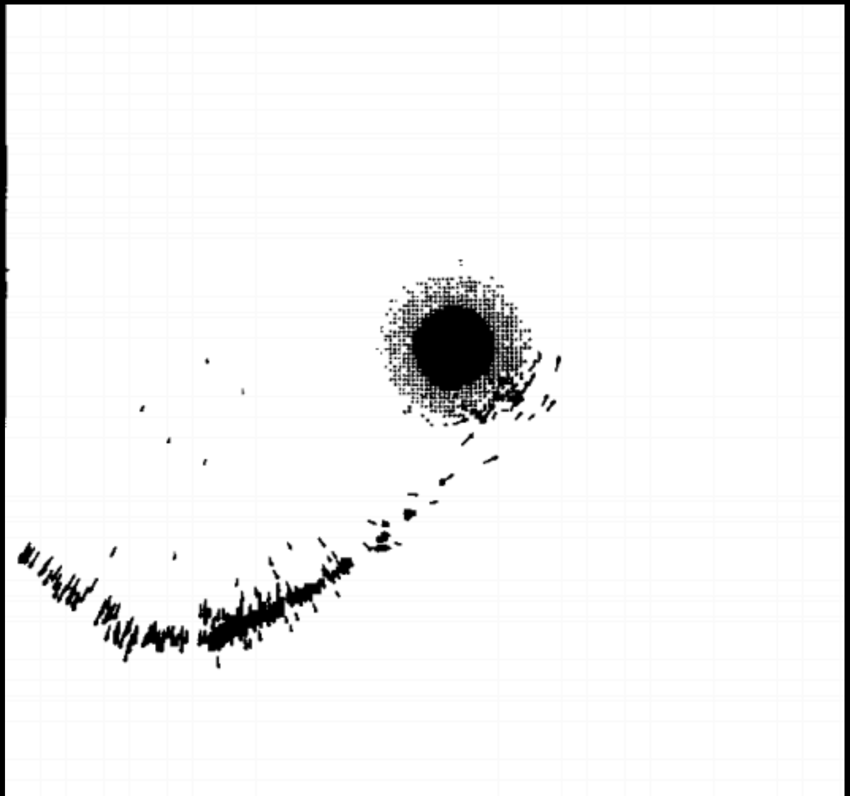
Credit: NASA LRO

Time	28 Feb 2016 05:00 UT
Phase	75.3% (19d 14h 21m)
Diameter	1770.8 arcseconds
Distance	404743 km (31.76 Earths)
Position	14h 29m 15s, 10° 38' 57"S
Subsolar	0.348°N 62.424°W
Sub-Earth	4.992°S 3.032°W
Pos. Angle	19.572°

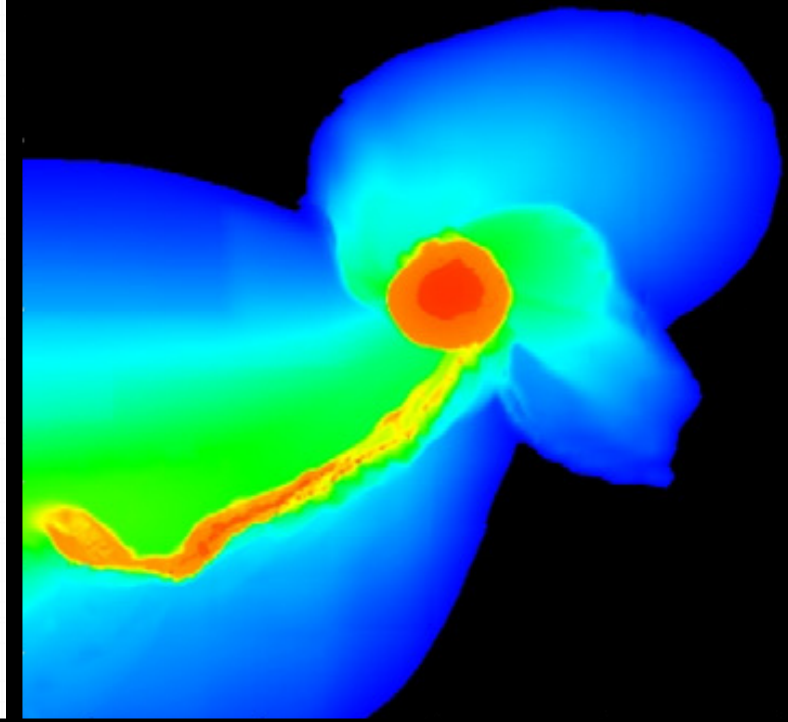
Nakajima & Stevenson (2014)
arXiv:1401.3036

Constraints:

- Orbital Configuration
- Magma Ocean/
  Lack of Volatiles
- Isotopes

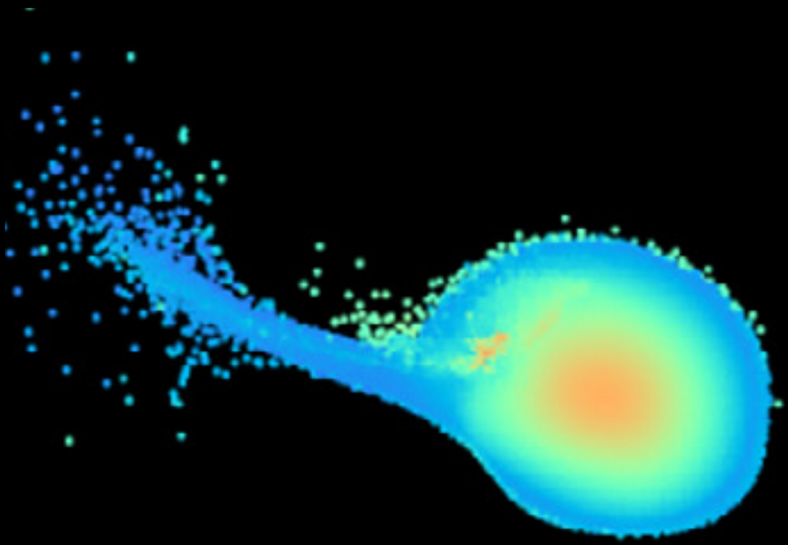


Benz et al. (1987)
Icarus 71, 30

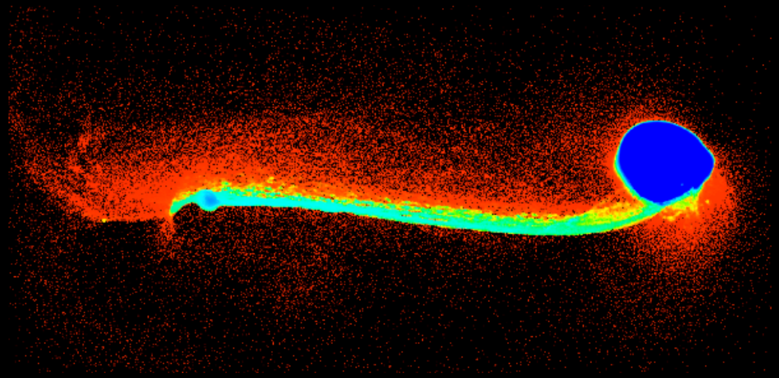


Canup et al. (2013)
Icarus 222, 1

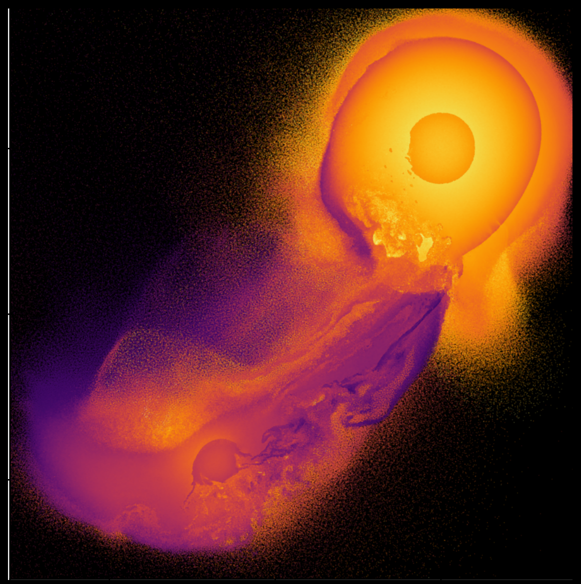
Nakajima & Stevenson (2014)
arXiv:1401.3036



Hosono et al. (2016)
arXiv:1602.00843



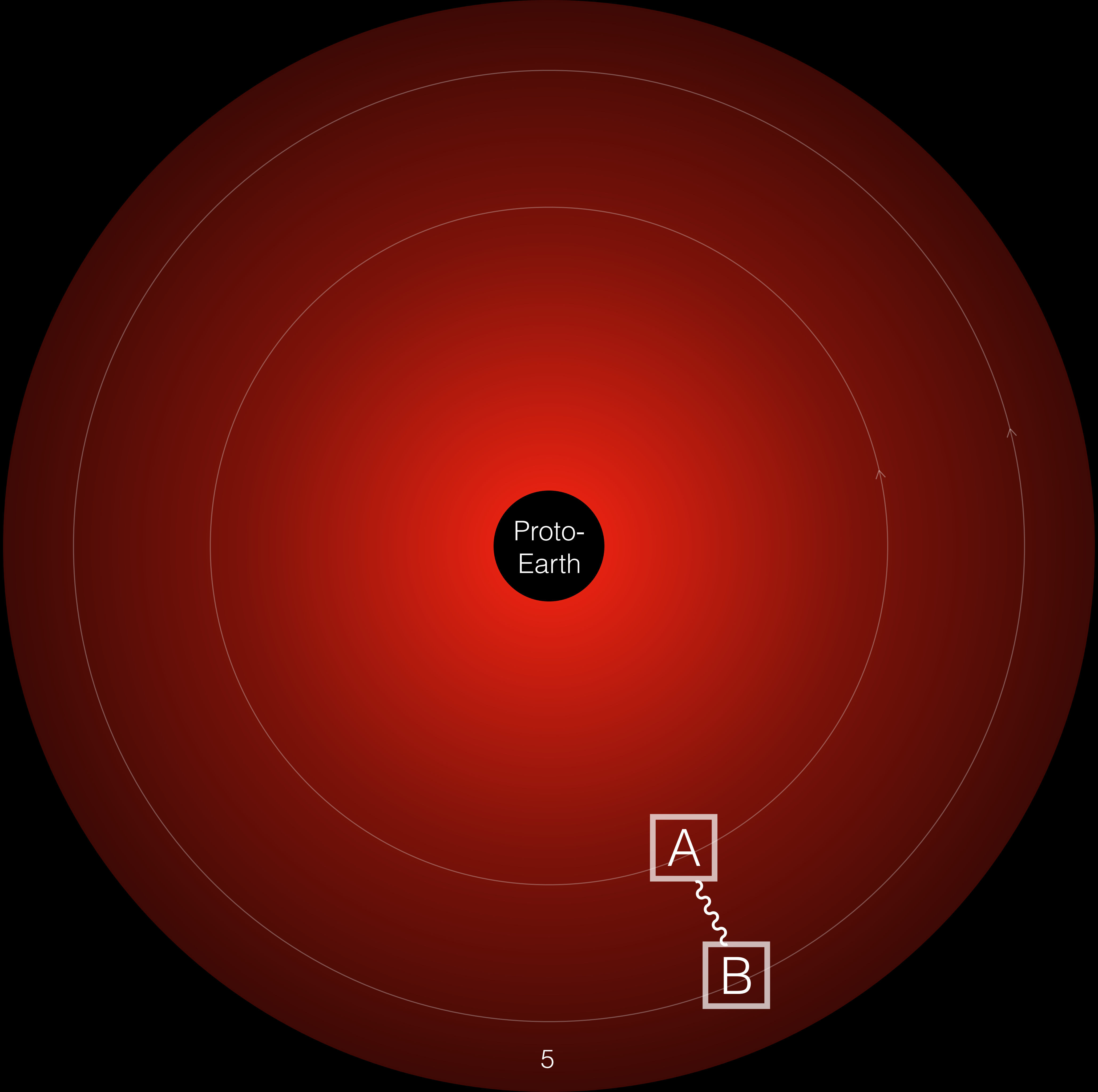
Reinhardt & Stadel (2017)
arXiv:1701.08296

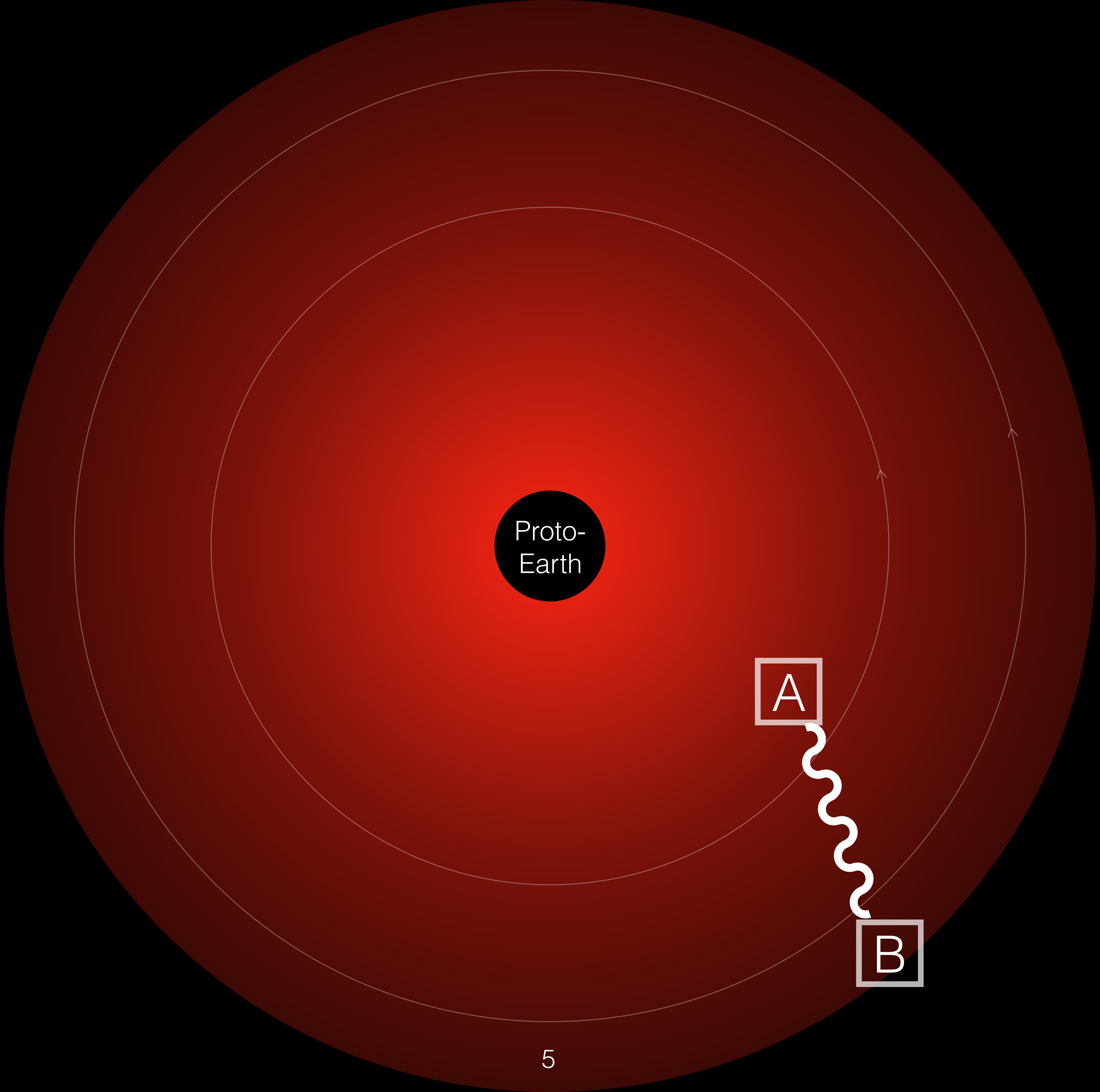


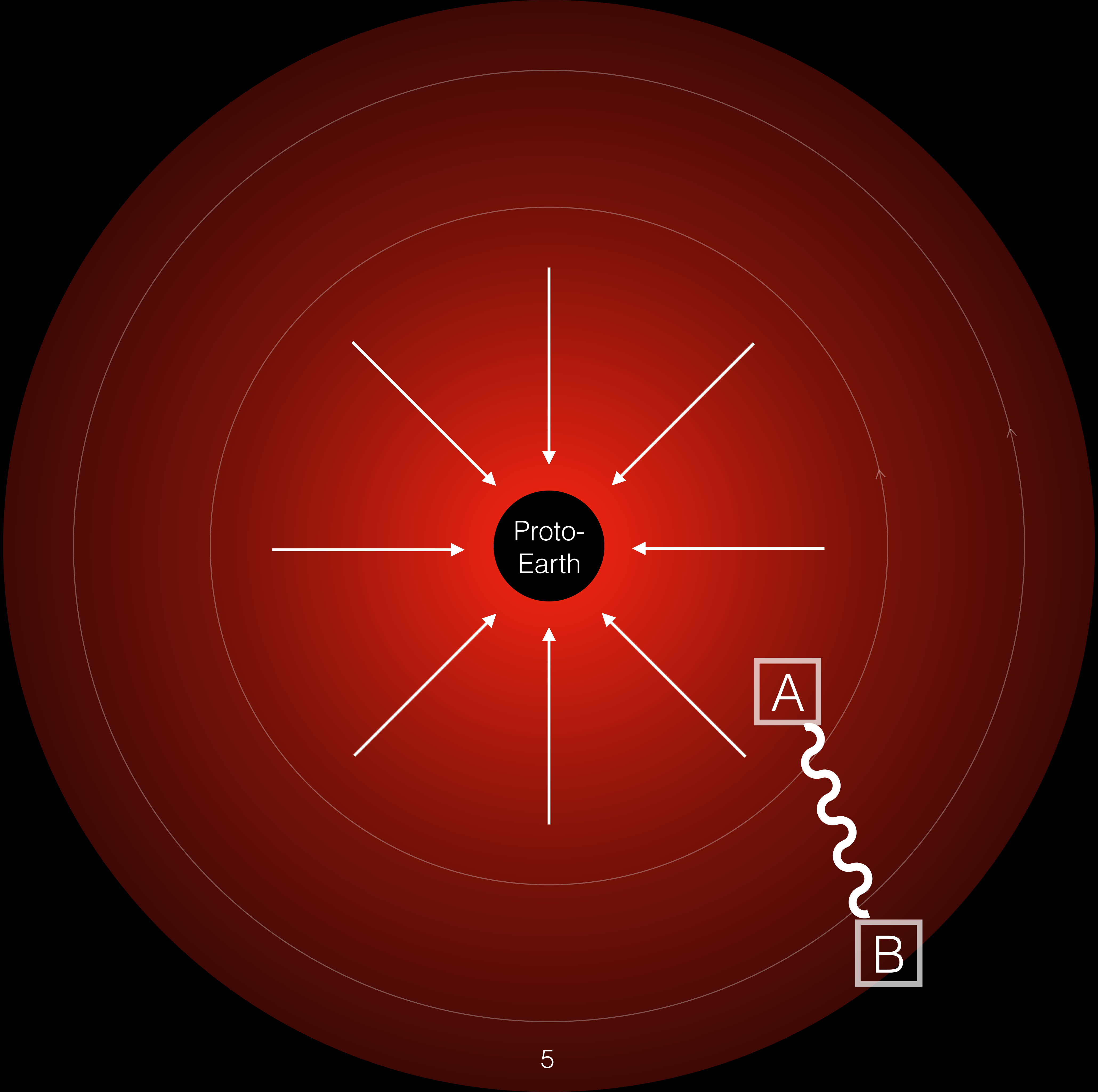
Kegerreis et al. (2019)
arXiv:1901.09934

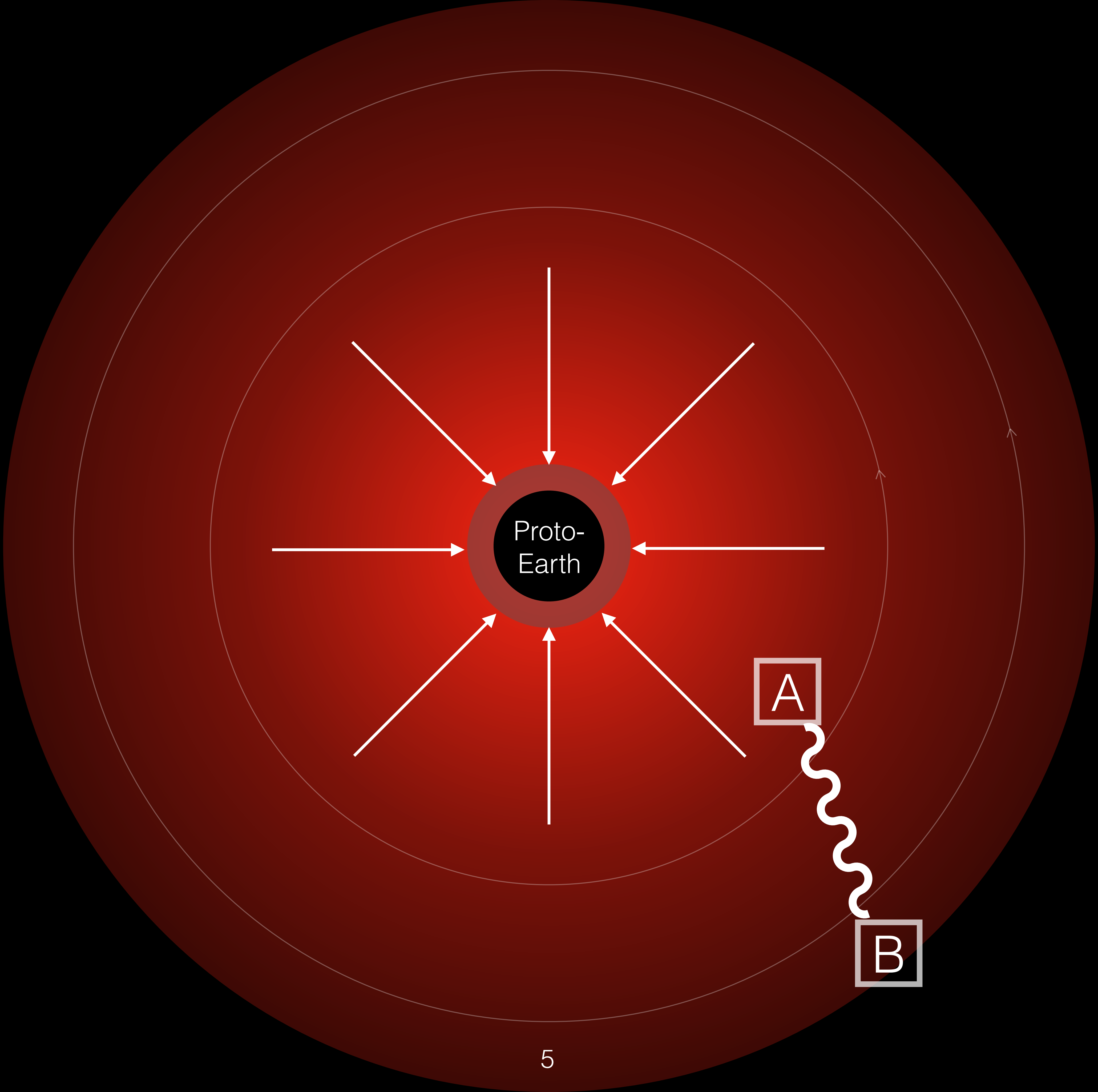
…But what about magnetic fields?

Gammie et al. (2016)
arXiv:1607.02132


Proto-
Earth
A
B


Proto-Earth
A
B


Proto-
Earth
A
B

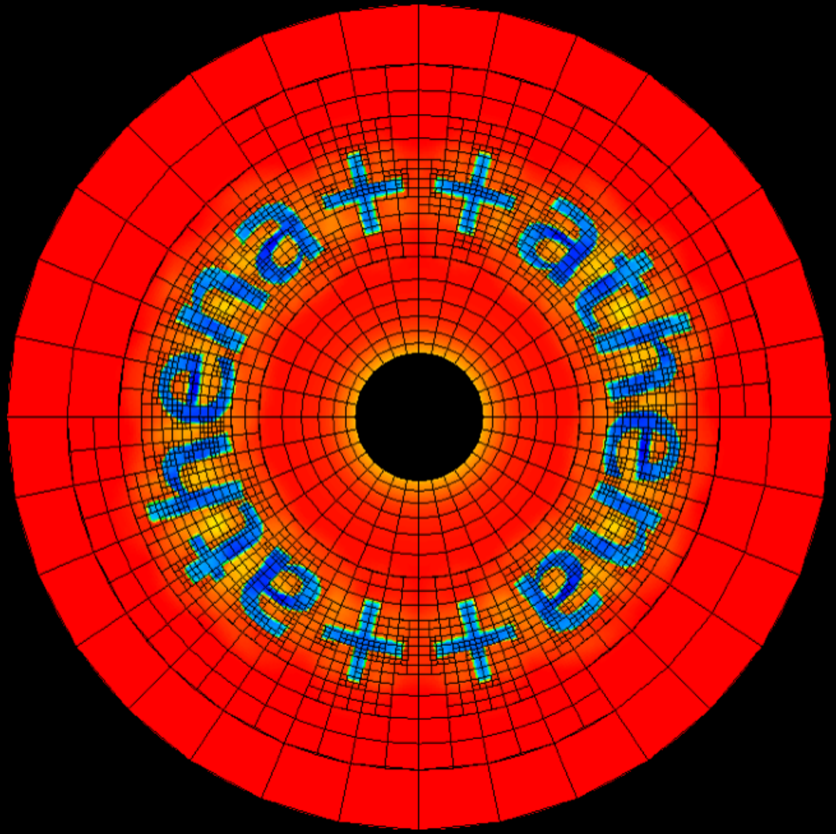

Proto-
Earth
A
B

A First-Take At A Magnetized Giant Impact?

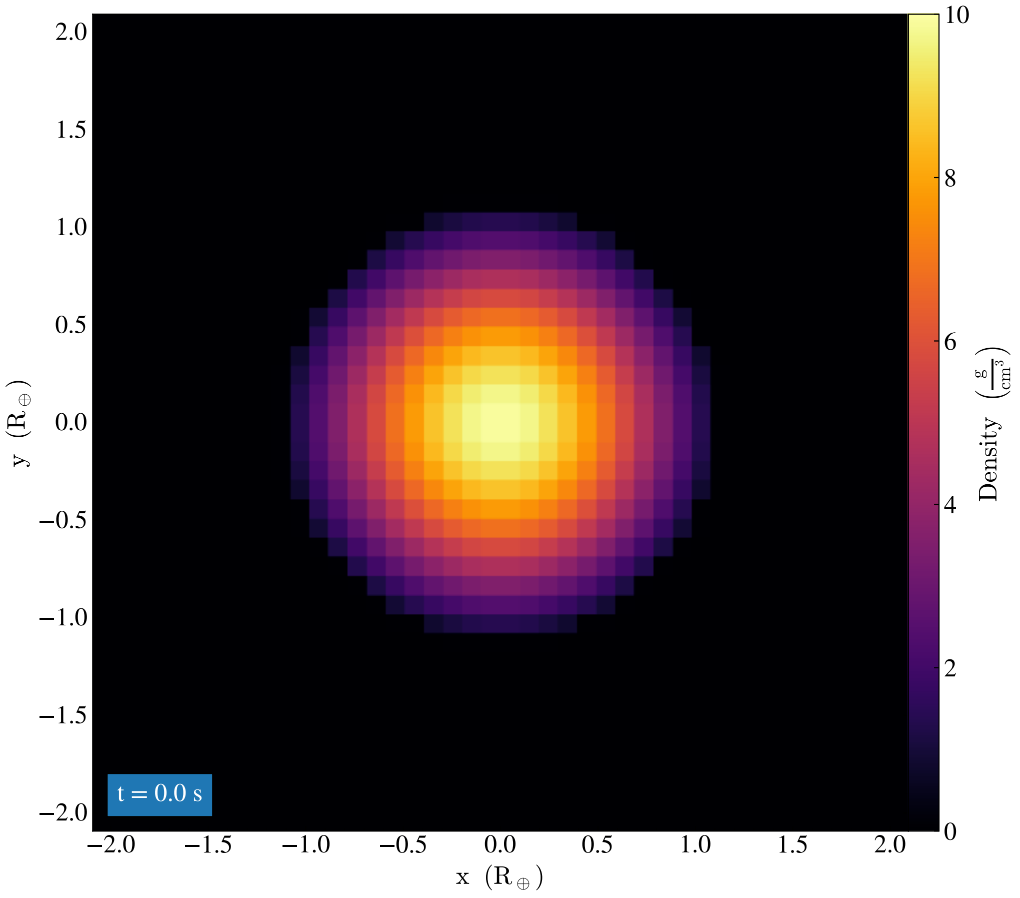
Configuration:

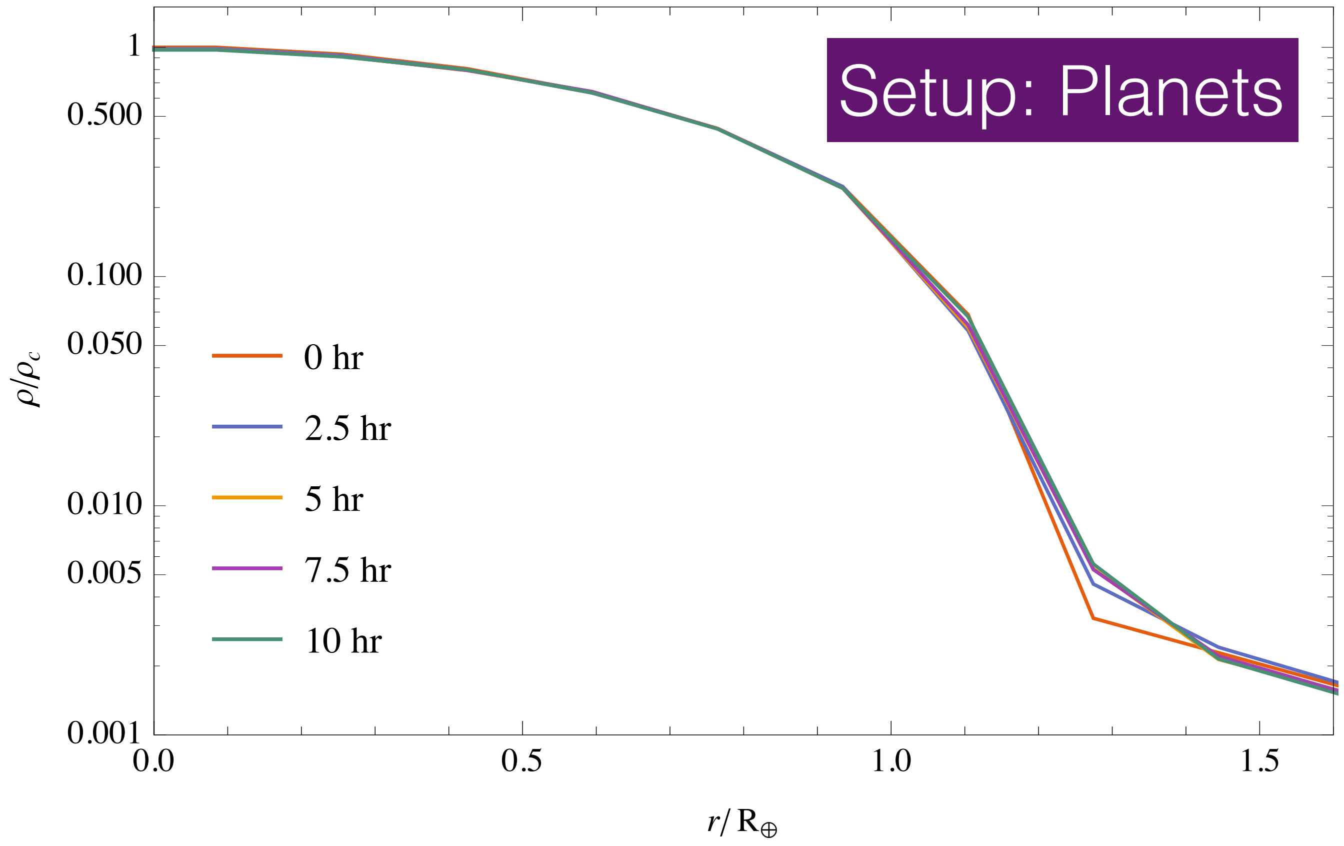
- Gamma Law EOS
- Adiabatic, Ideal MHD
- FFT Gravity Solver (Periodic BC’s)
- Cartesian, Uniform Grid

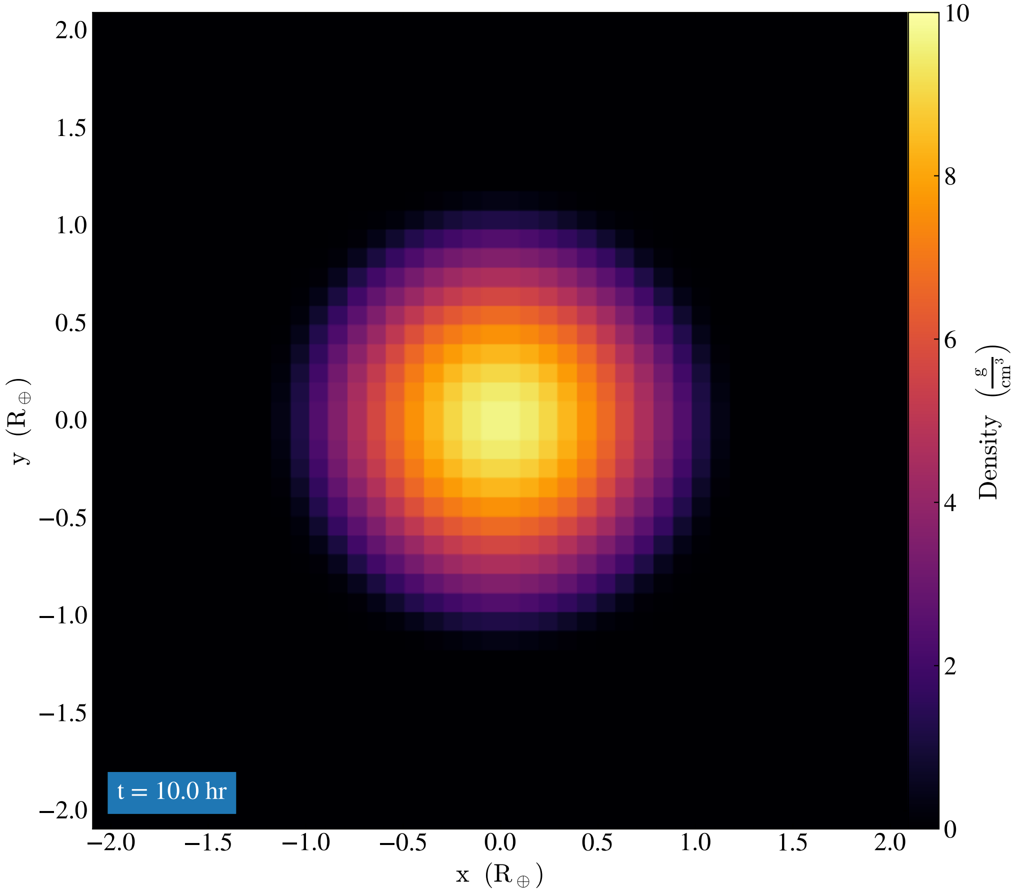
```
python configure.py
--prob=giant_impact -b
--grav=fft -fft
(--nghost=4 -mpi -hdf5)
```

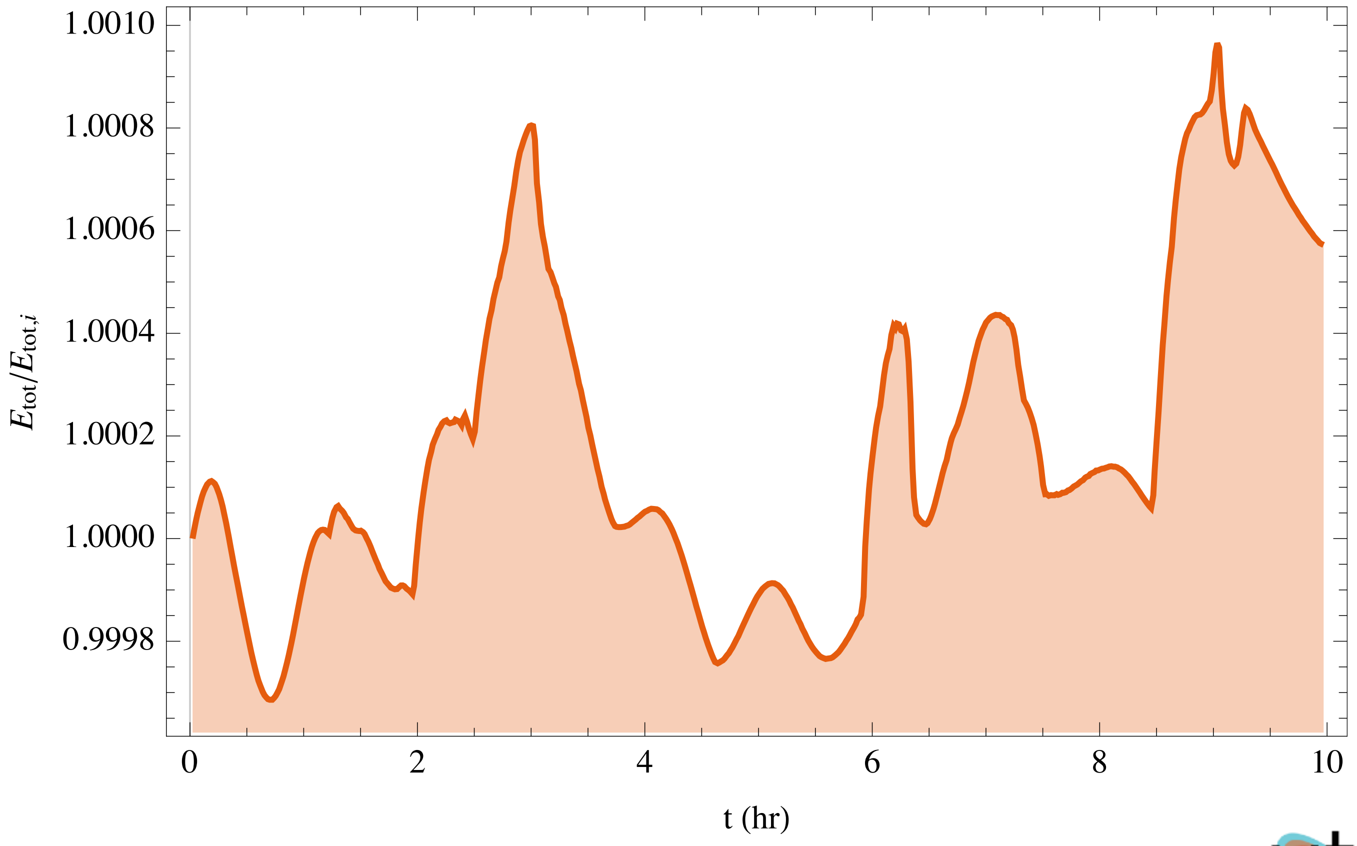


Setup: Planets



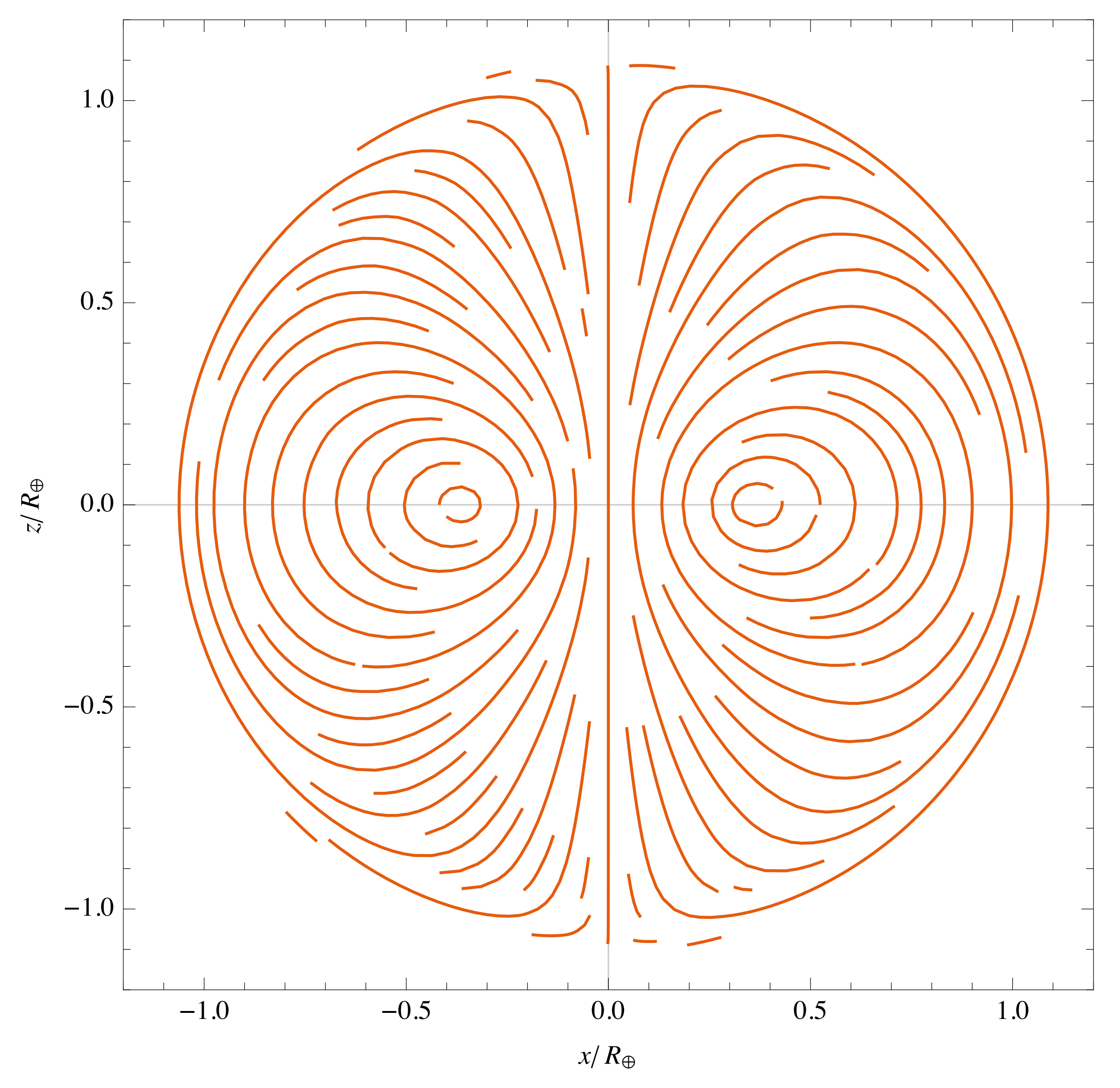






Visualization with yt

Setup: Setup Dipole Magnetic Fields

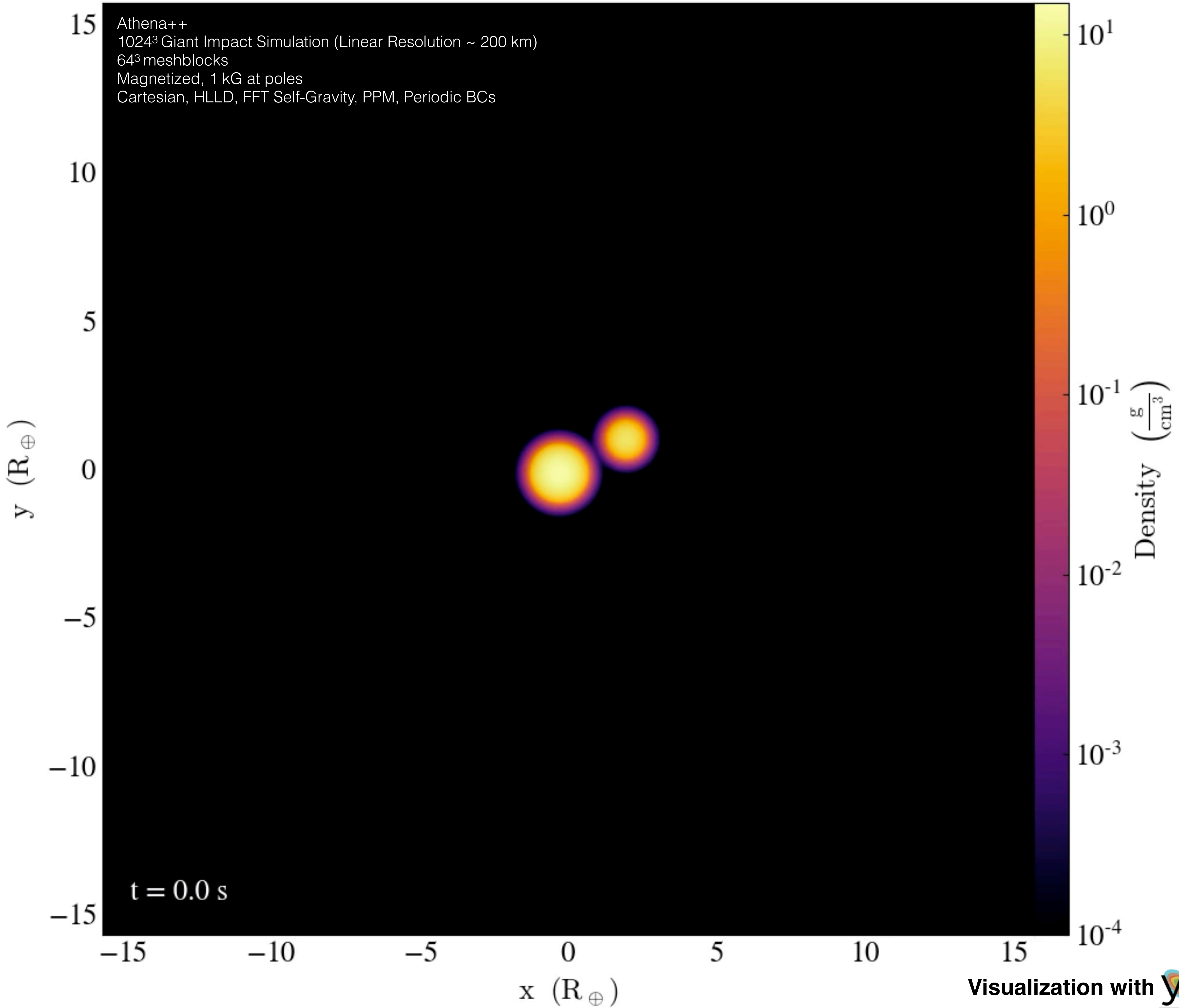


$$\vec{A}_\phi = \frac{\pi I_0 \varpi^2 r_0^2}{c(r_0^2 + r^2)^{3/2}} \left(1 + \frac{15 r_0^2 (r_0^2 + \varpi^2)}{8(r_0^2 + r^2)^2}\right)$$

$$b(r) = \begin{cases} A \exp\left(-\frac{\psi}{r_{\mathrm{cutoff}}^2 - r^2}\right) & \text{for } r < r_{\mathrm{cutoff}} \\ 0 & \text{otherwise} \end{cases}$$

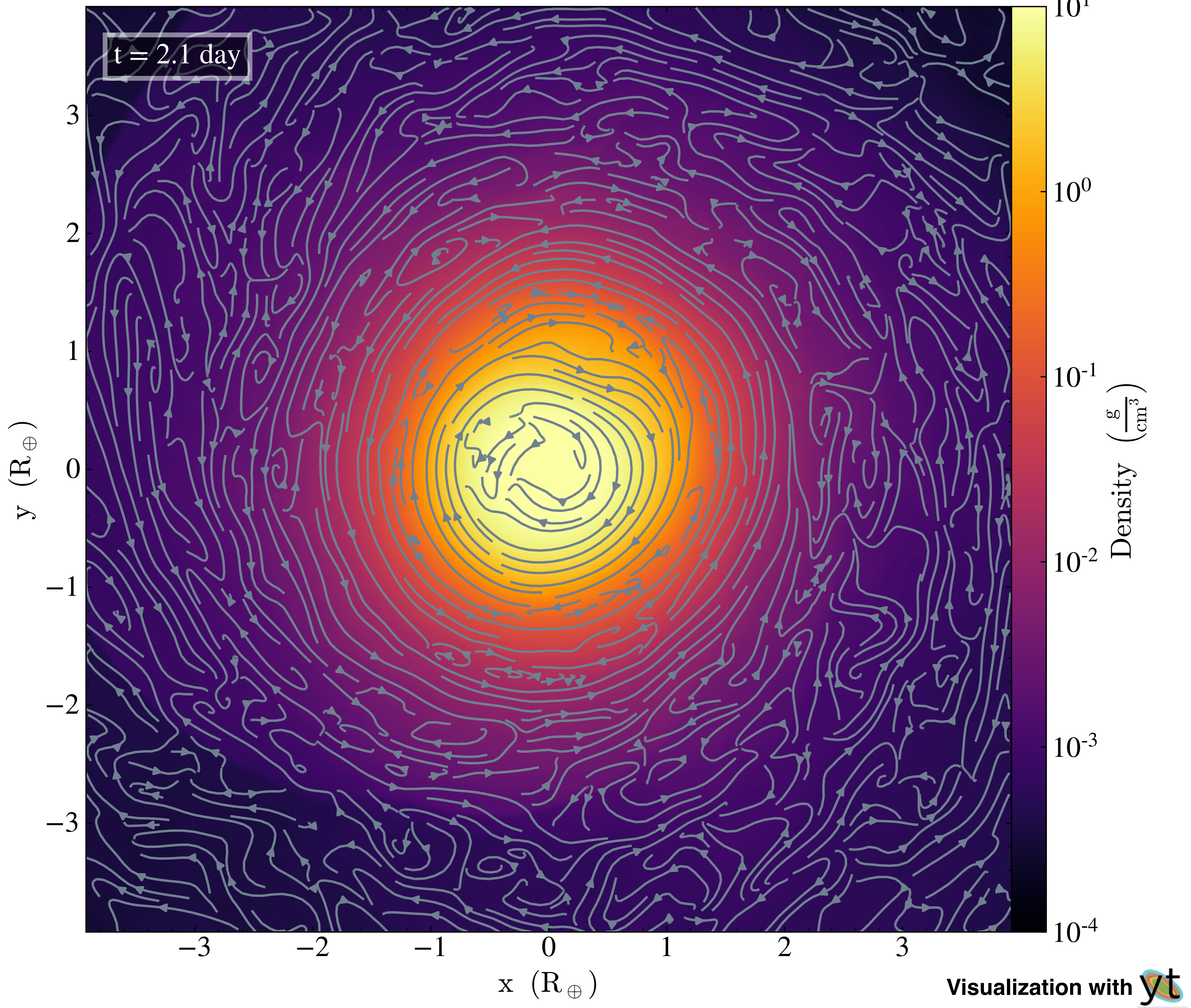
$$\vec{B} = \nabla \times (\vec{A}_\phi \cdot b(r))$$

c.f., Ruiz & Shapiro (2017)
arXiv:1709.00414



Athena++
1024^3 Giant Impact Simulation (Linear Resolution ~ 200 km)
64^3 meshblocks
Magnetized, 1 kG at poles
Cartesian, HLLD, FFT Self-Gravity, PPM, Periodic BCs

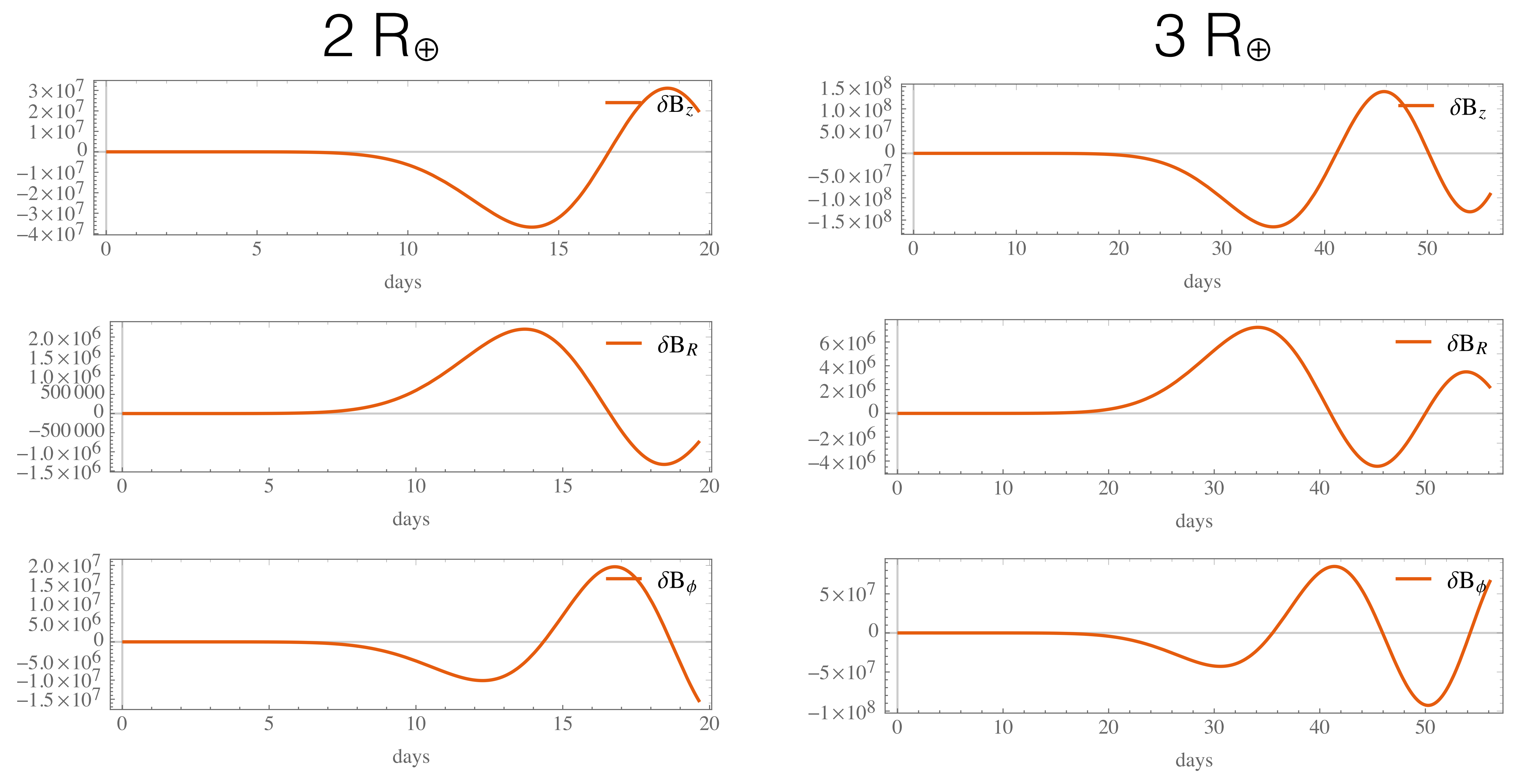
Visualization with yt


t = 2.1 day
3
2
1
0
−1
−2
−3
y (R$_\oplus$)
−3
−2
−1
0
1
2
3
x (R$_\oplus$)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Density $\left(\frac{\mathrm{g}}{\mathrm{cm}^3}\right)$
Visualization with yt

Balbus & Hawley 1992

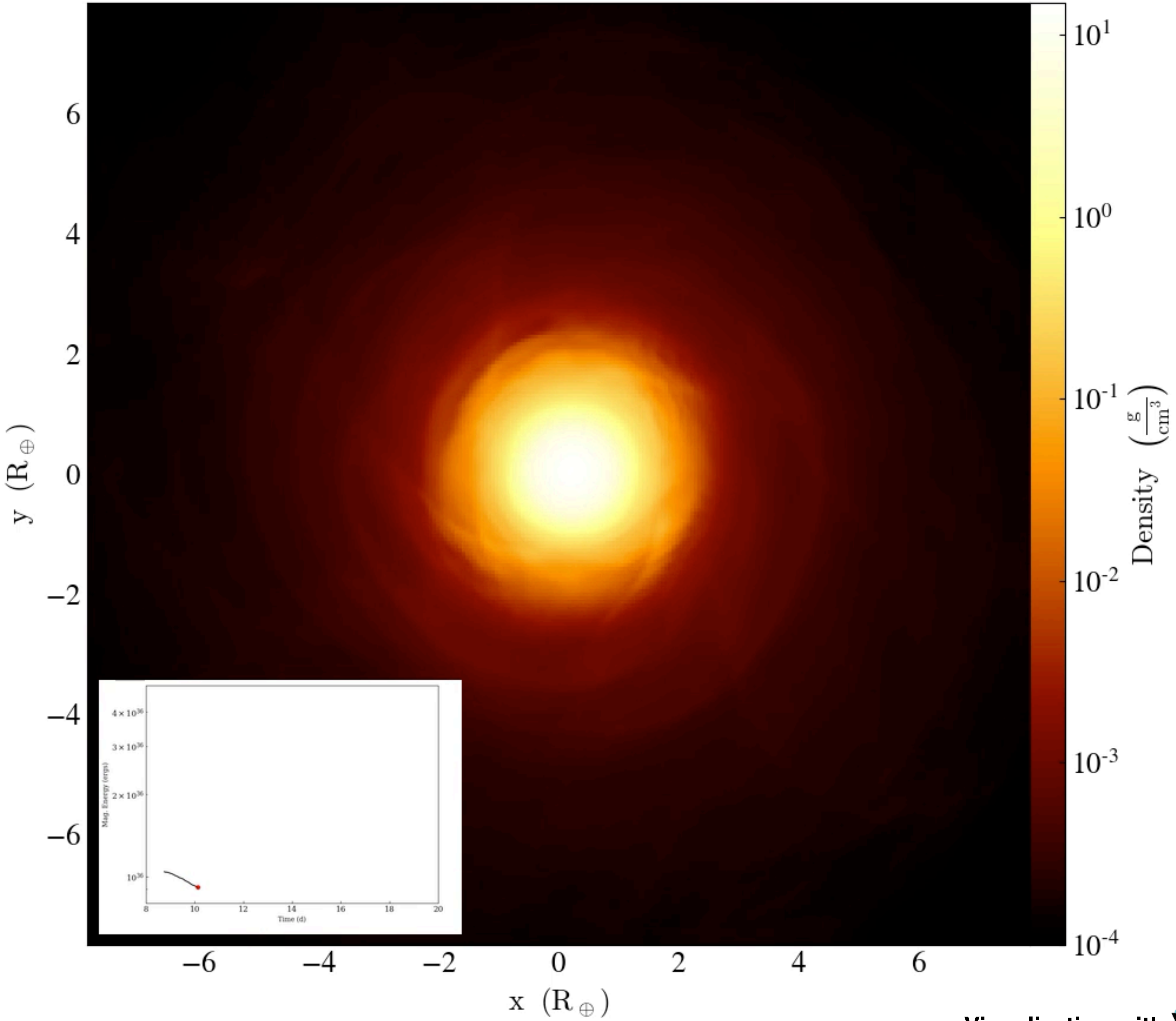
$$\frac{d^2\delta B_R}{d\tau^2} = -\frac{k_z^2}{k^2m^2}\left(\frac{4}{p}+\frac{2m^2}{R^2k_z^2}\right)\left(\tau\frac{d\delta B_R}{d\tau}\right) + \frac{4}{p^2m^2}\left(\frac{N^2}{\Omega^2}\frac{k_z\tau}{k^2R}\delta B_z - \frac{(\boldsymbol{k}\cdot\boldsymbol{v}_A)^2}{\Omega^2}\delta B_R\right) - \frac{4}{p}\frac{k_z}{k^2R}\left(1+\frac{R^2k_z^2}{m^2}\right)\frac{d\delta B_z}{d\tau},$$

$$\frac{d^2\delta B_z}{d\tau^2} = \frac{2}{p}\frac{k_z}{k^2R}\left(\frac{2\tau^2}{m^2}-p+2\right)\frac{d\delta B_R}{d\tau} + \frac{4}{pm^2}\frac{k_z^2}{k^2}\left(\tau\frac{d\delta B_z}{d\tau}\right) - \frac{4}{p^2m^2}\left(\frac{(\boldsymbol{k}\cdot\boldsymbol{v}_A)^2}{\Omega^2}+\frac{k^2-k_z^2}{k^2}\frac{N^2}{\Omega^2}\right)\delta B_z.$$



2 R⊕

3 R⊕



Visualization with yt

Conclusions:

- First numerical simulations of magnetized, Moon-forming giant impacts (Mullen & Gammie 2019, *in prep*).
- **Onset of the MRI in a Moon-forming giant impact debris disk** with growth times in **agreement with linear theory** (Balbus & Hawley 1992).
- Magnetic turbulence promotes **mixing** (Gammie et al. 2016, **arXiv**: 1607.02132).
- Accretion leads to **processing through the boundary layer** producing high entropy material; the boundary layer sources **sound waves** (c.f., Belyaev et al. 2016: **arXiv**:1709.01197) that propagate throughout the disk.

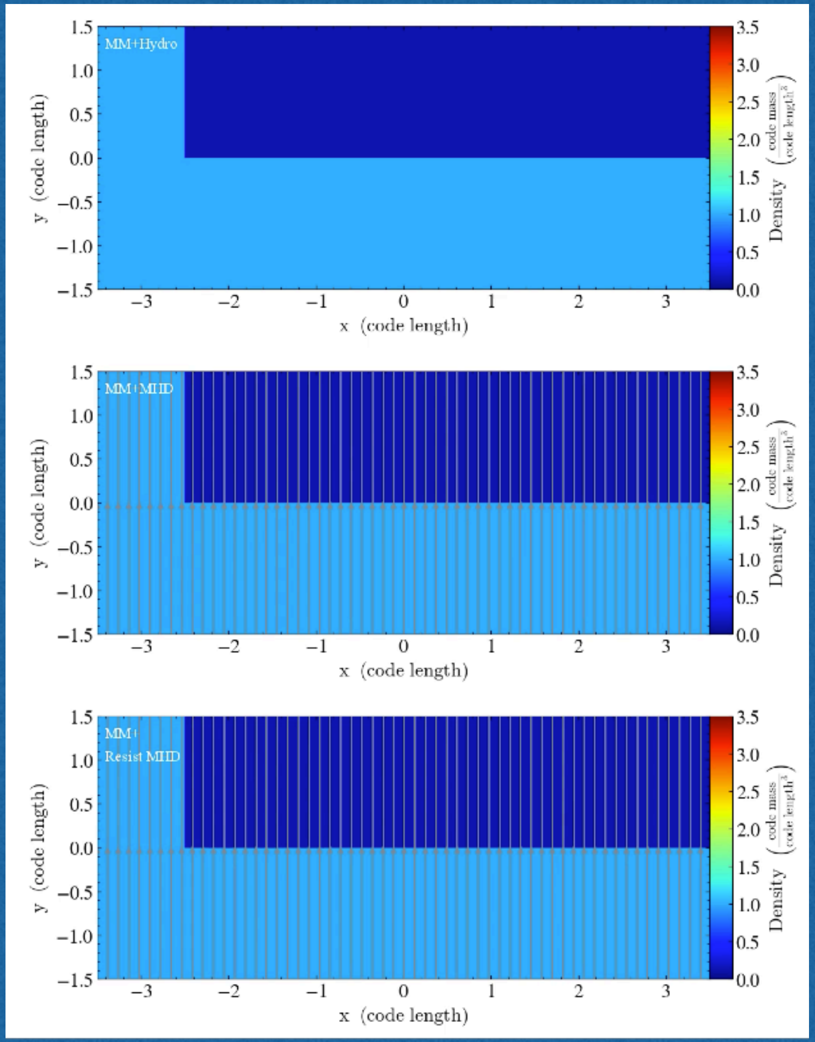
Caveats:

- Quantitative studies of mixing from magnetic turbulence requires **composition variables** (*in development*).
- Need to separately track **iron cores and silicate mantles** (*in development, see Dr. Roseanne Cheng's talk this afternoon!*).
- Need better treatment of **EOS** (*in development).*
- Need **open-BCs** for gravitational potential (*in development)*.
- Not all of the protolunar disk will be well-coupled to the magnetic field; need fast and efficient algorithms for **resistive MHD** (i*n development*).

Future Directions:

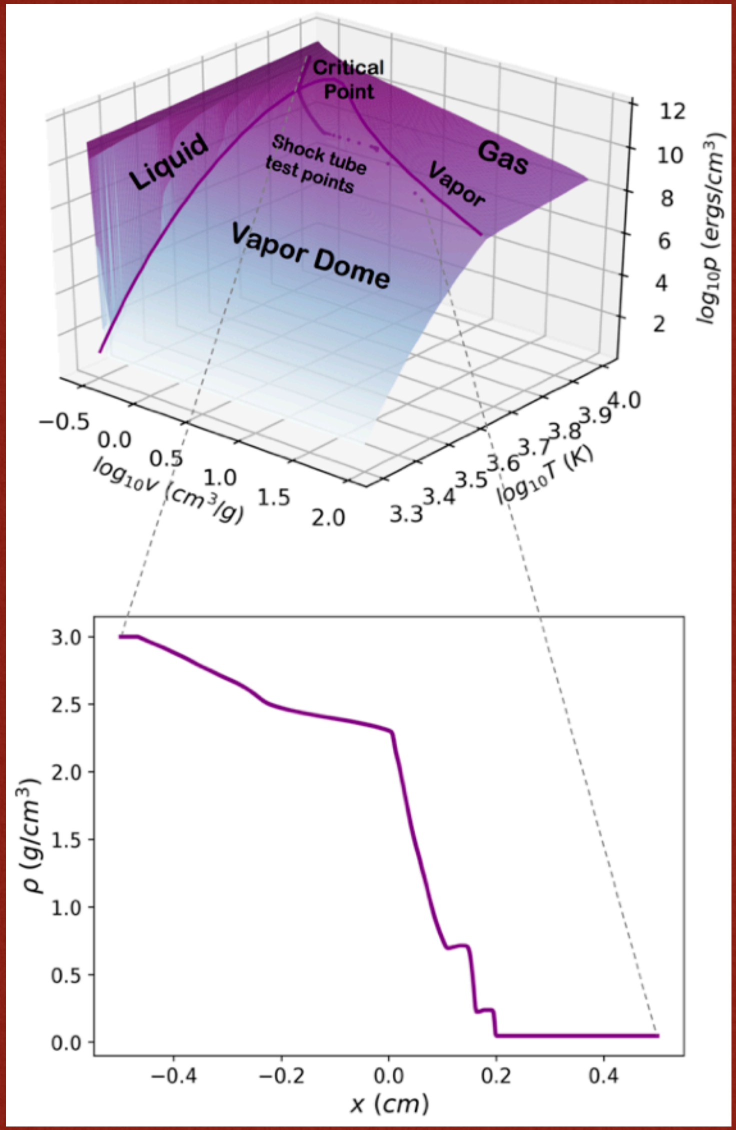
…towards multi-material resistive MHD with realistic EOS for astrophysical/planetary science applications

Multi-Material Evolution:



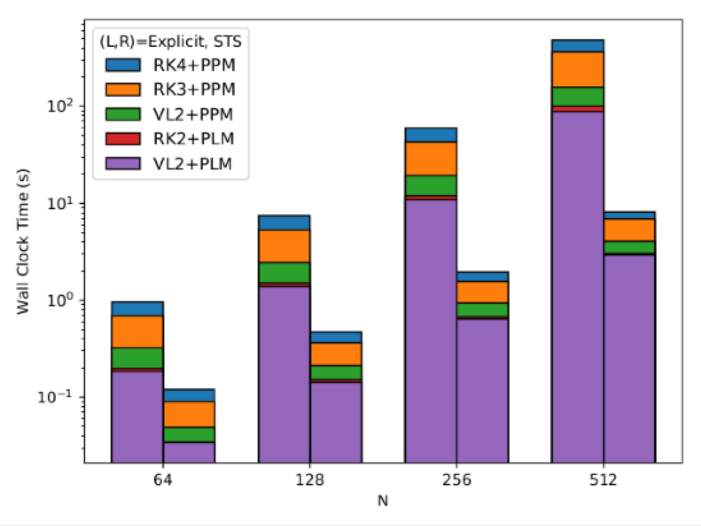
```
python configure.py
--prob=mm_triple_pt (-b)
-mm --nmat=3
```

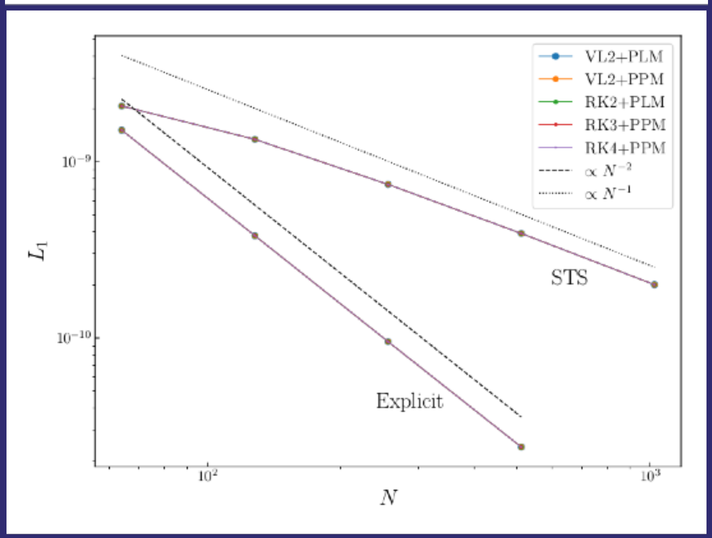
Realistic (Tabular) EOS:



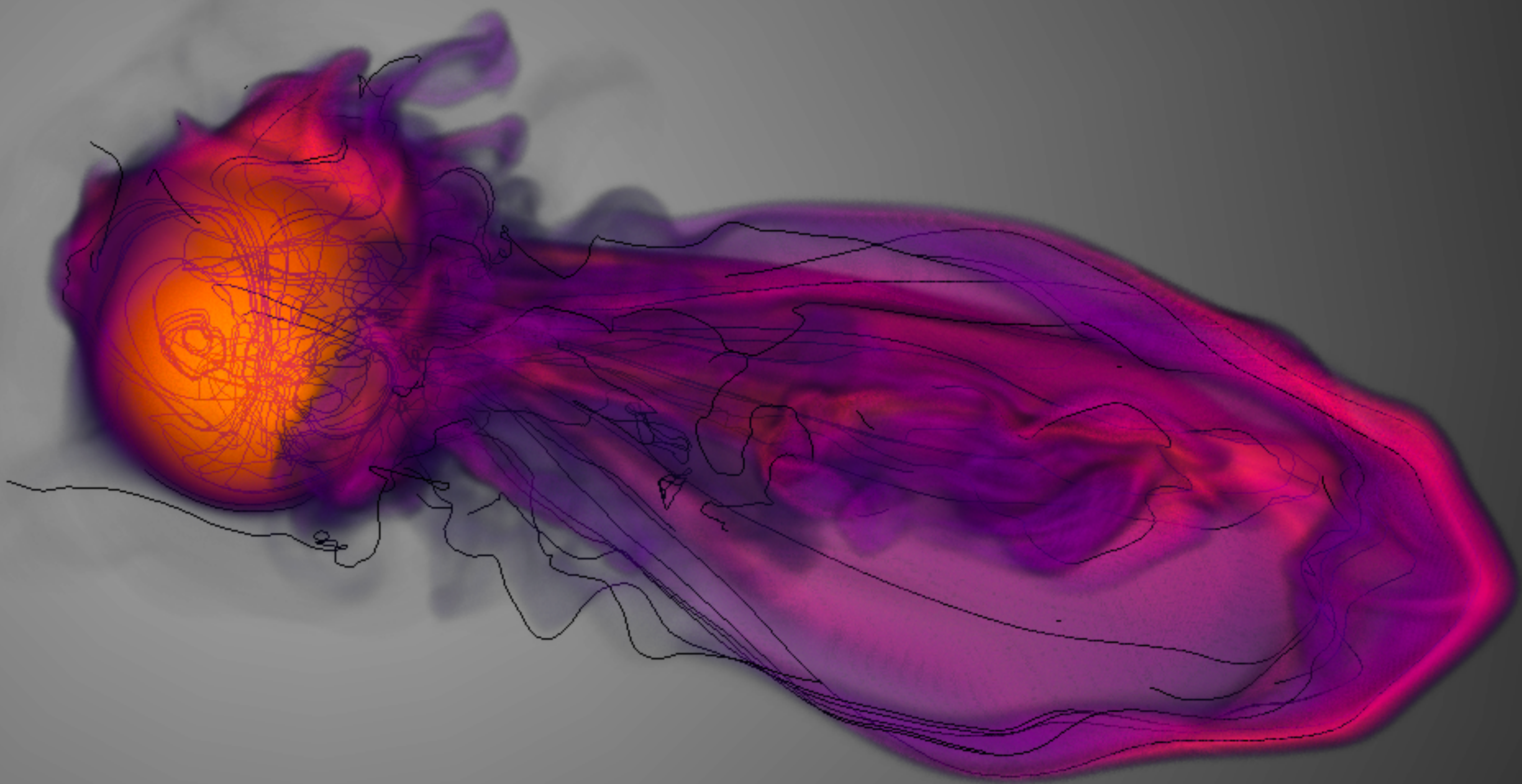
```
python configure.py
--prob=shock_tube
--eos=general/eos_table
```

Resistive MHD with Super-Time-Stepping:





```
python configure.py
--prob=resistive_diffusion
-sts
```



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Email: pmullen2@illinois.edu
GitHub: pdmullen

Thank You! Questions?