# Double Degenerate (WD) Mergers & Outcomes

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Collaborators: J. Frank, P. Motl, W. Even, D. Marcello, G. Clayton, C. Fryer, S. Diehl

# Key Questions

[that we *may* be able to answer with numerical simulations]

1. At onset, is mass-transfer stable or unstable?
2. If unstable, what is the *hydrodynamic* outcome of instability?
3. Do results depend on choice of numerical algorithm?
4. How does outcome depend on the system's ability to cool (via photon radiation)?
5. What about super-Eddington accretion?

# 1. Is mass-transfer stable or unstable?

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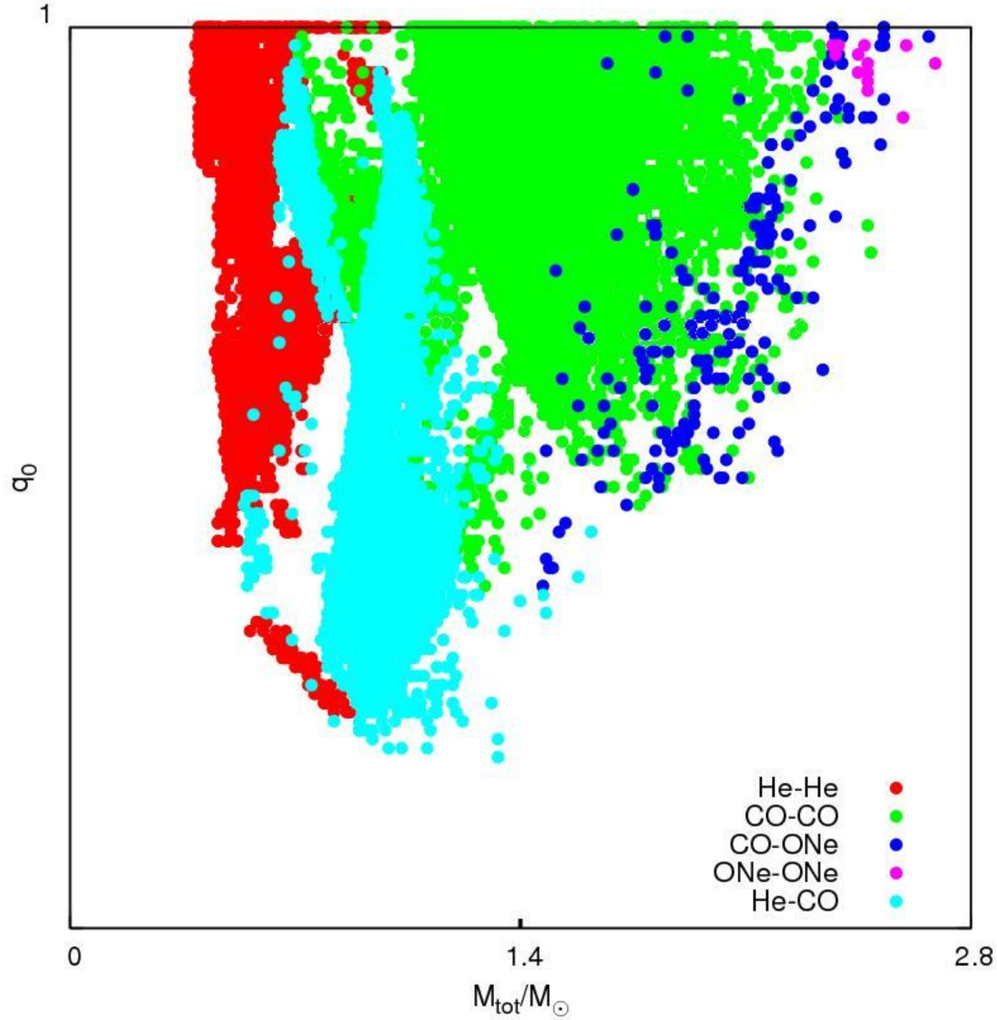
We'll discuss this question in the context of an "$M_{tot}$ - $q_0$" parameter-space diagram that contains a hypothetical population of newborn double white dwarf binaries …

# Possible $M_{tot}$ - $q_0$ Distribution at Birth

[borrowing Hurley's population synthesis code (2002)]



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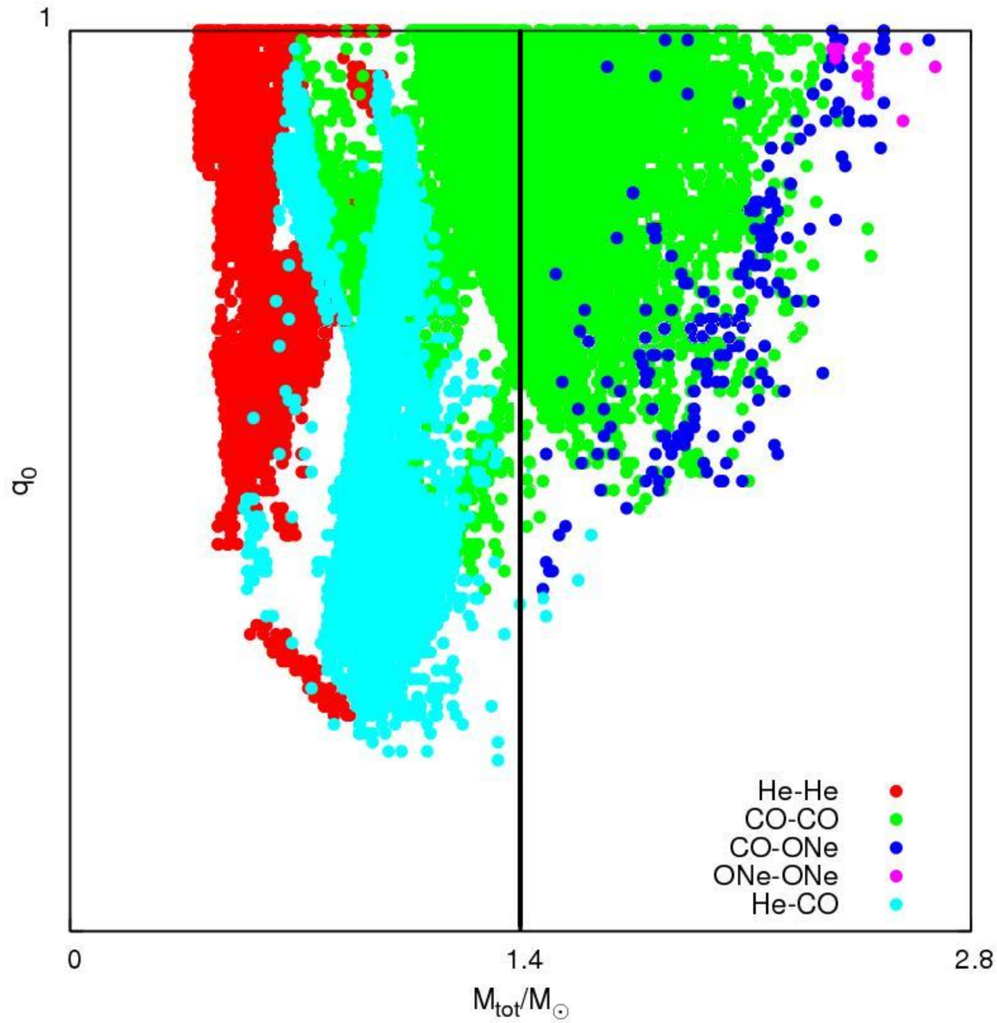

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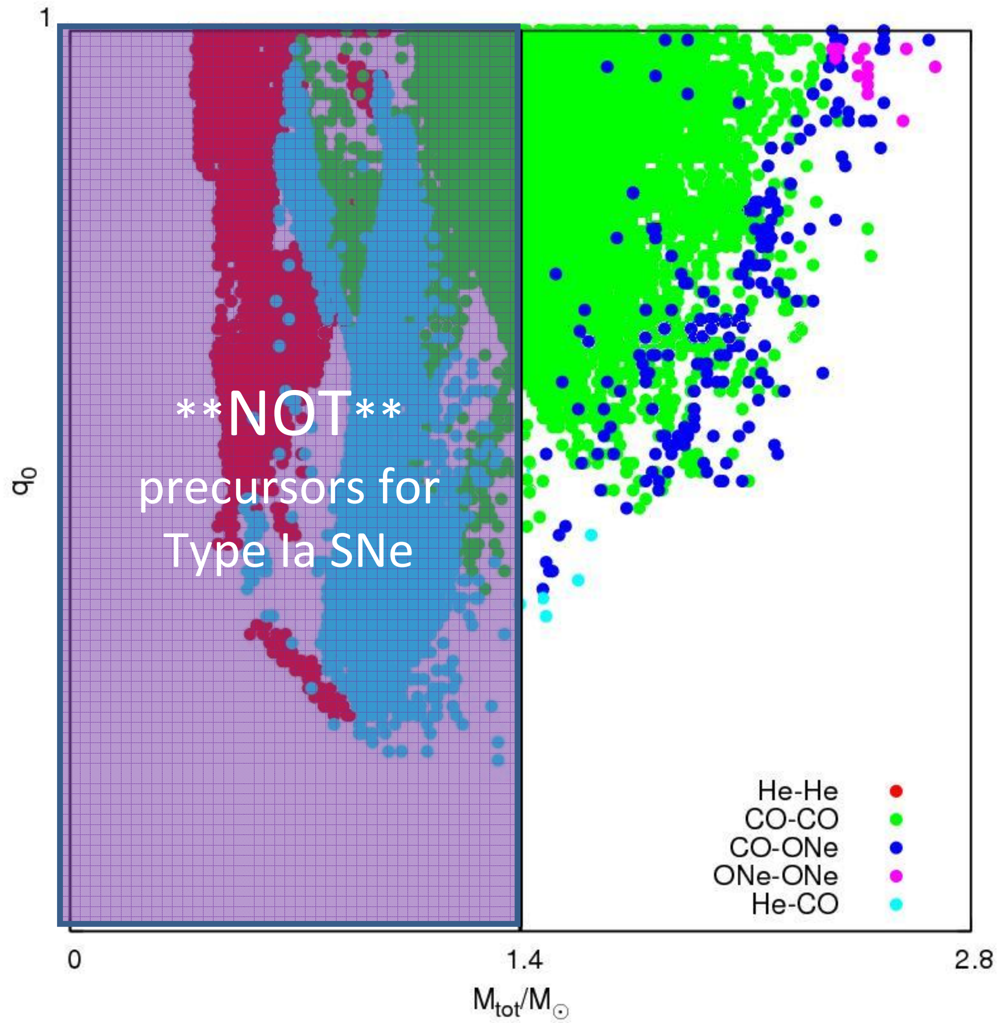

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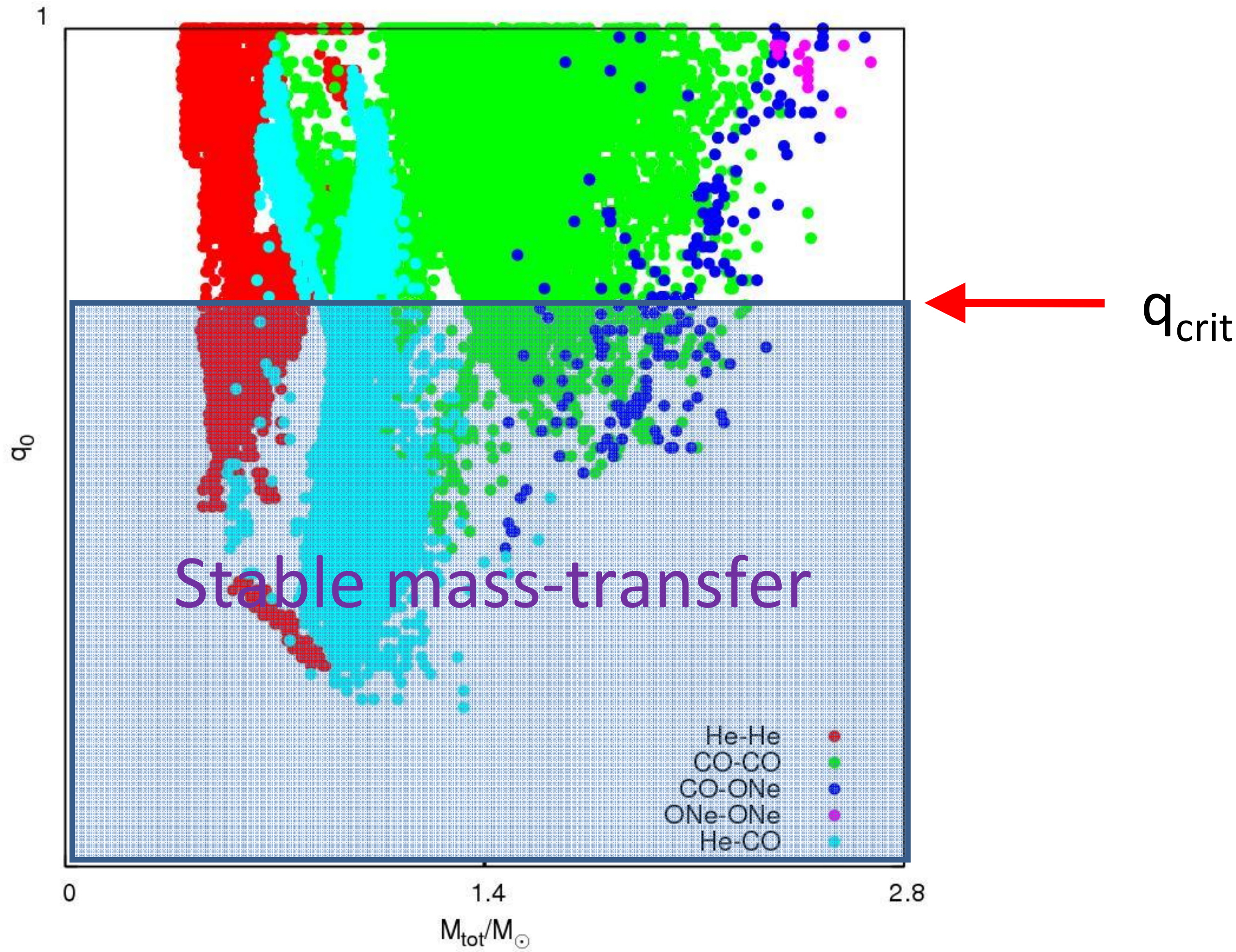

1
0
1.4
2.8
$q_0$
$M_{tot}/M_\odot$
He-He
CO-CO
CO-ONe
ONe-ONe
He-CO
Stable mass-transfer
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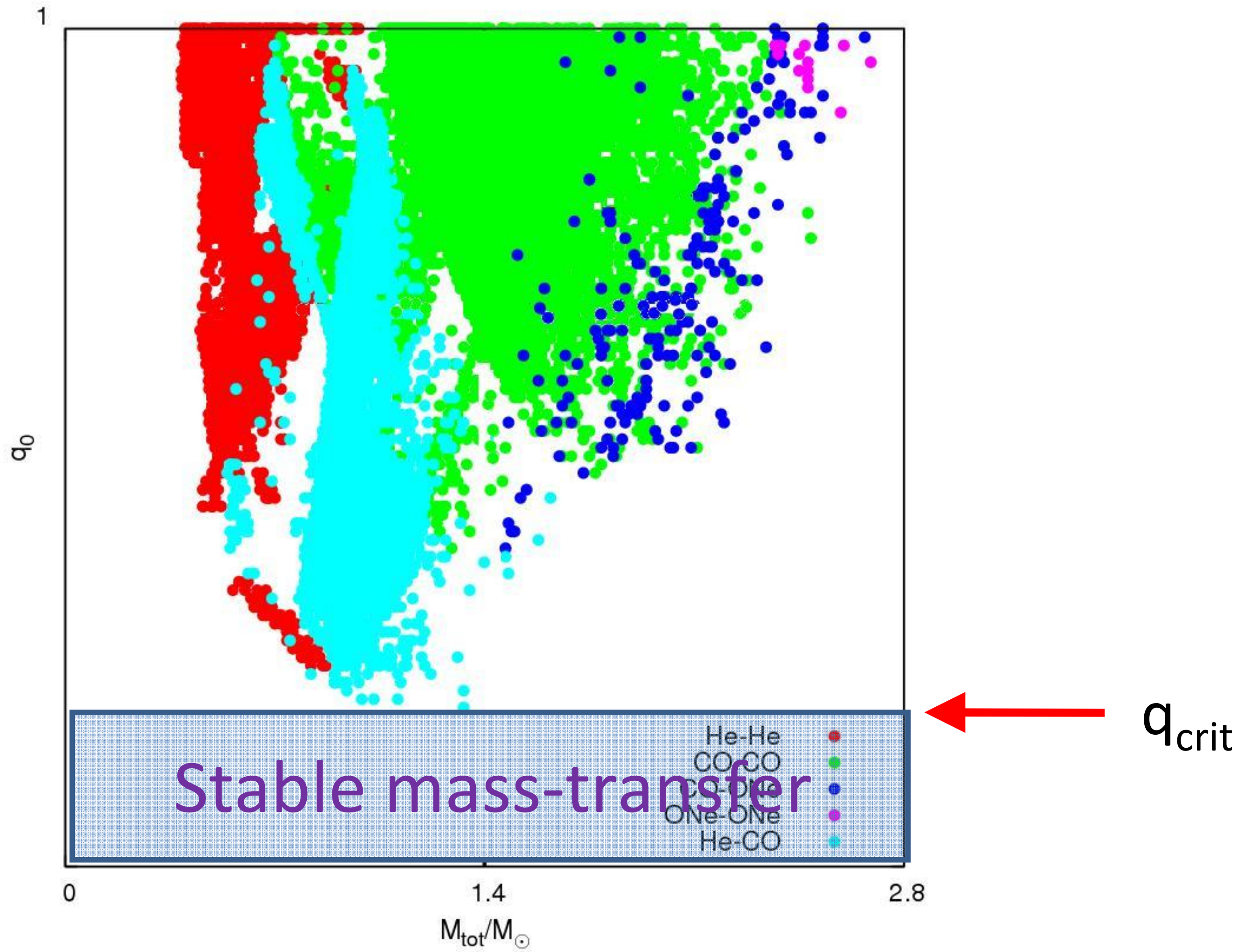
# If $q_{crit}$ = 1/5 …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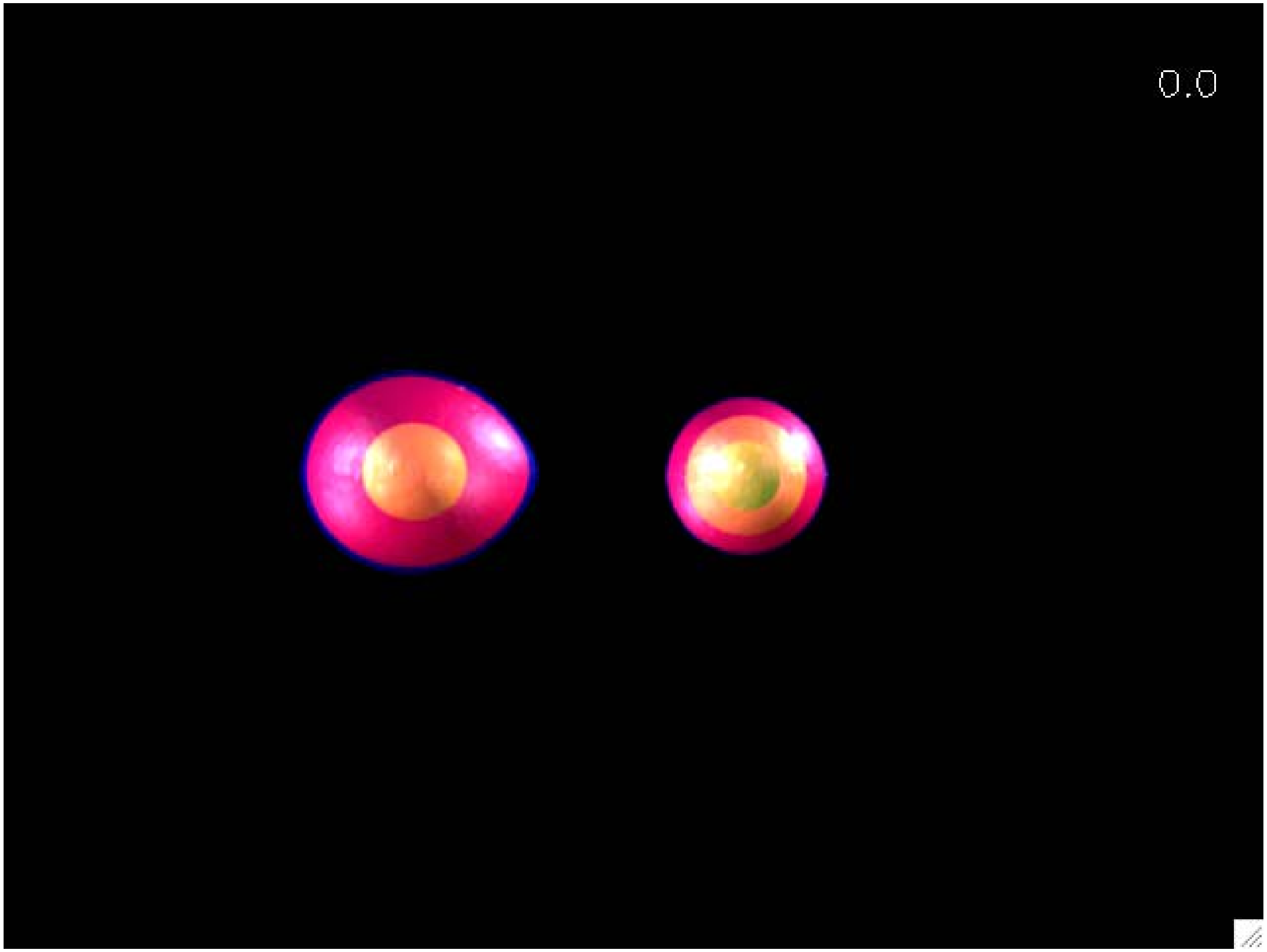
  - Almost certainly, $q_{crit} \leq 2/3$
  - But maybe, $q_{crit} \approx 1/5$ (due to direct-impact accretion)
- Numerical simulations (Motl *et al*. 2007) indicate that $q_{crit}$ is closer to 2/3 than to 1/5

# $q_0 = 0.4$ (stable mass-transfer)



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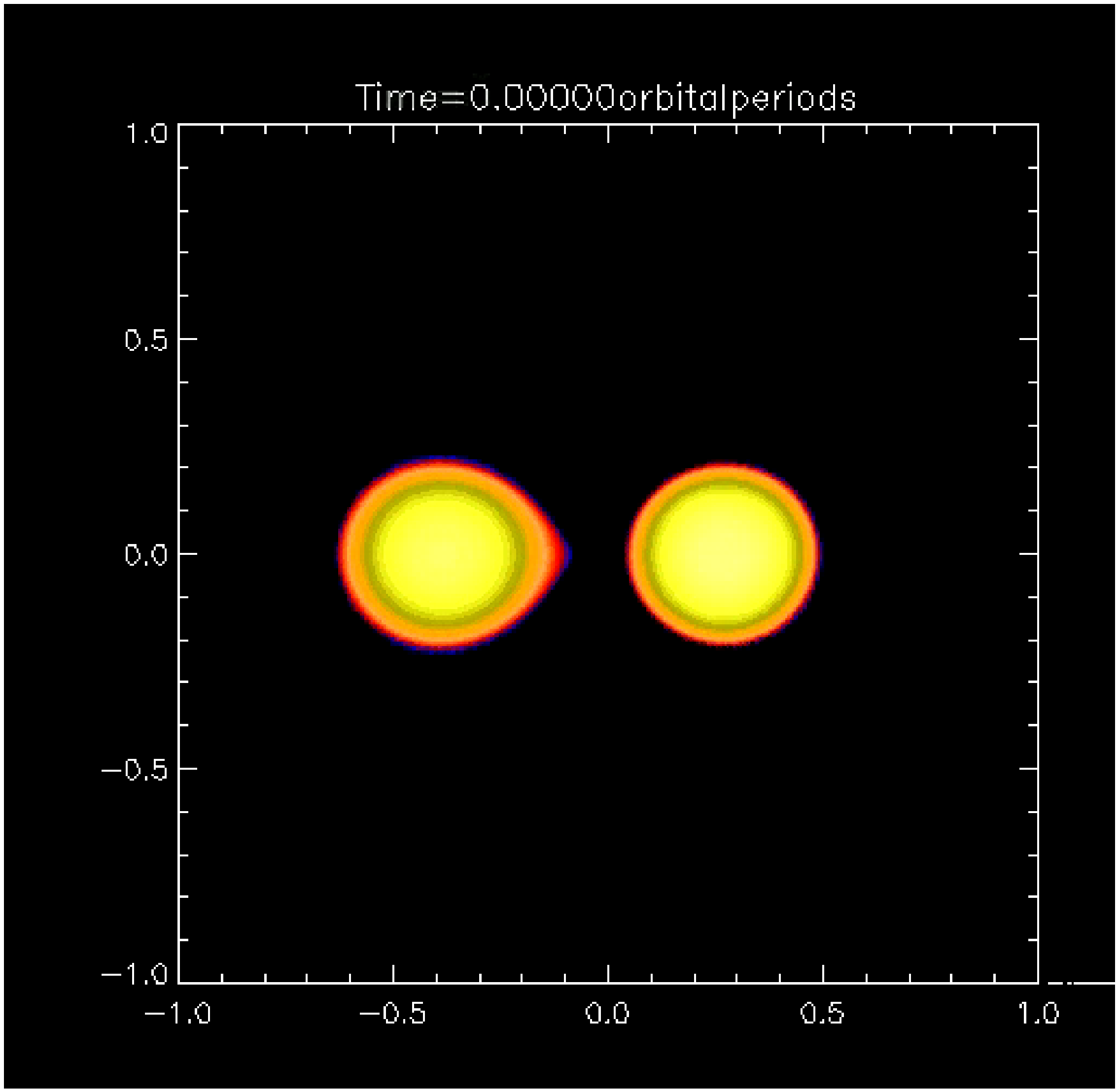
# $q_0 = 0.7$ (tidal disruption of donor)



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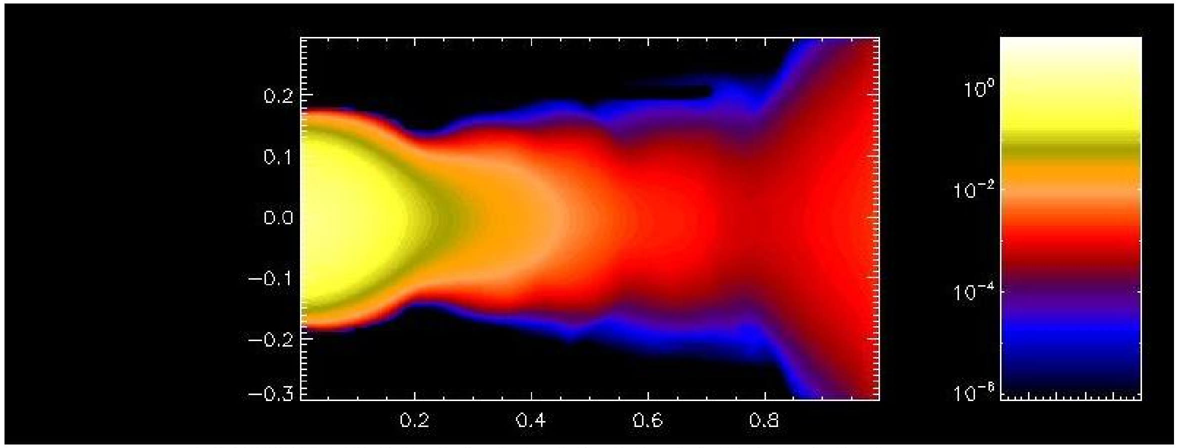


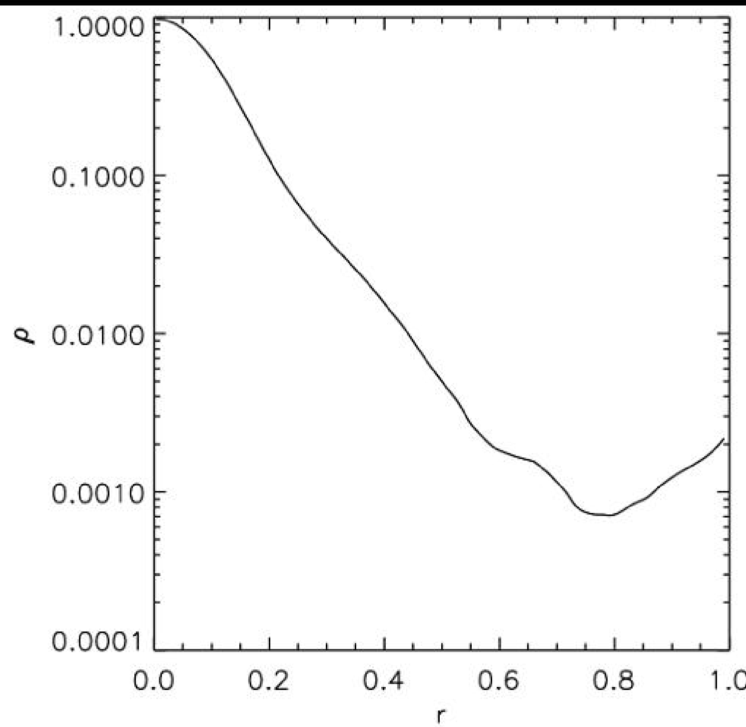


Credit: W. Even

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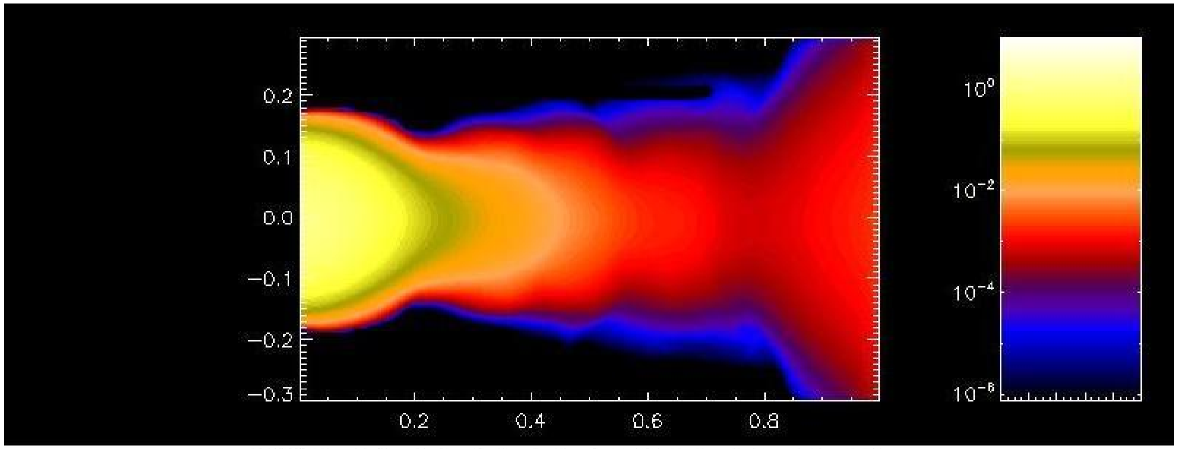


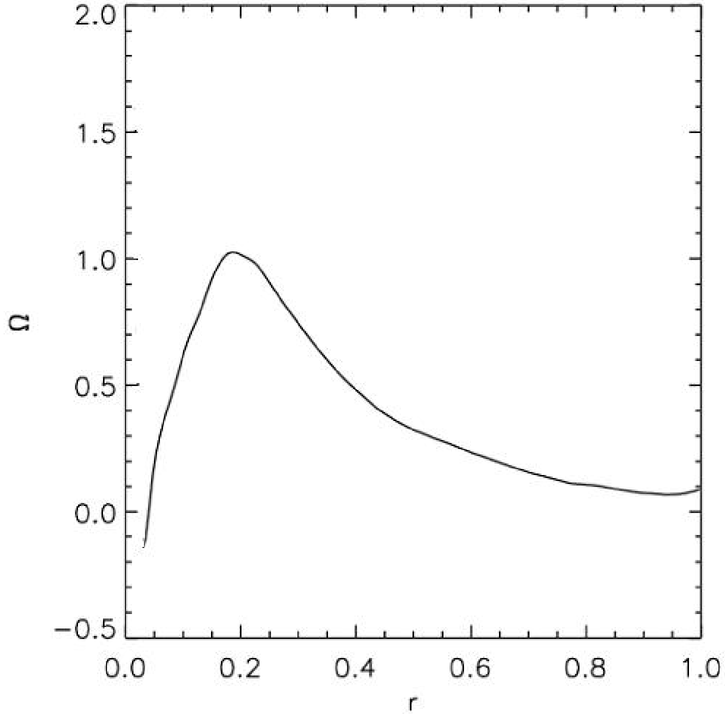


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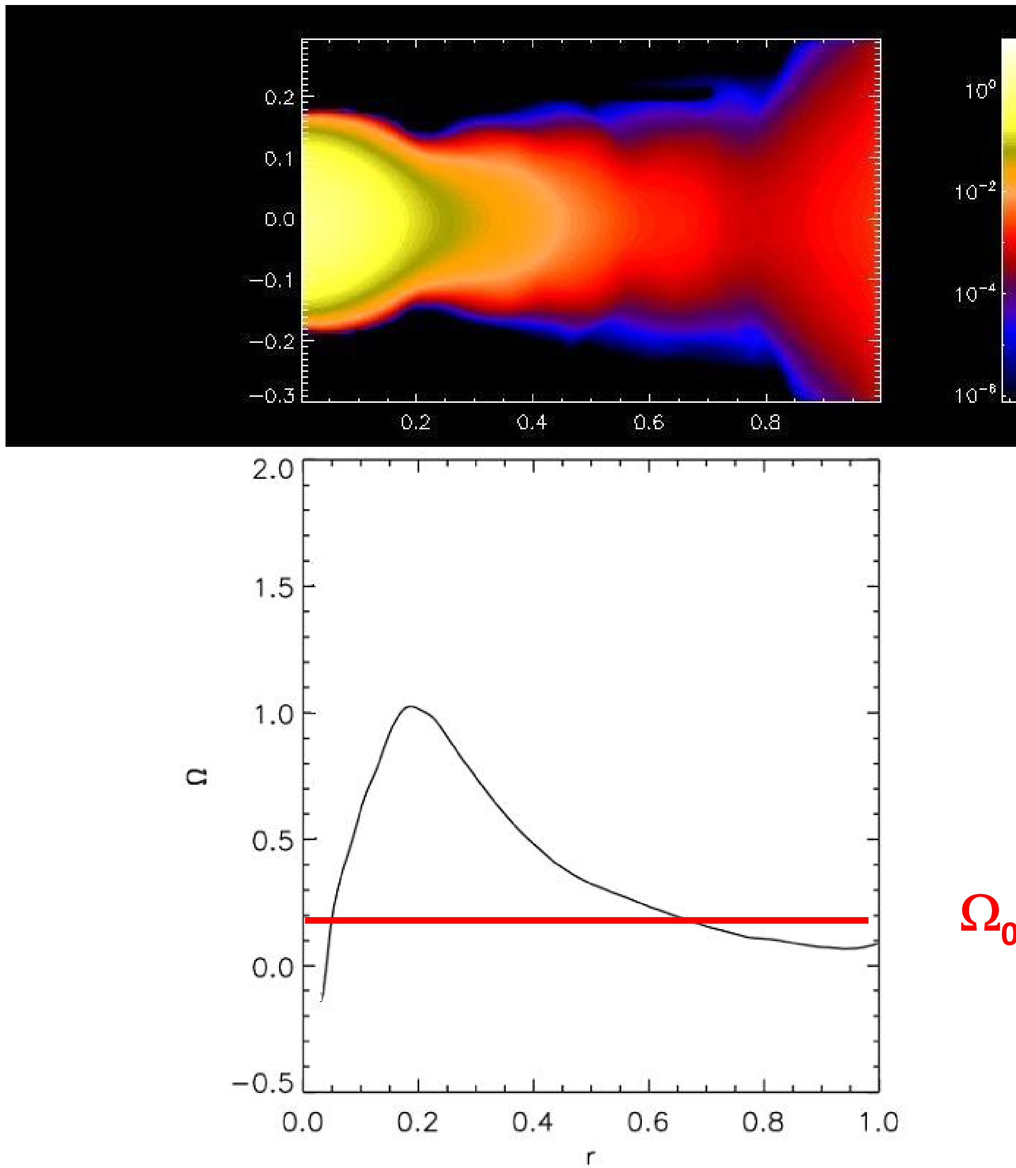


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# 2. What is *hydrodynamic* outcome of instability?

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| $q_{crit} < q_{merge} < q_0$ | donor plunges into accretor |
| $q_{crit} < q_0 < q_{merge}$ | tidal disruption of donor |

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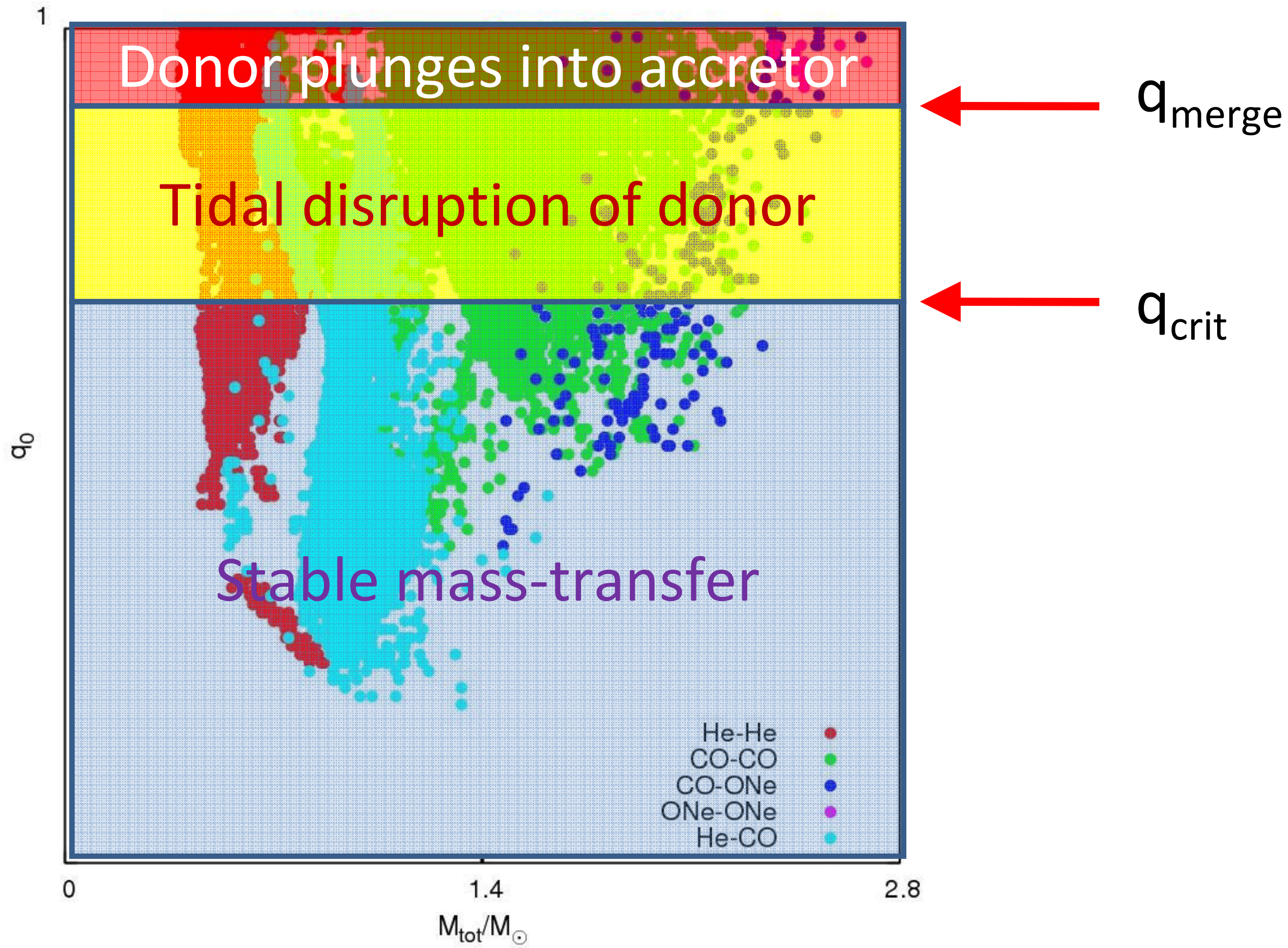
# If $q_{crit}$ = 2/3 and $q_{merge}$ = 0.9 …



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- We are in the middle of a collaborative project in which an extensive set of binary simulations is being carried out to compare results from two very different numerical algorithms:
  - Our grid-based, finite-volume hydrocode [P. Motl, W. Even, J.E. Tohline]
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- Preliminary report: Amazingly good agreement for unstable (*i.e.*, merger or tidal disruption) evolutions if …
  - Simulations start from identical "quiet" starts;
  - The number of SPH particles is comparable to number of grid cells.

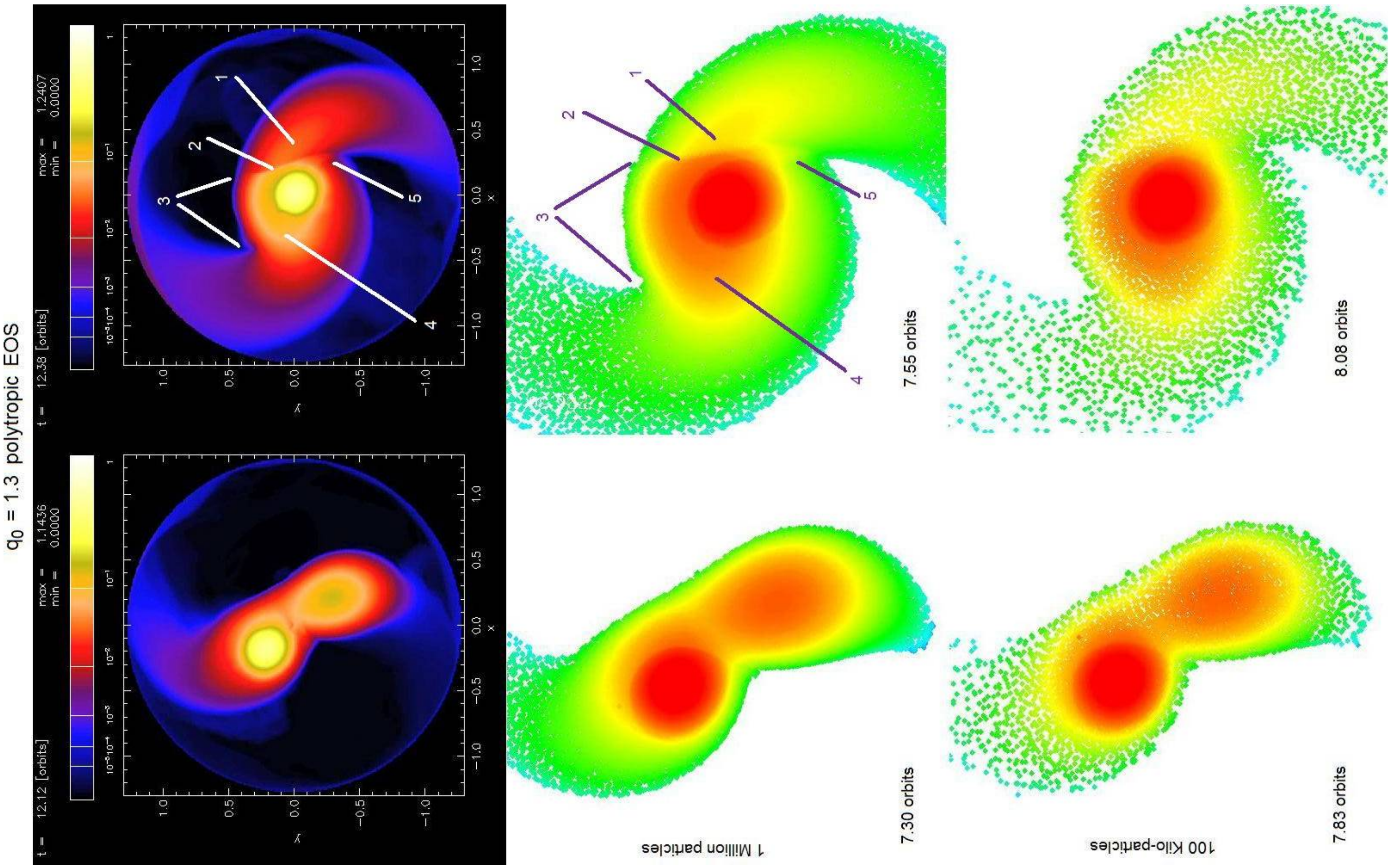
# Do Results Depend on Choice of Numerical Algorithm?

LSU grid code

LANL SPH code

$10^6$ particles

$10^5$ particles



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  - Using a "polytropic" equation of state, the accreted layers are allowed to cool back down to the specific entropy of the donor material
- Preliminary report: Unstable (*i.e.*, merger or tidal disruption) evolutions change only in relatively subtle ways when the "ideal-gas" EOS is used in place of the "polytropic" EOS. (On this point, as well, there is good agreement between the SPH and grid-code simulations.)

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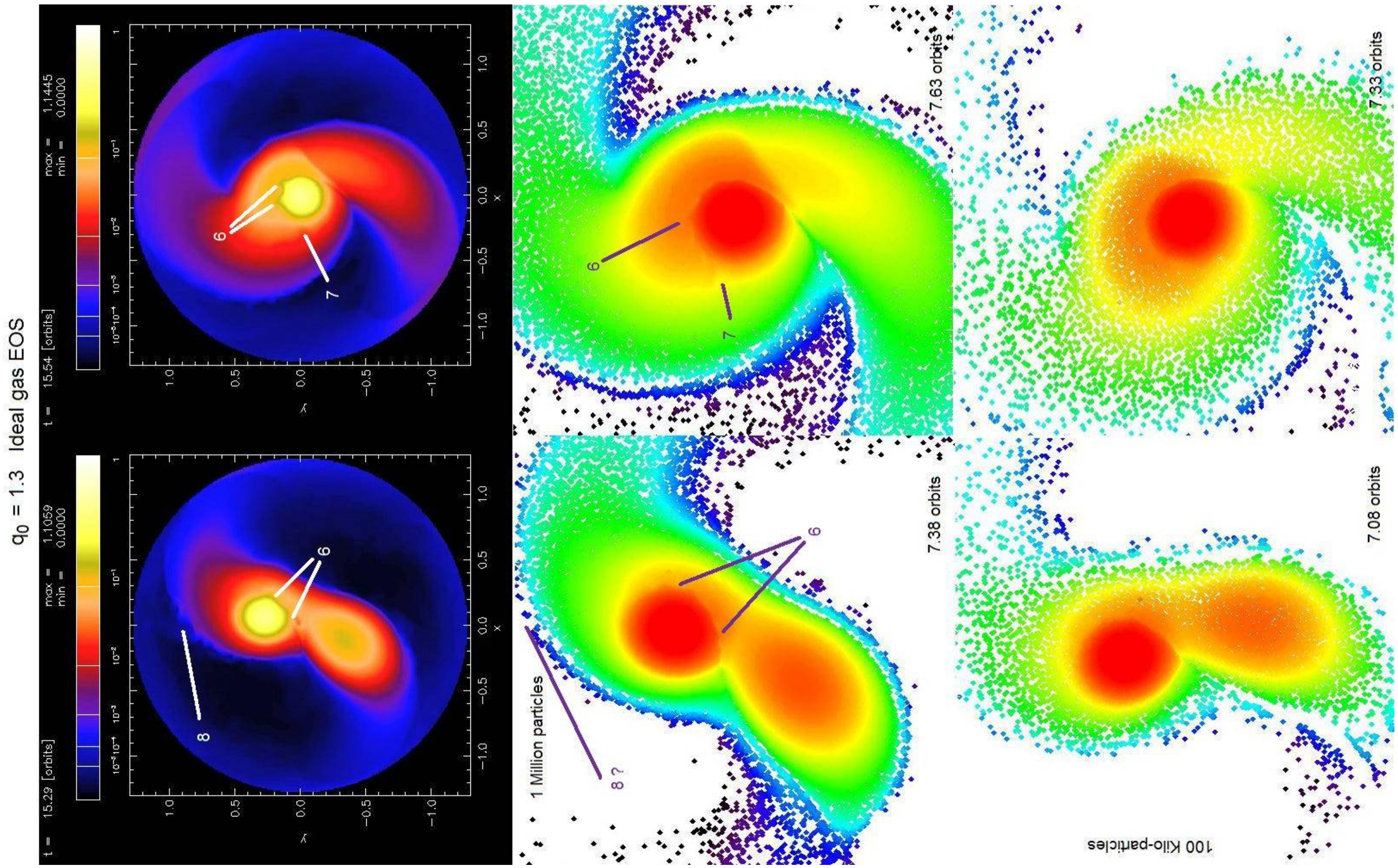

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- Up to now, our simulations have not included forcing due to a radiative flux. Hence, we have not been in a position to examine how the dynamics is altered when the accretion flow resulting from unstable mass-transfer becomes "super-Eddington".
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  - Does mass (and angular momentum) get ejected from the system?
  - Does a significant “common envelope” form as a result?
- We have recently modified our code to handle radiation transport in the flux-limited-diffusion approximation, *a la ZEUS-MP* (Hayes et al. 2006).

# Pure Hydro

$$
\begin{aligned}
\frac{d\rho}{dt} + \rho\nabla\cdot\mathbf{v} &= 0\,; \\
\rho\frac{d\mathbf{v}}{dt} &= -\nabla p - \rho\nabla\Phi_{\rm grav} \\
\rho\frac{d}{dt}\left(\frac{e}{\rho}\right) + p\nabla\cdot\mathbf{v} &= 0\,; \\
\nabla^2\Phi_{\rm grav} &= 4\pi G\rho\,;
\end{aligned}
$$

The Astrophysical Journal Supplement Series, 165:188–228, 2006 July


# SIMULATING RADIATING ~~AND MAGNETIZED~~ FLOWS IN MULTIPLE DIMENSIONS WITH ZEUS-MP

John C. Hayes,[1] Michael L. Norman,[1,2] Robert A. Fiedler,[3] James O. Bordner,[1,2] Pak Shing Li,[4]
Stephen E. Clark,[2] Asif ud-Doula,[5,6] and Mordecai-Mark Mac Low[7]

$$\begin{aligned}
\frac{d\rho}{dt} + \rho\nabla\cdot\mathbf{v} &= 0\,;\\
\rho\frac{d\mathbf{v}}{dt} &= -\nabla p - \rho\nabla\Phi_{\rm grav} + \left(\frac{\chi}{c}\right)\mathbf{F}\,;\\
\rho\frac{d}{dt}\left(\frac{e}{\rho}\right) + p\nabla\cdot\mathbf{v} &= c\kappa_E E - 4\pi\kappa_P B_P\,;\\
\rho\frac{d}{dt}\left(\frac{E}{\rho}\right) + \nabla\cdot\mathbf{F} + \nabla\mathbf{v}:\bar{\bar{\mathbf{P}}} &= 4\pi\kappa_P B_P - c\kappa_E E\,;\\
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\end{aligned}$$

---

**Optically thick regime in thermodynamic equilibrium:**

$$E(T) = aT^4 = \frac{4\sigma}{c}T^4 = \frac{4\pi}{c}\left(\frac{\sigma}{\pi}T^4\right) = \frac{4\pi}{c}B(T)$$

$$\mathbf{F} = -\left(\frac{c}{\chi}\right)\nabla\left(\frac{1}{3}E\right) = -\left(\frac{4\sigma}{3\chi}\right)\nabla(T^4) = -\left(\frac{c}{\chi}\right)\nabla p_{\rm rad}$$

# 5. What About Super-Eddington Accretion?

For an opacity of the form …

$$\chi = \kappa_p = \kappa_E \;=\; K_1 \rho \qquad \text{for example,} \qquad K_1 = \frac{\sigma_T}{m_p}$$

we can write …

$$L_{\rm Edd} \equiv \left(\frac{4\pi G M_a\, c}{K_1}\right)$$

$$L_{\rm acc} \equiv \left(\frac{G M_a}{R_a}\right) \dot{M}$$

so we can define,

$$f_{\rm Edd} \equiv \frac{L_{\rm acc}}{L_{\rm Edd}} = \left(\frac{K_1}{4\pi R_a c}\right) \dot{M} = \frac{M_{\rm tot}}{4\pi R_a P_{\rm orb}} \left(\frac{K_1}{c}\right) \dot{m}$$

where,

$$\dot{m} \equiv \dot{M} \cdot \frac{P_{\rm orb}}{M_{\rm tot}}$$

Then, $f_{Edd} > 1$ means super-Eddington accretion.

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$$f_{\rm Edd} = \frac{M_{\rm tot}}{4\pi R_a P_{\rm orb}}\left(\frac{K_1}{c}\right)\dot{m}$$

If we actually set … $K_1 = \frac{\sigma_T}{m_p}$

then, $f_{Edd}$ climbs above unity (i.e., the flow becomes super-Eddington) when $\dot{m}$ climbs above $10^{-12}$.

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Solution: Artificially lower $K_1$ by a factor of $10^{10}$. Then, $f_{Edd}$ will climb above unity when $\dot{m}$ climbs above $10^{-2}$.

# Very Preliminary Results from this new Radiation-Hydro code

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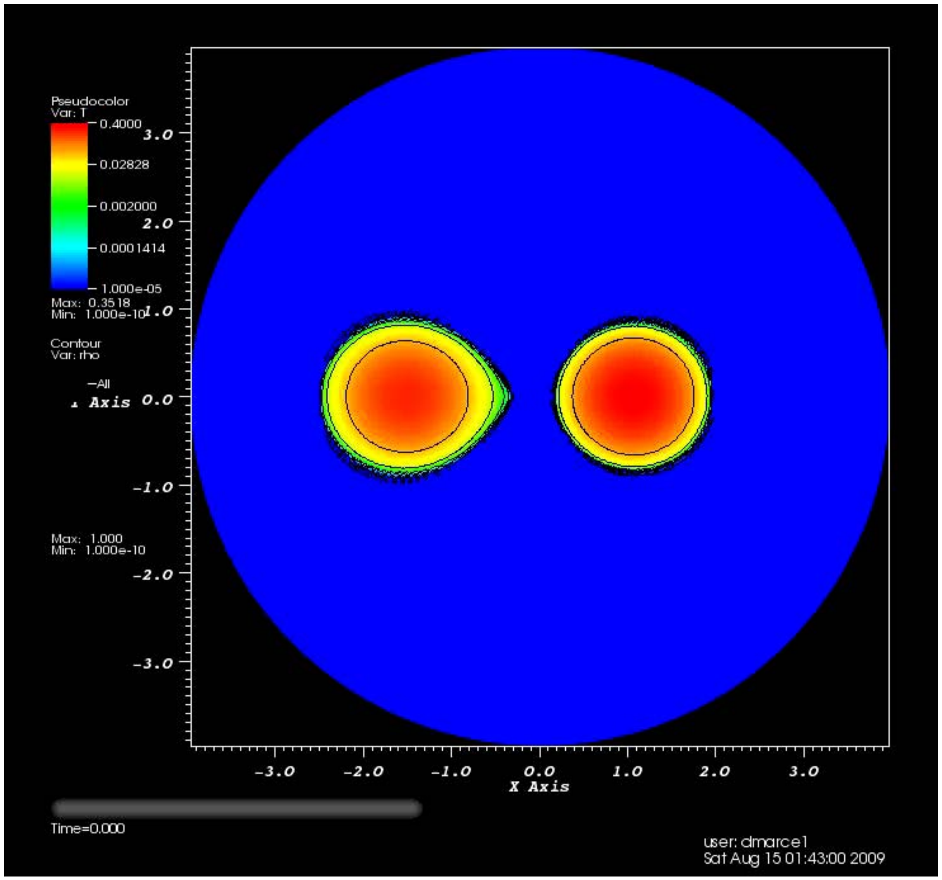
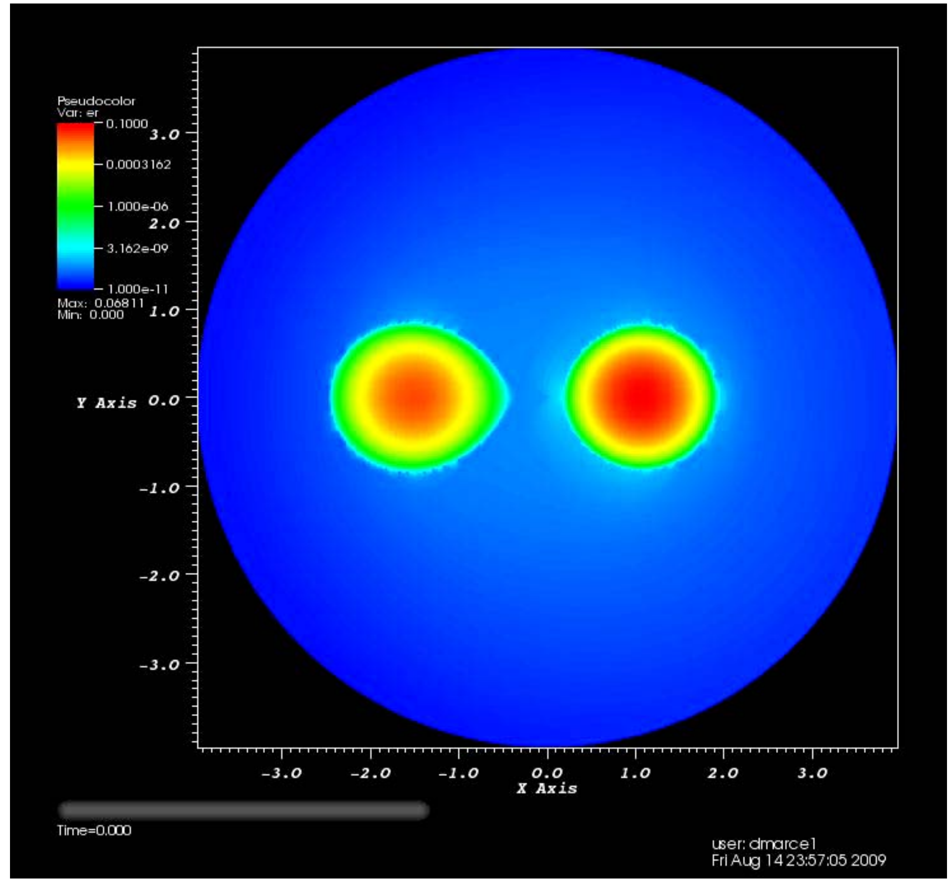
Credit: D. Marcello & P. Motl



# Thanks!