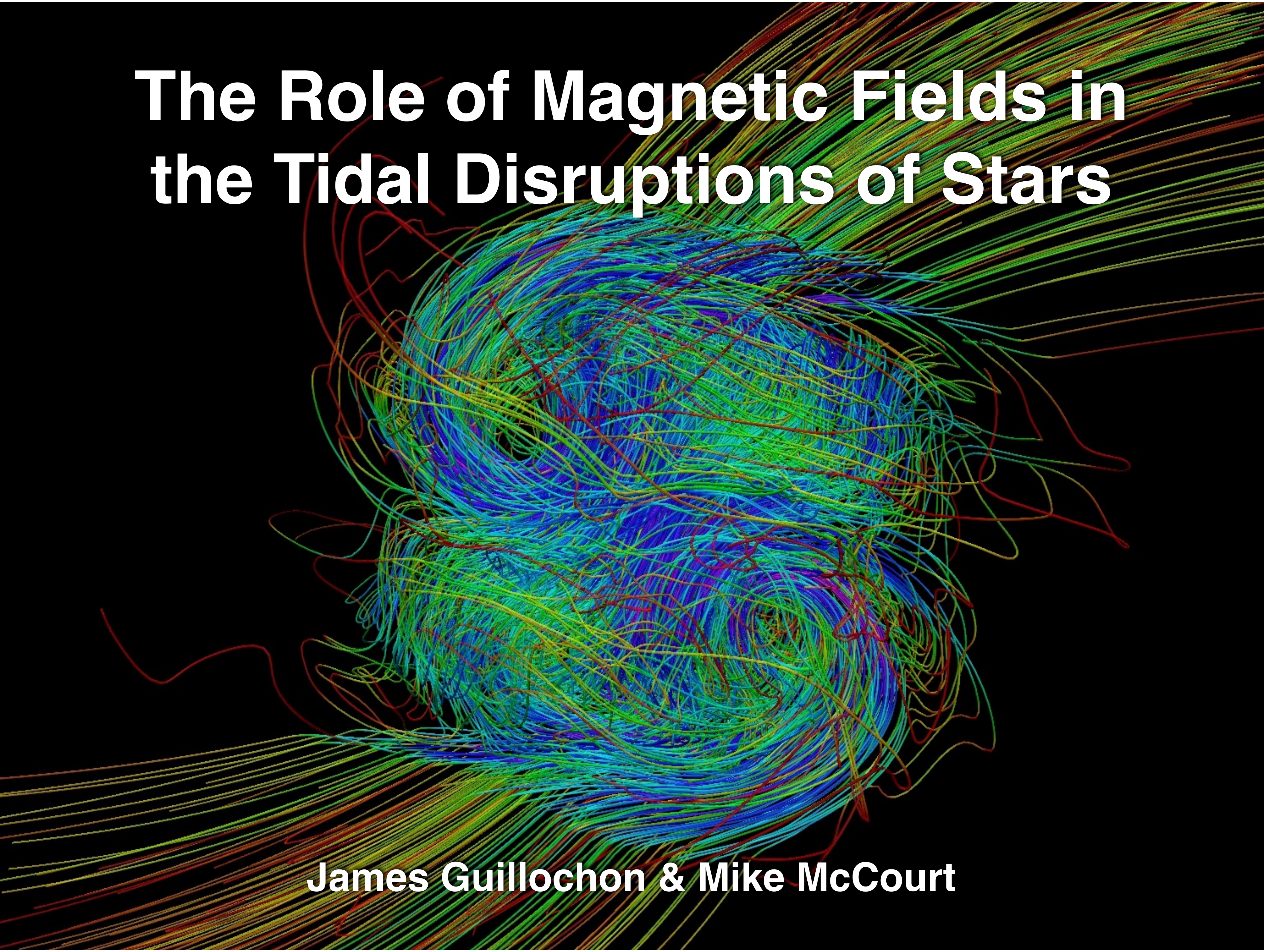
The Role of Magnetic Fields in the Tidal Disruptions of Stars



James Guillochon & Mike McCourt

Outline

- Magnetic fields in stars.
- Tiny overview of tidal disruptions.
- Magnetic fields and tidal disruptions: Why you should care.
- Preliminary Results in the form of interpretive dance (or movies, audience's choice).

Magnetic Fields in Stars

- Magnetic fields in most stars are very weak (less than one millionth the gas pressure), and are only competitive with gas pressure near or beyond the photosphere.

- The Sun is our best laboratory, but…

- We only really know the magnetic field structure well at or beyond the star's surface (star spots, corona, winds), and have limits on the interior field *strengths* (from asteroseismology), but not configurations.

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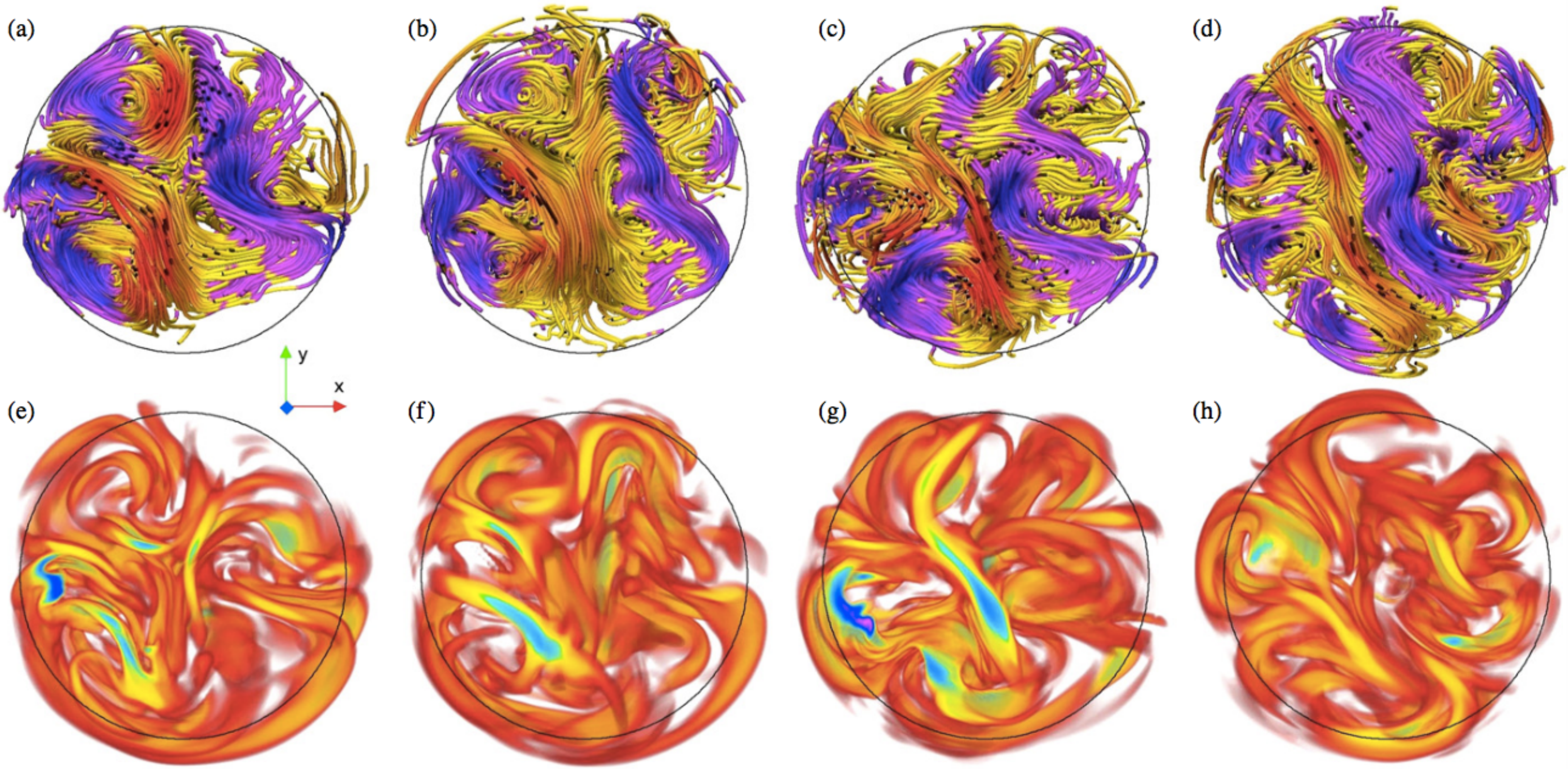
Photograph by NASA Solar Dynamics Observatory

SOLAR STORMS, JUNE 2012

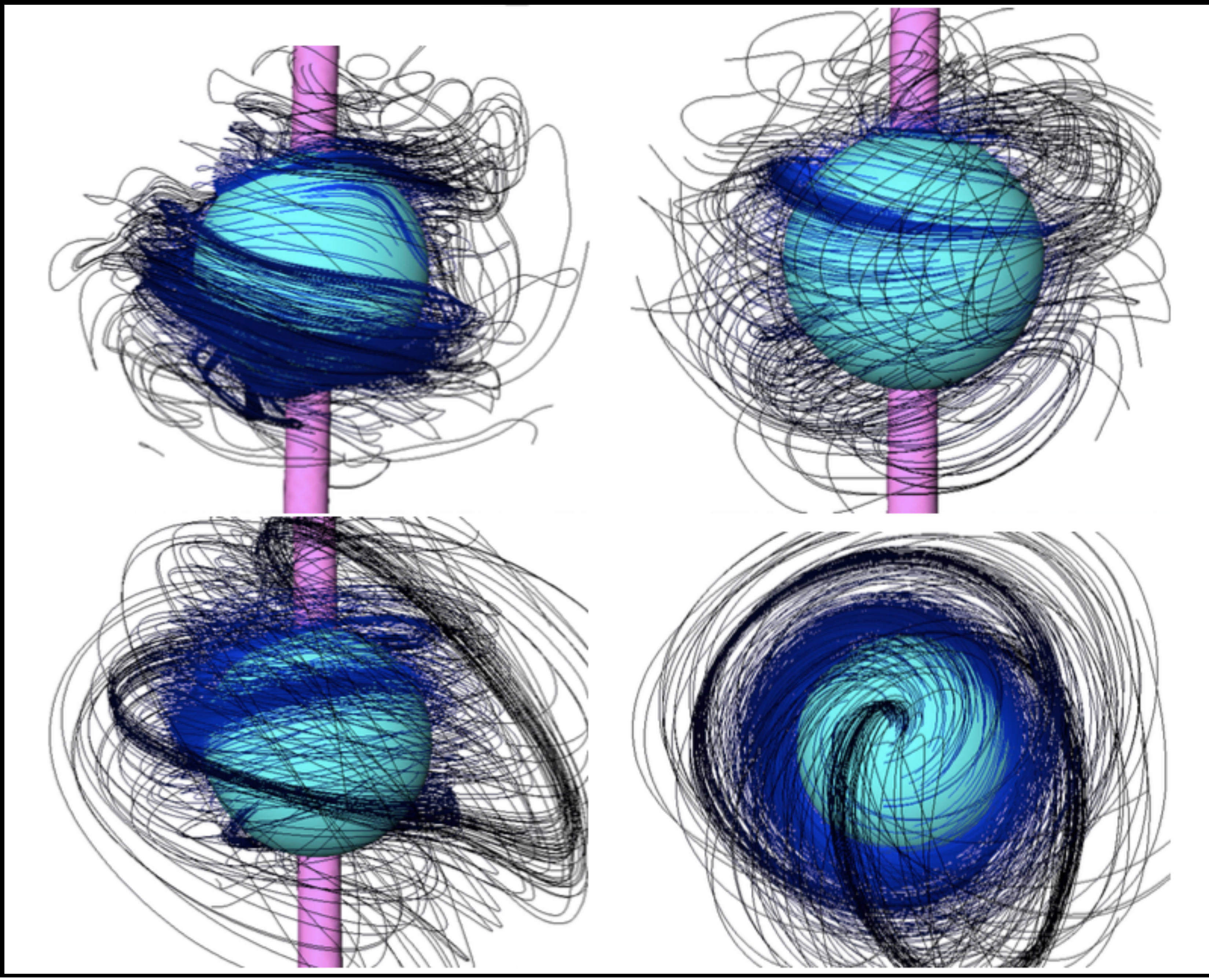
Some example interior configurations



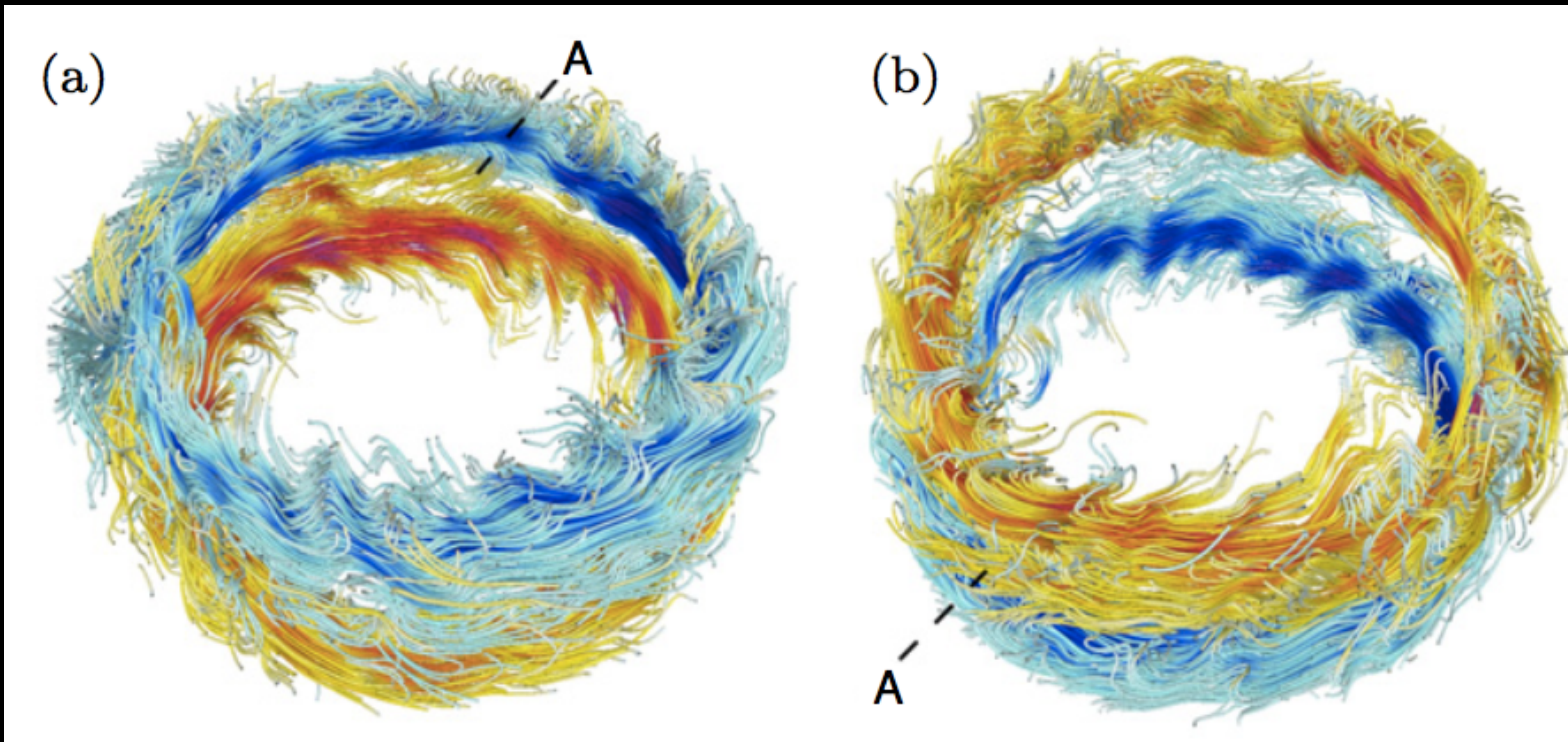
Ap Stars: Featherstone+ 2009

Some example interior configurations

Ap Stars: Braithwaite+ 2006



Some example interior configurations



Rapidly Rotating Sun: Brown+ 2010

The Most Magnetic Stars We Know

- Two flavors for currently magnetic stars:
  - Either the magnetic field is presently sustained by vigorous convective/ rotational motion…
    - Protostars
    - Ap stars
    - K- and M-dwarfs
    - Red giant stars
  - …or it had such motions in the past and the magnetic field has “frozen in.”
    - Magnetic white dwarfs
    - Magnetars
- Interestingly, the most magnetic objects have a similar values for the flux (independent of the object type, Reisenegger 2009): $\mathbf{\Phi_{max} \sim 10^{27.5}\ G\ cm^2}$.

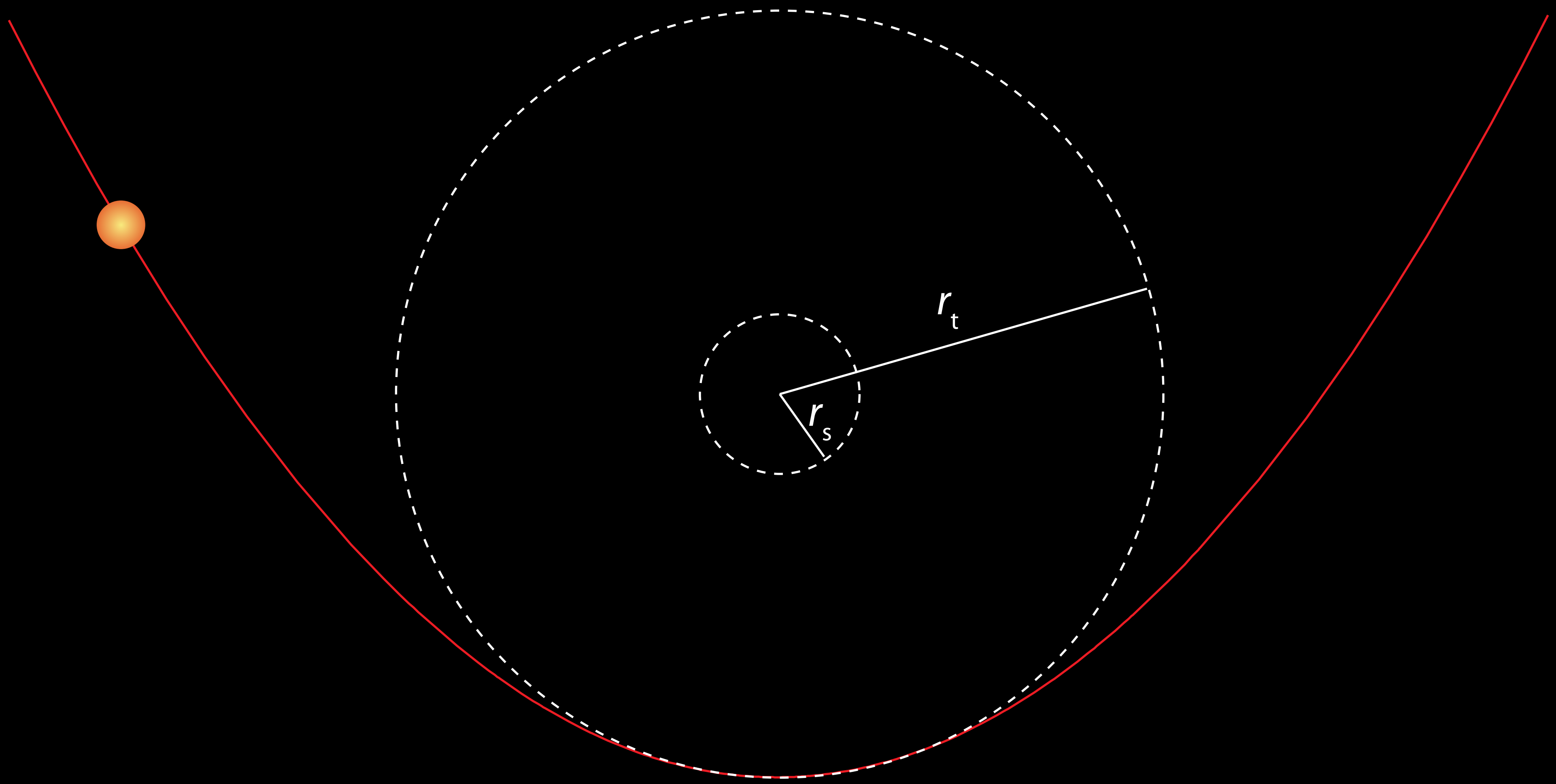
Tidal disruptions in brief

Schwarzschild Radius

$$r_{\rm s} = 3 \times 10^{11} M_6 \ {\rm cm}$$

Tidal Radius

$$r_{\rm t} = 7 \times 10^{12} \left(\frac{r_*}{r_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3} M_6^{1/3} \ {\rm cm}$$



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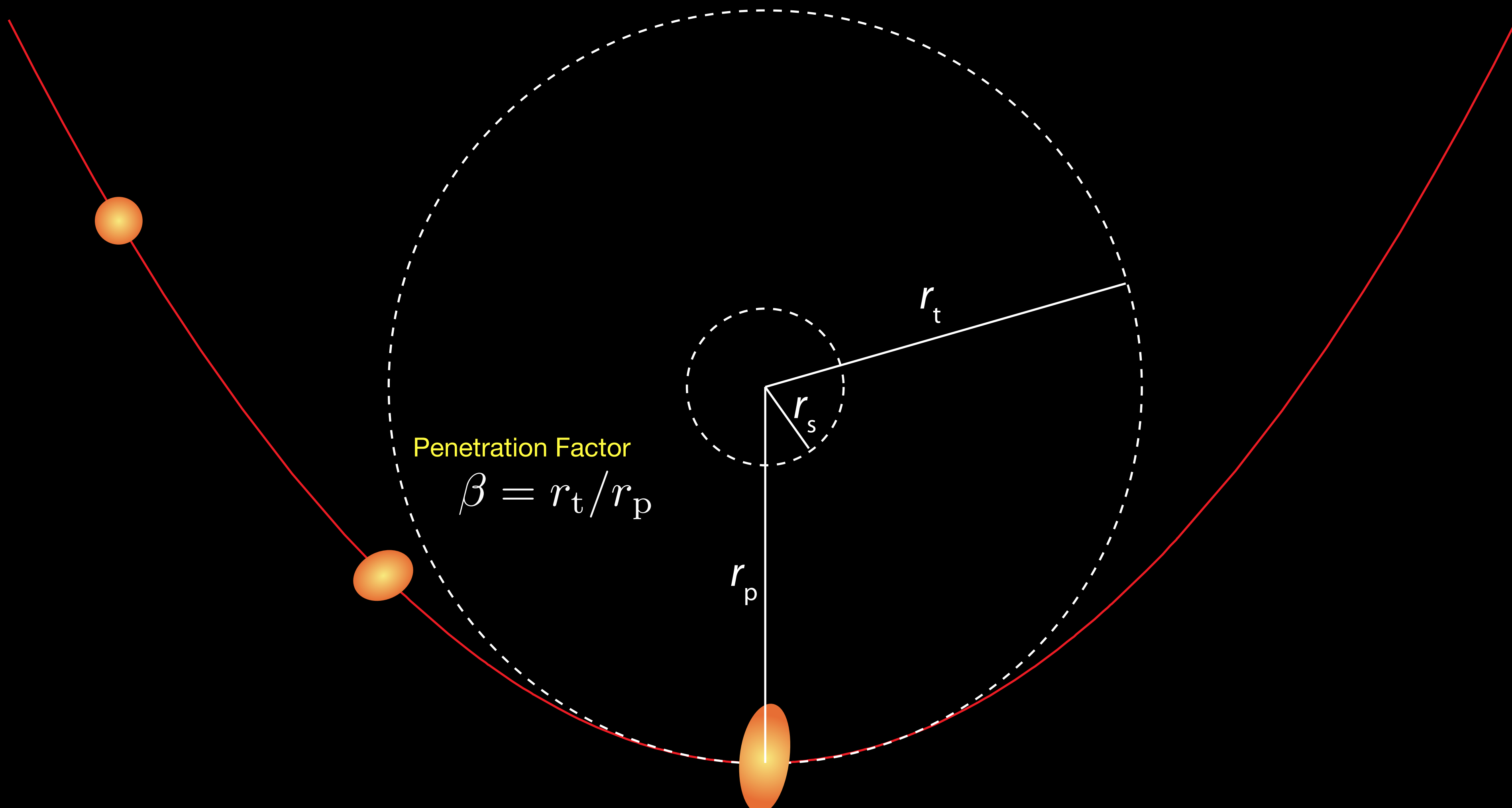
Penetration Factor

$$\beta = r_\mathrm{t}/r_\mathrm{p}$$



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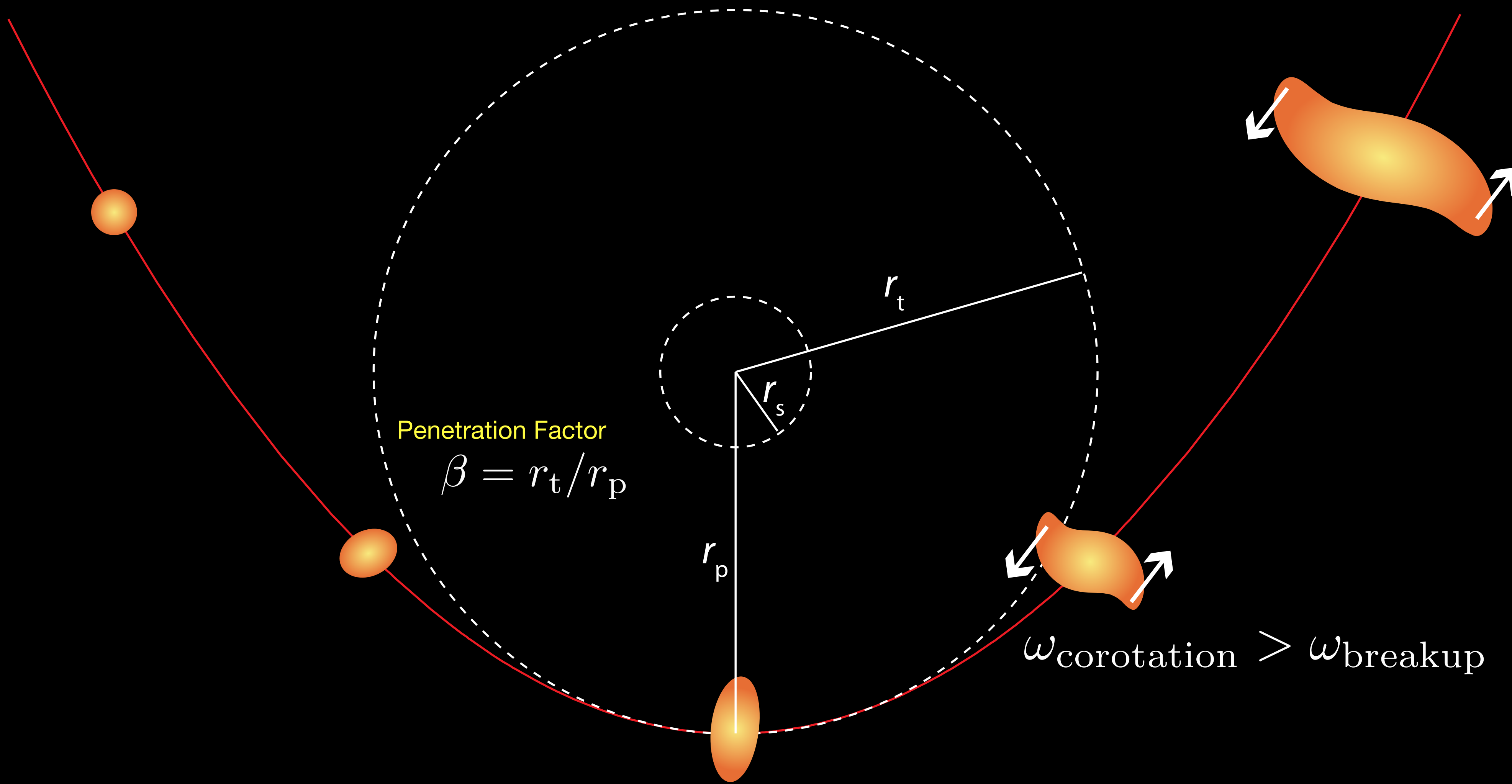

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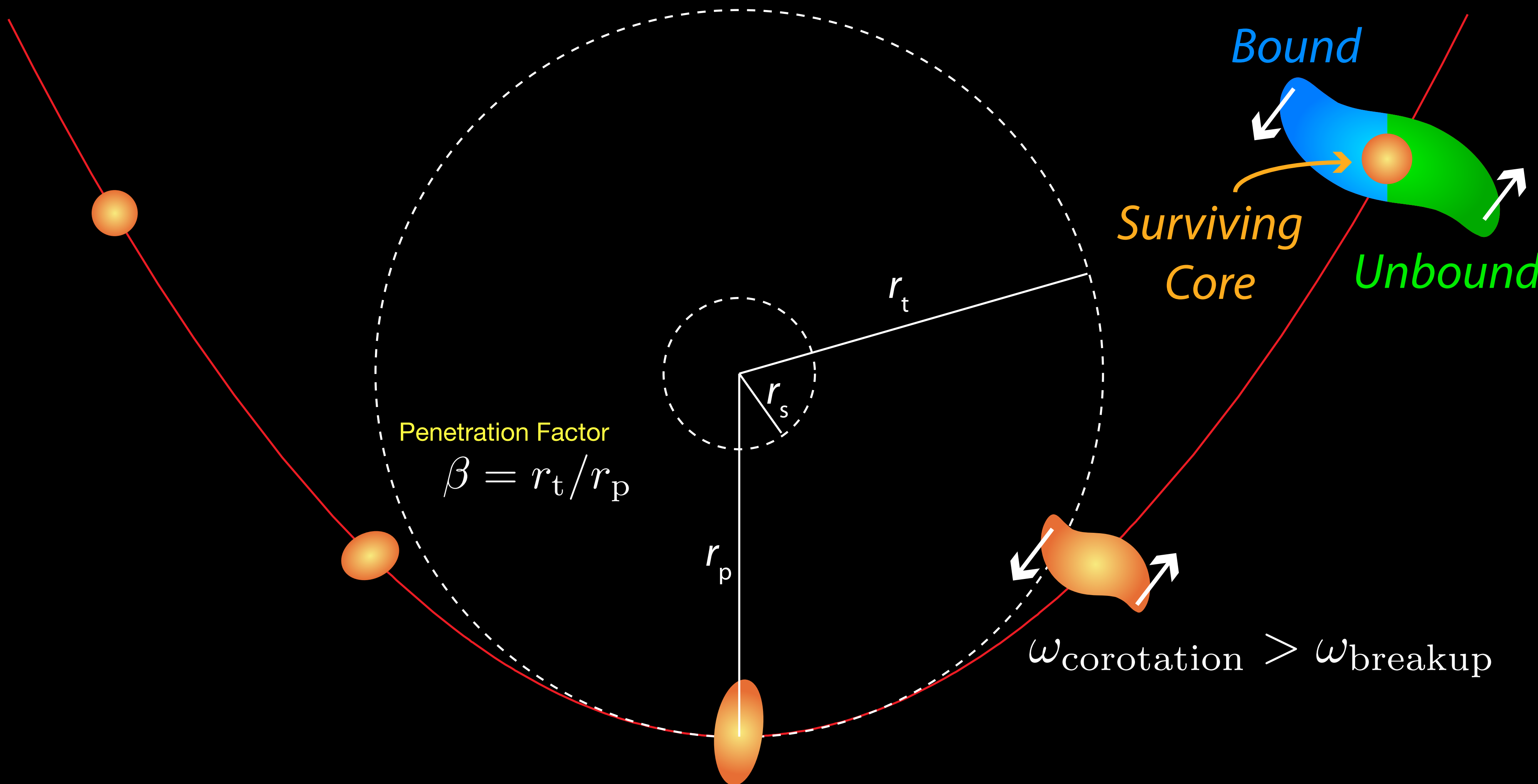
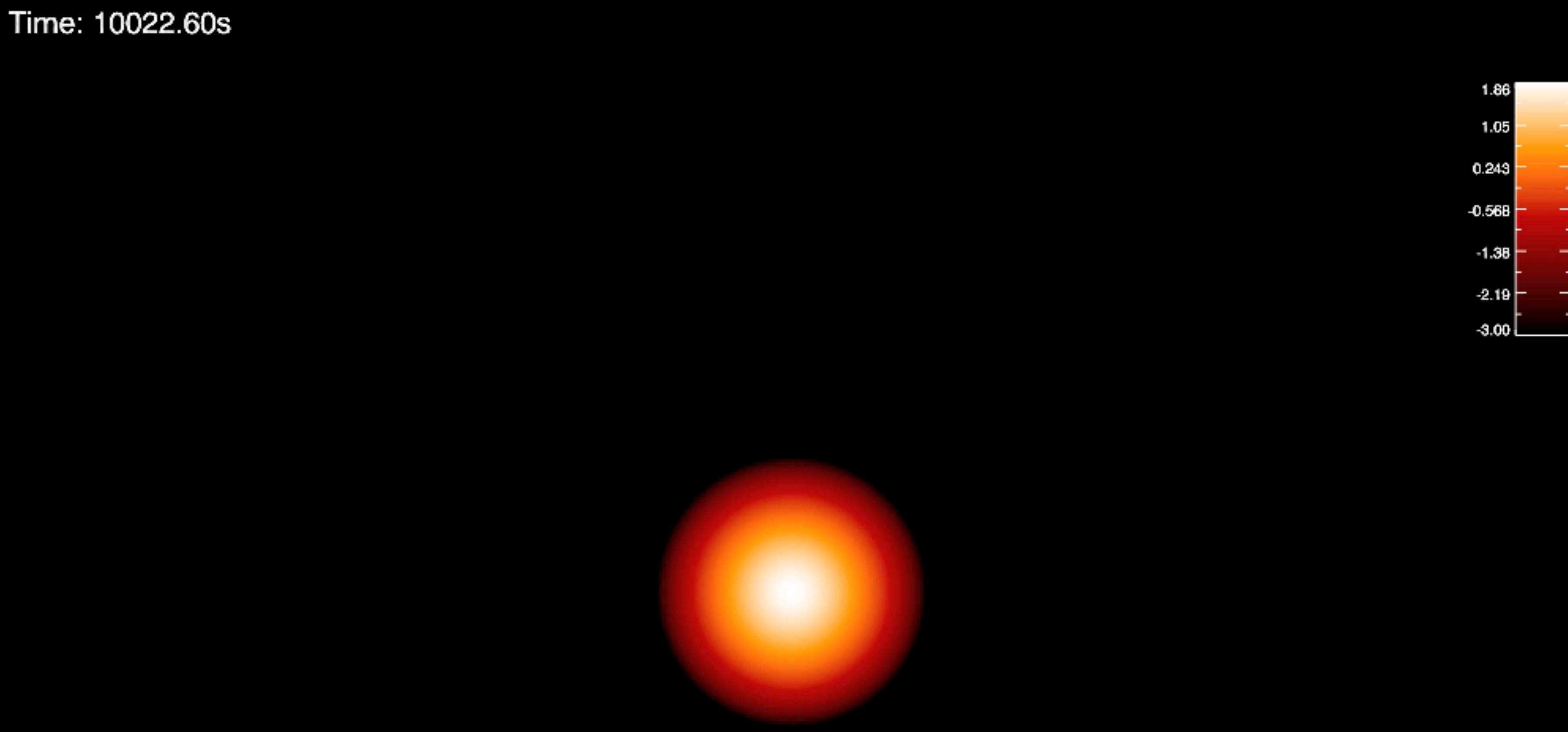
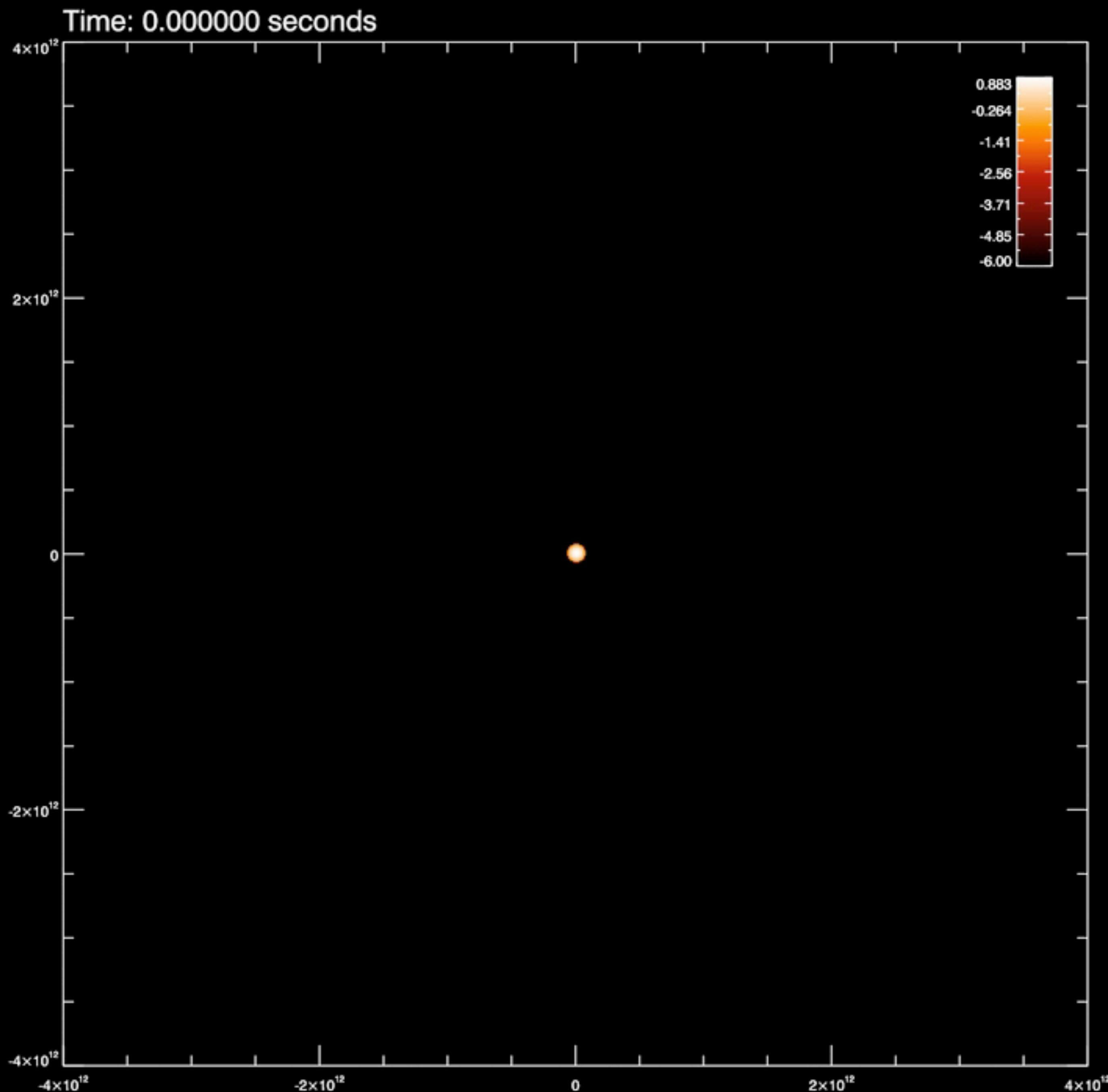


Example of a partial disruption



Example of a full disruption



Method

- Using FLASH (my bread & butter)
- Solver is an unsplit staggered mesh solver utilizing constrained transport.
- Main problem in most MHD codes is obeying Maxwell's simplest equation:

$$\nabla \cdot B = 0$$

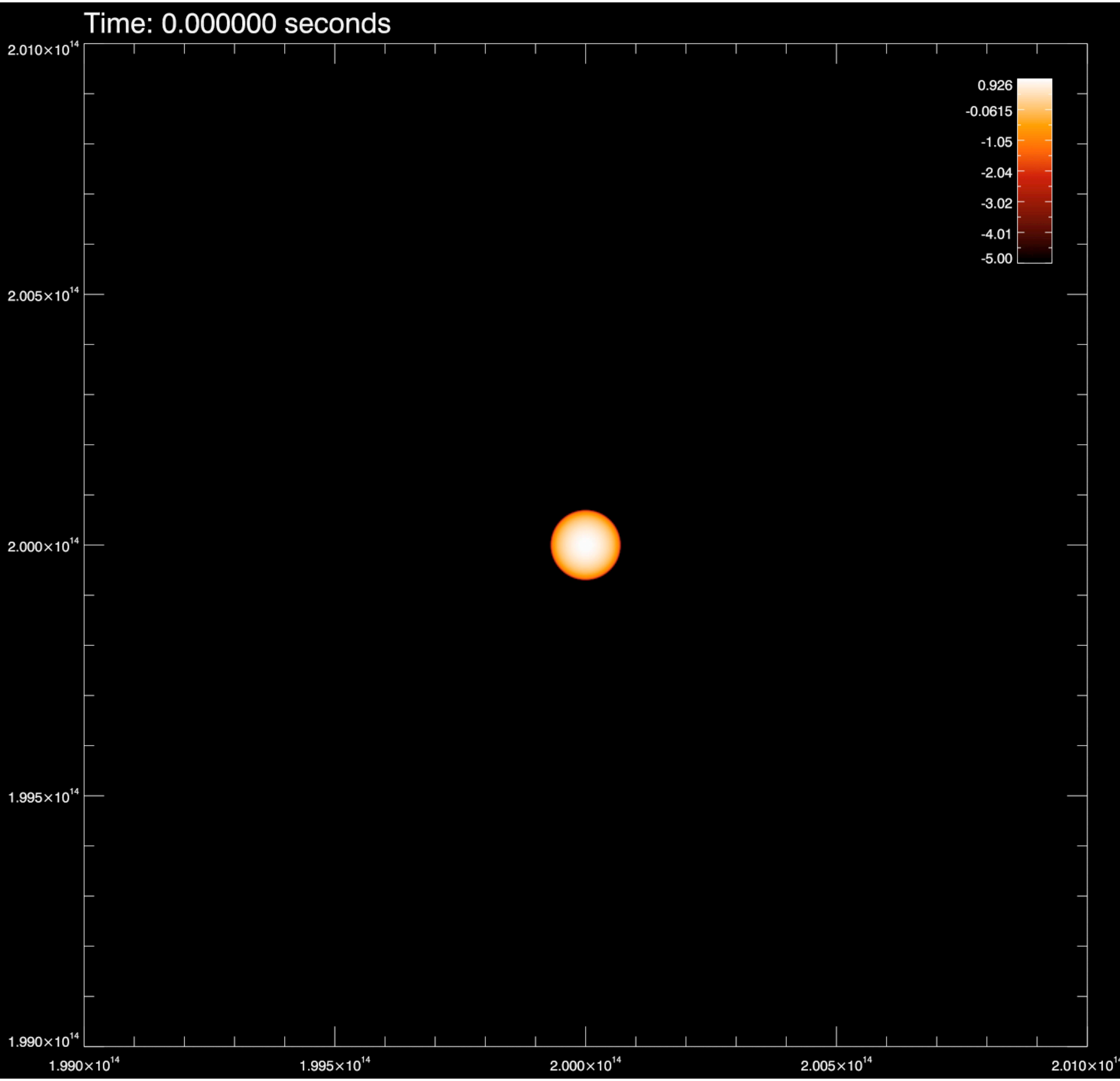
- FLASH does obey this expression to numerical precision even with the adaptive mesh enabled, *if the mesh is not derefined during the run.* Tests show that derefinement operations sometimes generate magnetic divergence
  (I think this is a bug rather than an issue with the method).
- Current work-around is to derefine as little as possible.
- Forces arising from errors are at most $\sim 10^{-3}$ the field strength, and mostly confined to "fluff" (the low-density background).

Initial conditions

- Two cases, a partial disruption and a full disruption ($\beta = 0.7$ and $\beta = 1.5$).
- Polytropic index = 3/2, i.e. fully-convective star.
- Initial magnetic field is seeded via a vector potential that's drawn from a Kolmogorov power spectrum convolved with the star's pressure gradient to ensure near-constant magnetic beta (similar to Braithwaite 2006), ***or*** a dipole configuration.
- We do it this way because we're guaranteed zero div B in the initial conditions:

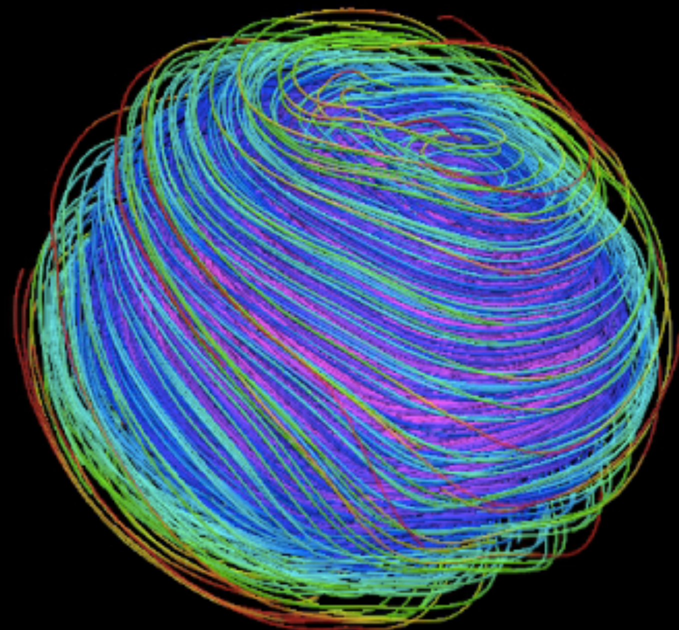
$$\nabla \times A = B, \quad \nabla \cdot (\nabla \times A) = 0$$

- Star initially resolved by ~100 cells in diameter.
- Ratio of gas to magnetic pressure ~10,000 (Megagauss fields, strong!).
- Field only defined within star. This is to avoid very large Alfven speeds exterior to the star.

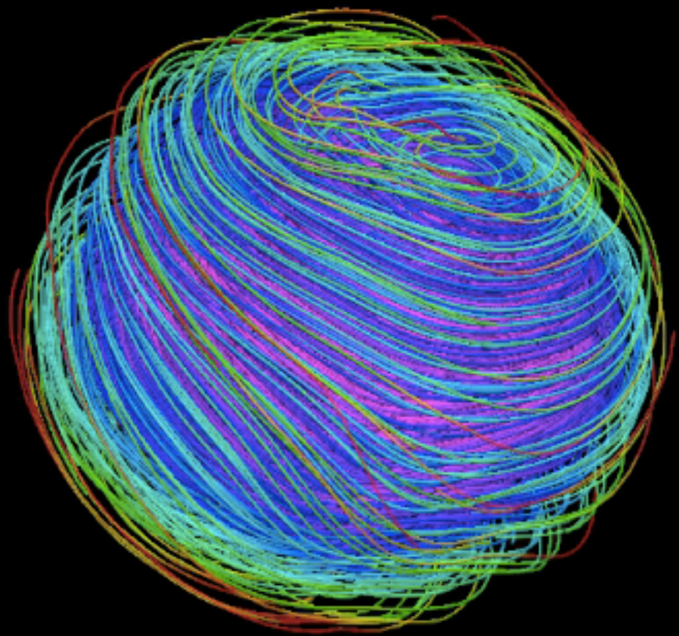


Partial disruption: Log Density

Initial conditions: Tangled field case



Initial conditions: Tangled field case



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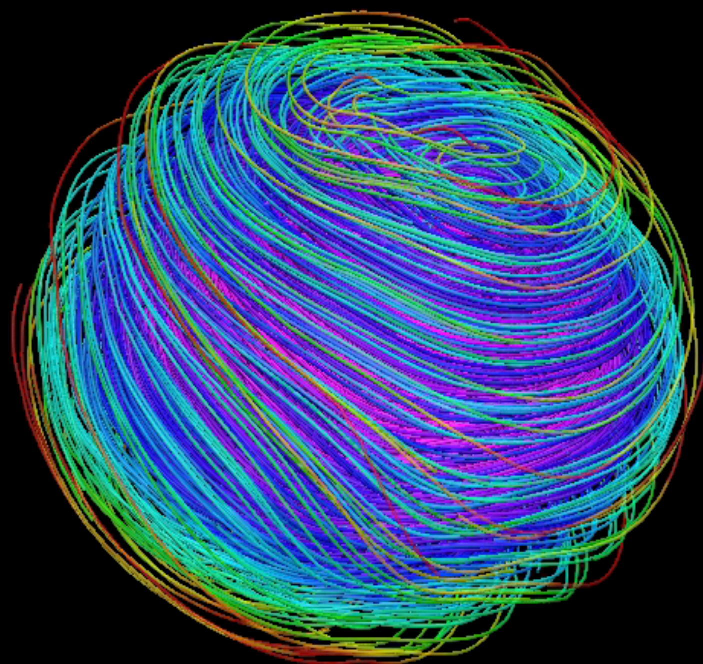
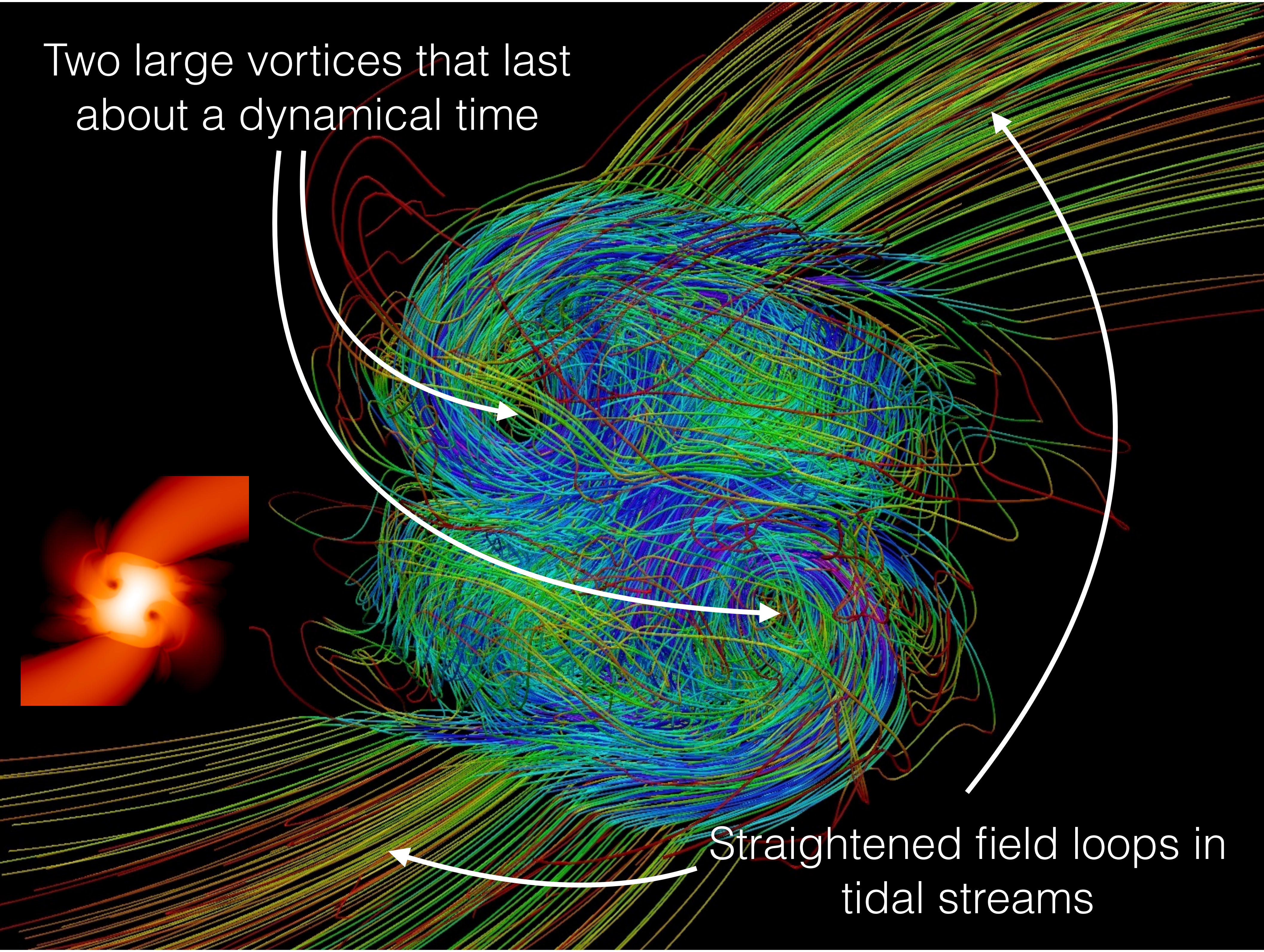
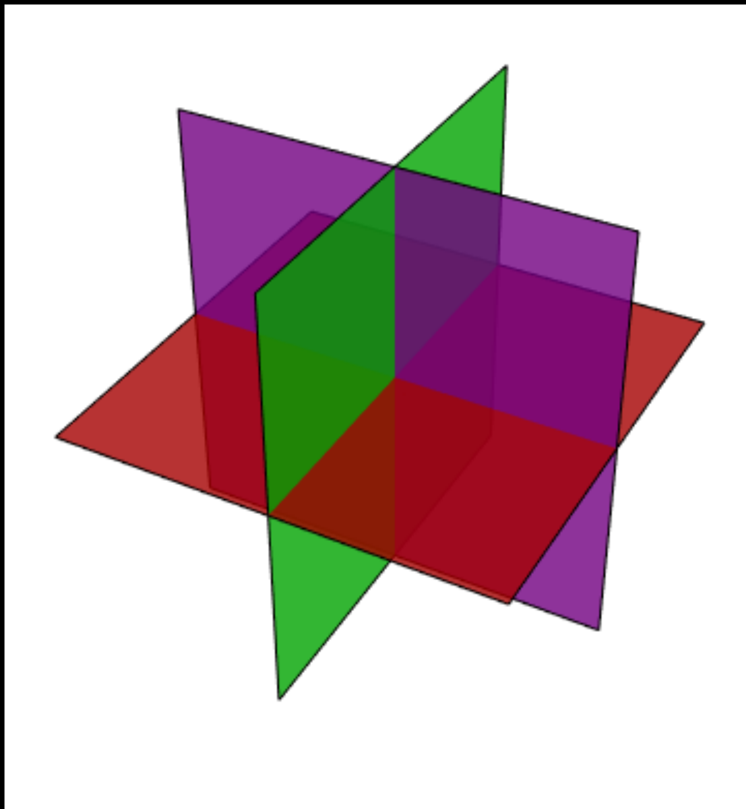
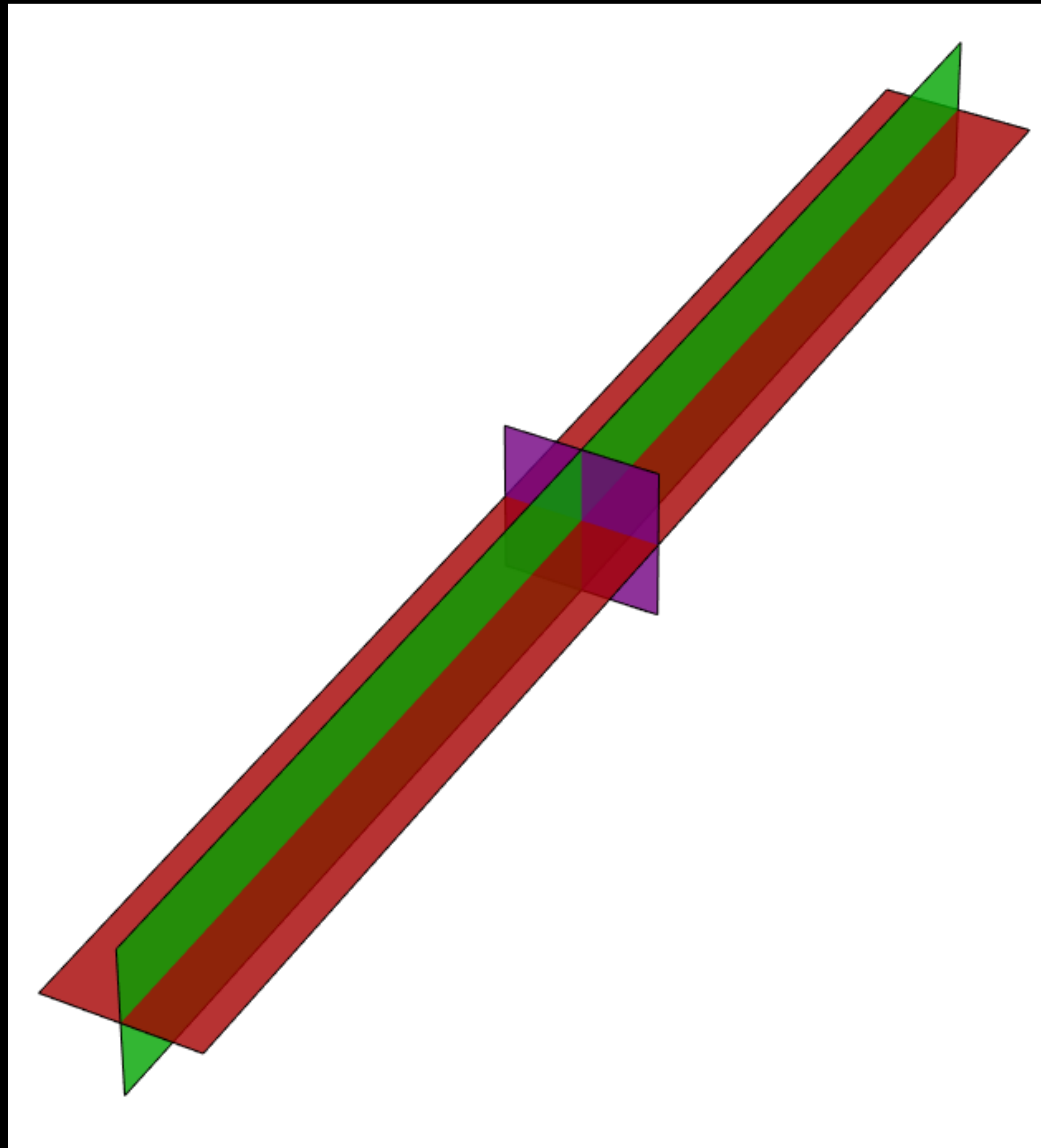



Two large vortices that last about a dynamical time
Straightened field loops in tidal streams

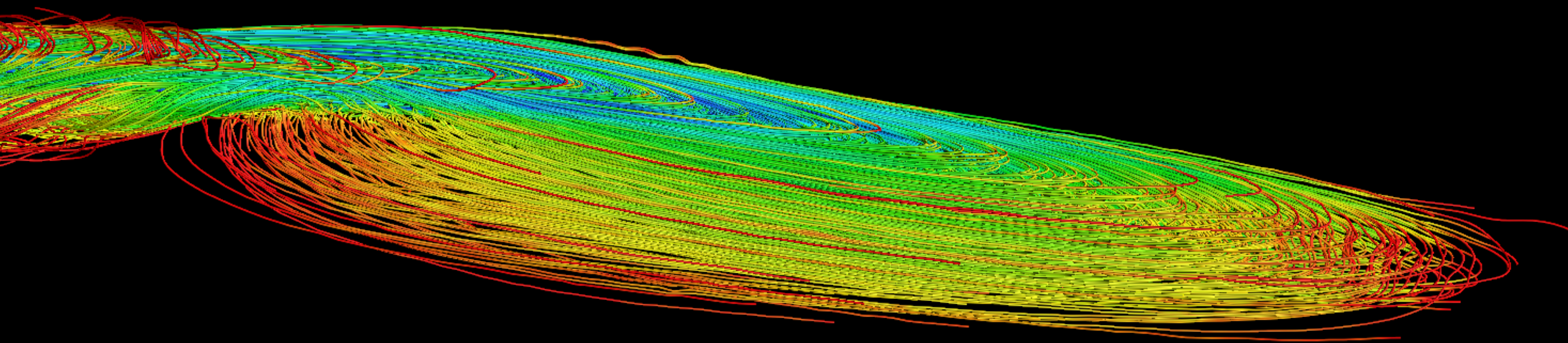


Fluxes through surfaces are conserved, thus B in directions perpendicular to stretching direction is degraded. B in direction parallel to stretching is unaffected.

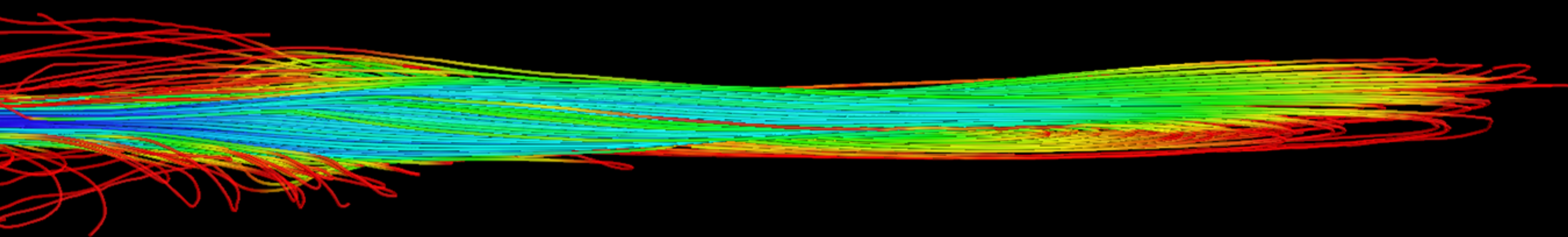


Full Disruption Field Geometry

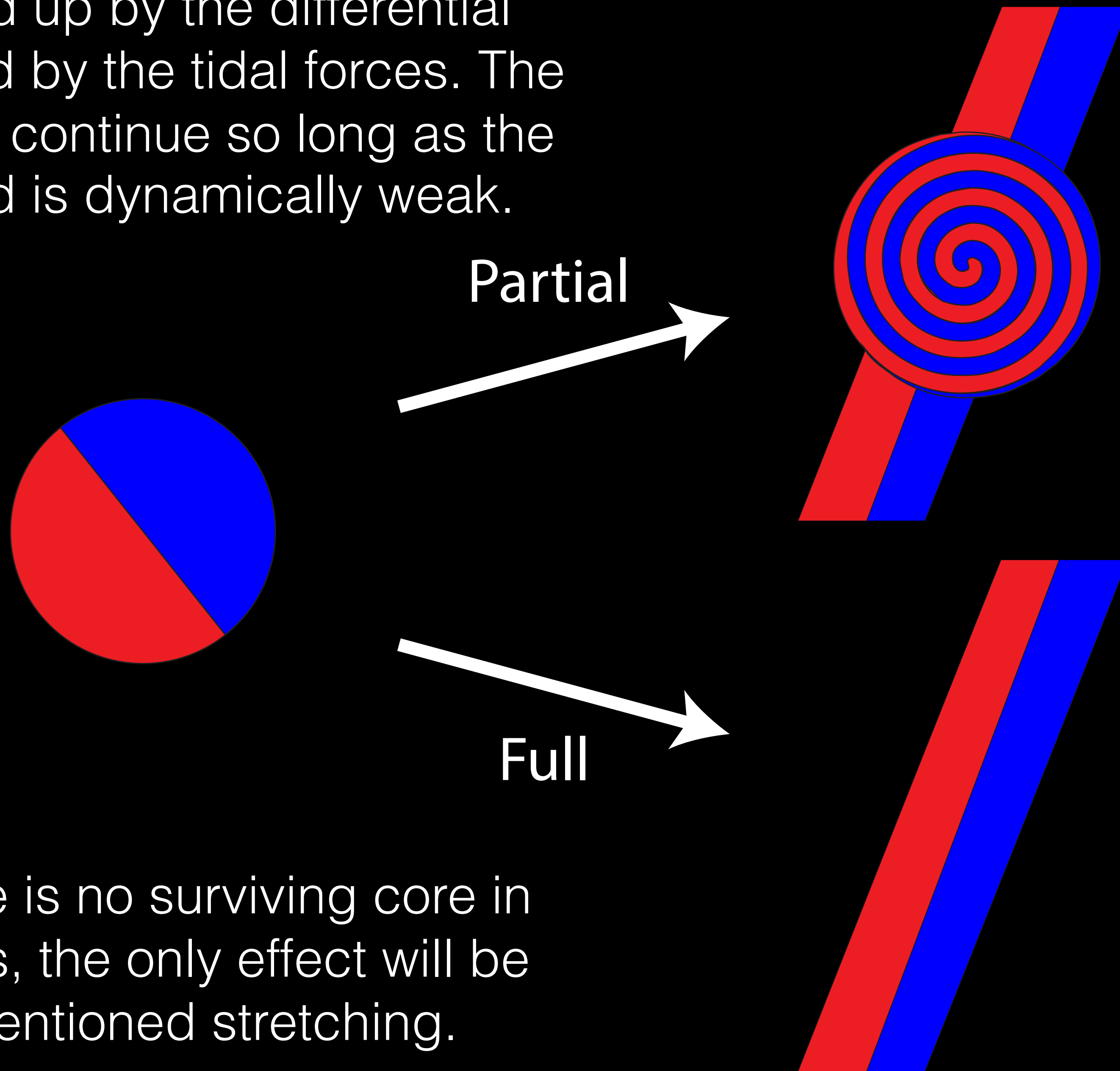
Top



Side

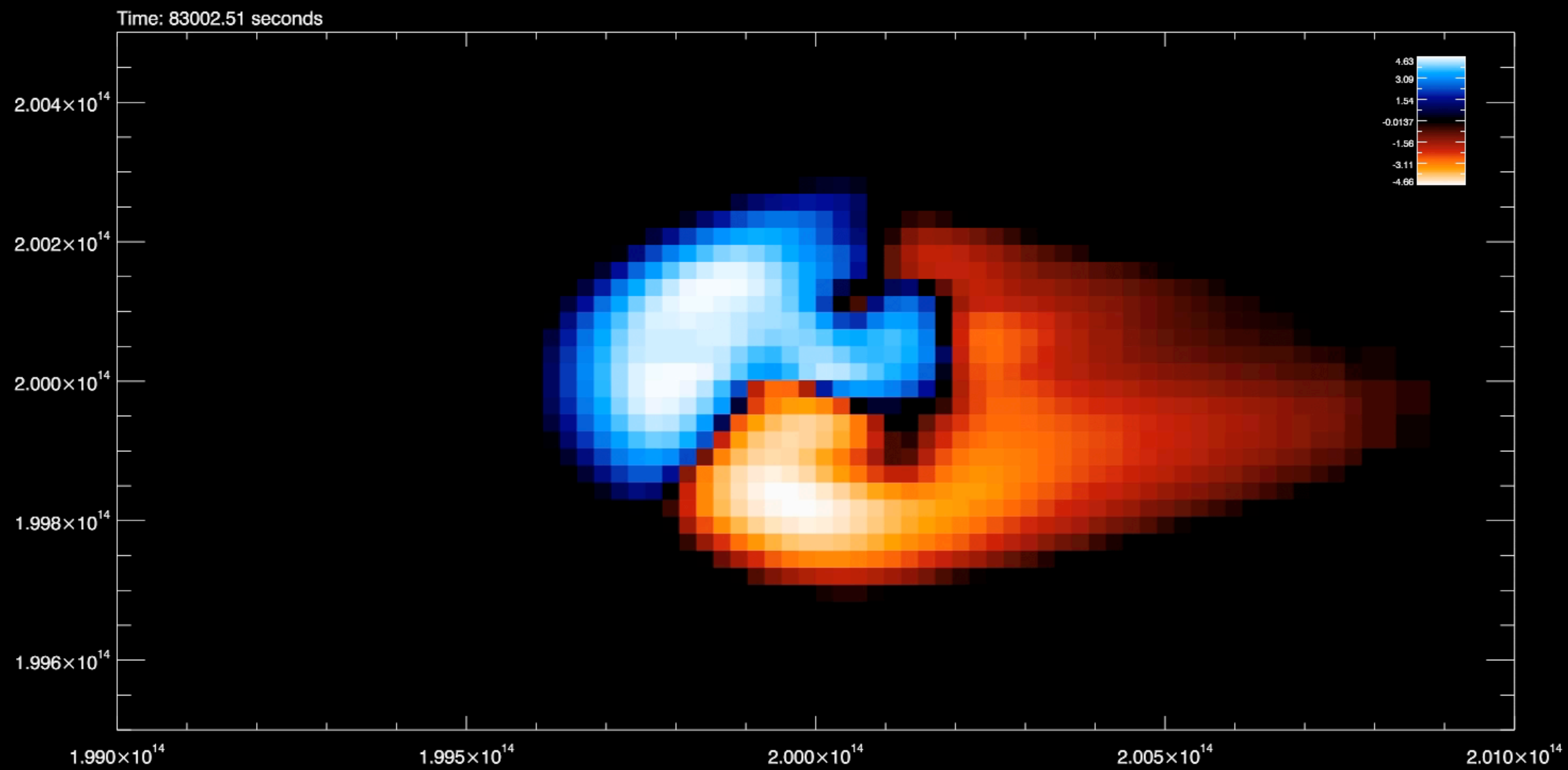


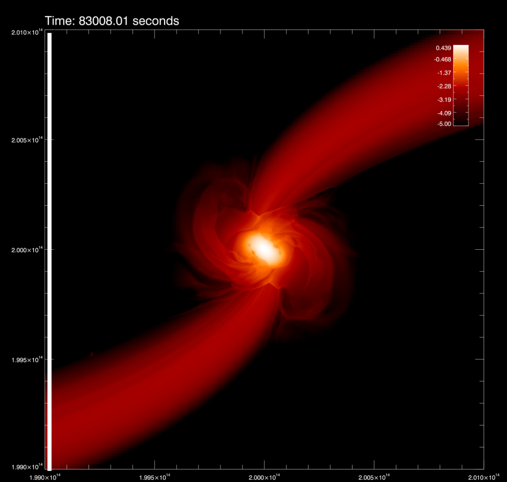
In partial disruptions, magnetic field lines will be twisted up by the differential rotation induced by the tidal forces. The twisting should continue so long as the magnetic field is dynamically weak.



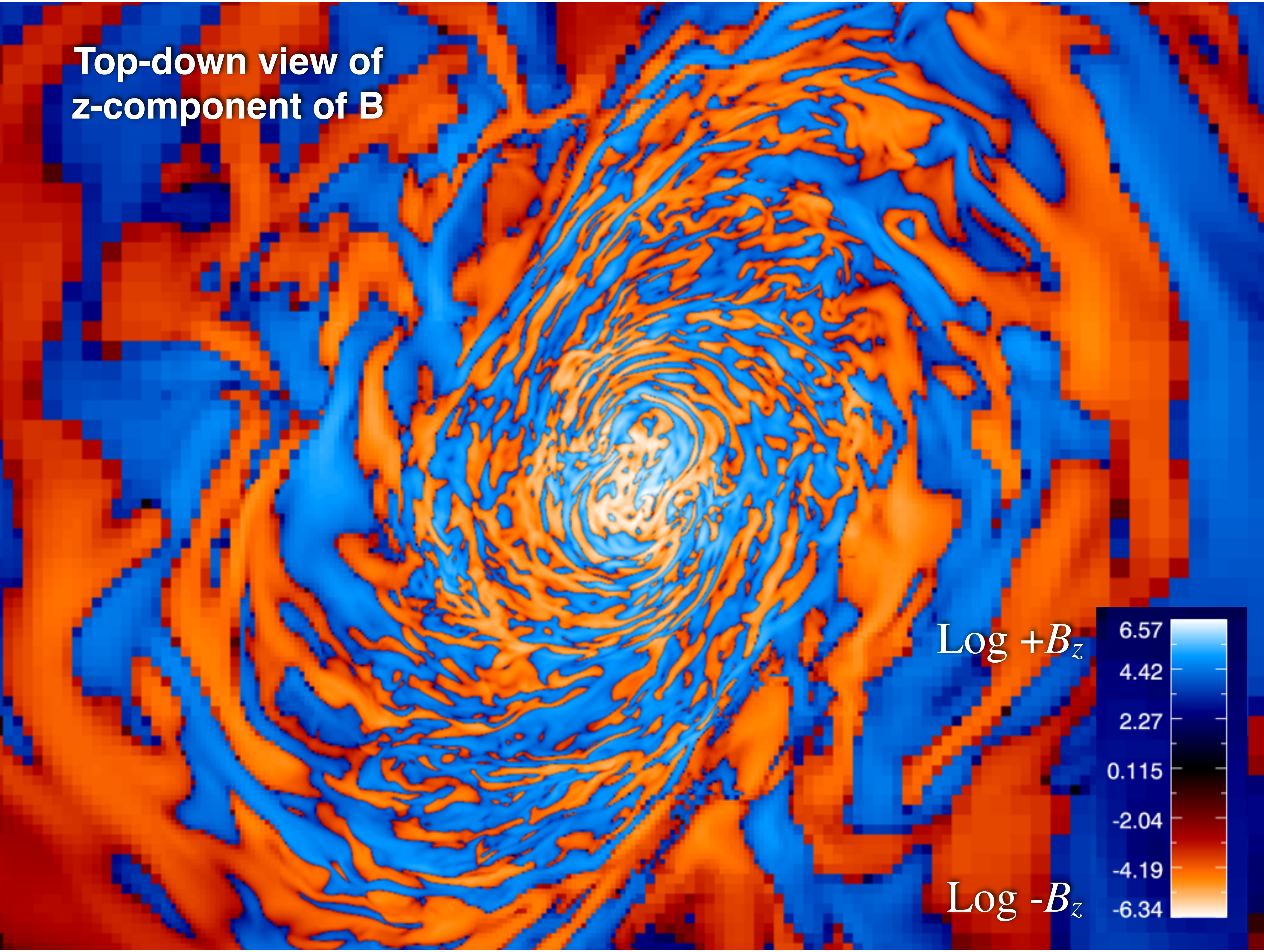
Because there is no surviving core in full disruptions, the only effect will be the aforementioned stretching.


5
Log β_M
0

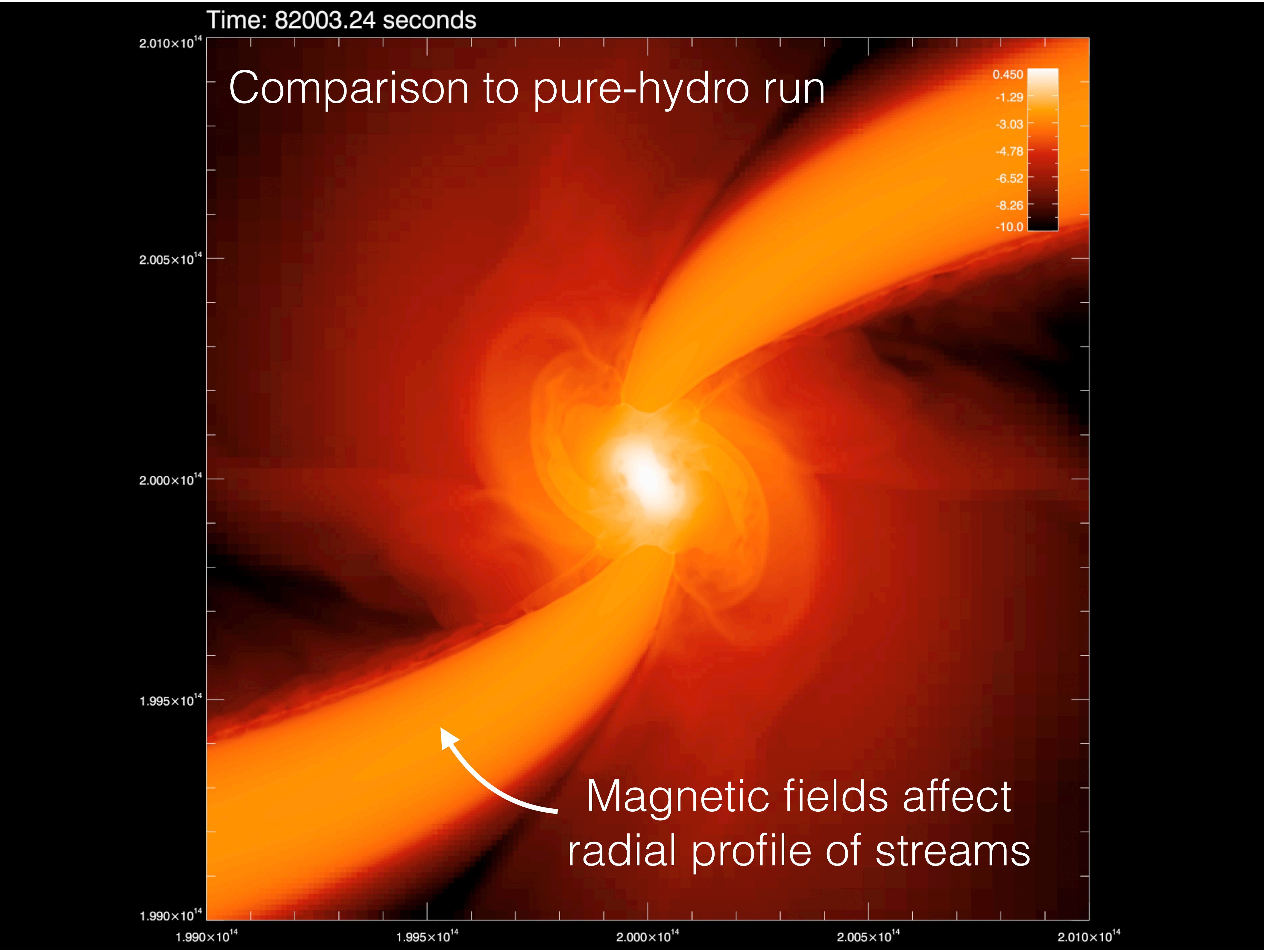


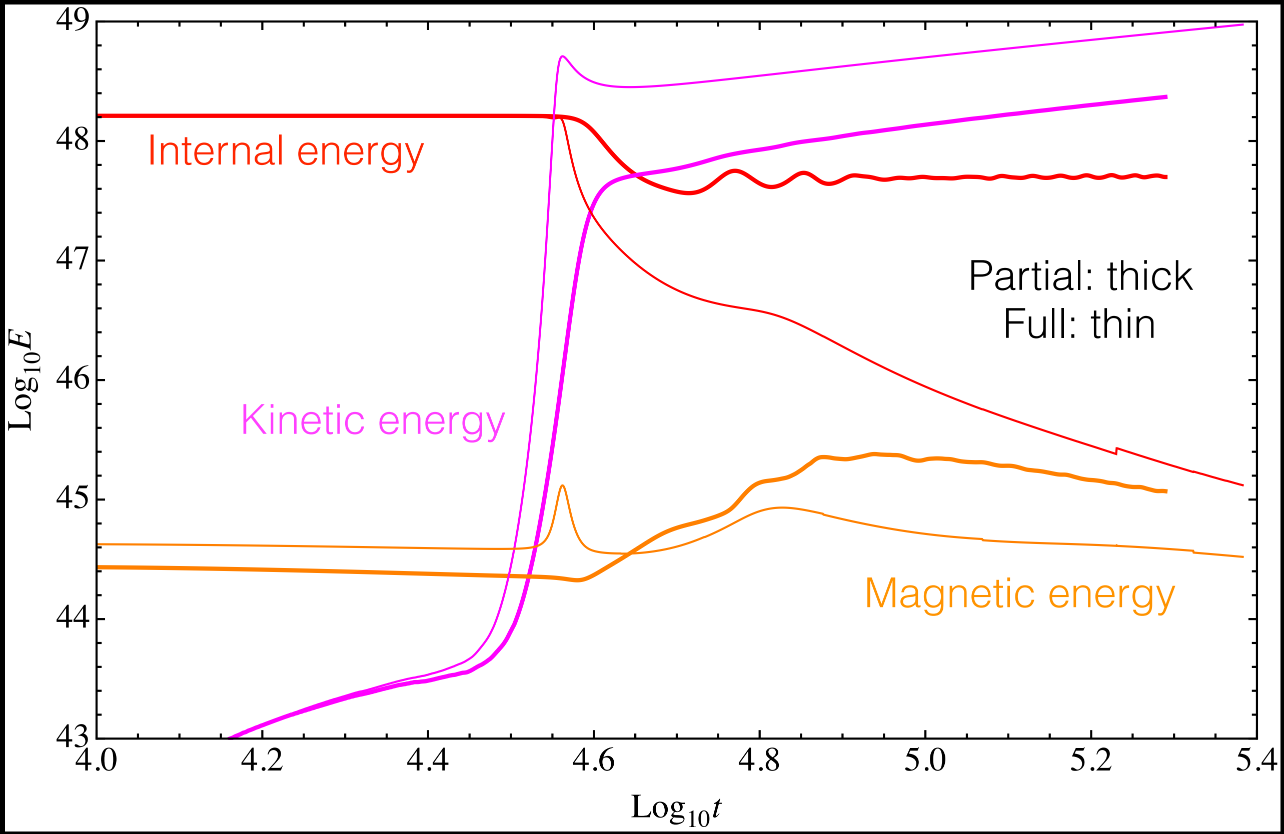


- Above: Showing “CAT” scan through volume, blue shows field out of the page, red into.
- Original field structure (and strength) preserved in tidal streams, twisted in surviving core.

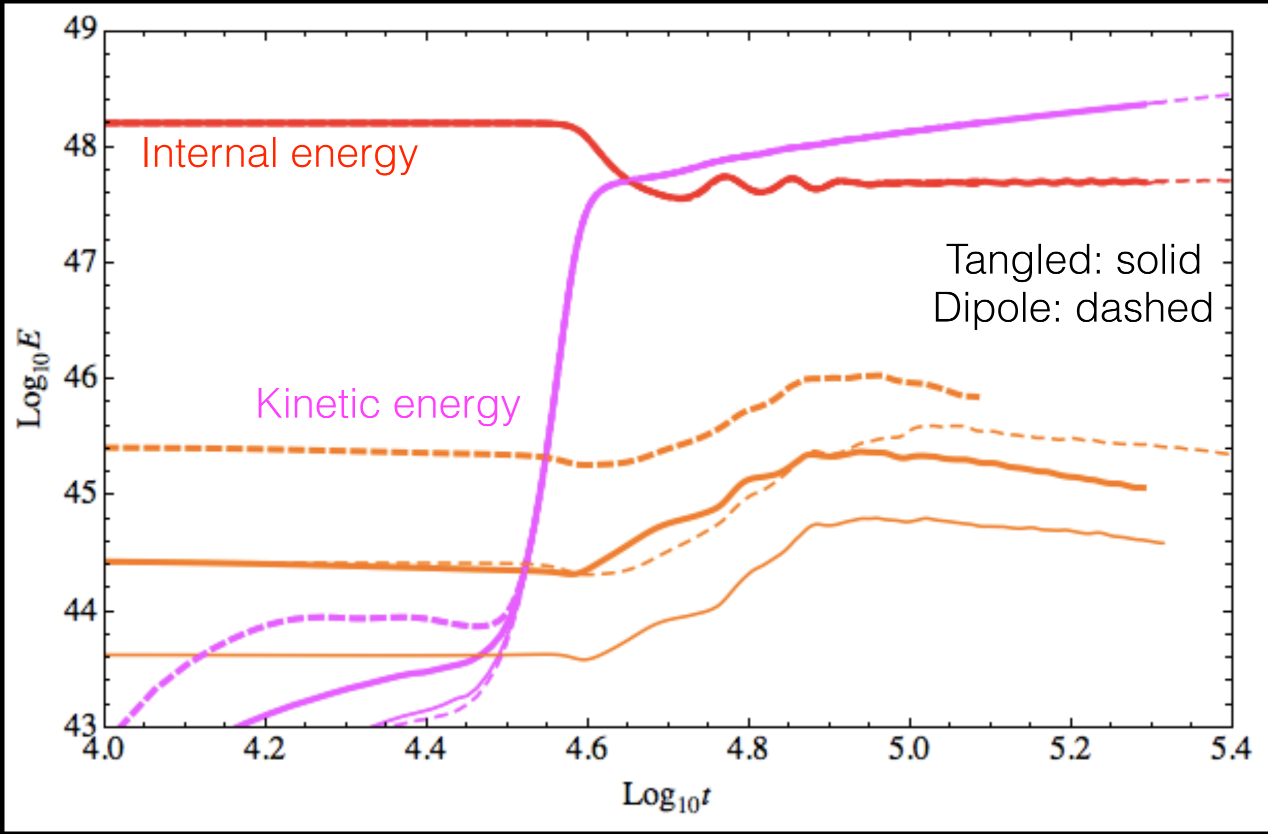


Top-down view of
z-component of B
Log $+B_z$
Log $-B_z$
6.57
4.42
2.27
0.115
-2.04
-4.19
-6.34


Time: 82003.24 seconds
Comparison to pure-hydro run
0.450
-1.29
-3.03
-4.78
-6.52
-8.26
-10.0
2.010×10^14
2.005×10^14
2.000×10^14
1.995×10^14
1.990×10^14
1.990×10^14
1.995×10^14
2.000×10^14
2.005×10^14
2.010×10^14
Magnetic fields affect
radial profile of streams



- Both cases: Kinetic energy grows from time of disruption onwards (due to continuous stretching of tidal streams by black hole).
- Partial disruption:
  - Internal energy drops post disruption until new equilibrium is reached.
  - Magnetic energy grows by a factor of 10, but shows gradual decline at later times.
- Full disruption:
  - Internal energy continuously drops, sharper at later times.
  - Magnetic energy grows slightly post-disruption, but then levels off, and then declines slightly due to $r^{1/4}$ width-distance relationship (Kochanek 1994).

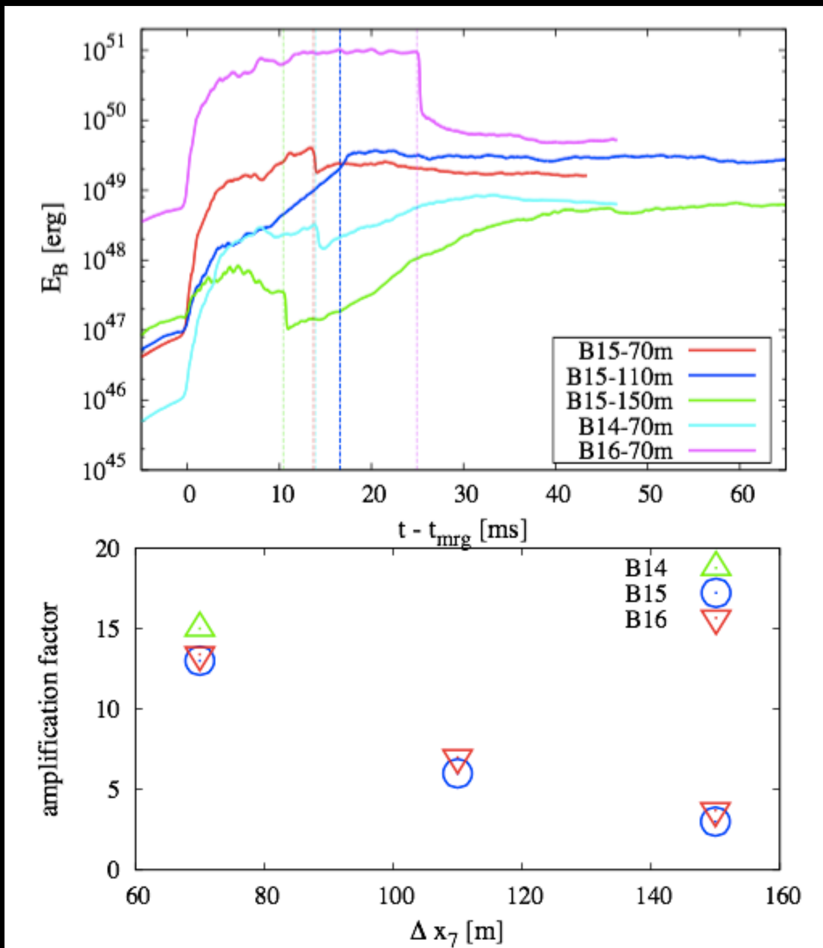


- Dipole vs. Tangled; Varying initial field strength
    - Field geometry has a mild effect on the resultant evolution, the dipole scenario is a bit more favorable for amplification since twisting can have more global symmetry.
    - Initial field strength seems to affect amplification factor slightly; stronger initial fields result in peak field strengths that are enhanced by a smaller factor.

Comparing to analogues

- Merging stars resemble the surviving cores from tidal disruptions: Large amounts of differential rotation induced in a violent event, small seed fields.
- As far as I'm aware, only WD-WD and NS-NS (or NS-BH) simulations have been done with magnetic fields.
- The NS simulations are the only ones that use constrained transport, WD merger simulations (so far) have either used "divergence cleaning" or (very recently, see Zhu+ 2015) an 8-wave solver.
- At the moment I trust the NS merger simulations more because div B in the WD merger calculations can be huge (order unity!).

Comparing to analogues



Kiuchi+ 2014

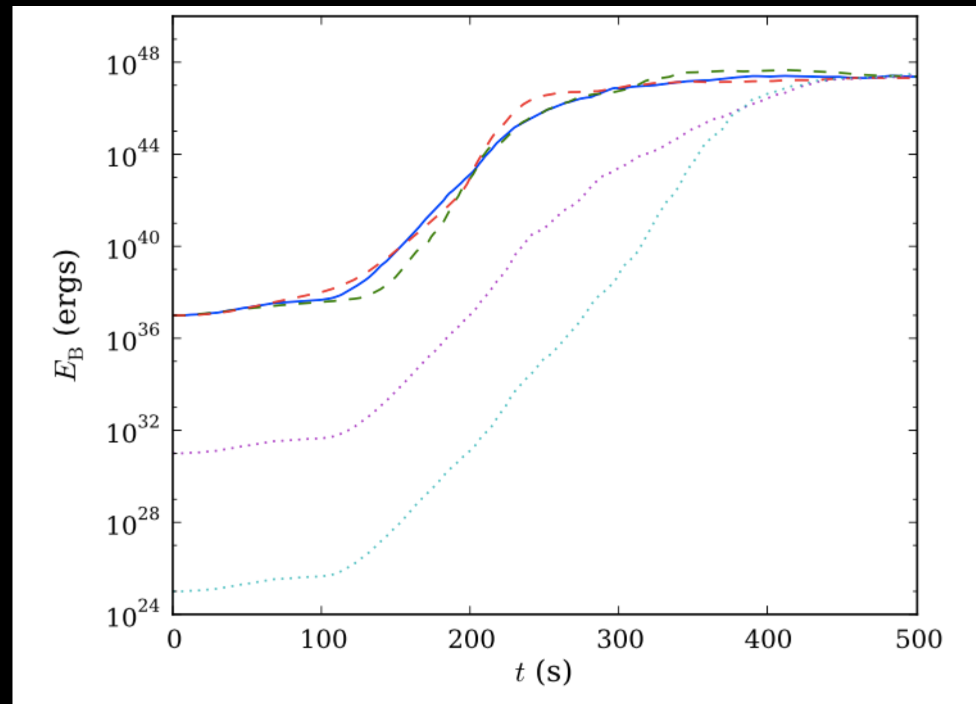
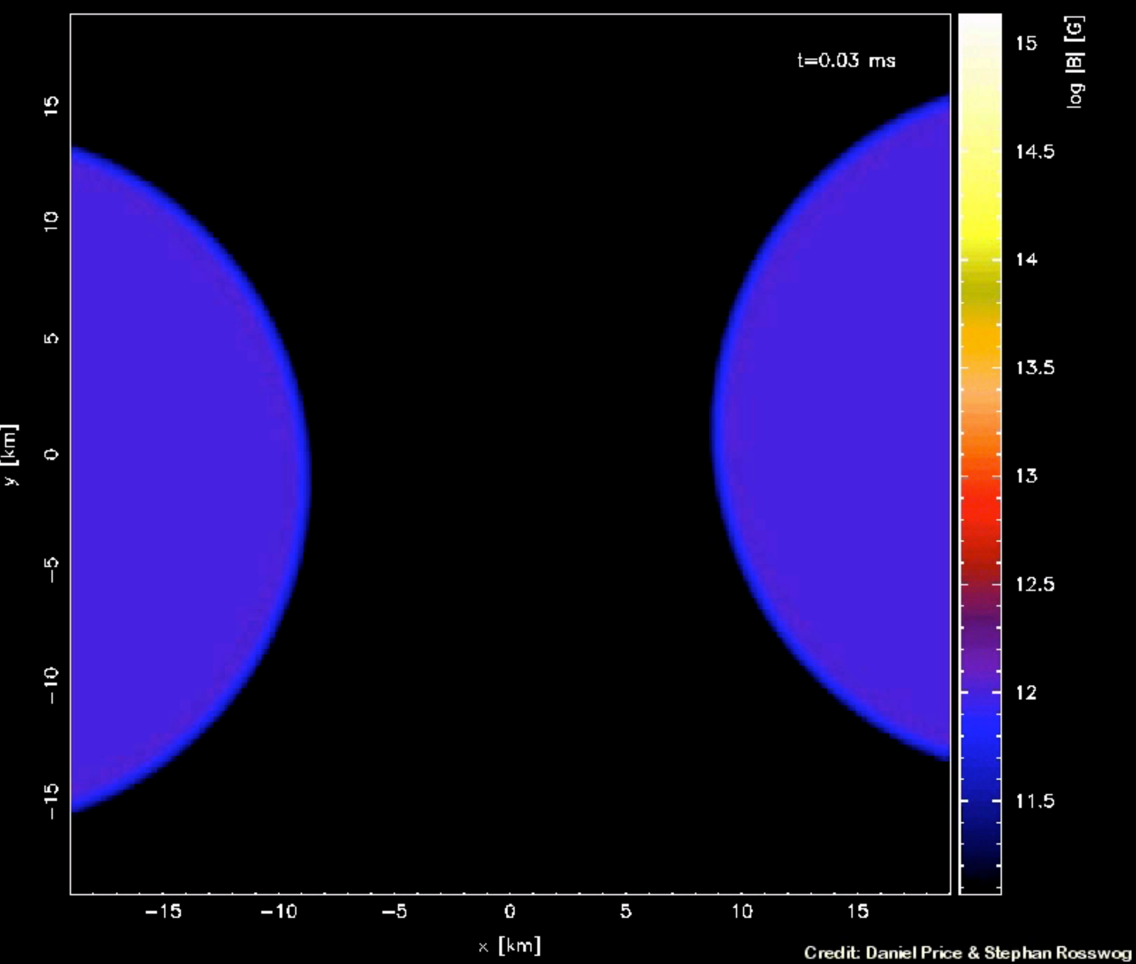


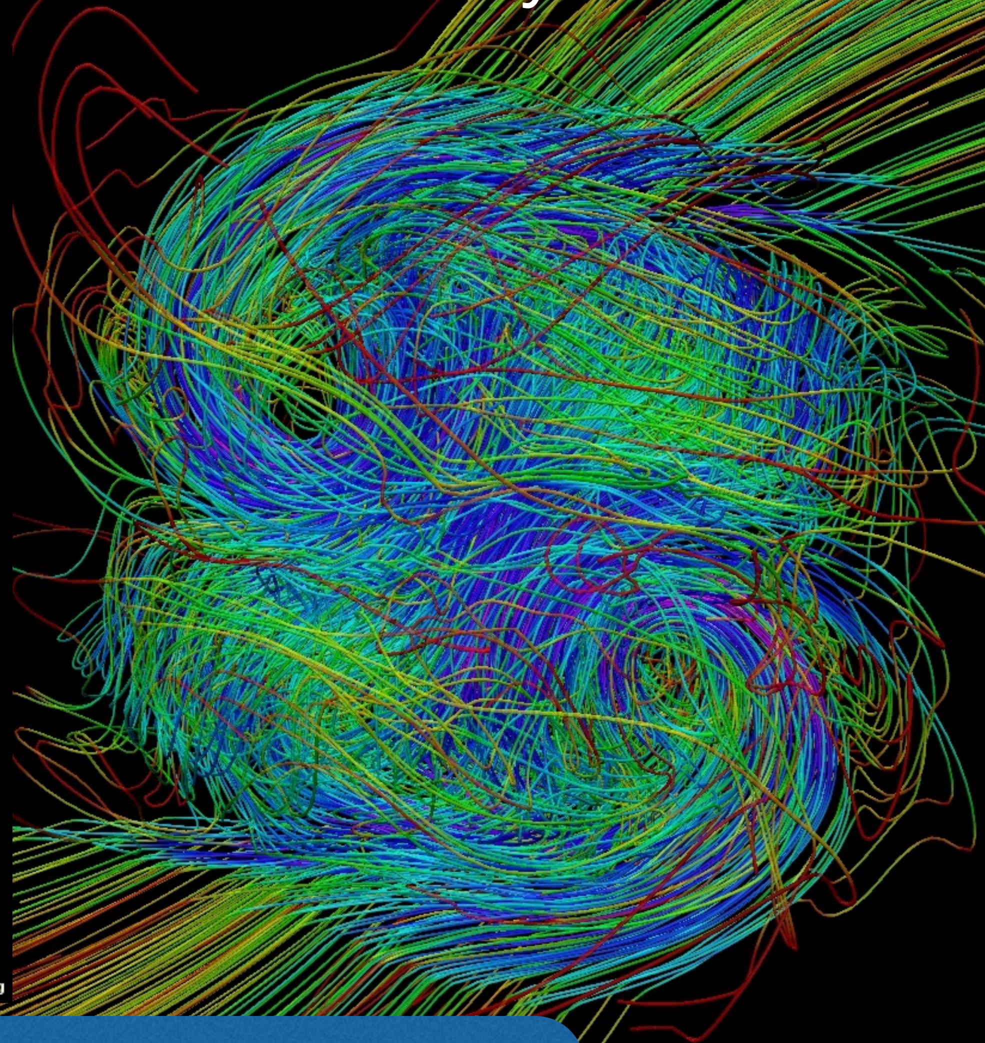
Figure 4. Total magnetic energy E_B over time for the fiducial (solid blue; $m_{cell} \approx 1 \times 10^{-6}\ M_{\odot}$, equatorial surface field strength $\sim 10^3$ G) simulation and the robustness tests. Dashed lines represent low (green; $m_{cell} \approx 5 \times 10^{-6}$ $M_{\odot}$) and high resolution (red; $m_{cell} \approx 2 \times 10^{-7}\ M_{\odot}$) simulations. Dotted lines represent ~ 1 G (magenta) and $\sim 10^{-3}$ G (cyan) low initial field simulations.

Zhu+ 2015

Lowest resolution of Kiuchi+ 2014 sees similar amplification to what we see (factor of 10). Our resolution is comparable to their medium resolution runs.

Growth in core is smaller than what others find in merger simulations. Why?

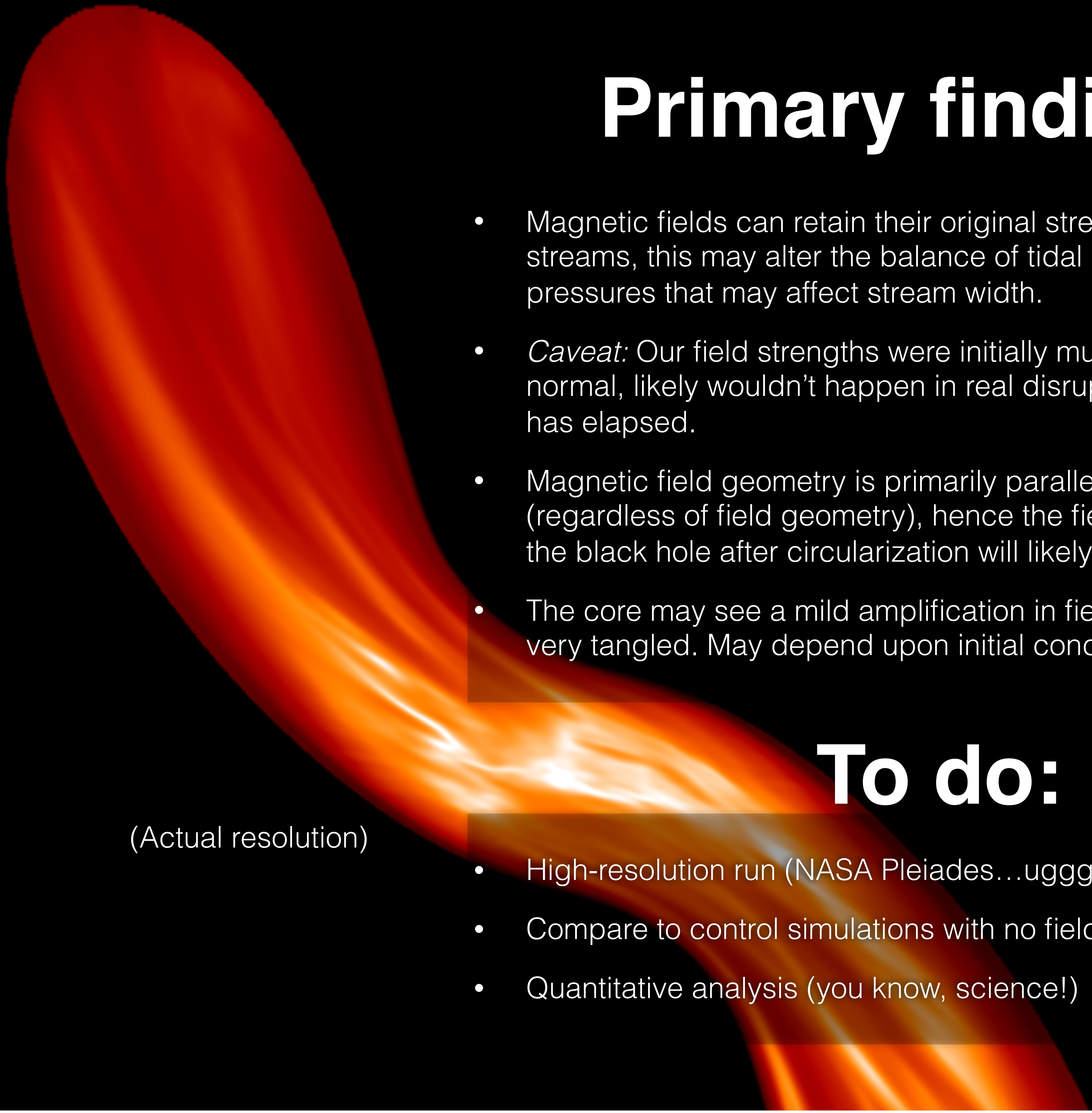




Perhaps the lifetime of the KH instabilities that generate the motions in mergers enables longer periods of amplification?

Perhaps we are not running with high enough resolution?

Maybe methods that don’t conserve div B are flawed for this problem?



(Actual resolution)

Primary findings:

- Magnetic fields can retain their original strength in the tidal streams, this may alter the balance of tidal gravity with internal pressures that may affect stream width.
- *Caveat:* Our field strengths were initially much stronger than normal, likely wouldn't happen in real disruptions until more time has elapsed.
- Magnetic field geometry is primarily parallel to the streams (regardless of field geometry), hence the field configuration about the black hole after circularization will likely be toroidal.
- The core may see a mild amplification in field strength, final field is very tangled. May depend upon initial conditions, resolution, etc.

To do:

- High-resolution run (NASA Pleiades…uggggghhhhh!!!).
- Compare to control simulations with no fields.
- Quantitative analysis (you know, science!)