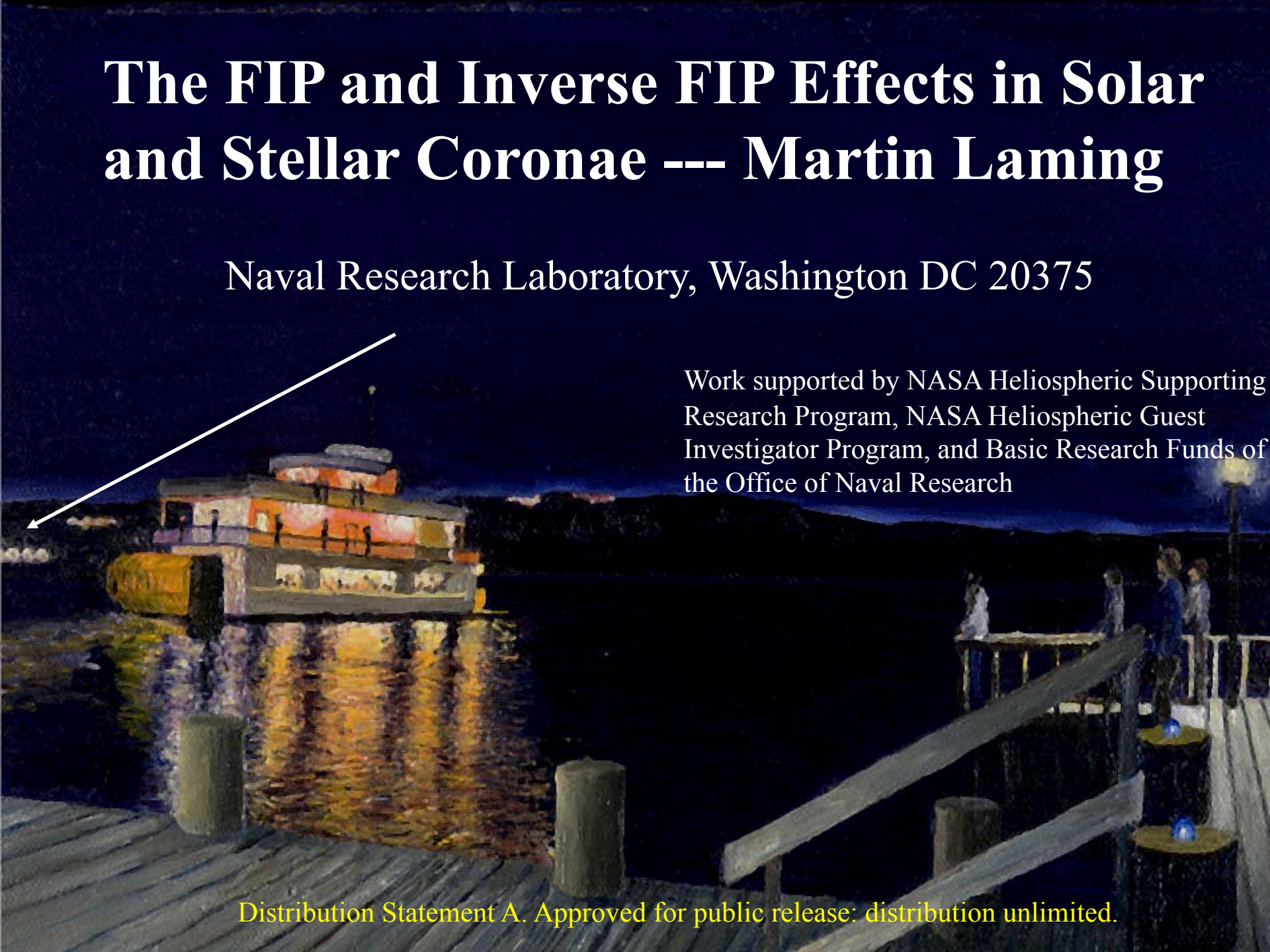


# The FIP and Inverse FIP Effects in Solar and Stellar Coronae --- Martin Laming

Naval Research Laboratory, Washington DC 20375

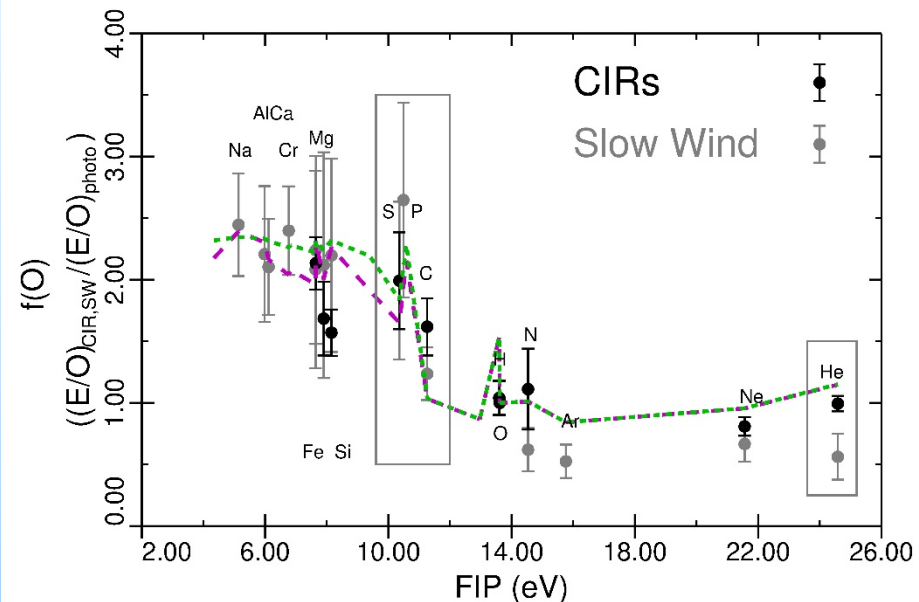
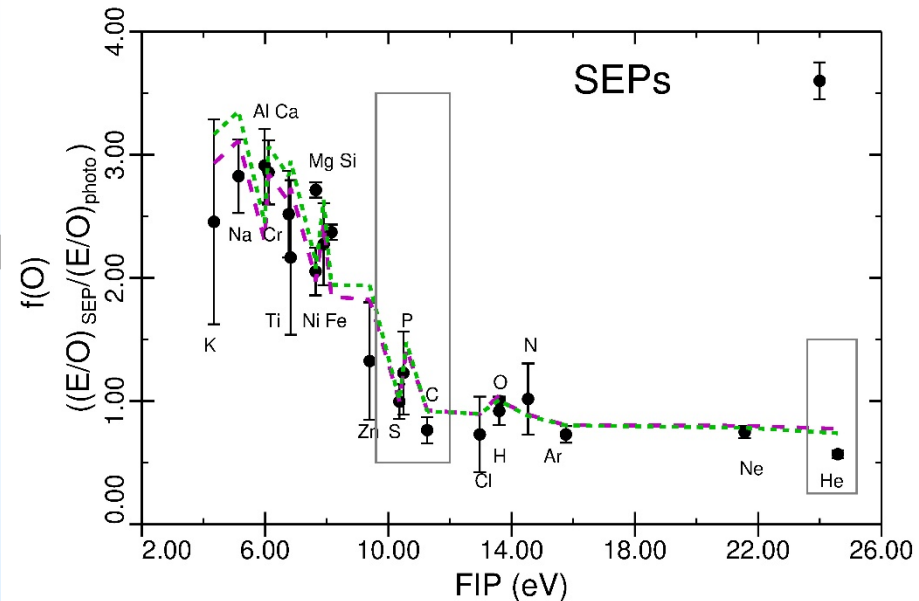
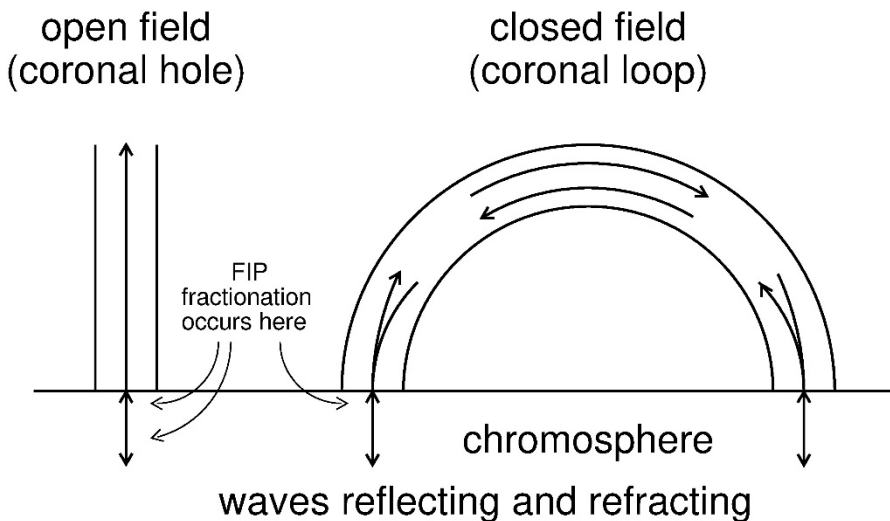
Work supported by NASA Heliospheric Supporting Research Program, NASA Heliospheric Guest Investigator Program, and Basic Research Funds of the Office of Naval Research

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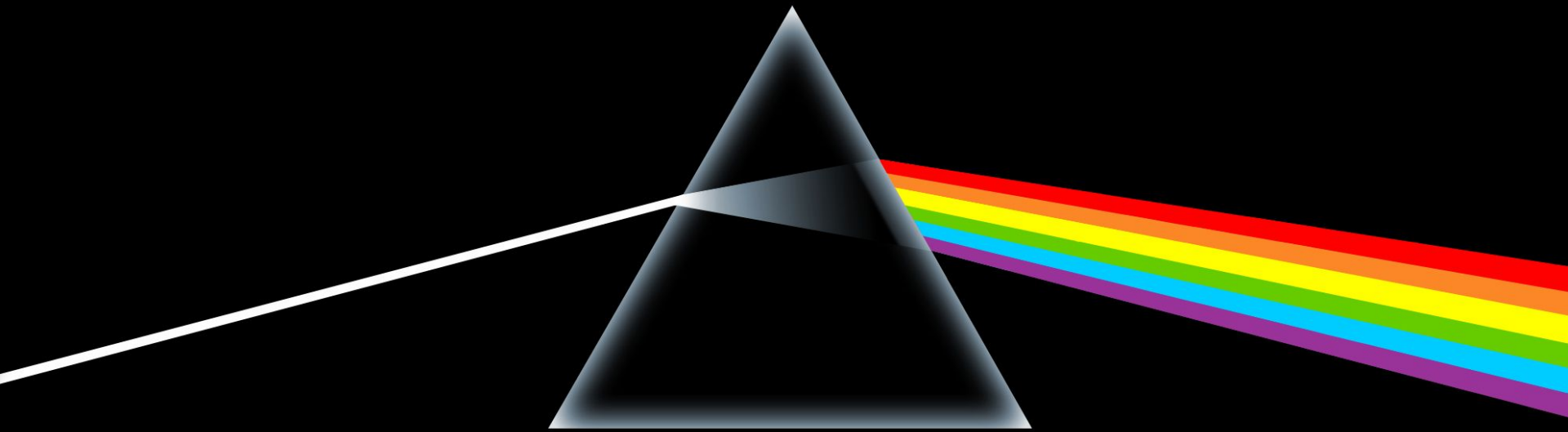
# First Ionization Potential Fractionation

- FIP Effect known (suspected) since Pottasch (1963, ApJ, **137**, 945).
- Now “understood” (Laming 2015, LRSP, **12**, 2; also 2004, 2009, 2012, 2017, 2019) as due to action of ponderomotive force in chromosphere.
- Most recent data from Reames 2018 Solar Phys. **293**, 47



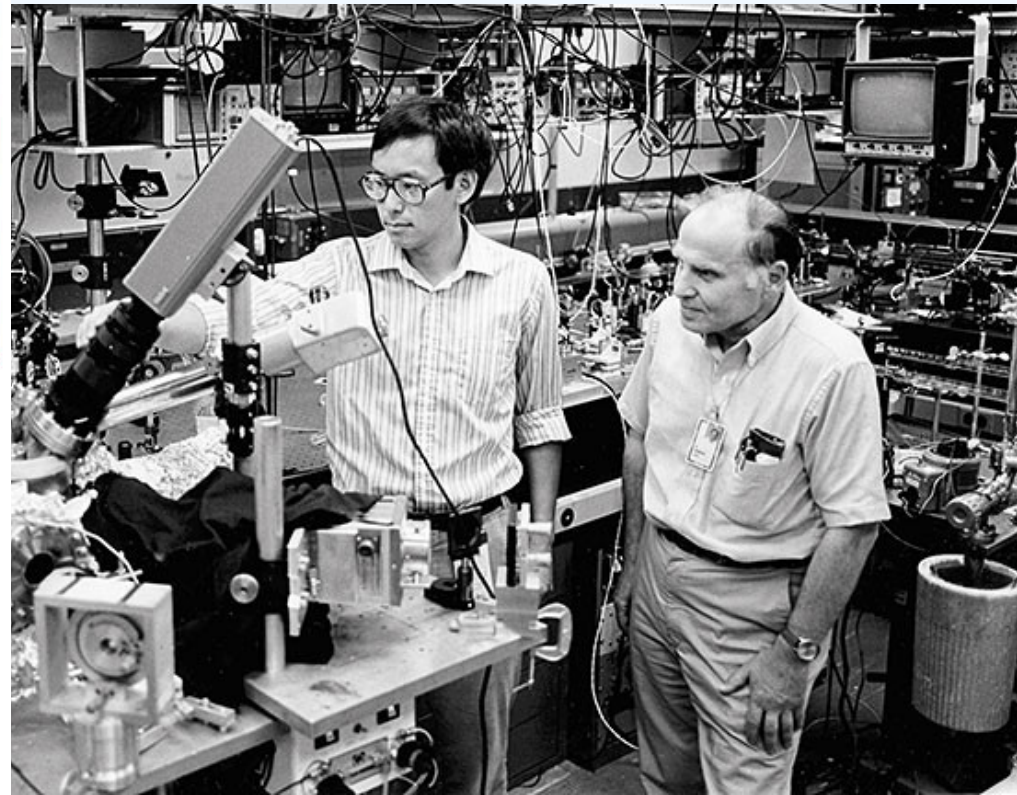
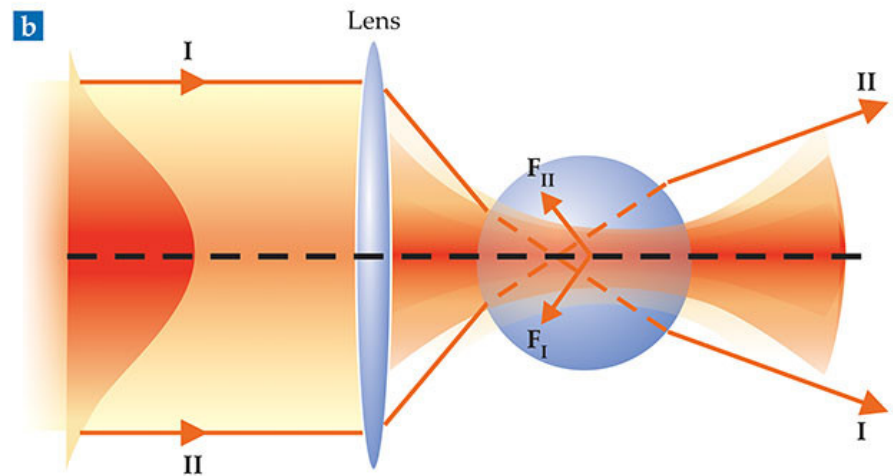
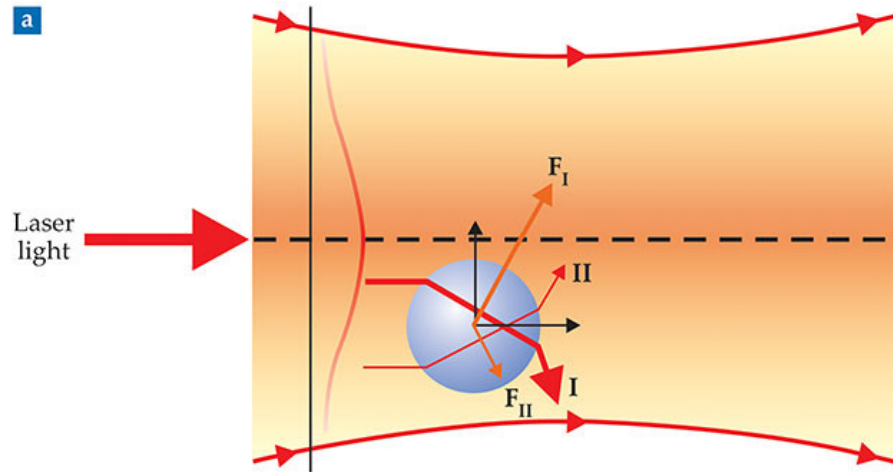
# Simple Case of the Ponderomotive Force

Which way does the prism move as the light refracts?



# Optical Analog; Laser Beam Particle Trapping

Steven Chu (Nobel Prize 1997) Arthur Ashkin (Nobel prize 2018)

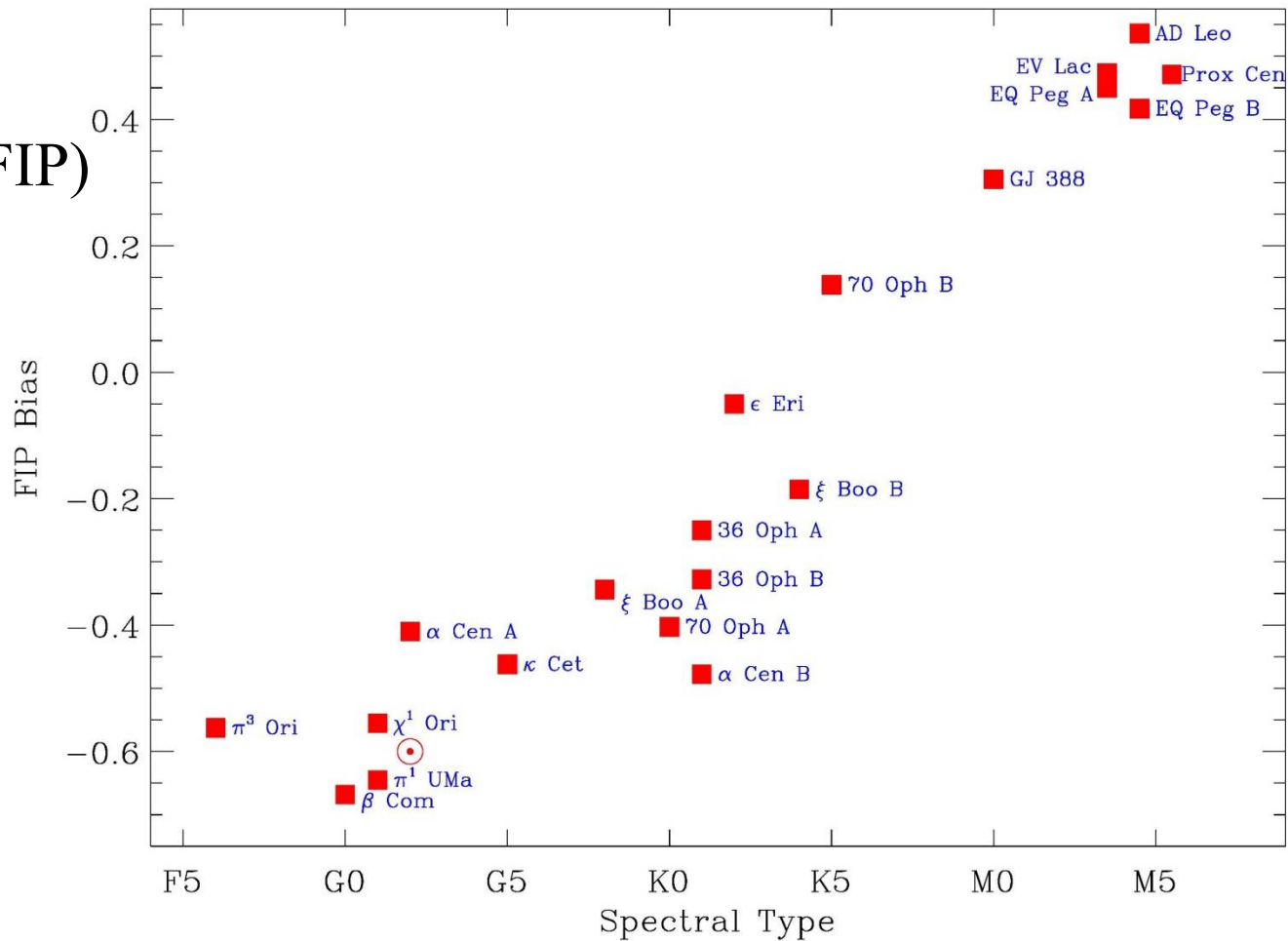


# Stellar Coronae: updated from Wood & Linsky (2010, ApJ, 717, 1279)

See also Seli et al. (2022, A&A, 659, A3)



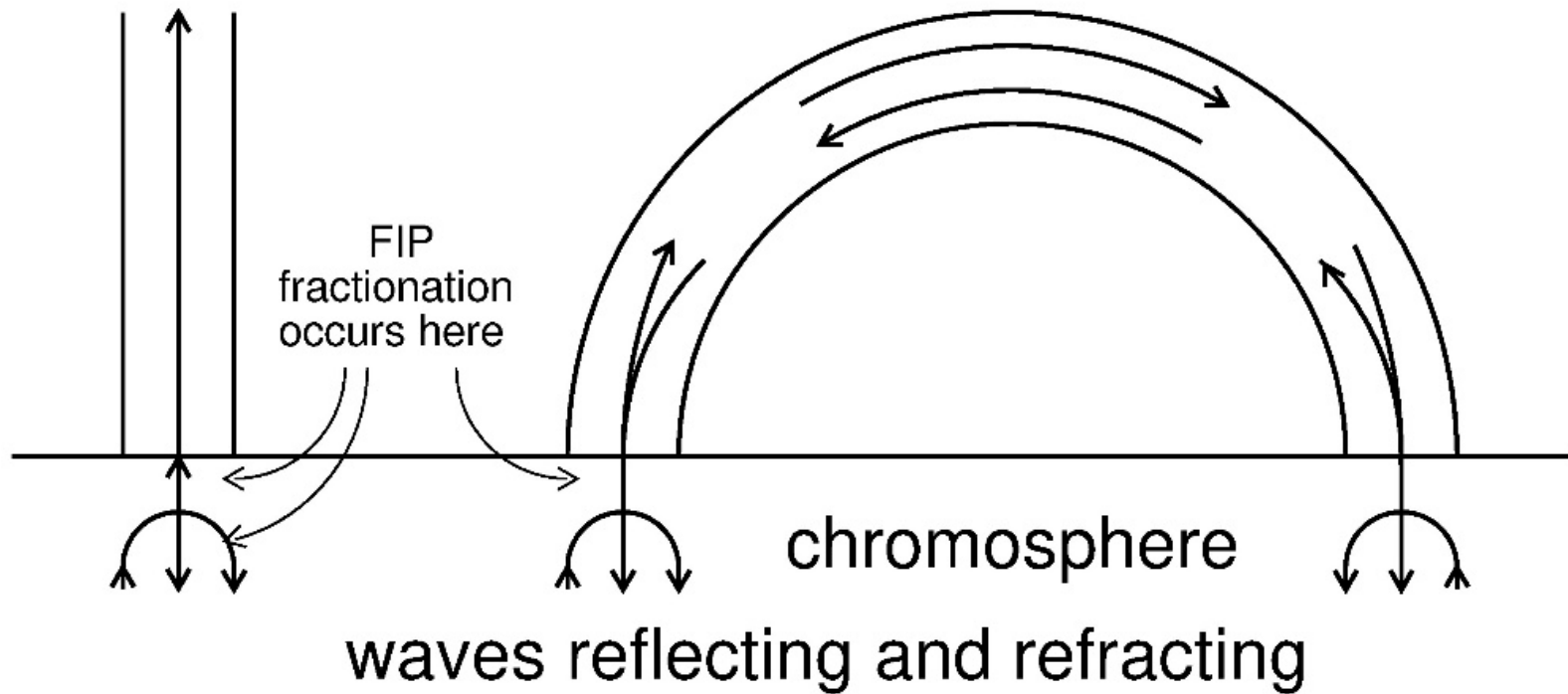
$\text{Log}_{10}(1/\text{FIP})$



# All Models Are Wrong, but some are Useful! Assume $\beta=0$ , etc.

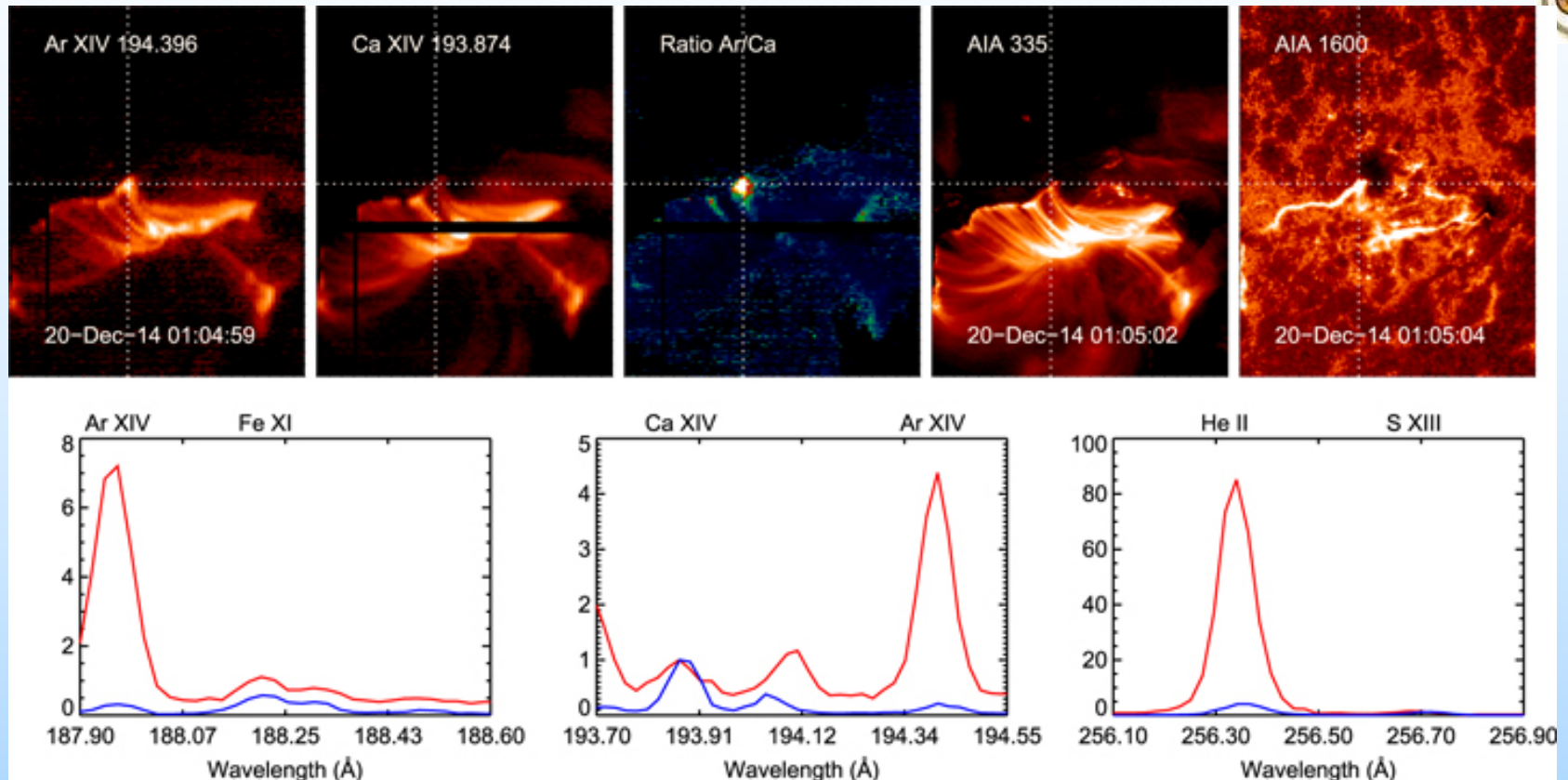
open field  
(coronal hole)

closed field  
(coronal loop)



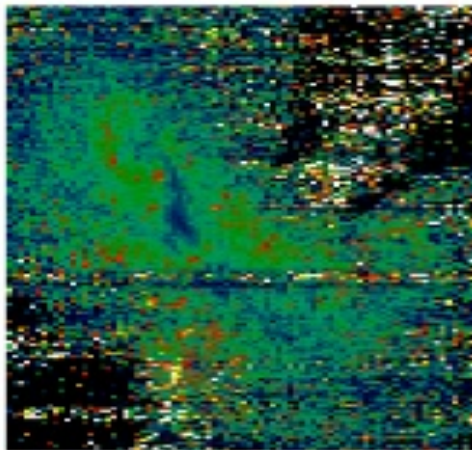
3)

# Inverse FIP Effect (Doschek, Warren & Feldman 2015, ApJ, 808, L7)

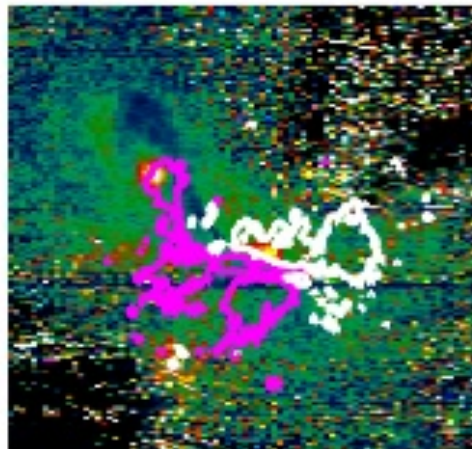
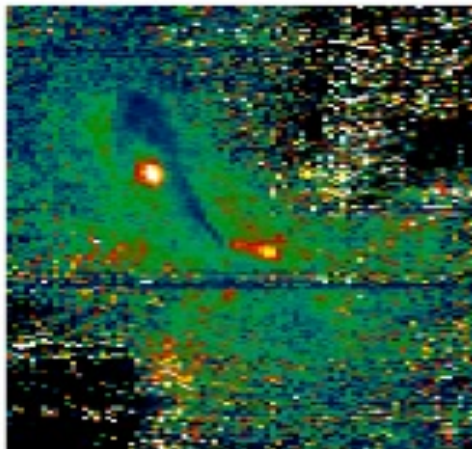
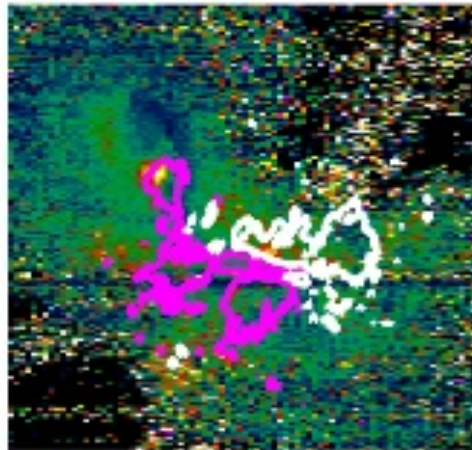
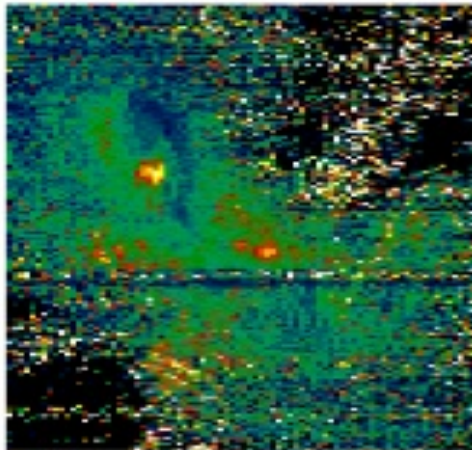
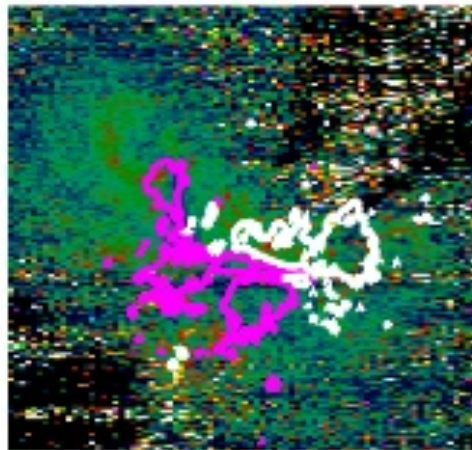


c.f. Katsuda et al. (2020); whole flare shows Inverse FIP

Ar XIV/Ca XIV Ratio



Ar XIV/Ca XIV Ratio



from Baker et al.  
ApJ, 875, 35  
(2019)



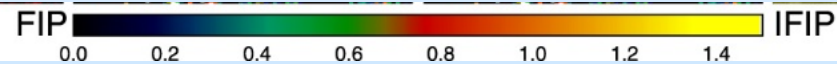
Mar 06, 2012

12:38 UT

12:47 UT

12:56 UT

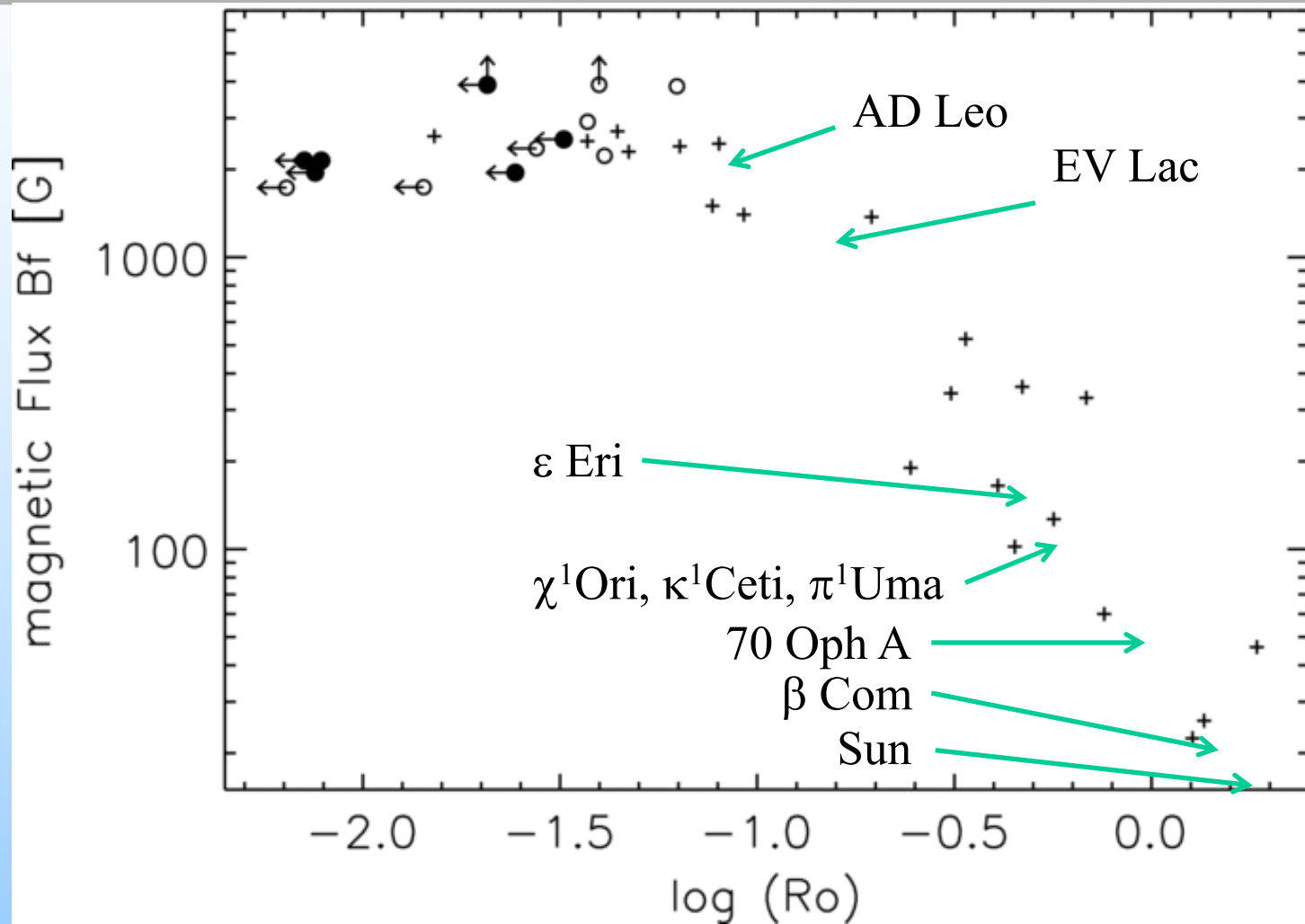
Hinode/EIS,



SDO/HMI contours  
+/- 500G (white/purple)

# Reiners, Basri & Browning 2009, ApJ, 692, 538; stellar magnetic flux against Rossby #

If  $\Delta B \sim 1500 \text{ G}$ ,  $\rho \sim 10^{17} \text{ cm}^{-3} \rightarrow \Delta v \sim 10 \text{ km s}^{-1}$ , sufficient for IFIP



# Conclusions



- The ponderomotive force is the key mechanism for ion-neutral separation in the chromosphere → FIP and IFIP Effects.
- Different magnetic geometries give all the variations so far observed.
- Novel diagnostics of waves and associated processes (wave origins, damping, turbulence) open up ....
- Observational correlations between Alfvén waves and FIP fractionation beginning to be documented. New wave observations becoming available.
- Similar Fe abundance enhancement in coronae of black hole accretion disks (e.g. Wilkins et al. 2021, Nature, 595, 657; Garcia et al. 2018, Am. Soc. Pac. Conf. Ser., 515, 282). All sorts of interesting conclusions if this is due to the same mechanism.
- Happy to answer any questions (there is a lot more to say)!