EPoS
The Early Phase of Star Formation
MPIA Conference Series at Ringberg Castle

A biased Conference Summary

Ringberg EPoS IV poster

Recap by Hans Zinnecker

- Some 60 astrophysicists in attendance, incl… due to lack of more space at Ringberg castle
- It started jointly watching Euro-cup soccer final on Sunday (Spain vs. Italy 4:0) over beers
- 35 talks, poster session, afternoon discussions, and focus groups. Moderators and conveners.
- Rule: young participants get to ask questions first (didn't quite work, but was a good try).

Ringberg workshop July 2012

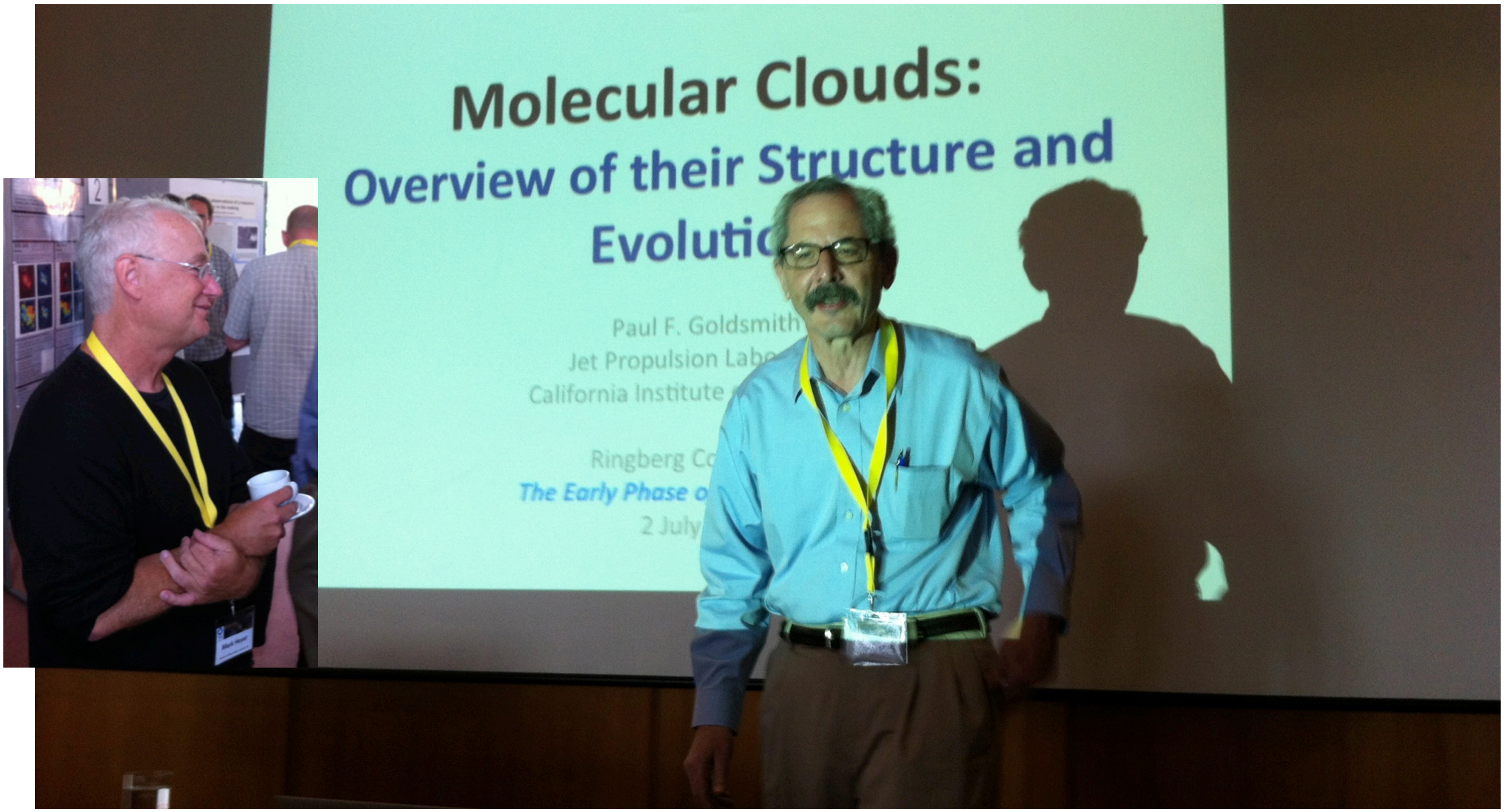
participants in attendance

Bate, Beuther, Burkert, Crutcher, Goldsmith, Goodman, Henning, Keto, Krumholz, R. Klein, Kuiper, Lazarian, Looney, McKee, Motte, Myers, Nordlund, Padoan, Pudritz, Robitaille, Steinacker, Tassis, Tobin, Tomisaka, Troland, van Dishoeck, Vazquez-Semadini, Vorobyov, Walmsley, Whitworth, Wootten, Yorke, HZ, …

Topics (sessions)

- Molecular clouds: bound or unbound?
- the origin/role of filaments in fragmentation
- Molecular cloud cores: evidence for collapse?
- Protostellar envelopes, early phases of disks
- Magnetic fields: their effect on fragmentation?
- Chemistry: essentially the origin of water …
- Summary (Harold Yorke):some slides from him

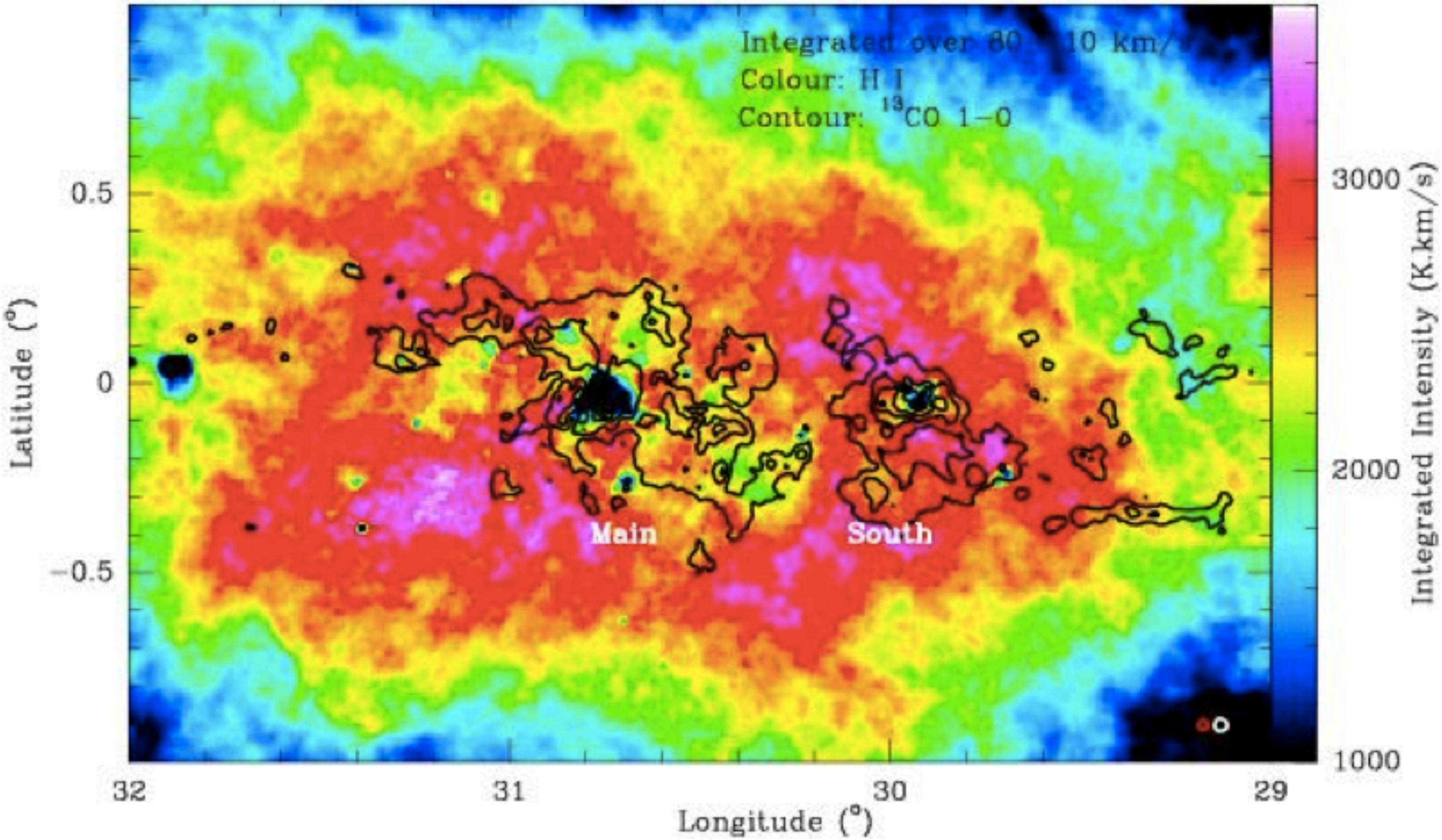
The first session: Molecular Clouds



The first session: Molecular Clouds

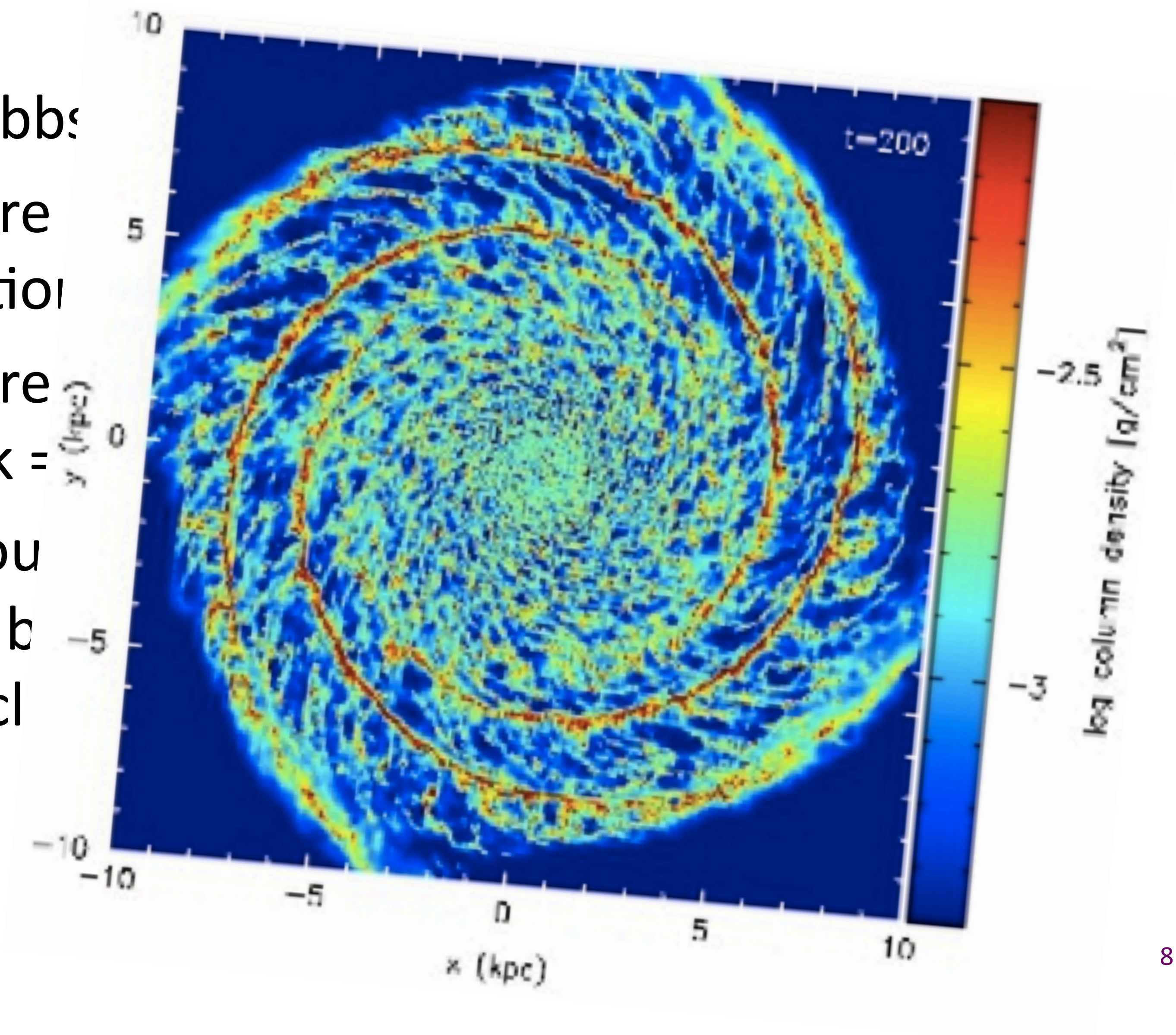
The first session: Molecular Clouds

- Frederique Motte: The mini-starburst W43 is one of the best



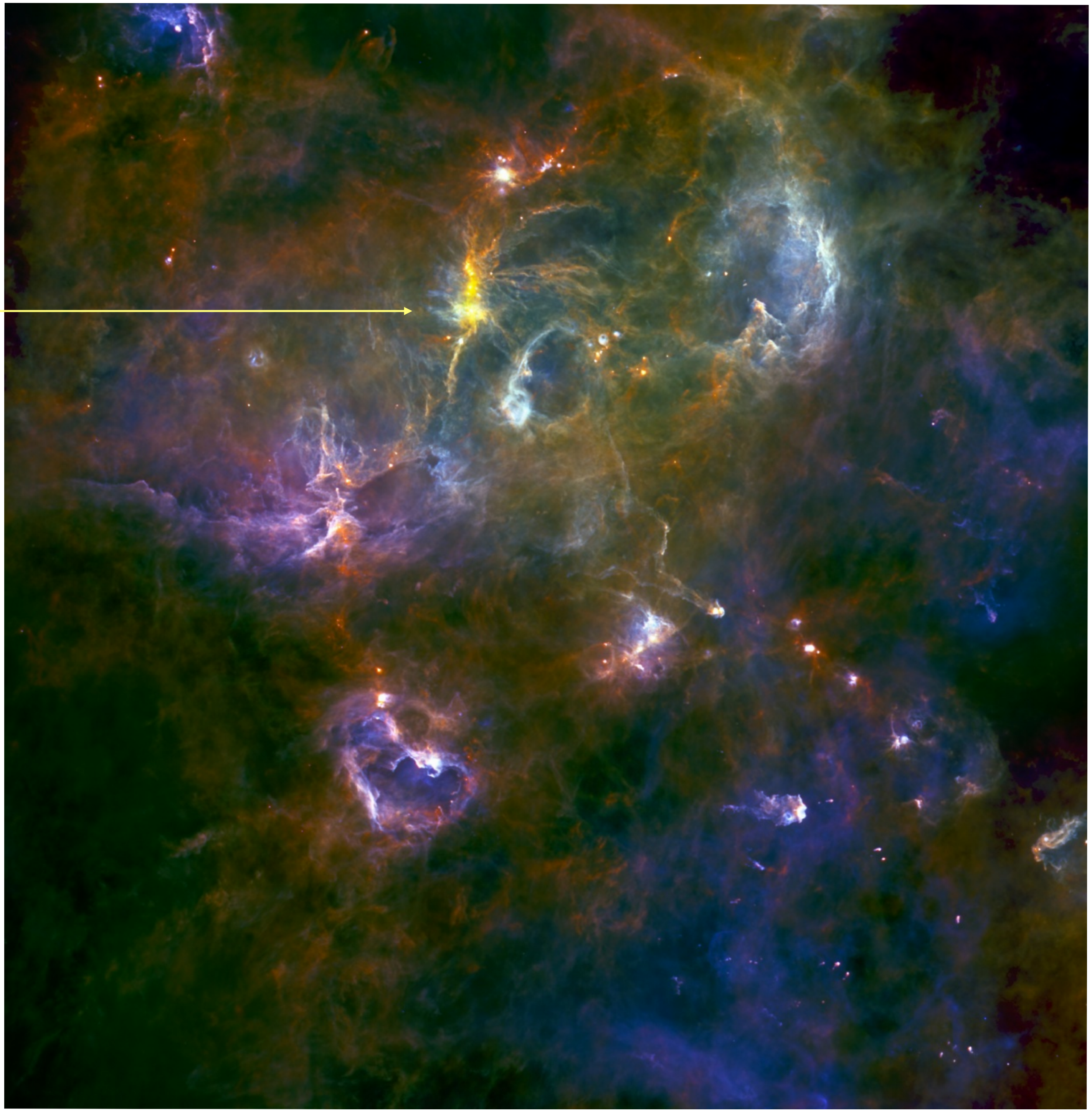
The first session: Molecular Clouds

- Clare Dobbs
- Clouds are observatio
- Clouds are feedback =
- Cloud bou difficult, b smaller cl



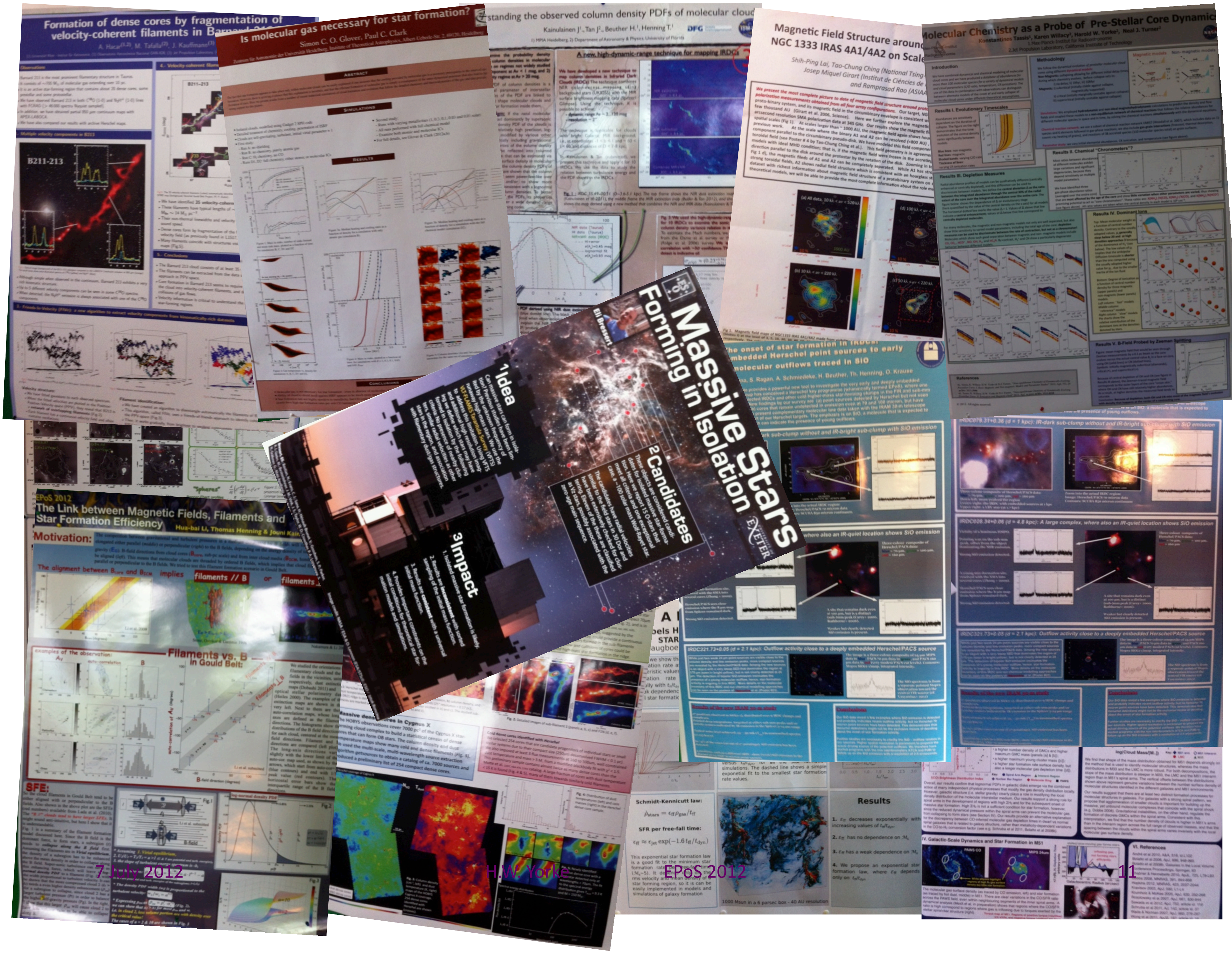
Cygnus-X

DR21



Herschel
PAC/SPIRE
(J. Hora)


I found a filament
that was **this** long!


Formation of dense cores by fragmentation of
velocity-coherent filaments in
Is molecular gas necessary for star formation?
Simon C. O. Glover, Paul C. Clark
Abstract
Simulations
Results
Conclusions
Kainulainen J., Tan J., Beuther H., Henning T.
A new, high-dynamic-range technique for mapping IRDCs
Magnetic Field Structure around
NGC 1333 IRAS 4A1/4A2 on Scale
Molecular Chemistry as a Probe of Pre-Stellar Core Dynamics
Konstantinos Tassis, Karen Willacy, Harold W. Yorke, Neal J. Turner
Massive Stars
Forming in Isolation
Eli Bressert
1 Idea
2 Candidates
3 Impact
EXETER
molecular outflows traced in SiO
EPoS 2012
The Link between Magnetic Fields, Filaments and
Star Formation Efficiency
Motivation:
Filaments vs. B
in Gould Belt:
SFE:
Schmidt-Kennicutt law:
SFR per free-fall time:
Results
1000 Msun in a 6 parsec box - 40 AU resolution
VI. References

Some speakers & highlights

Goldsmith/Dobbs/Goodman

Heitsch/Looney

Whitworth/Robitaille

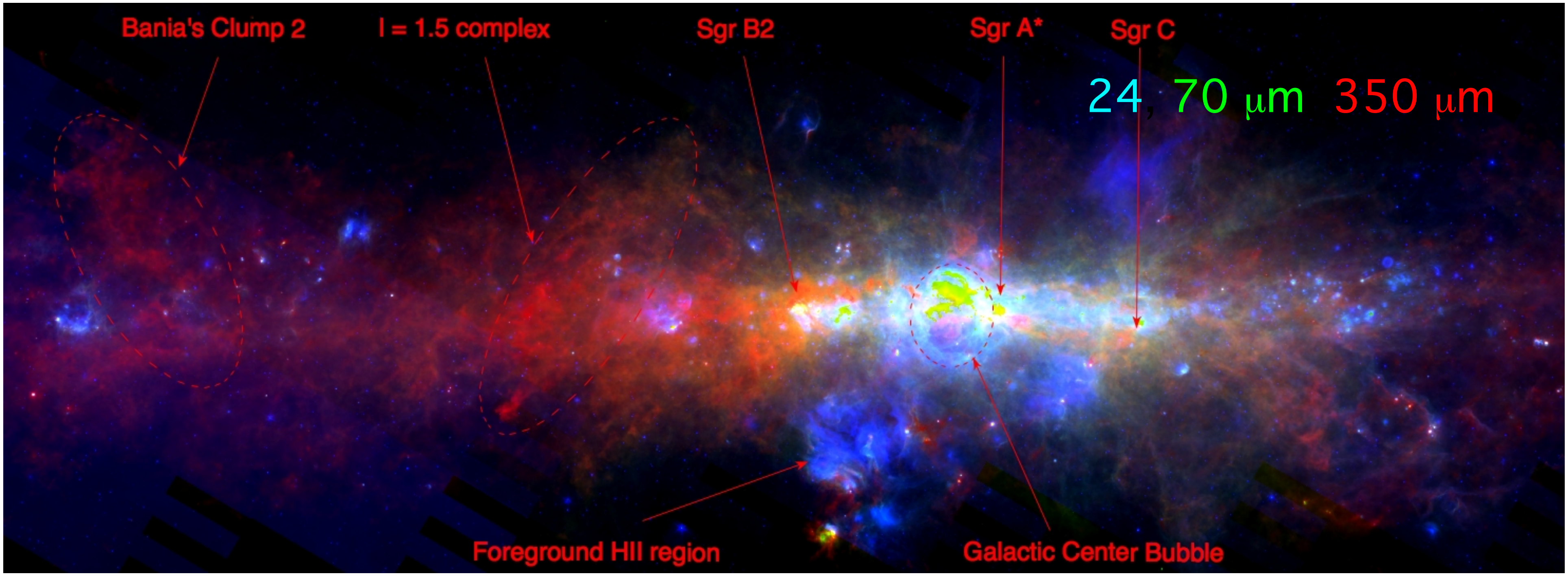
Banerjee/Vorobyov

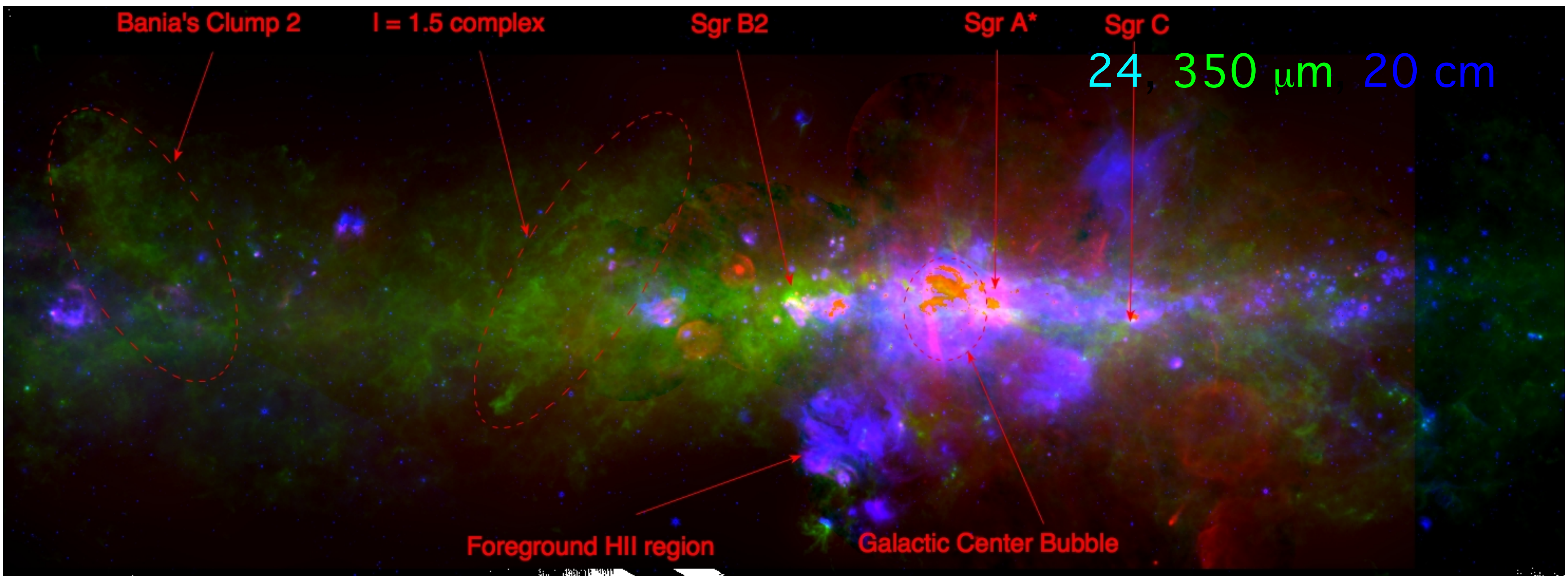
Crutcher/Lazarian

Klein/Kuiper

Walmsley/Tomisaka

Beuther/van Dishoeck


Bania's Clump 2
l = 1.5 complex
Sgr B2
Sgr A*
Sgr C
24, 70 μm 350 μm
Foreground HII region
Galactic Center Bubble


Bania's Clump 2
l = 1.5 complex
Sgr B2
Sgr A*
Sgr C
24, 350 μm 20 cm
Foreground HII region
Galactic Center Bubble

Relevance to SOFIA/ALMA

Edges of CO clouds --> detect dark H2 via [CII]
Episodic accretion --> monitor FIR flux variations
Filament accretion --> obs magn.field orientation
MHD collapse sim. --> study FIR dust polarization

W43 galactic starburst (SOFIA target) discussed +
evidence for global collapse in several SF regions
Disks in jet sources --> ALMA HH212 proposal
Rotating mol. disks --> detect and measure mass

Conclusions/take home news

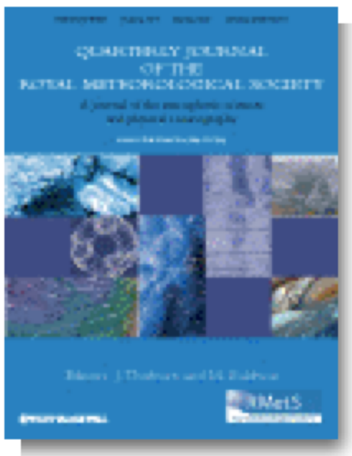
- Filamentology, dendrograms (hier. structure)
- Deficit of star formation (HII regions) in GalCtr

- focus groups (good forum for pm discussions)
- Pol: keep Ringberg alive, despite lack of space

- We, at Ames, have to come up with Science Lunch, to discuss ISM/SF etc issues in detail

Why me?

- Need to have someone experienced (old), who can resist presenting (just) his/her own work



Quarterly Journal of the Royal Meteorological Society

Volume 25, Issue 111, pages 203–206, 1899

CLIMATE OF JERSEY.

By the Rev. H. W. YORKE, M.A.

[Read March 15, 1899.]

Having resided in Jersey for the last twenty years, and during that period been directly or indirectly interested in various meteorological observations, I have thought that a paper, however incomplete, on the climate of this island might be of some interest to the Fellows of the Royal Meteorological Society, especially since, so far as I am aware, no such paper has been read before.

Collaborators

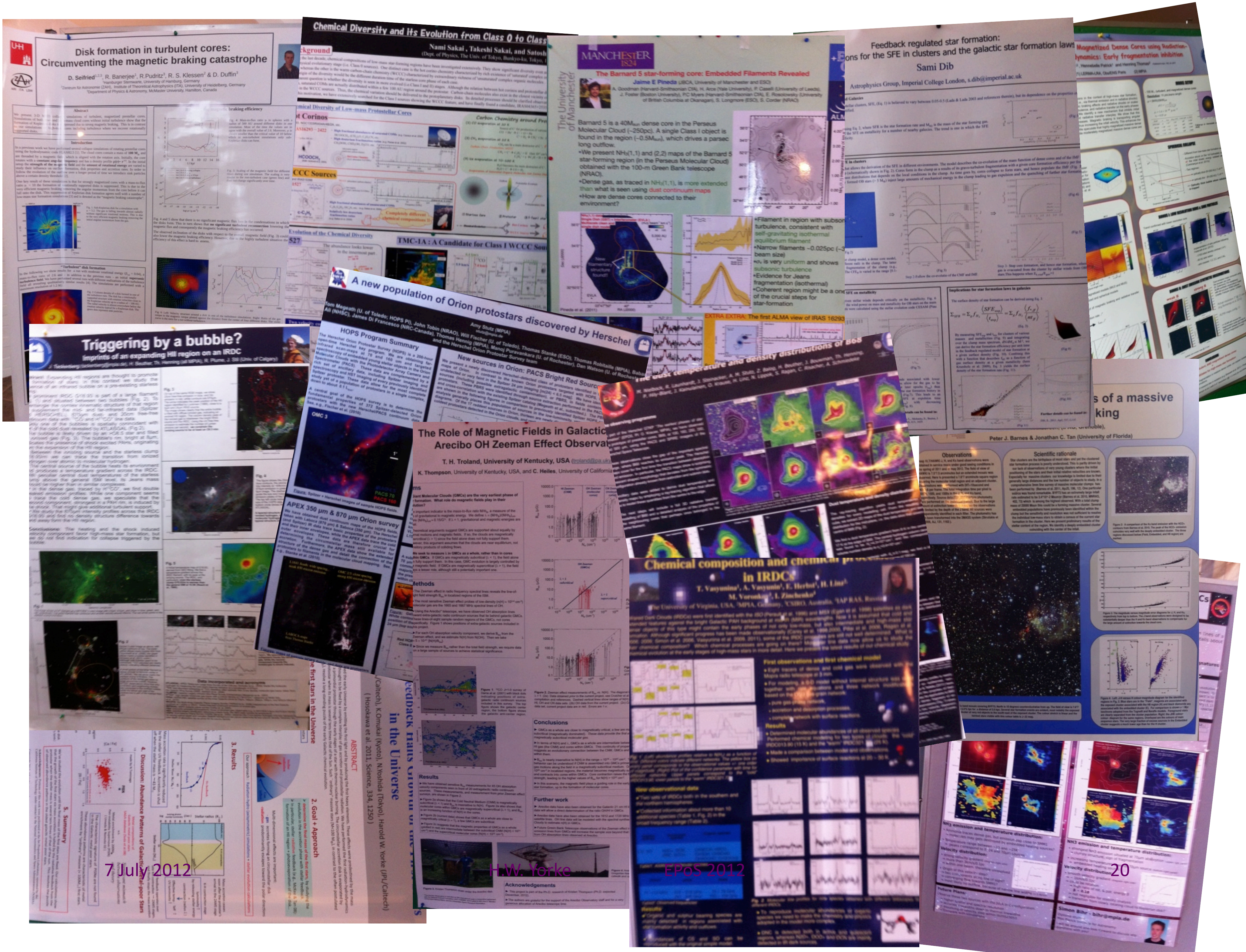
Yuri Aikawa Kobe University Kobe, Japan
Joao Alves Viena Univ. Viena, Austria
Morten Andersen IPAG Grenoble, France
Aurore Bacmann IPAG Grenoble, France
Robi Banerjee Univ. Hamburg Hamburg, Germany
Matthew Bate University of Exeter Exeter, UK
Henrik Beuther MPIA Heidelberg, Germany
Simon Bihr MPIA Heidelberg, Germany
Andrea Bracco IAS Orsay, France
Eli Bressert ESO Garching, Germany
Andy Burkert University Observatory Munich Munich, Germany
Benoit Commercon ENS Paris, France
Richard Crutcher University of Illinois Urbana, USA
Sami Dib Imperial College London, UK
Clare L. Dobbs University of Exeter Exeter, UK
Michael Dunham Yale University New Haven, USA
Simon Glover ITA/ZAH Heidelberg, Germany
Paul Goldsmith NASA/JPL Pasadena, USA
Alyssa A. Goodman HSCfA Cambridge, USA
Alvaro Hacar Observatorio Astronomico Nacional Madrid, Spain
Fabian Heitsch University of North Carolina Chapel Hill, USA
Martin Hennemann AIM CEA Saclay, France
Thomas Henning MPIA Heidelberg, Germany
Mark Heyer University of Massachusetts Amherst, USA
Annie Hughes MPIA Heidelberg, Germany
Jouni Kainulainen MPIA Heidelberg, Germany
Jens Kauffmann JPL Pasadena, USA
Eric R. Keto HSCfA Cambridge, USA
Helen Kirk HSCfA Cambridge, USA
Richard Klein UC Berkeley & LLNL Berkeley, USA
M. Krumholz University of California Santa Cruz, USA
Rolf Kuiper JPL Pasadena, USA
Shih-Ping Lai Institute of Astronomy, NTHUT Hsinchu, Taiwan
Alex Lazarian University of Wisconsin-Madison Madison, USA
Hua-bai Li MPIA Heidelberg, Germany
Zhi-Yun Li University of Virginia Charlottesville, USA
Hendrik Linz MPIA Heidelberg, Germany
Steven Longmore ESO Munich, Germany
Leslie Looney University of Illinois Urbana, USA
Rainer Mauersberger Joint ALMA Observatory Santiago,Chile
Anaelle J. Maury ESO Garching
Chris McKee UC Berkeley Berkeley, USA **S.**
Frederique Motte AIM/SAp, CEA Gif-sur-Yvette, France
Philip Myers HSCfA Cambridge, USA
Aake Nordlund NBI Copenhagen, Denmark
Paolo Padoan ICREA / ICC - University of Barcelona Barcelona, Spain
Jaime E. Pineda Univ. Manchester Manchester, UK
Ralph E. Pudritz McMaster University Hamilton, Canada
Sarah E. Ragan MPIA Heidelberg, Germany
Thomas Robitaille MPIA Heidelberg, Germany
Nami Sakai The University of Tokyo Tokyo, Japan
Daniel Seifried Hamburger Sternwarte Hamburg, Germany
Juergen Steinacker IPAG/MPIA Grenoble, France/Heidelberg, Germany
Amy Stutz MPIA Heidelberg, Germany
Jochen Tackenberg MPIA Heidelberg, Germany
Konstantinos Tassis MPIfR Bonn, Germany
John Tobin NRAO Charlottesville, USA
Kohji Tomisaka NAO Mitaka, Tokyo, Japan
Thomas H. Troland University of Kentucky Lexington, USA
Ewine van Dishoeck Leiden Observatory Leiden, The Netherlands
Tatiana Vasyunina University of Virginia Charlottesville, USA
Enrique Vazquez-Semadeni UNAM Morelia, Mexico
Eduard I. Vorobyov University of Vienna Vienna, Austria
Malcolm Walmsley INAF-OAdA Firenze, Italy
Anthony P. Whitworth Cardiff University Cardiff, Wales
Al Wootten NRAO Charlottesville, USA
Satoshi Yamamoto The University of Tokyo Tokyo, Japan
Hans Zinnecker NASA AMES Moffett Field, USA

Observations

- Participants were very focused and alert throughout the entire meeting; there were excellent discussions
- Theory and observations are improving
  - New instruments: higher resolution, better sensitivity, opening of new wavelength regimes
  - Numerical models: higher resolution, improved microphysics, higher level of confidence
- Our paradigm for star formation depends strongly on observing capabilities
  - Based on dust continuum maps => spherical cores
  - Herschel era: now we see filaments everywhere

The Poster Sessions

- We had a number of excellent posters…


Disk formation in turbulent cores:
Circumventing the magnetic braking catastrophe
Chemical Diversity and its Evolution from Class 0 to Class
The Barnard 5 star-forming core: Embedded Filaments Revealed
Feedback regulated star formation:
Sami Dib
Triggering by a bubble?
Imprints of an expanding HII region on an IRDC
A new population of Orion protostars discovered by Herschel
HOPS Program Summary
APEX 350 μm & 870 μm Orion survey
The Role of Magnetic Fields in Galactic
Arecibo OH Zeeman Effect Observa
Chemical composition and chemical
in IRDCs
Peter J. Barnes & Jonathan C. Tan (University of Florida)
Observations
Scientific rationale
Results
Conclusions
Further work
Acknowledgements

The first session: Molecular Clouds

- Goldsmith set the stage with his overview
- He introduced the descriptive terms "blobology", "filamentology", "core-ology"
- He reminded us that after H_2 and He, HI is the third most abundant species in molecular clouds (-> HINSA)
- He asked questions
  - The Environs of Molecular Clouds: Do molecular clouds exist in a vacuum?
  - Molecular Cloud Energetics? Role of turbulent heating?
  - What is the time-dependent picture: formation, evolution, destruction?

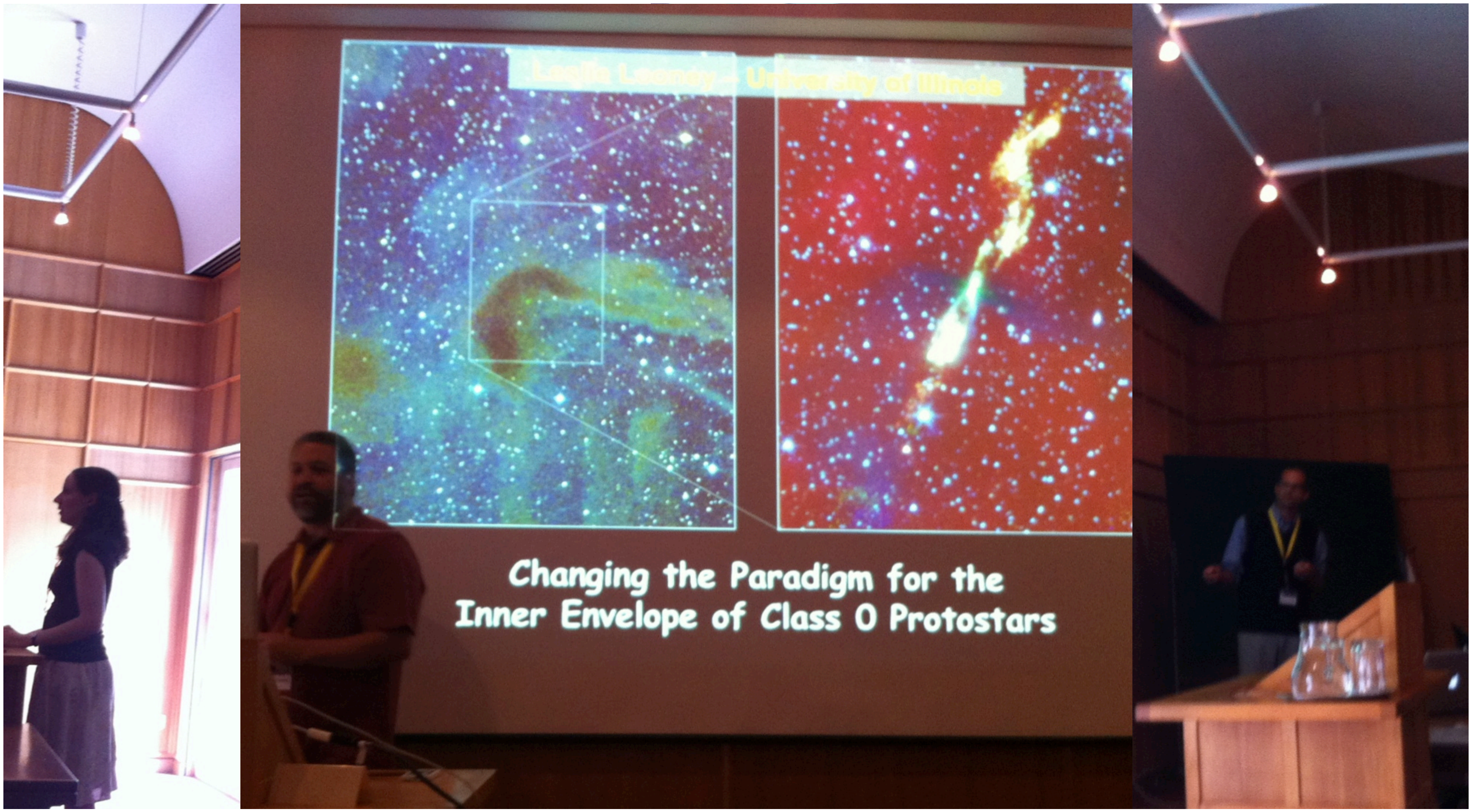
The first session: Molecular Clouds

- Mark Heyer's talk was complementary to Goldsmith's, concentrating on velocity information of GMC's
  - Kinematic properties of GMCs reflect supersonic turbulent flows
  - Gas velocities from spectroscopic imaging of molecular emission lines are key measurement in evaluating the physics of GMCs and star formation

The first session: Molecular Clouds

- Alyssa Goodman showed dendrogram decomposition of the Milky Way: going from p-p-p space to p-p-v space and back again
- She stressed the fact that statistical tests were necessary to really compare models with observations (to understand hierarchical structure), but no simulation has yet stood up to these tests
  - Warning: ^{13}CO misses high density, high pressure regions (the way that it is usually naively used, but of course Paul is not naive)
  - Hierarchical catalog of MW clouds & properties will soon be found at http://Universe3D.org (open wiki for external contributions)

The second session: Filamentology



The second session: Filamentology

- Filaments are found everywhere. They can be created by a variety of processes. Found in numerical studies
- But not all filaments are created equal…
- Filament fragmentation: critical line mass compared to critical sphere mass
  - A subcritical cylinder cannot be forced into collapse by external pressure
  - Subcritical cylinder with finite radius can be contained by external pressure
- Separation of cores/clumps (4.5 pc) along the Jackson, et al. 2011 “snake” (80 pc long) inconsistent with central densities (10^4 cm^{-3})
  - Solution: accretion onto filaments?

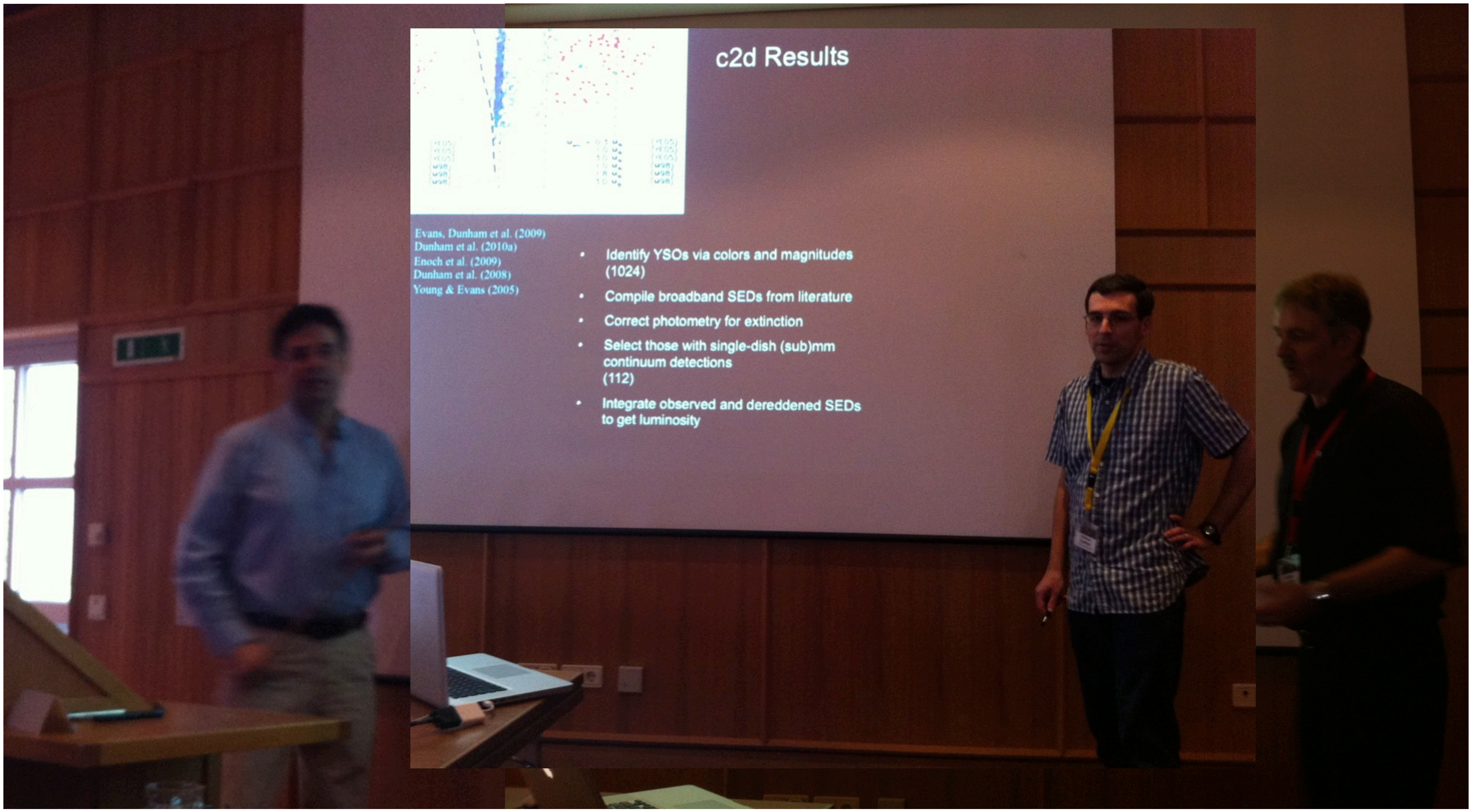
The second session: Filamentology

- Heitsch: Filaments can best get supercritical via accretion. Thus, star-forming filaments cannot be isolated
- The new paradigm?: Collapse sequence: global collapse, filament formation, fragmentation, core formation, accretion onto cores, core collapse, …
- Kirk: Serpens South excellent example of cluster forming in filament
  - Herschel data show typical filaments width ~0.1 pc (Looney: this width appears to be universal)
  - Mass accreting along filaments at 35 $M_{\odot}$/Myr, across filament at ~100$M_{\odot}$/Myr (depending on filament orientation)

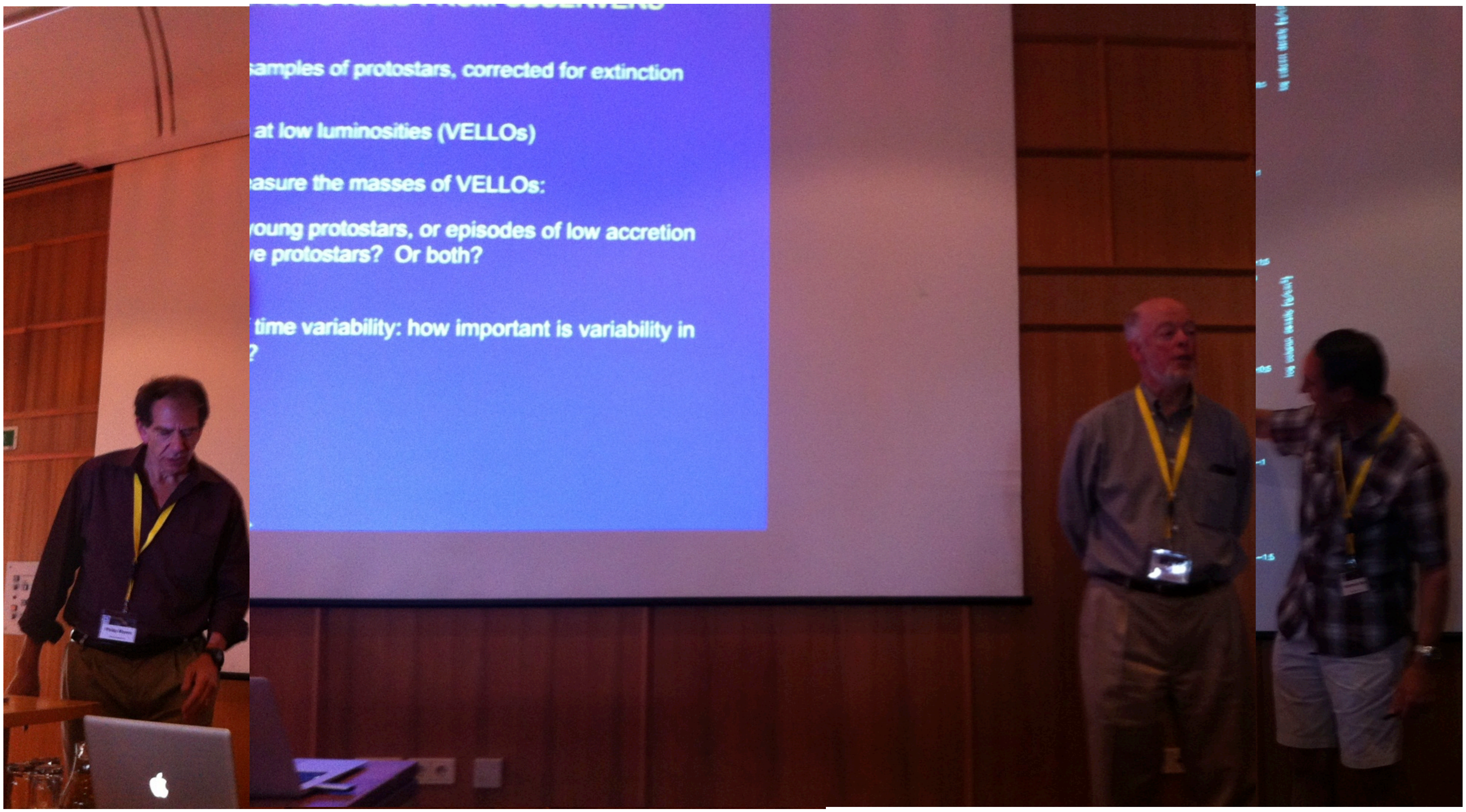
The second session: Filamentology

- Looney: Okay, so cores form in filaments; ~0.1pc structures of Class O protostars are mostly filamentary with centrally condensed structures at 0.01 pc size-scales
- Why is this not seen in starless cores?
  - > ALMA project to resolve sub-structure

The third session: Molecular Cloud Cores - Life and Collapse



The third session: Molecular Cloud Cores - Life and Collapse

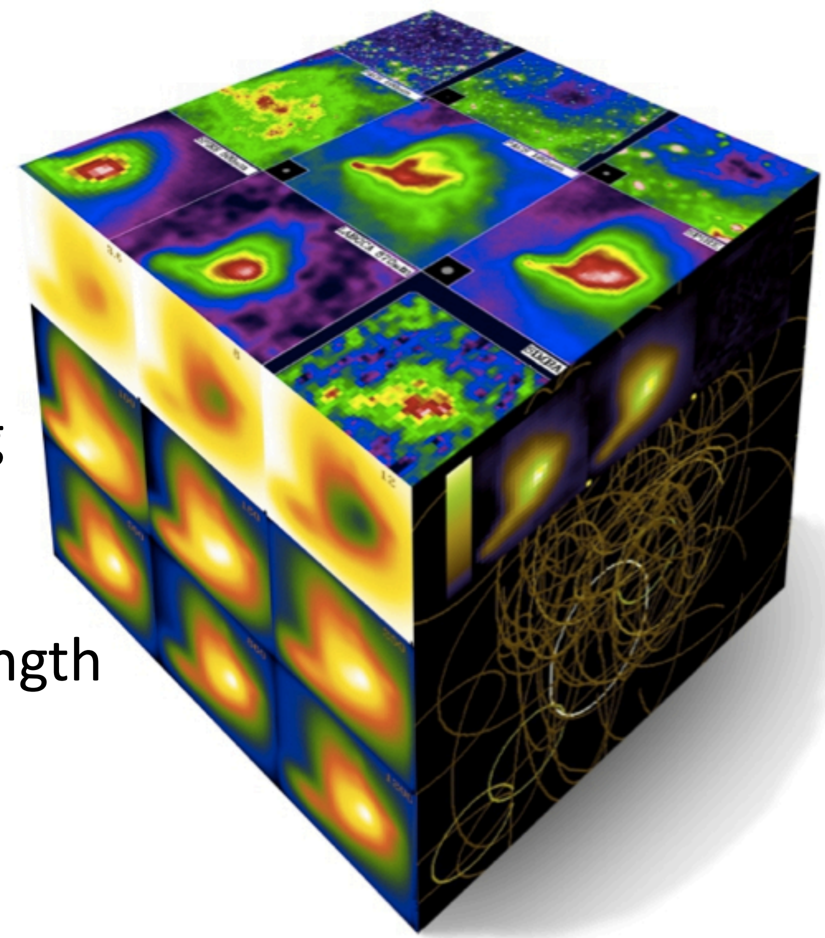


The third session: Molecular Cloud Cores - Life and Collapse

- What is a core?
  - Joao's Definition: "Cores are by definition ill-defined"
- "Cores have tails": they are simplest the densest parts of filaments
- Example B5: traditionally a core, but at higher resolution a filament
  - Hacar et al. 2011, 2012 (in prep.) "filaments of filaments" or "Bundles" (ISM=interstellar spaghetti medium)
  - Look at velocity components, then they break up into pieces of filaments
  - Some have lots of cores ("fertile"), some are "sterile"

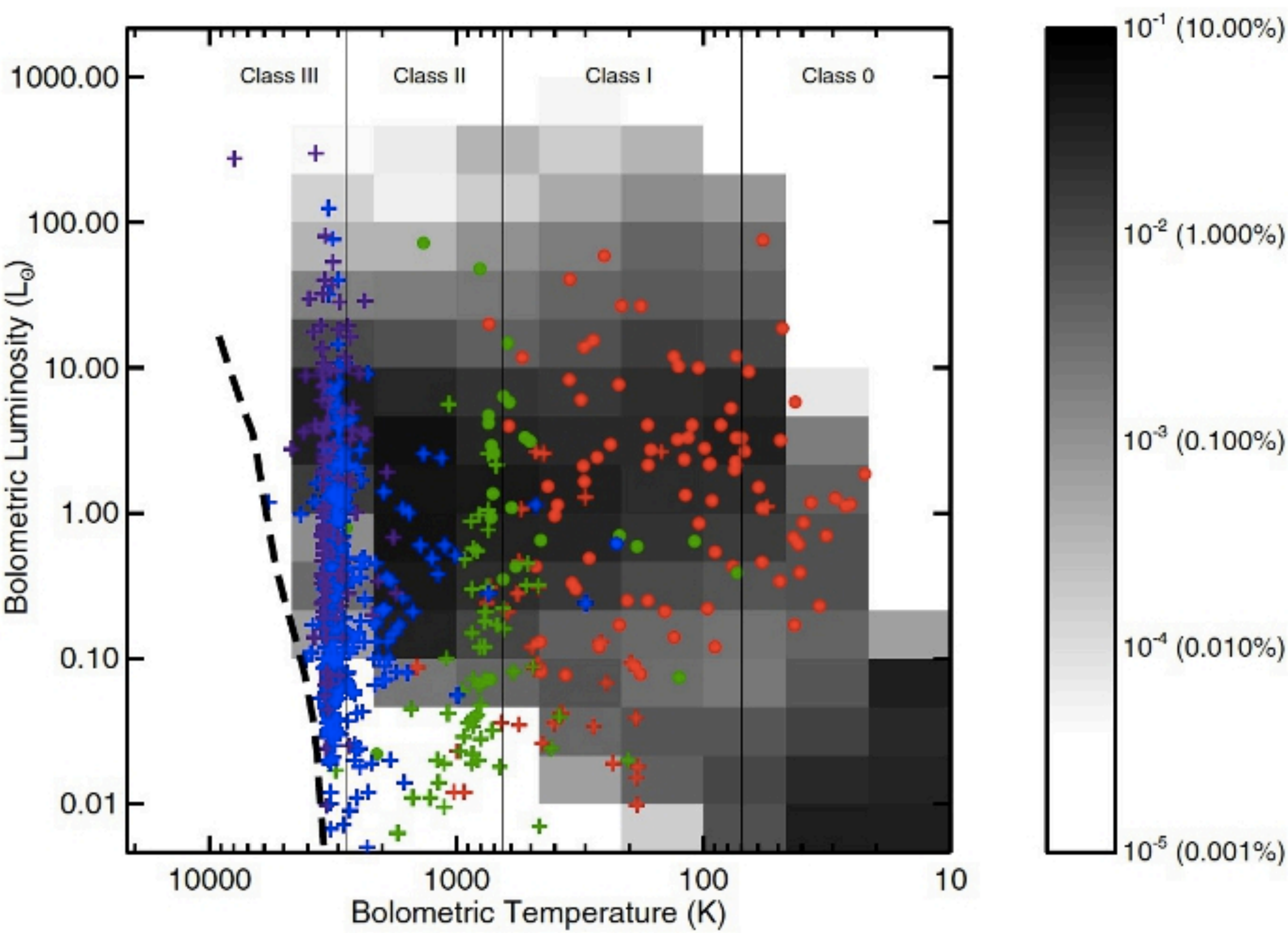
The third session: Molecular Cloud Cores - Life and Collapse

- A detailed model of B68 (which could be a merger)
- Azimuthally averaged radial core density profiles might be nicely modeled by a BE sphere profile
  - Although they are neither 1D, isothermal, nor isotropically illuminated
  - And they still can be oscillating around gravo-thermal balance
- If you see crude 1D models of beautifully resolved multi-wavelength images, feel uneasy



The third session: Molecular Cloud Cores - Life and Collapse

- Walmsley: Estimating protostellar accretion is hard
- Classical formula $dM/dt = 4\pi R^2 \rho v_{infall}$ may be very poor approximation (non-spherically symmetric accretion)
- Infall rates have to take serious account of the physics
- One may be better off with more excited transitions close to LTE



Class III
Class II
Class I
Class 0
1000.00
100.00
10.00
1.00
0.10
0.01
Bolometric Luminosity ($L_{\odot}$)
10000
1000
100
10
Bolometric Temperature (K)
10^{-1} (10.00%)
10^{-2} (1.000%)
10^{-3} (0.100%)
10^{-4} (0.010%)
10^{-5} (0.001%)

The third session: Molecular Cloud Cores - Life and Collapse

- Review by Bate: General picture of filaments and cores from both theory and observation
- But does gravity matter and is there a relation between filaments, cores, the CMF and the IMF?
  - Filaments are seen whether they are self-gravitating or not
  - Cores are seen whether they are self-gravitating or not
  - Why does the CMF look the same regardless of whether the cores are bound or not?
  - The peak of the CMF ranges from 10 Jupiter-masses to $3M_{\odot}$ from region to region: So if the IMF comes from the CMF, why is the IMF universal?
- Do magnetic fields matter?

The third session: Molecular Cloud Cores - Life and Collapse

- Whitworth: If/when we understand the origin of the present-day prestellar CMF, to what extent will we also understand the origin of the stellar IMF?
  - Possible answers: (1) largely, (2) partly, (3) not at all
  - Project: see if we can get (2=partly) to work

The third session: Molecular Cloud Cores - Life and Collapse

- Myers: How does nature make >100 stars in 1 pc within 1 Myr with an IMF as observed?
- Estimating ages of clusters problematical, especially the youngest
  - Episodic accretion causes some problems with uniqueness of HRD isochrones
  - Youngest clusters have zones of protostars < 1 Myr
  - Get age of cluster by determining protostar fraction
  - Identify, distinguish, and count PS, PMS+disk, and PMS +diskless stars
  - Protostar luminosity functions peak near 1 $L_{\odot}$

The third session: Molecular Cloud Cores - Life and Collapse

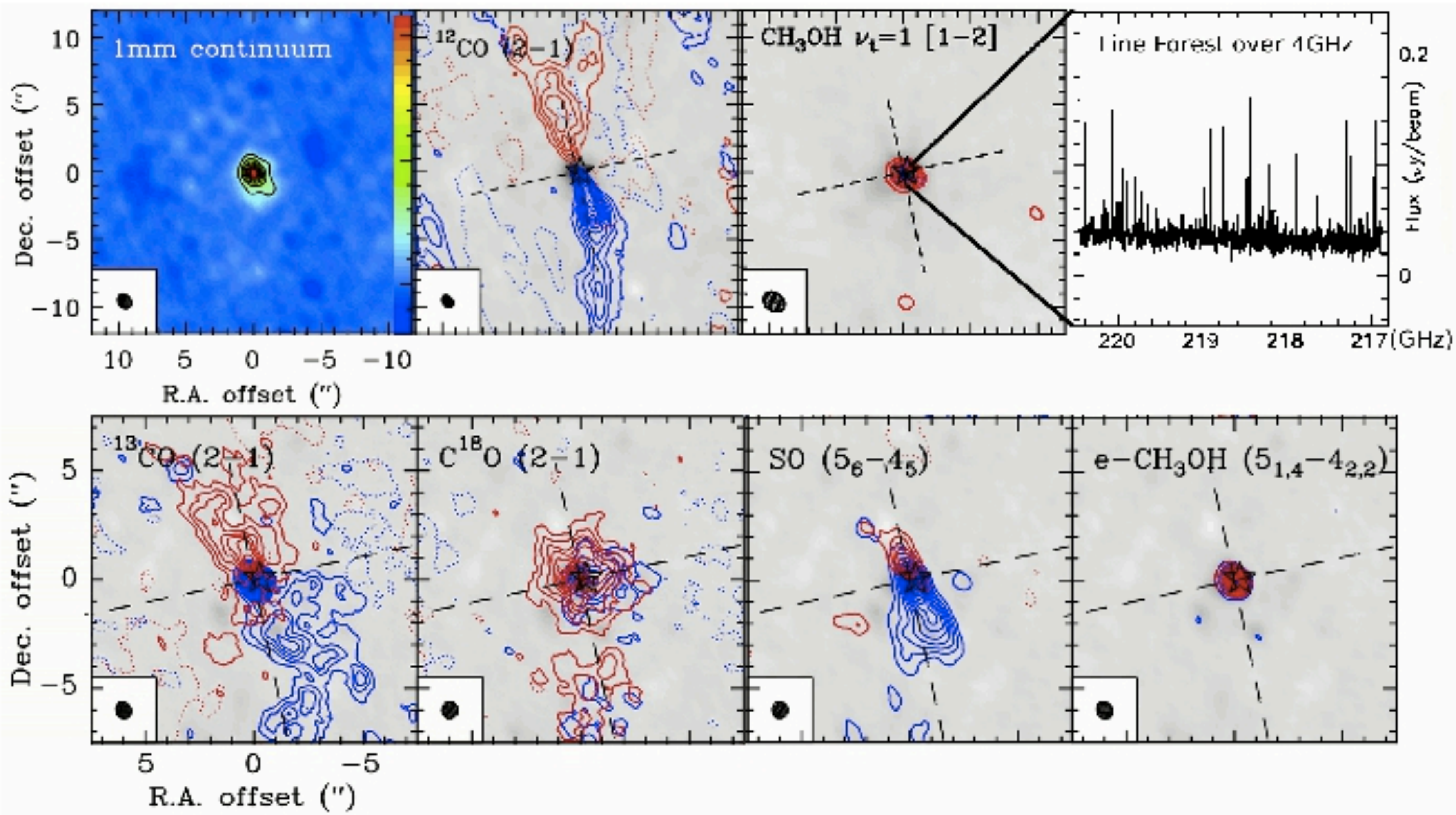
- McKee: Problems with Protostellar Luminosity Distribution (PLD) and with VELLOs
- We need from observers…
  - Larger complete samples of protostars, corrected for extinction
  - Accurate sampling at low luminosities (VELLOs)
    - Challenge: measure the masses of VELLOs
    - Are they young protostars, or episodes of low accretion in more massive protostars? Or both?
  - Characterization of time variability: how important is variability in determining the PLF?

The fourth session: Protostellar Envelopes

The fourth session: Protostellar Envelopes

- Tobin: “We are now in the age of filaments”
- Lots of issues modeling envelopes of protostars
  - Are large-scale kinematics really tracing core rotation or infall/cloud environment?
  - Close binary protostars exist
  - Are there protostellar disks in Class 0 protostars?

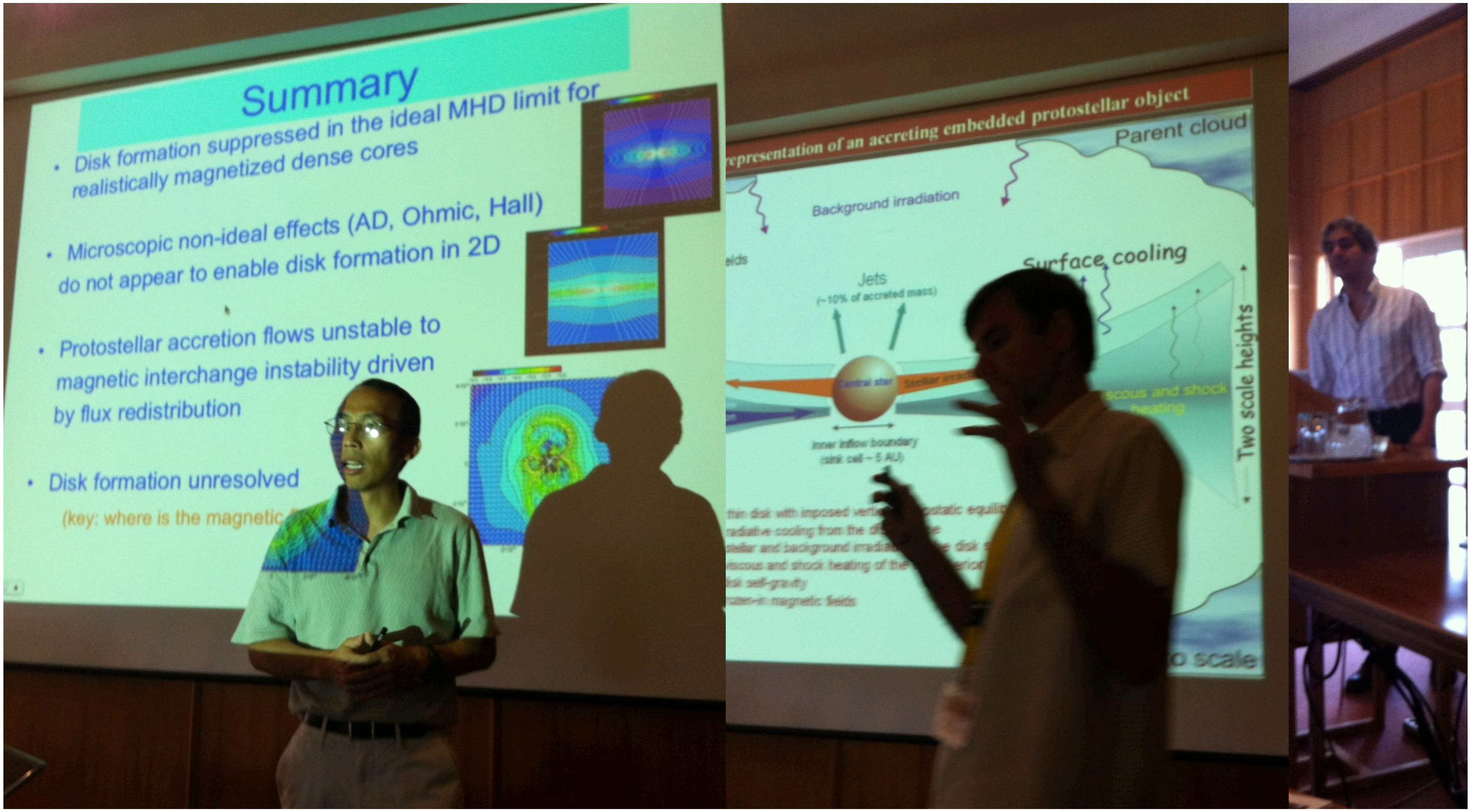
The fourth session: Protostellar Envelopes

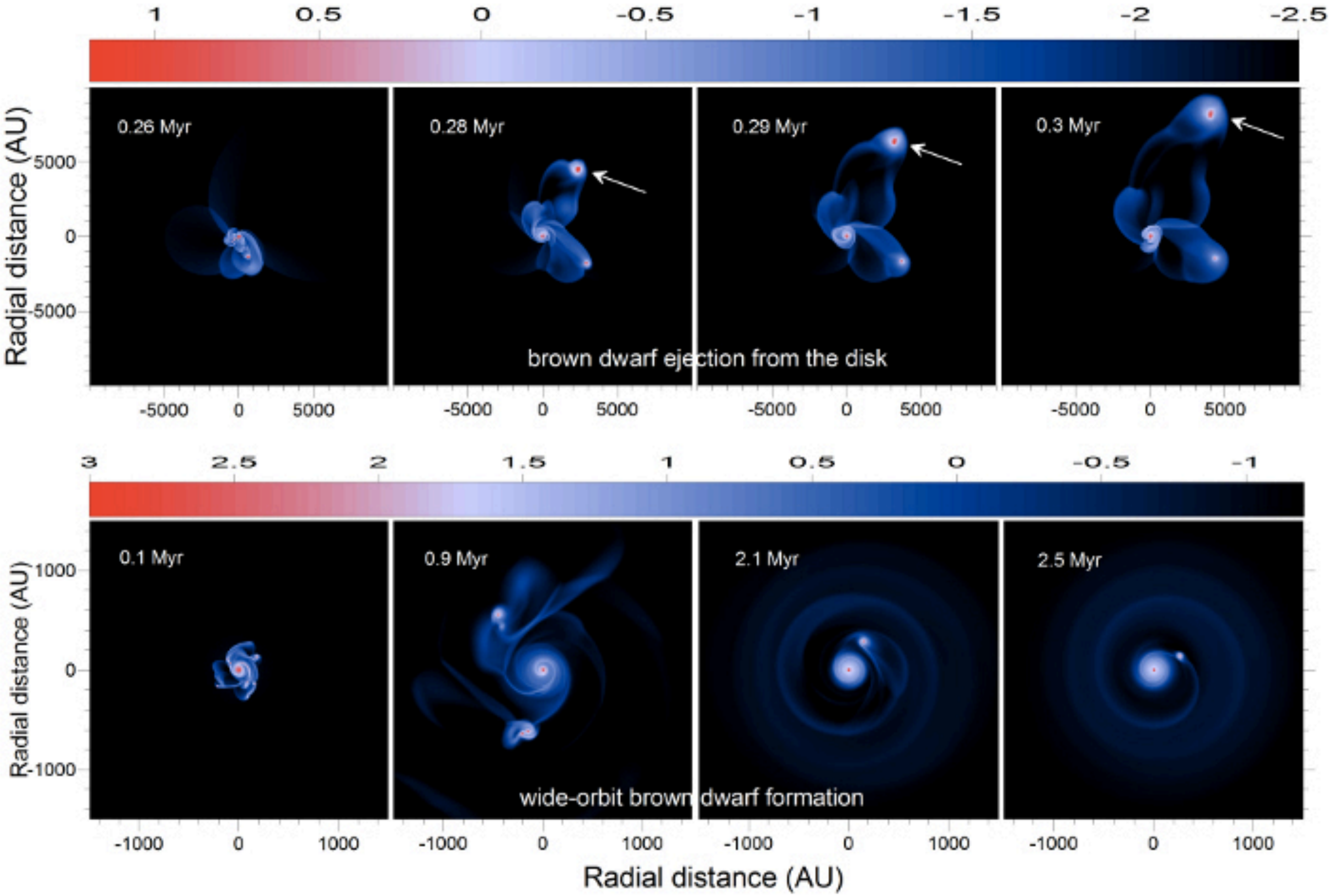


The fourth session: Protostellar Envelopes

- Robitaille: introduced new model grid of SEDs
- Hyperion 3D Monte-Carlo radiative transfer code http://www.hyperion-rt.org
- Warning: Need to understand what is being modeled
  - How appropriate is our analytical description of reality? Actual sources can be very complex and models do not actually correspond to reality
  - What do the parameters really correspond to?
  - Meaning of “envelope mass” and “disk mass”?

The fifth session: Early Phases of Disks




1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0.26 Myr
0.28 Myr
0.29 Myr
0.3 Myr
Radial distance (AU)
5000
0
-5000
brown dwarf ejection from the disk
-5000
0
5000
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0.1 Myr
0.9 Myr
2.1 Myr
2.5 Myr
1000
-1000
wide-orbit brown dwarf formation
-1000
0
1000
Radial distance (AU)

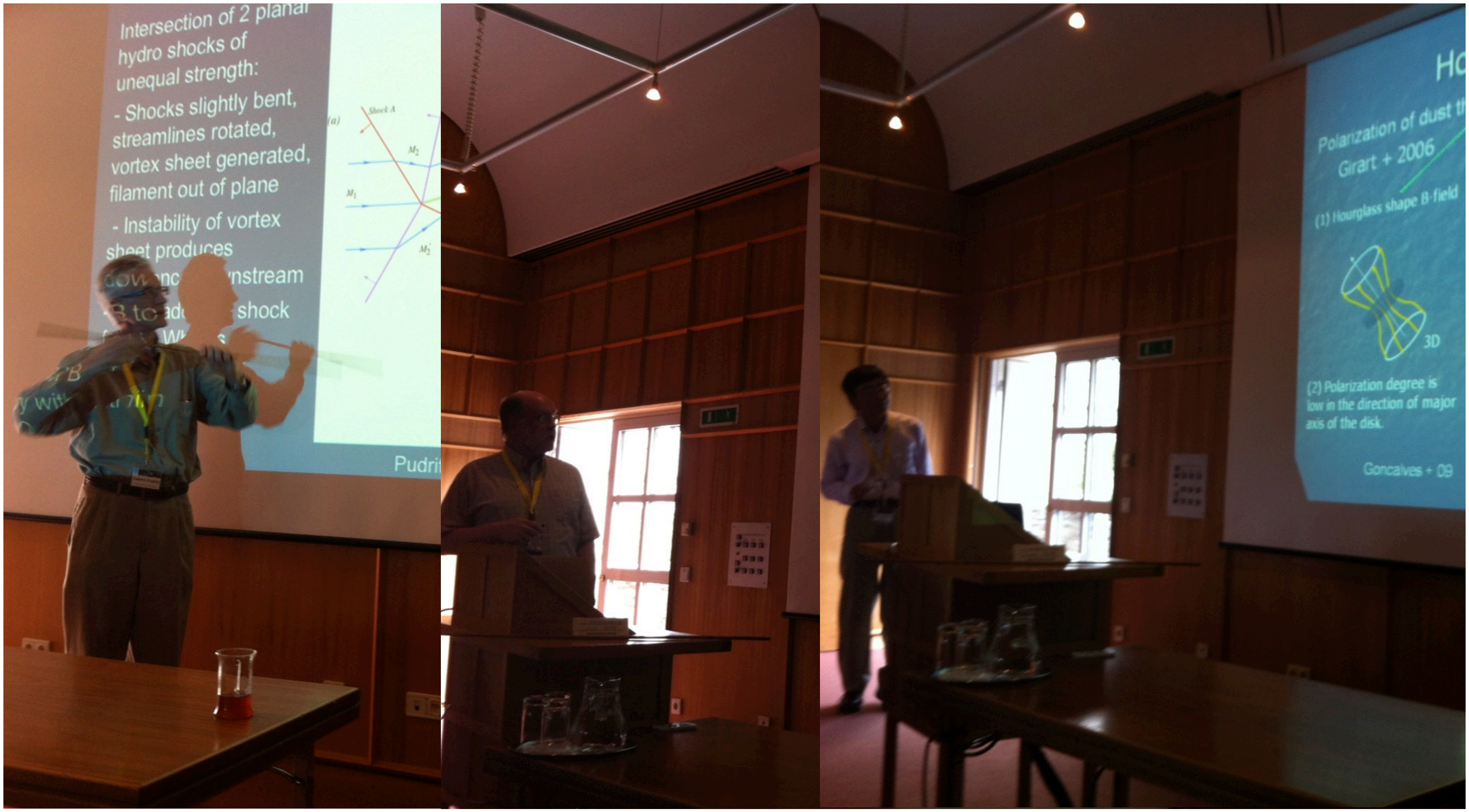
The fifth session: Early Phases of Disks

- Banerjee: It is easy to form disks
- No angular momentum problem I, principally because of gravitational torques
- Less worried about angular momentum problem II (too much magnetic braking) than Zhi-Yun Li (next slide)
- Unknowns
  - What determines fragmentation/binary formation?
  - How do we disperse envelopes?
  - What do disks look like?
- Questions & Answers
  - Troland: Anything can be fixed by turbulence or magnetic fields.
  - Turbulence and Magnetic Fields can be friends

The fifth session: Early Phases of Disks

- Zhi-Yun Li (regarding the angular momentum II problem: Can 3D effect save the disk?
- Magnetically supported disk is unstable in 3D: magnetic interchange instability destroys disk => low density, highly magnetic region close to star
- How to form rotationally supported disks?
  - Simplest solution: most dense cores weakly magnetized? Probably not
  - Late formation of large rotationally supported disks, because removal of envelope mass?
  - If someone claims disk formation with magnetic fields, please ask, "Where is the magnetic flux?"

The sixth session: Magnetic Fields



The sixth session: Magnetic Fields

- Pudritz review: Gravitational Instability in magnetized filaments as a formation mechanism of cores and CMF?
- Radiative / outflow feedback essential to suppress too much fragmentation – account for massive stars, and few brown dwarfs
- MHD turbulence essential for early formation of disks (essentially Keplerian). B fields critical for jets – key part of angular momentum flows

The sixth session: Magnetic Fields

- Crutcher:
  - CARMA maps of CN Zeeman sources
    - Assess feasibility of ALMA Zeeman studies
    - G10.6 and DR21 in CN, C18O, HCN, HCO+, N2H+, Cont
  - Zeeman results and magnetic diffusion (ambipolar diffusion and recombination)
    - Reconnection diffusion can successfully predict all 4 of the Zeeman observational results
    - Ambipolar diffusion has difficulty with all 4

The sixth session: Magnetic Fields

- Tomisaka showed models of MHD collapse under a variety of conditions and produced polarization maps at various viewing angles
  - Linear polarization of thermal dust emission is calculated for gravitational collapse
  - Poloidal field gives hourglass shape
  - Rotation amplifies toroidal B-field
- Identification of first core possible?
  - Lifetime ~1000 yr

The seventh session: Massive Stars

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- Beuther promised us: just a little filamentology
- Galactic structure, triggering and timescales
  - Galaxy-wide surveys (HIGAL, HOBYS, EPoS) allow us to study the Milky Way as a whole (spiral and bar structures, scale height, star formation efficiencies, …)
  - Herschel starting to unravel the earliest formation stages
  - Spectral line data important to study dynamics! => dynamical infall on all scales observed
- The "brick" near the GC
  - 1.5×10^5 $M_\odot$ almost devoid of star formation
  - Large linewidths

The seventh session: Massive Stars

- Klein described latest results of simulations
  - Protostellar outflows reduce the Eddington radiation barrier to high mass star formation by reducing the radiation force exerted on the infalling cloud gas, modified “flashlight effect”
  - No disks evident in simulations with MHD at this time $t < 0.45\ t_{ff}$
  - Radiation delays filament collapse

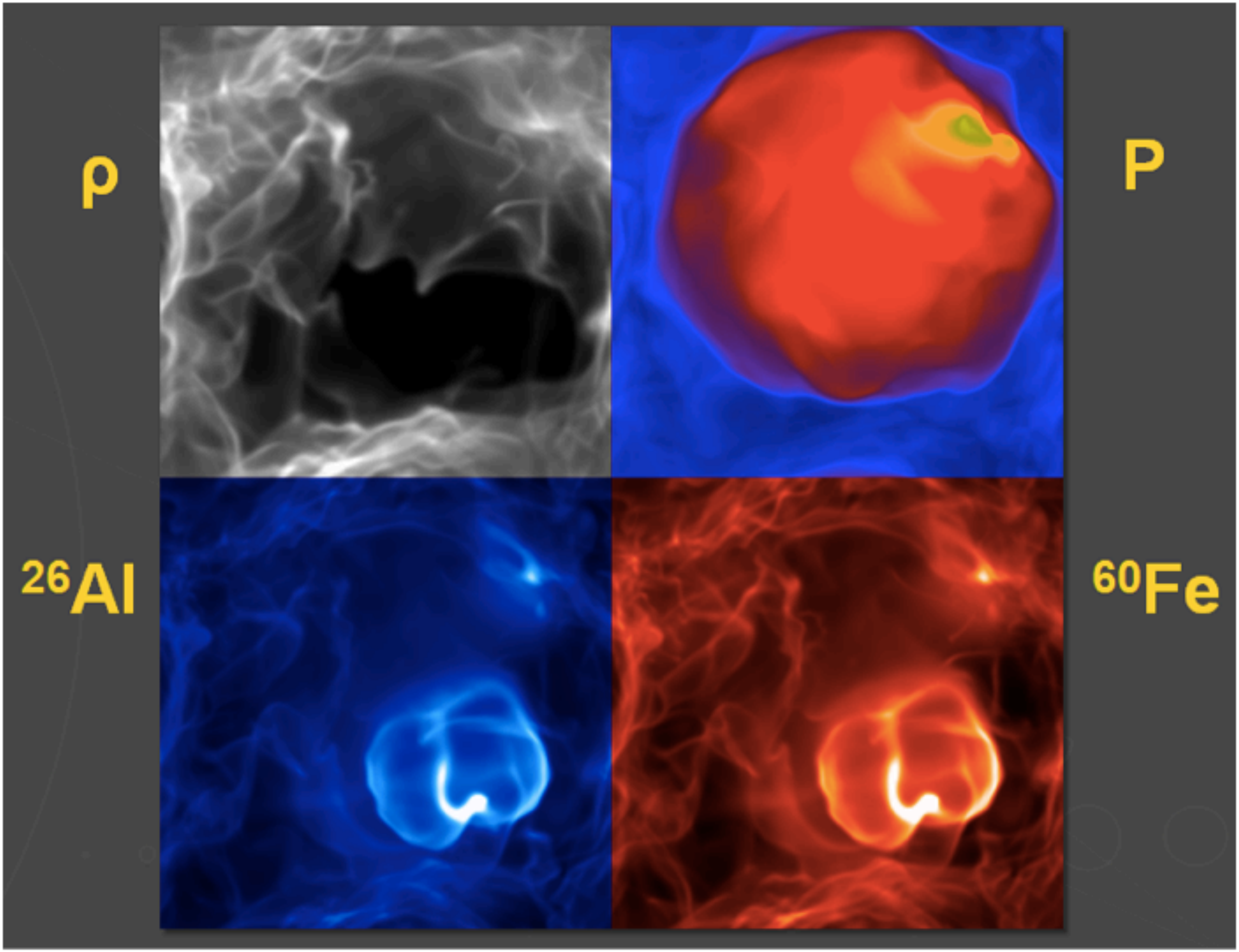
The seventh session: Massive Stars

- Kuiper described numerical simulations that study the relative importance of feedback on massive star formation
- No problem overcoming the radiation barrier (flashlight effect)
- 3D gives you episodic accretion events from gravitational instabilities in disk
- 2D alpha disks have same mean values on angular momentum transport but no episodic accretion
- Outflows actually diminish disk accretion rate, but unclear if final mass is smaller or larger

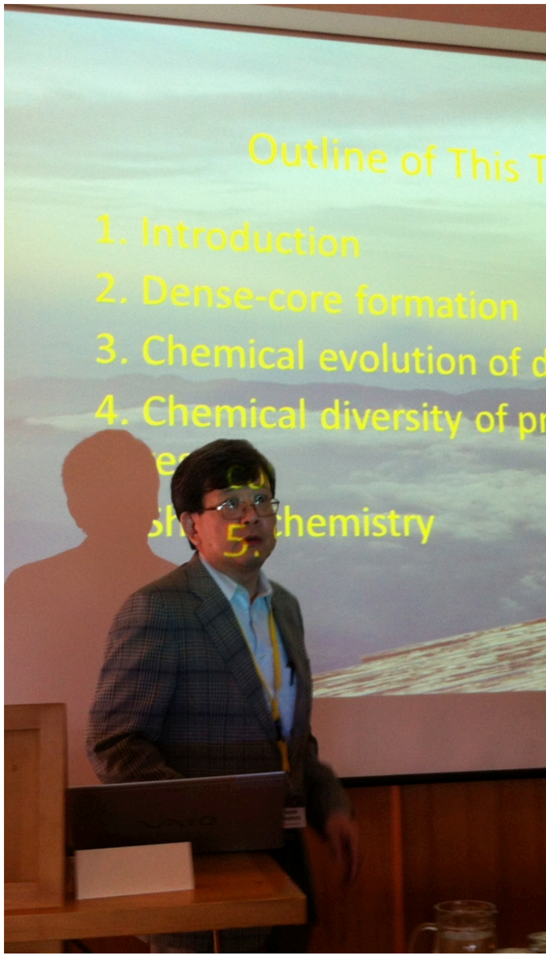
The eighth session: Triggered Star Formation, Feedback and Environment

The eighth session: Triggered Star Formation, Feedback and Environment

- Krumholz promised us No massive star formation, no flux-limited diffusion, no ray tracing
- Feedback processes:
  - Momentum (winds & outflows): magnetic fields essential
  - Radiation pressure: dominant on a global scale in 30 Dor, insignificant globally for Taurus MC
  - Hot gas (shocked winds, SN, photoionization)
  - Radiative heating: limits fragmentation, but is there a possibility of overheating (changes IMF)?
- Questions: Are the feedback effects universal? Is the IMF truly universal?


ρ
P
^{26}Al
^{60}Fe

The ninth session: Chemistry



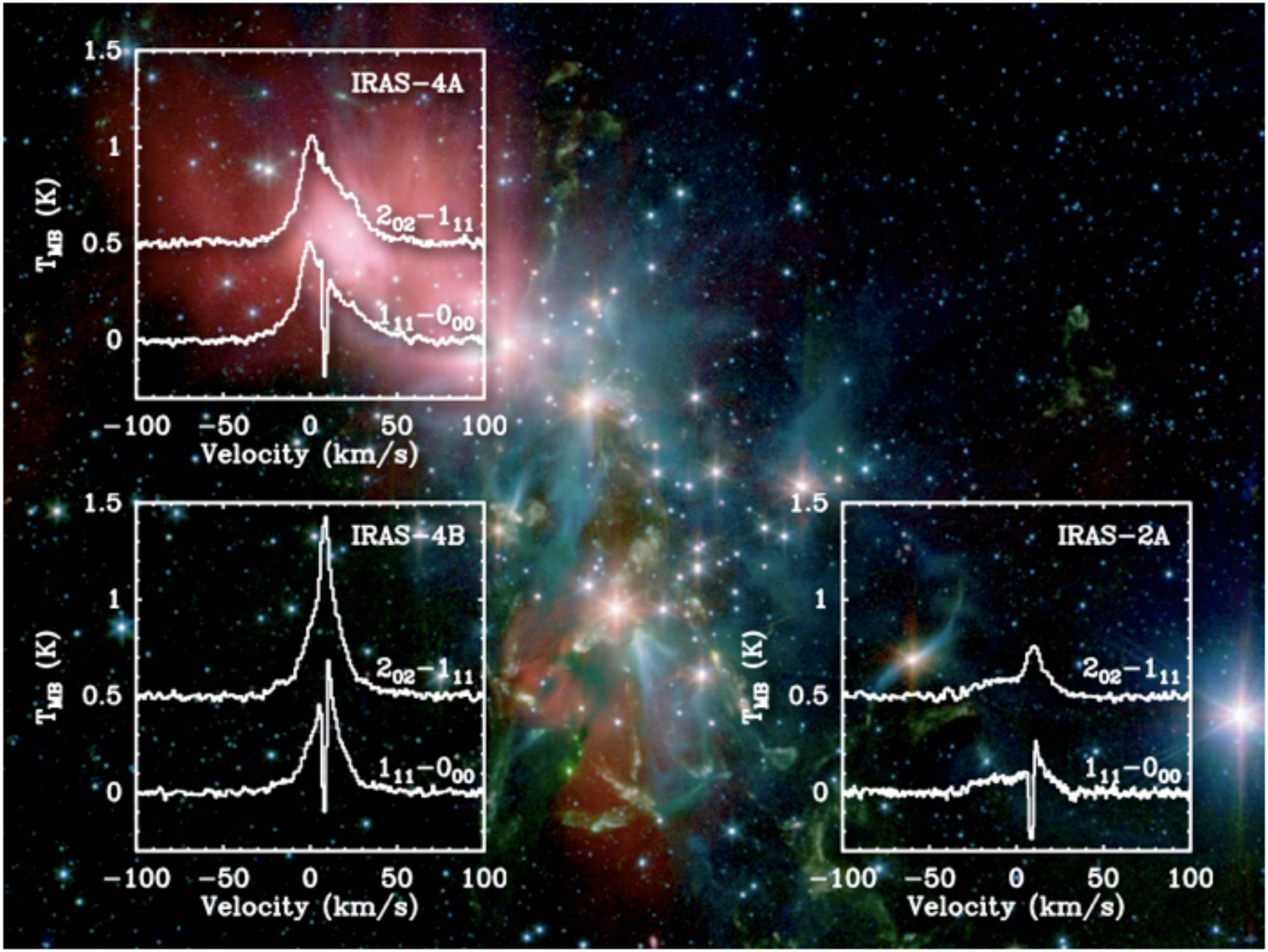
The ninth session: Chemistry

- Yamamoto: Molecule formation under the extreme condition of low T and low ρ
- Chemical composition tells past history
  - Taurus contains chemically young cores (4 out of 20 are CCPRs)
  - ρ Oph appears to have older cores (than Taurus); CCPRs locked into grains
  - Chemically young cores absent in Perseus, and Pipe
- NRO 45m line survey: rich chemistry in L1157 B1:
  - Complex organic molecules
  - Phosphorus bearing molecules are present
  - Shocks have apparently passed through

The ninth session: Chemistry

van Dishoeck: Water chemistry: hot and cold (WISH consortium)

- Questions
  - How formed: gas vs. grain?
  - What physical components does water trace?
  - What is the water “trail” from clouds to planets?
- H_2O lines in survey (observable with HIFI and PACS)
  - ~80 sources, low mass to high mass embedded
  - Water reveals complex dynamics
- How to produce H_2O: Low T, High T, Grain chemistry
  - Water is mostly formed on grains in cold cloud
  - Water is transported into disks mostly as ice
  - Photo-desorption controls gas-phase water abundance in cold clouds and disks; if you don’t have any UV, use cosmic ray induced UV photons


IRAS-4A
IRAS-4B
IRAS-2A
$2_{02}-1_{11}$
$1_{11}-0_{00}$
T_{MB} (K)
Velocity (km/s)
1.5
1
0.5
0
−100
−50
0
50
100

The ninth session: Chemistry

Bacmann: New results of detections of COMs (=complex organic molecule-s, have more than 5 atoms)

- In pre-stellar core L1689B
  - Detection of dimethyl ether, methyl formate, acetaldedyde, + H2CCO, CH3CN, C-chain molecules (multiple >10 transitions)
  - Comparison of L1689B and IRAS16293 (Class O) abundances consistent with these species being frozen-out on pre-stellar dust grains
  - Gas phase chemistry does not work in general, but perhaps some CH_3OCH_3 is gas phase product
- COMs are in pre-stellar cores (5 of 7), not only in hot regions (but lower abundances)
- Non-thermal formation mechanism in cores; Walmsley: "Grain surface chemistry is the last resort of the scoundrel"

The ninth session: Chemistry

- Aikawa describes molecular evolution and D/H abundance ratios from dense cloud cores to protostellar cores
  - gas-grain reaction network together with 1-D radiative hydrodynamic model with infalling fluid parcels.
- Evolution in disk approximated by assuming fluid parcels stay at a constant temperature (i.e. a fixed disk radius) after infall
- Results
  - Large organic molecules and carbon chains are both heavily deuterated.
  - Observed CH_2DOH/CH_3OH ratio towards protostars is reproduced if the grain-surface exchange and abstraction reactions of CH_3OH + D occurs efficiently
  - CH_3OCH_3 and $HCOOCH_3$ become more abundant in the disk than in the envelope

From the abstract of this Conference Summary…

- … And perhaps, after this summary we can more confidently answer the question of this conference: Do we have all pieces of the puzzle at hand for establishing an elaborate (new?) paradigm for star formation?
- We are now in the age of filaments”
- The new paradigm: “filamentology” (as apposed to “spherical Bonner-Ebert core-ology”)
- It took centuries before “astrology” and “astronomy” went their separate ways.
- I look forward to the time, when we can speak of blobonomy, filamentonomy, and core-onomy