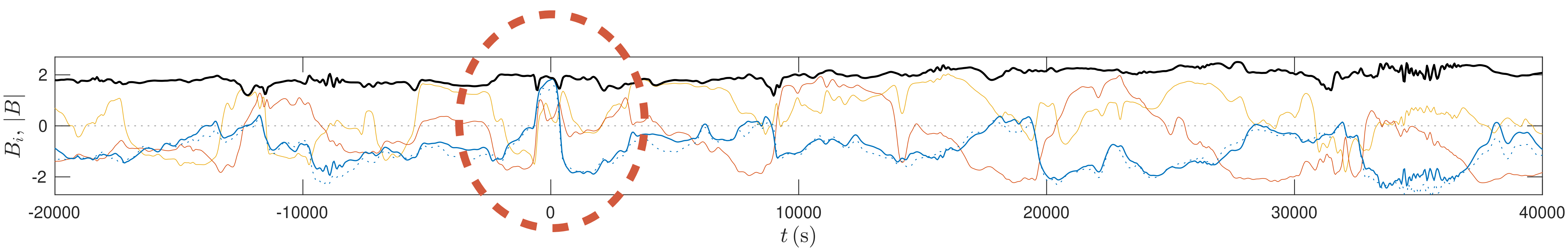
In-situ switchback formation

A computational study



Virtual Nordic Dynamo Seminar, Sep 2020

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In-situ Switchback Formation in the Expanding Solar Wind

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Abstract

Recent near-Sun solar-wind observations from *Parker Solar Probe* have found a highly dynamic magnetic environment, permeated by abrupt radial-field reversals, or "switchbacks." We show that many features of the observed turbulence are reproduced by a spectrum of Alfvénic fluctuations advected by a radially expanding flow. Starting from simple superpositions of low-amplitude outward-propagating waves, our expanding-box compressible magnetohydrodynamic simulations naturally develop switchbacks because (i) the normalized amplitude of waves grows due to expansion and (ii) fluctuations evolve toward spherical polarization (i.e., nearly constant field strength). These results suggest that switchbacks form in situ in the expanding solar wind and are not indicative of impulsive processes in the chromosphere or corona.

Unified Astronomy Thesaurus concepts: Space plasmas (1544); Alfven waves (23); Solar wind (1534); Solar magnetic fields (1503); Interplanetary turbulence (830)

1. Introduction

The recent perihelion passes of *Parker Solar Probe* (*PSP*) have revealed a highly dynamic near-Sun solar wind (Bale et al. 2019; Kasper et al. 2019). A particularly extreme feature compared to solar-wind plasma at greater distances is the abundance of "switchbacks": sudden reversals of the radial magnetic field associated with sharp increases in the radial plasma flow (Neugebauer & Goldstein 2013; Horbury et al. 2018, 2020). Such structures generally maintain a nearly constant field strength $|\boldsymbol{B}|$, despite large changes to $\boldsymbol{B}$. It remains unclear how switchbacks originate and whether they are caused by sudden or impulsive events in the chromosphere or corona (e.g., Roberts et al. 2018; Tenerani et al. 2020).

In this Letter, our goal is to illustrate that turbulence with strong similarities to that observed by *PSP* develops from simple, random initial conditions within the magnetohydrodynamic (MHD) model. Using numerical simulations, we show that constant-$|\boldsymbol{B}|$ radial-field reversals arise naturally when Alfvénic fluctuations grow to amplitudes that are comparable to the mean field. We hypothesize that the effect is driven by magnetic-pressure forces, which, by forcing $|\boldsymbol{B}|$ to be nearly

2. Methods

We solve the isothermal MHD equations in the "expanding-box" frame (Grappin et al. 1993), which moves outward in the radial (x) direction at the mean solar-wind velocity, while expanding in the perpendicular (y and z) directions due to the spherical geometry. We impose a mean anti-radial (sunward) field $\boldsymbol{B}_0 = -B_{x0}\hat{\boldsymbol{x}}$, with initial Alfvén speed $v_A = B_{x0}/\sqrt{4\pi\rho}$. The mass density ρ, flow velocity $\boldsymbol{u}$, and magnetic field $\boldsymbol{B}$ evolve according to

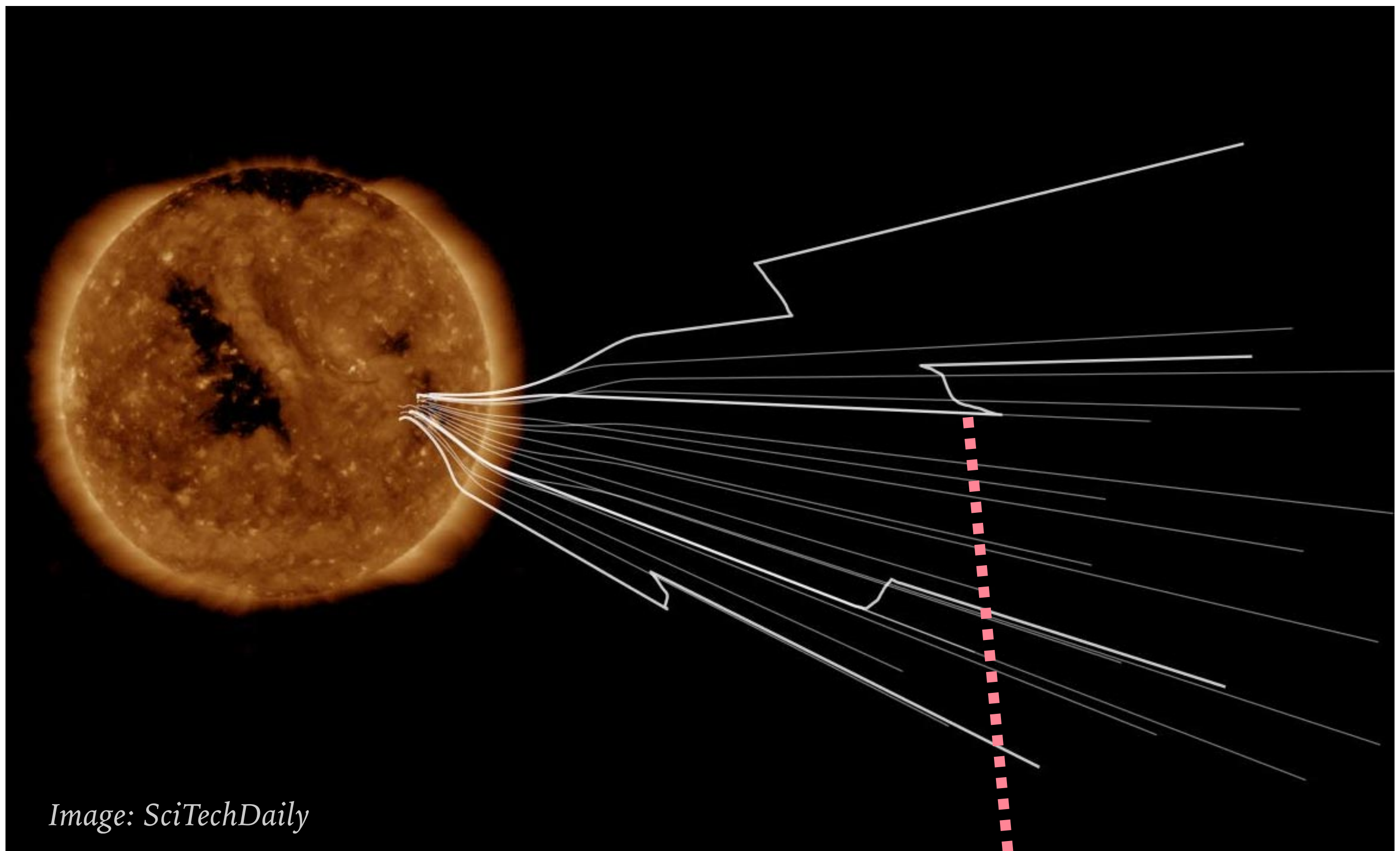
$$\partial_t \rho + \tilde{\nabla} \cdot (\rho \boldsymbol{u}) = -2\frac{\dot{a}}{a}\rho, \tag{1}$$

$$\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \tilde{\nabla}\boldsymbol{u} = -\frac{1}{\rho}\tilde{\nabla}\left[c_s^2(t)\rho + \frac{B^2}{8\pi}\right] + \frac{\boldsymbol{B}\cdot\tilde{\nabla}\boldsymbol{B}}{4\pi\rho} - \frac{\dot{a}}{a}\mathbb{T}\cdot\boldsymbol{u}, \tag{2}$$

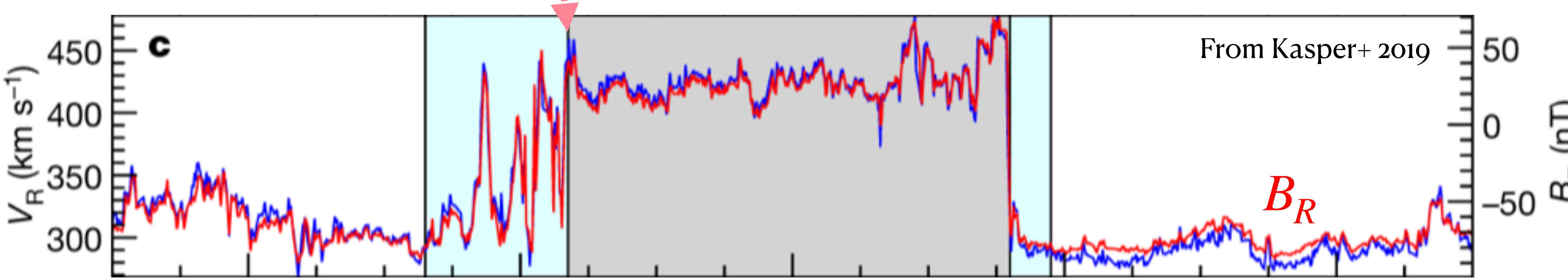
$$\partial_t \boldsymbol{B} + \boldsymbol{u}\cdot\tilde{\nabla}\boldsymbol{B} = \boldsymbol{B}\cdot\tilde{\nabla}\boldsymbol{u} - \boldsymbol{B}\tilde{\nabla}\cdot\boldsymbol{u} - \frac{\dot{a}}{a}\mathbb{L}\cdot\boldsymbol{B}. \tag{3}$$

Switchbacks

From *Kasper+ Nature (2019); Bale+ Nature (2019)*



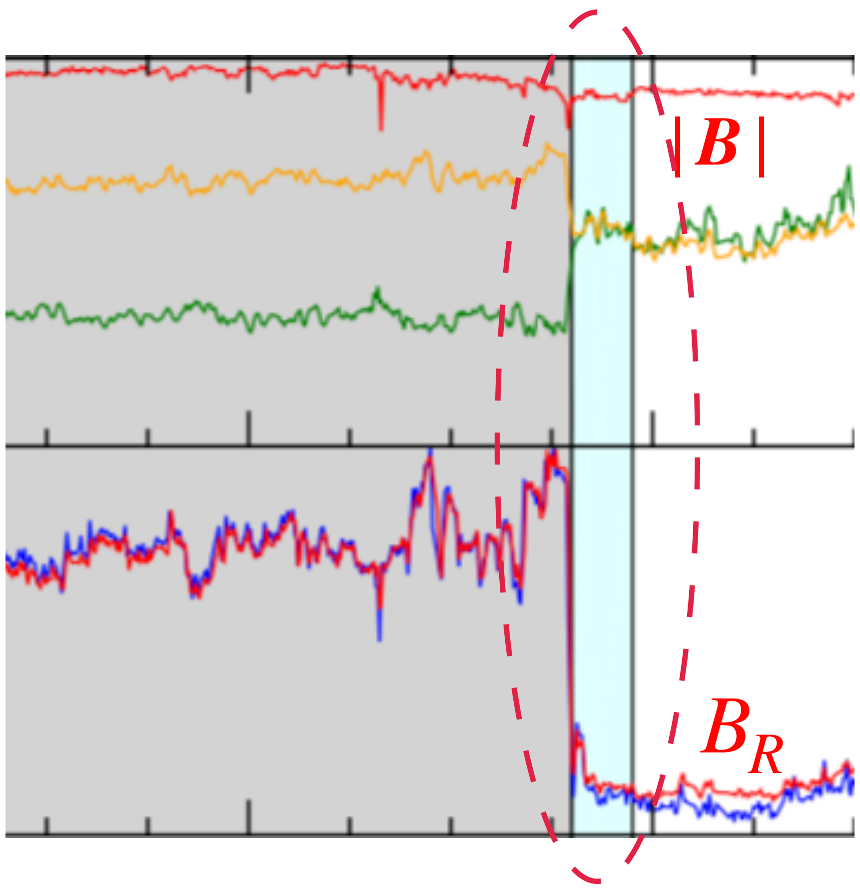
- Early passes of Parker Solar Probe have observed lots of "switchbacks"
- Sudden reversals of the radial magnetic field
- Nearly perfectly Alfvénic $\Delta U = \Delta B$

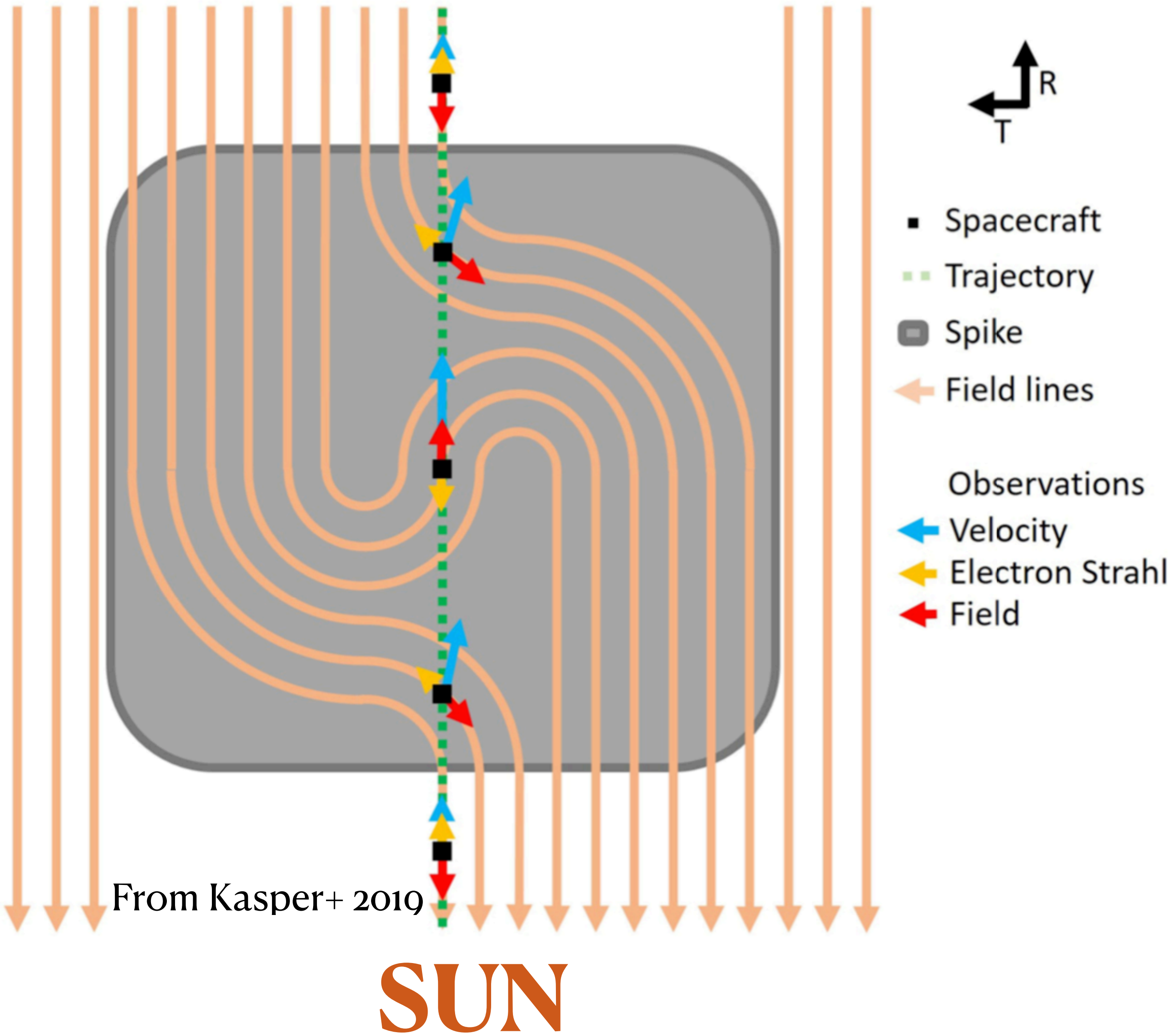


Switchbacks

From *Kasper+ Nature (2019); Bale+ Nature (2019)*

- Electron Strahl direction shows SB is a local bend in the field.
- Field strength $|\boldsymbol{B}|$ remains nearly constant.





Switchbacks

Some questions?

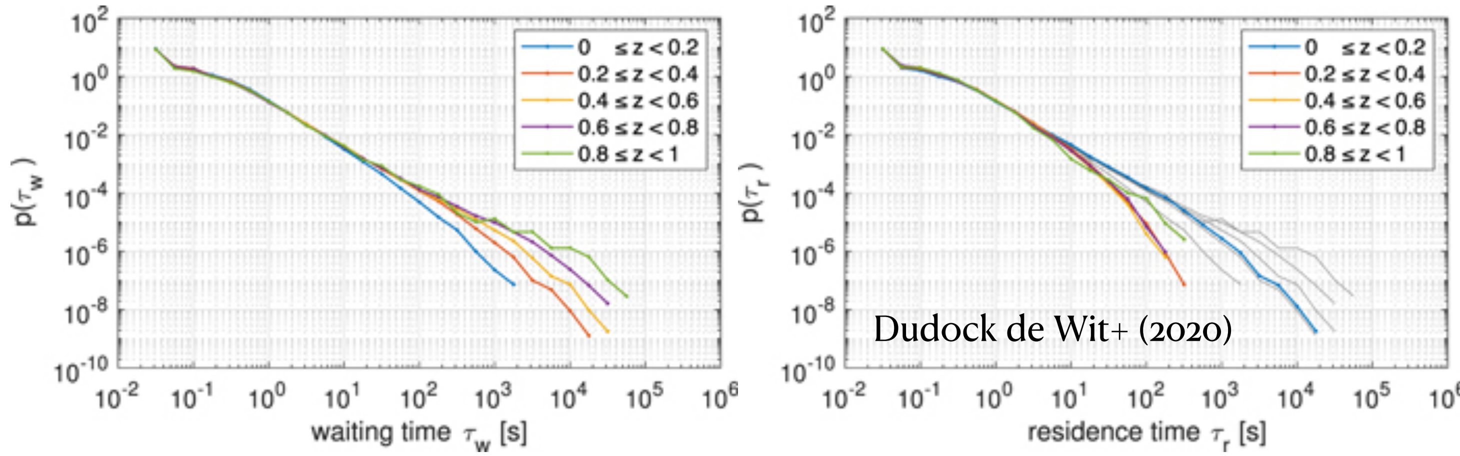
- What is their origin?
- What do they look like?
- Can they tell us about coronal heating?
- Can they tell us about solar-surface processes?
- Are they just a near-sun phenomenon? (*No*)
- What plasma conditions allow them to grow/survive?

Switchbacks

Some other relevant observations:

- They have no intrinsic scale – *switchback sizes have a power-law distribution*

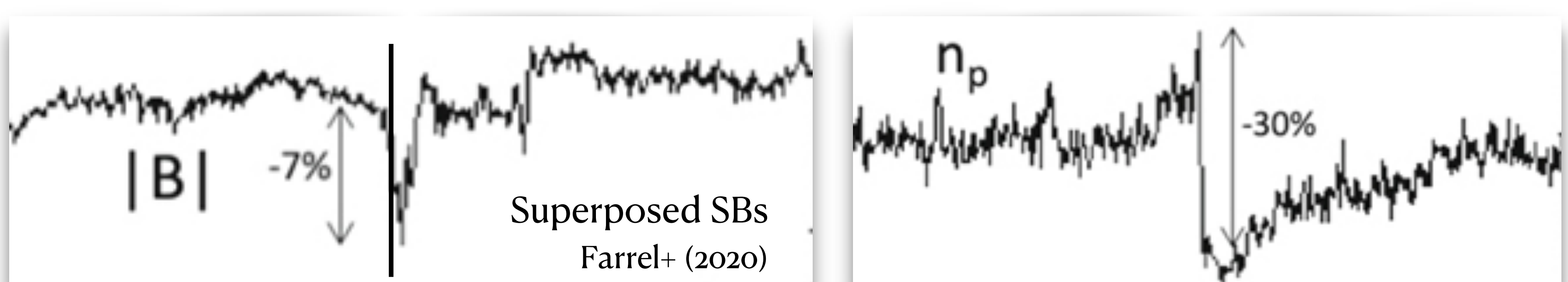
Dudock de Wit+ (2020)
Horbury+ (2020)



Dudock de Wit+ (2020)

- They are very Alfvénic – *No significant temperature variation; modest density change around SB; only small change to* $|\boldsymbol{B}|$

Wooley+ (2020)
Farrel+ (2020)



Superposed SBs
Farrel+ (2020)

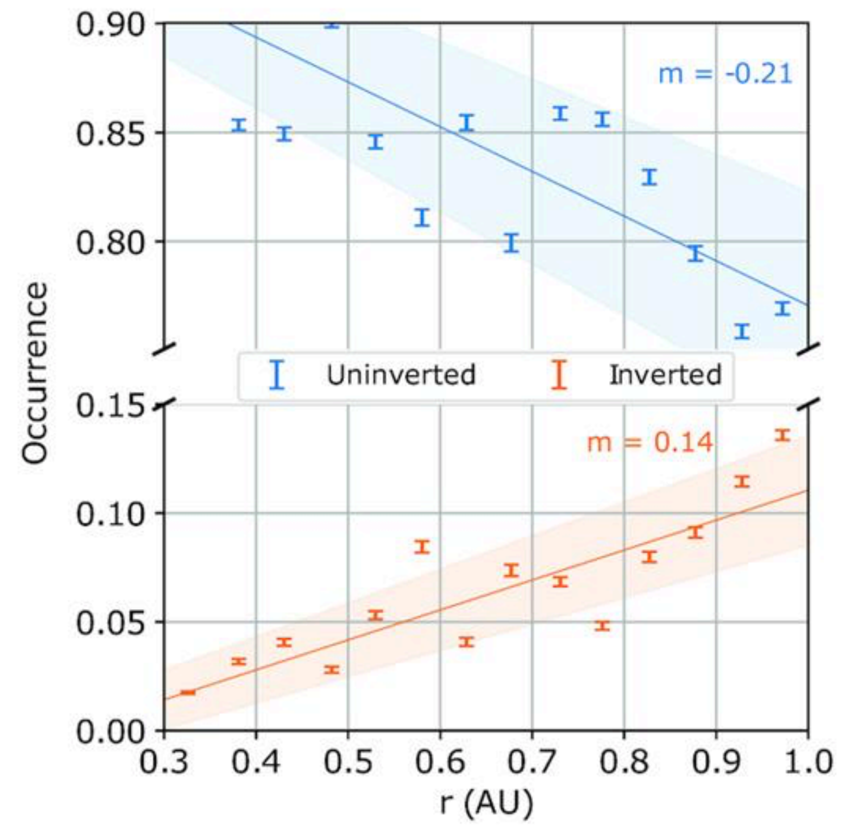
Switchbacks

Some other relevant observations:

- They also occur at large distances (~1AU)

MacNeil+ (2020)
Horbury+ (2018)
Neugebauer & Goldstein (2013)

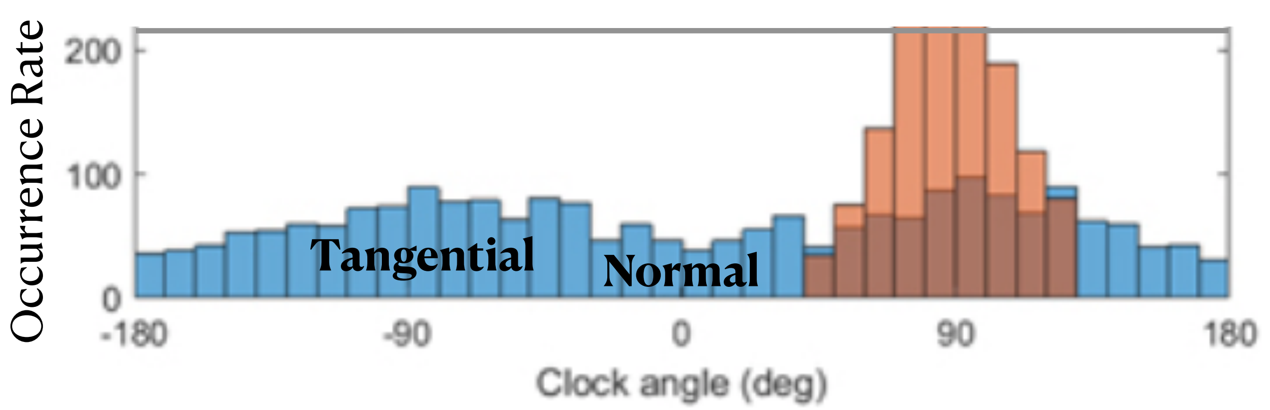
Occurrence increases at large radii in Helios data
(MacNeil+)



- More, larger SBs occur in tangential (Parker spriral) direction

Horbury+ (2020)

- Elongated in the radial direction Horbury+ (2020)



Their origin?

Ex-situ (solar surface/low Corona)

Switchbacks are telling us something about the solar surface, coronal heating, or solar-wind launching.

Reconnection? Streams? Photospheric convection?
(e.g., Richardson+ 2018, Roberts+ 2018, Shi+ 2020, Fisk & Kasper 2020, Phan+ 2020...)

Can they stably propagate outwards? (Probably) Tenerani+ 2020

In-situ

Switchbacks form naturally as wind flows outwards as a result of plasma processes.

Simplest explanation ***if*** it can fit the observations

Outline – *in-situ* switchback formation

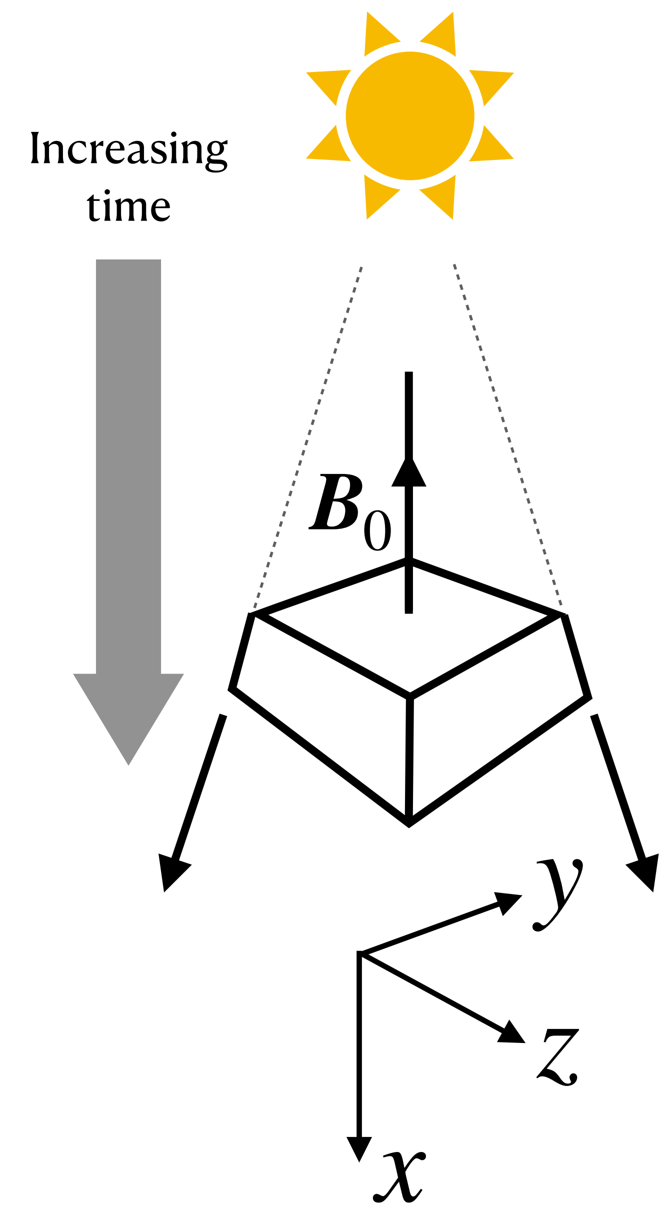
General philosophy: *simplest possible setup*
random initial conditions, no large-scale structures, radial background magnetic field

- Numerical methods
    - Expanding Box model (EBM)
    - Athena++ and Snoopy codes
- Results
    - Switchbacks form naturally!
    - Constant $|\boldsymbol{B}|$ (depending on β)
    - Turbulence and spectra
- Predictions and observations

Expanding Box Model

Grappin et al.1993, 1996

- Simplest model for local effect of outwards solar-wind flow
- We use isothermal compressible MHD
- $a(t) = 1 + \dot{a}t$ is current perpendicular box dimension
- Parallel dimension constant
- Launch waves outwards from transition region – how do they evolve?



Assumes $U \gg v_A$: not true through Alfvén point

Important for future work: *Accelerating* EBM (Tenerani & Velli 2017)

Expanding Box Model

Grappin et al.1993, 1996

Density decreases due to expansion

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = -2\frac{\dot{a}}{a}$$

Sound speed changes in time as $c_s \propto a(t)^{-4/3}$

$$\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{1}{\rho}\nabla\left[c_s^2(t)\rho + \frac{B^2}{8\pi}\right] + \frac{\boldsymbol{B}\cdot\nabla\boldsymbol{B}}{4\pi\rho} - \frac{\dot{a}}{a}\mathbb{T}\cdot\boldsymbol{u}$$

$$\partial_t \boldsymbol{B} + \boldsymbol{u} \cdot \nabla \boldsymbol{B} = \boldsymbol{B}\cdot\nabla\boldsymbol{u} - \boldsymbol{B}\nabla\cdot\boldsymbol{u} - \frac{\dot{a}}{a}\mathbb{L}\cdot\boldsymbol{B}$$

$$\mathbb{T} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathbb{L} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Gradient operator is $\nabla = (\partial_x, a^{-1}\partial_y, a^{-1}\partial_z)$ ***weaker perpendicular gradients***

Parallel and perpendicular components of u and B evolve differently

Expanding Box Model

Alfvén Waves

$$\omega \gg \frac{\dot{a}}{a}$$

- Waves grow due to ρ and B_x decrease (WKB regime)

$$\frac{B_\perp}{B_x} \propto a(t)^{1/2} \quad \frac{u_\perp}{v_A} \propto a(t)^{1/2}$$

- Very little wave reflection

$$\omega \ll \frac{\dot{a}}{a}$$

- Slow motions behave like mean fields

$$\frac{B_\perp}{B_x} \propto a(t) \quad \frac{u_\perp}{v_A} \propto a(t)^0$$

- Acts like a reflection term
- Manifestation of wave reflection from large-scale density gradient

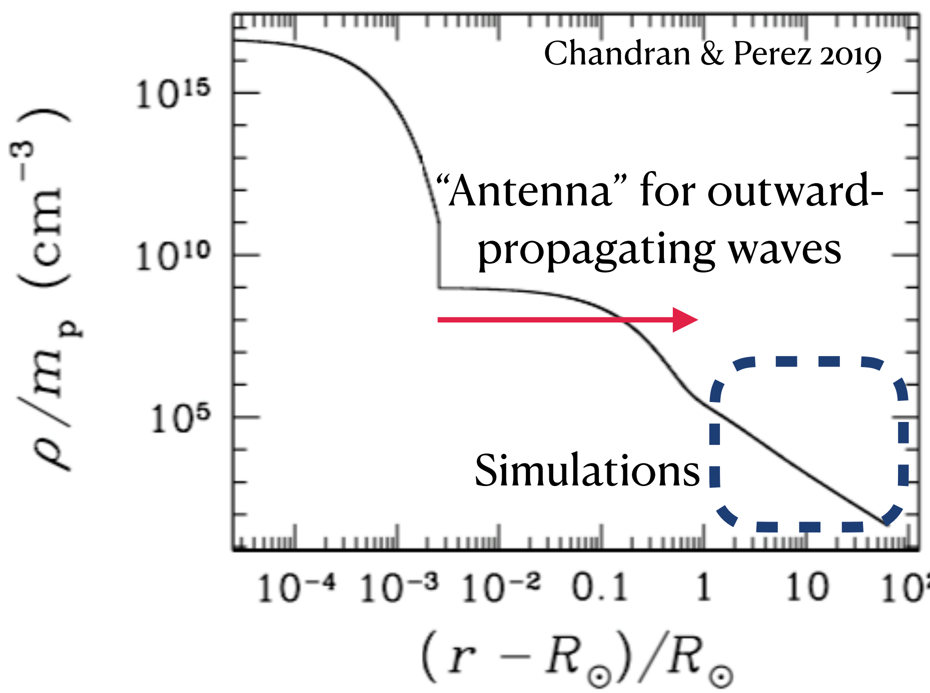
Large-scale waves in our boxes have $\omega \simeq \dot{a}/a$

This is also (approximately) solar wind's outer scale $\sim 10^{-4}\,\mathrm{Hz}$

Initial conditions

Aim to be as simple as possible, explore different possibilities

(Loose) physical picture: waves released from transition region propagate outwards



Three choices:

1. Isotropic spectrum at large scales: Gaussian or $E_\perp(k) \sim k^{-3}$
2. "Critically balanced" spectrum: $E_\perp(k_\perp, k_\parallel) \propto k_\perp^{-10/3} \exp(-k_\parallel L_\perp^{1/3}/k_\perp^{2/3})$
3. Equal power at all scales: $E_\perp(k) \sim k^{-1}$

Numerics

Two simulation sets, two codes, with different strengths

- **Fourier code (`Snoopy`)**
- Allows large expansion factors
- Not so good with shocks and sharp features

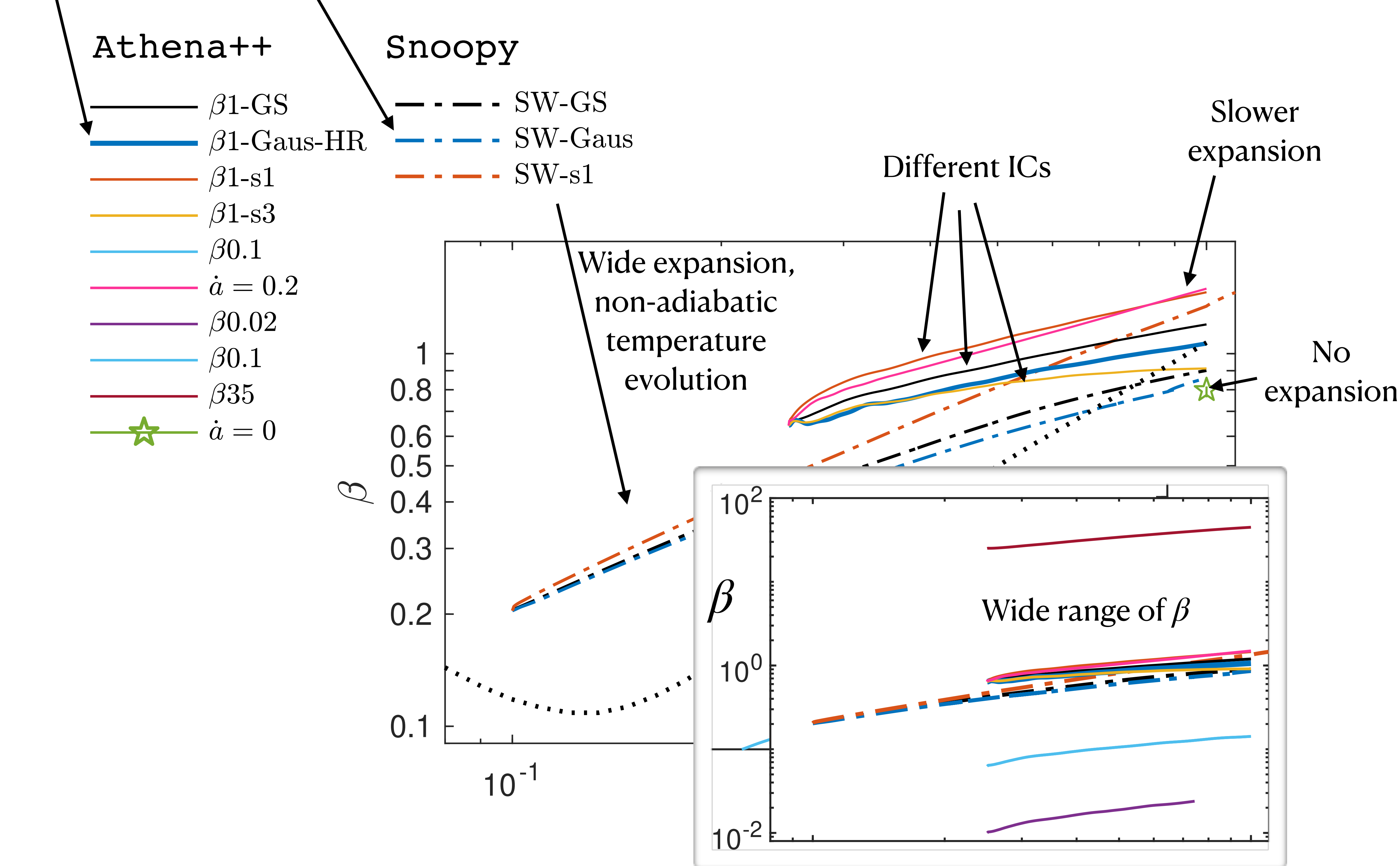
We use `Snoopy` to follow small amplitude waves into the nonlinear regime, with PSP-like parameters

- **Finite volume code (`Athena++`)**
- Good at capturing shocks, low-β regime
- Numerical instabilities if the expansion factor gets too large

We use `Athena++` to explore the physics of SB formation and its dependence on parameters

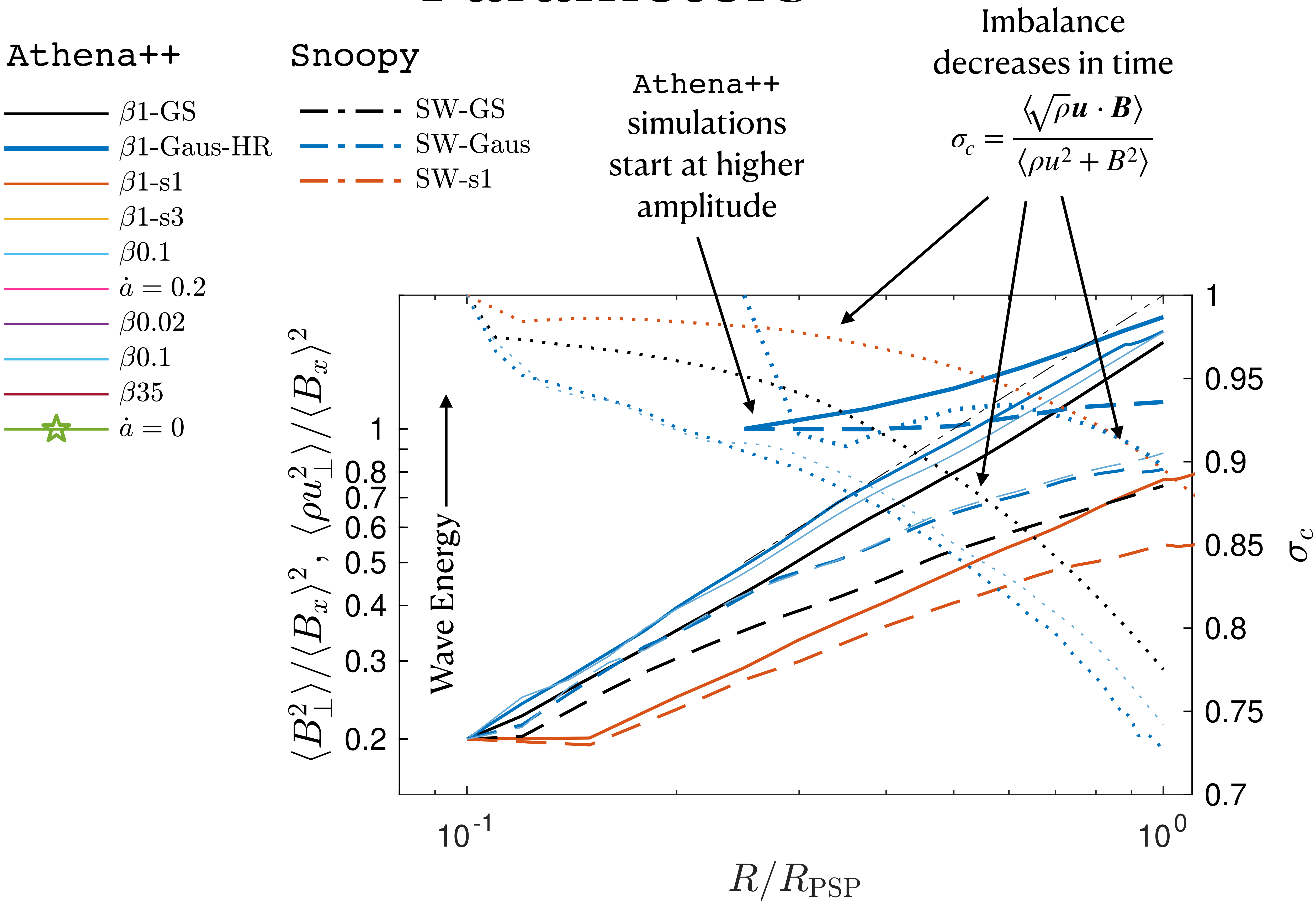
Both methods give similar results

Parameters



540×1120²
480³
Athena++
β1-GS
β1-Gaus-HR
β1-s1
β1-s3
β0.1
ȧ = 0.2
β0.02
β0.1
β35
ȧ = 0
Snoopy
SW-GS
SW-Gaus
SW-s1
Different ICs
Slower expansion
Wide expansion, non-adiabatic temperature evolution
No expansion
β
1
0.8
0.6
0.5
0.4
0.3
0.2
0.1
10^-1
Wide range of β
10^2
10^0
10^-2

Parameters



Athena++
β1-GS
β1-Gaus-HR
β1-s1
β1-s3
β0.1
ȧ = 0.2
β0.02
β0.1
β35
ȧ = 0
Snoopy
SW-GS
SW-Gaus
SW-s1
Athena++ simulations start at higher amplitude
Imbalance decreases in time
σc = ⟨√ρ u · B⟩ / ⟨ρu² + B²⟩
Wave Energy
⟨B⊥²⟩/⟨Bx⟩², ⟨ρu⊥²⟩/⟨Bx⟩²
R/RPSP
σc

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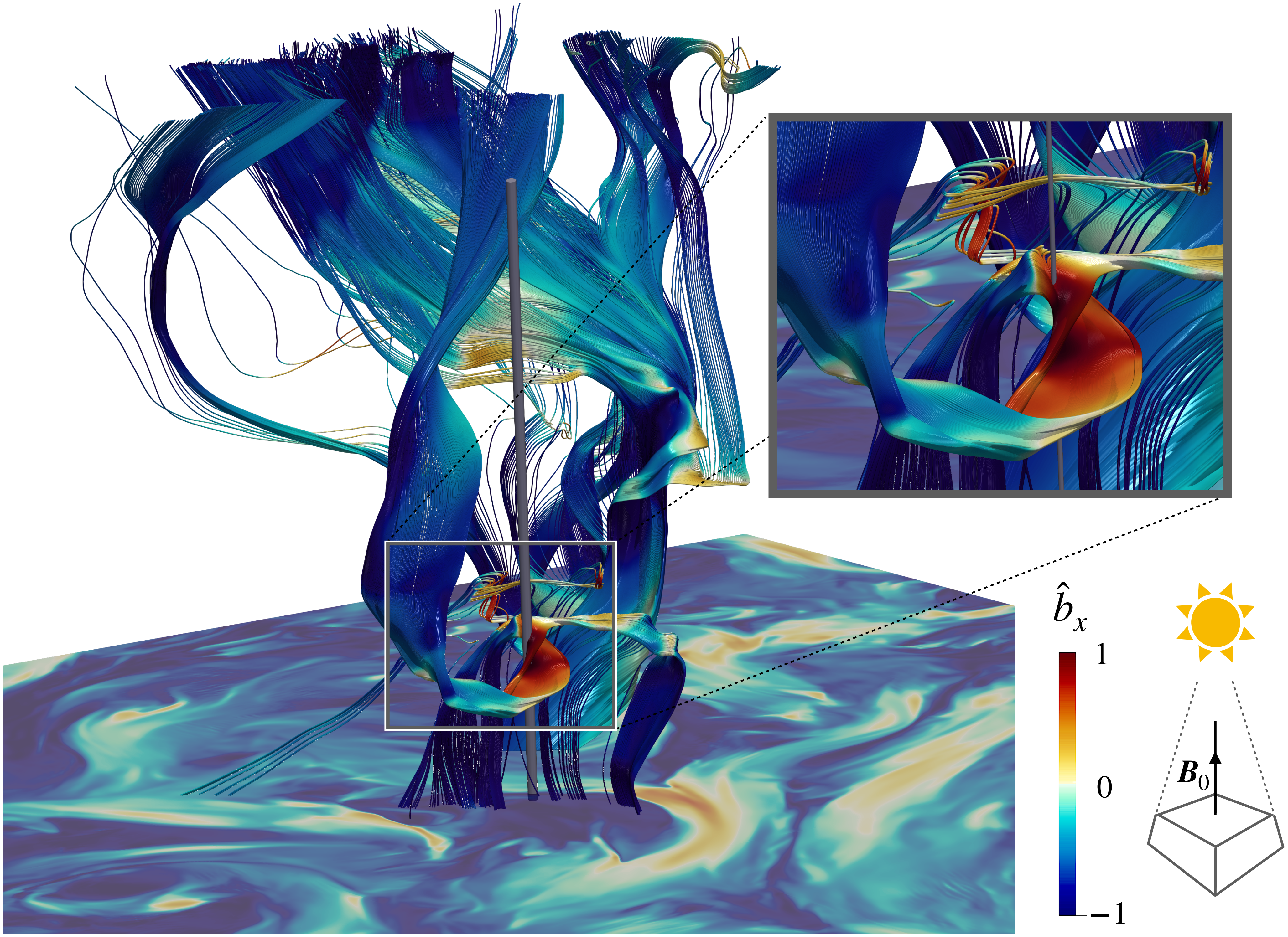
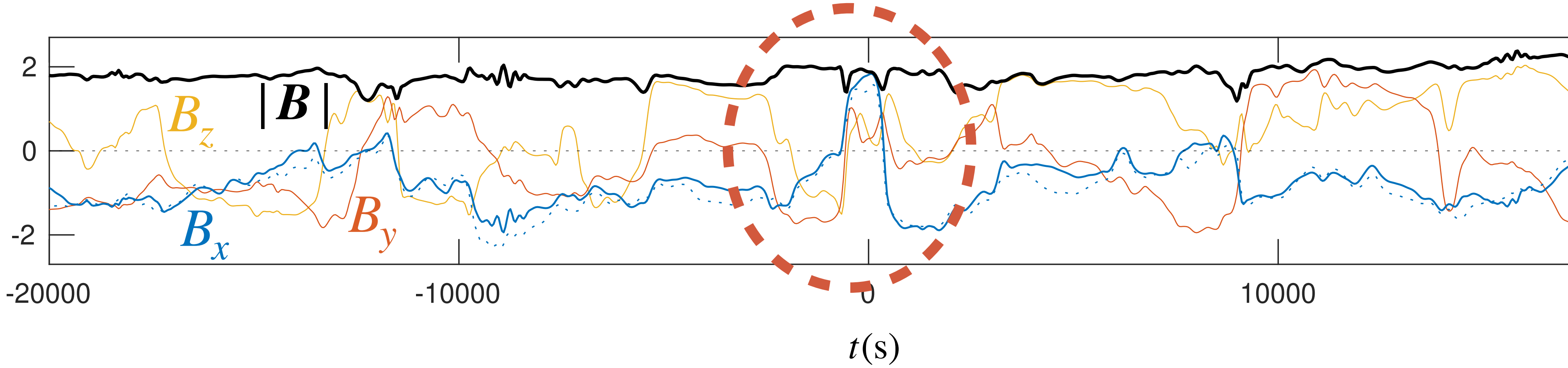
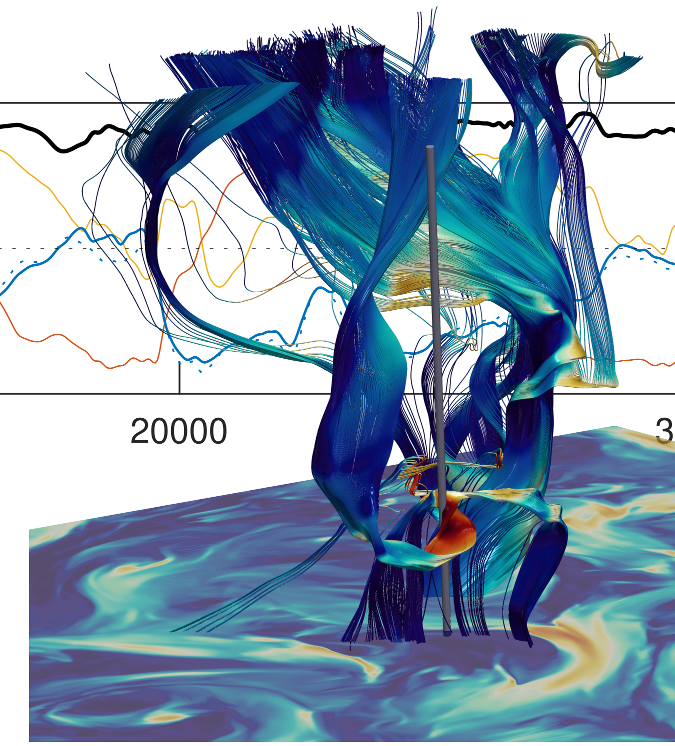
Switchbacks form robustly



`Athena++` HR simulation: Gaussian initial conditions

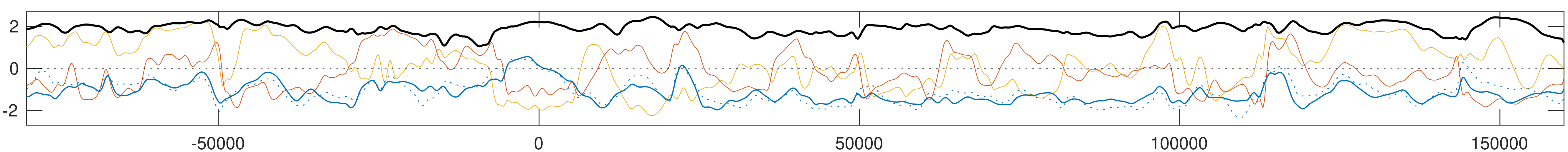
Switchbacks form robustly



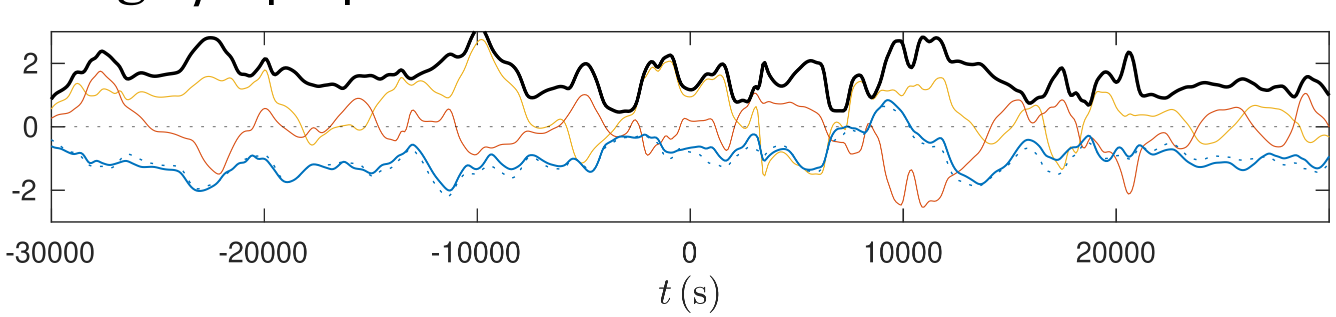


Trace along grey line – like SW moving past PSP

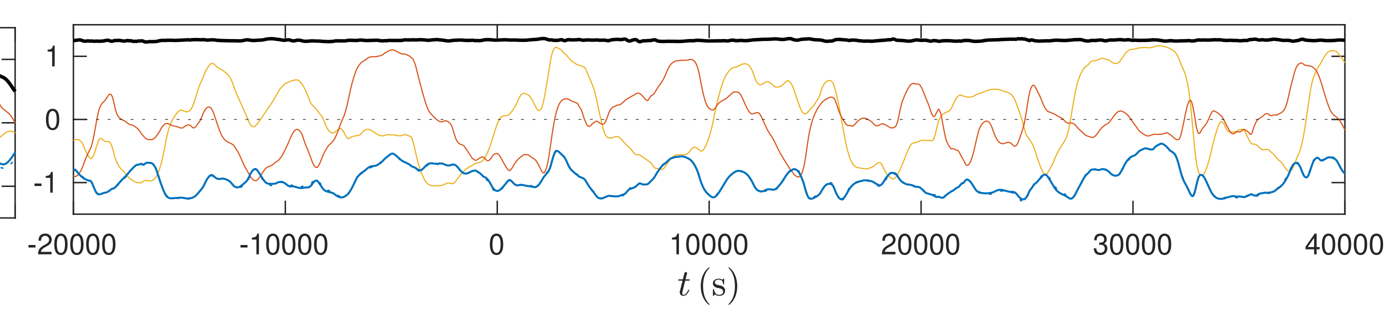
Snoopy simulation similar (more numerical dissipation, faster expansion)



High-β: $|\boldsymbol{B}|$ not constant

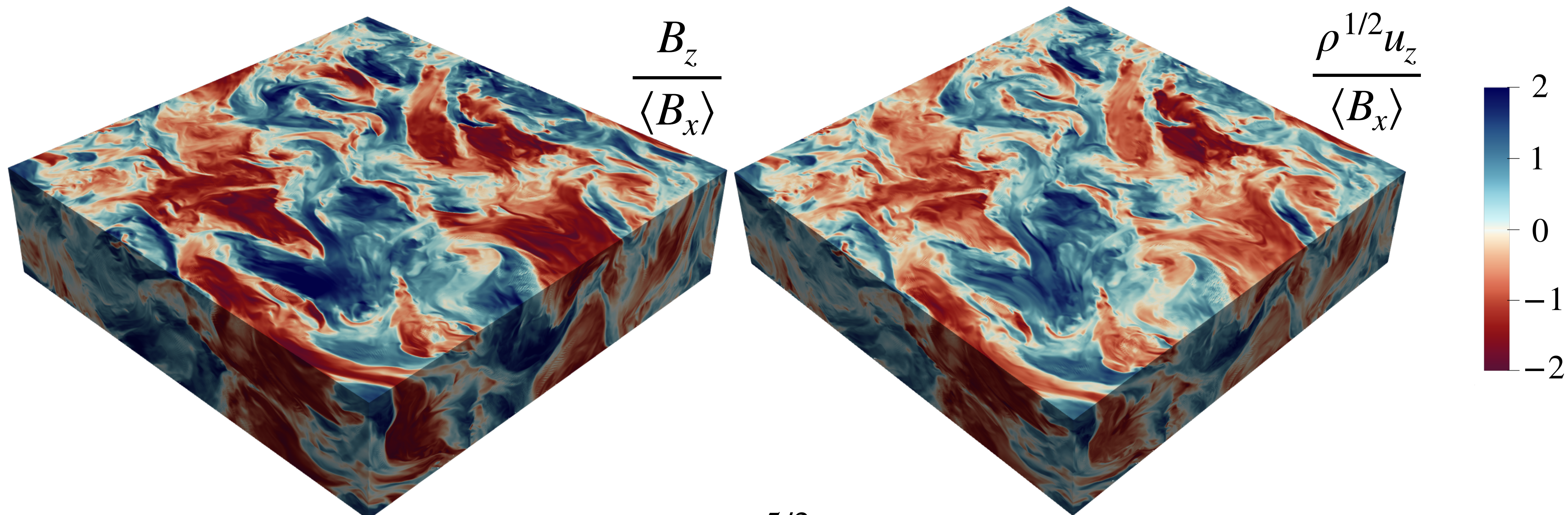


No expansion: no switchbacks

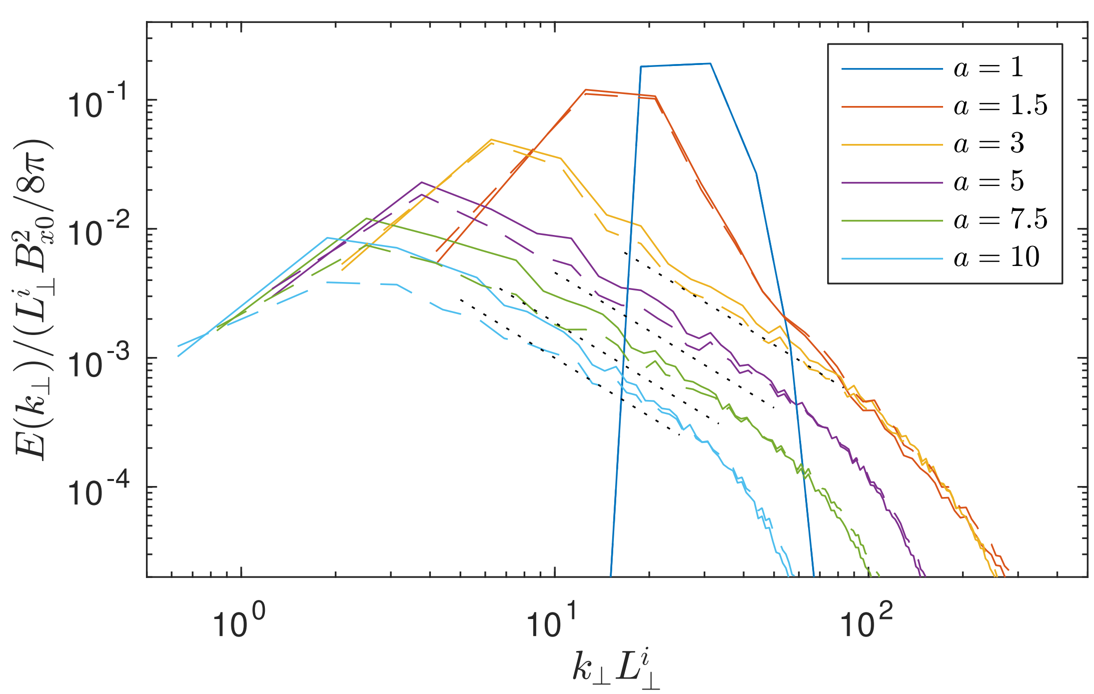


Switchbacks form robustly

Becomes robustly turbulent, $u_\perp \approx B_\perp$ (but $B \gtrsim u$)



Develops $\sim k^{-5/3}$ spectrum



Switchback fraction and spherical polarization

Quantify *switchback fraction* with

$f_{\hat{b}_x>0}$ = fraction of cells with reversed field

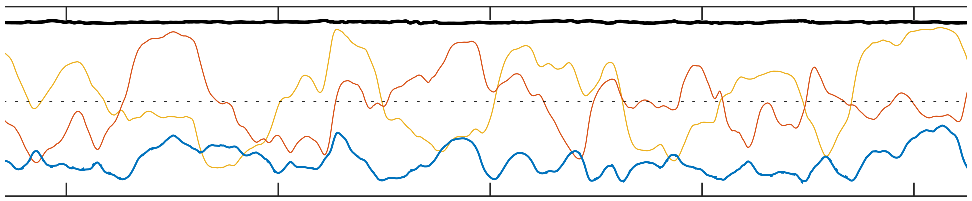
$P(|\delta_\ell \hat{b}_x| > 1) =$ proportion of $\hat{b}_x$ increments with a jump ≥ 1 across 8 grid cells

$(|\delta_\ell \hat{b}_x| \equiv |\hat{b}_x(\boldsymbol{x}+\boldsymbol{\ell}) - \hat{b}_x(\boldsymbol{x})|)$

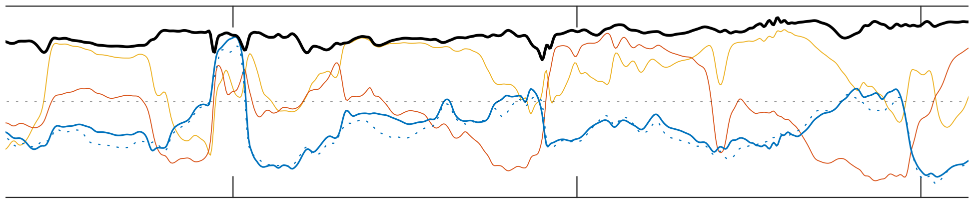
Clear that system minimizes the variation in $|\boldsymbol{B}|$ – quantify with

$$C_{B^2} \equiv \frac{\delta(|\boldsymbol{B}|^2)}{(\delta \boldsymbol{B})^2}$$

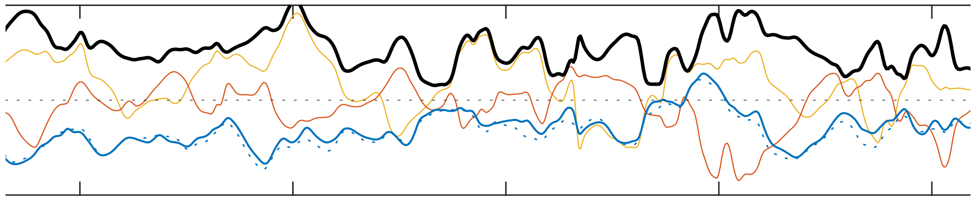
$C_{B^2} \approx 0.04$



$C_{B^2} \approx 0.4$

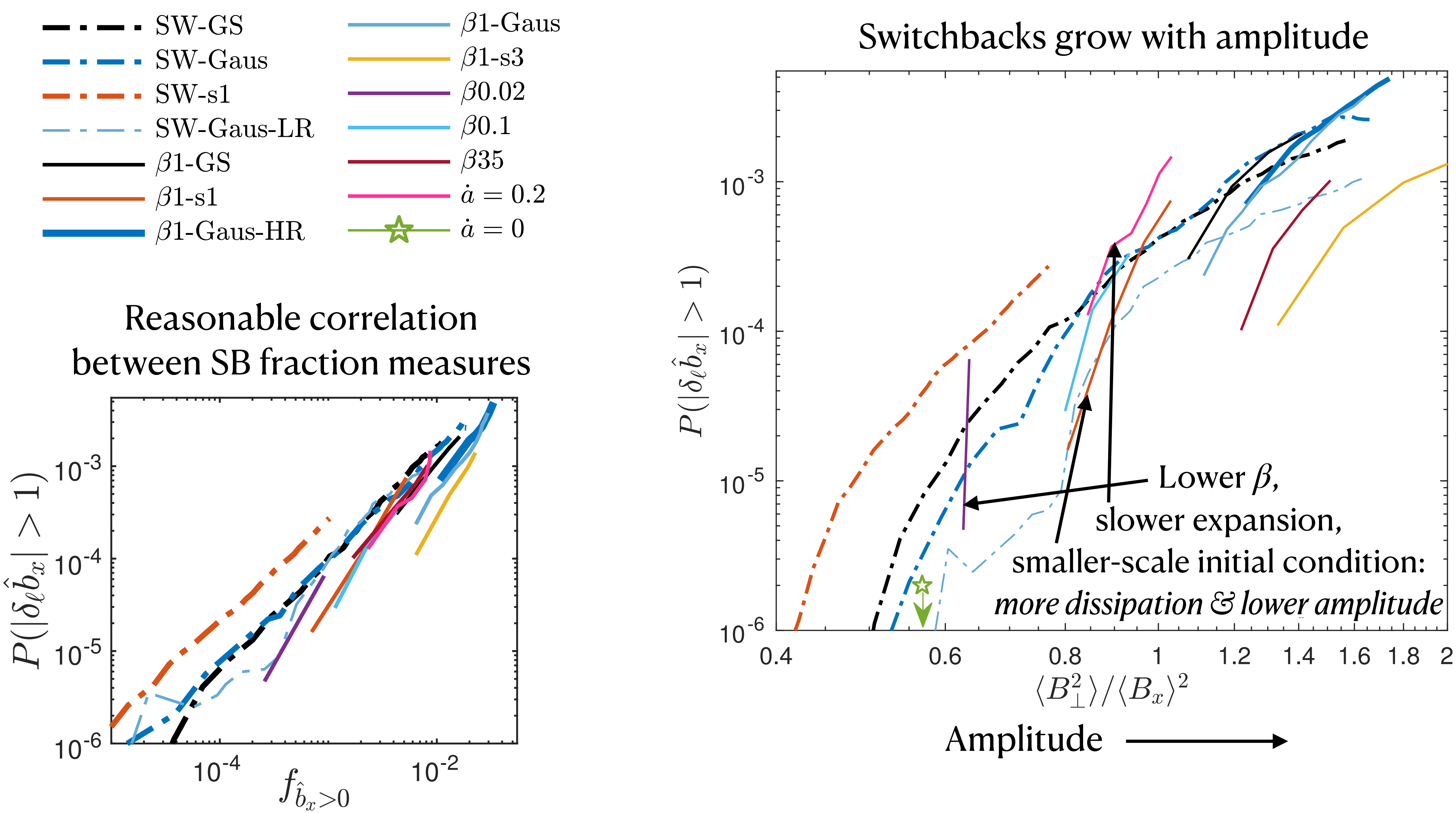


$C_{B^2} \approx 0.95$



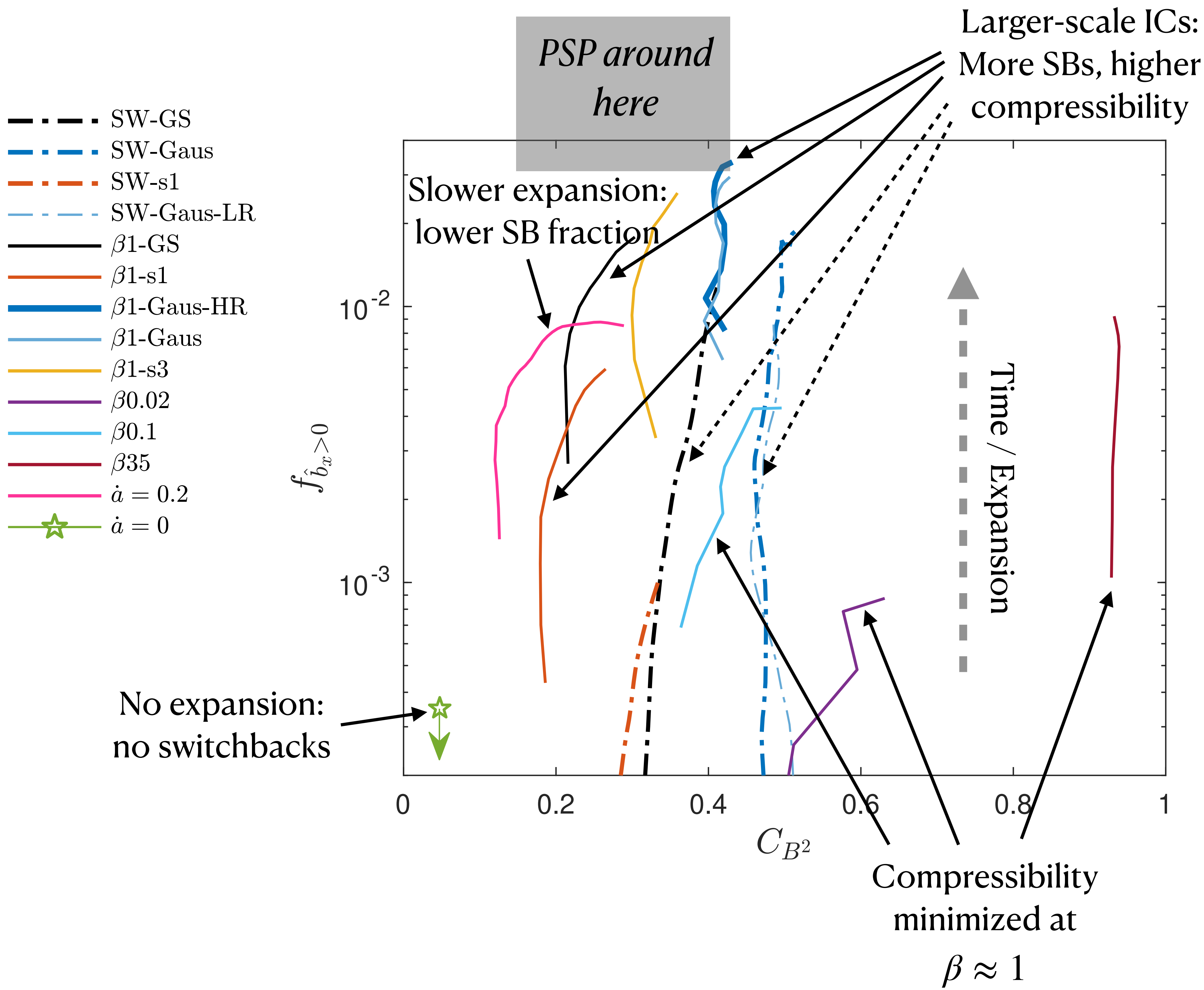
Switchback fraction and spherical polarization

Discontinuities and SB fraction grow with amplitude



Sharper fields have more reversals

Switchback fraction and spherical polarization



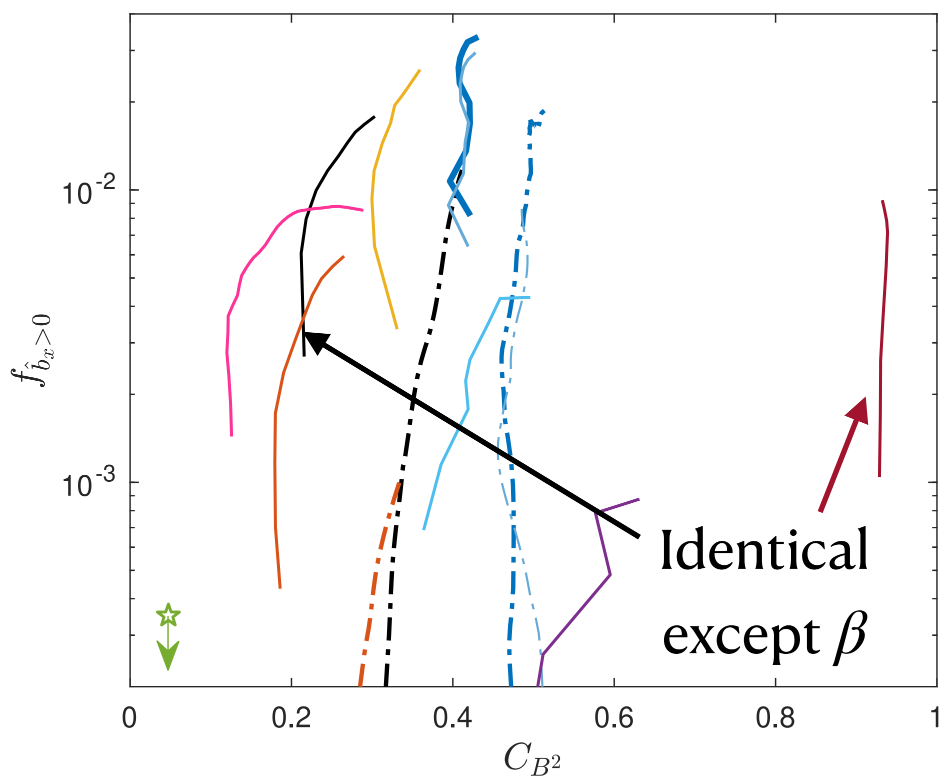
Switchback fraction and spherical polarization

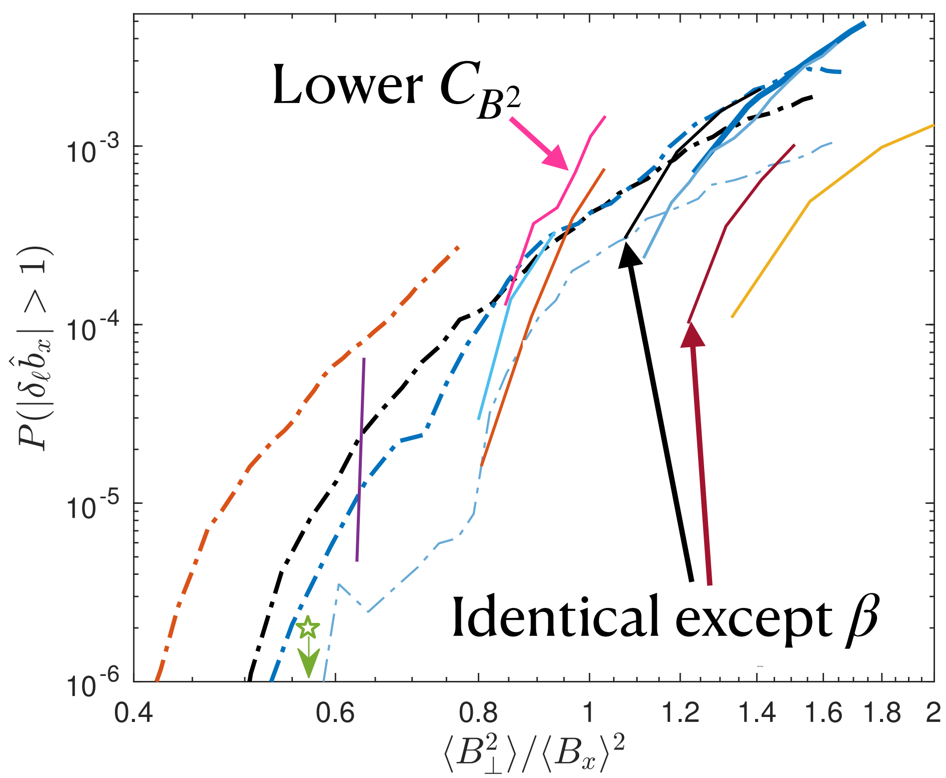
Interpretation

Large amplitudes and spherical polarization are incompatible $\Rightarrow$ discontinuities

Barnes & Hollweg 1974, Vasquez & Hollweg 1996, 1998

Magnetic pressure forces decrease C_{B^2} at $\beta \lesssim 1$





Higher β: *higher amplitude but lower SB fraction*

Lower β: *lower* C_{B^2} *causes more discontinuous field*

Clearly not the whole story:

some switchbacks at high β

why C_{B^2} *minimum* at $\beta \simeq 1$??

Cohen & Kulsrud 1974

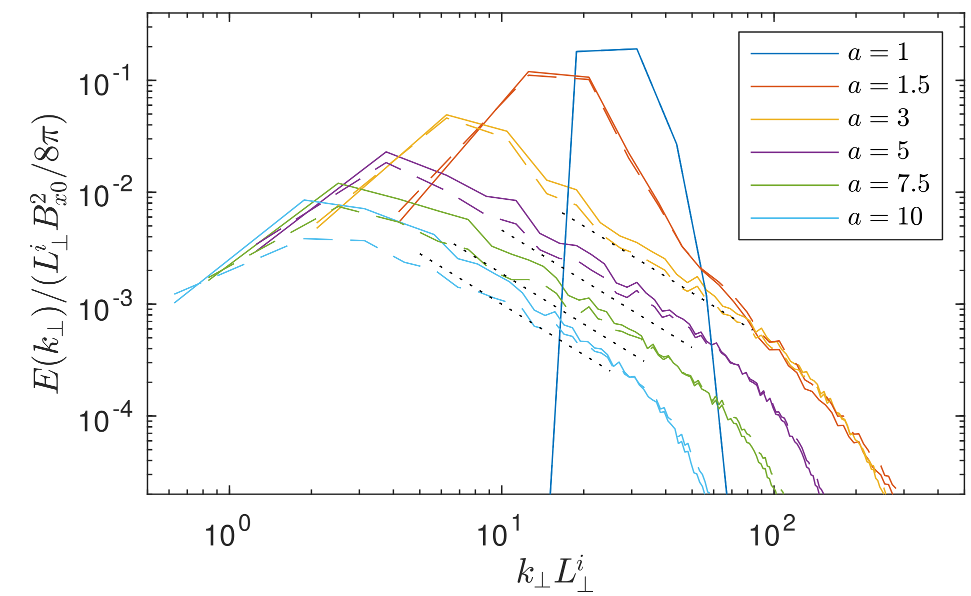
Parametric Decay?

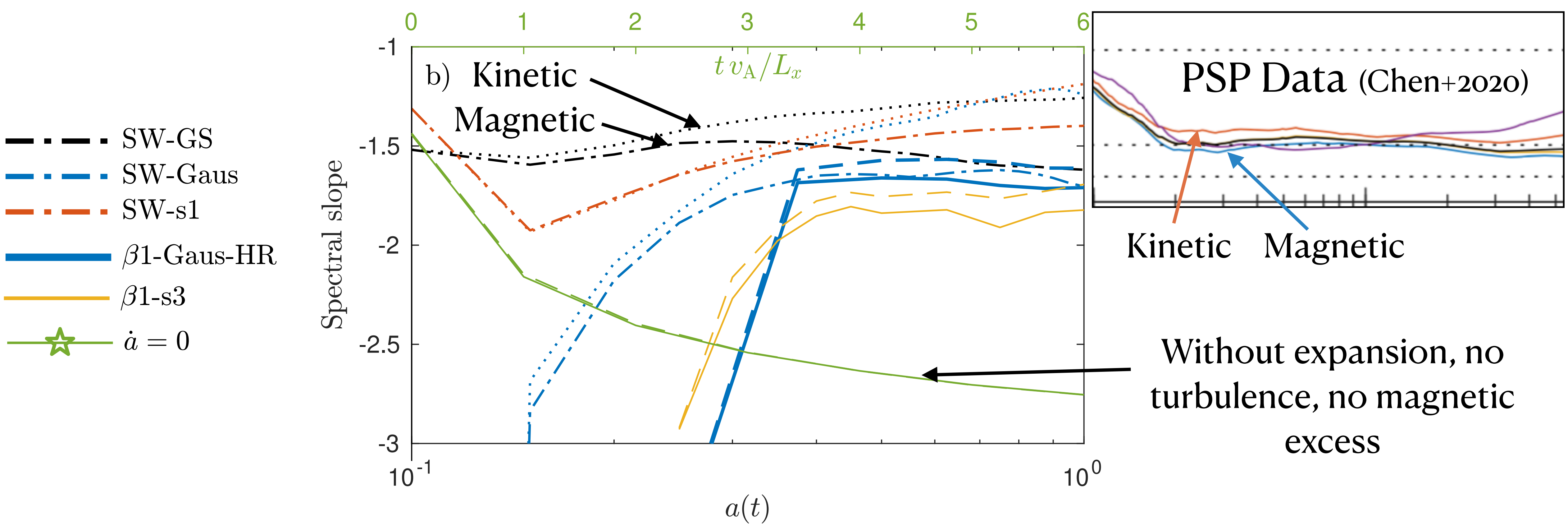
Turbulence

Turbulence caused by wave reflection

- Need backward-propagating waves for turbulence
- Wave reflection from expansion
- Steeper or flatter initial spectra approach $\sim k^{-1.5}$
- Excess of magnetic energy, steeper magnetic spectra (Chen 2020)

Snoopy from Gaussian ICs





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  - Athena++ and Snoopy codes
- Results
  - Switchbacks form naturally!
  - Constant $|\boldsymbol{B}|$ (depending on β)
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- Predictions and observations

Does it work?

In-situ hypothesis compelling *if* it matches observations

Does it?

Ex-situ (solar surface/low Corona)

Switchbacks are telling us something about the solar surface, coronal heating, or solar-wind launching.

- Reconnection? Streams? Photospheric convection?
  (e.g., Richardson+ 2018, Roberts+ 2018, Shi+ 2020, Fisk & Kasper 2020, Phan+ 2020...)
- Can they stably propagate outwards? (Probably) Tenerani+ 2020

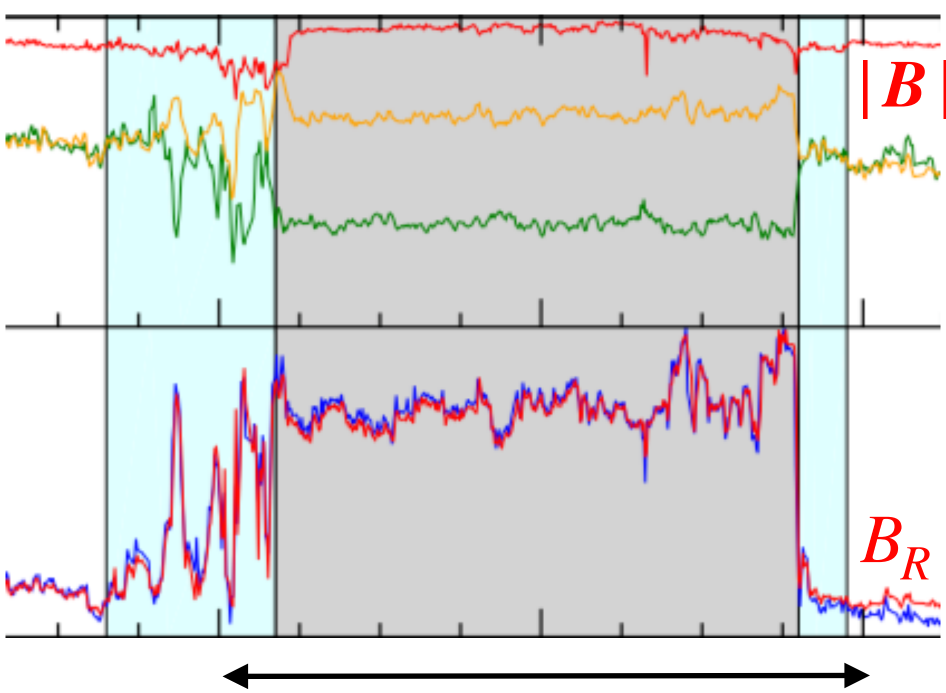
In-situ

Switchbacks form naturally as wind flows outwards as a result of plasma processes.

- Simplest explanation ***if*** it can fit the observations

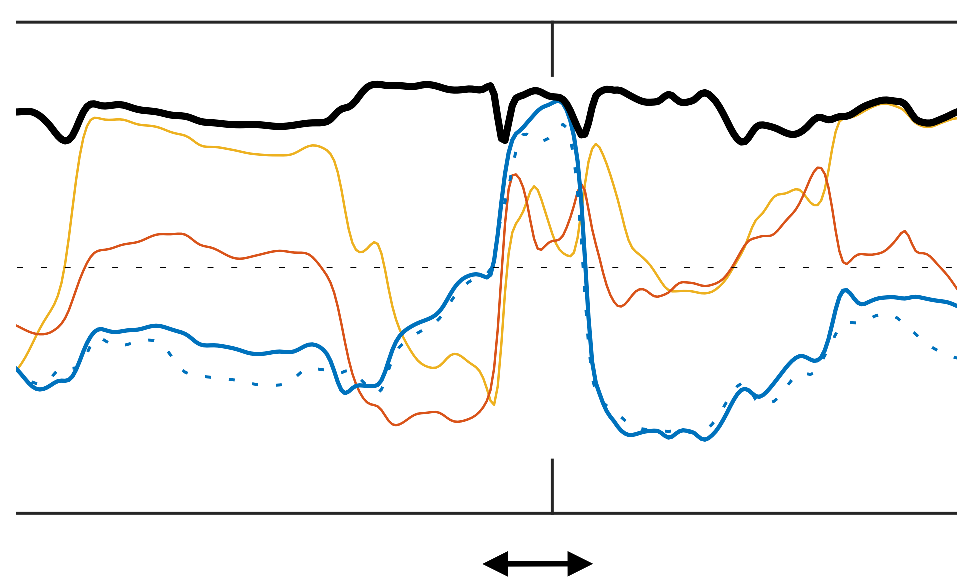
Very difficult to be as free from dissipation as the SW

PSP



~400s

Simulation



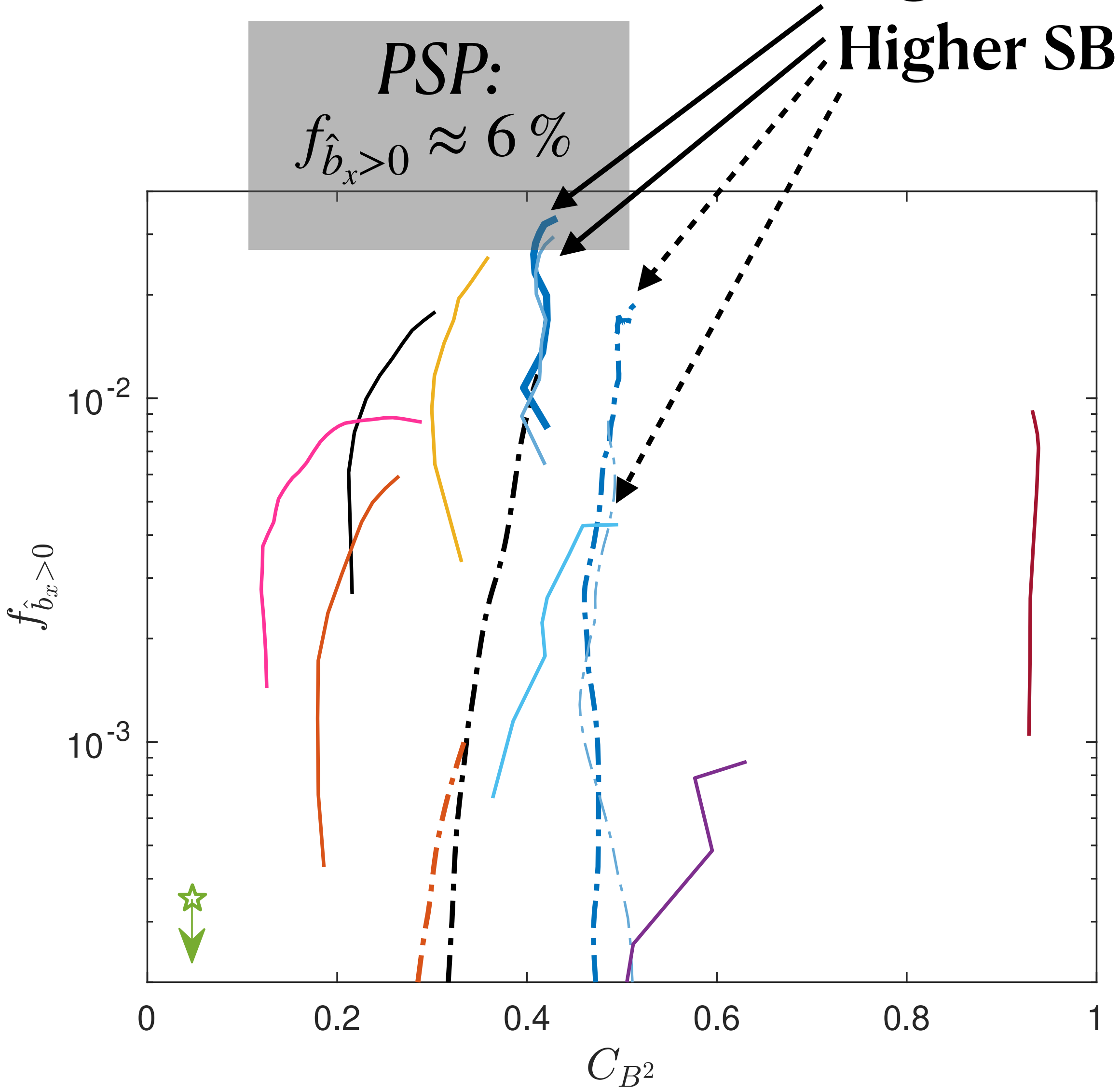
~1000s

Does it work?

Probably, but need higher-resolution, larger expansions

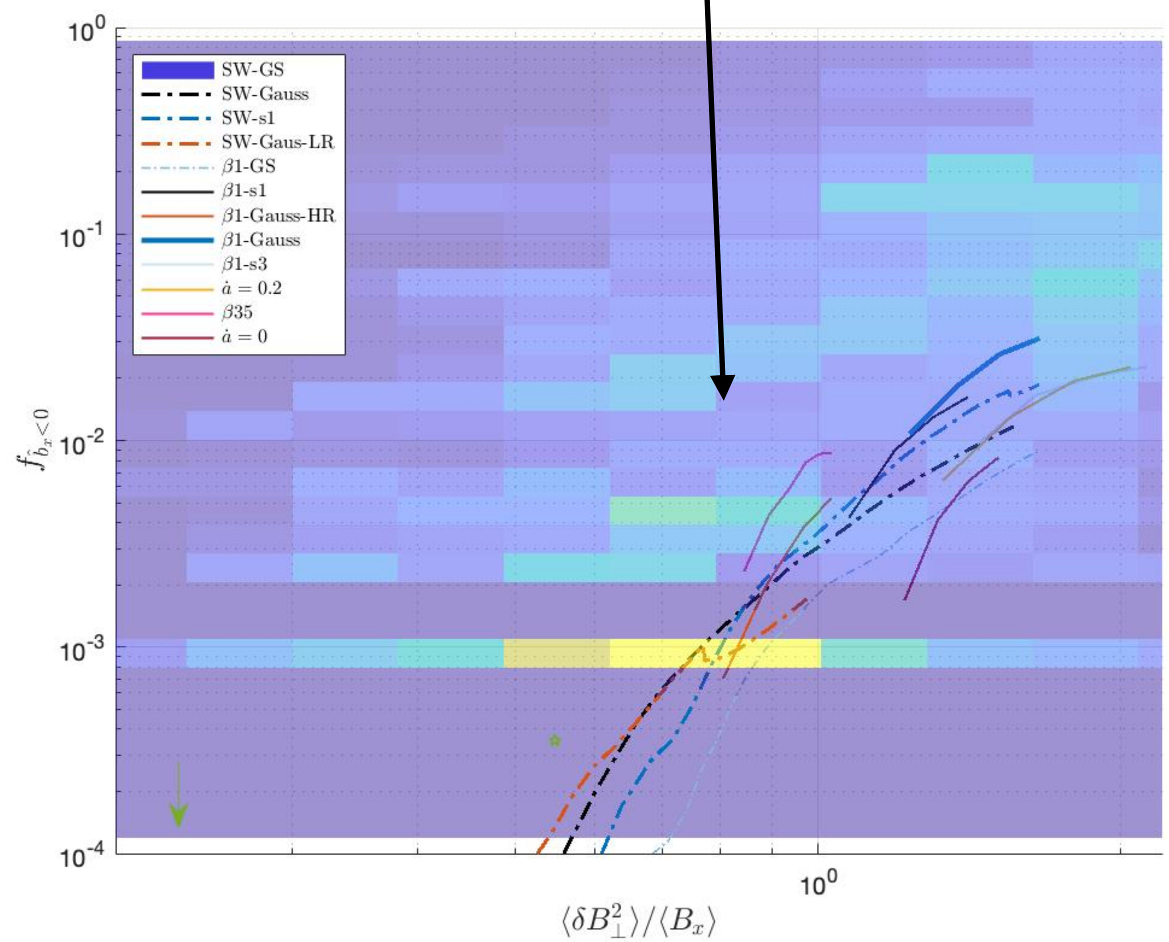
C_{B^2} is about right, $f_{\hat{b}_x<0}$ is a bit small

Higher Resolution:
Higher SB fraction



PSP data

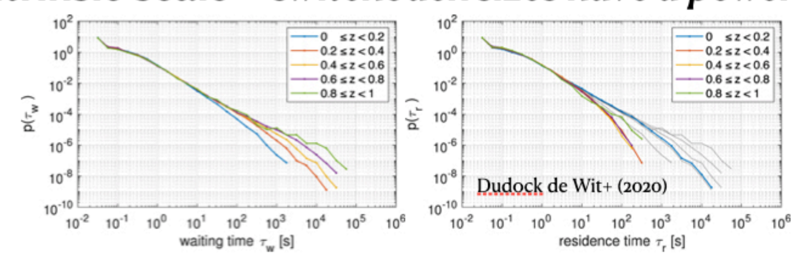
Larger $f_{\hat{b}_x>0}$ at smaller amplitudes



Does it work? Observational properties

- They have no intrinsic scale – *switchback sizes have a power-law distribution*

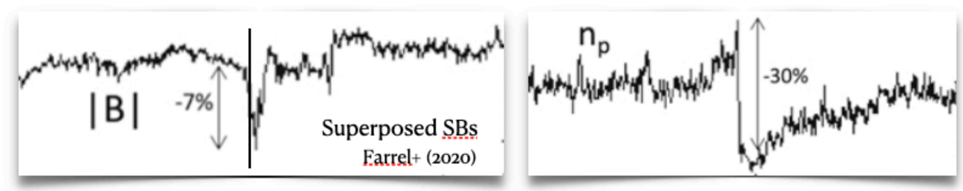
Dudock de Wit+ (2020)
Horbury+ (2020)



Need to test some properties more thoroughly

- They are very Alfvénic – *No significant temperature variation; modest density change around SB; only small change to* $|\boldsymbol{B}|$

Wooley+ (2020)
Farrel+ (2020)

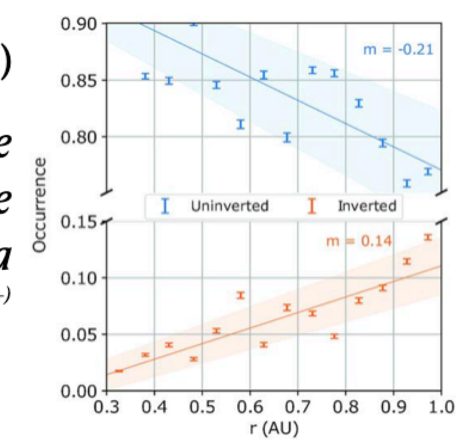


Favours strongly in-situ mechanism

- They also occur at large distances (~1AU)

MacNeil+ (2020)
Horbury+ (2018)
Neugebauer & Goldstein (2013)

Occurrence increases at large radii in Helios data
(MacNeil+)

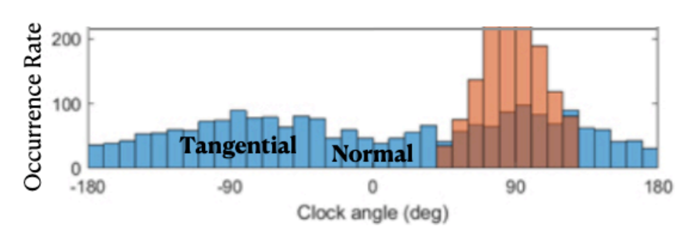


Perpendicular asymmetry not possible in our setup

- More, larger SBs occur in tangential (Parker spriral) direction

Horbury+ (2020)

- Elongated in the radial direction Horbury+ (2020)



Conclusion: Promising, but needs more work to be sure

- Switchbacks form naturally in expanding MHD from random ICs

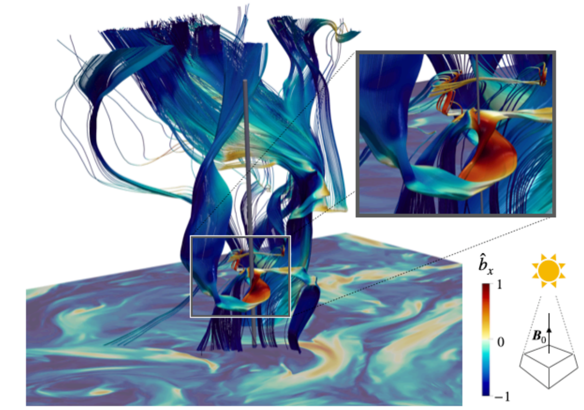
    Properties that are broadly consistent with PSP observations

- Correlations between components of $\boldsymbol{B}$ keep $|\boldsymbol{B}|$ constant; incompatible with large amplitudes $\Rightarrow$ switchbacks

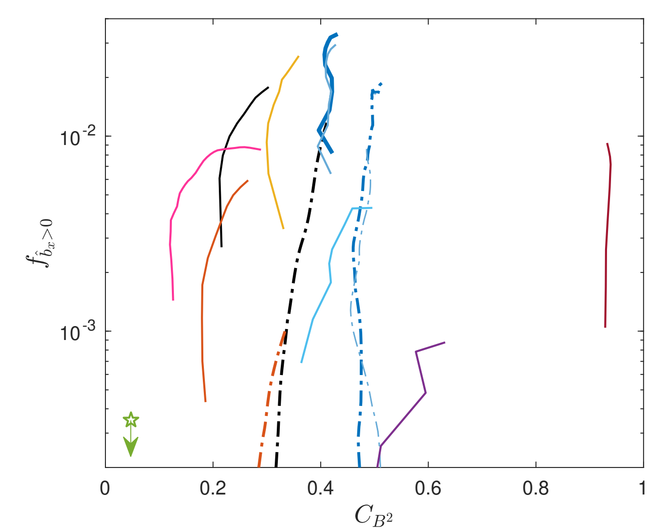
    Effect is strongest at $\beta \simeq 1$

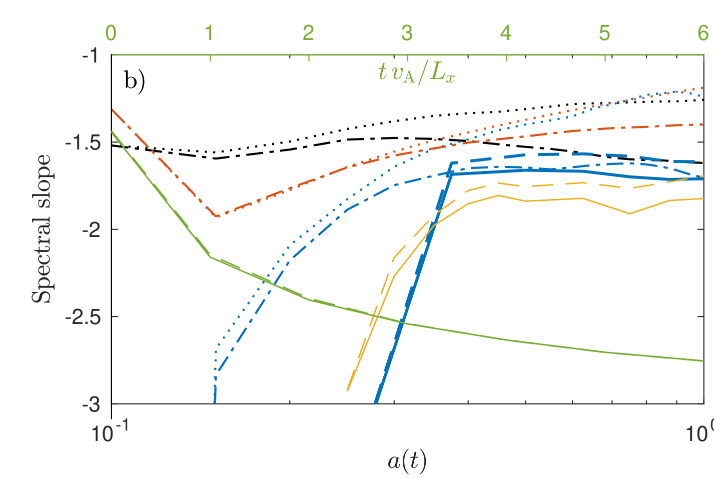
- Self-consistent turbulence broadly matches observations

Switchbacks form robustly



Athena++ HR simulation: Gaussian initial conditions





Switchback shapes