Fight between expansion and nonlinear coupling: solar wind modeling (global/local)

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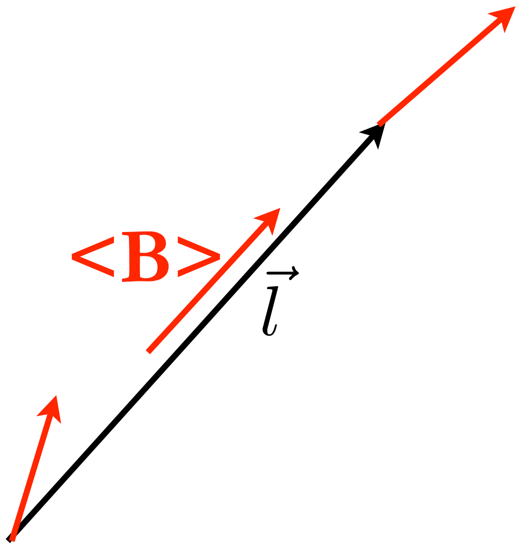
In homogeneous *incompressible* MHD turbulence with mean magnetic field, the turbulent cascade has two main properties

- Energy flux **perpendicular to the mean field**
- NL term ∝ **$z_- z_+$**
- z_- or $z_+ \rightarrow 0 \Rightarrow$ frozen turbulence

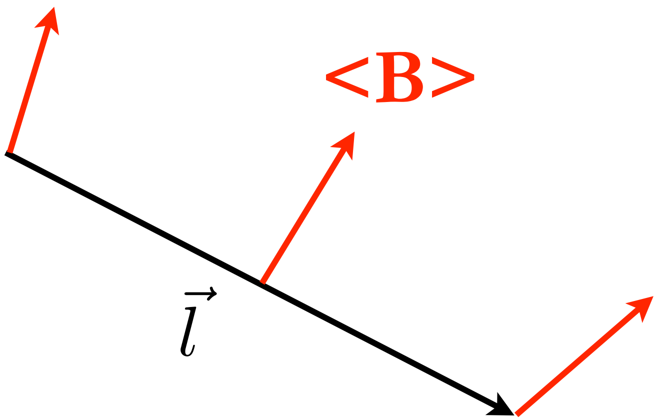
In the solar wind, the *transverse expansion* of a plasma box implies :

- the energy flux **perpendicular to radial is frozen**
- Energy flux (via scale) is thus controlled by expansion
- evolution $\rightarrow z_- \approx z_+$

Measuring anisotropy: structure functions w.r.t. local mean field



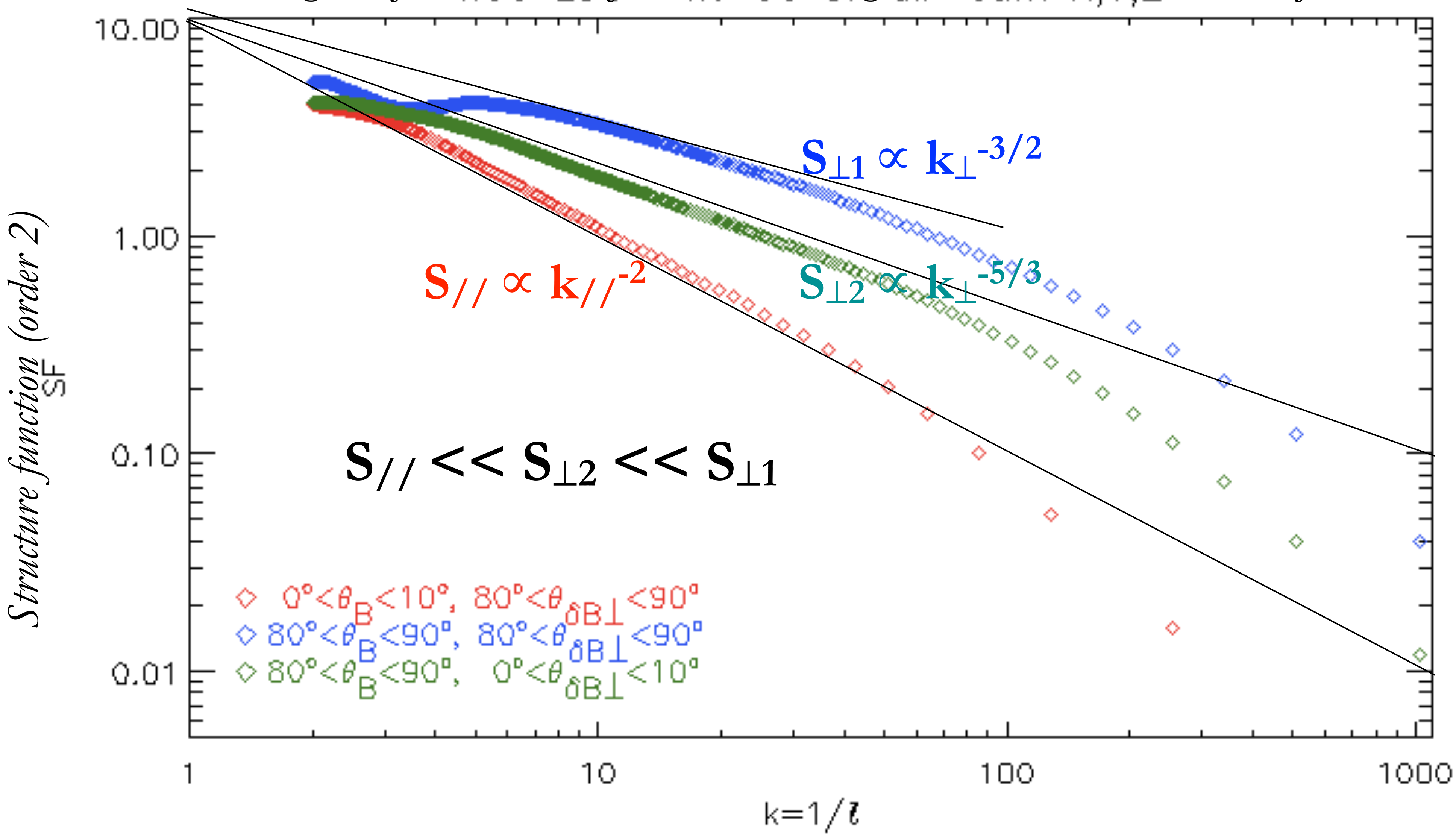
$\Rightarrow S_{//}(l)$



$\Rightarrow S_{\perp}(l)$

Spectral anisotropy (1) forced homogeneous turbulence

Magnetic field structure functions selecting directions w.r.t. local mean field



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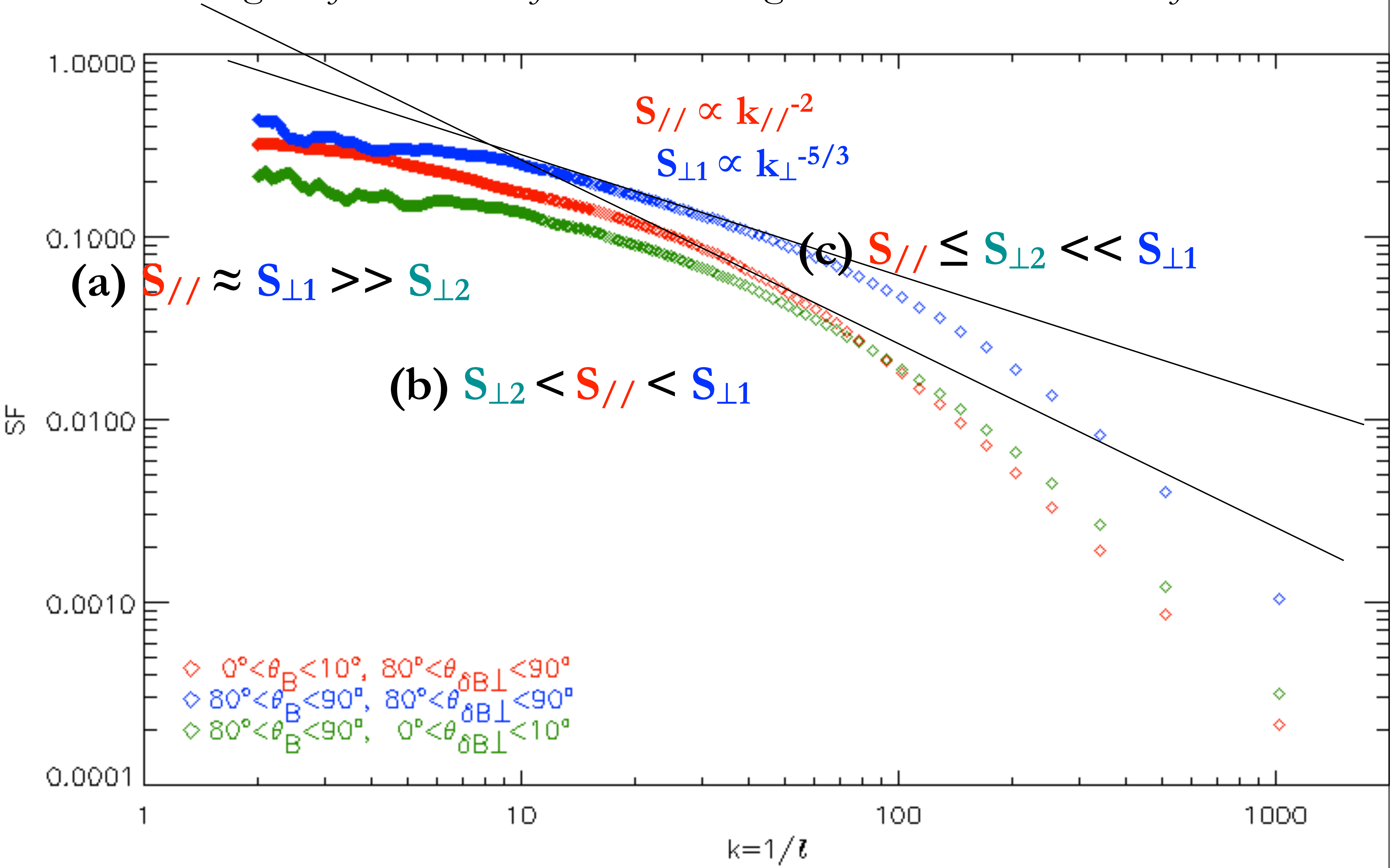
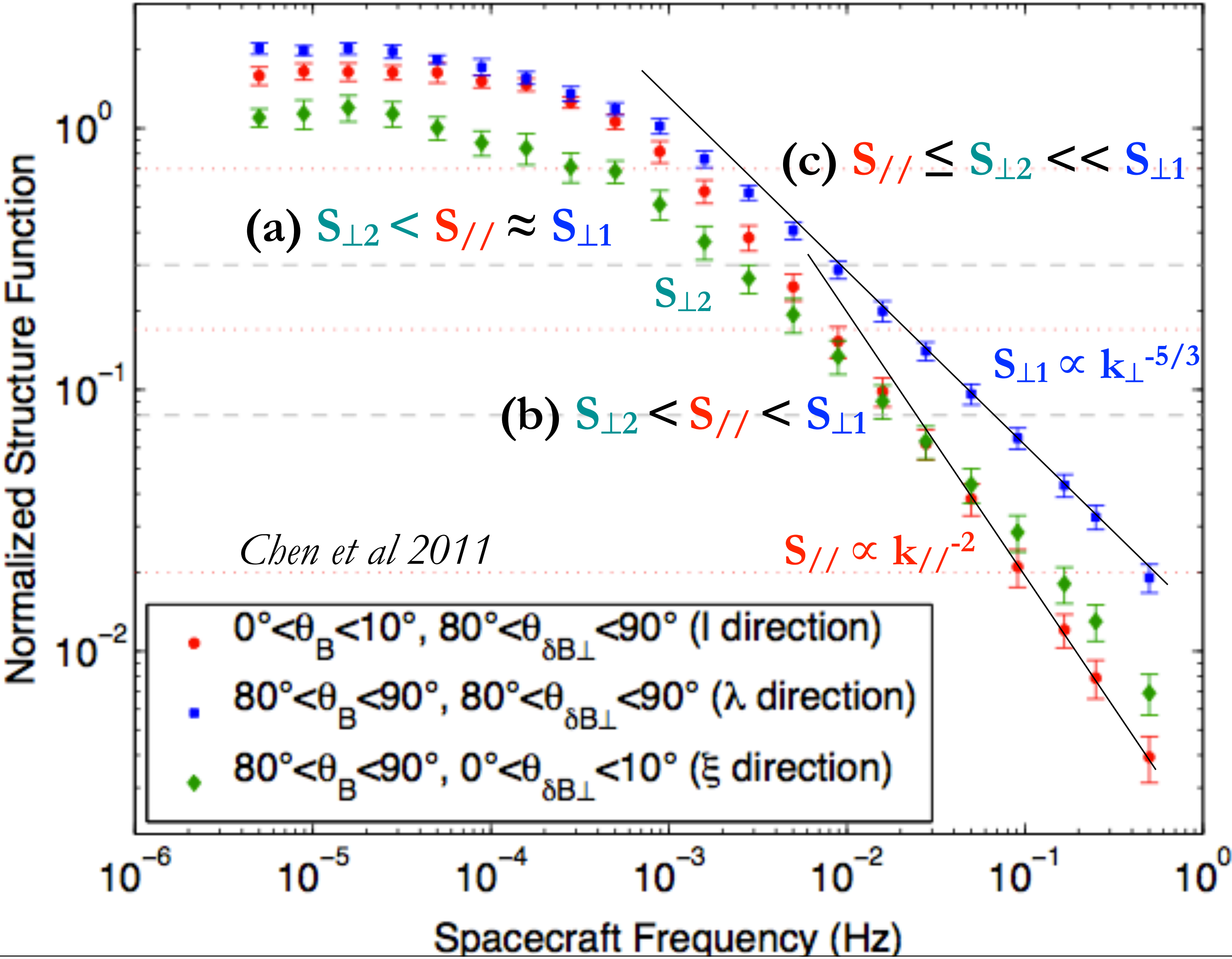
Spectral anisotropy (2) local model of SW turbulence

Magnetic field structure functions selecting directions w.r.t. local mean field

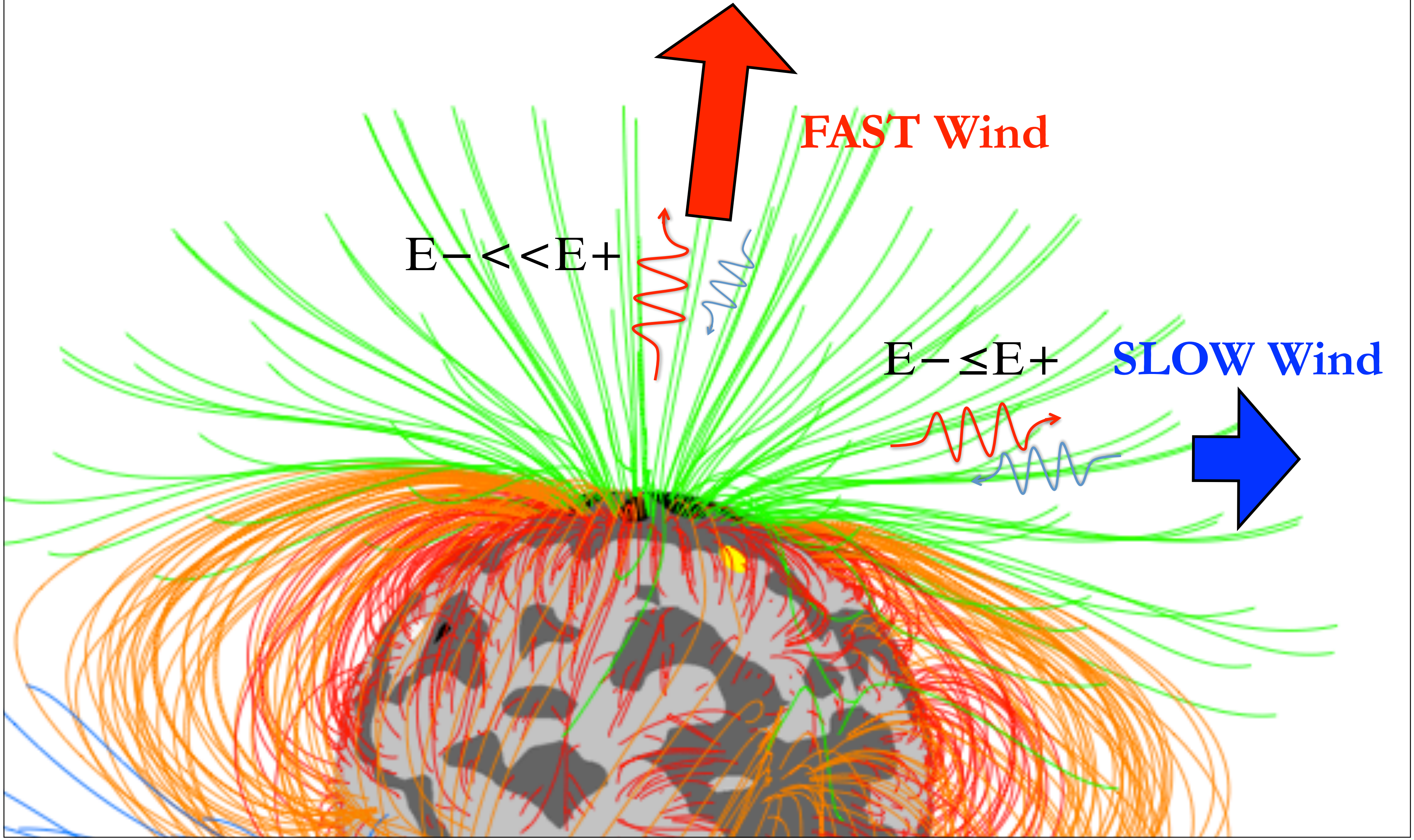


Spectral anisotropy (3) SW turbulence

Magnetic field structure functions selecting directions w.r.t. local mean field

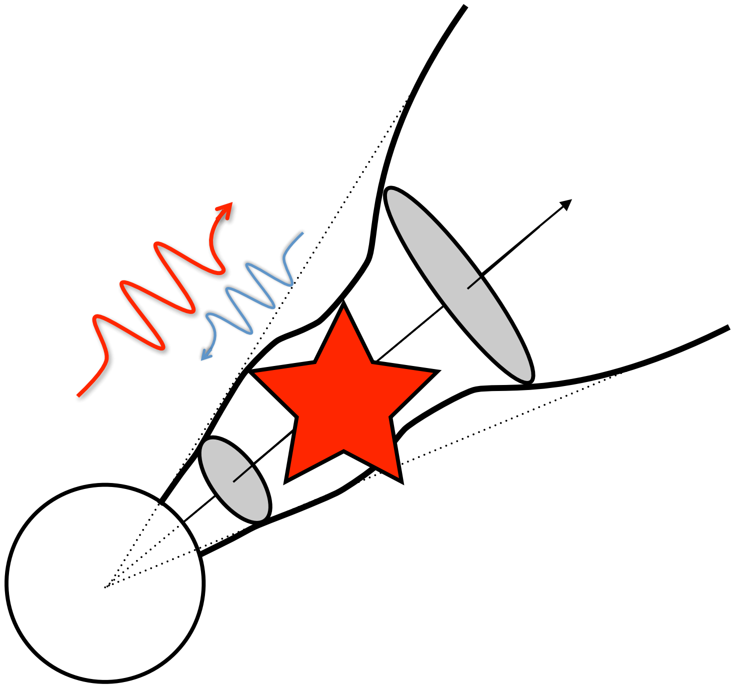


The sources of the wind AND turbulence



Tools/Models

Global: *eulerian 1D Hydrodynamics*

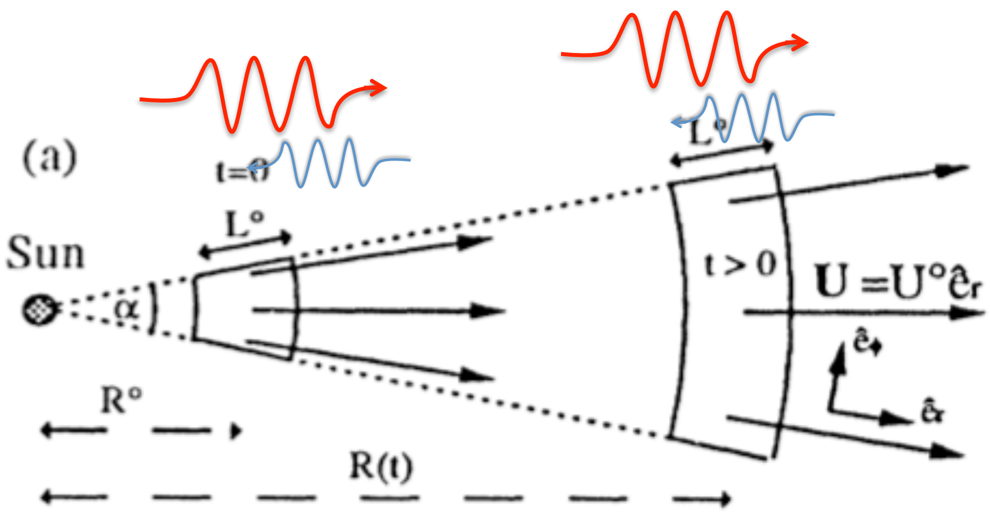


$$\frac{\partial \rho}{\partial t} + B\frac{\partial}{\partial r}\left(\frac{\rho u}{B}\right) = 0,$$

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial r} = -\frac{\partial p}{\partial r} - \rho\frac{GM_\odot}{r^2}, -\frac{\partial \delta B^2/2}{\partial r}$$

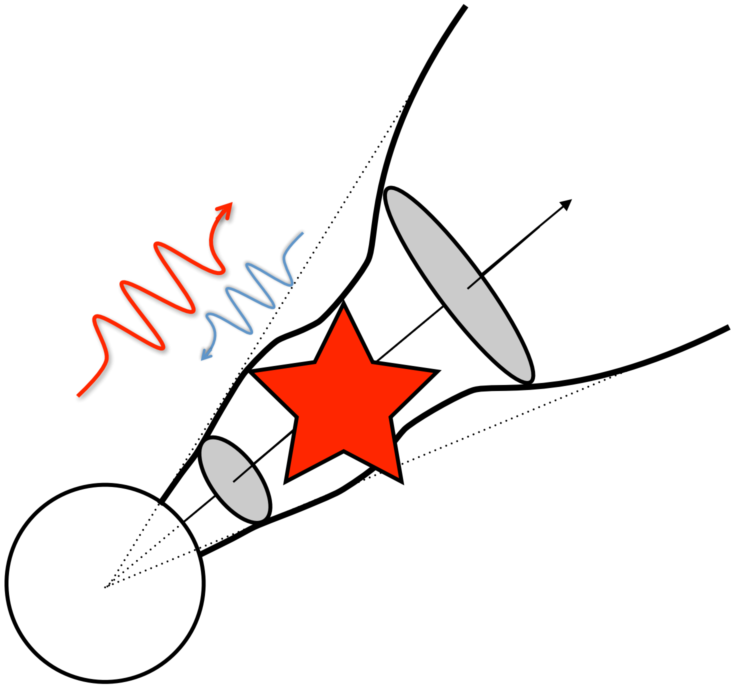
$$3nk\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial r}\right) + 2nkTB\frac{\partial}{\partial r}\left(\frac{u}{B}\right) = - B\frac{\partial}{\partial r}\left[\frac{(F_h + F_c)}{B}\right] - n^2\Lambda(T).$$

Local: *3D MHD expanding box model*



Tools/Models

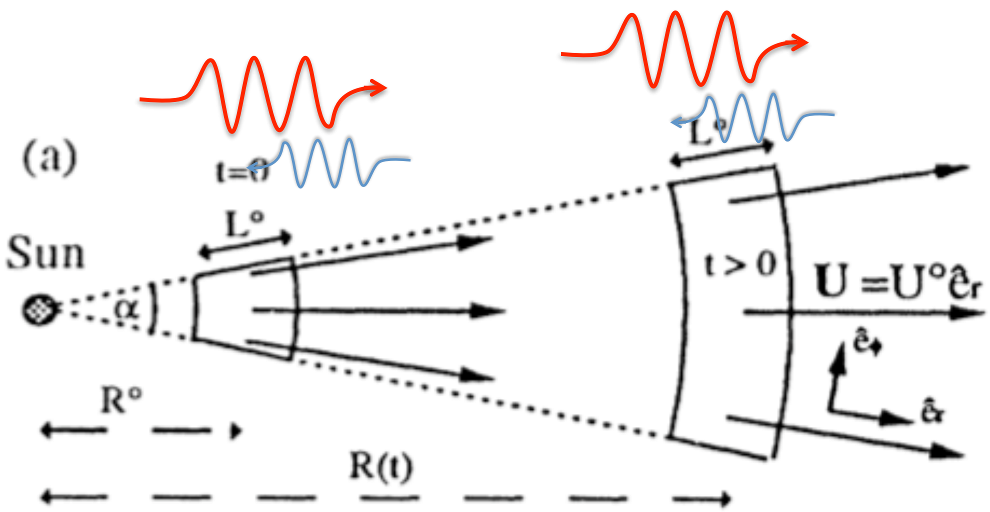
Global: *eulerian 1D Hydrodynamics*



•Control parameters:
- Coronal B field
- turbulent heating model
- ratio E_-/E_+

•Output:
- Wind properties
at earth's orbit: U, Va, Ti, n

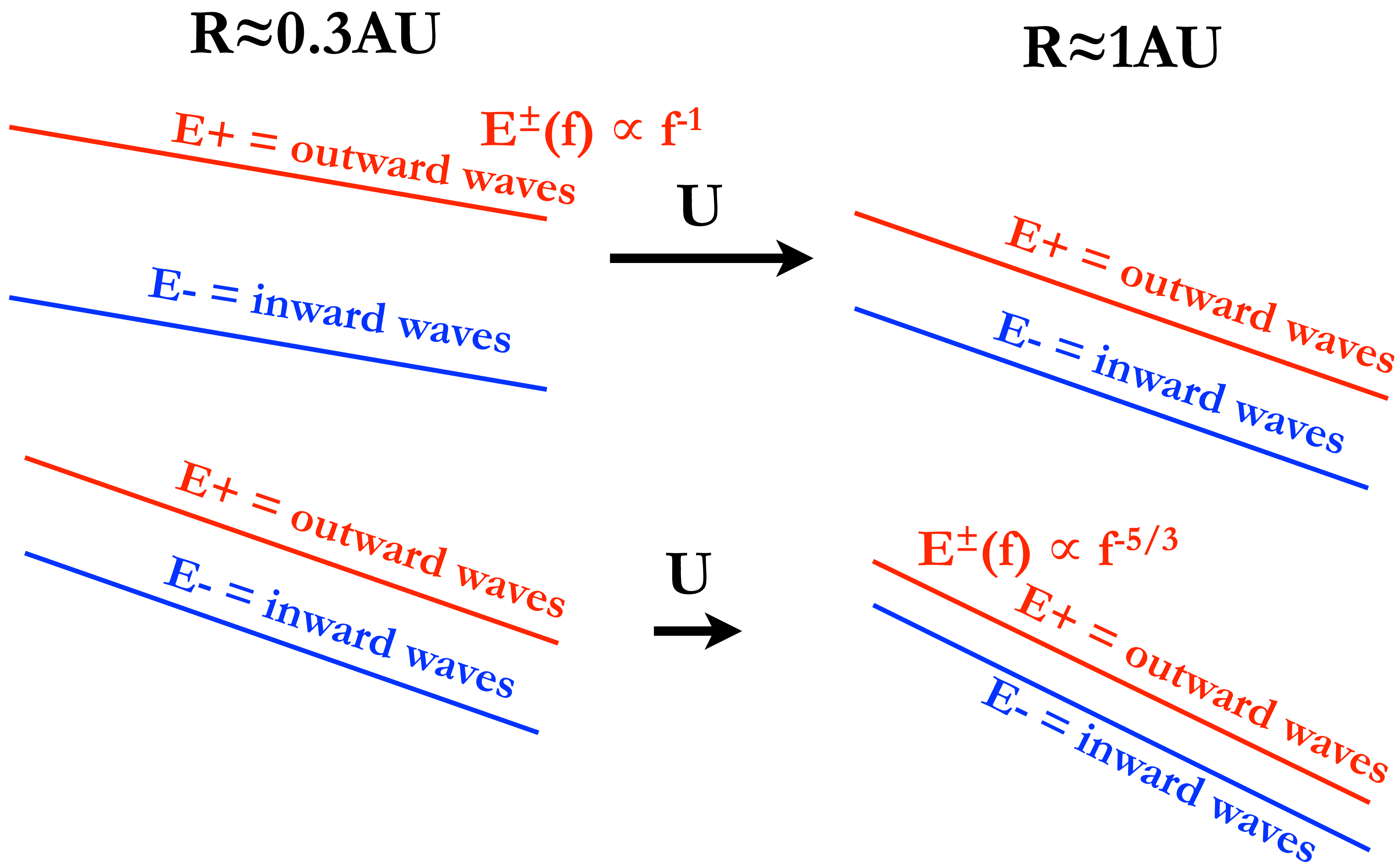
Local: *3D MHD expanding box model*



•Control parameters:
- Initial conditions at 0.1 AU
- (uniform) wind speed

•Output:
- turbulent spectra at 1 AU
- turbulent dissipation

Observations between 0.3 and 1 AU
Incident and reflected waves spectra $E_{\pm}(f)$



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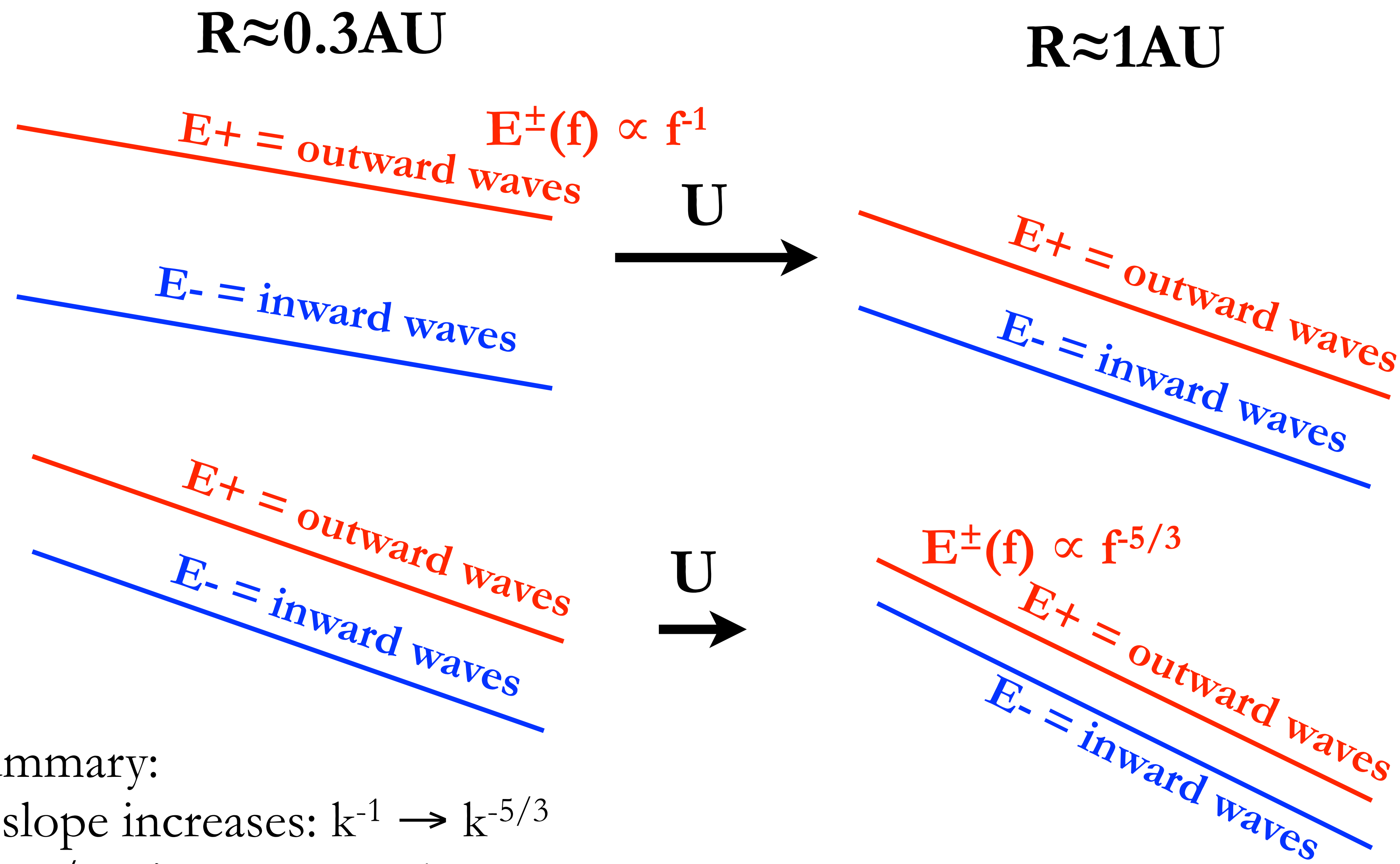


Summary:

1. slope increases: $k^{-1} \rightarrow k^{-5/3}$
2. E_-/E_+ increases $\rightarrow 1$
3. The process goes faster in slow winds

$E_{\pm}(f)$ Spectra compensated by $f^{-5/3}$

E+=outward

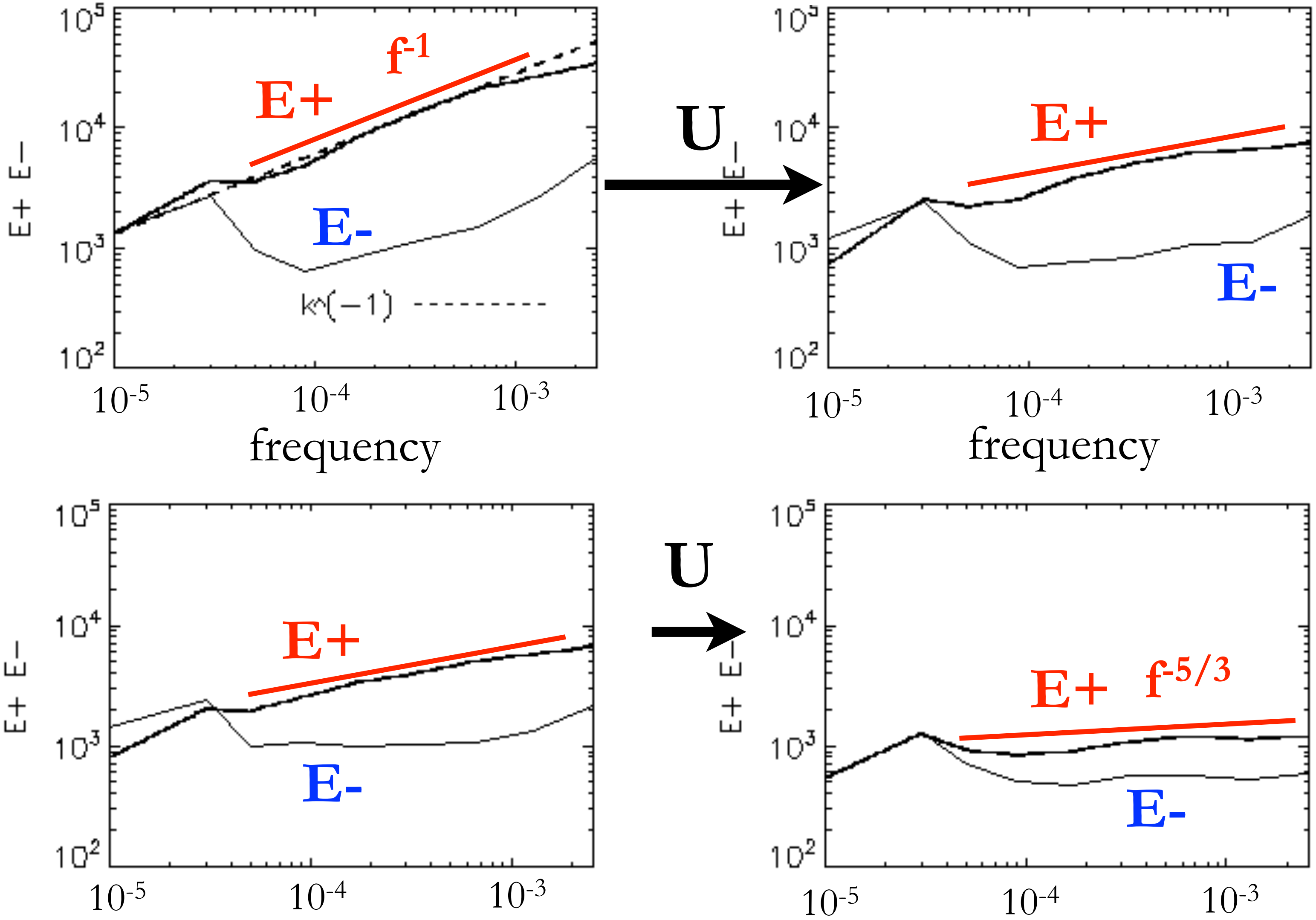
E- =inward

Compensated *spectra* $E^{\pm}(f)f^{5/3}$

R<0.5AU **R>0.8AU**

Fast winds
U>550km/s

Slow winds
U>550km/s



Observed vs local model output

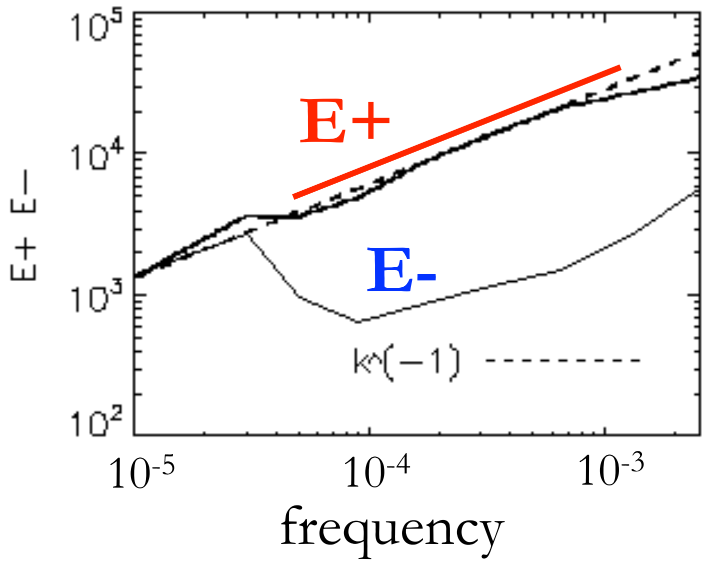
E+=outward

E- =inward

Compensated *spectra* $E^{\pm}(f)f^{5/3}$

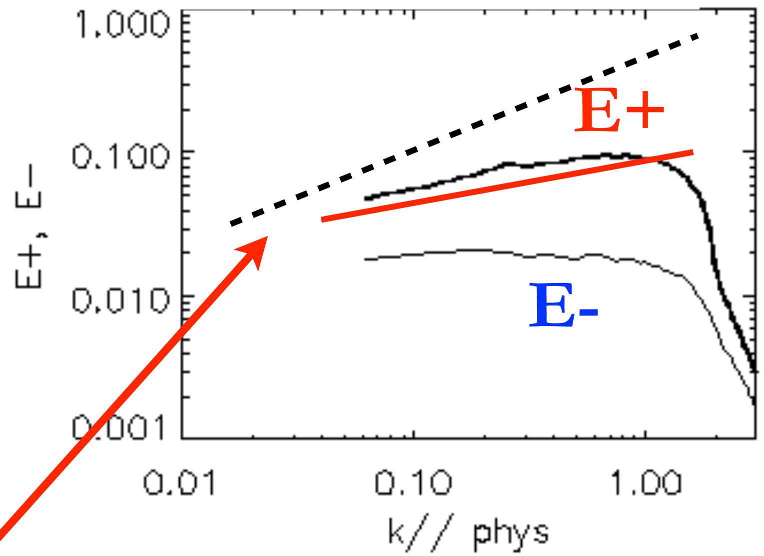
Observed

Fast winds
U>550km/s



R<0.5AU

Local model



R=0.4AU

⇒ Output of local model qualitatively OK but **proceeds too fast**:

- The large scale **f^{-1} range is missing**, "pushed" out of the spectral range
- Larger Reynolds would be needed to keep it within the domain
- This large-scale reservoir might help delaying inertial range evolution

Local model spectra vs distance and wind speed

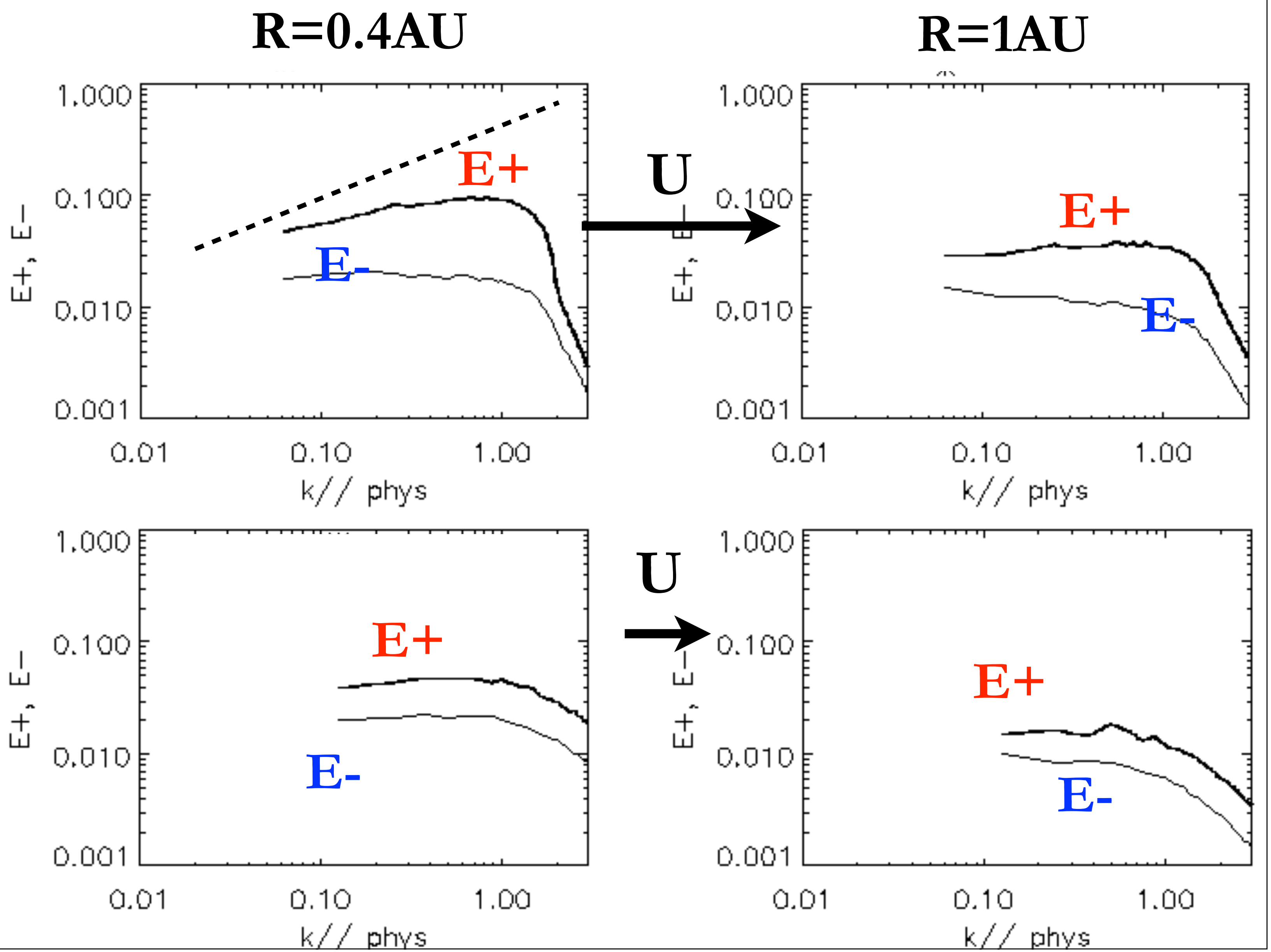
E+=outward

E- =inward

Compensated *spectra* $E^{\pm}(f)f^{5/3}$

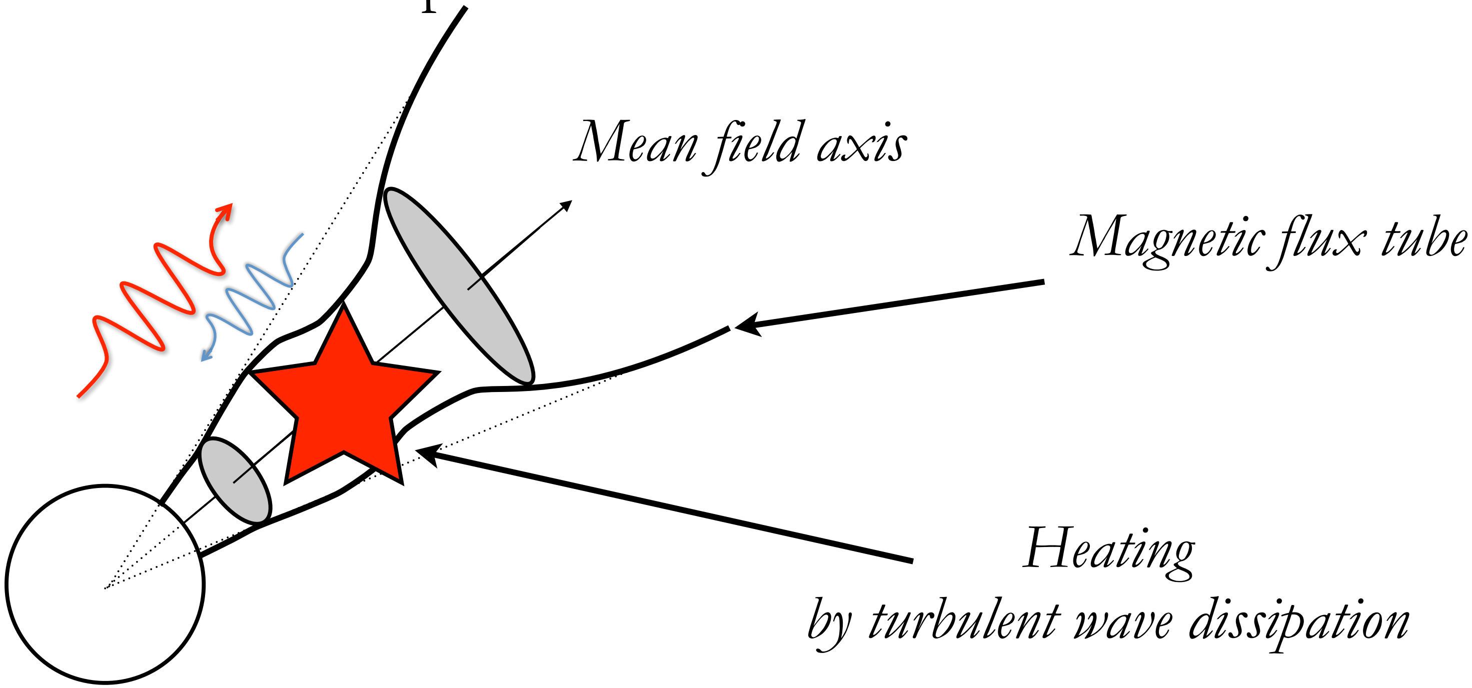
"Fast" wind

"slow" wind



Global model

1D Hydrodynamics + transport equation for Alfvén waves along mean field axis + wave dissipation



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$$3nk\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial r}\right) + 2nkTB\frac{\partial}{\partial r}\left(\frac{u}{B}\right) = - B\frac{\partial}{\partial r}\left[\frac{(F_\mathrm{h} + F_\mathrm{c})}{B}\right] - n^2\Lambda(T).$$

Turbulent heating: defining the model (1)

1. Hydrodynamics: **$du^2/dt \approx -u^3/L$**

2. MHD

Alfvén wave amplitude: $z^{\pm} = u \pm b/\sqrt{\rho}$

Model: strong NL coupling ($\perp$ to mean field)

$$dz_+^2/dt \approx -z_+^2 z_-/L$$
$$dz_-^2/dt \approx -z_-^2 z_+/L$$

L = characteristic size of "eddies" $\Rightarrow$ how to choose L?

Turbulent heating: defining the model (2)

Choosing characteristic size L for large scale "eddies"

- Choose the wave frequency

⇒ peak (solar surface) period $\boldsymbol{\tau}$ = **5 min**

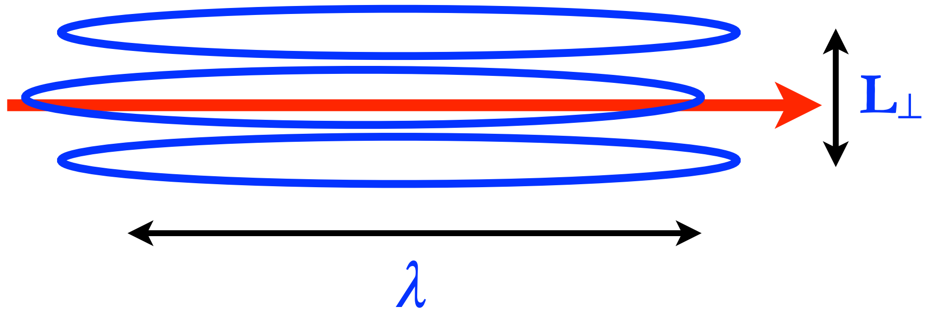
⇒ compute wavelength profile

$\lambda = (U+V_a)\tau$

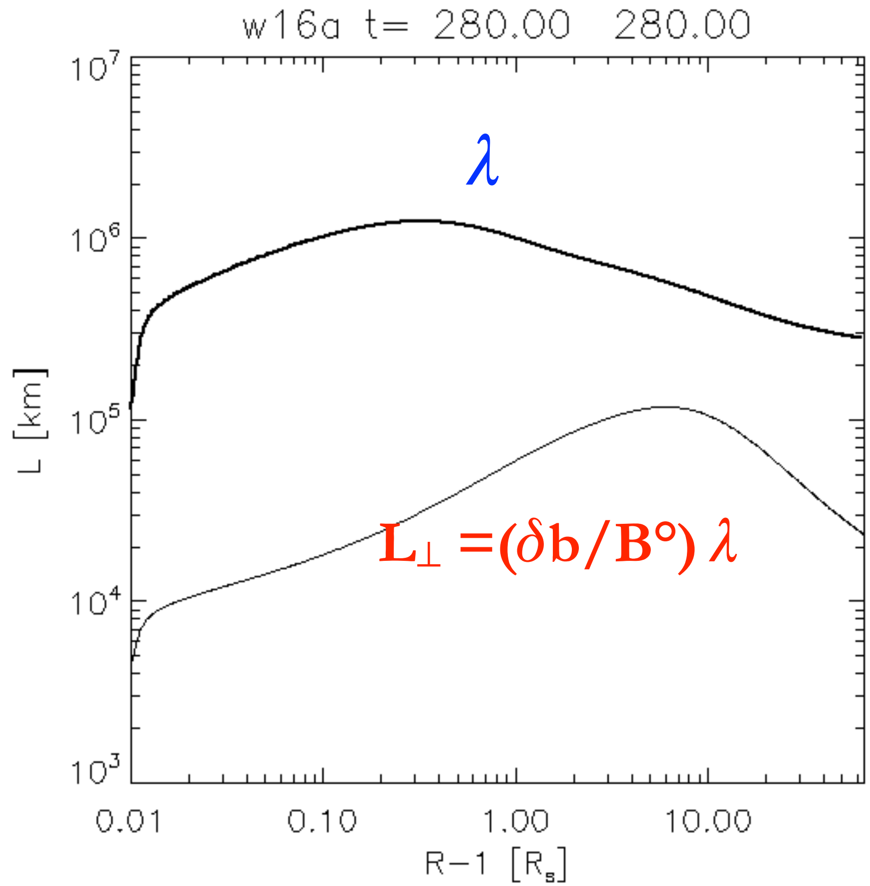
• ⊥ coupling ⇒ "integral" scale is

$L_\perp \approx \lambda\, \delta B/B°$

Sketch of wave isocontours when $\delta B << B°$



Wavelength and ⊥ scale vs altitude $R-R_s$



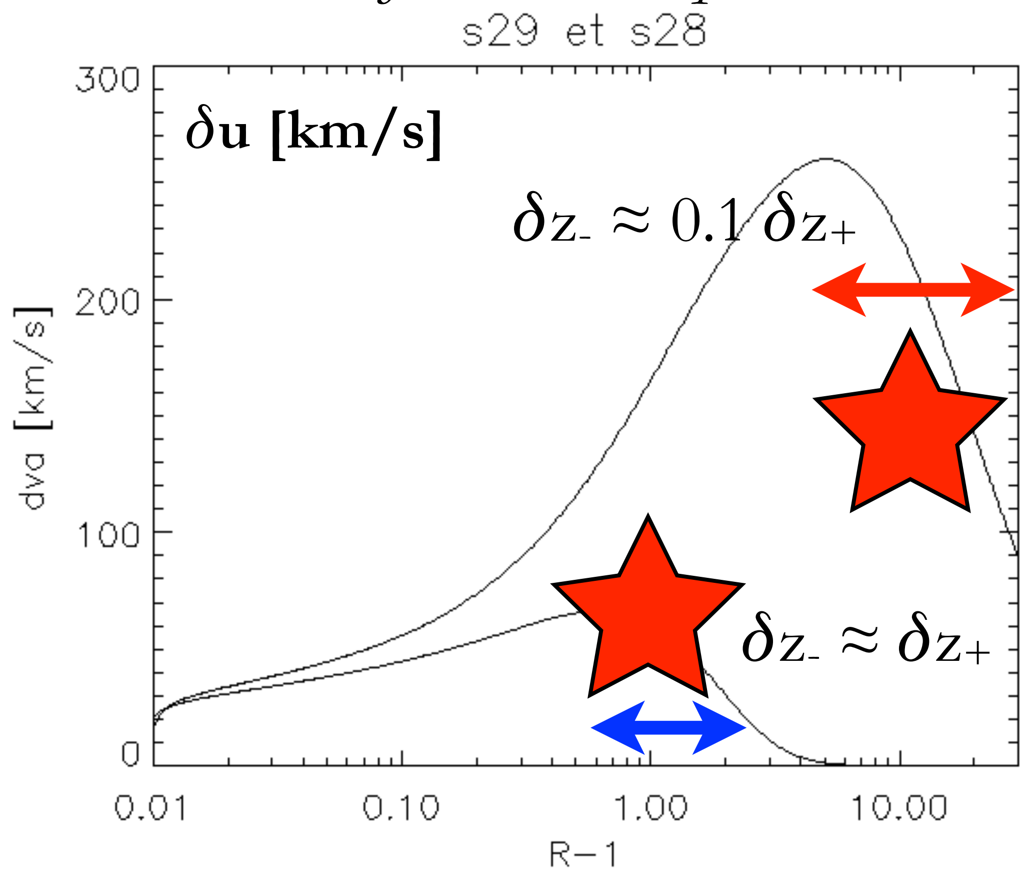
Global model results: wave amplitude vs reflected ratio

Two typical runs

small reflection $\delta z_- \approx 0.1\, \delta z_+ \Rightarrow$ weak *high* heating $\Rightarrow$ fast wind

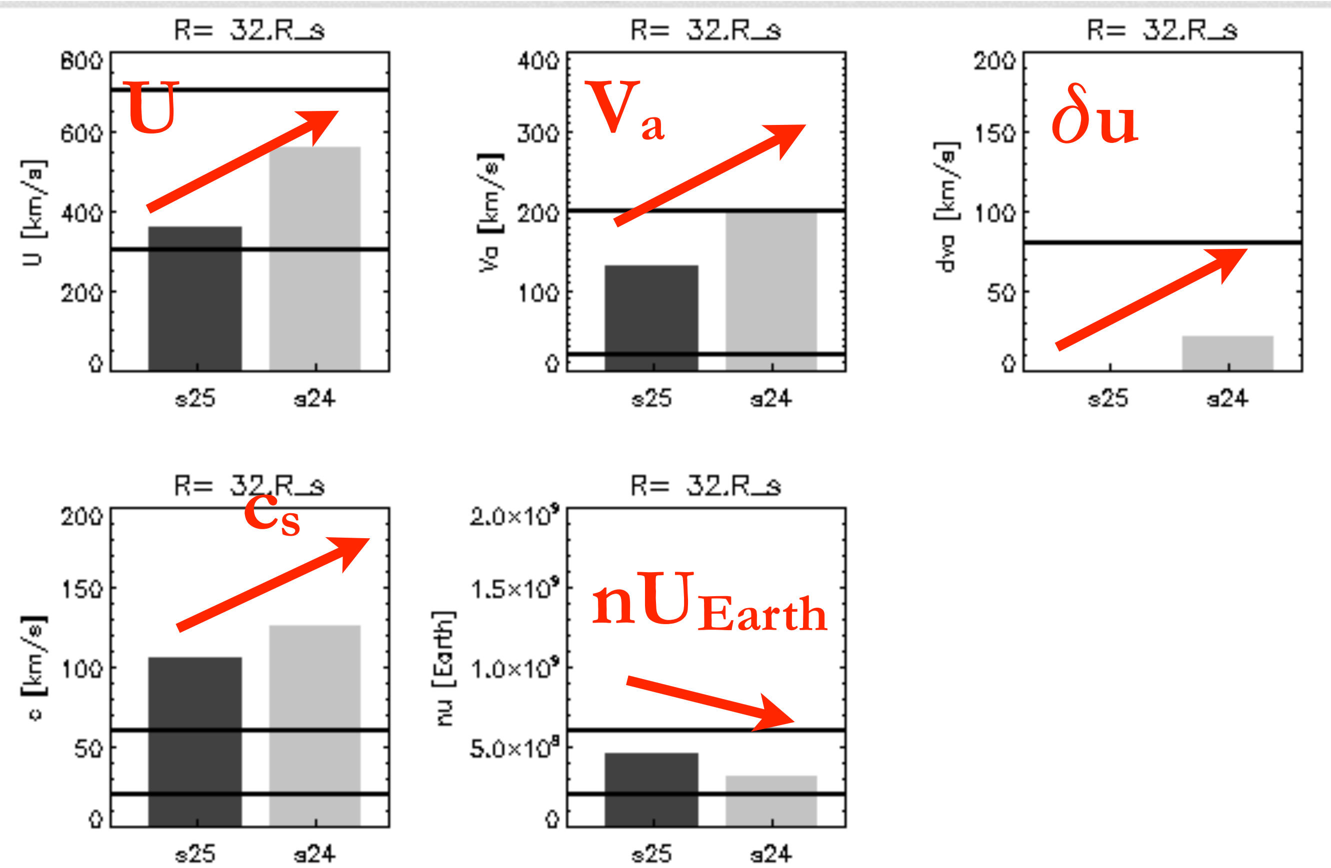
strong reflection $\delta z_- \approx \delta z_+ \Rightarrow$ strong *low* heating $\Rightarrow$ slow wind

Alfvén wave amplitude



Global model results at 0.15 AU: wind speed ... mass flux

Output of the global model at 32 $R_s \approx$ 0.15 AU



Summary

- Small reflection $\delta z_- \approx 0.1\, \delta z_+ \Rightarrow$ cold, slow wind, large mass flux
- Large reflection $\delta z_- \approx \delta z_+ \Rightarrow$ hot, fast winds, small mass flux

Isotropic local shell model

Shell model for turbulent energy u_n^2 within scale $1/k_n = 2^{-n}/k°$

•Two variants

- time t in units of nonlinear time $t_{NL}° = 1/(k°u°)$
- Distance to sun is $R=1+ \varepsilon t$

Control parameter: $\varepsilon = U°/R° \times t_{NL}°$

$R° = 0.1$ AU (starting distance), $U°$ = wind speed (given)

1. *Parallel cascade (* **k** //radial direction*)*

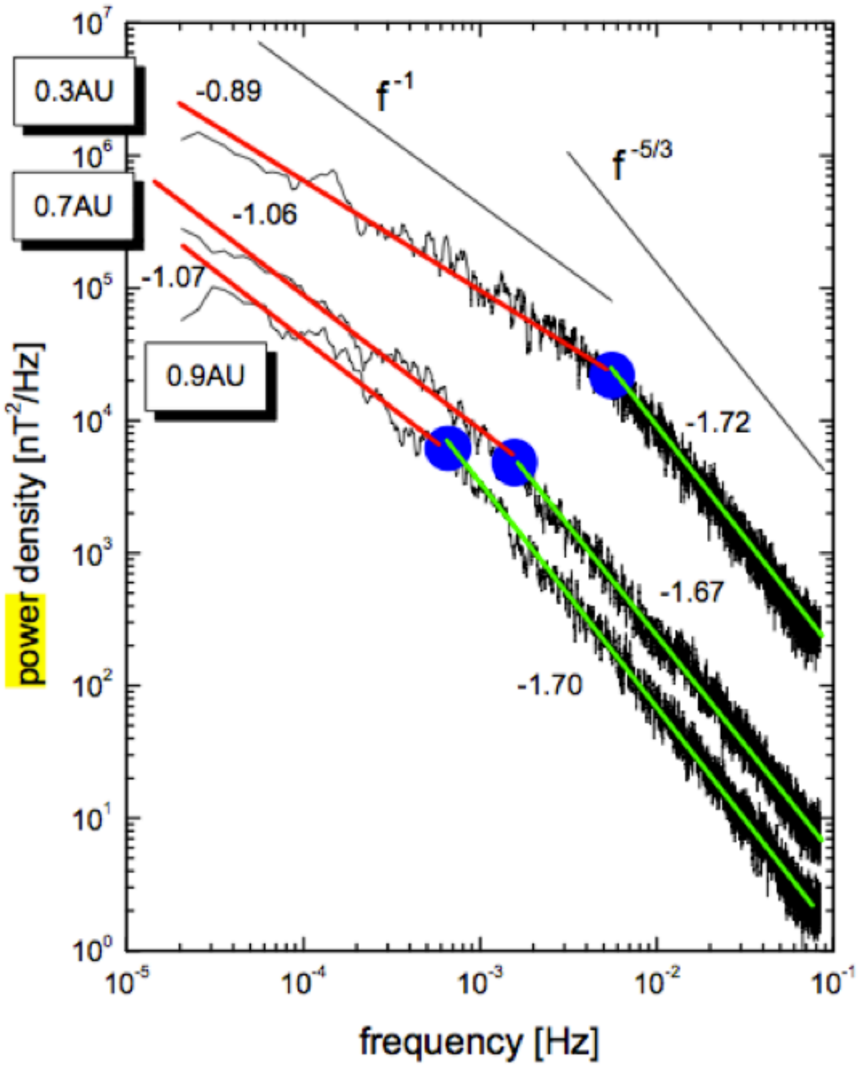
$\partial_t u_n = k_n u_{n-1}^2 - k_{n+1} u_n u_{n+1} -(\varepsilon/2R) u_n - \nu k_n^2 u_n$ $(k = k_{//})$

2. ⊥ *cascade (***k** ⊥ radial direction*)*

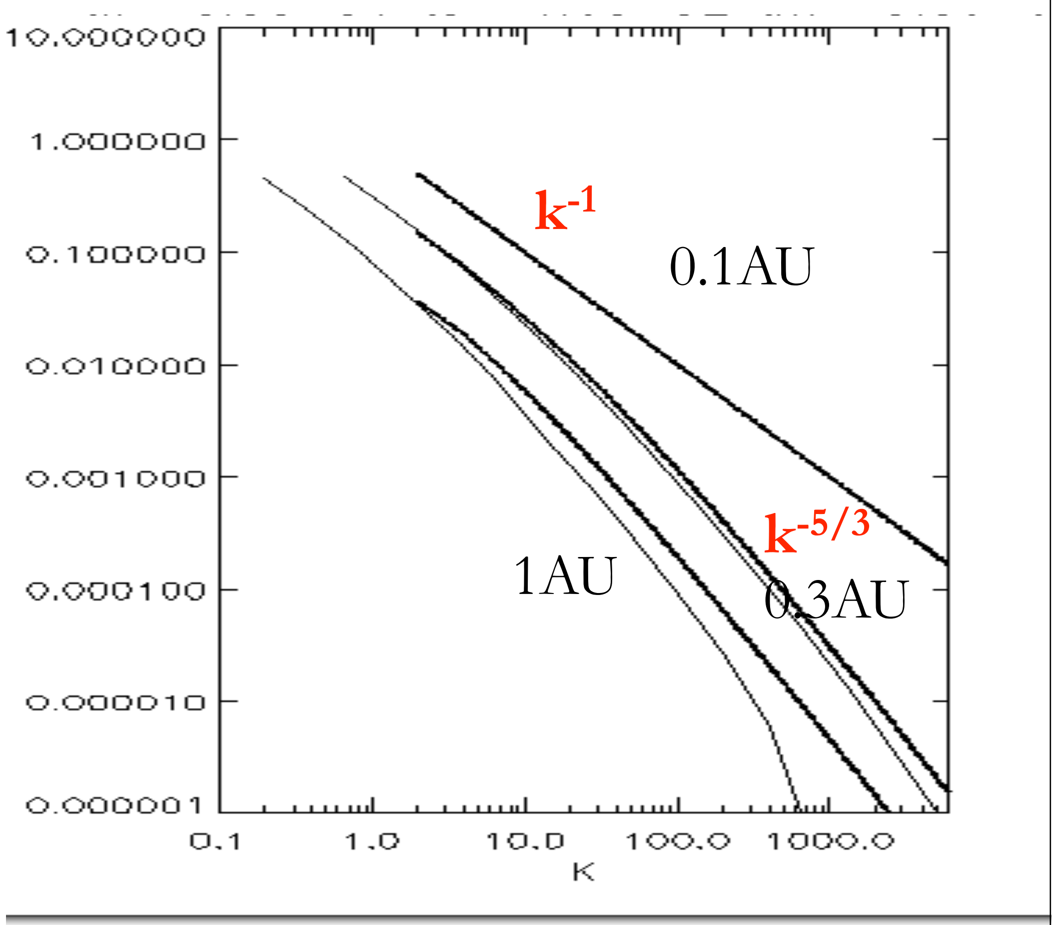
$\partial_t u_n = (1/R) k_n u_{n-1}^2 - (1/R) k_{n+1} u_n u_{n+1} -\varepsilon/(2R)\, u_n - \nu k_n^2 u_n$ $(k = k_\perp)$

Isotropic local shell model

Tu et al 1984, Tu and Marsch 1990...2000



Shell model spectra



Conclusion

1. Expanding box model
- starts with a flat k^{-1} spectrum

⇒ **Spectral slopes** and **z-/z+ ratio increase** as observed, but too fast

•Hint: evolution fast because large "frozen" scales are pushed out of the system (small Reynolds)

2. Global 1D model
- generates the thermal stratification + wind, with a *single* wave frequency

⇒ **z-/z+ controls the wind properties**

•to be confirmed...

3. Shell model

⇒ Due to the large Reynolds, the **2-slope spectrum** (-1 and 5/3) shows up

•but agreement *only qualitative*: (polarization anisotropy missing)

The expanding box model should help devising

a) a better global description

b) an anisotropic shell model