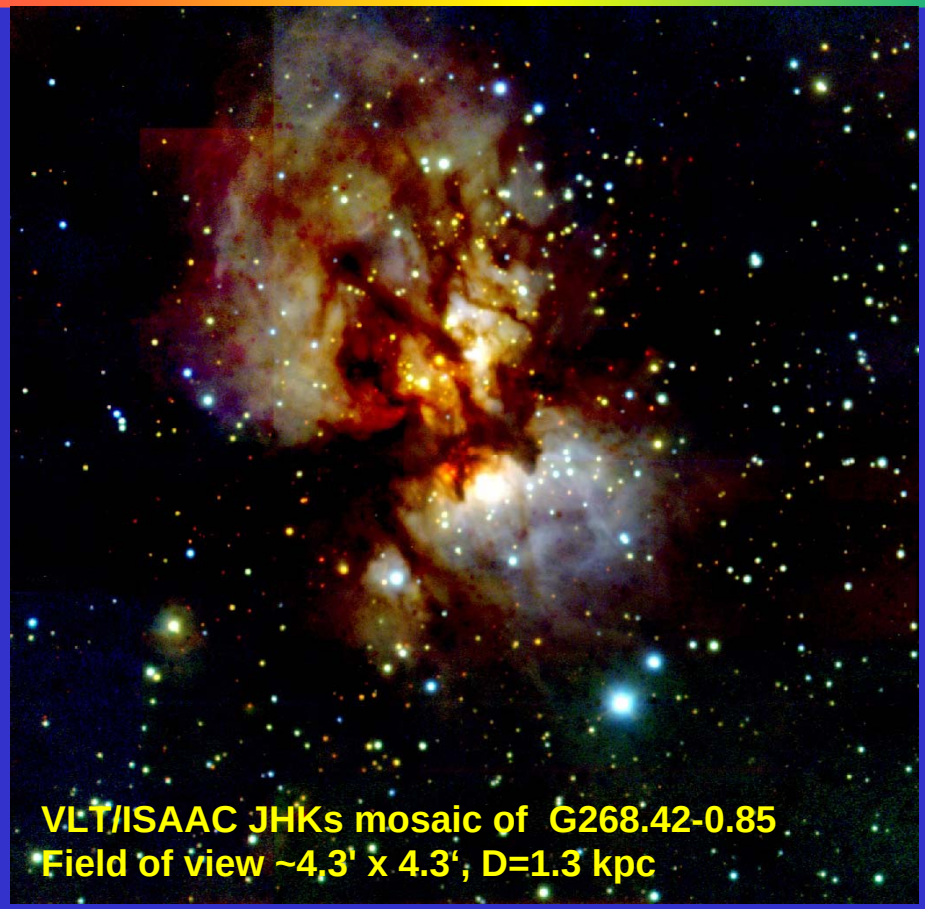
Massive Star Formation

The conference again or from α to Ω (The HZ effect)

Thomas Henning

Max-Planck-Institut für Astronomie, Heidelberg



Apai, Linz, Henning, Stecklum (2005)
0.5 arcsec ~ 500 AU

- „Clumps“ do not mean „spheres“ (filaments)
- NIR provides best spatial resolution over wide areas (without filtering)

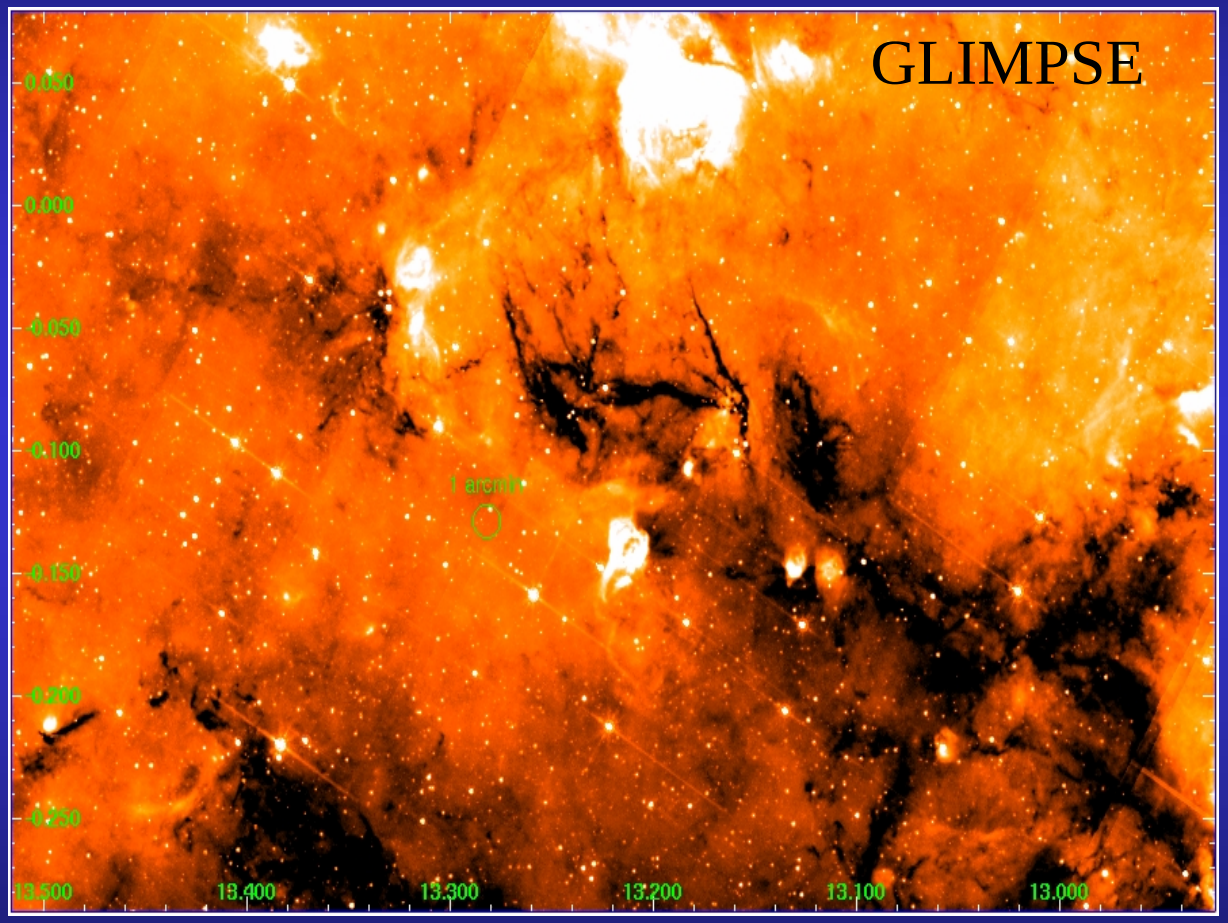
One ACS/WFC field centered on LH 95 in the LMC

Gouliermies, Henning ea.2007

Challenges: Rare objects, high and variable extinction, crowded regions, multiple sources, short timescales, complex physics ---> How to determine L (mass) of individual objects? (The Orion Debate)

Formation of Massive Stars

- Approach
- Tools
- Concepts
- Highlights
- The Meeting
- Future



Our approach – Are we making progress?

- Line/continuum submm/mm surveys over larger areas
  (Some guided by extinction maps: bias by background/outer galaxy):
  Cold regions are a hot topic!

- Infrared surveys (Spitzer-GLIMPSE: sensitivity), Herschel …
  ground-based NIR/MIR surveys (spatial and spectral resolution)

- Interferometry data: PdBI, SMA, …./Chemistry + RT?!

- High-resolution polarisation data are rare, but coming ….

- Infrared interferometry provides resolutions of few AU!!!

- High-resolution IR spectroscopy (Kinematics on interesting scales)

Our approach – Are we making progress?

- 3D line and continuum transfer codes (also for high optical depths)
- 3D MHD/AMR codes plus radiation transfer (flux limited)

Radiation transfer remains a challenge (6-dimensional problem)

„Expert“ meeting next year here in Heidelberg (J. Steinacker)

Resolution, Resolution, Resolution

Core/Trapezium Systems	10 000 AU, 10´´ at 1000 pc
Multiple Systems	1 000 AU, 1´´
Inner Disks/Close Binaries	100 AU, 0.1´´
Outflow Origin	1-10 AU, 0.01 – 0.001´´

And: Spectral resolution of a few km/s to resolve kinematics

And: High Sensitivity for most of the measurements

Resolution, Resolution, Resolution

Resolution, Resolution, Resolution

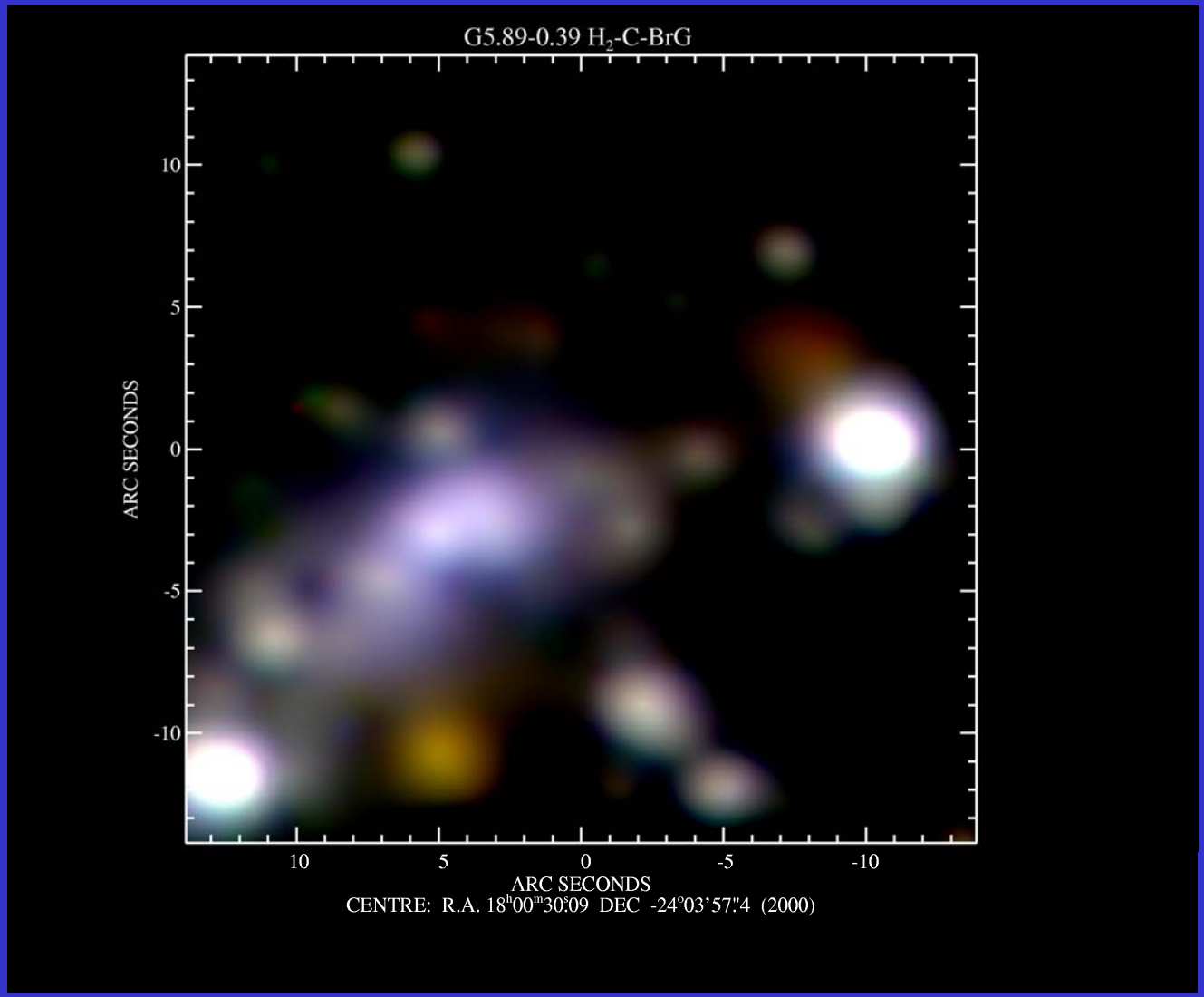
Orion at 5 kpc

Resolution, Resolution, Resolution

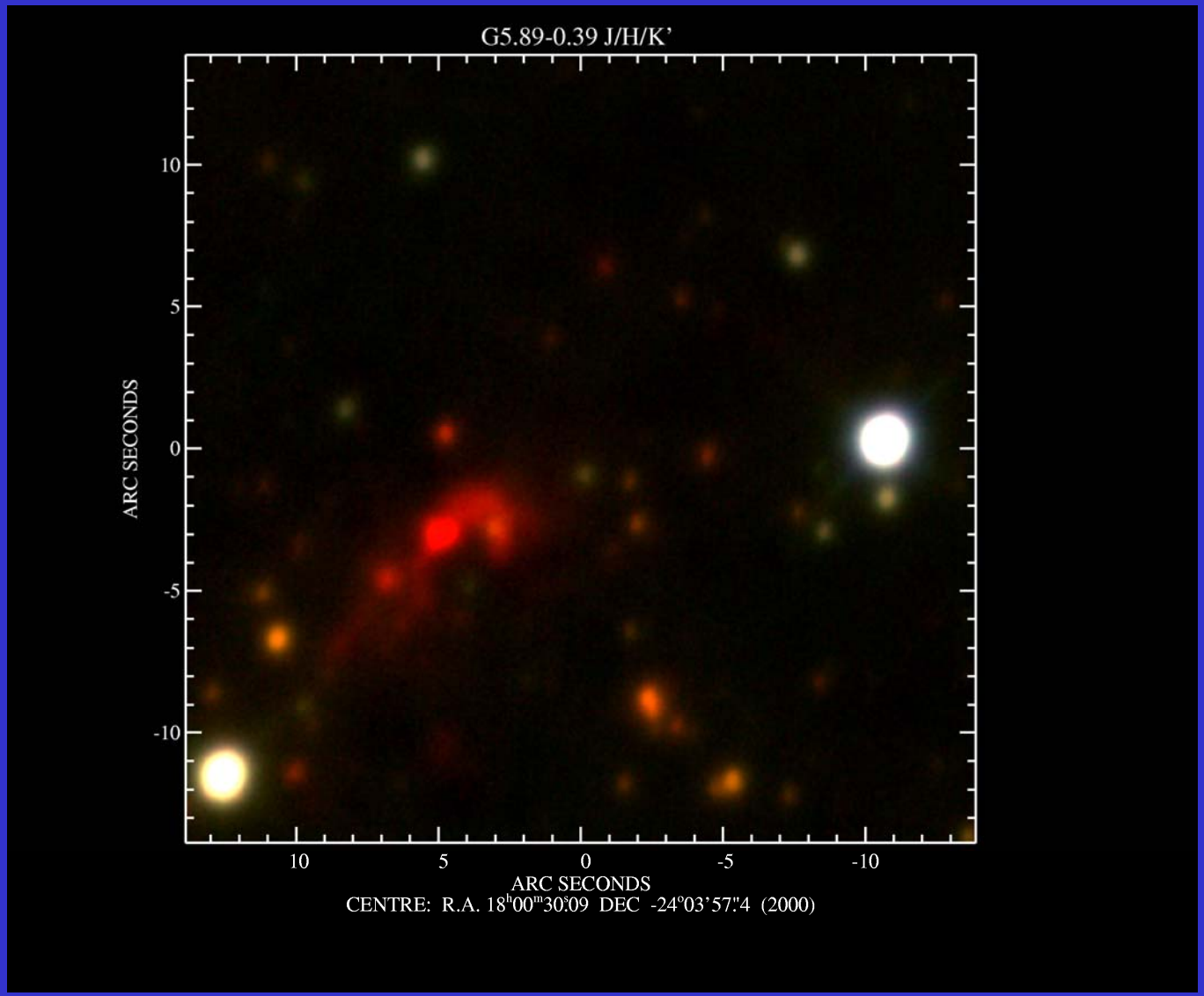
- Orion is not a region of massive star formation (see Westerlund 1, …) ?
- Orion is too evolved (interactions erase initial conditions) ?
- Orion provides many unsolved puzzles (Bally, Greenhill, Tan, Schulz)
- More puzzles to come …(X-rays)

Are we making progress with our tools?

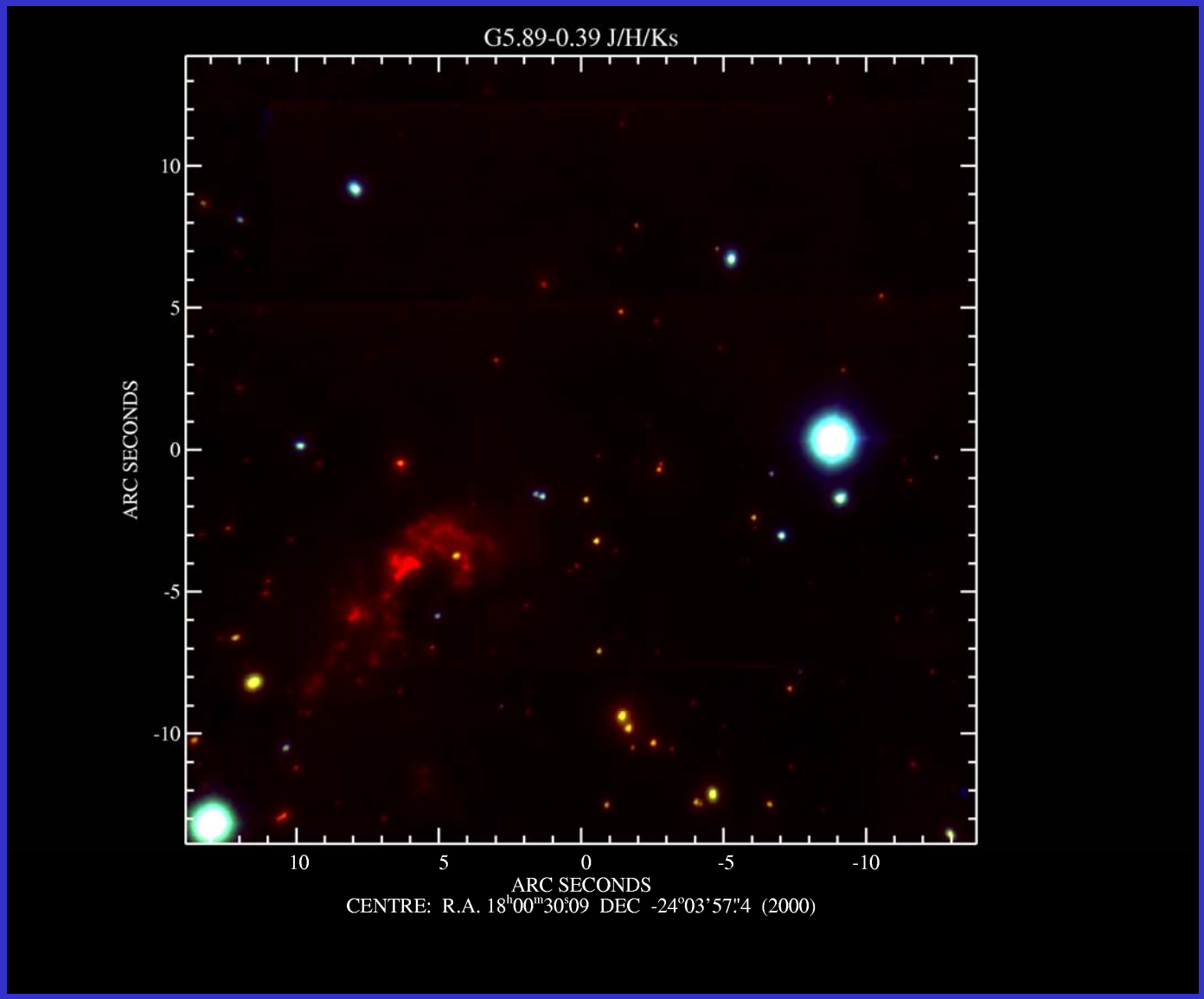
1998: IRAC2b @ 2.2m, ESO La Silla



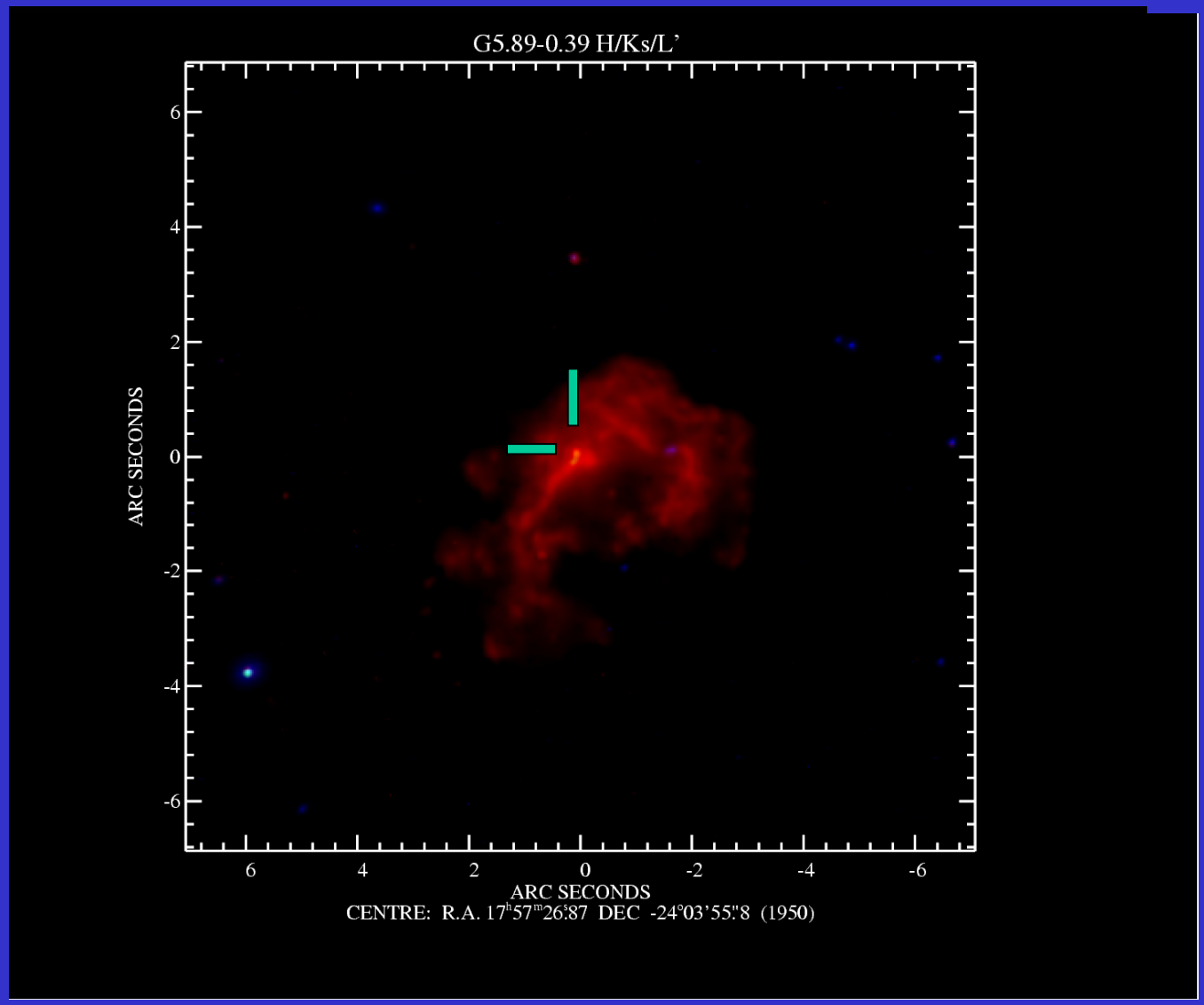
1999: ALFA / OMEGA @ 3.5m Calar Alto



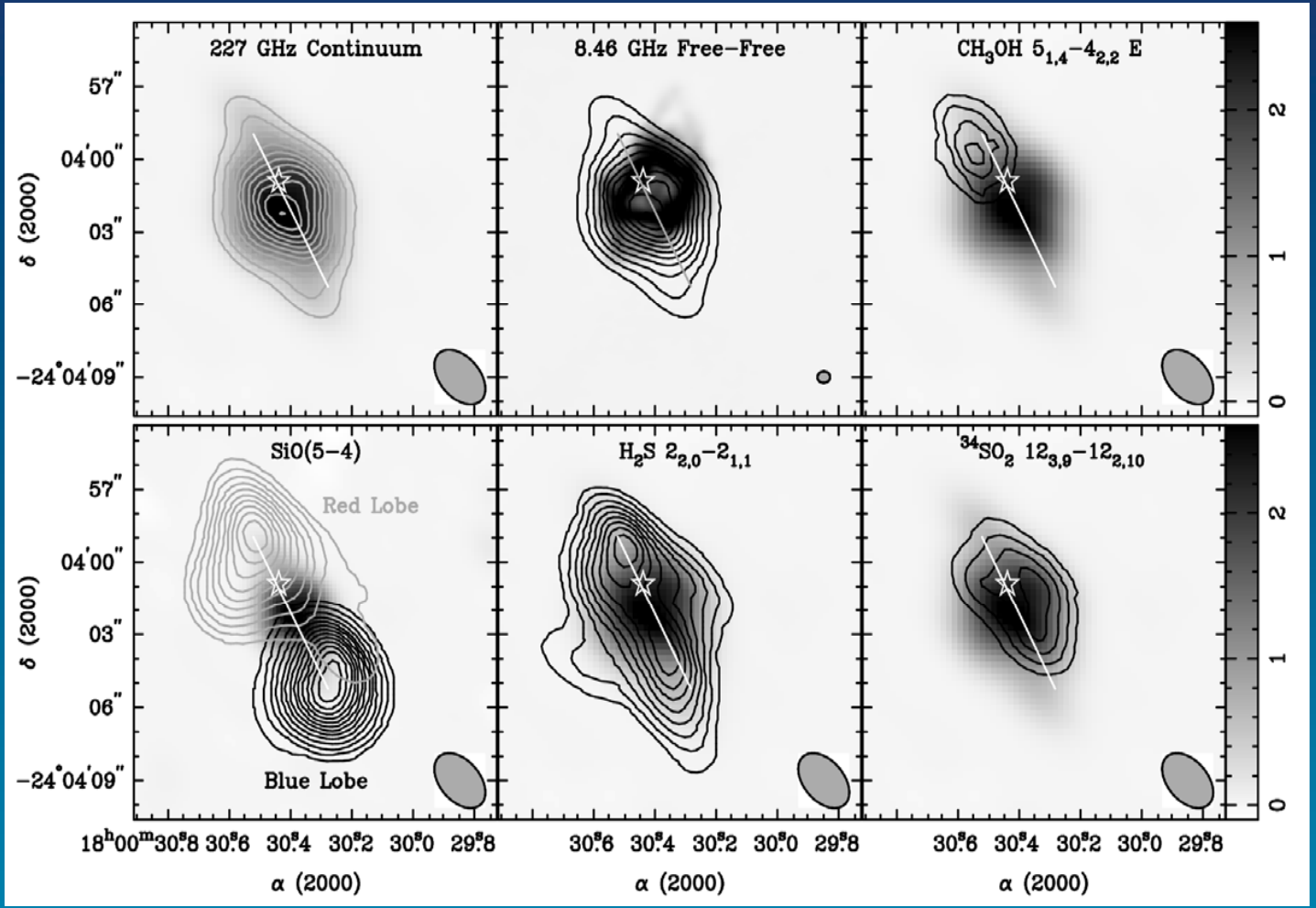
2002 NAOS-CONICA@ESO 8.0 m VLT UT4 „Yepun“



2002 NACO – New Wavelengths at sub-arcsecond scales



SMA Observations

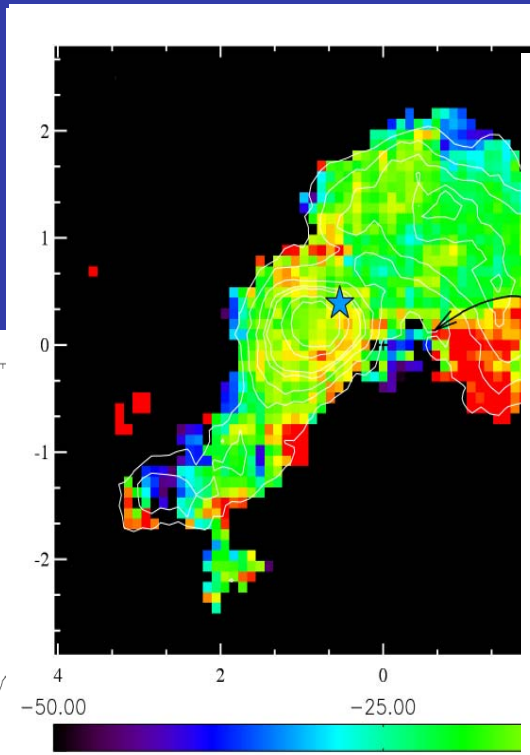


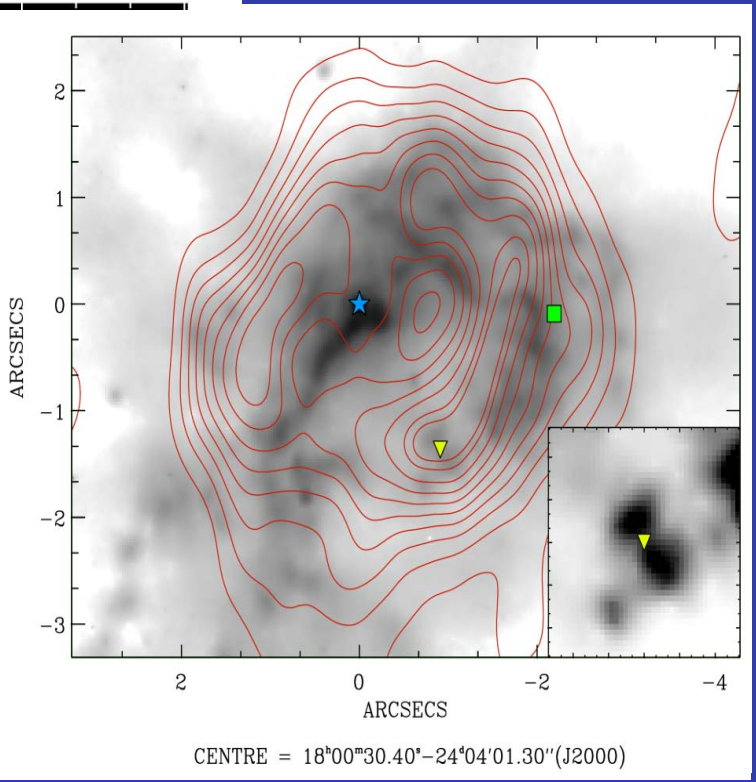
Sollins et al. (2004)

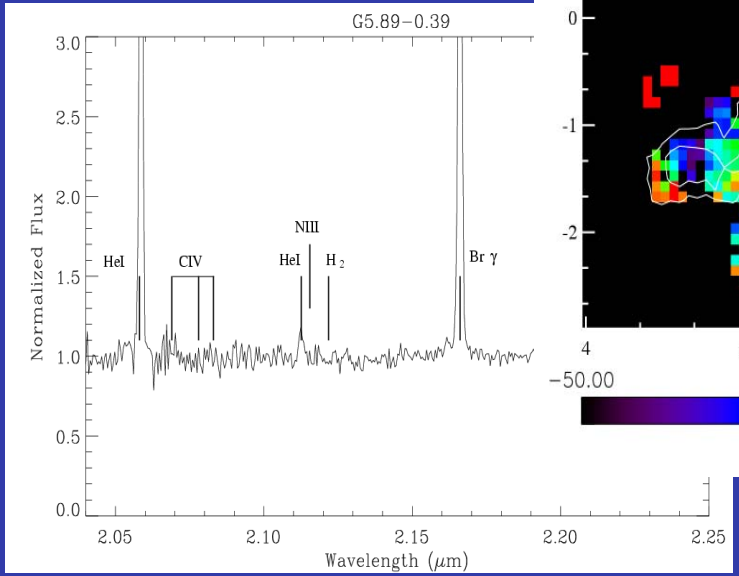
G5.89-0.39: More than just a spherical UCHII region

Puga, Feldt, Henning, et al.
2006
D=1.9 Kpc

ADONIS/GraF Fabry-Perot spectroscopy revealing the Br gamma velocity structure of the UCHII region (colour-coding in km/s).



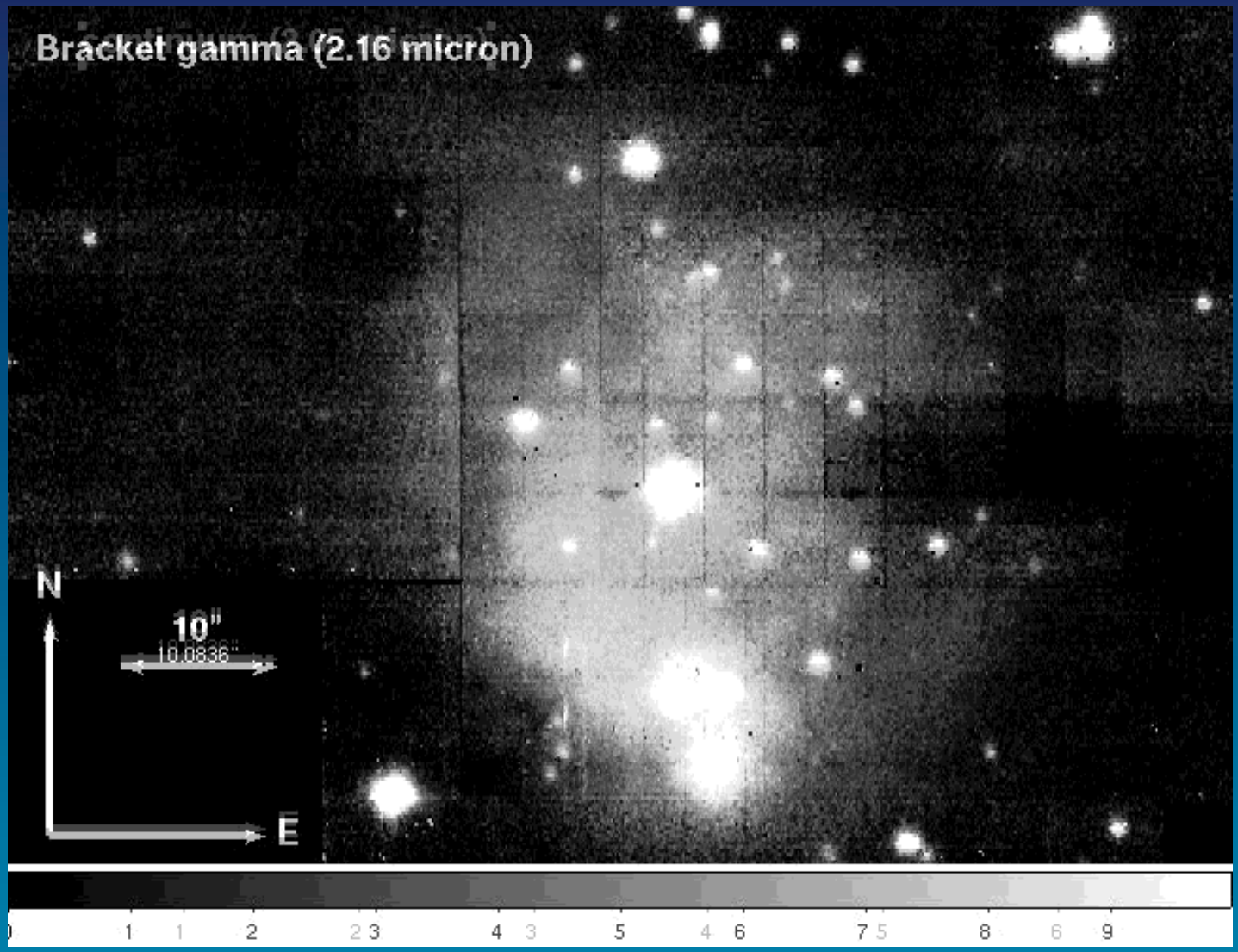




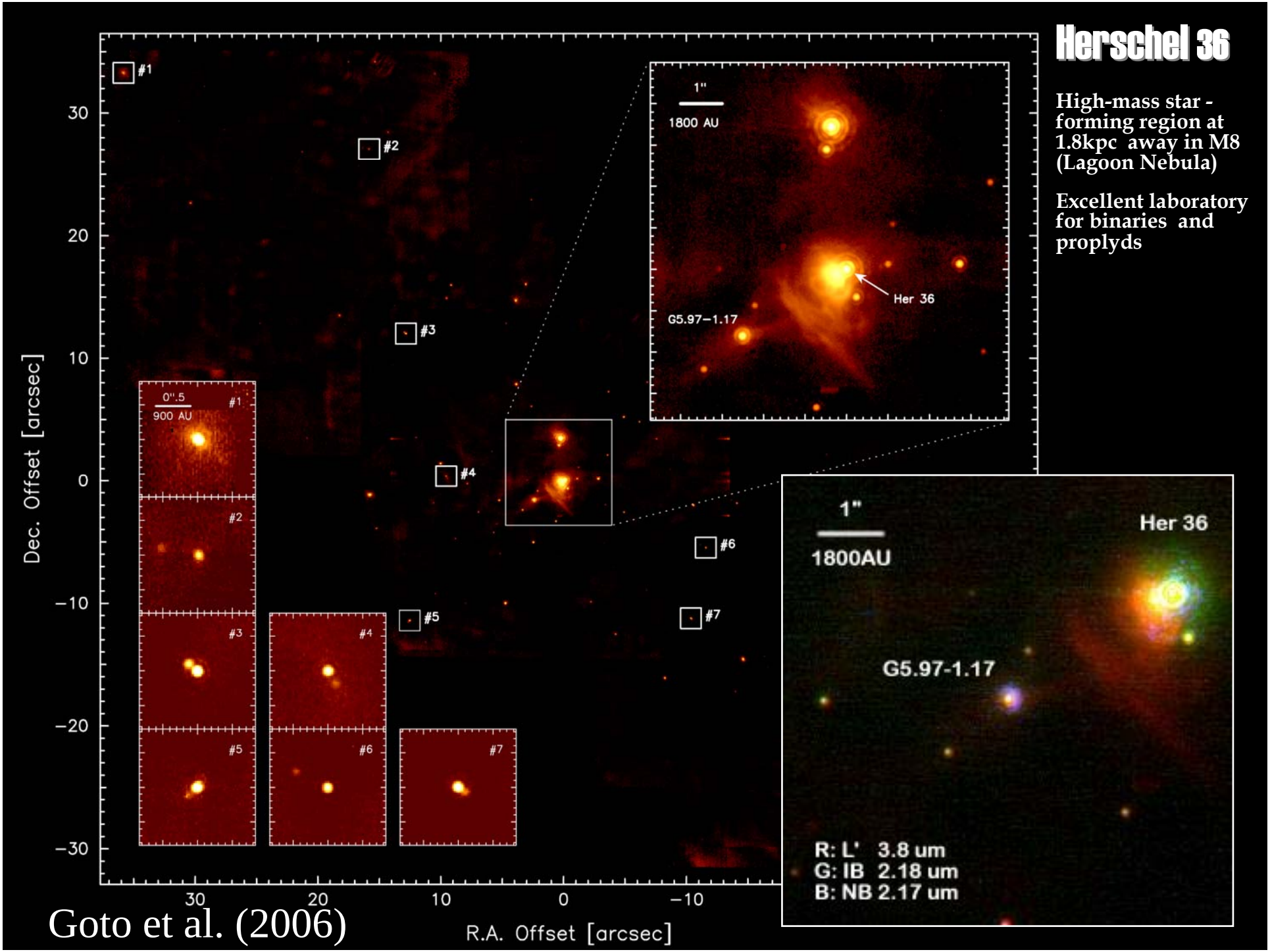
NACO long-slit spectrum of „central“ star confirms SpT ``earlier than O7V´´

NACO L' image + VLA 2cm contours.
The symbols denote the central O5-O7 star, the centre of the Brγ bipolarity, and the bipolar L' band structure related to the Sollins mm source (inset with more extreme L' cut levels for clarity)

SINFONI Project at the VLT – Heidelberg/Amsterdam/Madison



Observers start producing movies ---> Physical processes and kinematics


Herschel 36
High-mass star - forming region at 1.8kpc away in M8 (Lagoon Nebula)
Excellent laboratory for binaries and proplyds
#1
#2
#3
#4
#5
#6
#7
1"
1800 AU
Her 36
G5.97−1.17
0".5
900 AU
1"
1800AU
Her 36
G5.97-1.17
R: L' 3.8 um
G: IB 2.18 um
B: NB 2.17 um
Dec. Offset [arcsec]
R.A. Offset [arcsec]
30
20
10
0
−10
−20
−30
Goto et al. (2006)

Resolution, Resolution, Resolution

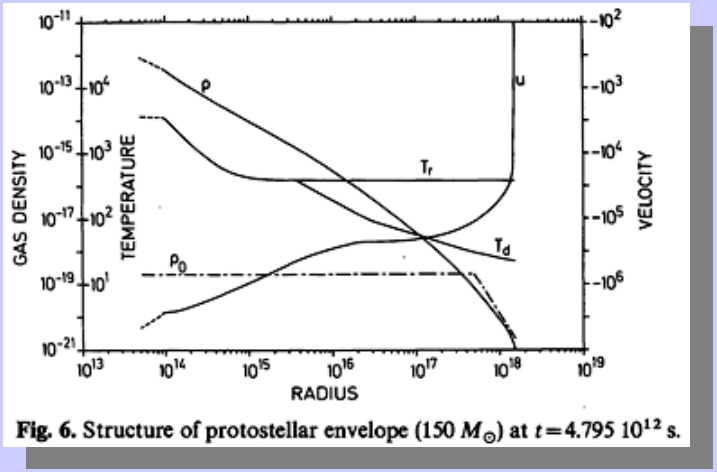
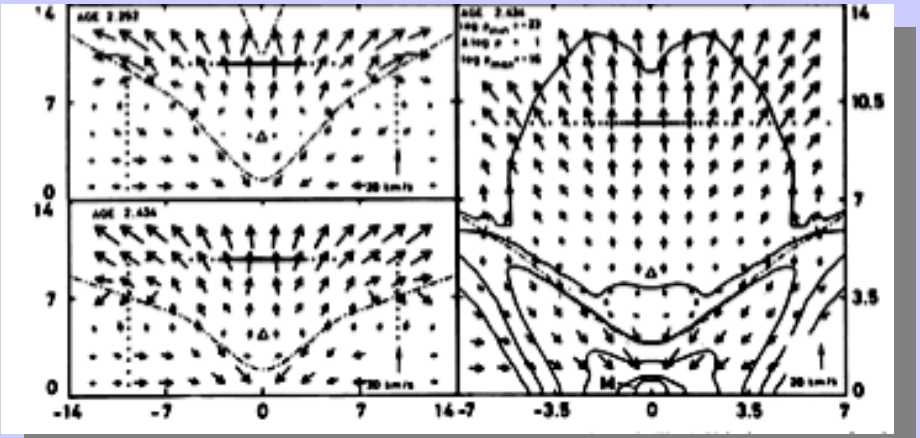
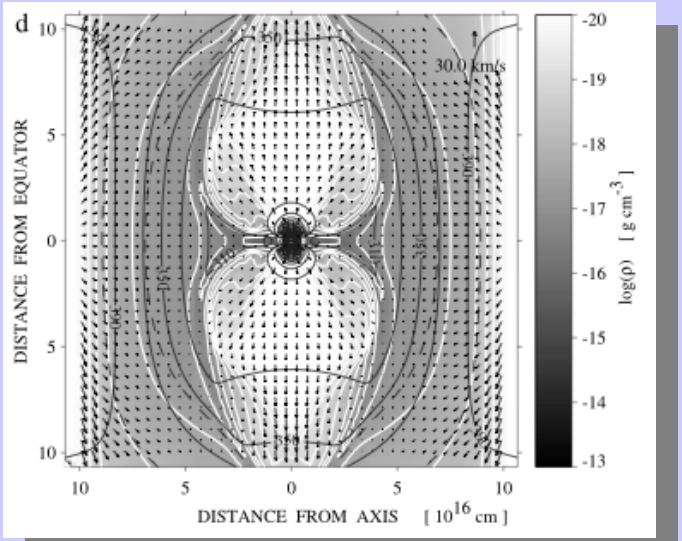


Fig. 6. Structure of protostellar envelope (150 $M_\odot$) at $t = 4.795\ 10^{12}$ s.

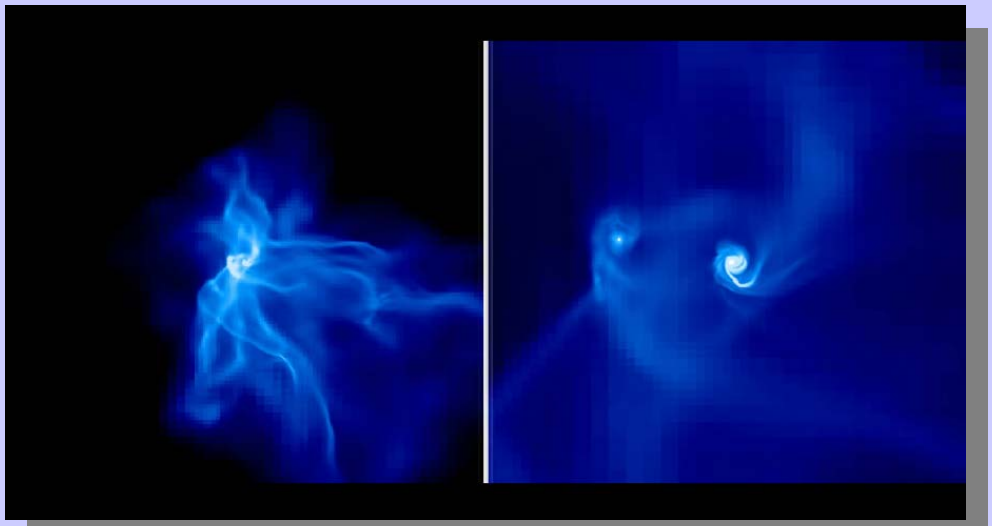
Yorke (Protostar) & Krügel 1977
1D 169 to 194



Yorke ea. 1982
2D 40x40



Yorke & Sonnhalter 2002
2D, 64x64, 3 3 nested grids



Krumholz, Klein, McKee
3D, 128x128x128, AMR

Concepts

MSF – No scaled-up version of low-mass star formation?

- Clustered mode of massive SF vs. isolated core collapse

  (We see only small number of isolated massive field stars, ….)

  T: Competitive accretion in which stage? Hierarchical systems?

  O: Global accretion vs. local accretion vs. disk accretion, non-thermal line widths = turbulence?

- Collapse from outside-in instead of inside-out; Concept of critical column density

- Overcoming accretion barrier? (gas parcels, high accretion rates? … ZY07)

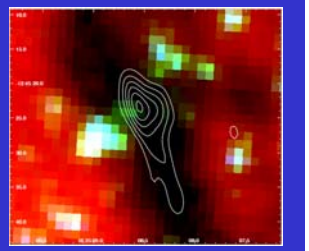
- „IMF“ of cores: Selection --- Only very few high-mass cold cores detected (simply rare …)

Concepts

MSF – No scaled-up version of low-mass star formation?

•Evolutionary scheme:

(1) Infrared dark clouds
(mass? activity level? underluminous? outer galaxy?)
---> Hot Cores ---> Massive YSOs in UC HII Regions



(2) Outflow scenario ----> O-stars ?

(3) Pre-stellar phase ---> Protostars ---> Stars (Timescales!!!)

(Be cautious with SED classification schemes – Resolution!
Better get T/L over the right scales – Hot Cores in Cold IRDCs)

Do massive pre-stellar cores exist (or $t_{for} < t_{ff}$) (Cores?, Scale-free?)
Bonnell et al. vs. McKee & Tan

Concepts (and Definitions)

Massive Protostars

- Gaseous object in hydrostatic equilibrium, which has not yet started hydrogen burning (ZY07)

- Gaseous object with luminosity mainly provided by accretion (AGN vs. starburst problem) (Henning07) (But observations: difficult to measure, short timescale, final mass?)

- Gaseous compact object in the build-up phase (accretion, Beuther07) – A pragmatic definition, but what is the final mass

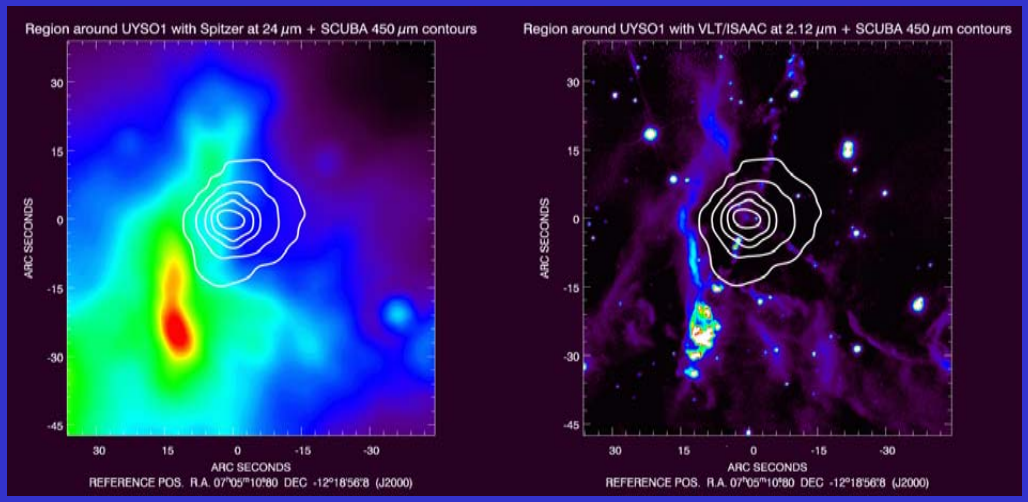
Other concepts – Progress?

- **„Turbulent“ clouds** – Dynamic range (Observations **and** Theory): Matt Redman, Chris Brunt (Drivers???)

- **Star Formation Efficiency** (time-dependent quantity, changing with location --- generally low over large area; L/M is not the same as star formation efficiency): Lori Allen, Jay Gallagher (spiral galaxies), W. Brandner ? (IMF: Stellar mass in low-mass stars, L: High-mass stars)

- **Triggered Star Formation**
  Mordecai-Mark Mac Low, Ed Churchwell, Lise Deharveng

To Remember



Forbrich, Henning, Klein ea., in prep.

- Local Schmidt-Kennicutt (500pc:THINGS, L.Allen, Y. Shirley), HI---H_2 transition
- Small groups of massive YSOs exist (hierarchical systems)
  ---> Runaway OB stars (Orion event 500 yrs ago)
- Role of outflows for high-mass SF (interactions: conditions change)
- High mass loss rates = high accretion rates = mass of star?
- Disks/Outflows and O stars (Wrong tracers? Not existent?)
- Mass segregation (Nature vs. Nurture)
- Sp-type of stars with accretion (stellar evolution)
- What is the upper mass limit?

Highlights (Talks)

- Strong observational bias (my eyes, …)
- Strong computational limitations (my brain, …)

Highlights (Talks) I

- Frederique Motte: Cygnus X complex --- Unbiased mapping of large (nearby) regions (Not a single massive pre-stellar core)
- Fabian Heitsch: Converging flows ---> Not just morphology
- James Jackson: IRDCs --- But where are the massive cores?
- Nicolas Peretto: Global accretion picture for NGC 2264
- Hendrik Linz/Thomas Preibisch: Infrared interferometry ---> inner disk regions
- Doug Gies: Binarity/multiplicity

Highlights (Talks) II

- Floris van der Tak: High ionization rate in galactic center environments (Oka legacy, Farhad Yusef-Zadeh)
- Shermila Goedhart: Periodic maser variability
- Karl Menten: Maser as distant tracers (W 3(OH))
- John Bally: Interaction in N clusters - Orion explosion
- Harold Yorke/Takashi Hosokawa: Stellar evolution with accretion
- M. Krumholz: Radiation is inhibiting fragmentation
- Andrea Urban: Adding Microphysics to SPH

Highlights (Talks) III

- Richard Klein: Radiation barrier discussion
- Lori Allen: Clustered vs. distributed SF (relaxation?, OB stars?)/ Classification scheme for clusters
- Wolfgang Brandner: Westerlund 1 --- Regions of massive star formation
- Lincoln Greenhill: VLBA 3D velocity/position movie
- Norbert Schulz: Fascinating X-ray emission
- Ed Churchwell: GLIMPSE survey
- Jay Gallagher: Different modes of star formation – Open for debate

Did we reach our goals?

- Observers (Give linear scales, mass, L/M, …,) Control terminology:
  Giant Molecular Clouds ---> „Clumps“ (filaments) ---> Cores

- Theoreticians (Give your assumptions and limitations, interpret
  simulation results in terms of physics,
  make (testable) predictions --- Popper paradigm)

To remember: 3D line and continuum RT, 3D MHD/AMR plus
radiation (but microphysics often limited:
abundances of coolants, dust properties, …)

We need stellar evolution models in order to produce the final result!

Abbreviations – The Peter S. Conti 2005 Sicily legacy
IRDC, HMPO, HMPS, LMSC, HMPC, HMPS, HCII, UHCHII, RMC, HMPC, LMSC..
Stop now!

The meeting I

- „Nice fit of observations to theoretical models …“
  An unidentified observerer showing a „slide with a theoretical model“ which was actually completely empty

- Everything observed was already predicted by theoreticians
  (The A_V problem: C. McKee): **Theory confronts observations**

- „Data are not important.“ (An observer – L. Greenhill)

- Observers start producing movies (Orion: L. Greenhill)

- „A model is not a theory.“ /“A theory without an observation is not a theory, but a hypothesis .„(Eric Keto)

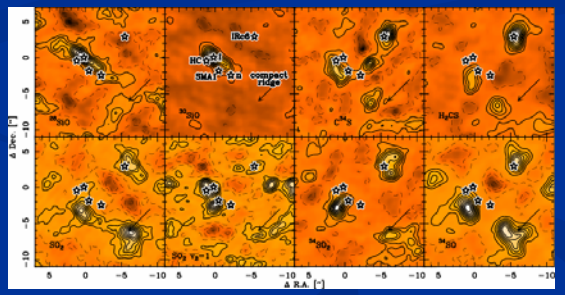
- No theoreticians allowed at telescopes – „Nothing works …“
  (E. Keto): Observers can keep talks in time (the night may be over)

The meeting II

- Heidelberg is full of disks … (filaments: bridges) (Qizhou Zhang)
- Heidelberg (HD license plate) ---> D_2O (???) ---> Wet Heidelberg ---> Wet disks (Floris van der Tak)
- MSF = Concentrate the mass in a hair (H.W. Yorke)
- Astronomers turn into their objects (The Jonathan Tan Orion)

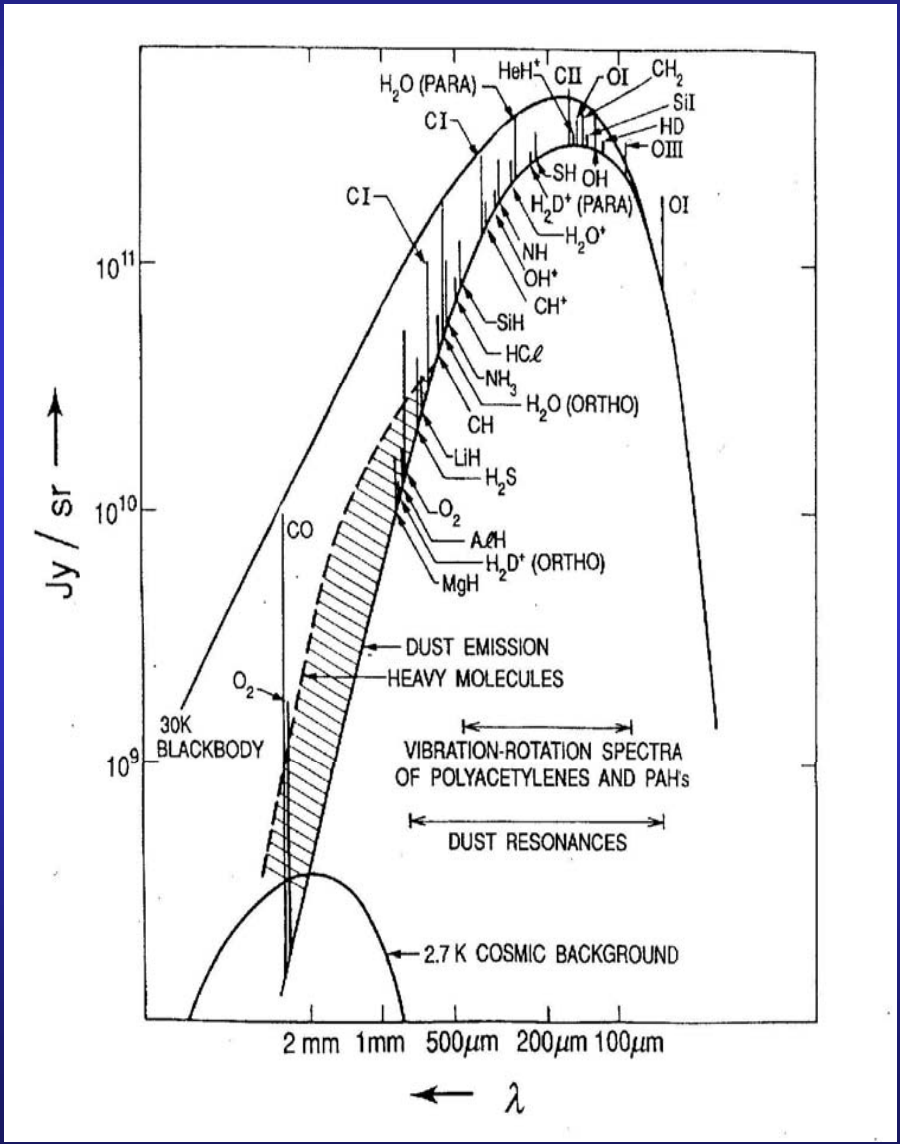
The meeting III

- Events which have „ages“ of 23 years can be observed …
- Cross-references to posters at other meetings (Karl Menten)/ Showing slides of another talk prepared for another conference (Sami Dib)/Participation in three parallel conferences---> Conference jetsetters
- Numerical calculations are like cooking (Mark Krumholz) (Numerical recipes), Ian Bonnell …



- Many bars in the galaxy,
- Germish, Frenchish, … Australian, Scottish, …, Astronomish (clumps, cores, clumps, cores)

The future is bright



Herschel 2008

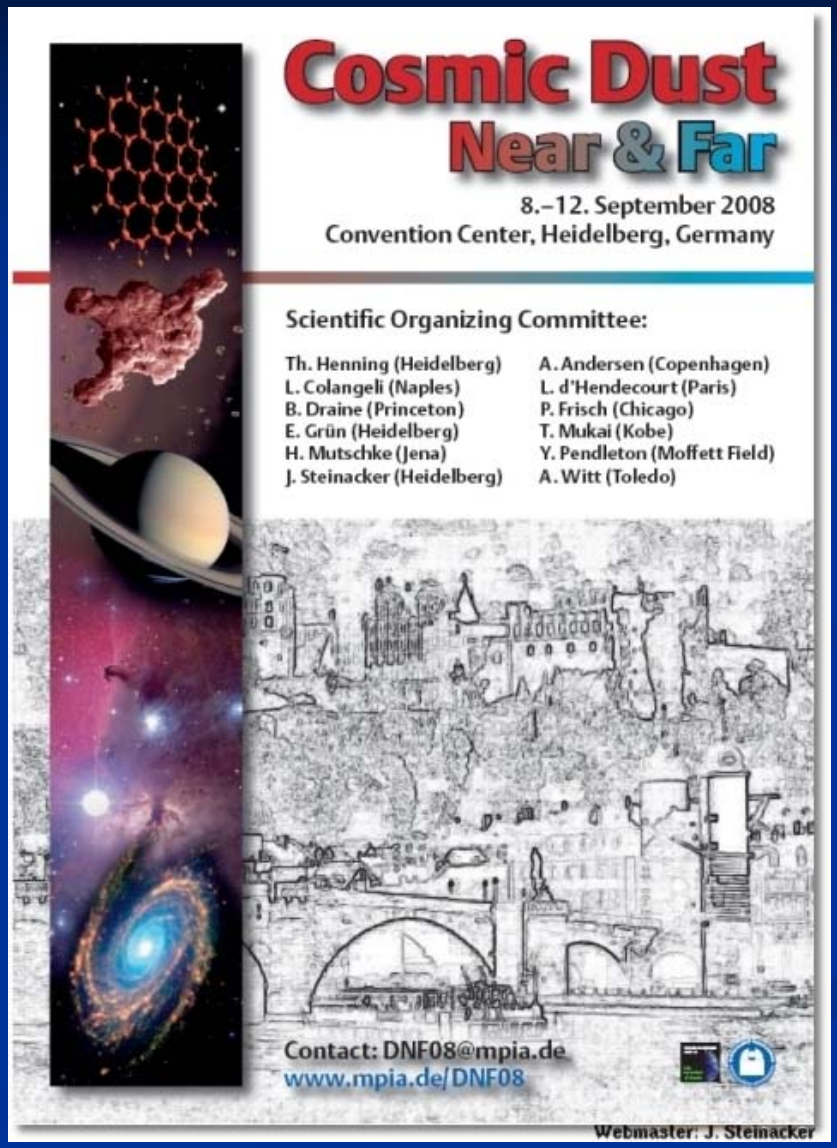
ALMA 2010

VLTI, Keck-I Now

People, People, People

Jetset: Summary of one meeting turns into opening of the next .

- Dust as an active player
  (Ionization, H_2 formation,
  radiation pressure)
- Analytic power
  (Masses, temperatures,
  chemistry)
- Extinction
  (Star formation rates, …)



- September 8th to 12th, 2008
- See DNF08 at MPIA
- Radiative Transfer Workshop (After Workshop)

Massive Star Formation: Observations confront Theory

We say good bye!

Thanks for coming to **Heidelberg!**
Henrik Beuther !!!!!
MPIA students and post-docs
MPIA technical staff (Maria Janssen-Bennynck, Frank Richter)
Uncle Max Planck (German taxpayers) for funding

SOC

H. Beuther (Chair)	S. Kurtz
M. Burton	K. Menten
E. Churchwell	F. Motte
G. Garay	F. Palla
Th. Henning	J. Tan
P. Ho	M. Walmsley