Ionization Feedback in Massive Star Formation

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Introduction

Why is the formation of massive stars interesting?

Massive stars

- govern matter cycle in galaxy
- produce heavy elements
- release large amounts of energy and momentum into ISM

Formation of massive stars is not understood!

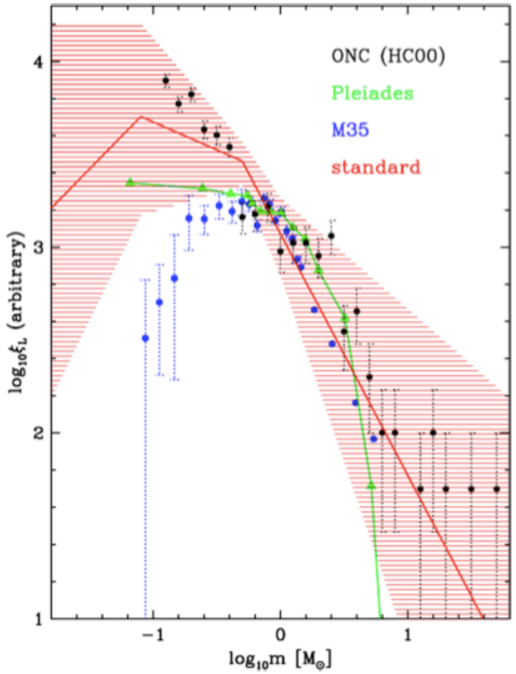
- begin hydrogen burning while still in main growth phase
- star has to accrete despite high luminosities

Is the accretion terminated by feedback processes?

Introduction

We want to address the following questions:

- What determines the upper stellar mass limit?
- What is the physics behind the observed HII regions?



IMF (Kroupa 2002)

Rosetta nebula (NGC 2237)

Feedback Processes

- radiation pressure on dust particles
- ionizing radiation
- stellar wind
- jets and outflows

Feedback Processes

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Radiation Pressure

has gained the most attention in the literature, most recent simulations by Krumholz et al. 2009

Ionization

only a few numerical studies so far (eg. Dale et al. 2007, Gritschneder et al. 2009), but H II regions around massive protostars can be observed!
$\longrightarrow$ direct comparison with observations possible

Simulation Method Summary

What FLASH can do now

- raytracing algorithm for ionizing and non-ionizing radiation
- rate equation for ionization fraction
- relevant heating and cooling processes
- sink particles as sources of radiation
- very simple prestellar model

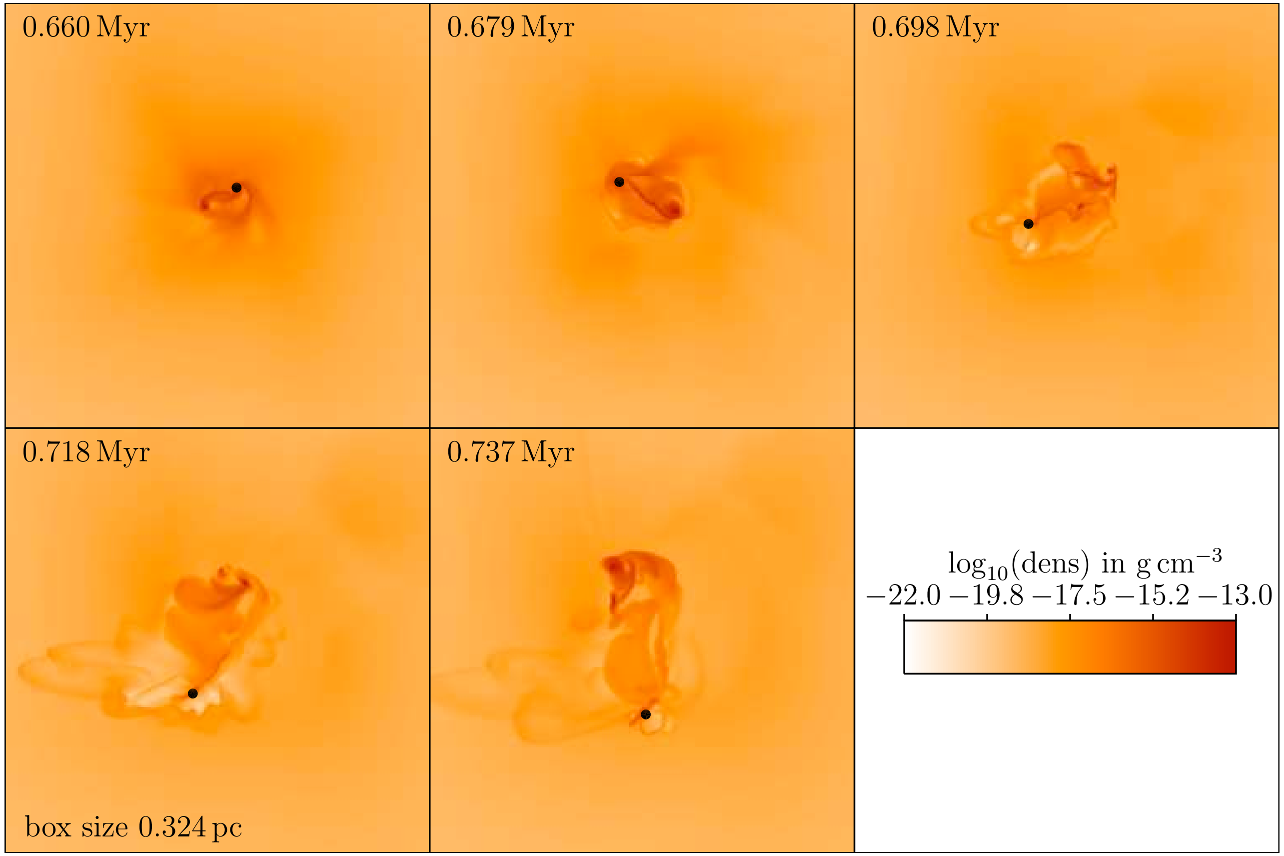
What we would like to simulate

- we would like to accrete $100 M_\odot$ on protostar
- start with $1000 M_\odot$ core and let it collapse
- study effects of ionization feedback on disk and envelope

Initial Conditions

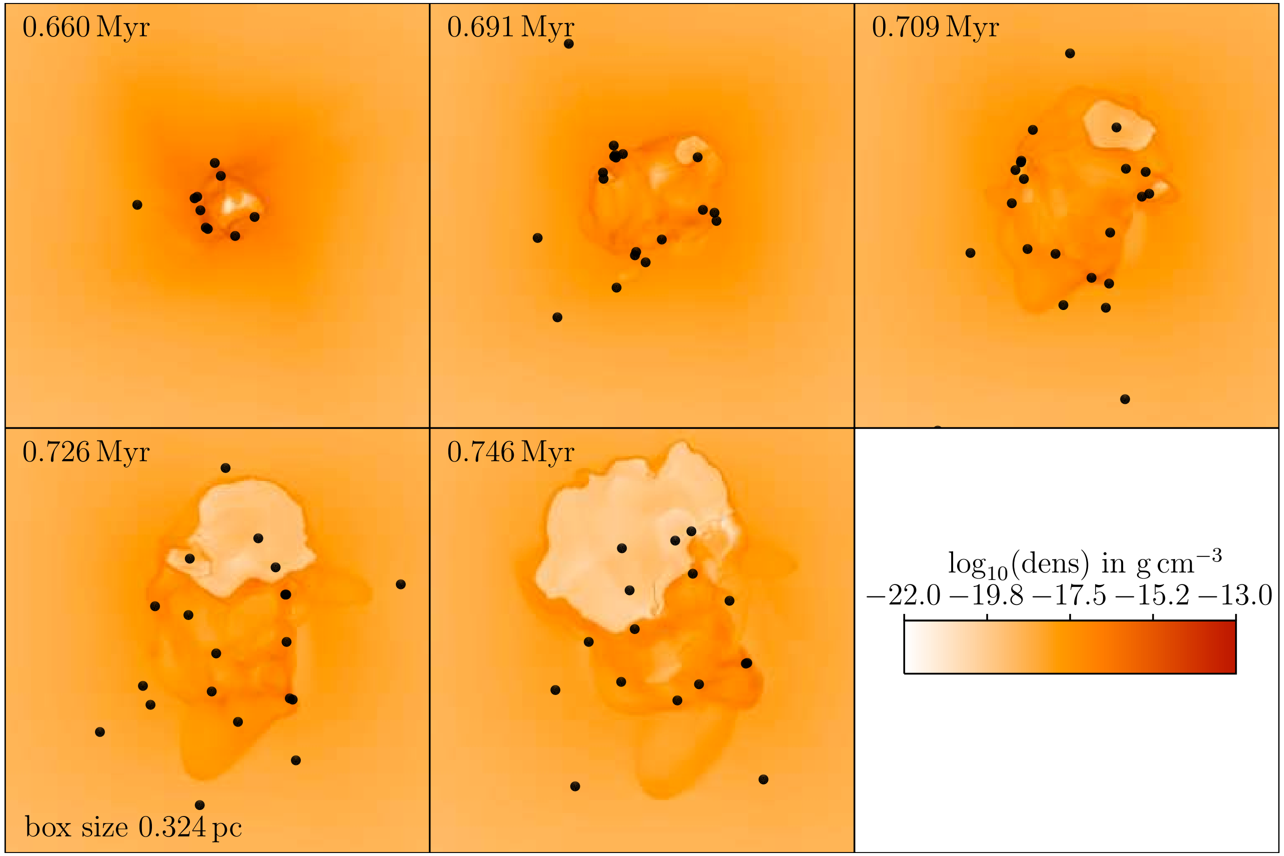
- massive core with $M = 1000 M_\odot$
- flat core within $r = 0.5\,\mathrm{pc}$ and $\rho(r) \sim r^{-3/2}$ density fall-off
- initial $m = 2$-perturbation
- core is initially rotating with $\beta = 0.05$
- no magnetic fields and turbulence at the moment
- sink particle radius is 600 AU
- cut-off density is $7 \times 10^{-16}\,\mathrm{g\,cm^{-3}}$
- cell size is 100 AU

Disk Fragmentation



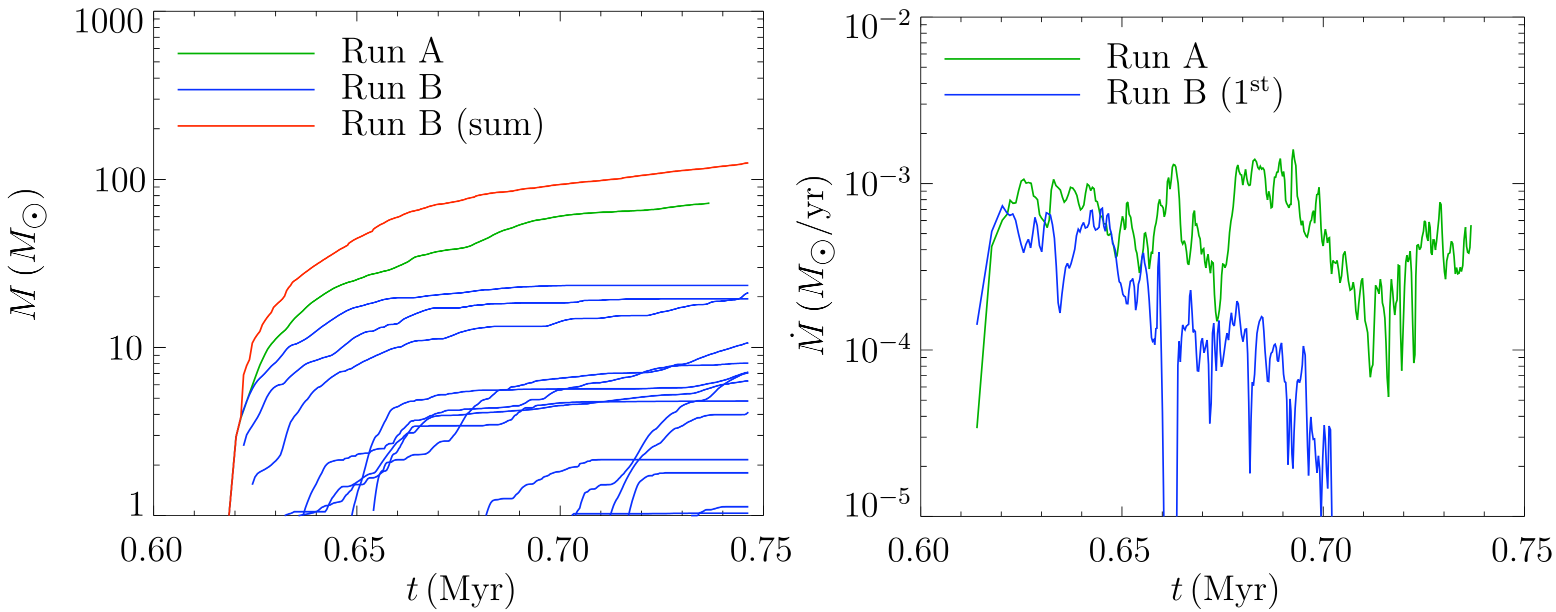
- disk is gravitationally unstable and fragments
- we suppress secondary sink formation by "Jeans heating"
- H II region is shielded effectively by dense filaments
- ionization feedback does not cut off accretion!

Disk Fragmentation



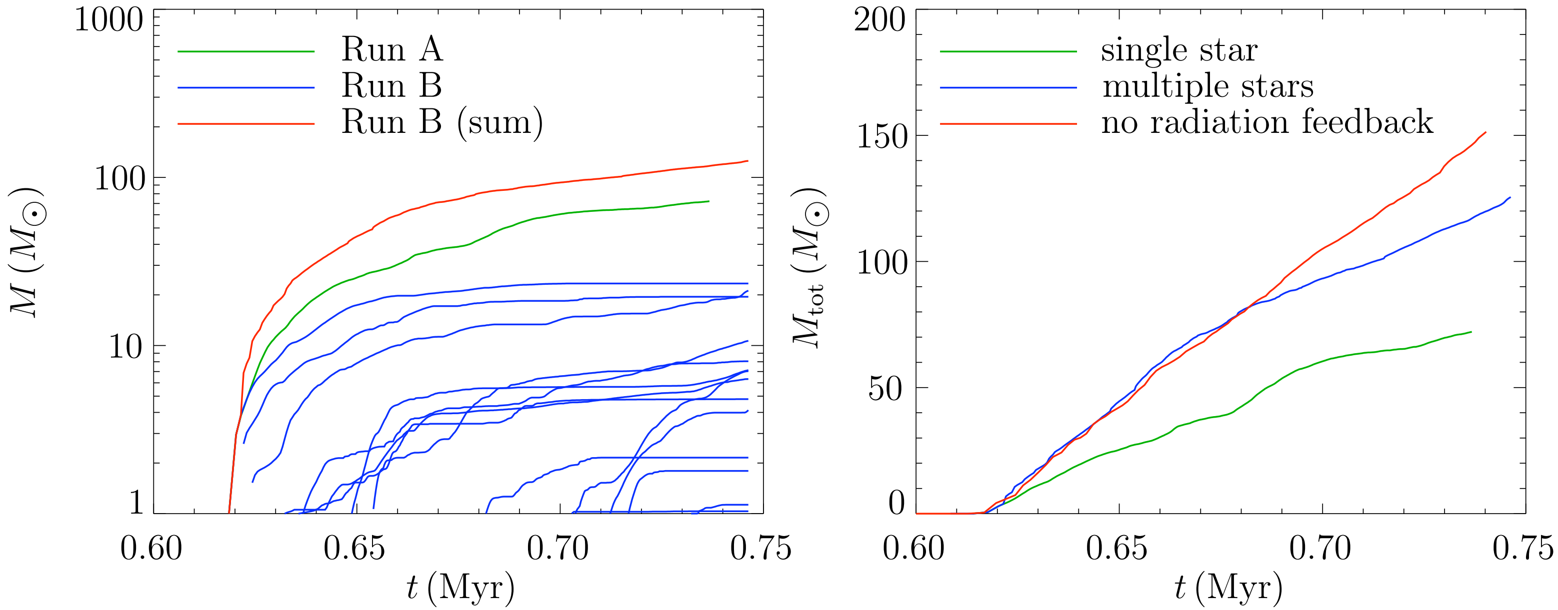
- all protostars accrete from common gas reservoir
- accretion flow suppresses expansion of ionized bubble
- cluster shows "fragmentation-induced starvation"
- halting of accretion flow allows bubble to expand

Accretion History



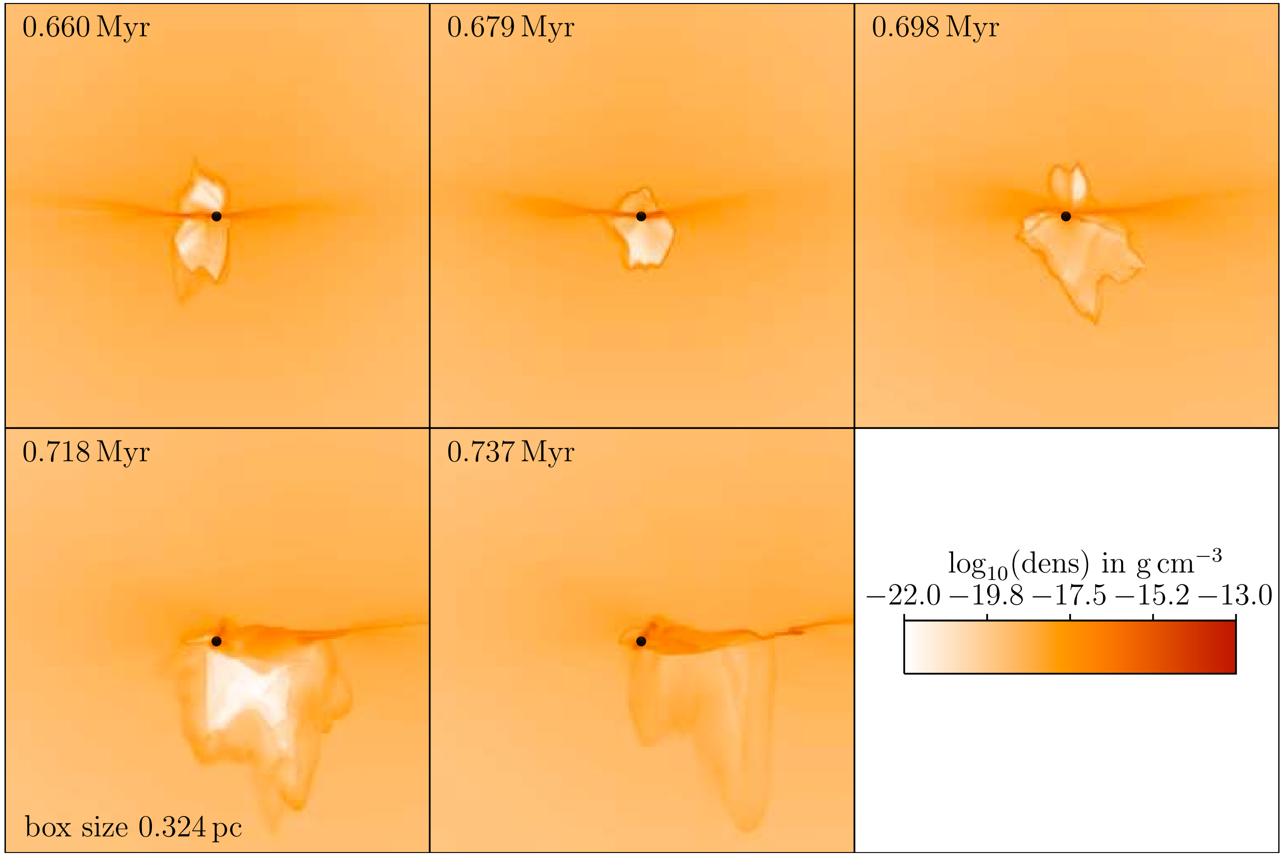
- single protostar accretes $72M_\odot$ in $120\,\mathrm{kyr}$ (Run A)
- ionization feedback alone is unable to stop accretion
- accretion is limited when multiple protostars can form (Run B)
- no star in multi sink simulation reaches more than $30M_\odot$

Accretion History



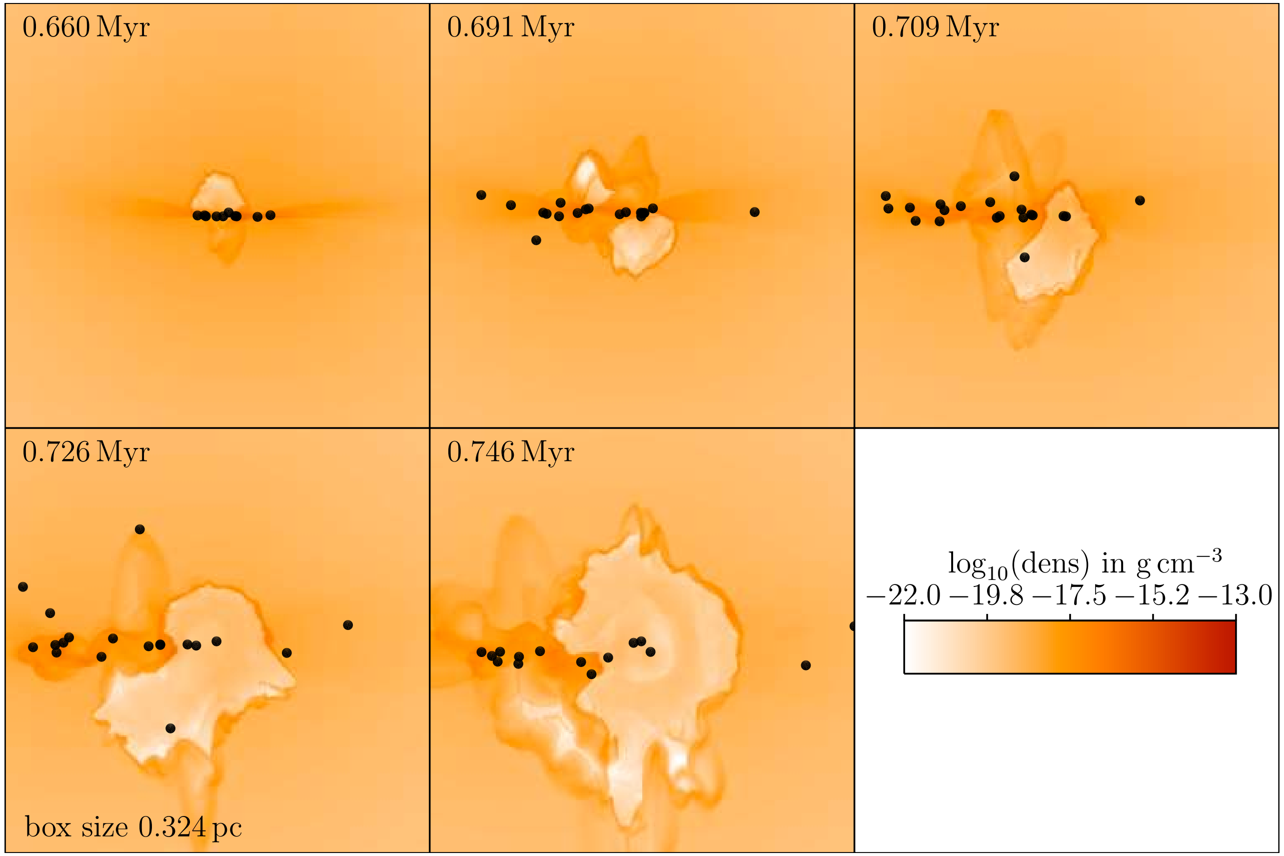
- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

Dynamics of the H II Region and Outflow



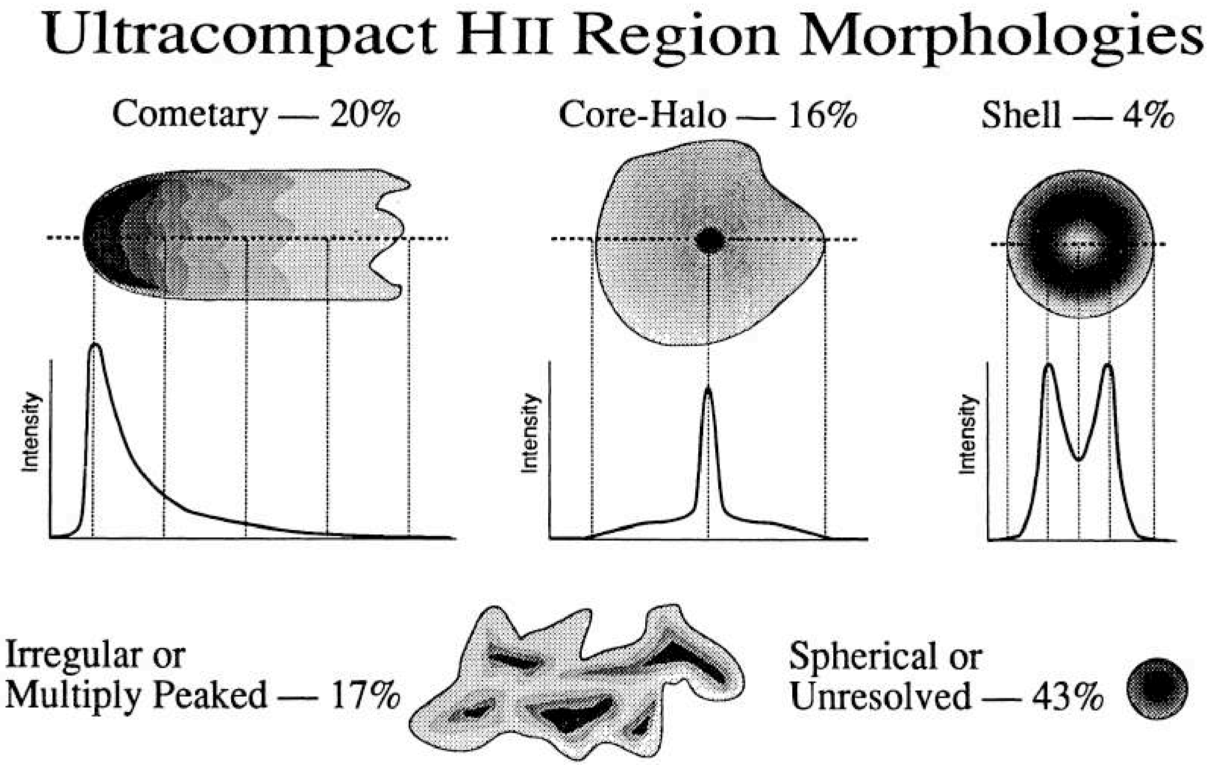
- thermal pressure drives bipolar outflow
- filaments can effectively shield ionizing radiation
- when thermal support gets lost, outflow gets quenched again
- no direct relation between mass of star and size of outflow

Dynamics of the H II Region and Outflow



- bipolar outflow during accretion phase
- when accretion flow stops, ionized bubble can expand
- expansion is highly anisotropic
- bubbles around most massive stars merge

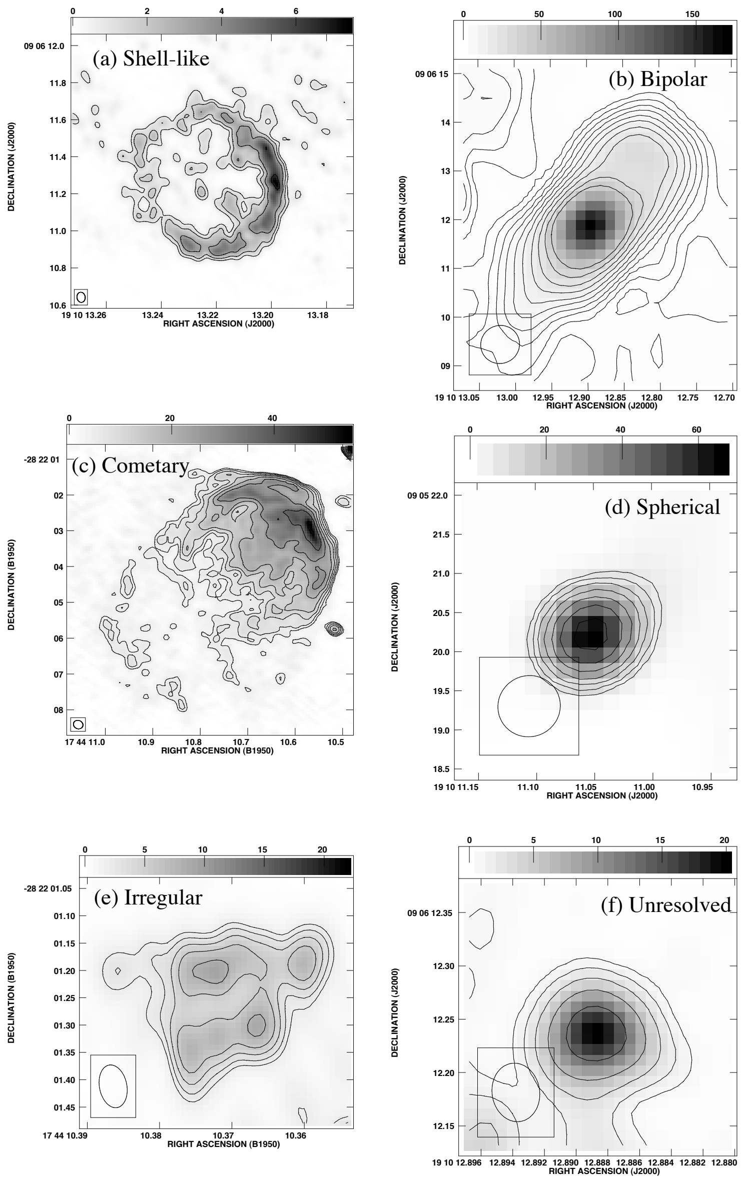
Classification of UC H II Regions



- Wood & Churchwell 1989 classification of UC H II regions
- Question: What is the origin of these morphologies?
- UC H II lifetime problem: Too many UC H II regions observed!

Classification of UC H II Regions

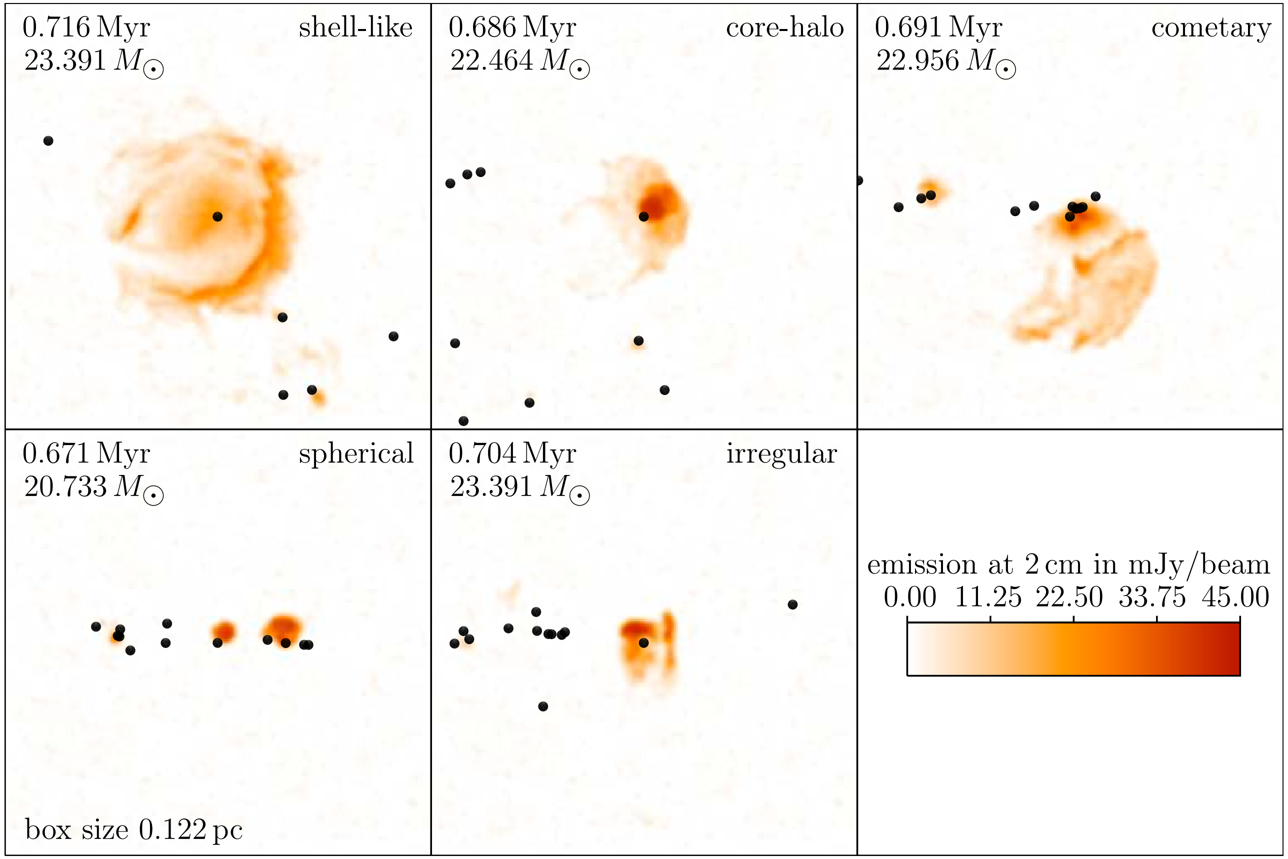
- comparison with De Pree et al. 2005 classification of UC H II regions in W49A and Sagittarius B2
- “irregular” is any resolved region which does fall into one of the other categories



Simulated Radio Continuum Maps

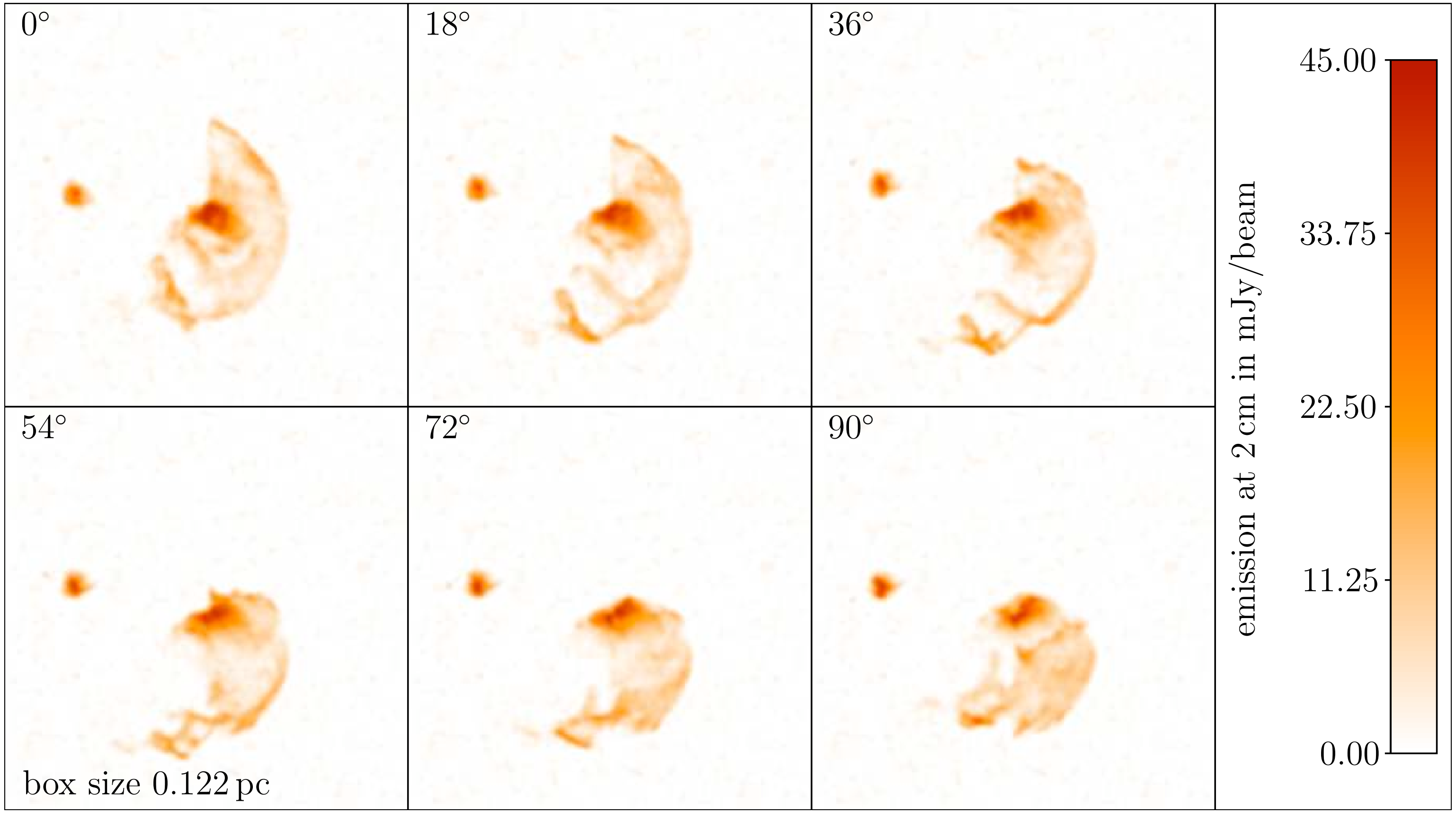
- numerical data can be used to generate continuum maps
- calculate free-free absorption coefficient for every cell
- integrate radiative transfer equation (neglecting scattering)
- convolve resulting image with beam width
- VLA parameters:
  - distance $2.65\,\mathrm{kpc}$
  - wavelength $2\,\mathrm{cm}$
  - FWHM $0\overset{\prime\prime}{.}14$
  - noise $10^{-3}\,\mathrm{Jy}$

H II Region Morphologies



- synthetic VLA observations at $2\,\mathrm{cm}$ of simulation data
- interaction of ionizing radiation with accretion flow creates high variability in time and shape
- flickering resolves the lifetime paradox!

H II Region Morphologies



- morphologies depend a lot on viewing angle
- example: shell morphology face-on turns into cometary morphology edge-on
- different behavior in each particular case

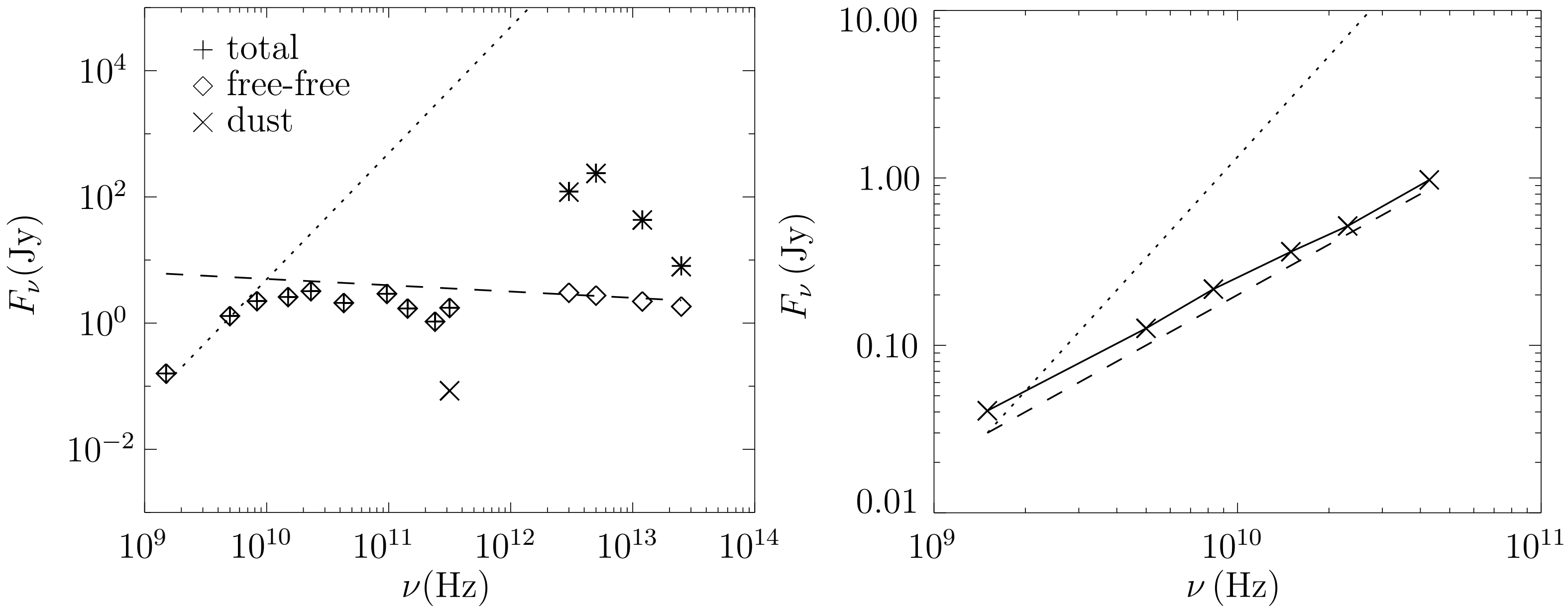
H II Region Morphologies

Type	WC89	K94	single	multiple
Spherical/Unresolved	43	55	19	60 ± 5
Cometary	20	16	7	10 ± 5
Core-halo	16	9	15	4 ± 2
Shell-like	4	1	3	5 ± 1
Irregular	17	19	57	21 ± 5

WC89: Wood & Churchwell 1989, K94: Kurtz et al. 1994

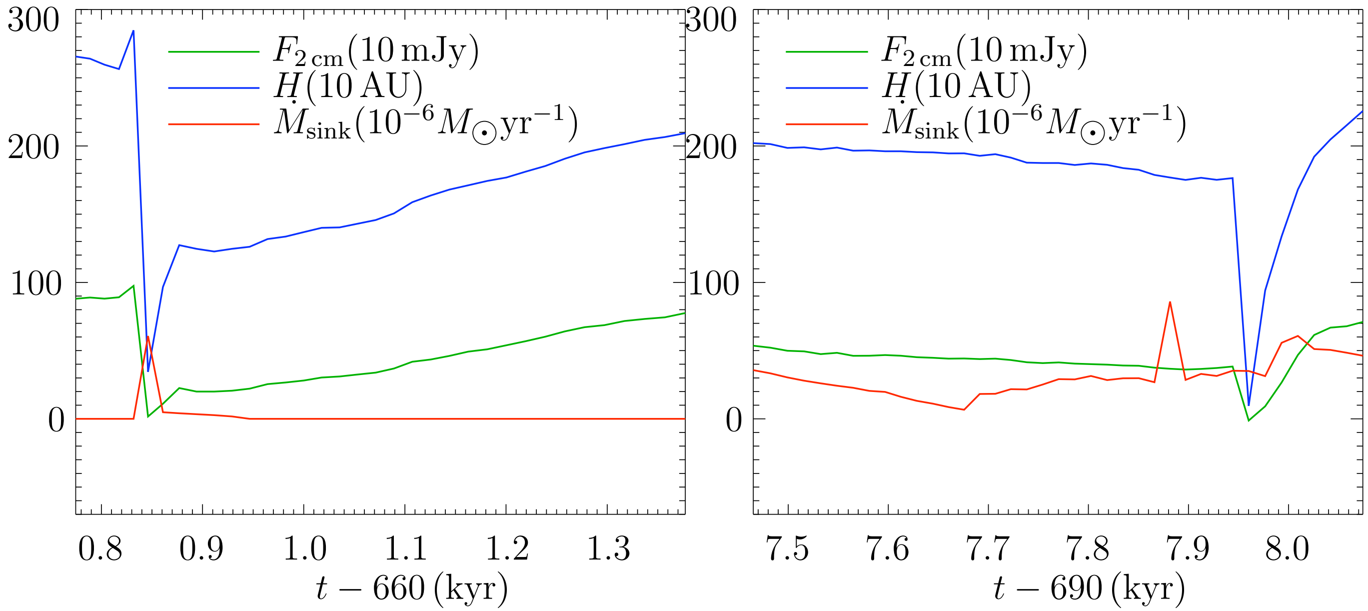
- statistics over 25 simulation snapshots and 20 viewing angles
- statistics can be used to distinguish between different models
- single sink simulation does not reproduce lifetime problem

Spectral Energy Distribution



- typical H II region SEDs of WC89 reproduced
- no dust emission in cm to sub-mm regime
- abnormal SEDs with $\alpha \approx 1$ caused by density gradients

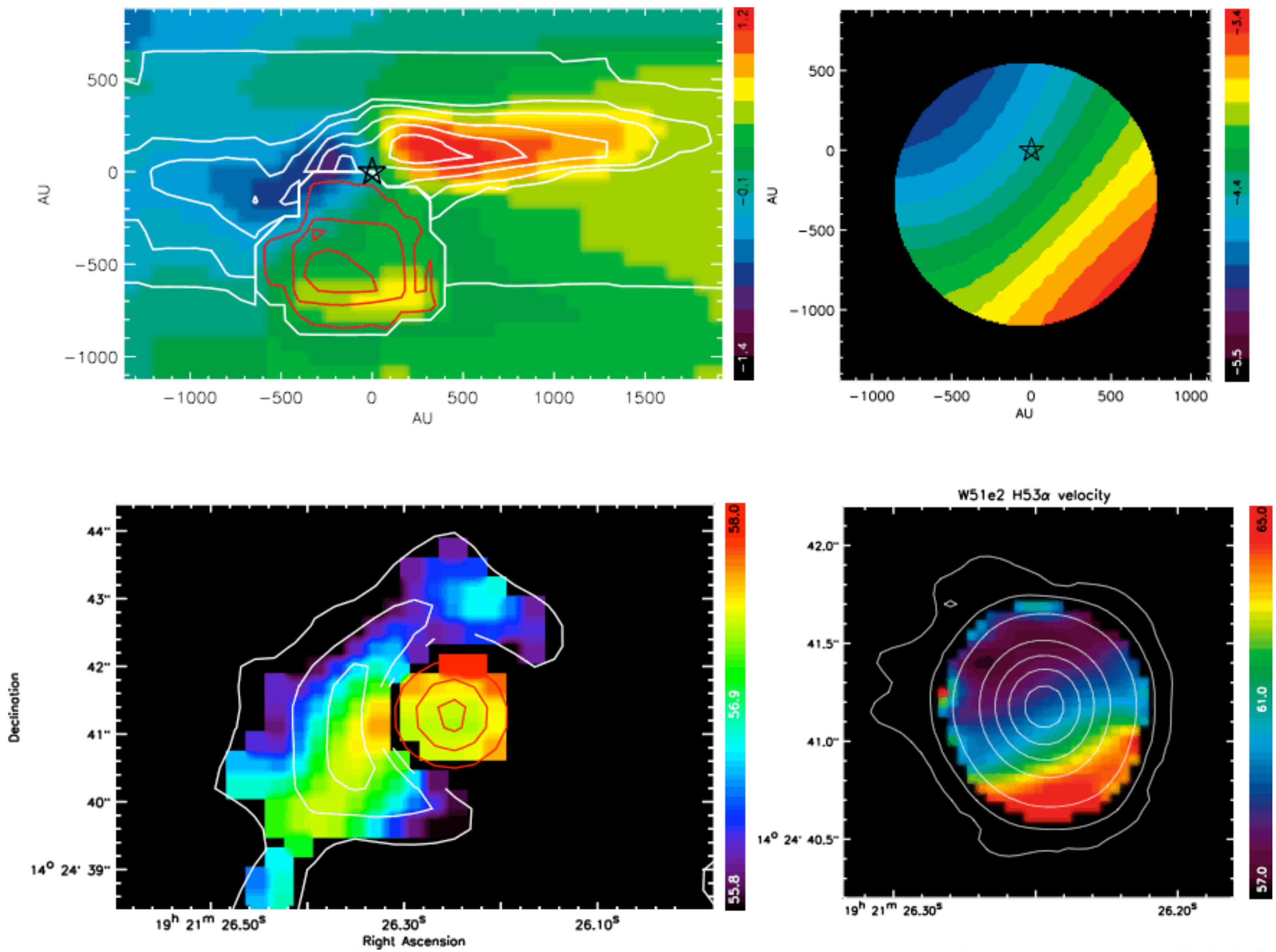
Time Variability



- correlation between accretion events and H II region changes
- time variations in size and flux have been observed
- changes of size and flux of 5–$7\%\mathrm{yr}^{-1}$ match observations

  Franco-Hernández et al. 2004, Rodríguez et al. 2007, Galván-Madrid et al. 2008

Comparison with observations: W51e2



Keto & Klaassen 2008

Conclusions and Outlook

Conclusions

- Ionization feedback cannot stop accretion
- Ionization drives bipolar outflow
- H II region shows high variability in time and shape
- All classified morphologies can be observed in one run
- Lifetime of H II region determined by accretion time scale
- Rapid accretion through dense, unstable flows
- Fragmentation-induced mass limits of massive stars

Conclusions and Outlook

Conclusions

- ionization feedback cannot stop accretion
- upper mass limit is set by fragmentation-induced starvation
- high variability in time and shape of H II regions
- all classified morpholgies can be found in a single simulation
- flickering resolves the UC H II lifetime problem
- observed size and flux changes are caused by accretion process

Outlook

- more realistic initial conditions
- study effects of turbulence and magnetic fields
- make predictions for ALMA and JWST
- application to primordial star formation