Modelling Herschel Observations of Hot Gas Emission in Low-Mass YSOs

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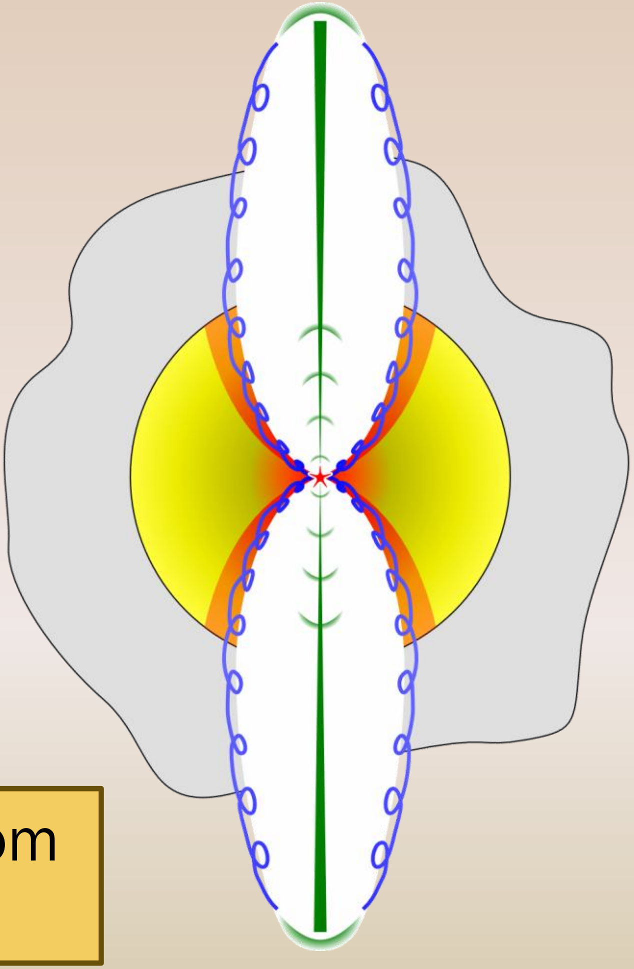
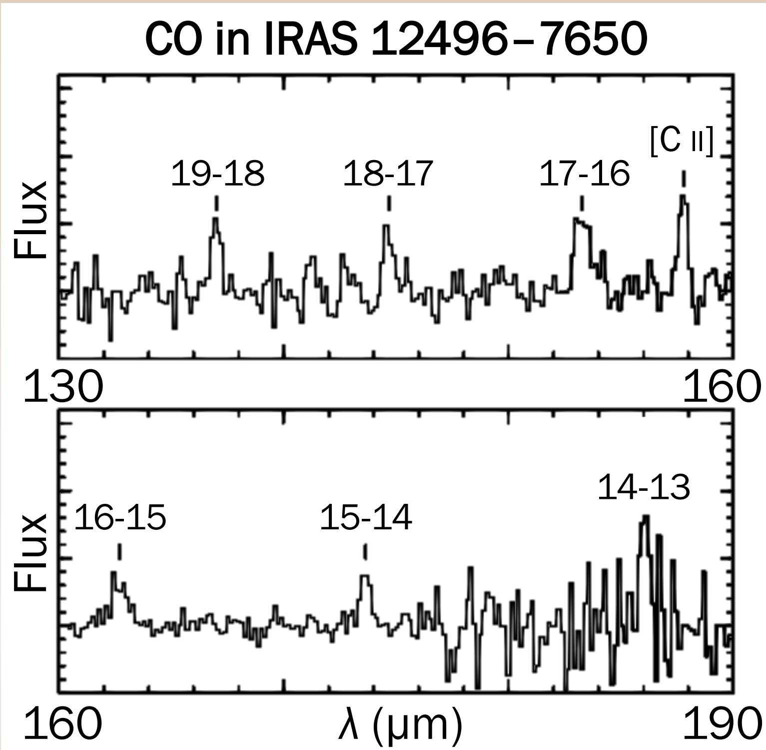
EMBEDDED PHASE OF STAR FORMATION

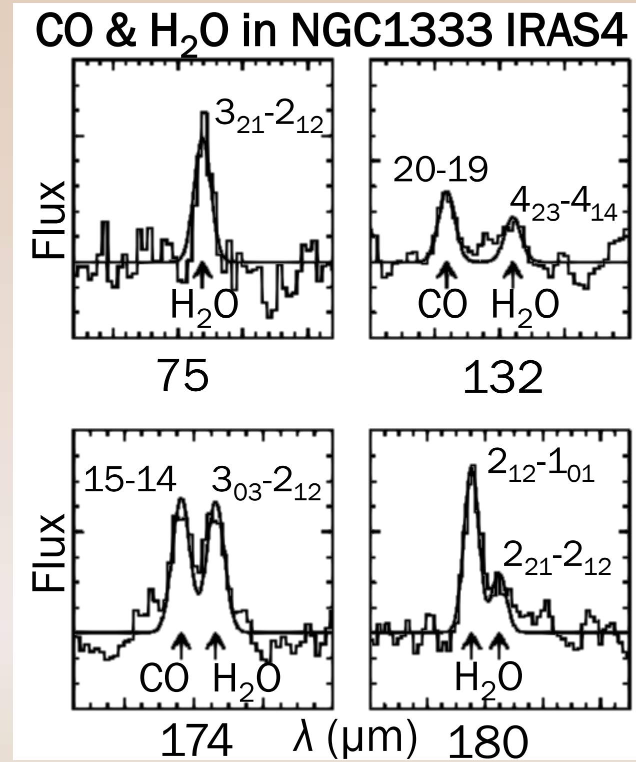
- Largely determines final $M_\star$
- Formation of protoplanetary disk
- Active chemistry (gas/grains)
- Violent and dynamic
  - Infalling envelope
  - Bipolar outflow
  - Jets and shocks
  - UV photons and X-rays



Science case: disentangle contribution from each component to observed emission

ISO: ROTATIONALLY EXCITED CO AND H_2O

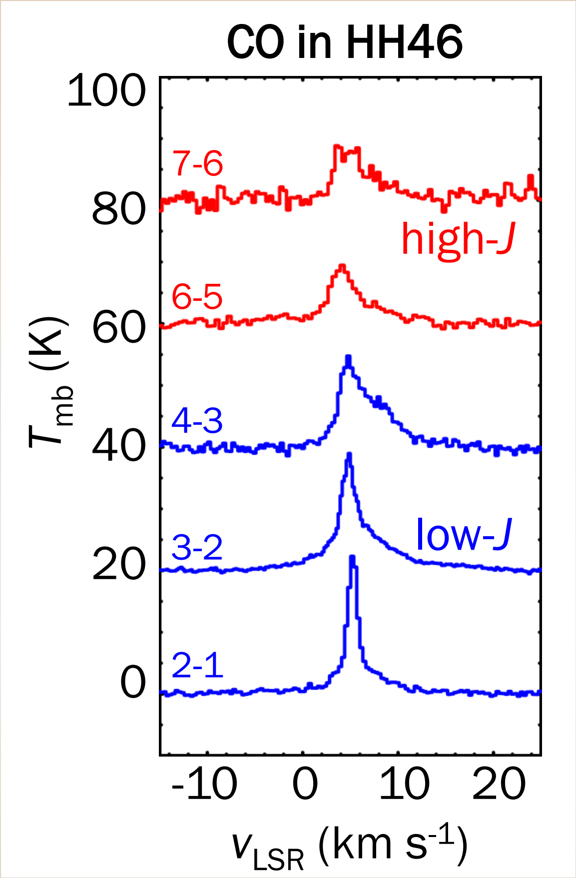




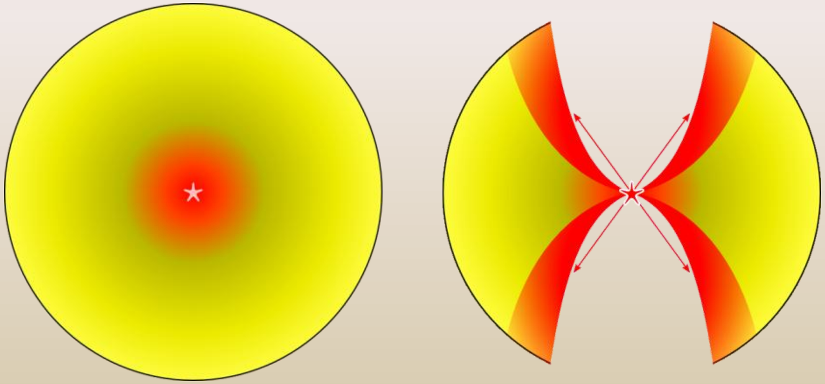
- CO up to $E_{up} \approx 1200$ K, H_2O up to $E_{up} \approx 400$ K
- Origin debated: dense inner envelope or shocks?

Giannini et al. (1999), Ceccarelli et al. (1999)

APEX: CO 2-1 UP TO 7-6



- High-*J* lines underproduced by spherical envelope model
- Narrow width of high-*J* lines argues against shocks
- Likely origin: hot gas in walls of outflow cavities



Spaans et al. (1995), van Kempen et al. (2009)

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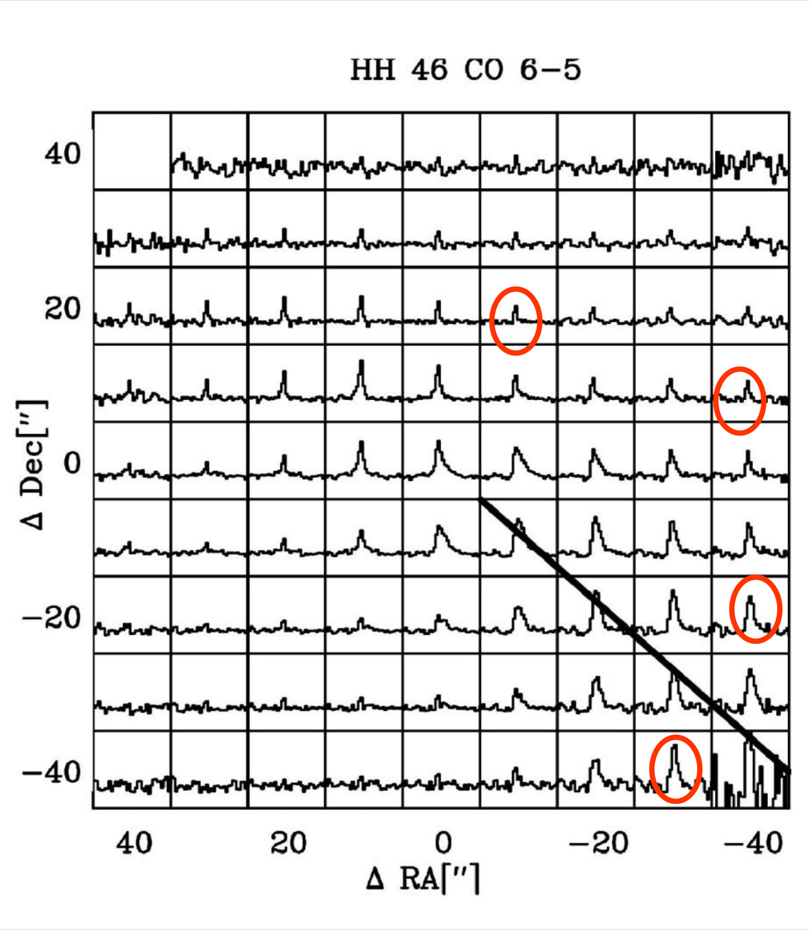

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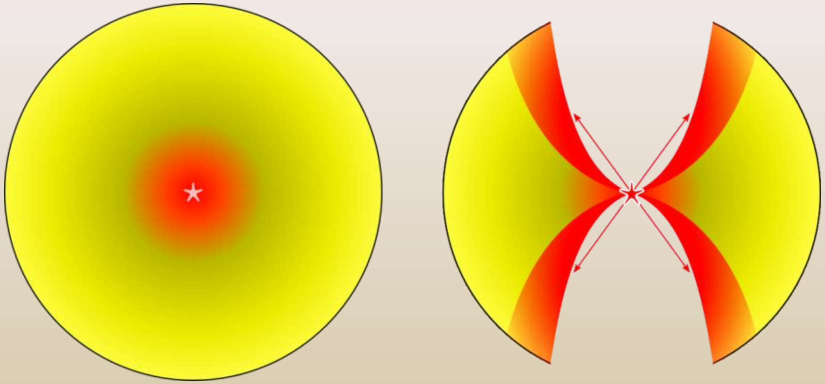
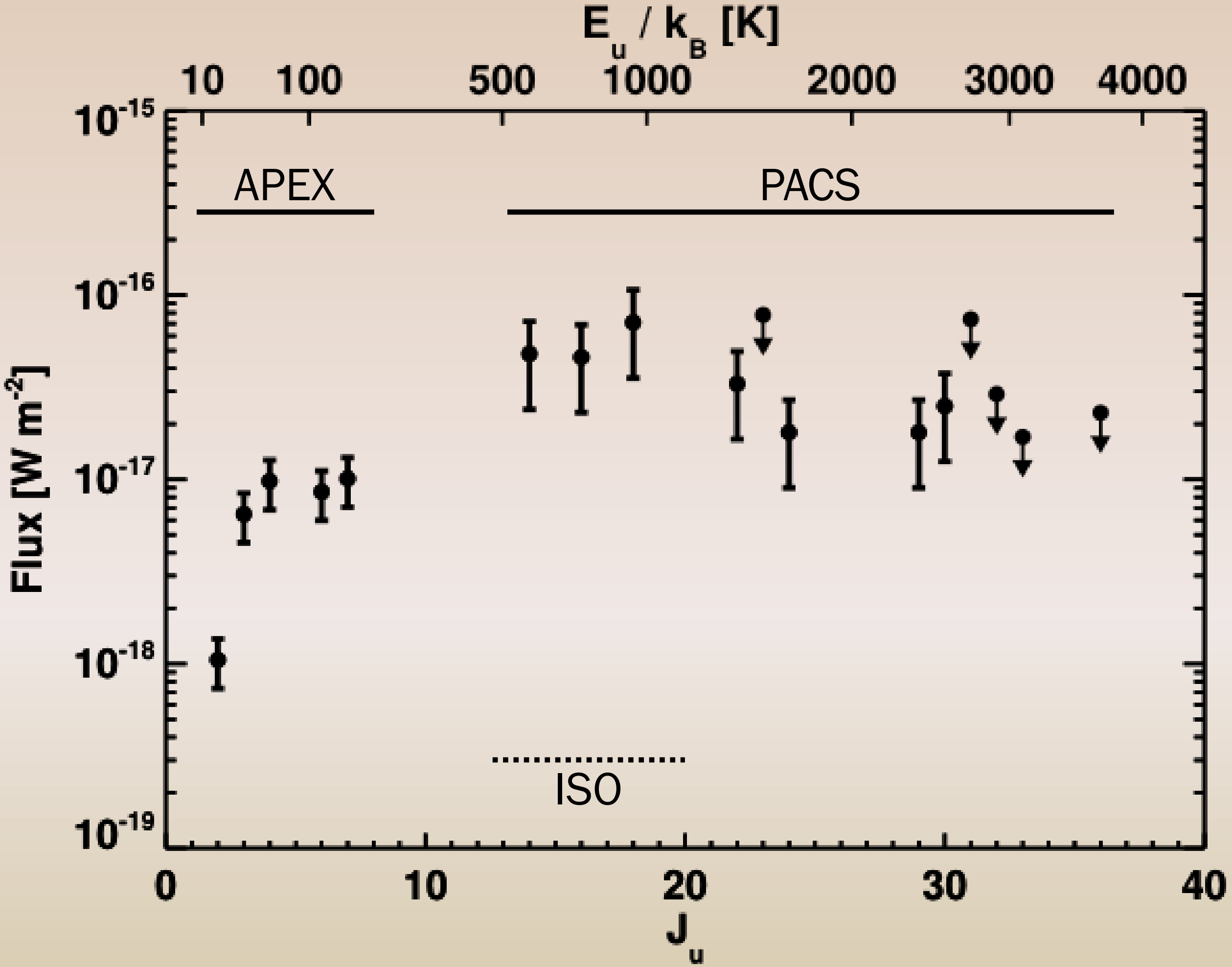


Spaans et al. (1995), van Kempen et al. (2009)

HERSCHEL-PACS: CO 14-13 UP TO 36-35

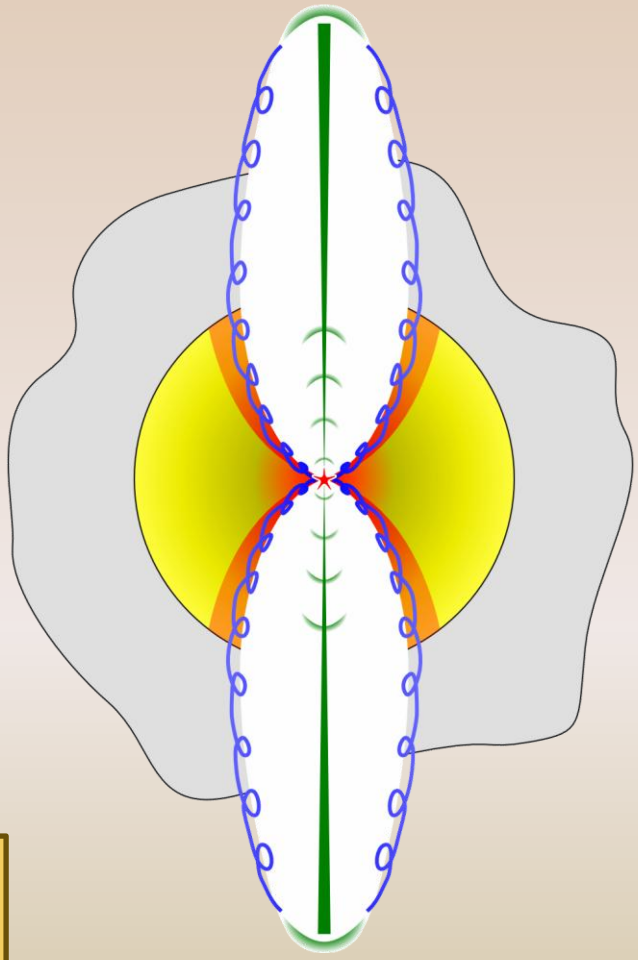


- CO detected up to 2700 K above ground state
- Origin of the cold and hot gas?
- Is it possible to reproduce the full ladder with models?

van Kempen, Kristensen, Herczeg, Visser, et al. (2010)

MODEL STEPS

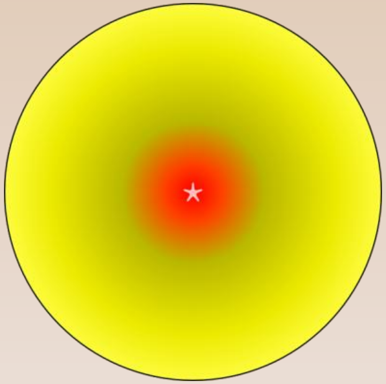
- Physical components:
  - Spherical envelope
  - Bipolar outflow cavity
  - Shocks along cavity wall
- Abundances from chemical network
- Compute line emission

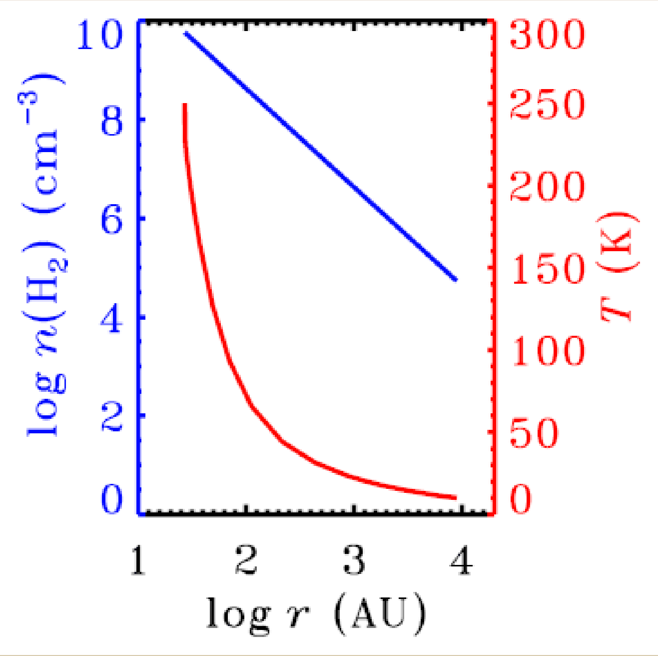


Put in what we think we know, see what comes out

PASSIVELY HEATED SPHERICAL ENVELOPE

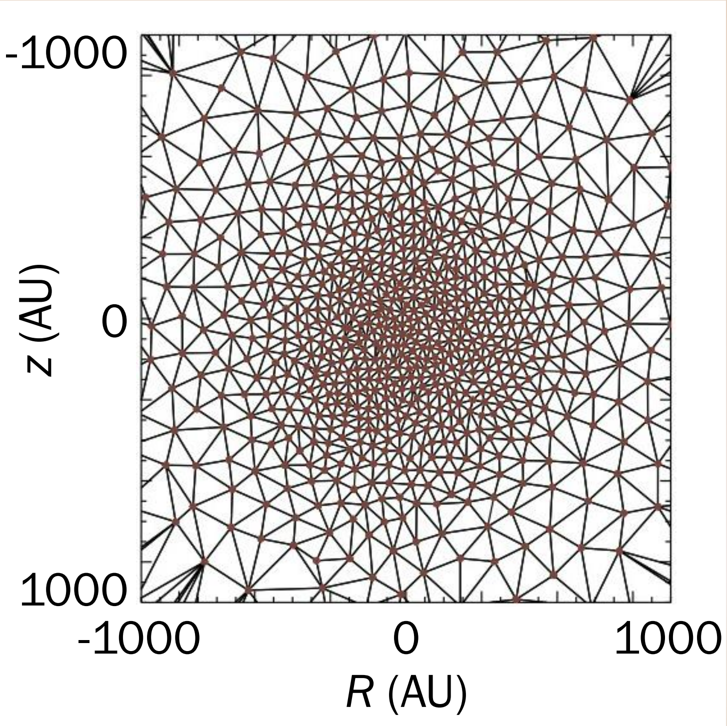
- Gas heated by protostellar luminosity
- Constrained from SED and sub-mm brightness profiles
- Power-law density
- T_{dust} from radiative transfer
- Gas-phase chemistry with:
  - freeze-out
  - photodesorption
  - thermal desorption,
  - photodissociation/ionization



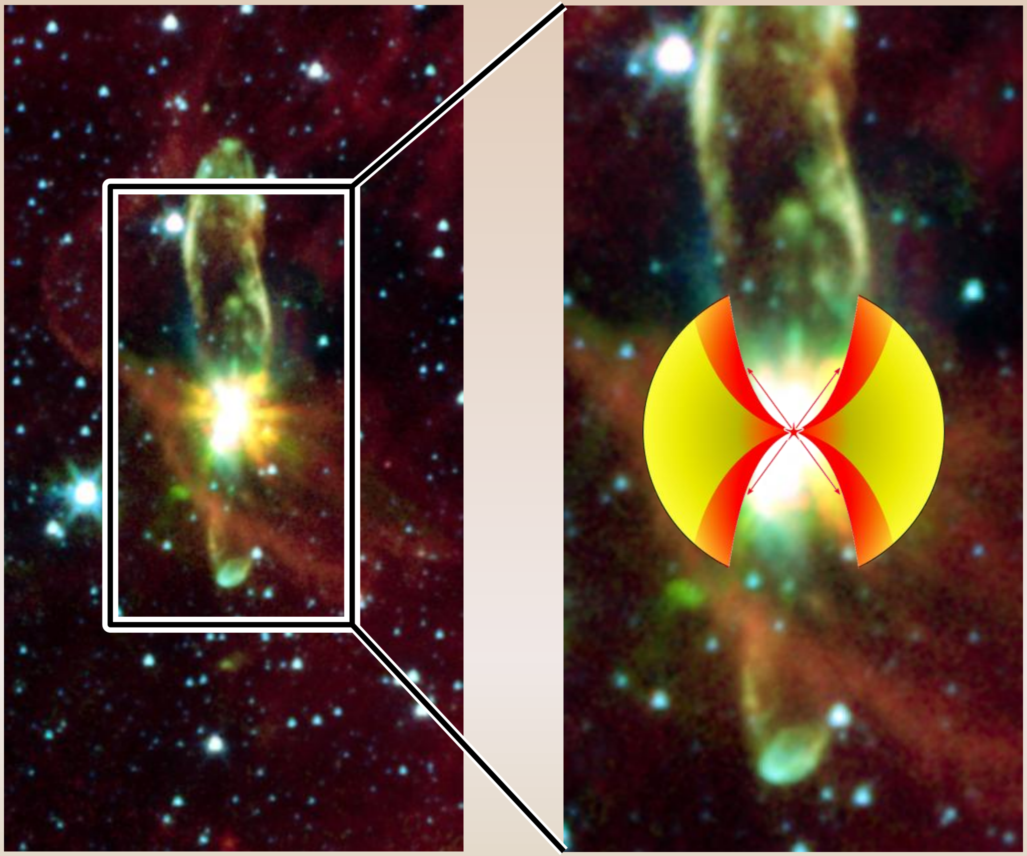


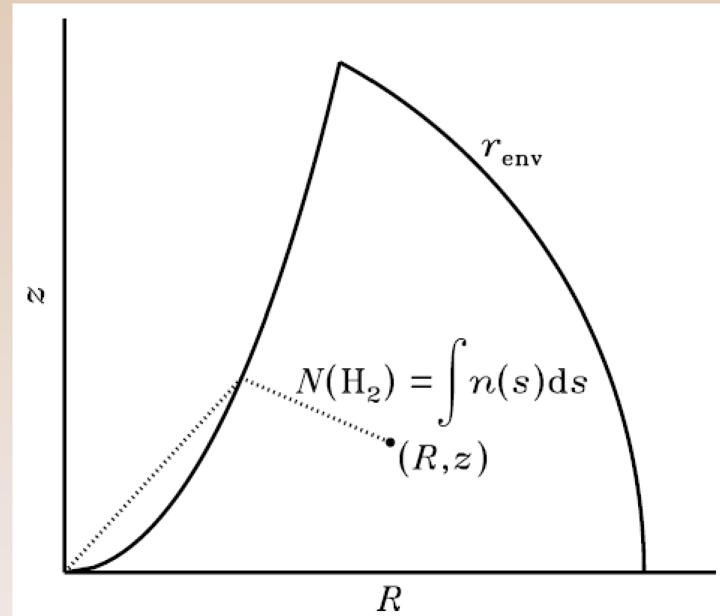
EXCITATION AND RADIATIVE TRANSFER

- LIME:
  Line Modelling Engine
  (Brinch & Hogerheijde 2010)
- Developed from RATRAN
- Non-LTE, full 3D
- Random grid points weighted by density
- Output: spectral cube



UV-HEATED OUTFLOW CAVITY WALLS





- Ellipsoid outflow cavity
- Free parameter: L_{UV}
- 2D, axisymmetric
- UV field done in 1+1D
- Raytracing with LIME

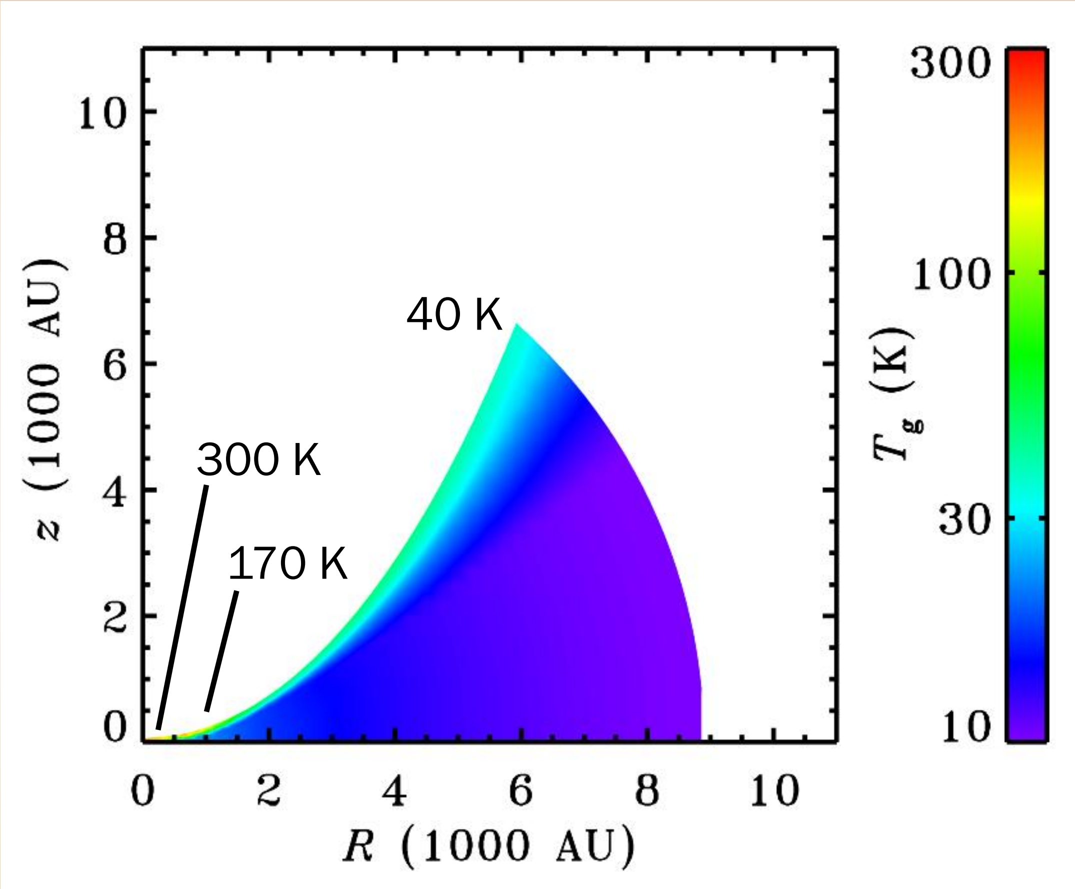
Spitzer image from Velusamy et al. (2007)

GAS TEMPERATURE

- At cavity wall: $T_{\mathrm{surf}} = f(n_{\mathrm{H}}, F_{\mathrm{UV}})$
- Problem: large variations in literature

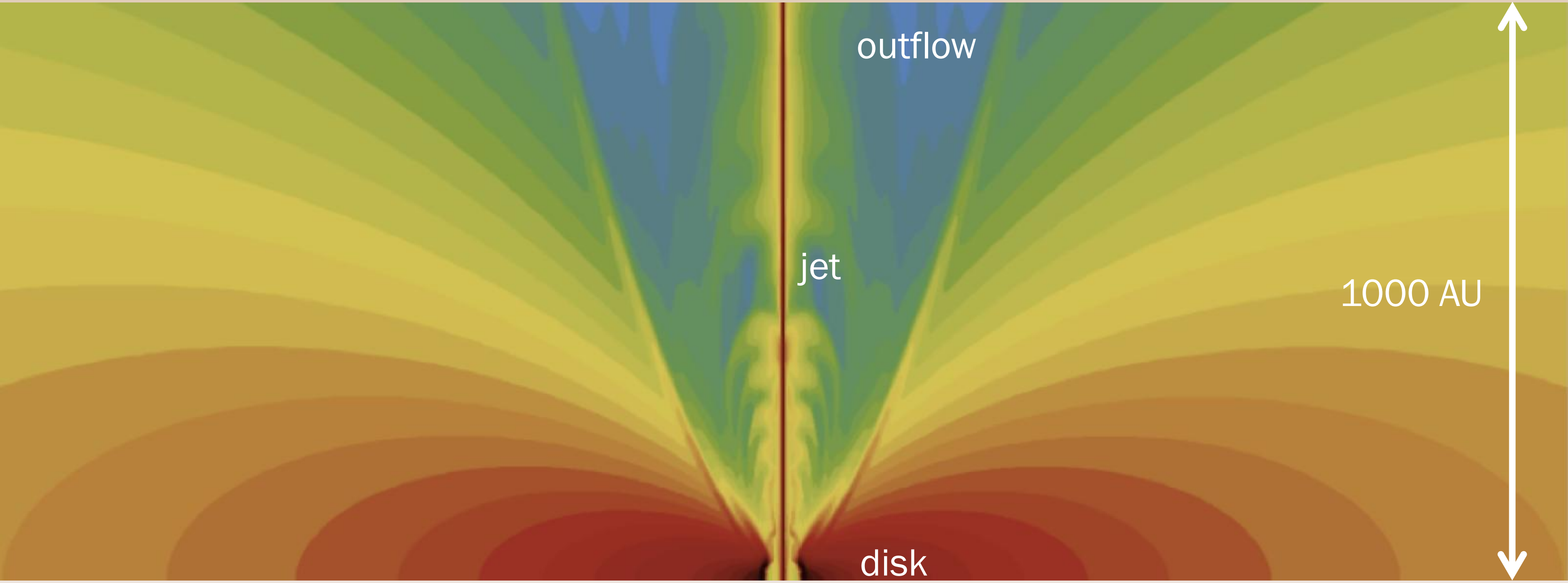
- In envelope: $T = T_{\mathrm{surf}} \exp(-0.6A_{\mathrm{V}})$
- Problem: depth dependence (A_{V}) is poorly known

With temperatures from Kaufman et al. (1999):



Visser, Kristensen et al. (in prep.)

SHOCKS ALONG THE CAVITY WALLS



- Full MHD, 2D axisymmetric
- Interaction of disk wind with envelope
- C-type shocks

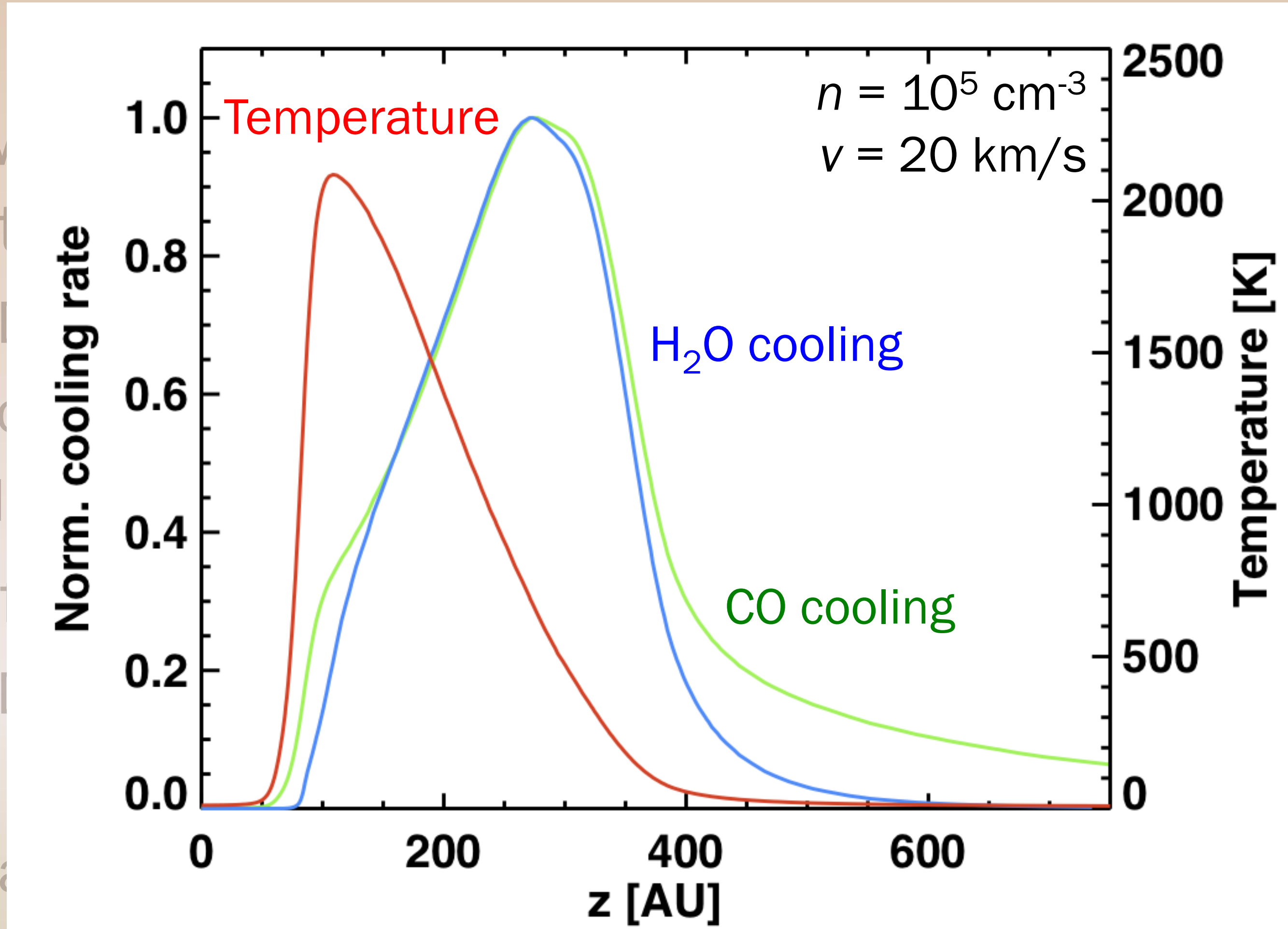
Shang et al. (2006)

FROM MHD SIMULATIONS TO LINE FLUXES

- Flower & Pineau des Forêts (2003), Kristensen et al. (in prep.):
  - 1D, MHD, sophisticated chemistry (with grains)
  - Cooling lengths for CO, H_2O, …
  - Fluxes not yet calculated (work in progress)
- Kaufman & Neufeld (1996)
  - 1D, MHD, simple chemistry (no grains)
  - Line fluxes from 1D C-type shocks
  - Range of pre-shock densities: 10^4–$10^{6.5}$ cm^{-3}
- Combine to get fluxes for our model

FROM MHD SIMULATIONS TO LINE FLUXES

- Flow
  Krist
  - 1I
  - Co
  - Fl
- Kau
  - 1I
  - Li
  - Ra



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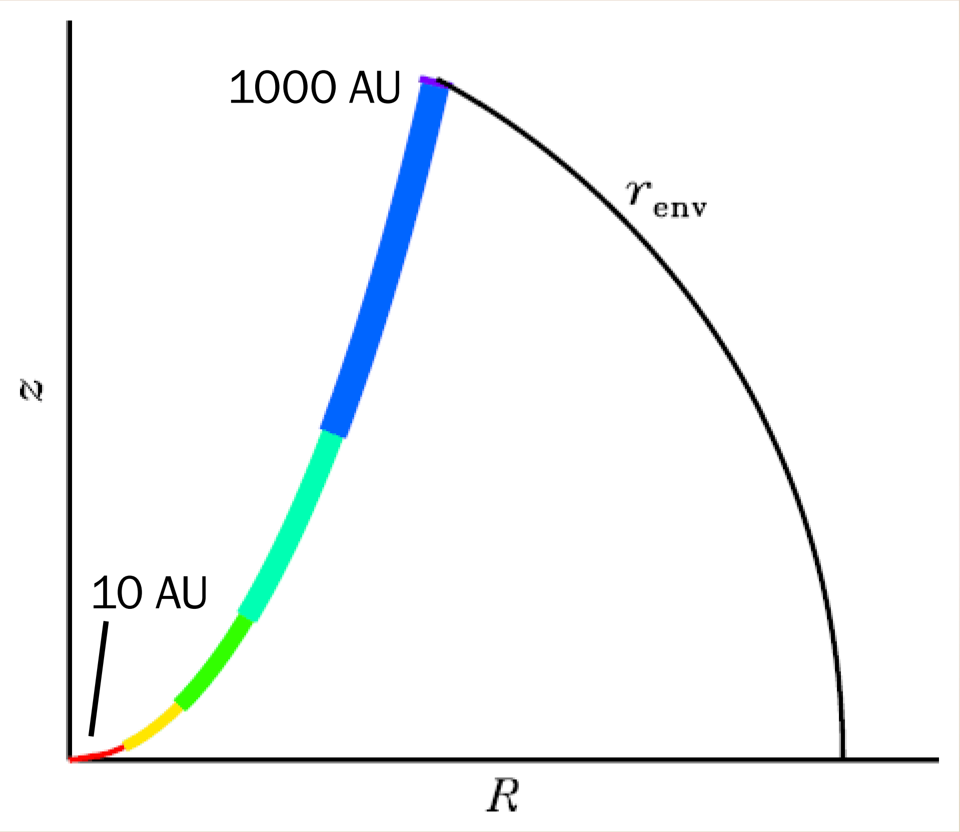
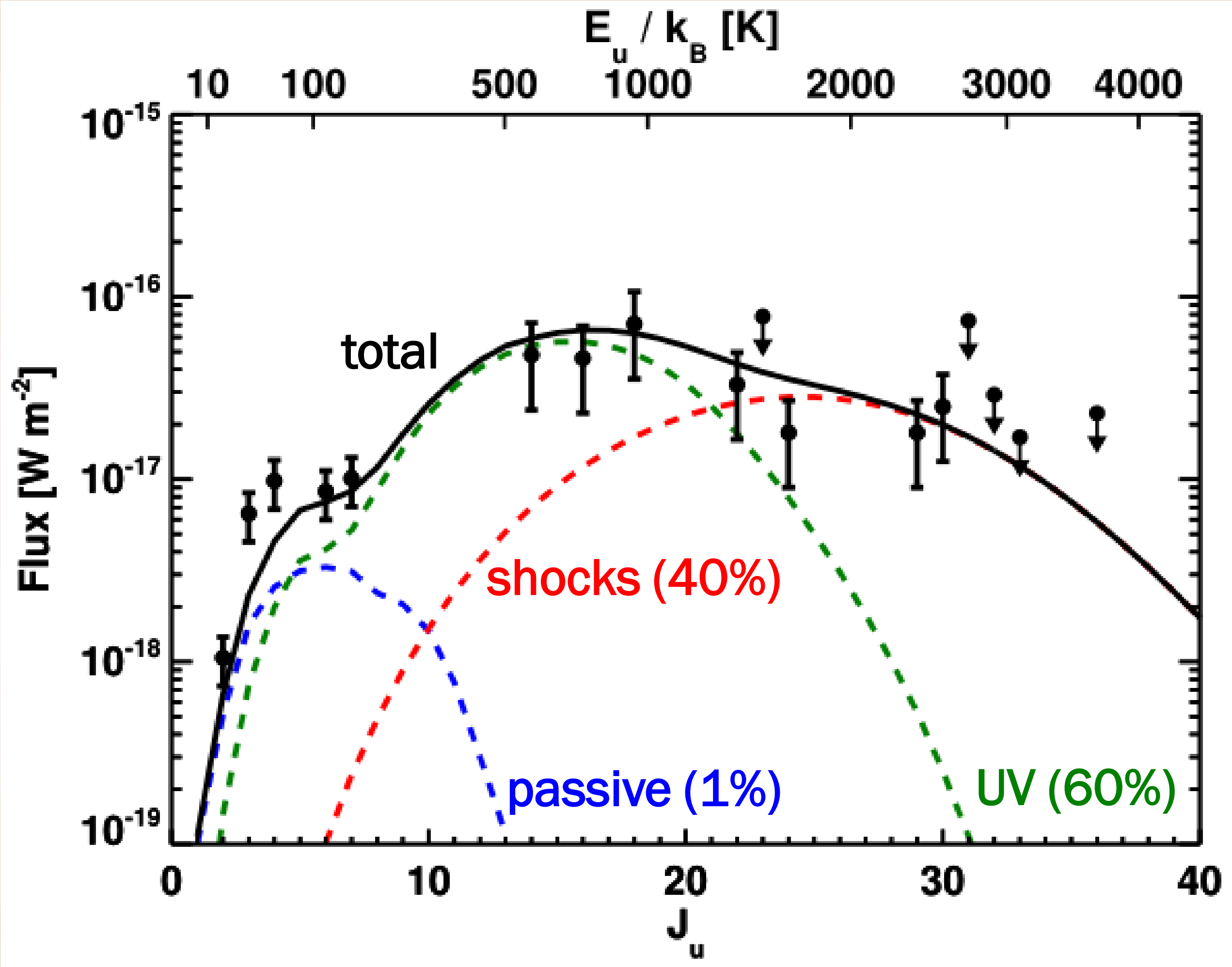
SHOCKS ALONG THE CAVITY WALLS

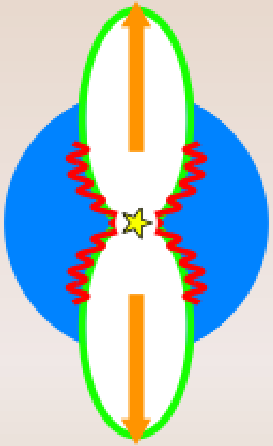
- Cooling length (shock width) decreases with density
- Magnetic *b* set to 1
- Shock velocity:
  - assumed constant along wall
  - treated as free parameter
  - best fit: 20 km/s

Cooling lengths



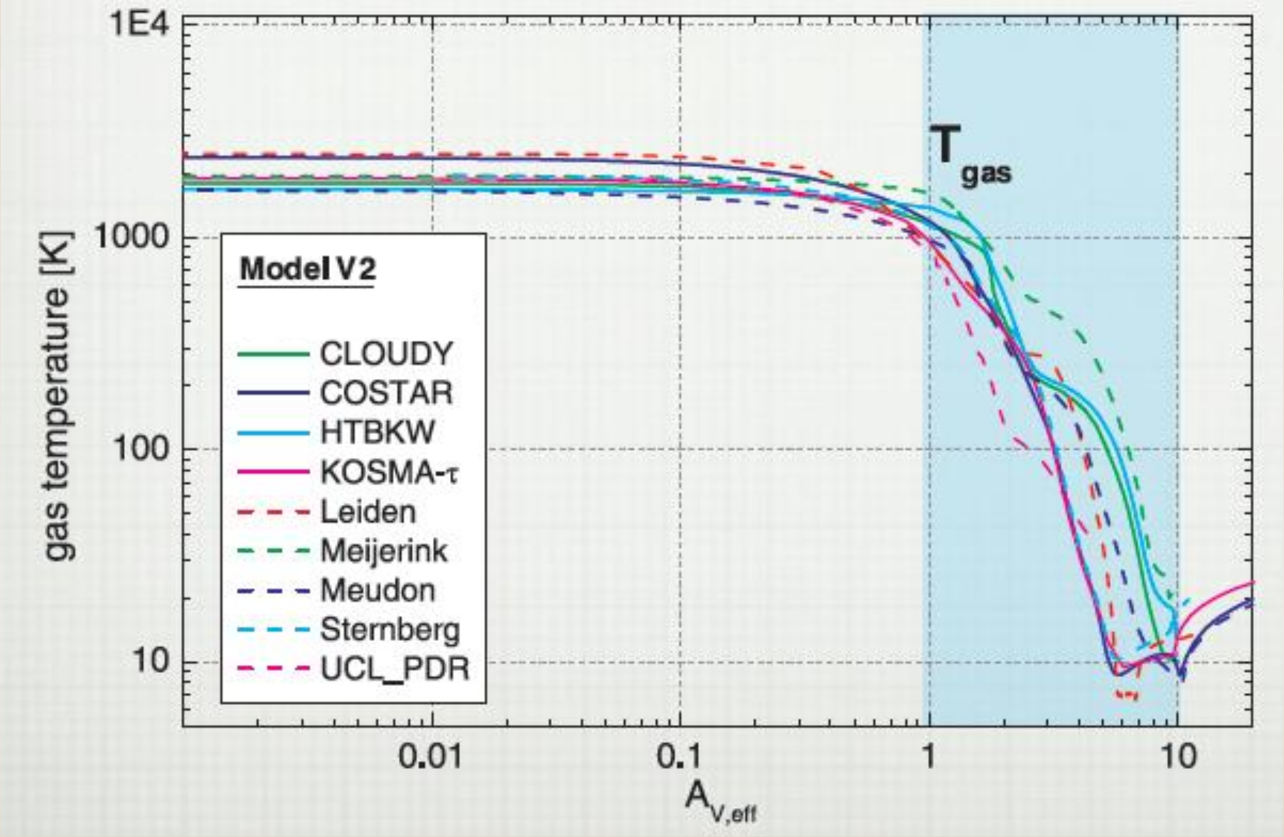
THE FULL CO LADDER





van Kempen, Kristensen, Herczeg, Visser, et al. (2010)

MAIN UNCERTAINTY: GAS TEMPERATURE

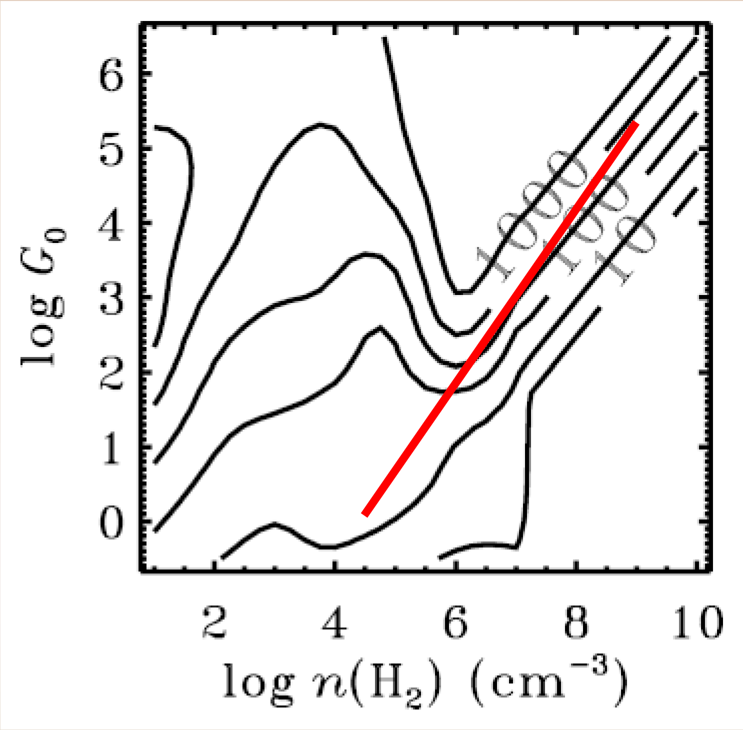


- PDR code comparison
- $n(H_2)=10^3$ cm^{-3} $G_0=10^5$
- Factor 10 differences in A_v range of interest
- $T \sim \exp(-0.6A_V)$

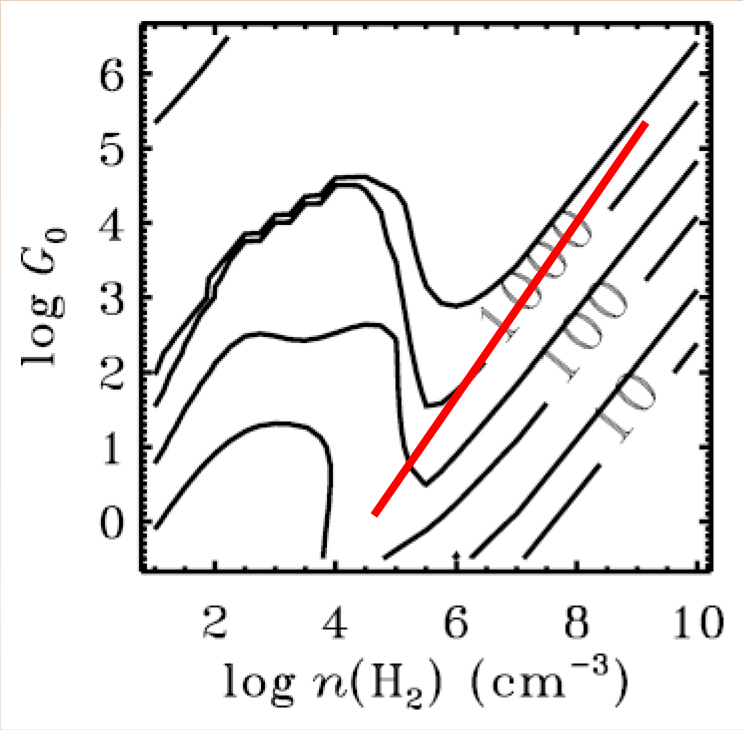
Röllig et al. (2007)

MAIN UNCERTAINTY: GAS TEMPERATURE

Kaufman et al. (1999)

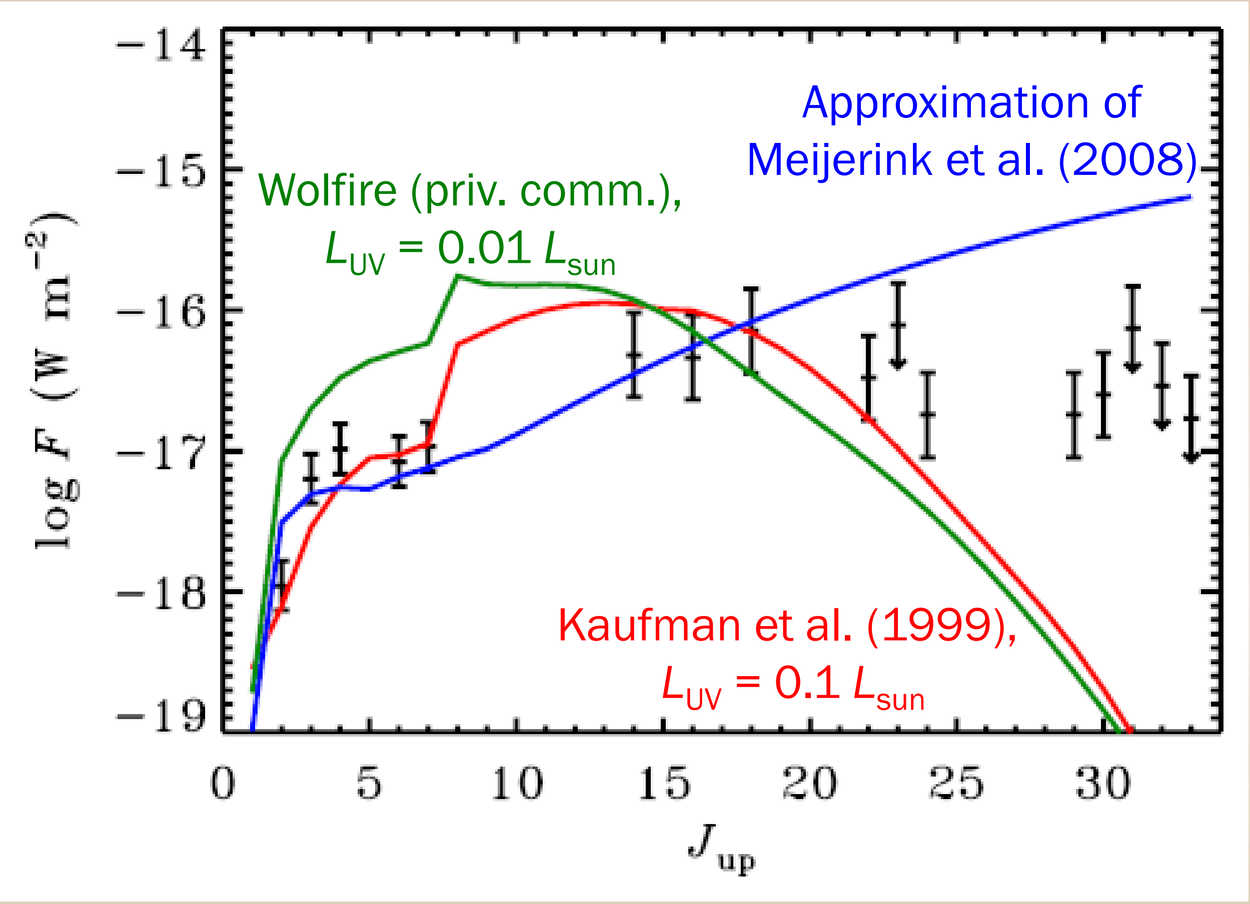


2010 update (Wolfire, priv. comm.)



- Factor 10 difference for part of $n(H_2)$–G_0 space
- Absolute CO fluxes and shape of CO ladder change

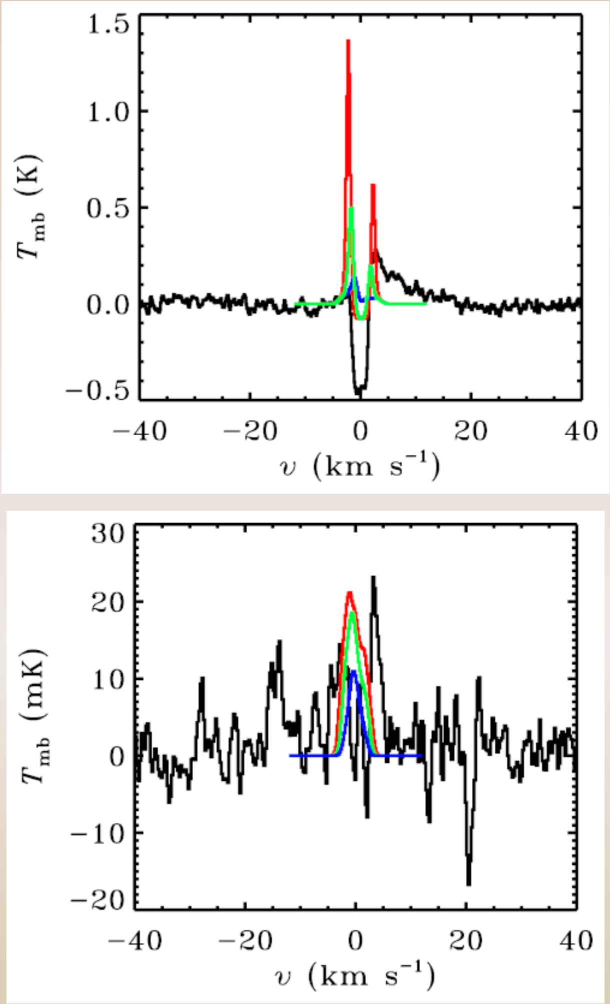
CO LADDER REVISITED



- Passive & UV only (no shocks)
- No curve fits all observations: shocks are always needed
- Resolved line profiles needed to confirm quantitative conclusions

OTHER SPECIES: CHEMICAL EVOLUTION

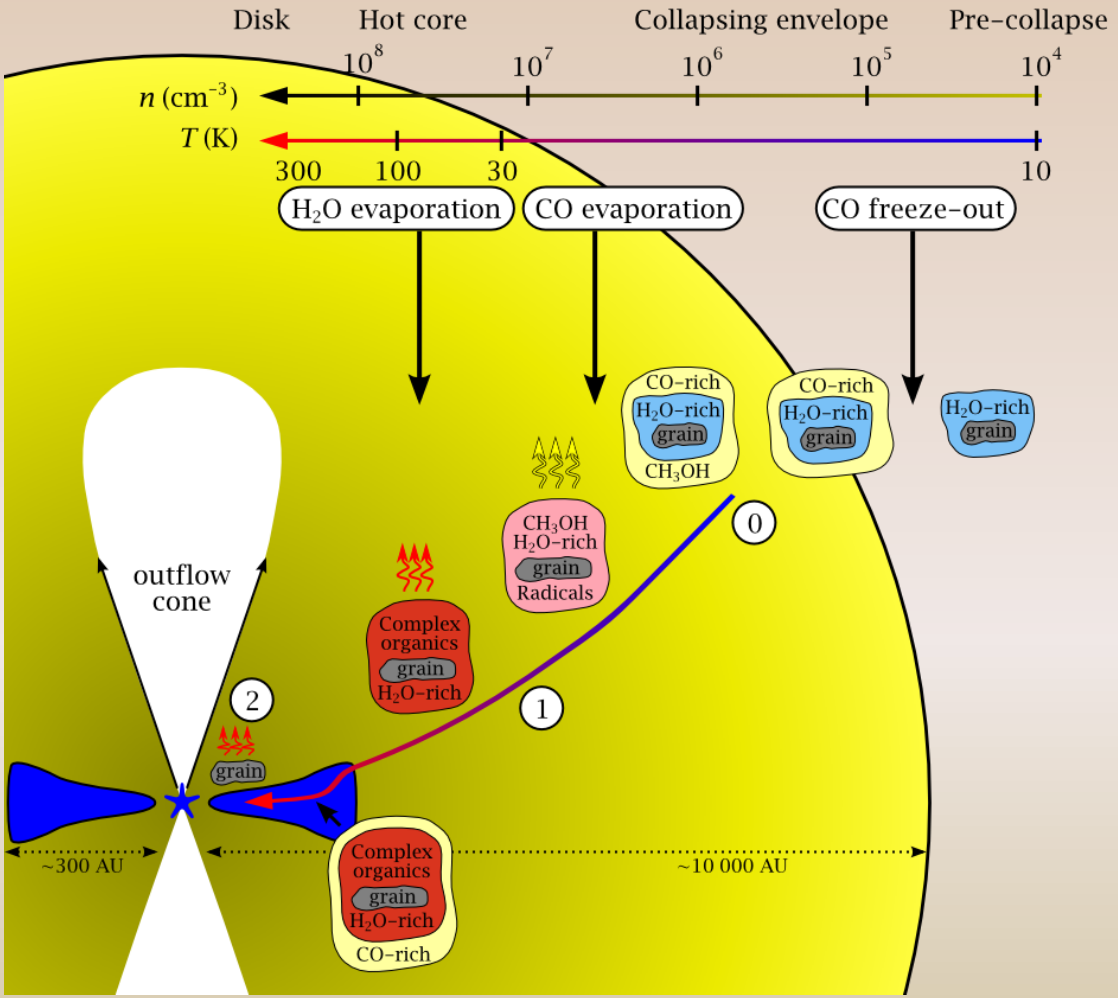
- CO used to "calibrate" the models
- Main goal in WISH: H_2O
  - H_2O radiative transfer much harder than CO
  - LIME works better than RATRAN
  - First H_2O model results in three WISH papers



Kristensen, Visser et al. (2010)

H_2O ABUNDANCE FROM CORES TO DISKS

- WISH first results:
  Pre-stellar cores: $<10^{-9}$
  Class 0/I: 10^{-8} – 10^{-5}
  Disks: $<10^{-8}$
- Challenges:
  - H_2O chemical evolution
  - Effects on other species, e.g. complex organics



Herbst & van Dishoeck (2009), Visser et al. (2009)

WORK IN PROGRESS

- Apply model to other Class 0/I sources: NGC1333 IRAS2A, DK Cha
- Adapt model for disks: HD100546
- Couple with VLT-CRIRES observations of warm gas in inner disk (poster #13 by D. Harsono)
- Calculate fluxes from Flower & Pineau des Forêts (2003) shock models

CONCLUSIONS

- Hot gas emission from embedded YSOs can be reproduced quantitatively
- Results very sensitive to gas temperature
- For HH46, the CO ladder up to *J*=36-35:
  - ~1% passively heated envelope
  - ~60% UV-heated outflow cavity walls
  - ~40% shocks along cavity walls