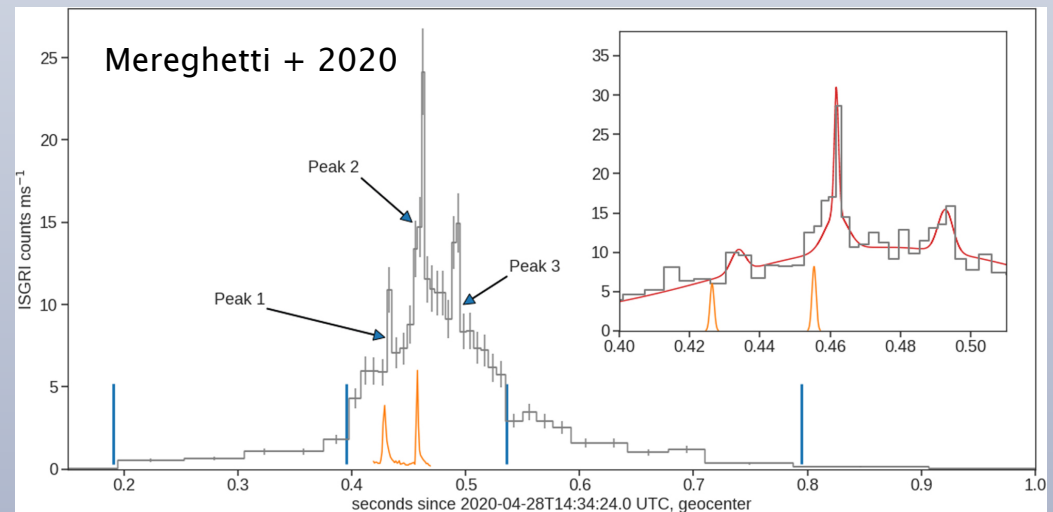
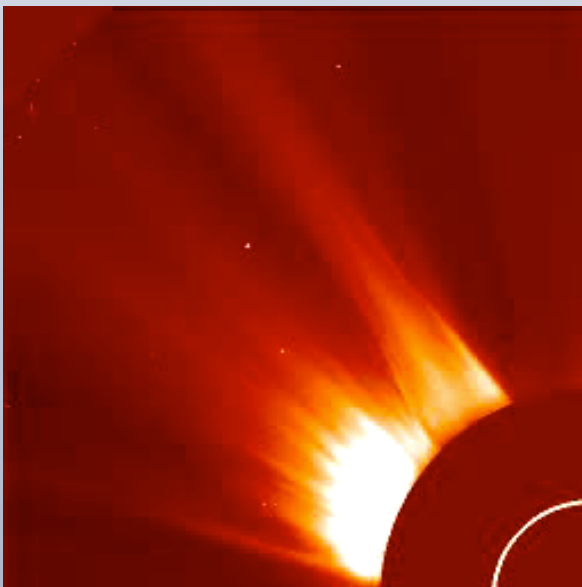
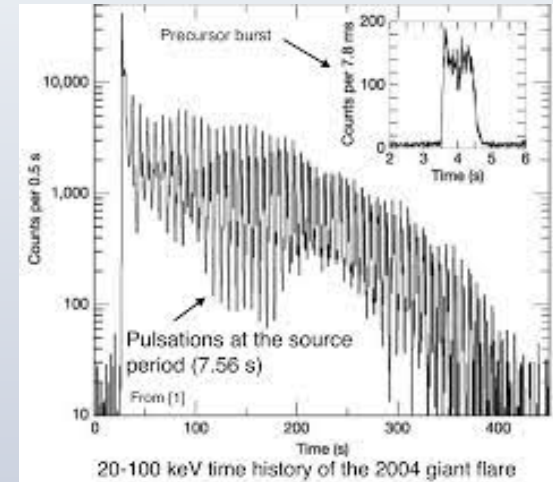


# Relativistic magnetic bombs

**Maxim Lyutikov (Purdue University)**

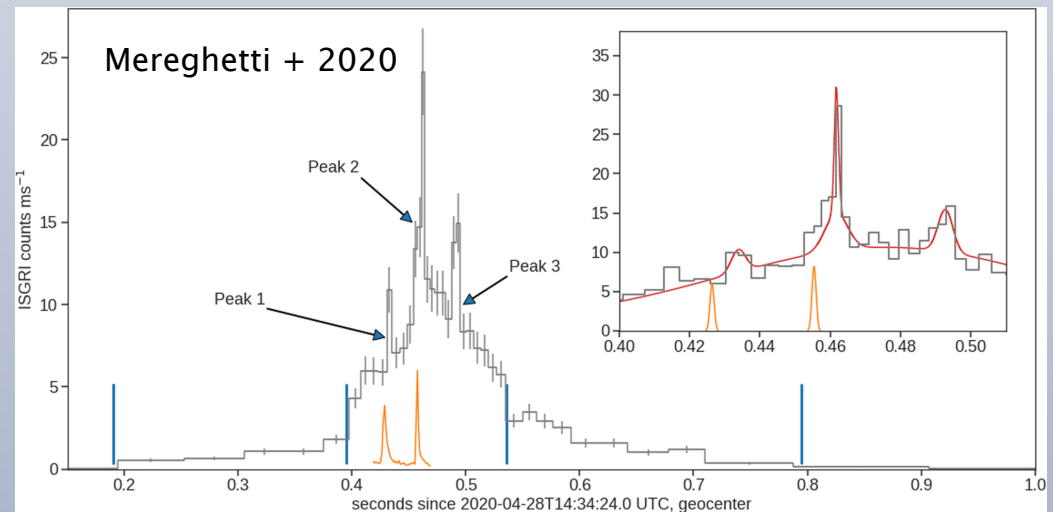
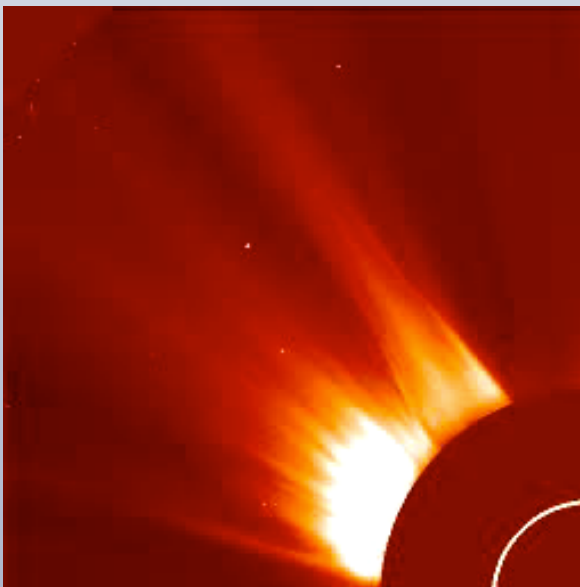
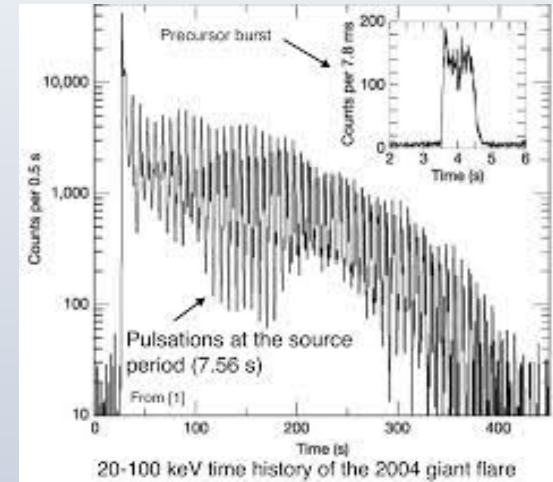
# (Relativistic) Magnetically-driven explosions

- Magnetars' bursts and flares
- FRBs
- "Solar Physics of Magnetars"  
(Lyutikov 2002, 2006)



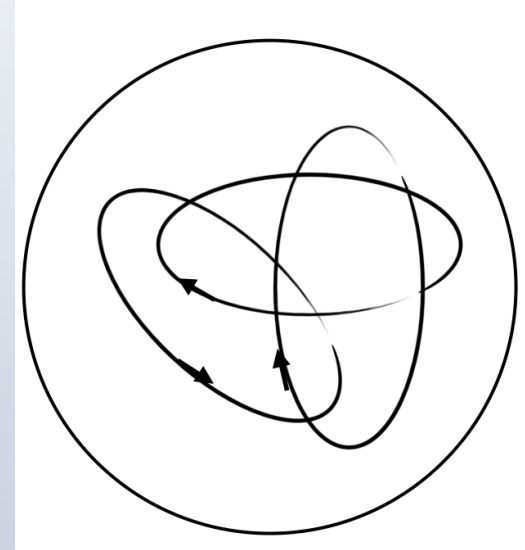
# (Relativistic) Magnetically-driven explosions

- Magnetars' bursts and flares
- FRBs
- "Solar Physics of Magnetars"  
(Lyutikov 2002, 2006)



# The question:

- How to make “magnetic bomb”
- We have a highly over-pressurized ( $B^2$ ) magnetically dominated ball with tangled magnetic field: how will it expand?





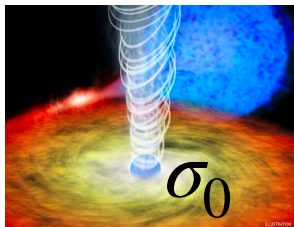
# Relativistic magnetic explosions: not hydro, not stationary, not 1D

- Relativistic hydro explosion (Goodman-Paczynski)



$$\Gamma \propto r, \Gamma_{max} \sim E/M$$

- Magnetically-driven winds (AGNe, NSs: **steady** - Michel, Peter G.)

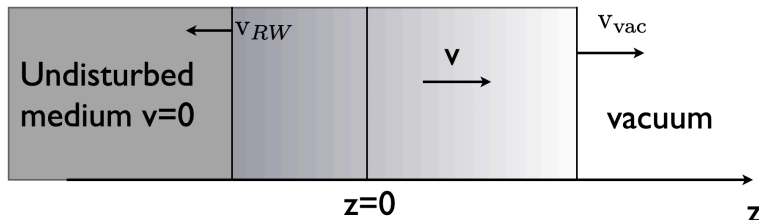


$$\Gamma \propto r, \Gamma_{max} \sim \sigma_0^{1/3}$$

$$\sigma_0 = \frac{B^2}{4\pi r c^2}$$

(flow remains magnetically-dominated:  
conservation of flux! - the “sigma” problem of K-C)

- Magnetically-driven 1D (Lyutikov 2011)



$$\Gamma \propto t^{1/3}, \Gamma_{max} = 1 + 2\sigma_0$$

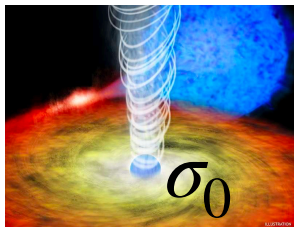
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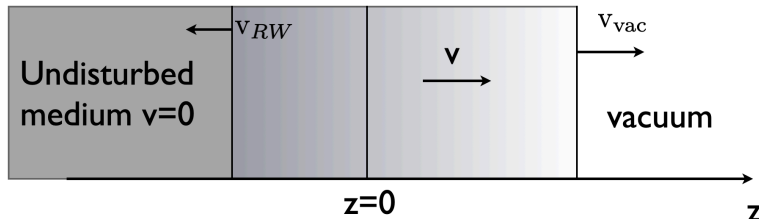


$$\Gamma \propto r, \Gamma_{max} \sim \sigma_0^{1/3}$$

$$\sigma_0 = \frac{B^2}{4\pi\rho c^2}$$

(flow remains magnetically-dominated:  
conservation of flux! - the “sigma” problem of K-C)

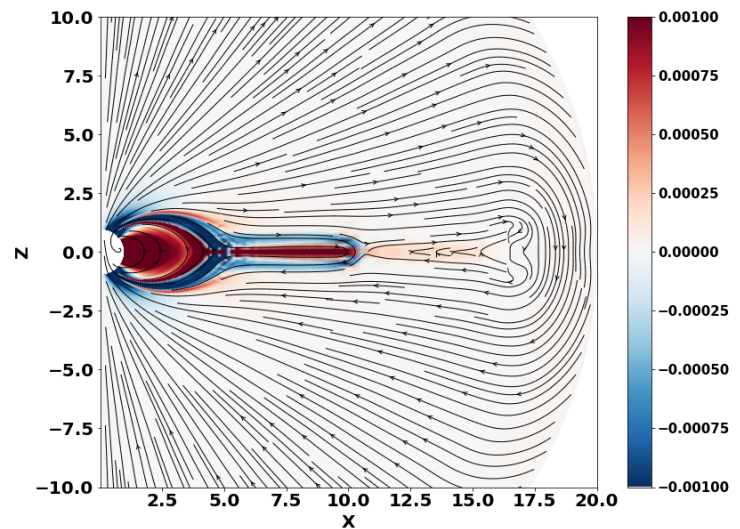
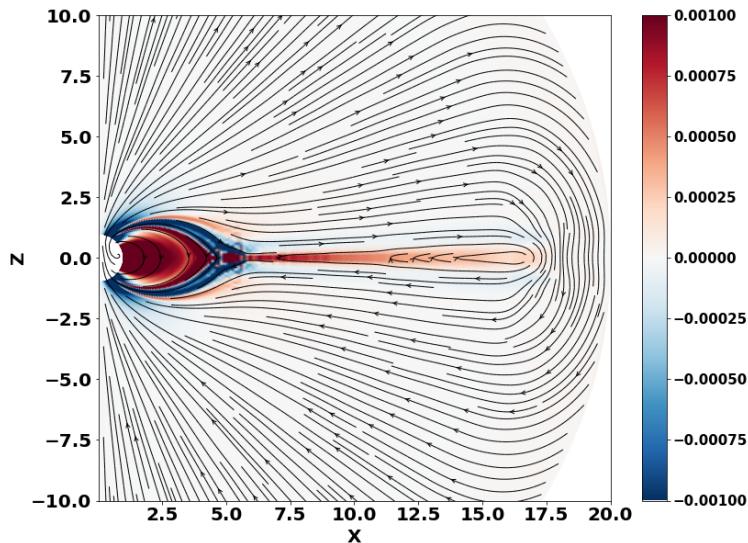
- Magnetically-driven 1D (Lyutikov 2011)



$$\Gamma \propto t^{1/3}, \Gamma_{max} = 1 + 2\sigma_0$$

# 1. Generation of Relativistic Coronal Mass Ejections: (*a la* Solar flares)

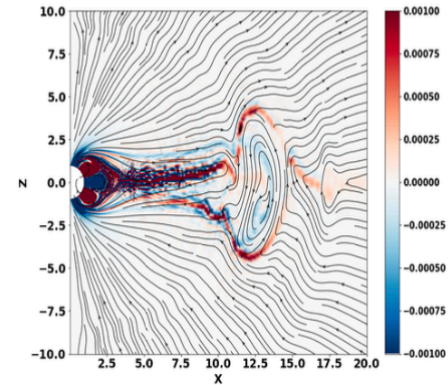
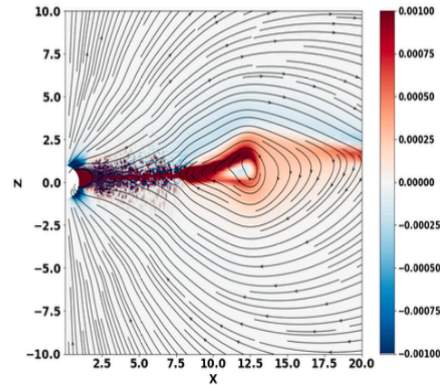
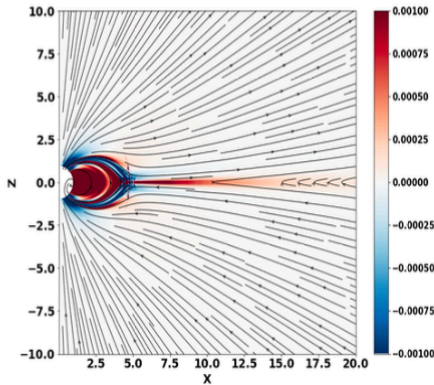
- CME: Coronal Mass Ejection (not really “mass” in our case)
- Solar CMEs - no rotation, need complicated geometry, reconnection
- NS: rotation!
- Rotating dipole: frequent mild ejections (unstable Y-point)



# Rotation, shear, complexed geometries

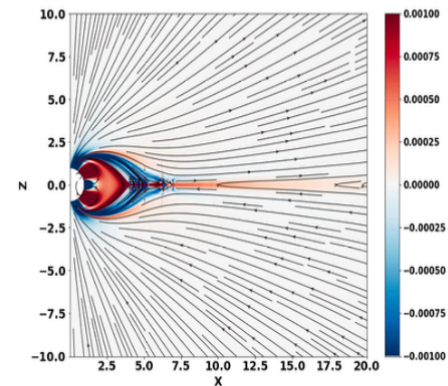
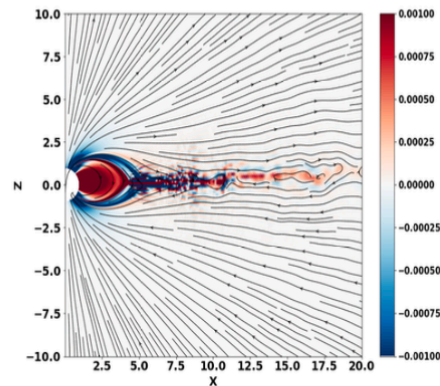
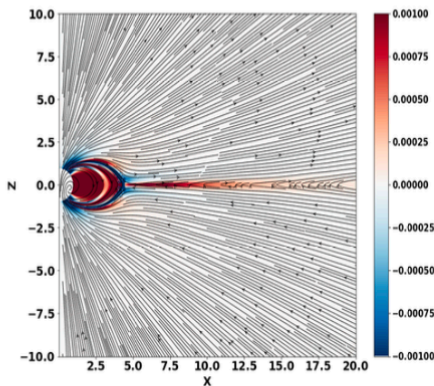
shearing  
near equator

$\theta = 90^\circ, \xi = 0.5$



shearing  
near the pole

$\theta = 10^\circ, \xi = 0.5$



(a) Dipole

(b) Dipole+Quadrupole

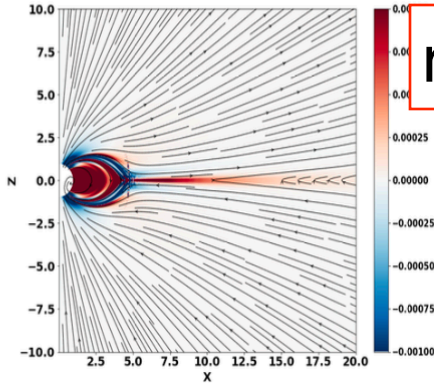
(c) Dipole+Octupole



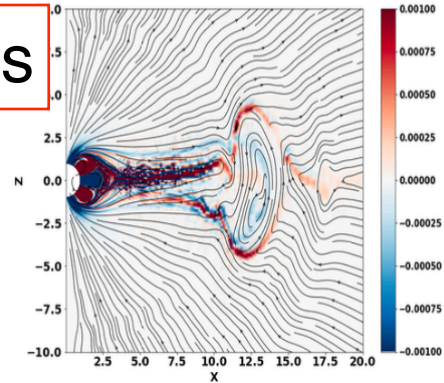
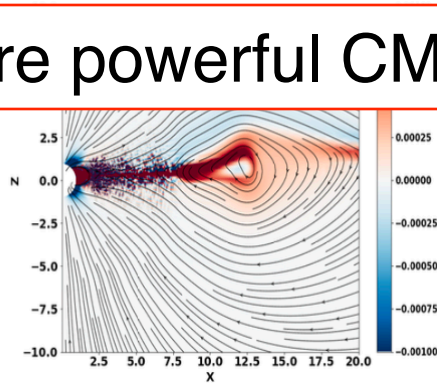
# Rotation, shear, complected geometries

shearing  
near equator

$\theta = 90^\circ, \xi = 0.5$

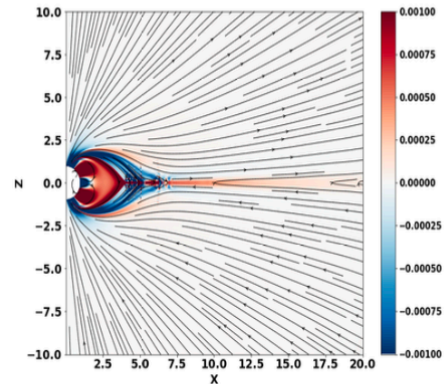
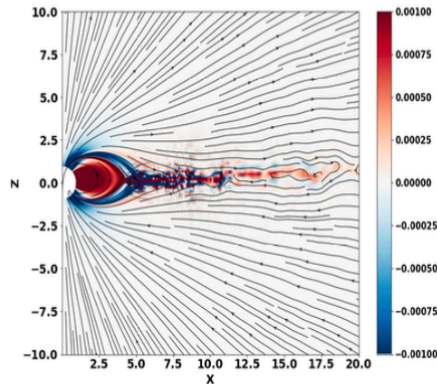
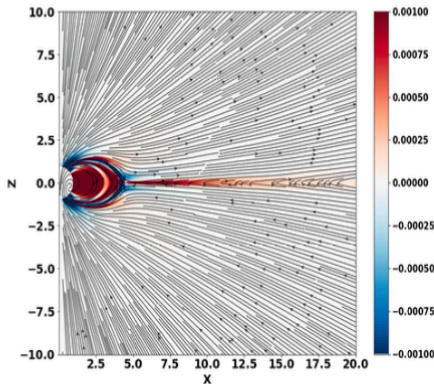


rare powerful CMEs



shearing  
near the pole

$\theta = 10^\circ, \xi = 0.5$



(a) Dipole

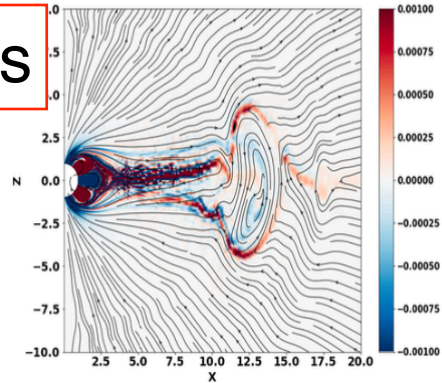
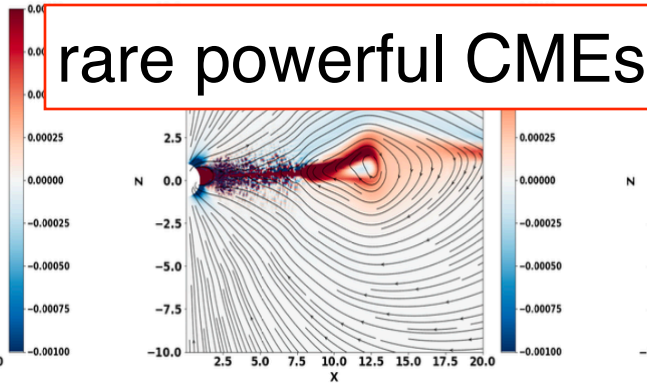
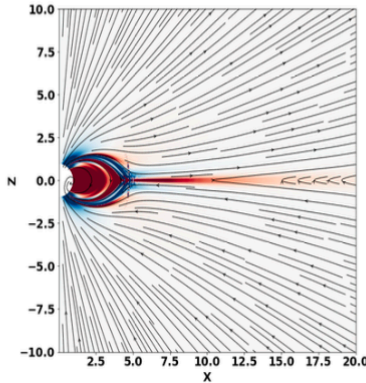
(b) Dipole+Quadrupole

(c) Dipole+Octupole

# Rotation, shear, complected geometries

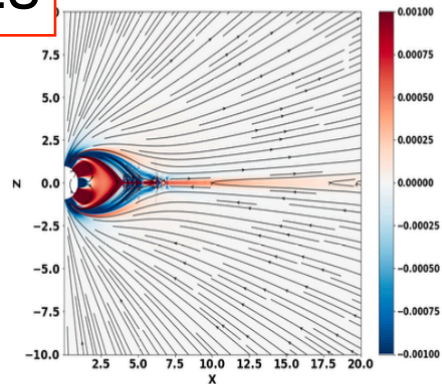
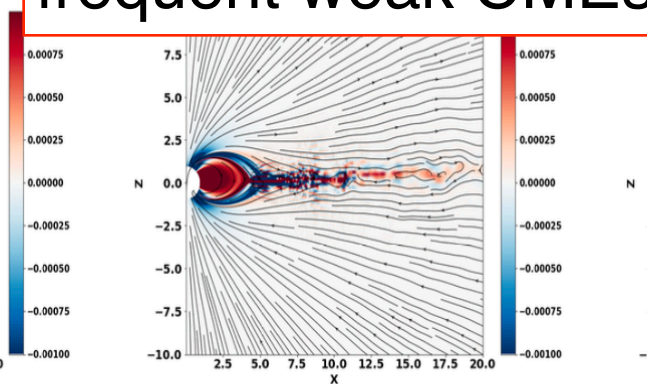
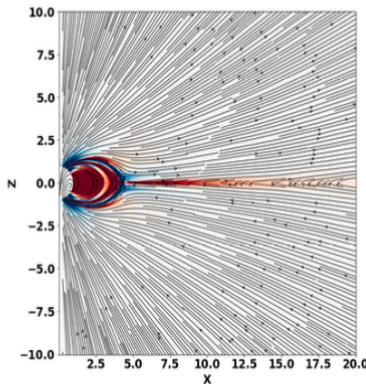
shearing  
near equator

$\theta = 90^\circ, \xi = 0.5$



shearing  
near the pole

$\theta = 10^\circ, \xi = 0.5$



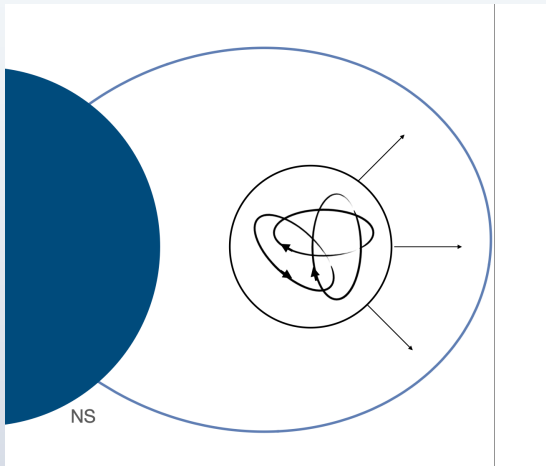
(a) Dipole

(b) Dipole+Quadrupole

(c) Dipole+Octupole

# 2. Magnetic bomb

Lyutikov 2022  
Barkov+ 2022



- Conservation of magnetic flux: **Magnetic loading**:  $E \sim 1/t$

Force-free bomb: Prendergast problem

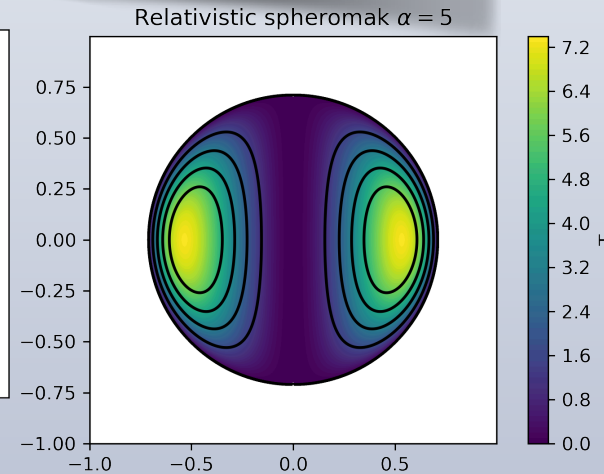
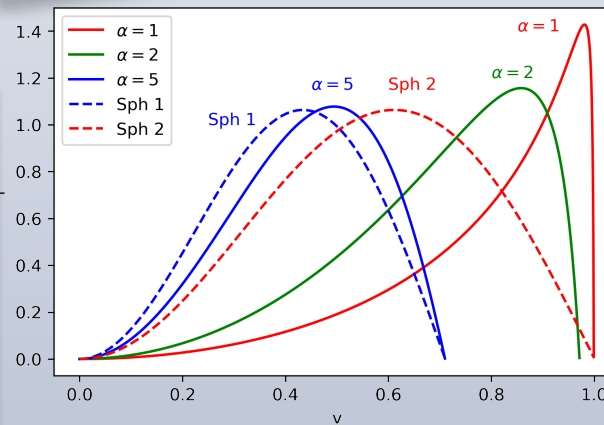
$$f = \cos \xi - \frac{\sin \xi}{\alpha v},$$

$$\xi = \alpha \operatorname{arctanh}(v)$$

$$v = r/t$$

$$\mathbf{B} = \nabla \Psi \times \nabla \phi + \frac{v}{1-v^2} \frac{\alpha \Psi}{r} \nabla \phi$$

$$\mathbf{E} = v \mathbf{e}_r \times \mathbf{B}$$



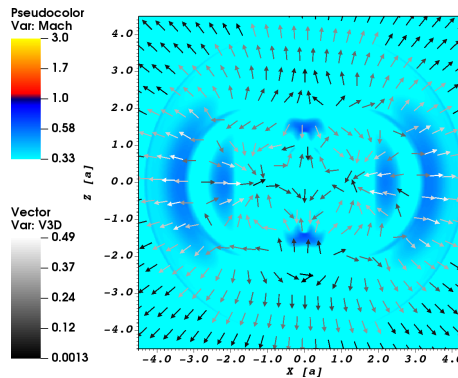
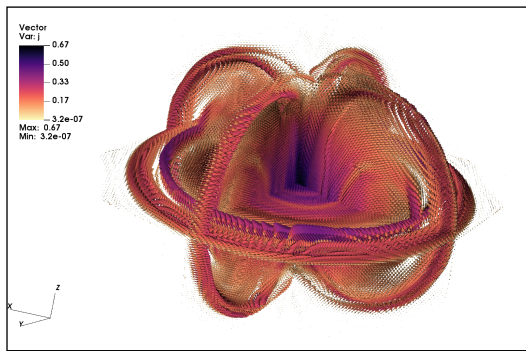
Spheromak-like)  
Mostly near the surface,  $\sim$  magnetic shell



# Magnetic bomb (MHD simulations)

Lyutikov 2022  
Barkov+ 2022

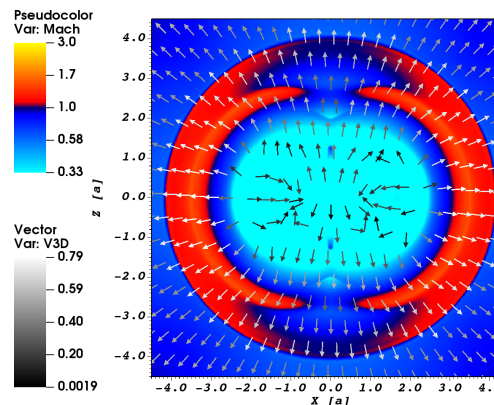
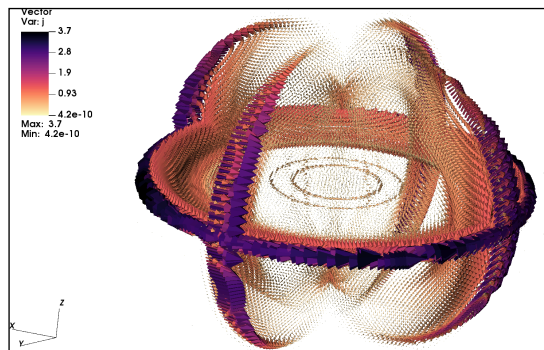
- Puff-ups or detonates, need



puff-up, slowly expands  
(filled-in structure)

$$E_0 \frac{R_0}{R_{LC}} \gg B_{LC}^2 R_{LC}^3$$

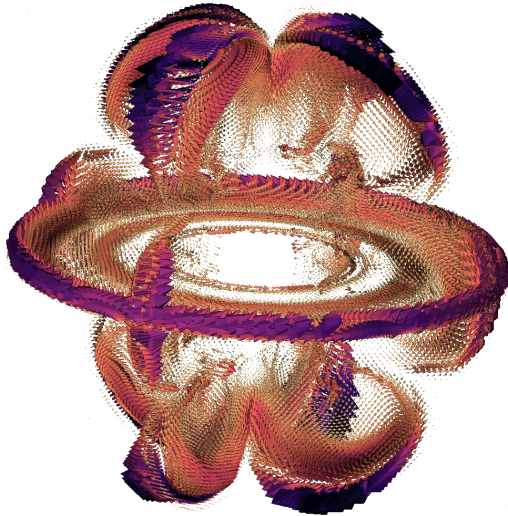
detonates  
(magnetic shell)



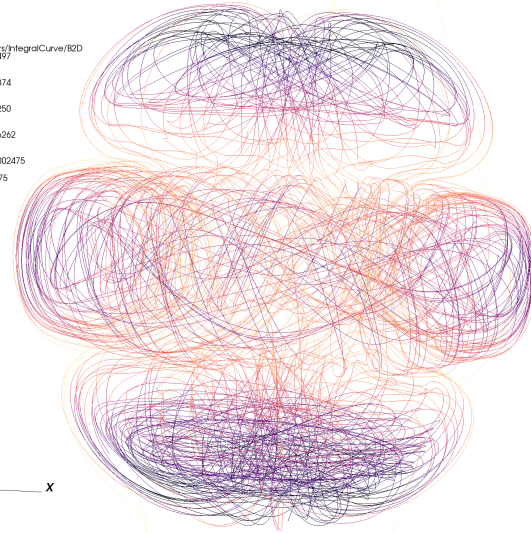


# Higher order (more tangled)

Vector  
Var: j  
2.2  
1.7  
1.1  
0.55  
1.5e-10  
Max: 2.2  
Min: 1.5e-10



Pseudocolor  
Var: operators/IntegralCurve/B2D  
0.2497  
0.1874  
0.1250  
0.06262  
0.0002475  
Max: 0.2497  
Min: 0.0002475

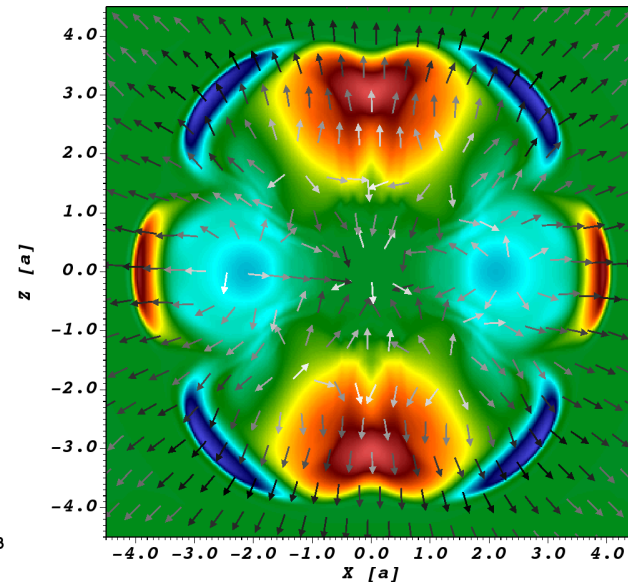


0.031  
0.0050  
0.074  
0.018  
Pseudocolor  
Var: operators/IntegralCurve/B2D  
0.51

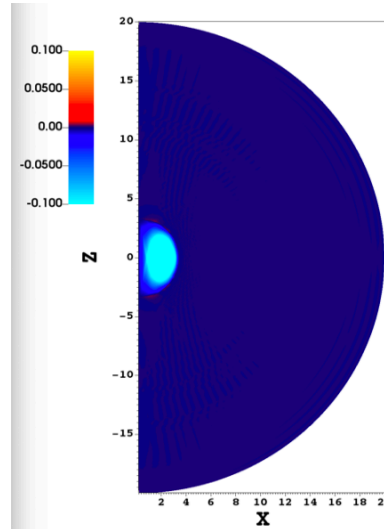
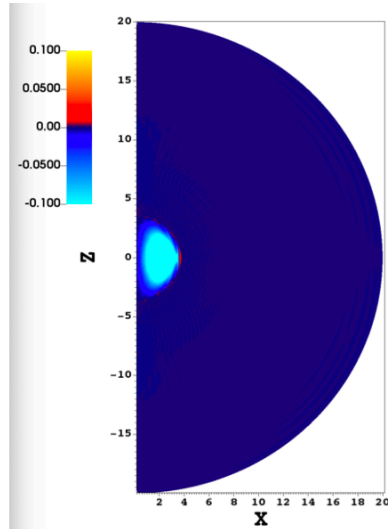
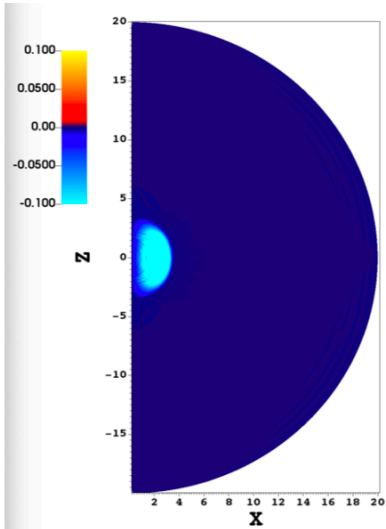


Pseudocolor  
Var: Bz  
0.20  
0.11  
0.031  
-0.051  
-0.13  
Max: 0.20  
Min: -0.13

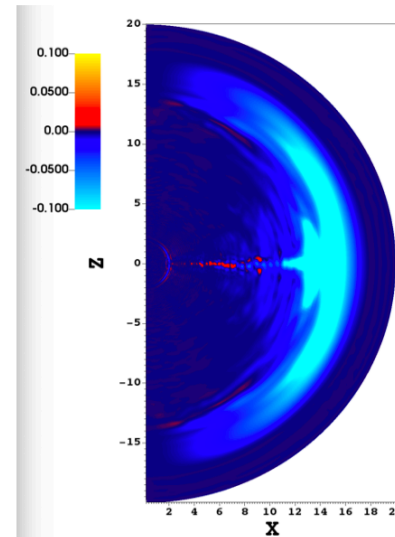
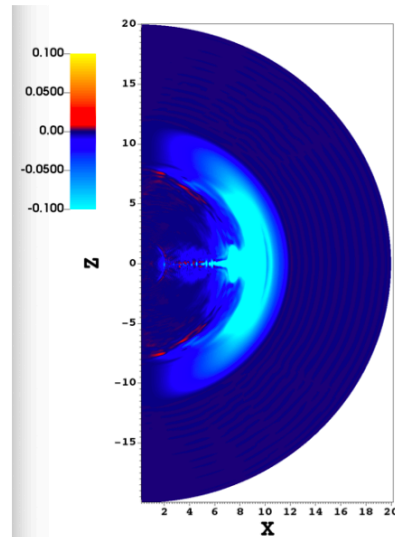
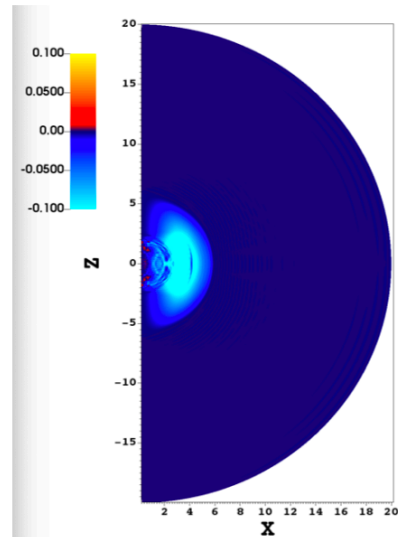
Vector  
Var: V3D  
0.78  
0.59  
0.39  
0.20  
-0.0058



# Magnetic bomb (force-free simulations with PHAEDRA)



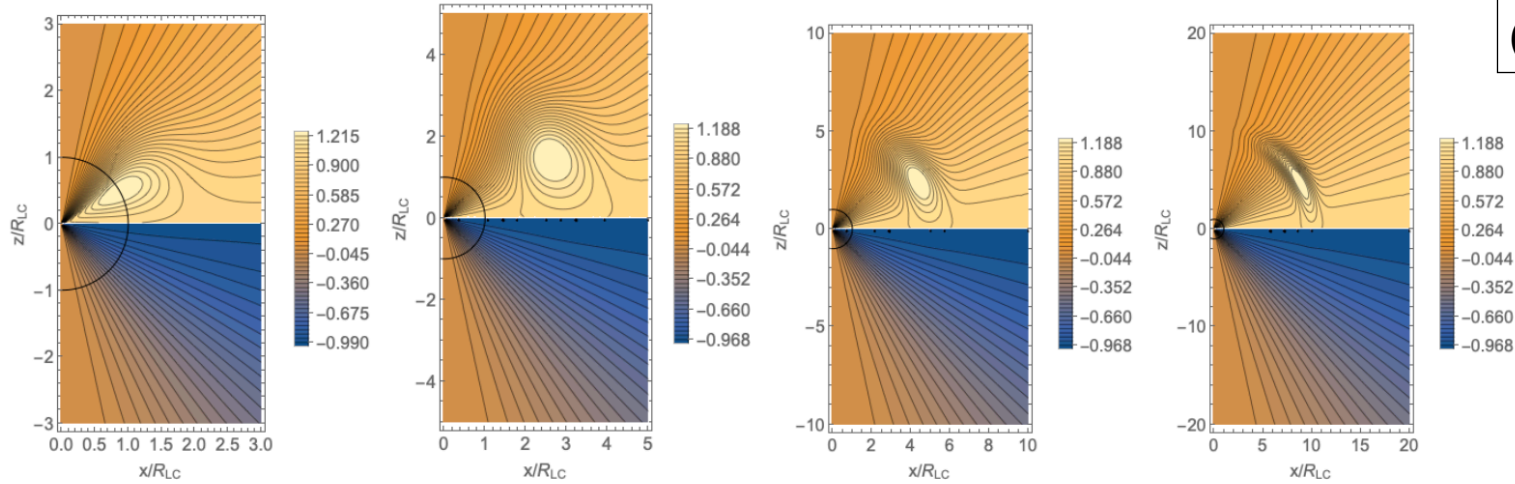
puffs-up



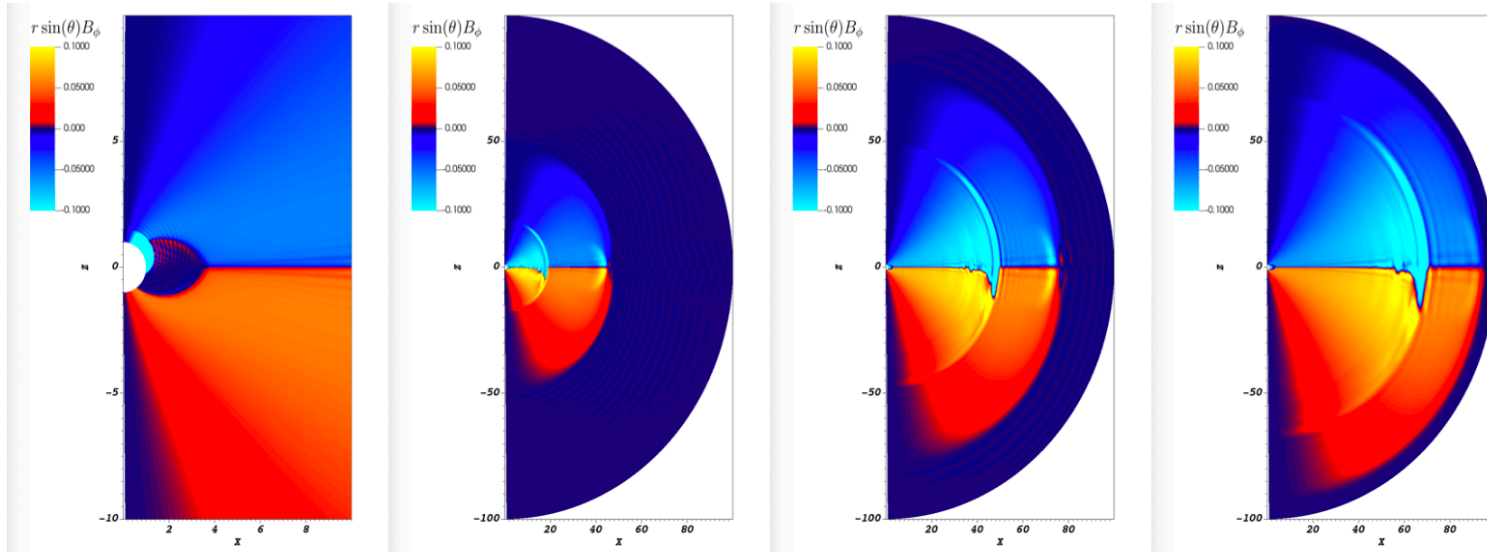
detonates

# 3.a CME in the wind - locally jerked magnetosphere

Sharma+ in prep

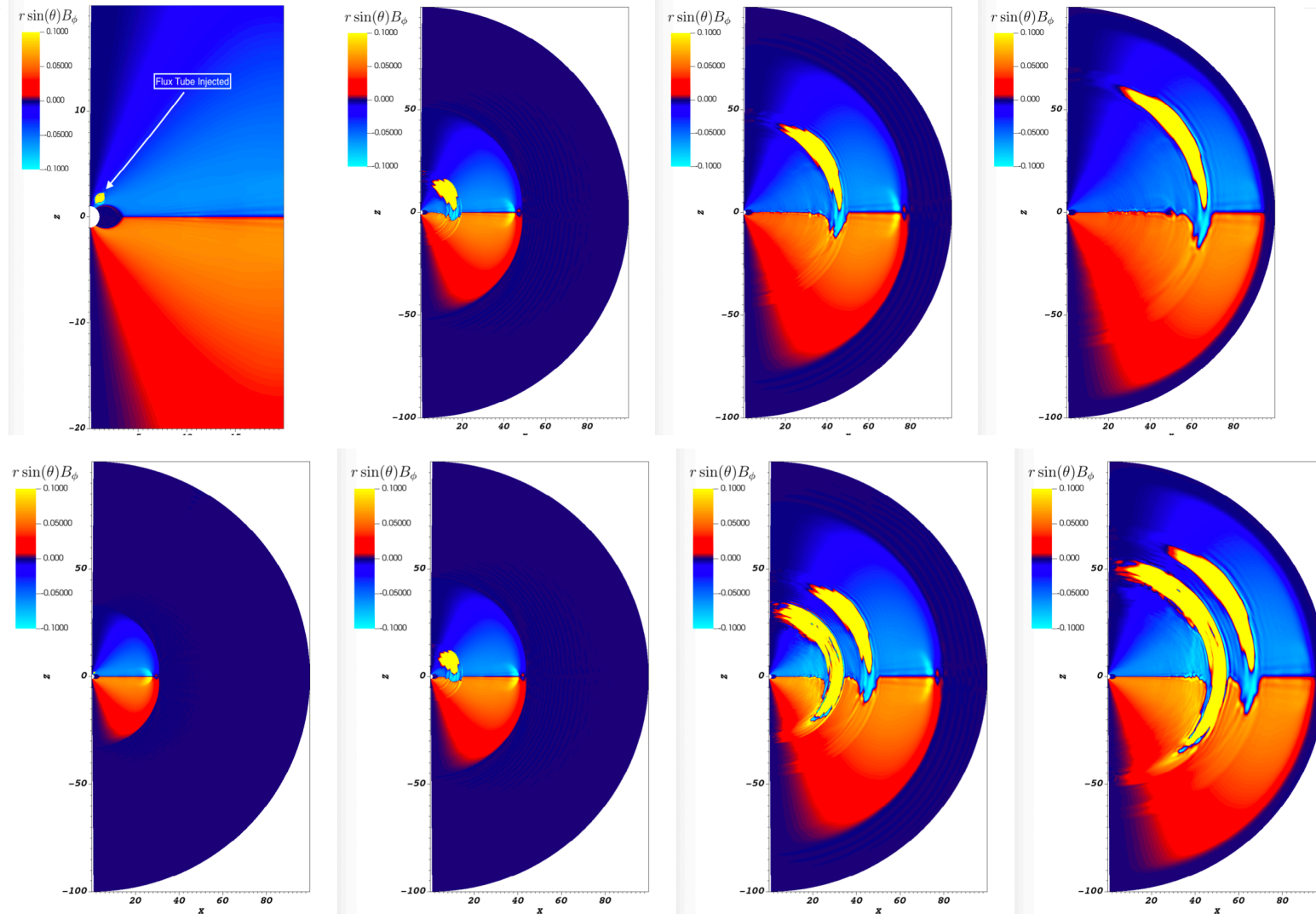


(analytical)



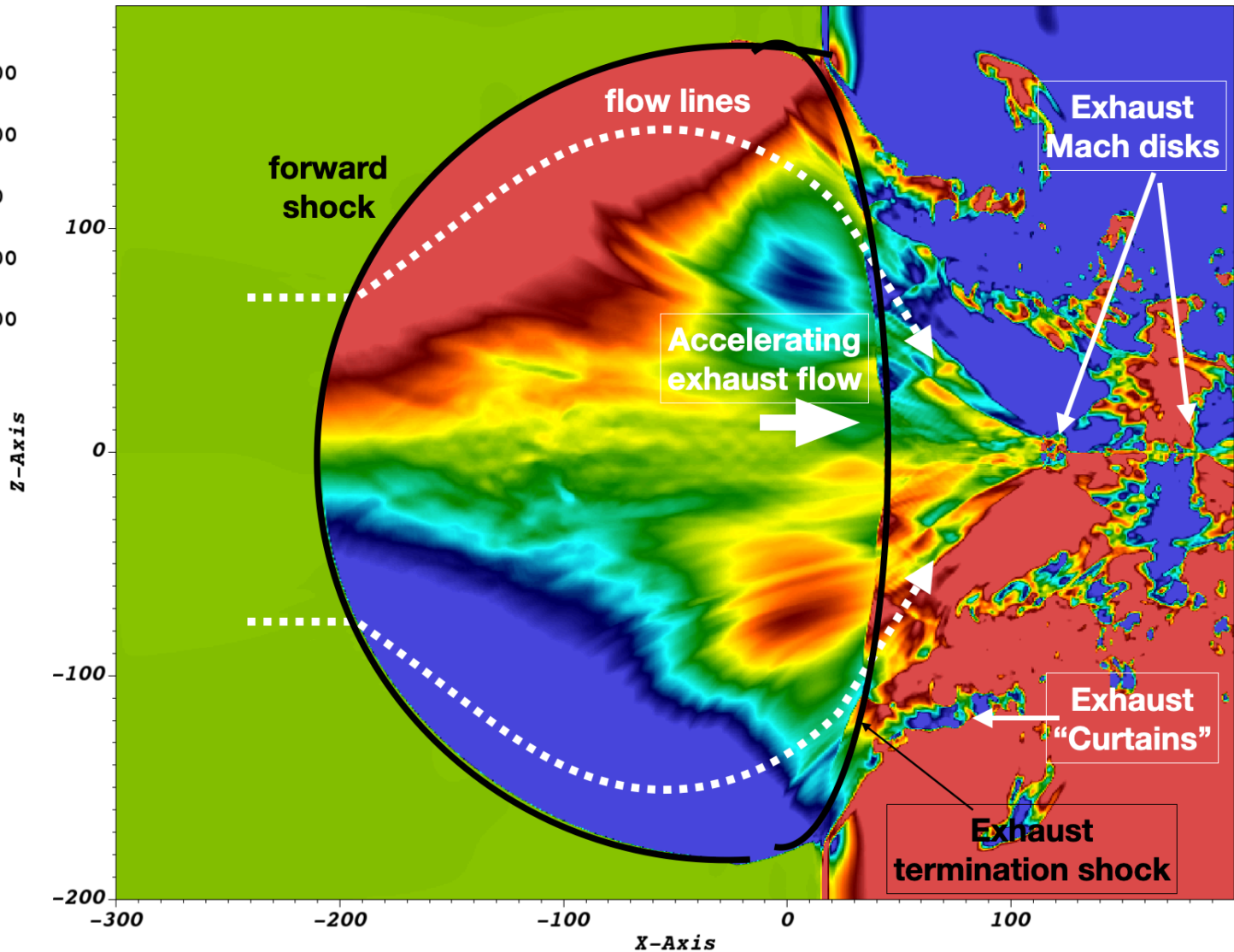
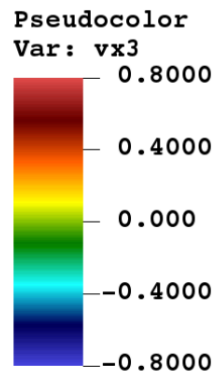
force-free

# 3.b CME in the wind ejected flux tubes



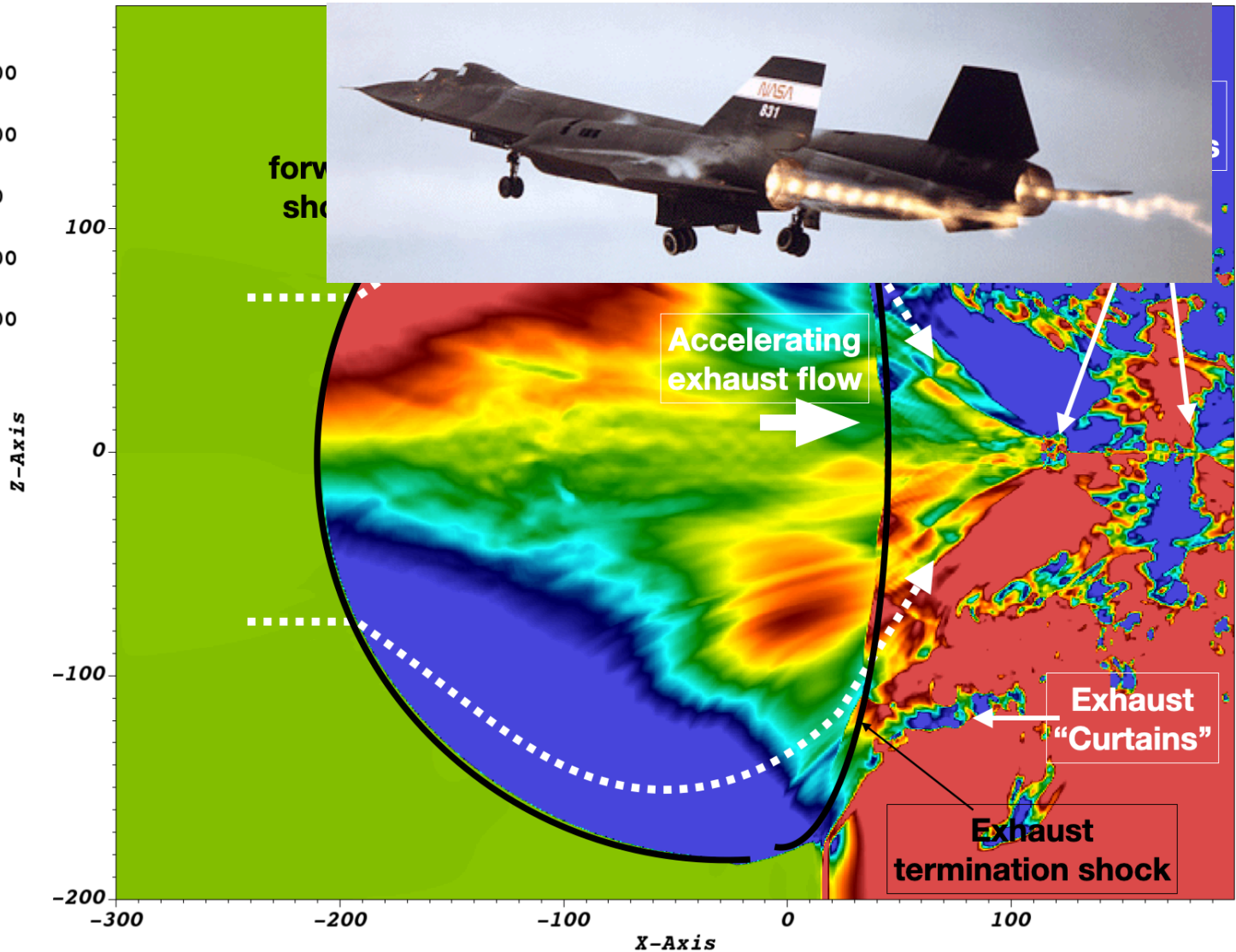


# 4. Relativistic CME: late-life, the crash (SGR afterglow) (Mehta + 2021)

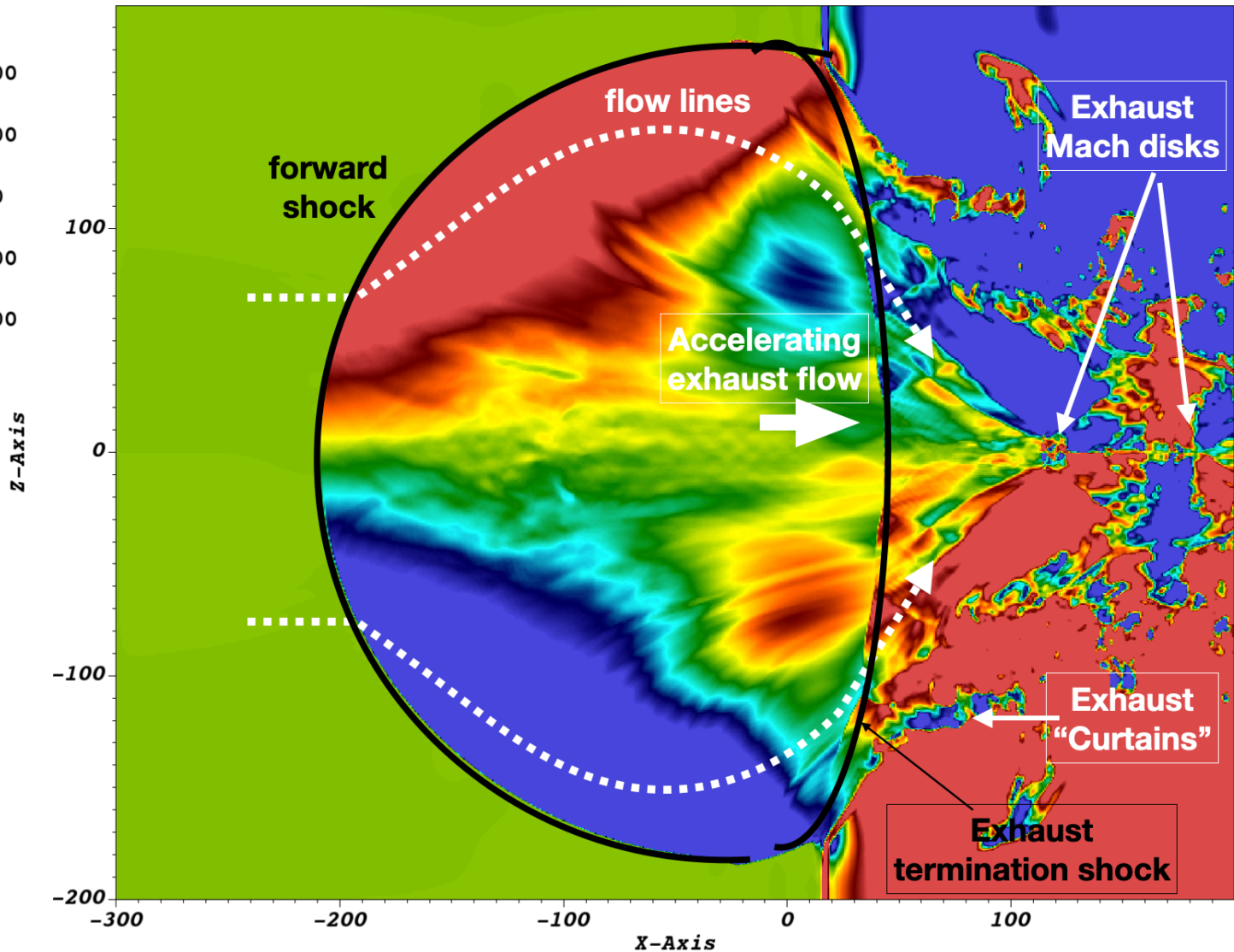
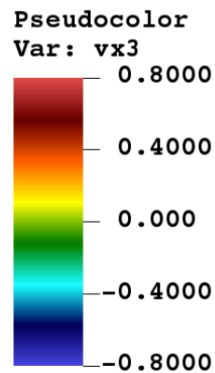


# 4. Relativistic CME: late-life, the crash (SGR afterglow) (Mehta + 2021)

Pseudocolor  
Var: vx3  
0.8000  
0.4000  
0.000  
-0.4000  
-0.8000

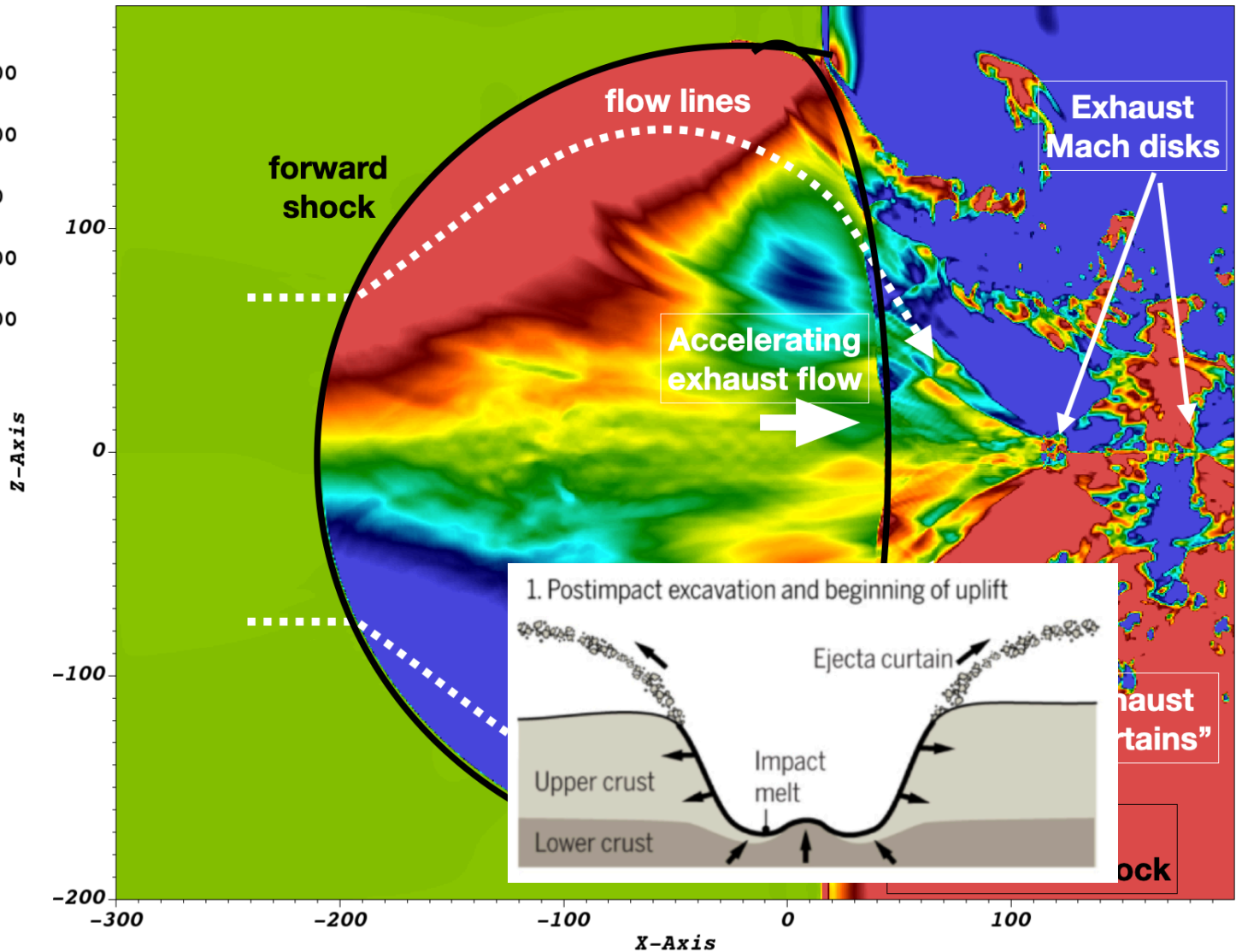


# 4. Relativistic CME: late-life, the crash (SGR afterglow) (Mehta + 2021)



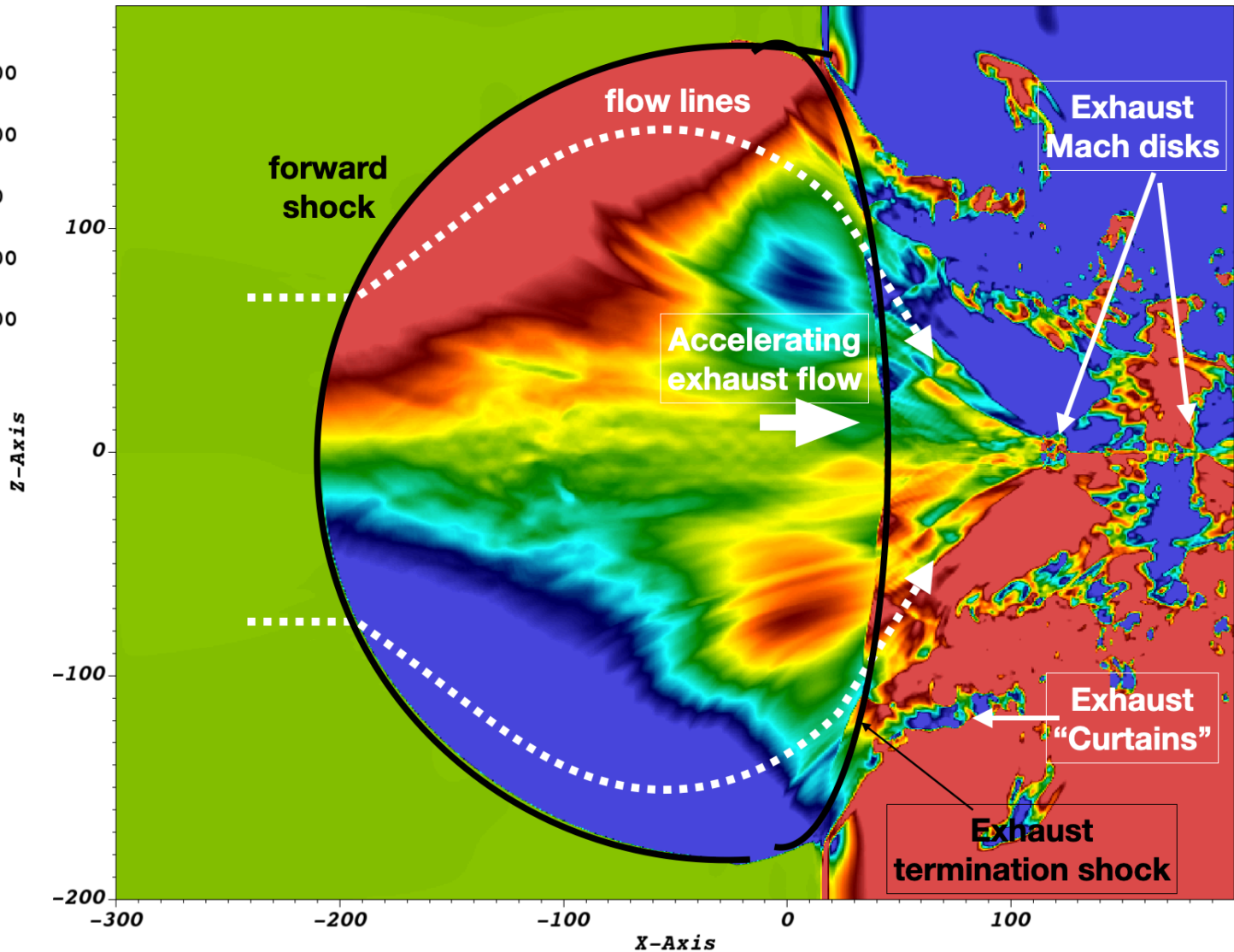
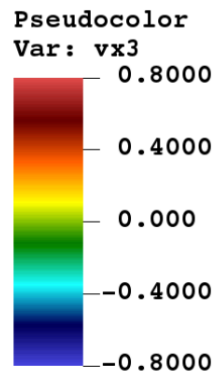
# 4. Relativistic CME: late-life, the crash (SGR afterglow) (Mehta + 2021)

Pseudocolor  
Var: vx3  
0.8000  
0.4000  
0.000  
-0.4000  
-0.8000

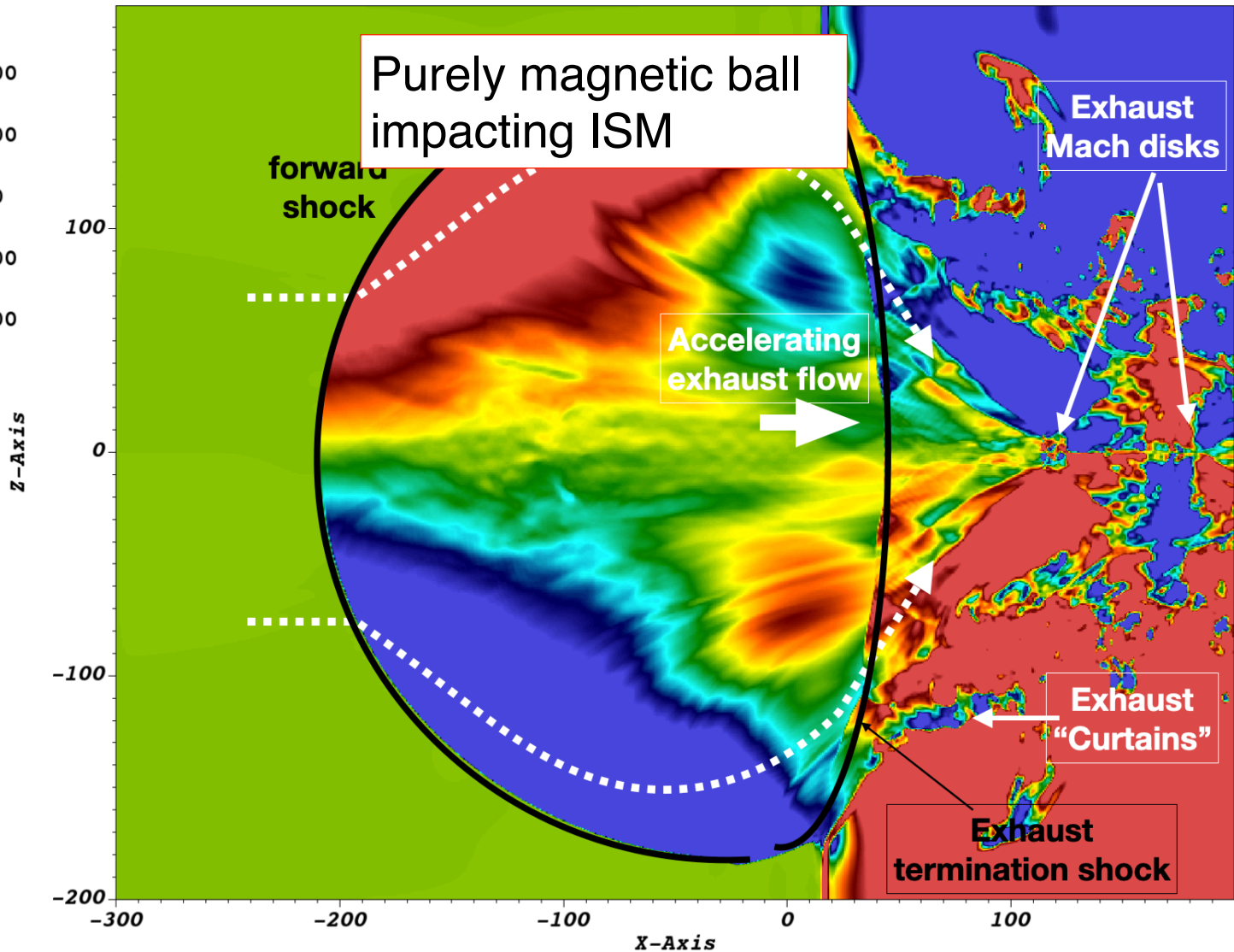
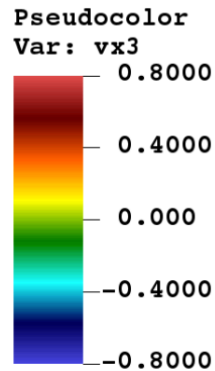




# 4. Relativistic CME: late-life, the crash (SGR afterglow) (Mehta + 2021)



# 4. Relativistic CME: late-life, the crash (SGR afterglow) (Mehta + 2021)



# Conclusion

- Magnetic explosions are different from fluid: conservation of magnetic flux!
  - c.f. sigma problem in pulsar winds
  - magnetic pressure along B-field is negative
- (relativistic) Solar flares
  - light cylinder is important
  - location of shear is important
- Threshold for becoming causally disconnected
- Mostly just EM pulse, not a strong shock
- Afterglows: magnetically dominated ball interacting with ISM