Simulating Binary Star Systems

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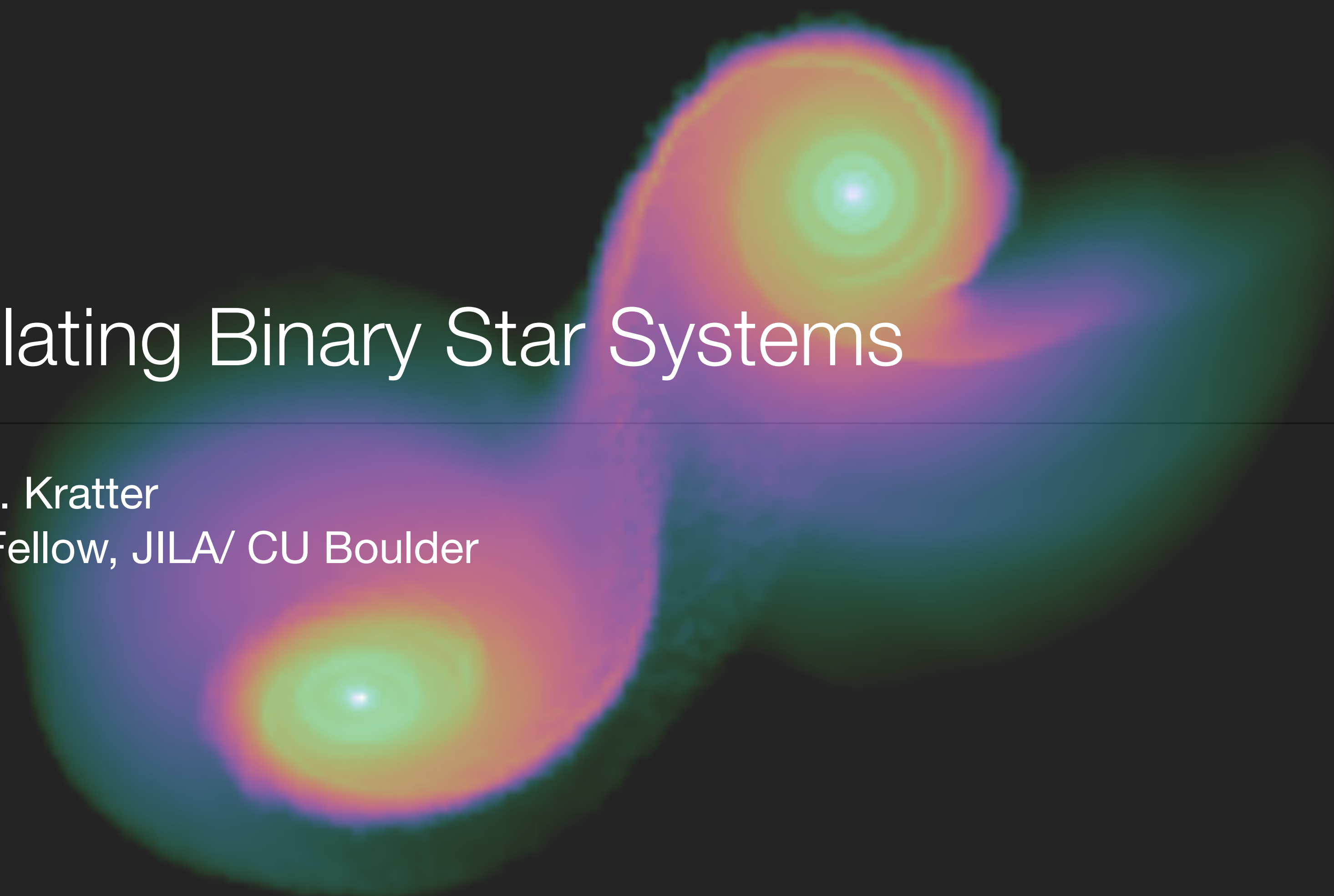


Outline

Why bother with binaries?

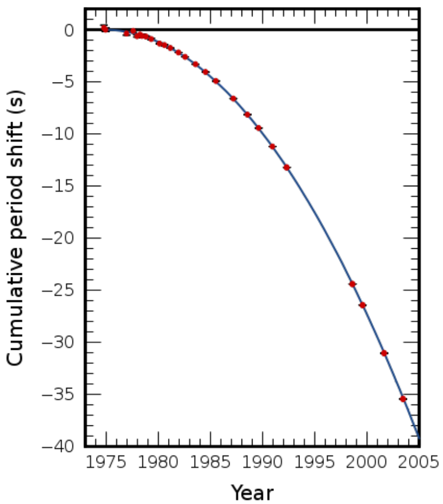
How do they form?

What challenges do binaries pose from a numerical perspective?

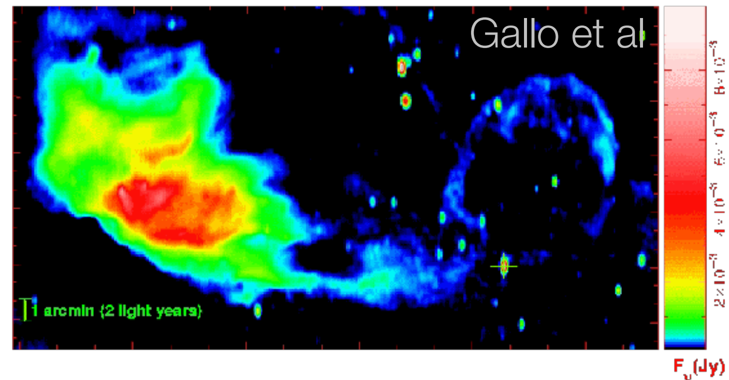
Example Calculations

Binaries Matter

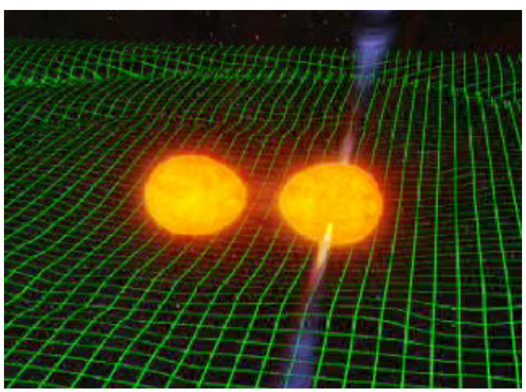
Type Ia supernovae / dark energy



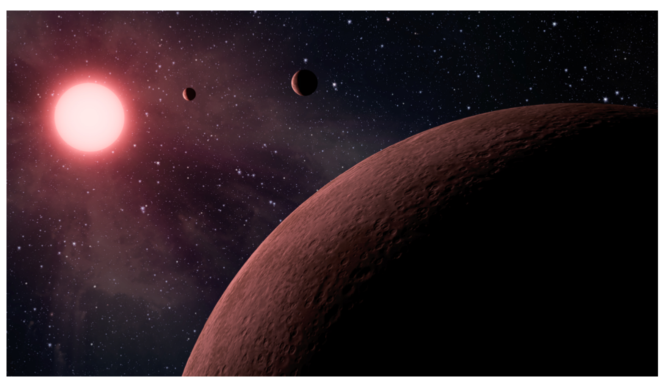
GR confirmation



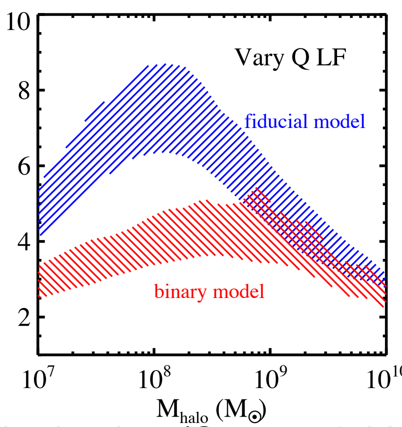
Confirmed BH



GW signal



Exoplanet characterization



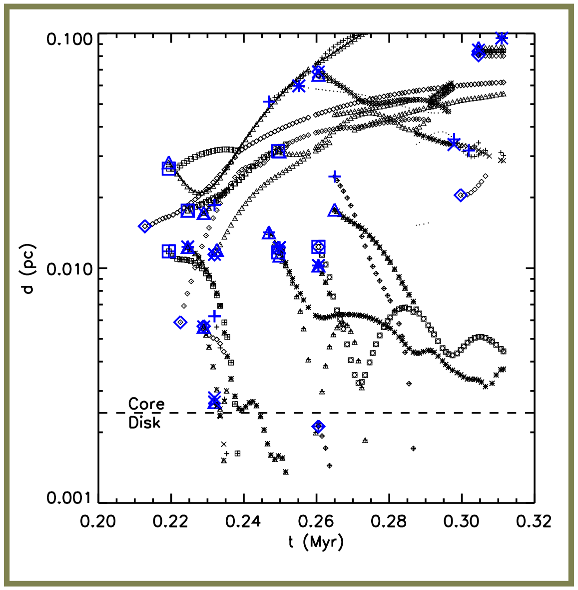
Reionization (Conroy & Kratter 2012)

What we (theorists) “know”:

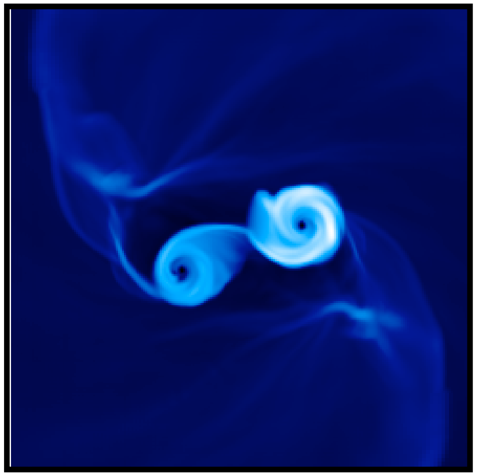
- Multiple systems help solve the “angular momentum problem” (R. Larson)
- There are multiple pathways to form binaries
- The cluster population should be distinct from the field population
- The formation mechanism ***should*** leave an imprint on the population

Binary Formation

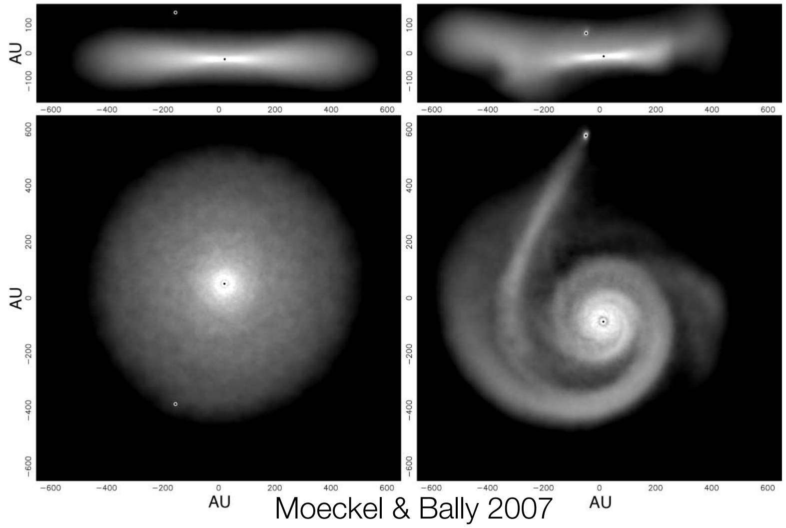
- Three modes
  - Capture /ejection
  - Turbulent Fragmentation
  - Disk Fragmentation



Offner, Kratter et al 2010



Kratter et al 2010



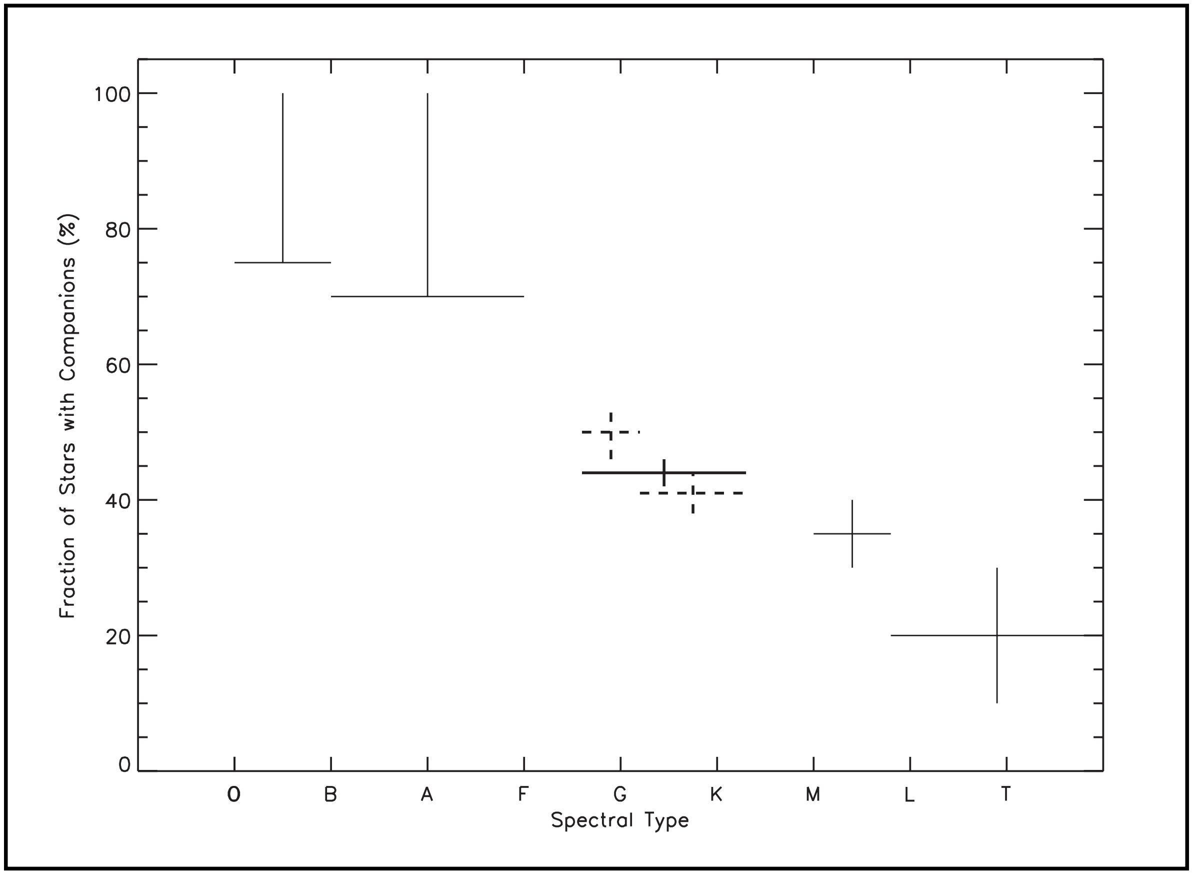
Moeckel & Bally 2007

What observations show us:

- For solar type stars, the distribution is log-flat from 5-3000 AU with no apparent break in slope or frequency
- Lower mass stars have separations typically < 200 AU (except the wide ones)
- Higher mass stars are incomplete but high multiplicity. May show a preference for more equal mass ratio at smaller separation, and a correlation between mass ratio and separation
- For solar type and lower mass stars, all companions masses are equally probable
- Separation in field is log normal, and the frequency is lower

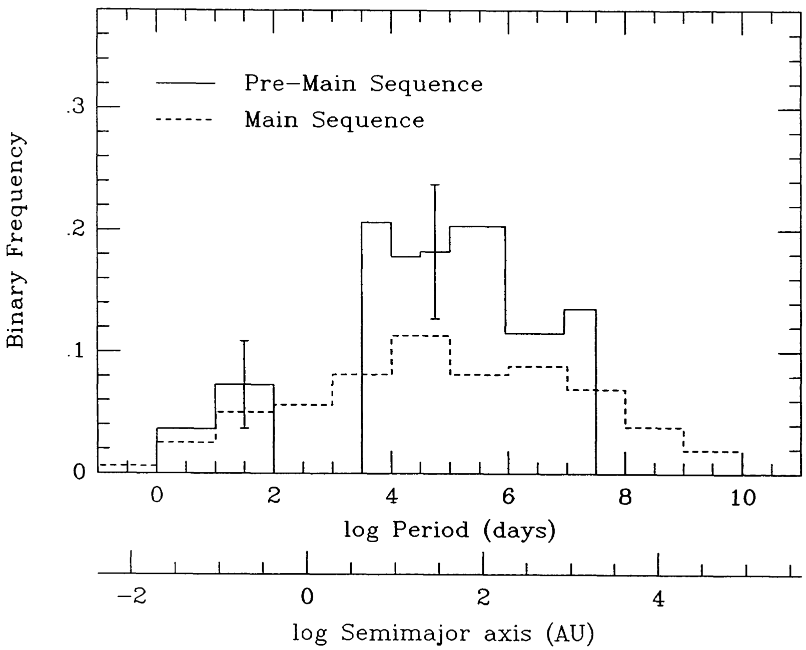
Kraus et al 2011, Raghavan et al 2010, Sana & Evans 2011

Multiplicity is **Mass** Dependent

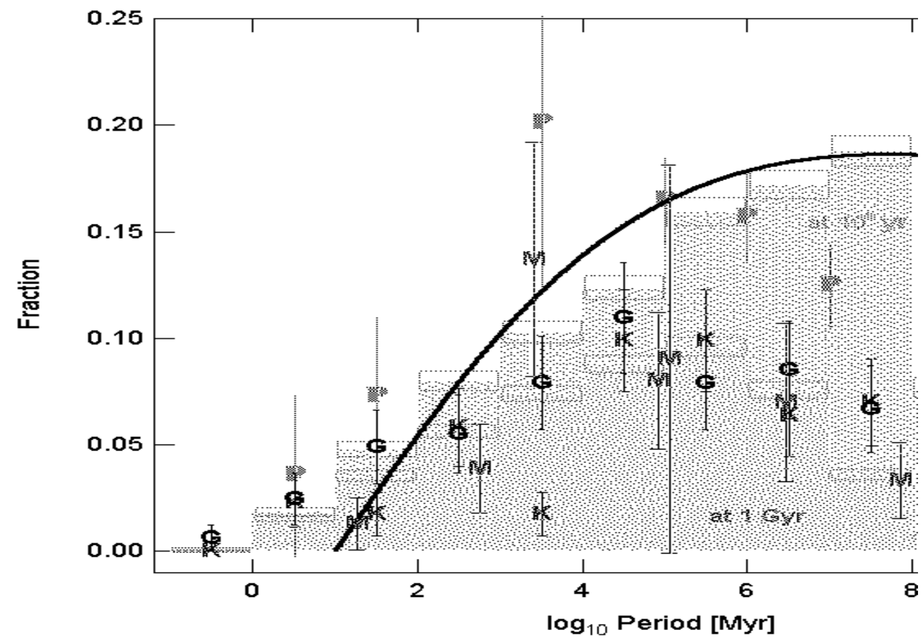


Raghavan et al 2010

Pre-Main Sequence stars have a higher multiple fraction

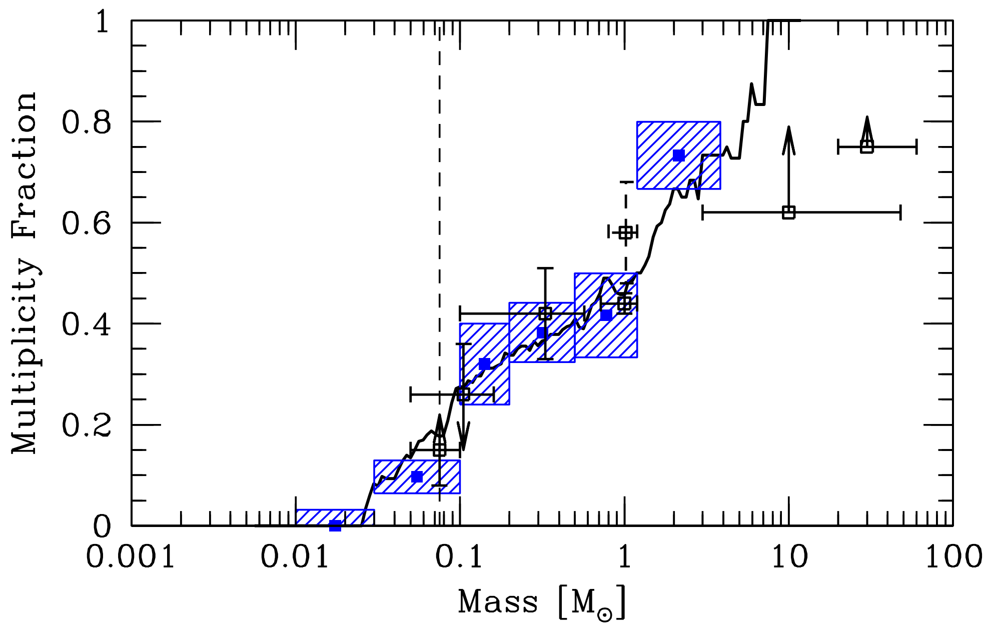


Mathieu 1994



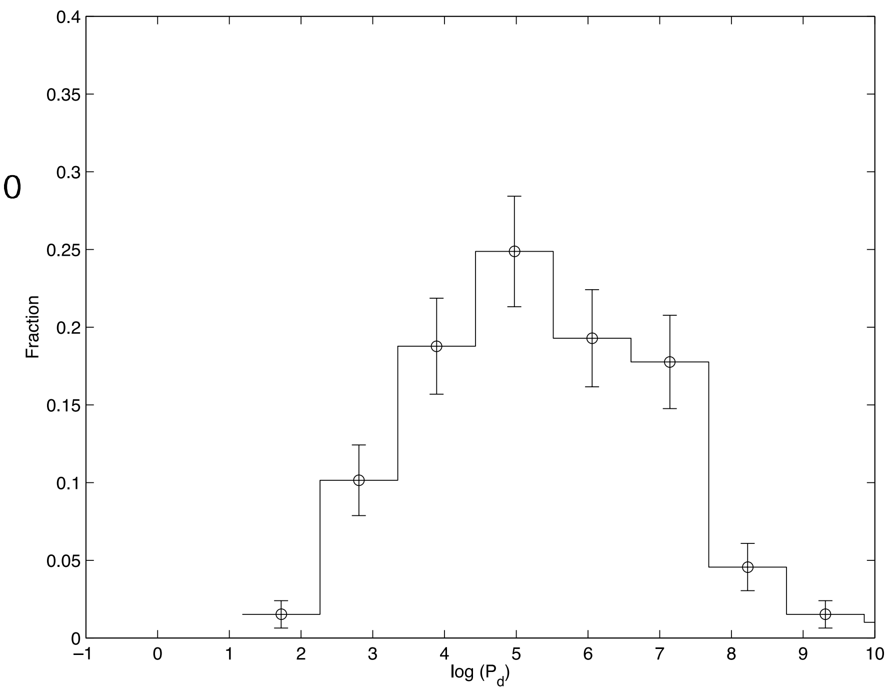
Goodwin et al 2007

Two Right Answers



Bate 2012: controversial ICs, right (field) distribution

Fisher 2004: less controversial ICs, no “physics”, right (field) distribution



Current Binary Star “Problems”

- **Binary Formation and Early Evolution:**
    - Large Scale - collapse from GMCs
    - Mid Scale - formation from individual core
    - Small Scale - formation within / interaction with protostellar disks
- Evolved Binaries
    - Common Envelope Phases
    - Supernovae / Tidal Disruptions

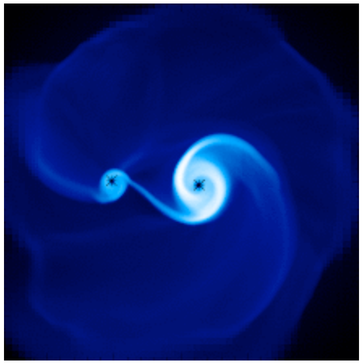
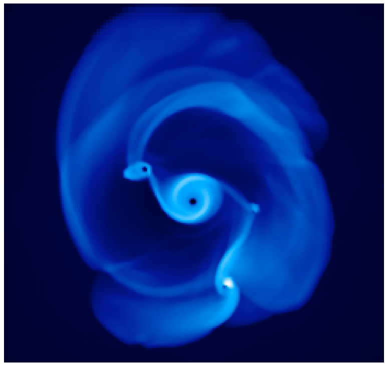
Simulating Binaries: What we want

- Robust hydrodynamic scheme (shock capturing, *low numerical diffusion)
- Dynamic Range
  - AMR
  - Sink Particles
- (Self) Gravity
- No enforced axisymmetry
- MHD? Radiation? Cooling / complex EOS?

What we get with...Cartesian Grid Codes

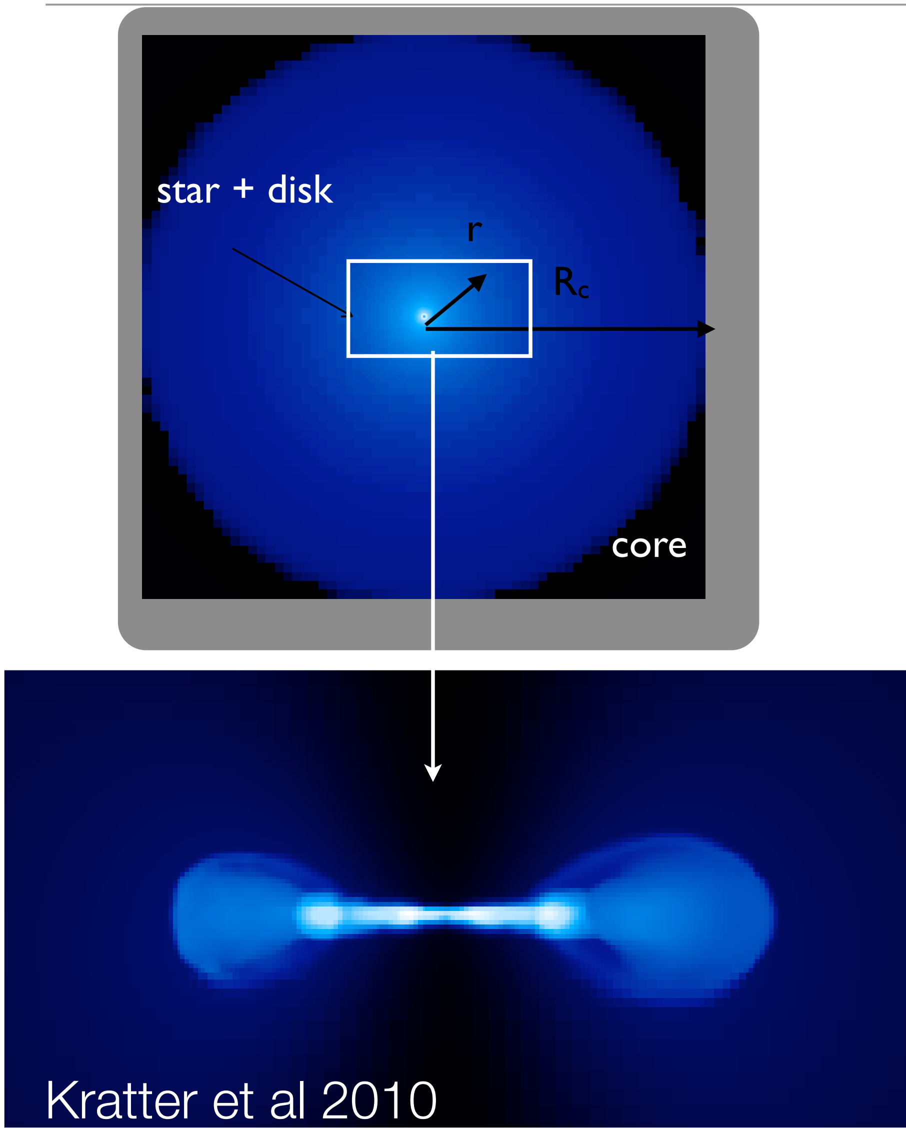
- PRO:
  - AMR
  - Sink Particles
  - (Self) Gravity (FFT / multigrid)
  - Shock capturing hydro (Reimann solvers)
  - (non-ideal) MHD, radiation, EOS, etc
  - (somewhat) flexible w.r.t symmetry

- CON:
  - linear vs angular momentum conservation
  - “high Mach number” problem
  - resolving spheres with cubes
  - some dynamic range limitations (courant, alfven speed)

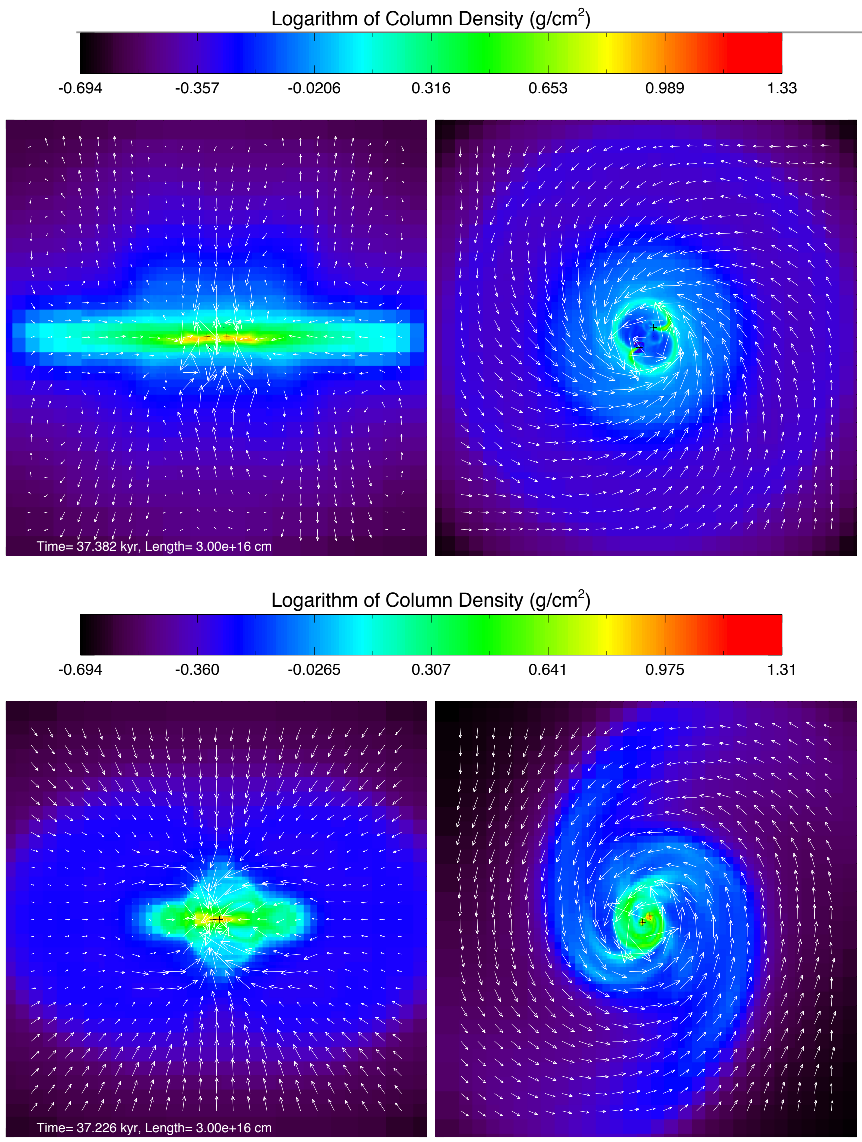
Kratter et al 2010

Example 1: Binaries via disk fragmentation

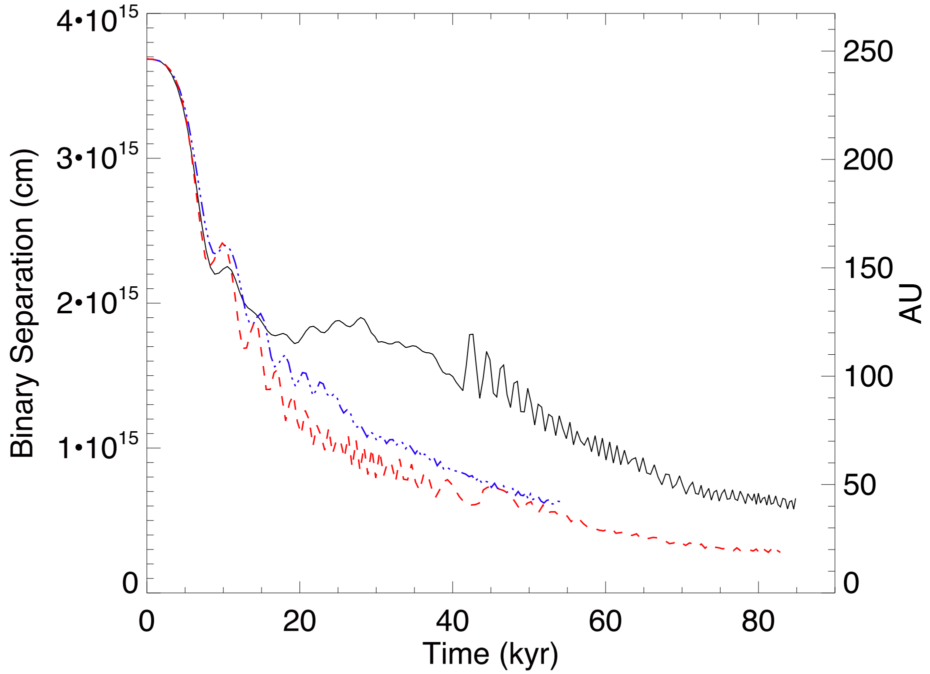


- Numerical Experiments:
  - ORION: Parallel, Adaptive Mesh Refinement, hydro + SG + sink particles, isothermal limit (Klein 99, Truelove 98, Krumholz 2004)
- Goals
  - study role of rapid infall and fragmentation caused by self gravity
  - Understand conditions for binary and multiple formation
  - Conduct resolution study

Example 2: Binary Orbital Evolution with MHD



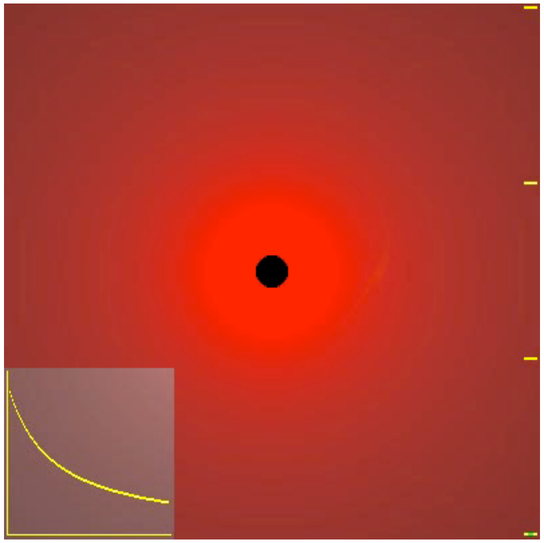
- Evolution of binary orbits with a misaligned magnetic field and core rotation axis (Enzo)



Zhao, Li, & Kratter, in prep

What we get with...Cylindrical / Spherical Grid Codes

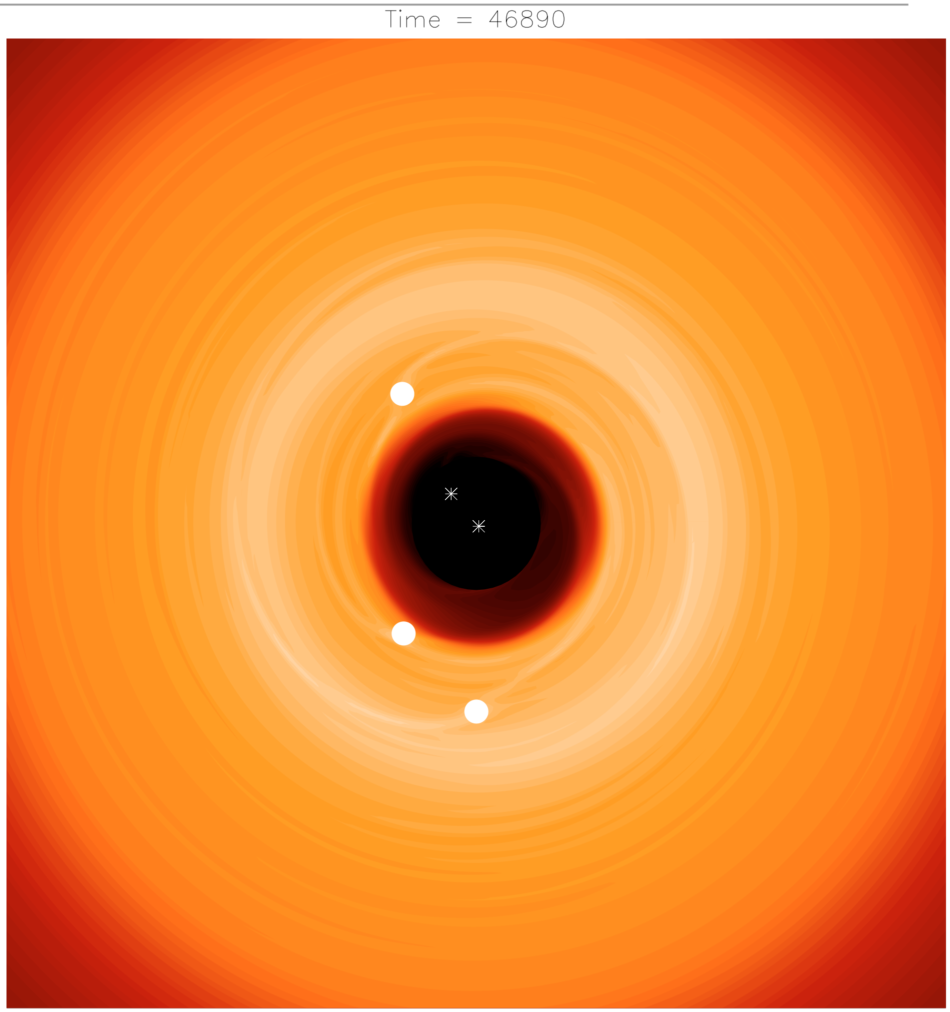
- PRO:
  - aligned flows and grids (disks / spheres)
  - Sink Particles
  - (Self) Gravity
  - Shock capturing hydro
  - (non-ideal) MHD, radiation, EOS, etc
  - angular momentum conservation
  - FARGO type algorithm
- CON:
  - “high Mach number” problem
  - constrained axis of symmetry
  - some dynamic range limitations (courant, alfven speed)



P. Armitage

Example 1: Binary - disk interaction with Binary off-grid

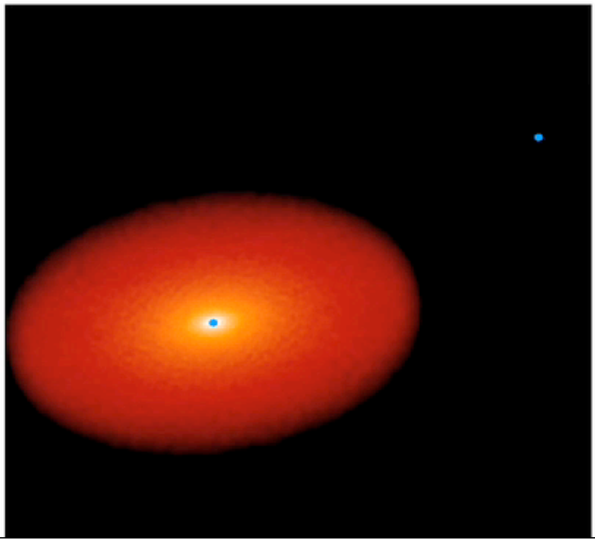
- “Live” binary at the center, but not “on” the grid



Pierens & Nelson, 2008

What we get with...SPH

- PRO:
  - Lagrangian solution to dynamic range problems
  - Sink Particles
  - (Self) Gravity (tree)
  - angular momentum conservation
  - No imposed symmetries / domain geometry
- CON:
  - complexities in addressing numerical diffusion
  - some dynamic range limitations (courant, alfven speed)
  - some shock capturing challenges
  - some uncertainties in convergence



N. Moeckel

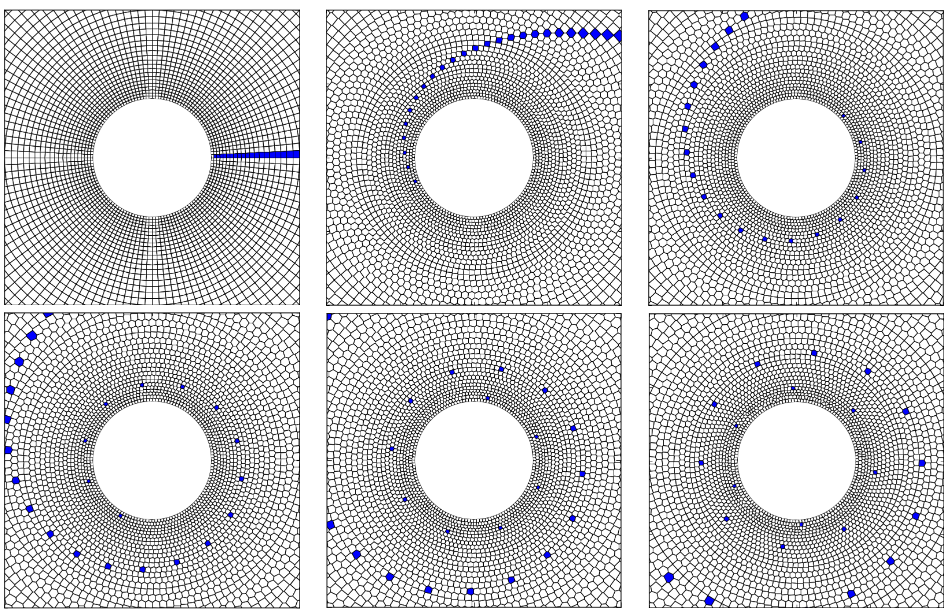

M. Bate, 2011

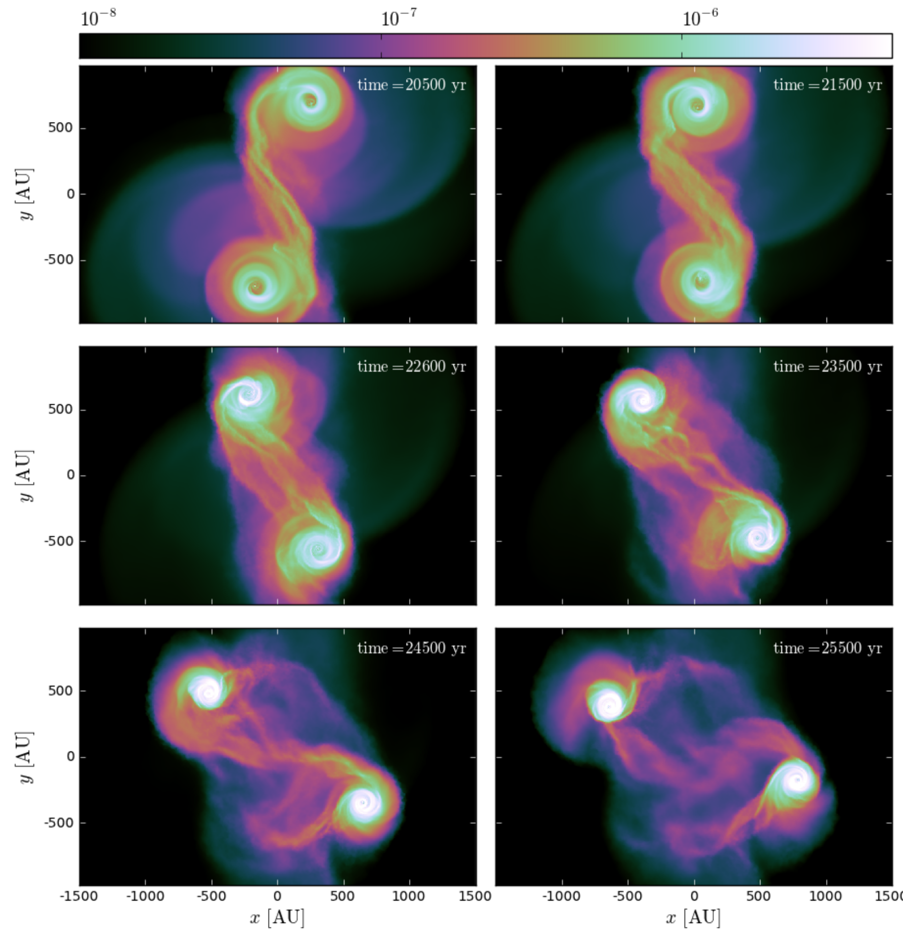
What we get with...Moving Mesh

- PRO:
  - Lagrangian solution to dynamic range problems
  - Sink Particles
  - (Self) Gravity (tree)
  - No imposed symmetries / domain geometry
  - Reimann solver hydro
  - no high-mach number flows across the mesh
- CON:
  - complexities in addressing numerical diffusion and conservation
  - slower due to tesselation requirements
  - complex boundary conditions
  - grid sampling noise

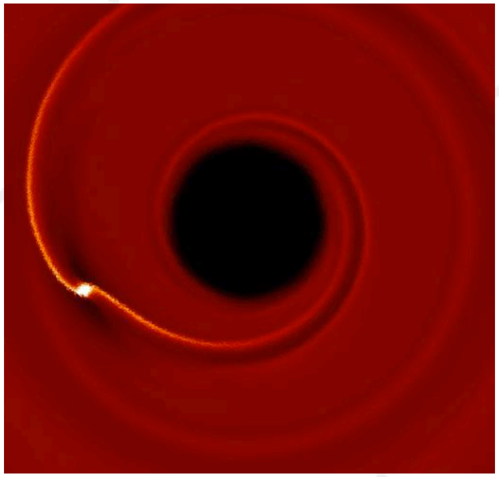
Moving Mesh Codes (e.g. AREPO, Springel 2009)

- Mesh is made every timestep to track the motion of the cell center of mass
- Reimann problem is solved in the cell face frame (boosted)

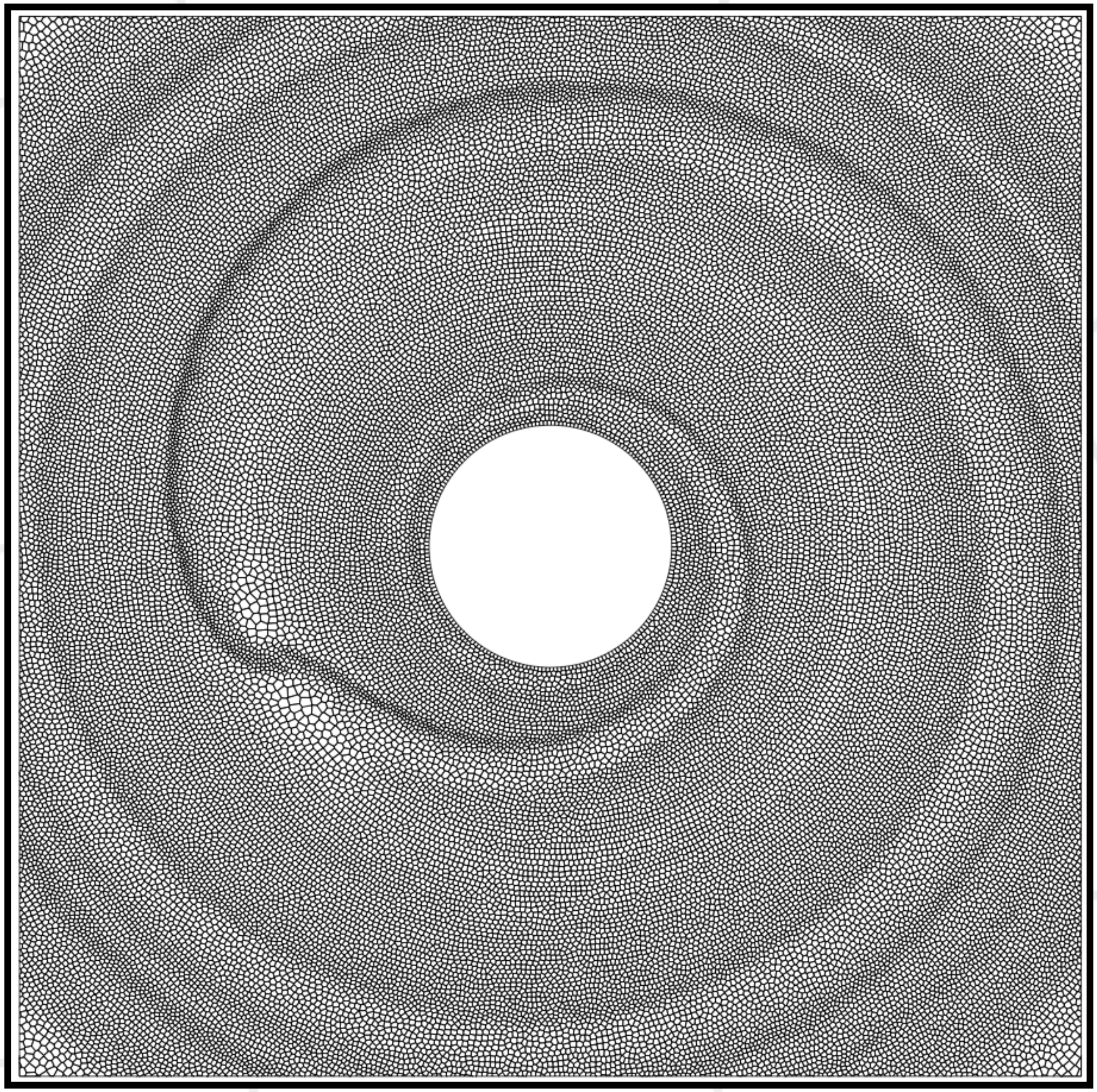




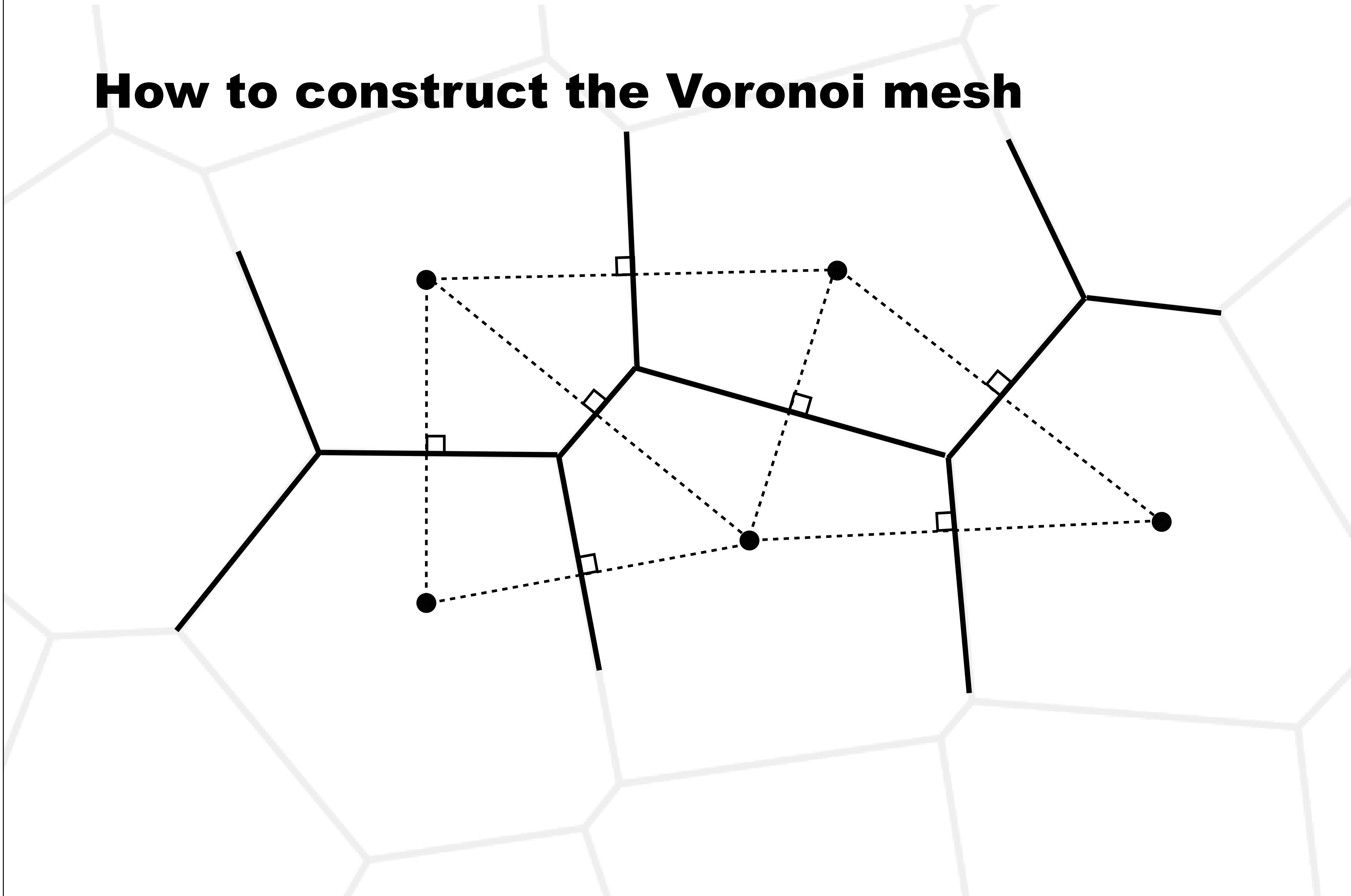
Diego Munoz, 2013



example: density wake in a
small mass ratio binary



How to construct the Voronoi mesh



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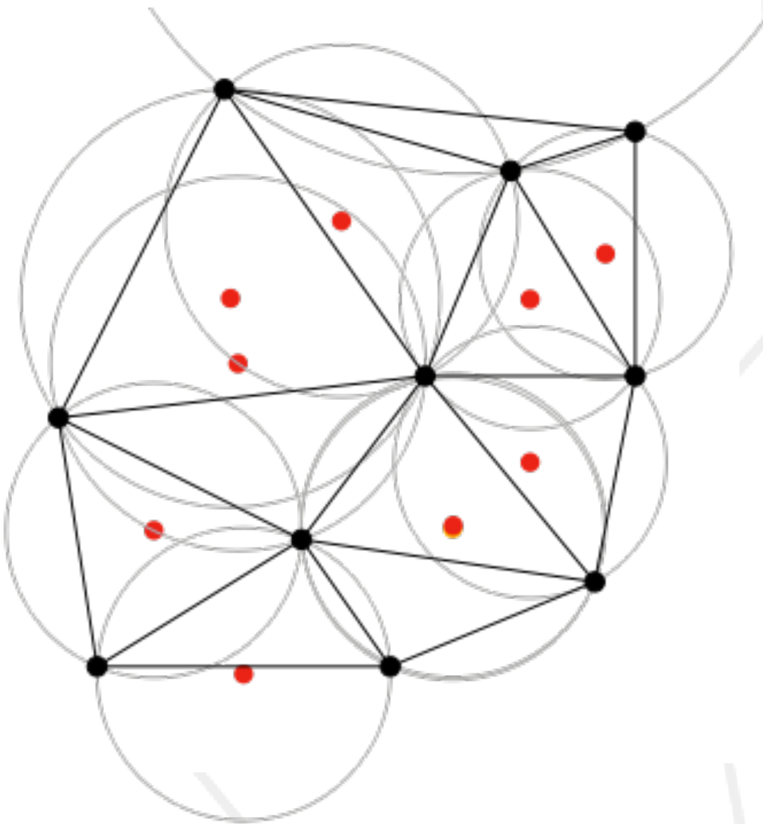

Each Voronoi cell contains the **space closest** to its generating point

The Delaunay triangulation contains only triangles with an **empty circumcircle**. The Delaunay tiangulation maximizes the minimum angle occurring among all triangles.

The centres of the circumcircles of the Delaunay triangles are the vertices of the Voronoi mesh. In fact, the two tessellations are the topological **dual graph** to each other.

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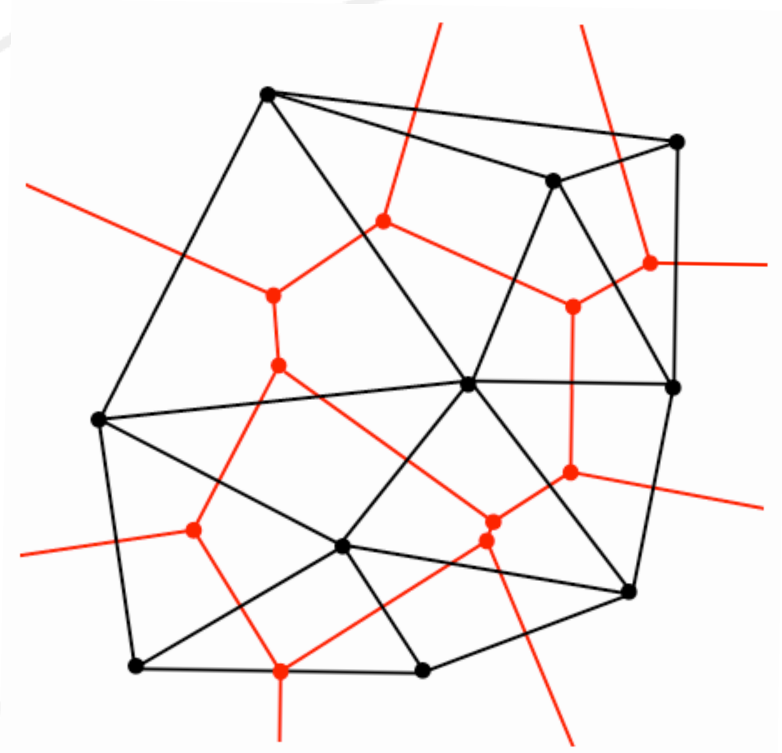

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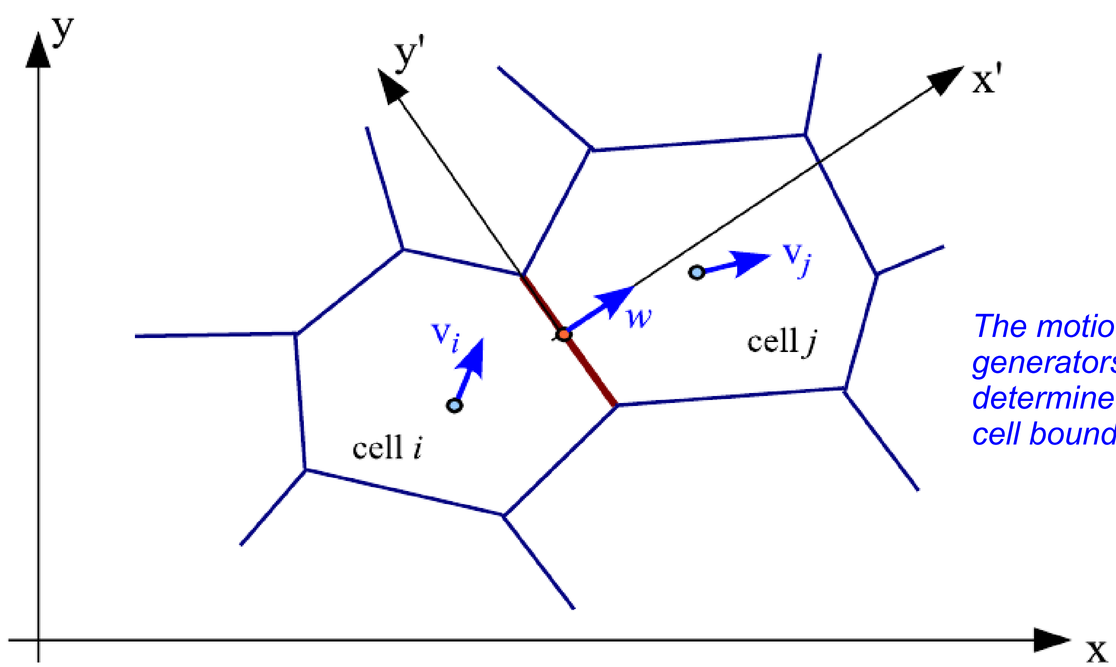
The fluxes are calculated with an exact Riemann solver in the frame of the moving cell boundary

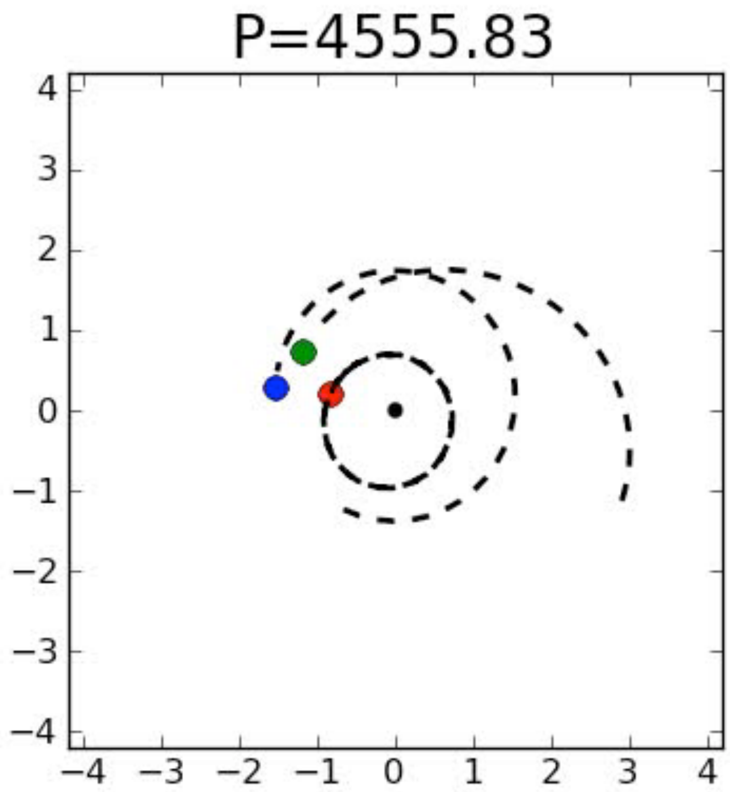
SKETCH OF THE FLUX CALCULATION



The motion of the mesh generators uniquely determines the motion of all cell boundaries

State left of cell face $\begin{pmatrix} \rho_L \\ \mathbf{v}_L \\ P_L \end{pmatrix}$ **State right of cell face** $\begin{pmatrix} \rho_R \\ \mathbf{v}_R \\ P_R \end{pmatrix}$ —— **Riemann solver** (in frame of cell face) → $\begin{pmatrix} \rho \\ \mathbf{v} \\ P \end{pmatrix}$ → $\mathbf{F}(\mathbf{U})$

Another kind of n-body



- After the hydrodynamics is mostly done, we need to worry about dynamics
- For planetary dynamics, precision requires direct integration of the equations of motion
  - Easy: 4th order Runge-Kutta
  - Efficient: Symplectic Methods, e.g. Wisdom-Holman Mapping
  - Robust: Bulirsch-Stoer

Many dynamics problems are “Embarrassingly Parallel”

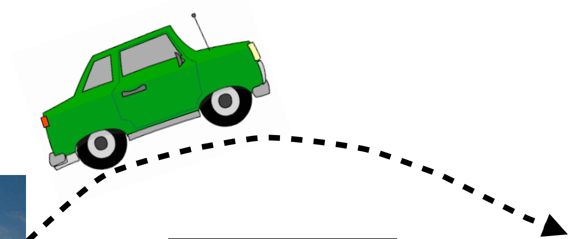
U of A: Not just telescopes!

Gurtina Besla: Galaxy Formation / Dynamics

Travis Barman (LPL): planetary atmospheres

me!

Andrew Youdin: Planet / solar system formation



YOU?!

New Theory Fellowship, coming this fall...