Forecasting a CME's Altered Trajectory: ForeCAT

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Latitudinal Deflections

- Latitudinal CME deflection first measured by Skylab and SMM coronagraph (MacQueen et al. 1986)
- During solar minimum CMEs deflect latitudinally toward solar equator from polar coronal holes (CHs)
  - Fast solar wind (Cremades & Bothmer 2004)
  - CH magnetic fields (Kilpua et al. 2009)

Observations and Models of Deflection

- Deflections close to surface of Sun
  - Longitudinal deflections observed using multiple spacecraft and 3D reconstruction
  - A few degrees to ~30˚ within ~10-20 Rs (Byrne et al. 2010, Liu et al 2010)
- MHD model shows 2005 August 22 CME deflecting 10˚ within 5 R_s due to magnetic forces (Lugaz et al. 2011)
  - Expect additional deflection if captured slow rise

Suggested Causes of Deflection

- Reconnection on a side of a CME (Lugaz et al. 2011)
- Influence parameter of a CH based on CH size, magnetic strength, and distance (Gopalswamy et al. 2009, 2010)
- Gradients in magnetic pressure (Shen et al. 2011, Gui et al. 2011)

Basics of ForeCAT

- Both components of Lorentz force act upon CME altering its path
  - Ignore non-magnetic sources of deflection (interactions with other CMEs, fast solar wind)
  - No reconnection
- Treat CME as a rigid flux-rope-like structure
- Look at cross section in 2 dimensional "deflection plane"
- Radial propagation and CME expansion independent from deflection forces

Deflection Plane

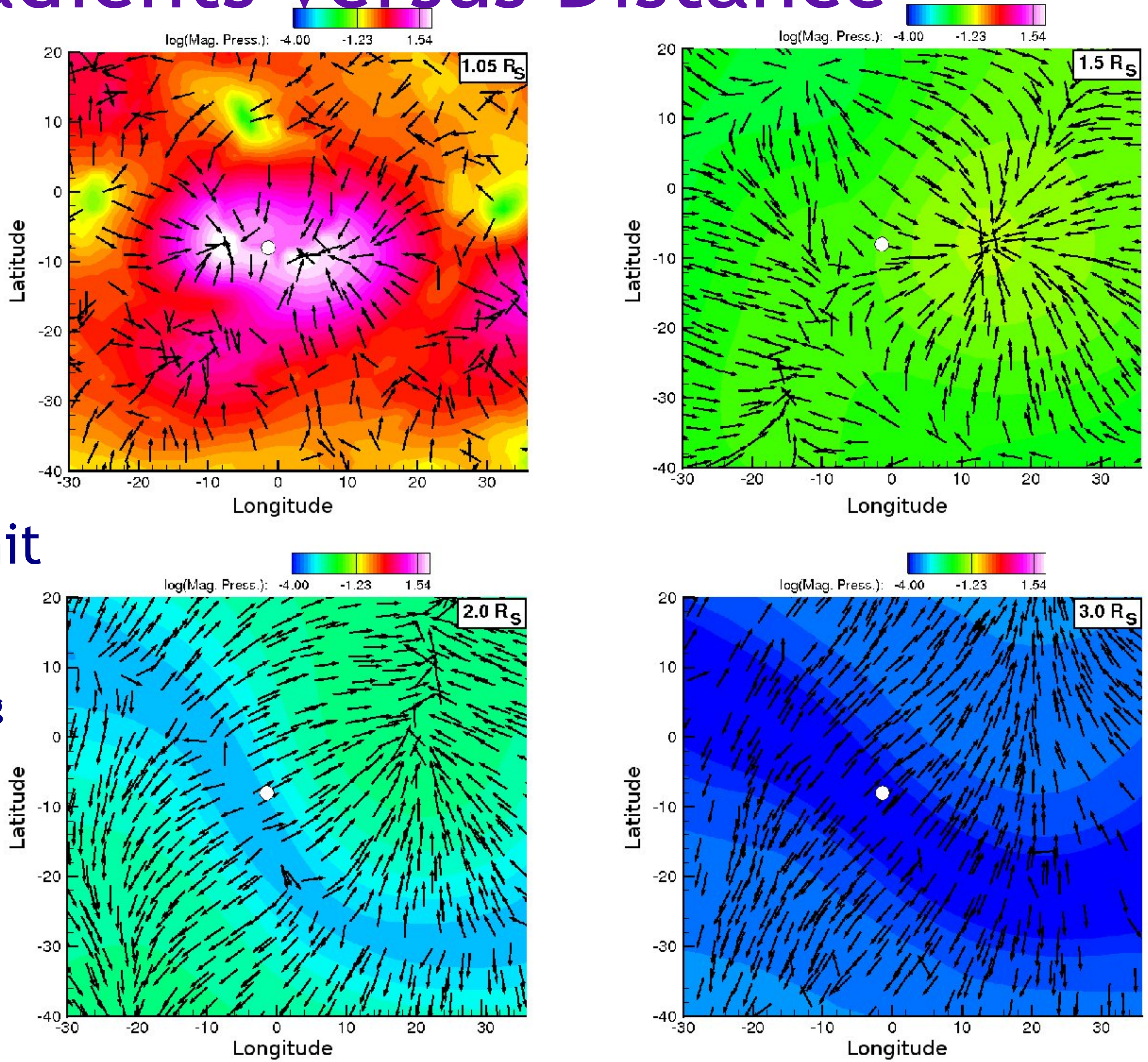
- Deflection plane defined using initial radial direction and direction of maximum global magnetic pressure gradients

$$\vec{n} = \vec{R}_0 \times \frac{-\vec{\nabla} B^2}{8\pi}$$

  - Radial vector determined by initial latitude and longitude
  - Use gradient vector at a point in space $\longrightarrow$ need to pick a height

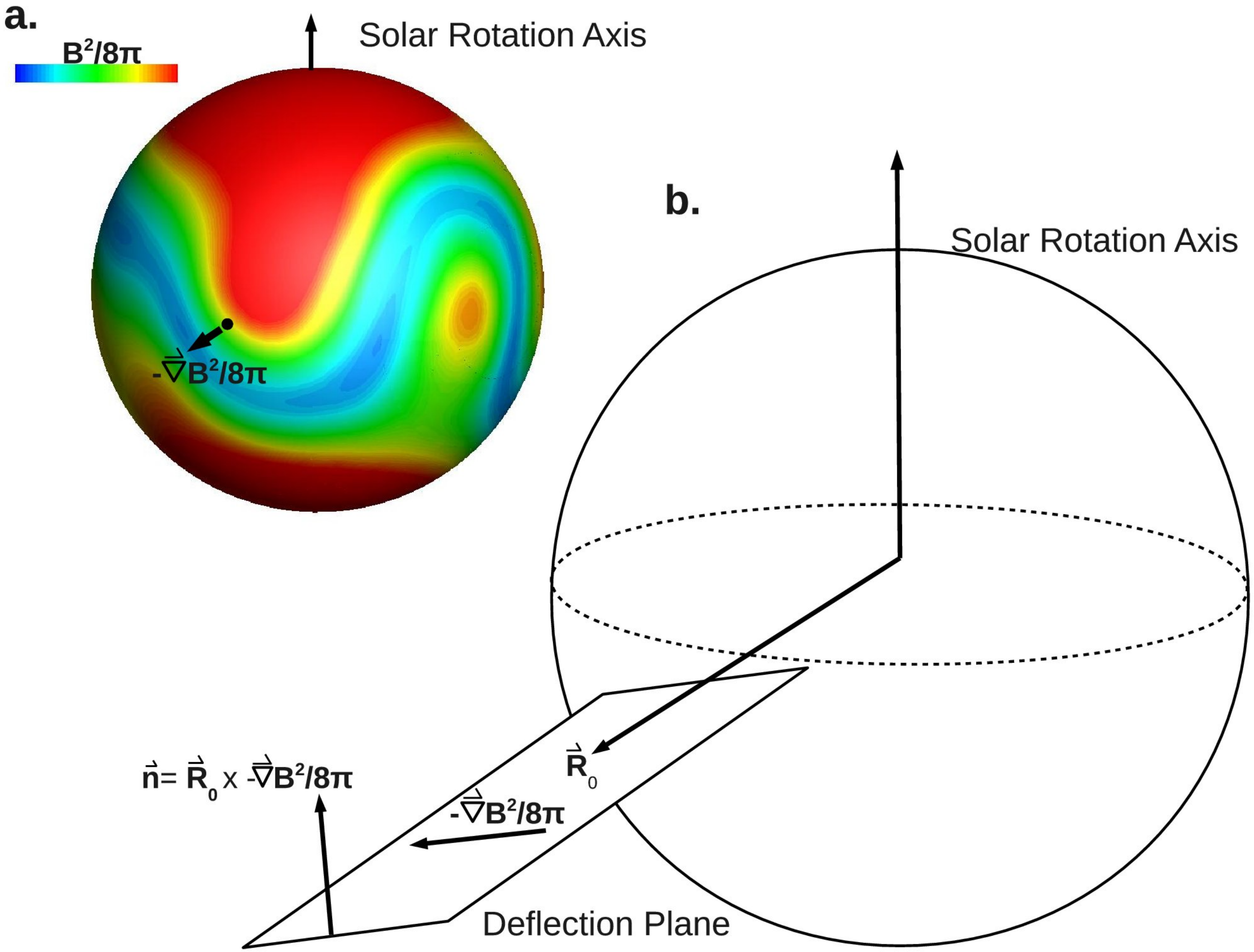
Gradients versus Distance

- Color contours = $\log(P_{mag})$
- Vectors = unit vectors showing P_{mag} gradient

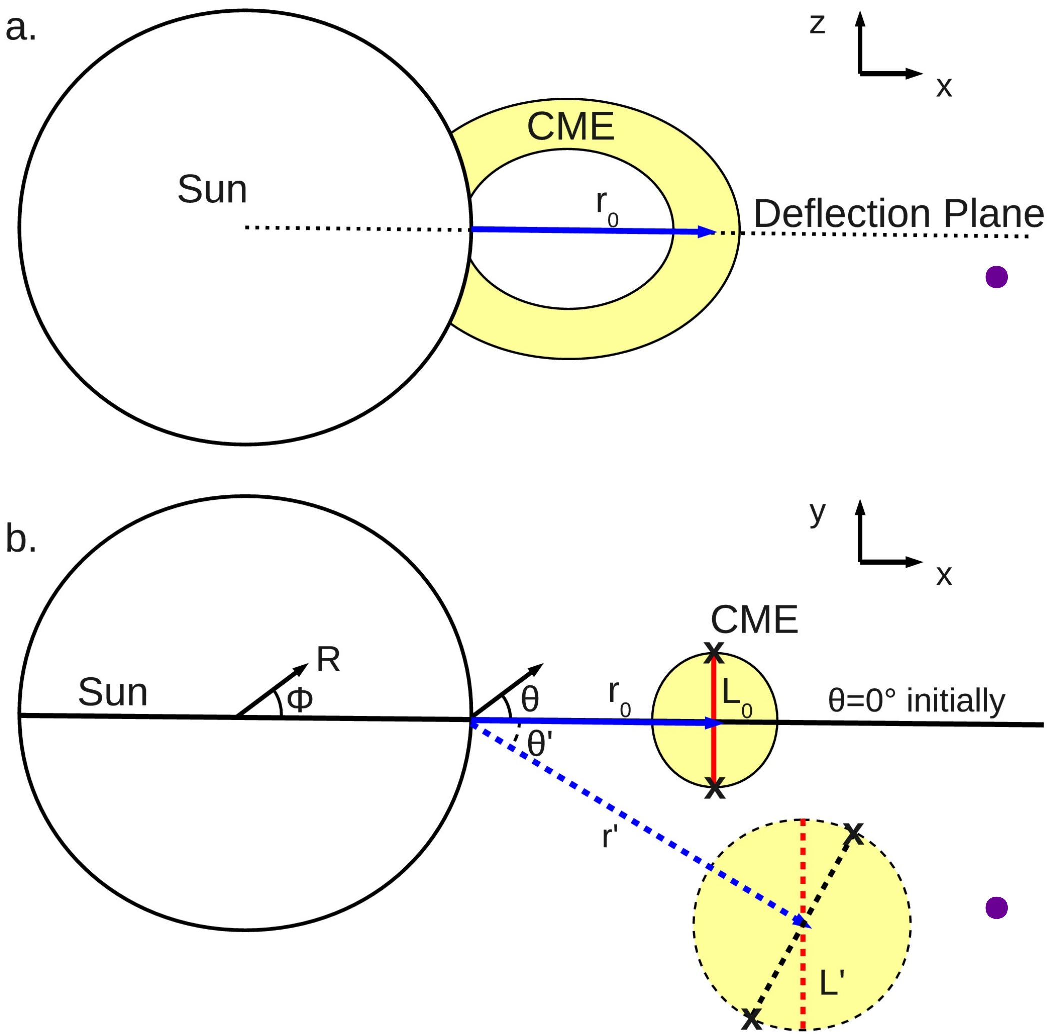


Deflection Plane

- Use gradients at 2 R_S – closest distance where global effects dominate



Advancing CME Parameters in Time



- Calculate forces on two edges and sum to find net force on CME: θ ⟶ θ'
- Update CME radius independently using Melon Seed OverExpansion equation (Siscoe et al. 2006): L ⟶ L'
- Three phase radial propagation (Zhang et al. 2001): r ⟶ r'

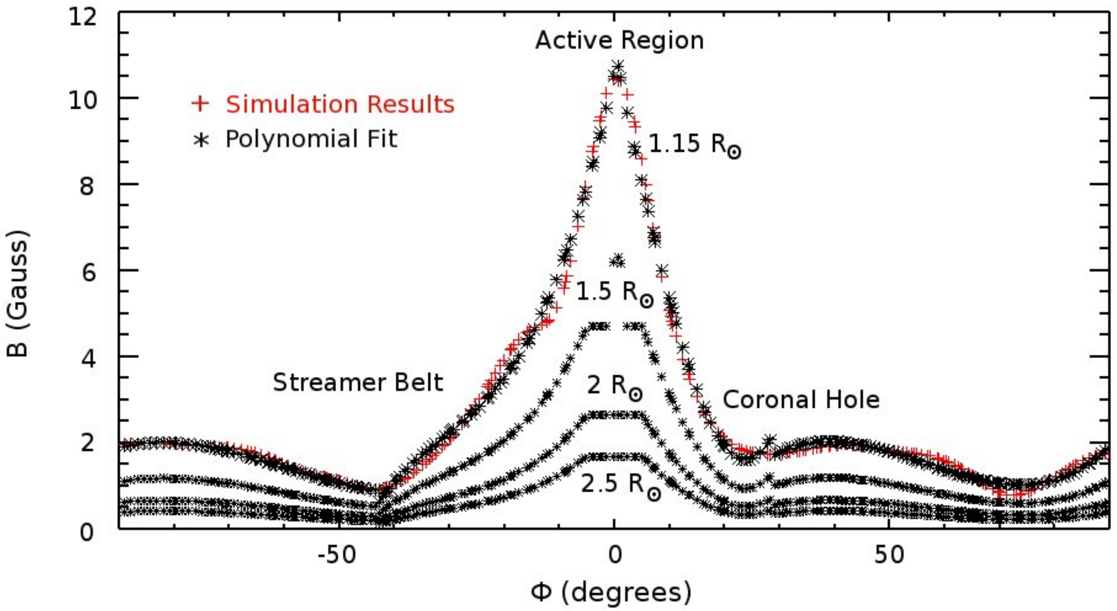
Two Contributions to Deflection

- Magnetic Tension Force
  - Assume background magnetic field drapes around CME $\longrightarrow$ curvature equal to curvature of CME
- Magnetic Pressure Gradients
  - Influence of CHs and streamer belts

$$F = \rho a = \kappa \frac{B^2}{4\pi} - \frac{\nabla_\perp B^2}{8\pi} = \frac{1}{L} \frac{B^2}{4\pi} - \frac{\partial B}{\partial \phi} \frac{B}{4\pi R}$$

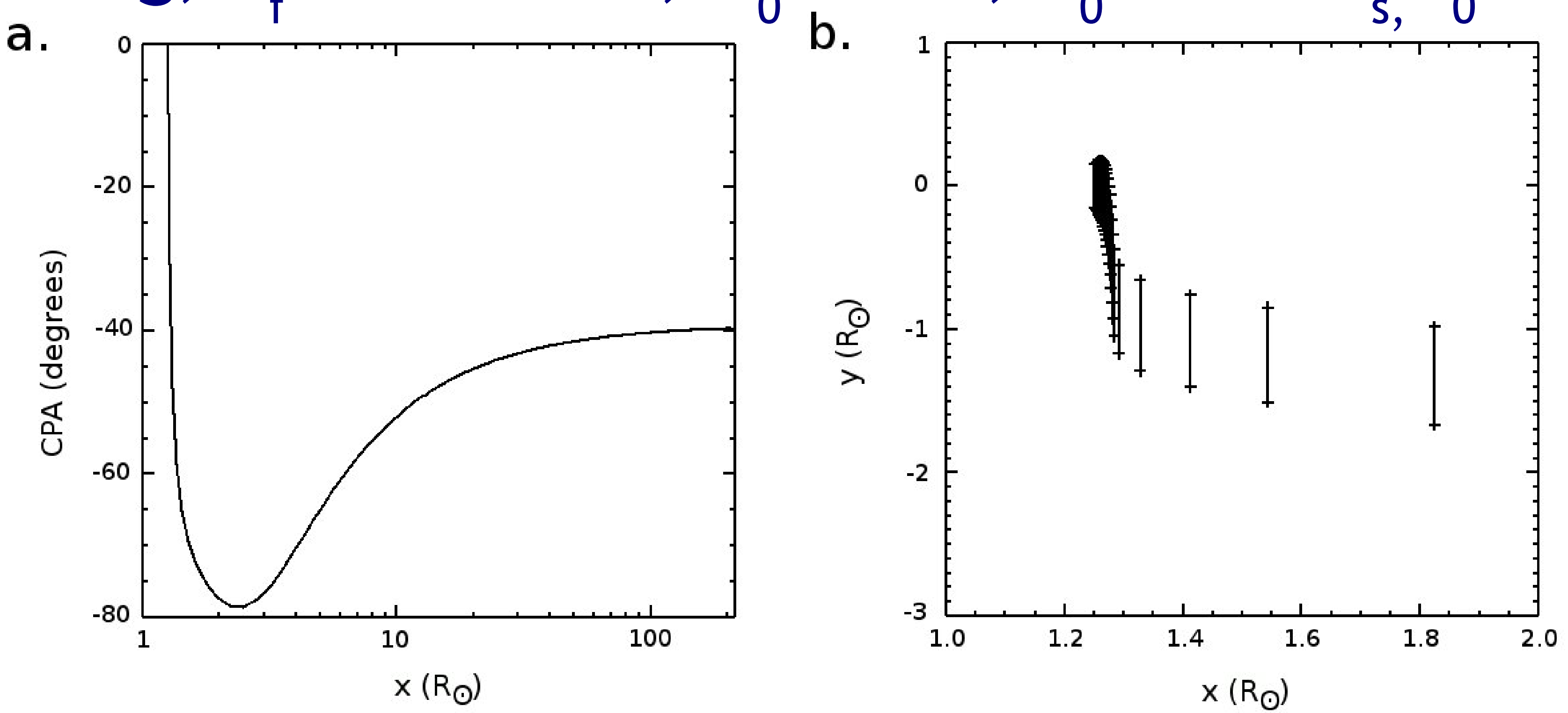
Magnetic Background for Test Case

- Obtain MHD steady state solar wind solution from Space Weather Modeling Framework (Toth et al. 2011) with Alfven wave driven solar wind with surface Alfven wave damping (Evans et al. 2012)
- Fit multiple polynomials to $B(\Phi, R=1.15\ R_s)$
- Scale to larger R using R^{-3} near AR (dipole) and R^{-2} otherwise (Mann et al. 2003)



ForeCAT Results for Test Case

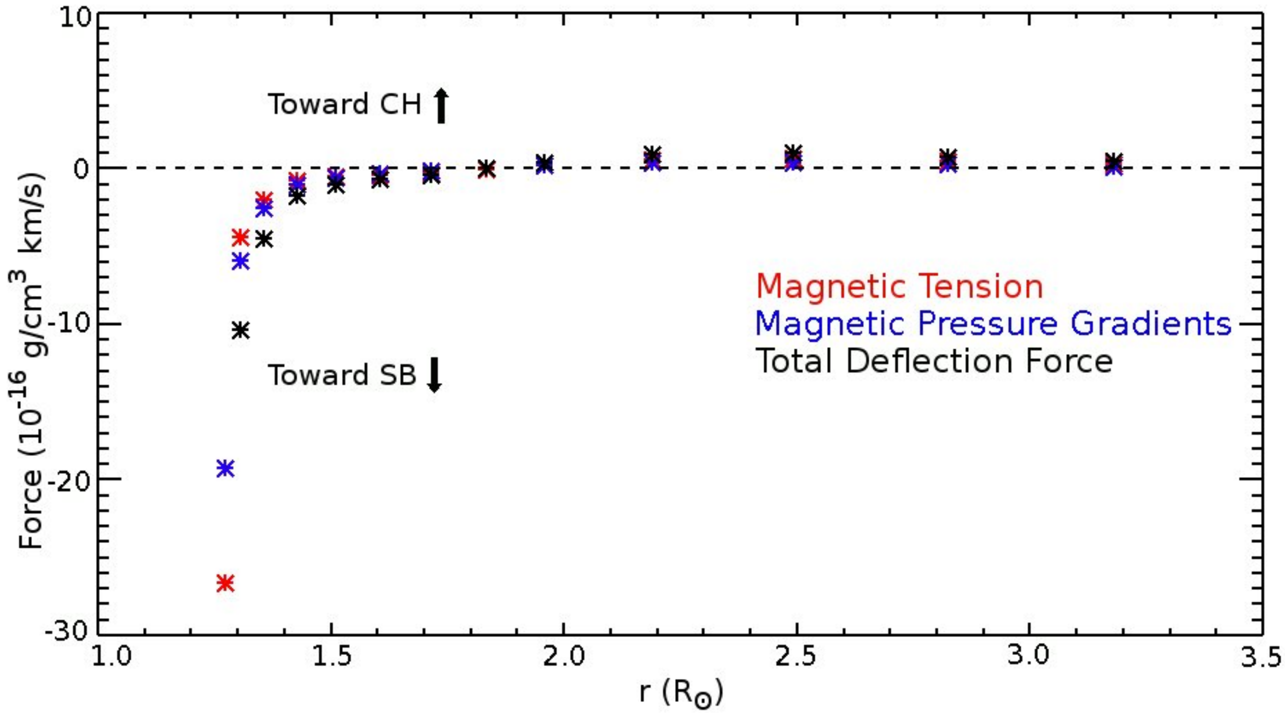
- CR 2029 (April 21-May18 2005), AR 0758 → located between SB and CH
  - Expect strong deflections
- $M=10^{15}$ g, $v_f=475$ km/s, $B_0=10$ G, $L_0=0.15\ R_s$, $r_0=0.25\ R_s$

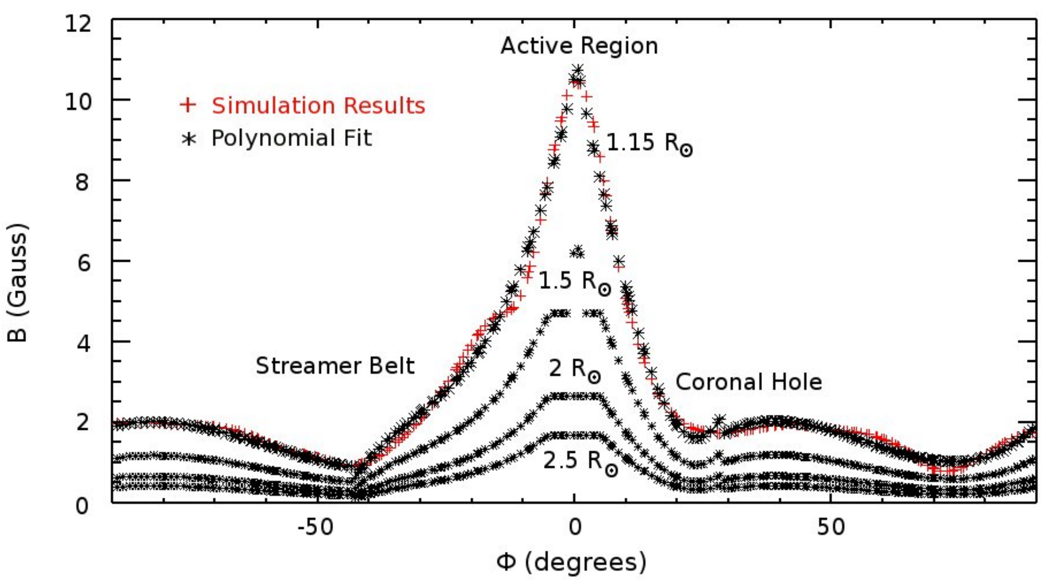


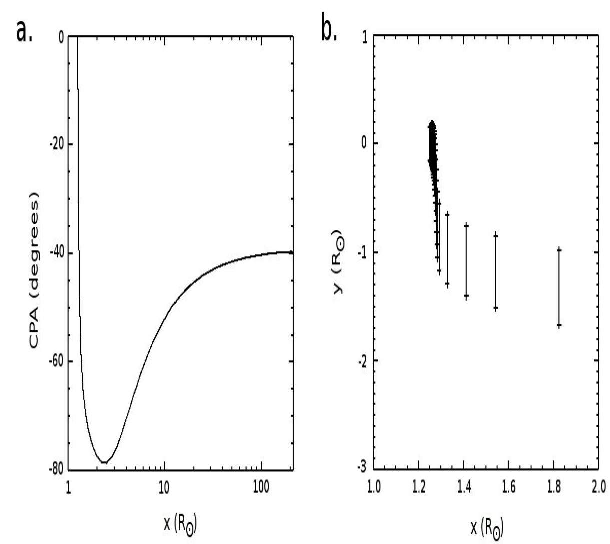
- Deflects 39.7° → 36.0° in latitude, 19.3° in longitude

Total Deflection Forces

- Initially pushed away from CH toward SB
- Reaches point where an edge crosses minimum in B

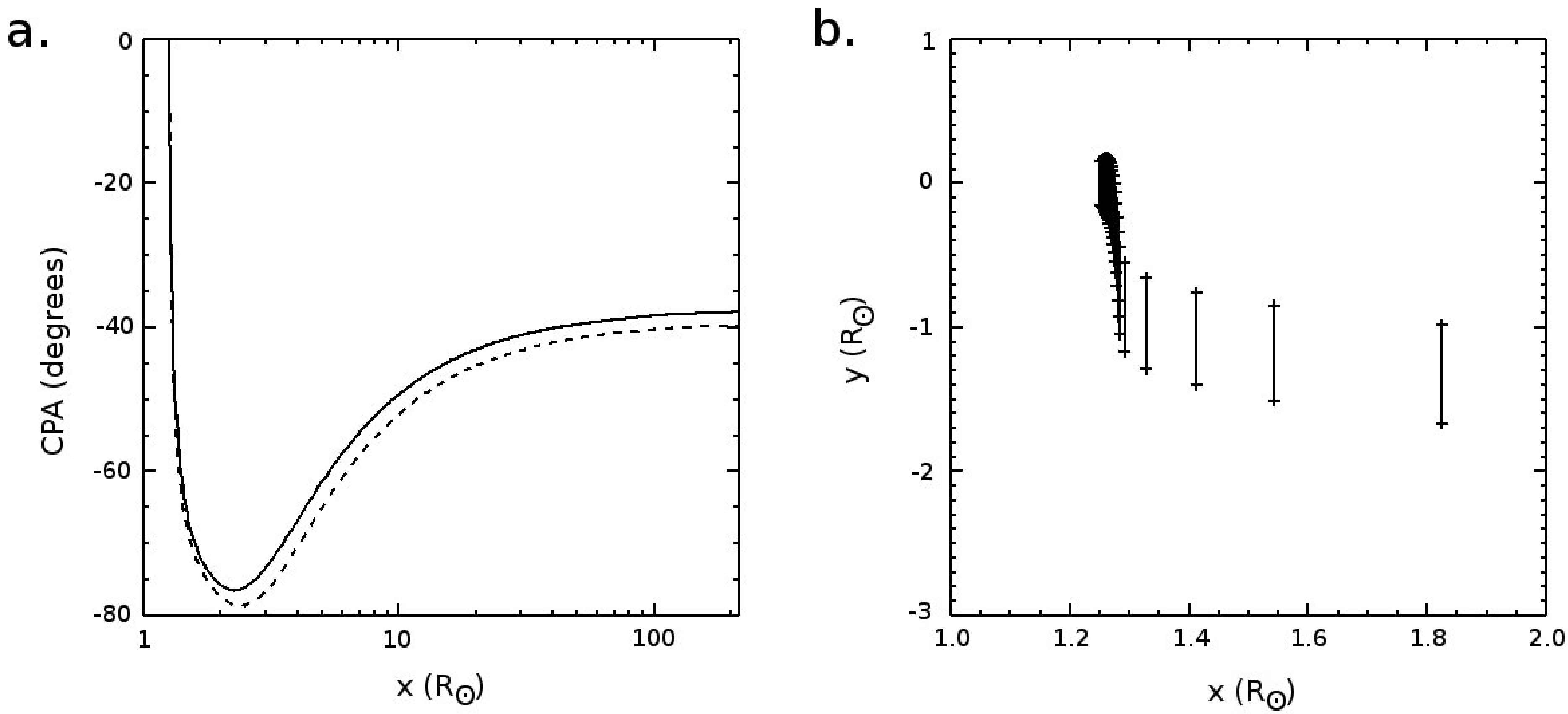




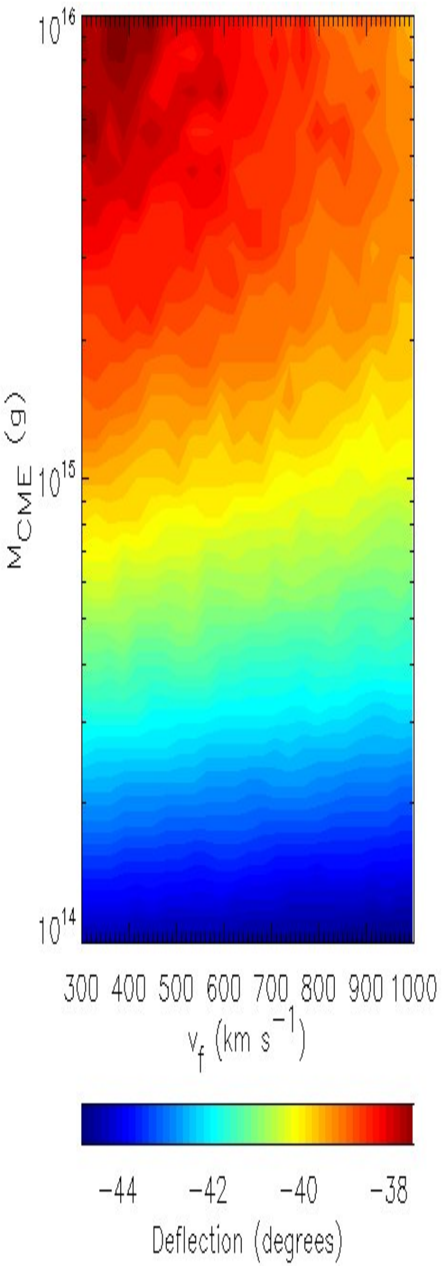


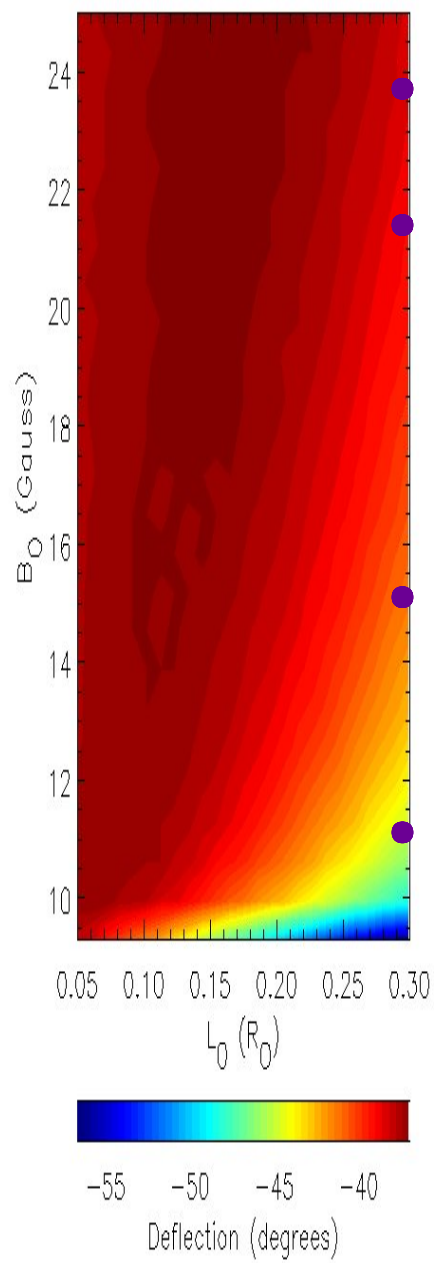
Trajectory for High Mass Case

- Increase mass by order of magnitude, all other parameters same $\longrightarrow$ 37.8° deflection (1.9 less than control)



Mass and Velocity Sensitivity

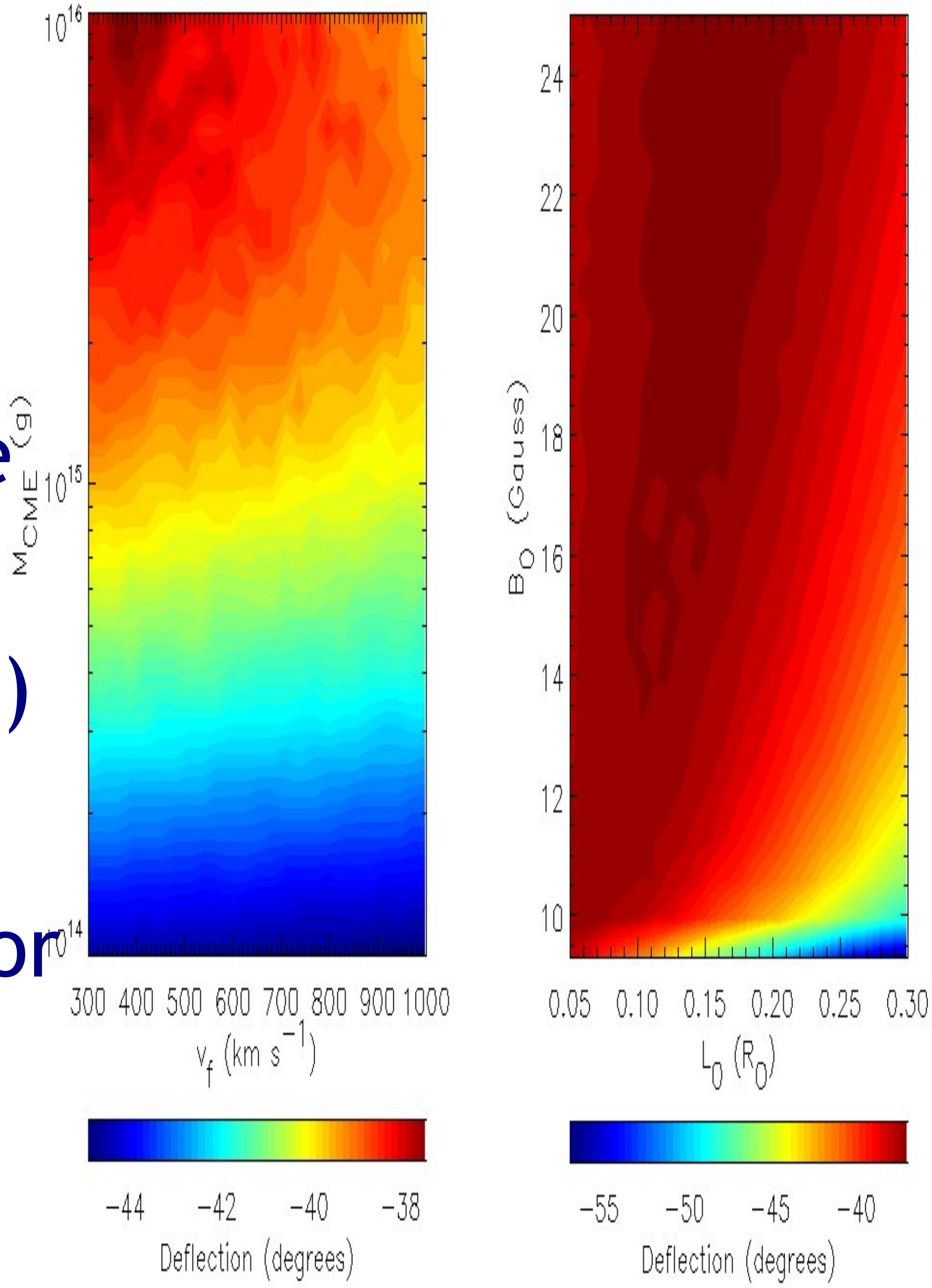




- Trends for our background
- Run 25x25 CMEs
  - Mass: 10^{14} to 10^{16} g
  - Velocity: 300 to 1000 km/s
- More massive → less deflection
- Faster → less deflection
  - Not as sensitive as mass

Initial Size and Mag. Field Sensitivity

- B_0 : 9.3 to 25 G
- L_0 : 0.05 to 0.35 R_s
- Larger initial size $\longrightarrow$ more deflection
- Higher B_0 (more expansion) $\longrightarrow$ less deflection
- Most extreme deflection for initially large with little expansion



Active Region Effects

- Defined deflection plane to not include AR effects
  - Reasonable assumption?
  - Observationally known to affect prominences (Panasenco et al. 2010)
- Look at AR deflection plane defined using orientation of two opposite polarity flux systems of the AR

AR Effects

Title:newBAR.eps
Creator:GIMP PostScript file plugin V 1.
CreationDate:Wed Jan 16 15:01:56 2013
LanguageLevel:2

- Control CME launched near PIL $\longrightarrow$ 2.1 deflection out to 30 Rs
- More significant deflections if launched to side of AR
- Conclusion: Reasonable to look at only global gradients for CMEs near PIL

Conclusions

- See significant deflection of CMEs close to the surface of the Sun
  - Forces orders of magnitude smaller beyond 2-3 R_S
- More massive, faster, and larger CMEs tend to deflect less
- The effects of global magnetic gradients dominate those of local ones from CMEs launched near the PIL of an AR

Future Work

- Comparison to observations
  - 2008 December 12 CME : separate observations of both lat. and lon. def
- Run more background cases → investigate different coronal conditions and magnetic fall off
- Use higher resolution magnetogram of AR and investigate prominence rolling
- Make available for public use and space weather prediction