Massive Star Formation

Boot Camp: SFDE 2017

Ralph E. Pudritz
Dept. of Physics and Astronomy, and
Origins Institute, McMaster University

Students, postdocs, and collaborators

McMaster: Ph.Ds. Mikhail Klassen, Helen Kirk (Banting Fellow, HIA)

Hamburg/Heidelberg: Robi Banerjee, Daniel Seifried (Ph.D.)
Ralf Klessen

MPIA / Tübigen: Thomas Peters (MPA), Rolf Kuiper

PPVI Li et al team – disks: (Zhi-Yun Li, Jes Jørgensen, Hsien Shang, Ruben Krasnopolsky, Anaëlle Maury)

I. Overview – General Principles

Differences between low and high mass star formation?

Eg. How can you make the most massive stars ~ 150 M_{sun} ?

1. Birth of star (measured by Kelvin-Helmholtz time); Nuclear burning in massive stars starts BEFORE accretion ends: ie BORN ON M.S.

2. Importance of radiation fields:

- Small effects in low mass star formation, major effects for massive stars: (dust destruction, ionizing radiation photoevaporates disks and envelope)

Simplest Geometry: 1 D, spherical

- Eddington limit for most massive star $M_{edd} \sim 40 M_{sun}$

(Larson & Starrfield 1971, Kahn 1974, Yorke & Krügel 1977, Wolfire & Cassinelli 1987,..).

3. Role of Outflows? Jets ubiquitous for lower mass star formation.

(reviews Pudritz+ 2007, Ray + 2007, Frank+ 2014).

What about jets during O star formation ?

Kelvin-Helmholtz timescales..

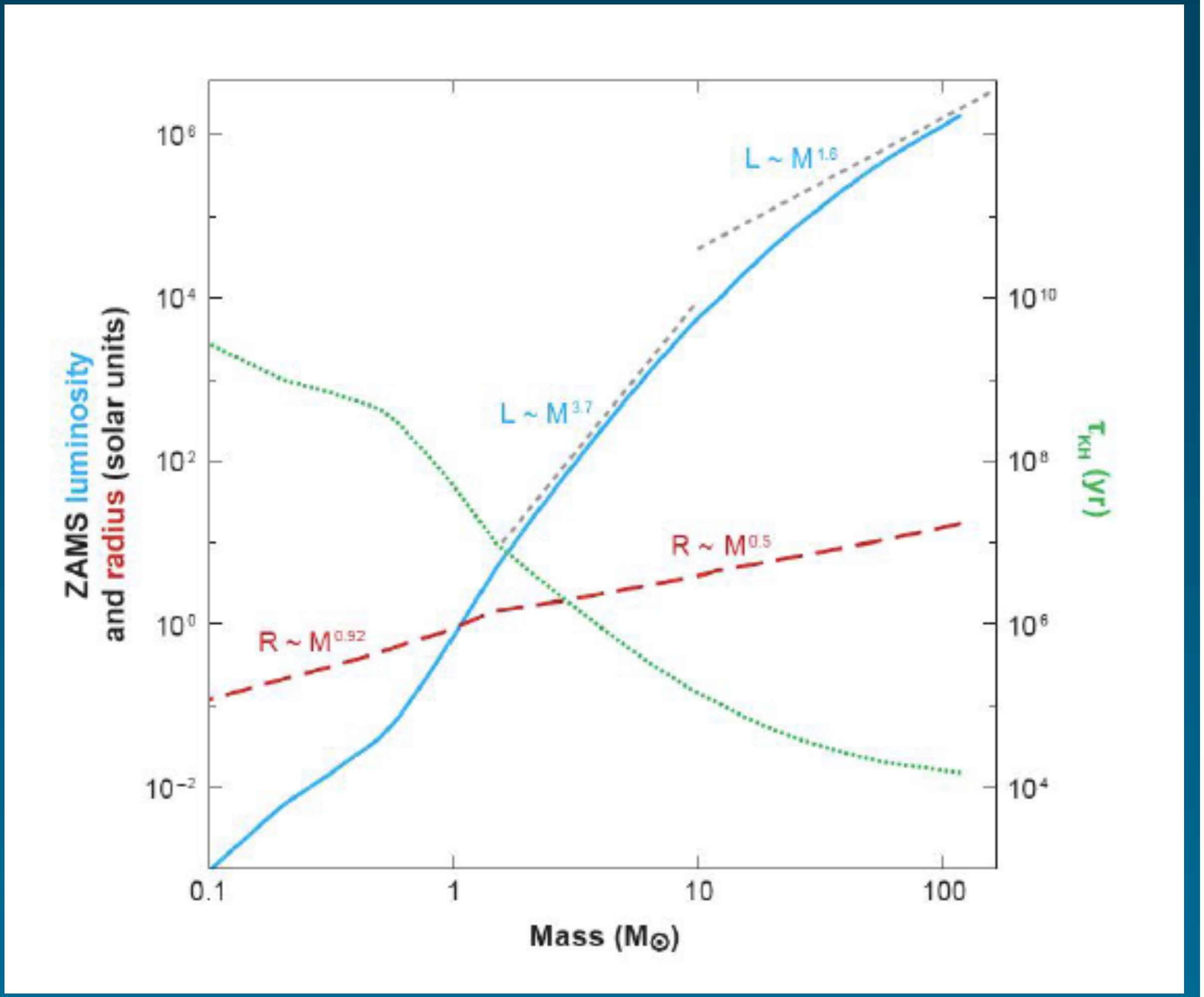
The K-H timescale depends on luminosity of the star.

$$\tau_{KH} \sim GM_*^2/R_*L_*$$

- Green: K-K time scale for stars of different masses.

- Note scaling of L and R with stellar mass

- Low masses, $t_K >> t_{ff}$ … stars accrete material and THEN start to burn.



Zinnecker & Yorke 2007

Eddington Luminosity and Mass…

Force balance in self gravitating, radiating gas:

- In equilibrium, radiation pressure balances (outward) pushing on gas – BALANCES – gravitational force:

1. Hydrostatic balance:

$$-\frac{\nabla p}{\rho} - \nabla\Phi = 0$$

2. Radiation pressure related to flux F_{rad}:

$$-\frac{\nabla p}{\rho} = \frac{\kappa}{c} F_{\text{rad}}$$

   (κ is gas opacity: for a star, gas is fully ionized, so opacity is Thompson scattering by electrons)

3. Gives Eddington limit: $L = L_{Edd} = 4\pi GMc / \kappa$

   (for hydrogen): $= 3.2\text{x}10^4 (M / M_{sun}) L_{sun}$

4. Since $L \sim M^{\alpha}$ -> There is an Eddington Mass M_{Edd}

Pre-Main-Sequence Evolution

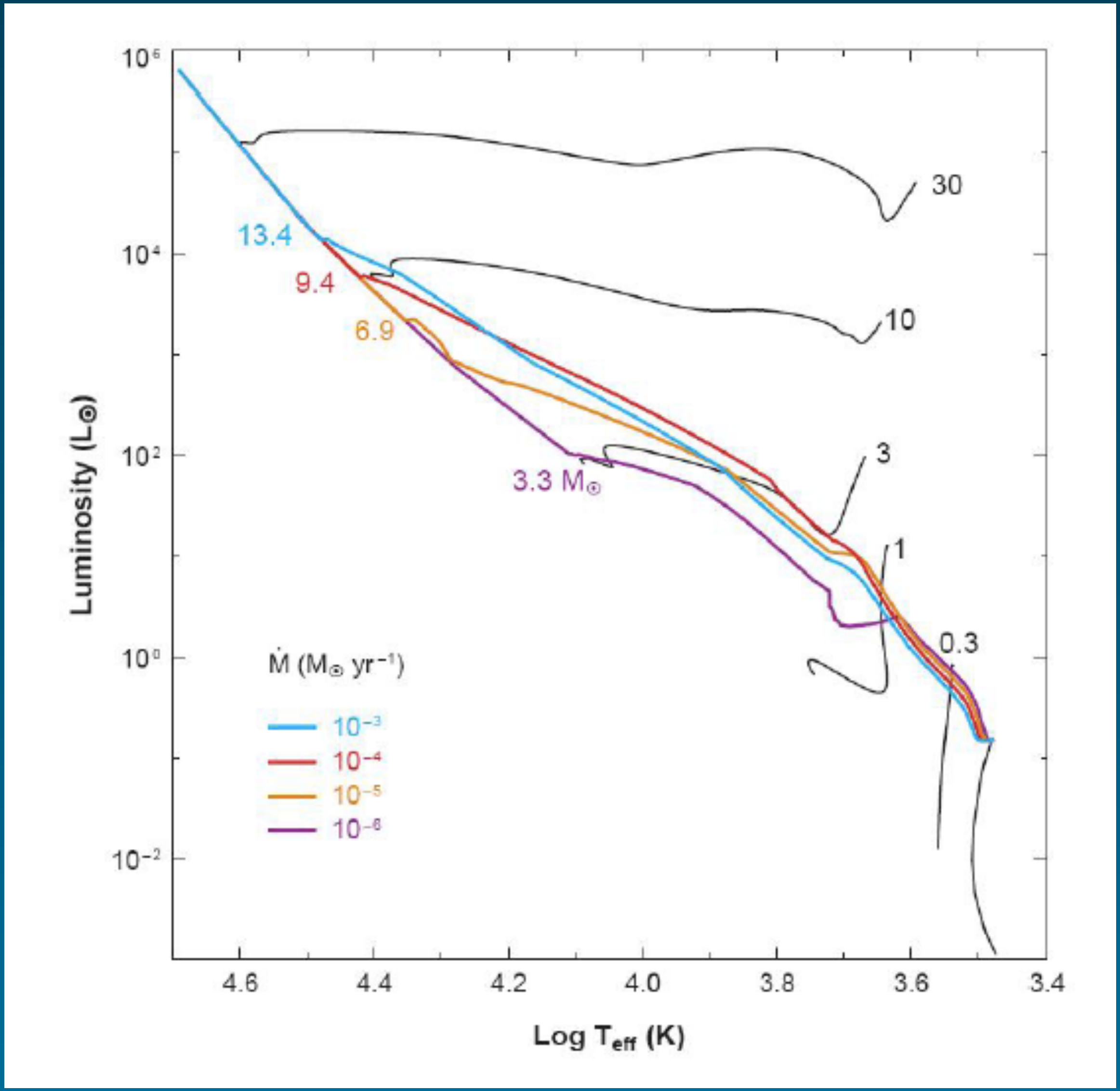
Compare:

Pre-main seq evolution tracks (no accretion) -

with –

Protostellar cores accreting at a constant rate..

(latter start at protostellar “birthline” @ 0.1 M_{Sun}

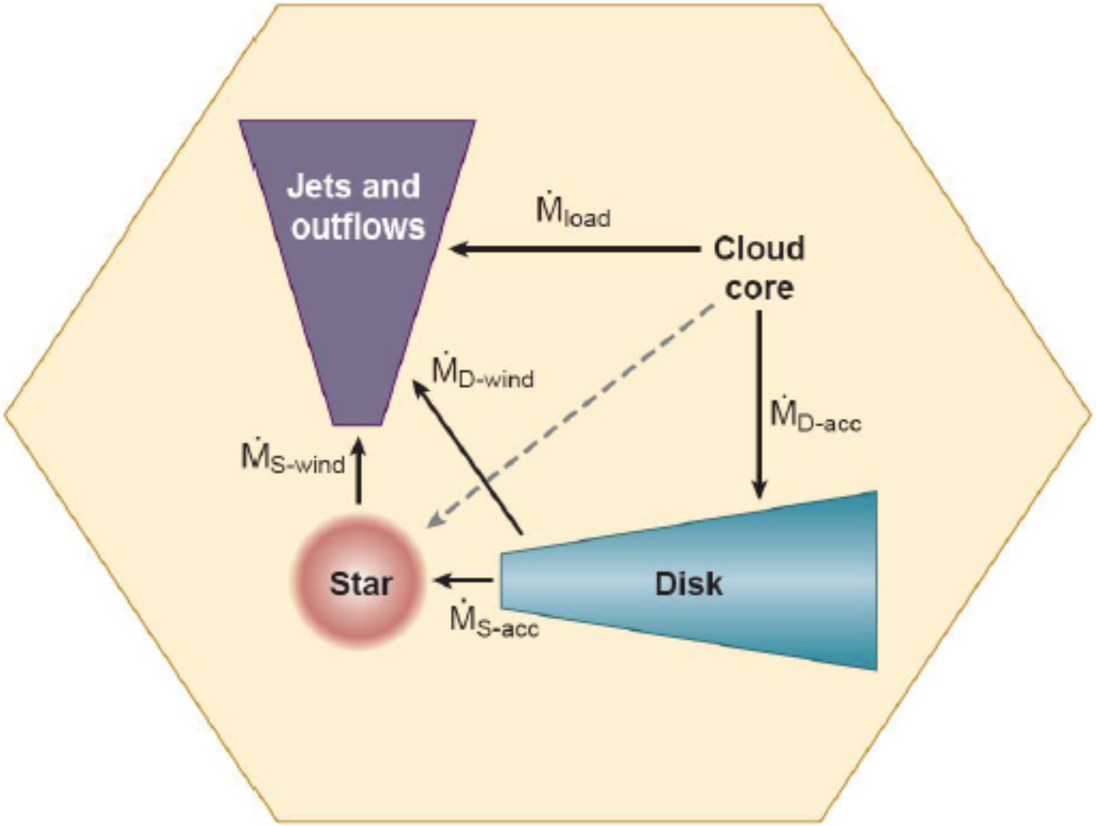


Zinnecker & Yorke 2007

An organizing diagram: accretion and mass loss

Gas exchange between cloud core, accretion disk and star:

- Mainly collapses into disk -some intercepted by outflows (disk wind, photoevaporative disk wind, stellar wind)
- Jets and disk outflows can clear cavities *before* radiation pressure from star, or stellar winds

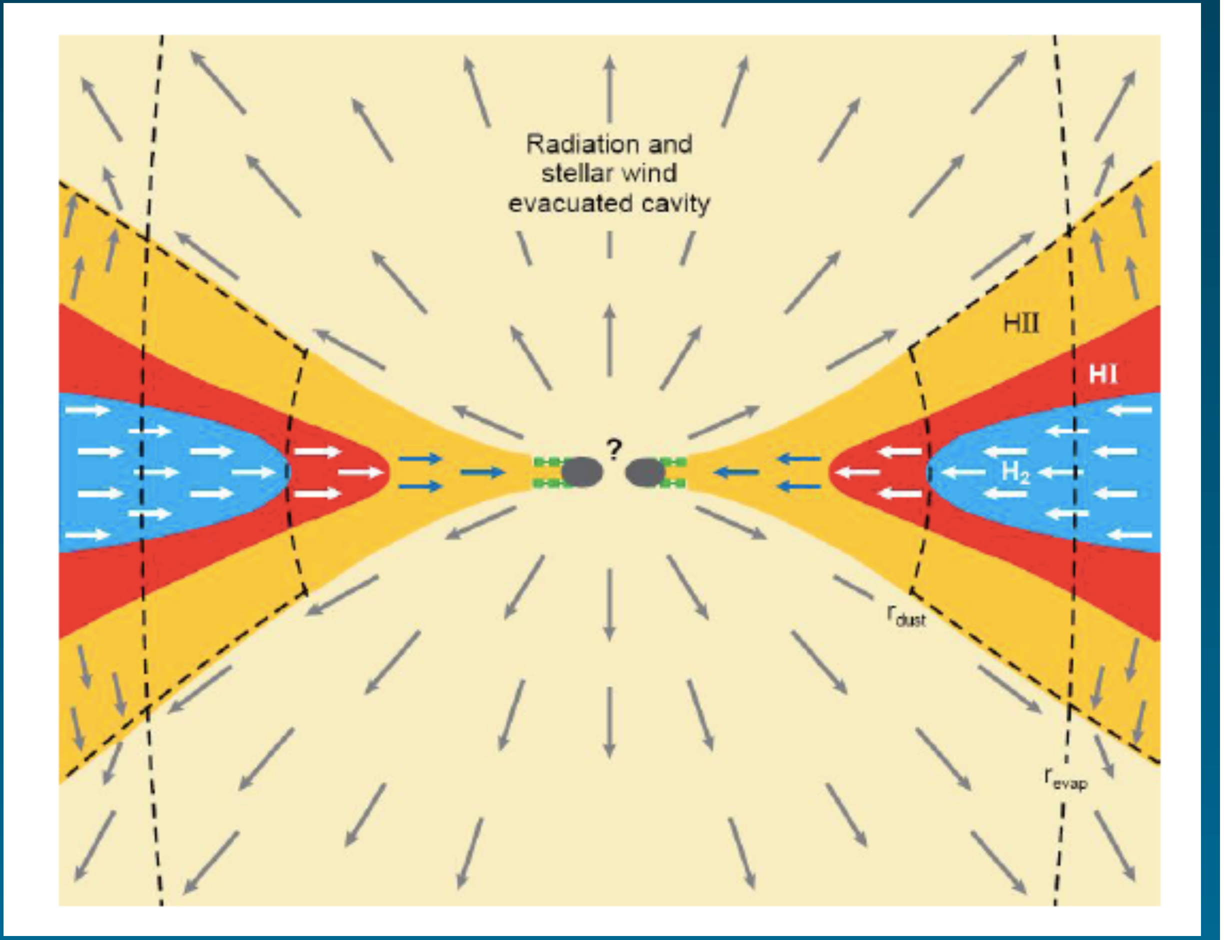


Zinnecker & Yorke 2007

Disk accretion and massive star formation

Inner disk:

- Polar cavity evacuated by radiation and wind (from disk and star)
- Disk surface layer is ionized (HII) by EUV. Self shielding gives rise to inner HI heated by FUV. Dust / molecules shield interior from FUV allowing cold H_2
- Dust destruction front r_{dust} (little opacity inside this region
- Photoevaporative outflow beyond r_{esc}



Zinnecker & Yorke 2007

II. Recent Observations

Sites – massive cores in filaments

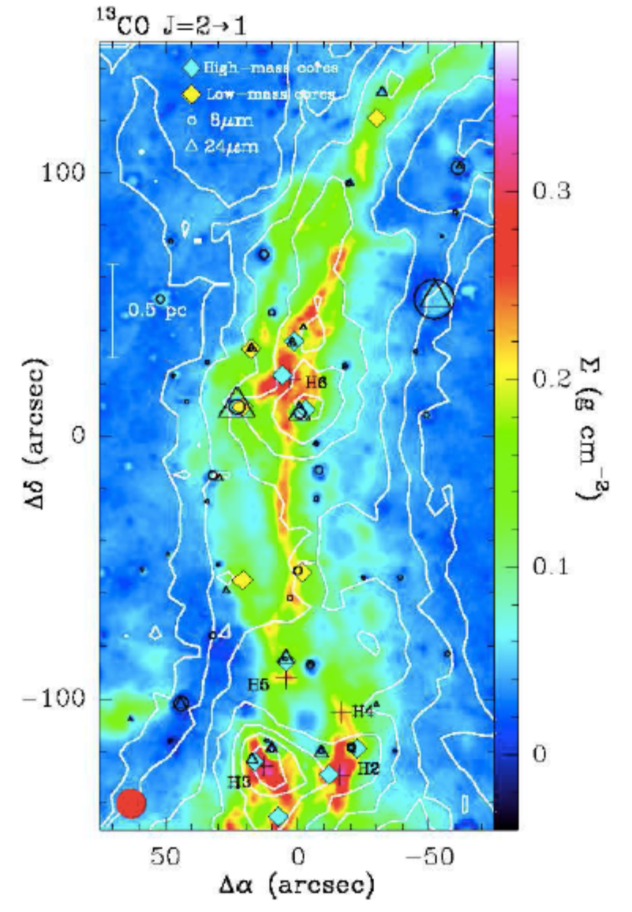
What determines max mass of stars?

> 150 M_{sun} (Crowther + 2010)

Infrared Dark Clouds (cold and dense) good for finding massive star formation

Core accretion picture for massive stars?

- In IRDC clouds M_{core}~$100M_{Sun}$ in 0.1pc

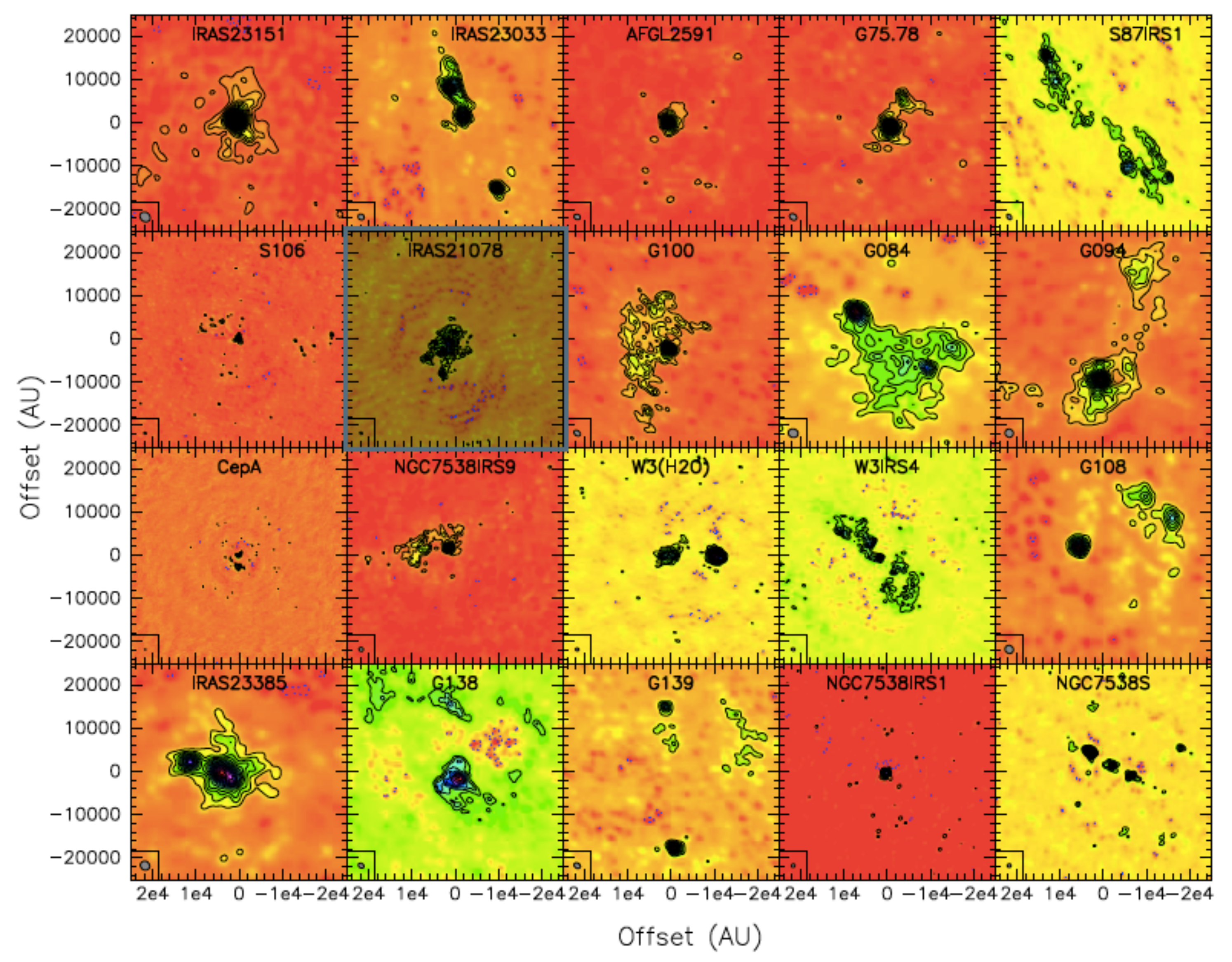


^{13}CO observations of G035.39-00.33 – crosses are high mass cores (from Jimenez-Serra + 2014)

Close- ups: CORE Survey of 20 massive star forming regions see http://www.mpia.de/core/

Noema millimetre array + IRAM 30m;

- L > 10^4 L_{Sun}
- 1.3 mm continuum -
@ 0.3-0.4” res.



Beuther, Ahmadi, Mottram, Bosco, Klaasen, and CORE Team 2017

Questions – and Properties

Explore clumps in which high mass stars form:

- How turbulent are these regions?
- How fragmented are they?
- Rotating structures and outflows related to massive star formation?
- Are outflows present?
- Chemical processes unique to high mass sf?

First results:

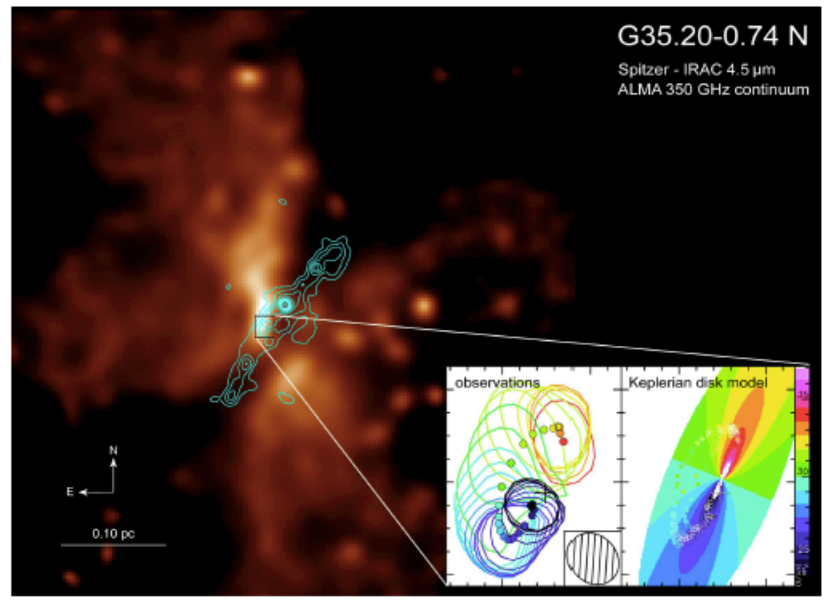
- Fragment masses from 0.1-40 M_{sun}, high column densities (10^{23} – 10^{25} cm^{-2}), densities 10^{6} – 10^{8} cm^{-3}
- Separations of cores ~ 1000 AU ~ Jeans scale -> turbulence plays a secondary role
- High B field measured in 2 regions with low fragmentation (B fields support regions against collapse): (Chen+ 2012, Frau+ 2014)

Disks around massive stars

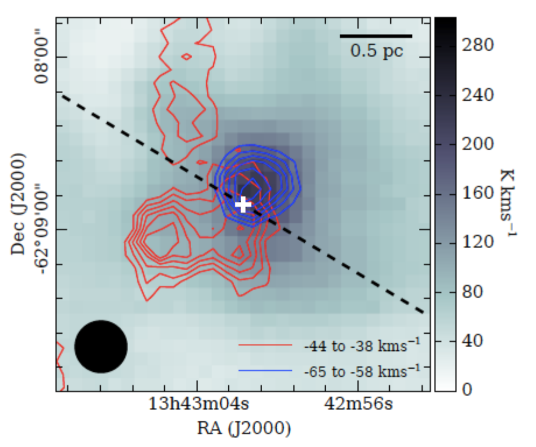
Keplerian disks observed around 8-30 M_{sun} stars (review: Bertran & De Witt 2013)

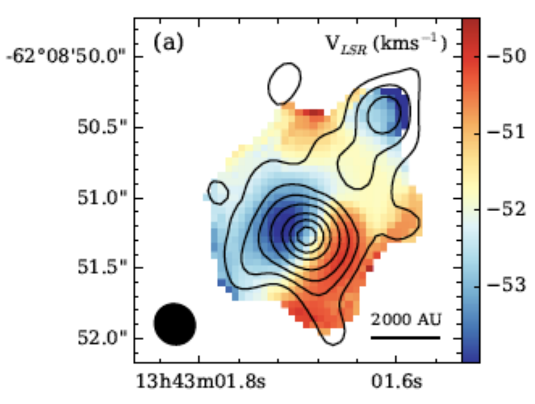
Disk radii ~ few 1000 AU, masses from 4 to a few 10s of M_{Sun}

Core-accretion picture favoured? (Myers & Fuller 1997, McLaughlin & Pudritz 1997, McKee & Tan 2002)..



Best fit is Keplerian disk; velocity peaks of different tracers: (Sanchez-Monge + 2013)





ALMA maps: Keplerian disk around forming O7 star in AFGL 4176 mm1:

25 M_{sun} star, with 12 M_{sun} disk.

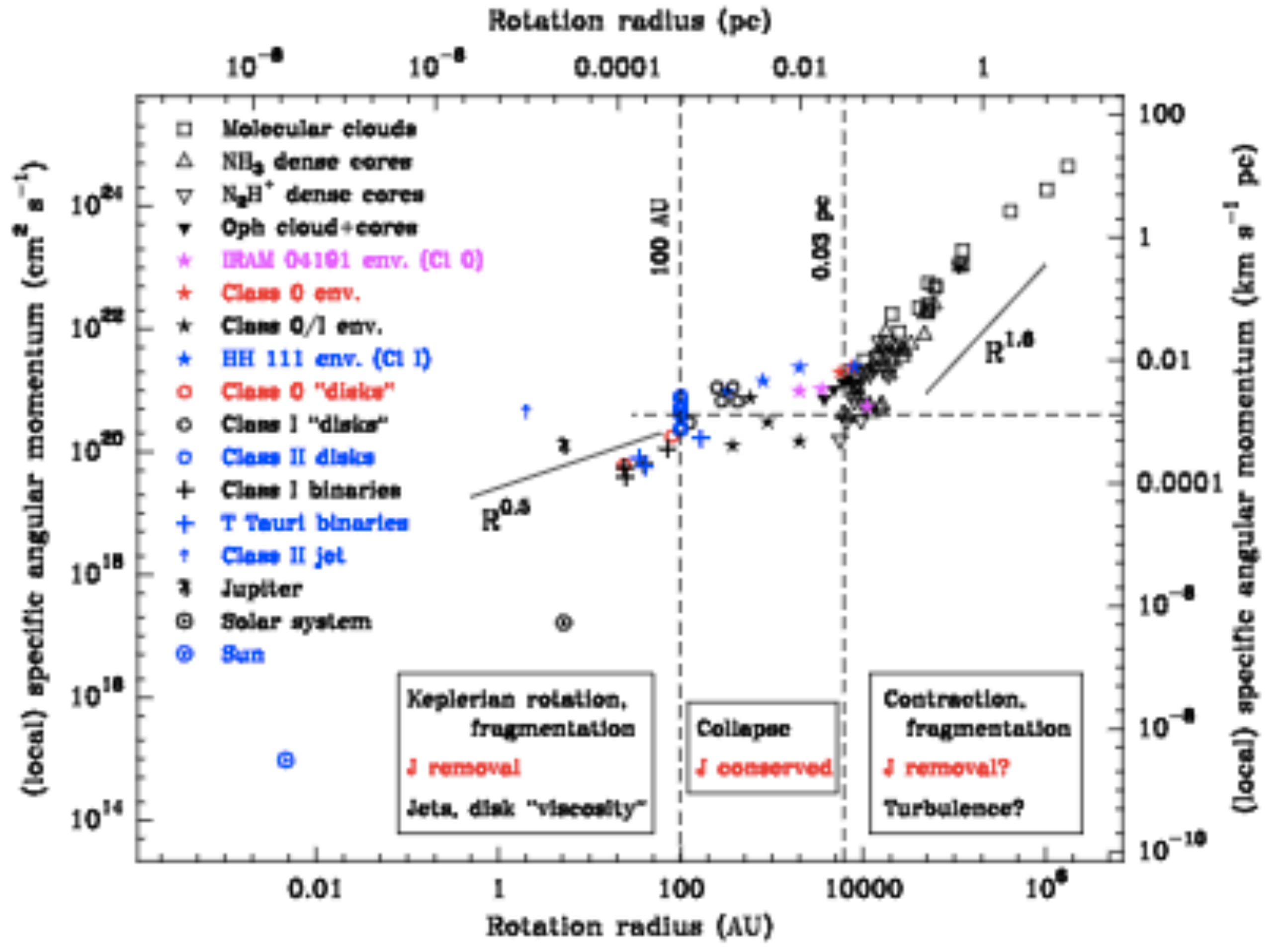
Top: outflow perp to disk
Bottom: CH_3CN (J=13-12)
(Johnston + 2015)

Observed angular momentum distributions

Cloud to YSOs: Specific angular momentum j as a function of scale and YSO evolutionary stage:

- j conserved on core infall scales

- Keplerian inside 100 AU



Belloche 2013

II Theory and Simulations

Theory: turbulence, gravity and fragmentation

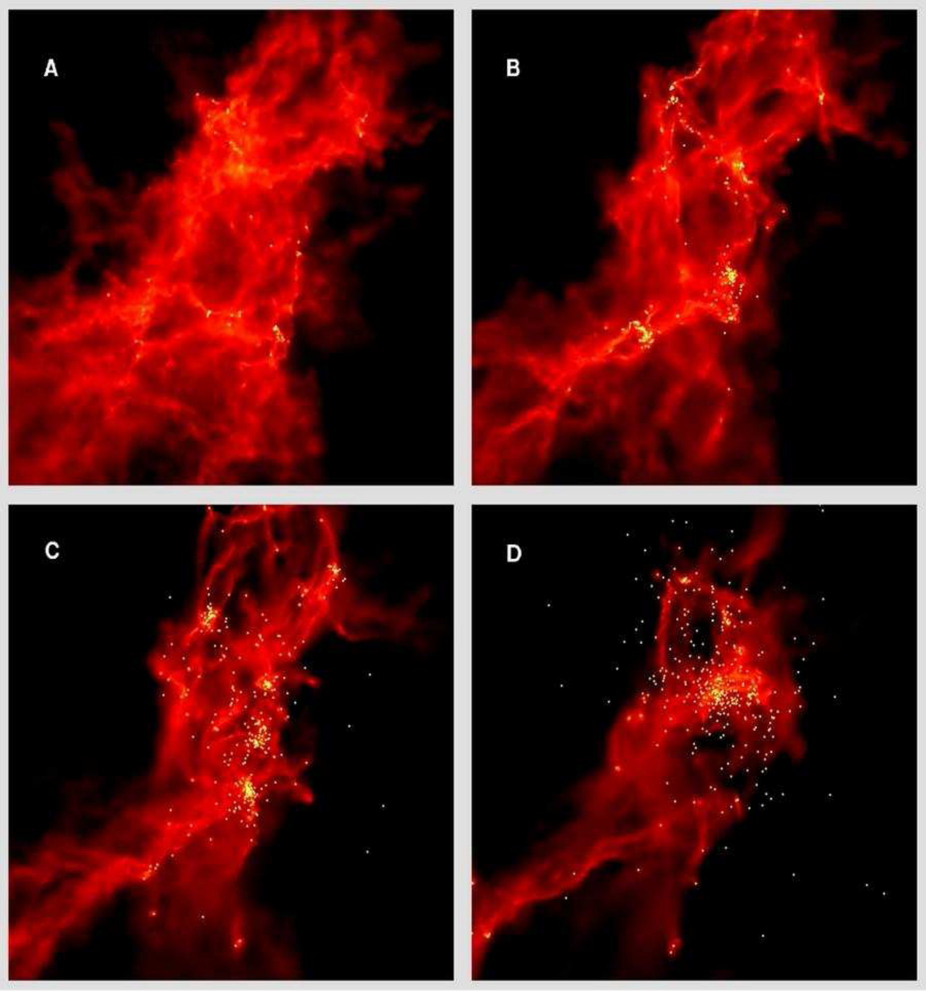
Turbulence, filaments, and turbulent fragmentation

-Theory; eg. Larson 1981; Elmegreen & Scalo (2003)

-Reviews: eg. MacLow & Klessen 2004; McKee & Ostriker 2007; Bonnell et al 2007

- Simulations; Porter et al 1994; Vazquez-Semadeni et al 1995, Bate et al 1995, Klessen & Burkert 2001; Ostriker et al 1999, Padoan et al 2001; Tilley & Pudritz, 2004,2007; Krumholz et al 2007, Federrath et al 2010,…

Shocks dissipate turbulent support as t^{-1} (eg. Ostriker 2001)



Bonnell et al (2003)

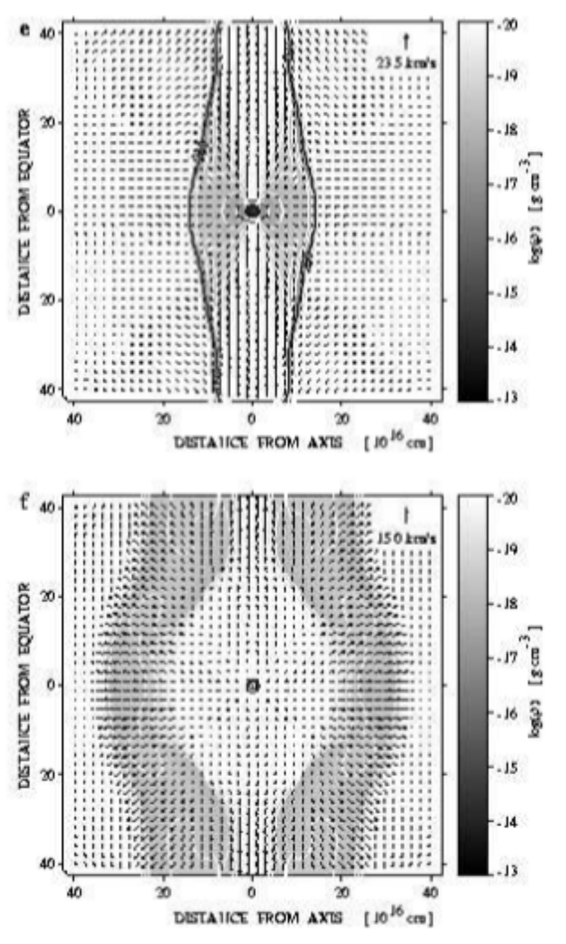
Massive star formation – how do you make a 150M_{Sun} ?

-1D sims give M_{max} ~ 40 M_{sun} independent of core mass > 60 M_{sun} (Kuiper + 2010).

Disk accretion -> asymmetry to radiation field (Nakano 1989) - "flashlight" effect (Yorke & Bodenheimer 1997)

- 2D disk sim, multifrequency FLD but unresolved dust sublimation front;
  - similar mass limit (Yorke & Sonnalter 2002): Disk in 120 solar mass case quickly destroyed

The problem: need to resolve dust sublimation region!



Yorke & Sonnalter 2002

Pure FLD vs Hybrid Radiative Feedback

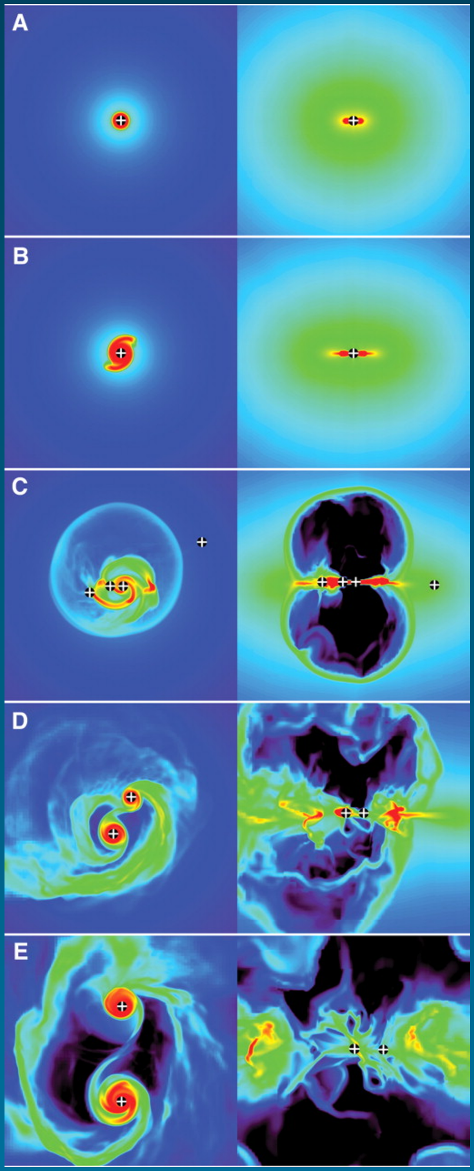
(Krumholz+2009 – Kuiper + 2010)

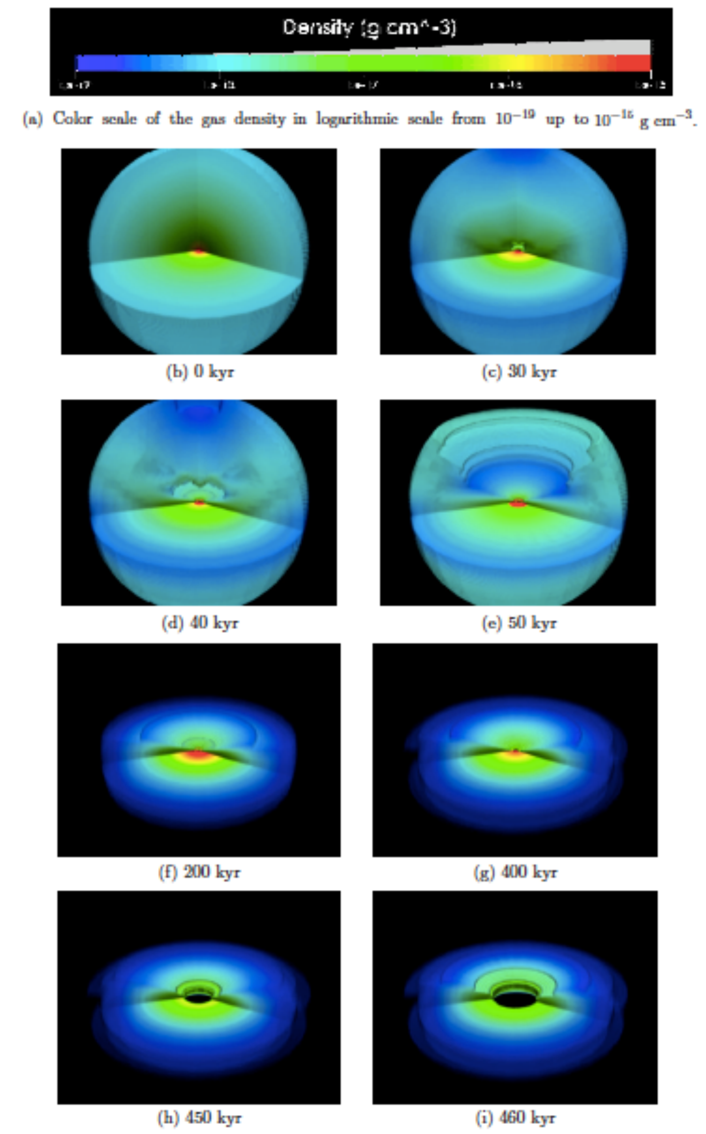
Pure FLD in a 3D AMR code: initial 100 M_{sun} core, $r^{-1.5}$ density profile, no turbulence..

- R-T instabiltiies @ 41.7kyr, multiple fragmentation

Hyrbid code (ray trace + FLD) - 2D: 120 M_{sun} shown over long time 460kyr

– no R-T instabilities





(a) Color scale of the gas density in logarithmic scale from 10^{-19} up to 10^{-15} g cm^{-3}.

(b) 0 kyr (c) 30 kyr

(d) 40 kyr (e) 50 kyr

(f) 200 kyr (g) 400 kyr

(h) 450 kyr (i) 460 kyr

Radiative Feedback and Massive Star Formation

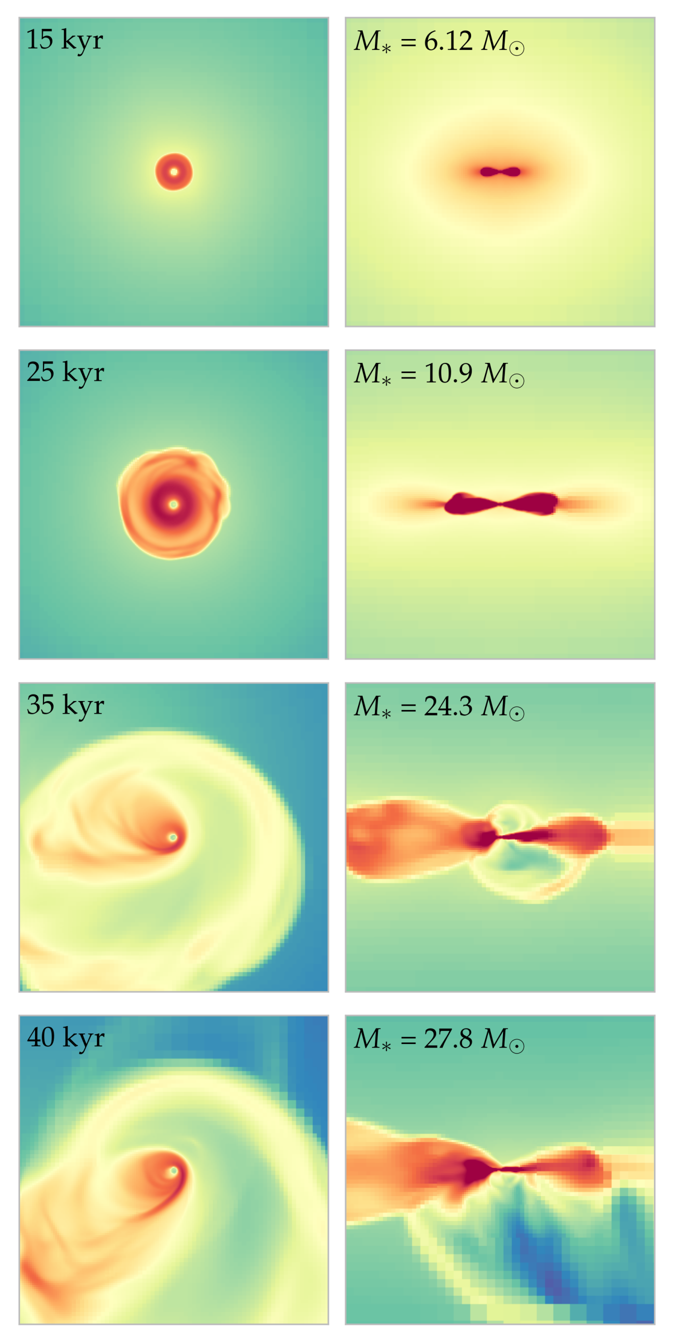
(Klassen, Pudritz, Kuiper, Peters, & Banerjee 2016, ApJ) - using Hybrid AMR FLASH radiative transfer (Klassen+ 2014)

4 stages:

- Gravitational collapse
- Disk formation - smooth
- Disk instability and massive episodic accretion
- Radiative feedback – radiatively driven bubbles

No R-T instability seen (remove ray trace and RT develops, Kuiper+2012)

No disk fragmentation up to 50kyr.



100 M_{sun} mode: left face on, right edge on

Time evolution of central “sink” (massive star) for 3 sims - 30, 100, and 200 M_{sun} cores

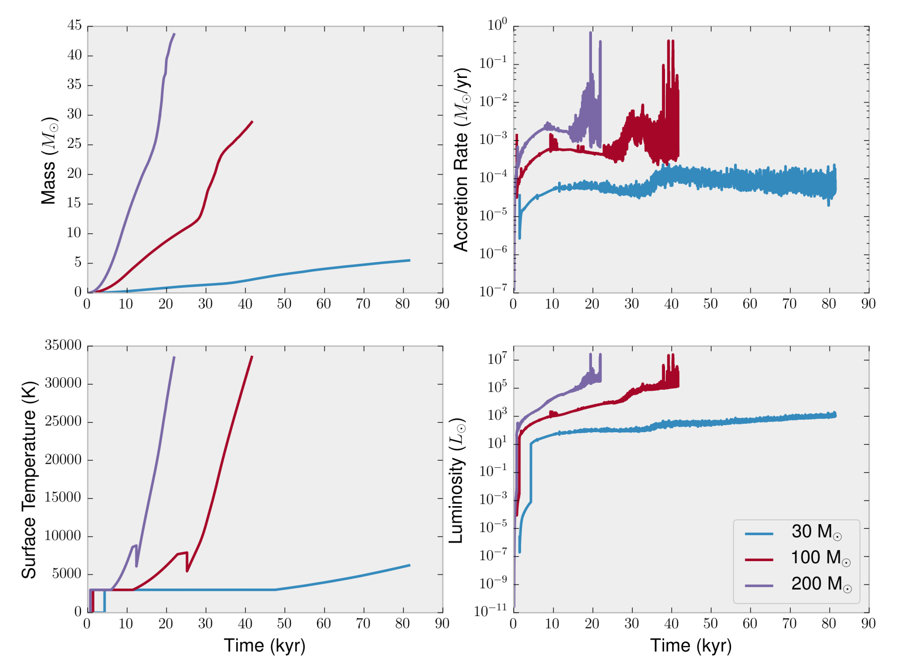
1. Initial phase of accretion:

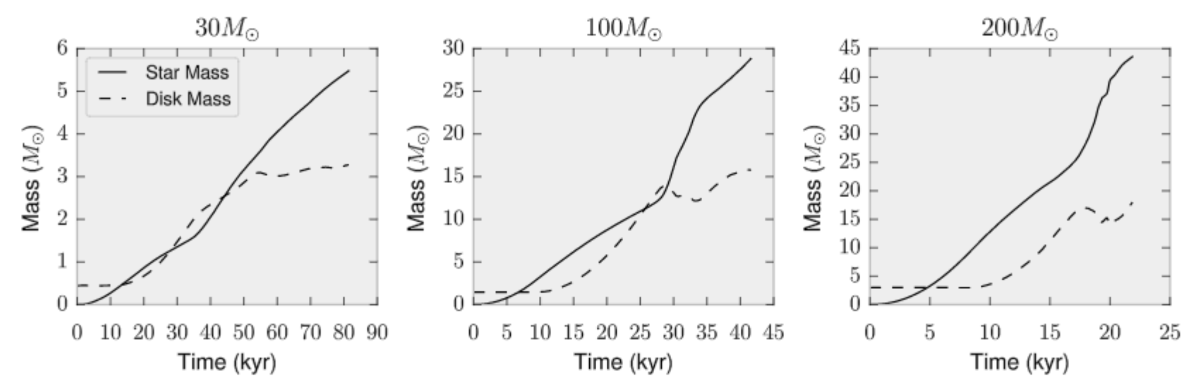
- core collapse

$dM/dt = m_o c_s^3 / G$

$m_o \sim N_J$ (number of Jeans masses) (Shu,1977 Giichidis + 2012)

2. Disk accretion - epsodic driven by onset of GI. (Vorobyov & Basu 2007). Disk mass levels out…





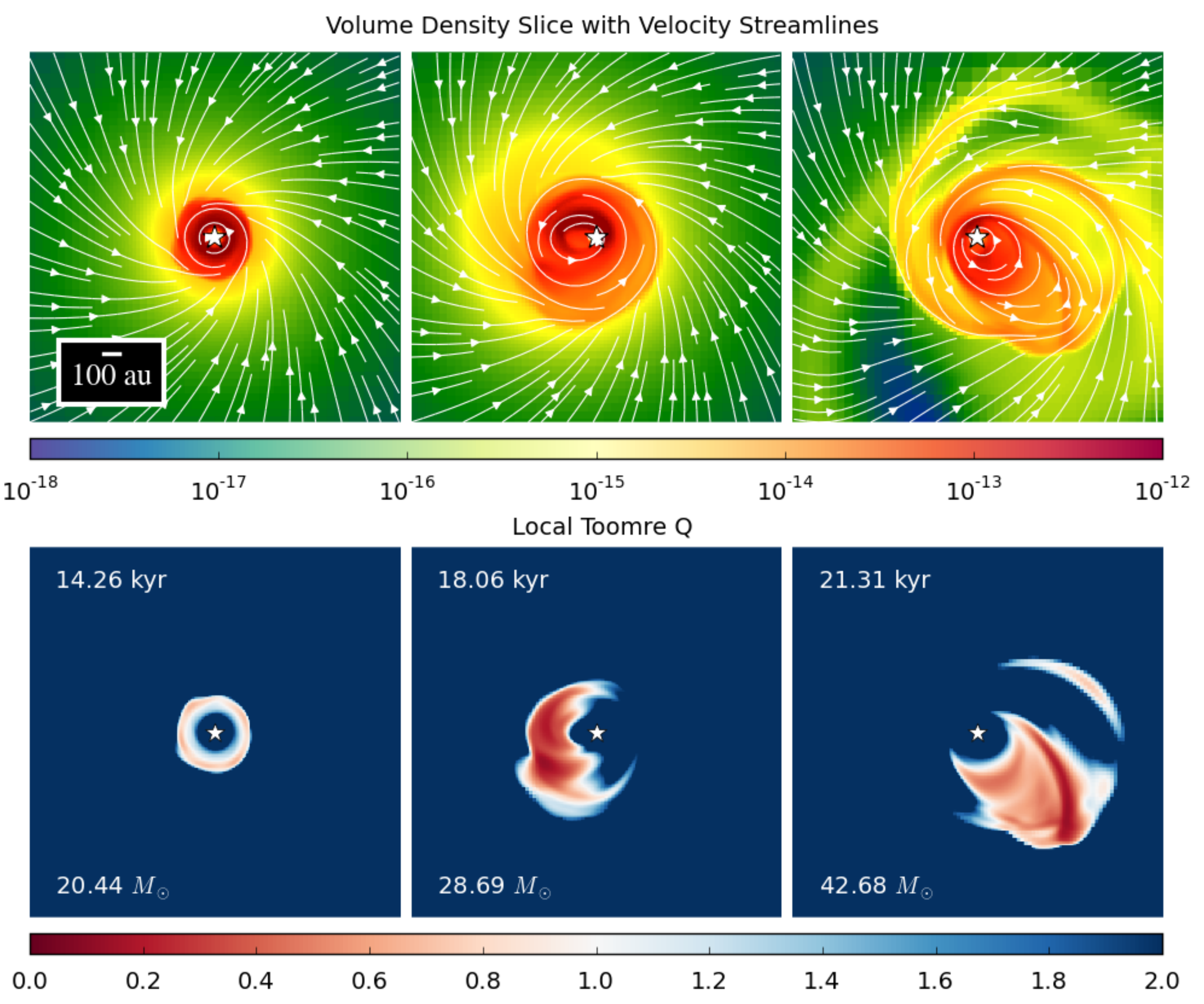
Edge- on view of collapse of 200 M_{sun} core zoom in to central region

Disk dynamics and Toomre Q

Snapshots of disk velocity field and Toomre

$Q = \kappa c_s / \pi G \Sigma$

$Q < 1$ unstable



Scale bars:

Top: Column density

Bottom: values of Toomre Q

200 M_{sun} model

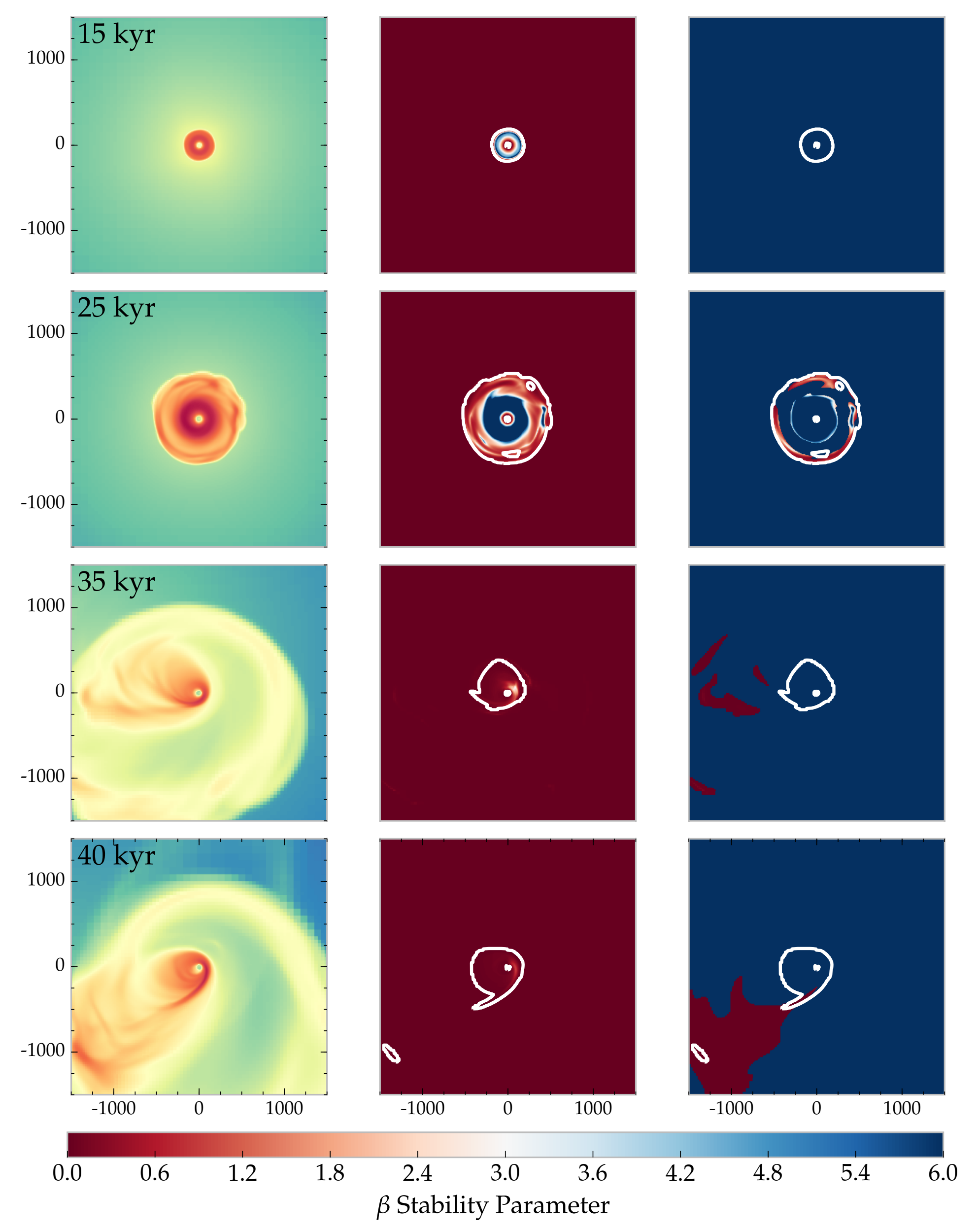
Fragmentation and cooling… mostly stable

Fragmentation of disks requires both Q< 1, AND rapid cooling (Johnson & Gammie 2003)

$t_{cool}\Omega = \beta < 1$

Middle: β map (cooling from flux radiative flux loss):

Right column: Q<1 in dark blue: maybe one fragments ~ 1000 AU



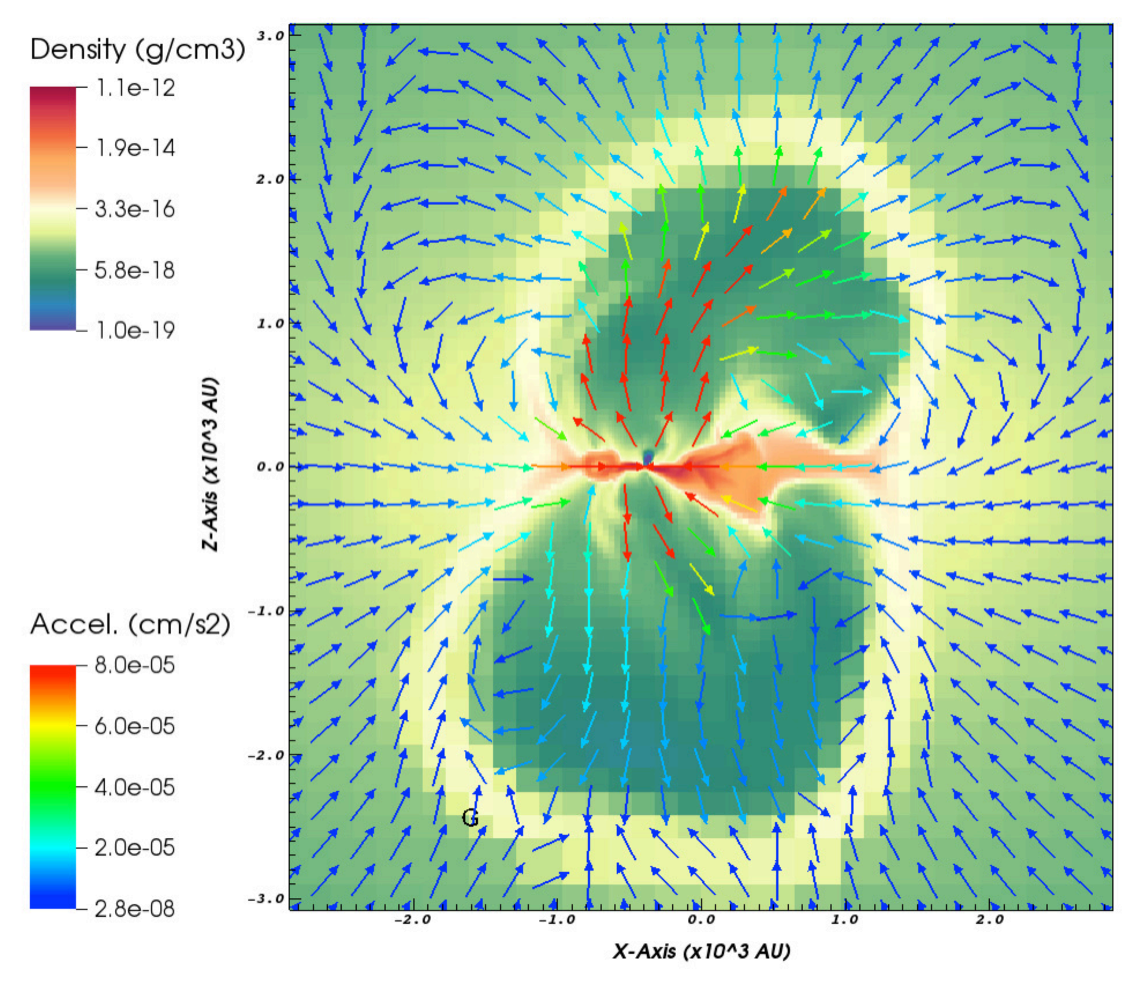
No Rayleigh- Taylor instabilities in bubble wall

R-T: light fluid supporting heavier fluid… net force must be dominated by gravity.

- Net acceleration vectors (radiation – gravity) outwards…

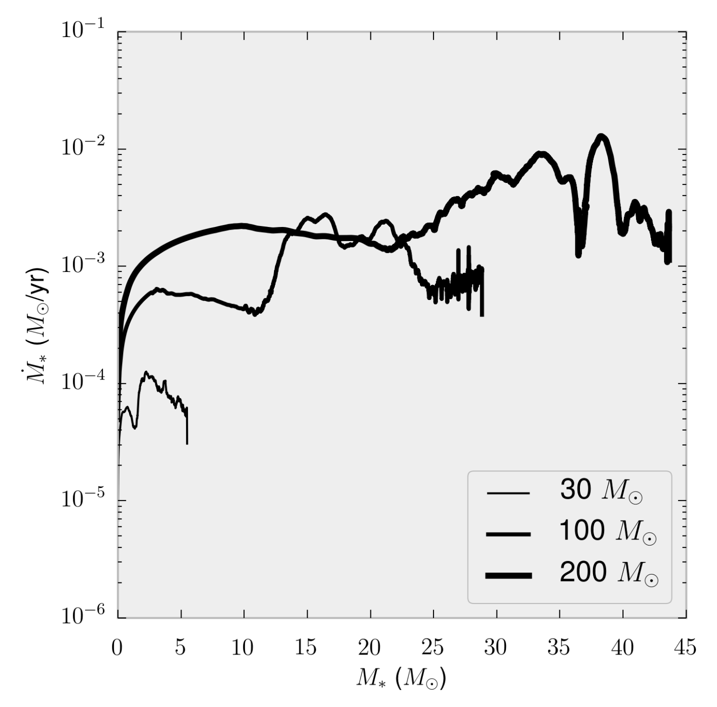
  stable.

- For reply to this using Orion hybrid code: Rosen+ 2016

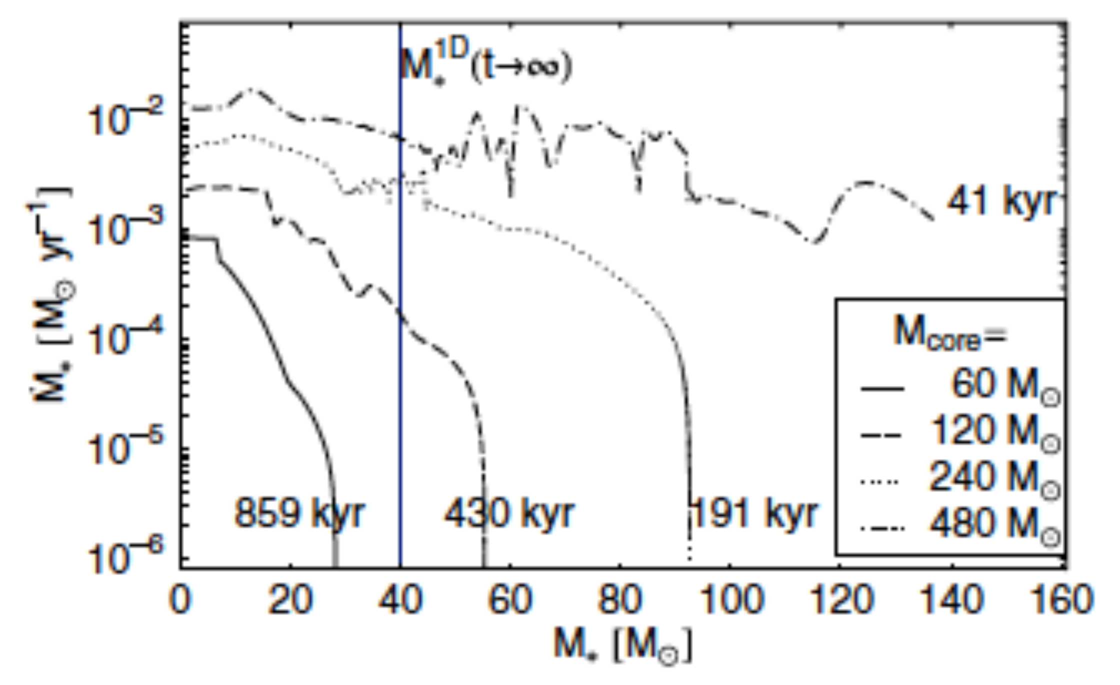


Accretion rates, mass reservoirs, and stellar masses

Only limit on stellar mass is size of mass reservoir….



Klassen + 2015 - onset of disk accretion marked

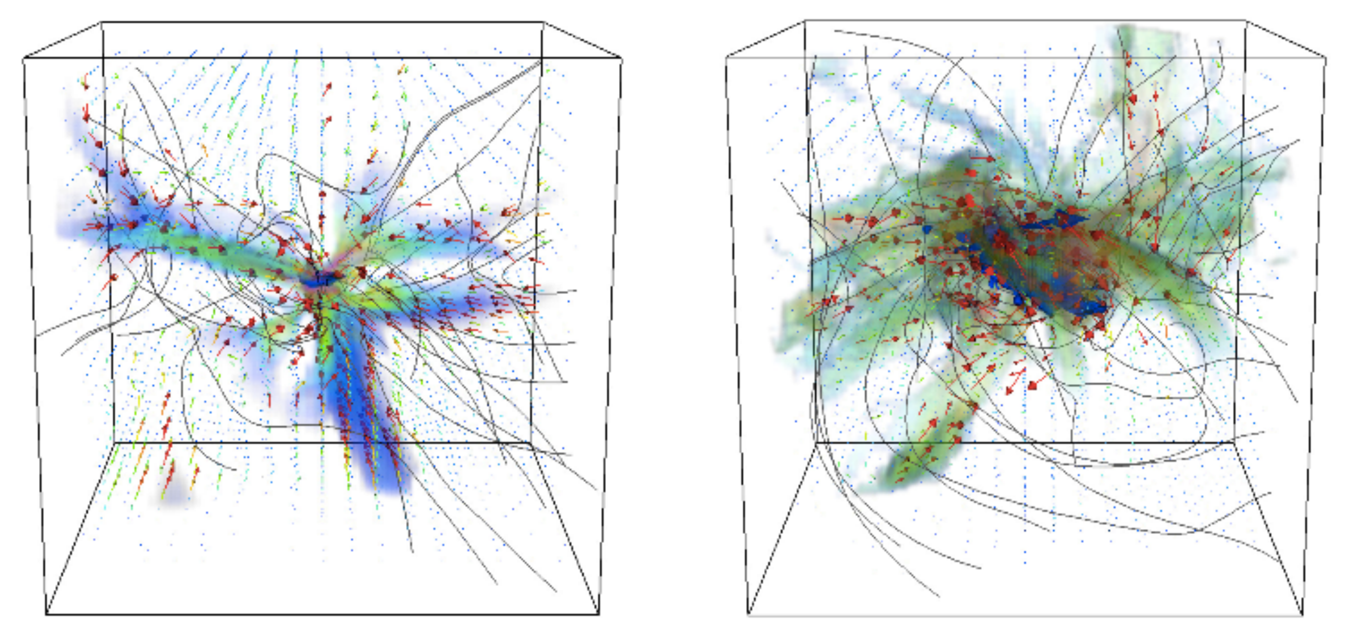


Kuiper + 2010 sims - similar trends, not as marked disk accretion increase

DISKS: turbulence + B field…

1. Quiescent rotating core with B field:
   Magnetic braking "catastrophe" NO DISK FORMS!
   (Mellon & Li 2008, Hennebelle & Fromang 2008, review Z-Y Li+ 2014)

2. Turbulent MHD – degrades torque, disk forms – accretion from a few filaments covering only 10% of area   (Seifried+2012, 2013, 2015)



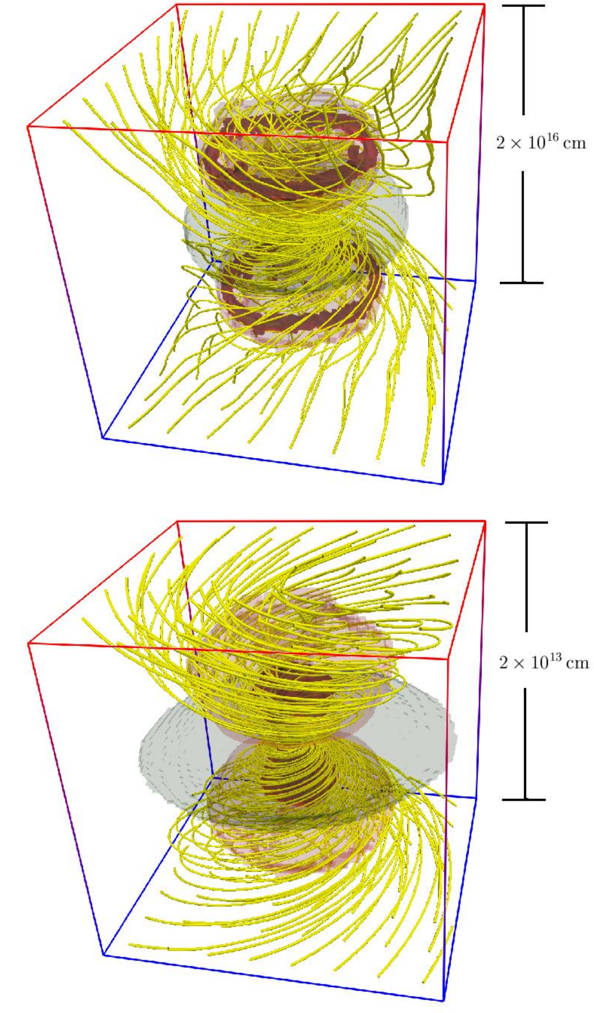
1300 AU scale, no initial rotation, velocity vectors, B (black lines), forming Keplerian disk (blue), filaments (green). Seifried, Banerjee, Pudritz, & Klessen (2015)

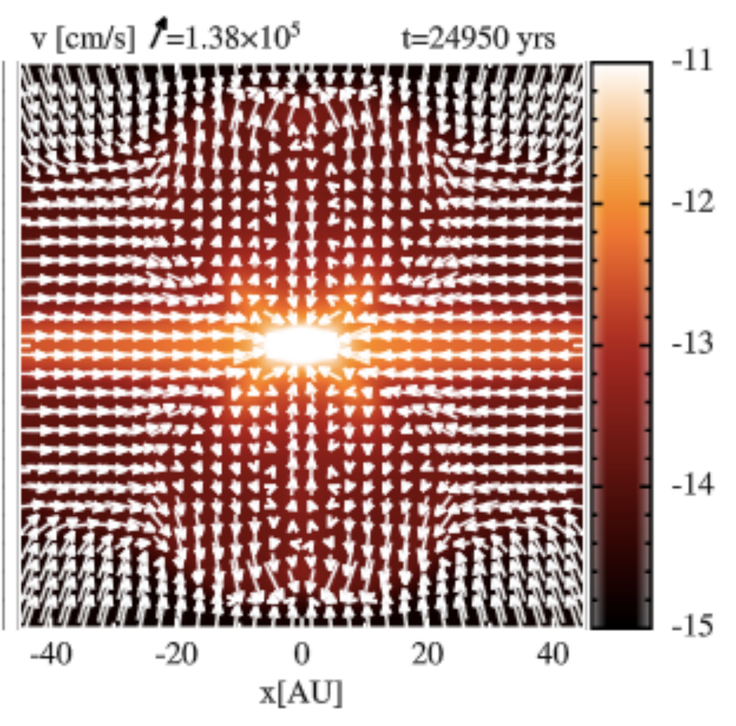
2.6   and   100 $M_\odot$

Outflows

Early stages: gravitational collapse of rotating, magnetized cores produces disks and disk winds (Banerjee & Pudritz 2006, rev. Pudritz +2007): PRECEEDS Radiative feedback…

2 components of the flow
- Upper; magnetic tower flow
- Lower; zoomed in by 1000, centrifugally driven disk wind



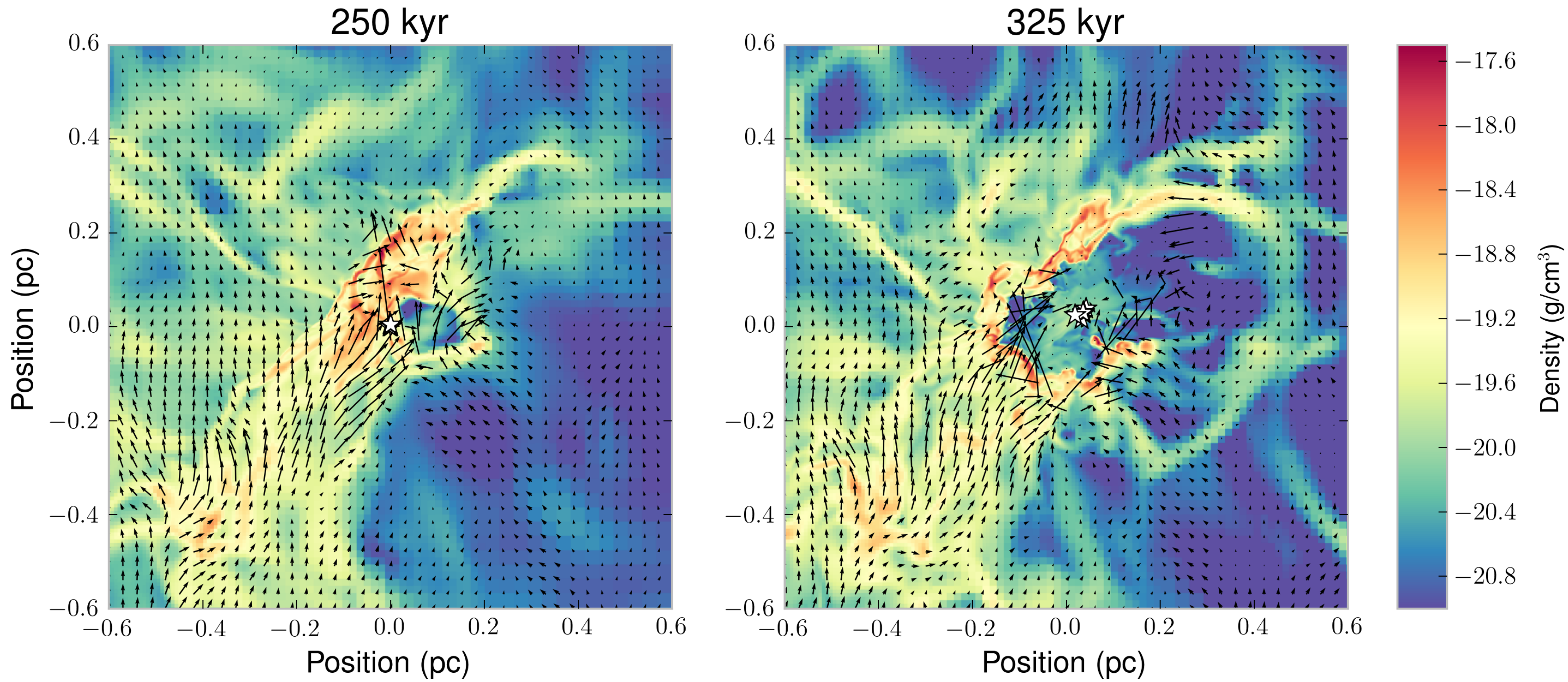


MHD outflows associated with formation of first hydrostatic core (Bate+2014)

Finite mass reservoirs:

Feedback in filamentary clouds: B and ρ in slice

(Klassen, Pudritz, and Kirk 2016, MNRA)



Bubble disrupts filament and B structure, ending filament accretion In 1200 solar mass simulation that forms a 16 M_{Sun} star.

SUMMARY

- Radiation feedback and massive star formation:

 - is likely a disk mediated process; not fallback. Gravitational instability in massive disks creates highly episodic, massive accretion bursts.

 - accretion is probably not limited by radiation – reservoir limited process.

- We still don’t really know how does cloud structure promotes formation of massive cores…

- Early outflows, if universal, probably clear out the first channels out of which radiation escapes.