Outflows and Jets: Theory and Observations

Summer term 2011
Henrik Beuther & Christian Fendt

15.04 Today: Introduction & Overview (H.B. & C.F.)
29.04 Definitions, parameters, basic observations (H.B.)
06.05 Basic theoretical concepts & models (C.F.)
13.05 Basic MHD and plasma physics; applications (C.F.)
20.05 Radiation processes (H.B.)
27.05 Observational properties of accretion disks (H.B.)
03.06 Accretion disk theory and jet launching (C.F.)
10.06 Outflow interactions: Entrainment, instabilities, shocks (C.F.)
17.06 Outflow-disk connection, outflow entrainment (H.B.)
24.06 Outflow-ISM interaction, outflow chemistry (H.B.)
01.07 Outflows from massive star-forming regions (H.B.)
08.07 Observations of extragalactic jets (C.F.)
15.07 Theory of relativistic jets (C.F.)

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss11.html
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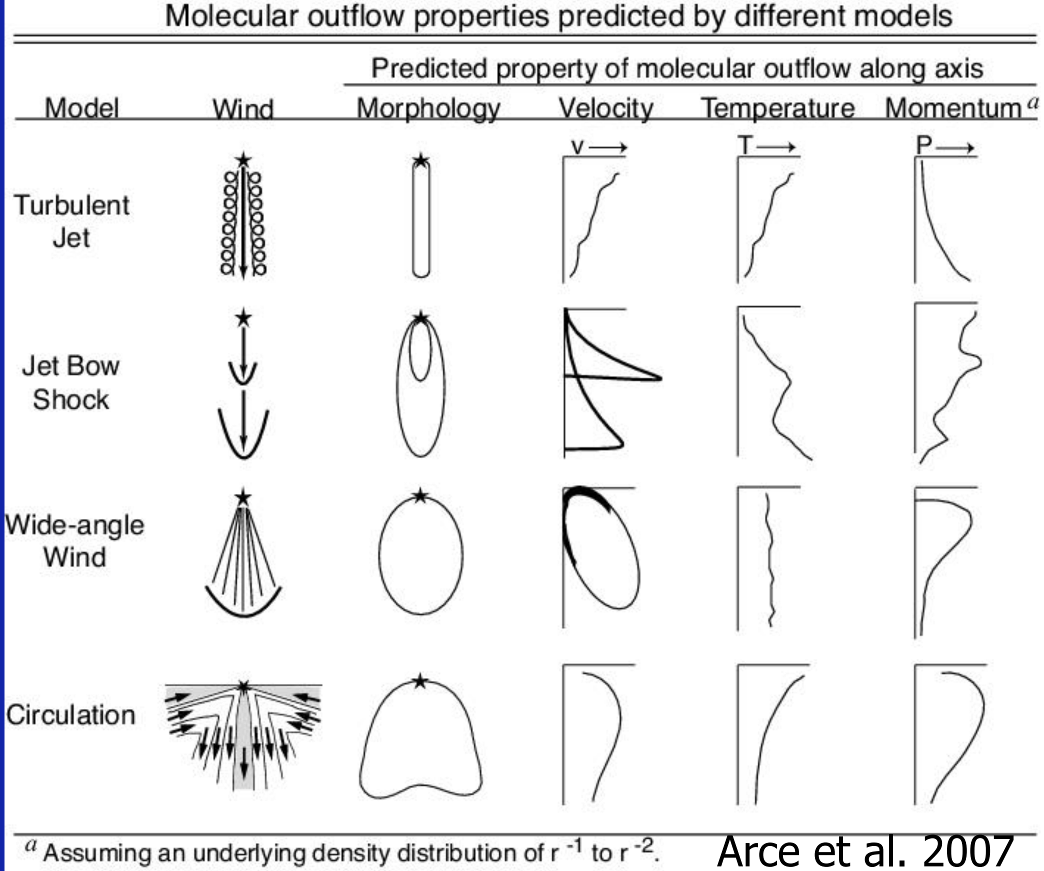
Last week

- Protostellar jets are launched magnetohydrodynamically from the disk and then accelerated magneto-centrifugally.
- Outside the Alfven radius r_A (kin. energy equals magn. energy) B_ϕ dominates and collimation happens via Lorentz-force.
- Jet-launching discussed as disk-wind or X-wind. Observations support disk-wind scenario (although X-wind can be considered as special case of disk-wind at the inner disk-truncation radius).
- Various outflow-entrainment models: jet-entrainment and wide-angle wind are likely the two most reasonable mechanisms.
- Outflows/jets are likely episodic.
- Observational tools like pv-diagrams, mv-diagrams and various different jet/outflow tracers allow to constrain the models.


Molecular outflow properties predicted by different models

Model	Wind	Morphology	Velocity	Temperature	Momentum[a]
		Predicted property of molecular outflow along axis			
Turbulent Jet					
Jet Bow Shock					
Wide-angle Wind					
Circulation					

[a] Assuming an underlying density distribution of r^{-1} to r^{-2}.

Arce et al. 2007

Impact on surrounding cloud

- Partly responsible to maintain turbulence on cluster-scale.

- Entrain large amounts of cloud mass with high energies.

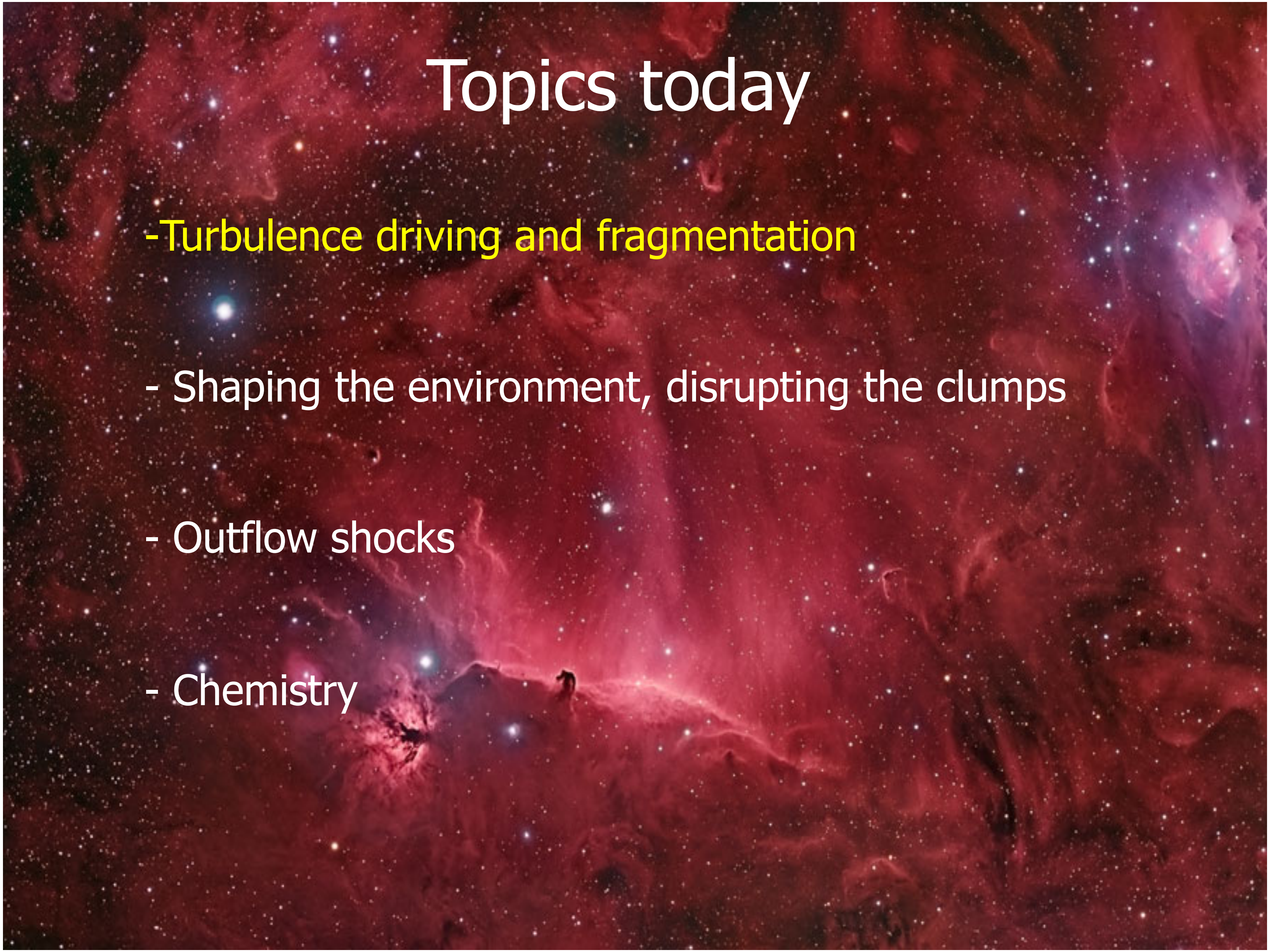
- Can finally disrupt the cores to stop any further accretion.

- Can erode the clouds and alter their velocity structure.

- Via shock interactions heat the cloud.

- Alter the chemical properties.

- May trigger collapse in neighboring cores.



Topics today

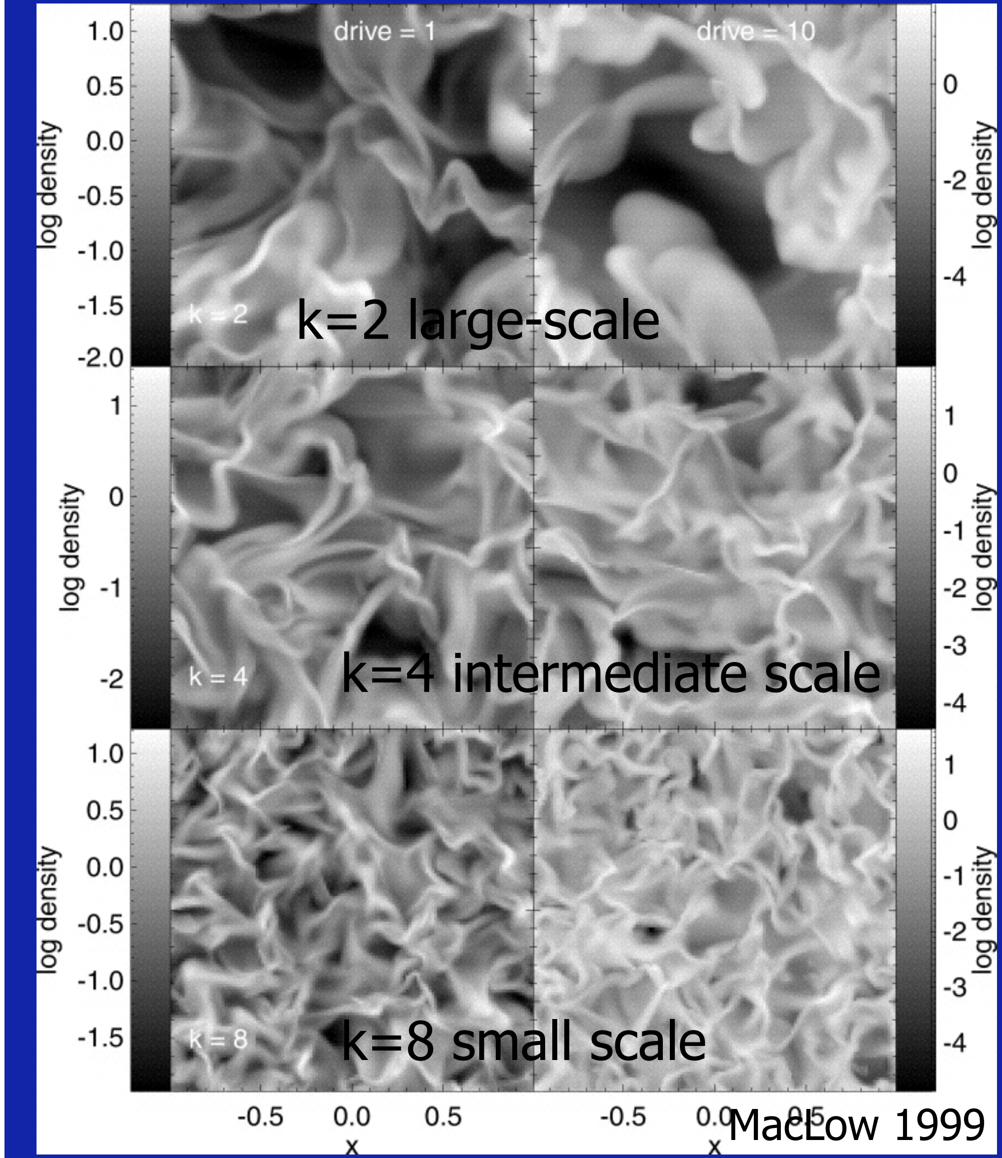
- -Turbulence driving and fragmentation

- - Shaping the environment, disrupting the clumps

- - Outflow shocks

- - Chemistry

Interstellar Turbulence



MacLow 1999

- Supersonic → creates network of shocks
- Shock interactions create density fluctuations $\delta\rho \propto M^2$ which can be relatively quiescent.
- In these higher-density regions, H and H_2 may form rapidly
- $t_{form} = 1.5 \times 10^9 yr / (n/1 cm^{-3})$ (Hollenbach et al. 1971)

→ either molecular clouds form slowly in low-density gas or rapidly in $\sim 10^5$yr in $n = 10^4 cm^{-3}$

- Decays on time-scales of order the free-fall time-scale

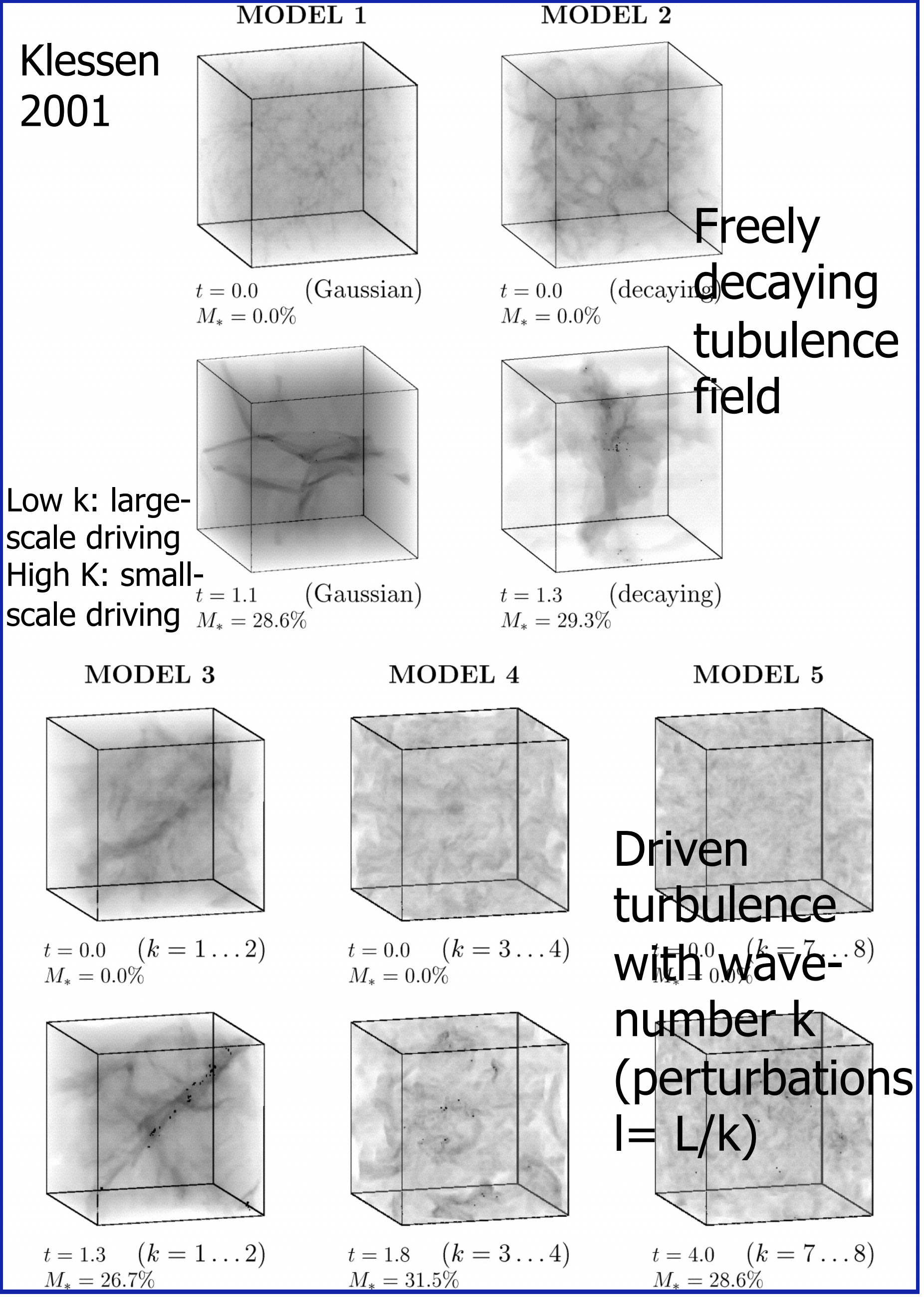
→ needs to be replenished and continuously driven

Candidates: Protostellar outflows, radiation from massive stars, supernovae explosions …

(Gravo)-turbulent fragmentation I

- Turbulence produces complex network of filaments and interacting shocks.
- Converging shock fronts generate clumps of high density.
- Collapse when the local Jeans-length [$\lambda_J = (\pi a_t^2/G\rho_0)$] gets smaller than the size of fluctuation.
- Have to collapse on short time-scale before next shock hits the region.

→ Efficiency of star formation depends strongly on the wave-number and strength of the turbulence driving.
  → Large-scale less strongly driven turbulence results in clustered mode of star formation.
  → Small-scale strong driving results in more low-mass protostars and more isolated star formation.



Klessen 2001

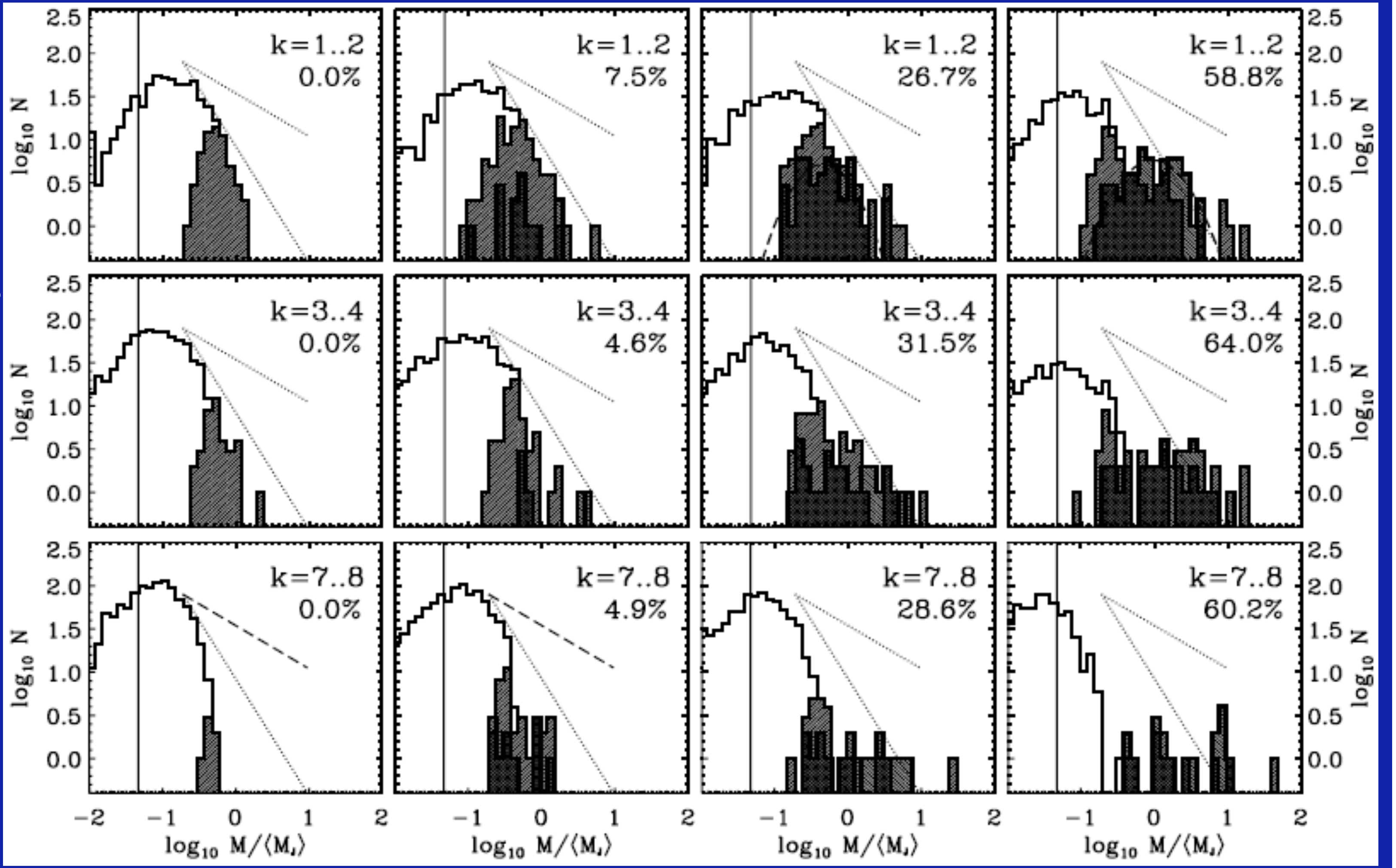
Freely decaying tubulence field

Low k: large-scale driving
High K: small-scale driving

Driven turbulence with wave-number k (perturbations l= L/k)

(Gravo)-turbulent fragmentation II

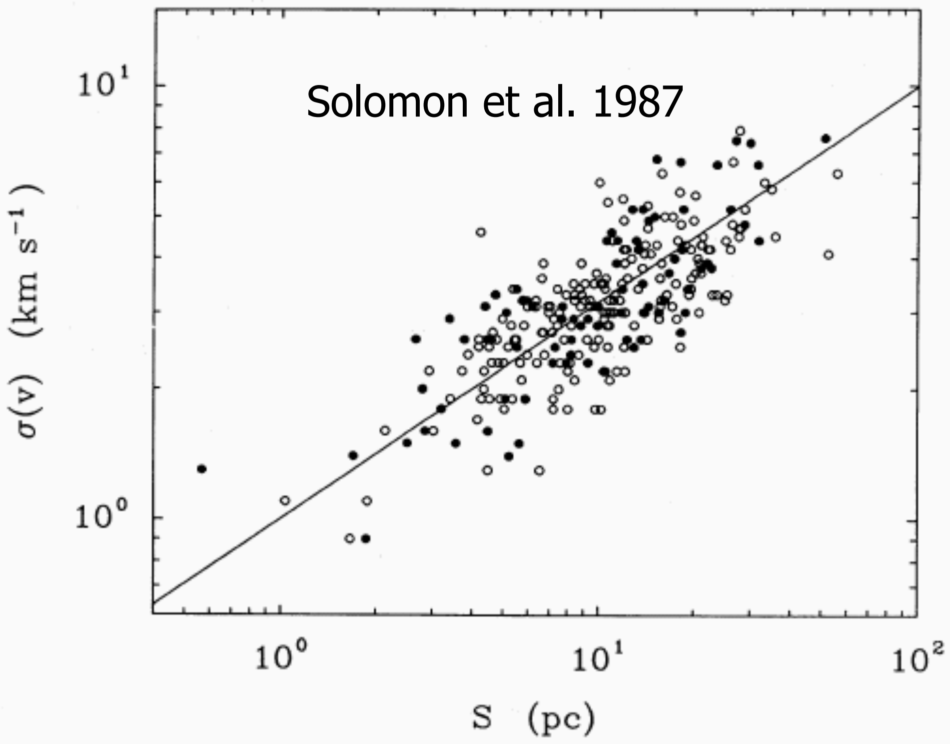
Histogram:
Gas clumps
Grey:
Jeans unstable clumps
Dark:
Collapsed core



- 2 steps: 1.) Turbulent fragmentation --> 2.) Collapse of individual core
- Large-scale driving reproduces shape of IMF.
- However, under discussion whether largest fragments really remain stable or whether they fragment further ...

Klessen et al.

Line-width size relation



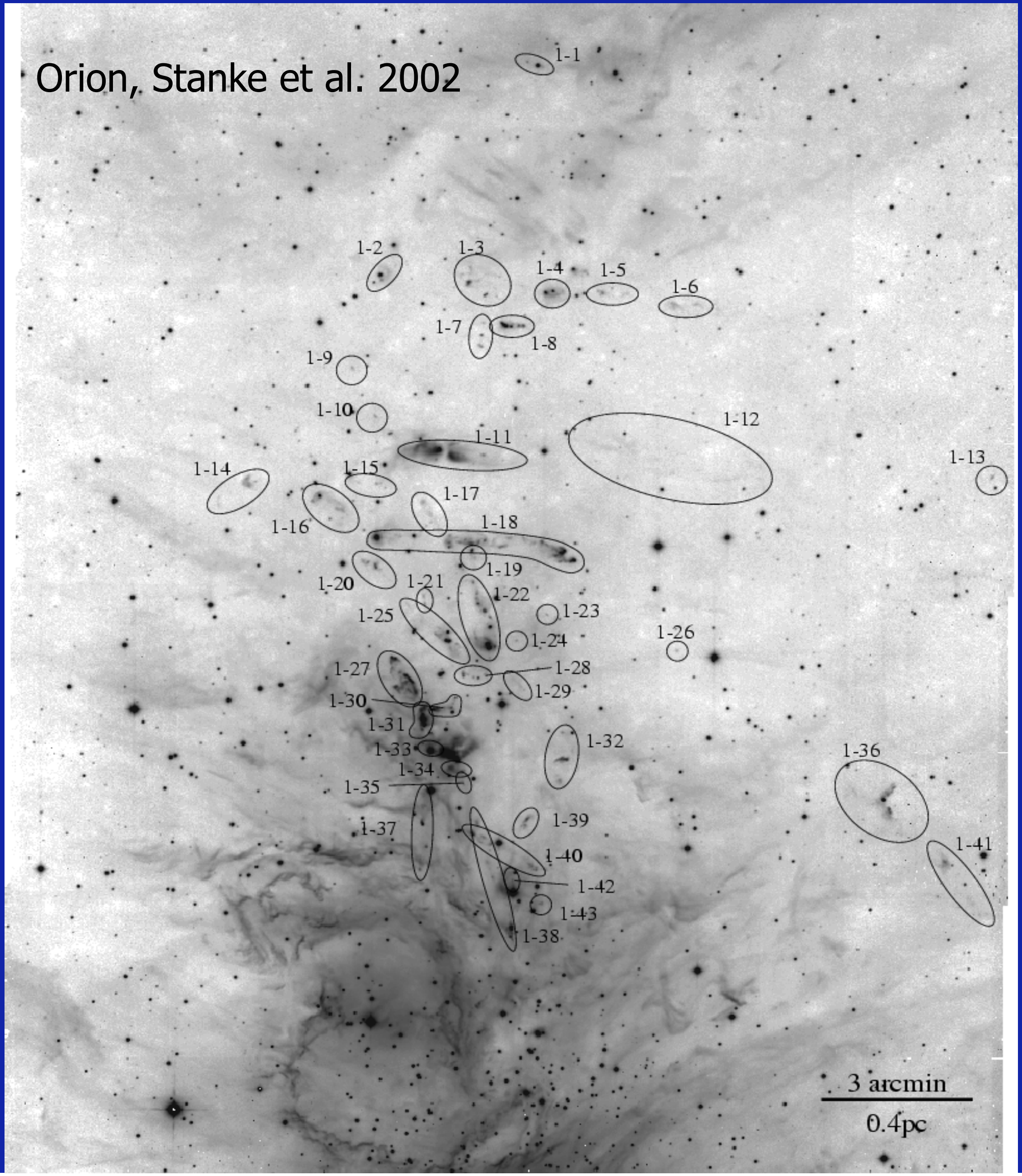
- Turbulence observed on molecular cloud scales is likely driven on large scales (>GMCs) and dissipated on small scales (0.05pc).

- Since the molecular clouds show increasing energy content going to larger scales, driving this large-scale turbulence by outflows appears unlikely.

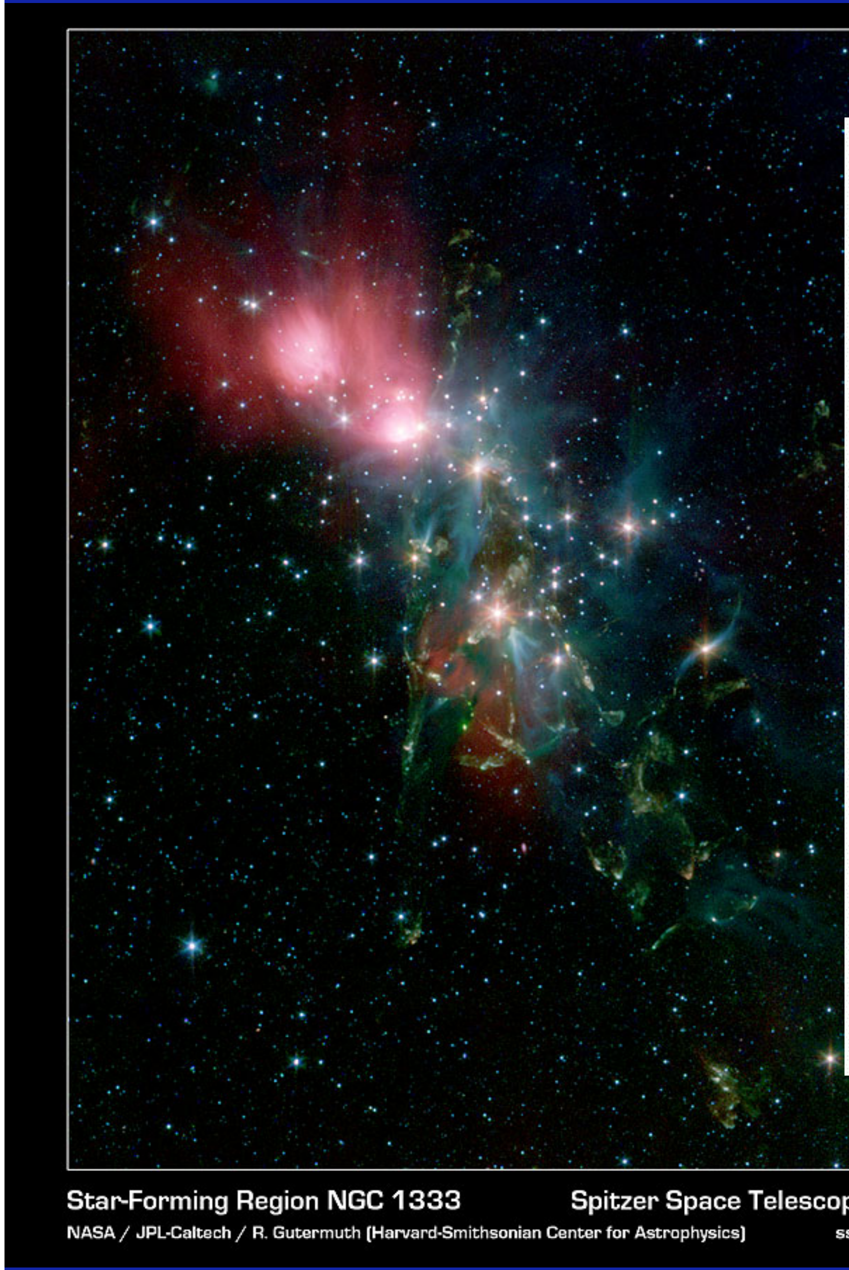
- Supernovae are good candidates for large-scale driving.

- However, there may be differences on smaller scales of cluster-forming regions.

Outflow multiplicities in clustered star-forming regions

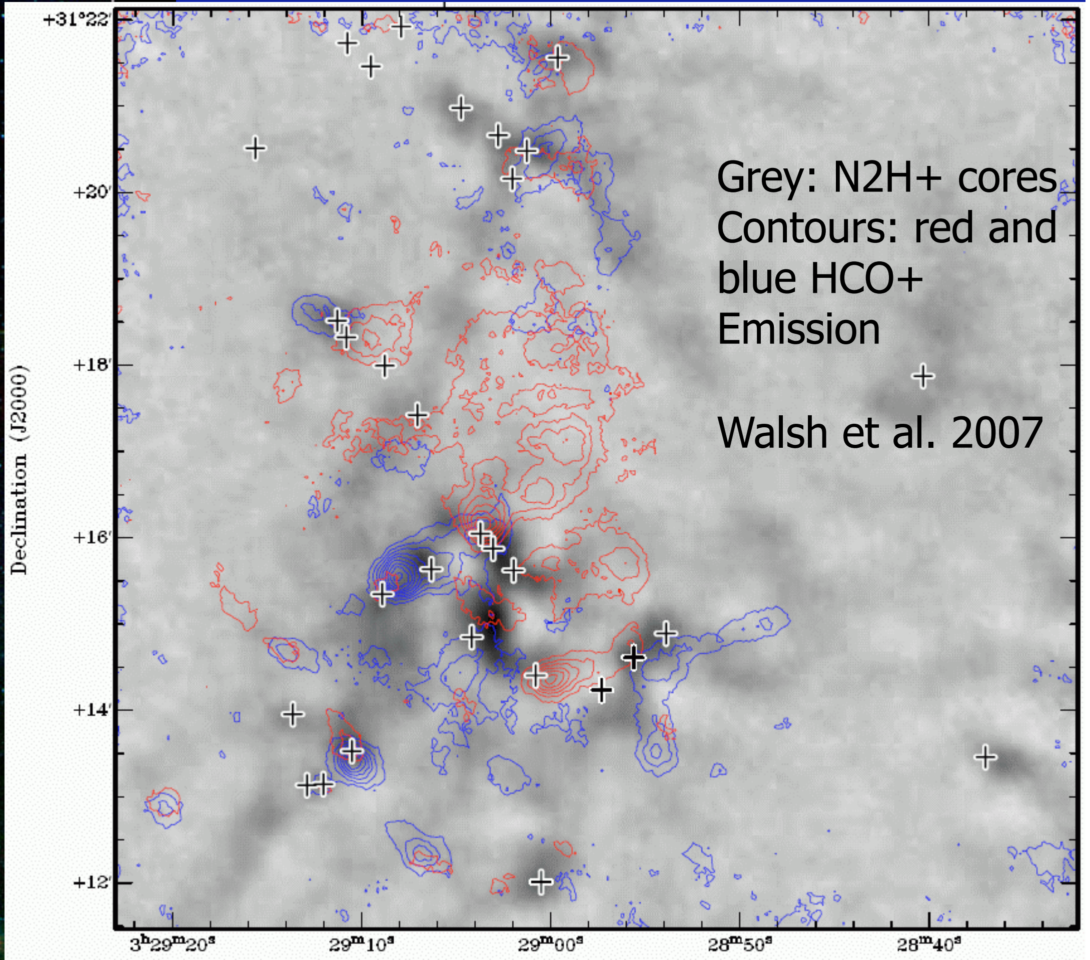

Orion, Stanke et al. 2002

The case of NGC1333: I



Star-Forming Region NGC 1333 Spitzer Space Telescope • IRAC

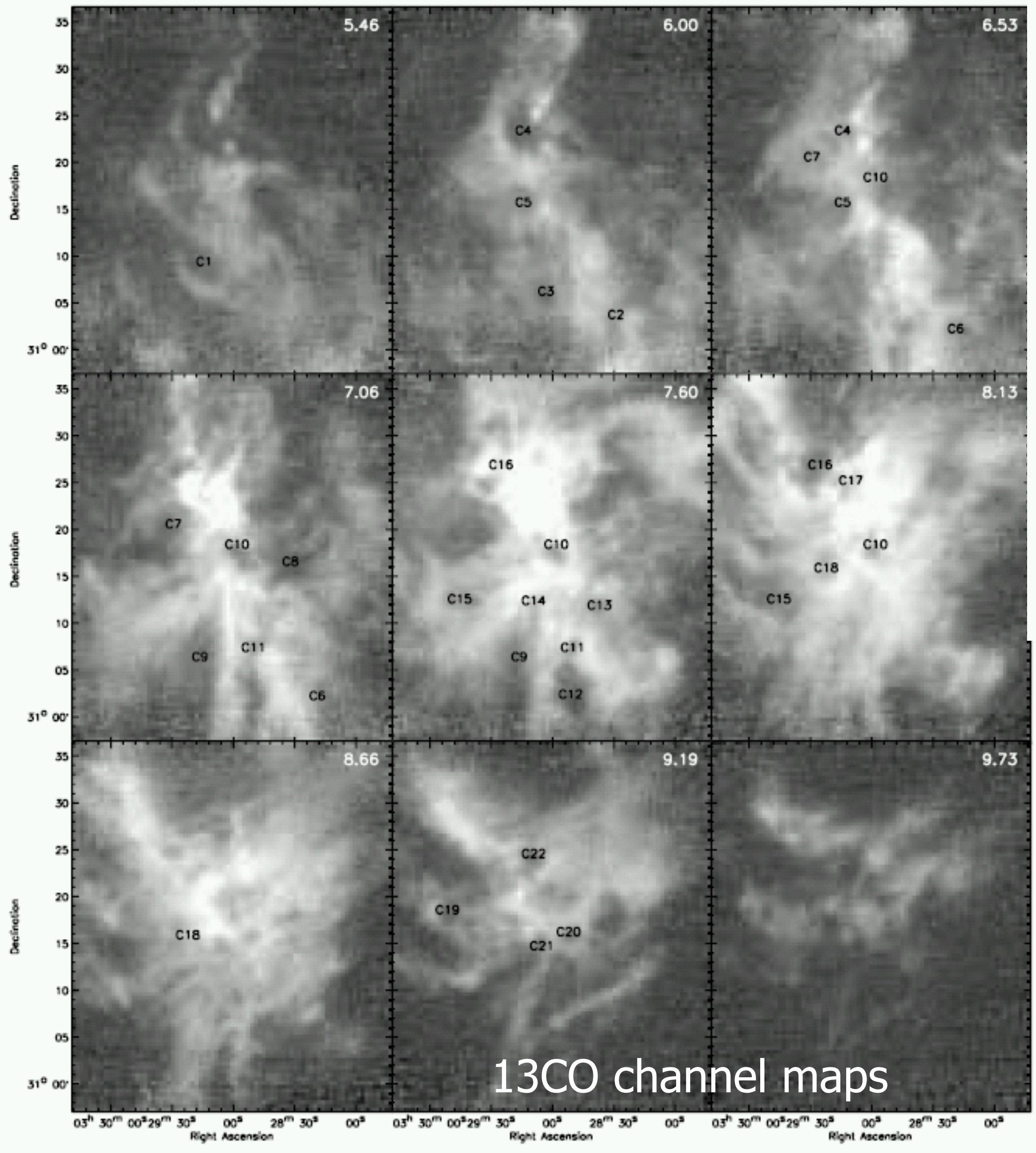
NASA / JPL-Caltech / R. Gutermuth (Harvard-Smithsonian Center for Astrophysics) ssc2005-24a



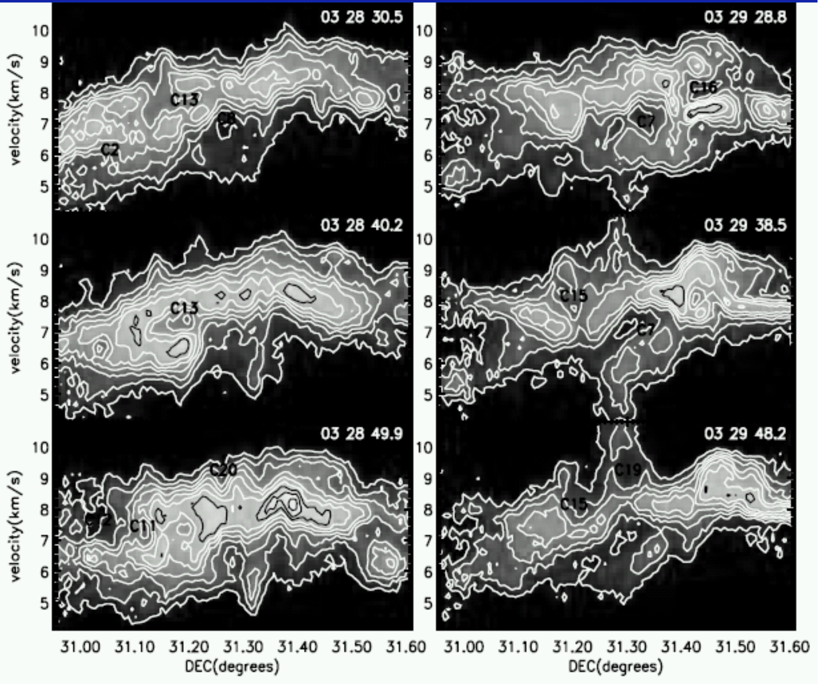
Grey: N2H+ cores
Contours: red and blue HCO+ Emission

Walsh et al. 2007

The case of NGC1333: II



13CO channel maps



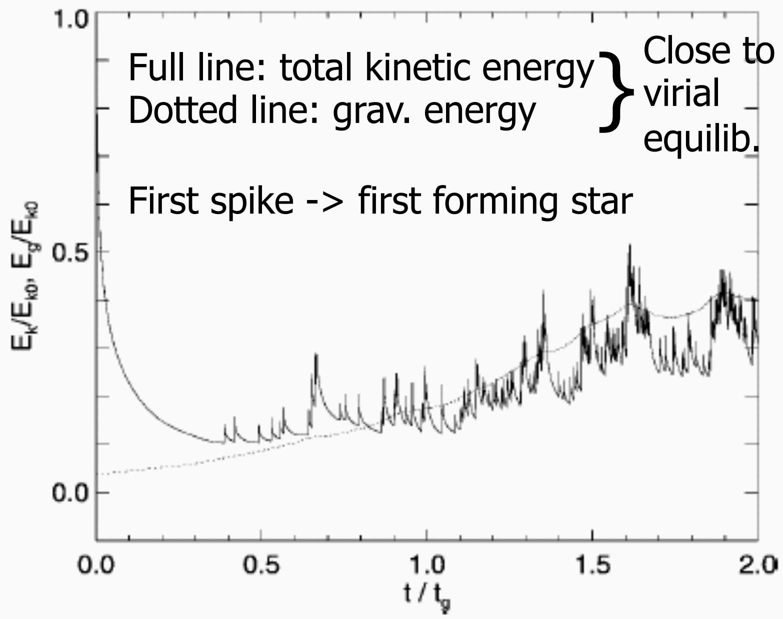
- Channel and pv-maps show 13CO cavities with size 0.1-0.2pc and width 1-3 km/s
  → remnants of past YSO activity

- Momentum and energy of expanding cavities sufficient to power turbulence.

Quillen et al. 2005

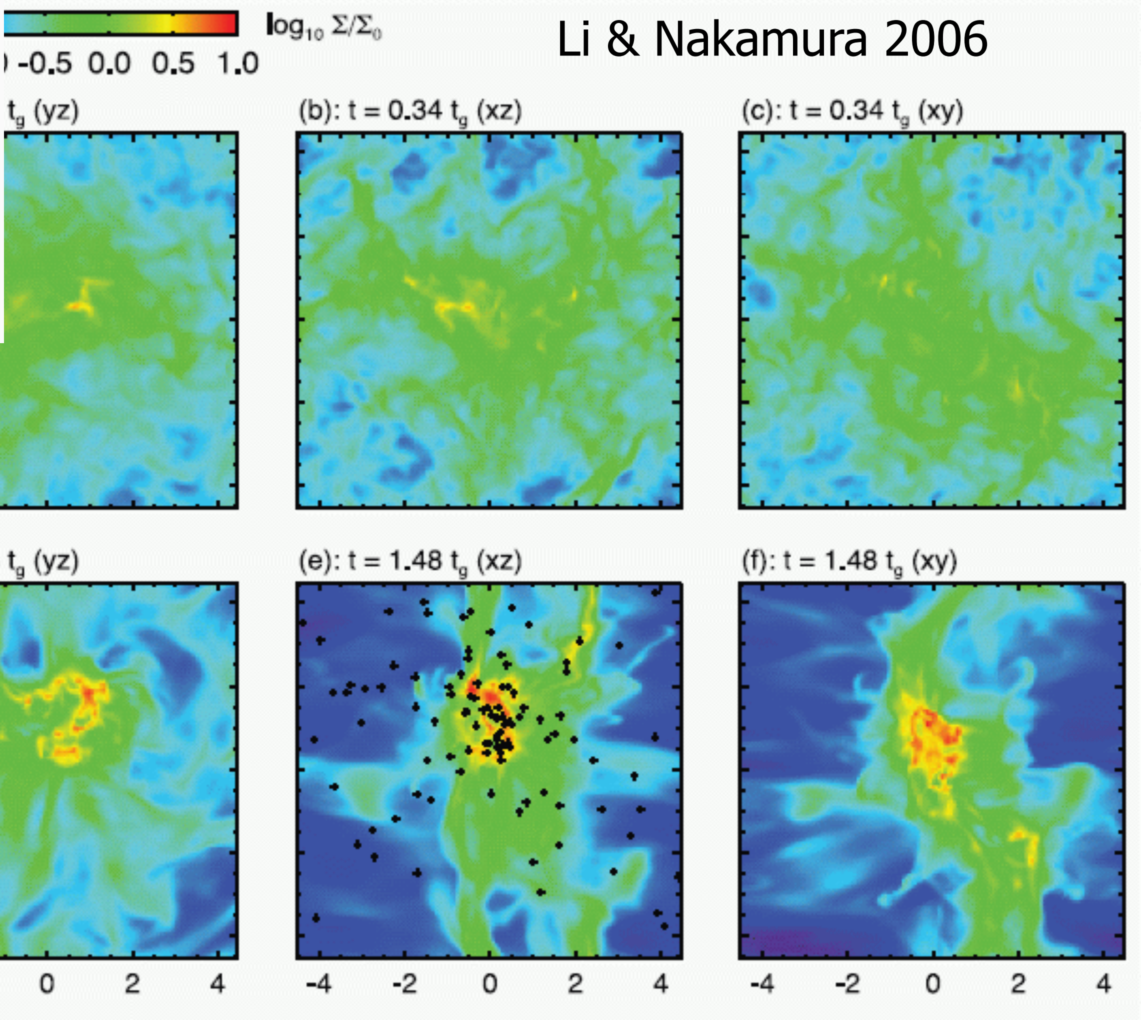
“Protostellar” turbulence

3D MHD simulations



Full line: total kinetic energy
Dotted line: grav. energy } Close to virial equilib.

First spike -> first forming star



Li & Nakamura 2006

The “protostellar” turbulence produces different structures than the original “interstellar” turbulence.

In this model, initial “interstellar” turbulence is relatively quickly replaced by “protostellar” turbulence.

Topics today

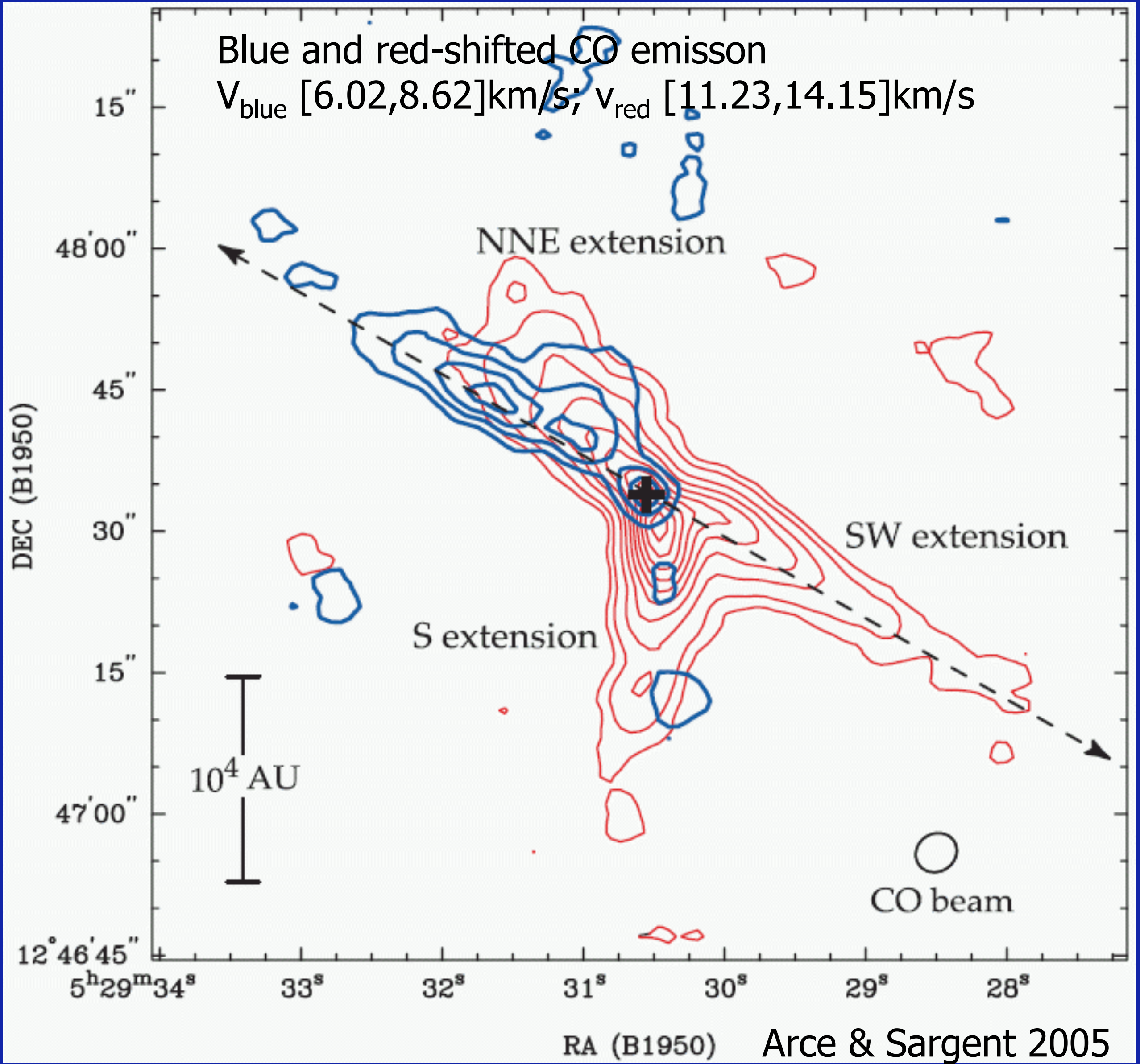
-Turbulence driving and fragmentation

- Shaping the environment, disrupting the clumps

- Outflow shocks

- Chemistry

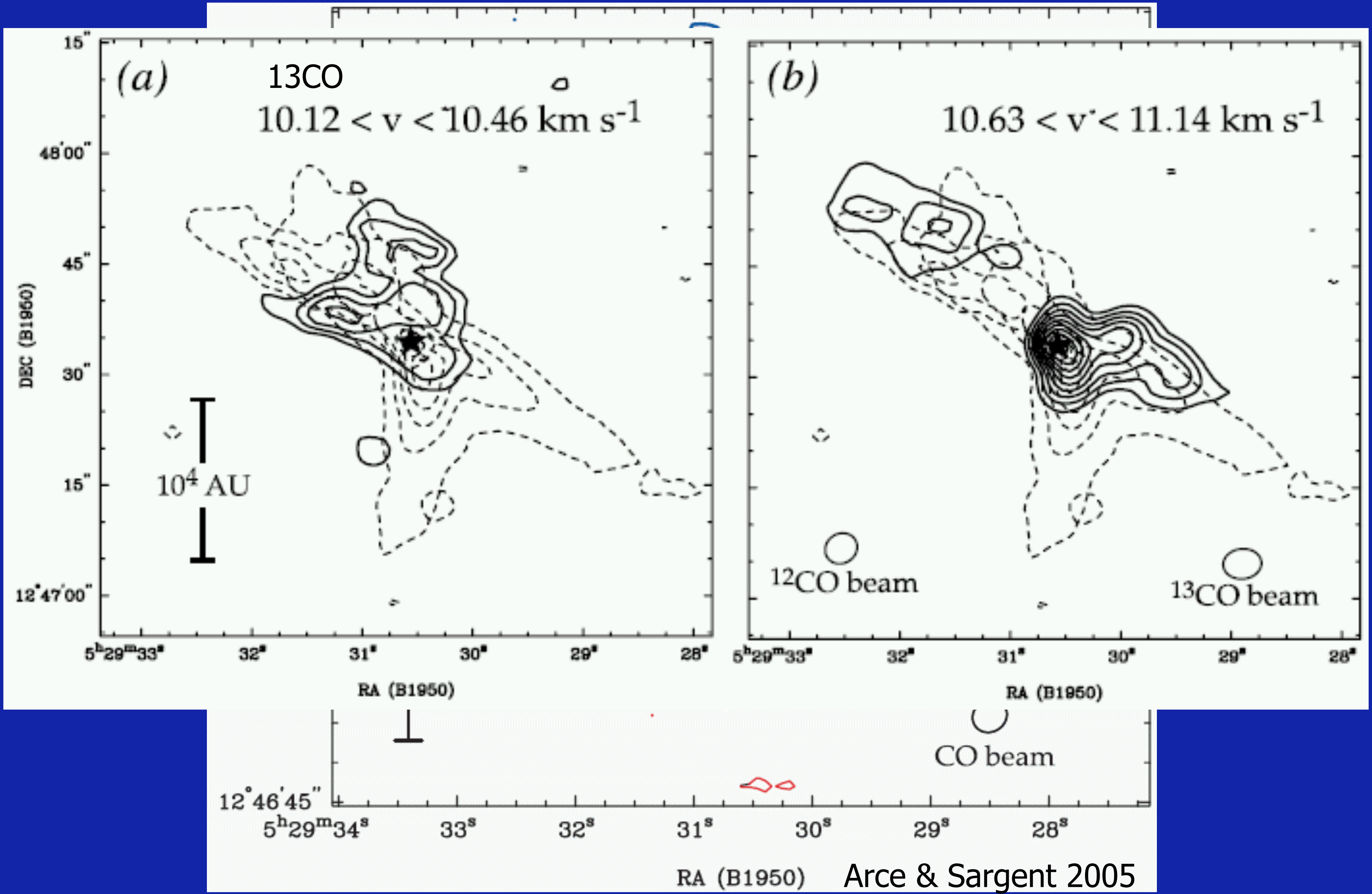
Outflows shaping the core: the class 0 case RNO43


Blue and red-shifted CO emisson

V$_{blue}$ [6.02,8.62]km/s; v$_{red}$ [11.23,14.15]km/s

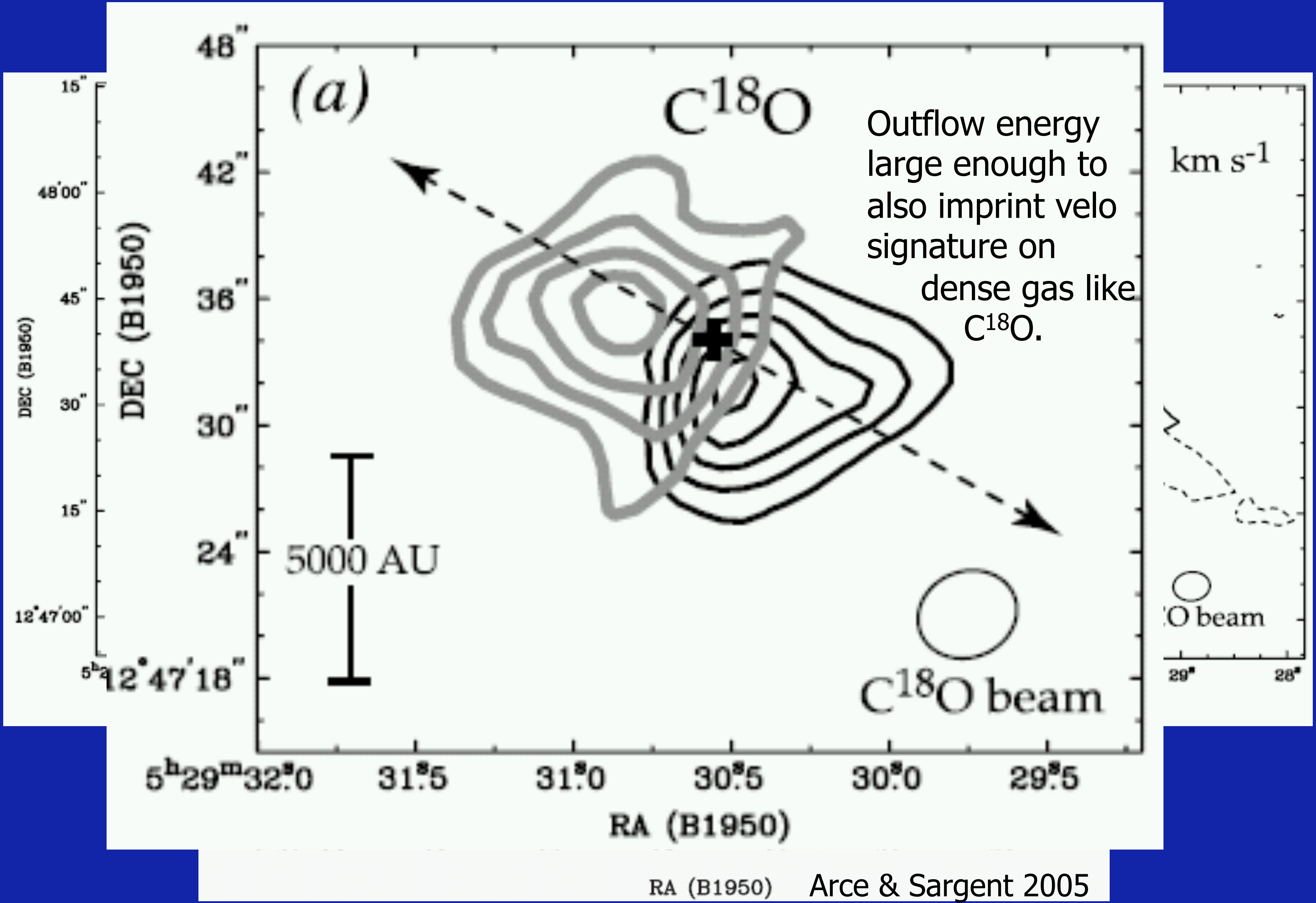
Arce & Sargent 2005

Outflows shaping the core: the class 0 case RNO43



Arce & Sargent 2005

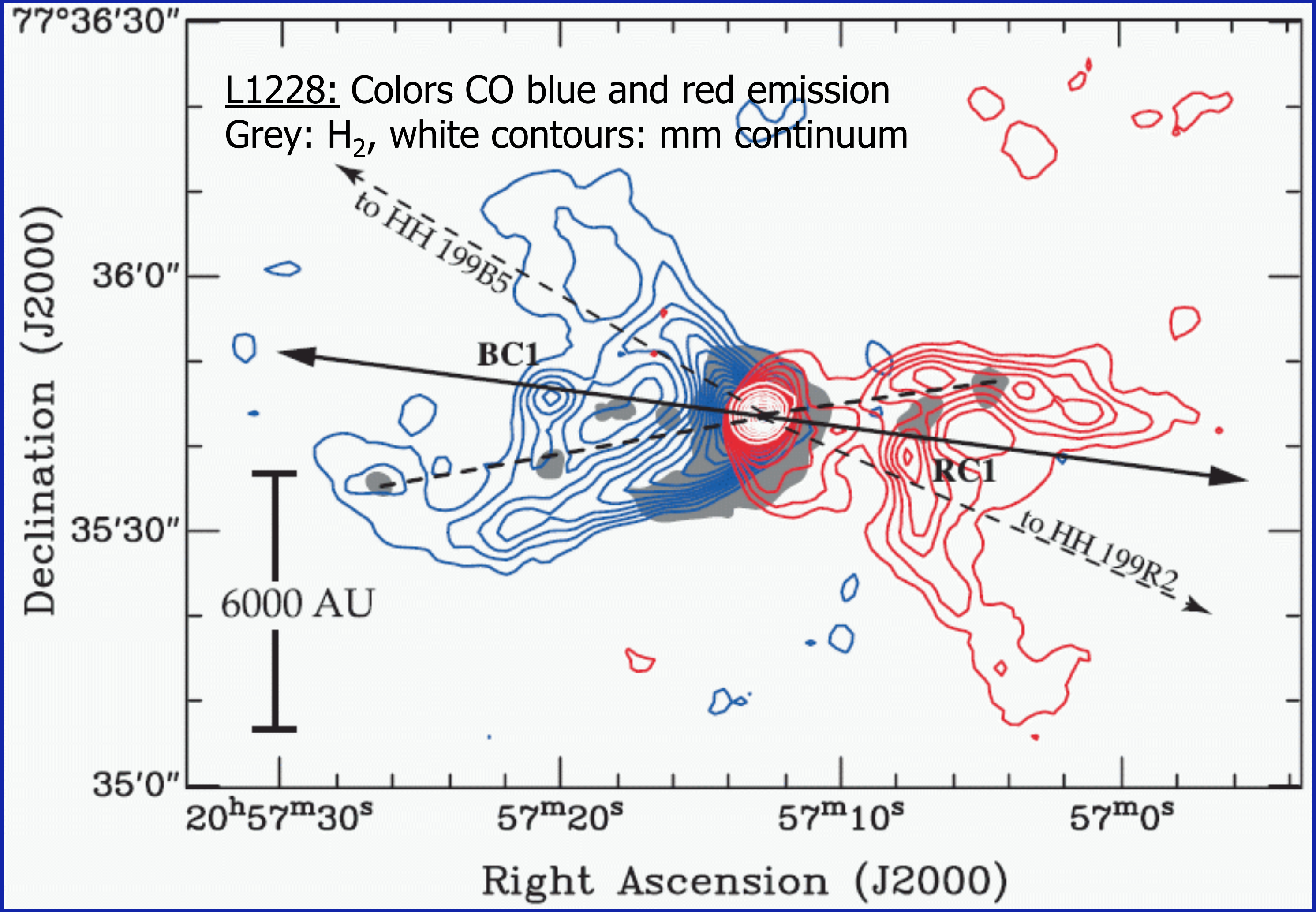
Outflows shaping the core: the class 0 case RNO43



Outflow energy large enough to also imprint velo signature on dense gas like $C^{18}O$.

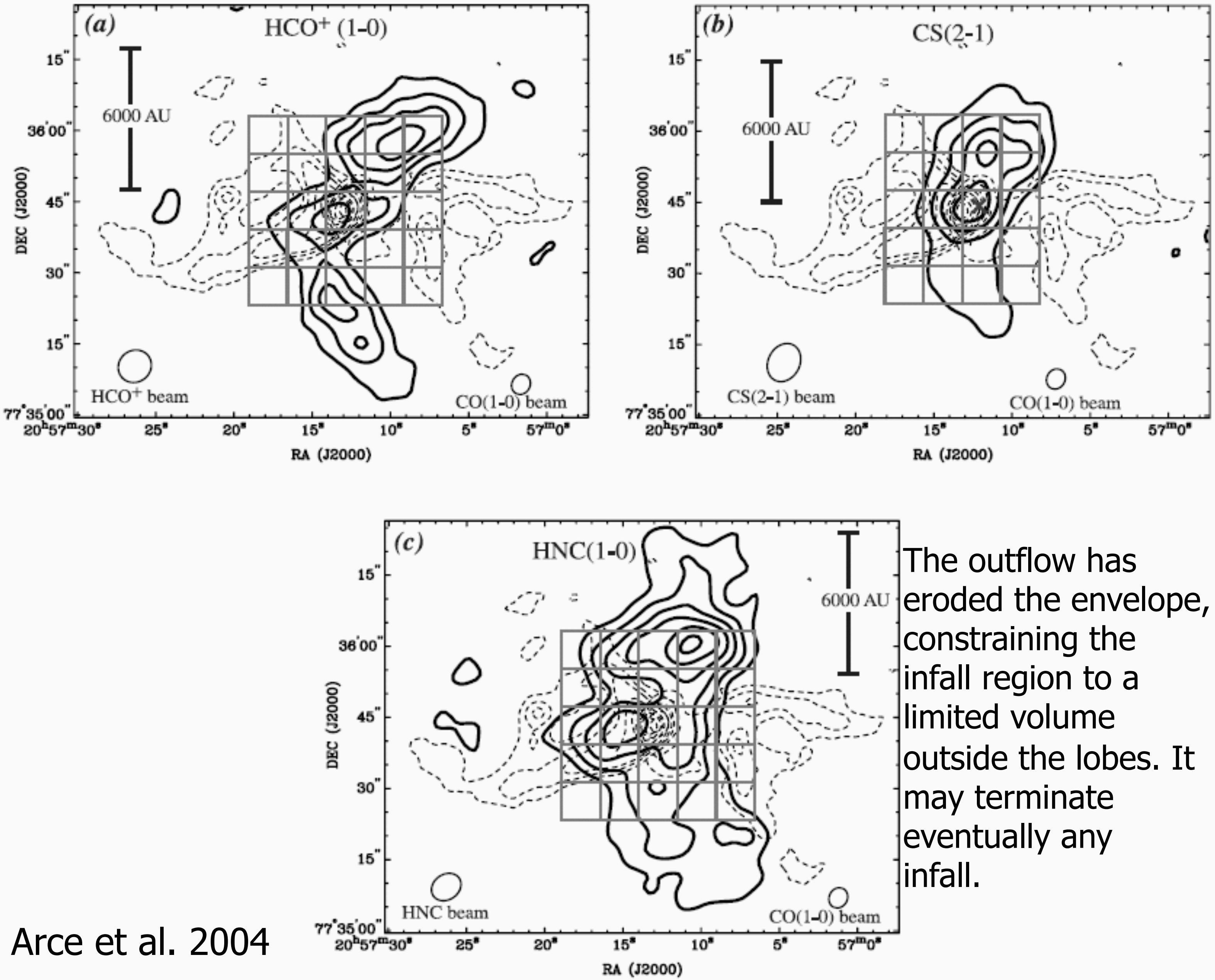
Arce & Sargent 2005

Outflows shaping the core: the class I case L1228



L1228: Colors CO blue and red emission
Grey: H_2, white contours: mm continuum

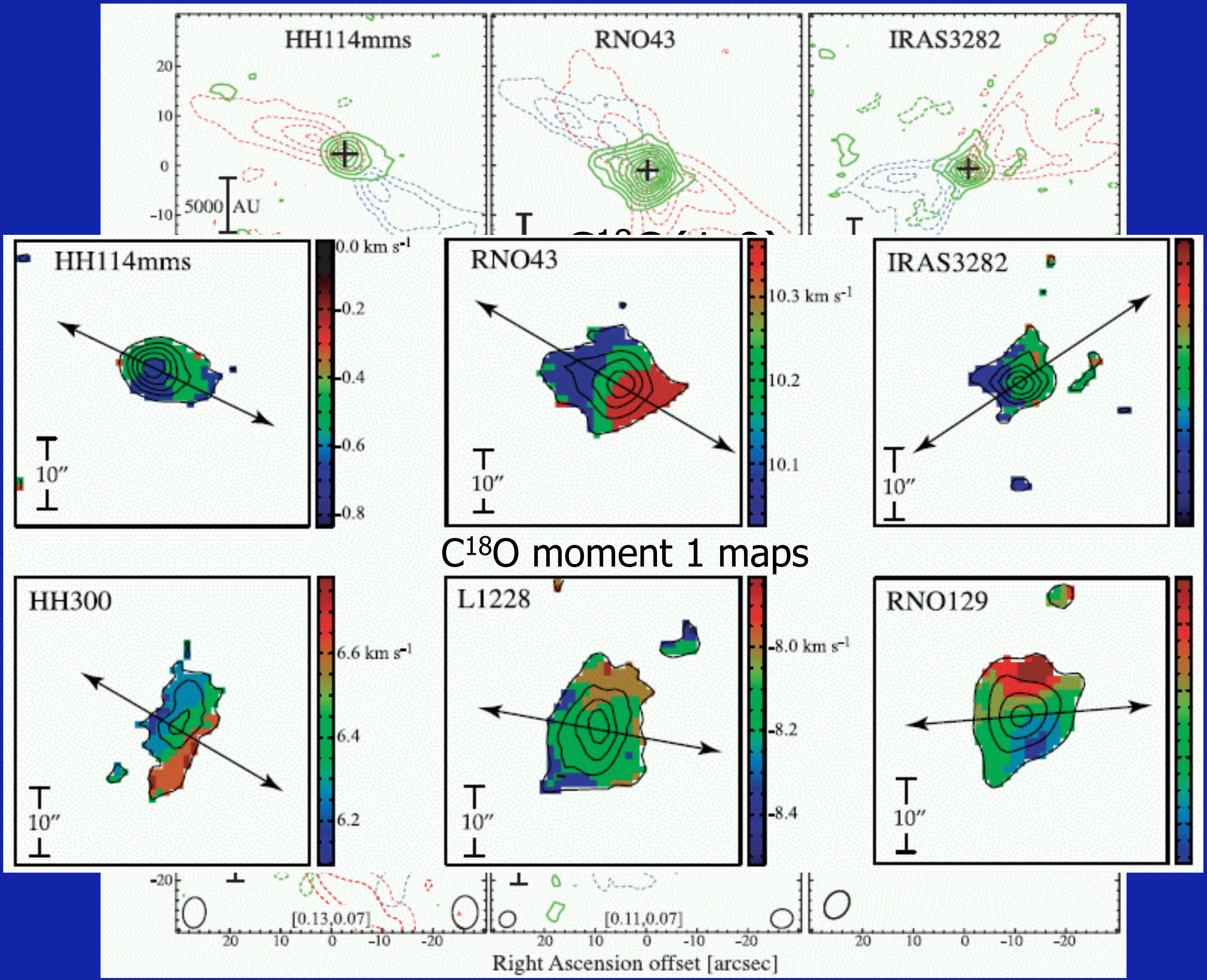
Outflows shaping the core: the class I case L1228



The outflow has eroded the envelope, constraining the infall region to a limited volume outside the lobes. It may terminate eventually any infall.

Arce et al. 2004

Evolutionary effects of outflow-envelope interaction I



C^{18}O moment 1 maps

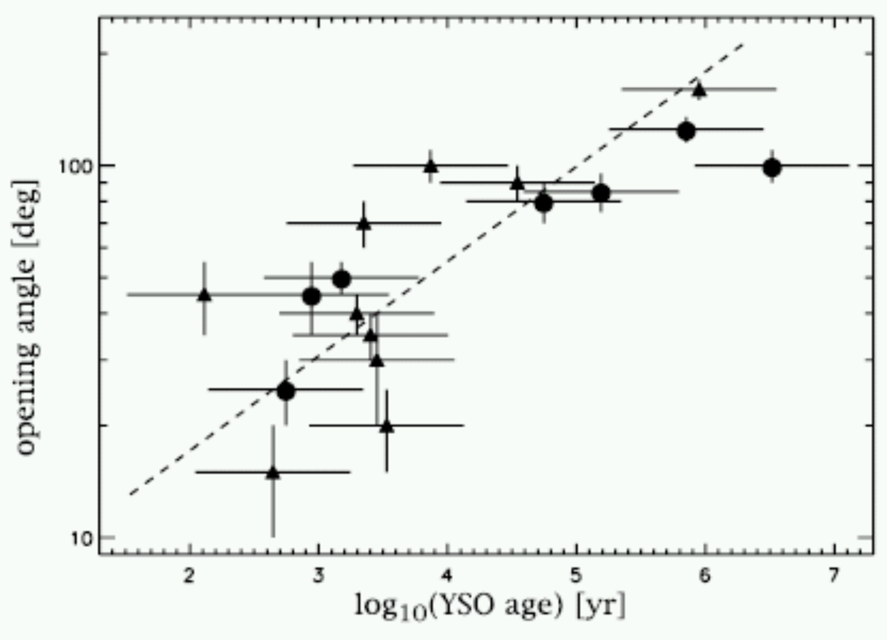
Class 0

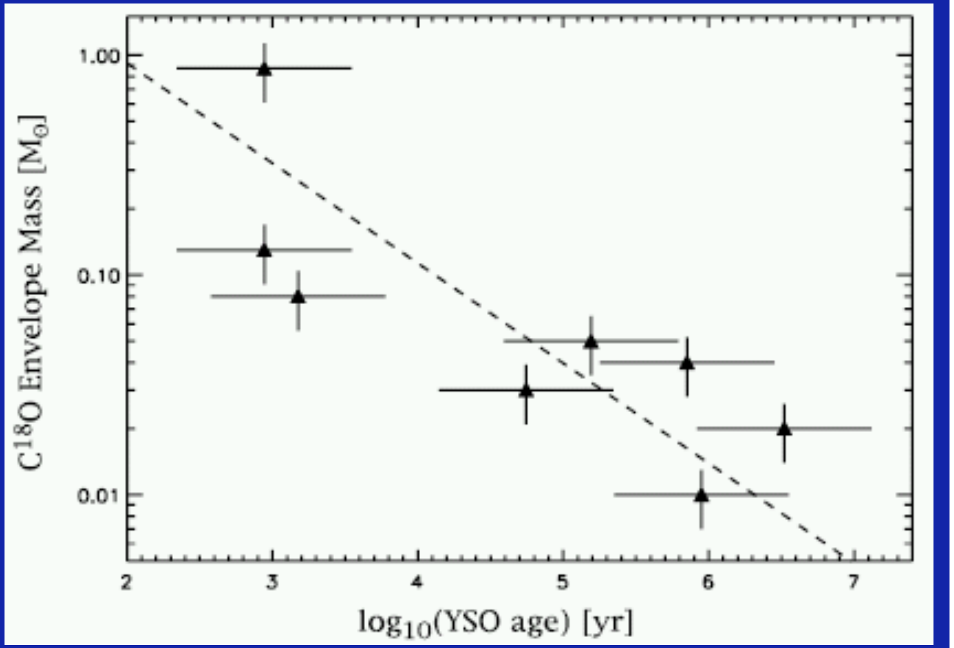
Class I

Class II

Arce & Sargent 2006

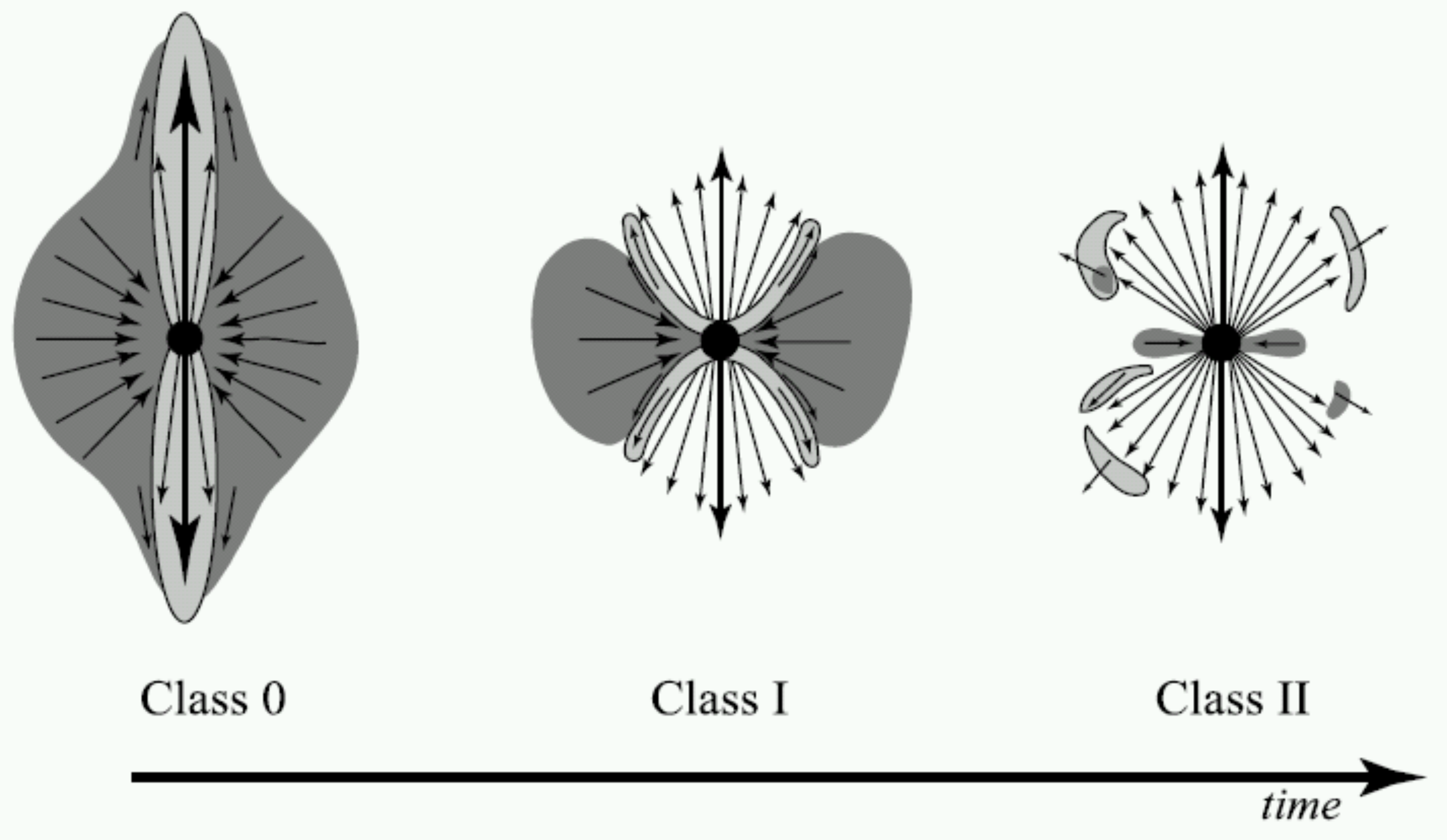
Evolutionary effects of outflow-envelope interaction II





Arce & Sargent 2006

Evolutionary effects of outflow-envelope interaction II



Arce & Sargent 2006

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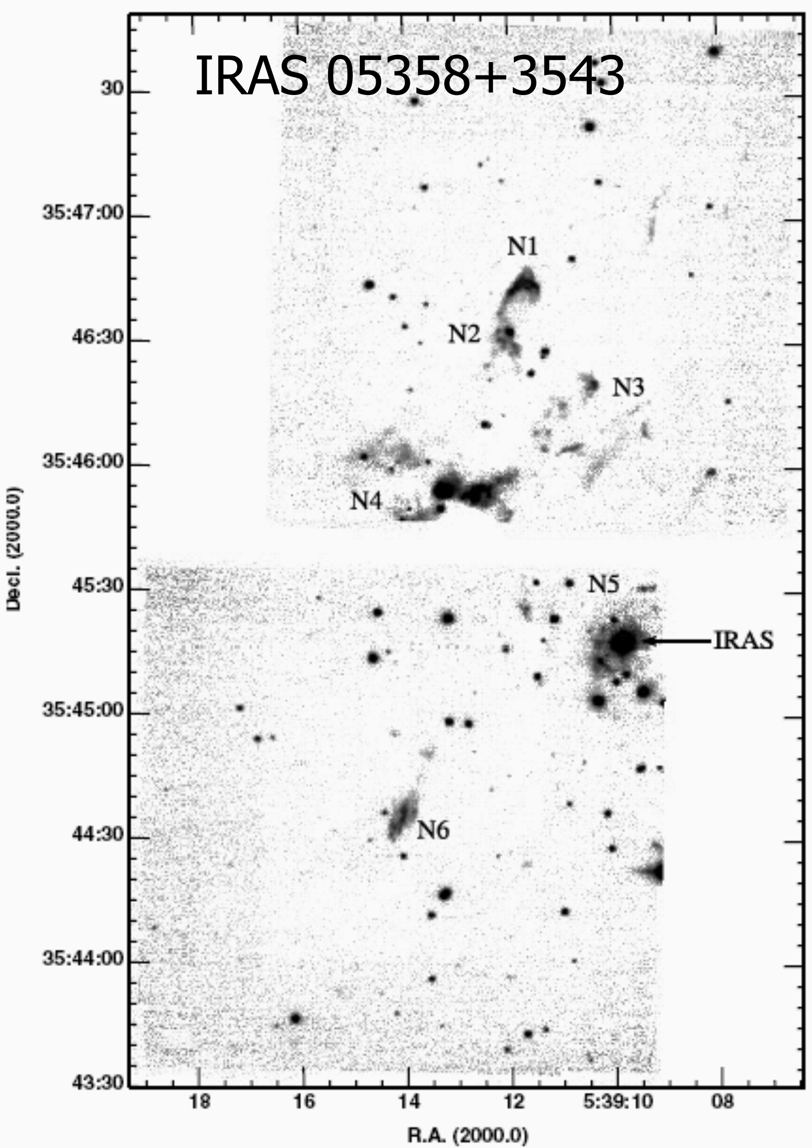
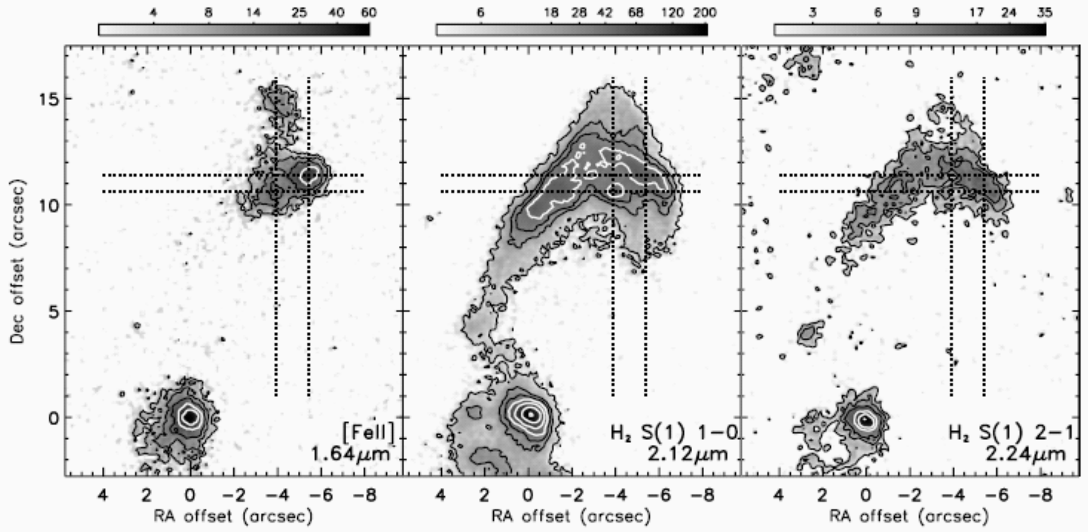
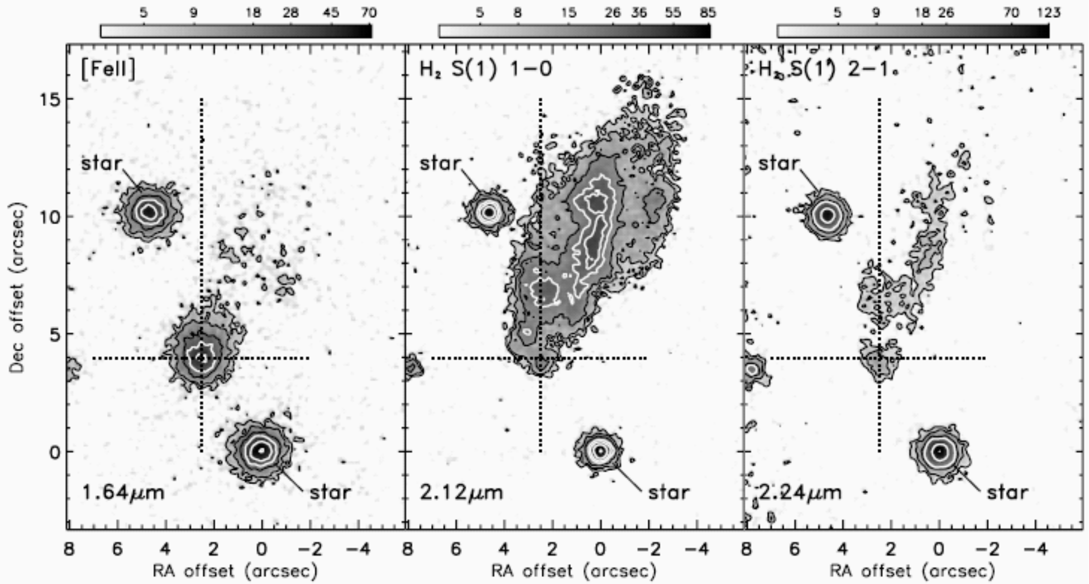
Outflow shocks I

E_{lower}/k:	2694K	170K	6140K
E_{upper}/k:	11445 K	6956K	12550K





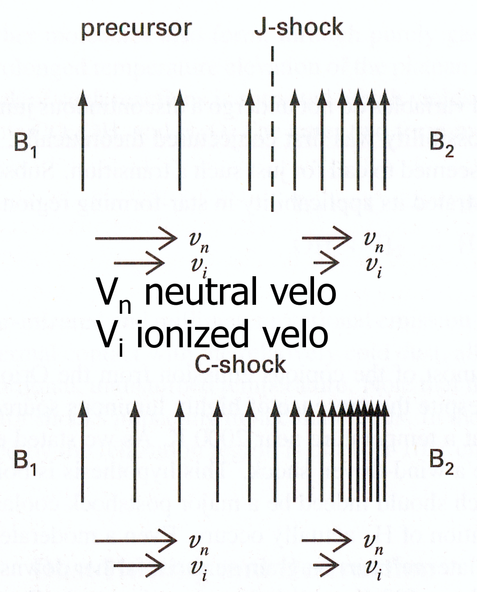


Khanzadyan et al. 2004

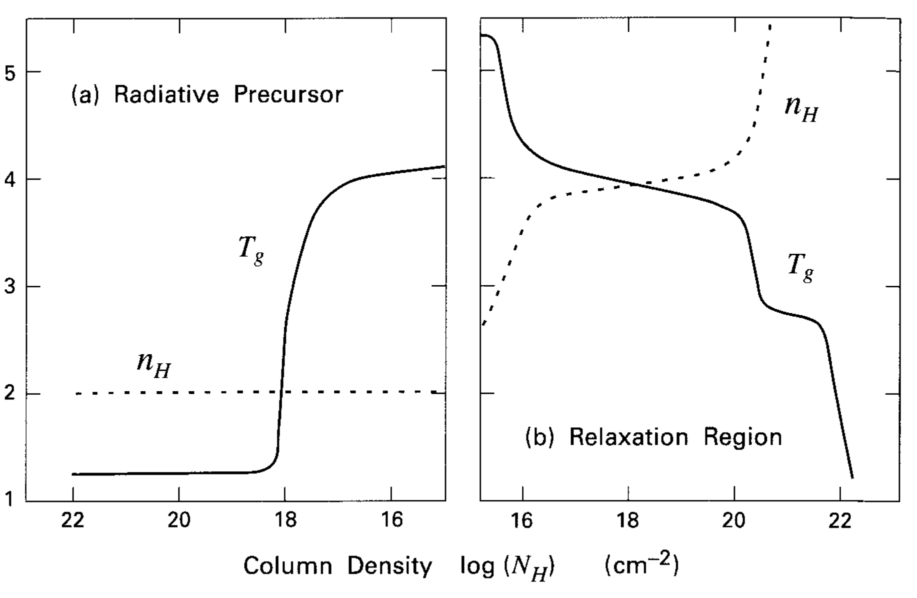
Outflow shocks II

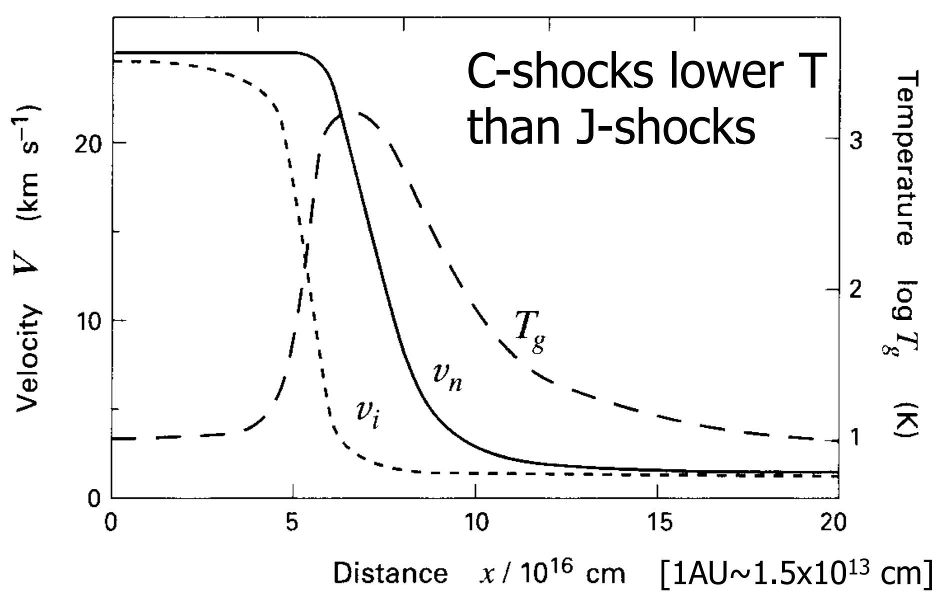
J-shocks: Jump shocks compress, heat and accelerate the surrounding medium "discontinuous" very thin layers → high ionization degree.

C-shocks: Continuous shocks continuously heat and compress the gas over larger spatial scales, magnetic field important.
→ lower ionization degree, lower temperatures.



V_n neutral velo
V_i ionized velo





C-shocks lower T than J-shocks

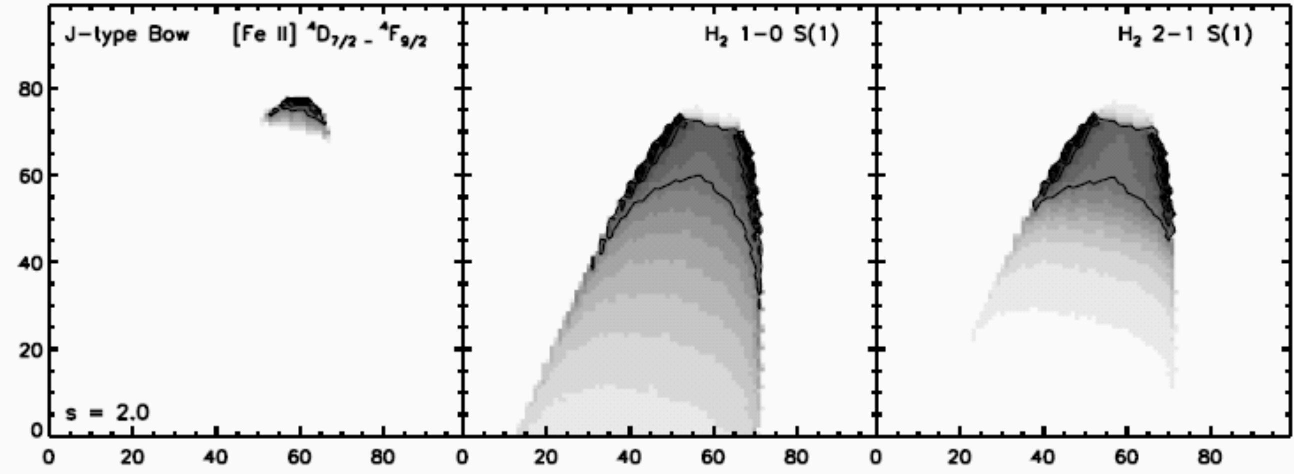
[1AU~1.5x10^{13} cm]

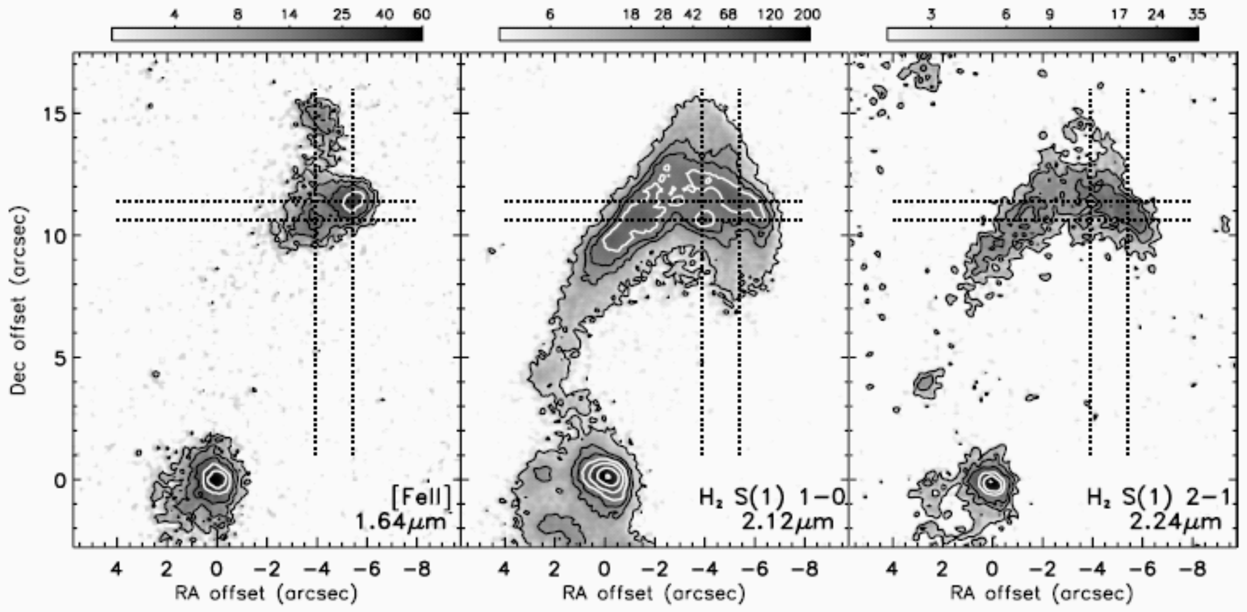
J-shock: v_{shock} = 80 km/s. The shock front itself is this layer of mean free-path length between e^- and ions ~4e10cm(~0.57R_{sun})

C-shock: v_{shock} = 25km/s
Difference between neutral and ionized velocities, because ions directly couple to B.

Outflow shocks III

In principal H_2 is produced in C-shocks because it does not survive the high temperatures of J-shocks. In contrast [Fe II] needs the ionization power of J-shocks. In reality both types of shocks can co-exist, e.g., J-shocks at the bow-apex and C-shocks at its flanks.





Khanzadyan et al. 2004

Outflow shocks V

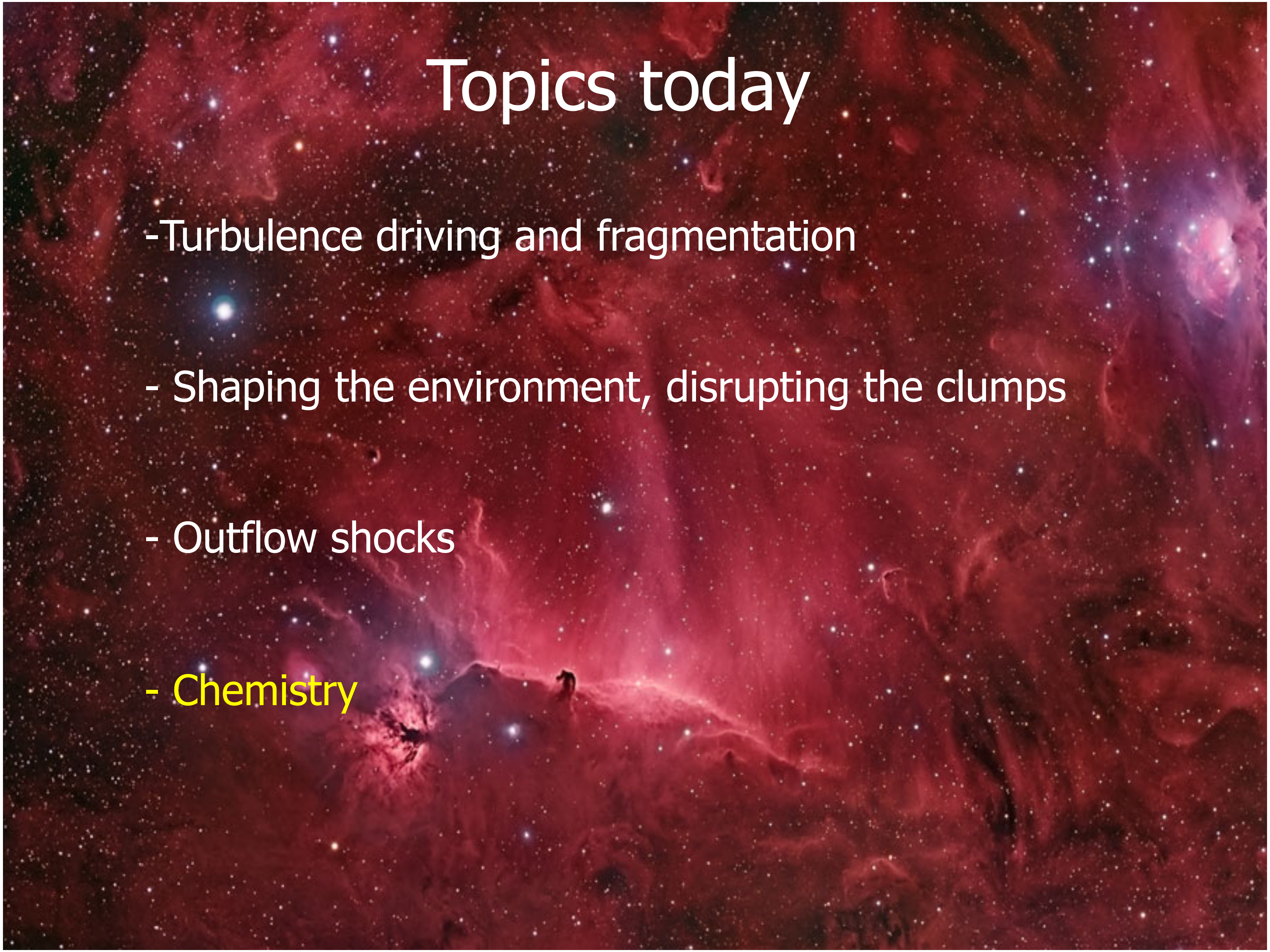
The rapid heating and compression triggers different microscopic processes, e.g.,

- molecular dissociation
- endothermic chemical reactions “using” the excess heat
- ice sublimation
- dust grain disruption
- sputtering of molecules from dust grains

Since shock-timescales are short (10^2-10^4yr), the chemical composition within shocks is quickly distinct from the ambient unperturbed gas.

The shock cooling time is fast ($\sim10^2$yr), so high-temperature reactions only early after the shock, then low-temperature chemistry again
→ Chemical anomalies in outflow can be considered as indicator of age.
Effects most strongly visible in young class 0 sources.

Non-dissociative C-shocks are particularly efficient in triggering different chemistries.



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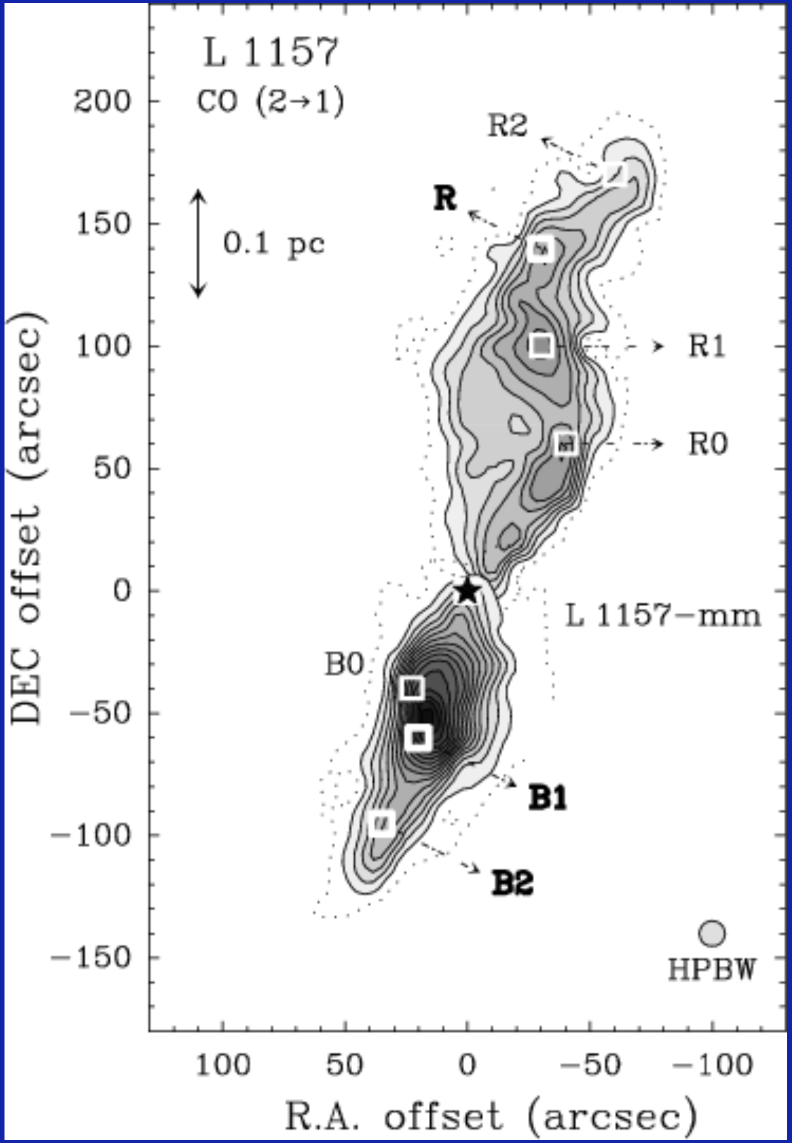
- Chemistry

Molecules in Space

2	3	4	5	6	7	8	9	10	11	12	13 atoms
H2	C3	c-C3H	C5	C5H	C6H	CH3C3N	CH3C4H	CH3C5N?	HC9N	CH3OC2H5	HC11N
AlF	C2H	l-C3H	C4H	l-H2C4	CH2CHCN	HCOOCH3	CH3CH2CN	(CH3)2CO			
AlCl	C2O	C3N	C4Si	C2H4	CH3C2H	CH3COOH?	(CH3)2O	NH2CH2COOH?			
C2	C2S	C3O	l-C3H2	CH3CN	HC5N	C7H	CH3CH2OH	CH3CH2CHO			
CH	CH2	C3S	c-C3H2	CH3NC	HCOCH3	H2C6	HC7N				
CH+	HCN	C2H2	CH2CN	CH3OH	NH2CH3	CH2OHCHO	C8H				
CN	HCO	CH2D+?	CH4	CH3SH	c-C2H4O	CH2CHCHO					
CO	HCO+	HCCN	HC3N	HC3NH+	CH2CHOH						
CO+	HCS+	HCNH+	HC2NC	HC2CHO							
CP	HOC+	HNCO	HCOOH	NH2CHO							
CSi	H2O	HNCS	H2CHN	C5N							
HCl	H2S	HOCO+	H2C2O	HC4N							
KCl	HNC	H2CO	H2NCN								
NH	HNO	H2CN	HNC3								
NO	MgCN	H2CS	SiH4								
NS	MgNC	H3O+	H2COH+								
NaCl	N2H+	NH3									
OH	N2O	SiC3									
PN	NaCN	C4									
SO	OCS										
SO+	SO2										
SiN	c-SiC2										
SiO	CO2										
SiS	NH2										
CS	H3+										
HF	SiCN										
SH	AlNC										
FeO(?)	SiNC										

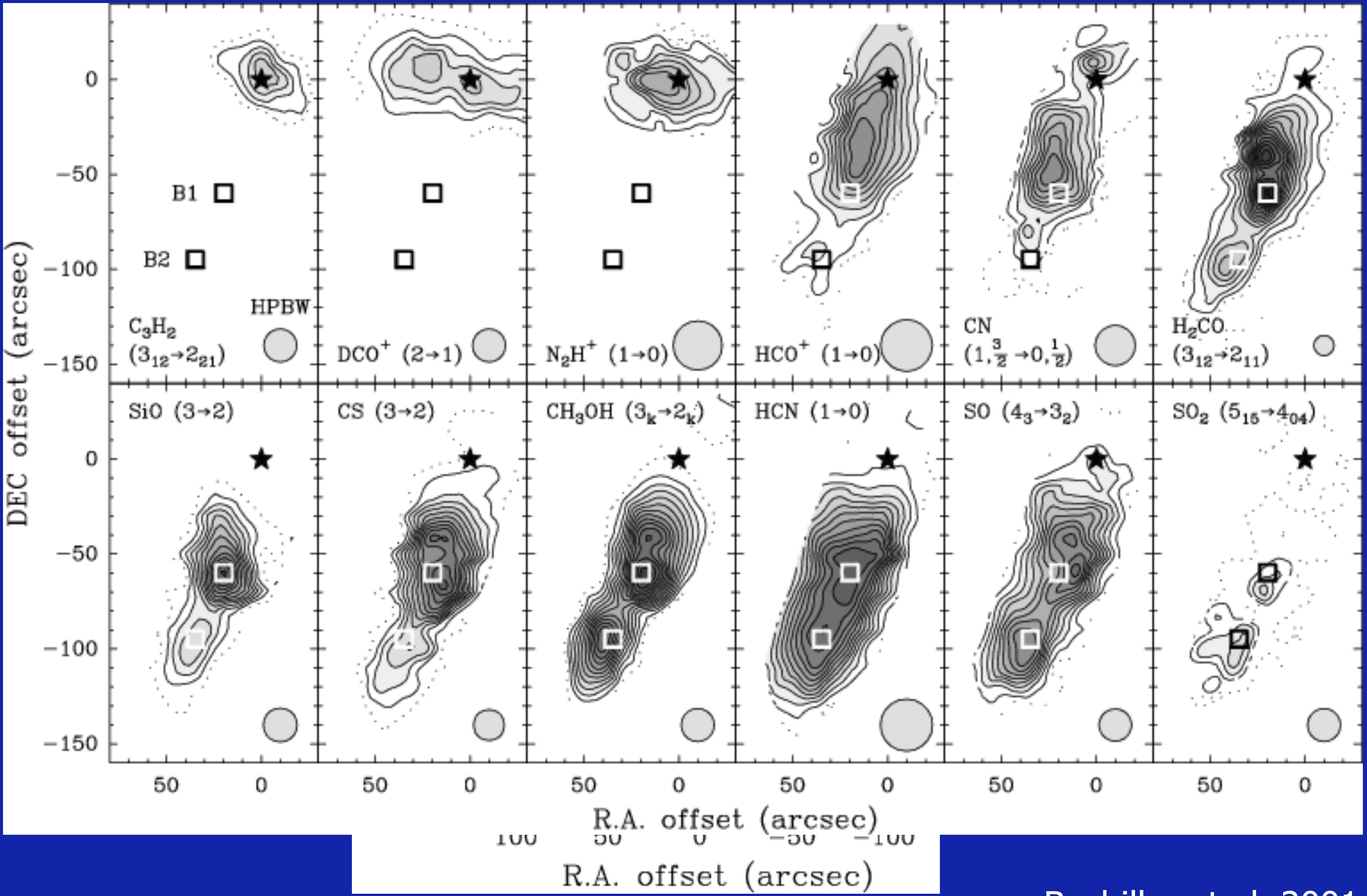
About 160 detected interstellar molecules as of June 2011 (www.cdms.de).

Outflow chemistry I



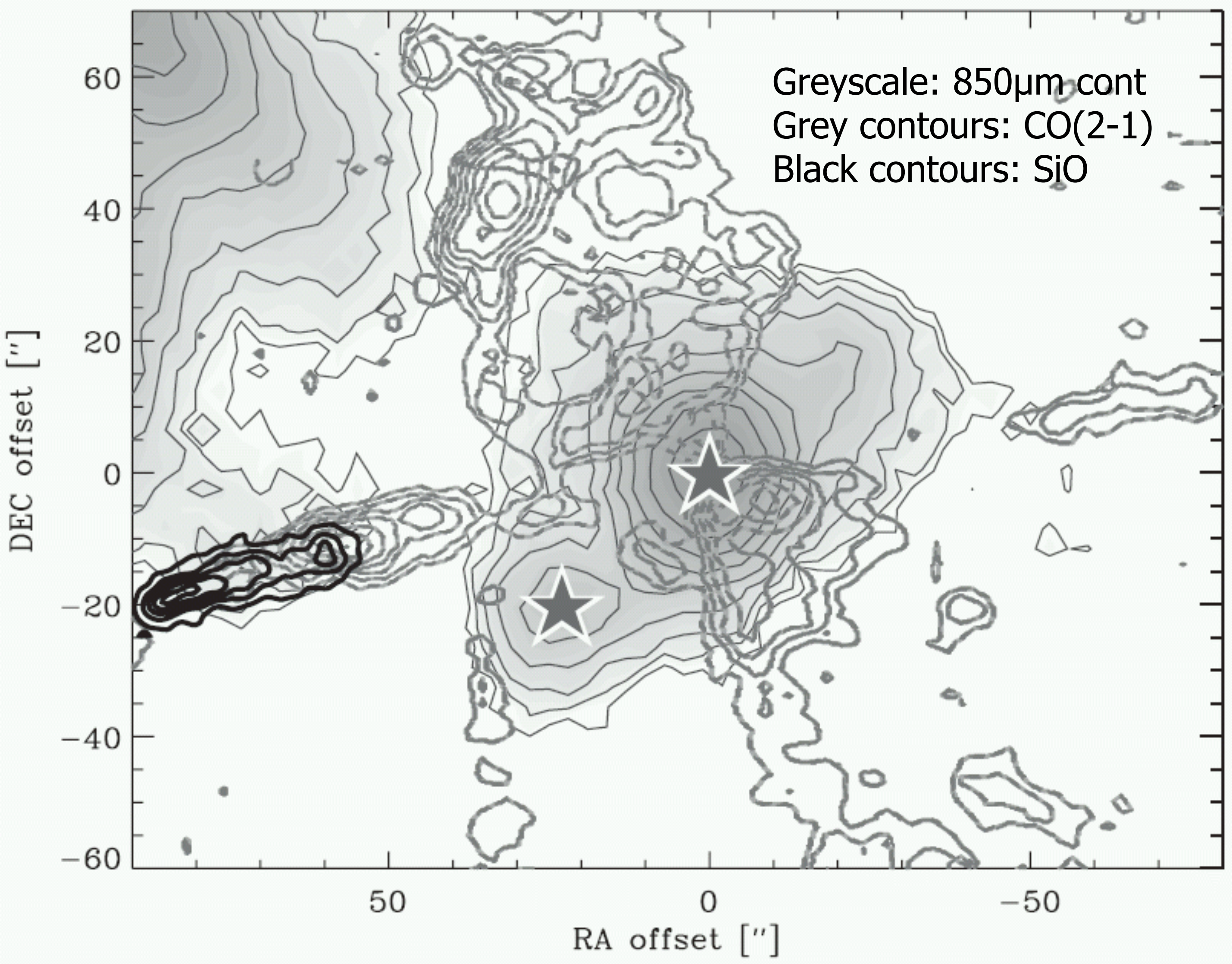
Bachiller et al. 2001

Outflow chemistry I



Bachiller et al. 2001

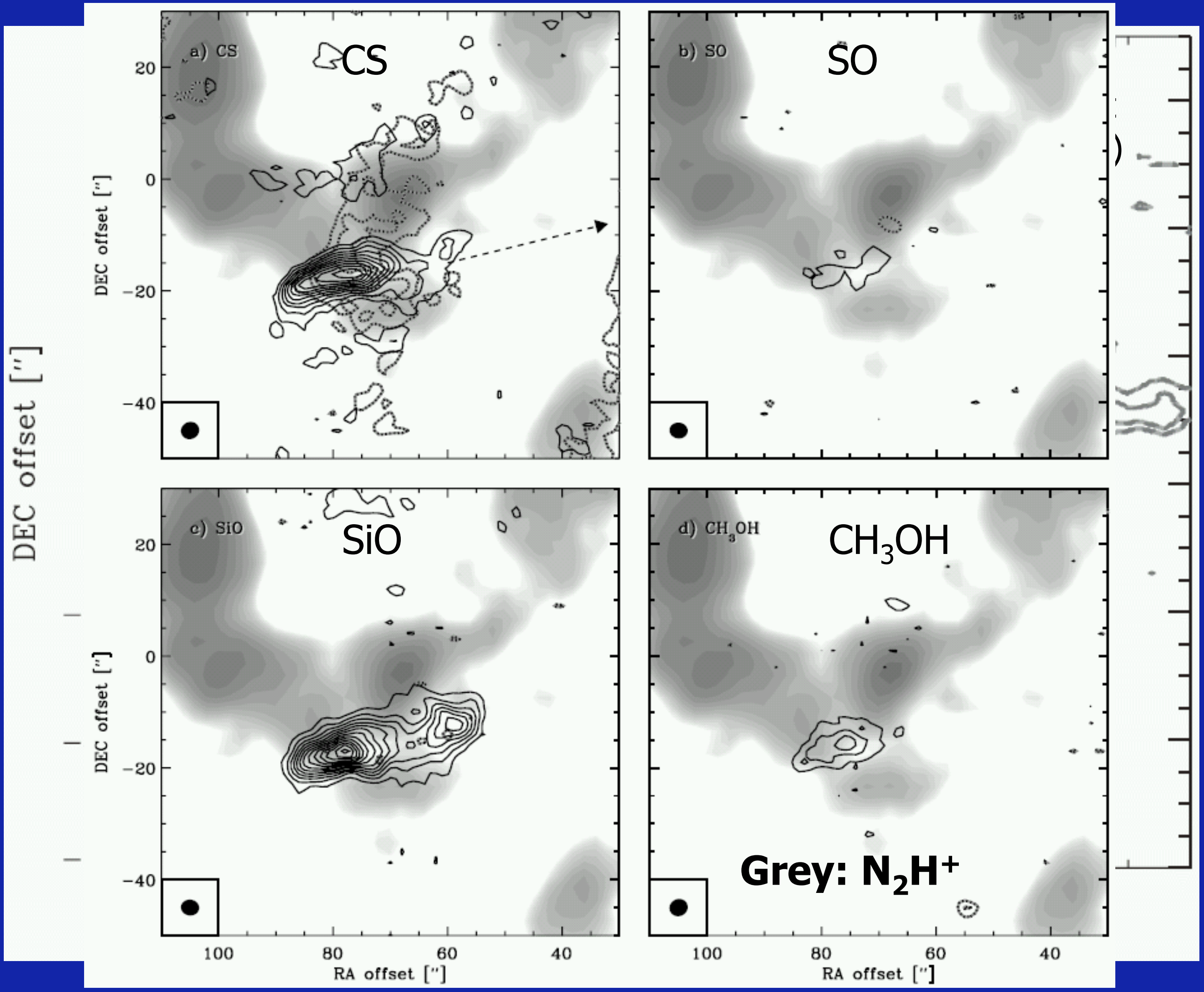
Outflow chemistry II



Greyscale: 850µm cont
Grey contours: CO(2-1)
Black contours: SiO

NGC1333 IRAS 2A, Joergensen et al. 2004

Outflow chemistry II



Grey: N_2H^+

NGC1333 IRAS 2A, Joergensen et al. 2004

Outflow chemistry III

SiO exhibits most extreme molecular enhancement factors up to 10^6 with respect to the unperturbed medium. It is produces by sputtering from dust grains at velocities >25km/s → SiO usually shows strong line wings.

CH_3OH and H_2CO also overabundant in outflows up to a factor 100. They are likely directly evaporated from icy grains. Terminal velocities usually lower than SiO because they do not survive that high velocities.

Because SiO may reincorporate faster into dust grains than more volatile CH_3OH and H_2CO, high abundance of the latter could mark later stages than SiO rich outflows.

Sulpher-chemistry particularly interesting because it may serve as a chemical clock. H_2S believed to harbor most S on grains. Once ejected from grains its abundance will decrease quickly ($\sim 10^4$yr) reacting with O and OH and producing SO and SO_2. H_2S/SO ratios are promising for relative shock ages.

Summary

Large-scale turbulence is likely driven by supernovae.

Smaller-scale turbulence can also be significantly driven by molecular outflows.

Outflows affect the envelopes of star-forming regions significantly. Early-on, they move large gas masses along with them. Lateron, they evacuate the core, and the gas can only fall in perpendicular to the outflow.

The outflows cause shocks with high temperatures and pressures.

In these high-T and high-P regions, distinctively different chemical networks are observed compared to the unperturbed gas.

Chemical properties may be used for (relative) age dating.

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