Star-formation in the E-ELT era

STEEL, Erice, 8-20/10/15

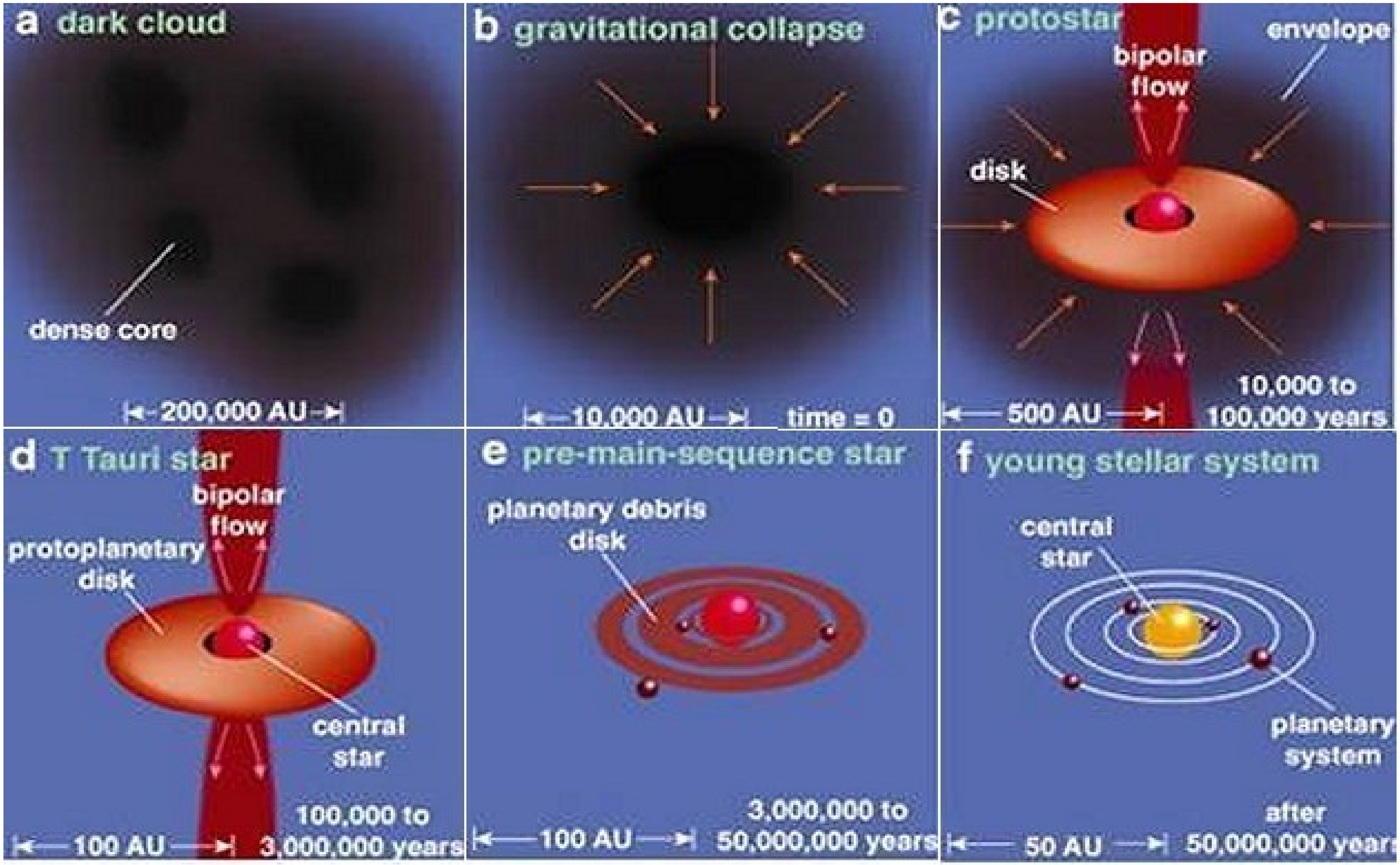
Suzanne Ramsay

European Southern Observatory

Outline of the talk

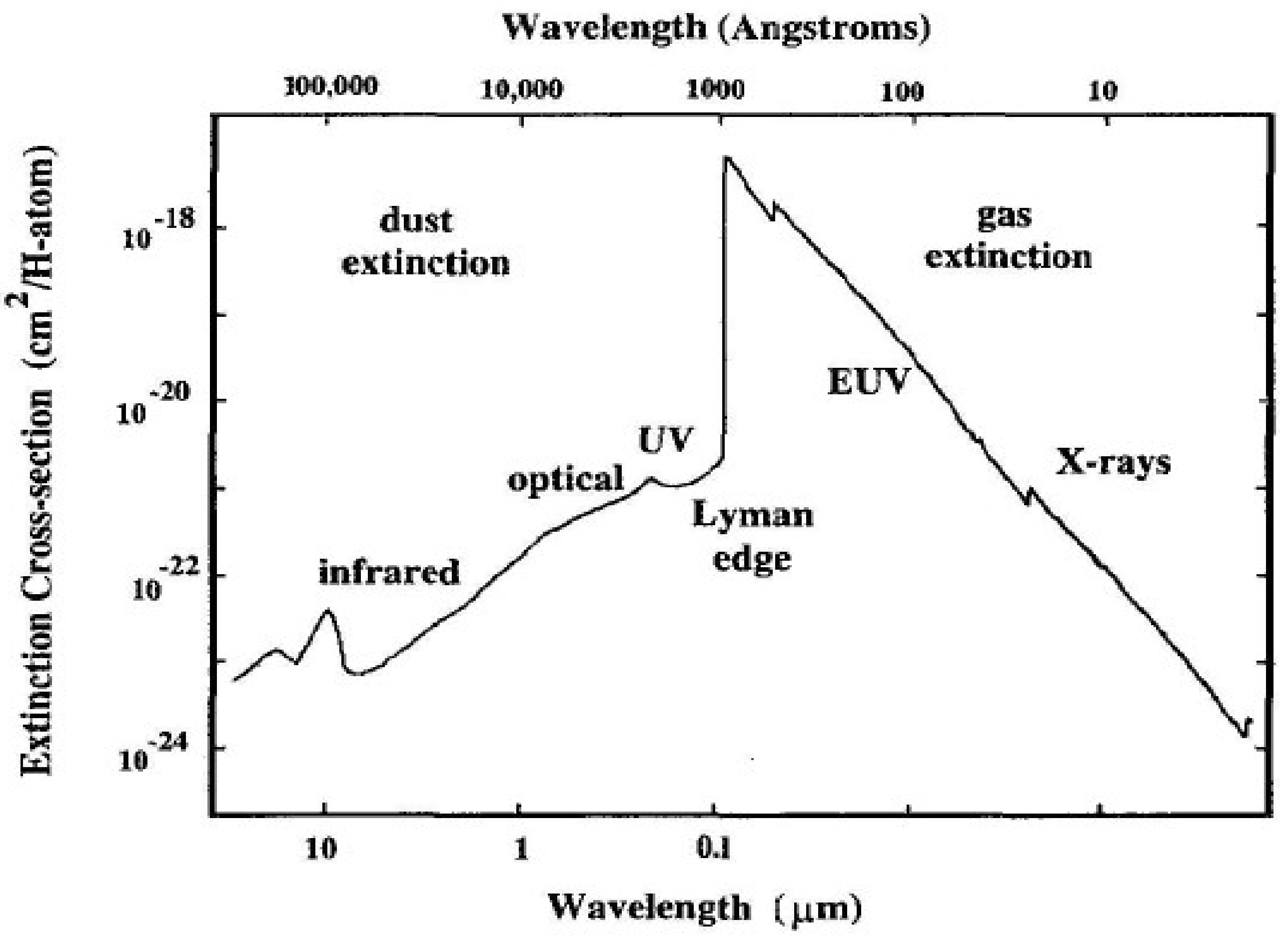
- Overview of our current understanding
- The formation of massive stars
- Feedback from massive stars
- Prospects for the E-ELT

A star formation cartoon

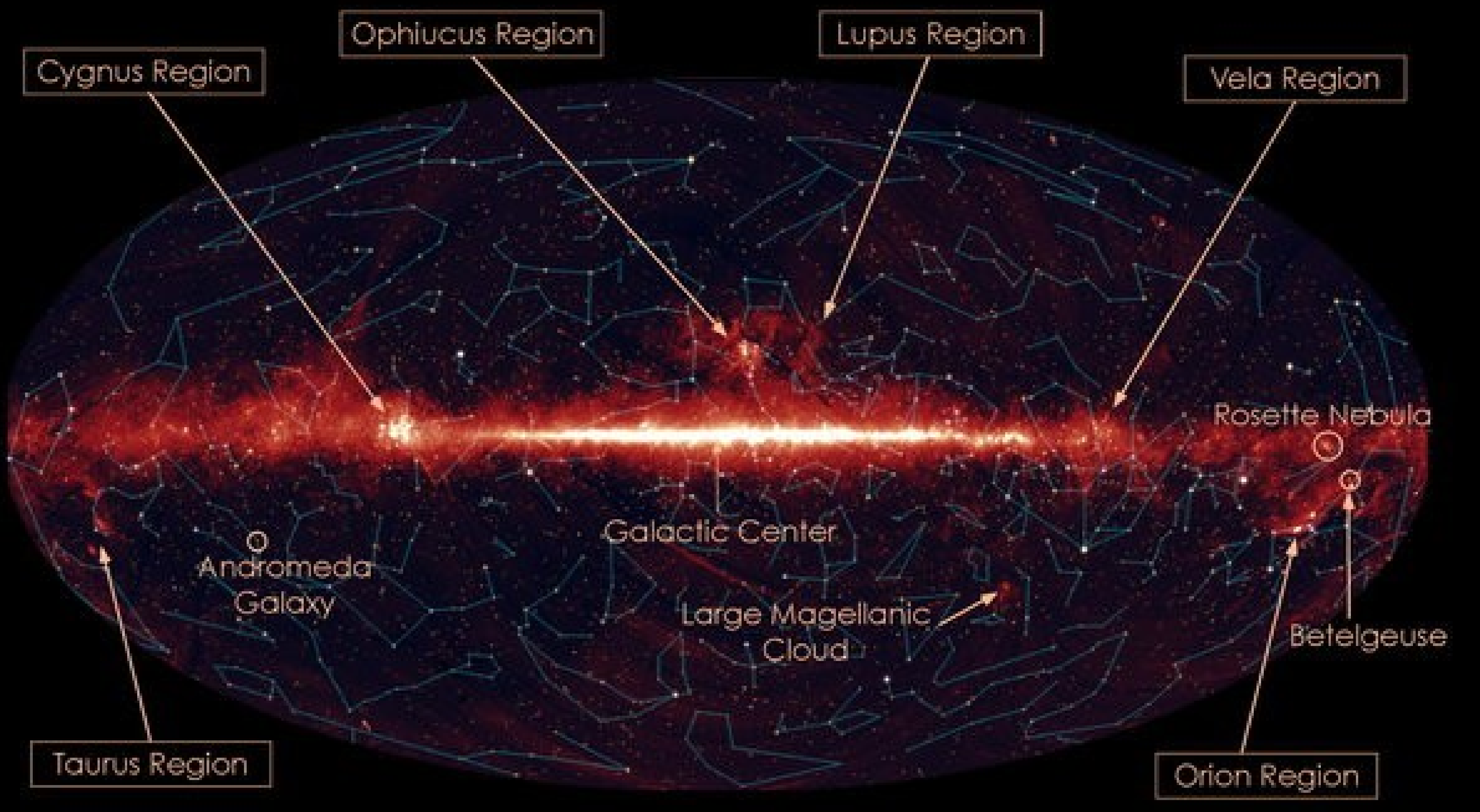


The visible sky

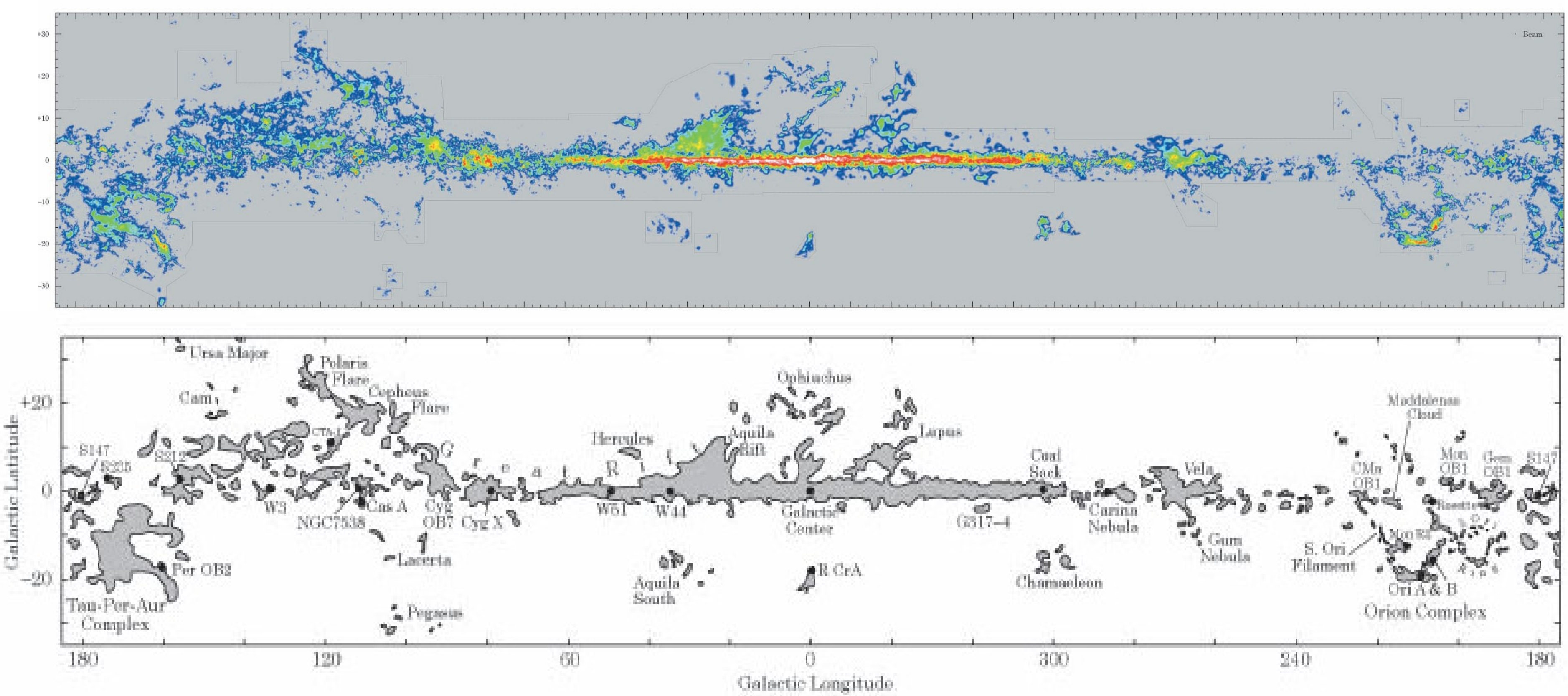
Extinction revisited



Infrared sky from the Akari satellite

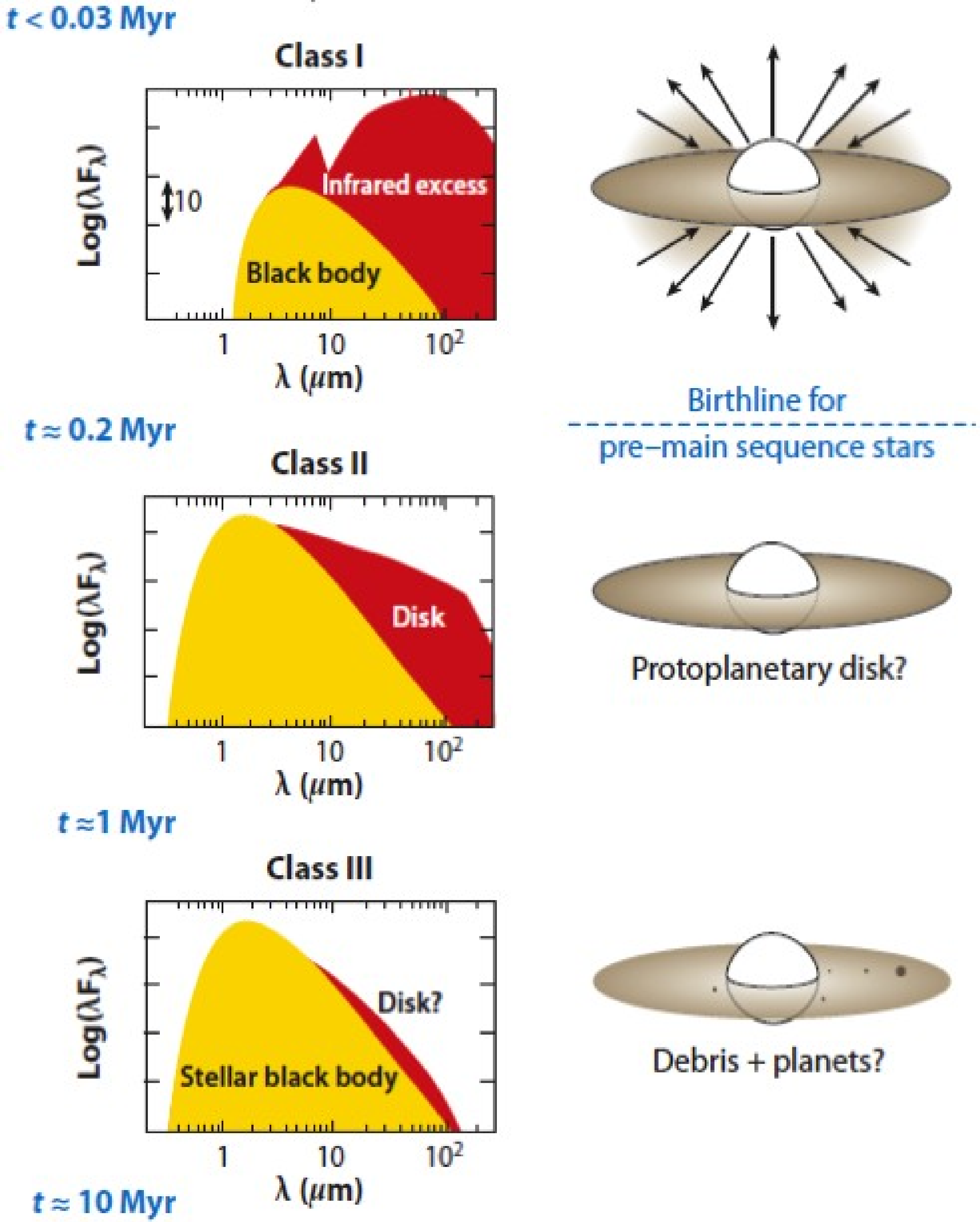


Giant Molecular Clouds



- Size scales 2-100 parsecs
- Mass 6 x 10^4 – 6x10^6 Msolar
- Lifetime 10^7 years

Dame, Hartmann & Thaddeus 2001.

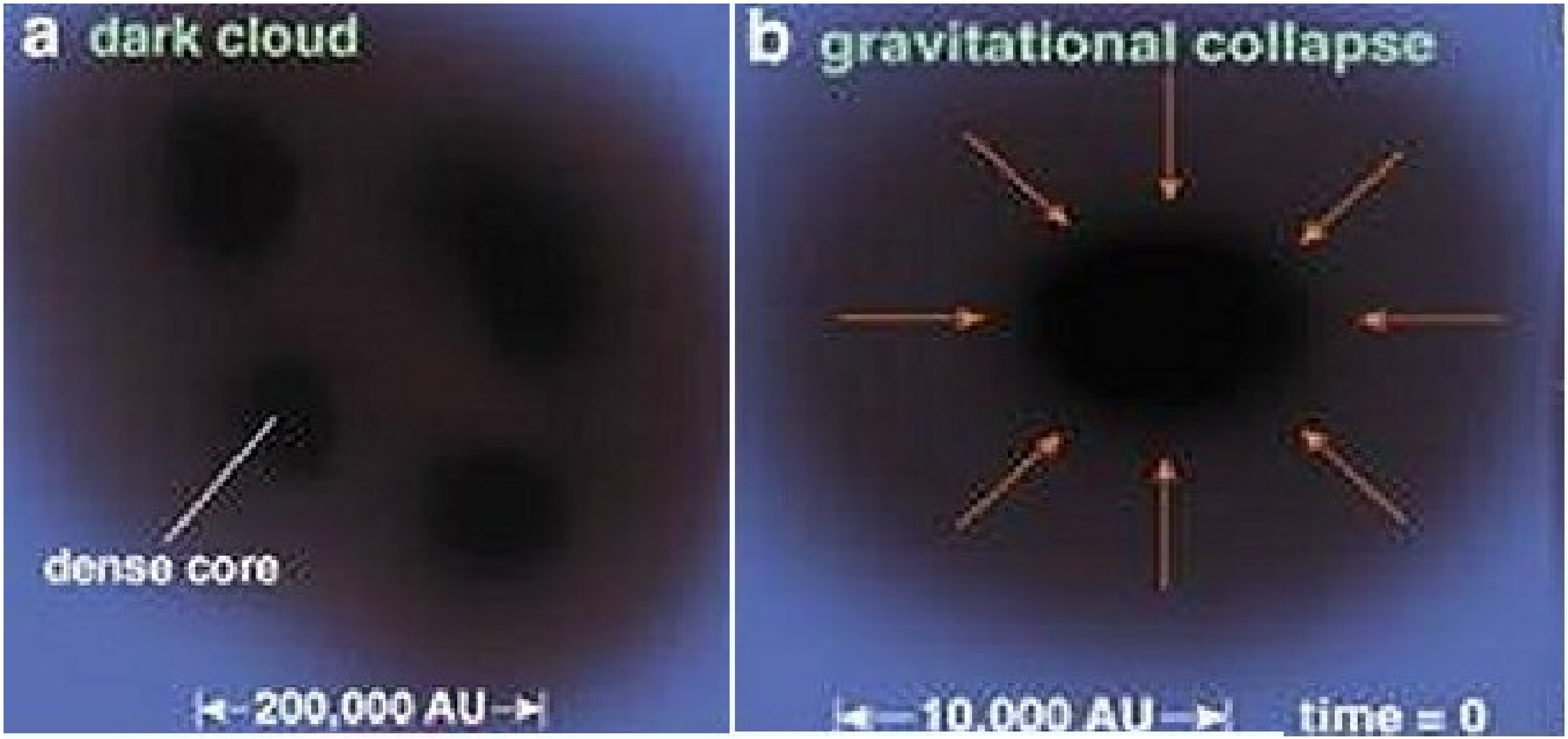


Evolution of a protostar

Classification of protostars from Lada 1987

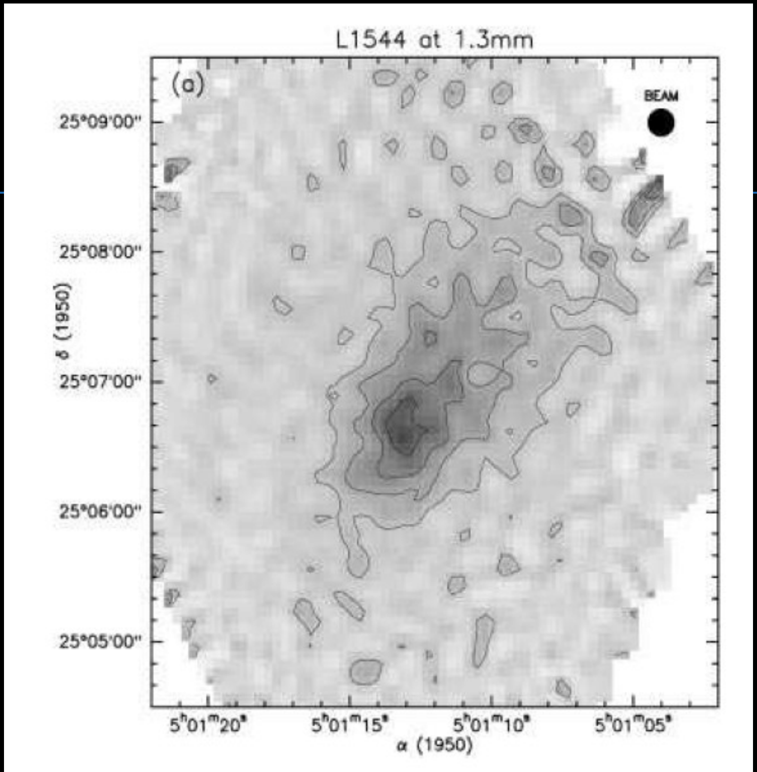
First Class 0 source VLA 1623 discovered in Rho Ophiucus in 1993 using the JCMT and the IRAM 30-m.

Starless cores and Class 0 objects



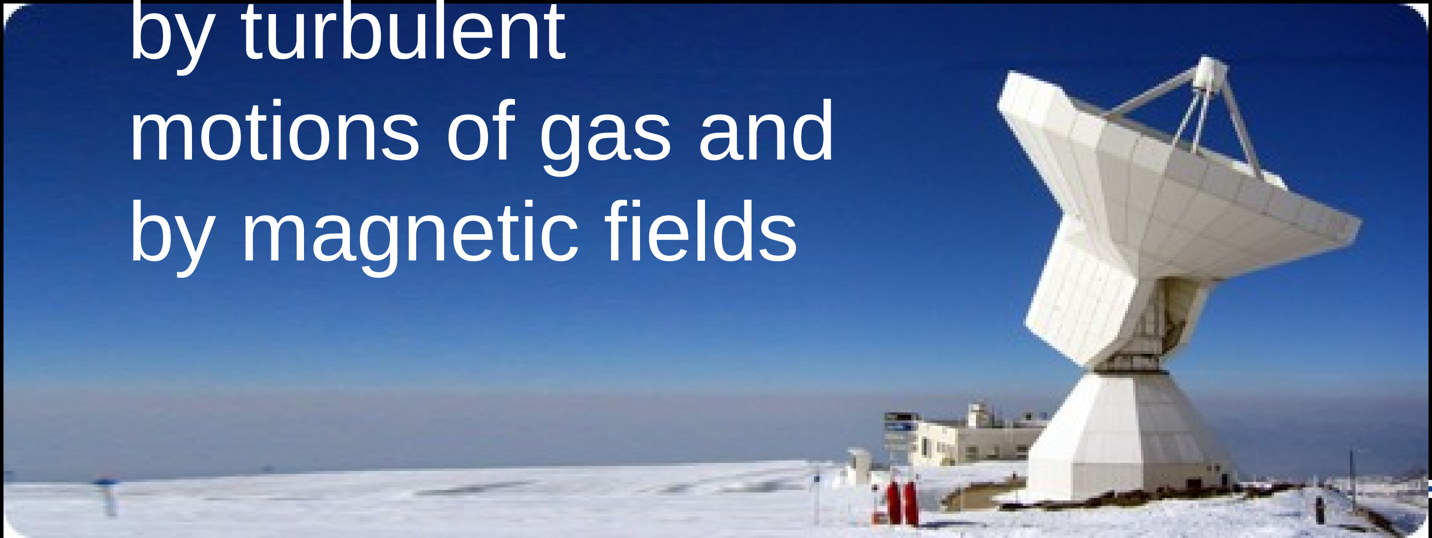
Starless cores

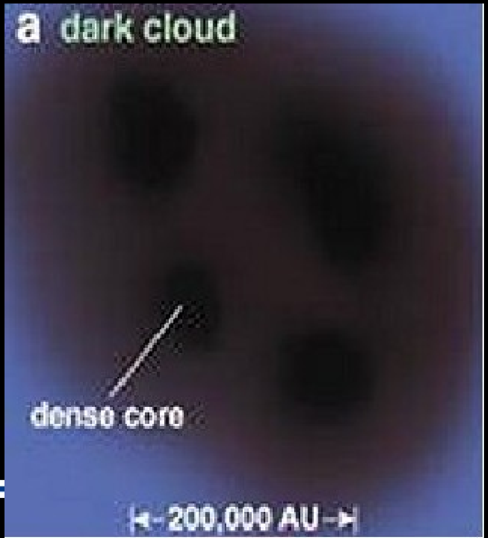
L1544, observed at the IRAM 30-m telescope



Cores are supported by turbulent motions of gas and by magnetic fields

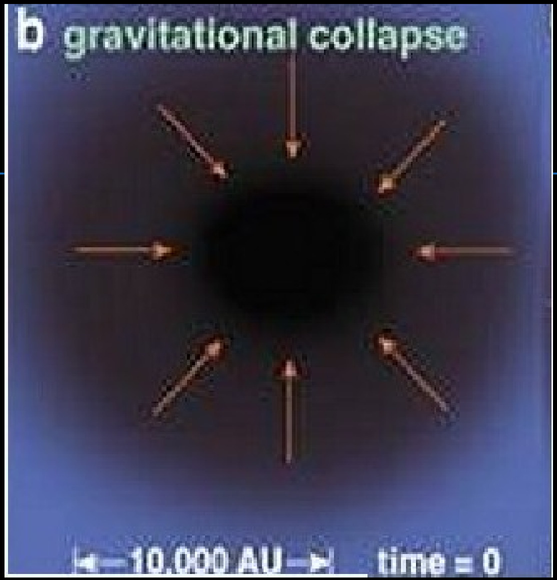
Ward-Thompson, Motte, Andre 1999

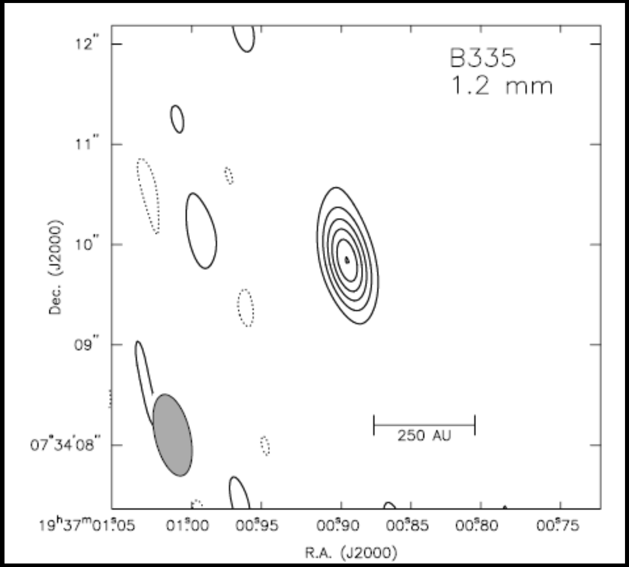


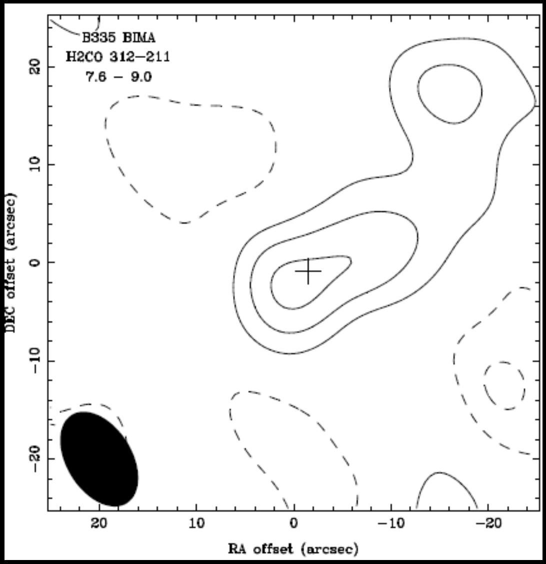


Class 0: B335

- Contains an embedded source 3 times as bright as the Sun
- Contains a disk, radius 100AU
- It has an outflow
- Outer envelope is 5000AU





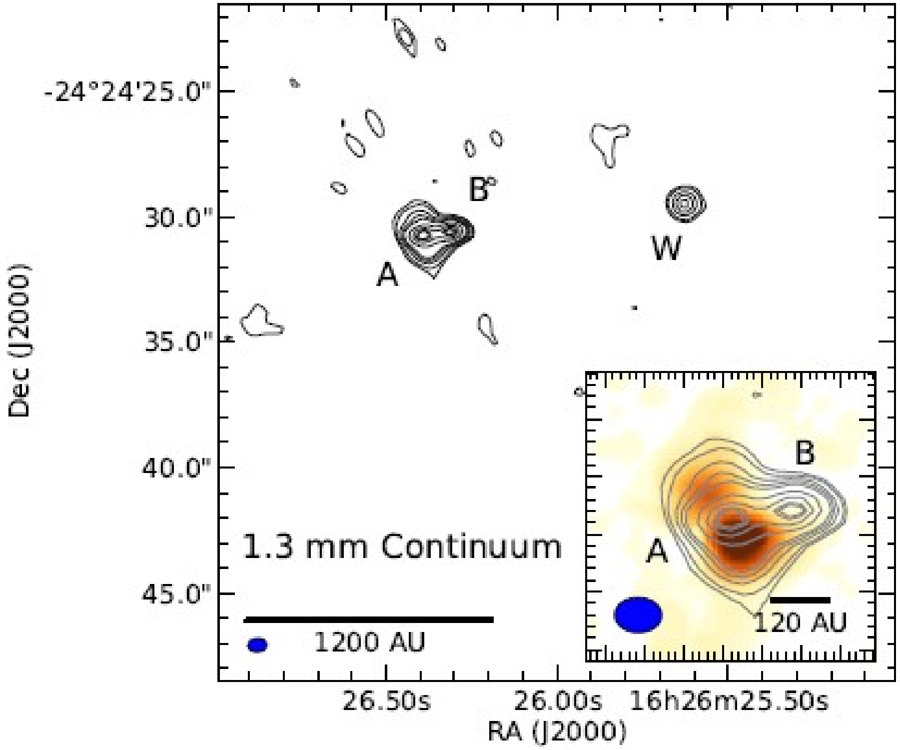


- Dust envelope

Disk

Outflow

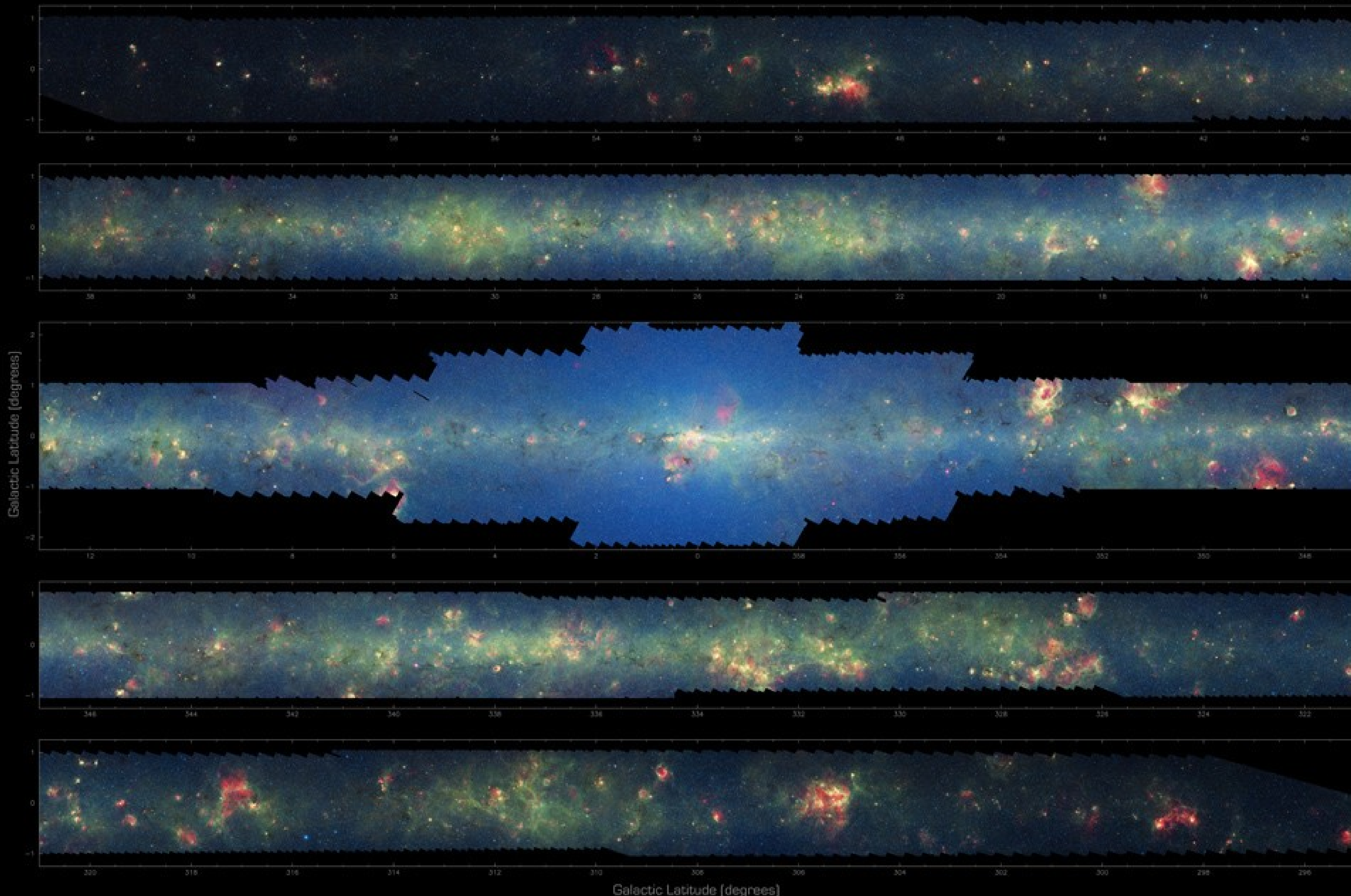
ALMA observations of VL1623



C18O observations show a disk in Keplerian rotation around this source (Murillo et al. 2013)

THE INFRARED MILKY WAY: GLIMPSE/MIPSGAL (3.6–24 microns)

SPITZER SPACE TELESCOPE



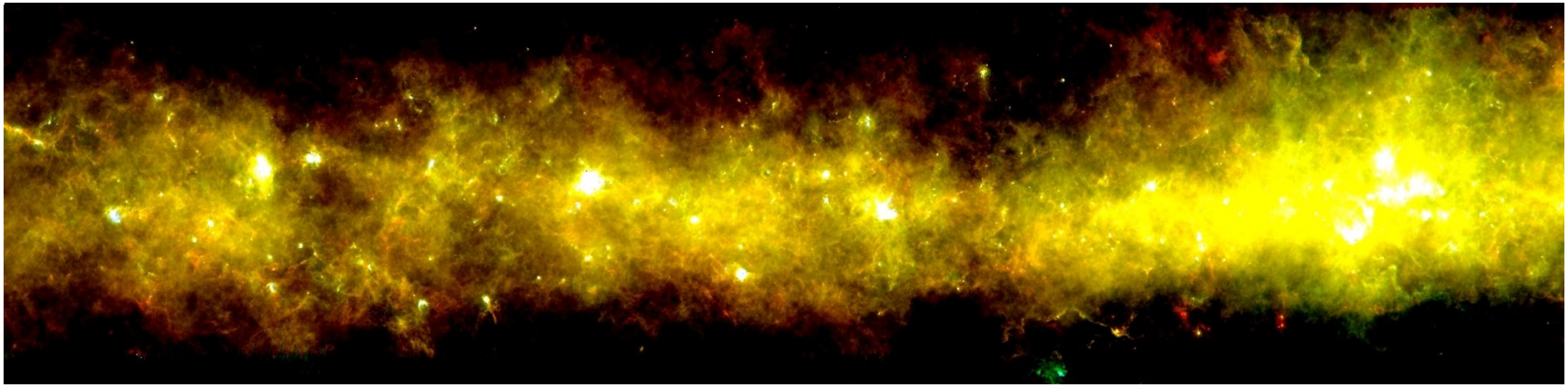
GLIMPSE team: Ed Churchwell (PI), Marilyn Meade, Brian Babler, Rémy Indebetouw, Barbara Whitney, Christer Watson, Bob Benjamin, Steve Bracker, Thomas Robitaille, Stephan Jansen, Doug Watson, Mark Wolfire, Mike Wolff, Matt Povich, Tom Bania, Dan Clemens, Martin Cohen, Claudia Cyganowski, Katie Devine, Fabian Heitsch, Jim Jackson, Katharine Johnston, Chip Kobulnicky, John Mathis, Emily Mercer, Jeonghee Rho, Marta Sewilo, Susan Stolovy, Brian Uzpen

MIPSGAL team: Sean Carey (PI), Alberto Noriega-Crespo, Don Mizuno, Sachin Shenoy, Roberta Paladini, Kathleen Kraemer, Stephan D. Price, Nicolas Flagey, Erin Ryan, Daniela Goncalves, Remy Indebetouw, Thomas Kuchar, Eli Bressert, Francine Marleau, Jim Ingalls, Deborah Padgett, Luisa Rebull, Bruce Berriman, Babar Ali, Francois Boulanger, Roc Cutri, Bill Latter, Peter Martin, Marc-Antoine Miville-Deschenes, Sergio Molinari, Russell Shipman, Leonardo Testi

Poster designed by Thomas Robitaille and Robert Hurt

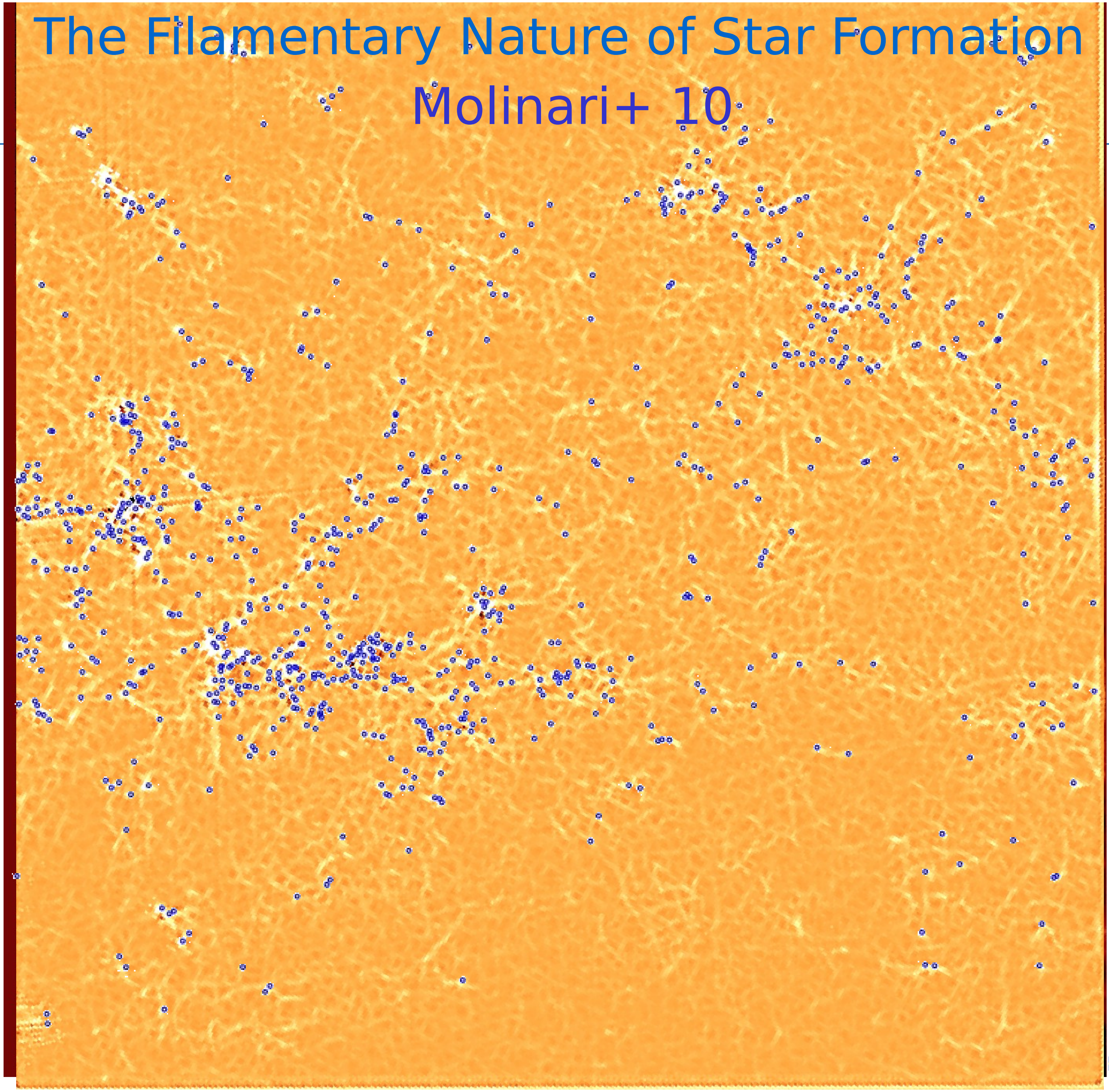
Hi-GAL/Herschel

-70°< *l* < 70° |*b*|<1° - 70/160/250/350/500μm – 343 hours (Molinari et al)



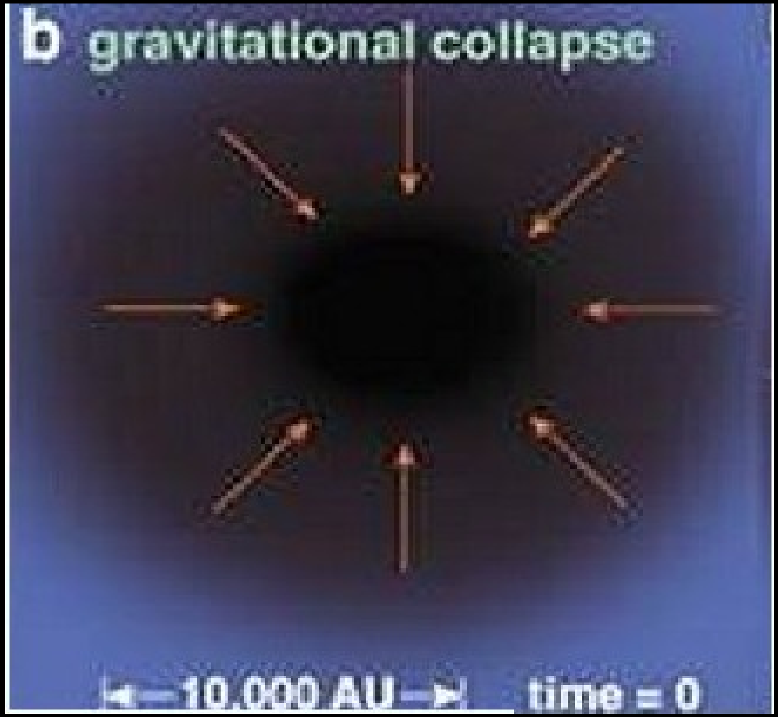
The Filamentary Nature of Star Formation

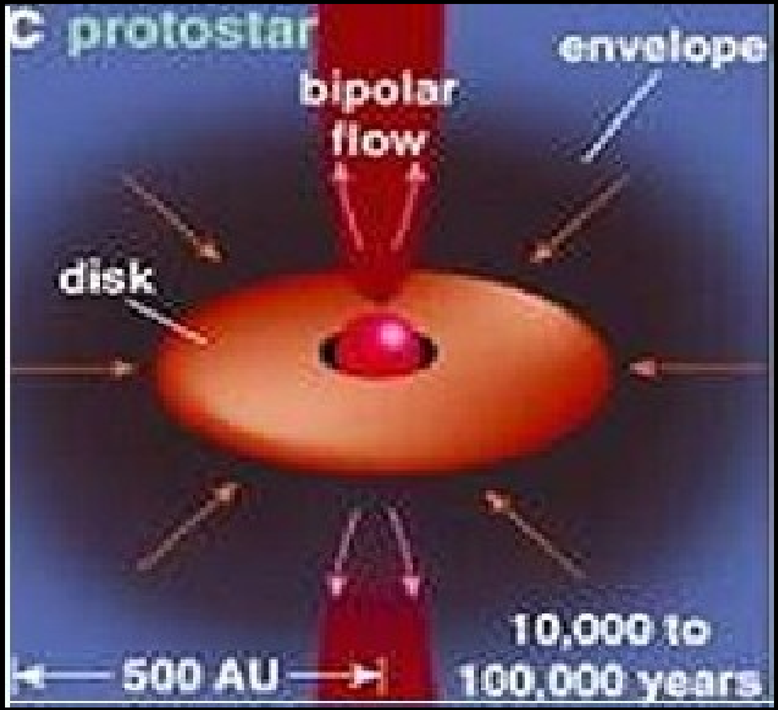
Molinari+ 10



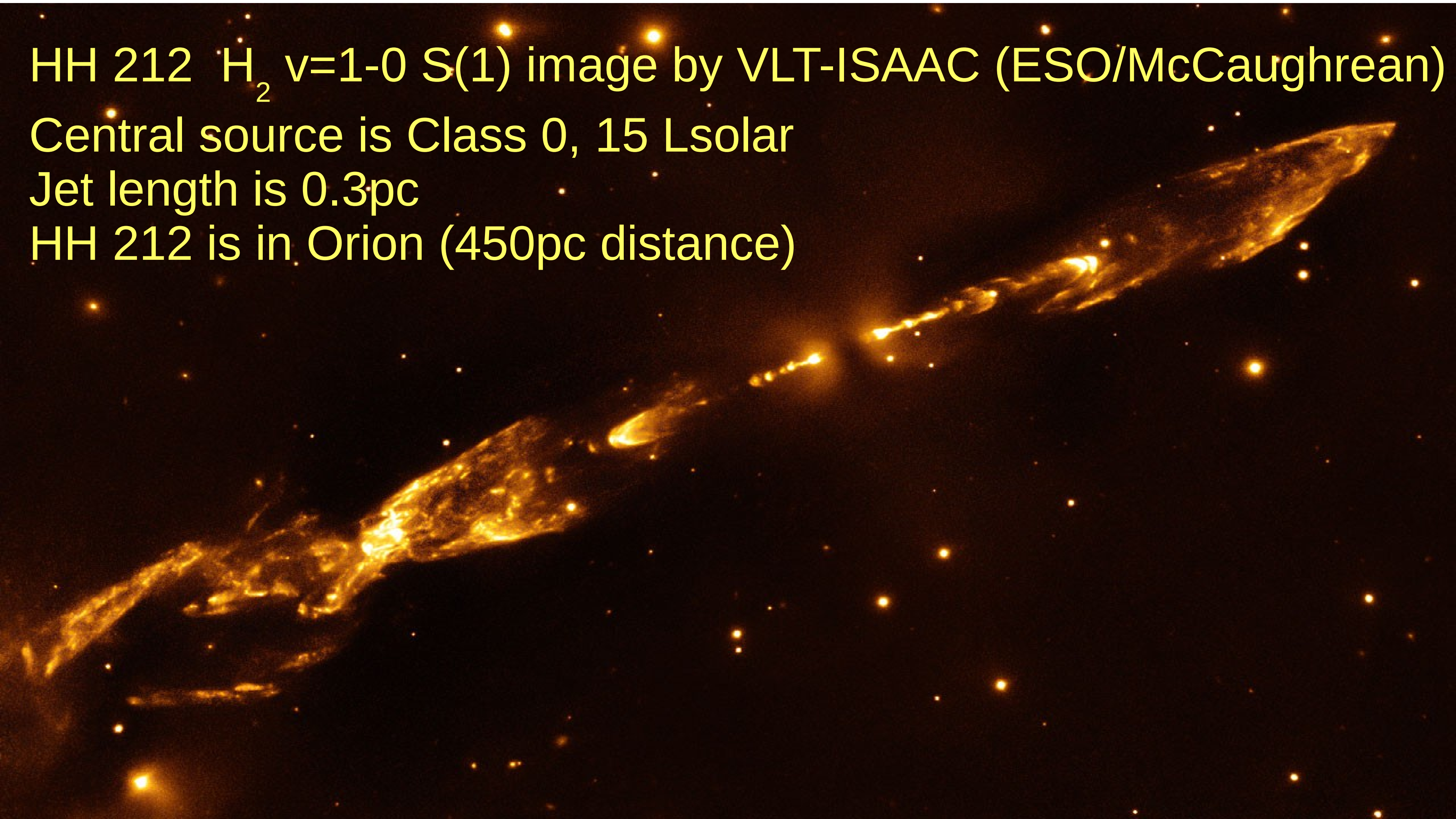
Protostar Evolution

- Most of the core mass must be ejected to evolve from Class 0 to Class I





HH 212 : a bi-polar jet powered by a Class 0 source

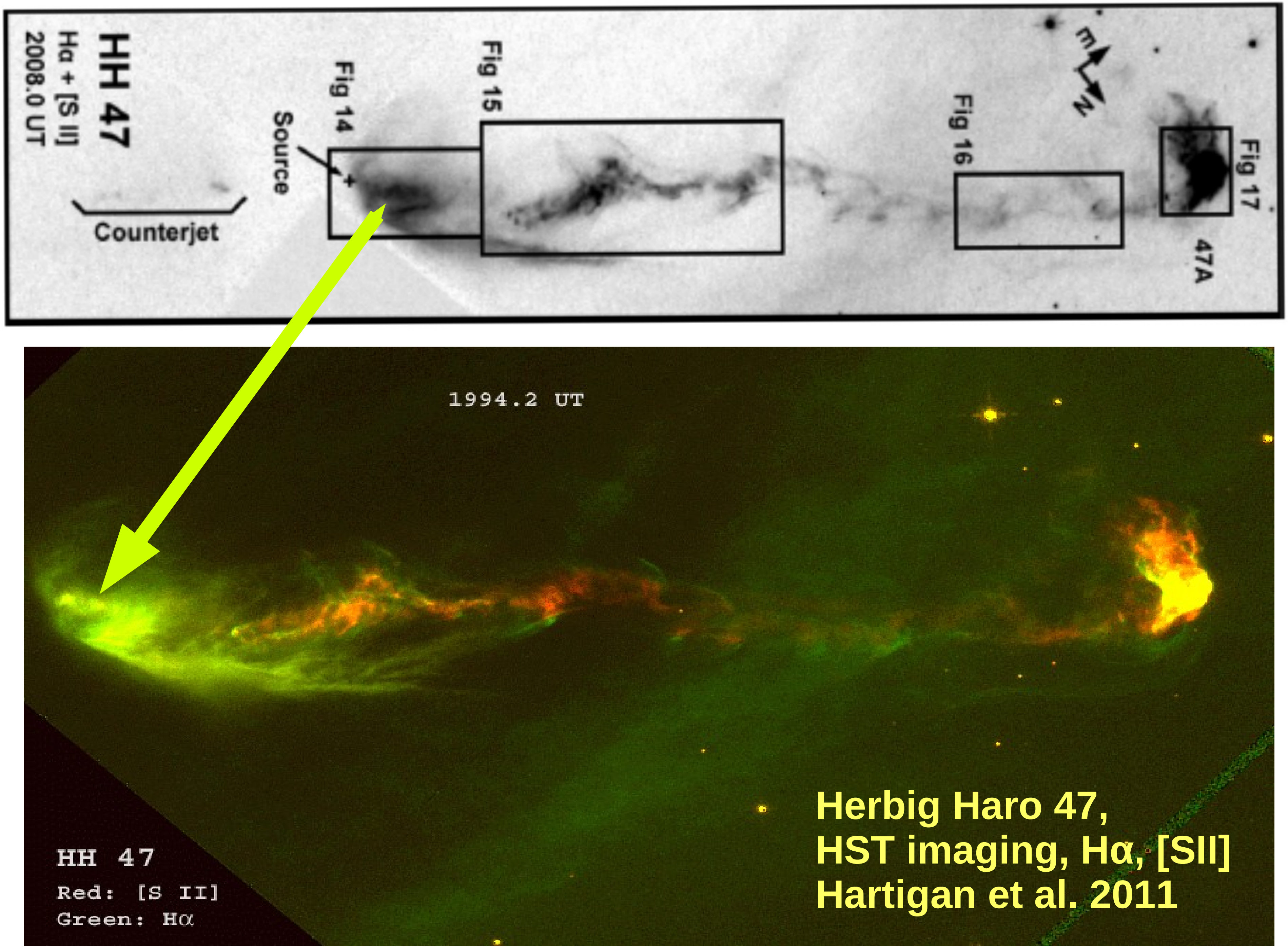


HH 212 H_2 v=1-0 S(1) image by VLT-ISAAC (ESO/McCaughrean)

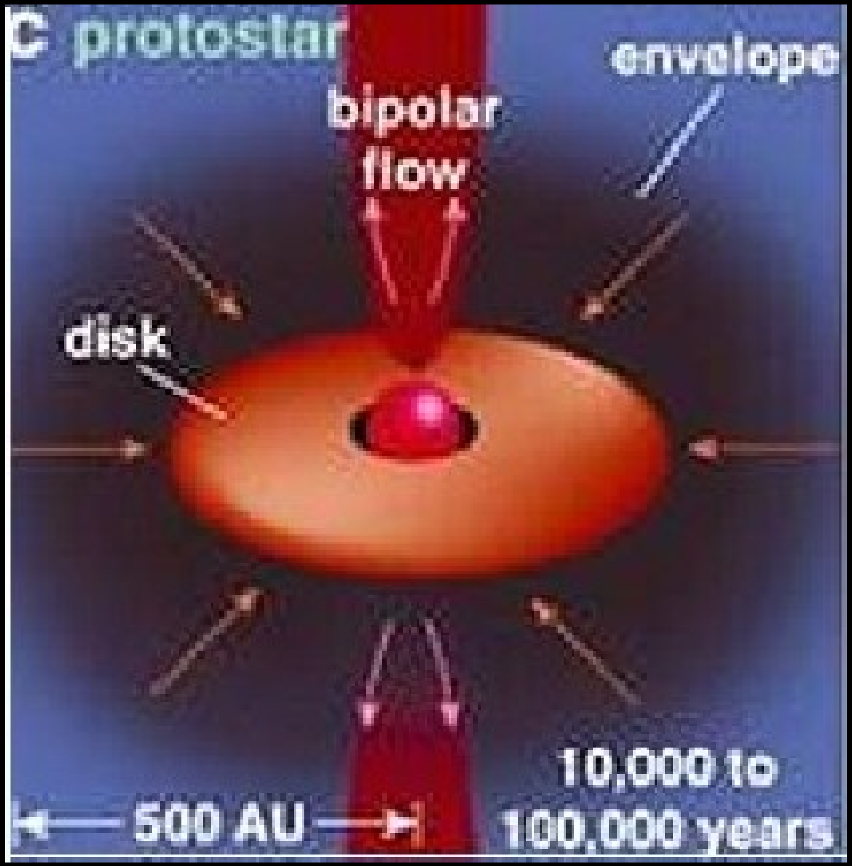
Central source is Class 0, 15 Lsolar

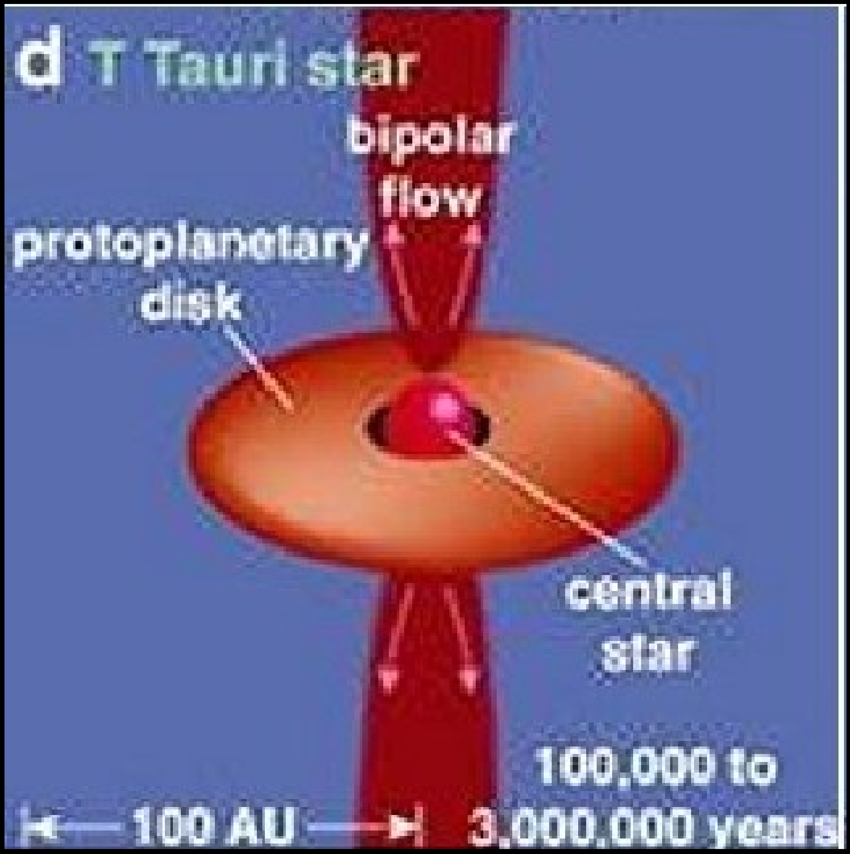
Jet length is 0.3pc

HH 212 is in Orion (450pc distance)


HH 47
Hα + [S II]
2008.0 UT
Counterjet
Source
Fig 14
Fig 15
Fig 16
Fig 17
47A
E
N
1994.2 UT
HH 47
Red: [S II]
Green: Hα
Herbig Haro 47,
HST imaging, Hα, [SII]
Hartigan et al. 2011

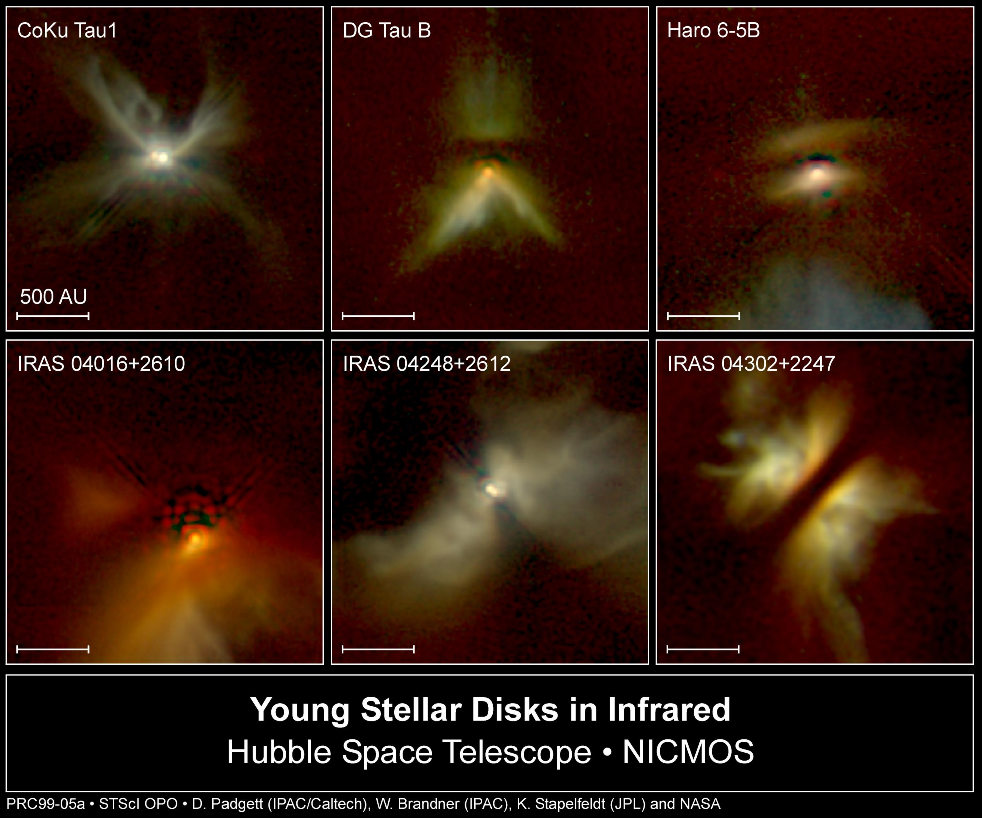
Protostar evolution





Class II / Classical T Tauris

T Tauri.
2MASS Atlas Image mosaics by E. Kopan, R. Cutri, and S. Van Dyk (IPAC).



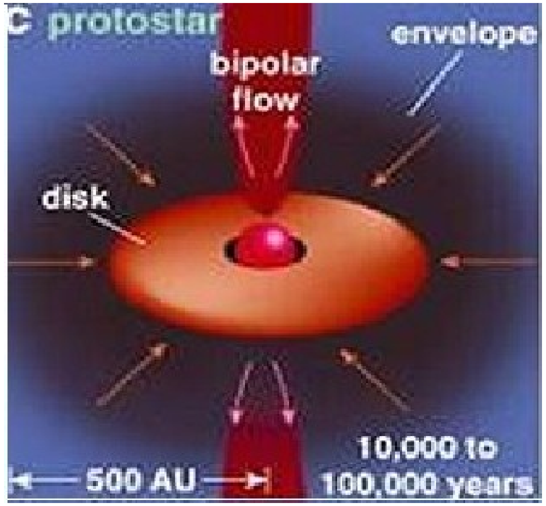
A conceptual problem with forming massive stars

- Time to reach the main sequence (Kelvin Helmholtz timescale) ~10^4 - 10^5 years for 10-100Msolar stars $\tau_{kh} = GM^2/Lr$
- For reasonable accretion rates (10^{-3} – 10^{-5} Msolar year^{-1}) there is not enough time to "grow" a massive star
- For the star to increase in mass, the gravitational attraction of the core on the dusty material must exceed the radiation pressure on that material

$$\kappa_{eff} L/4\pi r^2 c < GM/r^2$$

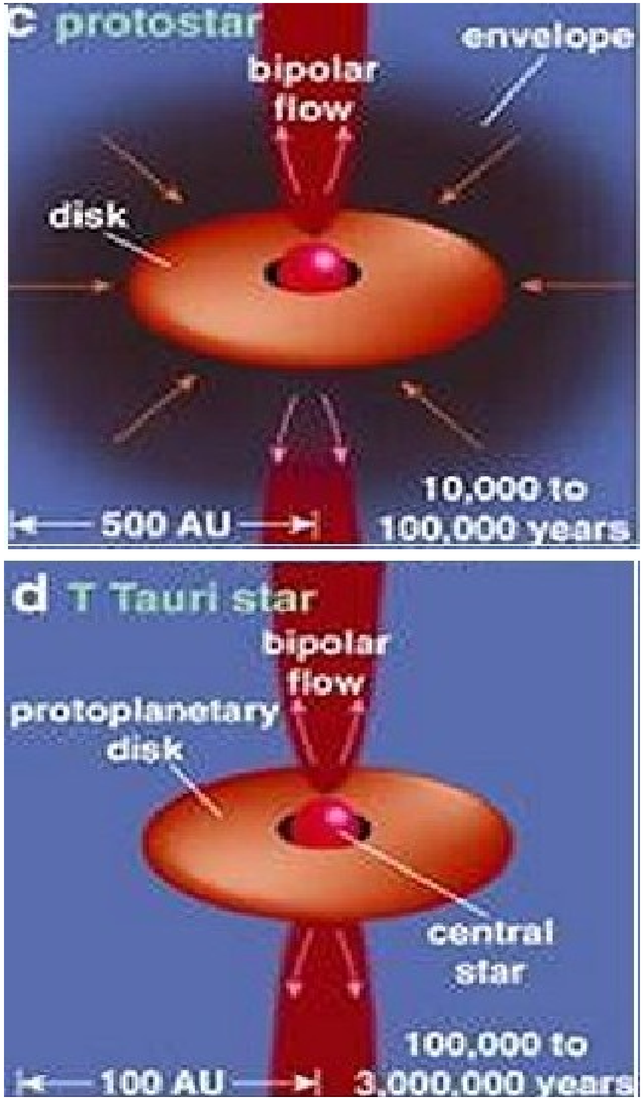
- κ_{eff} - dust opacity
-

- Theoretical efforts developed to explain how to overcome this limit for ~>10Msolar
- Alternative scenarios for formation include by collision and merger of smaller bodies



Observational Challenges

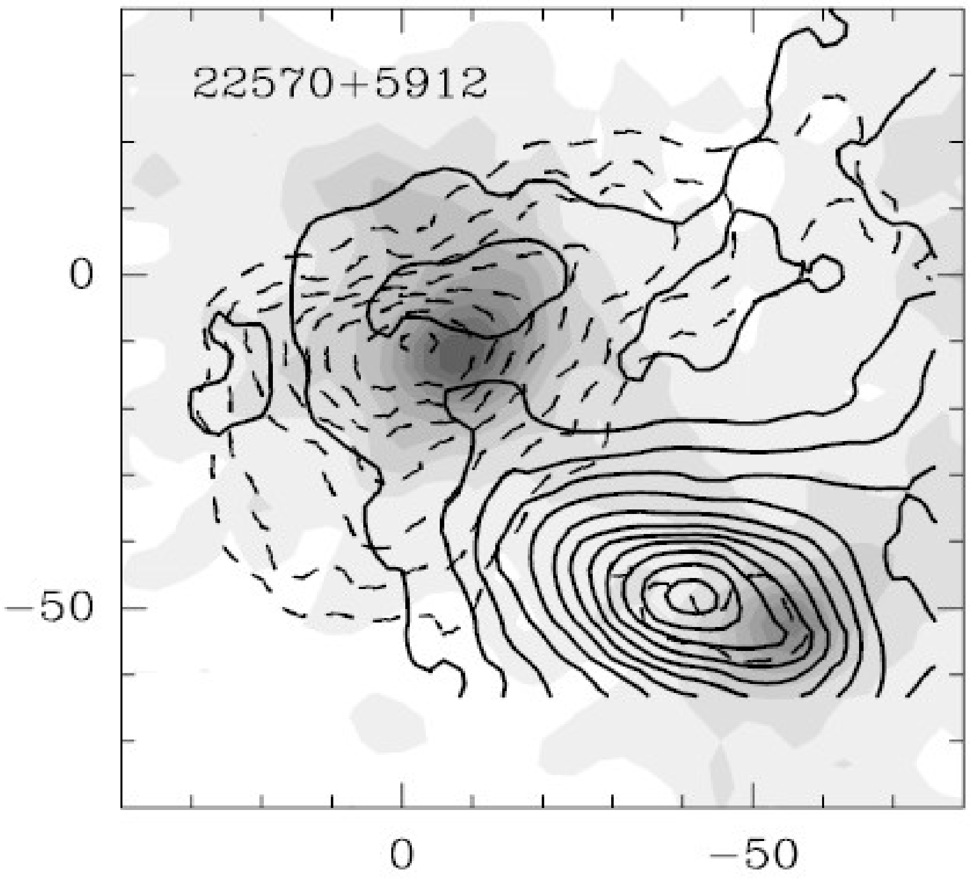
- Shorter evolutionary timescales
- Formation in clusters, requiring high spatial resolution
- Comparatively high distances (>kpc)
  - Low mass stars: Upper Sco (145pc), Taurus (140pc)
    - 100AU ~ arcsec scales
  - High mass stars:Orion (450pc), typically > few kpc
    - 100AU ~ 0.1 arcsec scales



Observational Challenges

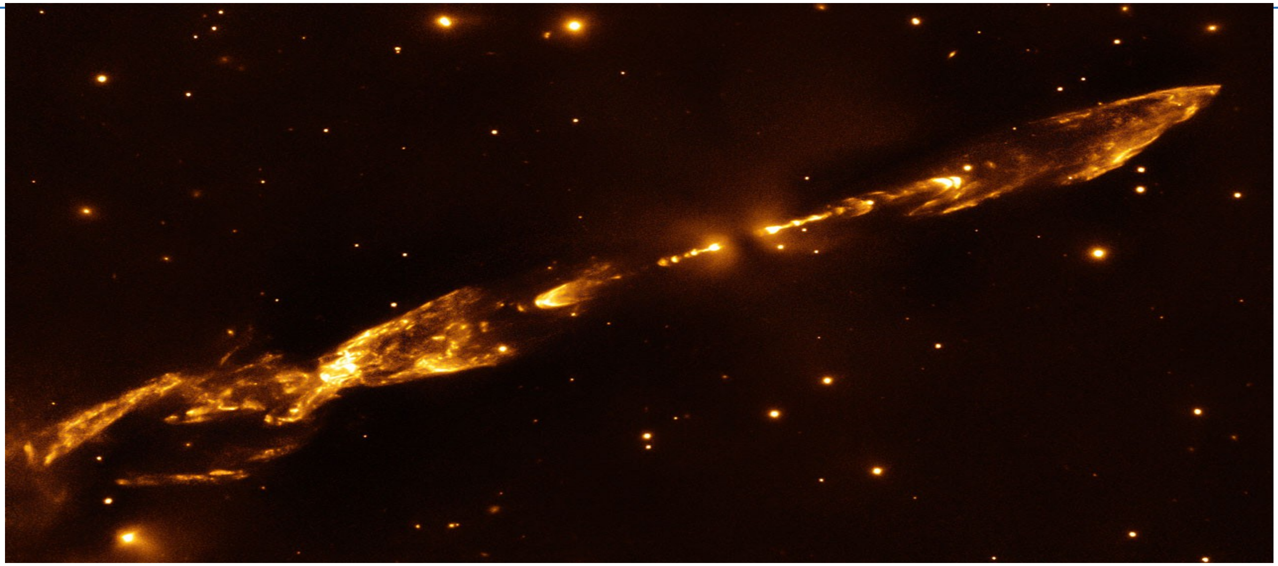
- Substantial surveys for HMYSOs candidates start to become available mid-1990s
- Signatures of massive star formation
  - Tracers of dense gas: NH_3 (1,1) and (2,2) emission (Molinari et al. 1996), H_20 and CH_3OH maser emission (Sridharan et al. 2002)
  - Evidence of outflows: High velocity CO (Shepherd & Churchwell 1996, Beuther 2002)
  - Radio continuum emission (evidence of an HII region)
- Growing evidence for the accretion scenario supported by work on small numbers of sources

Collimated Outflows from high mass young stellar objects?



CO map of
IRAS 22570+5912
Beuther et al. 2002

Surveying for Outflows



Emission from v=1-0 S(1) H_2 at 2.122µm, excited by shocks, is an excellent tracer of jets from YSOs.

NIR instrumentation on 4-m class telescopes offers sufficient sensitivity and high spatial resolution over arcminute scales.

NIR imaging K band+ H_2 1-0 S(1) filters.

UK Infrared Telescope

Surveying for Outflows

From a sample of 50 objects

- New embedded young star clusters revealed

  H_2 is commonly observed: 76% of sources have H_2 emission

IRAS 20062+3550

d=4.9kpc, L=3.2x10^3 L_o

IRAS 20162+4104

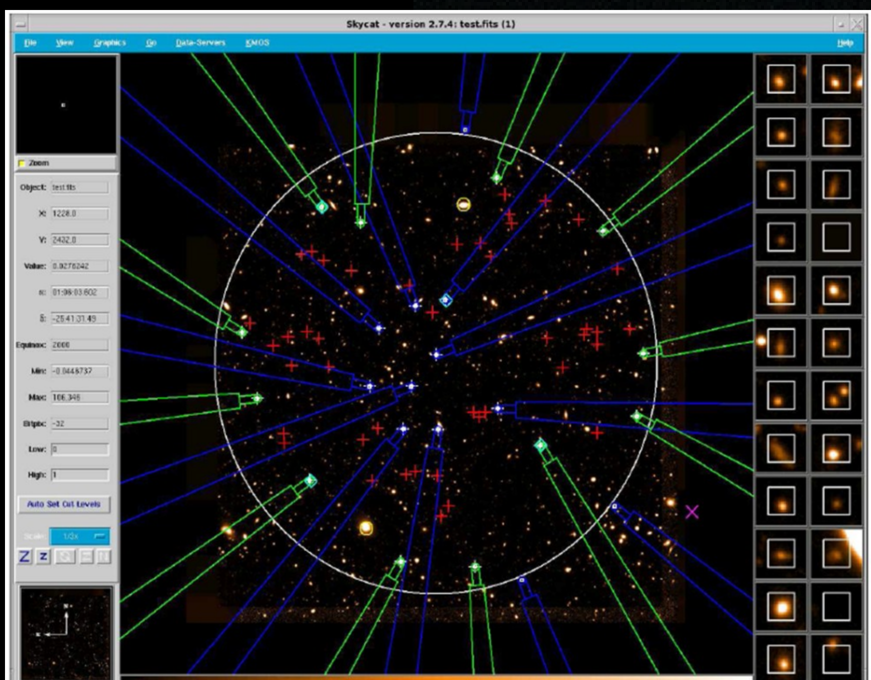
d=1.7kpc, L=10.0x10^3 L_o

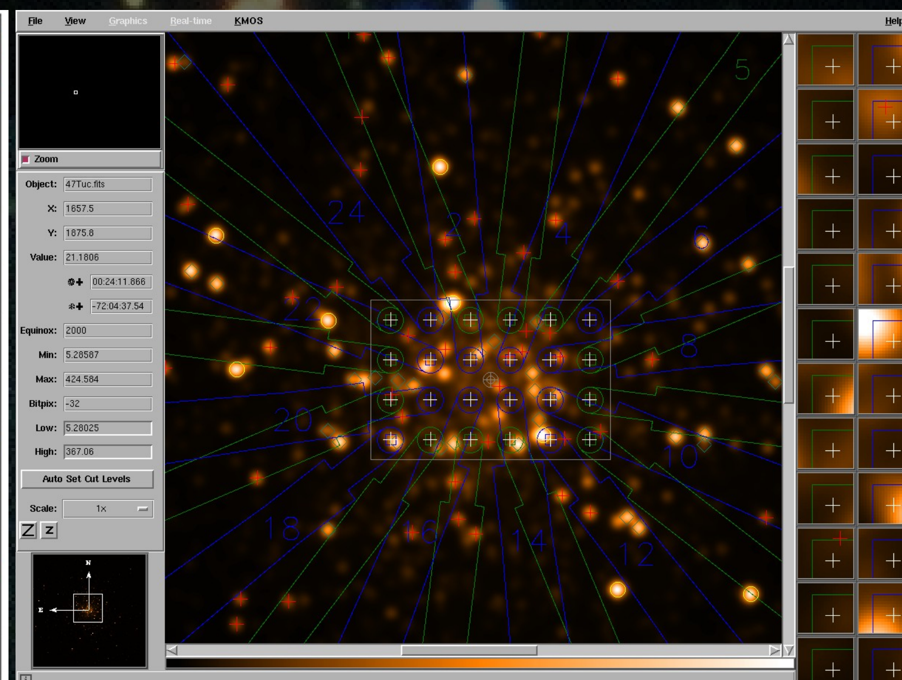
IRAS 22570+5912

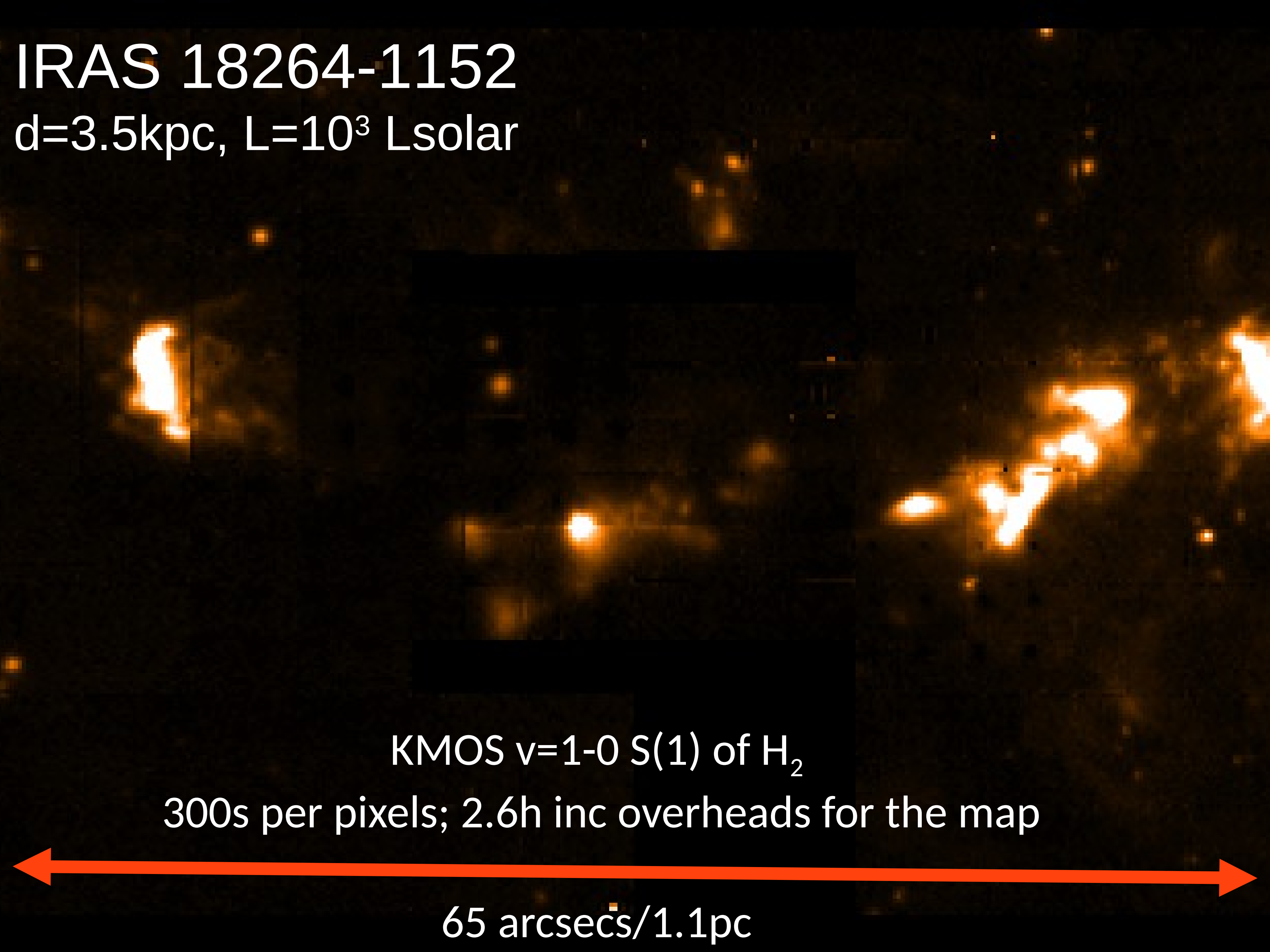
d=2.92kpc, L=20.1x10^3 L_o

KMOS observations

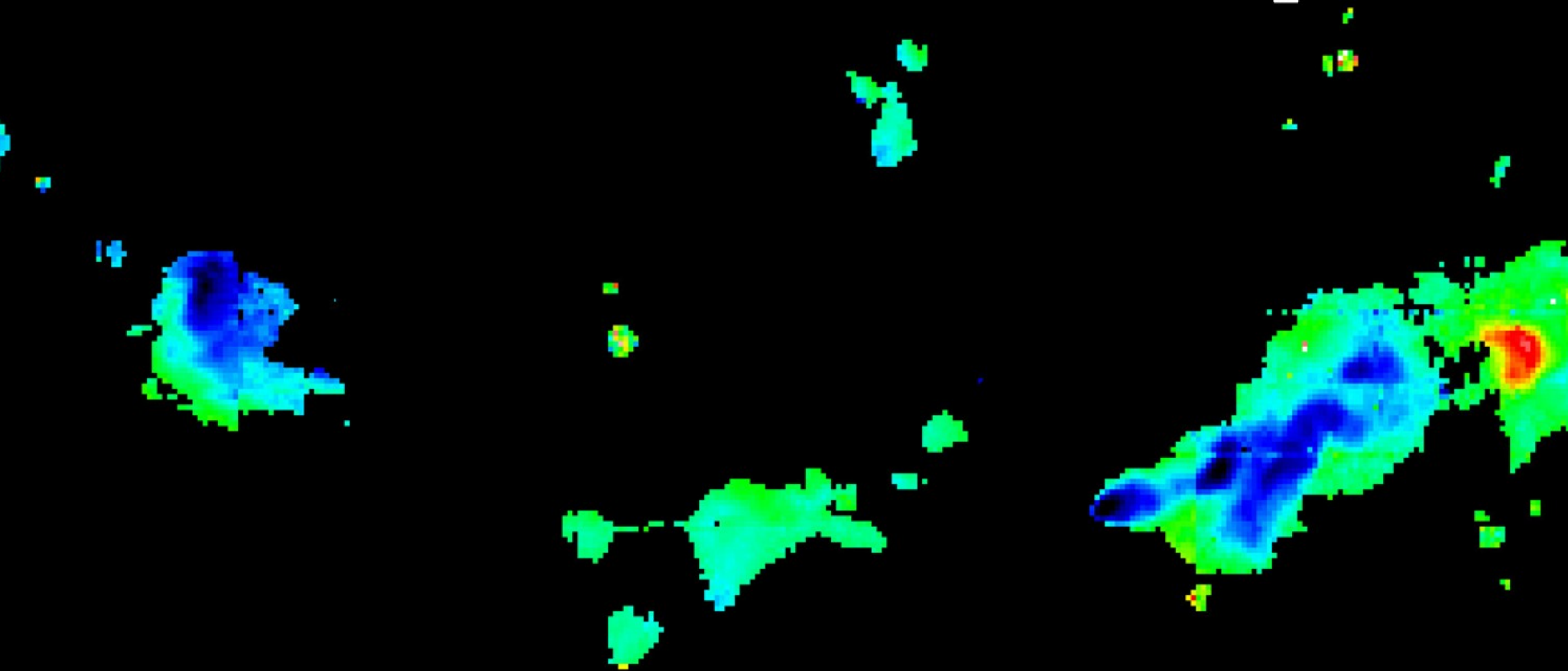
- KMOS is a multi-integral field unit spectrograph on VLT
  - 24 fields of 2.8arcsecs x 2.8 arcsecs can be observed simultaneously
  - Near infrared 0.8-2.5um
  - Mosaic mode, K band (1.9-2.45µm) grating with R~4000 (75km/s)






IRAS 18264-1152
d=3.5kpc, L=10^3 Lsolar
KMOS v=1-0 S(1) of H_2
300s per pixels; 2.6h inc overheads for the map
65 arcsecs/1.1pc

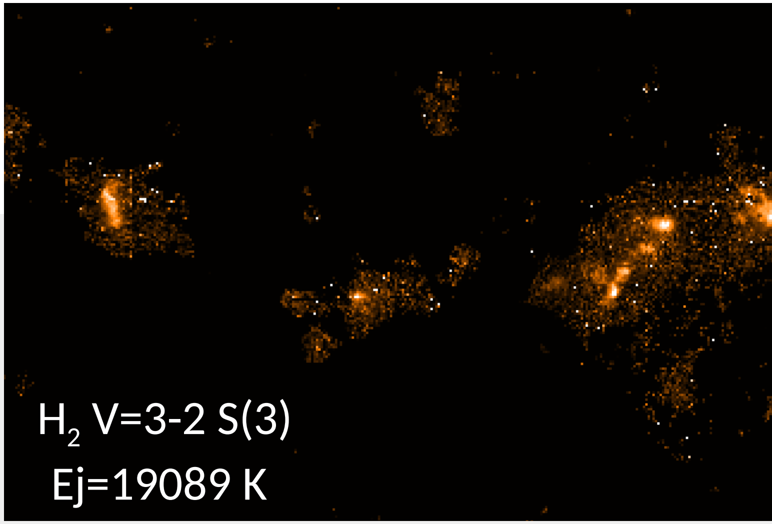
Velocity map in 1-0 S(1) H_2

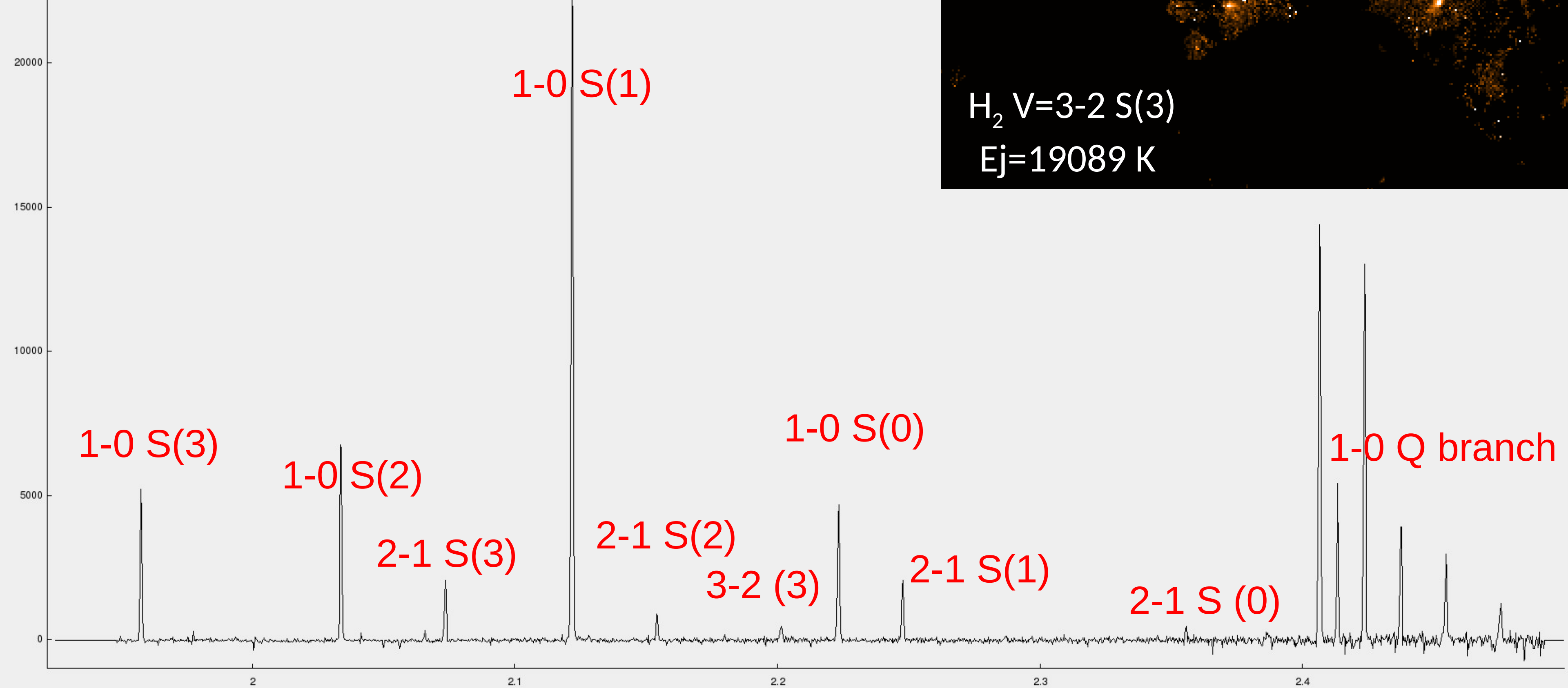


Black: -60km/s <v<-30km/s
Blue: -30km/s <v<0km/s
Green: 0<v<30km/s
Red: 30<v<60km/s
Radial velocity of IRAS18264-1152: 43.6km/s (Bronfman, Nyman & May 1996)

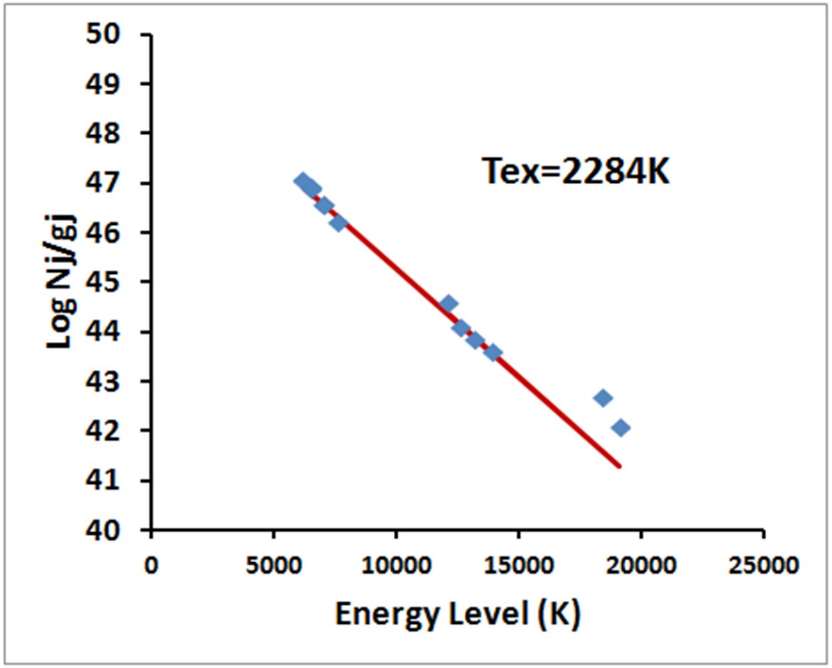
Rich H_2 rotational-vibrational line spectrum

H_2 rotational-vibrational line spectrum typical of shock excitation





Properties of the outflow



The brightest knots have L_{H2}~$3L_{solar}$, typical of other HMYSO outflows

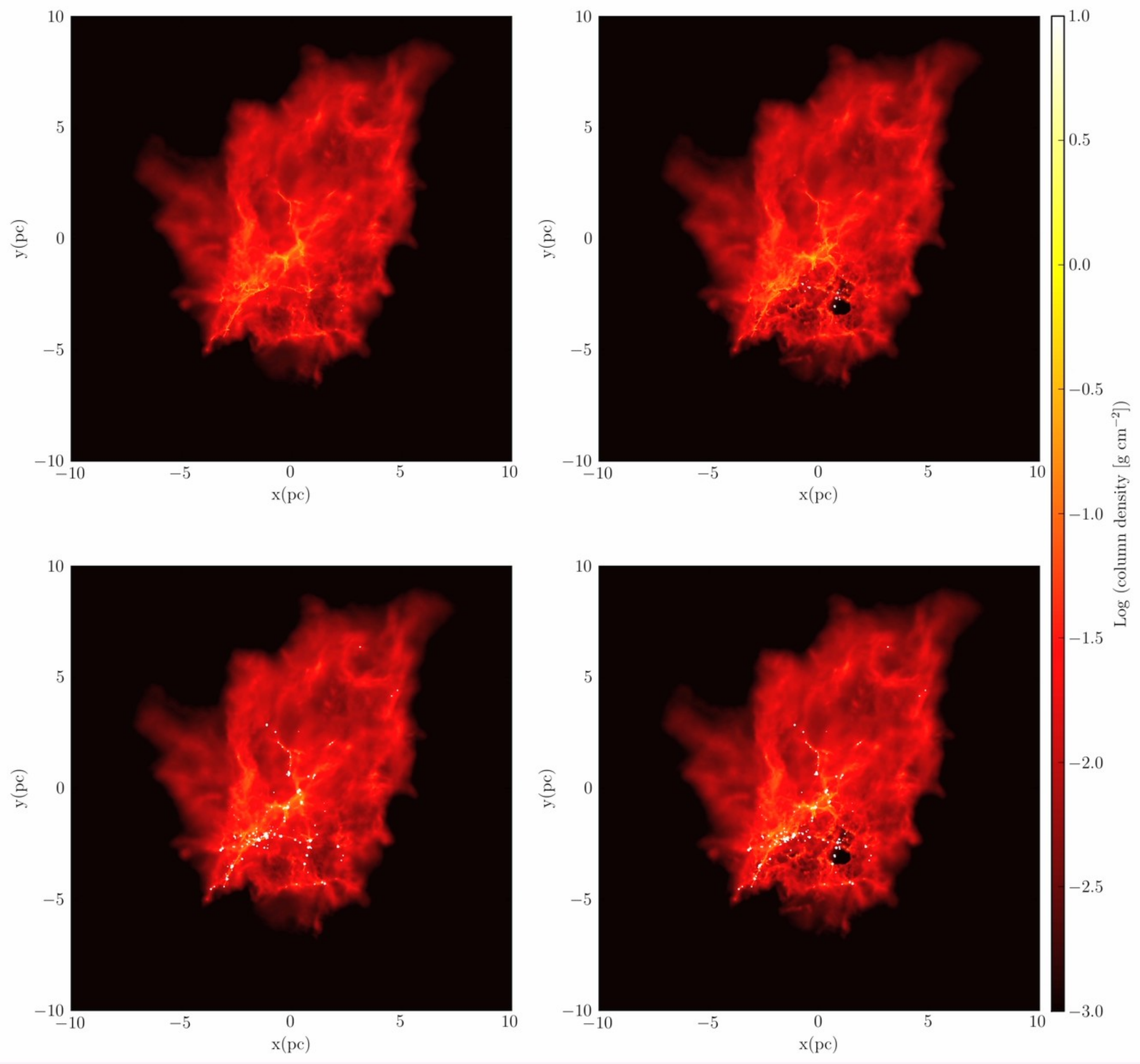
- **In total ~$17L_{solar}$**

Mechanical luminosity in CO ~20Lsolar (Beuther et al. 2002)

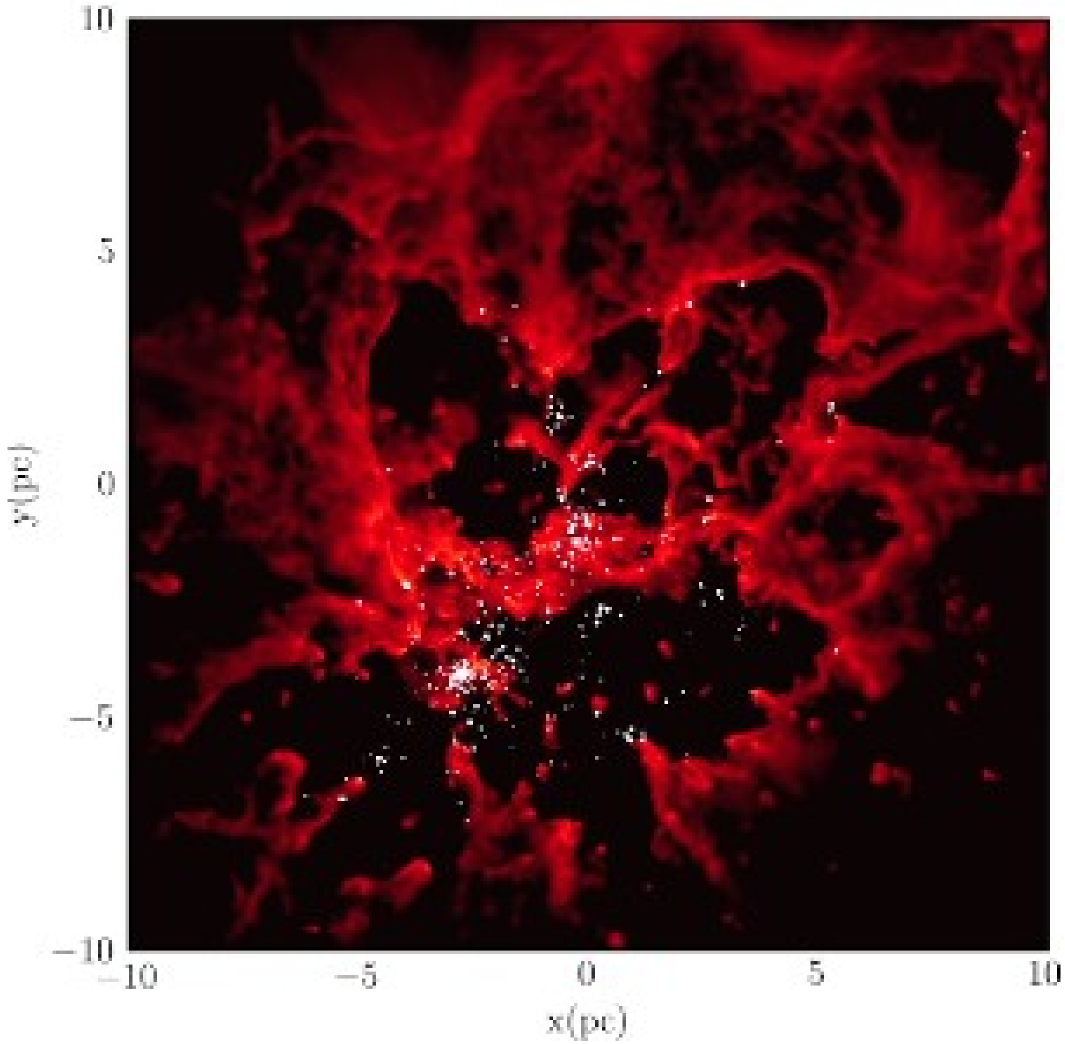
Outflow rate ~$10^{-7.5}$ Msolar yr^{-1}

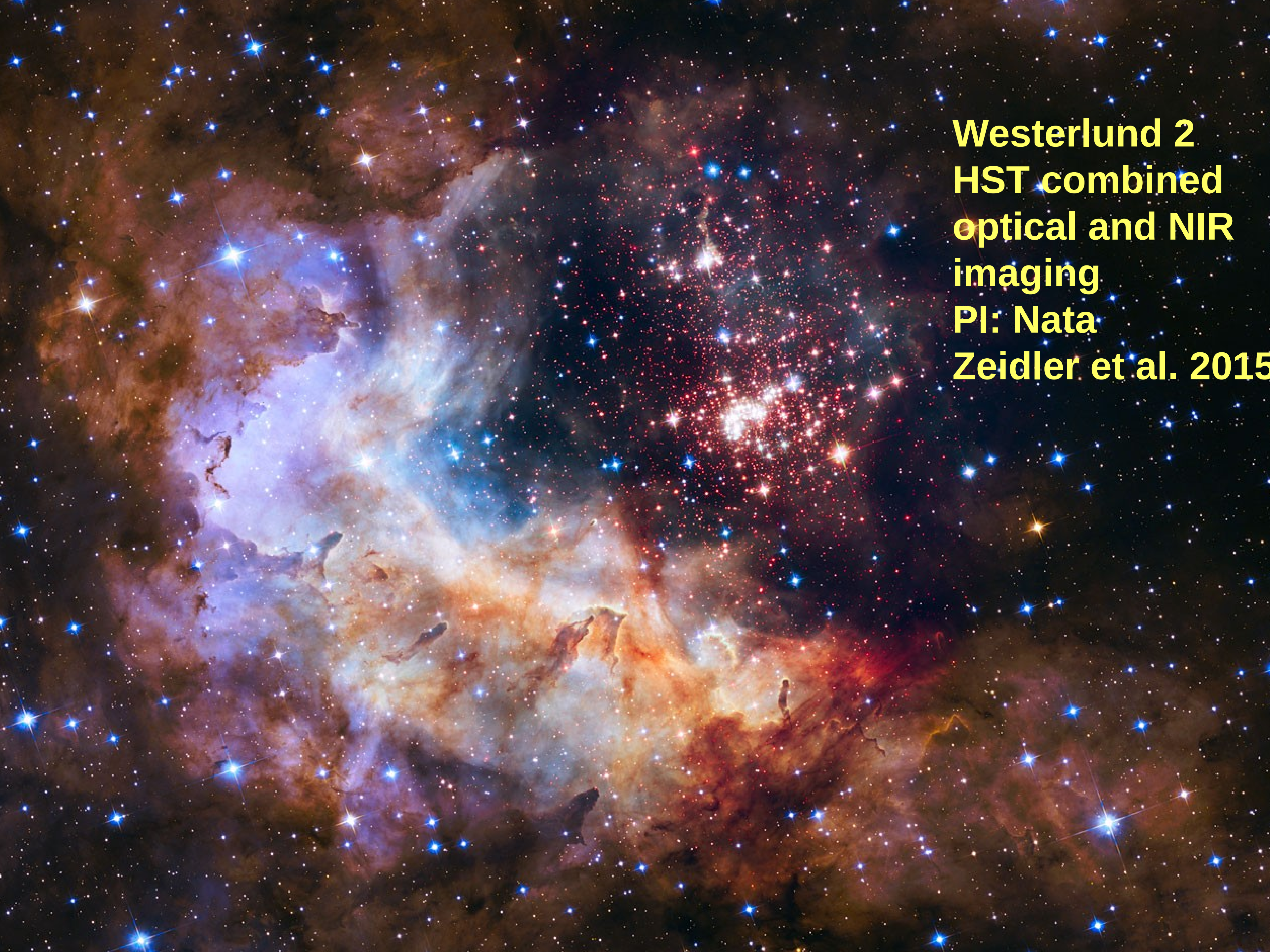
What next for these regions?

Feedback in massive star forming regions

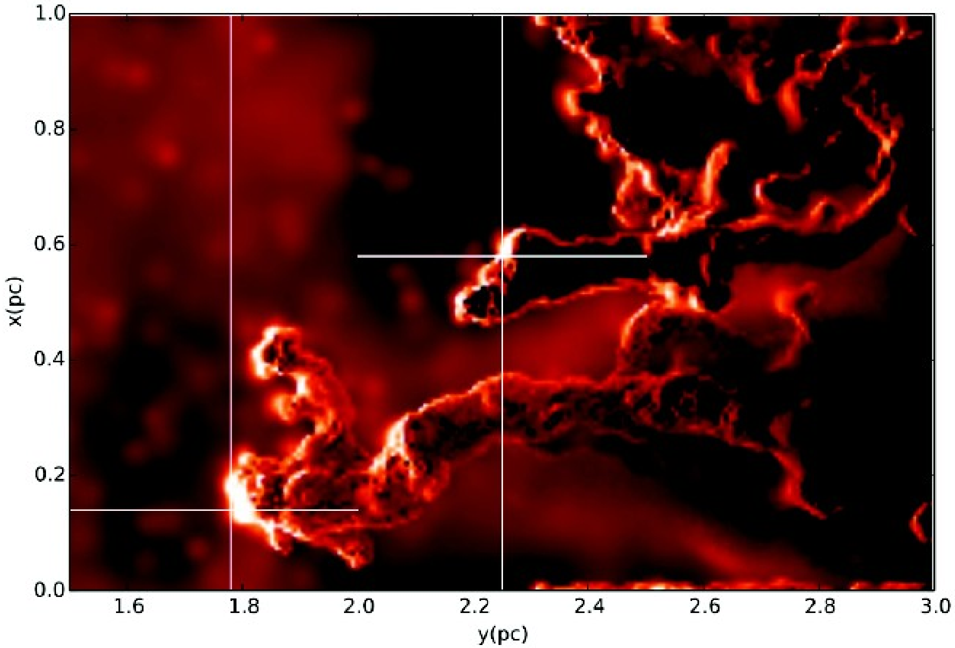


Simulation: James Dale, LMU


y(pc)
10
5
0
−5
−10
−10
−5
0
5
10
x(pc)


Westerlund 2
HST combined
optical and NIR
imaging
PI: Nata
Zeidler et al. 2015

Simulated observations

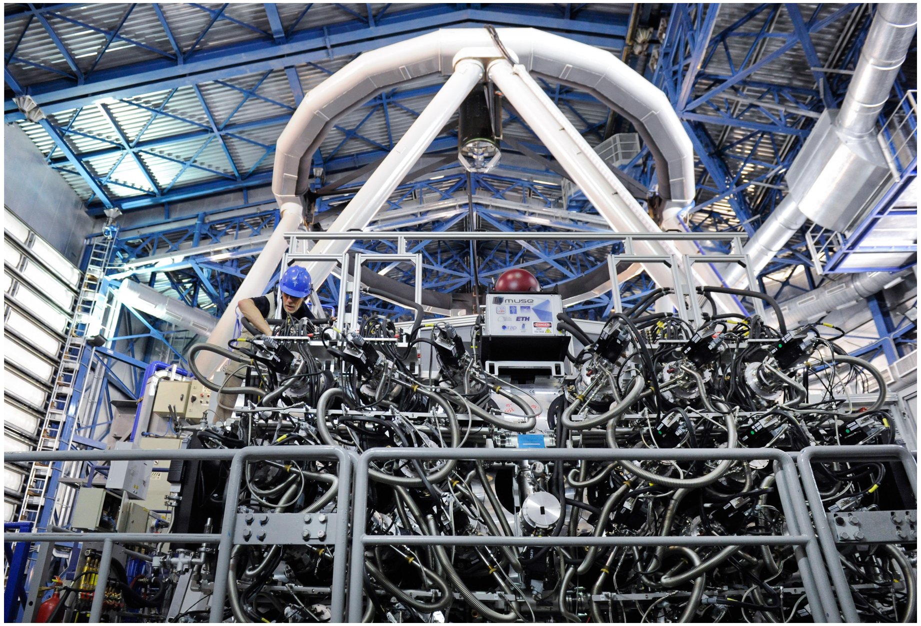


Log(Hα intensity) for simulated "pillars of creation" from Ercolano et al 2012

- Simulations are from 'DIVINE' SPH code DIVINE (Gritscheneder et al. 2009, Ercolano & Gritscheneder 2011)
- Post-processed with photo-ionisation code 'MOCASSIN' to give line maps (Ercolano et al. 2012)
- Diagnostic lines: Hα, [O III] λ5007, [N II] λ6584, [S II] λ6716

MUSE on VLT

- Simultaneous coverage 4750-9350A
- Velocity resolution from 150kms^{-1} – 75kms^{-1}
- 0.2arcsec pixels, 1arcmin x 1arcmin field
- 90 000 spaxels



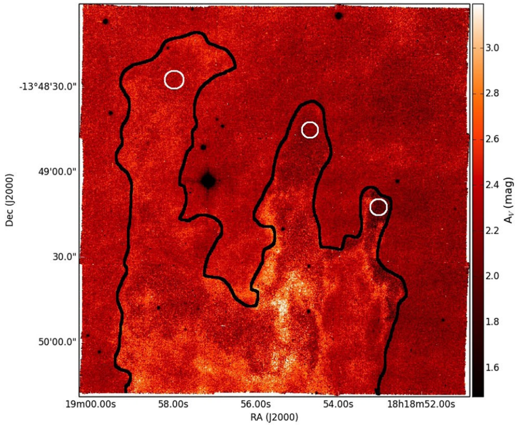
MUSE observations of M16

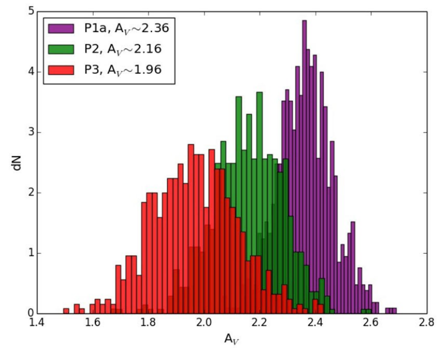
McLeod + 2015

- Pillars are being photo evaporated by the nearby (2pc) massive NGC6611 cluster (Hester et al. 1996)

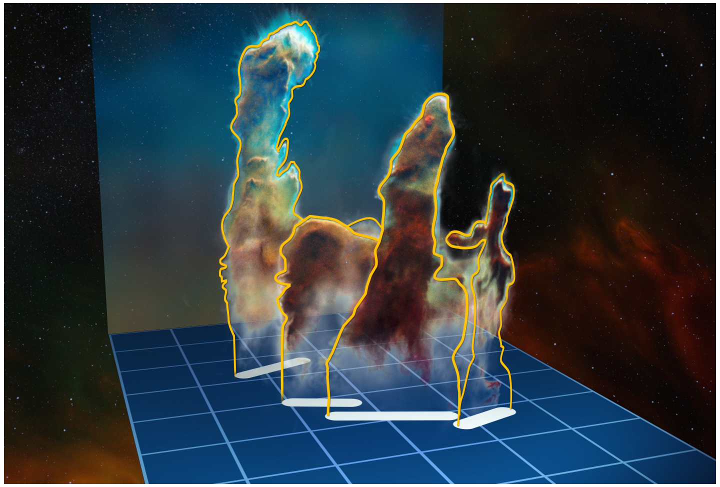
0.2arcsec pixels (1.9e-3pc; 390au)
RGB is [S II] λ6717; Hα, [O III] λ5007
The image is 3 x 3 grid from MUSE
Exposure time per pixel is 3x30seconds
Total exposure time 8100seconds
Deeper (130s) exposures used in analysis

Extinction, ionization structure and geometry of the Pillars

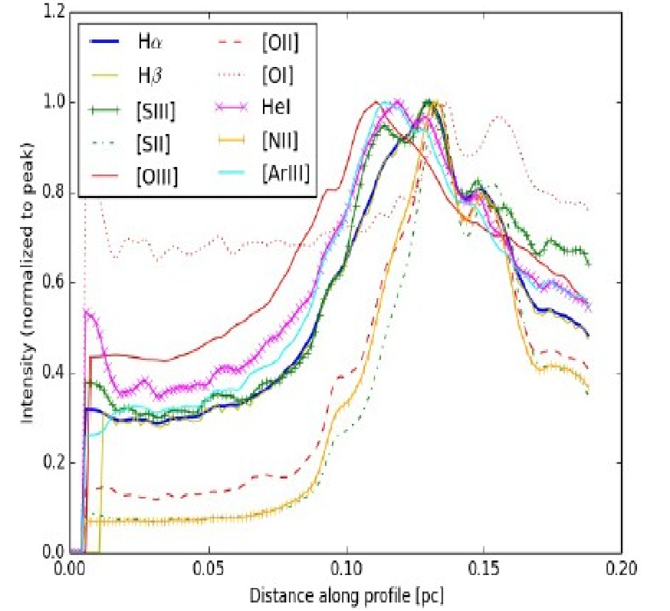




Extinction measured using Balmer decrement method with Hα, Hβ.

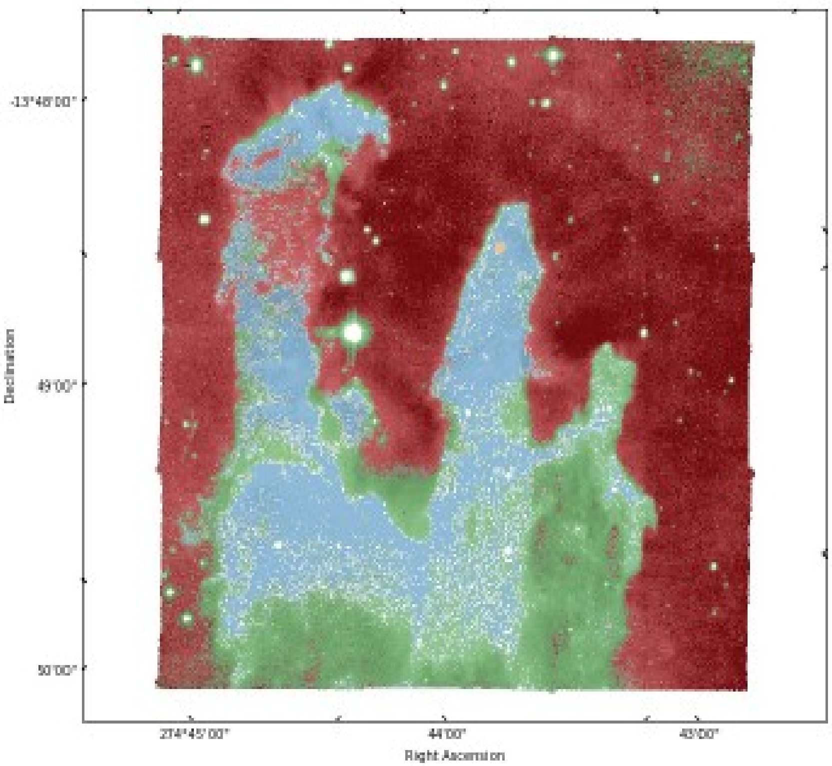


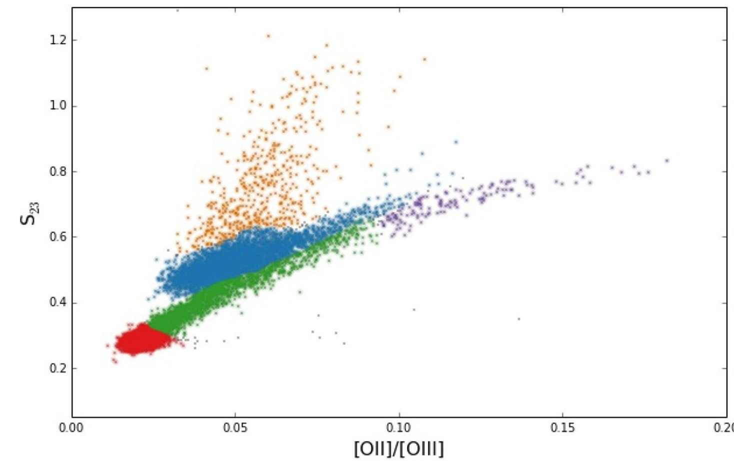
Stratified ionization structure from an increased range of lines



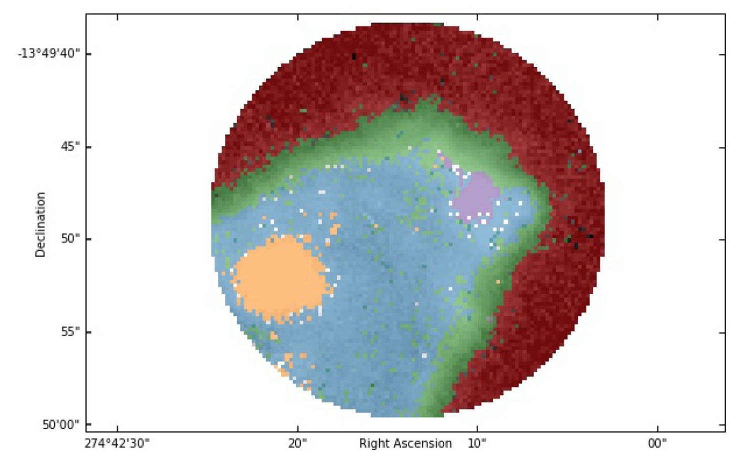
	[ArIII]	HeI	[SIII]	$H\alpha,\beta$	[NII]	[SII]	[OII]	[OI]
P1	0.296	0.739	1.775	1.923	2.218	2.218	2.218	2.514
P2	0.296	0.296	0.444	0.444	0.592	0.739	0.739	1.627
P3	0.296	0.296	0.296	0.296	0.592	0.592	0.592	0.887
E_{ion} (eV)	27.63	24.59	23.23	13.59	14.53	10.36	13.62	-

The S23 abundance parameter





(a)

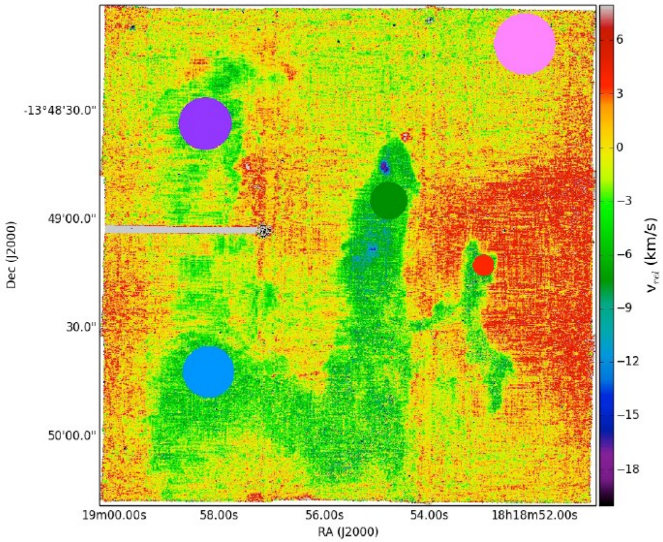


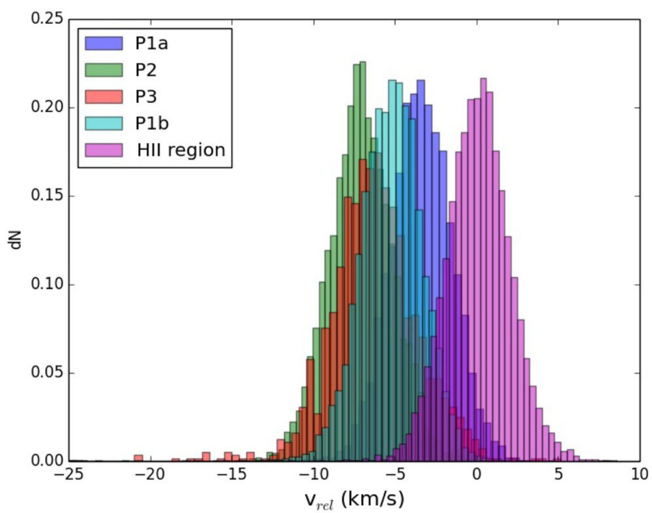
(b)

The S23 parameter (Vilchez&Esteban 1996) clearly distinguishes between the HII region, pillar material and the interface …. also outflows!

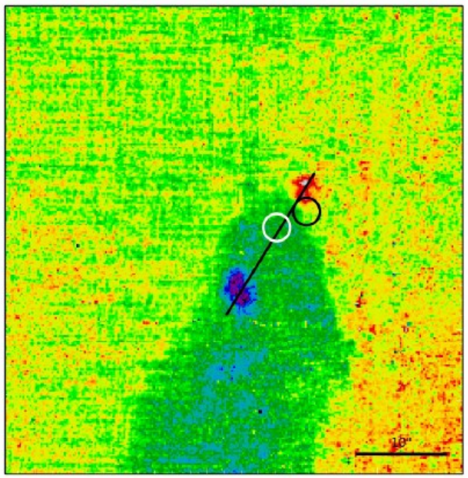
$$S_{23} = ([SII]\lambda 6717{,}31 + [SIII]\lambda 9068{,}9532)/H\beta$$

Velocity structure





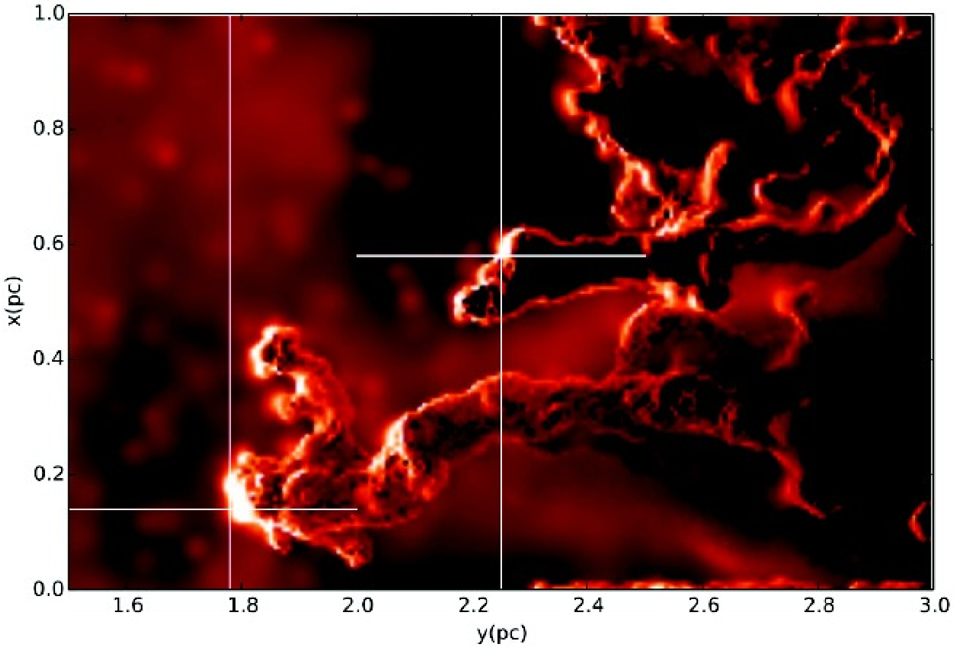
- Pillars show small blue shifted velocities relative to the HII region
- New outflow red and blue shifted lobes

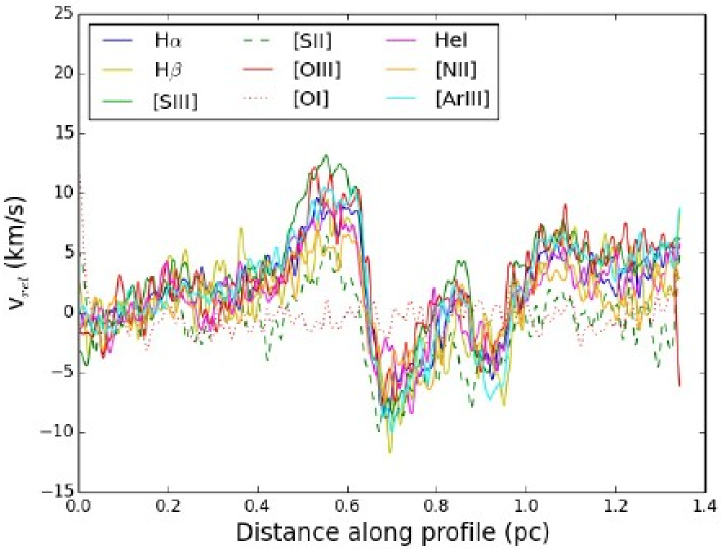


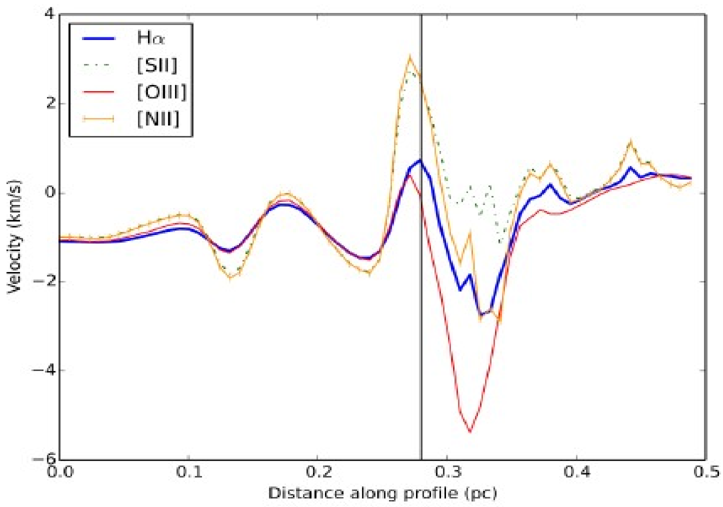
Black circle: candidate T Tauri star (Sugitani et al. 2002)
White circle: maser (Healy et al. 2004)

Velocity structure

- Velocity profile along Pillar 3 in good qualitative agreement with simulations







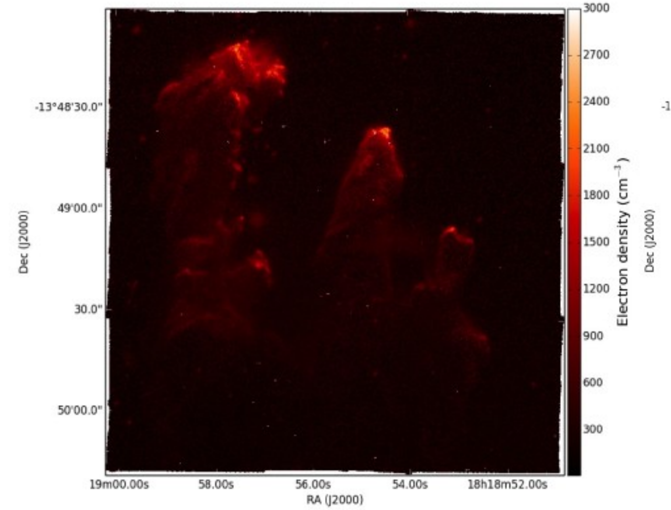
Lifetime of the Pillars

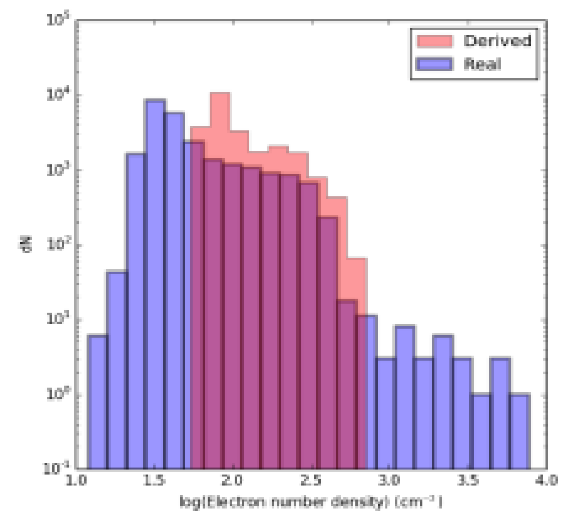
[SII] λ6731 line luminosity (130Lsolar)

Electron density (2800cm-^{3}), temperature (10^{4}K)

Velocity ~8kms^{-1}
Mass loss rate ~70Msolar yr $^{-1}$

Lifetime ~3Myr for 200Msolar total mass (White et al. 1999)



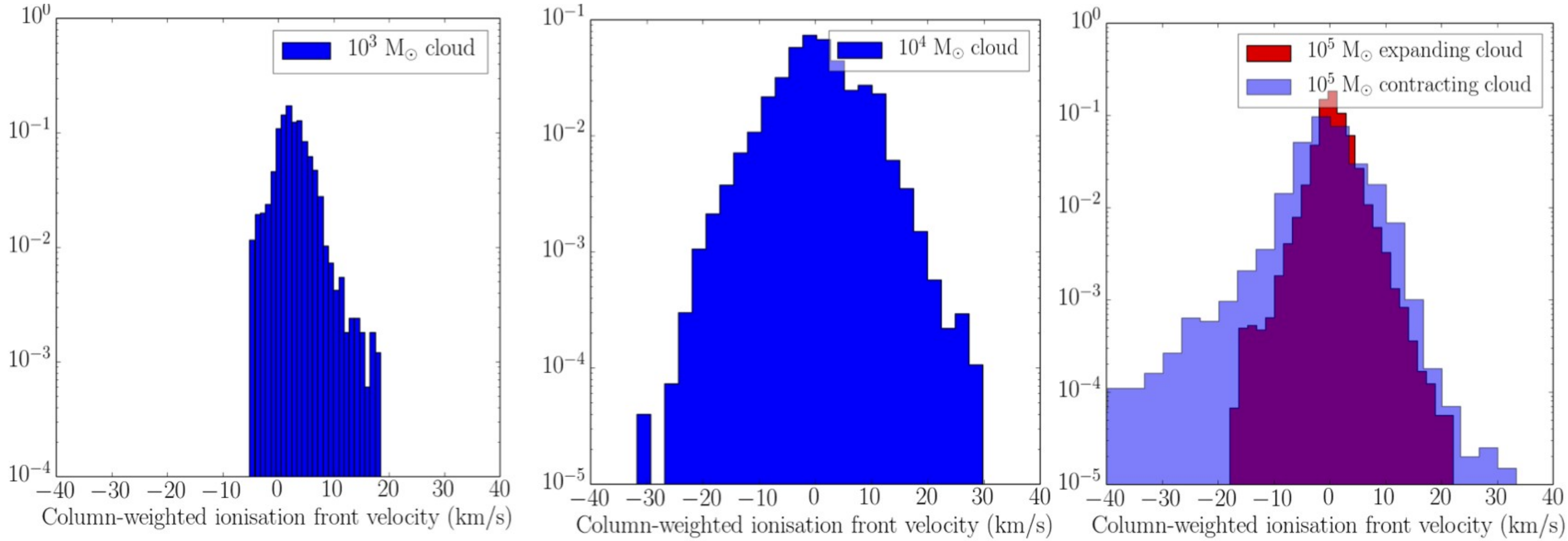


KMOS FuSIOn observations

Sources from SIMBA survey of southern high mass star forming regions (Faundez et al. 2004), Bolocam Galactic Plane Survey (Ginsburg et al. 2012)

Range of masses 0.3-15 x 10^4Msolar

Kinematics of the ionised (Brγ), molecular (H_2) gas



Conclusions

- The current generation of wide field IFU spectrographs are proving invaluable for these studies
  - High fidelity comparison of line strengths, velocities
  - Continuum subtraction compared with narrow band imaging
  - Unbiased spatial coverage compared with long slit spectroscopy
- Substantial progress on the model/observation connection expected in the next few years

And in the E-ELT era?

E-ELT plus HARMONI and MICADO will allow us to extend this work to extragalactic sources

HARMONI

Sensitivity to narrow line emission (R>>4000)

Velocity resolution ~>50km/s

Comparable numbers of spaxels to MUSE, KMOS

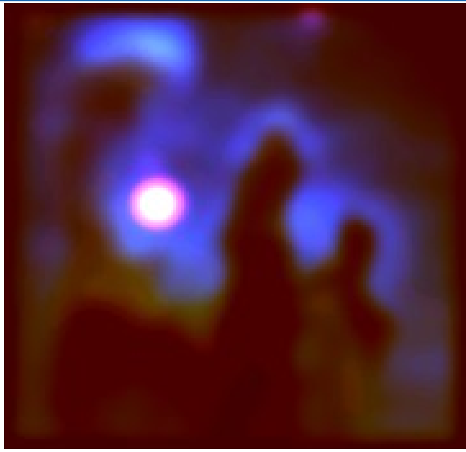
Access to all the diagnostic lines described

MICADO

Huge advance in sensitivity for detection of protostar clusters

High angular resolution >> detailed shock physics via proper motion studies

Feedback in external galaxies



Optical observations

- Exploit x20 sensitivity boost
- Global properties e.g. S23 diagnostics

Adaptive optics assisted NIR observations at the distance of the LMC (50kpc) will be comparable to local HMYSOs (5kpc)

- 1pc scale structures well matched to the widest FOV
- Sensitivity to extended features comparable to KMOS
- Extended studies to “unremarkable” YSOs