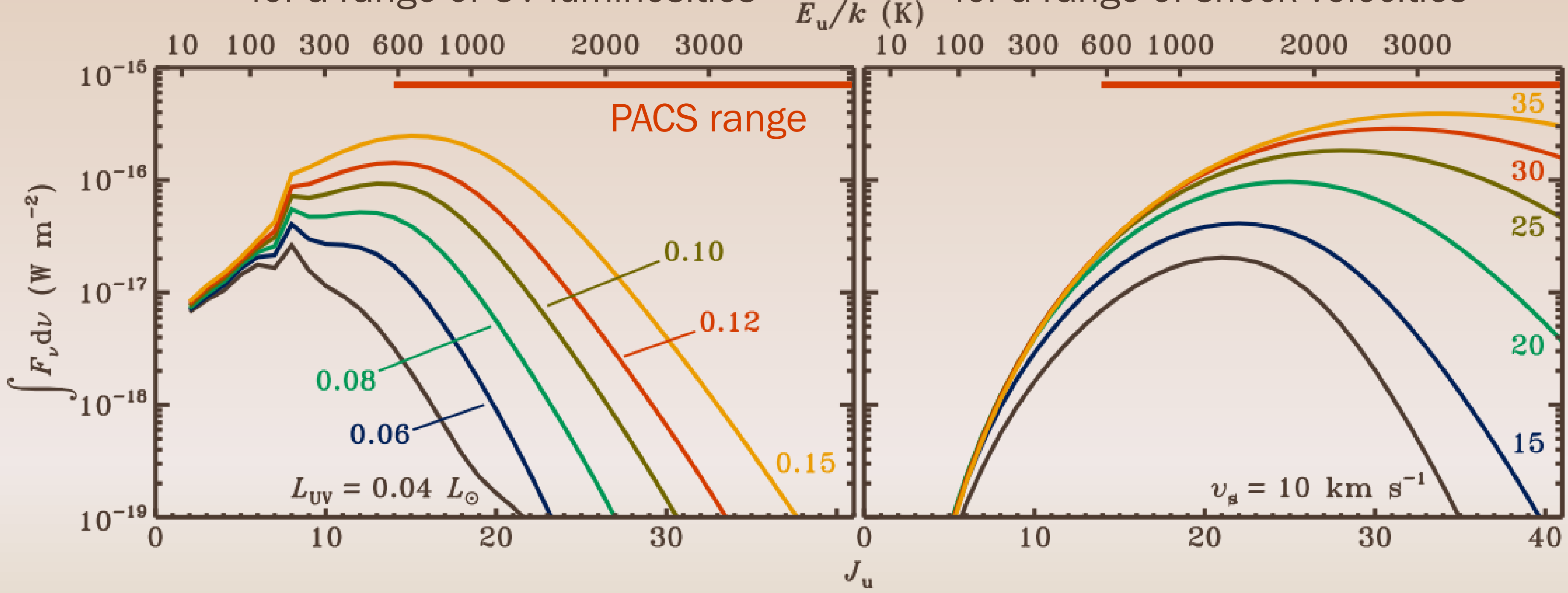
"Typical" temperatures

- UV: few 100 K
- shocks: few 1000 K

CONSTRAIN L_{UV}, V_S FROM HIGH-J CO EMISSION

UV heating
for a range of UV luminosities

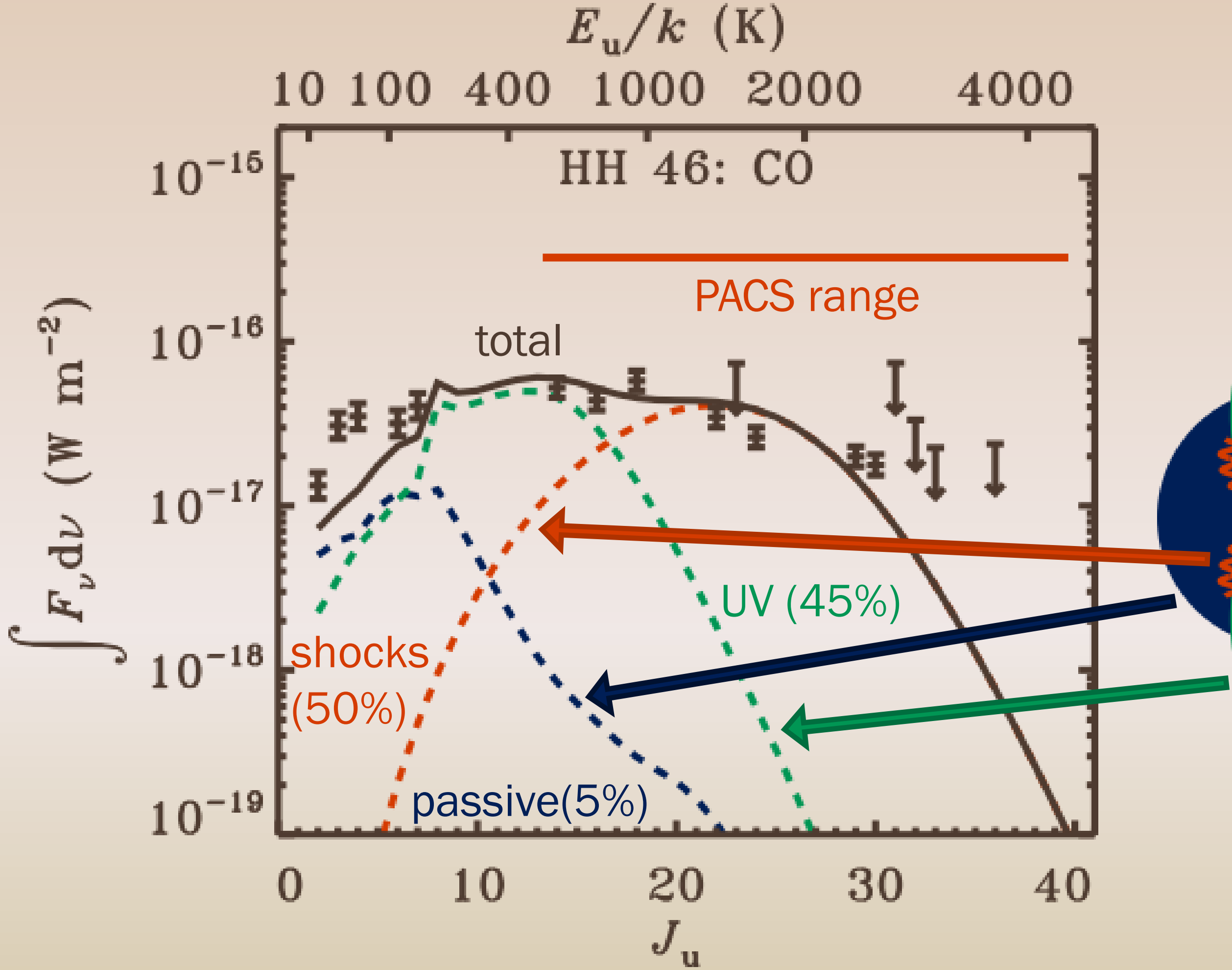
shock heating
for a range of shock velocities



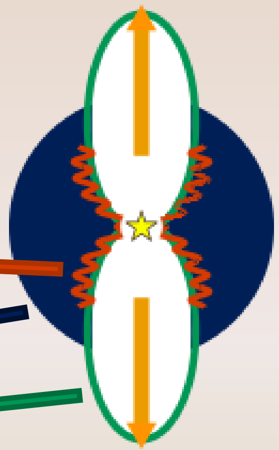
UV-heated gas emits at lower J than shocked gas

Visser et al. (2012)

CO LADDER DECOMPOSITION FOR HH 46

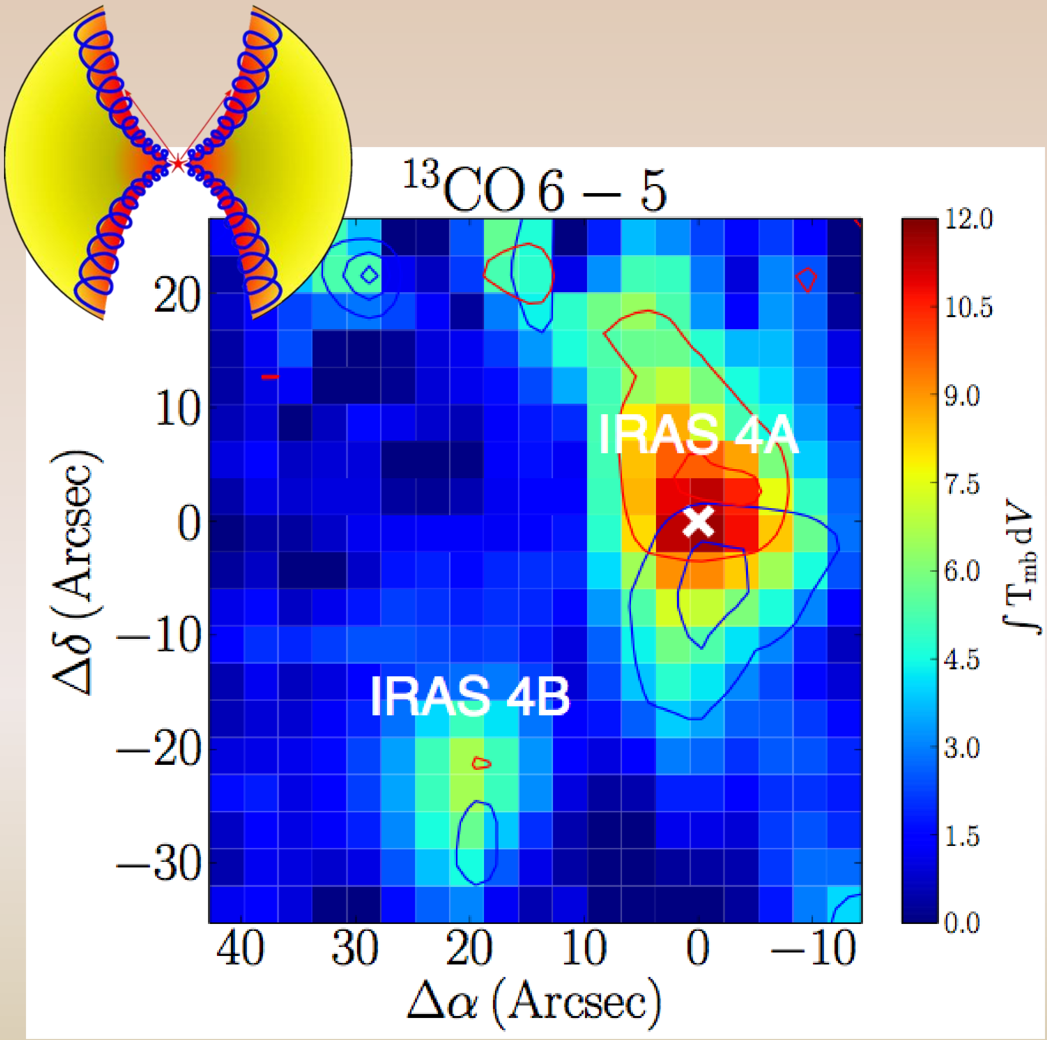


Class I
d = 450 pc
L_{bol} = 26 $L_\odot$
M_{env} = 1.7 $M_\odot$



van Kempen et al. (2010), Visser et al. (2012)

DIRECT EVIDENCE OF UV-HEATED GAS



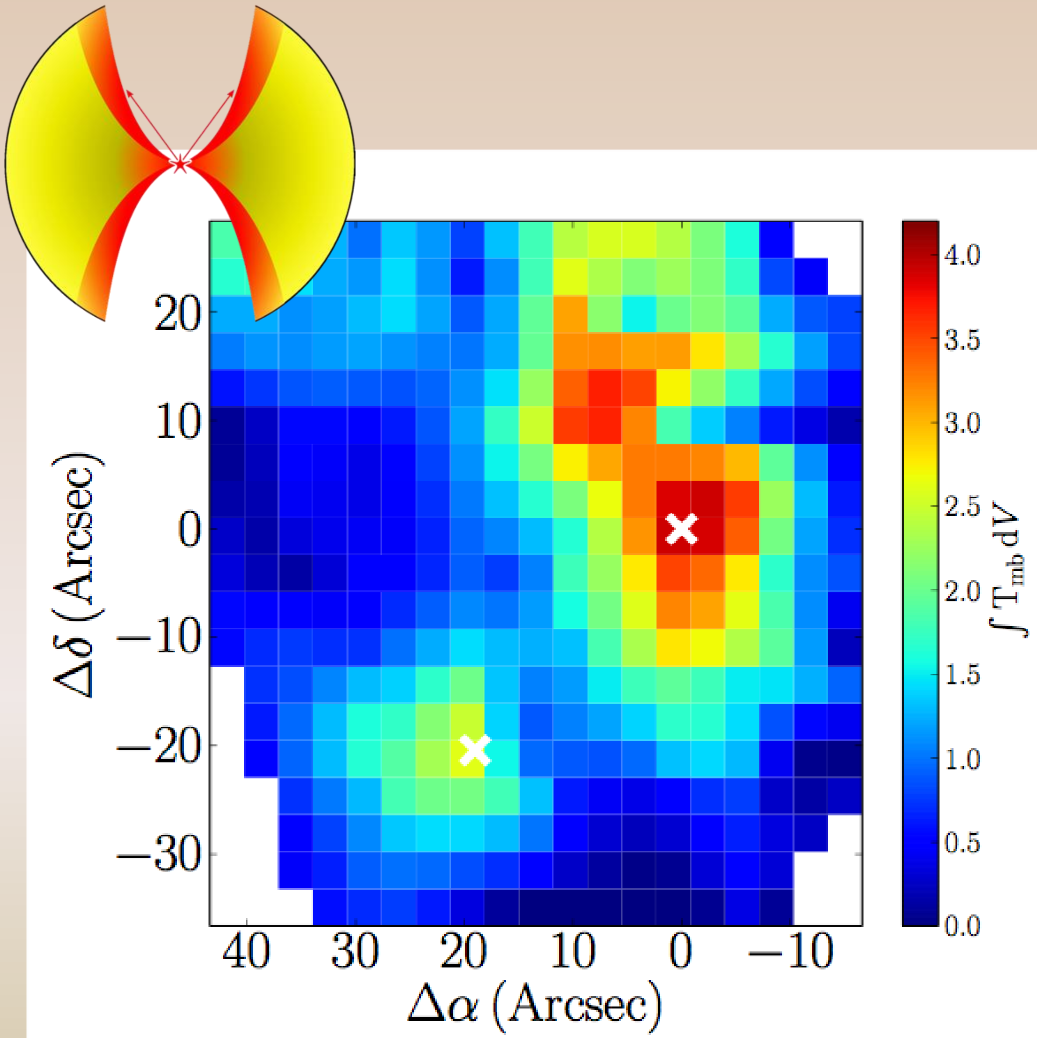
Observed Spectra

- ^{13}CO 6–5 in NGC1333 IRAS4A/4B with APEX
- IRAS 4A: mass of UV-heated gas same or more than mass of outflow

Note that the intensity scale changes

Yıldız et al. (2012)

DIRECT EVIDENCE OF UV-HEATED GAS



Observed Spectra – Outflow

- ^{13}CO 6–5 in NGC1333 IRAS4A/4B with APEX
- IRAS 4A: mass of UV-heated gas same or more than mass of outflow

Note that the intensity scale changes

Yıldız et al. (2012)

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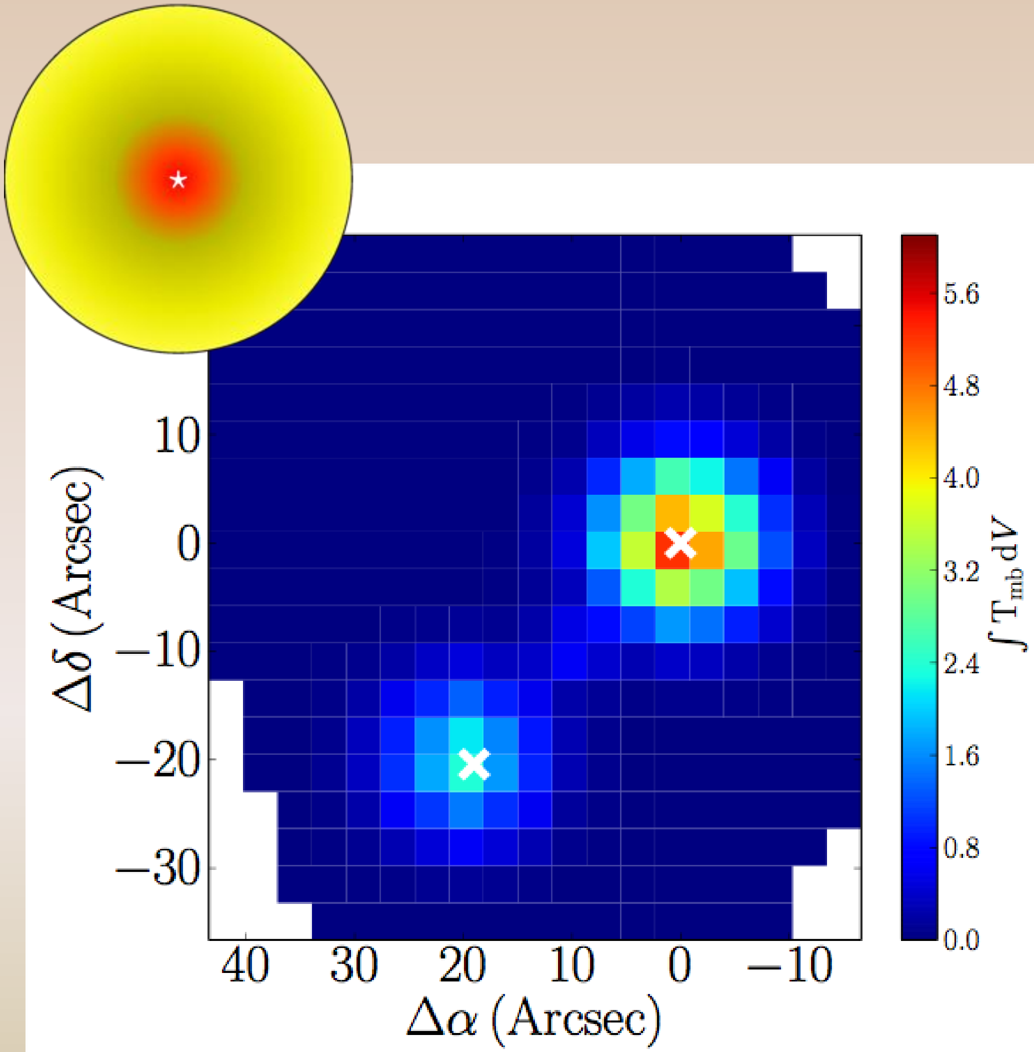

Observed Spectra
– Outflow
– Envelope Emission

- ^{13}CO 6–5 in NGC1333 IRAS4A/4B with APEX
- IRAS 4A: mass of UV-heated gas same or more than mass of outflow

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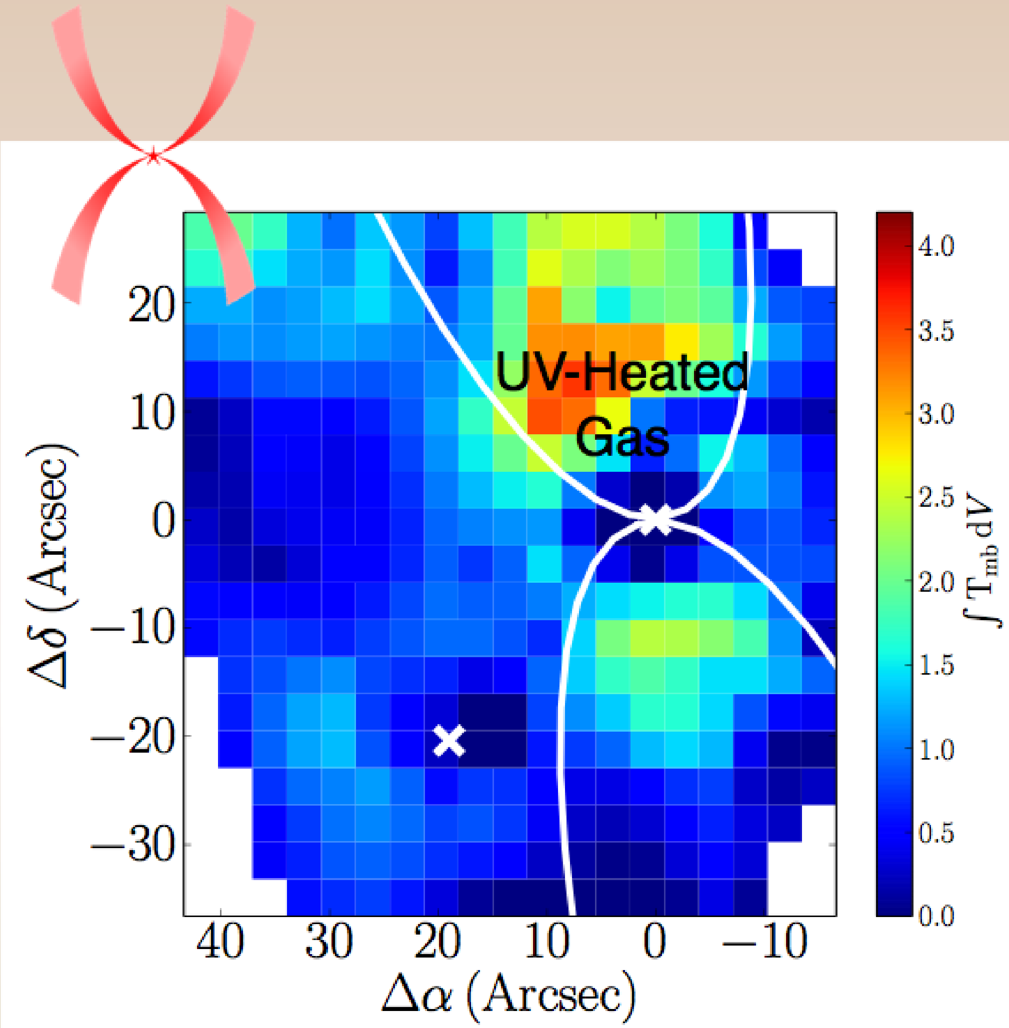

Observed Spectra
− Outflow
− Envelope Emission
= UV heated gas

- ^{13}CO 6–5 in NGC1333 IRAS4A/4B with APEX
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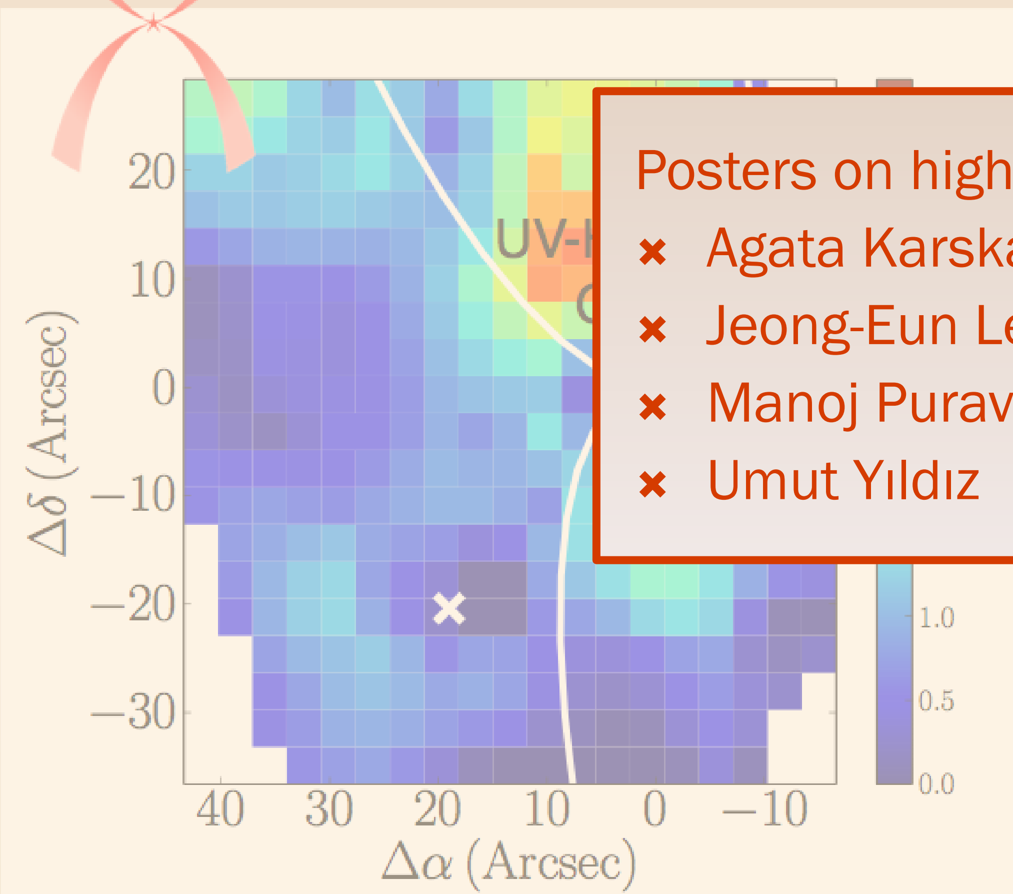
Yıldız et al. (2012)

DIRECT EVIDENCE OF UV-HEATED GAS



Posters on high-*J* CO

- Agata Karska
- Jeong-Eun Lee
- Manoj Puravankara
- Umut Yıldız

Observed Spectra

flow

elope Emission

heated gas

O 6–5 in NGC1333

S4A/4B with APEX

- IRAS 4A: mass of UV-heated gas same or more than mass of outflow

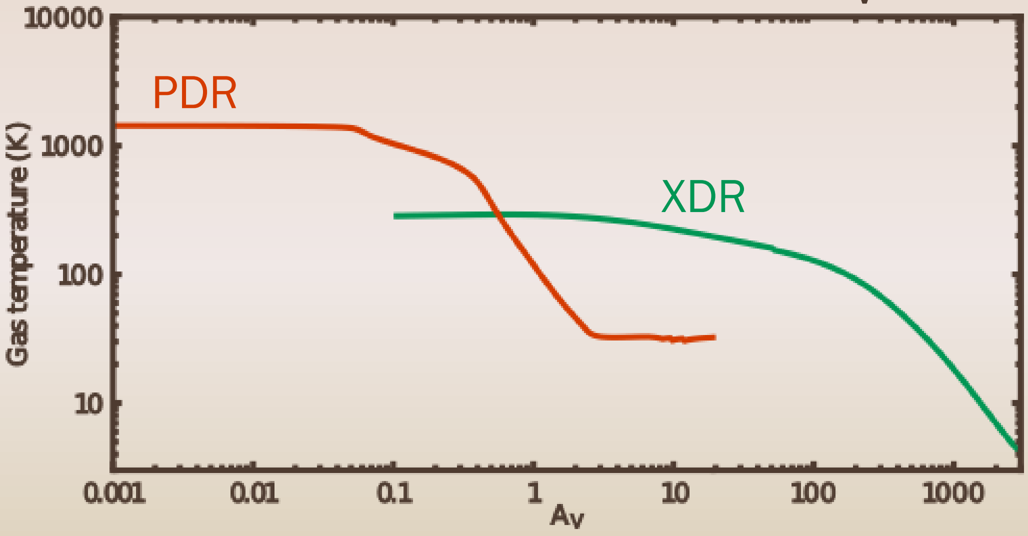
Note that the intensity scale changes

Yıldız et al. (2012)

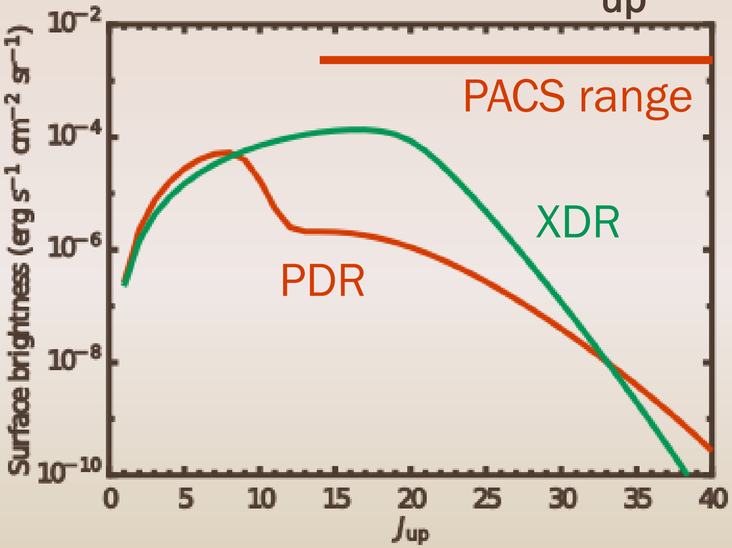
PDRs versus XDRs

$n(H_2) = 10^6$ cm^{-3}, $F_{UV} = F_X = 27$ erg s^{-1} cm^{-2} ($\chi = 10^4$)

Gas temperature vs. A_V



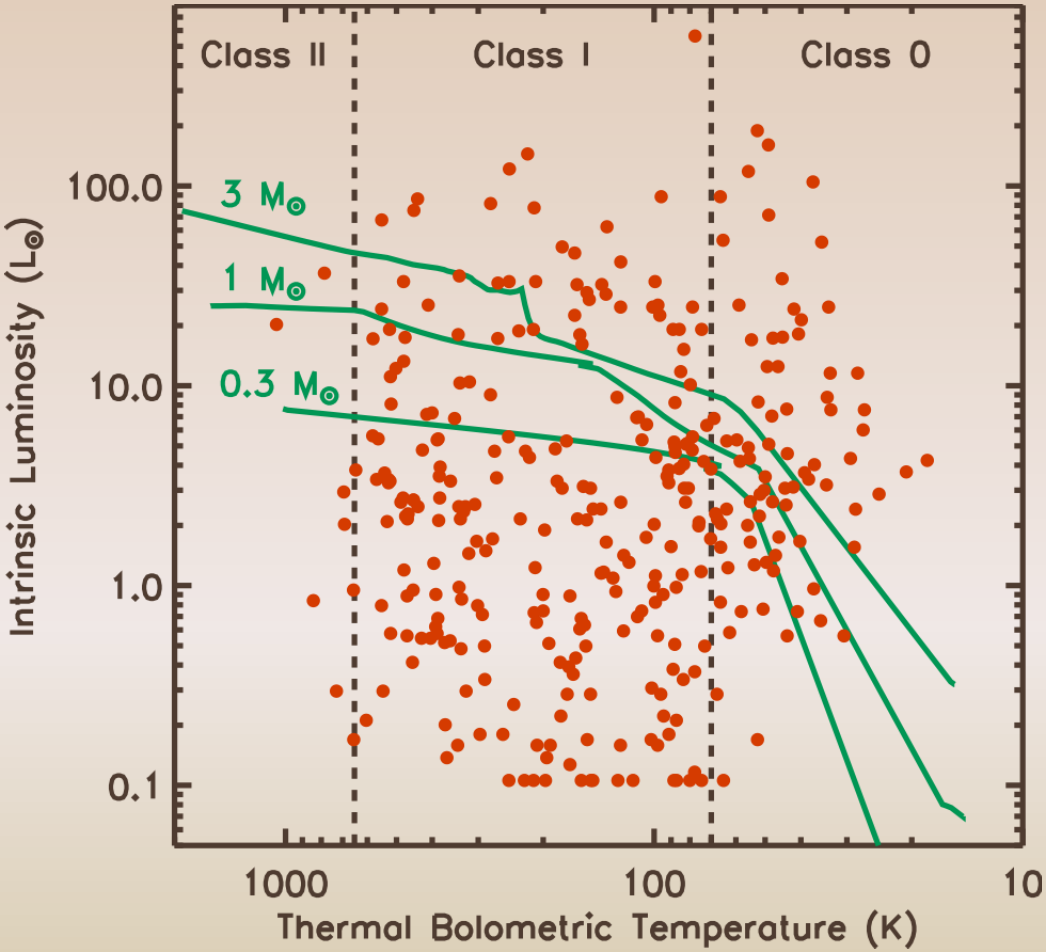
CO line flux vs. J_{up}



models by Simon Bruderer; see also extragalactic papers

3. Episodic Accretion

THE LUMINOSITY PROBLEM

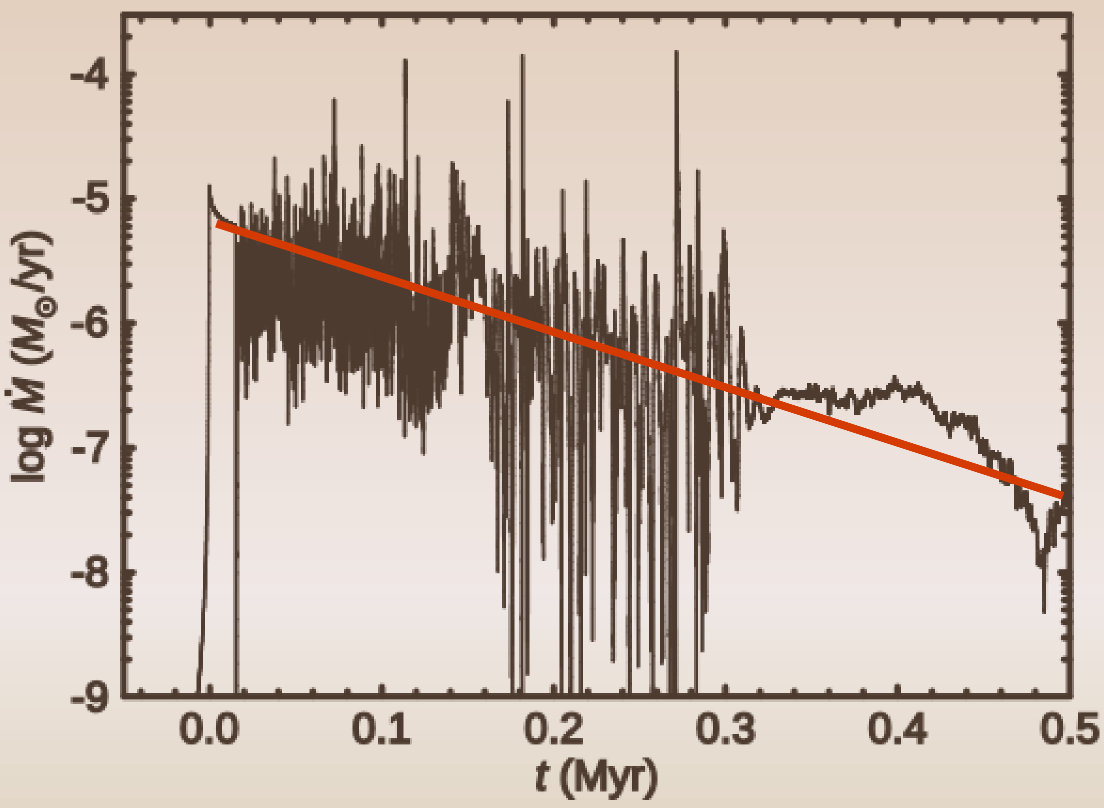


- $L_{acc} \propto M_* \dot{M}$
- Theoretical *L* factor 100-1000 higher than observed
- Episodic accretion?

combined c2d + HOPS samples

Kenyon et al. (1990, 1994, 1995), Enoch et al. (2009), Evans et al. (2009)

HYDRODYNAMICAL SIMULATIONS



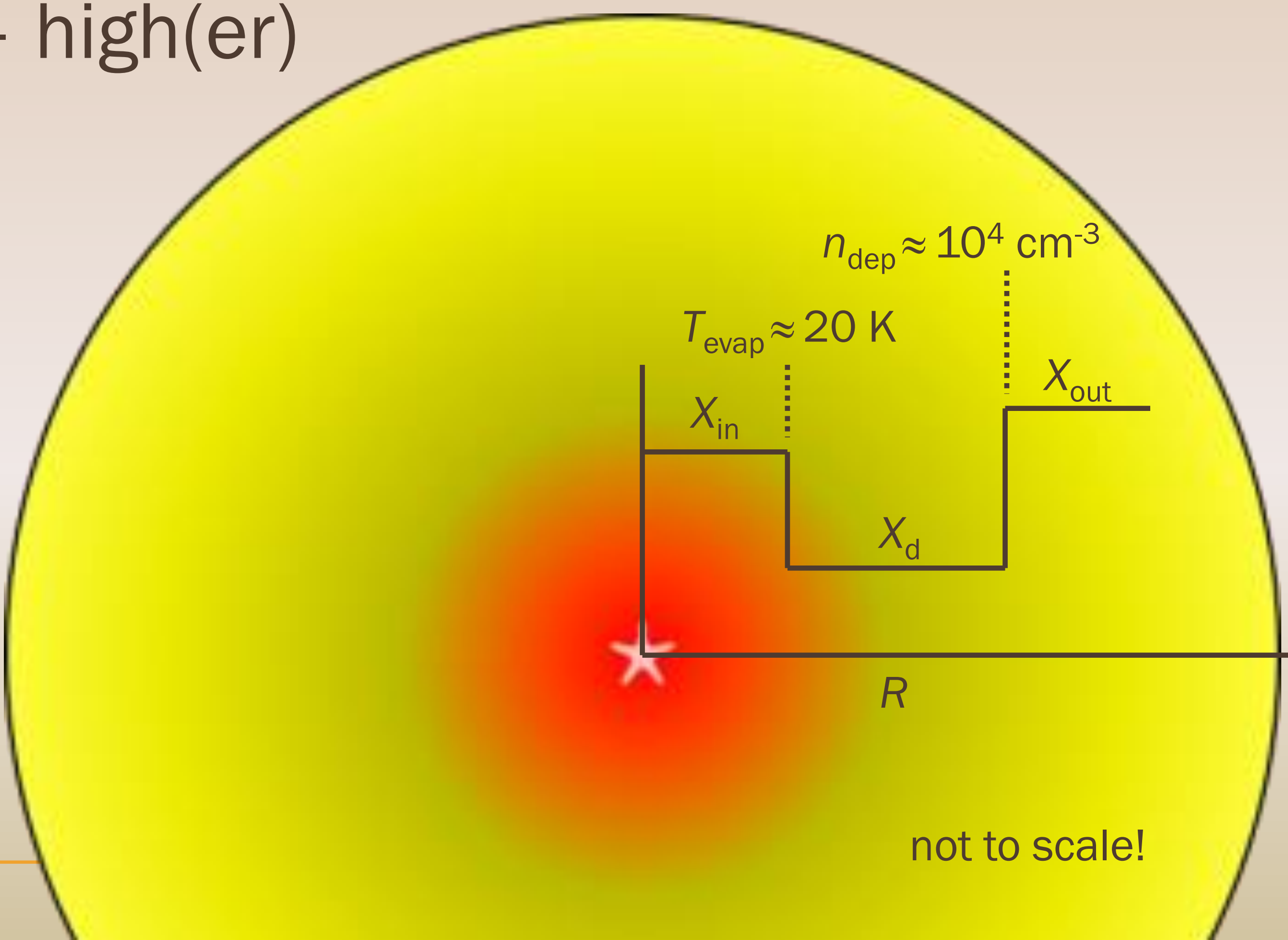
- Variability on 10^2–10^4 yr timescales
- Reproduces L_{bol}, T_{bol} distributions
- Repeated heat-cool cycles may affect chemistry

Vorobyov & Basu (2005–10), Zhu et al. (2009–10), Dunham & Vorobyov (2012)

4. Chemistry

PARAMETERIZED ABUNDANCE PROFILES: CO

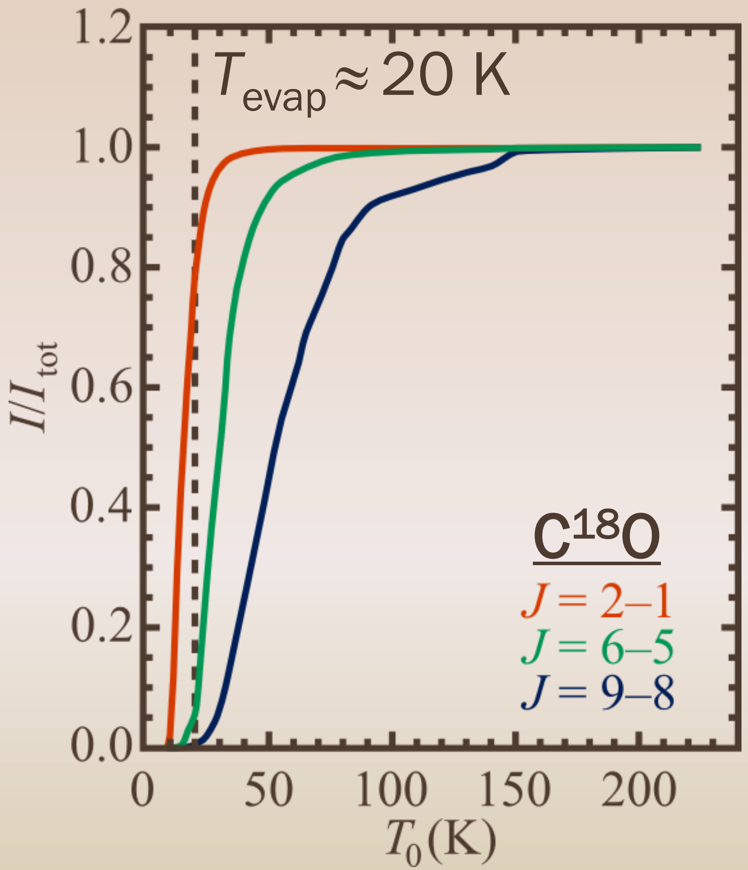
- Drop abundance:
  high – low – high(er)



Parameterized abundance profiles: CO

- Drop abundance: high – low – high(er)
- Pre-Herschel problem: only 20% of low-J flux from $T > 20$ K
- Herschel data: X_{in} factor 3–7 below canonical

Fraction of line flux emitted at $T < T_0$



Yıldız et al. (2010)

Chemistry problems initiated by Herschel

- Hot cores/corinos are dry (first hinted at by ISO)
  - $X(H_2O) = (1–5)\times10^{-6}$ in three low-mass sources
  - X-ray chemistry? (cf. Stäuber et al. 2006)
- Diversity in HDO/H_2O
  - <0.0006 to 0.03 in three hot cores
  - <0.005 to >0.01 in three cold envelopes
- Water o/p ratio: ~3 or lower?
- Nitrogen chemistry models
  - NH, NH_2 are fine, NH_3 underproduced

Hily-Blant et al. (2010), Coutens et al. (2012), Visser et al. (in prep.)

Models

are a means,

not an end

Take-home messages

Herschel offers great constraints on SED modeling, energetic feedback and chemistry

Hot cores are dry

High-*J* CO is ubiquitous in protostars; origin in UV- and shock-heated gas?