Angular Momentum and the Formation of Stars and Black Holes

Richard B. Larson

Yale University

Conclusions

- Compact objects such as stars and black holes generally form in larger systems such as binaries, multiple systems, star clusters, or galaxies.

- Gravitational interactions in these larger systems play a major role in the formation of compact objects by transporting angular momentum.

- The formation of objects like stars and black holes is then a much more complex, dynamic, and chaotic process than in standard models.

- Gravitational interactions tend to couple the mass of a forming object to the mass of the system, and this may have implications for the mass ratios in binaries, the upper IMF in clusters, and the masses of the central black holes in galaxies.

The angular momentum problem

The specific angular momentum of a star-forming cloud core is 3 orders of magnitude more than the maximum that can be contained in a single star, even rotating at breakup speed.

The specific angular momentum of matter in a galactic bulge is 4 – 5 orders of magnitude more than can be contained in a maximally rotating black hole.

Questions:

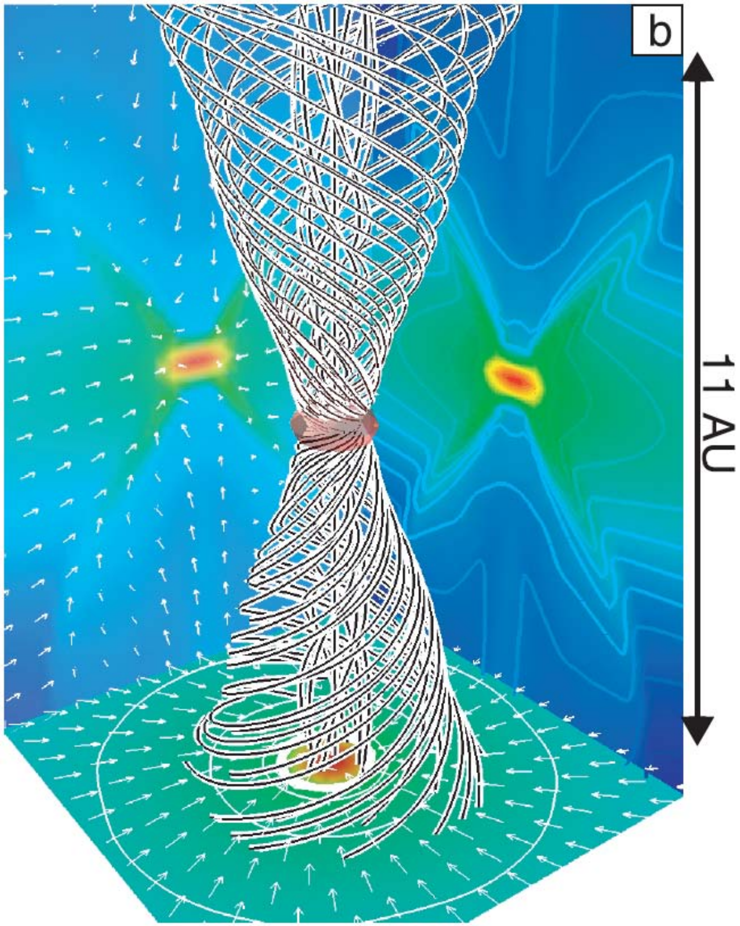
- Where does the excess angular momentum go? Into residual gas, other stars, or other objects (e.g. planets)?
- How does it get there? What processes transport it? What is the role of magnetic, gravitational, and pressure forces?

Can magnetic fields solve the problem?

- Magnetic braking can remove angular momentum from diffuse clouds, but not from their dense collapsing cores where the field decouples from the gas.

- Rotating magnetized outflows can remove angular momentum from a newly formed object or ionized inner disk region around it. →

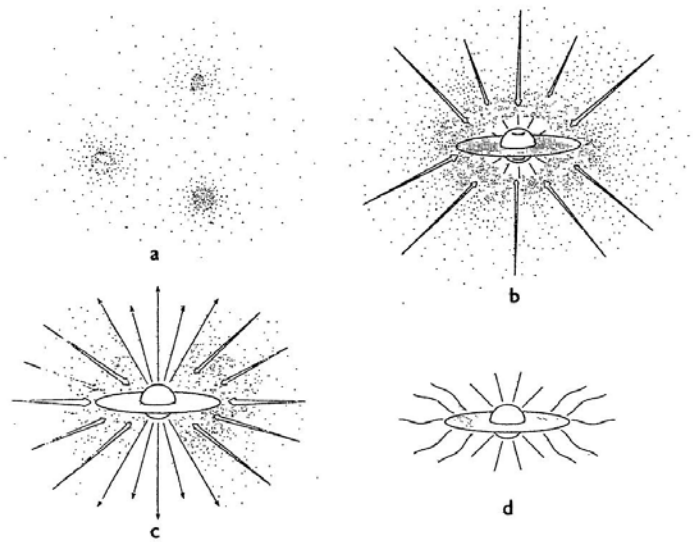
- At intermediate densities, magnetic transport is ineffective and the angular momentum of the gas must still be reduced by more than 2 orders of magnitude by other effects.



Machida et al 2007

The standard model

Most of the angular momentum goes into an accretion disk in which it is transported outward by an assumed intrinsic ‘disk viscosity’.



Shu, Adams, & Lizano 1987

Some problems:

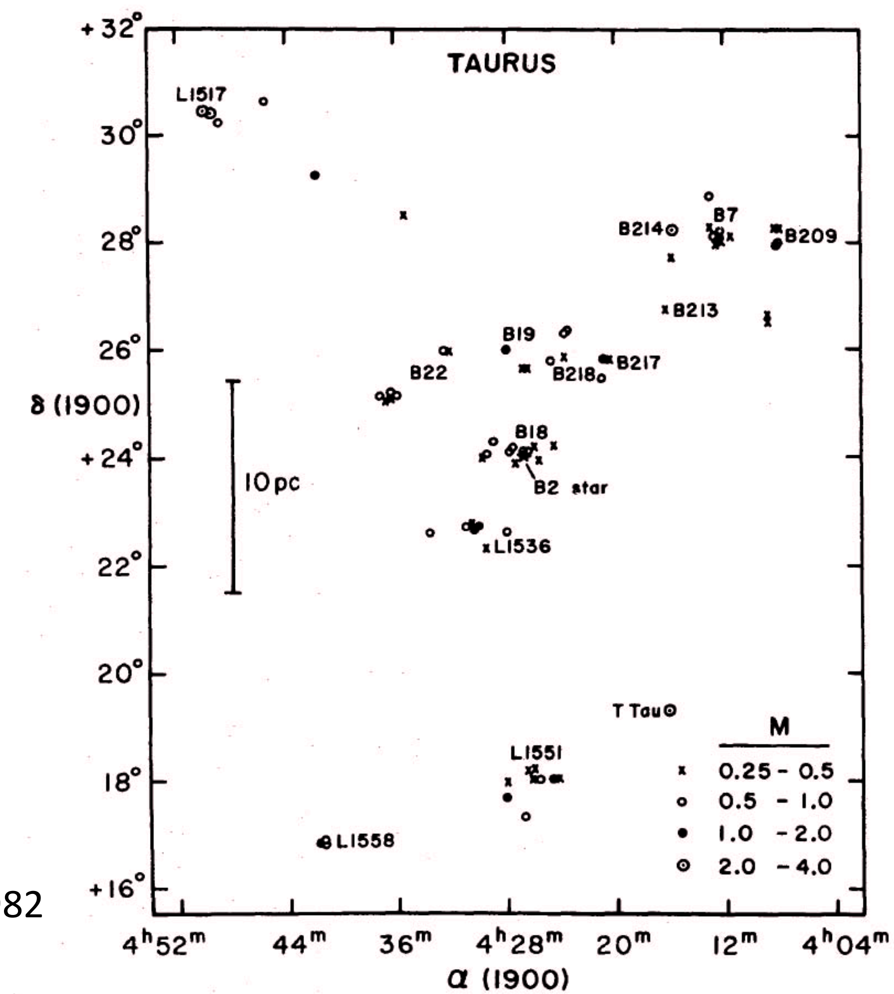
- The assumed ‘viscosity’ is problematic because all known transport mechanisms depend in some way on external circumstances (e.g. ionization).
- A very large disk is needed and transport times are very long (10^3 to 10^6 rotation periods) because disks are fragile and cannot sustain a large torque.
- Most disks probably do not last this long before being disrupted by violent interactions in a realistic system of forming stars because . . .

Most stars form in binary and multiple systems

➢ About 30% of M stars, 50% of G stars, and >70% of O stars have binary companions. This mass dependence is expected if most stars form in multiple systems that decay and preferentially eject low-mass stars.

➢ The binary frequency in some star-forming regions is up to twice that in the field.

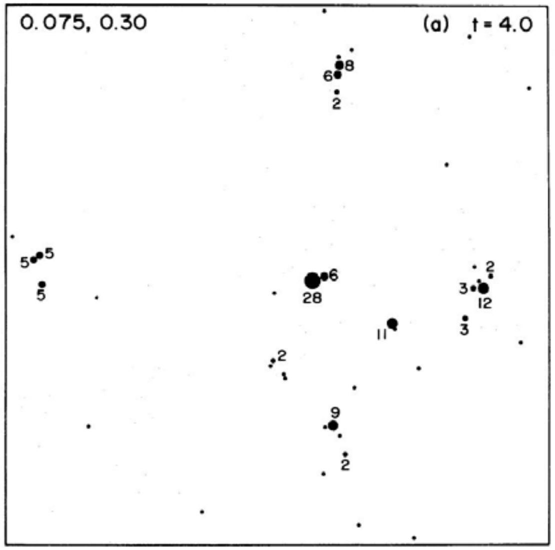
➢ Most young stars are also found in groups and clusters, possibly in a fractal-like hierarchy.



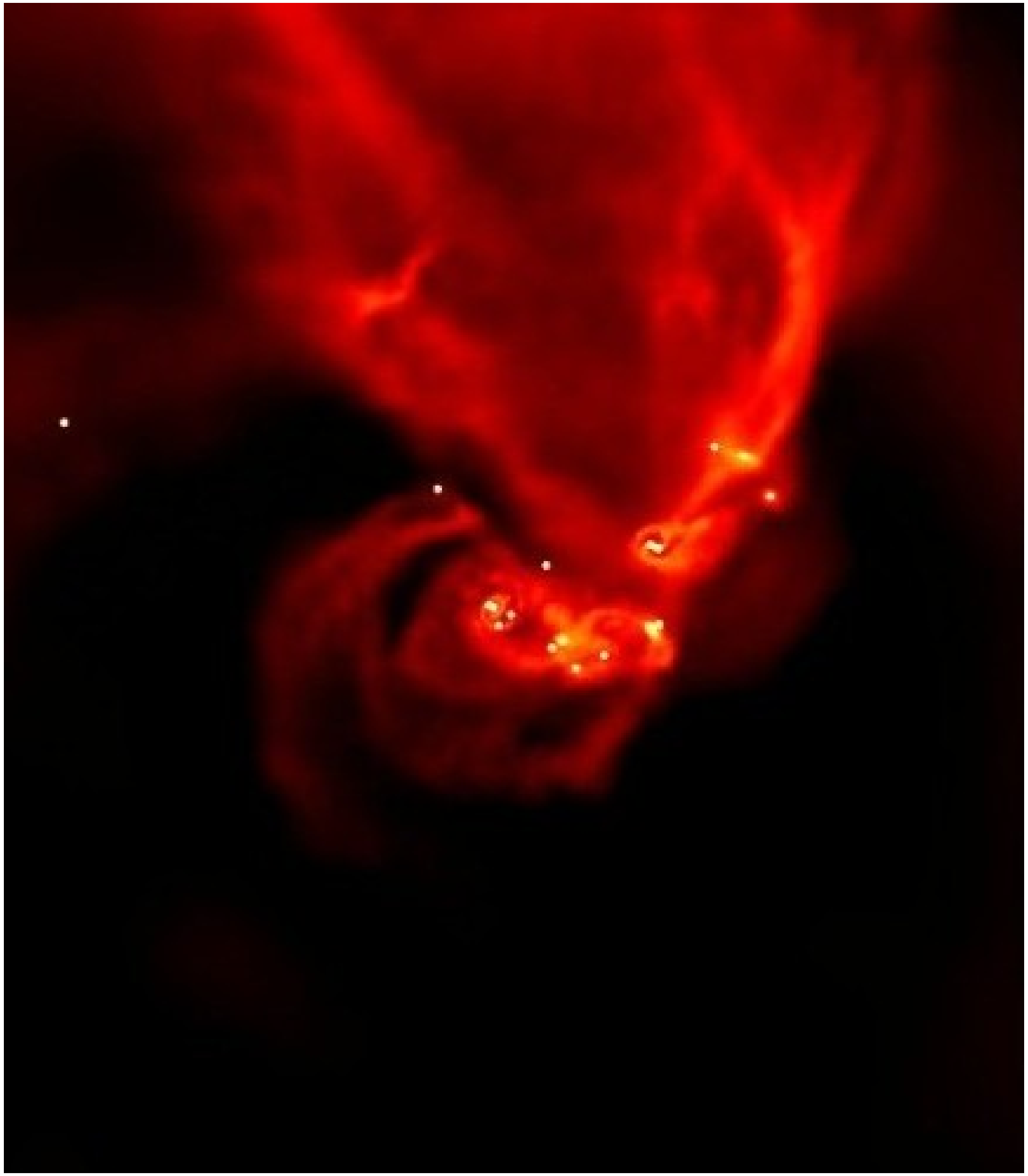
Larson 1982

3D simulations of star formation

also yield many binary and multiple systems:

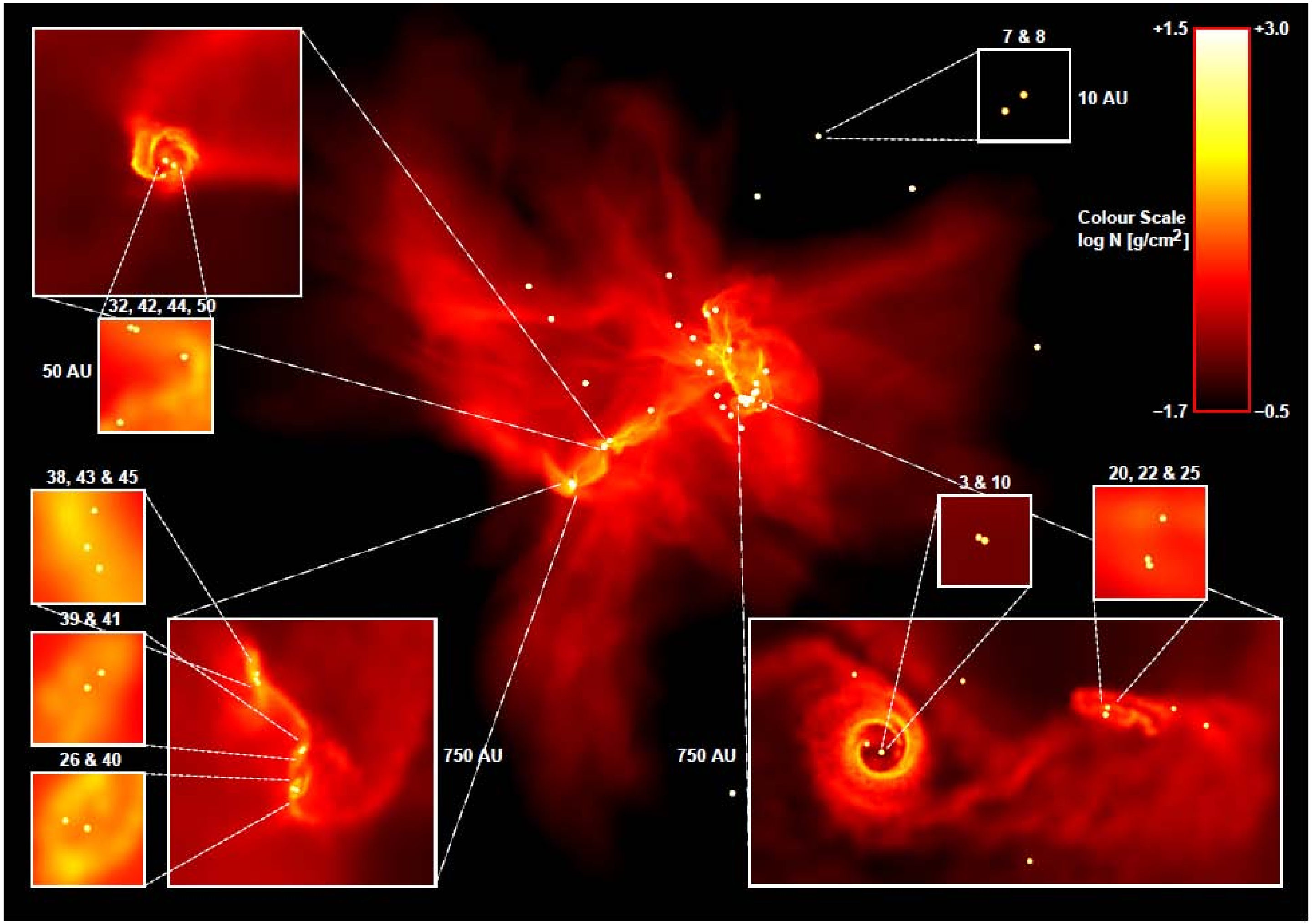


Larson 1978



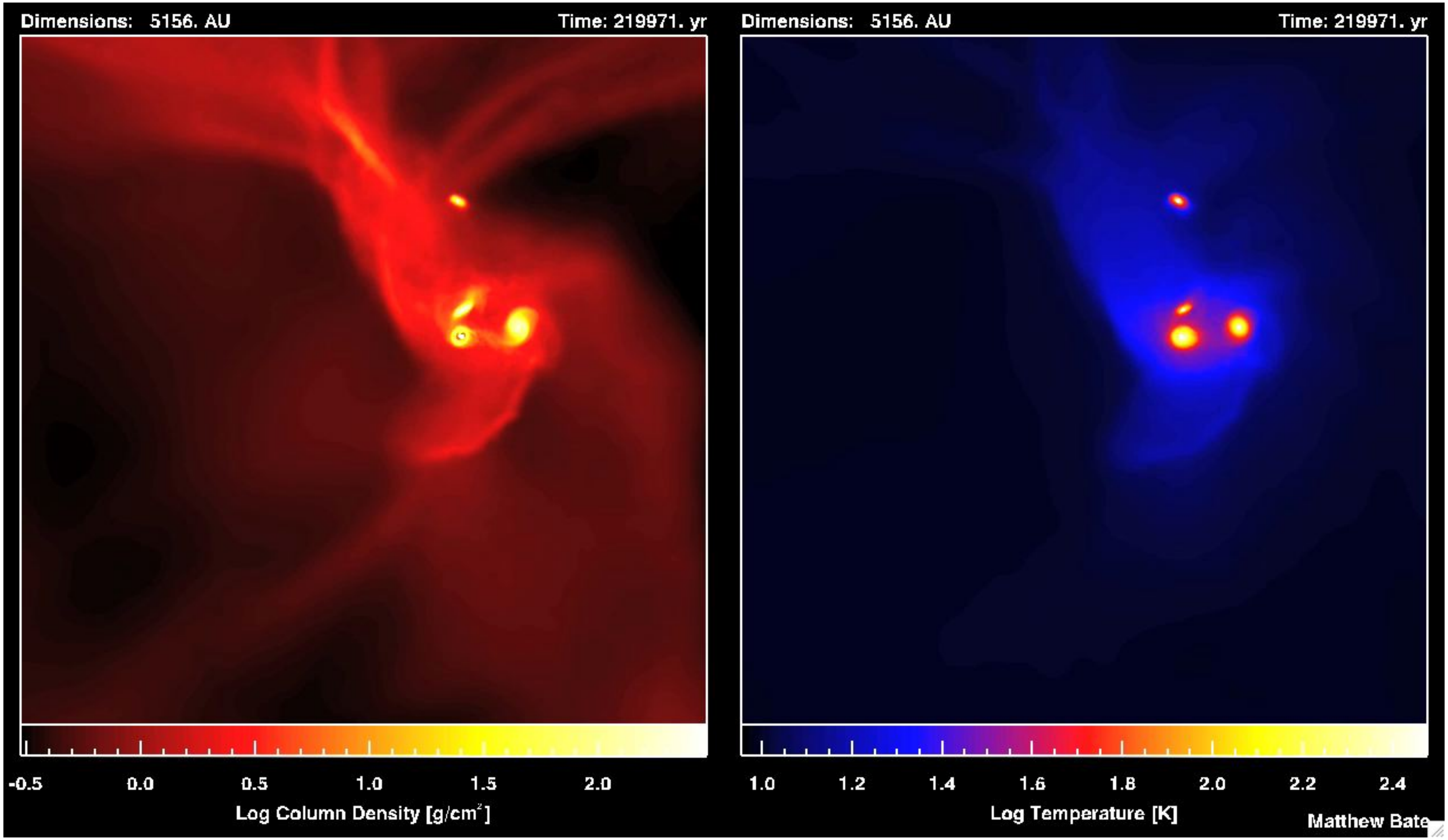
Bate, Bonnell, & Bromm 2003

The simulated binaries resemble observed ones:



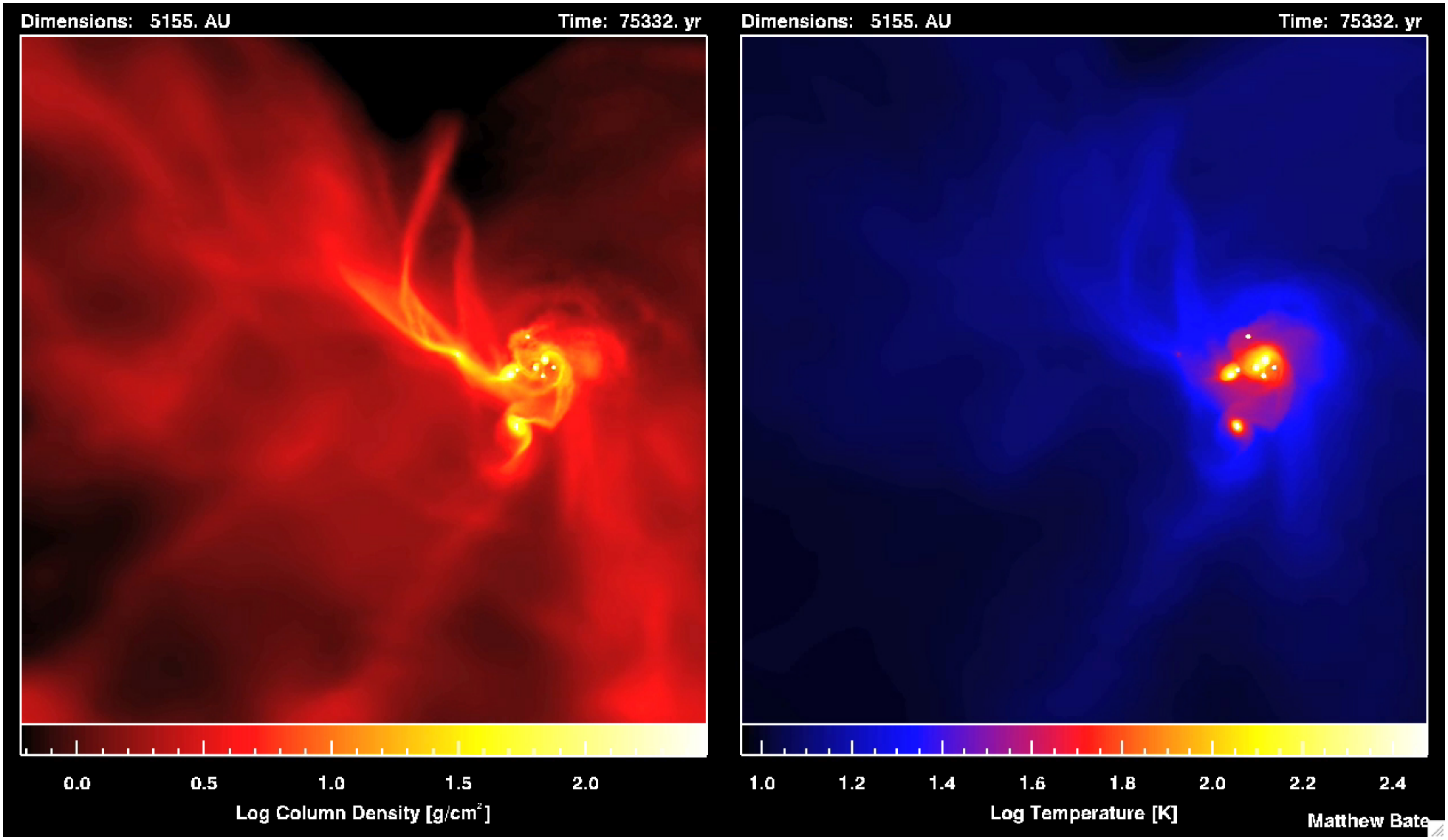
Bate, Bonnell, & Bromm 2002

Simulations including radiative heating show that tidal interactions are important in driving accretion onto forming stars:



Bate 2009b

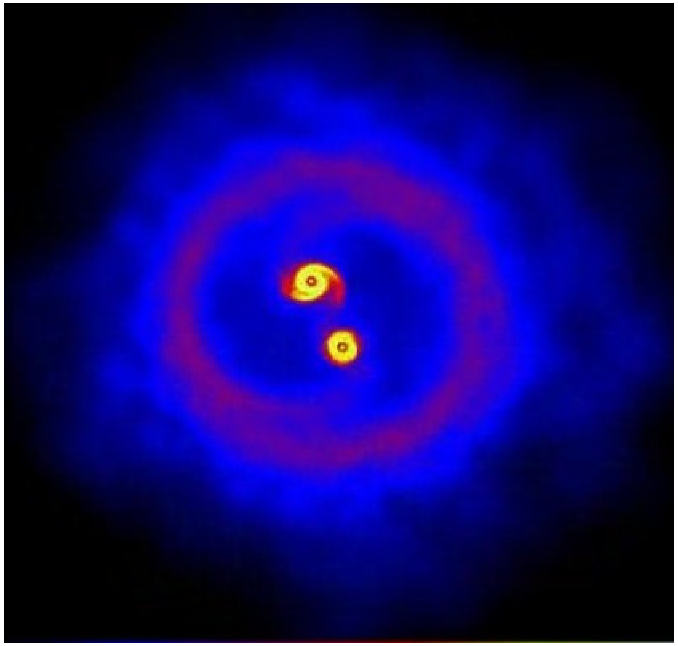
Simulations including radiative heating show that tidal interactions are important in driving accretion onto forming stars:



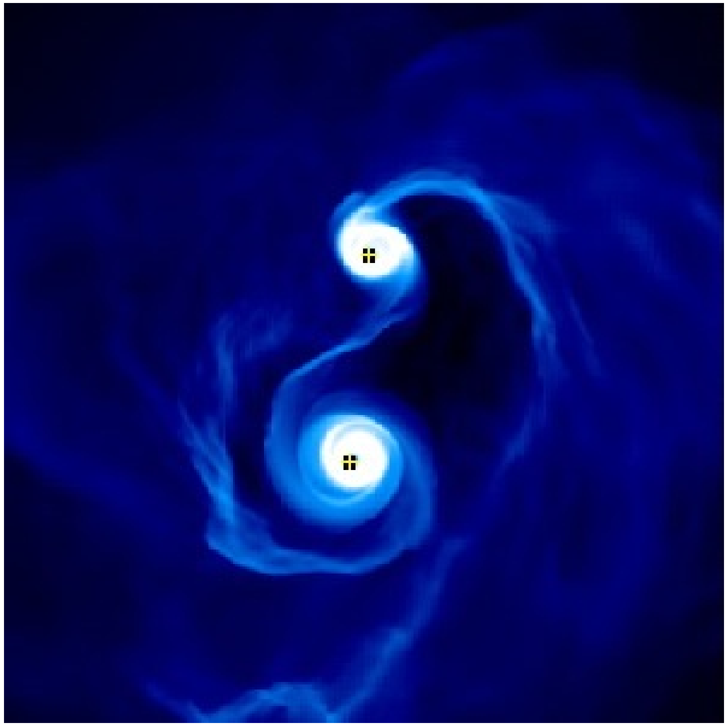
Bate 2009b

Tidal interactions

transfer angular momentum from circumstellar disks to stellar orbital motions, driving time-dependent accretion.



Bate 2000

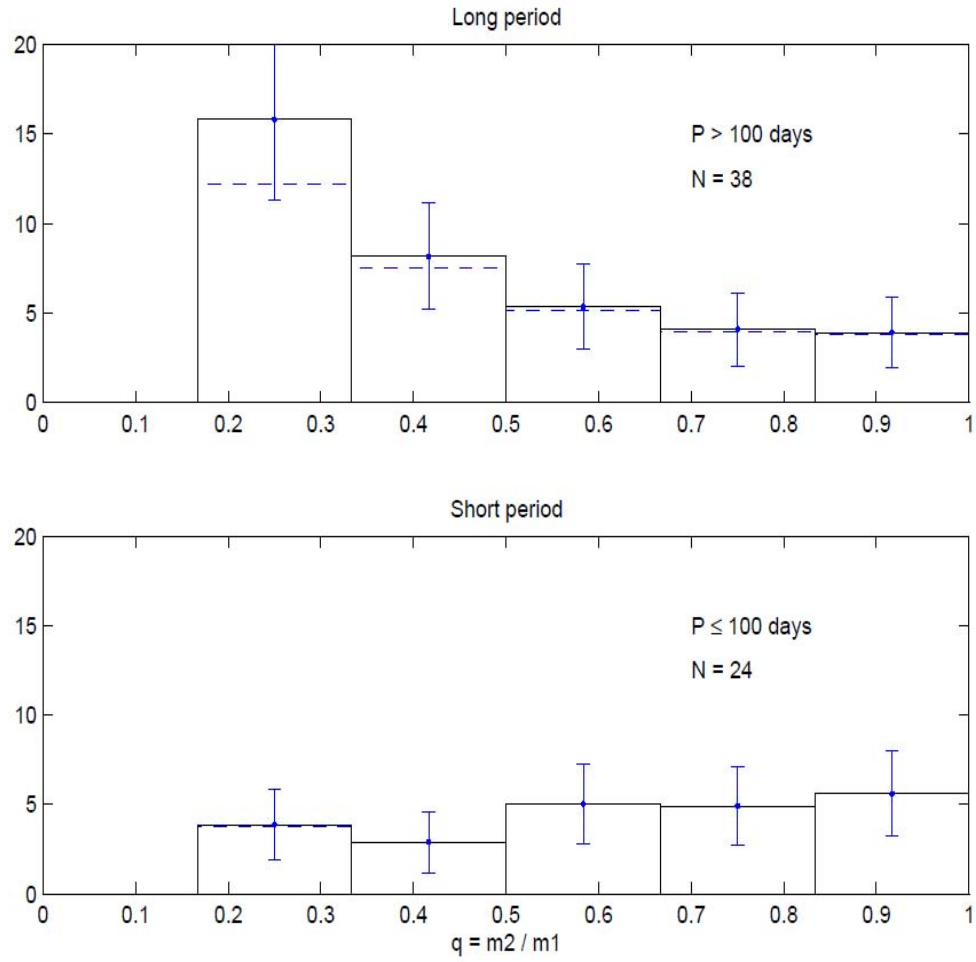


Krumholz et al 2009

Mass ratios in binaries

Tidally-driven accretion couples the masses because the less massive star tends to accrete more rapidly and the masses tend to equalize.

For close binaries, the distribution of mass ratios is roughly flat, implying a strong preference for nearly equal masses.



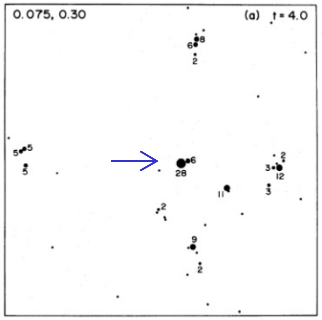
Mazeh et al 2003

Massive stars form in denser environments with more and bigger companions:

➢ The binary frequency of massive stars approaches 100%, and their companions are typically massive and close.

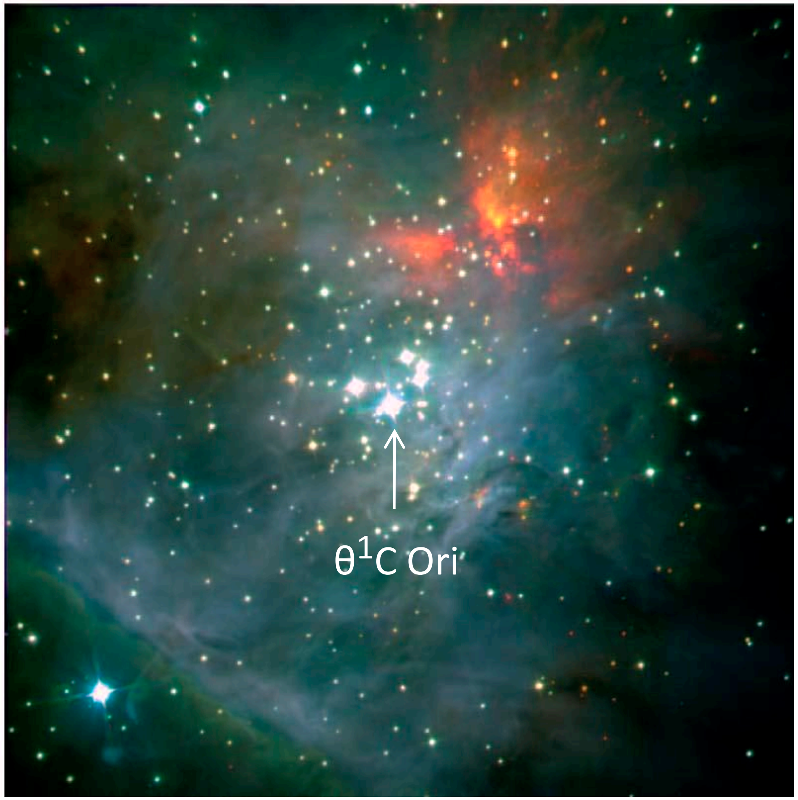
➢ Massive stars are also often in Trapezium-like multiple systems and are strongly concentrated in clusters and associations.

➢ In simulations and observations, the most massive stars are often at the cluster centers:



Larson 1978

Orion Trapezium

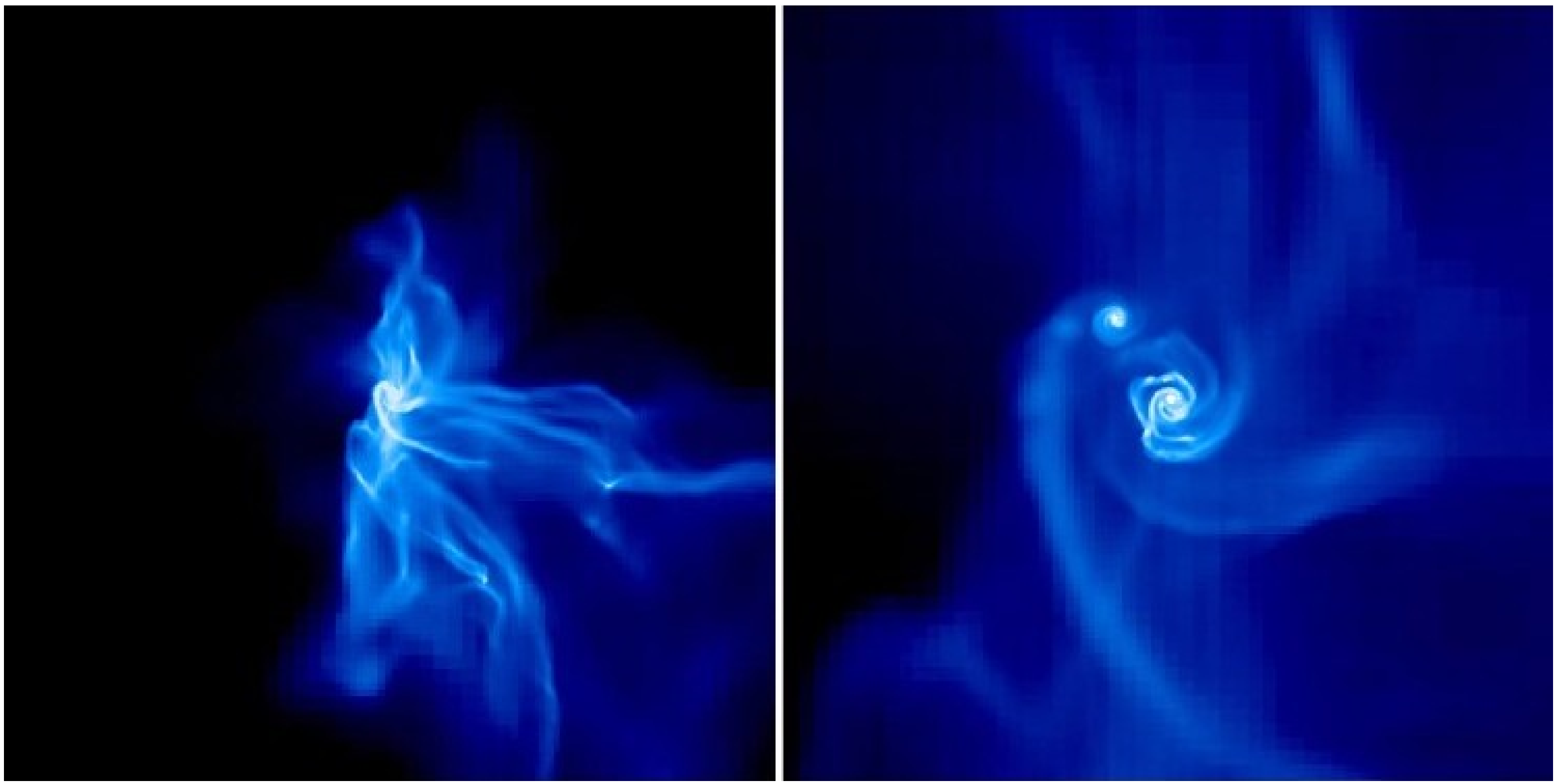


Muench et al 2002

“Core collapse” or “competitive accretion”?

Maybe both. Simulations of the collapse of massive cores with radiative heating yield interacting binary systems, just as with low-mass stars:

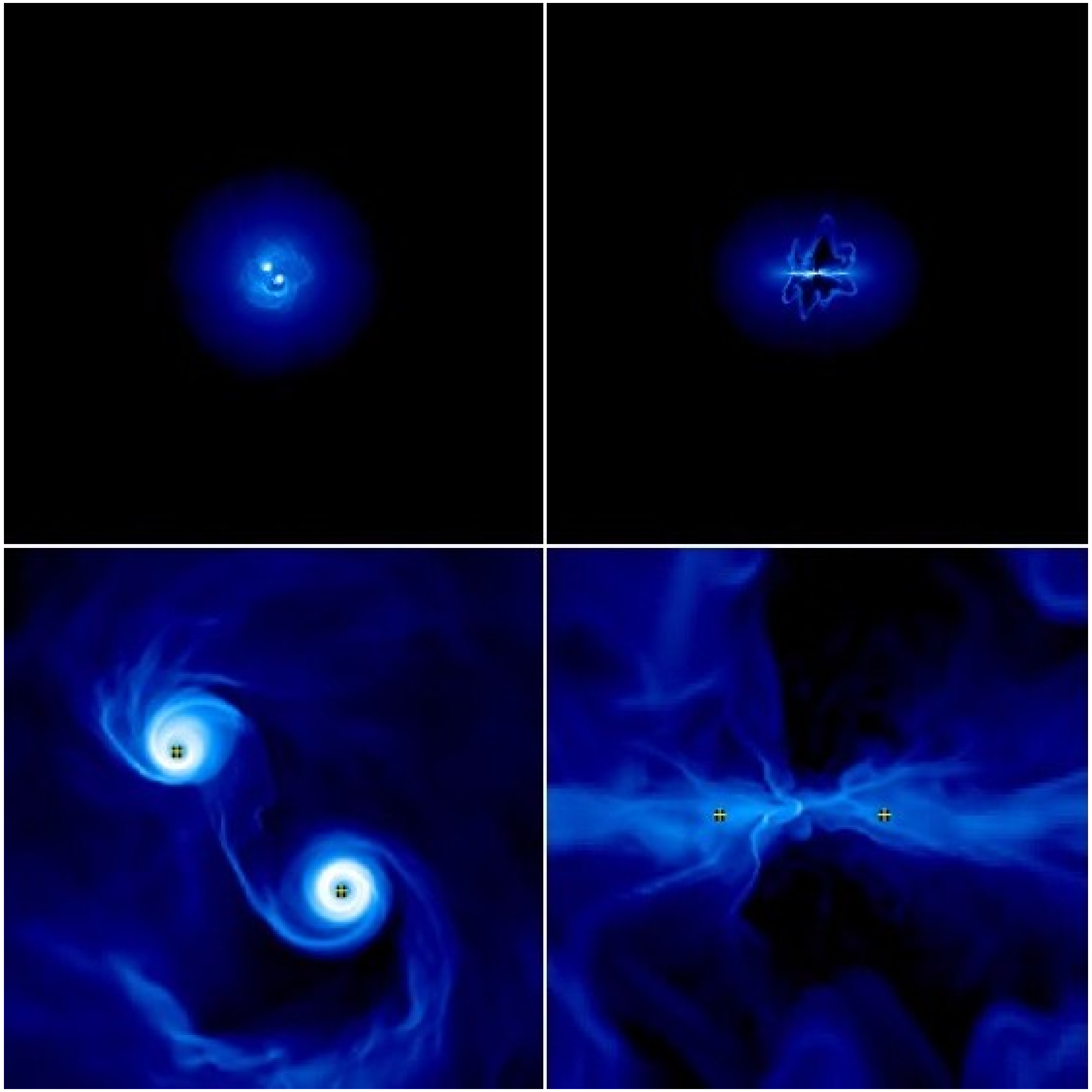
8 × zoom



Krumholz, Klein, & McKee 2007

Massive interacting binaries form even when radiation pressure is included:

Radiation pressure makes bubbles but doesn't stop collapse.

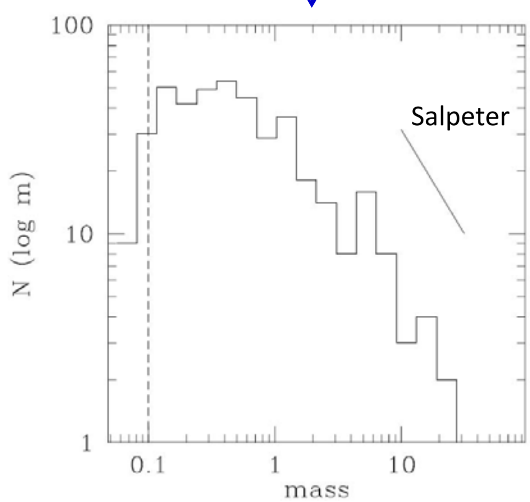


Krumholz et al 2009

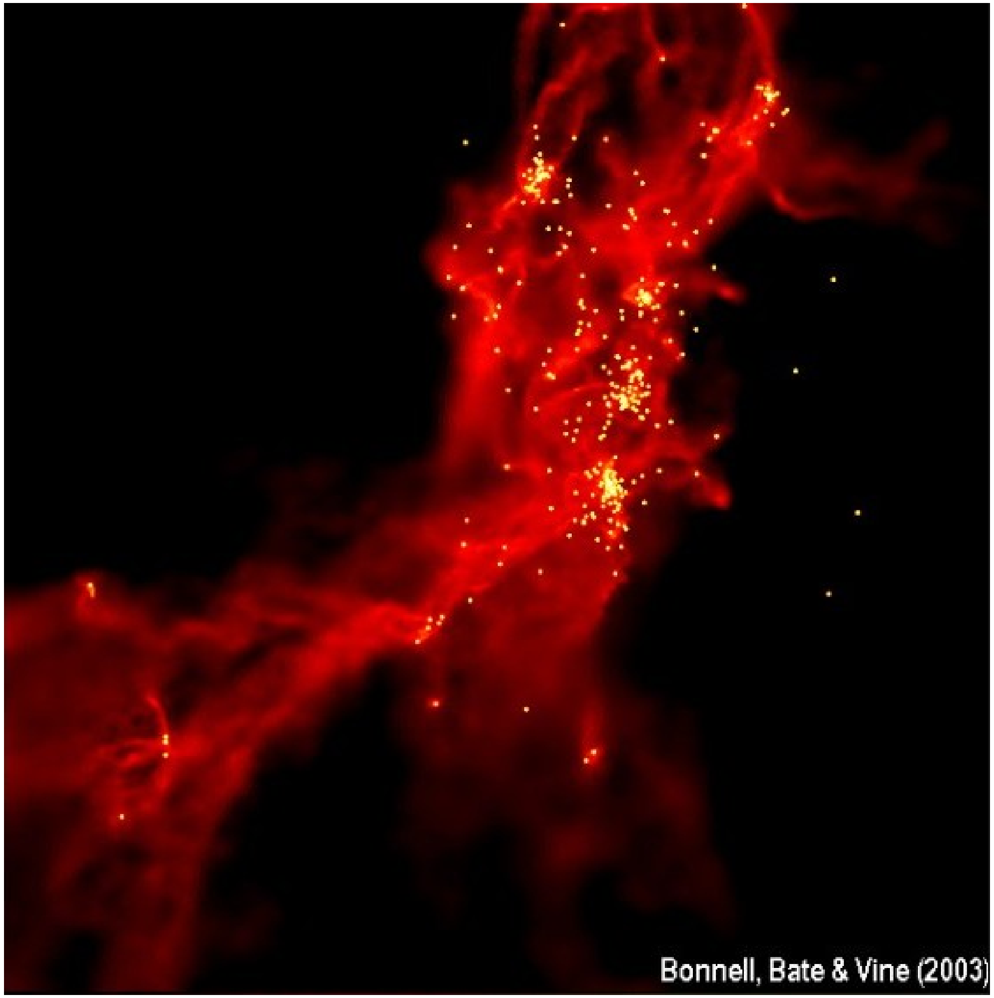
Simulations of cluster formation

reproduce the observed clustering of young stars and show massive stars forming in dense regions:

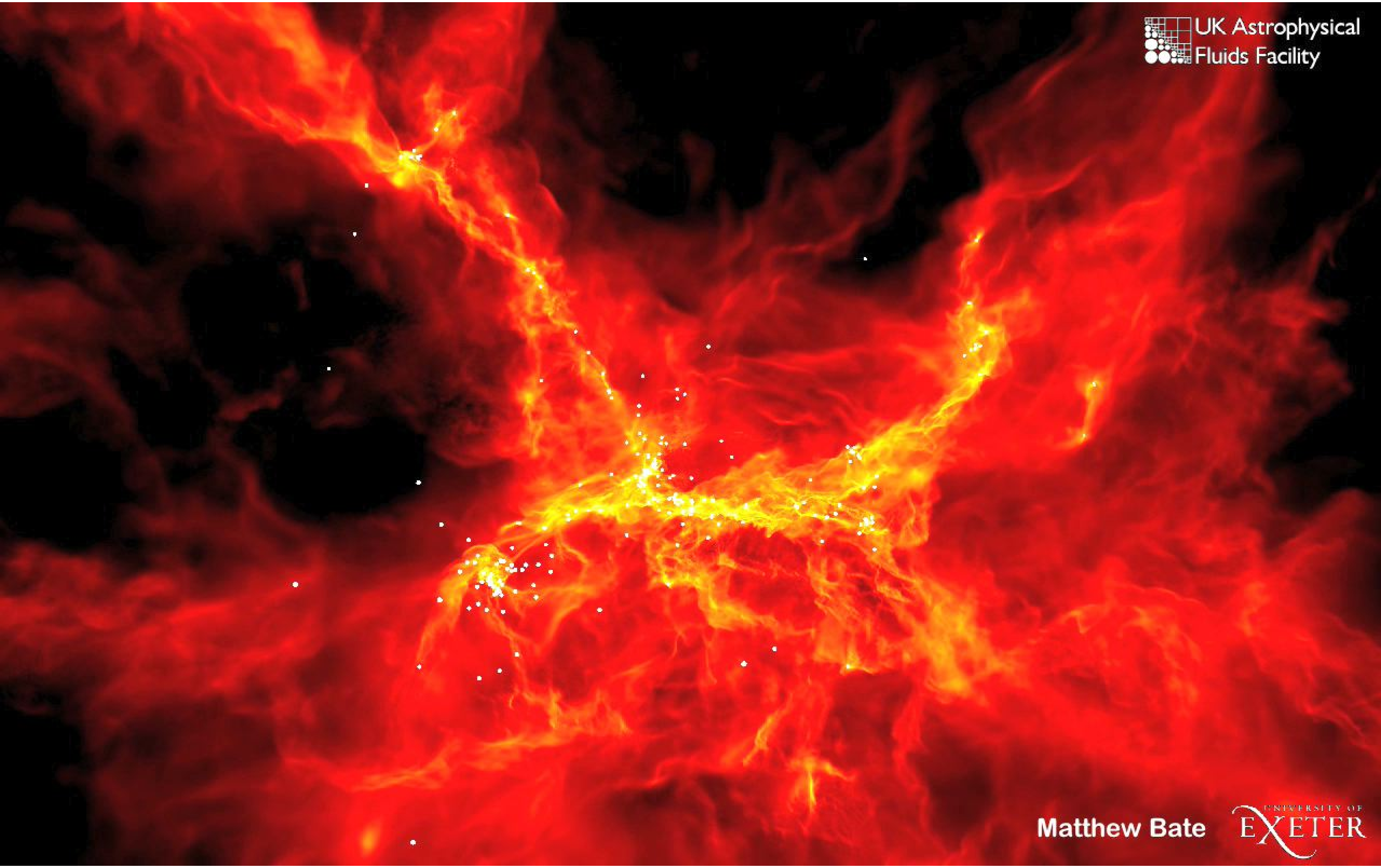
They also yield a realistic-looking stellar IMF:



Bonnell, Bate, & Vine 2003



Cluster formation resembles galaxy formation

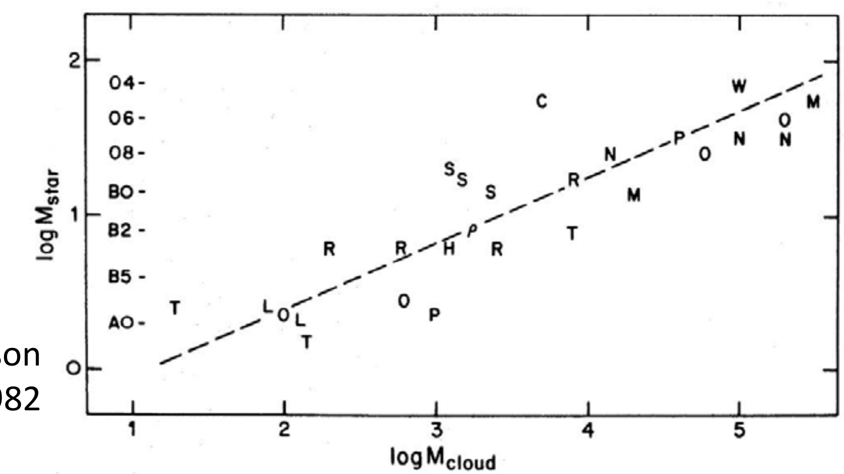


Bate 2009a

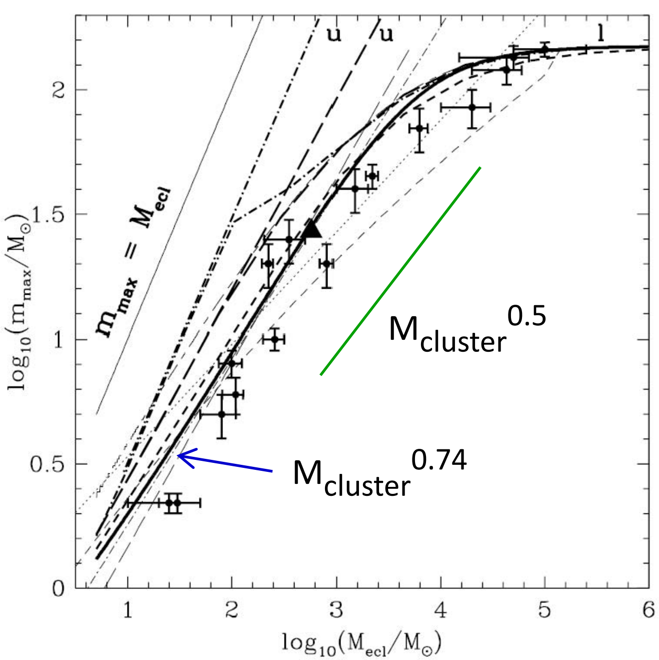
Bigger clusters make bigger stars

The mass of the most massive star in a young cluster increases with cluster mass roughly as

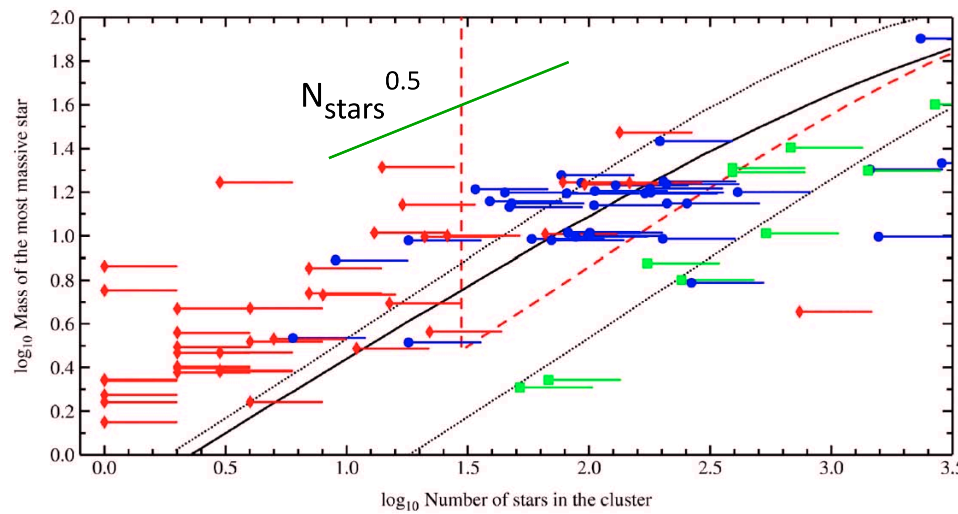
$M_{max} \sim M_{cluster}^{n}$, $n \sim 0.5$.



Larson 1982



Weidner & Kroupa 2006



Maschberger & Clarke 2008

This can produce a power-law upper IMF:

If stars form in a clustering hierarchy and the mass of the most massive star in each group increases as a power n of the group's mass, a power-law IMF results:

$$dN/d\log m \sim m^{-x}, \quad x = 1/n$$

A Salpeter IMF ($x = 1.35$) results if $n = 0.74$, possibly consistent with observations for masses below 30 $M_{\odot}$ (Weidner & Kroupa 2006).

The mass of the most massive star in a cluster should increase with cluster mass because a bigger cluster can redistribute more mass and angular momentum.

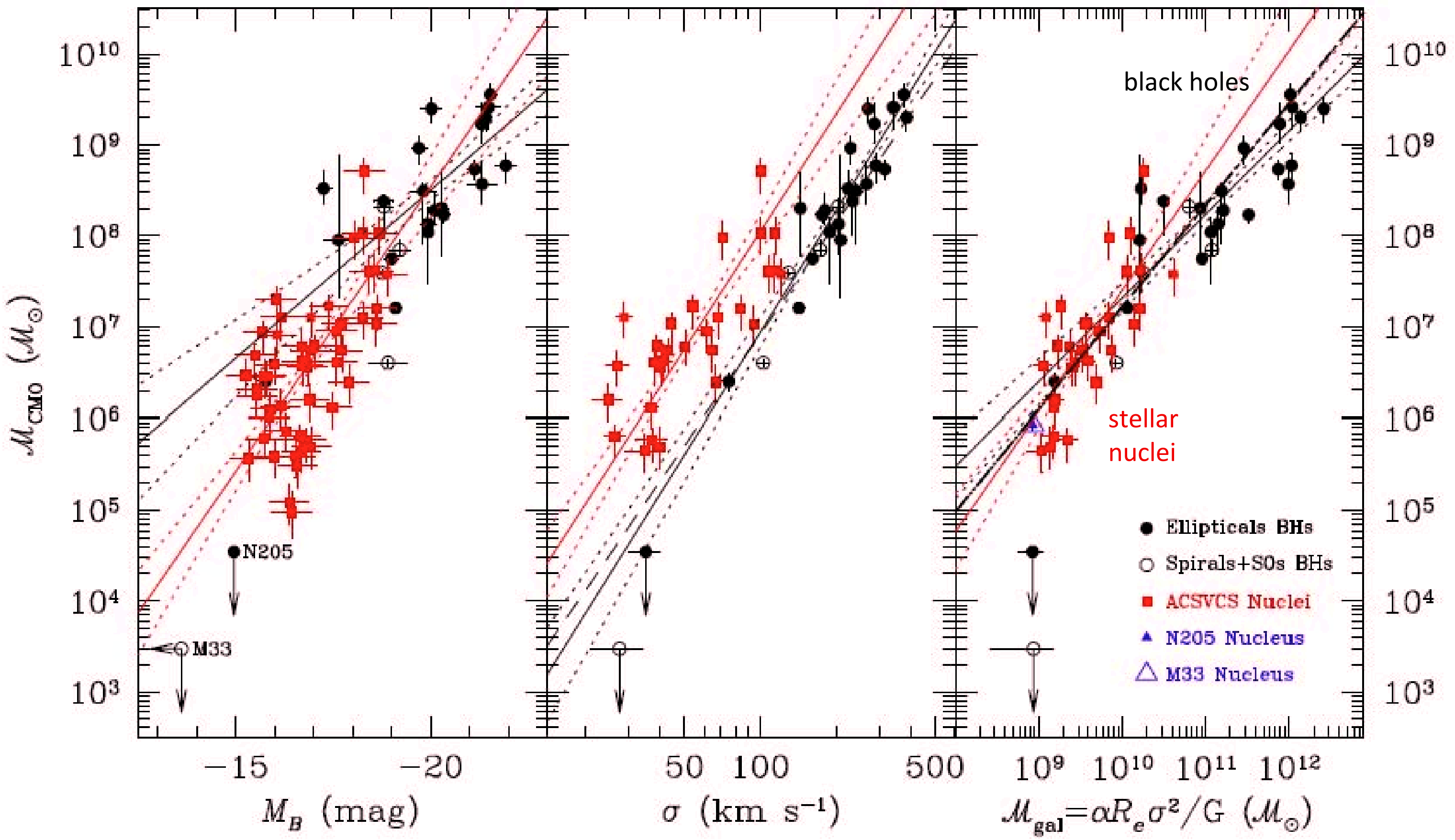
In both binary systems and clusters, the mass of the most massive object may then be coupled to the mass of the system.

This seems to be true also in galaxies . . .

Bigger galaxies make bigger black holes

The masses of central black holes and stellar nuclei in galaxies scale roughly with bulge mass as

$$M_{BH} \sim 0.0015\, M_{bulge}$$



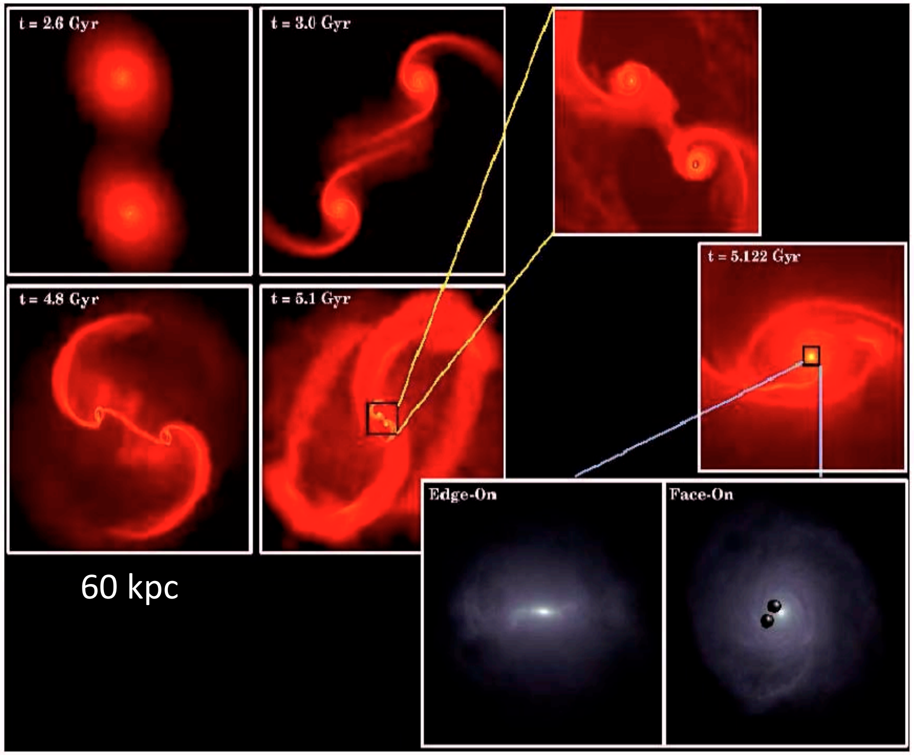
Ferrarese et al 2006

Black hole building can occur by merging or by gas accretion:

Merging of the central black holes of merging galaxies can occur by a combination of large-scale dynamical friction and small-scale gravitational drag effects:

120 kpc

8 kpc

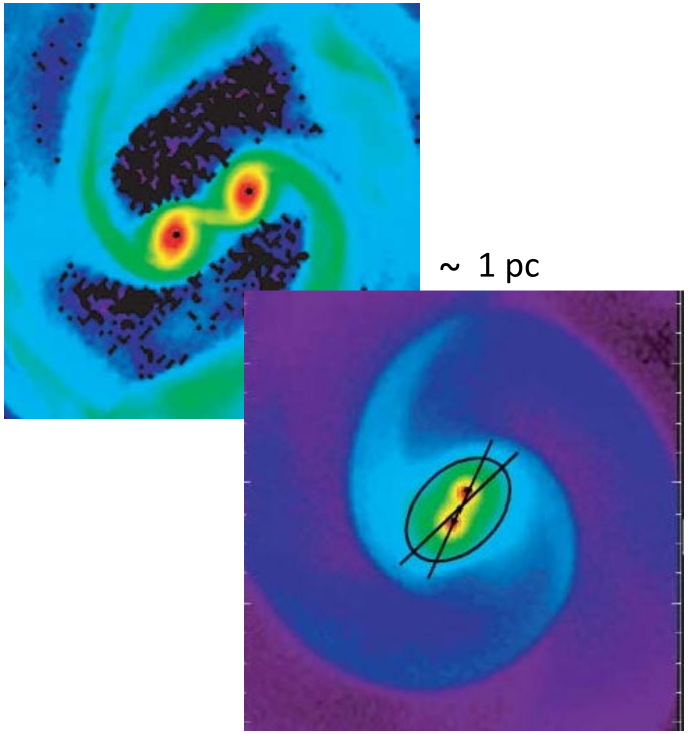


160 pc

Mayer et al 2007

~ 100 pc

~ 1 pc



Escala, Larson, Coppi, Mardones 2005

Black hole growth by gas accretion

Standard accretion disks become inefficient and unstable at radii > 0.1 pc, so if gas is to get into such a region from a galactic bulge, its angular momentum must be reduced by at least 3 orders of magnitude in some other way.

Some possibilities:

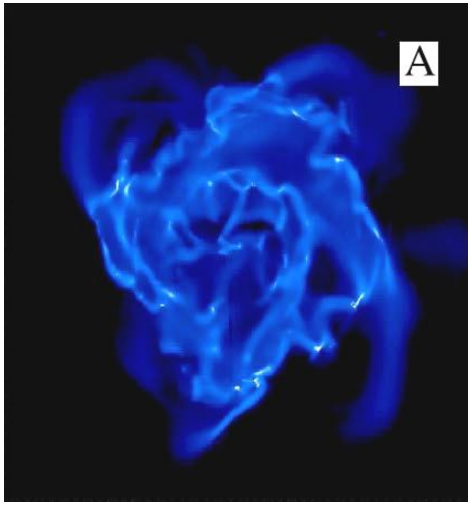
- A more extended gravitationally unstable gas disk may develop spiral features and gravitational torques that drive inflows.

- Massive clumps may also form and lose angular momentum by gravitational drag and fall inward.

- Galactic bars and disk asymmetries can exert torques on the gas and drive inflows on a large range of scales.

All of these phenomena could be consequences of galaxy interactions and mergers, and all are seen in simulations.

Evolution of a massive nuclear gas disk

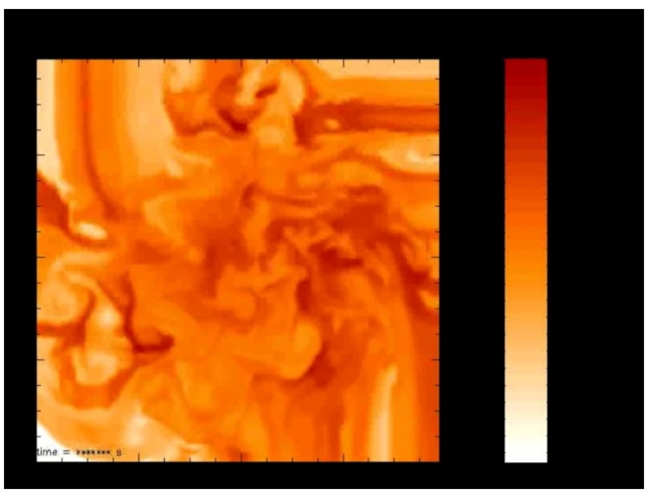


A massive unstable gas disk like those observed in ULIRGs can fragment into clumps and filaments that simultaneously form stars and drive an inflow.

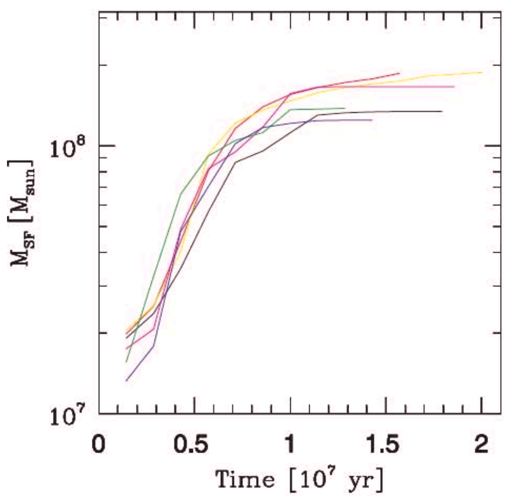
Escala & Larson 2008

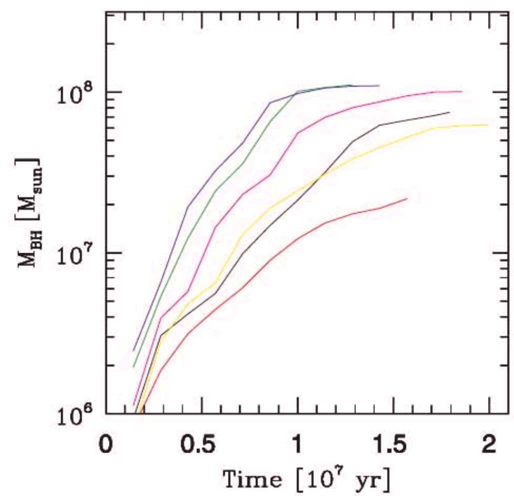
500 pc

The dynamics of such a gas disk can be violent and chaotic, and can lead to comparable rates of star formation and black hole feeding.



Escala 2006 (unpublished)

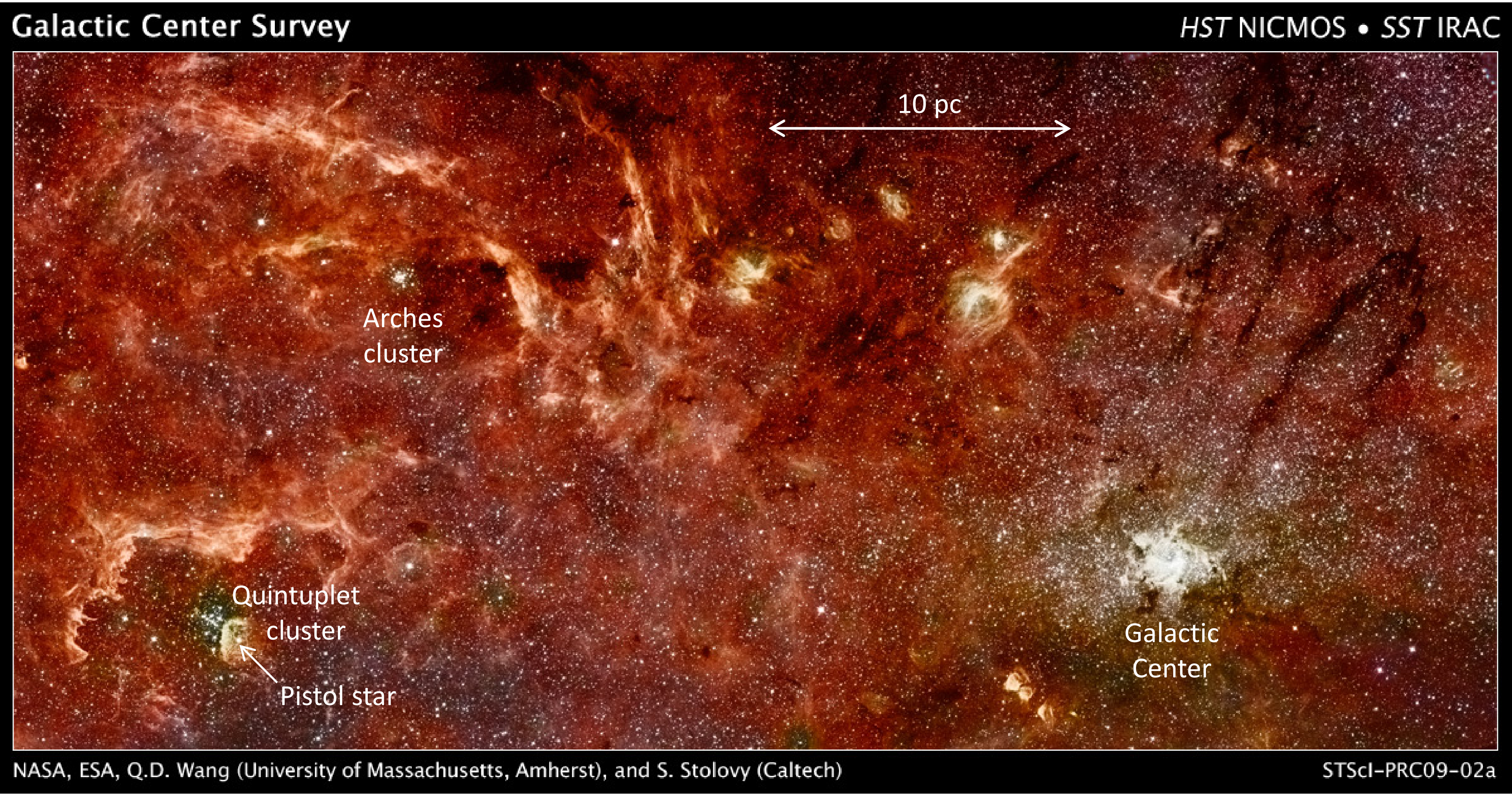




Escala 2007

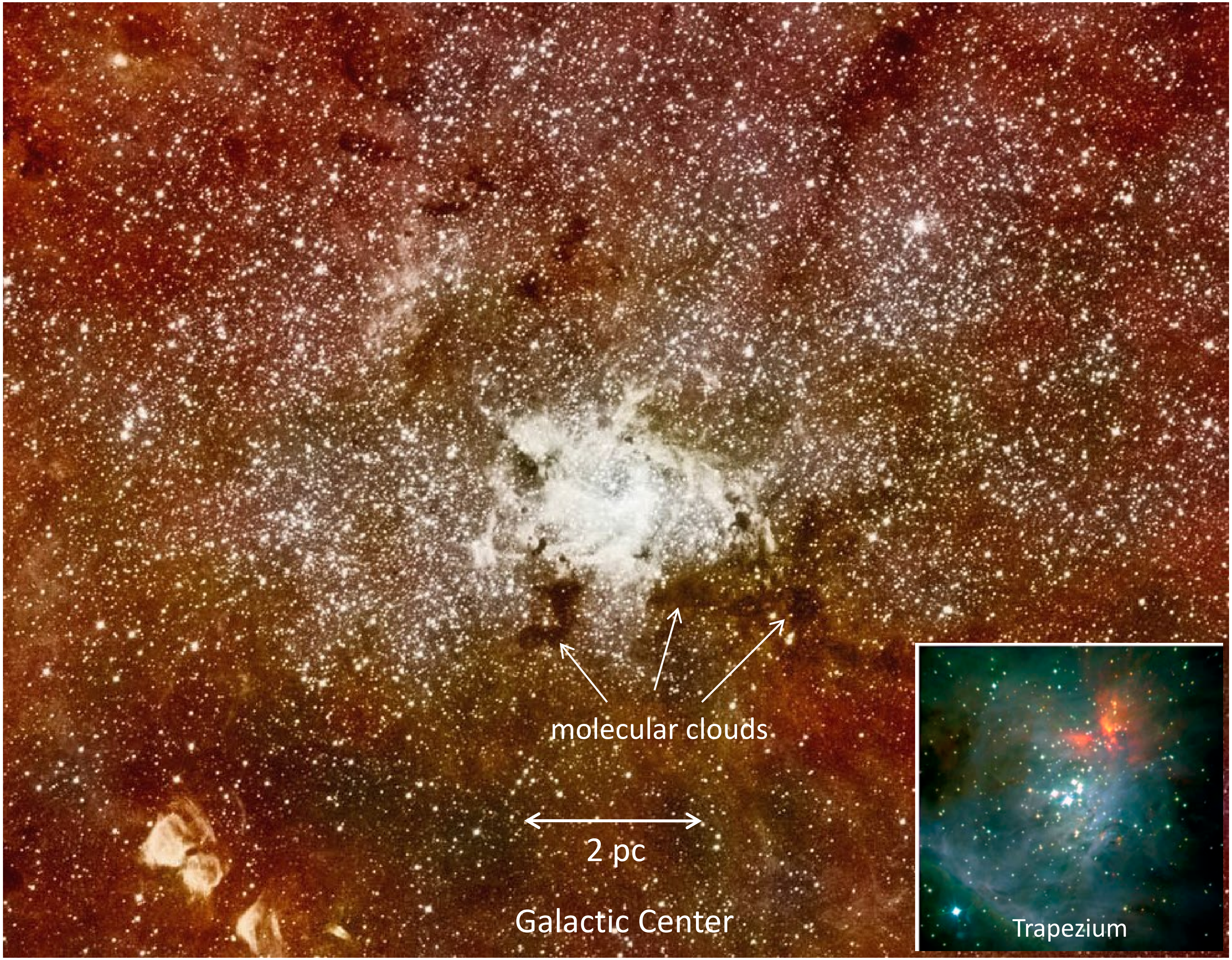
Massive clusters and star formation near the Galactic Center

Hubble-Spitzer Galactic Center mosaic



HST NICMOS 1.87 µm (Paα) + Spitzer 3.6, 4.5, 5.8, 8.0 µm

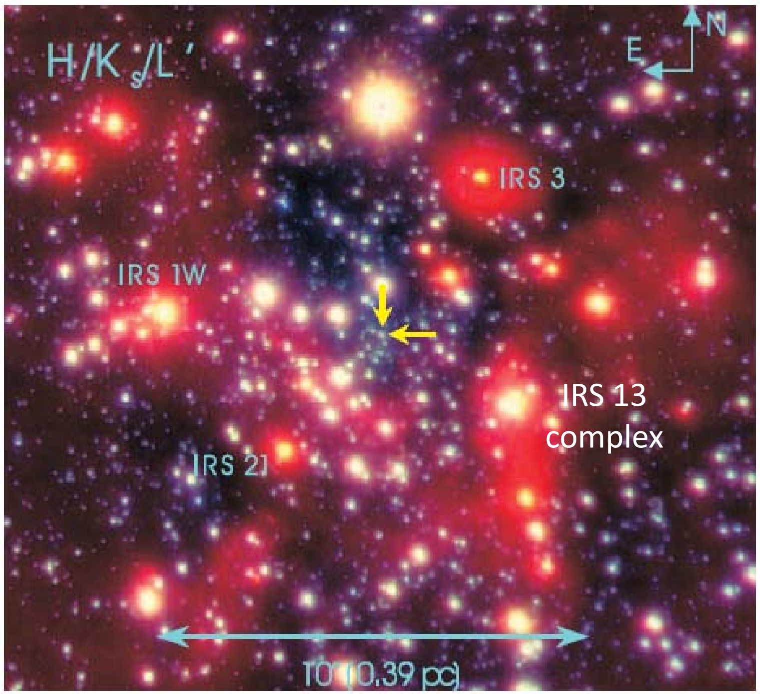
Hubble-Spitzer Galactic Center mosaic



Compact nuclear clusters in the Milky Way and M31

Compact clusters of massive young stars less than 1 pc in size surround the central black holes of both the Milky Way and M31:

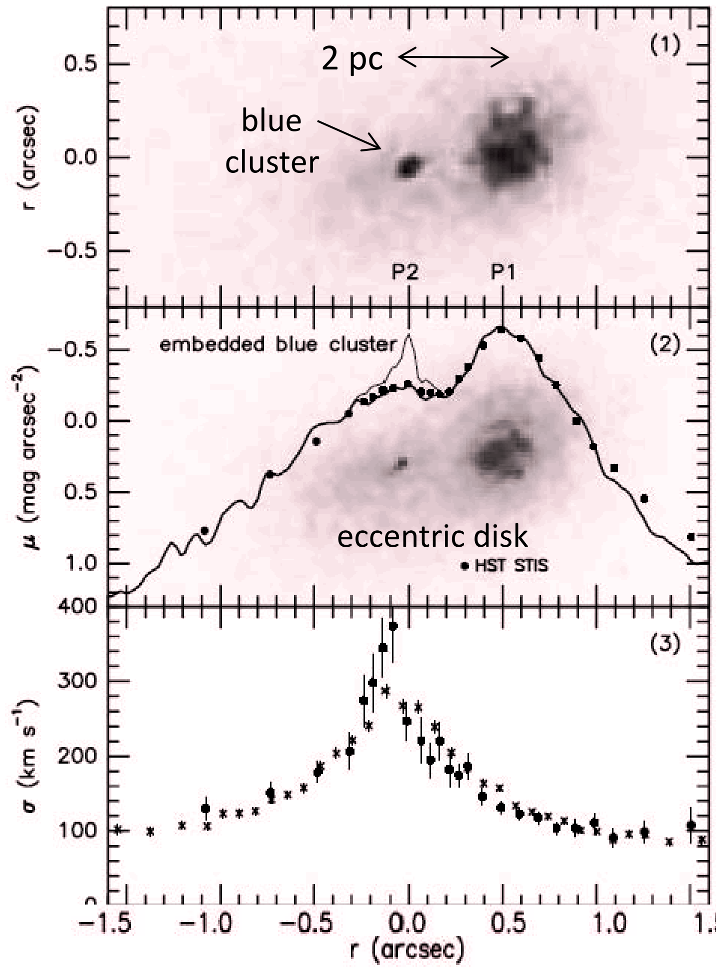
MW Sgr A*



0.7 pc

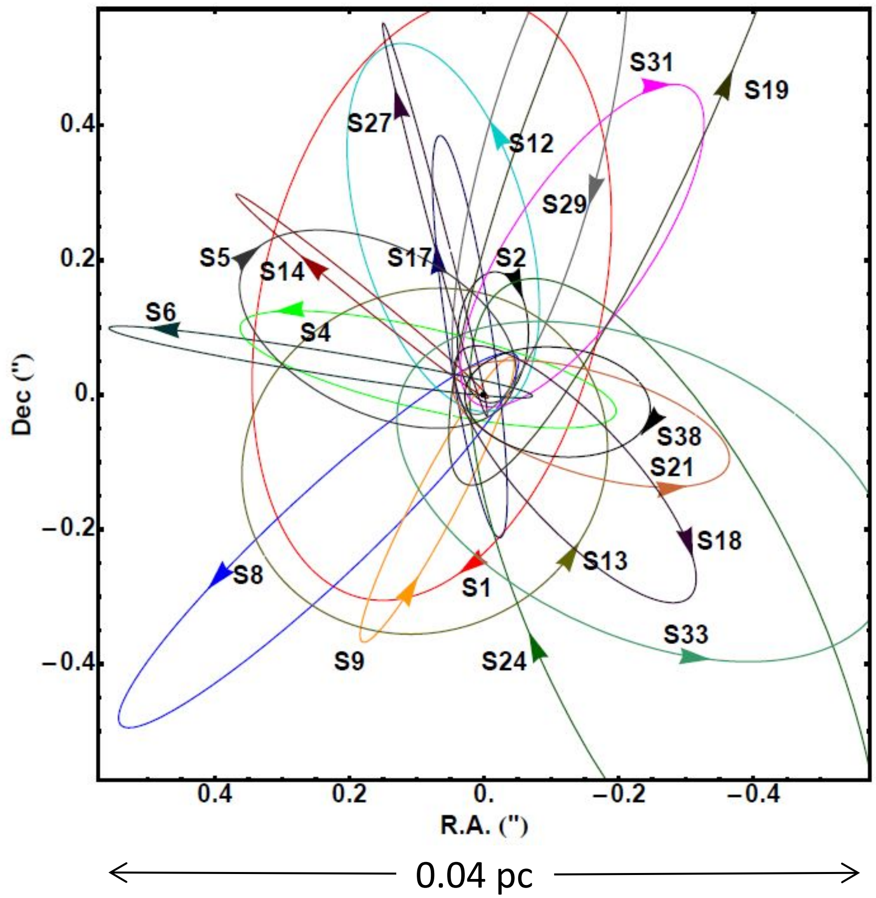
Genzel et al 2003

M31 nucleus



Bender et al 2005

The Galactic Center Cluster extends to within 50 AU of the central black hole!



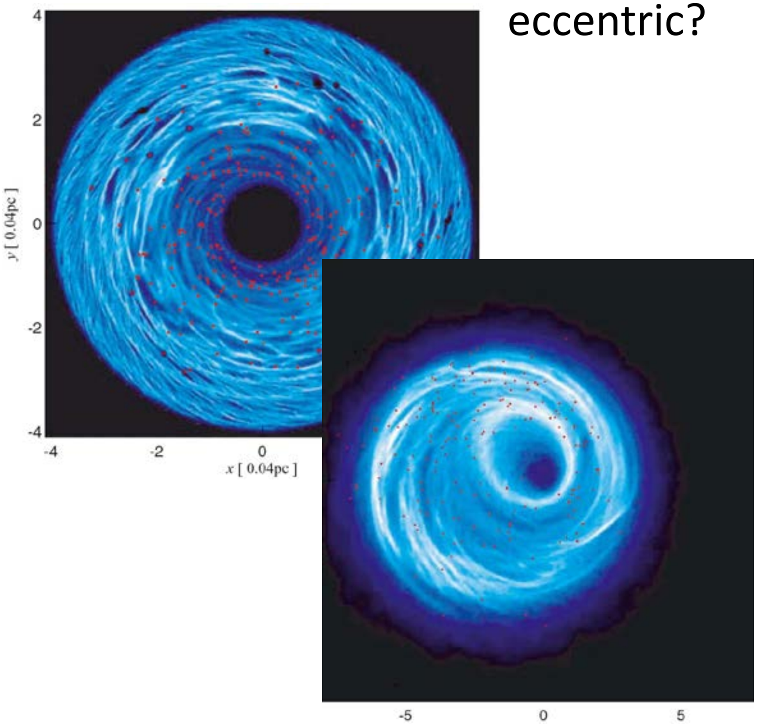
Gillessen et al 2010

So whatever made these stars brought matter very close to the black hole.
These stars may then be leftovers from a black-hole feeding event.

Star formation near a central black hole

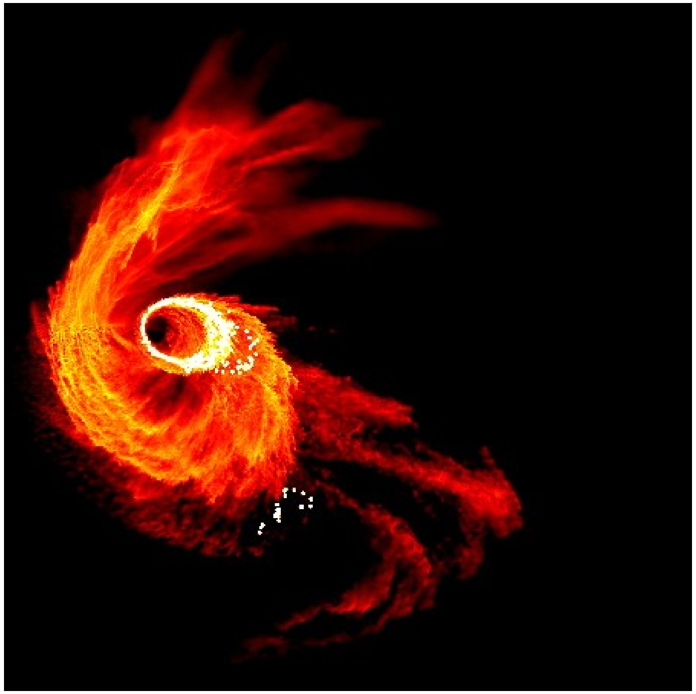
How did the observed massive stars form within a few tenths of a parsec of the central black holes in both the Milky Way and M31?

In an accretion disk, possibly eccentric?



Nayakshin, Cuadra, & Springel 2007

In gas captured into orbit around the BH?



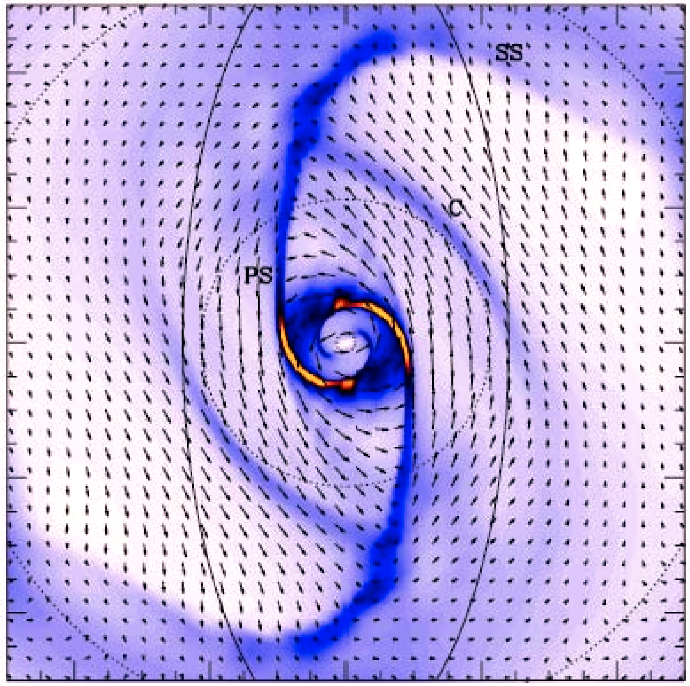
Bonnell & Rice 2008

In either case, a significant fraction of the gas may be accreted by the black hole.

Bars and asymmetric disks can also drive inflows:

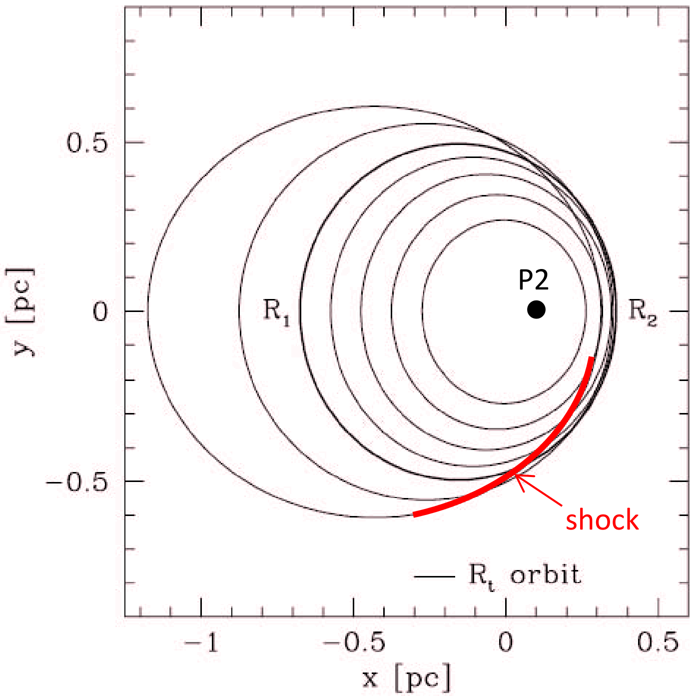
Bar torques can drive gas into the inner kiloparsec of a galaxy, and nuclear bars or spirals may drive inflows on smaller scales. Asymmetric nuclear disks like that seen in M31 can similarly produce torques that drive inflows in the inner few parsecs.

Effect of a galactic bar



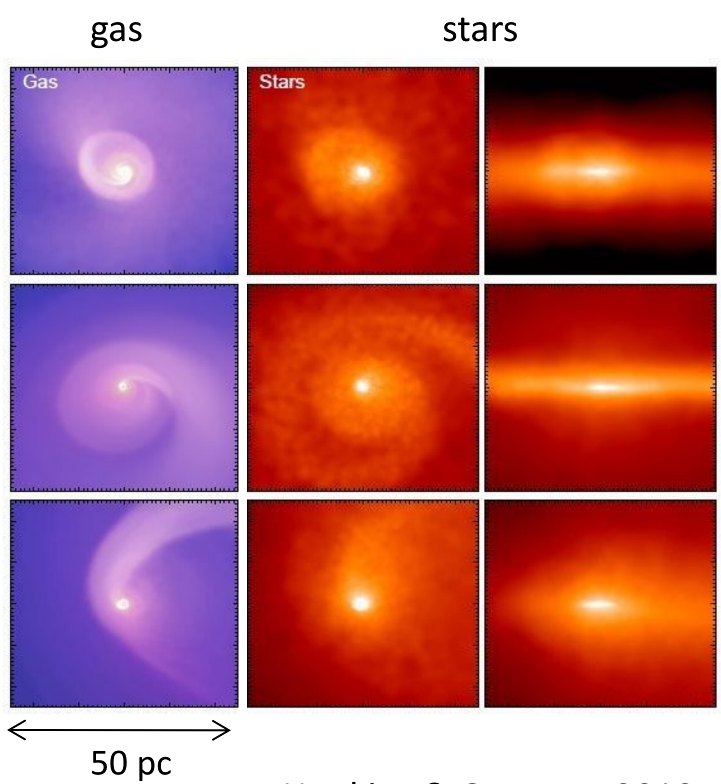
Maciejewski et al 2002

Gas orbits in the inner parsec of M31

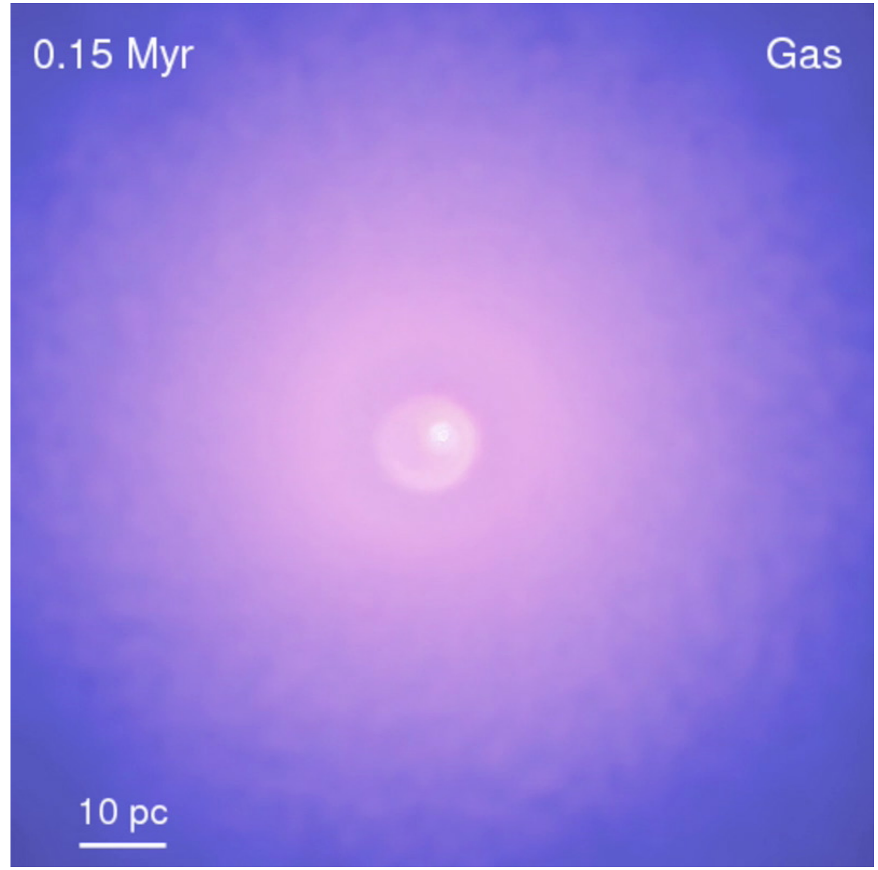


Chang et al 2007

Simulations show that gas falling into a galactic nucleus forms an asymmetric disk like that in M31, and that the gravitational torque due to the disk drives continuing gas infall toward the black hole:

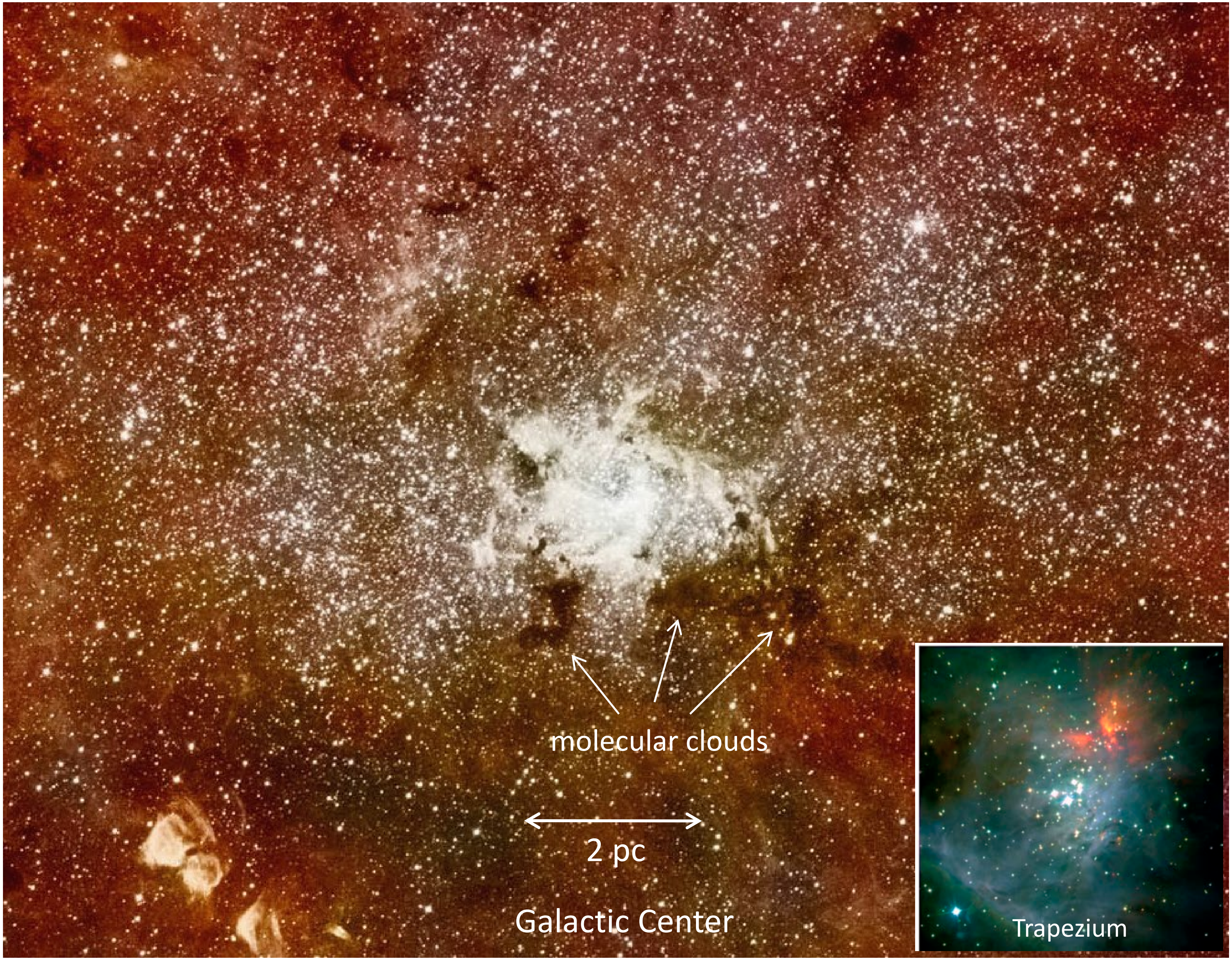


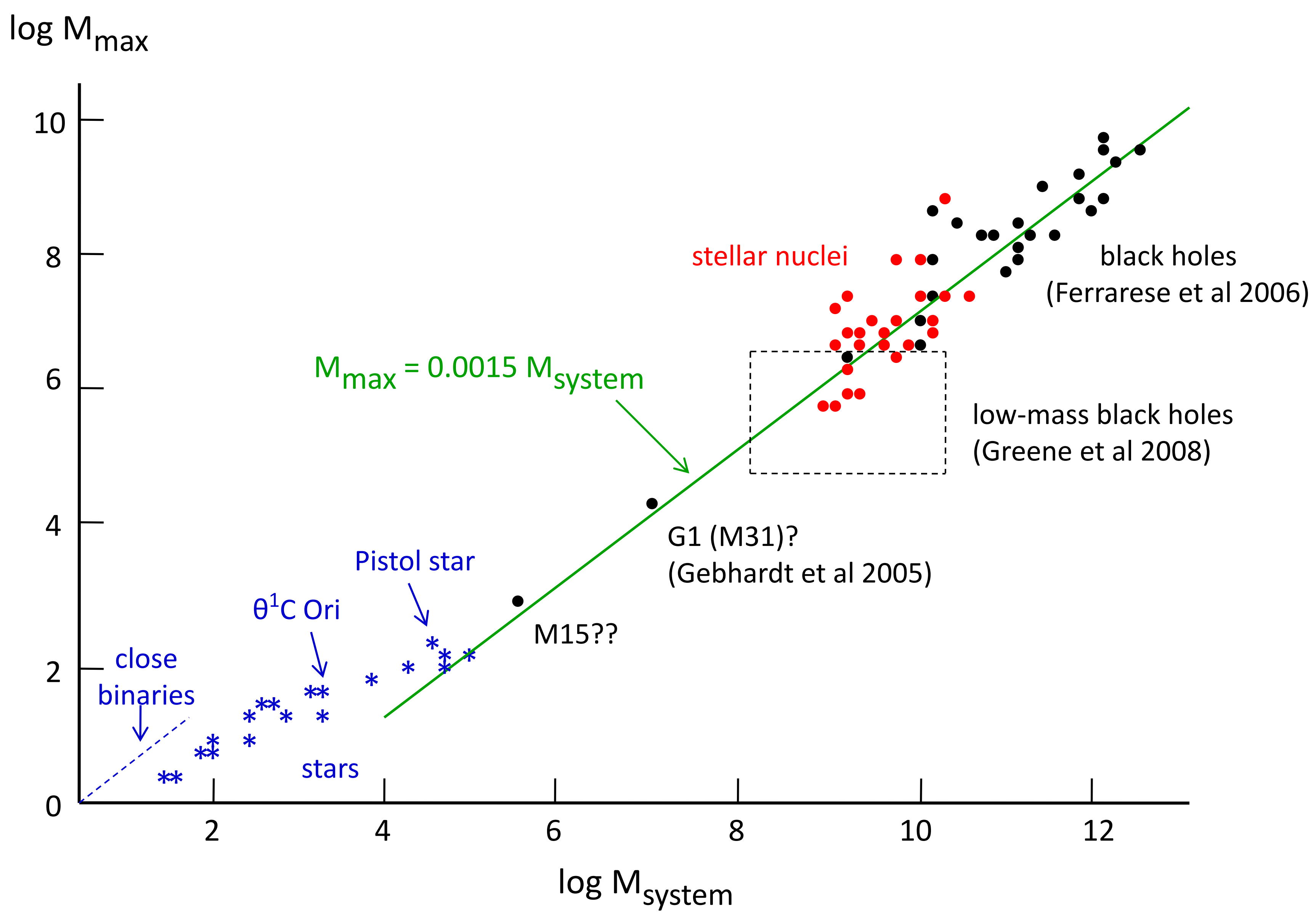
Hopkins & Quataert 2010



The angular momentum of the gas accreted by the black hole then ends up mostly in stars, and it is transmitted to them by gravity.

Hubble-Spitzer Galactic Center mosaic





log M_max
10
8
6
4
2
0
2
4
6
8
10
12
log M_system
M_max = 0.0015 M_system
stellar nuclei
black holes
(Ferrarese et al 2006)
low-mass black holes
(Greene et al 2008)
G1 (M31)?
(Gebhardt et al 2005)
M15??
Pistol star
θ1C Ori
close
binaries
stars

Conclusions

- Compact objects such as stars and black holes generally form in larger systems such as binaries, multiple systems, star clusters, or galaxies.

- Gravitational interactions in these larger systems play a major role in the formation of compact objects by transporting angular momentum.

- The formation of objects like stars and black holes is then a much more complex, dynamic, and chaotic process than in standard models.

- Gravitational interactions tend to couple the mass of a forming object to the mass of the system, and this may have implications for the mass ratios in binaries, the upper IMF in clusters, and the masses of central black holes in galaxies.