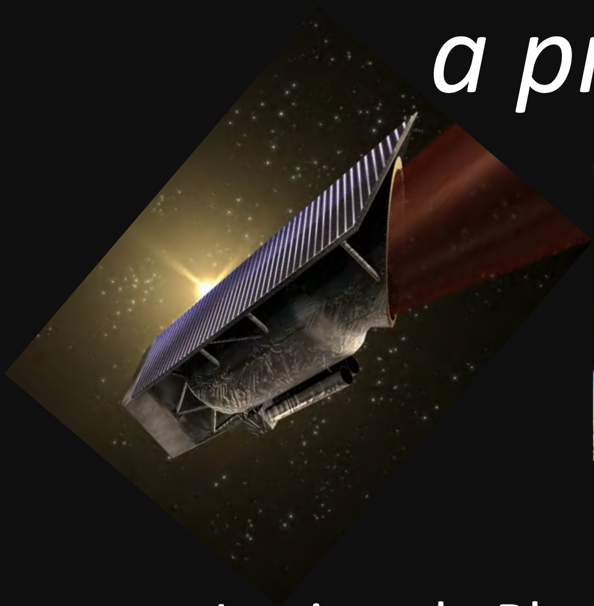
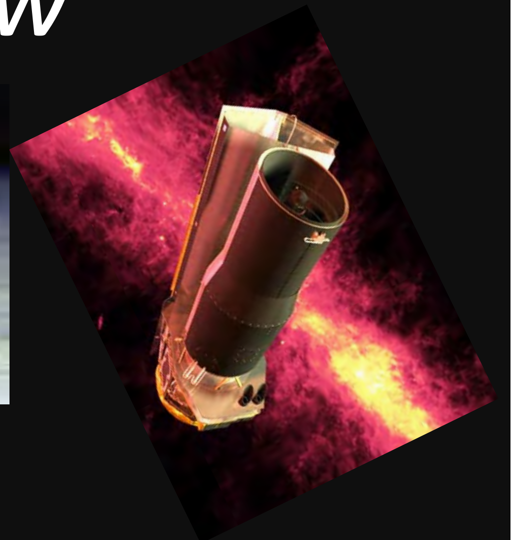
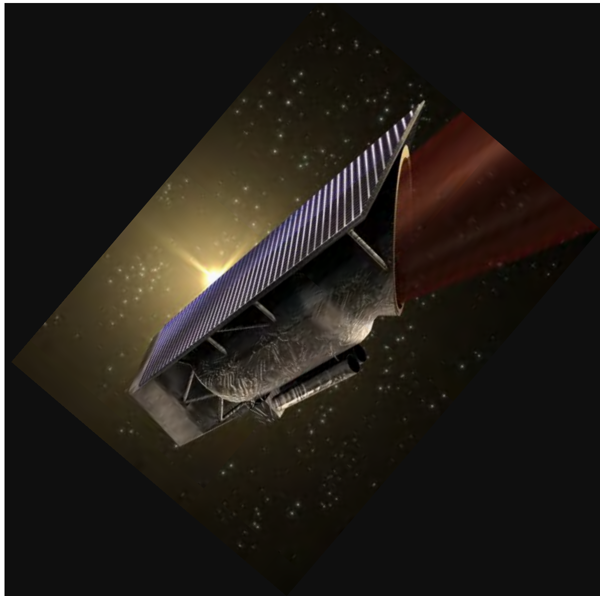
Protostellar phase, a pre-Herschel review

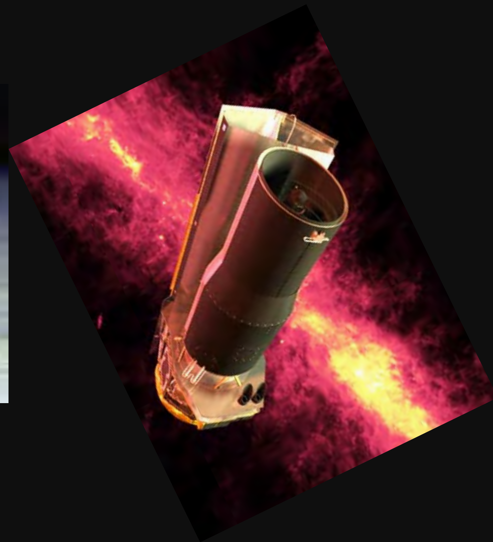


Cecilia Ceccarelli
Institut de Planétologie et d'Astrophysique de Grenoble

Some related reviews:
Van Dishoeck 2004, ARAA; Nisini et al. 2005, SSR; Ceccarelli et al. 2007, PPV; Melnick 2009, ASP; Evans 2011, IAU





OUTLINE

1. The census
2. The structure
3. The chemistry
4. The dynamics
5. The outflow

From ISO to SPITZER: the heritage and open questions.
My a priori apologizes for what I left out….

OUTLINE

1. The census
2. The structure
3. The chemistry
4. The dynamics
5. The outflow

THE CENSUS

IN ORDER TO STUDY THE STRUCTURE AND EVOLUTION OF PROTOSTARS WE NEED TO HAVE THE OBJECTS TO STUDY: THE LARGEST POSSIBLE SAMPLE COVERING THE LARGEST POSSIBLE ENVIRONMENT CONDITIONS, POSITIONS IN THE GALAXY, AND EVOLUTIONARY STATUS.

↓

WE NEED A CENSUS OF THE PROTOSTARS IN OUR GALAXY

THE CENSUS

IRAS: THE START OF THE STORY WITH THE FIRST CATALOGUE

LIMITED SENSITIVITY, SPATIAL RESOLUTION AND FREQUENCY COVERAGE

➔ DEFINITION OF CLASS I, II, III

GROUND BASED SURVEYS IN THE IR AND mm

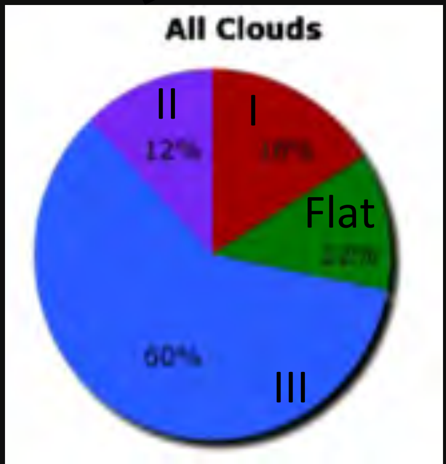
➔ INTRODUCTION OF CLASS 0 (and CLASS –I /prestellar cores)

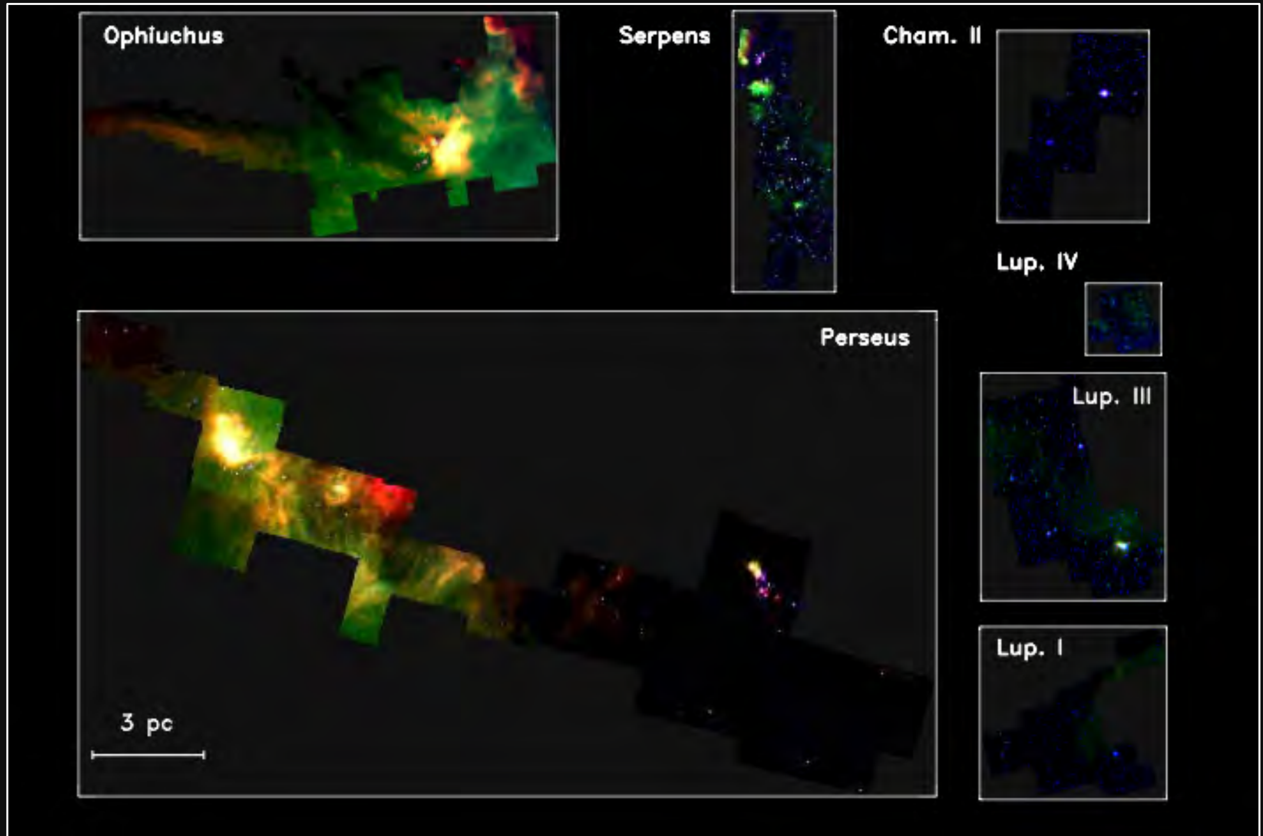
ISO: ISOCAM MAPPED IN THE MIR (7 and 14 μm) A FEW deg^2 OF NEARBY STAR-FORMING REGIONS

SPITZER: MAPPED 15.5 deg^2 OF FIVE LARGE NEARBY MOLECULAR CLOUDS

➔ DISCOVERY OF THE VELLOS

THE SPITZER SURVEY of the Core to Disk (c2d) LP (Evans et al. 2003)





Evans et al. 2009

RESULTS

- RIVISITED LIFETIMES: ≈2Myr Class II, ≈0.5Myr Class I, ≈0.16-0.043 Class 0
- CONFIRMATION OF THE "LUMINOSITY PROBLEM" → NON-STEADY ACCRETION?

OUTLINE

1. The census
2. The structure
3. The outflows
4. The chemistry
5. The dynamics

THE STRUCTURE OF THE PROTOSTAR

WHY: WE WANT TO KNOW WHAT ARE THE DENSITY AND TEMPERATURE PROFILES TO UNDERSTAND WHAT ARE THE ACTORS/PROCESSES ENTERING THE STAR FORMATION PROCESS

OBSERVED PROFILES ⟷ **MODEL PREDICTIONS**

↓

How important are the magnetic fields, the turbulence? What did start the collapse?...

THE STRUCTURE OF THE PROTOSTAR

DERIVATION OF THE DENSITY AND TEMPERATURES PROFILES:

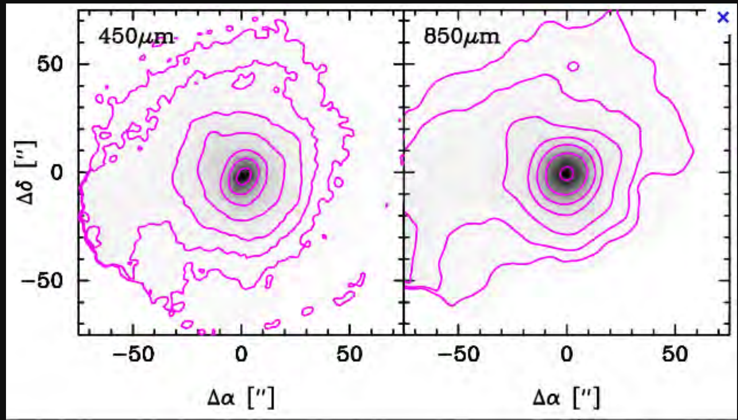
1) Dust density and temperature profiles
   ➔ continuum spectral energy distribution + emission maps

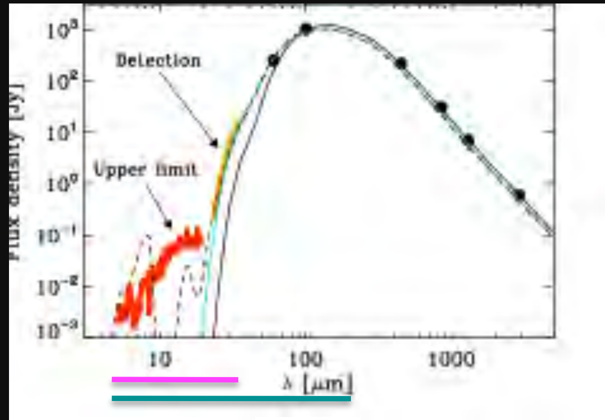
2) Gas density and temperature profiles
   ➔ line spectra (emission + absorption)

OFTEN, SPHERICAL SYMMETRY ASSUMED

Dust temperature and density profiles

Shoier et al. 2002





Shoier et al. 2007

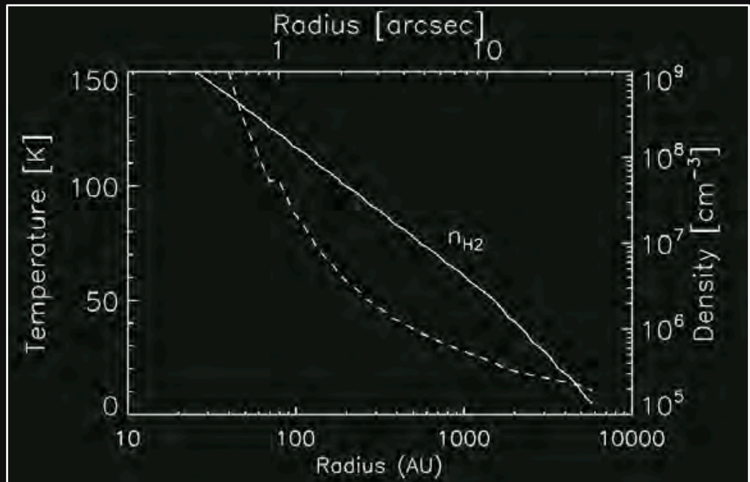
Spitzer

ISO

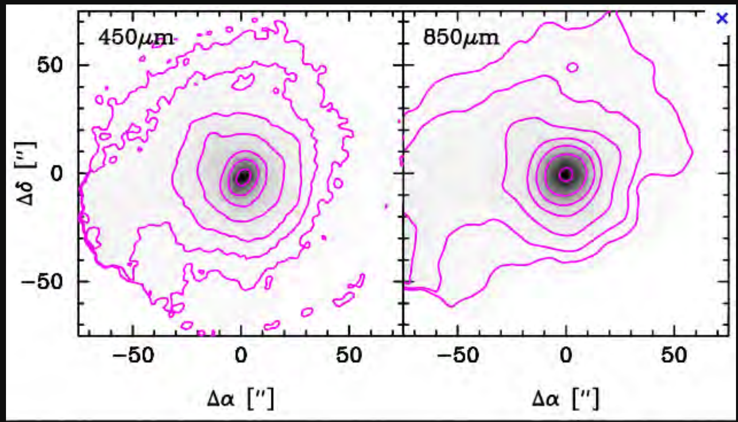
via dust radiative transfer modeling

e.g. DUSTY (Ivezik & Elitzur 1997,
but see also Withney et a. 2003; Robitaille et al. 2007, 2011)

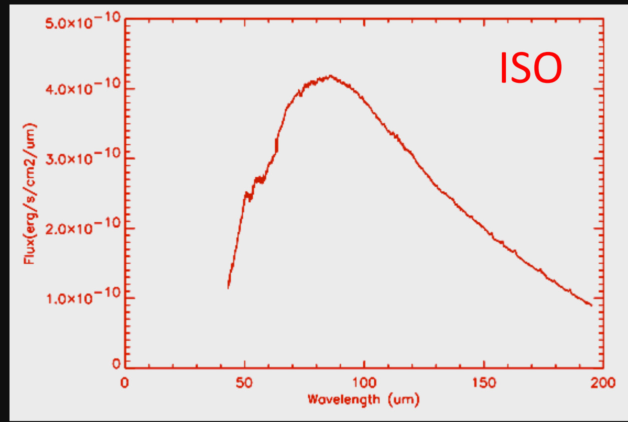
Crimier et al. 2010



Dust temperature and density profiles



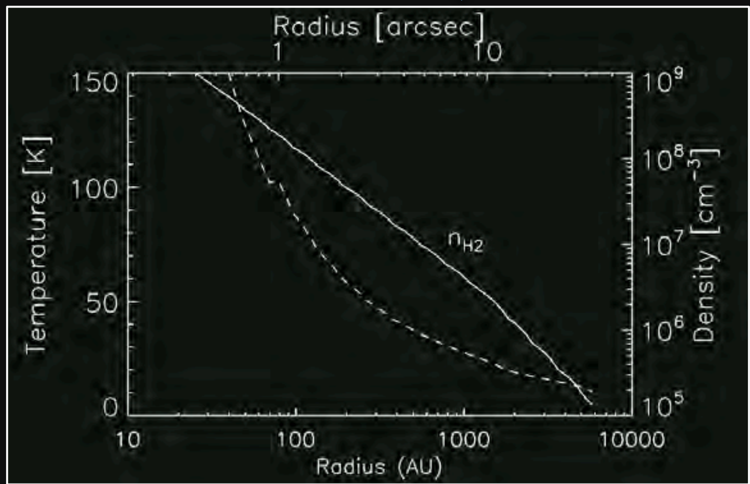
Shoier et al. 2002



Ceccarelli et al. 2000

via dust radiative transfer modeling

e.g. DUSTY (Ivezik & Elitzur 1997,
but see also Withney et a. 2003; Robitaille et al. 2007, 2011)

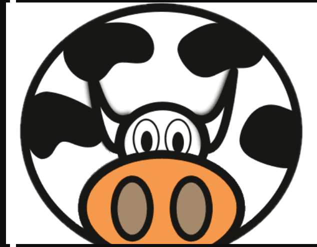


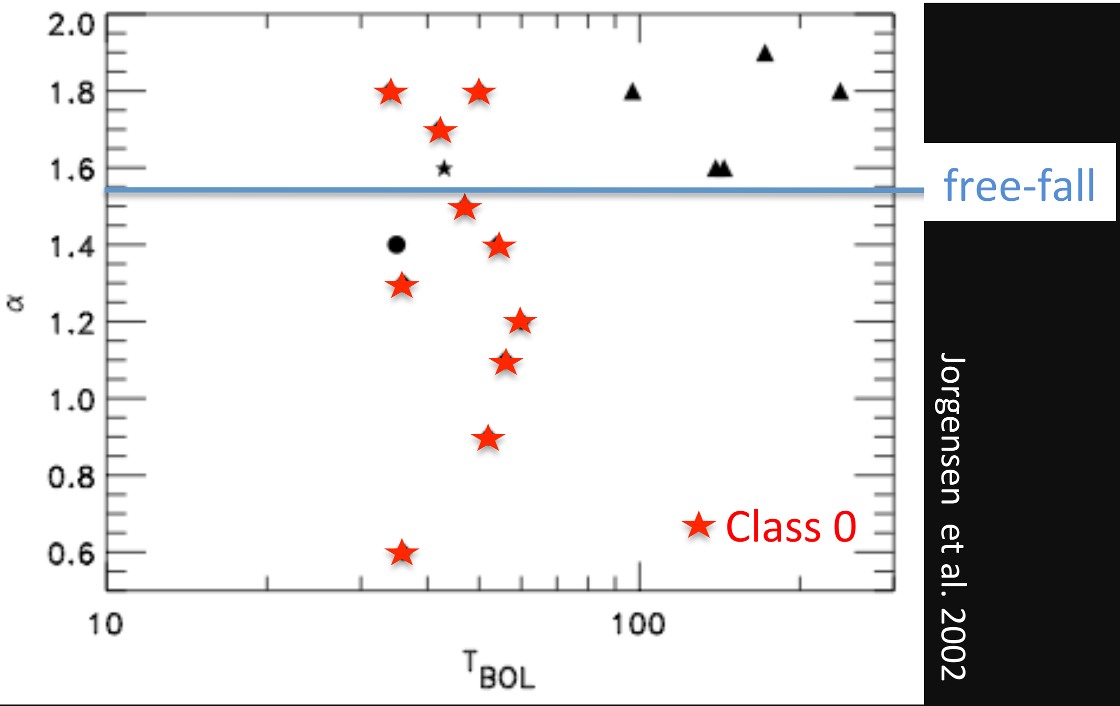
Crimier et al. 2010

Dust temperature and density profiles

RESULTS

Most of the density profiles of Class 0 sources are consistent with the free-fall structure, within the error bars, with a few exceptions.





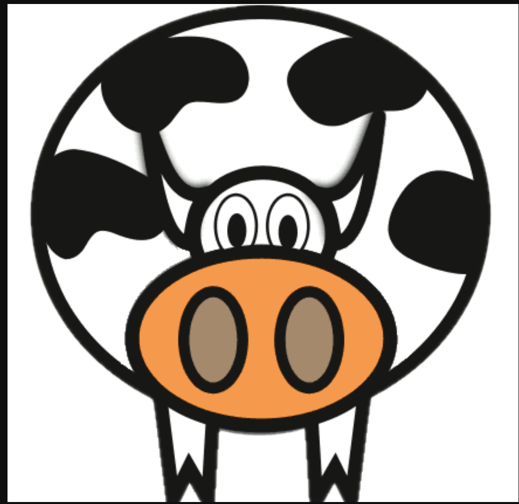
Jorgensen et al. 2002

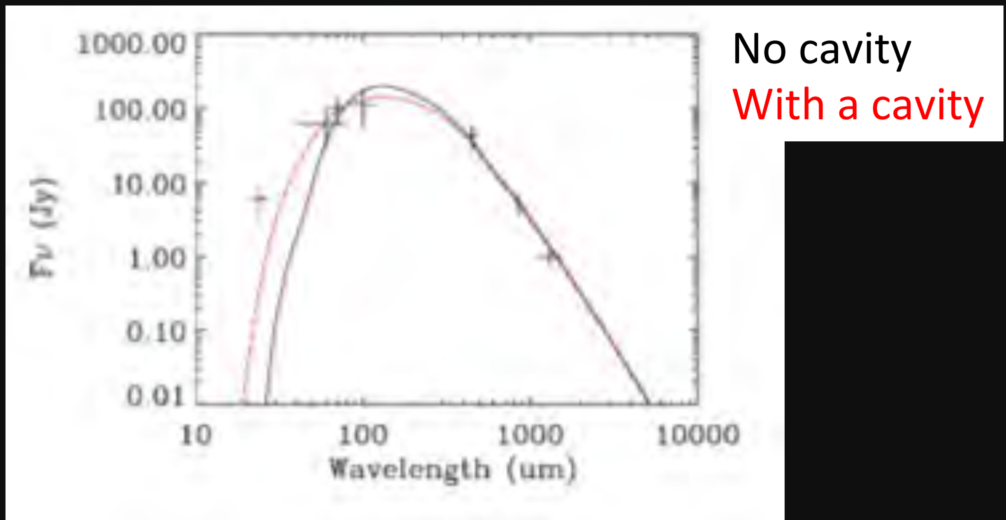
HERSCHEL, HELP WITH NUMBERS !

Dust temperature and density profiles

BUT IS THE COW REALLY SPHERICAL?

THE SPITZER OBSERVATIONS HAVE RAISED THE QUESTION WHETHER LARGE CAVITIES ARE PRESENT IN SOME PROTOSTELLAR ENVELOPES
(e.g. Schoier et al. 2004, Jorgensen et al. 2005)





Crimier et al. 2010

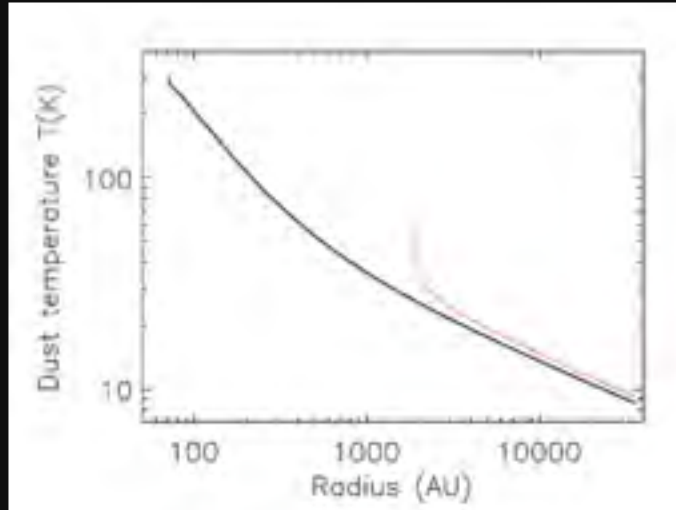
Dust temperature and density profiles

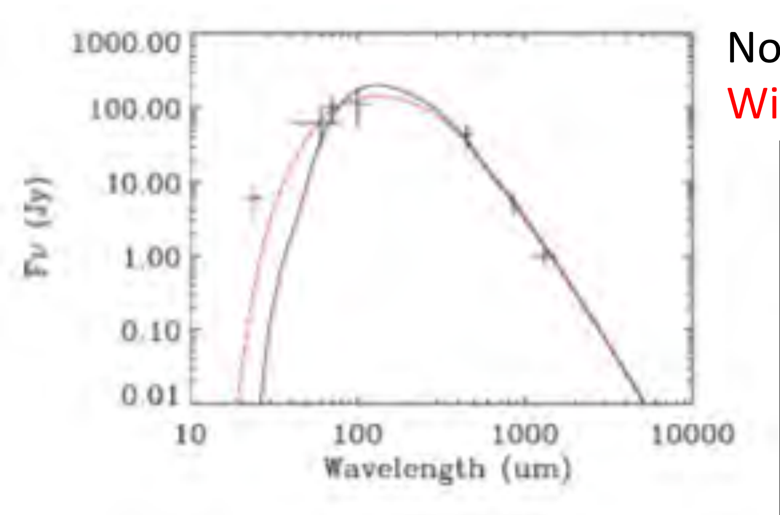
BUT IS THE COW REALLY SPHERICAL?

THE CAVITY MODEL FITS THE SPITZER DATA BUT NOT THE LARGE SCALE MAPS (e.g Crimier et al. 2010)

..???....

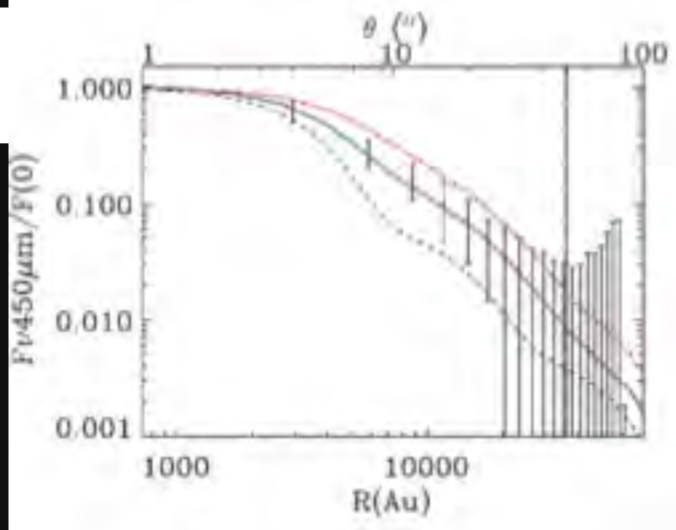
IS THE NIR DUE TO A DISK?





No cavity

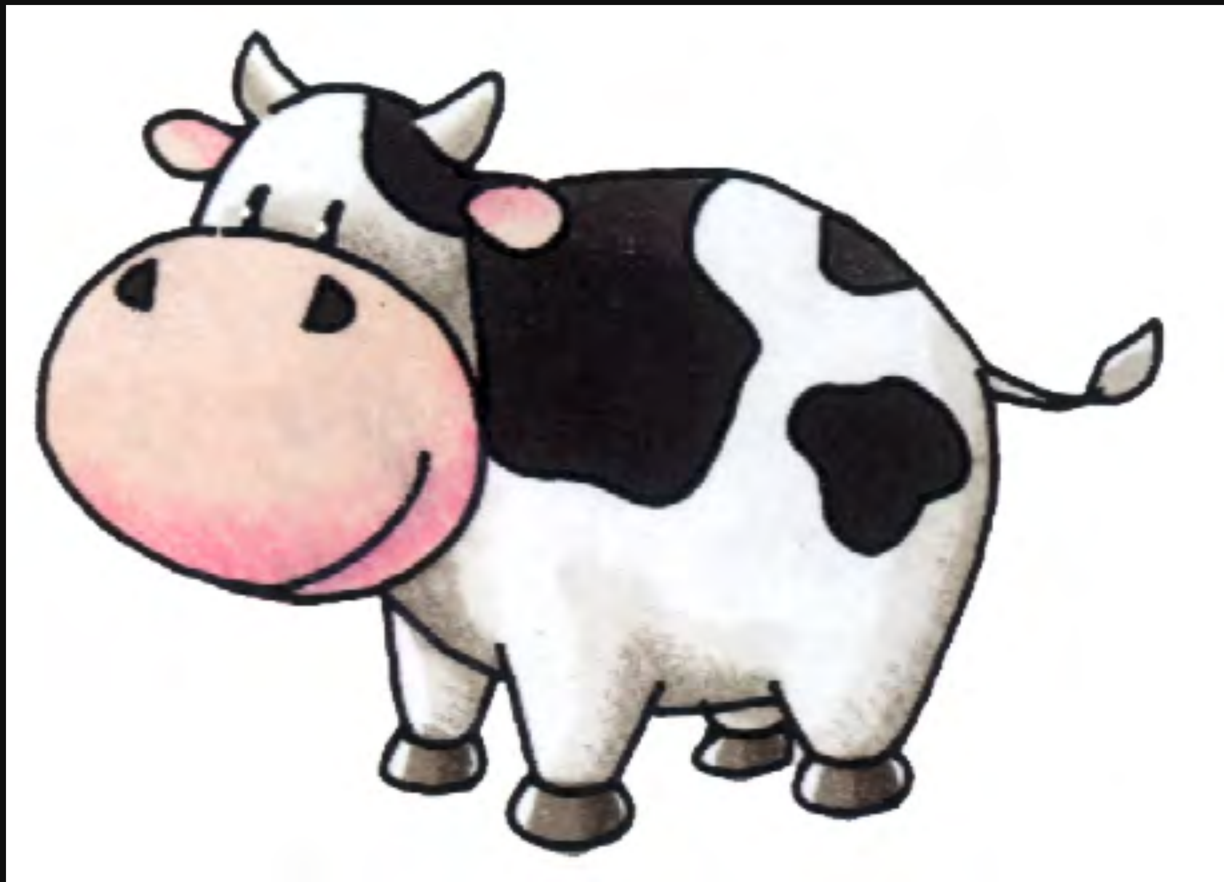
With a cavity



Crimier et al. 2010

Dust temperature and density profiles

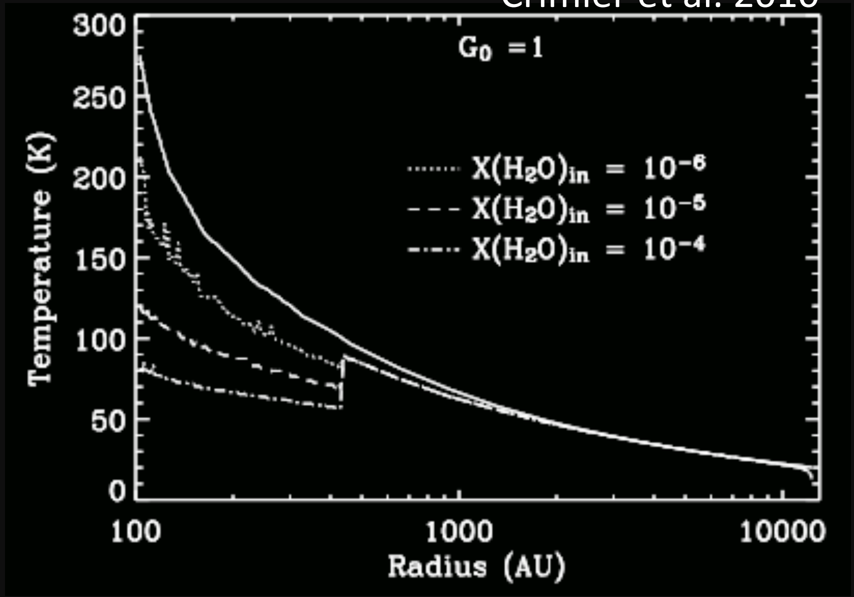
HERSCHEL + ALMA WILL SETTLE THE QUESTION SOON..



Gas temperature and density profiles

MODELS PREDICT THAT THE GAS MAY BE THERMALLY DECOUPLED BY THE DUST AT THE BORDER AND IN THE INNER REGION (WHERE $T_{DUST} > T_{ICE-SUBLIMATION}$) OF THE ENVELOPE

Crimier et al. 2010



THE DECOUPLING IN THE INNER REGION DEPENDS ON THE QUANTITY OF SUBLIMATED WATER

HERSCHEL, HELP!

OUTLINE

1. The census
2. The structure
3. The chemistry
4. The dynamics
5. The outflow

THE CHEMICAL COMPOSITION

WHY: WE WANT TO KNOW WHAT IS THE CHEMICAL COMPOSITION ACROSS THE ENVELOPE TO UNDERSTAND THE PHYSICAL STATUS OF THE GAS AND THE HISTORY OF THE PROTOSTAR

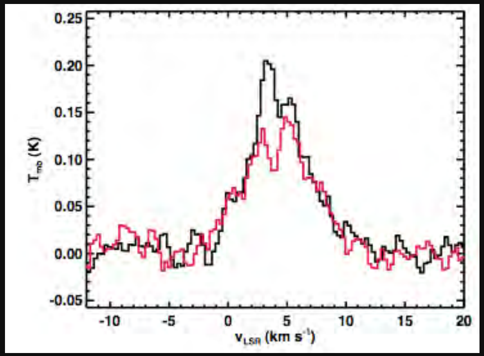
OBSERVED SPECIES ⟷ **MODEL PREDICTIONS**

How is the gas cooled? What is the ionization? Why? Which species are in the gas phase, which are frozen? Why? What is the age of the protostar? What is the molecular complexity during the star formation process?...

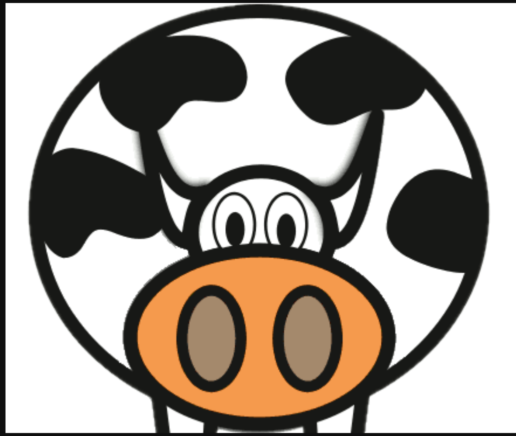
THE CHEMICAL COMPOSITION

DERIVATION OF THE SPECIES ABUNDANCE PROFILES:

→ line spectra (emission + absorption)



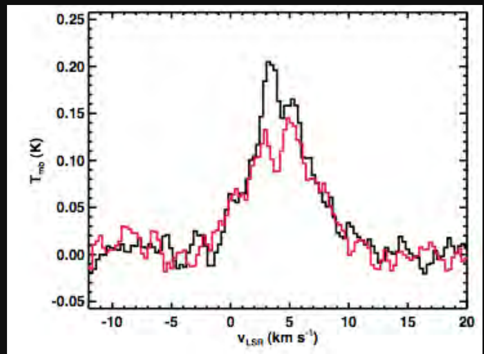
OFTEN, SPHERICAL SYMMETRY ASSUMED



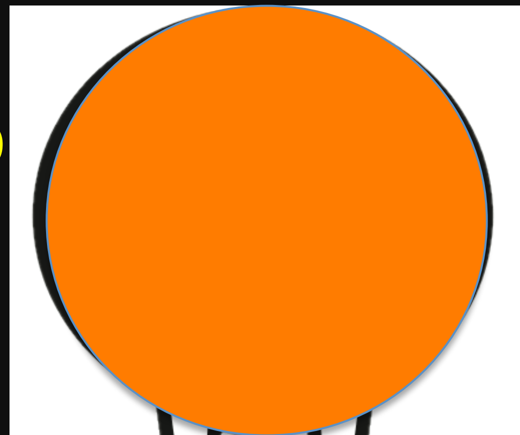
THE CHEMICAL COMPOSITION

DERIVATION OF THE SPECIES ABUNDANCE PROFILES:

➔ line spectra (emission + absorption)



OFTEN, SPHERICAL SYMMETRY ASSUMED



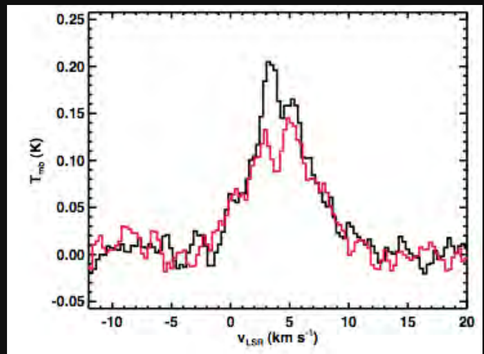
➔ collisional coefficients

OFTEN, LTE POPULATION ASSUMED

THE CHEMICAL COMPOSITION

DERIVATION OF THE SPECIES ABUNDANCE PROFILES:

➔ line spectra (emission + absorption)



OFTEN, SPHERICAL SYMMETRY ASSUMED

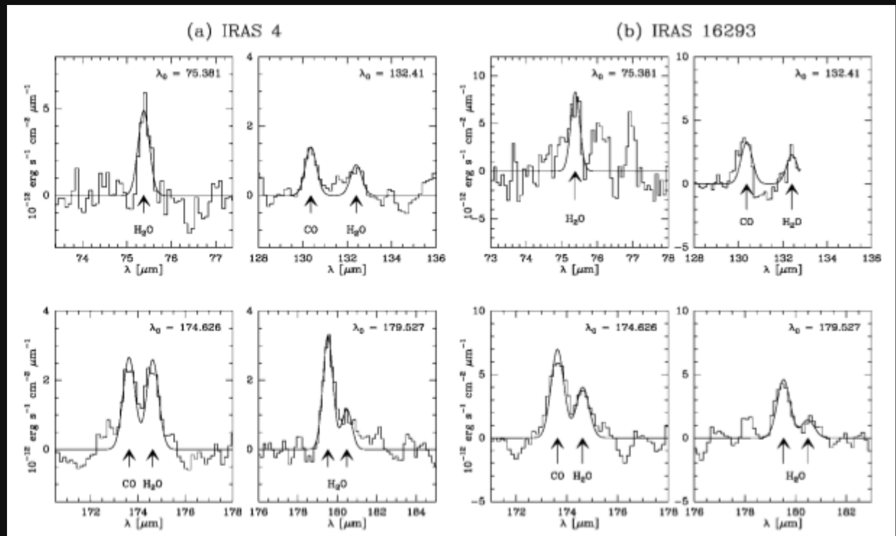
➔ collisional coefficients

SOMETIMES, LTE POPULATION ASSUMED

THANKS to Daniel, Dubernet, Faure, Flower, Green, Lique, Valiron, Wiesenfeld…

THE WATER CONTENT

WITH THE EXCEPTION OF A FEW MASER TRANSITIONS WATER WAS FIRST OBSERVED TOWARDS *LOW-MASS PROTOSTARS* BY ISO-LWS



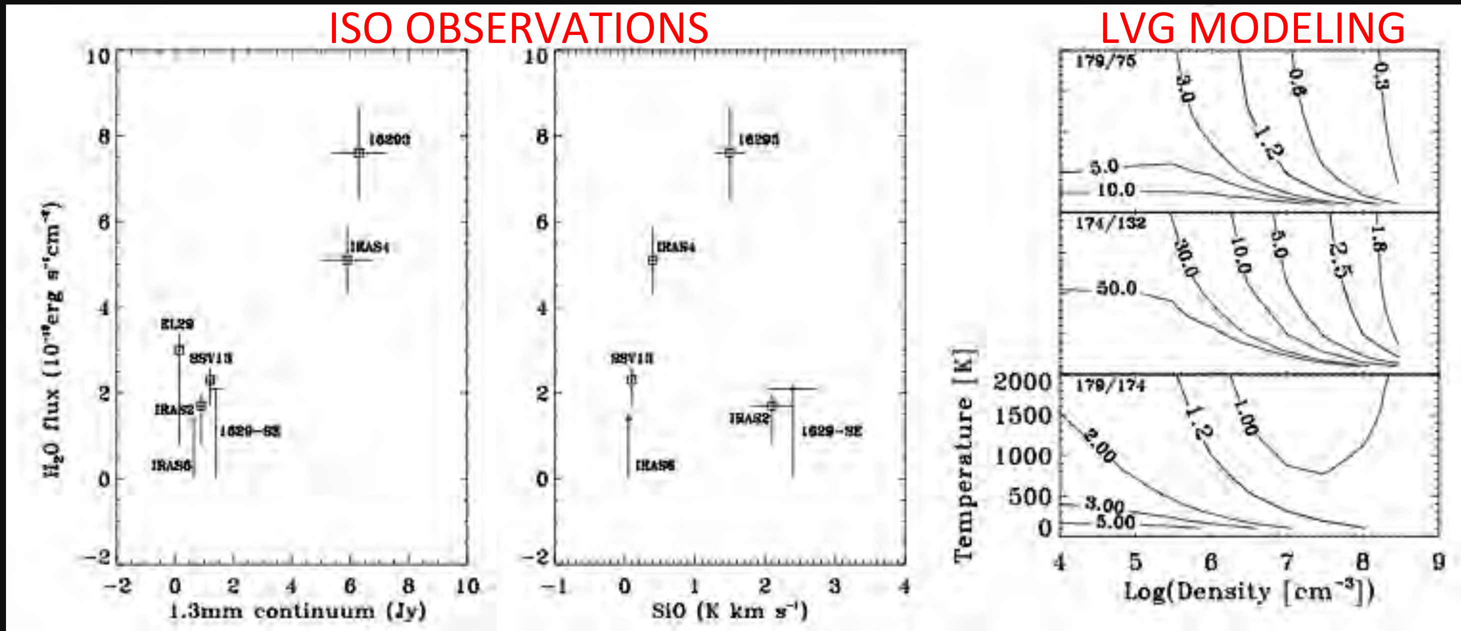
Ceccarelli et al. 1999

WITH A SPATIAL RESOLUTION OF ≈80" AND A SPECTRAL RESOLUTION OFTEN OF ≈200 (=1500km/s), FEW TIMES 10^4 (≈30km/s)

→ MULTIPLE COMPONENTS IN THE BEAM

→ MULTIPLE LINES IN THE SPECTRAL ELEMENT

THE WATER CONTENT OF CLASS 0 SOURCES



Warm & dense gas

Ceccarelli et al. 1999

1) WATER EMISSION DOES NOT CORRELATE WITH SiO EMISSION

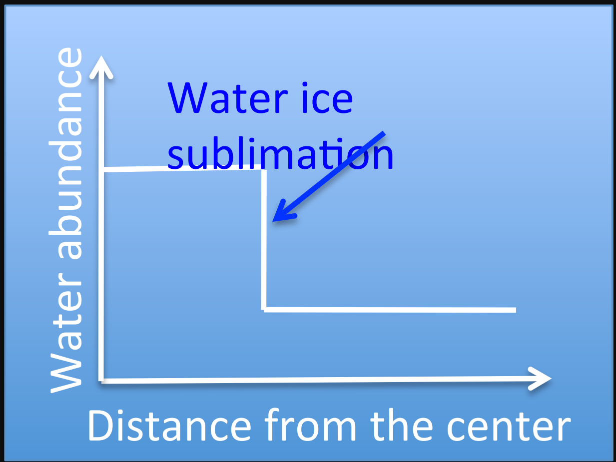
water forms in low velocity shocks (which do not occur where the high velocity shocks are found) or water does not originate in shocks

2) WATER EMISSION DOES CORRELATE WITH 1.3mm CONTINUUM

water emission is associated to thermal emission from the envelopes or it originates in shocks where the shocked material belongs to the envelopes

THE WATER CONTENT OF CLASS 0 SOURCES
1) The thermal emission from the envelope

Model of IRAS16293-2422 (Ceccarelli et al. 2000a)



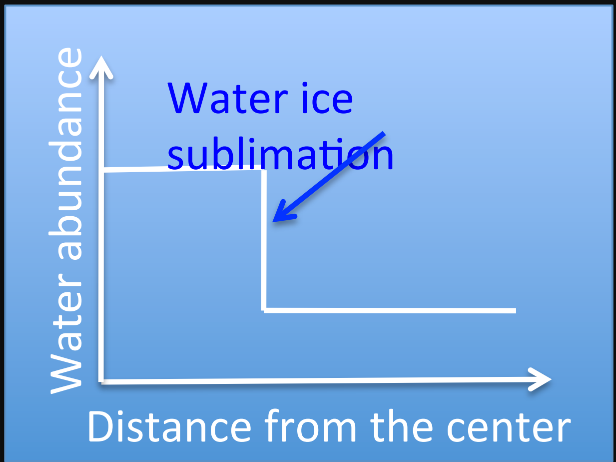
RESULTS
$x_{outer}(H_2O) \approx 5x10^{-7}$
$x_{inner}(H_2O) \approx 3x10^{-6}$

(START OF THE HOT CORINO SAGA with the measured jump of the abundance of other species sublimated from the mantle)

QUESTION: WHY THE WATER ABUNDANCE IN THE ICE SUBLIMATED HOT CORINO REGION IS ONLY $3x10^{-6}$ RATHER THAN $\approx 10^{-4}$???

HERSCHEL, HELP!

THE WATER CONTENT OF CLASS 0 SOURCES
1) The thermal emission from the envelope
THE WATER DEUTERATION



RESULTS

$x_{outer}(H_2O) \approx 5x10^{-7}$

$x_{inner}(H_2O) \approx 3x10^{-6}$

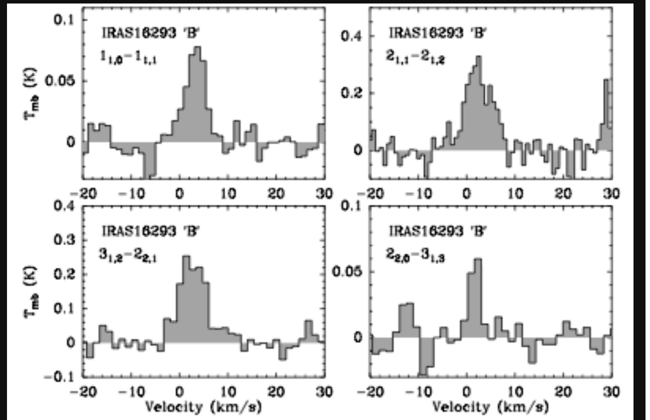
$x_{outer}(HDO) < 1x10^{-9}$

$x_{inner}(HDO) \approx 1x10^{-7}$

HDO/H_2O

outer ≤ 0.002

Inner ≈ 0.03



HDO OBSERVATIONS in IRAS16293-2422

(Stark et al. 2004, Parise et al. 2005)

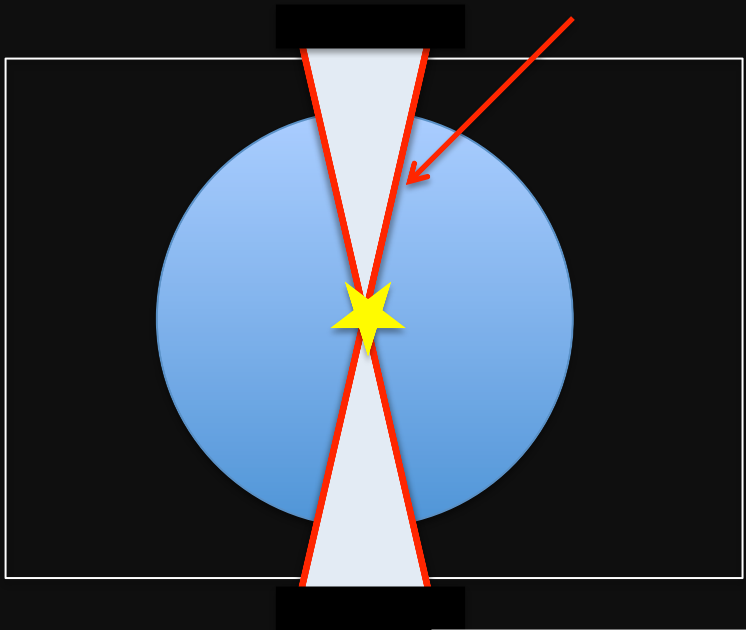
HERSCHEL, HELP!

H_2O and HDO obs in more sources!

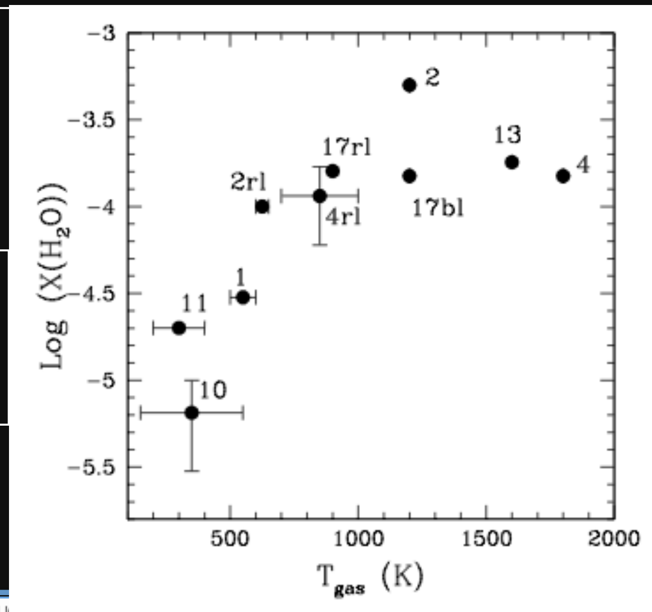
BTW, what is the o/p H_2O ratio ???

THE WATER CONTENT OF CLASS 0 SOURCES
2) The emission from dense shocks

Dense shocks in the inner envelope (Giannini et al. 2000; Nisini et al. 2002)



ALL FIR LINES ORIGINATE IN DENSE SHOCKS, with TEMPERATURE AND DENSITY derived by CO SPECTRA:
T_{GAS}=100-2000 K & n_{GAS}=10^4-10^7cm^{-3}

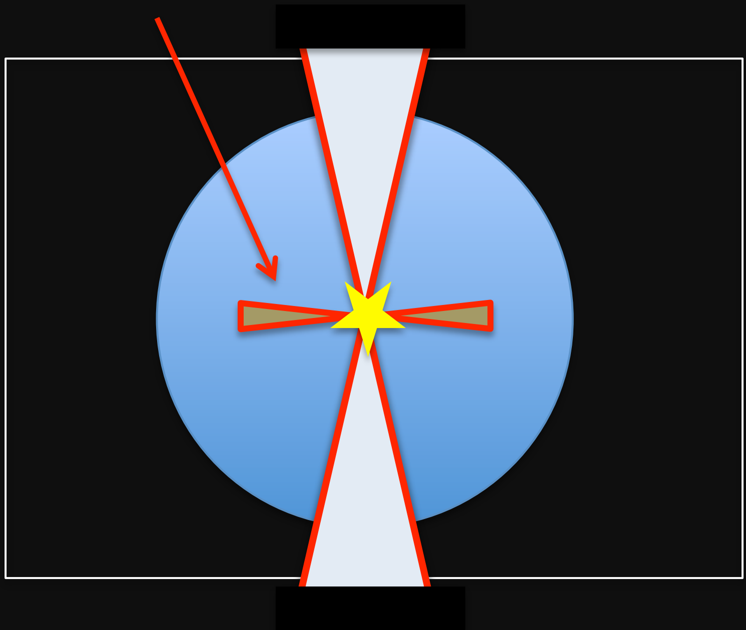


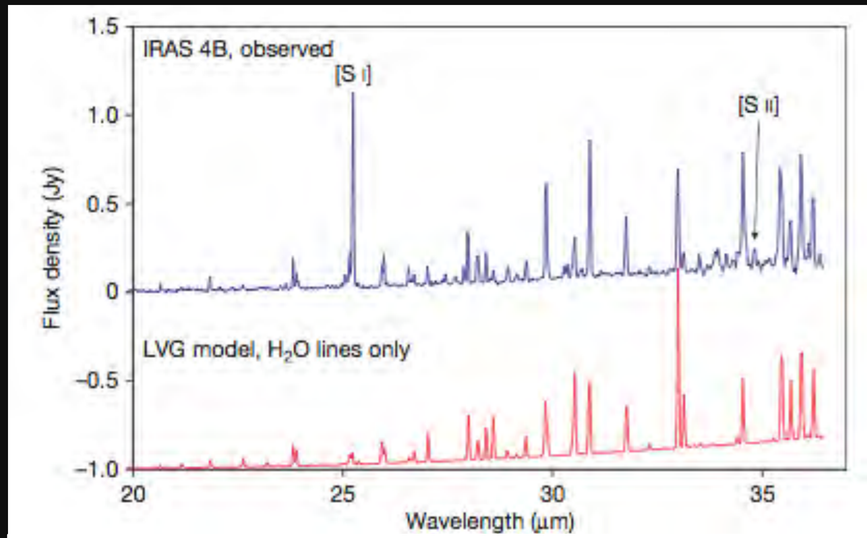
HERSCHEL, HELP!

RESULTS
$x(H_2O) \approx 0.2\text{-}2 \times 10^{-4}$

THE WATER CONTENT OF CLASS 0 SOURCES
3) The emission from the circumstellar disk

Shocks at the surface of the inner disk (Watson et al. 2007)

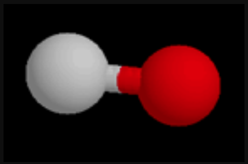




HERSCHEL, HELP!

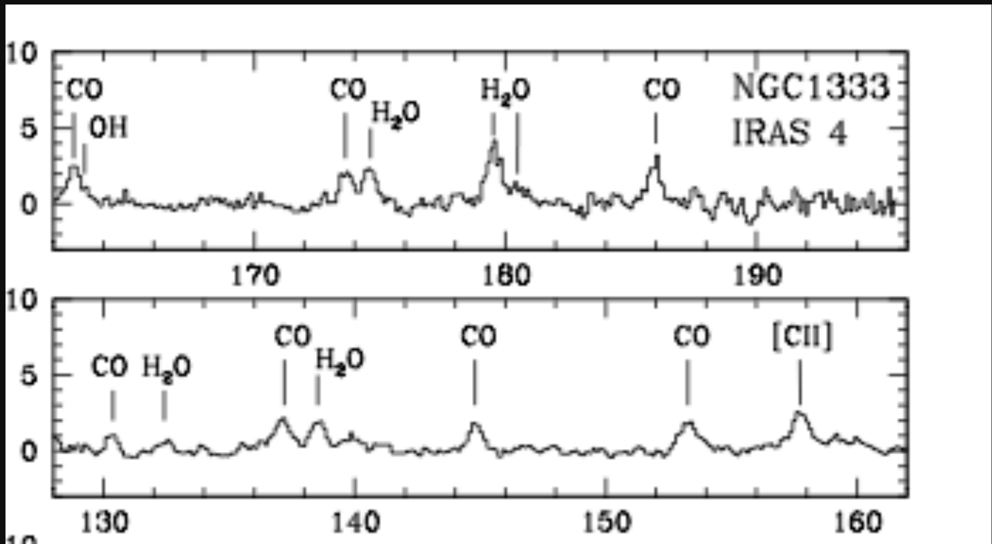
SPITZER OBSERVATIONS

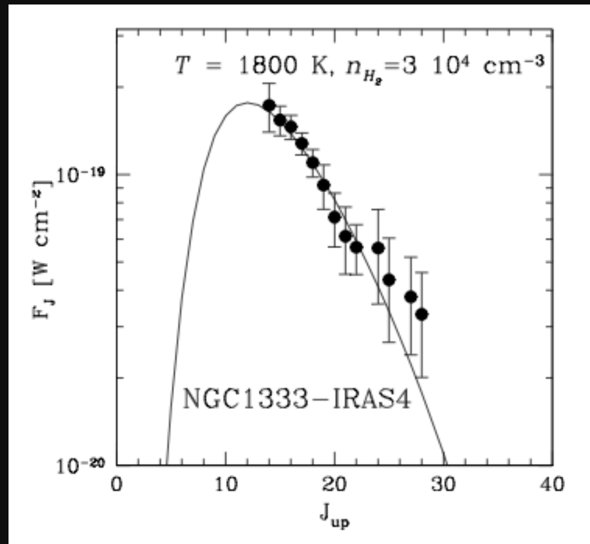
Disk-surface temperature ≈ 170K
Disk-surface density ≈ 10^{10}cm^{-3}
Emitting area ≈ 6000AU^2
Total H_2O luminosity ≈ 0.03L_o



THE CO EMISSION in LOW-MASS PROTOSTARS

J=13-29 CO LINES WERE FIRST OBSERVED TOWARDS *LOW-MASS PROTOSTARS* BY ISO-LWS

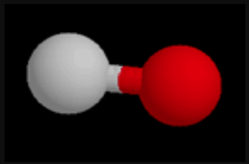




Giannini et al. 2000

QUESTION: WHAT IS THE ORIGIN OF THE CO EMISSION ?

1) DENSE SHOCKS IN THE INNER ENVELOPE
2) UV ILLUMINATED GAS

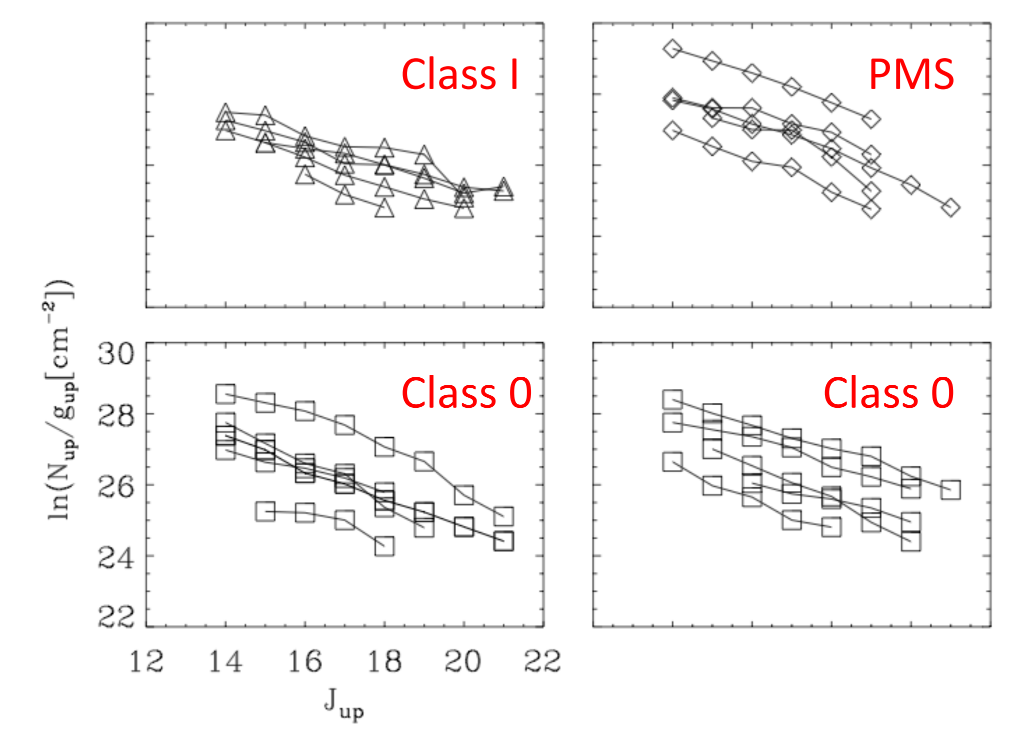


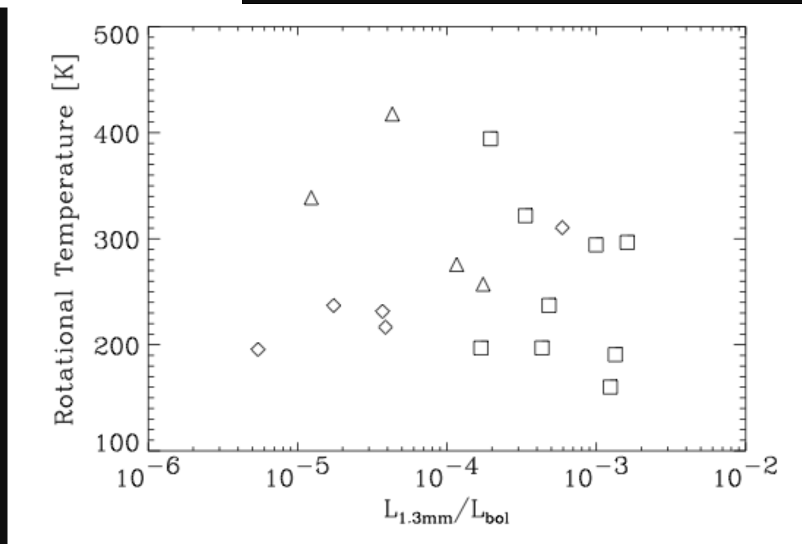
THE CO EMISSION in LOW-MASS PROTOSTARS

QUESTION: WHAT IS THE ORIGIN OF THE CO EMISSION ?

1) DENSE SHOCKS IN THE INNER ENVELOPE
2) UV ILLUMINATED GAS

ROTATIONAL DIAGRAMS





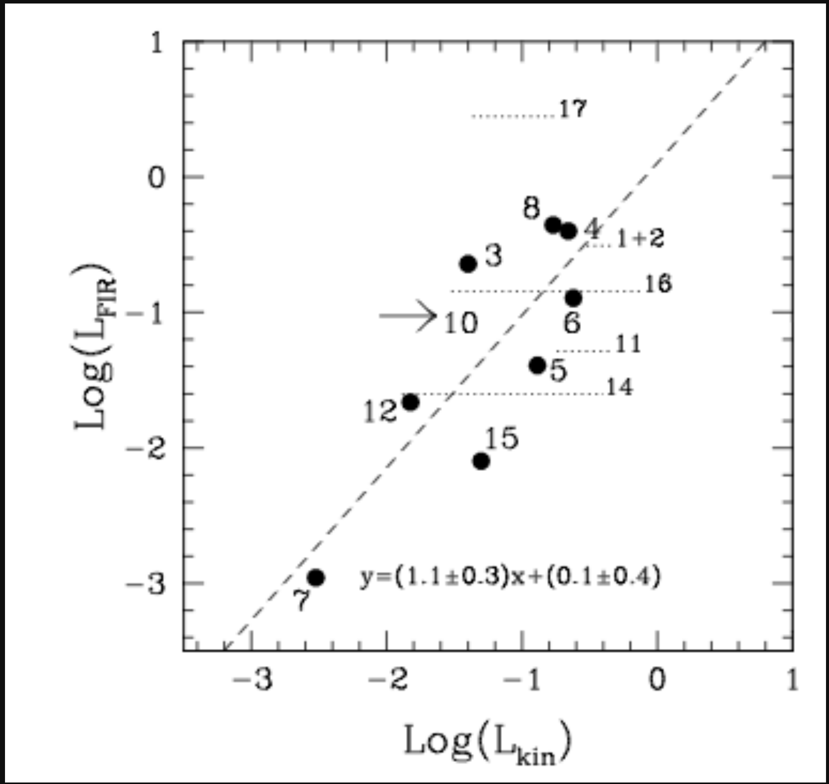
THE SIMILARITY OF THE CO ROTATIONAL TEMPERATURE OF PMS, CLASS I AND 0 SOURCES WOULD ARGUE FOR A COMMON ORIGIN

THE CO EMISSION in LOW-MASS PROTOSTARS

QUESTION: WHAT IS THE ORIGIN OF THE CO EMISSION ?

1) DENSE SHOCKS IN THE INNER ENVELOPE

Giannini et al. 2000



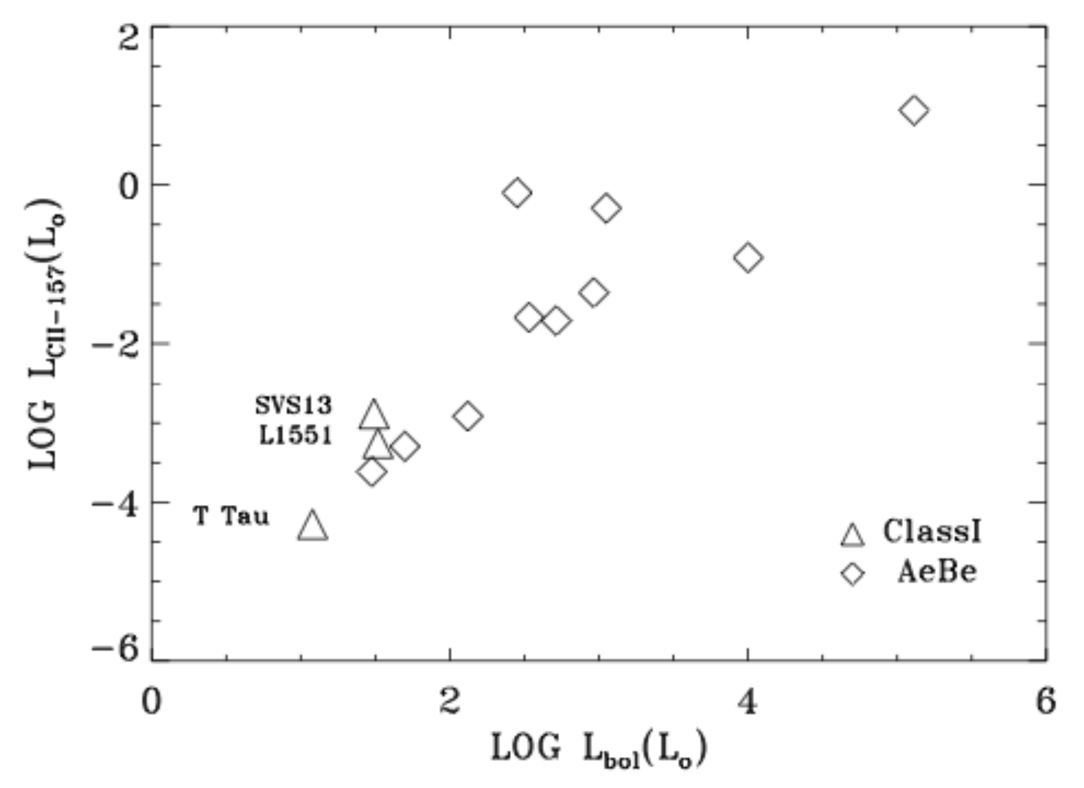
HERSCHEL, HELP!

THE POSSIBLE CORRELATION BETWEEN THE CO (+H_2O+OI) LUMINOSITY IN CLASS 0 SOURCES IS IN FAVOR OF THE DENSE SHOCK ORIGIN

THE CO EMISSION in LOW-MASS PROTOSTARS

QUESTION: WHAT IS THE ORIGIN OF THE CO EMISSION ?

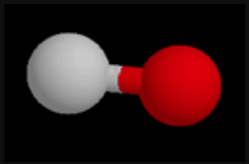
1) UV ILLUMINATED GAS



DATA ADAPTED FROM:
Lorenzetti et al. 1999,
Molinari et al. 2000,
Spinoglio et al. 2000 and
White et al. 2000

HERSCHEL, HELP!

THE CORRELATION BETWEEN THE CII LUMINOSITY IN AeBe and CLASS I SOURCES TESTIFIES FOR THE PRESENCE OF A PDR INNER REGION

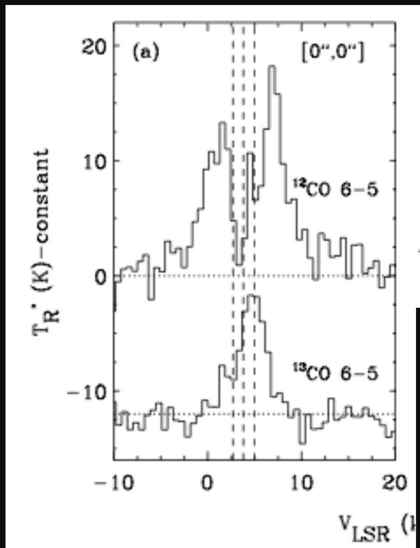


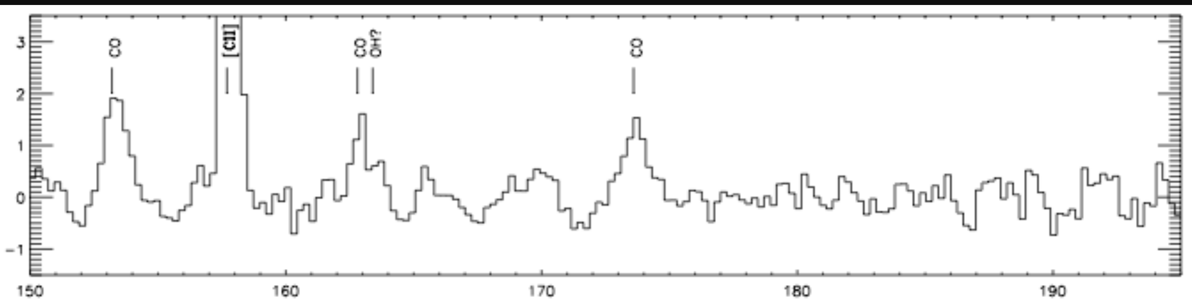
THE CO EMISSION in LOW-MASS PROTOSTARS

QUESTION: WHAT IS THE ORIGIN OF THE CO EMISSION ?

1) UV ILLUMINATED GAS

The case of EL 29: heated disk surface?



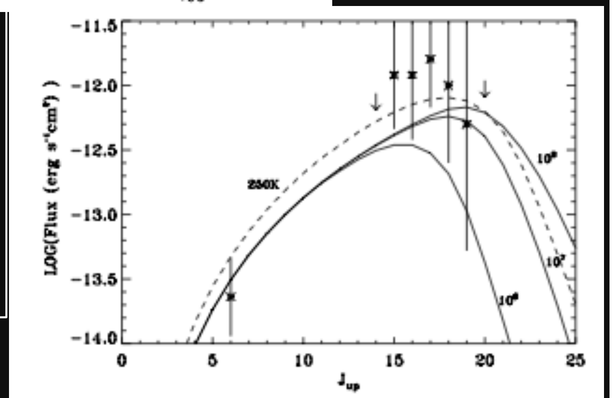


CSO + ISO observations (Ceccarelli et al. 2002)

$T_{gas} \approx$ 170-250 K

Density > $10^6 cm^{-3}$

Radius ≈ 250AU

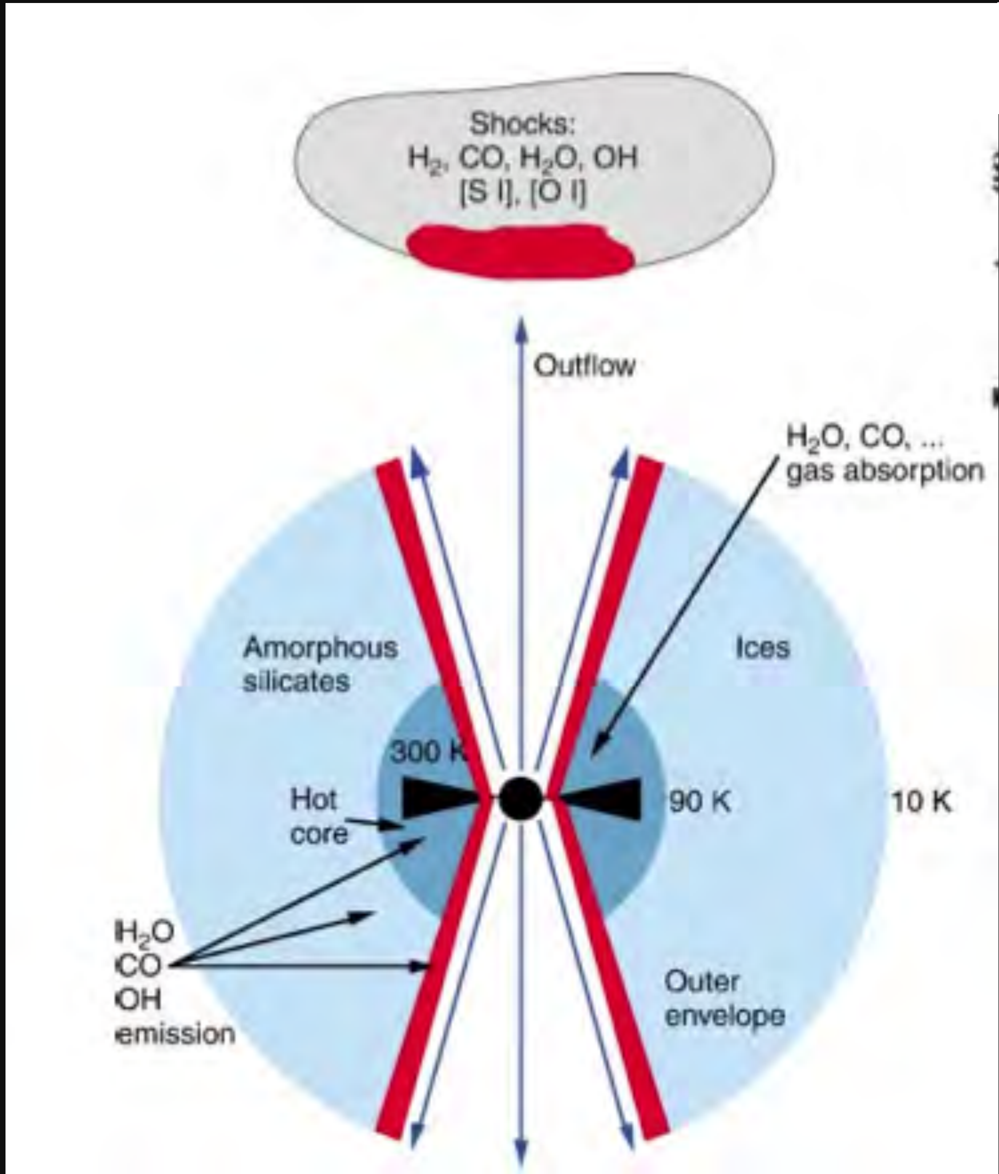


HERSCHEL, HELP!

THE IONISATION IN THE INNER REGIONS OF LOW-MASS PROTOSTARS

ISO PROVIDED VERY LITTLE INFORMATION ON THIS.
THE ONLY DETECTED ION IS C^{+}, WHOSE EMISSION IS DOMINATED BY THE PDR ENVELOPPING THE PARENTAL CLOUD

HERSCHEL, HELP!



ADAPTED FROM
van Dishoeck 2004, ARAA

ISO PROVIDED A COMPLEX PICTURE OF THE STRUCTURE OF LOW-MASS PROTOSTARS:

1. COLD ENVELOPE
2. HOT CORINO
3. INNER SHOCKS
4. UV ILLUMINATED GAS
5. INNER DISK

HERSCHEL, HELP!

OUTLINE

1. The census
2. The structure
3. The chemistry
4. The dynamics
5. The outflow

THE DYNAMICS

There are no doubts:
To form a star from a diffuse cloud, matter MUST collapse.

THE HOLY GRAAL FOR PROTOSTARS HUNTERS: THE COLLAPSE SIGNATURE

OBSERVED LINE PROFILE ⟷ **MODEL PREDICTIONS**

↓

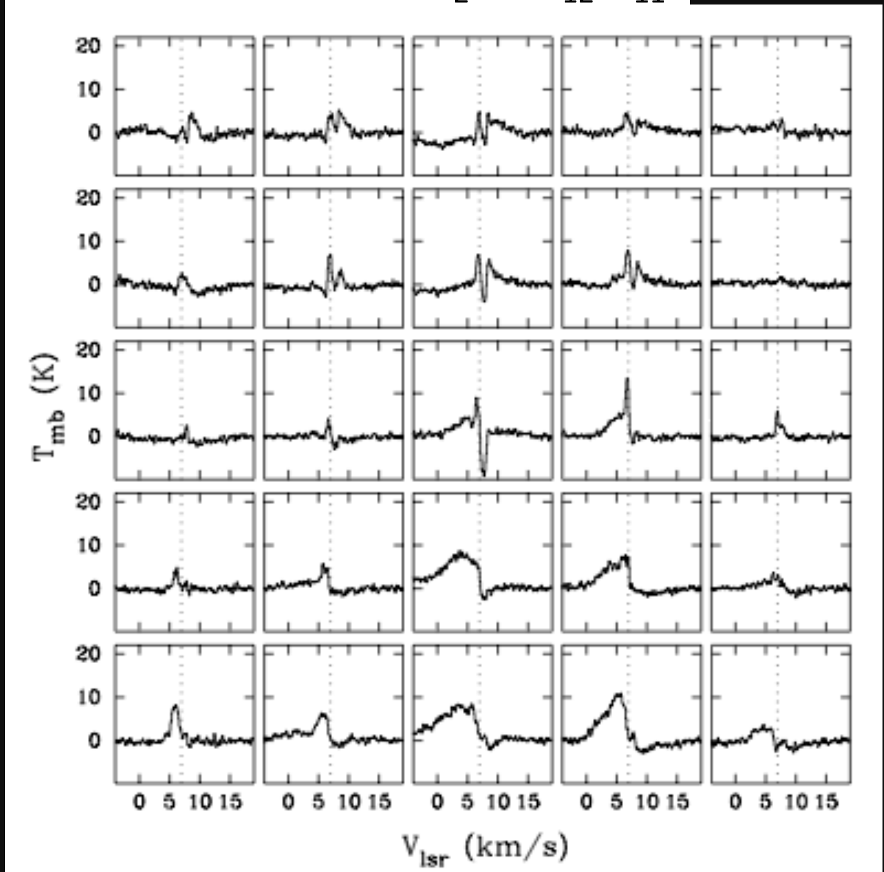
Can we observe the collapse movement? What is the velocity field? How does it depend on the time? What is the infalling rate? What causes the collapse? External compression?...

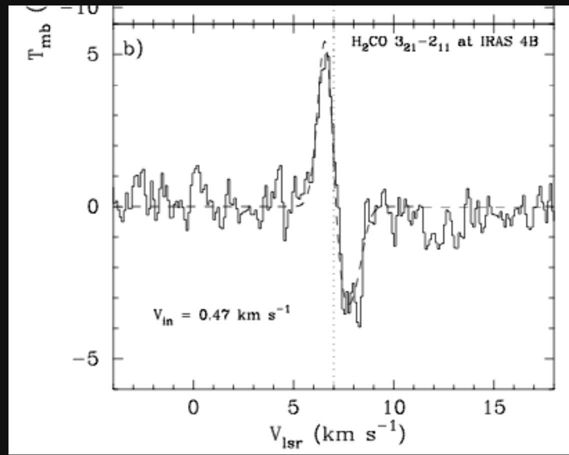
THE DYNAMICS

The example of NGC1333-IRAS4b

Di Francesco et al. 2001, see also Belloche et al. 2006

PdB observations of H_2CO 3_{12}-2_{11}





observed inverse P Cygni profile

⬇

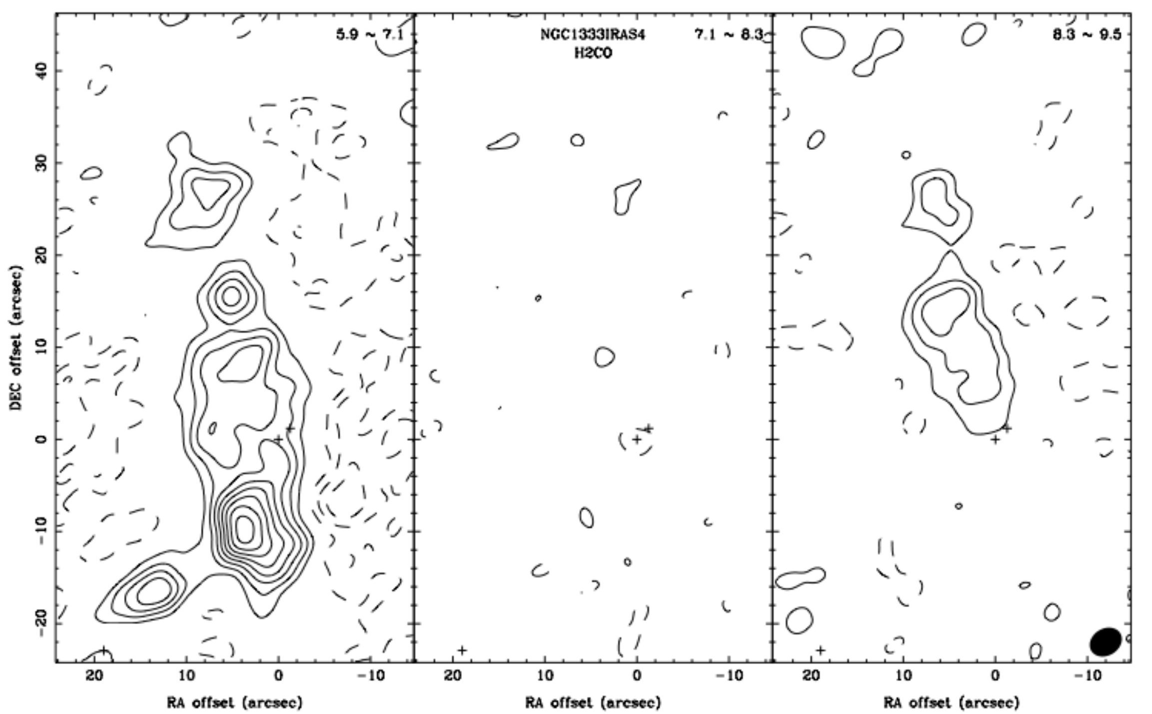
infall motion

$M_{acc} \approx 10^{-4} M_o/yr$

THE DYNAMICS

The example of NGC1333-IRAS4b

Large scale NMA observations of H_2CO 2_{12}-1_{11}



Choi et al. 2004, 2005

PRESENCE OF A COLD FOREGROUND GAS LAYER ABSORBING @ 8km/s ➔ NO inverse P Cygni profile
➔ NO infall motion

HERSCHEL, HELP!
with high lying lines not present in foreground gas

OUTLINE

1. The census
2. The structure
3. The chemistry
4. The dynamics
5. The outflow

THE OUTFLOW

WHY: OUTFLOWS ARE UBIQUITOUS AND A KEY INGREDIENT IN THE STAR FORMATION PROCESS: THEY GET RID OF THE ANGULAR MOMENTUM, DISSIPATE THE PLACENTAL ENVELOPE, DESTROY THE PARENTAL CLOUD INJECTING TURBULENCE IN ISM

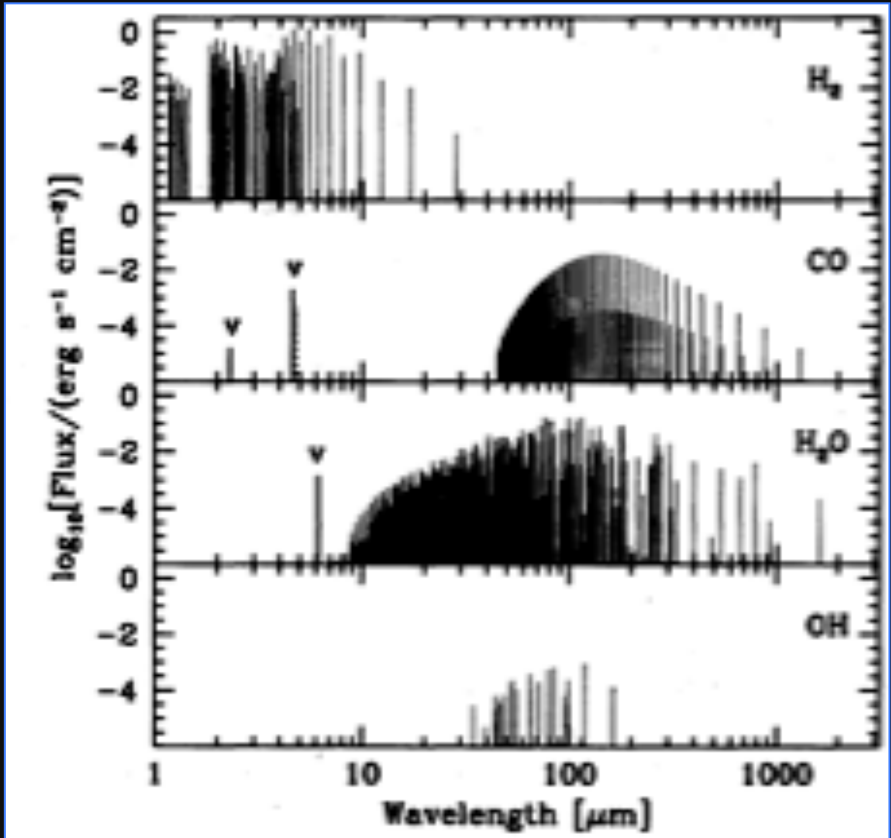
OBSERVED PROPRIETIES ⟷ **MODEL PREDICTIONS**

↓

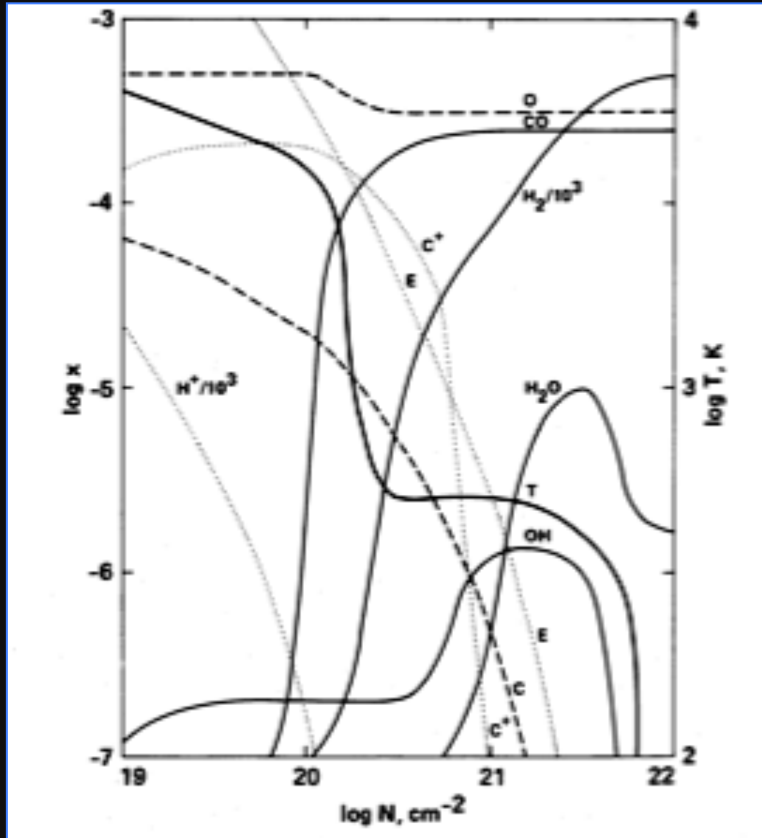
How much energy is injected in the ISM? How? What kind of shocks are created? How are they cooled? How are they generated? Jets/wide winds? What species are injected in the ISM from those shocks?

THE OUTFLOW

MOLECULAR SHOCKS: EXPECTED WATER FUNTAINS



C-shocks (Kaufman & Neufeld 1996)

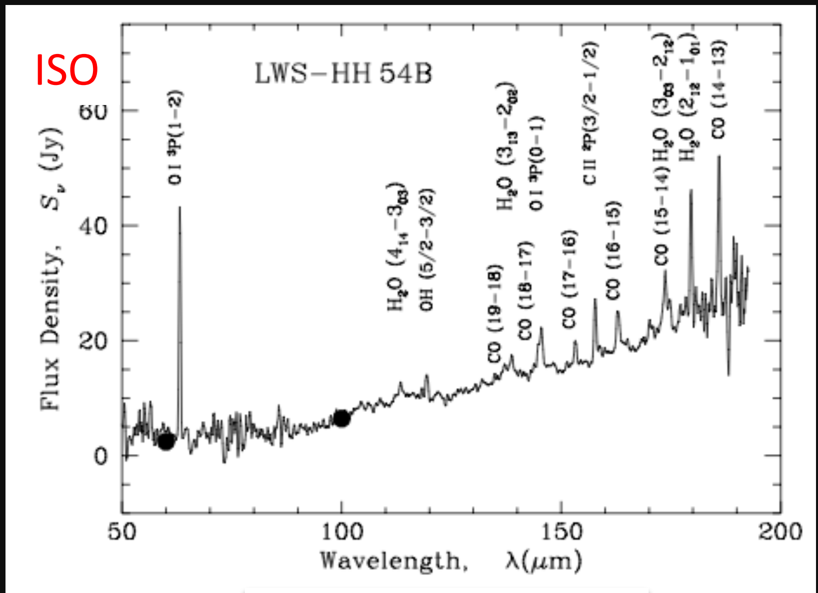


J-shocks (Hollnbach & mcKee 1979)

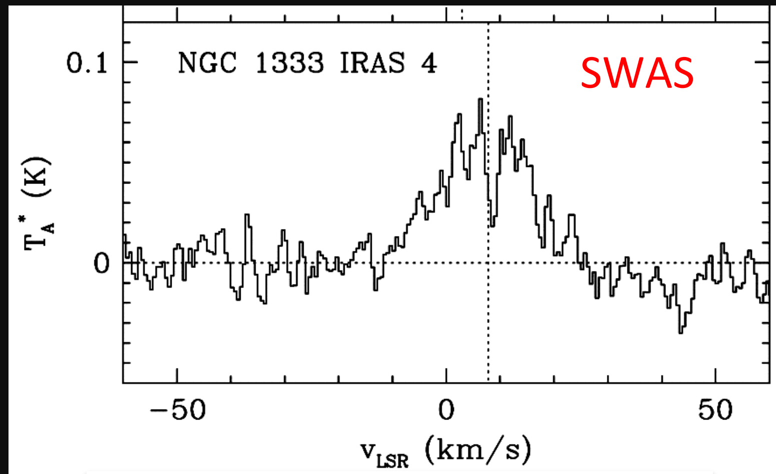
THE OUTFLOW

OBSERVATIONS OF WATER IN MOLECULAR OUTFLOWS OBTAINED WITH ISO (many lines, poor spectral resolution ≈ 200), SWAS AND ODIN (fundamental o-H_2O line @557GHz, high spectral resolution ≈ 10^6, poor spatial resolution ≈ 1.5-4')

Liseau et al. 1996



$x(H_2O) \approx 10^{-5}$



Bergin et al.2003

$x(\text{o-}H_2O) \approx 10^{-7}\text{-}10^{-5}$

YES, WATER IS ABUNDANT INDEED…BUT NOT SO MUCH AS EXPECTED

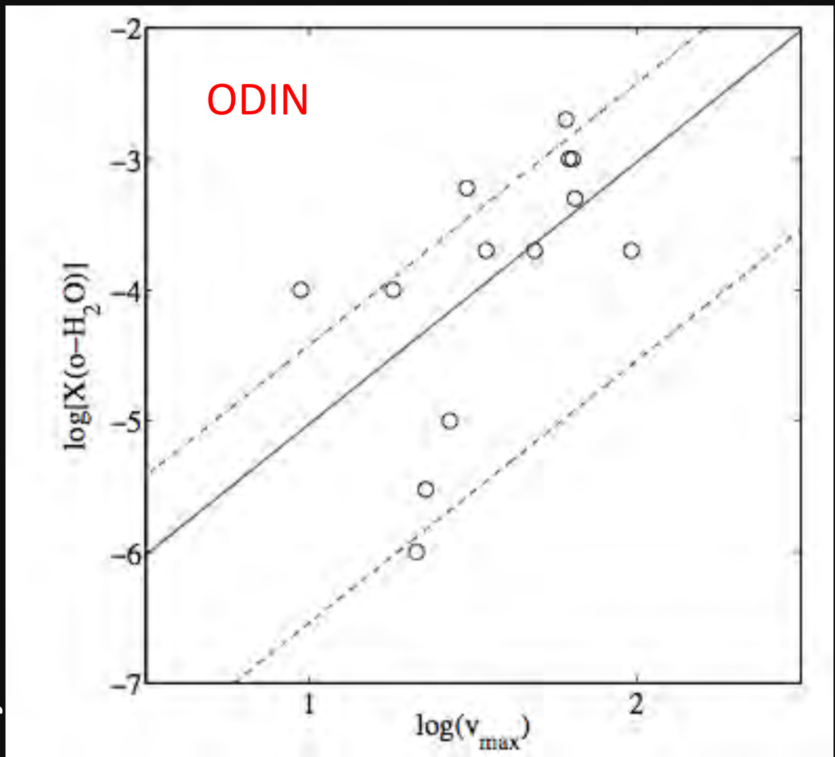
THE OUTFLOW

YES, WATER IS ABUNDANT INDEED…

BUT NOT SO MUCH AS EXPECTED

(ISO: Nisini et al. 2002, SWAS: Franklin et 2008, ODIN: Bjerkeli et al. 2009…)

Bjerkeli et al.2009



THE WATER ABUNDANCE INCREASES WITH THE GAS TEMPERATURE/MAX VELOCITY in rough agreement with predictions for non-dissociative C-shocks

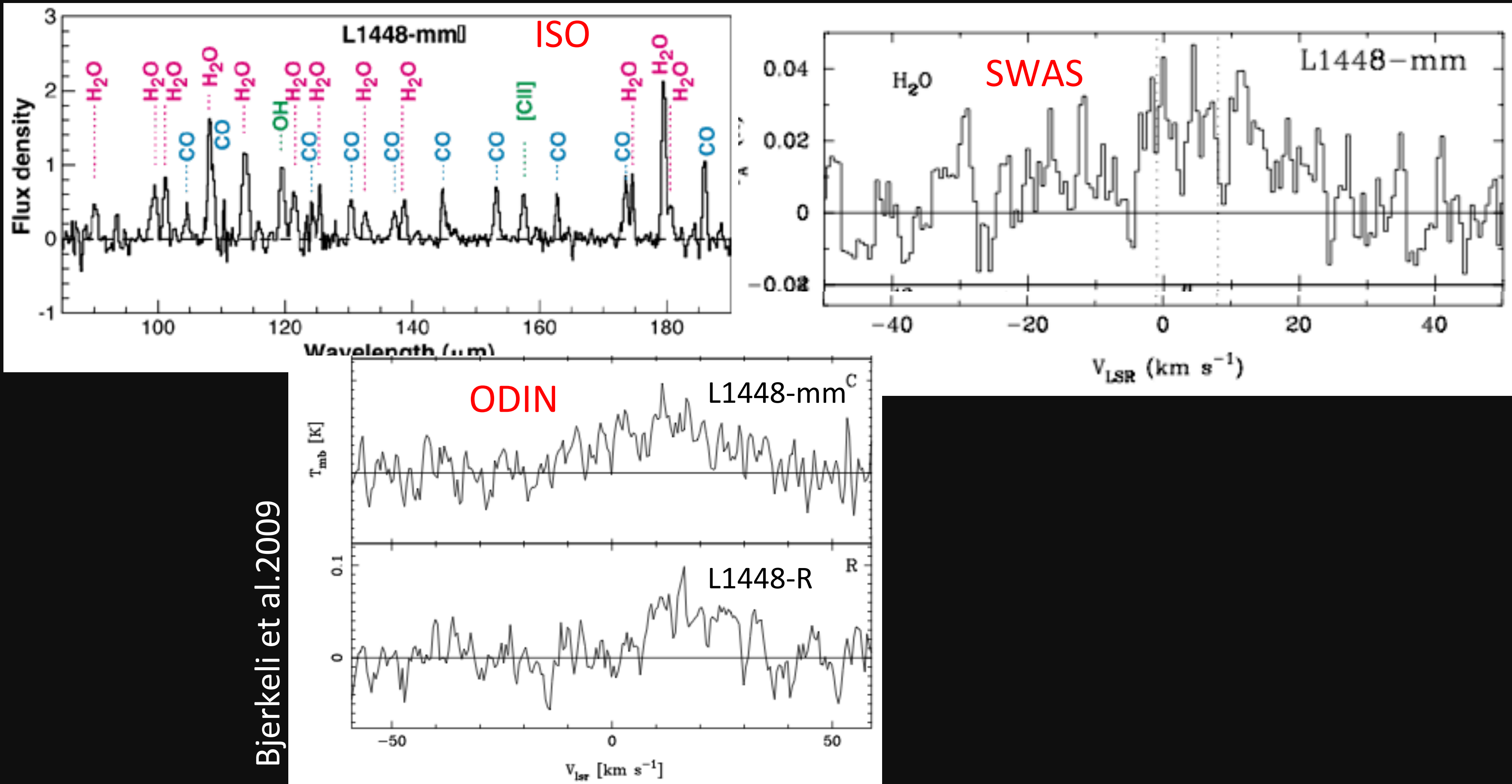
HERSCHEL, HELP!

THE OUTFLOW

Nisini et al. 2000

Franklin et al.2008

Bjerkeli et al.2009

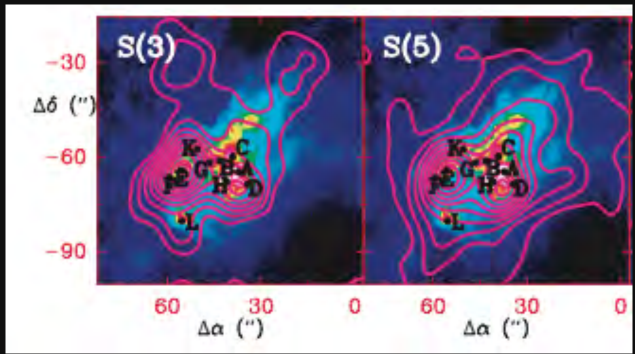


ISO AND SWAS/ODIN DO NOT PROBE THE SAME GAS (Franklin et al. 2008)

→MORE THAN ONE COMPONENT NEEDED: DIFFERENT SHOCKS?

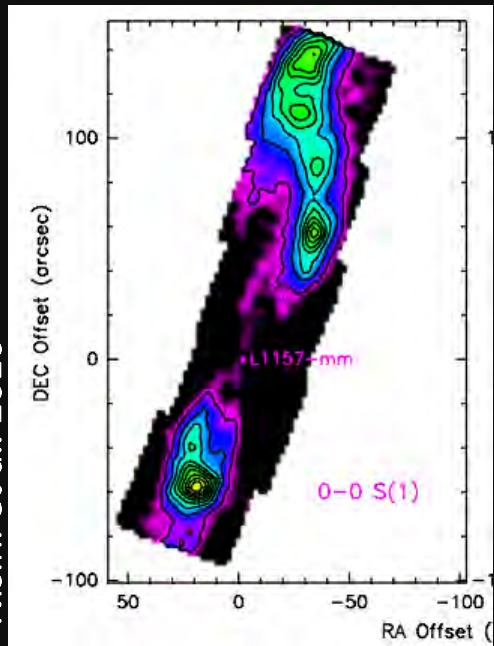
THE OUTFLOW

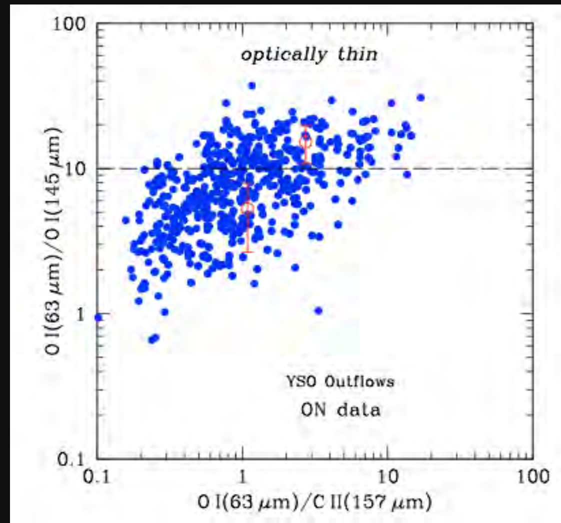
HOW MANY COMPONENTS? HOW MANY SHOCKS?



Lefloch et al.2003

Nisini et al. 2010





Liseau et al. 2006

BTW MIND THE ABSORBING OI

H_2 EMISSION OBSERVED BY ISO/SPITZER TESTIFIES OF NON DISSOCIATIVE SHOCKS

OI EMISSION OBSERVED BY KAO/ ISO TESTIFIES OF DISSOCIATIVE SHOCKS

HERSCHEL, HELP!

with your high spectral and spatial resolution

CONCLUSIONS

HELP IS ALREADY HELPING TO SOLVE THE SEVERAL OPEN QUESTIONS LEFT BY ITS PRECEDESSORS AND MORE WILL COME IN THE COMING YEARS

1. The census
2. The structure
3. The chemistry
4. The dynamics
5. The outflow

PLEASE, CROSS YOUR FINGERS: TODAY HIFI WILL BE WAKEN UP!