

# Anisotropies in the turbulent solar wind, perspective on multipoint observations from numerical simulations

## Part 2

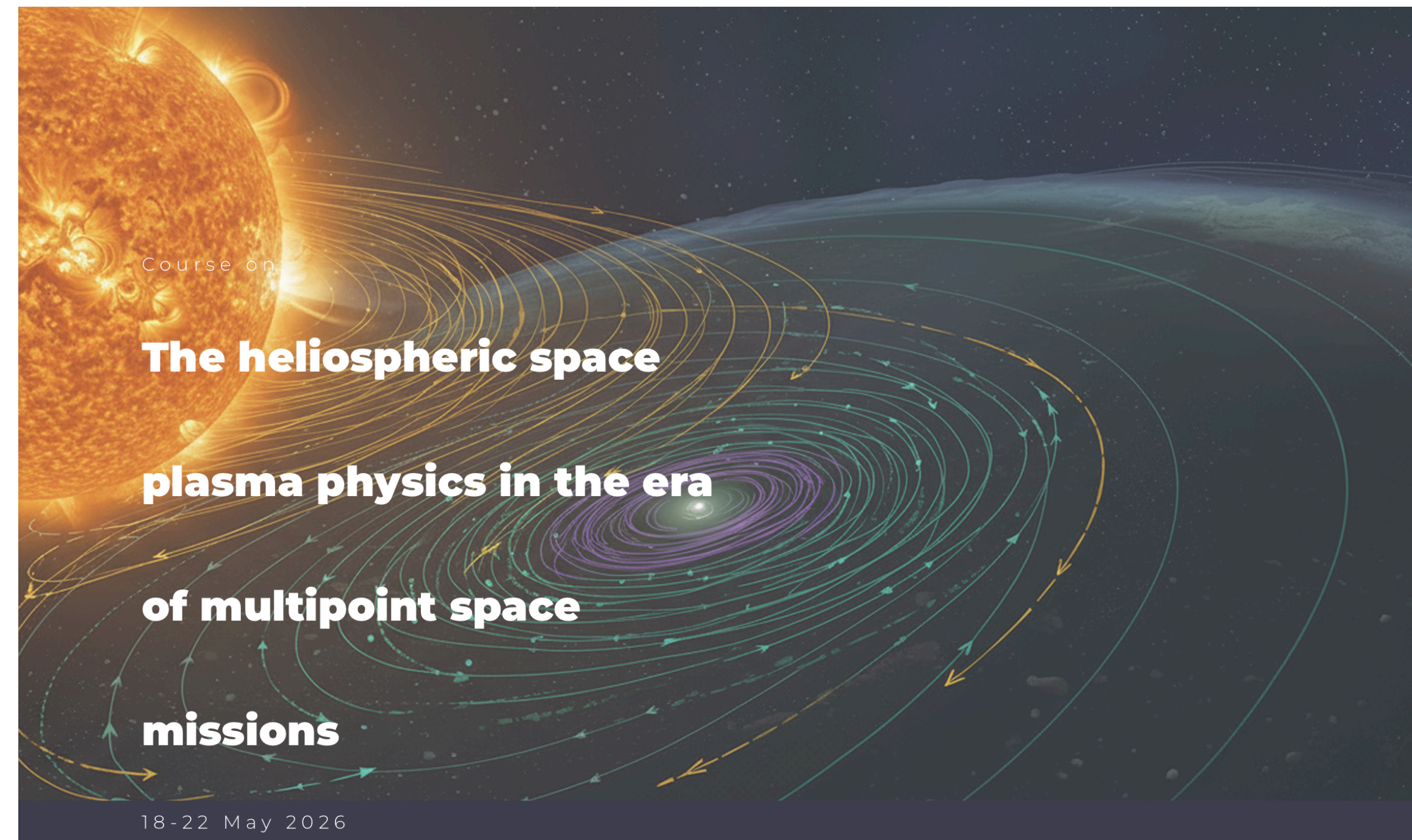
Andrea Verdini

University of Firenze, Department  
of Physics & Astronomy

[andrea.verdini@unifi.it](mailto:andrea.verdini@unifi.it)

Arcetri Space & Astrophysical Plasma (ASAP) group

<https://sites.google.com/unifi.it/asap>



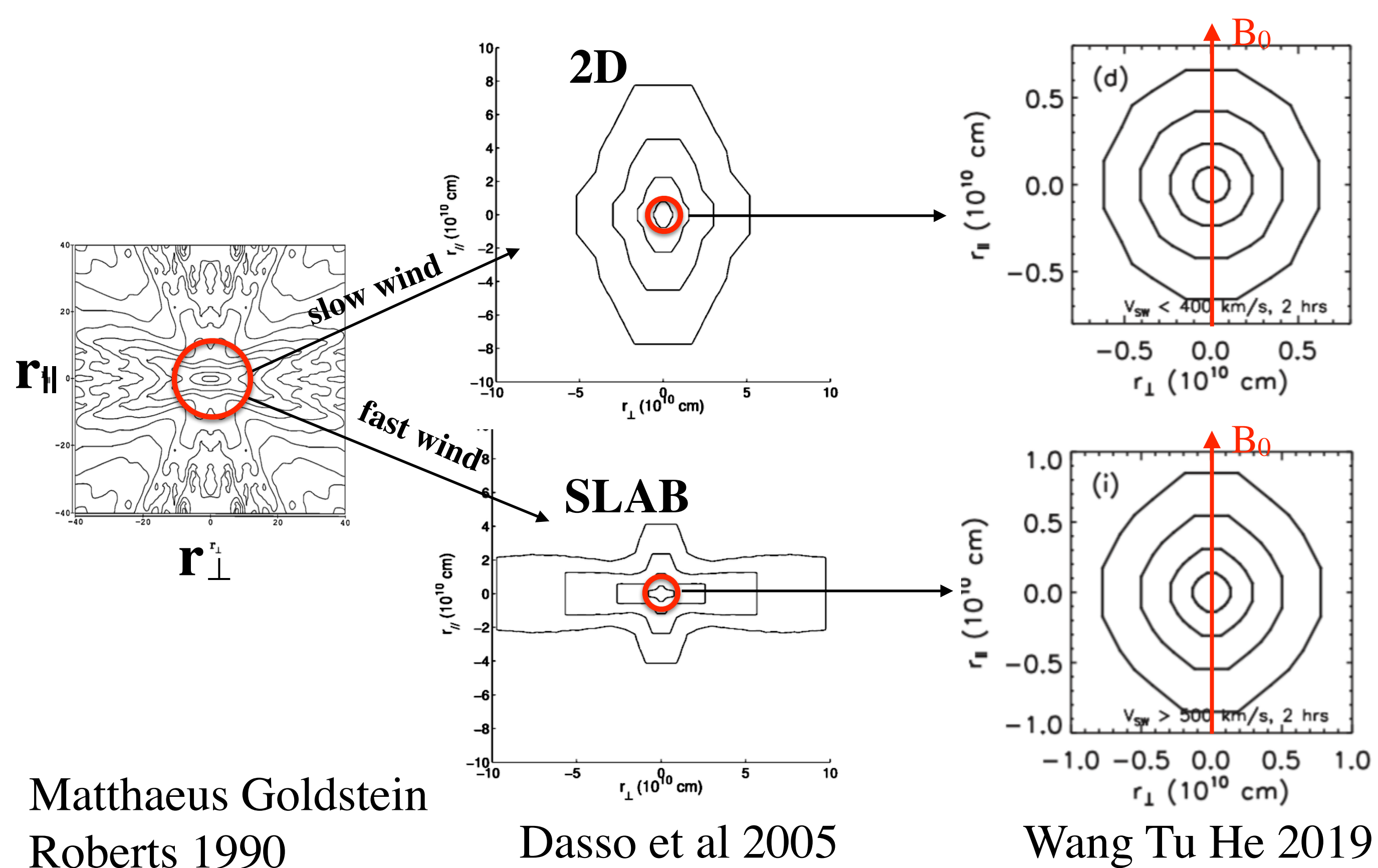
# Outline

- What anisotropy? (spectral and scale dependent anisotropy)
- Why anisotropy ? (a semi-quantitative argument)
- How anisotropy is driven ? (anisotropy of the cascade)
- Measurements in the solar wind, some surprises:
- Special solar wind anisotropy (Maltese Cross) at different scales
- Scale dependent anisotropy
  
- Solar wind radial expansion: side effects
- some explanations for the observed solar wind anisotropies
- Why do we need multi-spacecraft ?
  - an example by revising spectral anisotropy
  - anisotropy of the cascade (the driver) revealed?

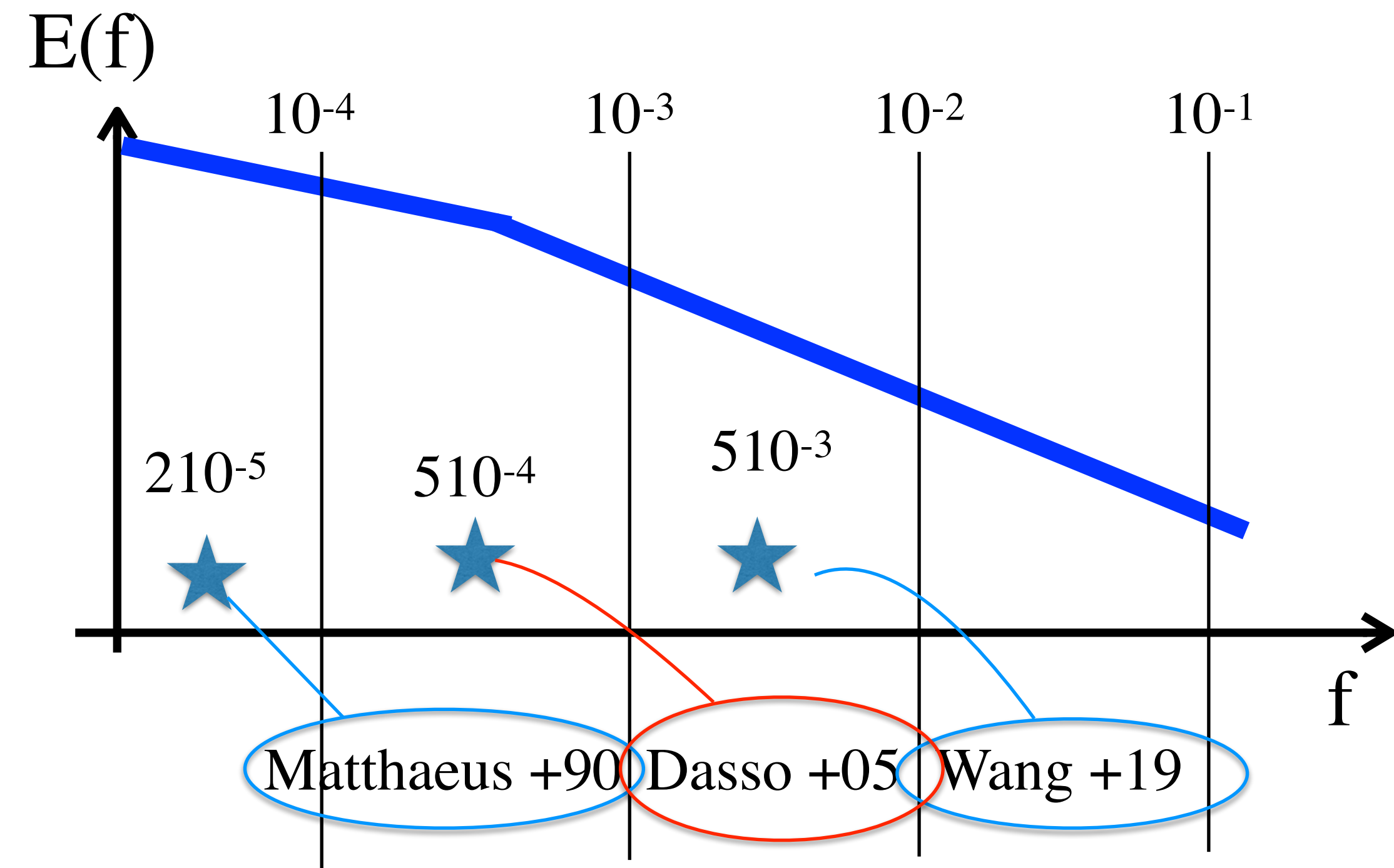


Expanding  
Box Model  
mirabilia

# Observed Anisotropy in the SW



Assume Axisymmetry around  $B^0$



Maltese cross

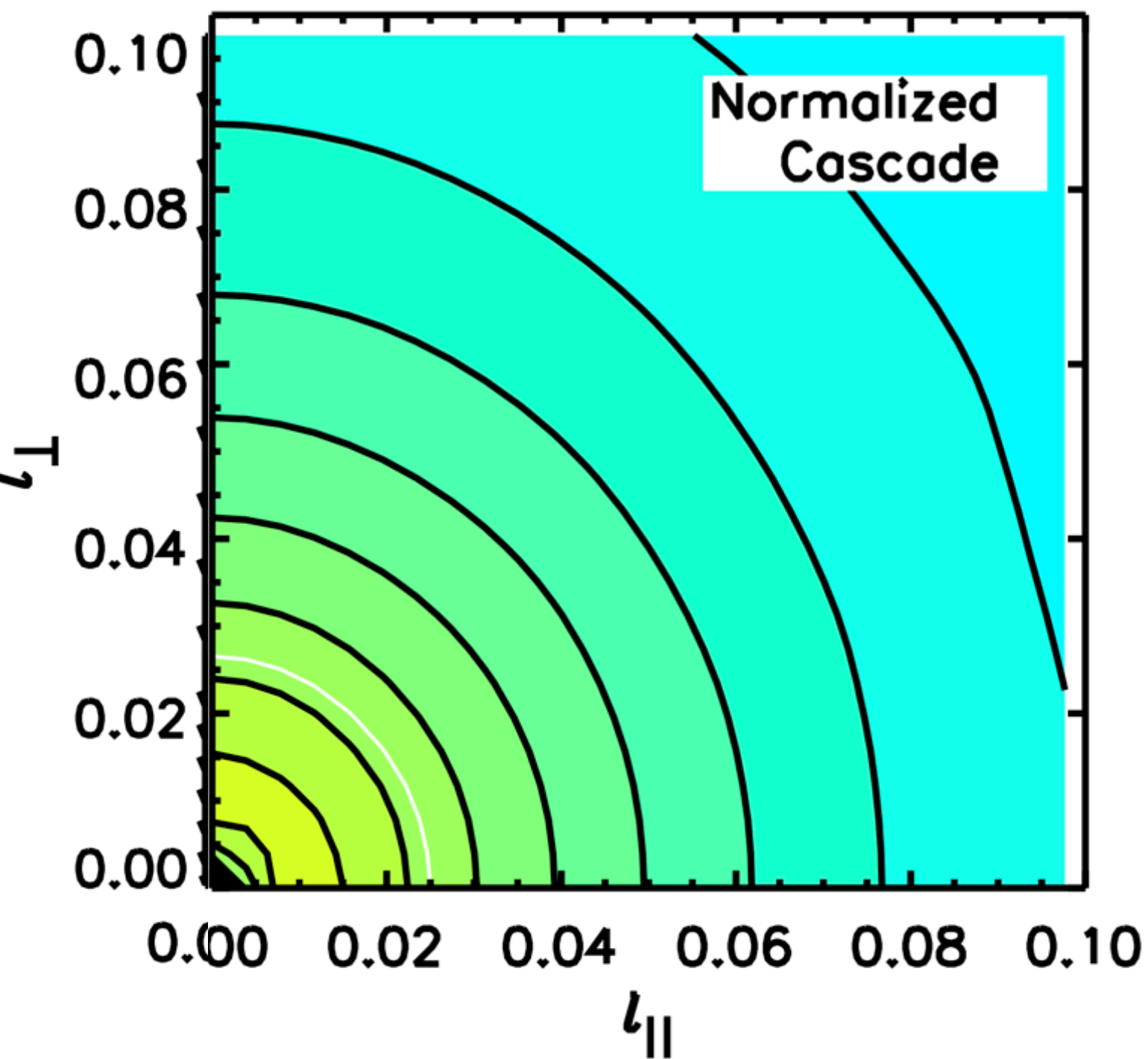
SLAB in fast wind  
2D in slow wind

Isotropic

# Cascade anisotropy

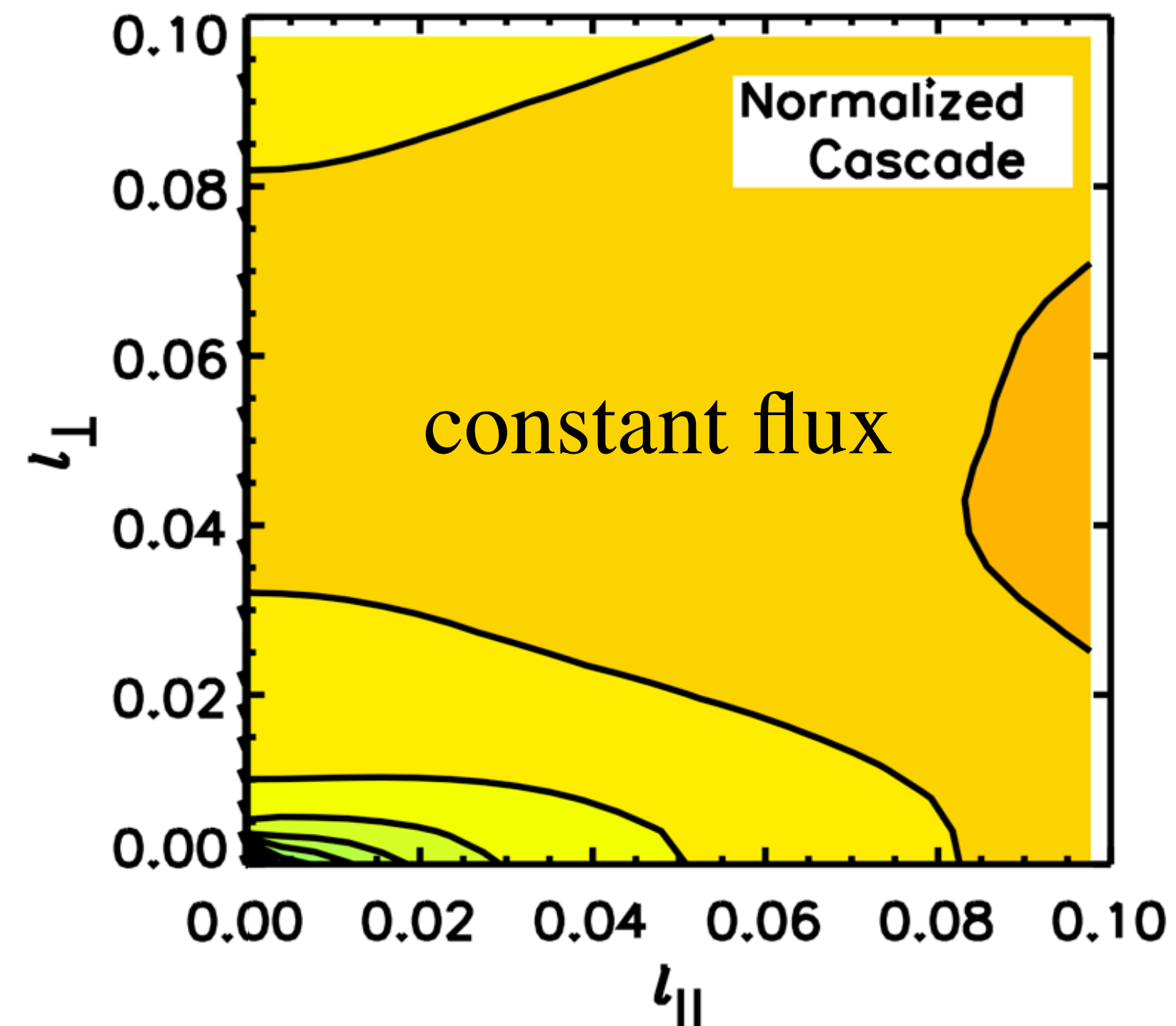
Cascade = The Flux of energy through scales

ISOTROPIC



ANISOTROPIC

$$-\nabla \cdot \mathbf{Y} / 4\varepsilon$$



Cascade  $\Leftrightarrow \nabla \cdot \mathbf{Y} = \text{const}$

# The Expanding Box Model

Grappin Velli Mangeney 1993 PRL, Grappin & Velli 1996 JGR

Volume is transported by the constant **radial** wind flow

time  $\Leftrightarrow$  Distance

$$R = R^{\circ} + V_{sw}t$$

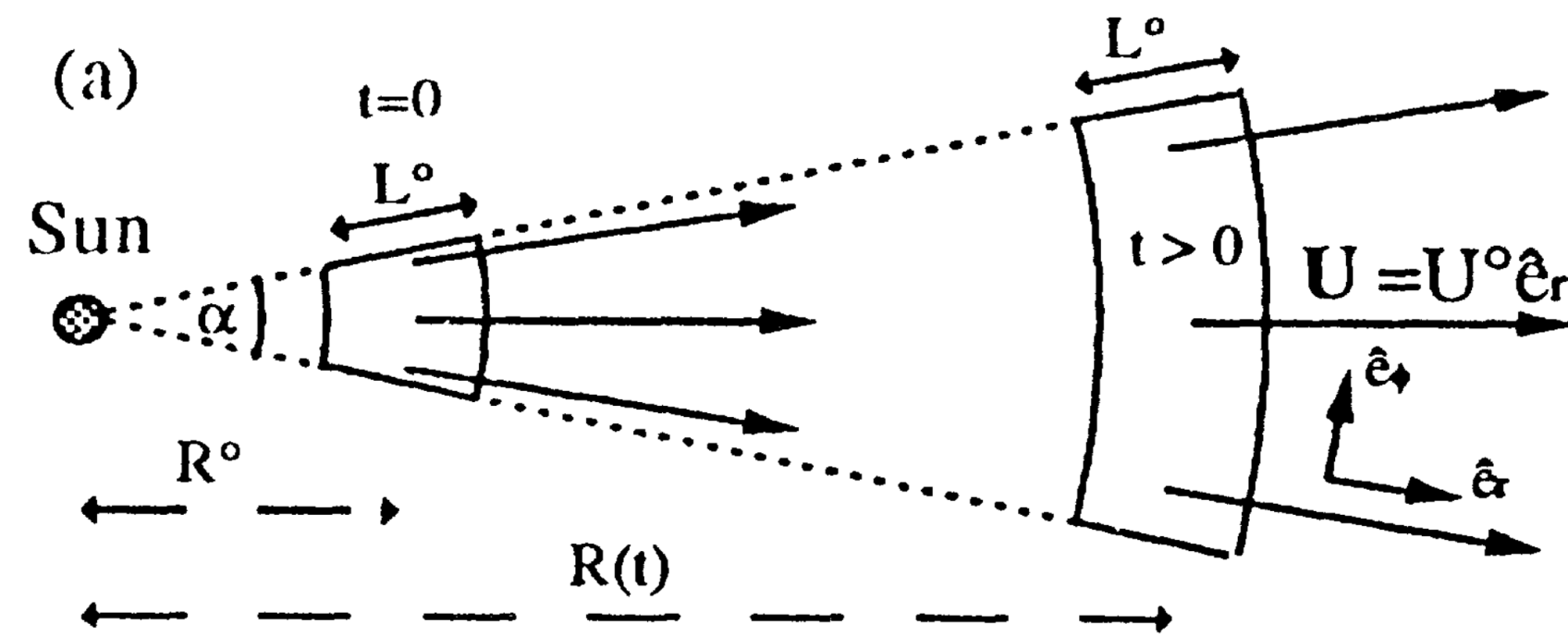
Usual MHD timescales

New expansion timescale

$$t_{NL} = L^{\circ} / \delta u$$

$$t_{exp} = R^{\circ} / V_{sw}$$

$$t_A = L^{\circ} / Va$$



# The Expanding Box Model

Grappin Velli Mangeney 1993 PRL, Grappin & Velli 1996 JGR

Volume is transported by the constant **radial** wind flow

time  $\Leftrightarrow$  Distance

$$R = R^\circ + V_{sw}t$$

Usual MHD timescales

New expansion timescale

$$t_{NL} = L^\circ / \delta u$$

$$t_{exp} = R^\circ / V_{sw}$$

$$t_A = L^\circ / Va$$

Volume expands only in directions  $\perp$  to the radial

$L_\perp$  increases  
( $k_\perp$  decreases)

**Anisotropic Stretching**

Transform to **cartesian** coordinates  
(neglect curvature effects)

Conservation of

Mass flux

Angular Momentum

Magnetic Flux

$$u_\perp \sim 1/R$$

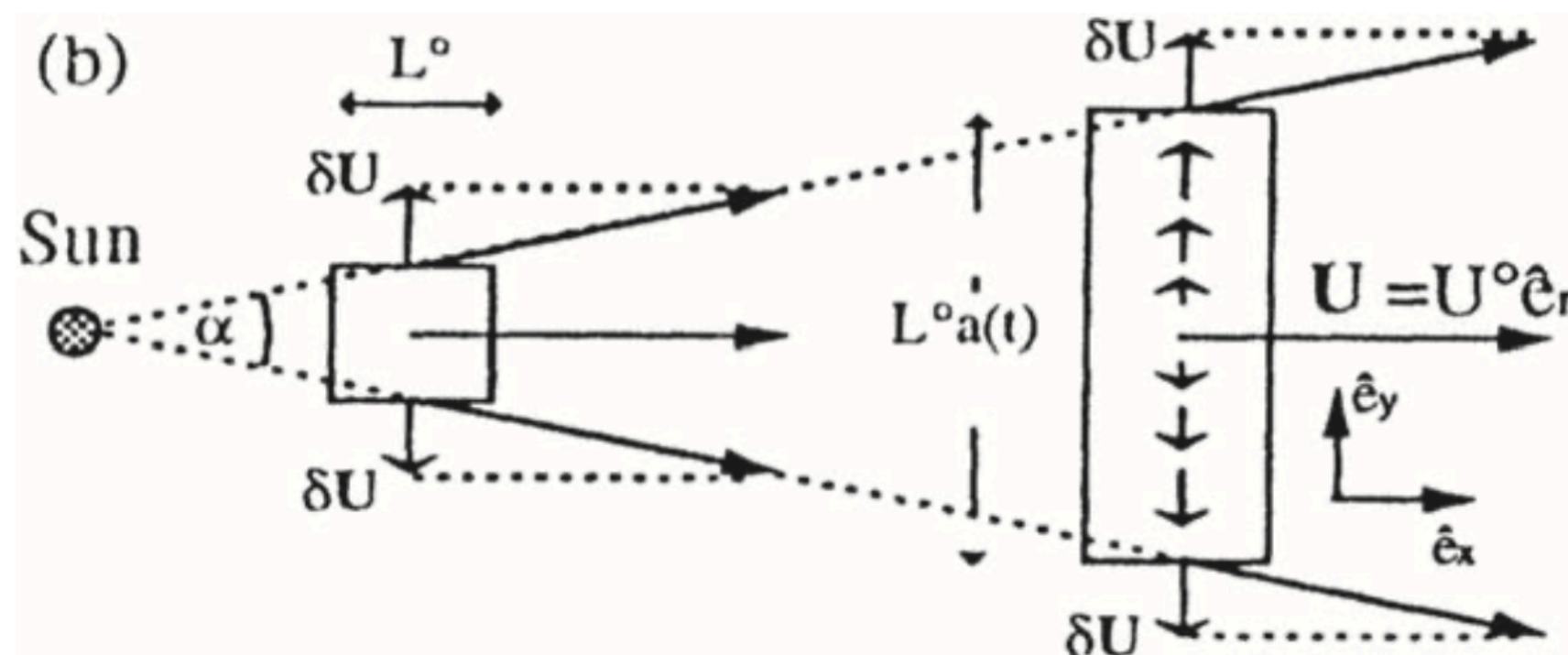
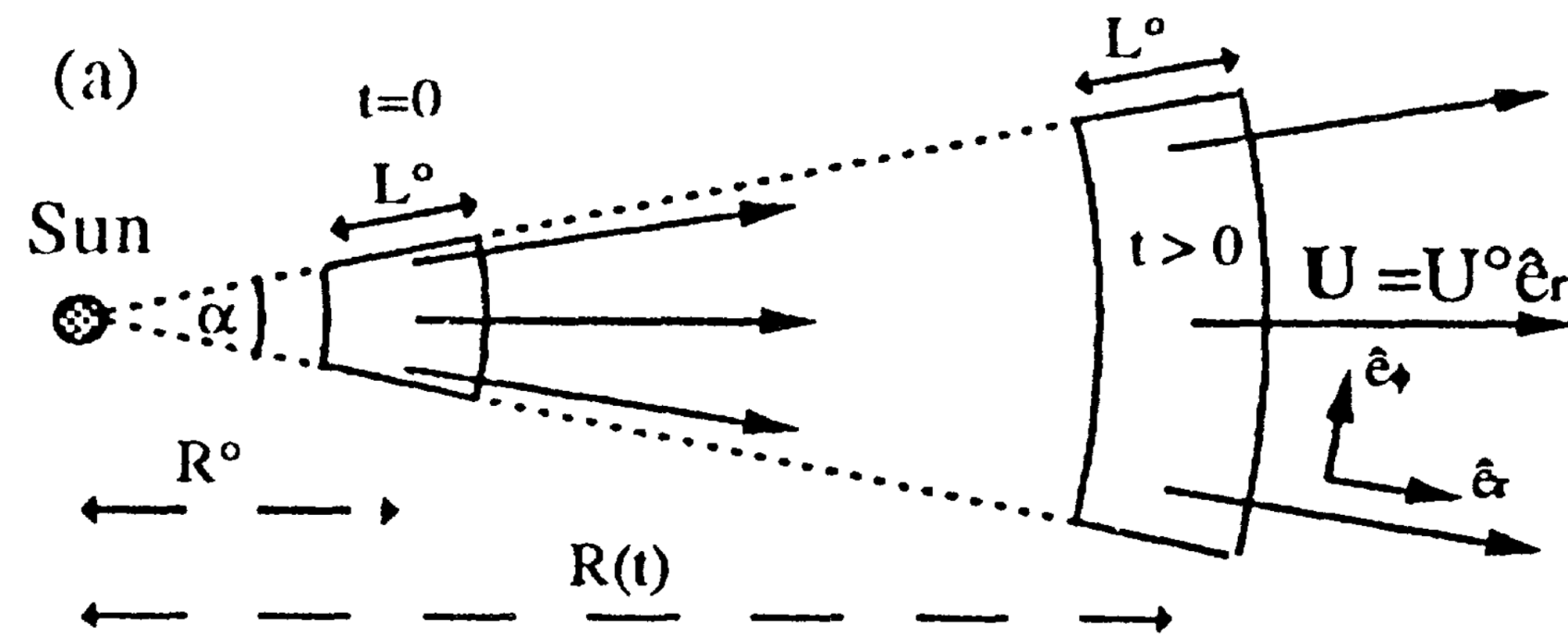
$$u_\parallel \sim \text{const}$$

$$B_\perp \sim 1/R$$

$$B_\parallel \sim 1/R^2$$

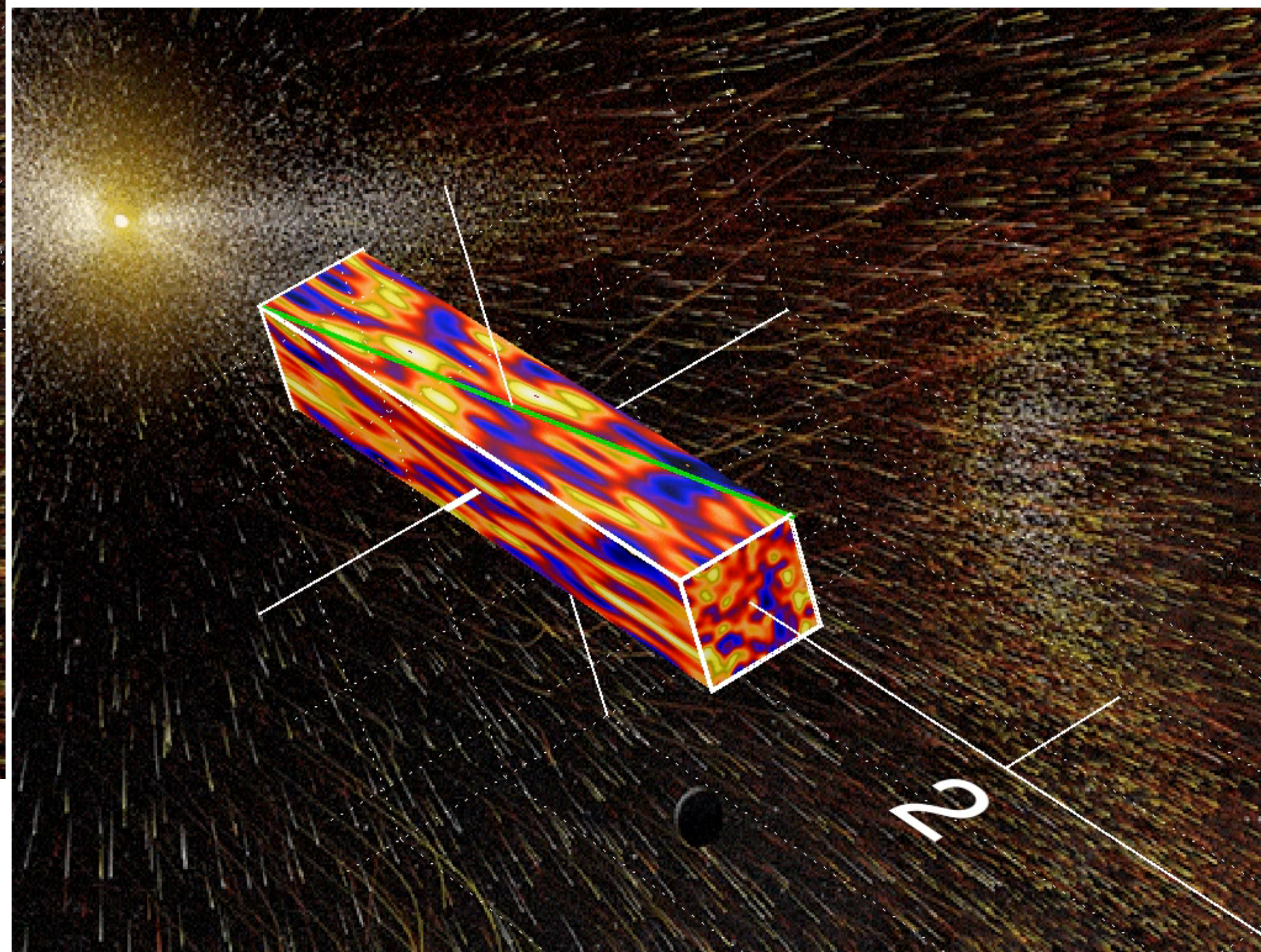
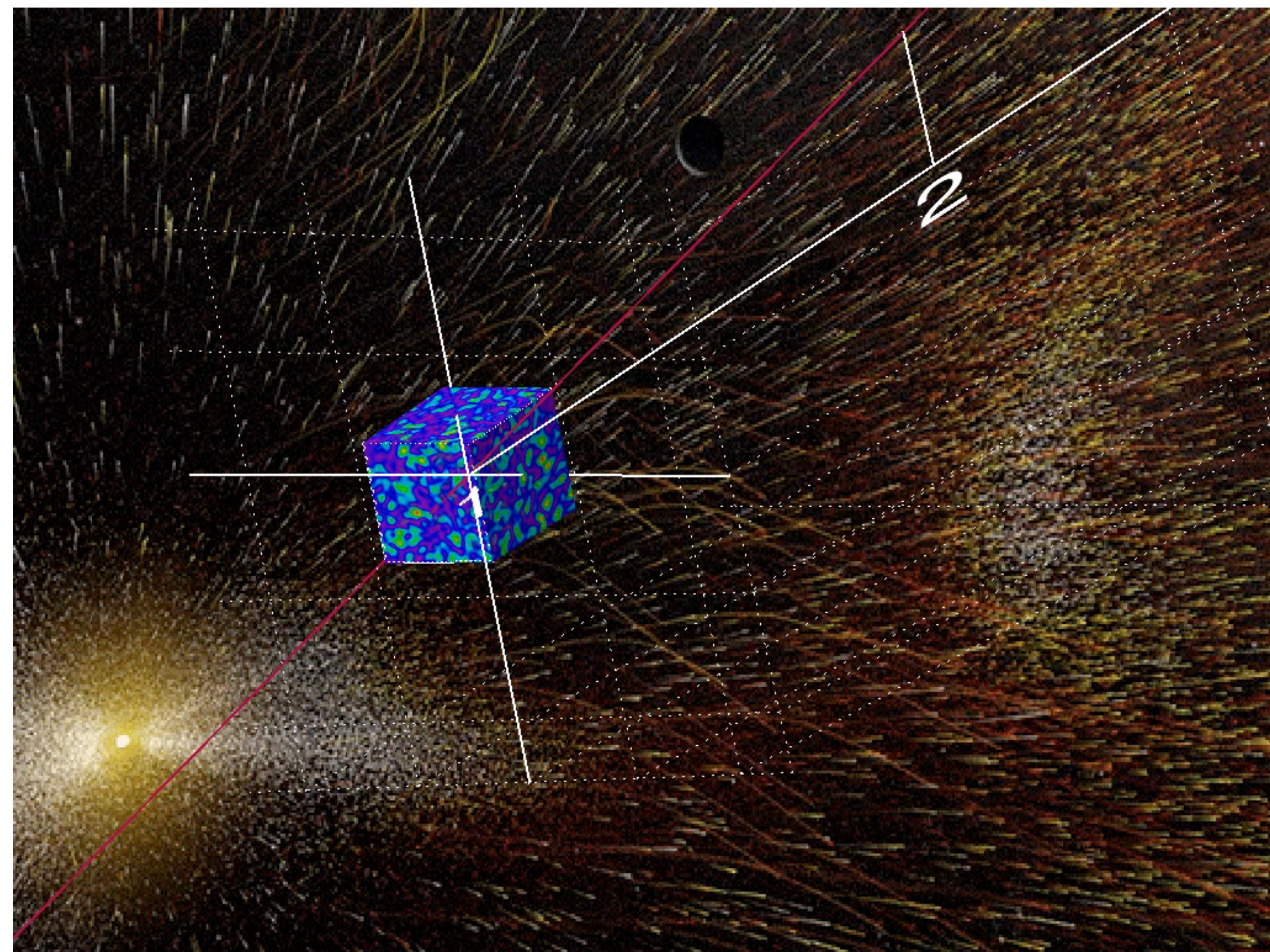
**Selective Decay**

( $B^\circ$  turns as in Parker Spiral)



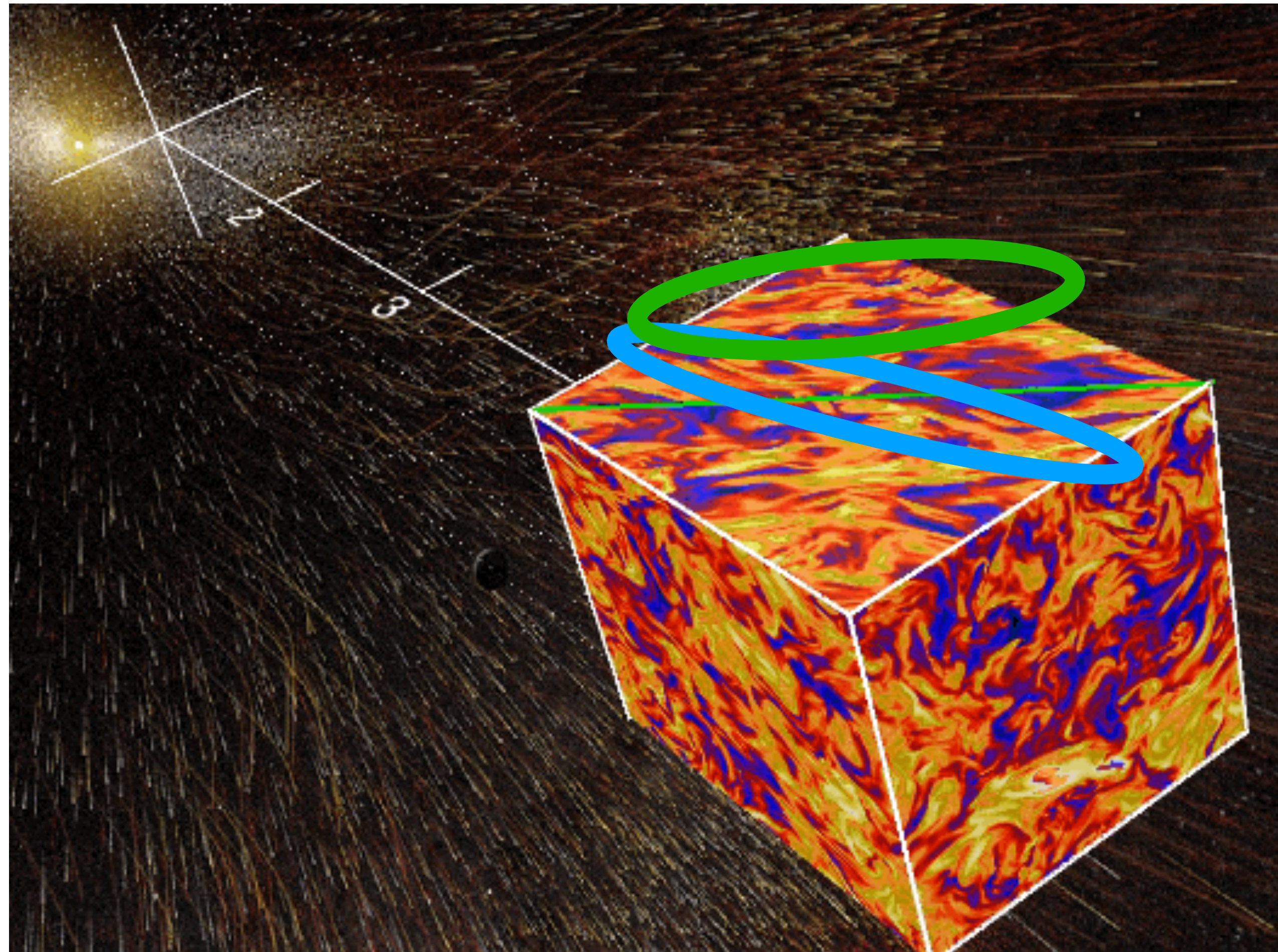
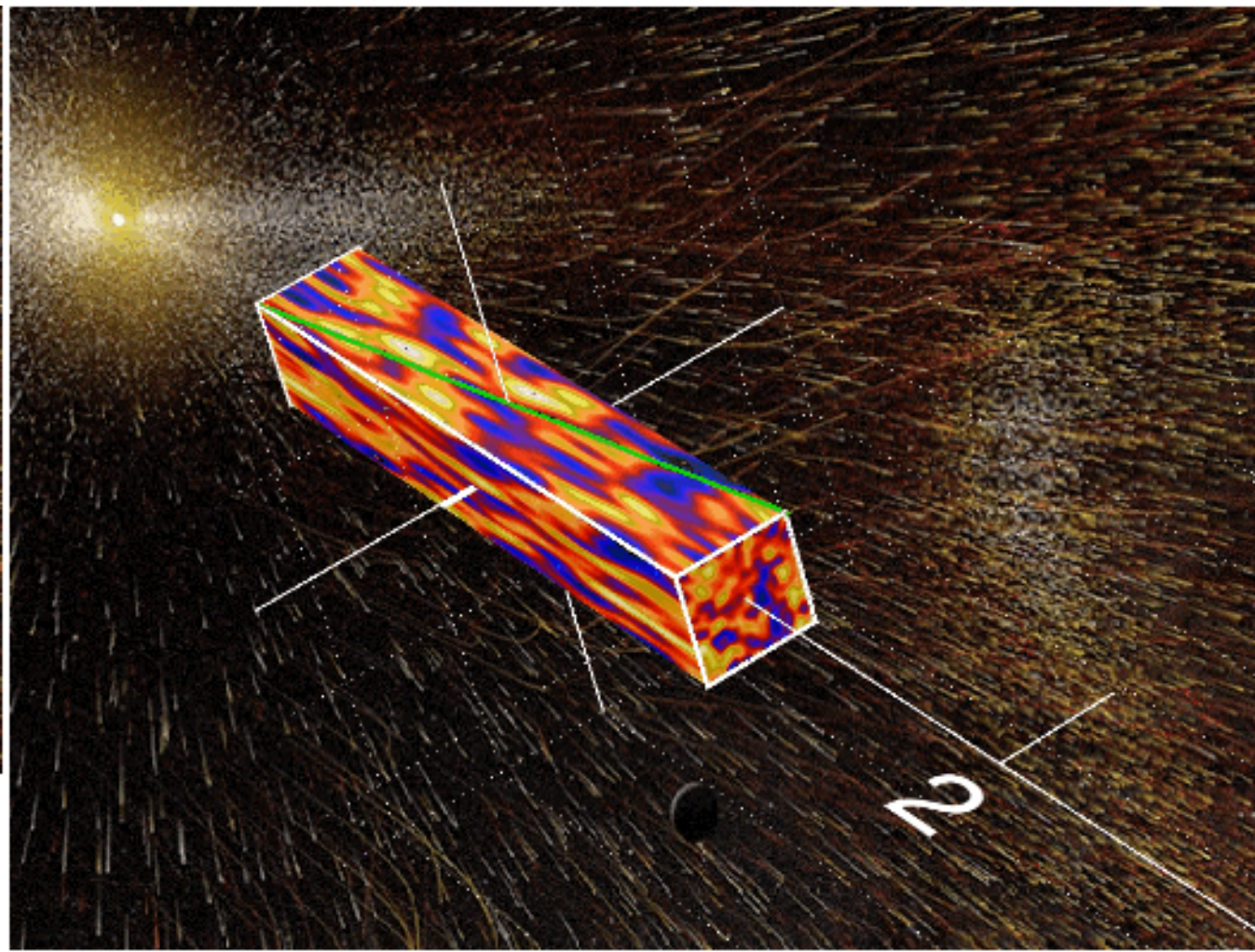
# Expanding Box in a couple of Movies

movies on a separate GIF



# Expanding Box in a couple of Movies

structures elongated along  $B^\circ$  and along  $R$

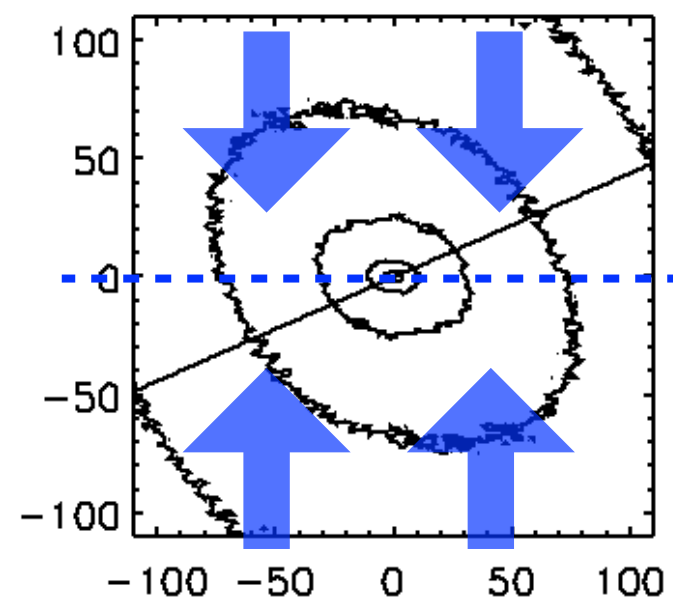
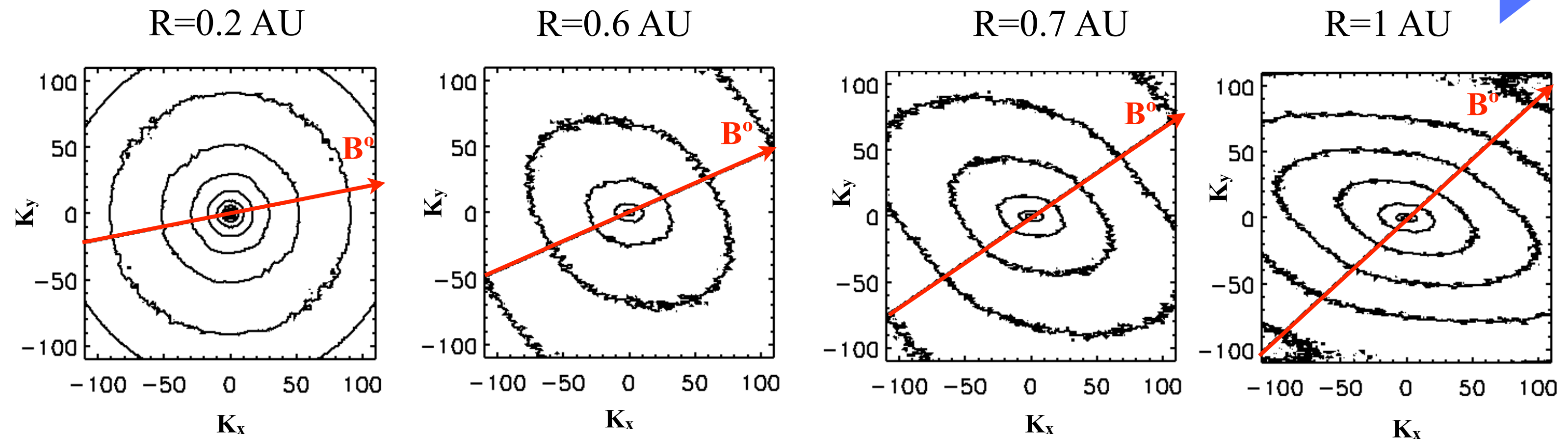
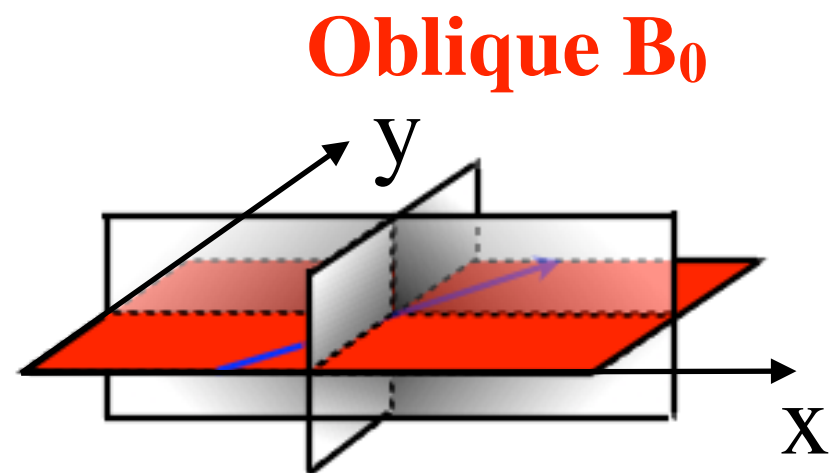


# Anisotropy: a new axis of symmetry

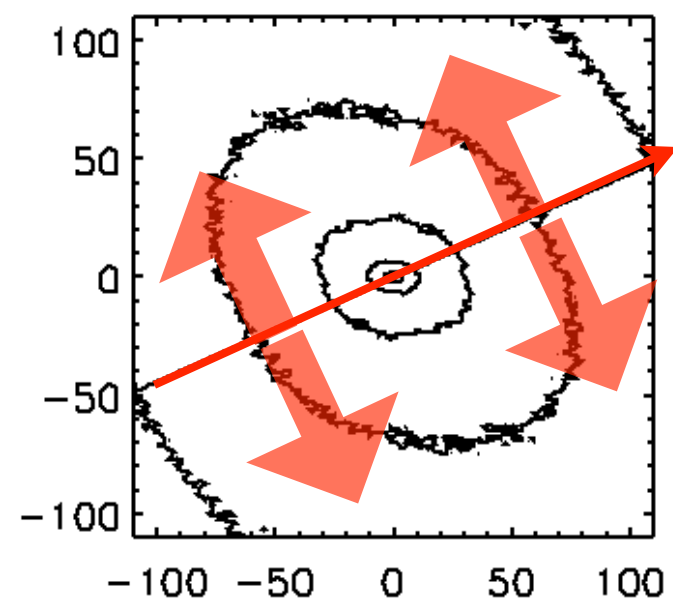
$V_{sw}$

Dong+ 2014 ApJ

time (distance)



**SW Expansion**  
contraction of Fourier space  
in directions  $\perp$  to  $R$



**Nonlinear Interactions**  
Cascade in the directions  
 $\perp$  to  $B^0$

Relative strength is controlled by the ratio of

$$t_{exp} = R/V_{sw}$$

$$t_{NL} = 1/k\delta u(k)$$

Since  $t_{NL}$  decreases with scale at some  $k^*$   $t_{NL} < t_{exp}$   
 $\Rightarrow B^0$  is the symmetry axis at small scales

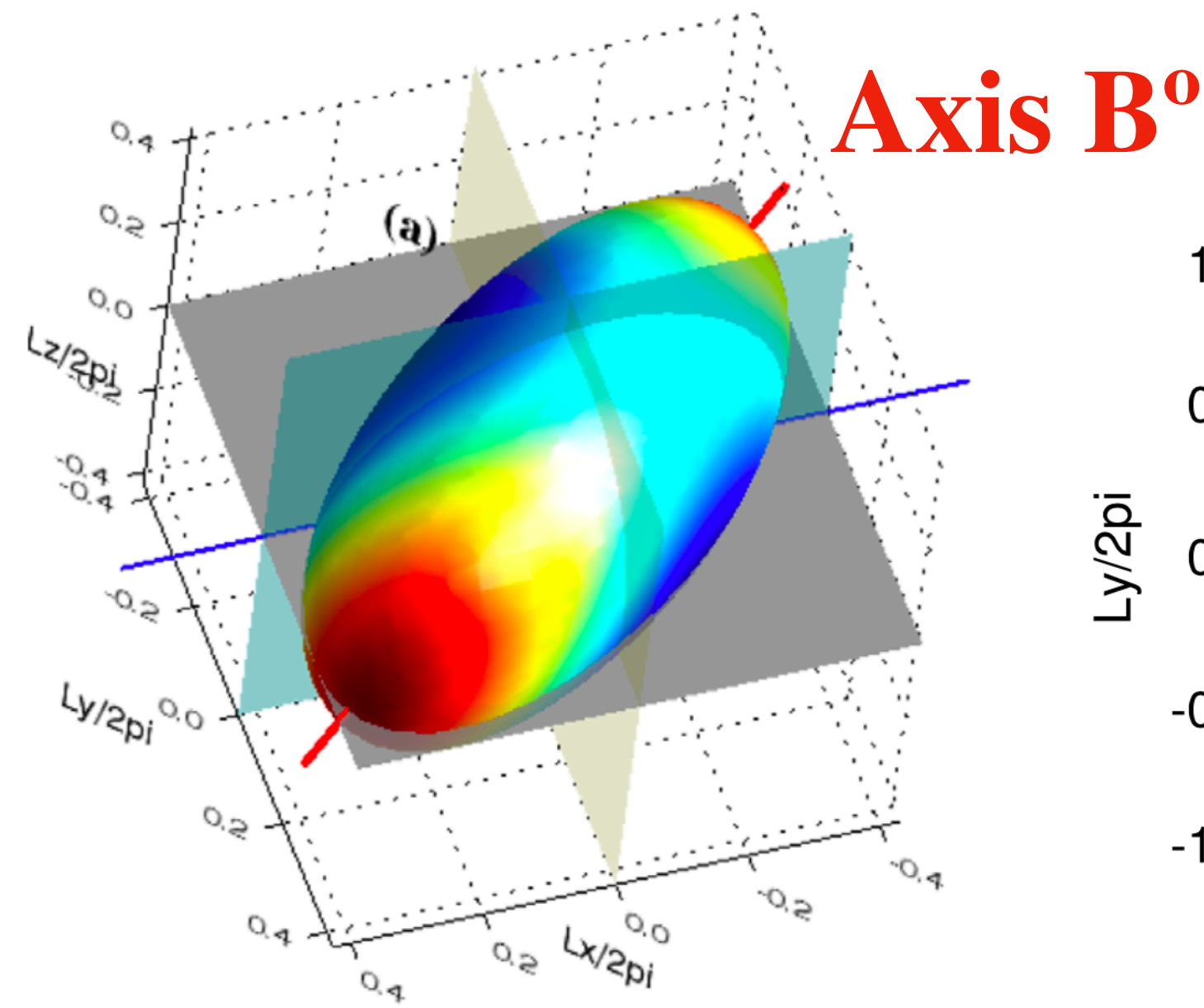
# Slow And Fast wind anisotropy

## Slow Wind

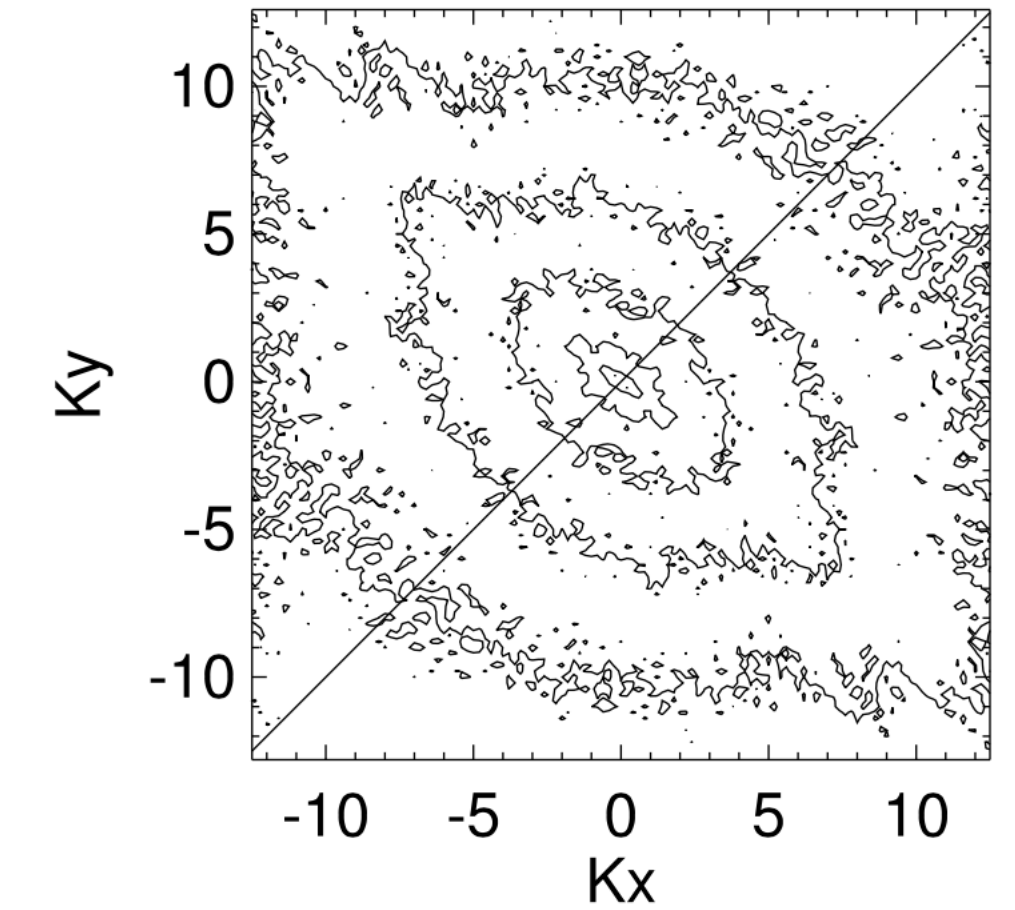
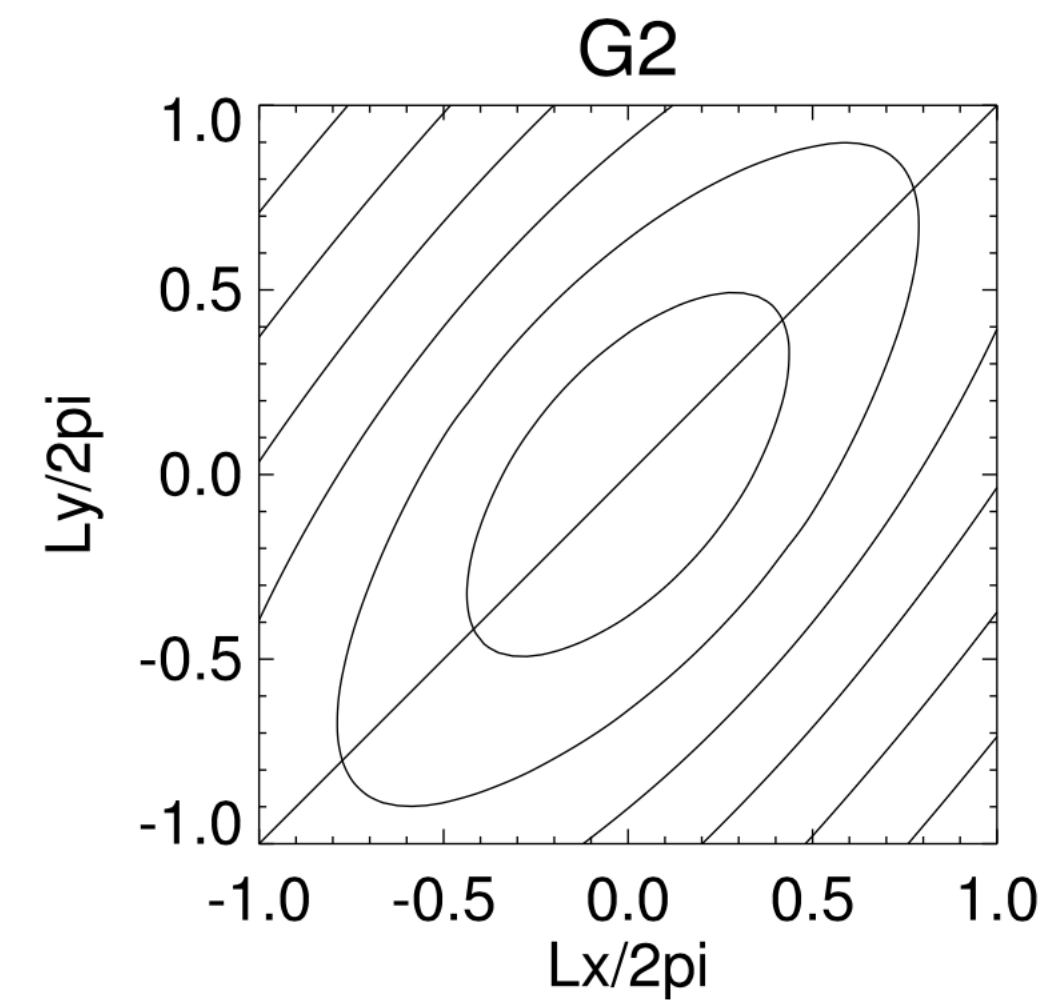
Small Expansion

Not Alfvénic  $\sigma_c=0$

$$t_{NL}/t_{exp} \sim 0.2$$



Montagud-Camps+ 2020 ApJ

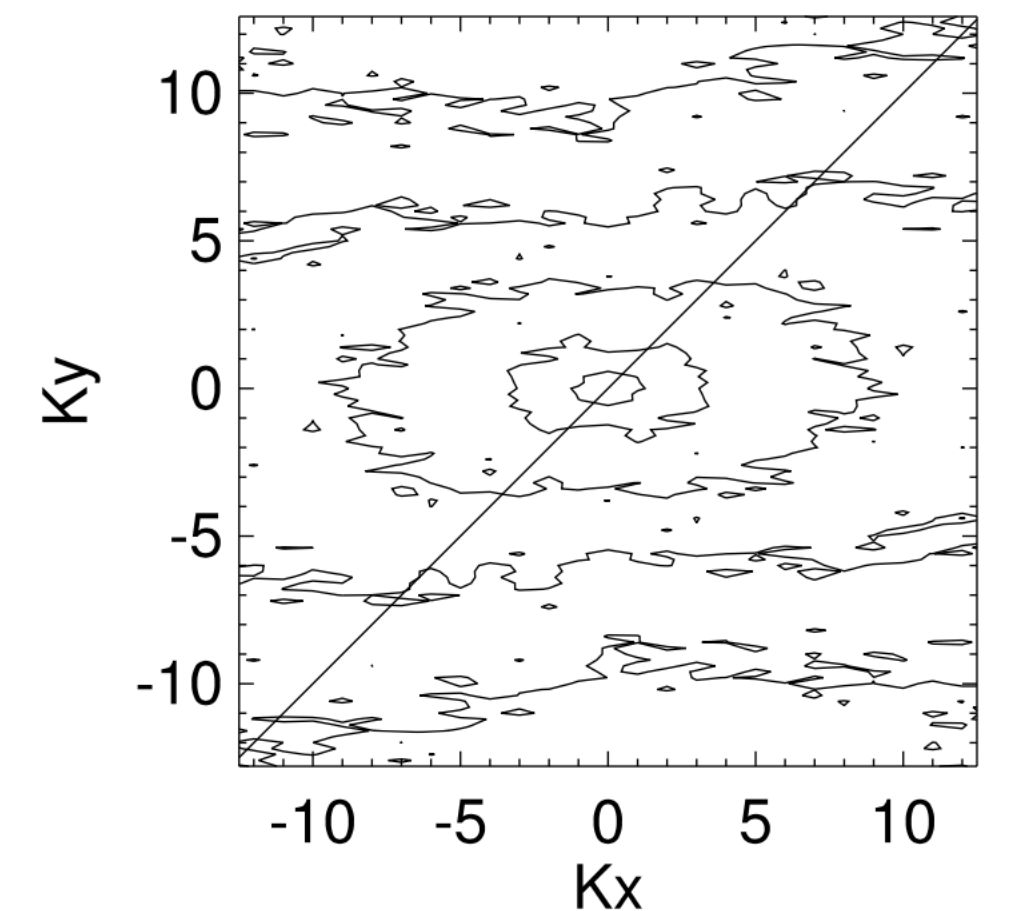
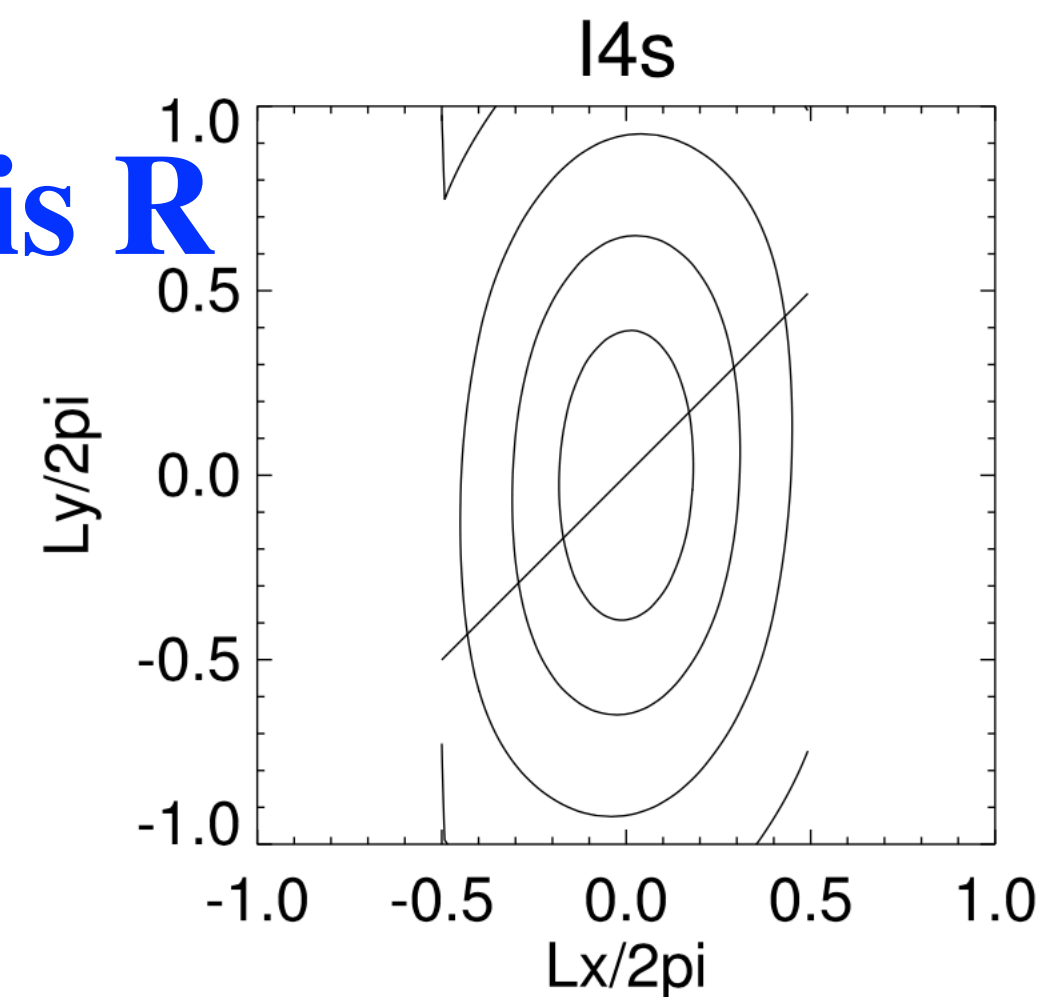
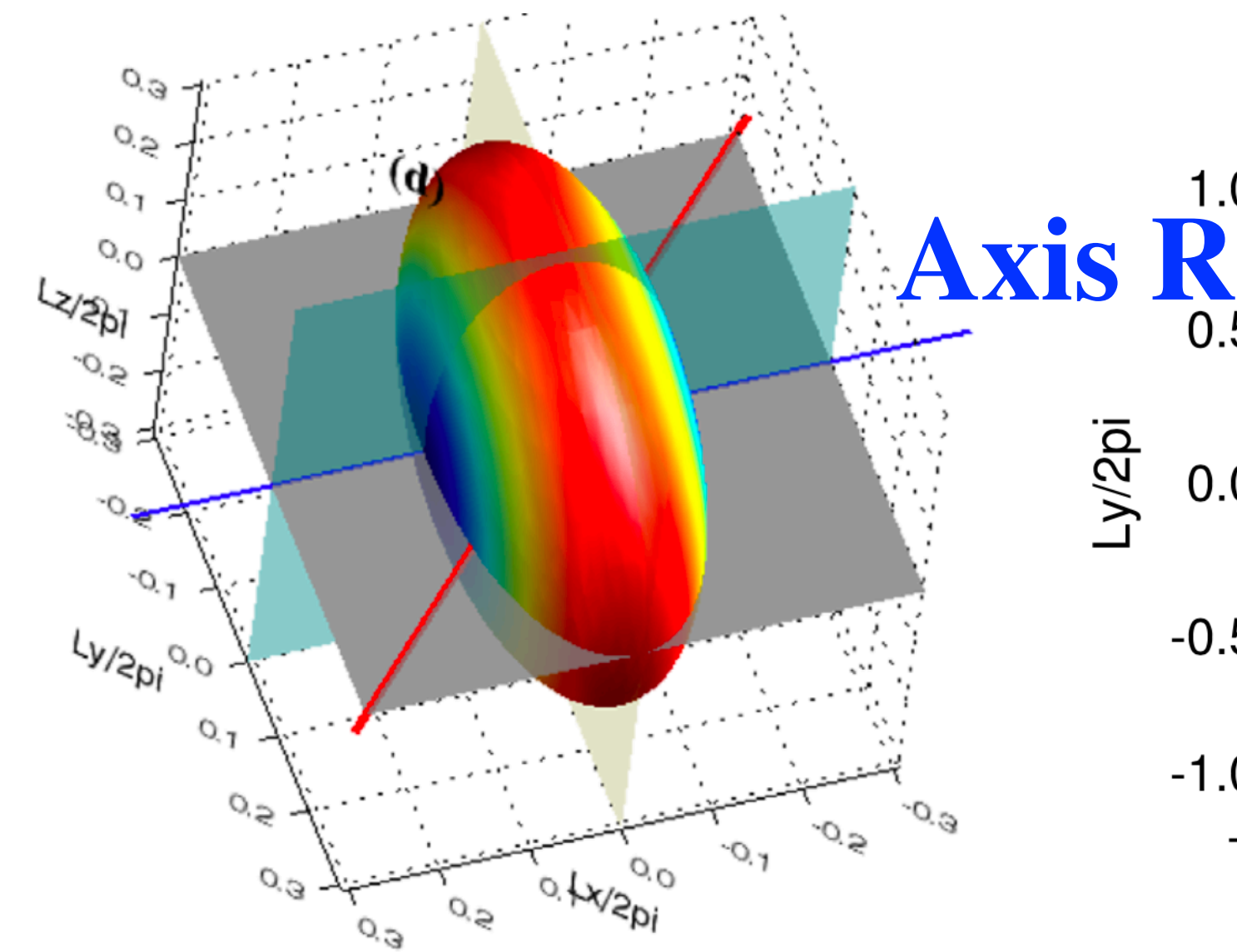


## Fast Wind

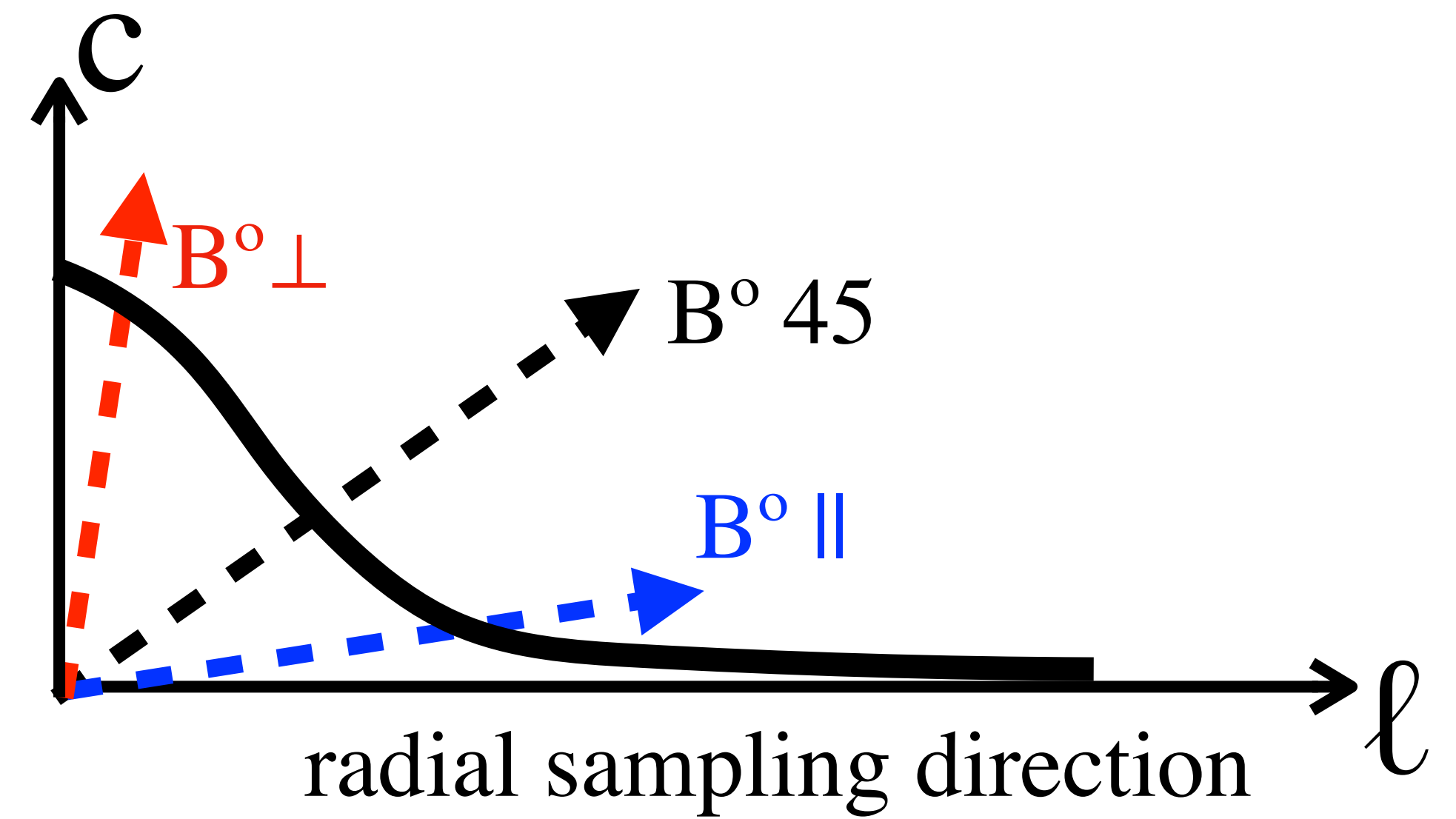
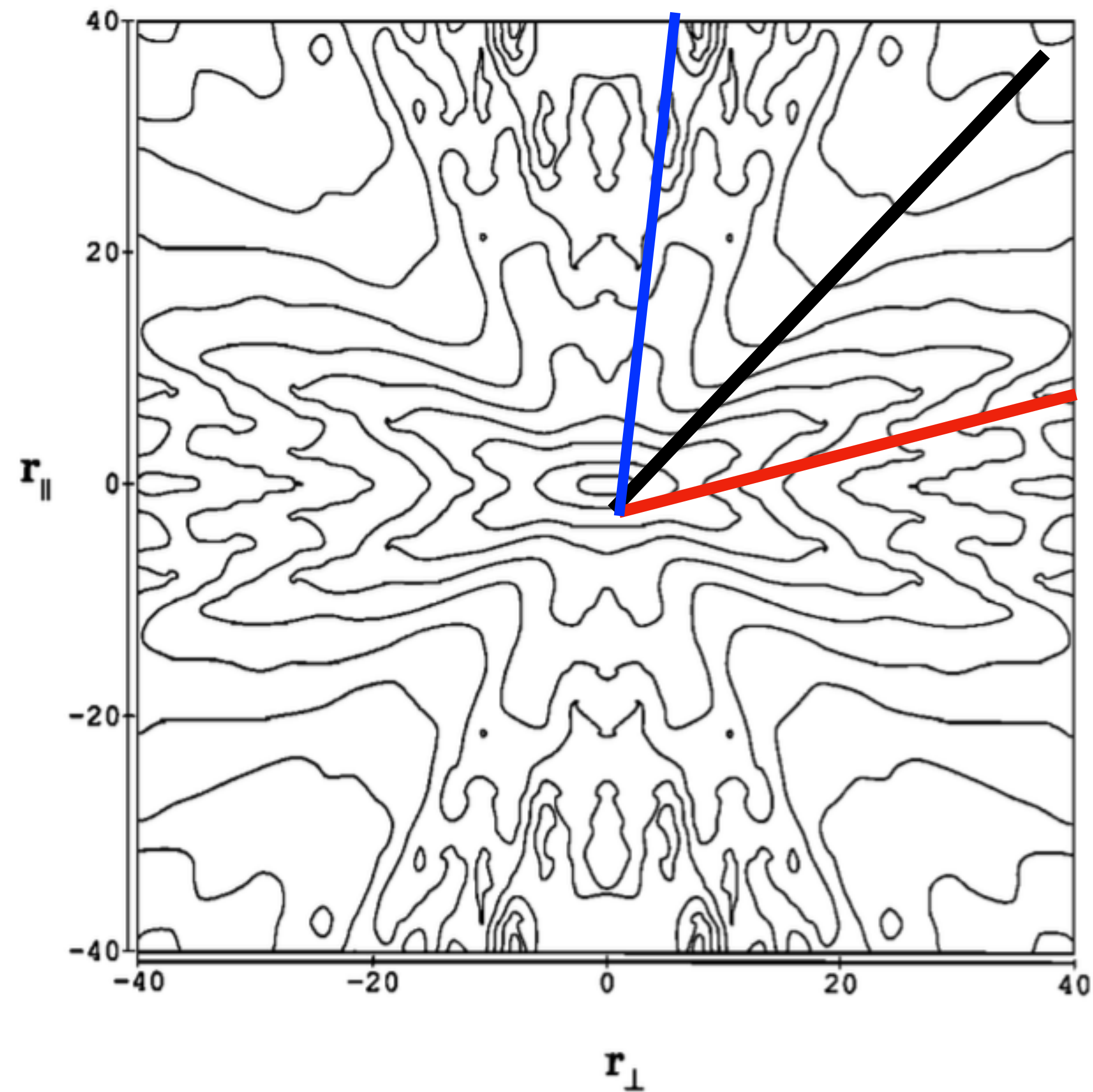
Fast Expansion

Alfvénic  $\sigma_c=0,95$

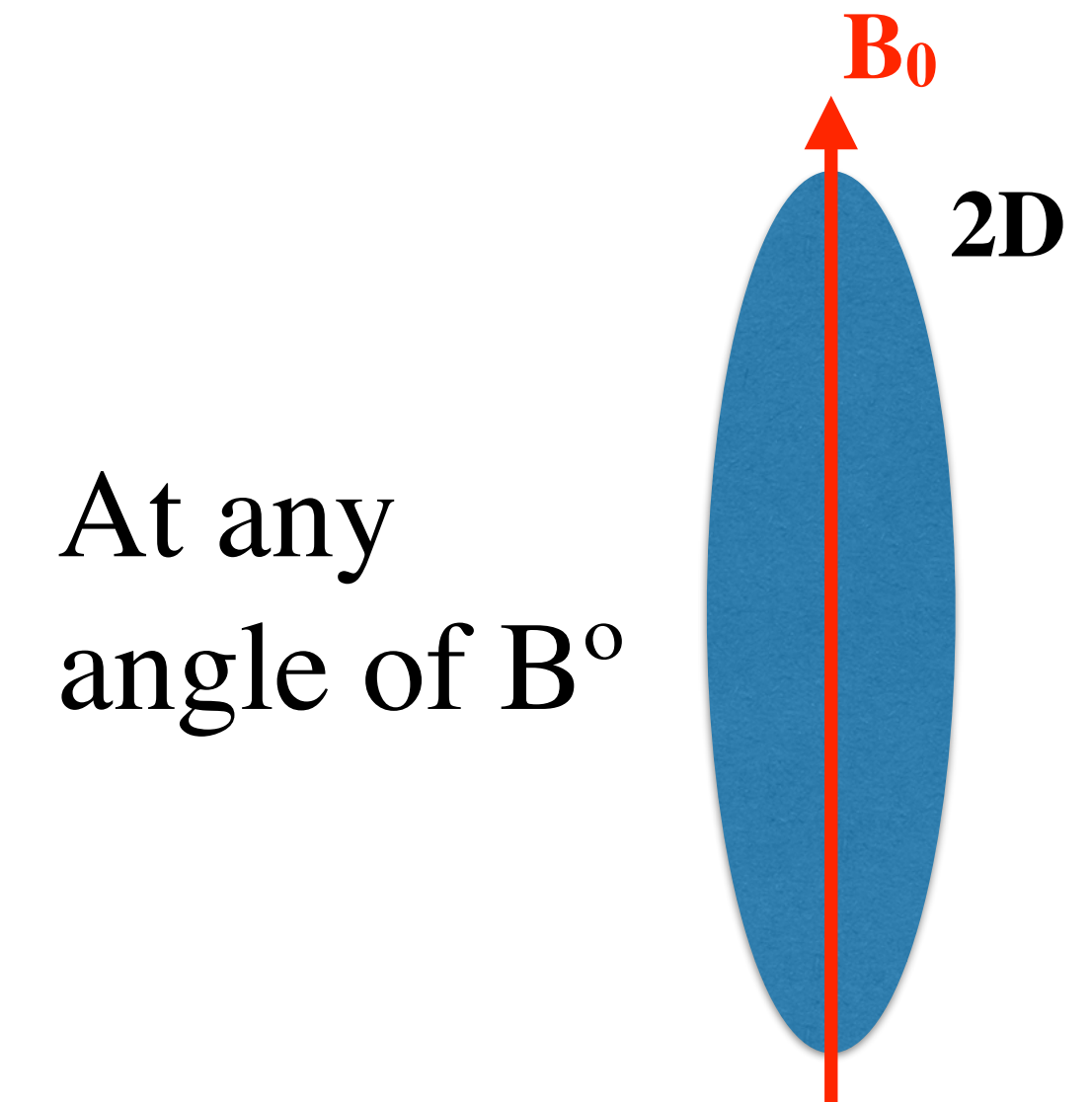
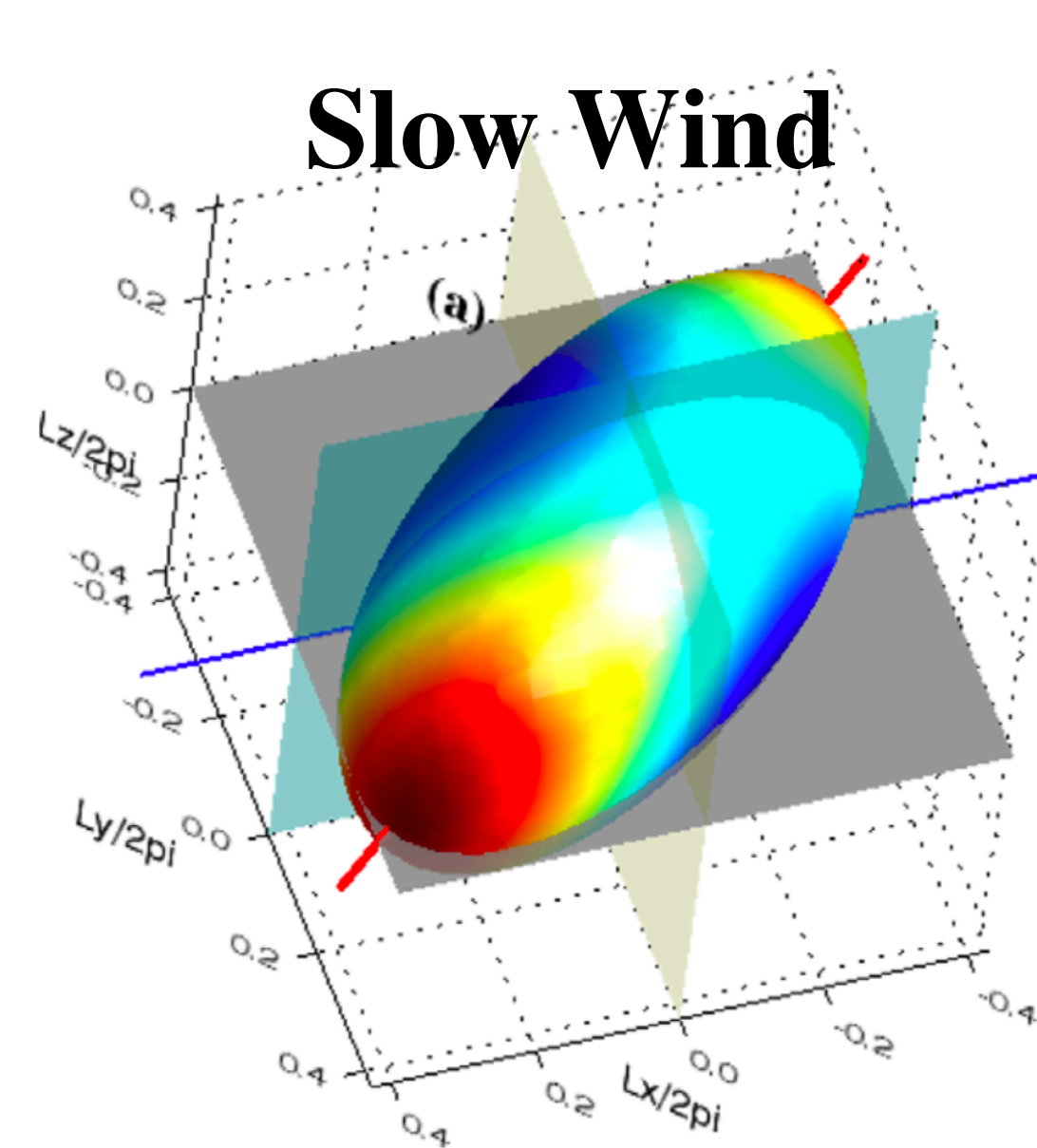
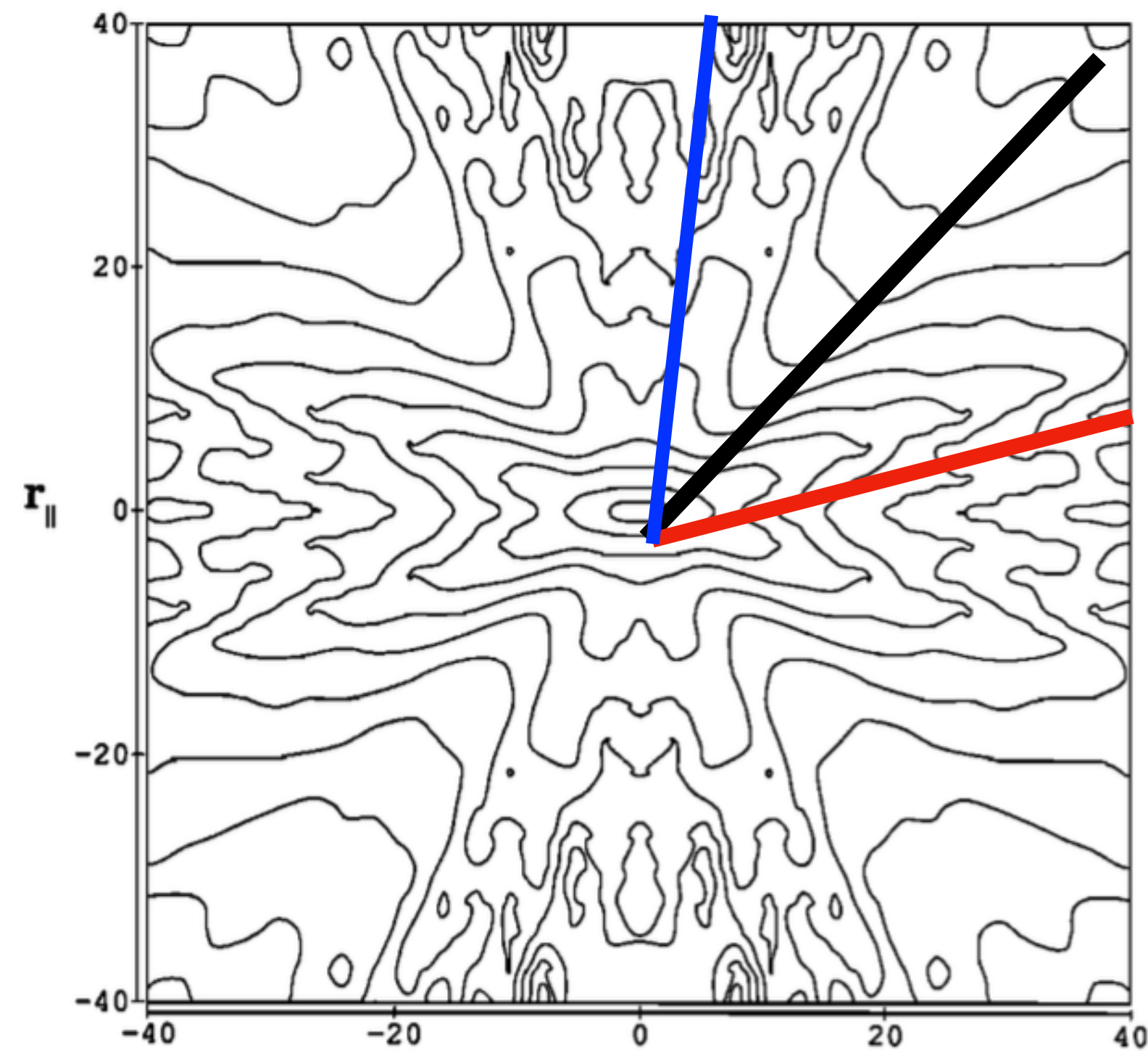
$$t_{NL}/t_{exp} \gtrsim 1$$



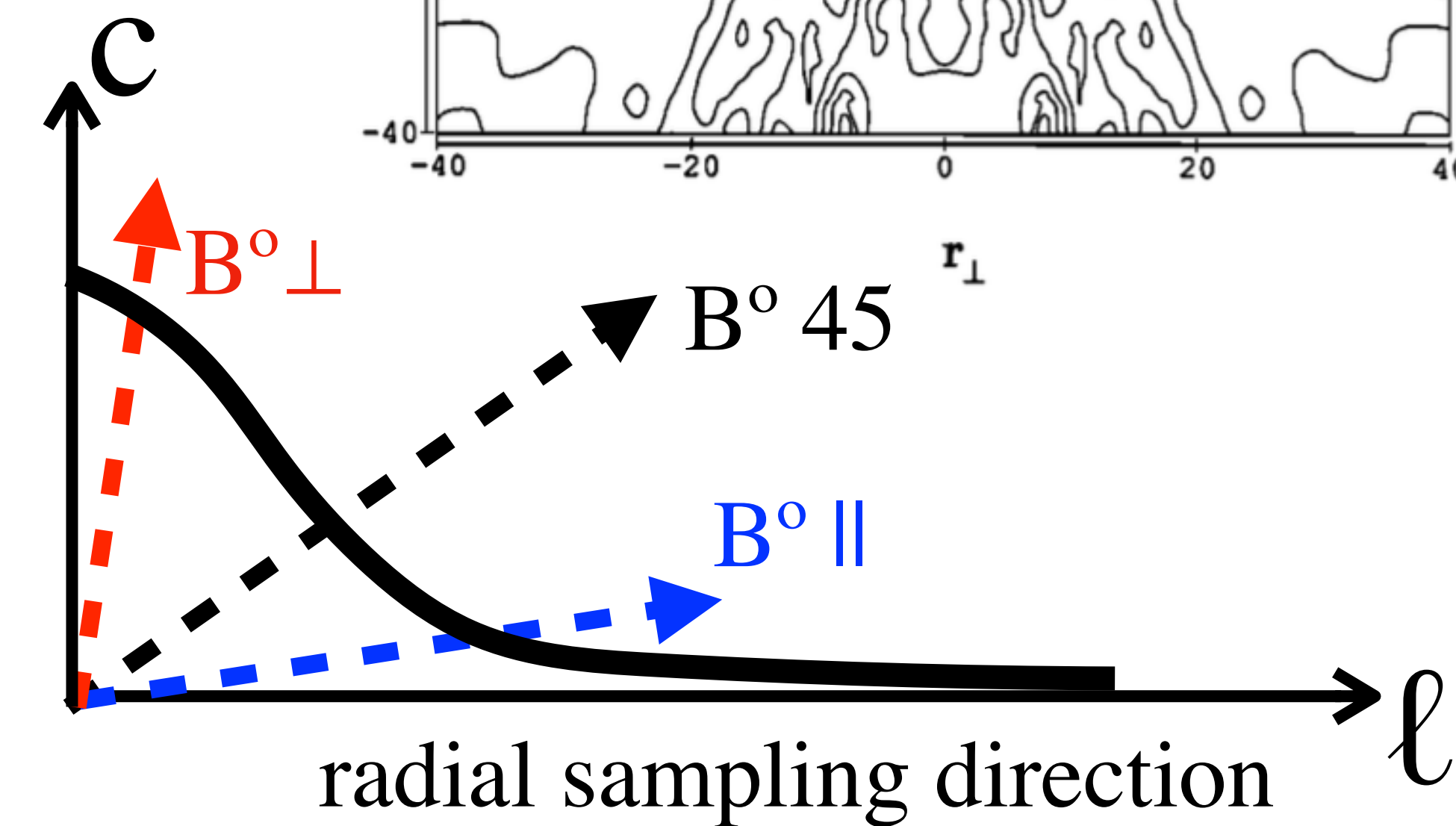
# An Explanation for the Maltese Cross



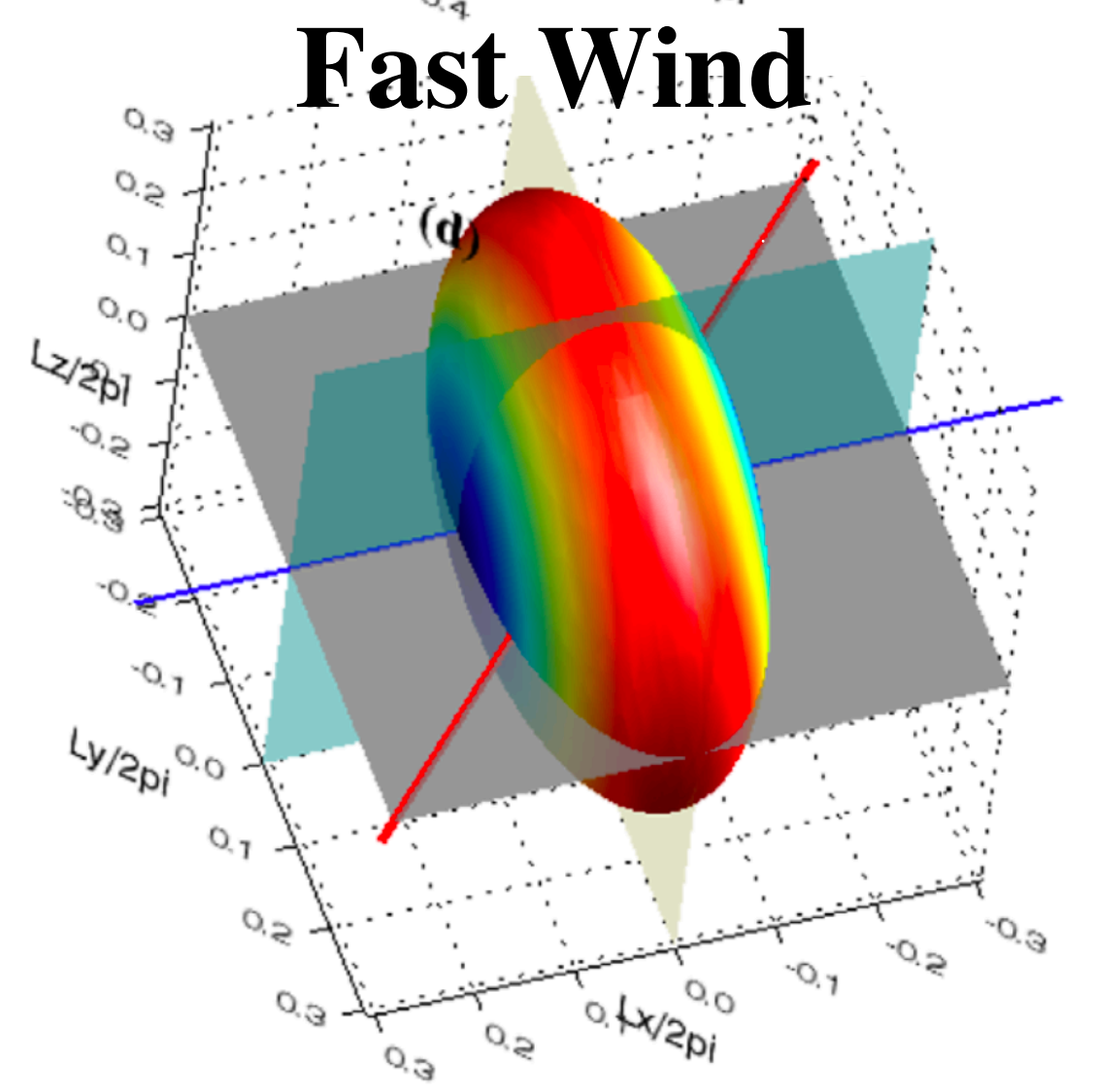
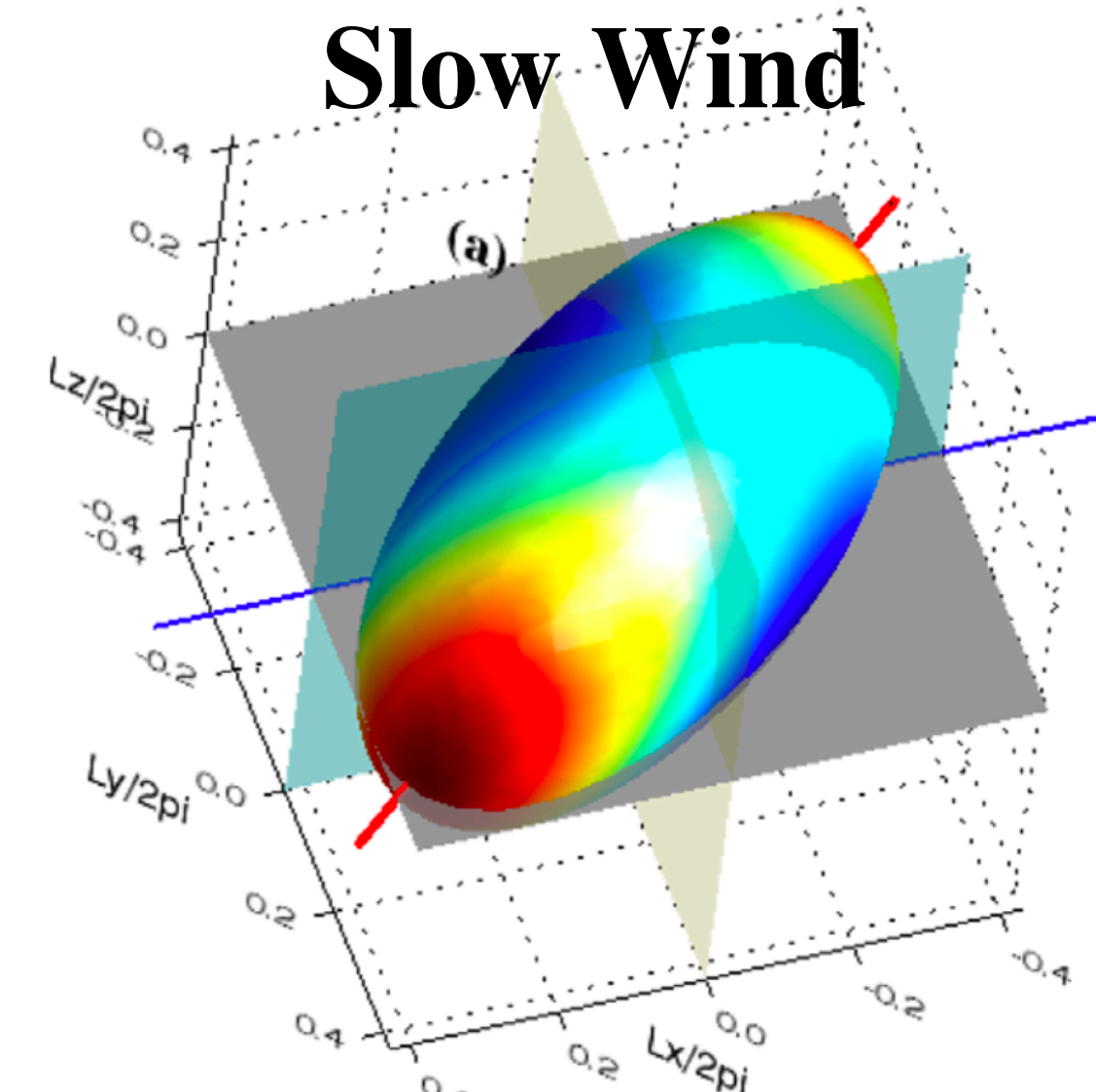
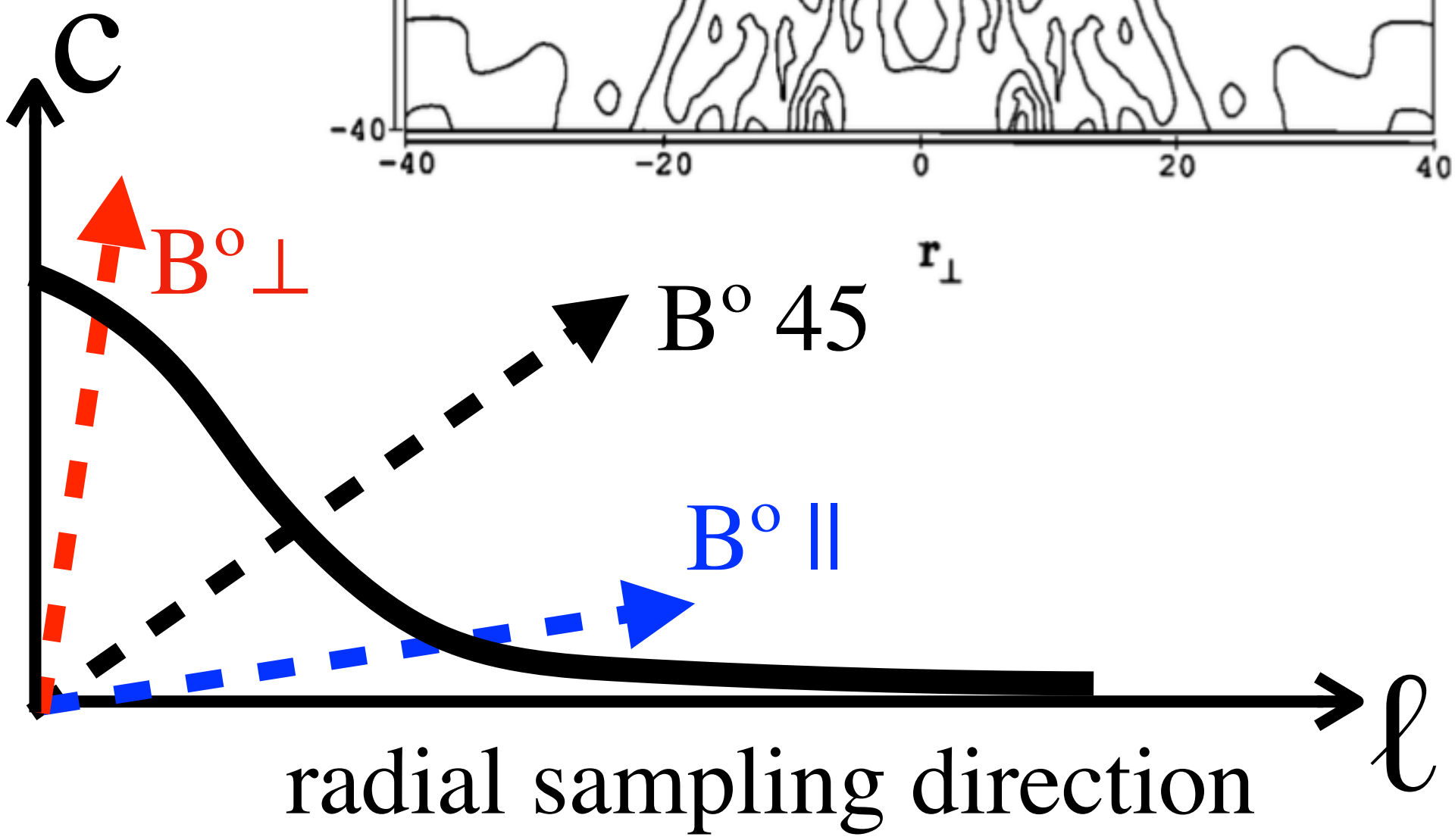
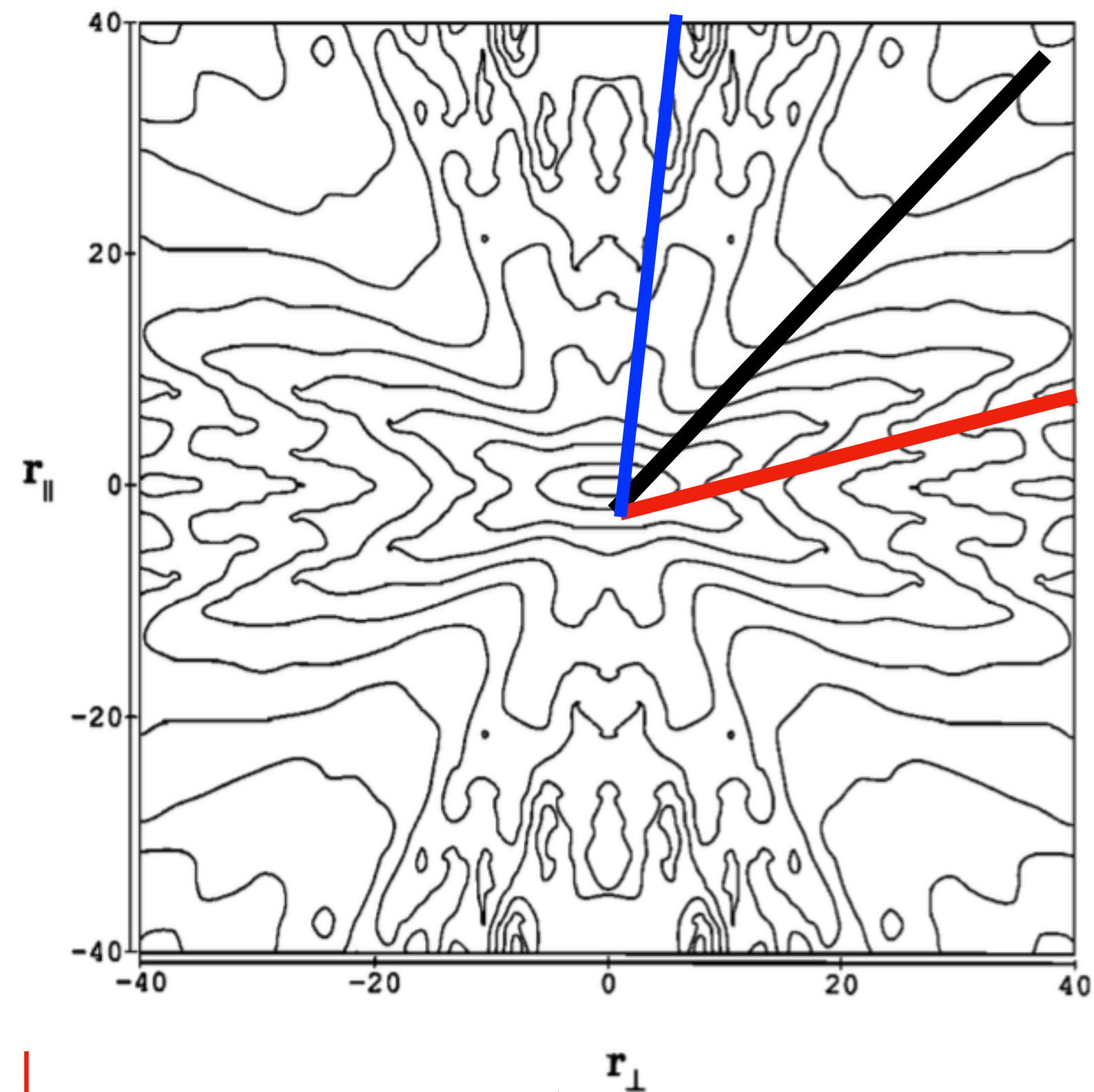
# An Explanation for the Maltese Cross



At any angle of  $B^\circ$

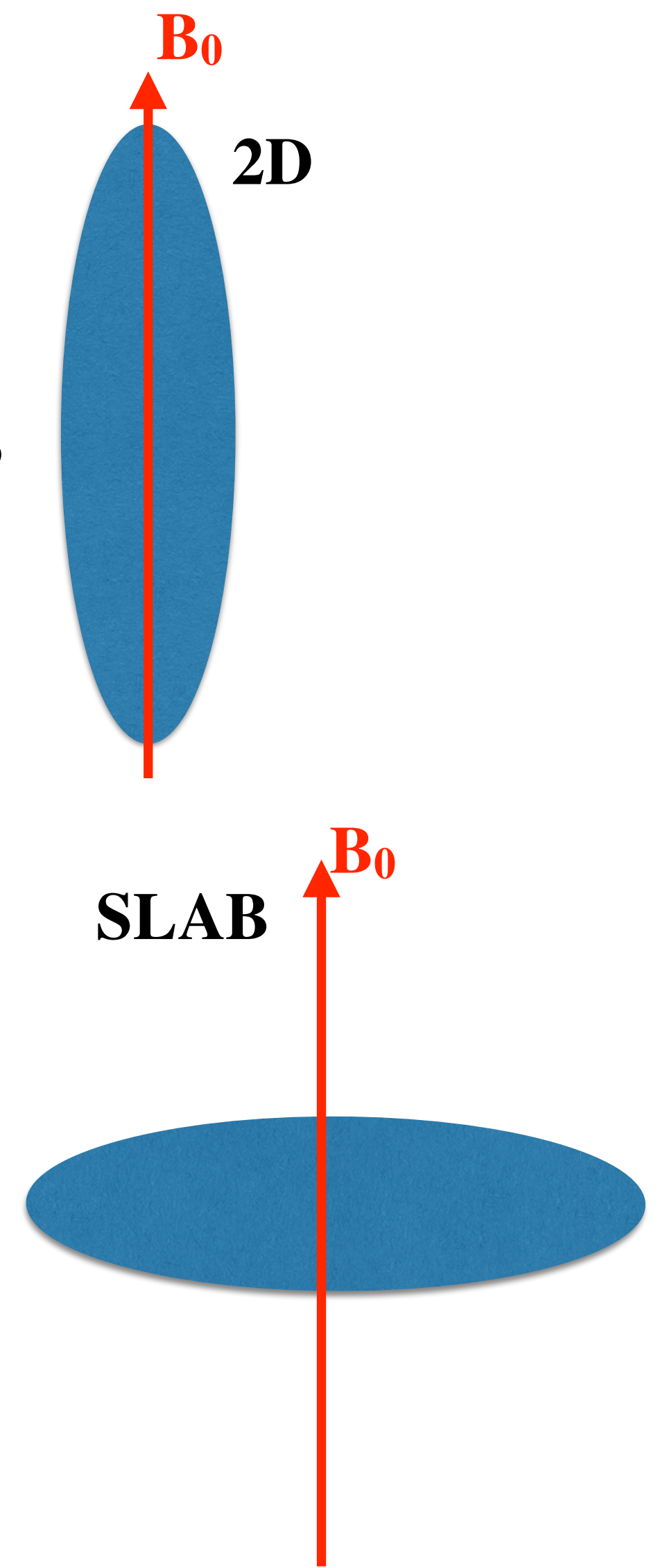


# An Explanation for the Maltese Cross



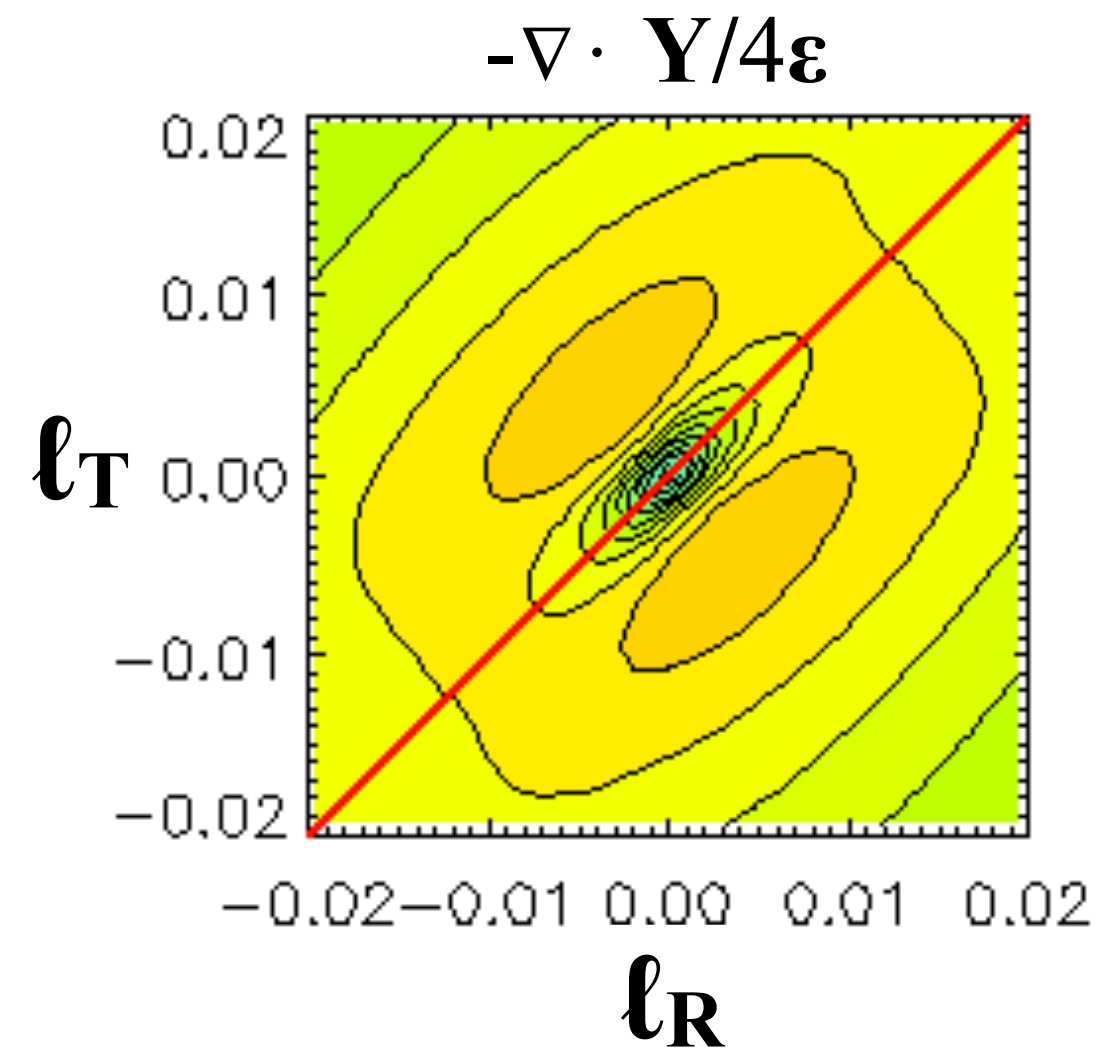
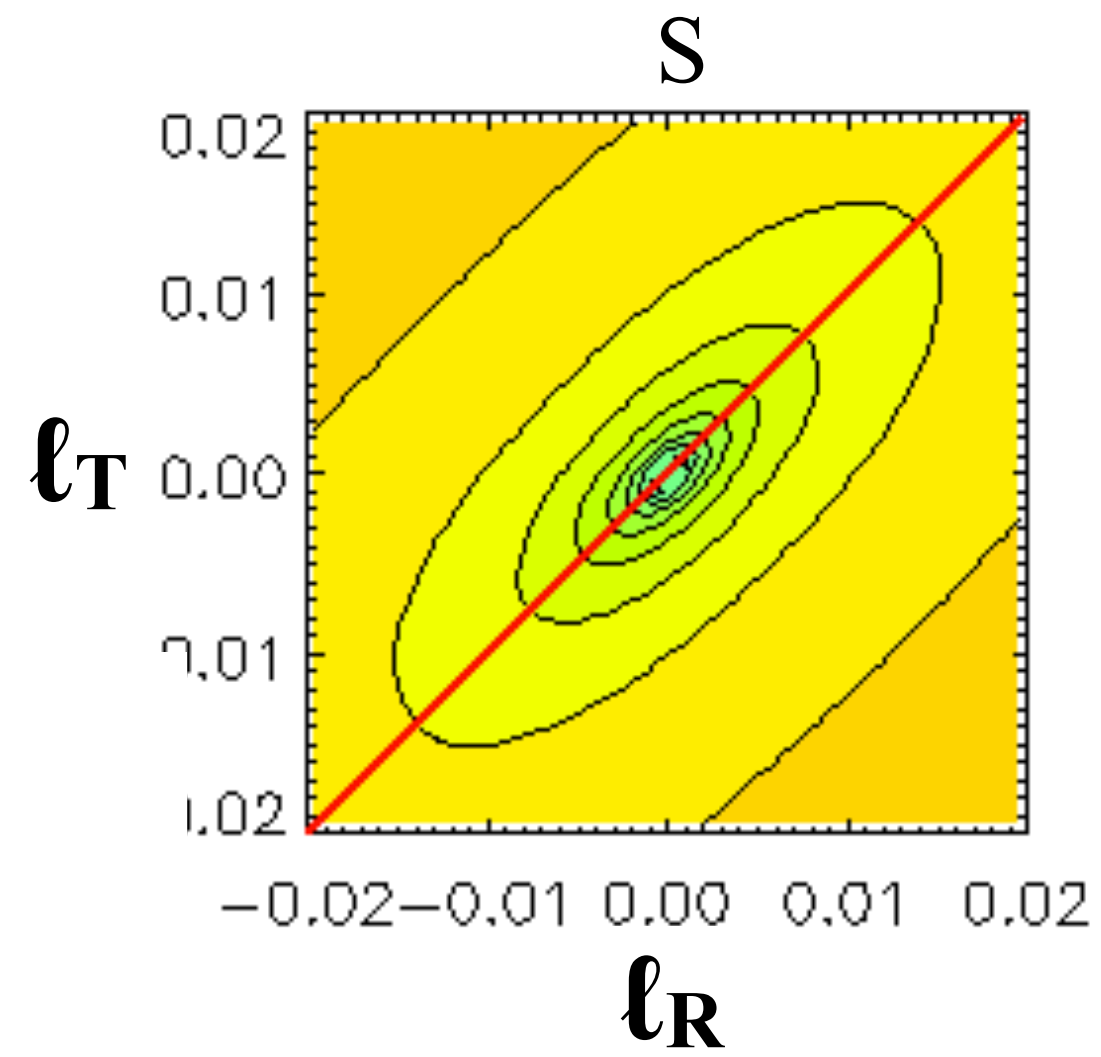
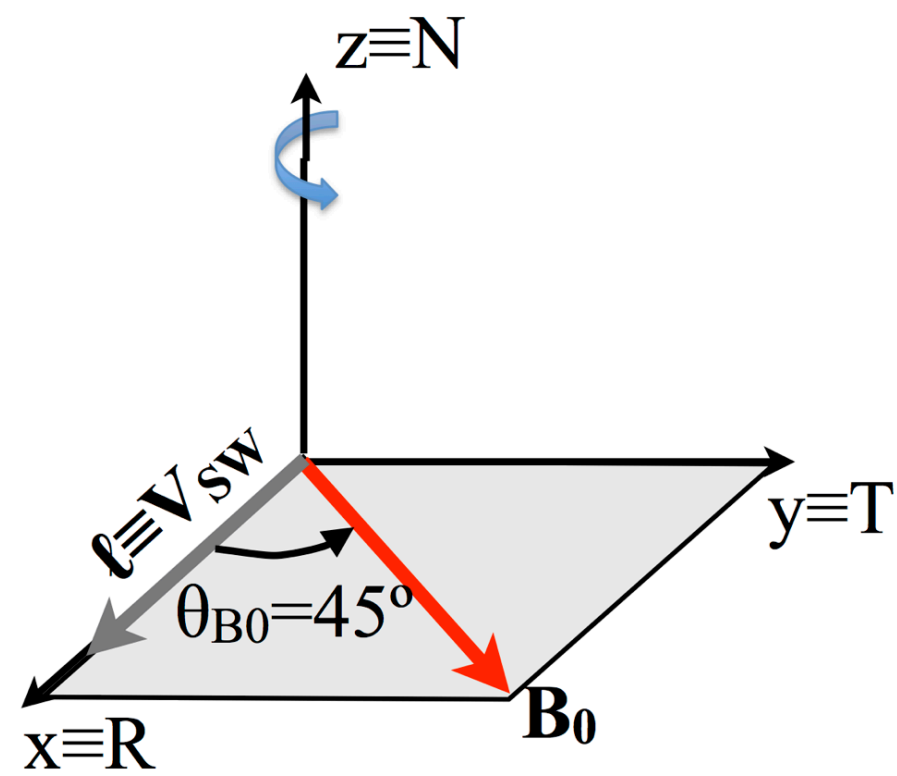
At any angle of  $B^{\circ}$

when  $B^{\circ}$  is close to radial



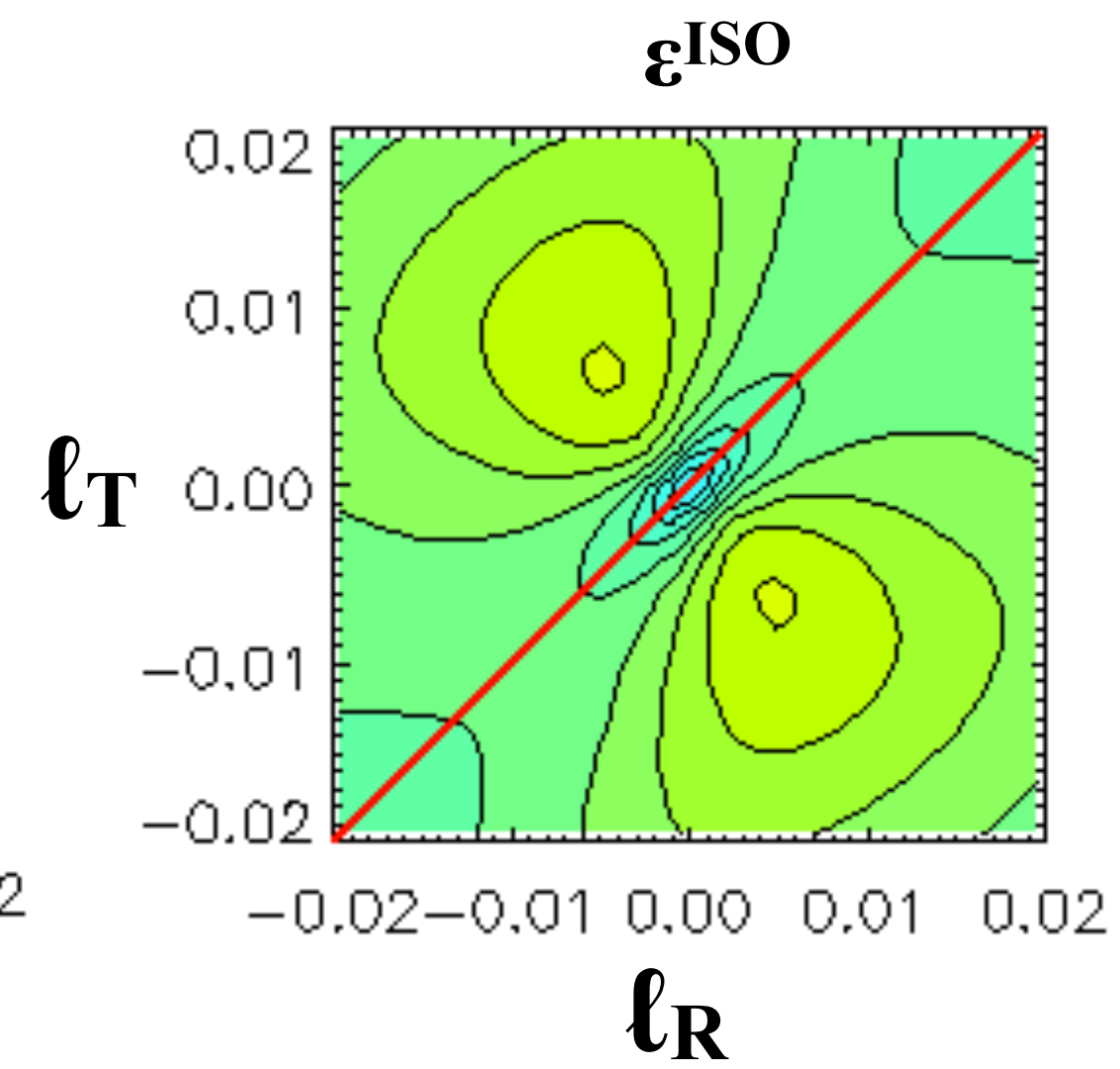
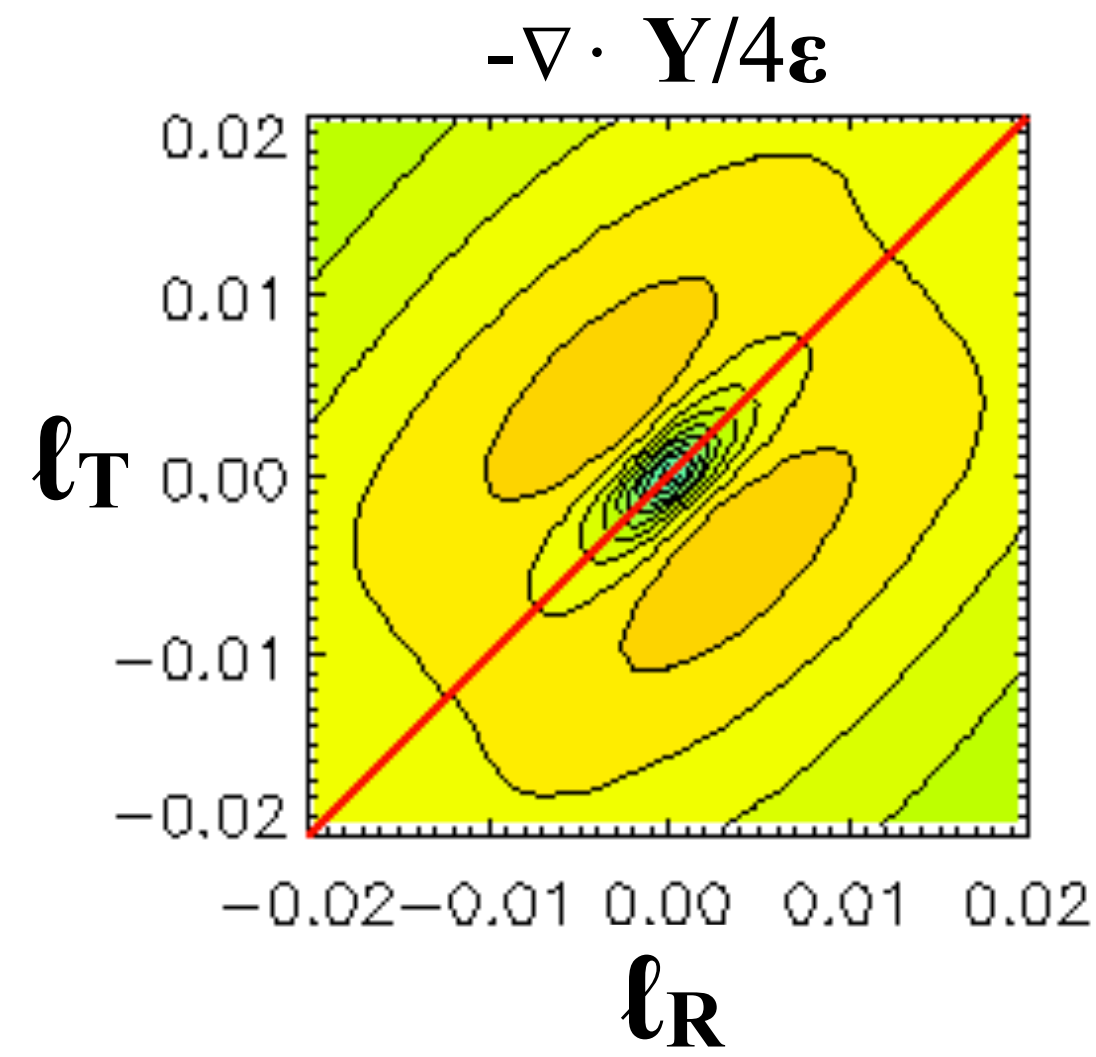
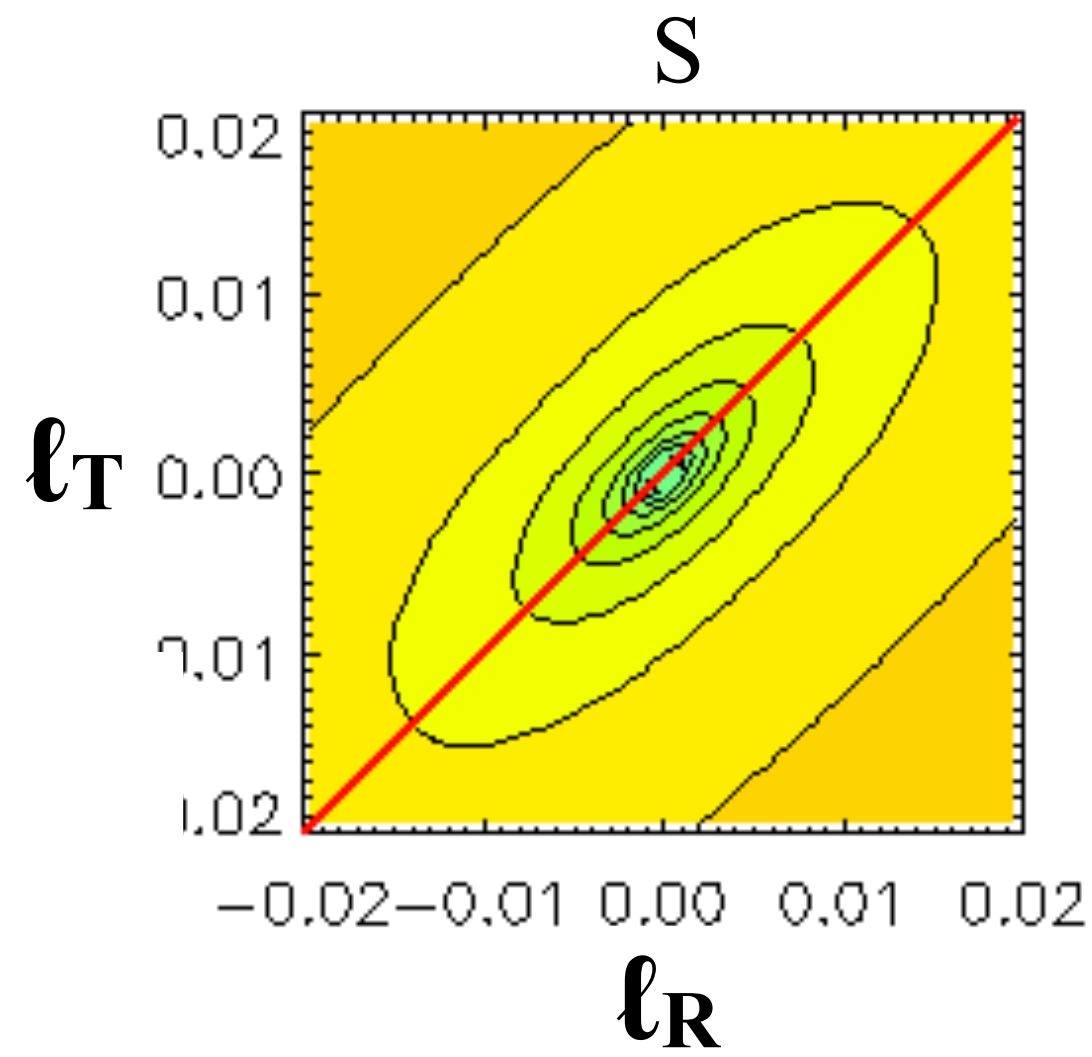
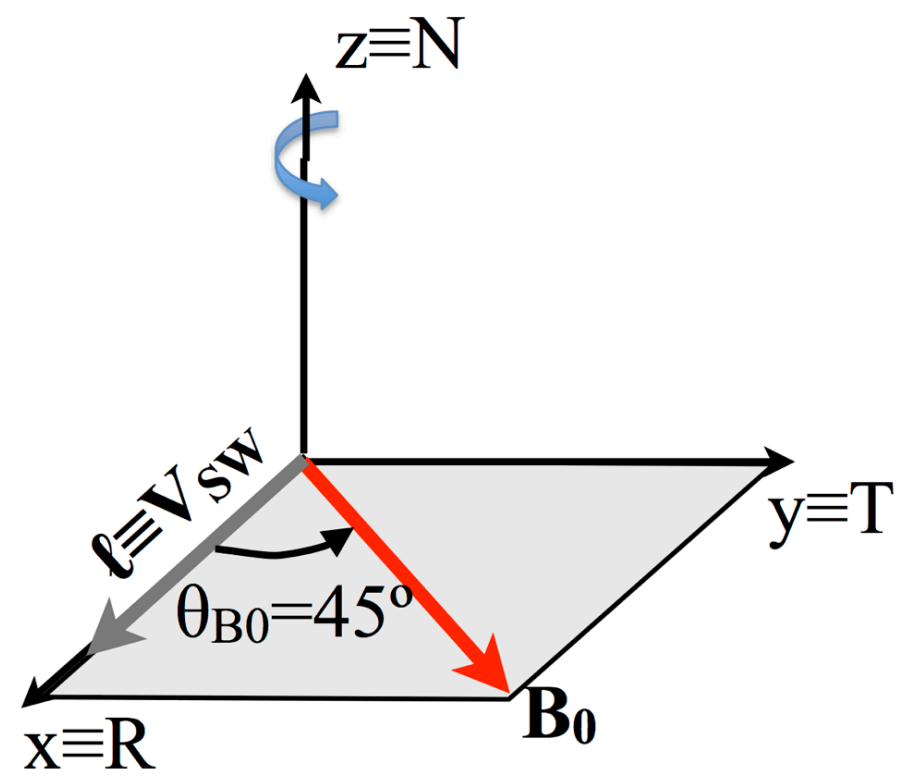
# Cascade Anisotropy

**without  
Expansion**  
(or small  
expansion)



# Cascade Anisotropy

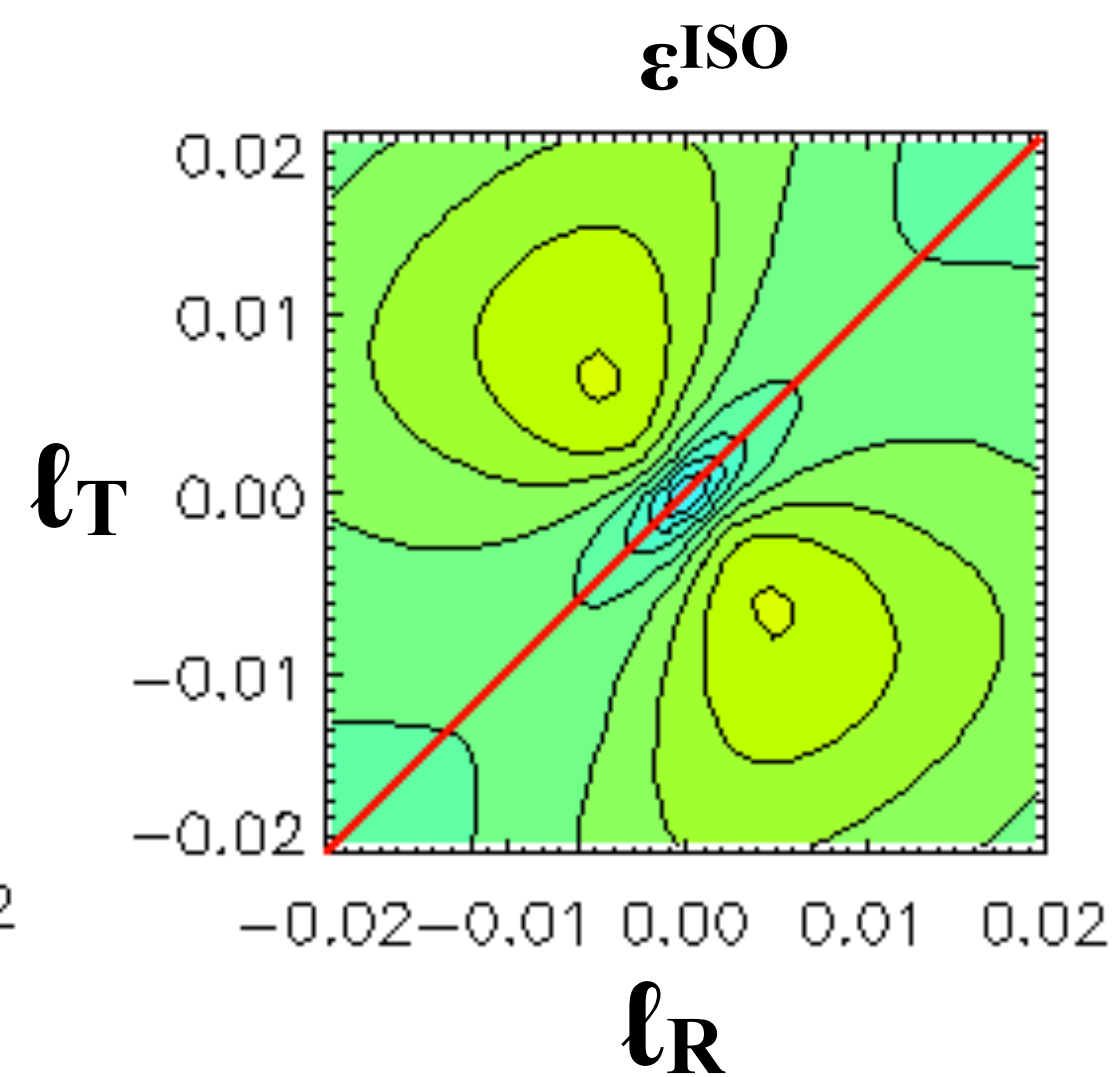
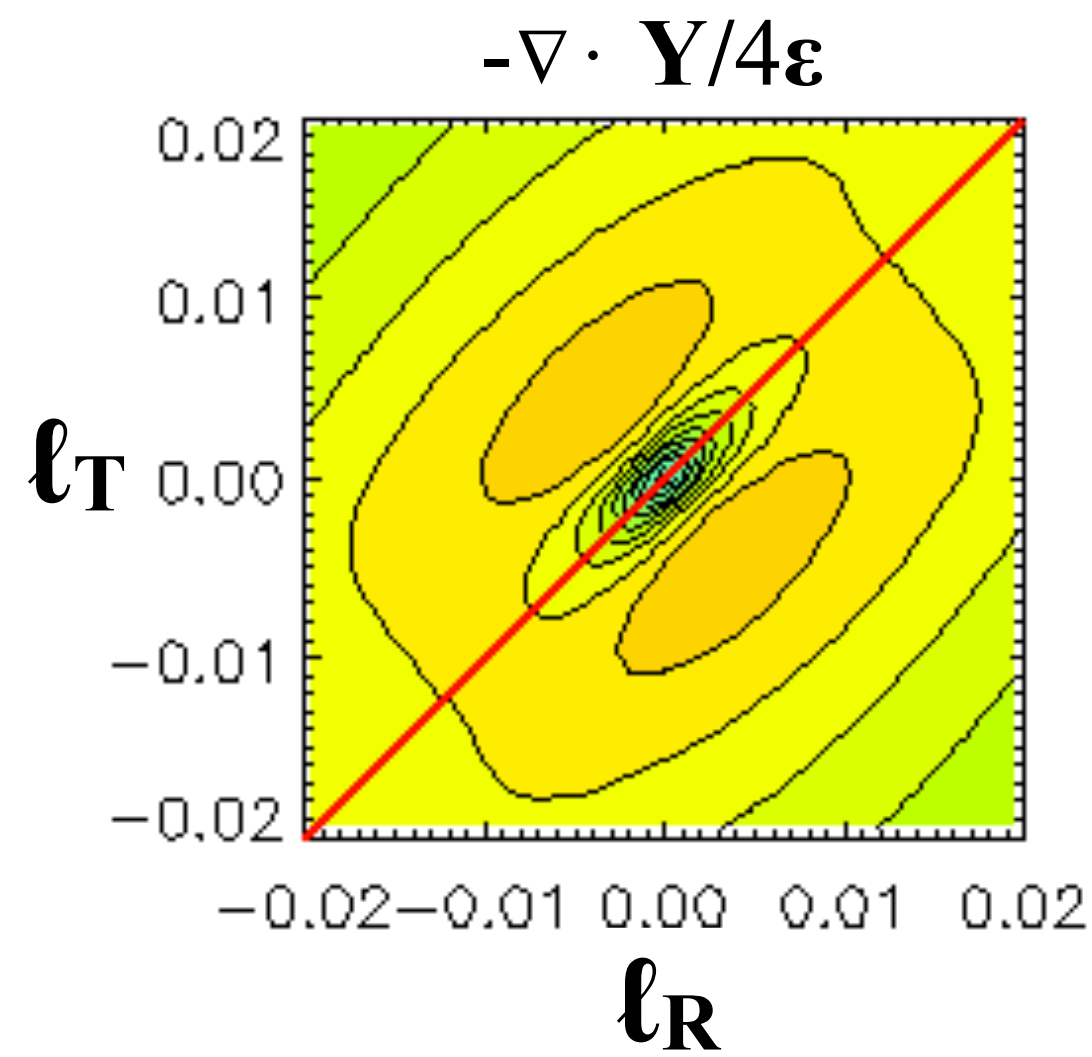
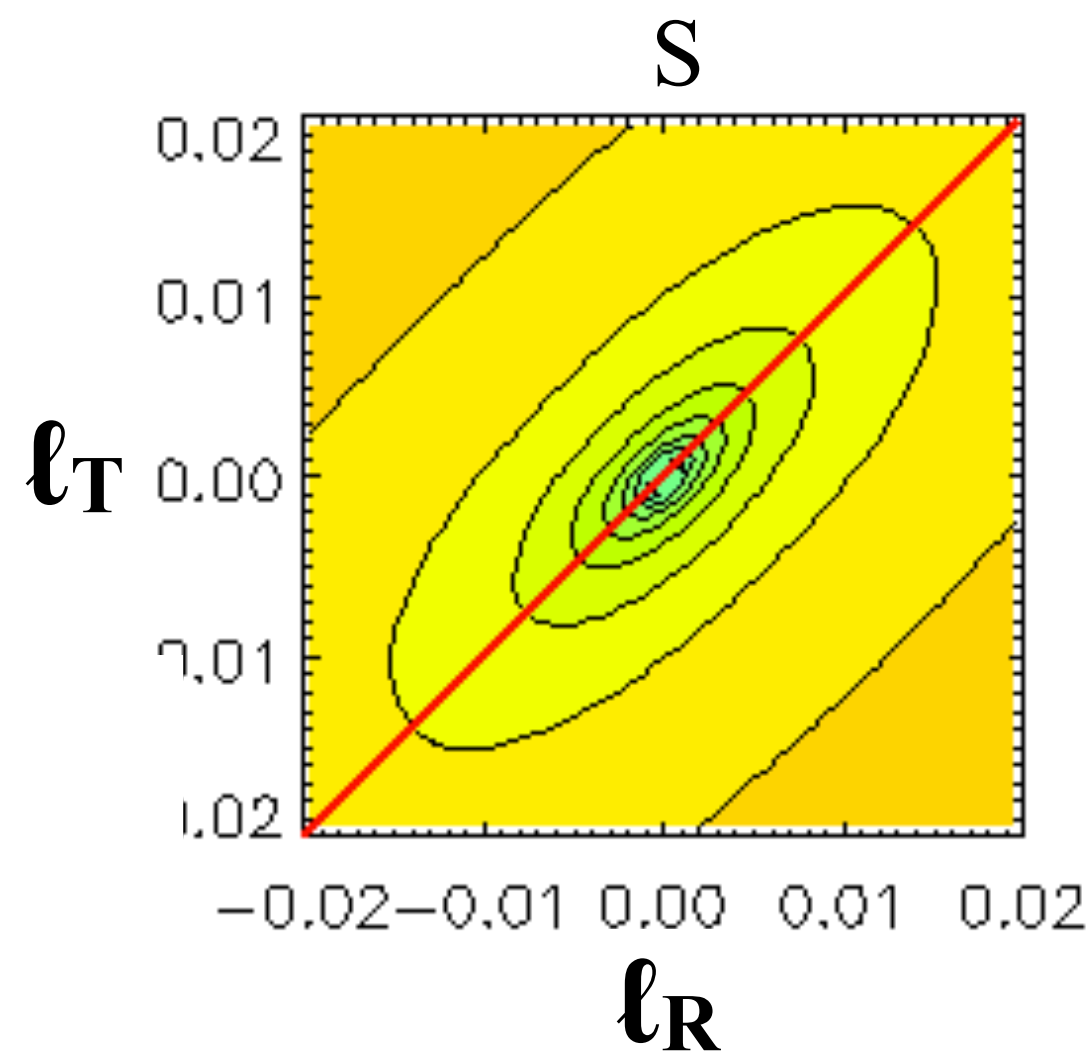
without  
Expansion  
(or small  
expansion)



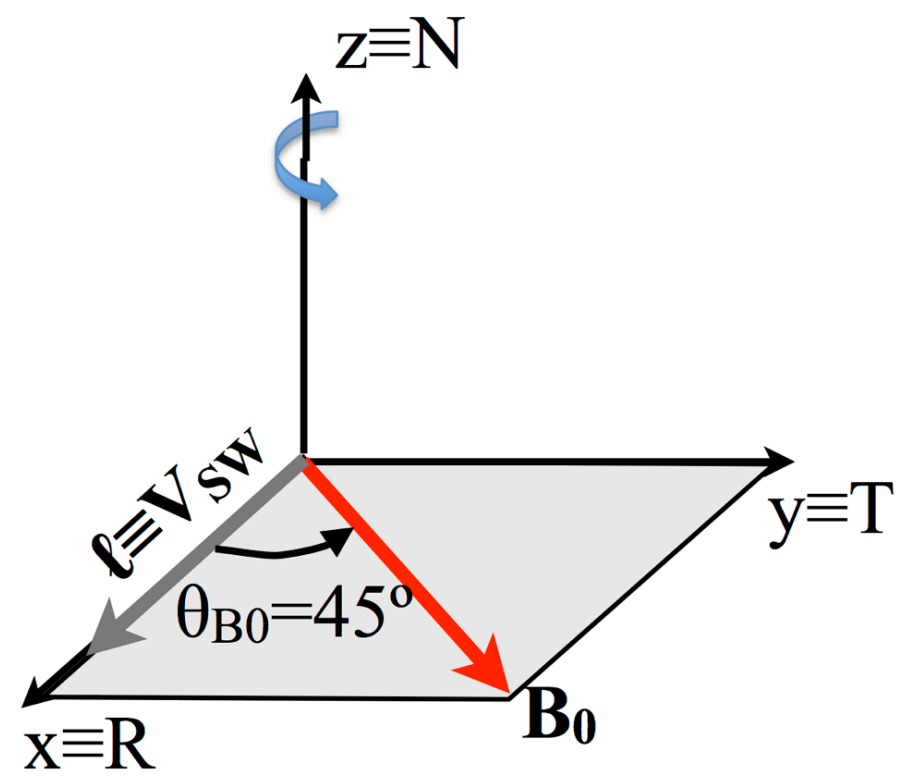
$$\epsilon^{ISO} = -\frac{3}{4} \frac{\mathbf{Y} \cdot \hat{l}}{l}$$

# Cascade Anisotropy

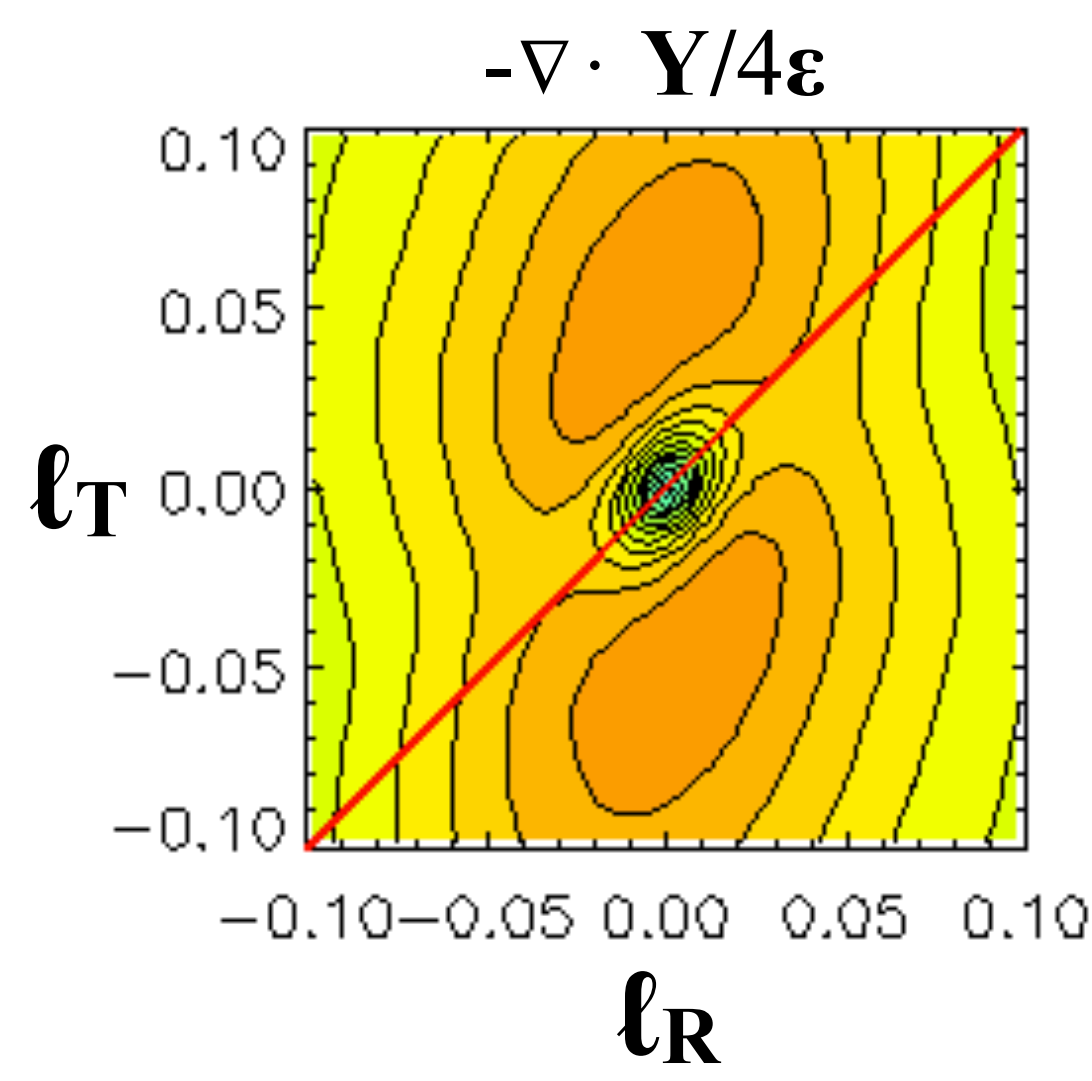
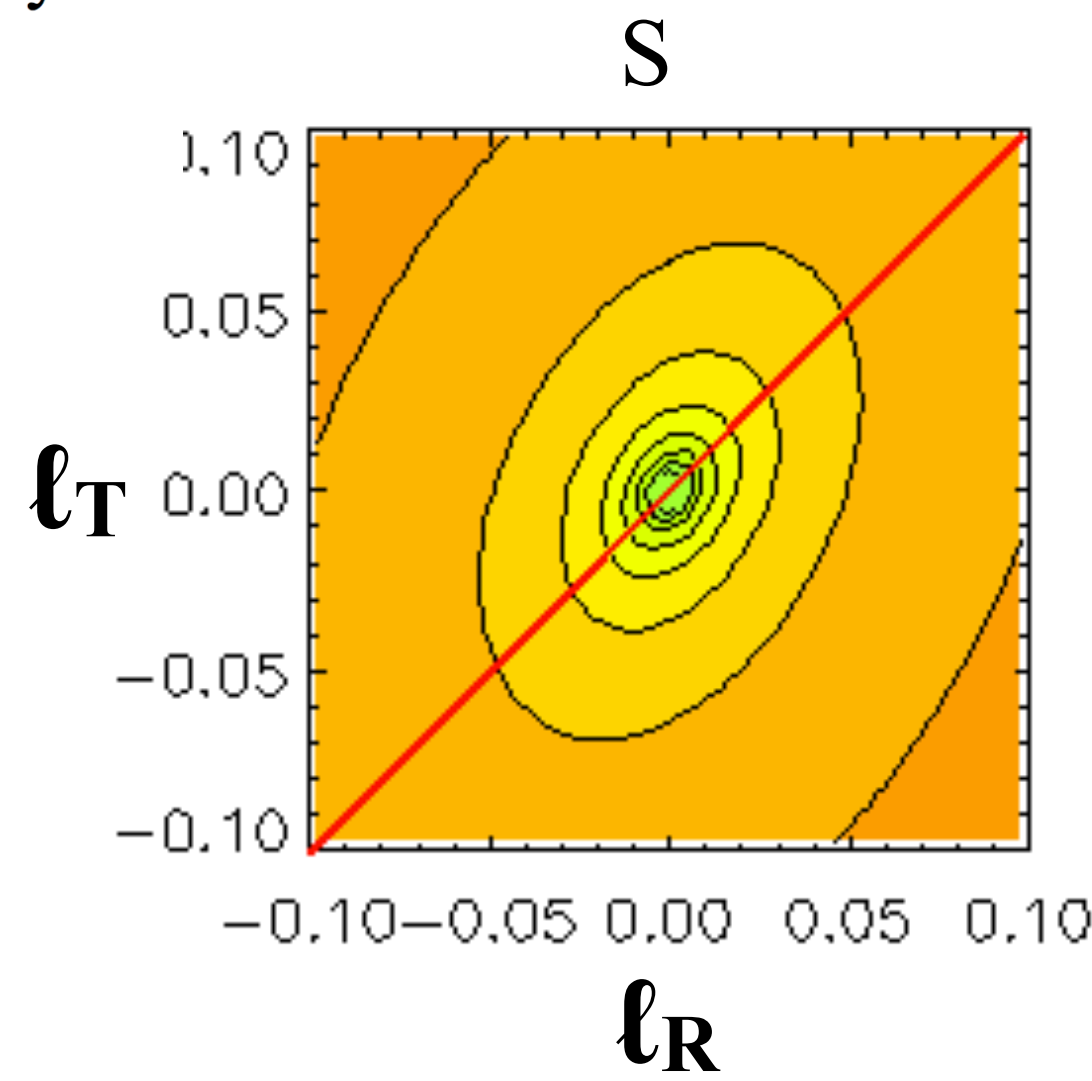
**without  
Expansion**  
(or small  
expansion)



$$\epsilon^{ISO} = -\frac{3}{4} \frac{\mathbf{Y} \cdot \hat{\ell}}{\ell}$$



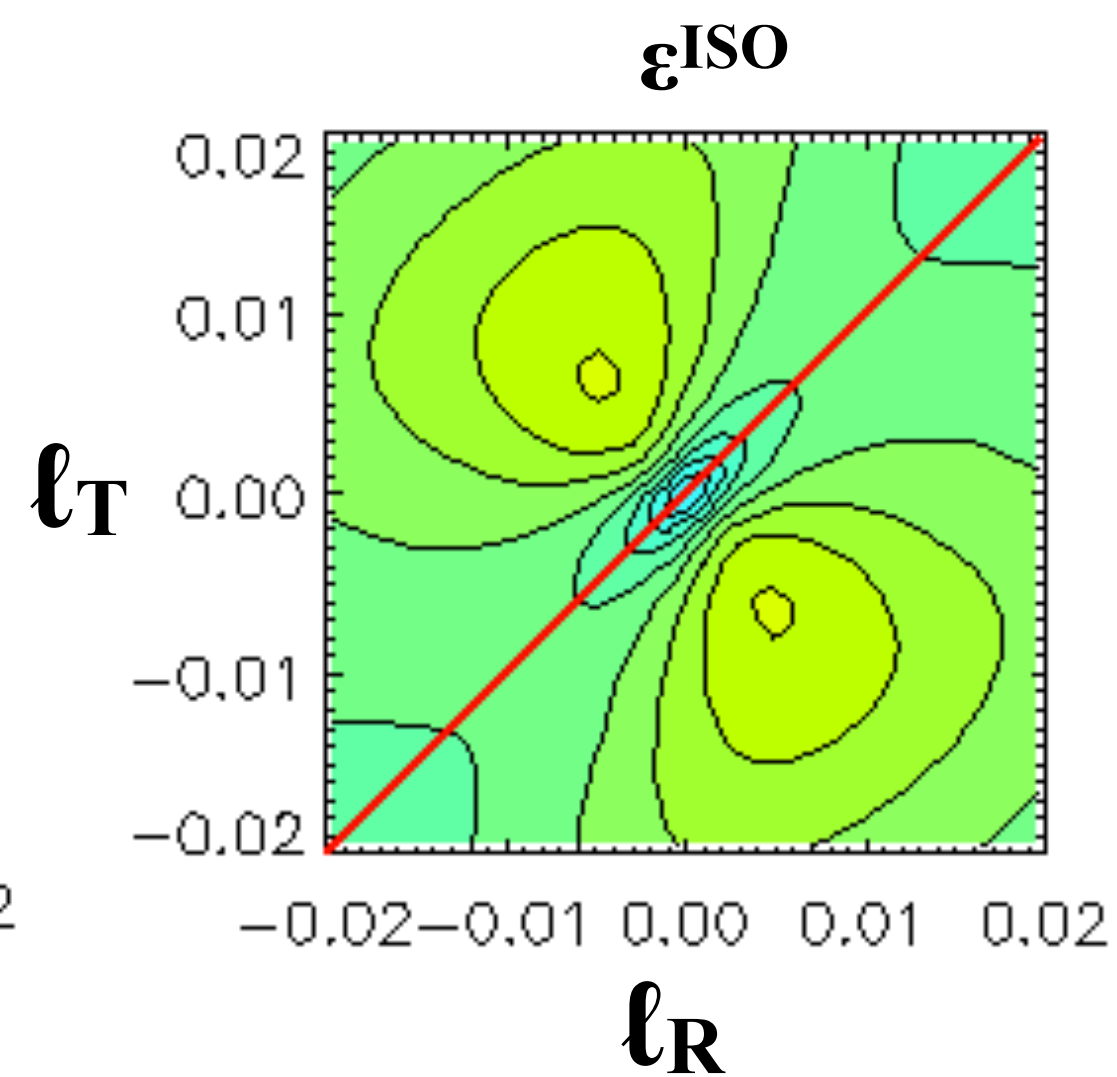
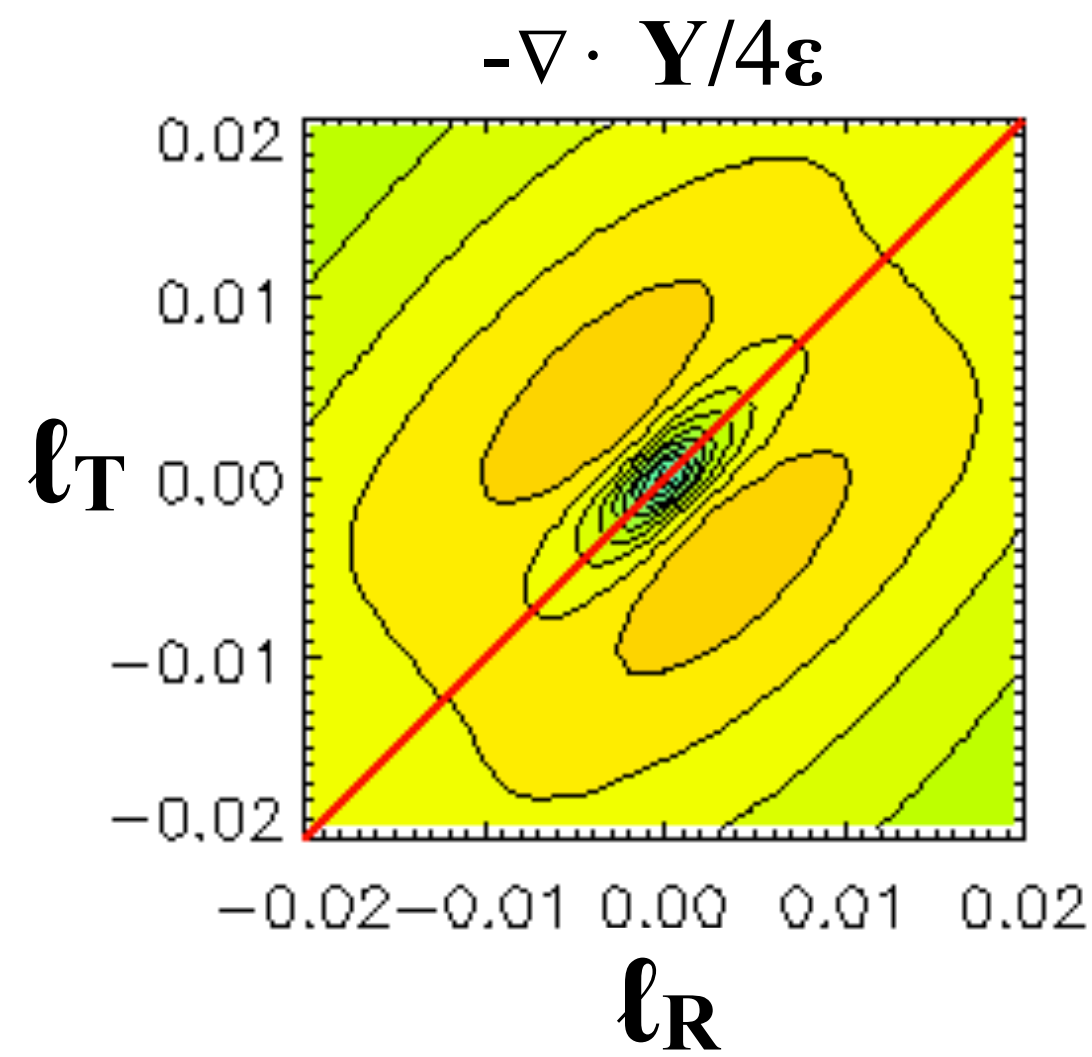
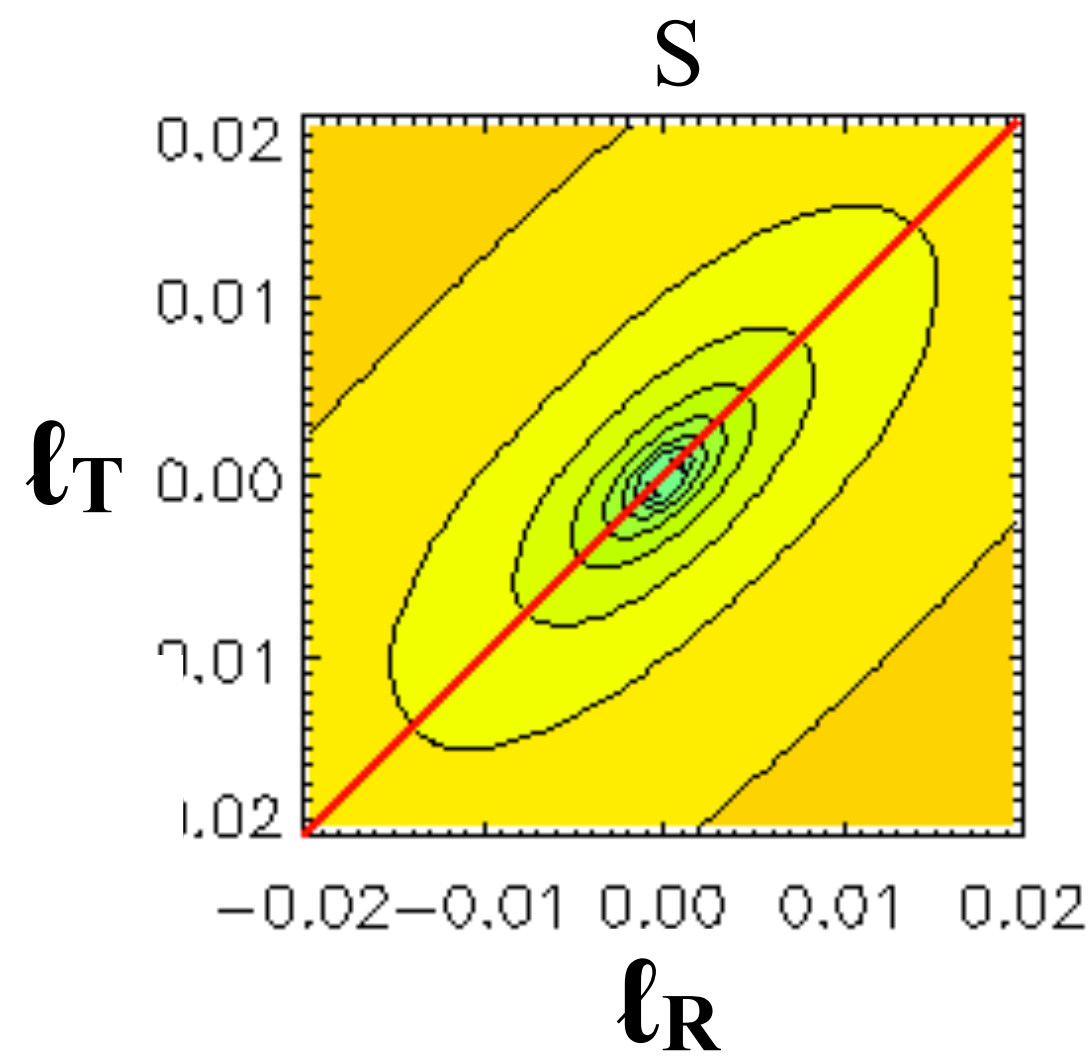
**With  
Expansion**



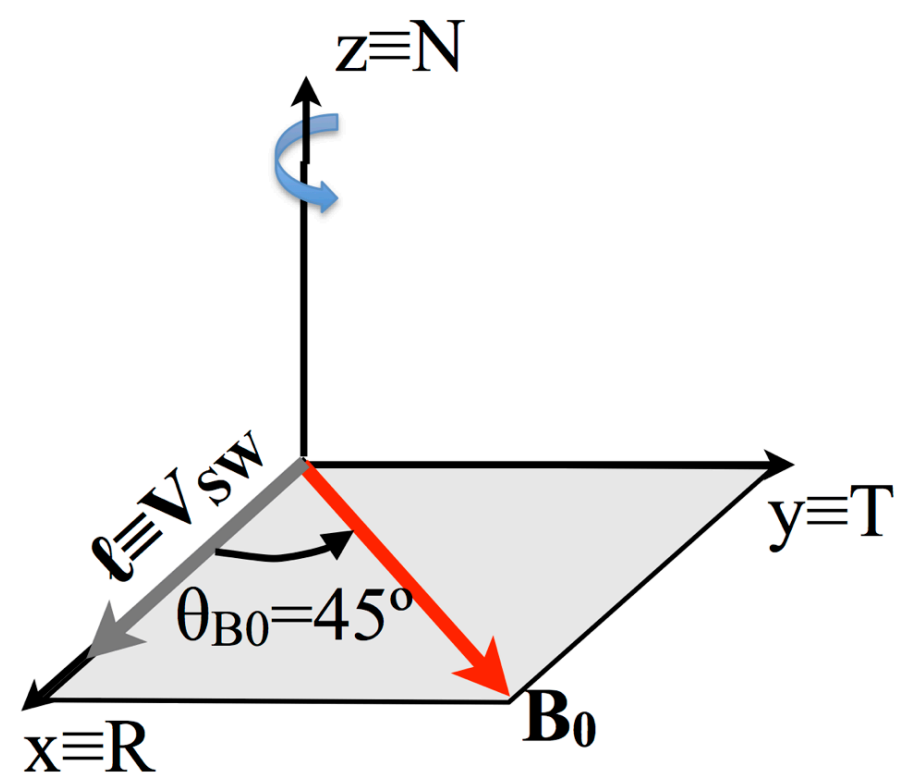
**Cascade  
is not strictly  
 $\perp$  to  $B^0$**

# Cascade Anisotropy

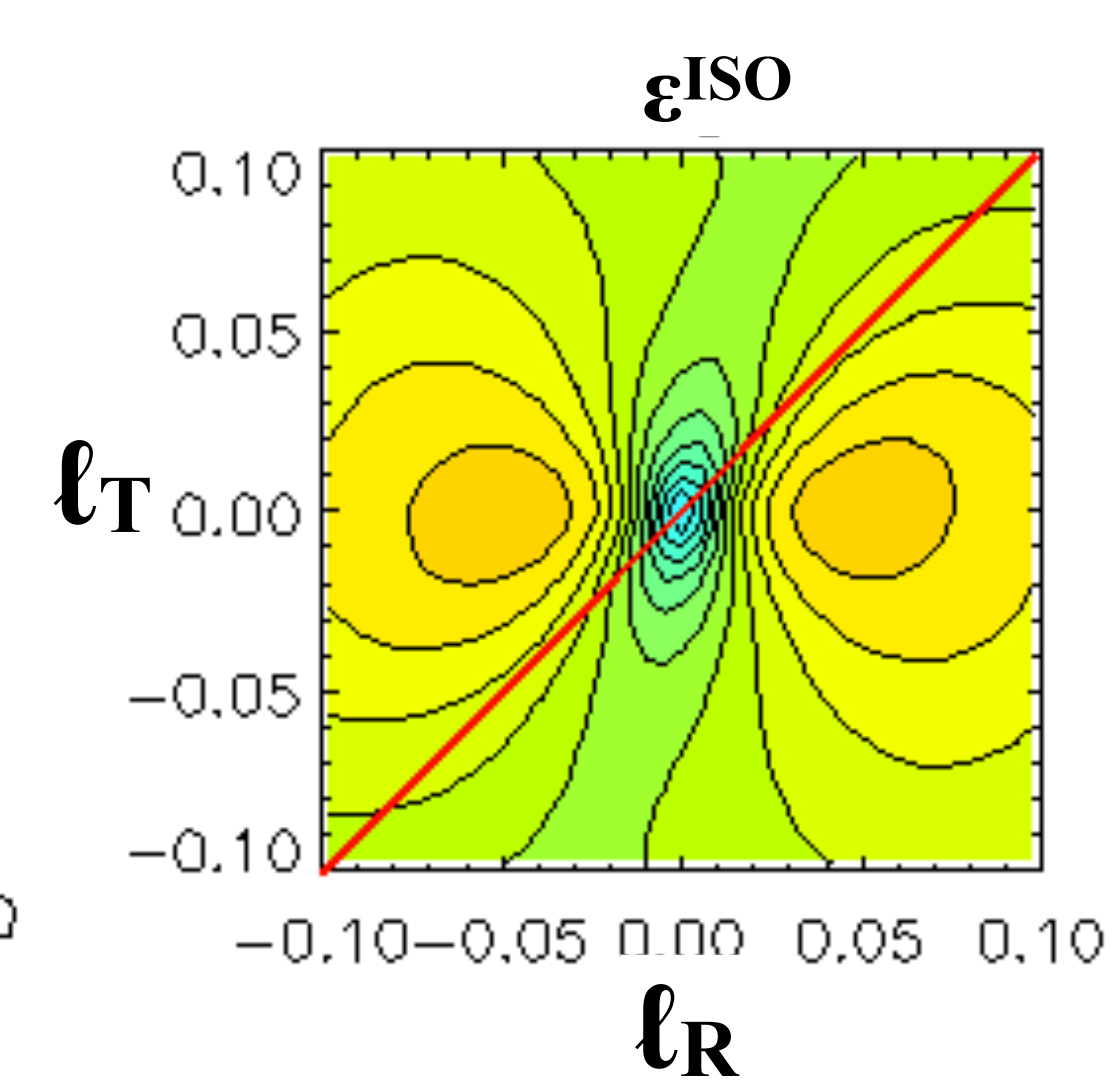
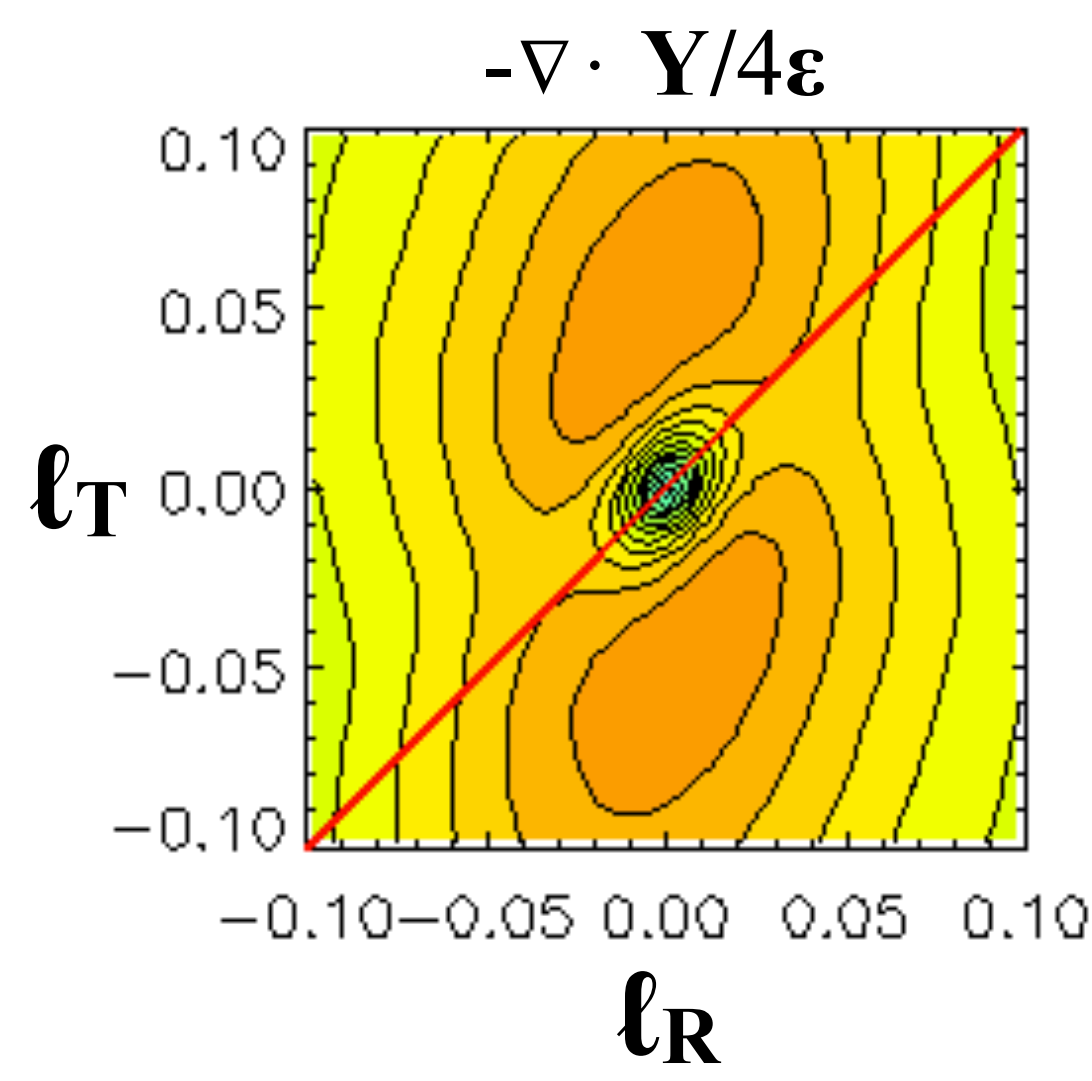
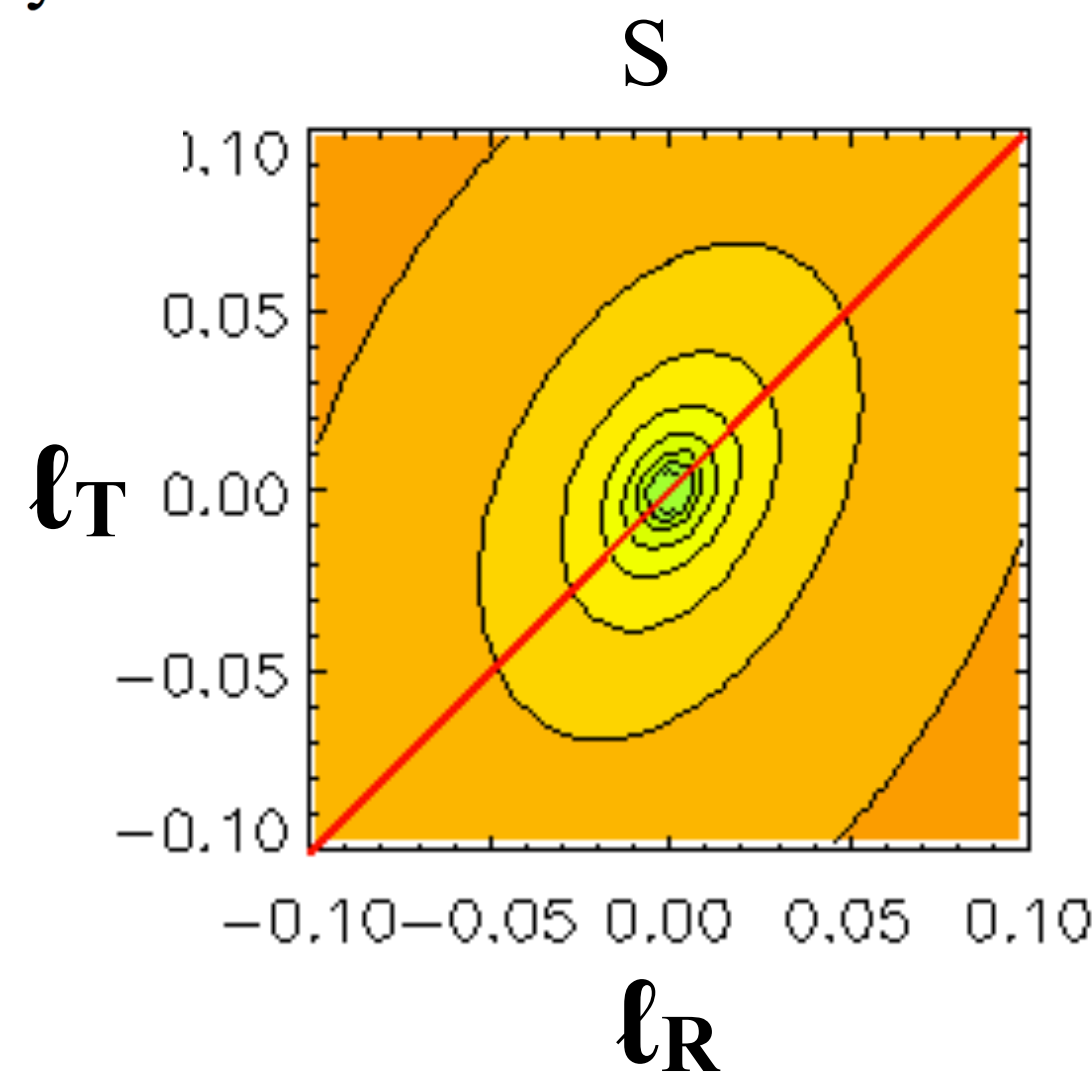
**without  
Expansion**  
(or small  
expansion)



$$\epsilon^{ISO} = -\frac{3}{4} \frac{\mathbf{Y} \cdot \hat{\ell}}{\ell}$$



**With  
Expansion**

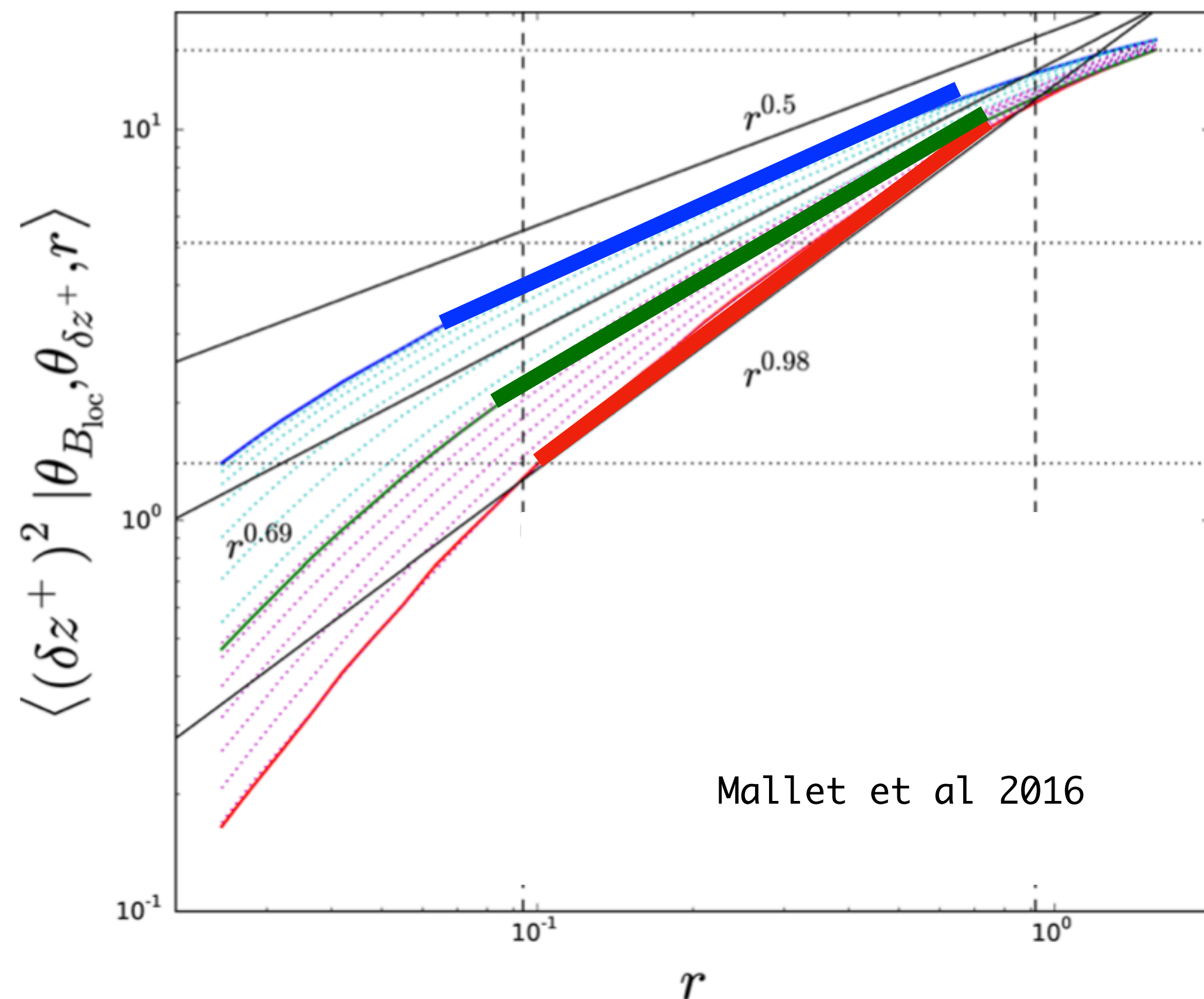


**The isotropic  
prescription  
Fails to capture  
anisotropy of  
the cascade**

# Scale dependent anisotropy

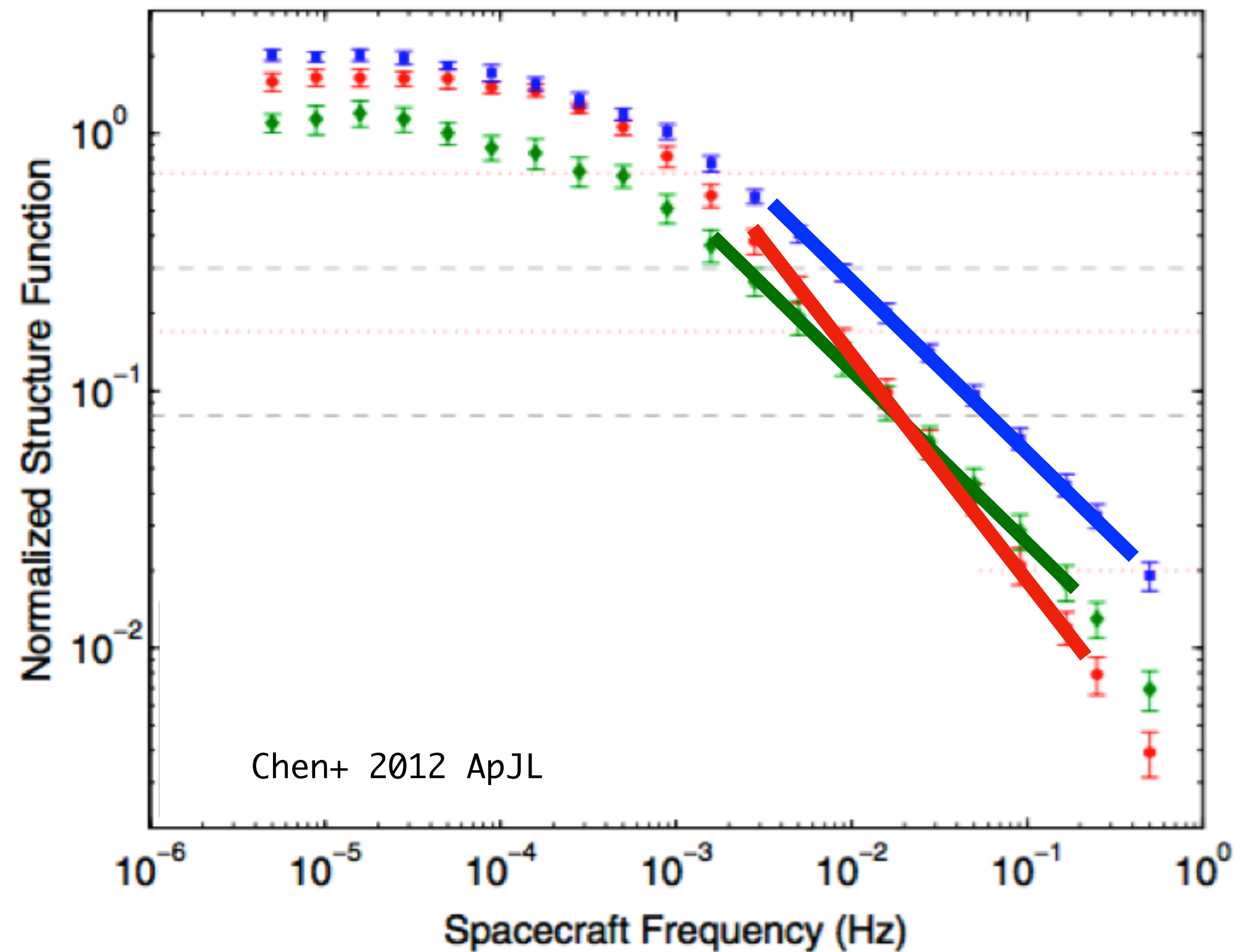
## Simulations

3 different scaling for  $\ell_{\parallel}$ ,  $\ell_{\perp 1}$ ,  $\ell_{\perp 2}$



## Solar Wind Observations

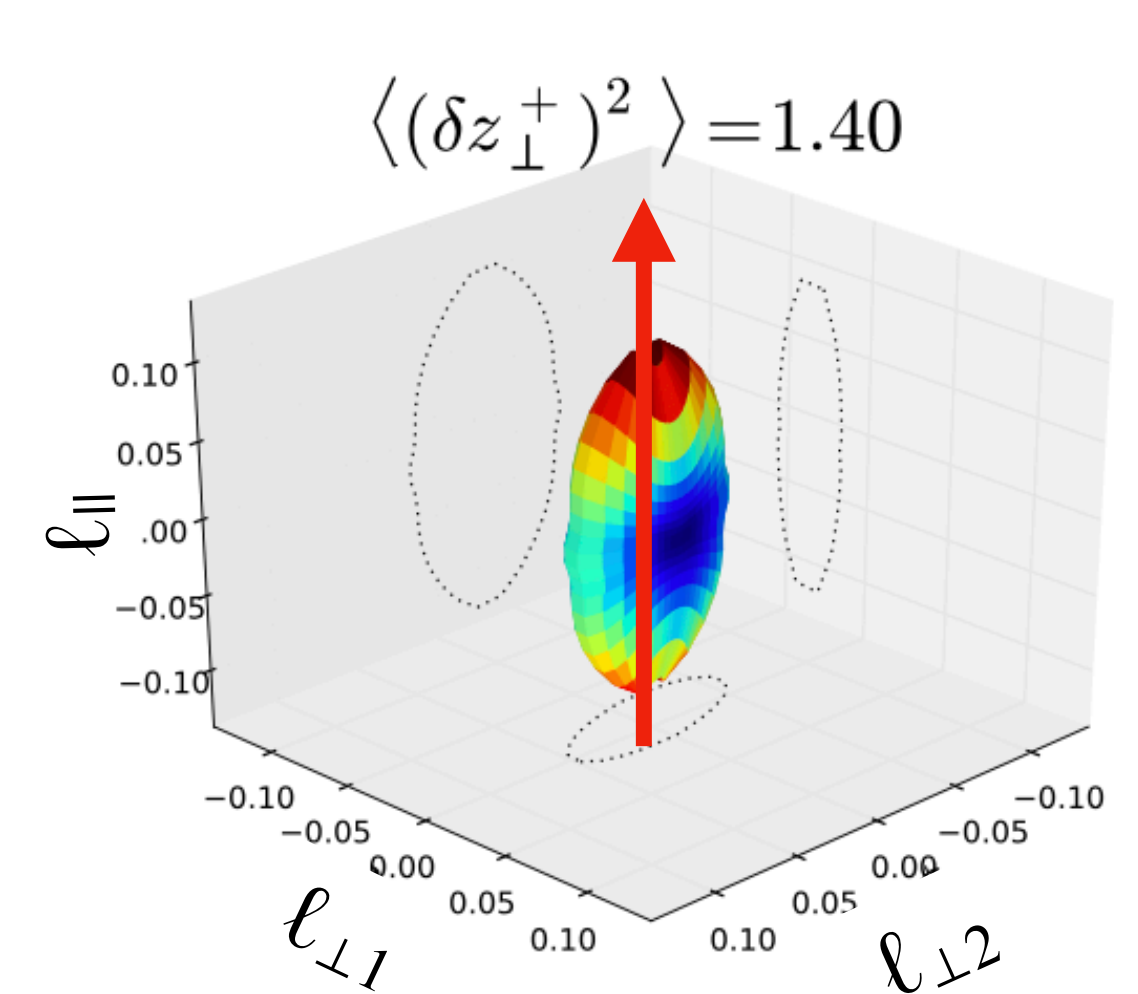
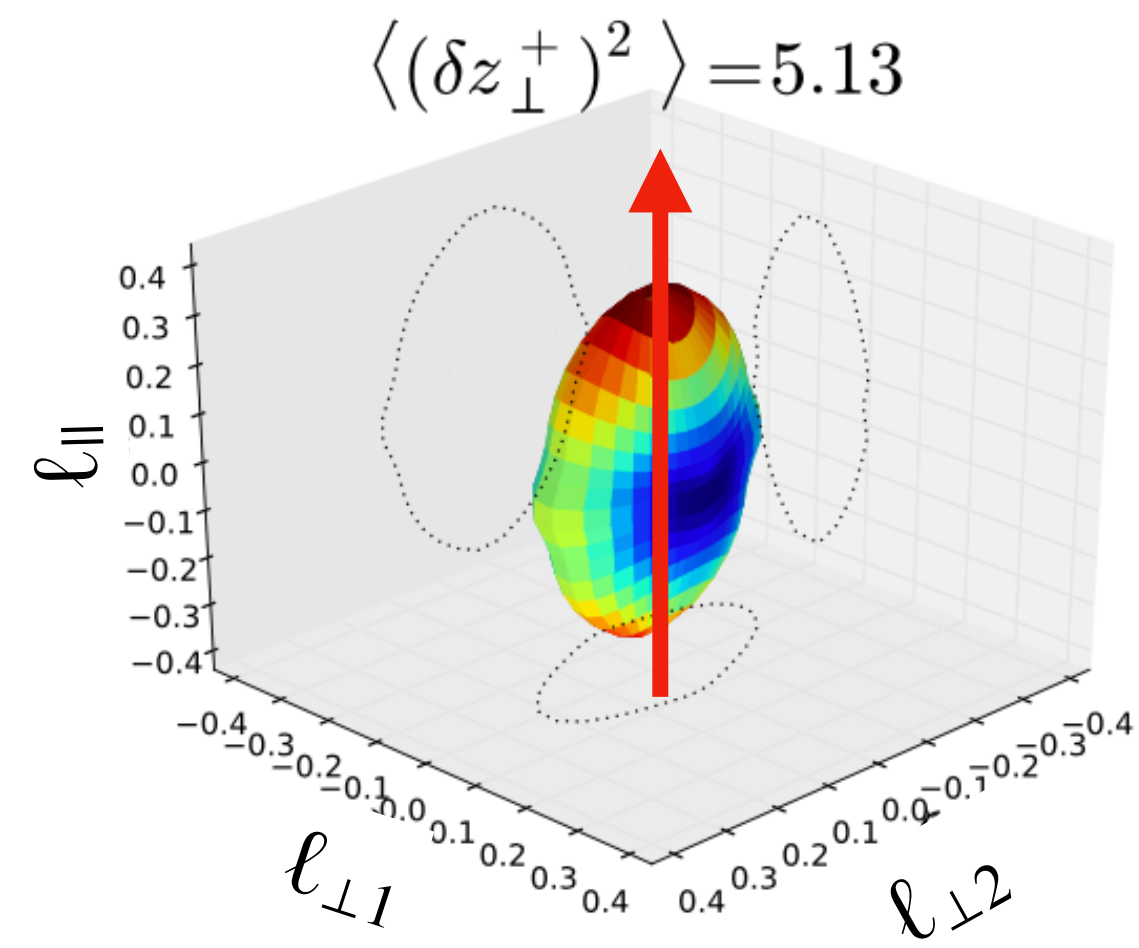
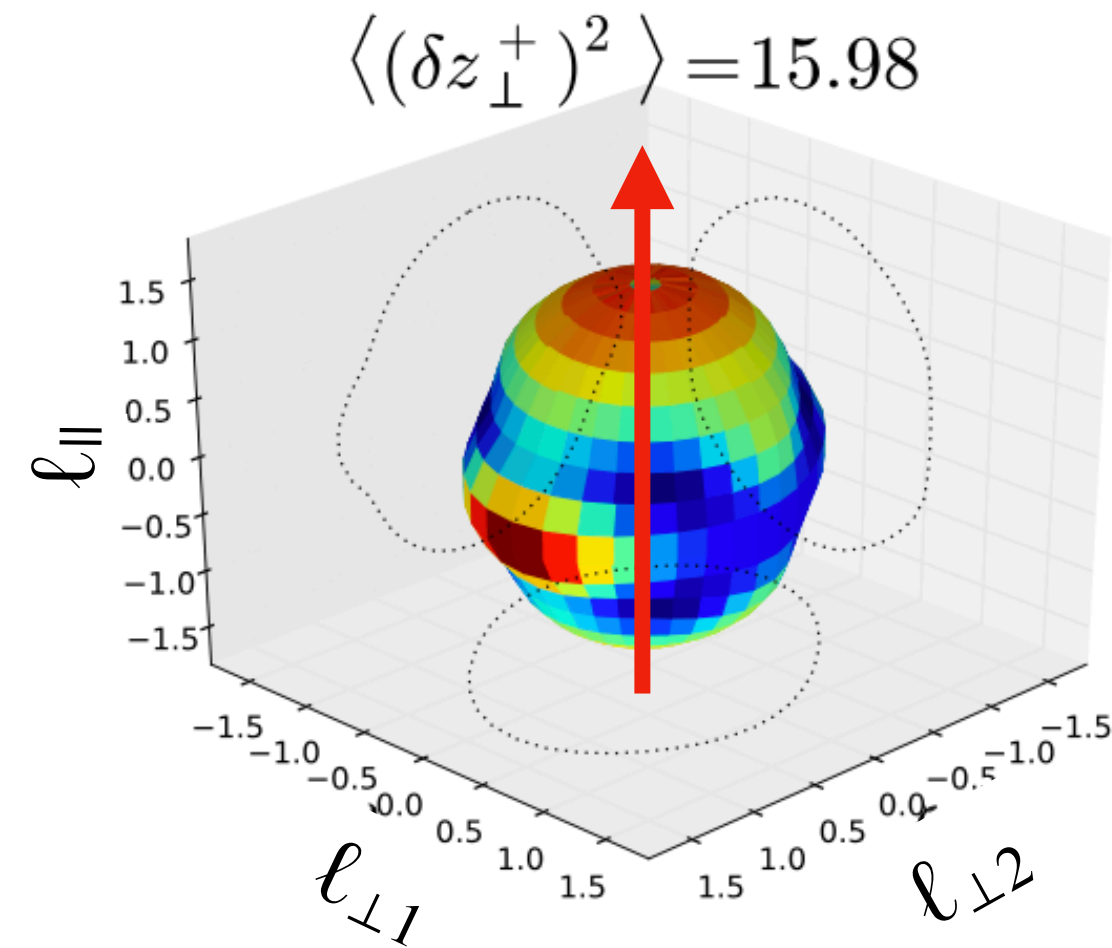
2 different scaling for  $\ell_{\parallel}$  and  $(\ell_{\perp 1}, \ell_{\perp 2})$



# Scale dependent anisotropy

## Simulations

Mallet et al 2016

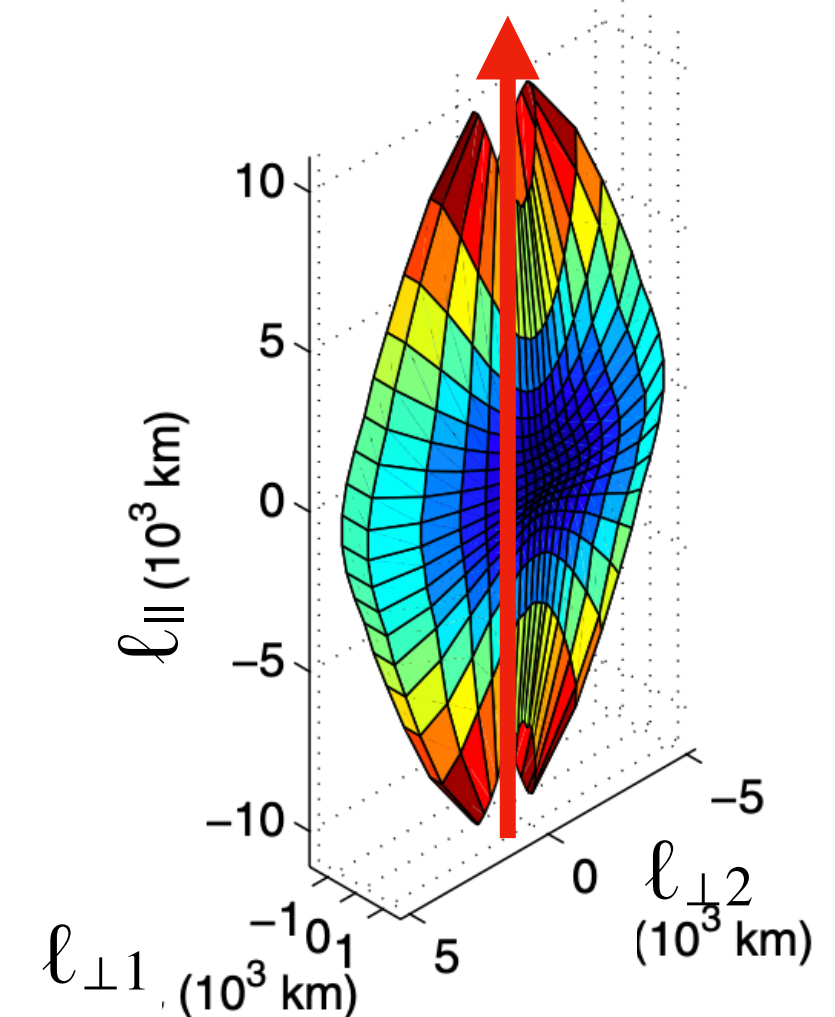
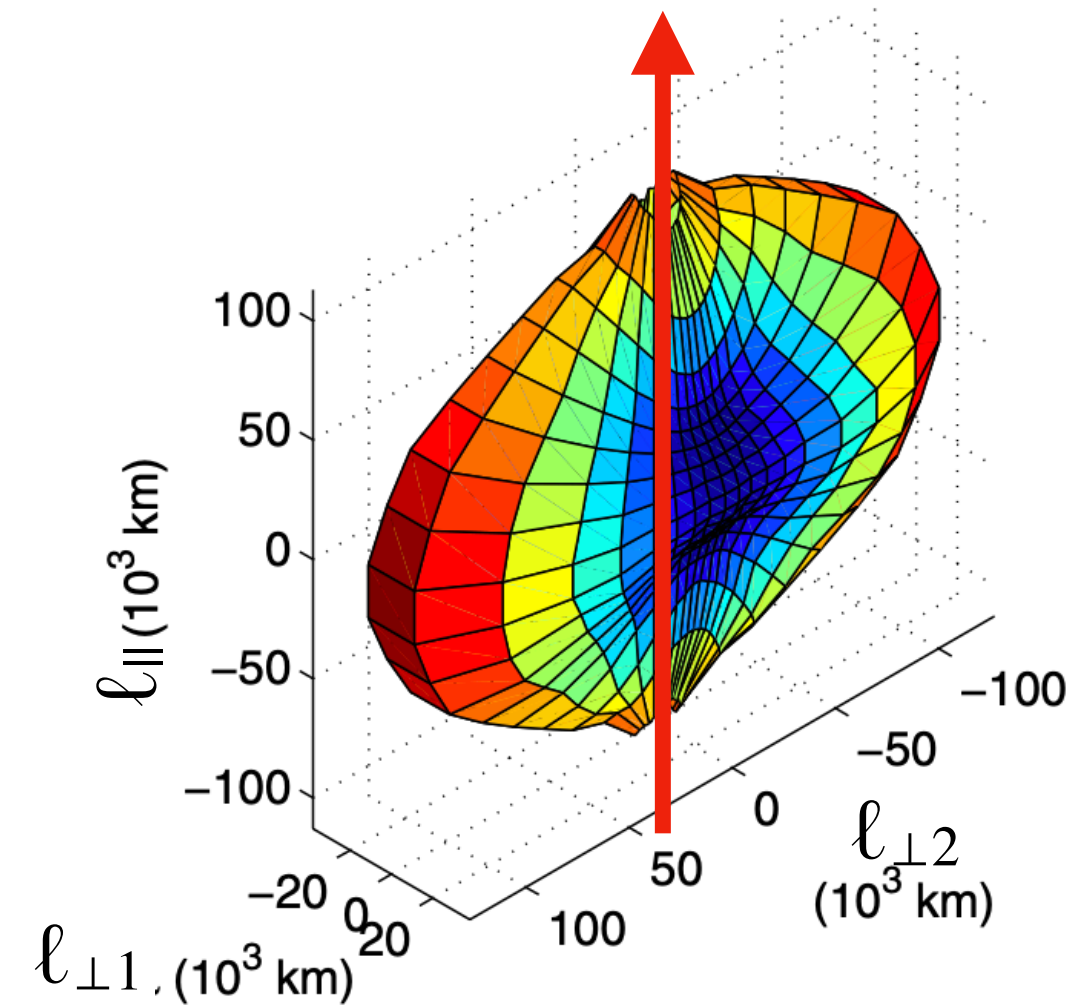
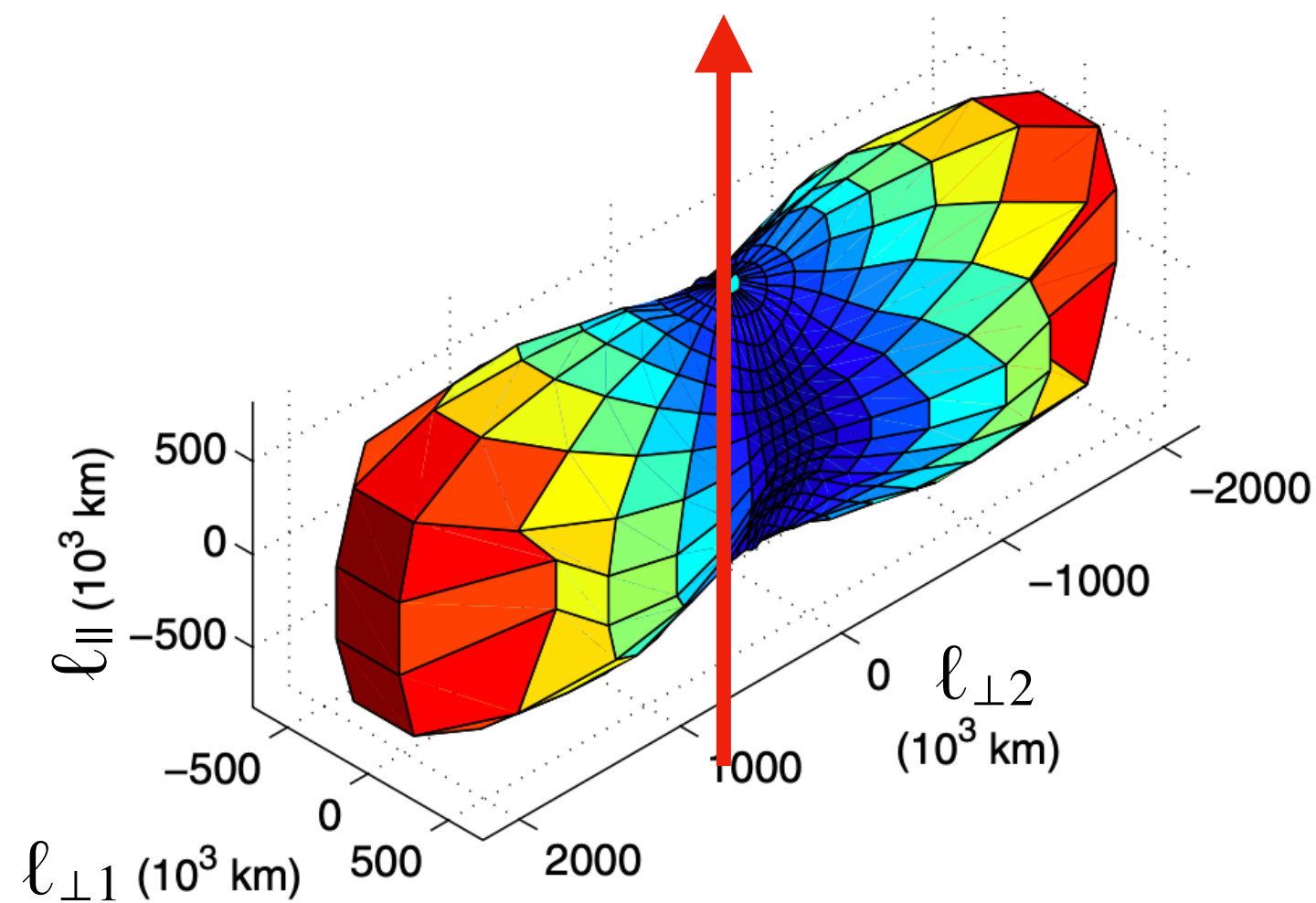


smaller energies (smaller scales)

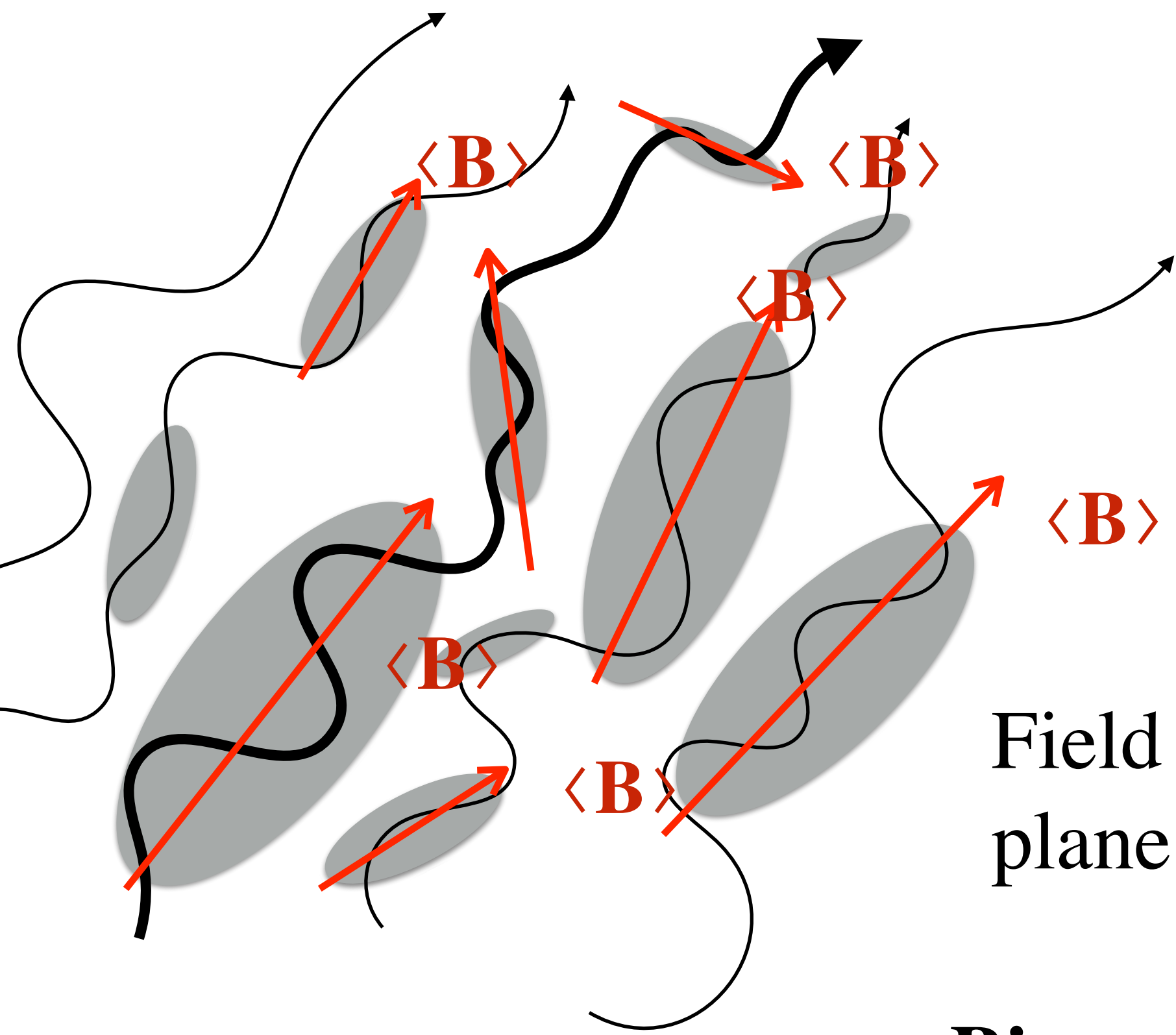


## Solar Wind Observations

Chen+ 2012 ApJL



# Selective decay in EBM Simulations



In the Solar wind  
 $\delta B/B^0 \sim 1$

Selective Decay

$$B_{\perp} \sim 1/R$$

$$B_{\parallel} \sim 1/R^2$$

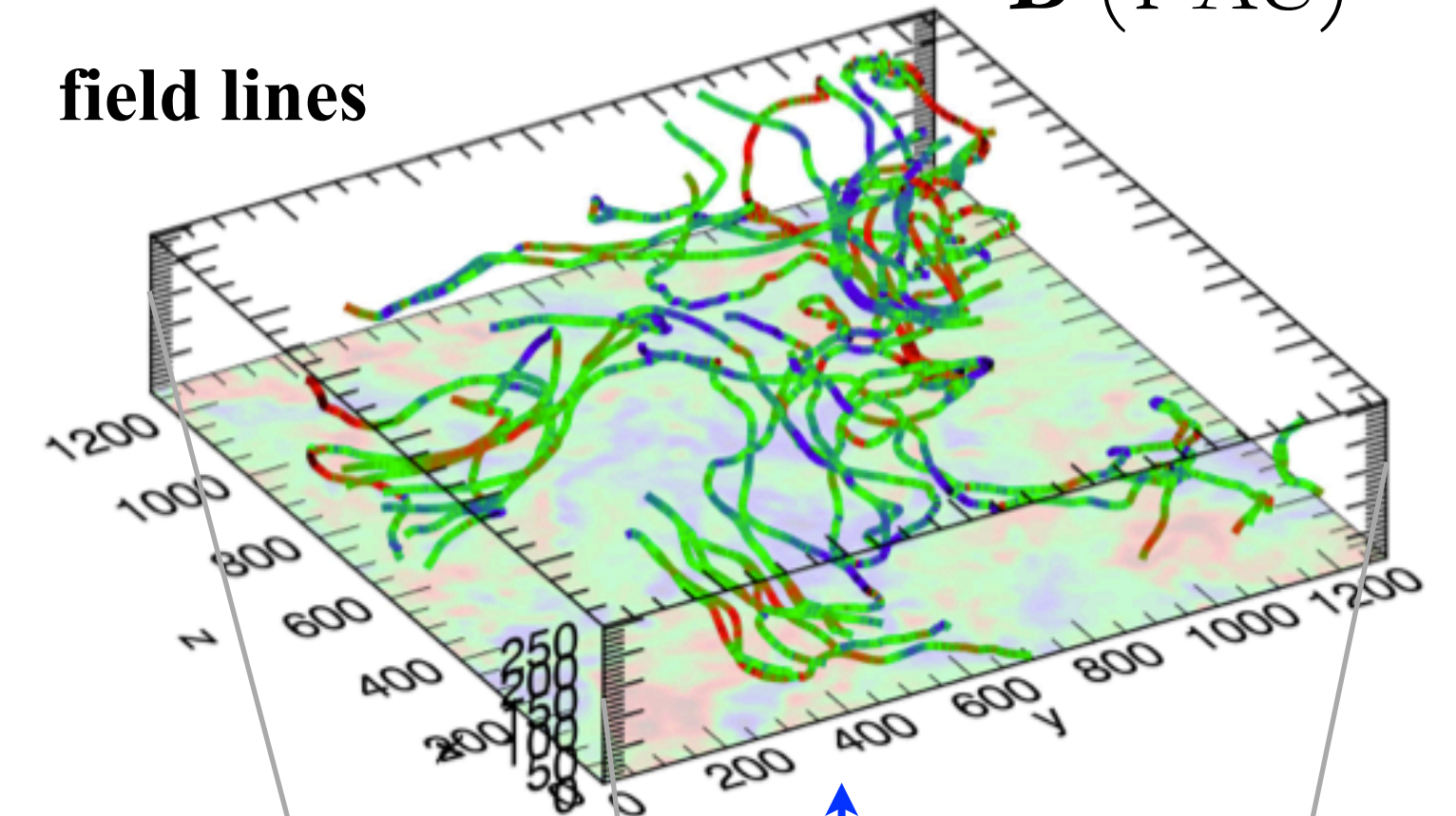
Field lines tend to flatten in the plane perpendicular to the radial

**Bias on the Local Mean Field**  
statistics when sampling along R

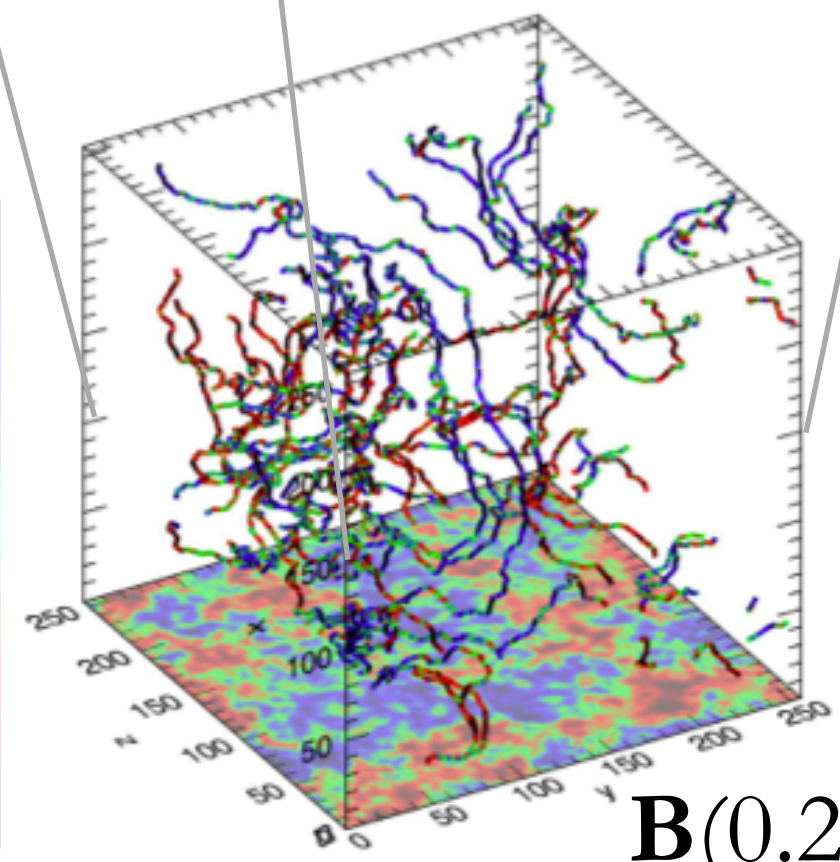
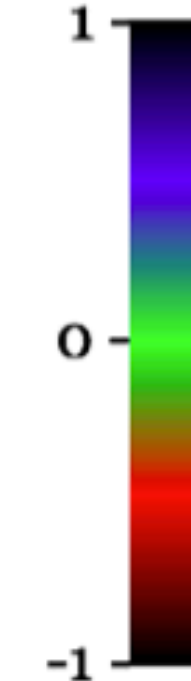
Dong, Verdini, Grappin, ApJ 2014

$\mathbf{B}$  (1 AU)

field lines



$\cos(\theta)$

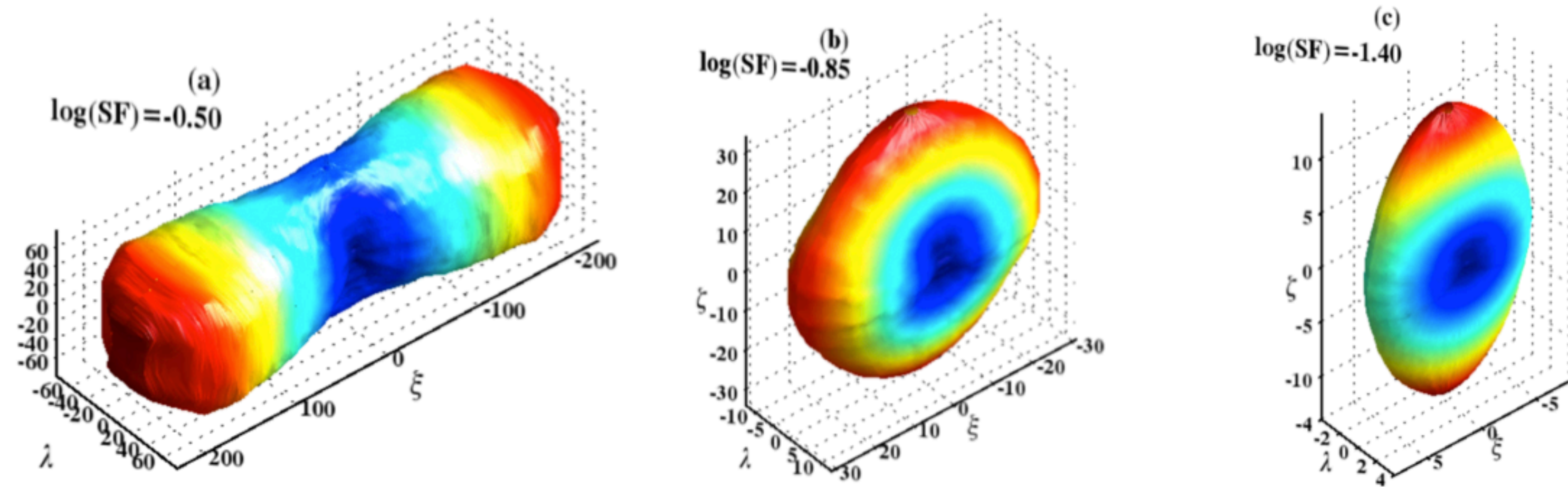


$\mathbf{B}$ (0.2 AU)

# Scale Dependent Anisotropy in EBM

## EBM Simulations

Verdini & Grappin 2015 ApJL

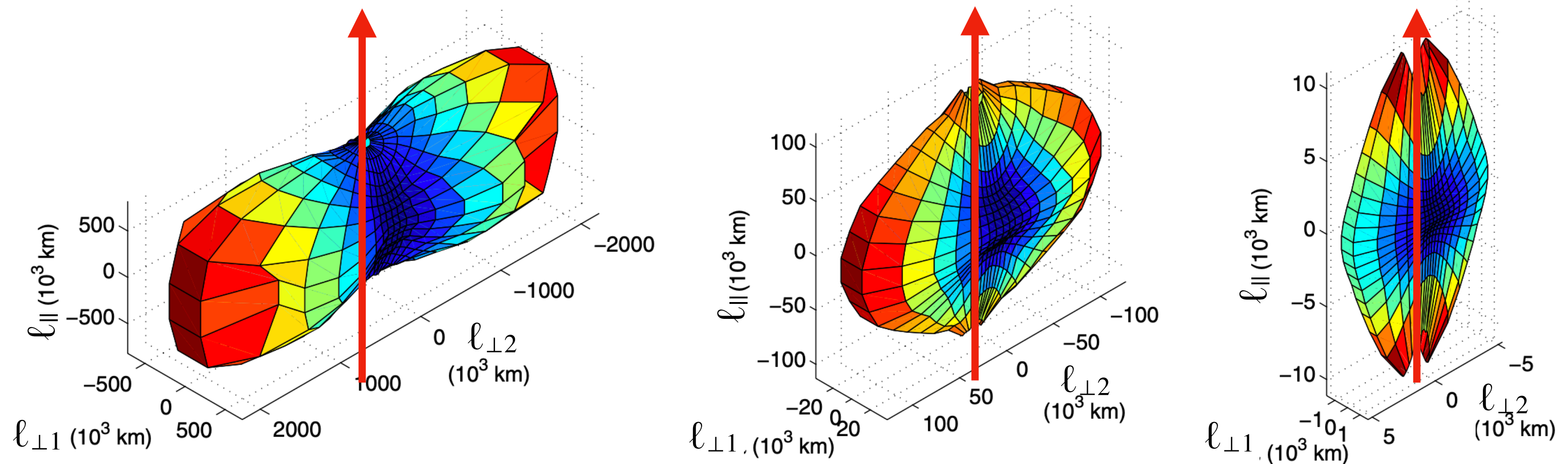


smaller energies (smaller scales)



## Solar Wind Observations

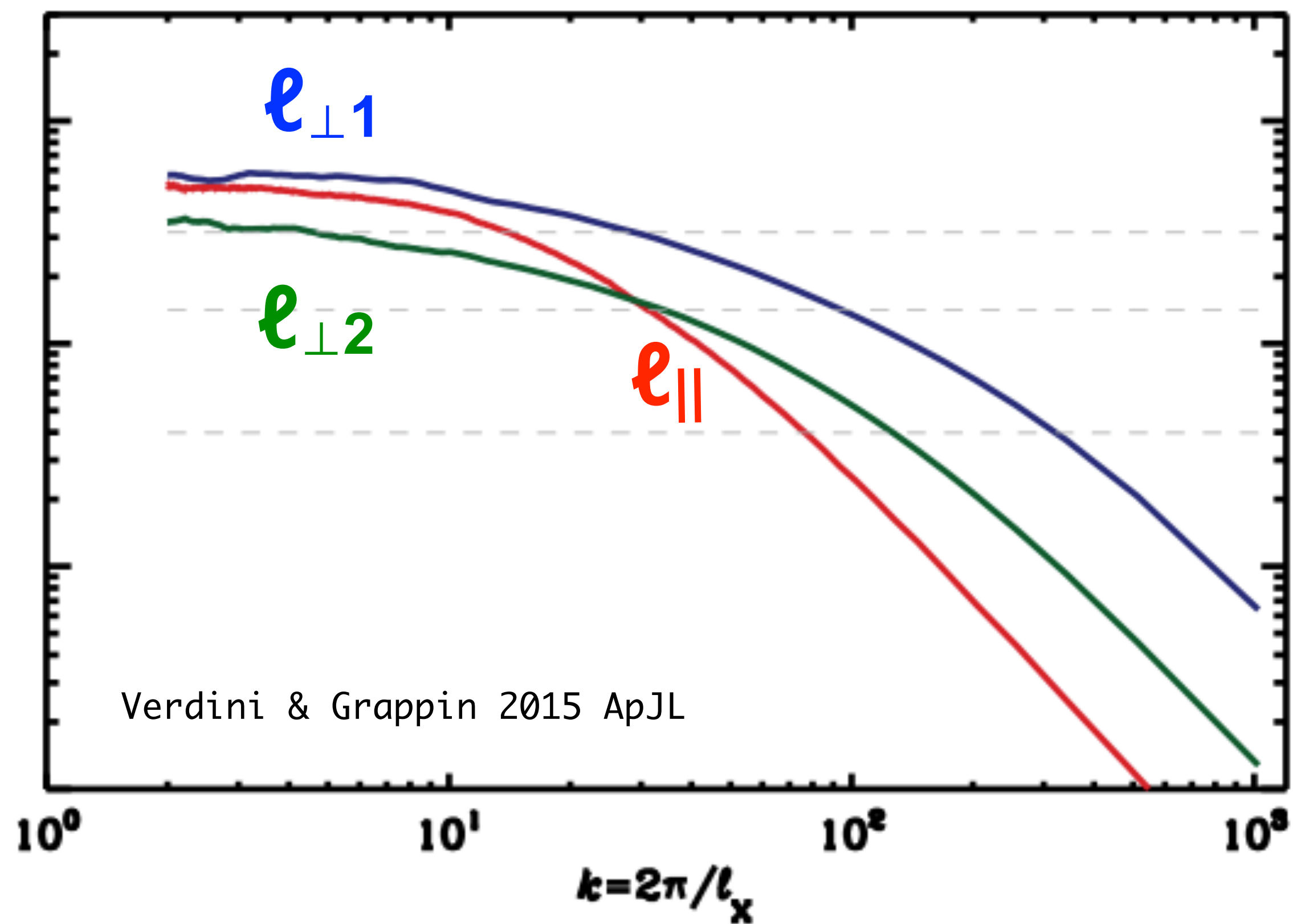
Chen+ 2012 ApJL



# Scale Dependent Anisotropy in EBM

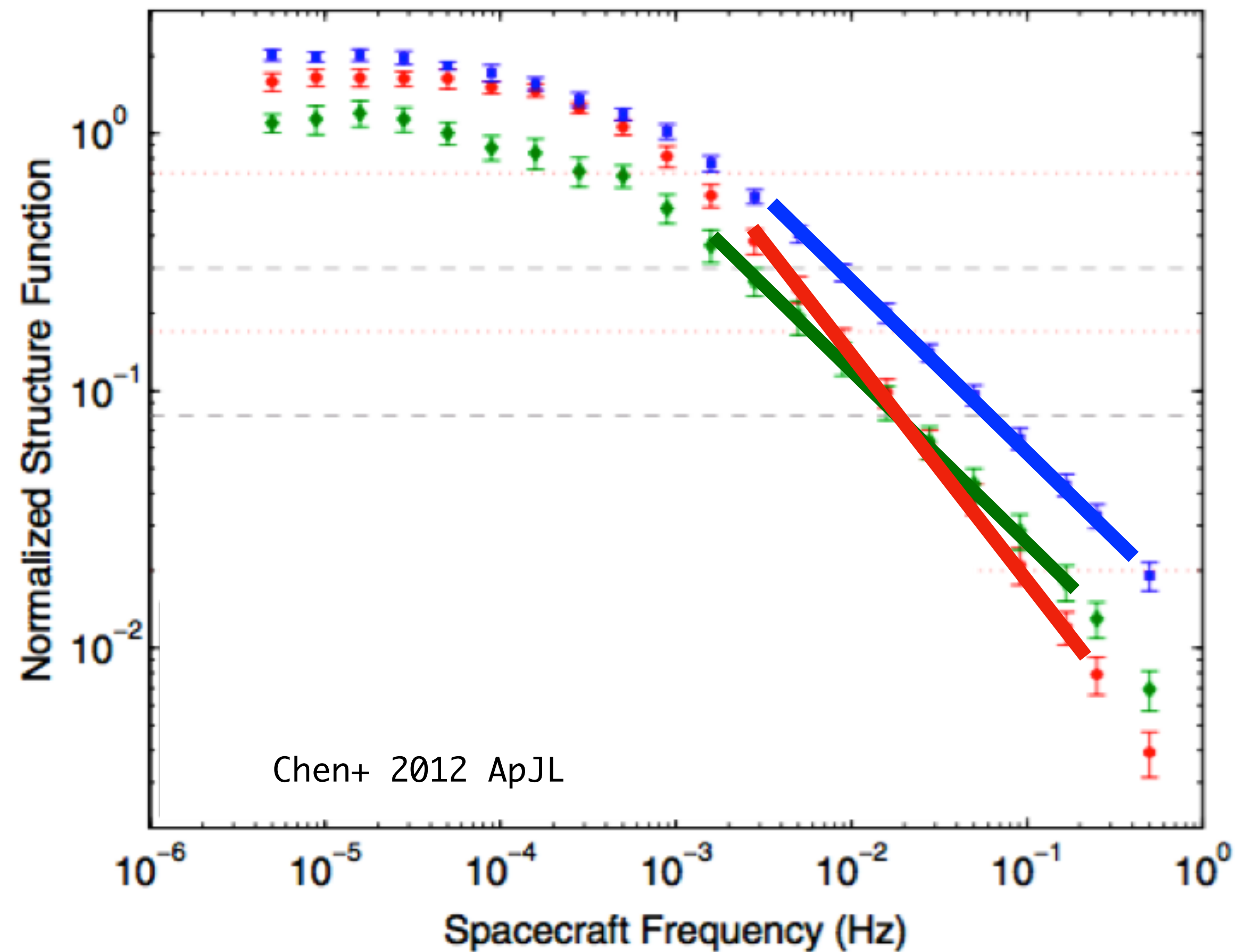
## EBM simulations

2 different scaling for  $\ell_{\parallel}$  and  $(\ell_{\perp 1}, \ell_{\perp 2})$



## Solar Wind Observations

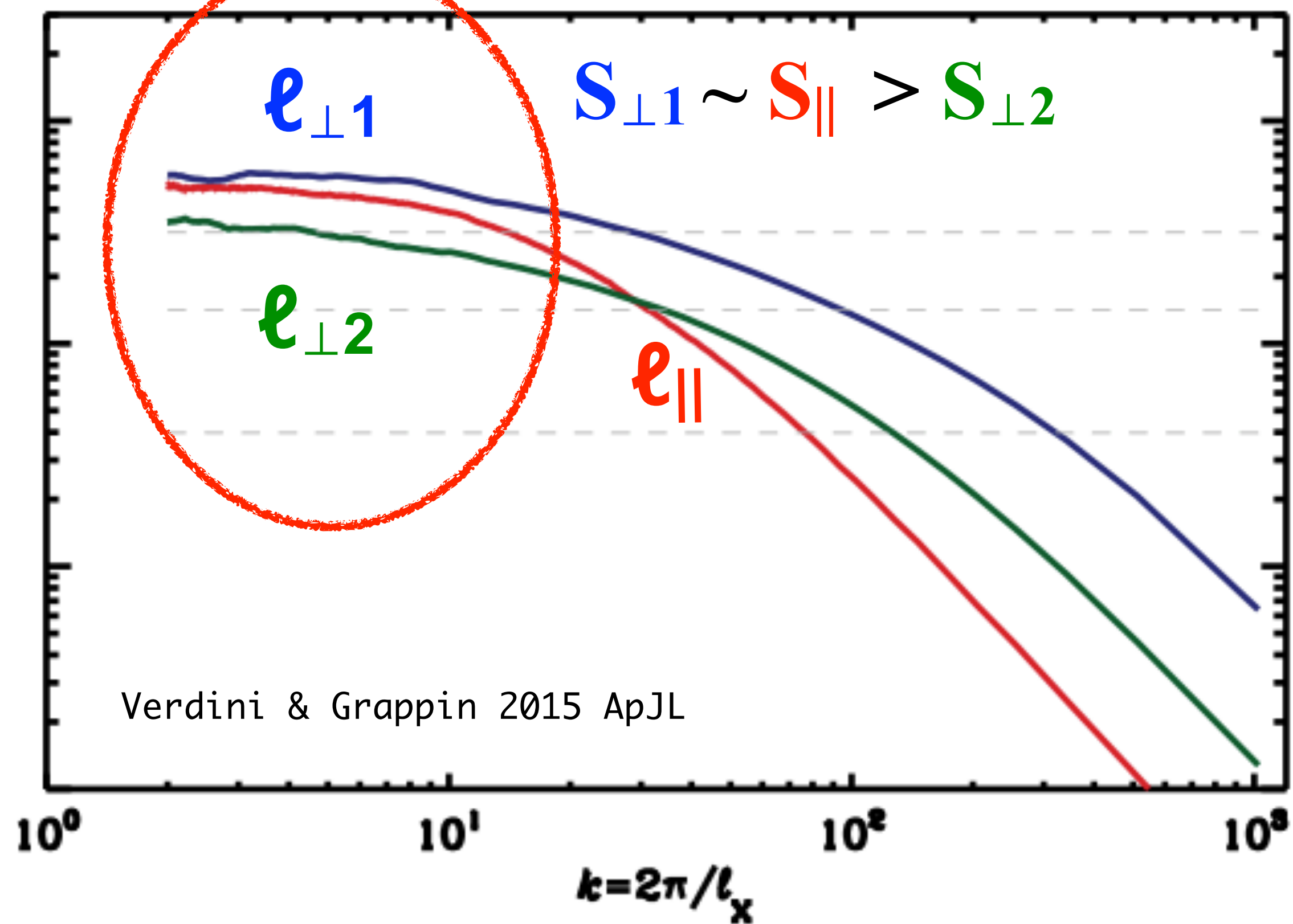
2 different scaling for  $\ell_{\parallel}$  and  $(\ell_{\perp 1}, \ell_{\perp 2})$



# Scale Dependent Anisotropy in EBM

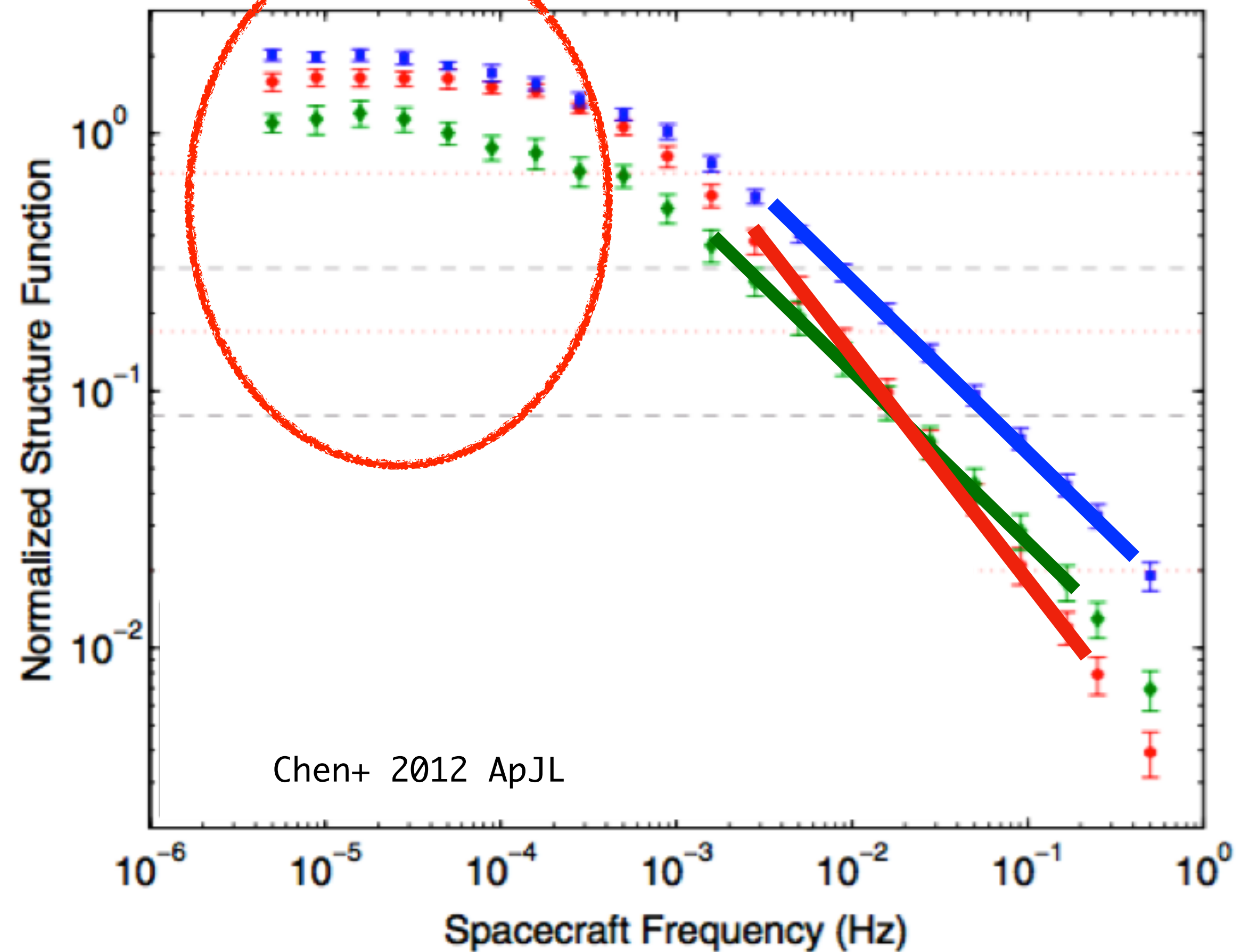
## EBM simulations

2 different scaling for  $\ell_{\parallel}$  and  $(\ell_{\perp 1}, \ell_{\perp 2})$



## Solar Wind Observations

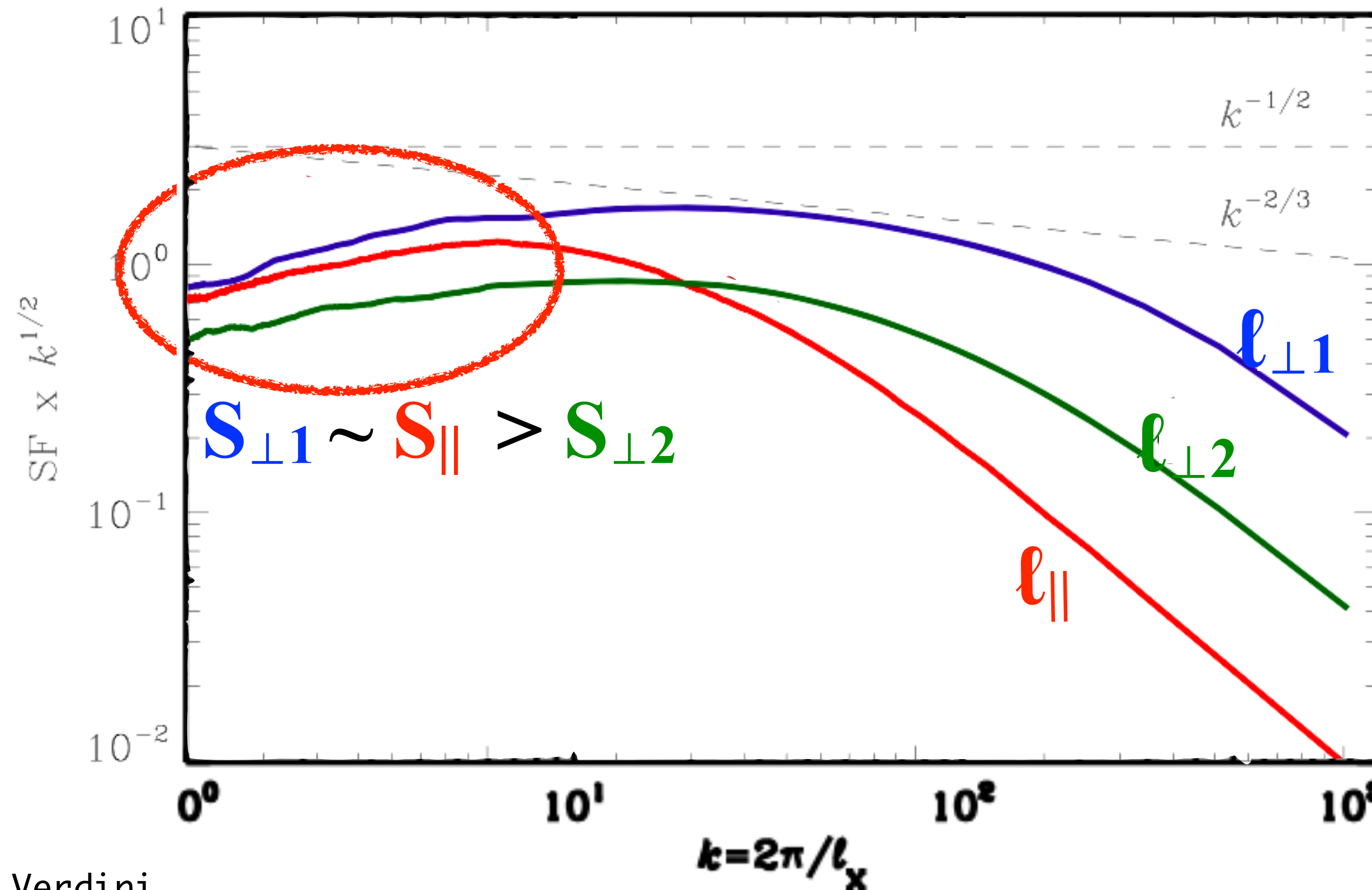
2 different scaling for  $\ell_{\parallel}$  and  $(\ell_{\perp 1}, \ell_{\perp 2})$



# Scale Dependent Anisotropy in EBM

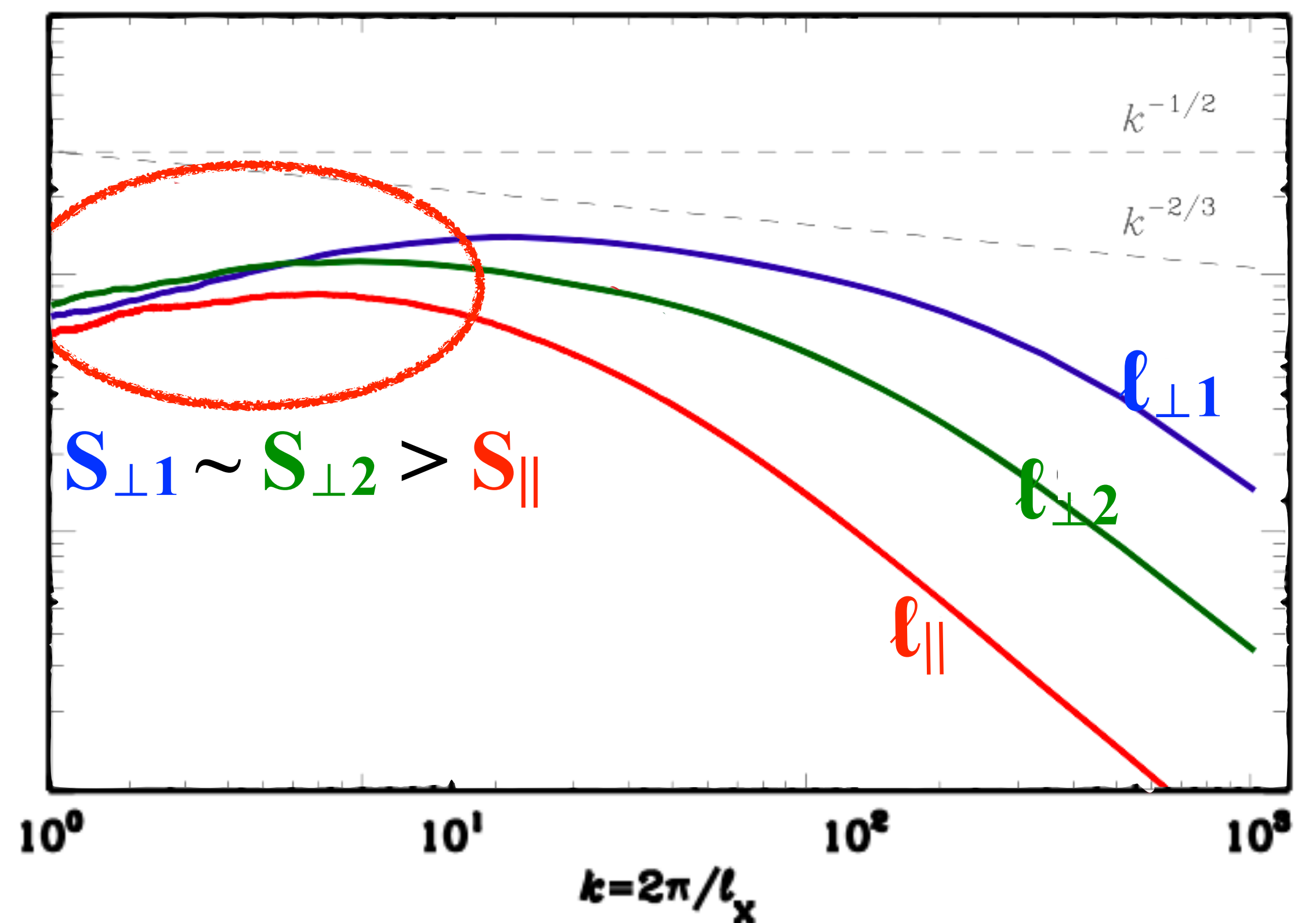
**Sampling along R**  
as in observations

(a) run B, increments along  $l_x$



**Sampling along T**  
as in simulations w/o expansion

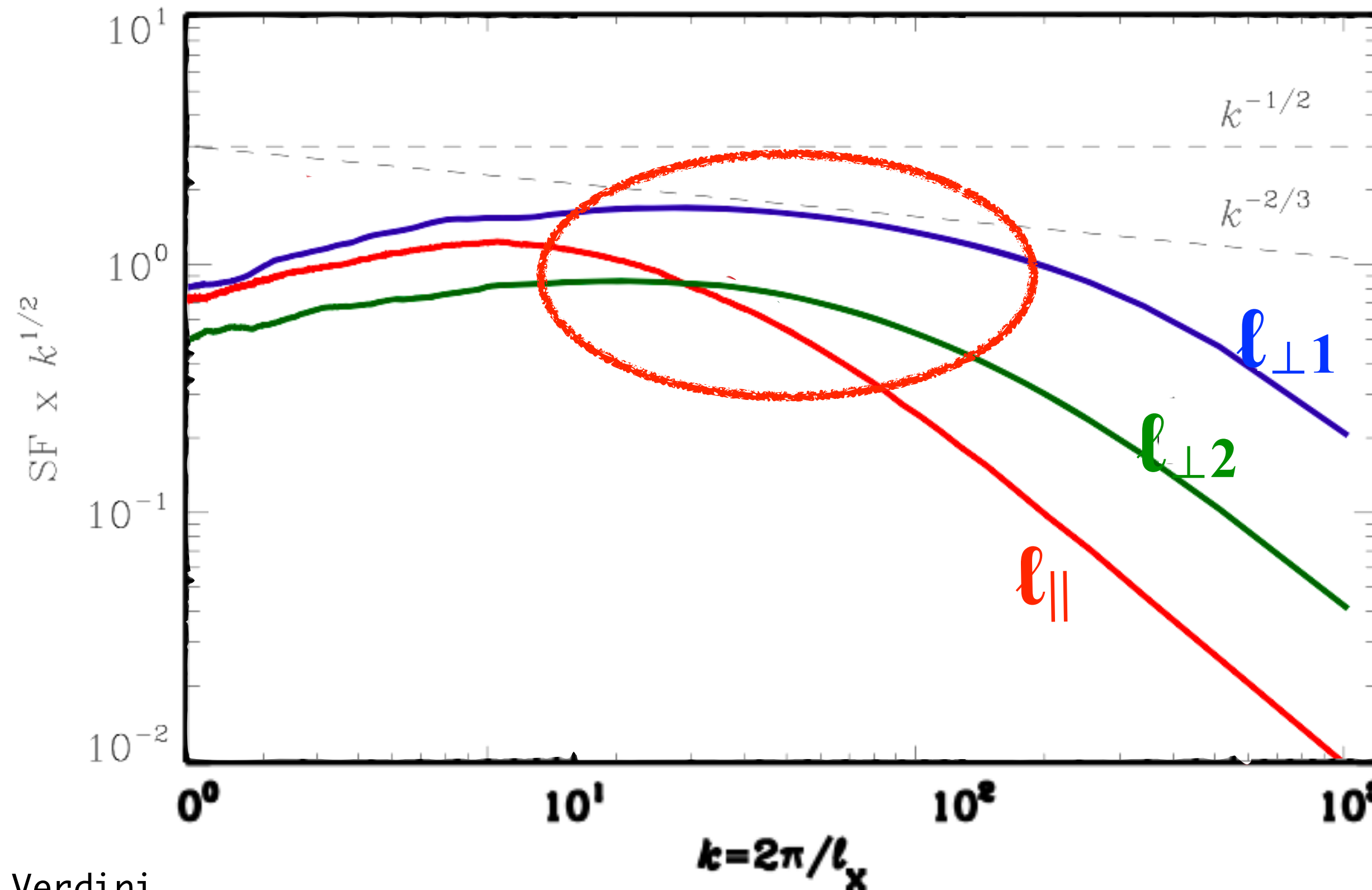
(b) run B, increments along  $l_v$



# Scale Dependent Anisotropy in EBM

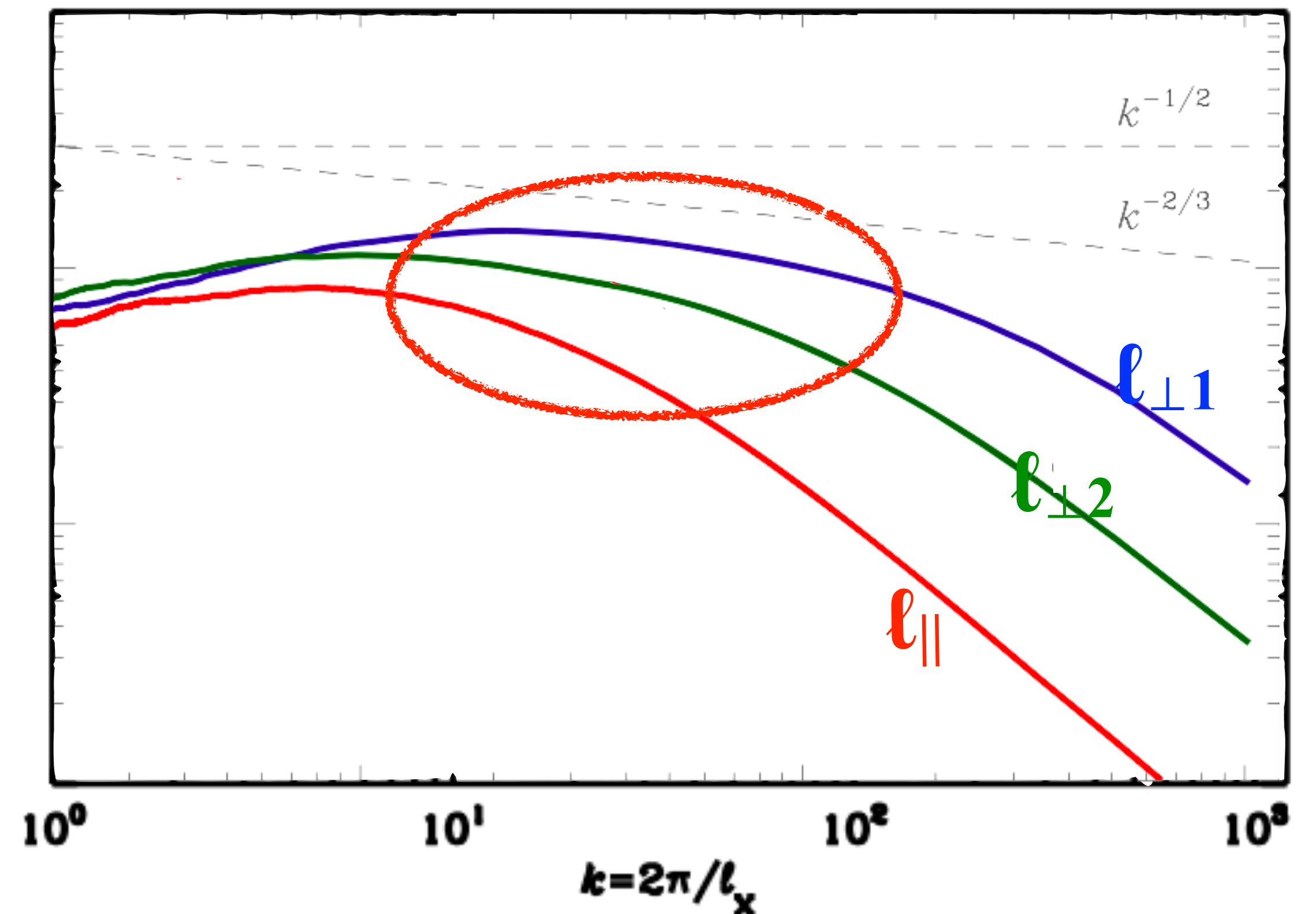
**Sampling along R**  
as in observations

(a) run B, increments along  $l_x$

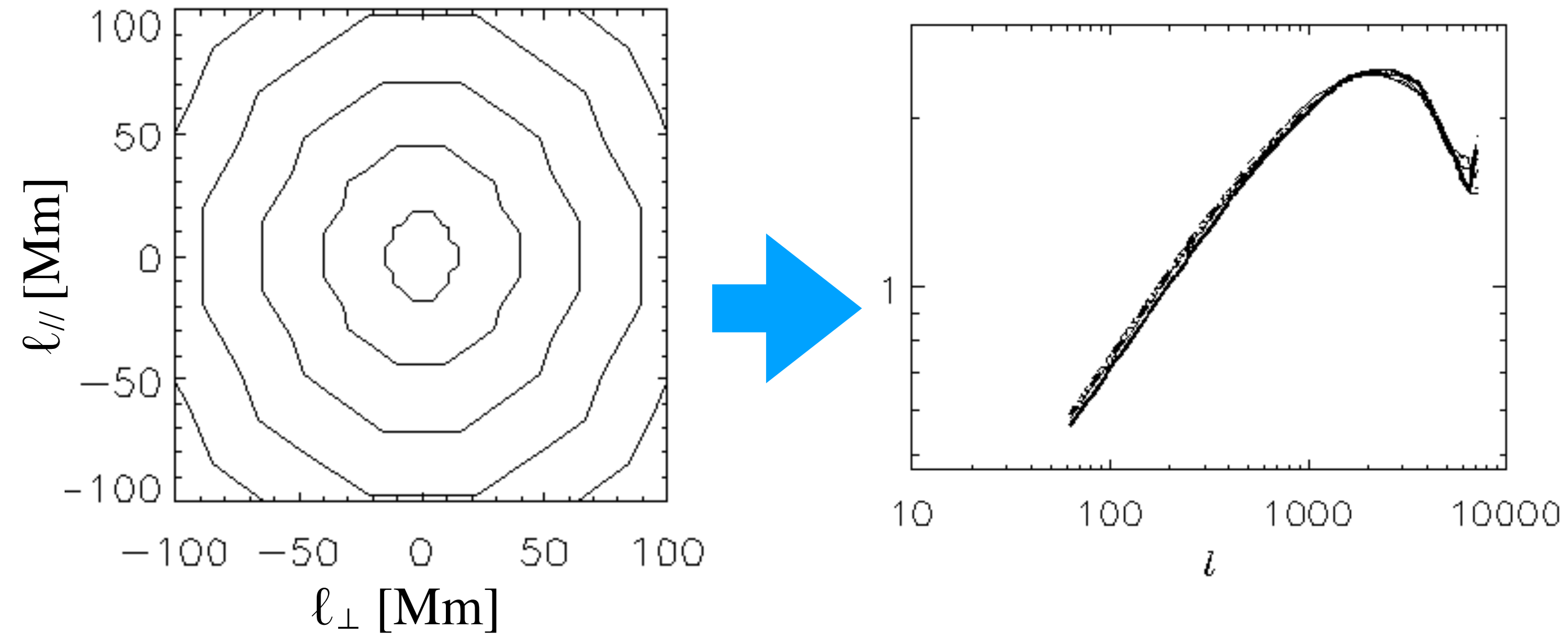


**Sampling along T**  
as in simulations w/o expansion

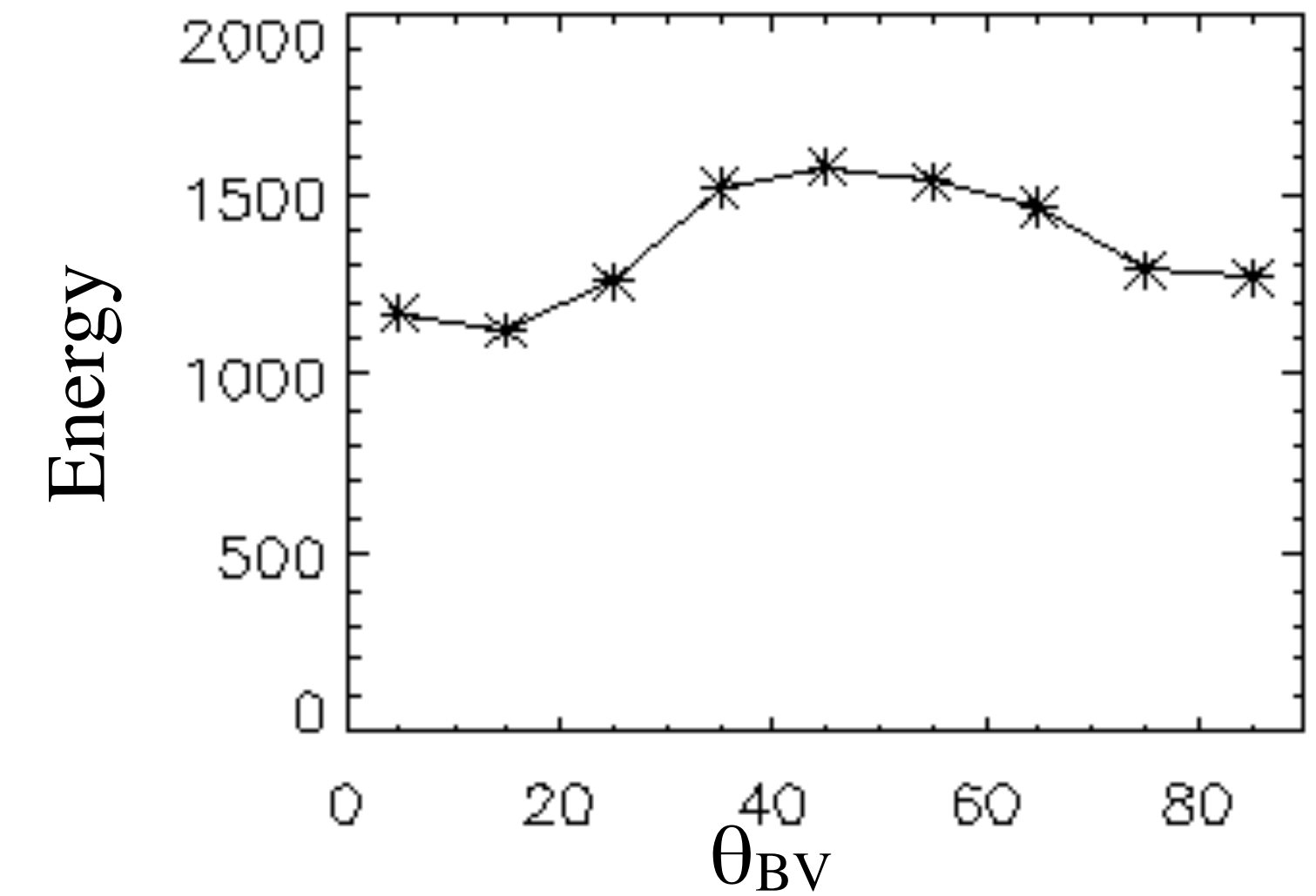
(b) run B, increments along  $l_y$



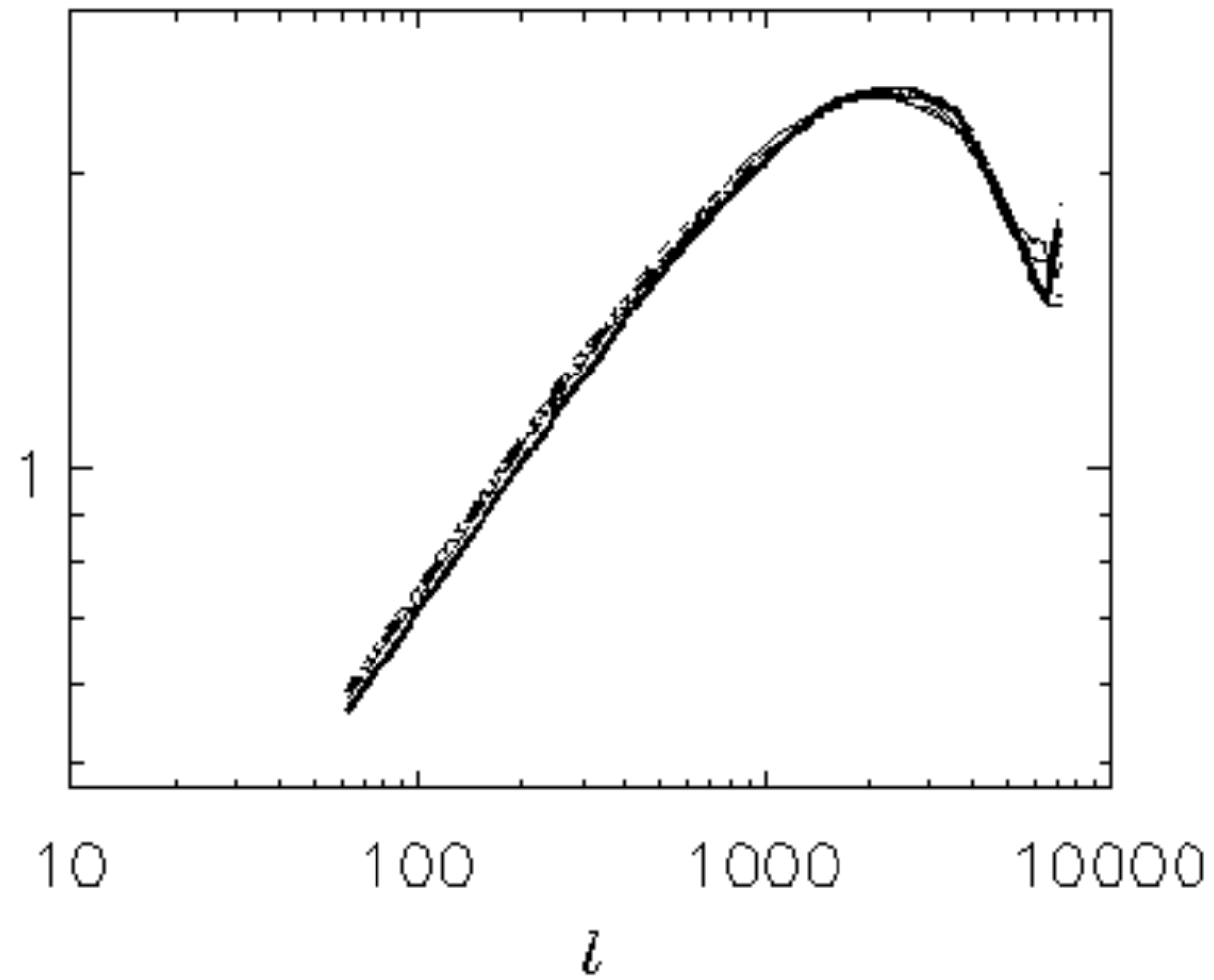
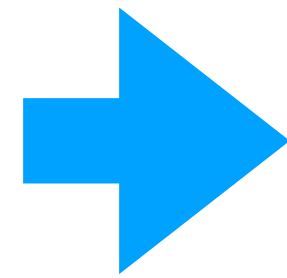
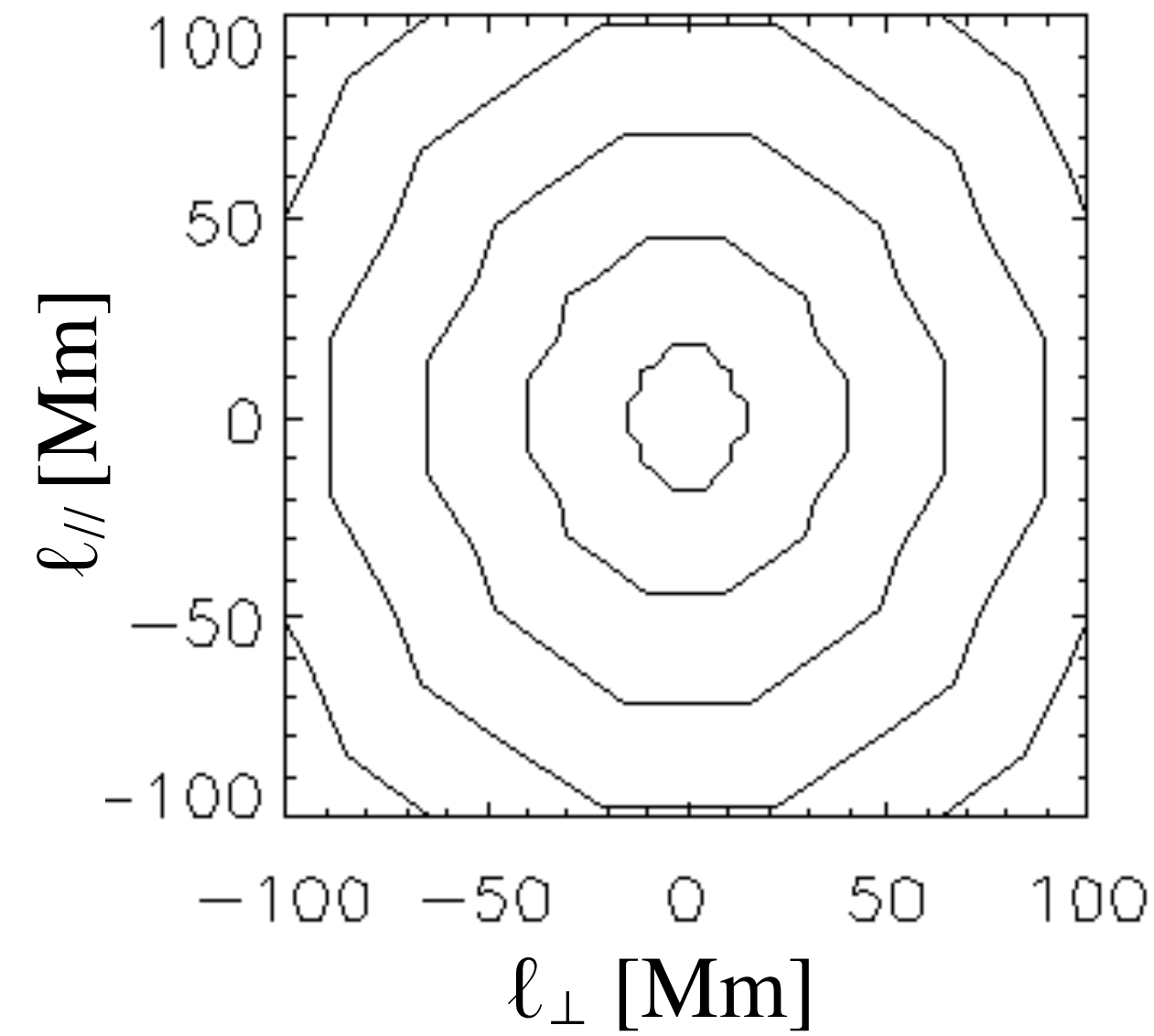
# Spectral Anisotropy: isotropy @ small scale



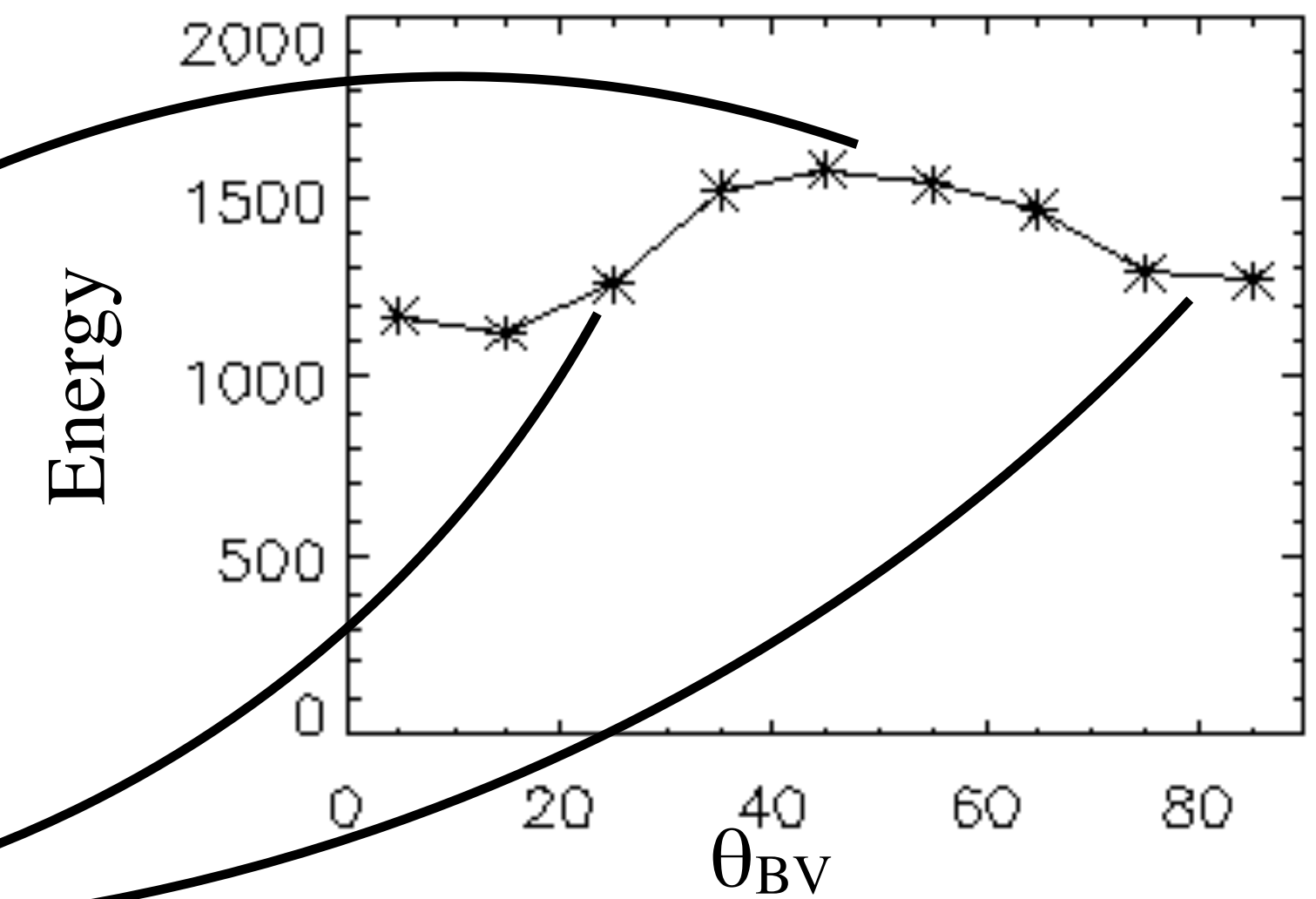
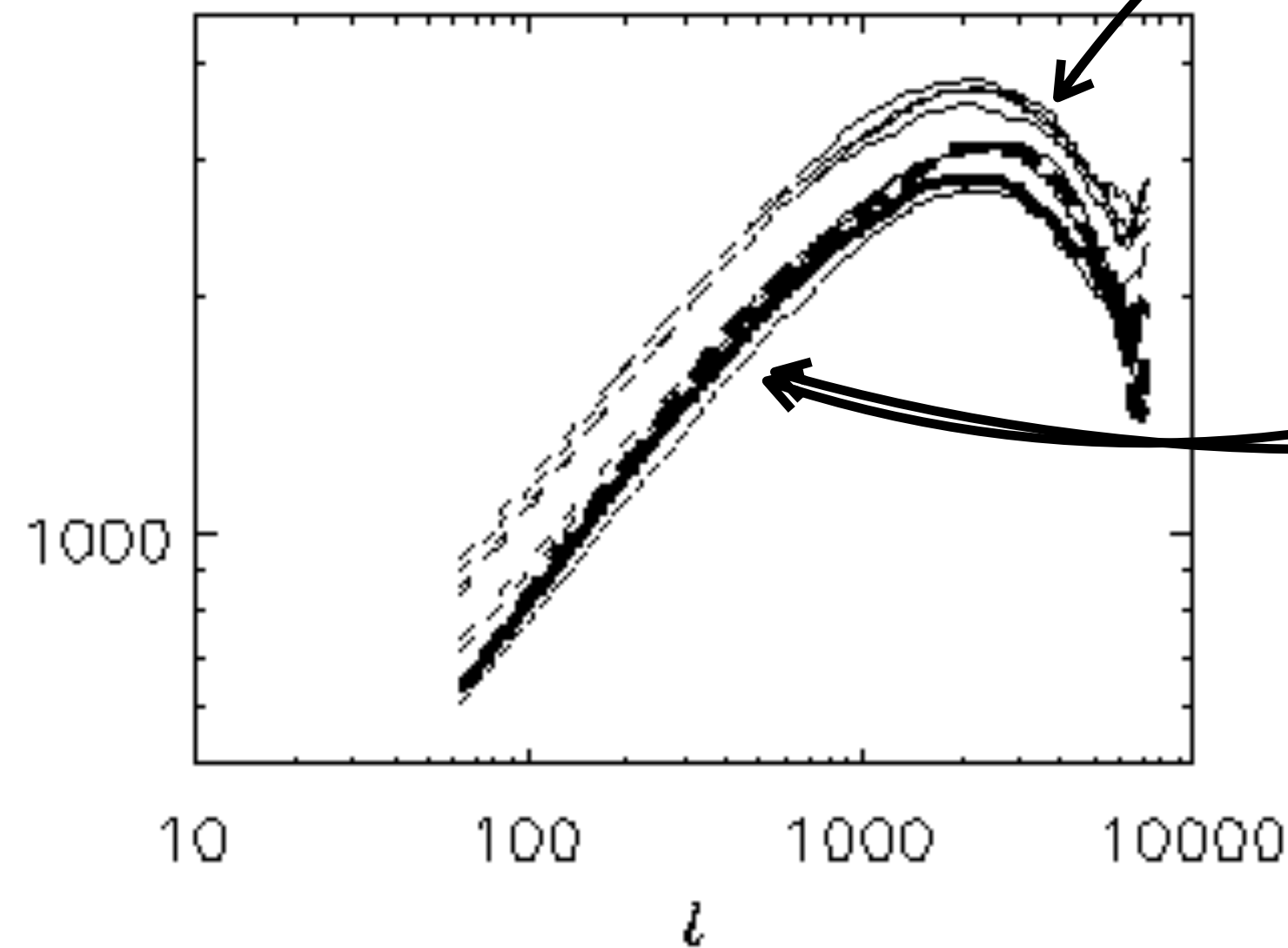
The SF (or C) are Normalized



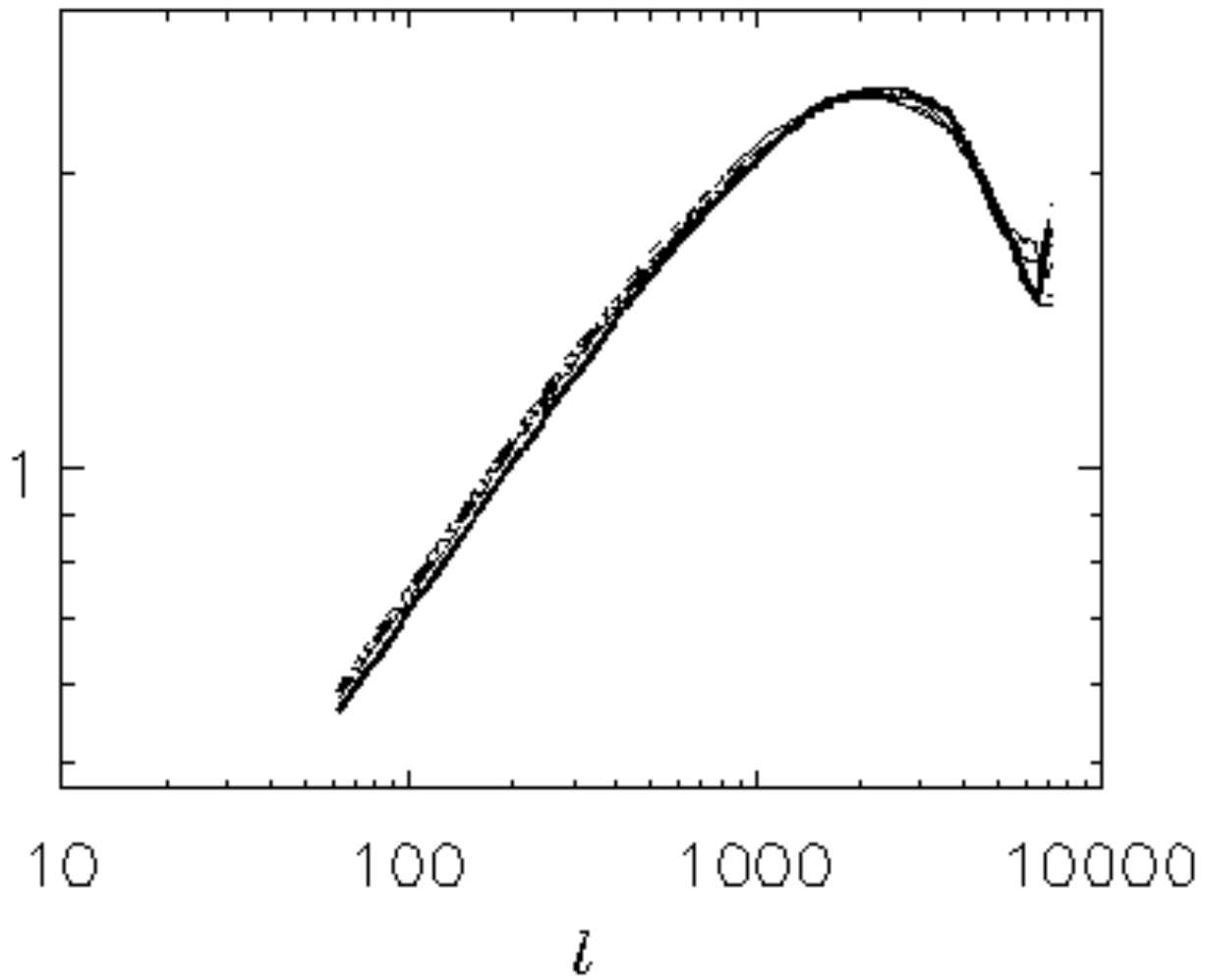
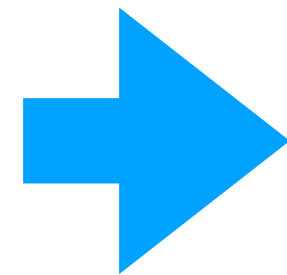
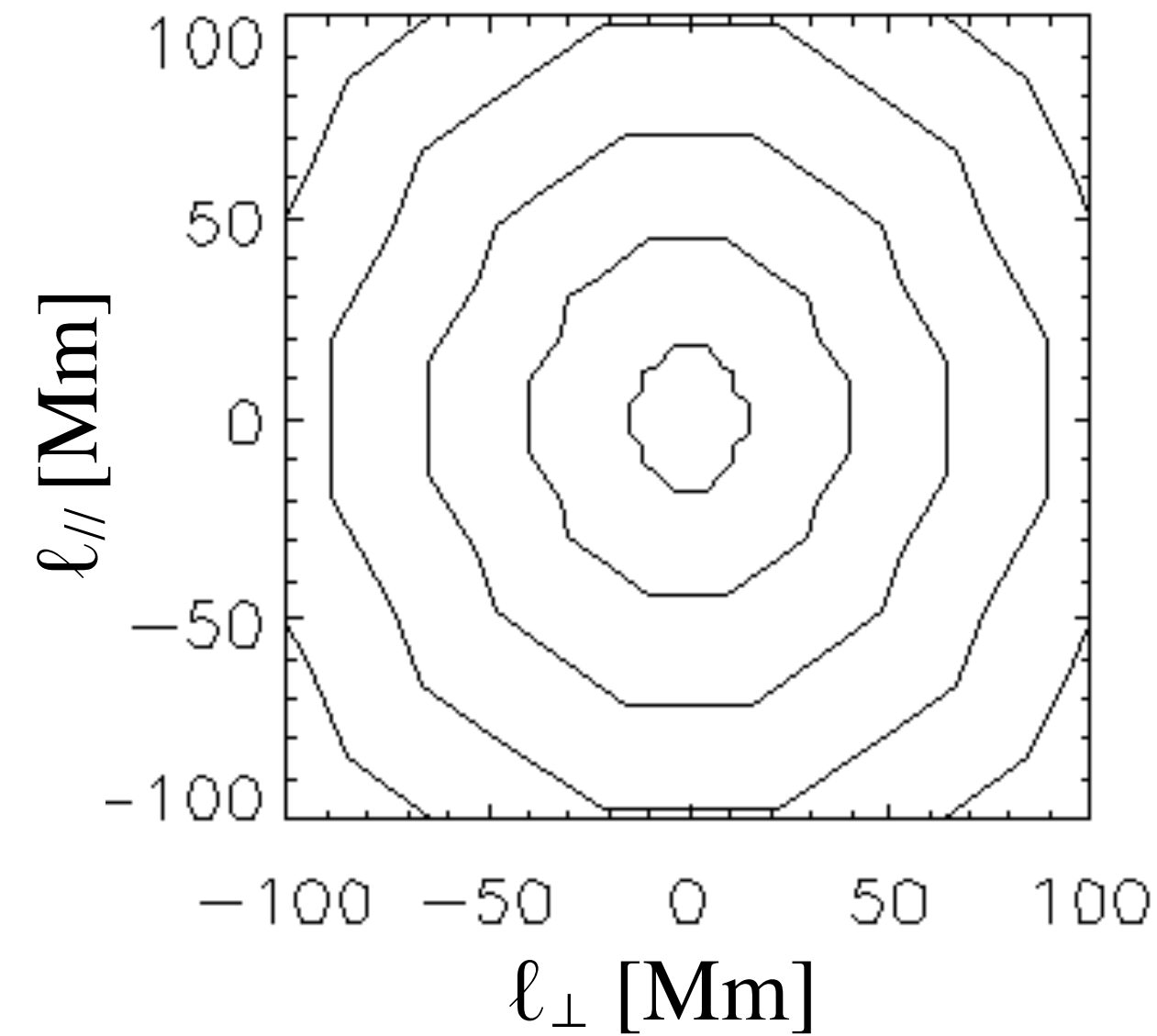
# Spectral Anisotropy: isotropy @ small scale



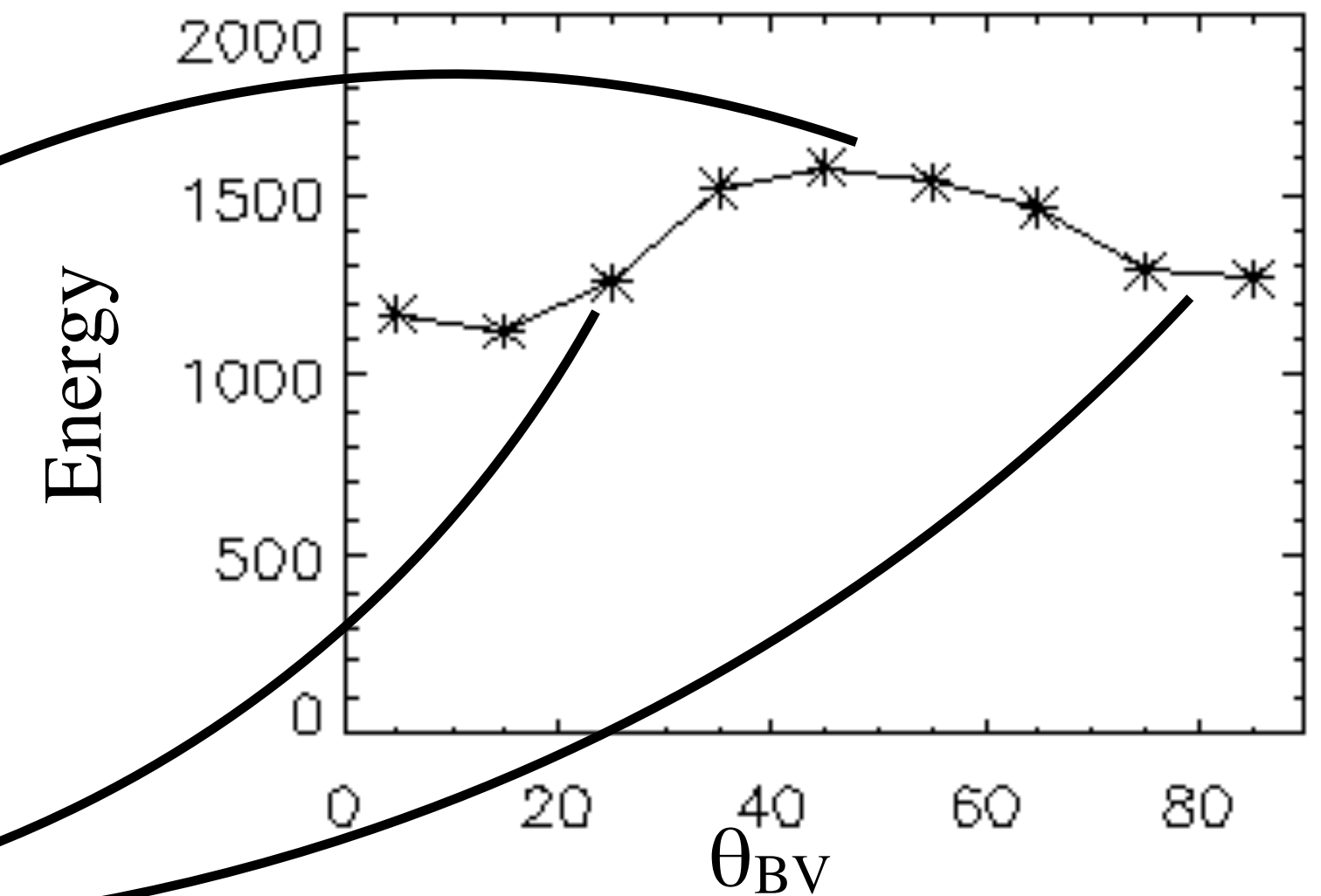
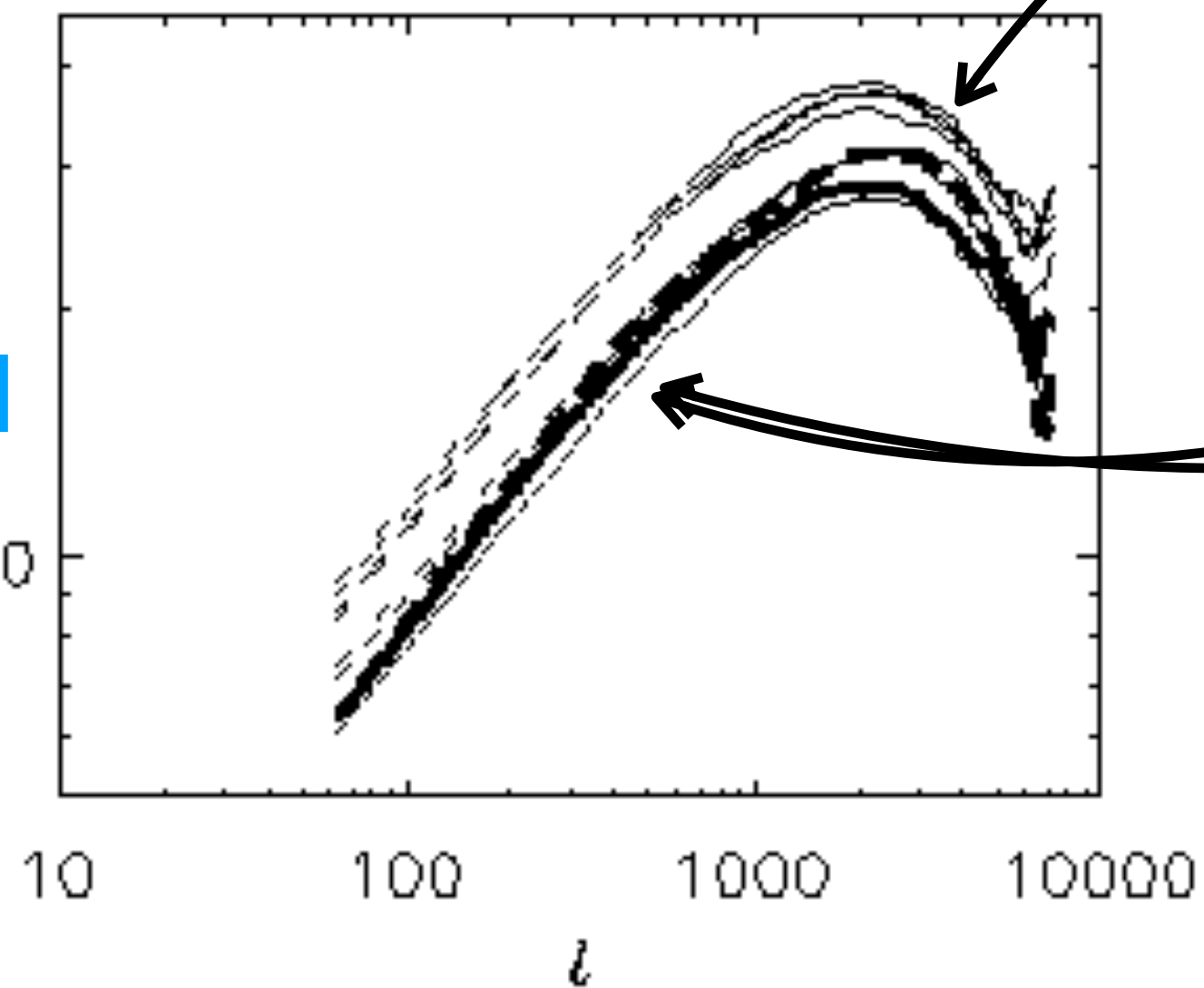
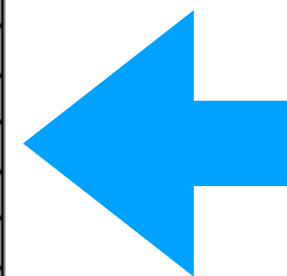
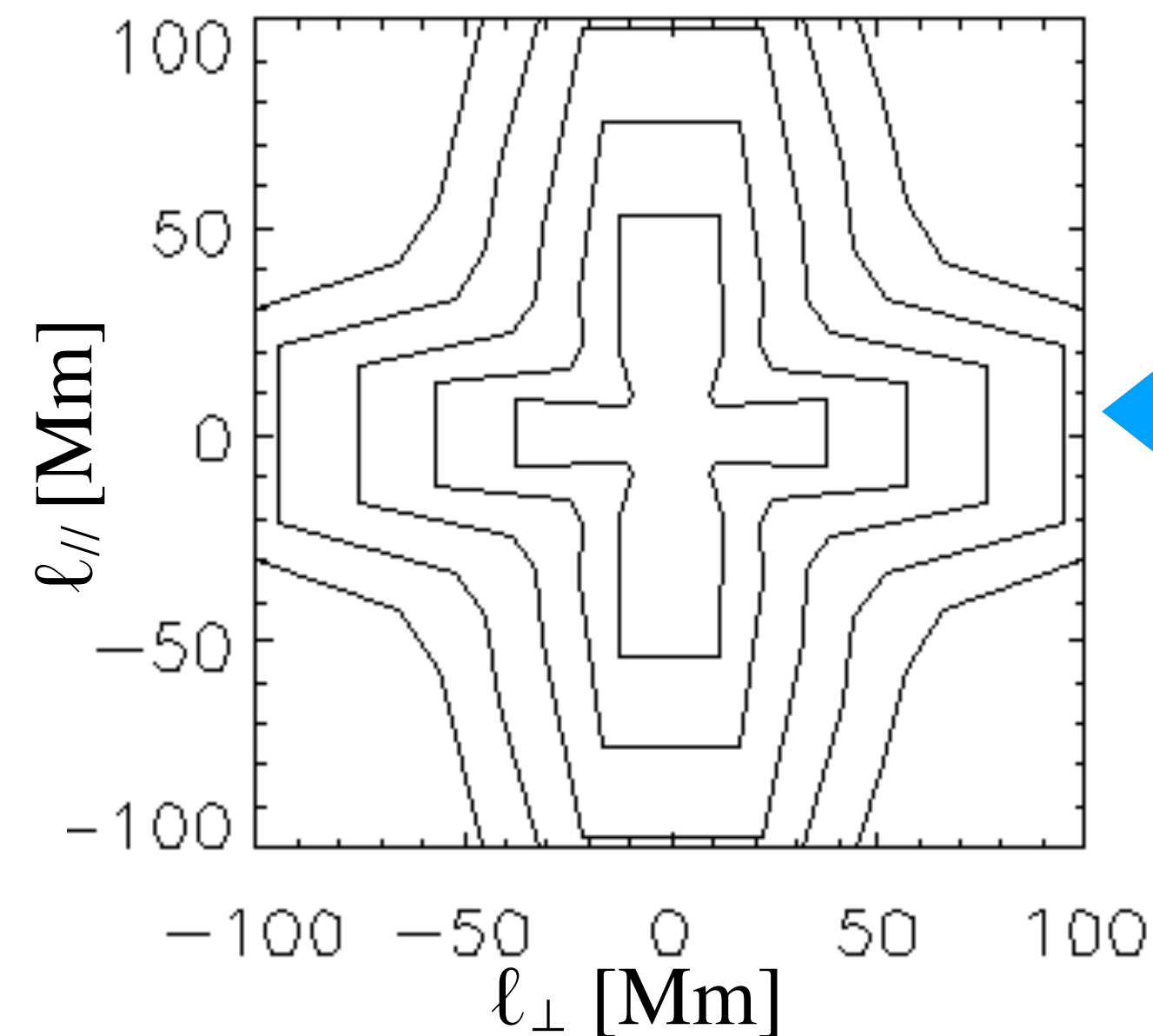
The SF (or C) are Normalized



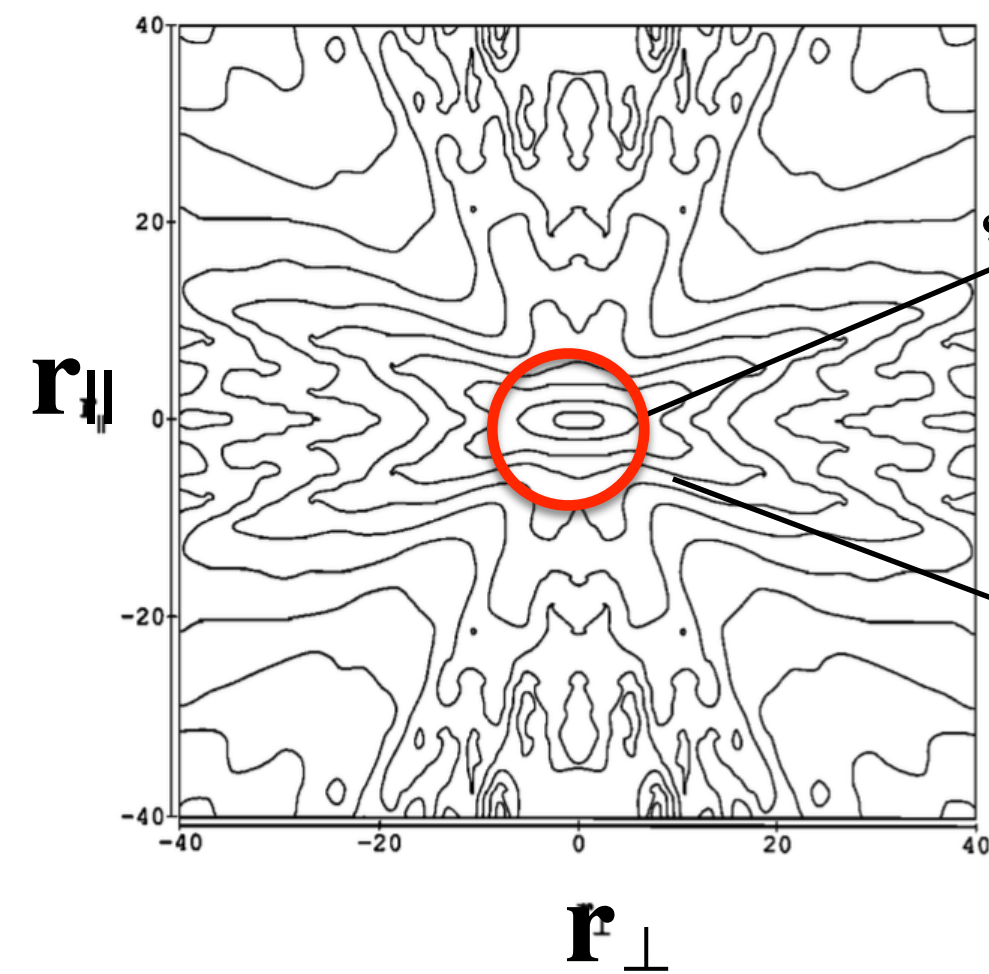
# Spectral Anisotropy: isotropy @ small scale



The SF (or C) are Normalized



# Observed Anisotropy in the SW

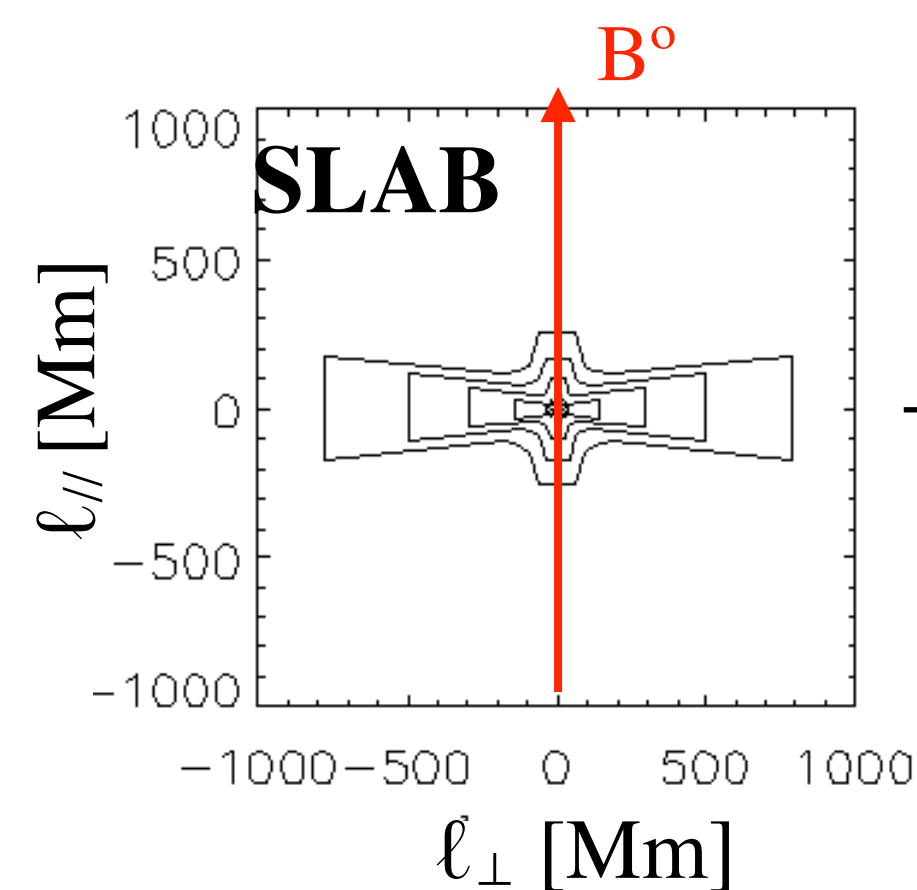
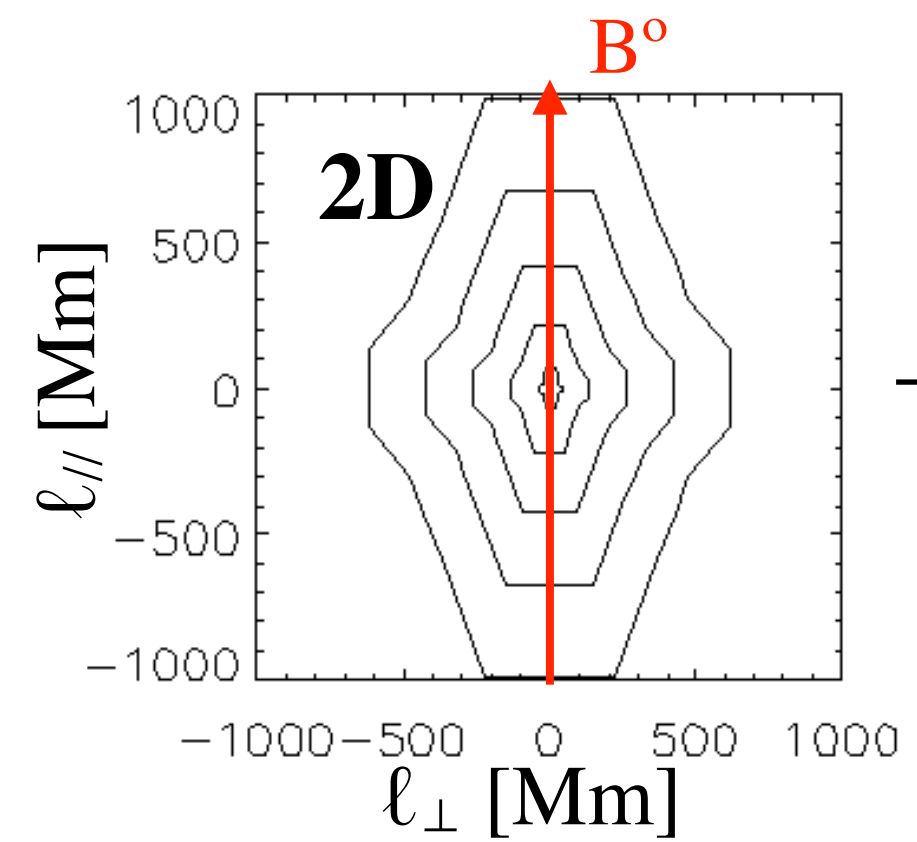


Matthaeus Goldstein  
Roberts 1990

Maltese cross

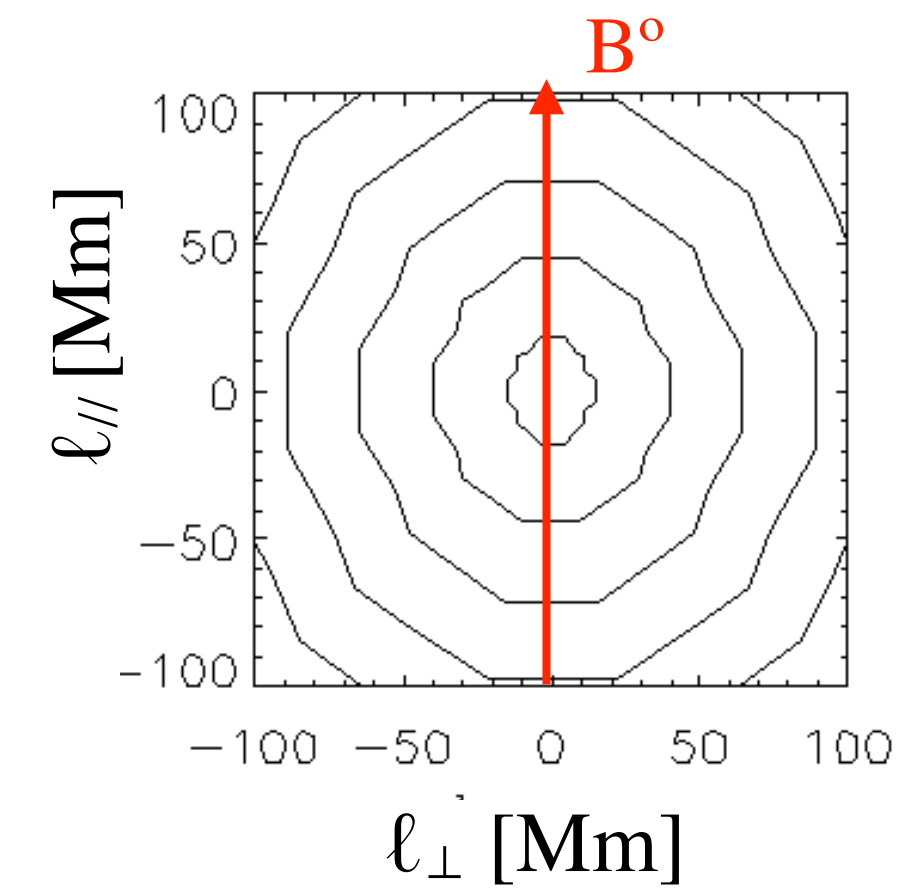
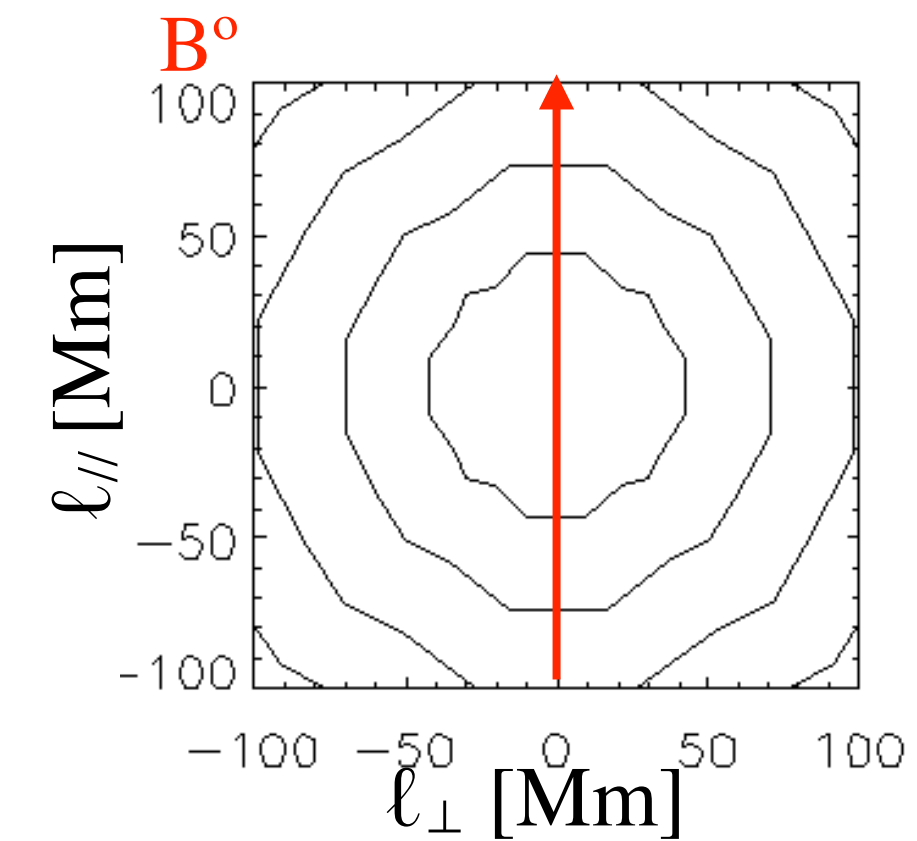
slow wind

fast wind



Dasso et al 2005

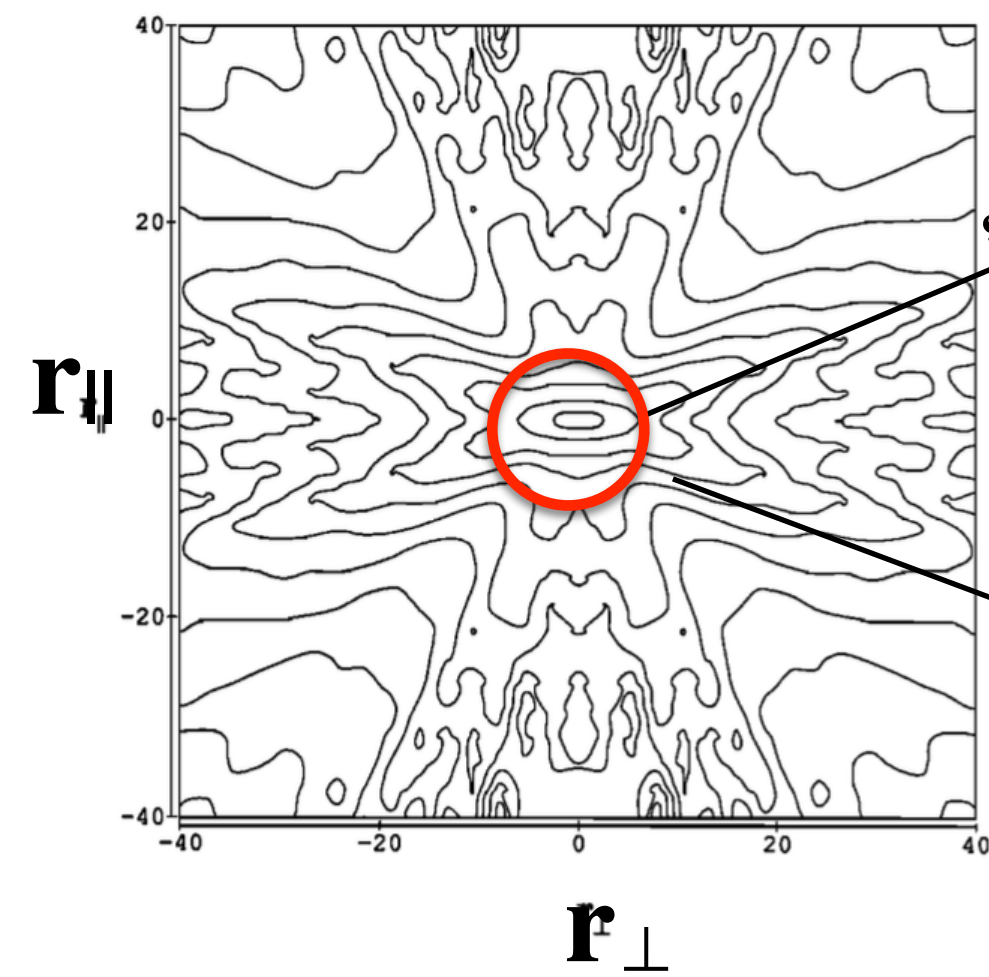
SLAB in fast wind  
2D in slow wind



Wang Tu He 2019

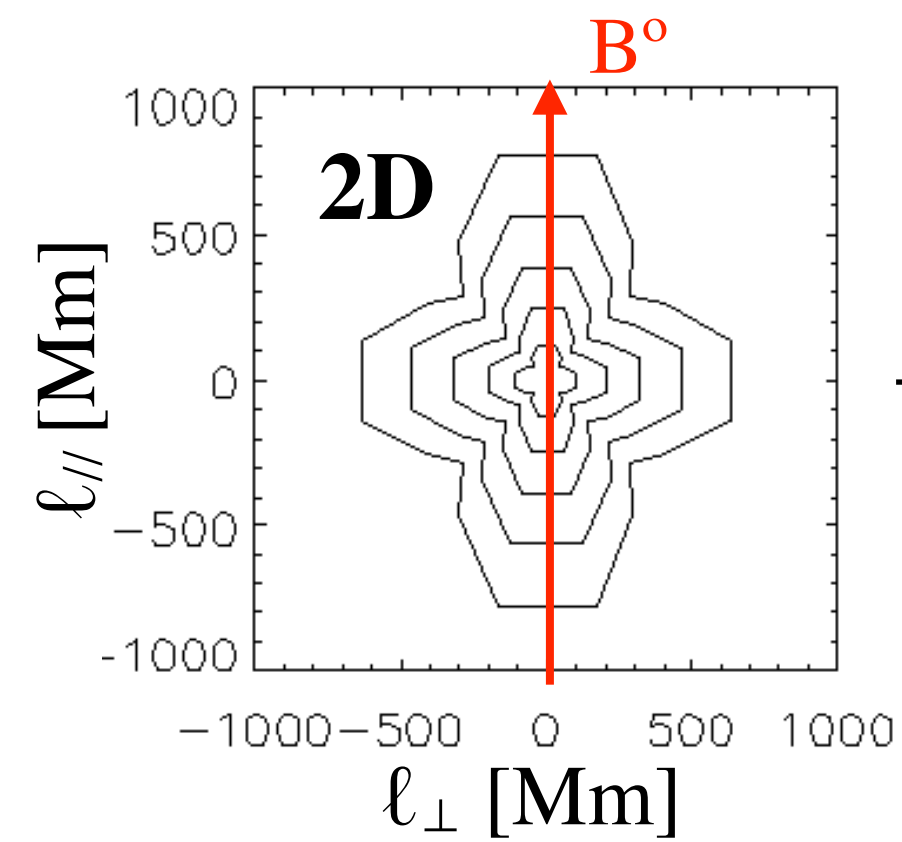
Isotropic

# Observed Anisotropy in the SW



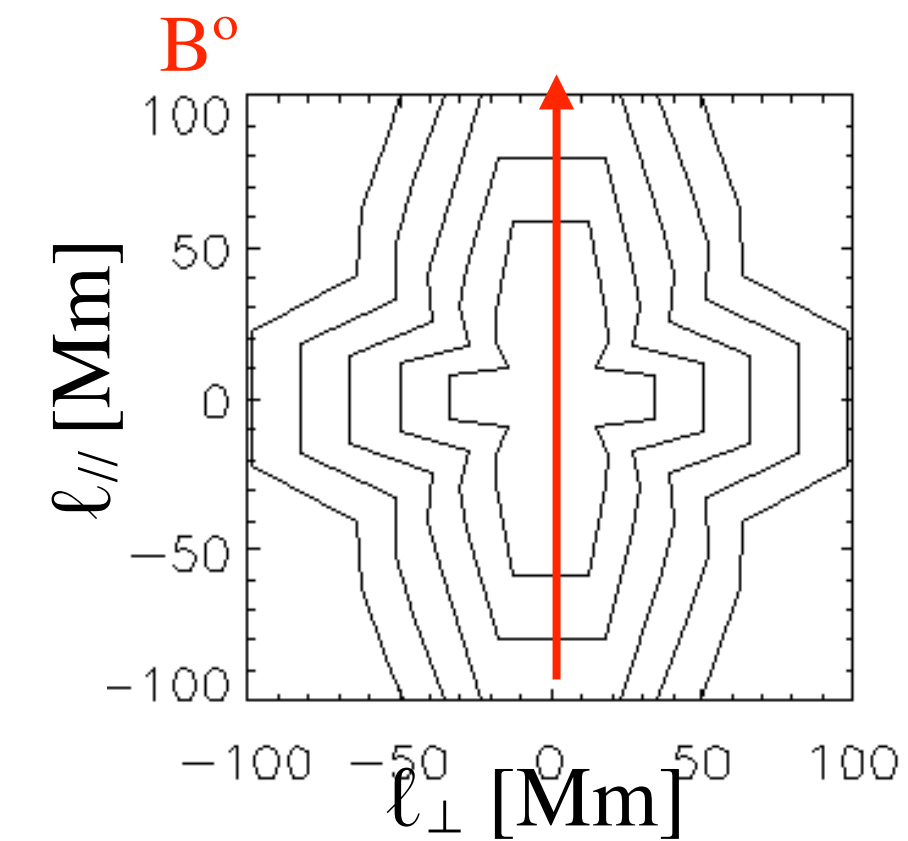
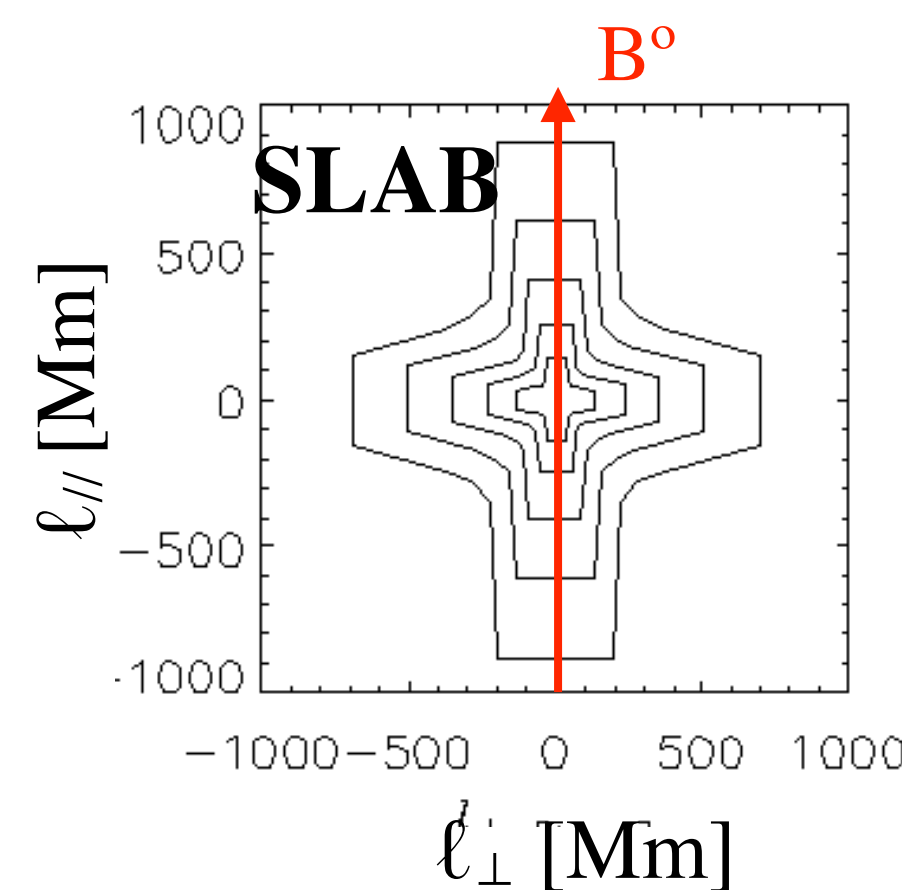
Matthaeus Goldstein  
Roberts 1990

Maltese cross



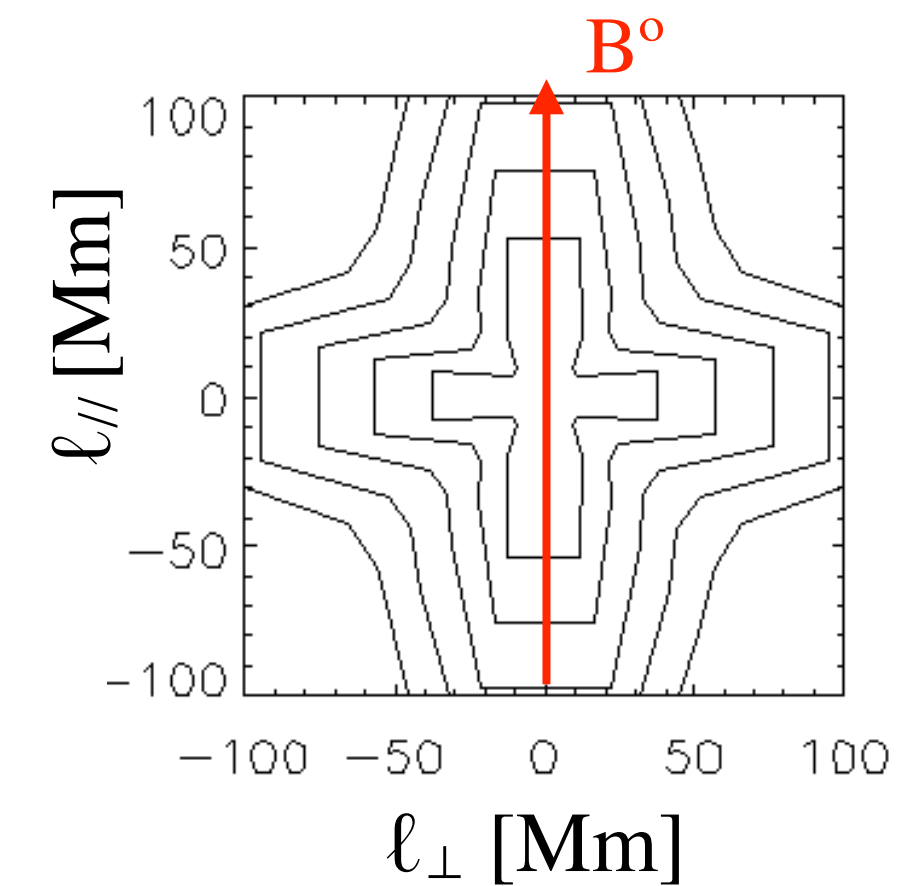
Dasso et al 2005

SLAB in fast wind  
2D in slow wind



Wang Tu He 2019

Isotropic



# Summary - Conclusions

Anisotropy, Cascade, Statistical Eddy Shape in the solar wind can be reproduced reasonably well in numerical simulations (sometimes expansion is a necessary ingredient)

Anisotropy is ruled by two axis of symmetry,  $B^\circ$  (turning) and R, their relative importance depends on scale (not in a trivial way)

## Limitations of s/c data analysis

Only the anisotropy w.r.t.  $B^\circ$  can be captured, while that w.r.t. to R can only be guessed indirectly

Bias the statistics of spectral anisotropy (because of correlation among  $V_{sw}$ ,  $\delta B$ ,  $\theta_{BV}$ )

Bias the statistics of scale dependent anisotropy (eddy shape) because of selective decay of B

Multi point measurement techniques (LPDE, but also simpler reconstruction of the 3D autocorrelation are necessary to reveal when and at which scale  $B^\circ$  dominates over R and if and when Slow and Fast stream differ in their anisotropy and cascade