Magnetohydrodynamics turbulence simulations as testing ground for PUNCH

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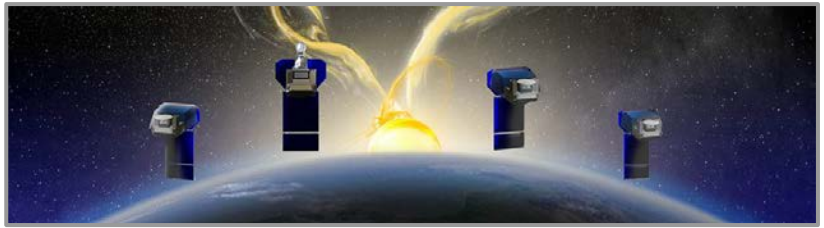
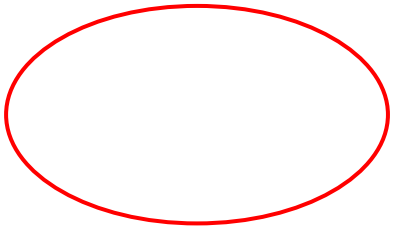


Punch science objectives

1. **Understand how coronal structures become the ambient solar wind.**
2. Understand the evolution of transient structures (such as CMEs) in the young solar wind.

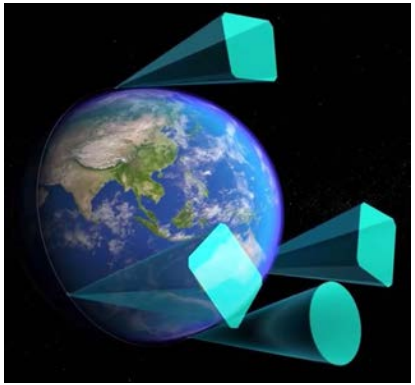


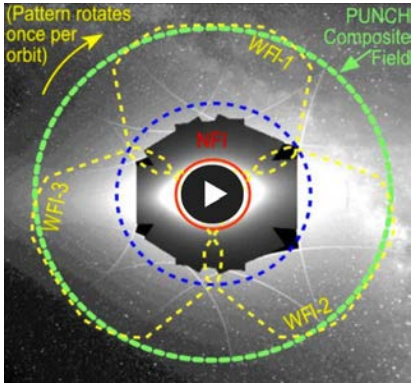
I. Slow solar wind near Earth is dominated by fluctuations of unknown origin.
   - Do they form mainly from turbulence in the solar wind?
   - Or is the slow solar wind intrinsically intermittent from its origins?

II. Track observed coronal microstructures in 3D as they form, evolve and propagate into the heliosphere.

III. Detect the onset of turbulence through spatial spectrum steepening.

Punch scales





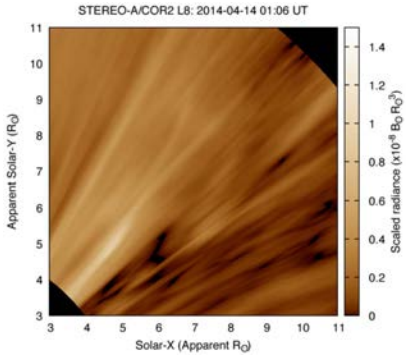
- Narrow Field Imager (NFI) 6 $R_\odot$ - 32 $R_\odot$
  Resolution: 0.67 arcmin ~ 0.04 $R_\odot$ ~ 28 Mm
- Wide Field Imagers (WFI) 20 $R_\odot$ - 180 $R_\odot$
  Resolution: 1.33 arcmin ~ 0.08 $R_\odot$ ~ 56 Mm
- 4-min cadence observations – longer than the crossing time of a 140 Mm structure

i. Disentangling space-time correlation
ii. Tracking of structures
iii. Evolution of turbulence

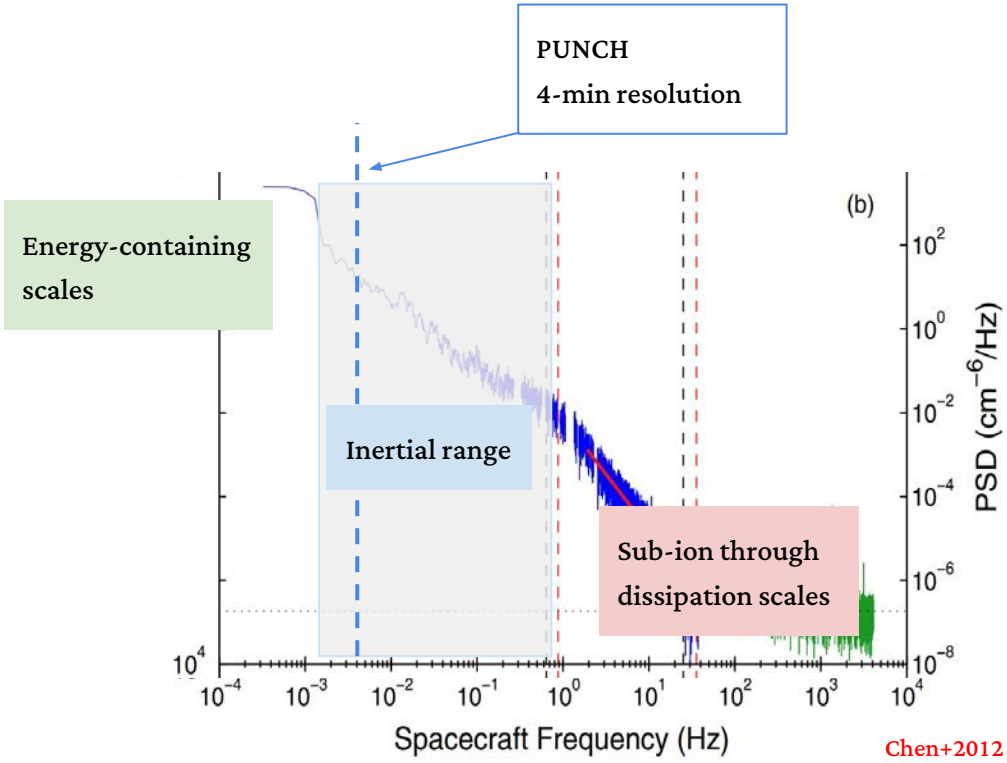
1. **Understand how coronal structures become the ambient solar wind.**

Observations in the inertial range

PUNCH will provide observations in the inertial range



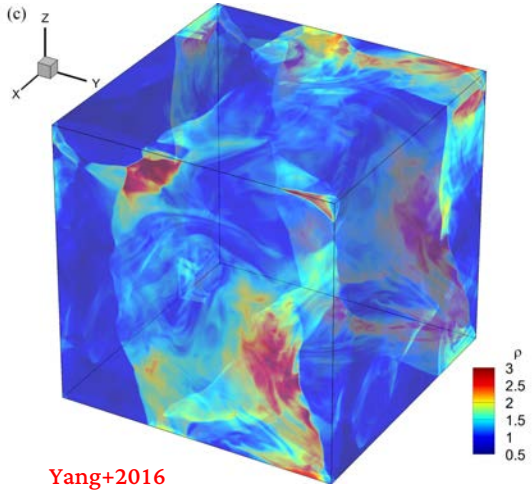
DeForest+2018



Chen+2012

e- density, Artemis @ 1AU

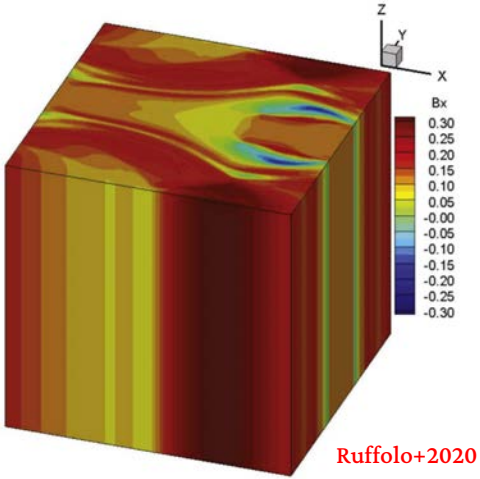
Simulation campaign



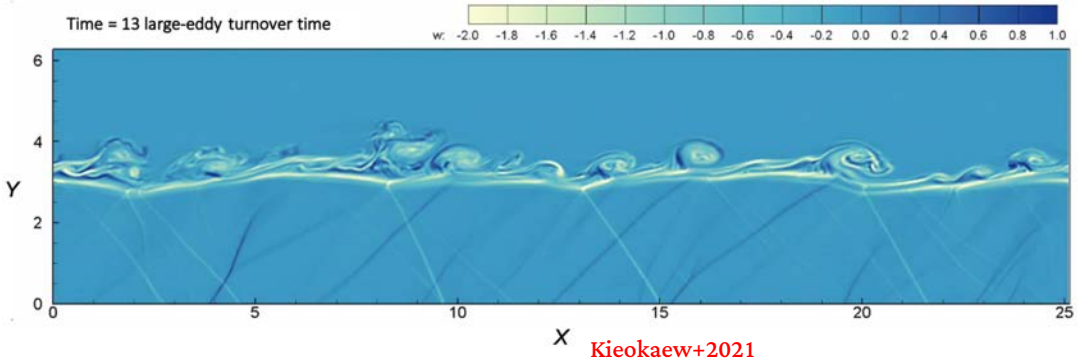
Yang+2016

Several MHD simulations:

- Isotropic (no mean B_0)
- Anisotropic (mean B_0)
- Shear (Kelvin-Helmholtz)
- Different spectral slopes

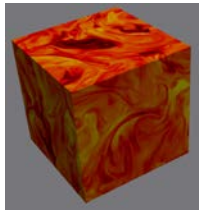


Ruffolo+2020



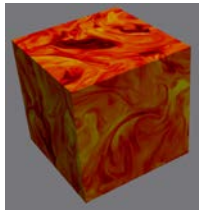
Kieokaew+2021

Rubik's heliosphere



Pecora+ in prep

Rubik's heliosphere



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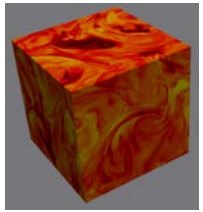

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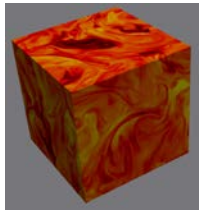

Pecora+ in prep

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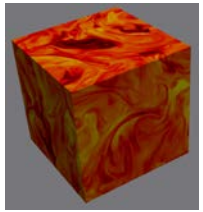
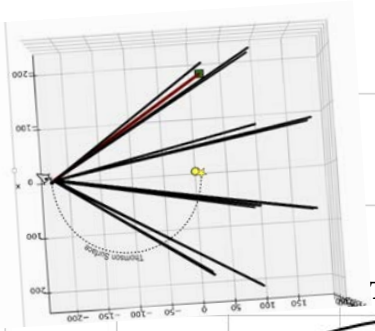


Pecora+ in prep

Forward modeling



Thomson's surface

Far FOV

Mid FOV

Near FOV

FORWARD tool

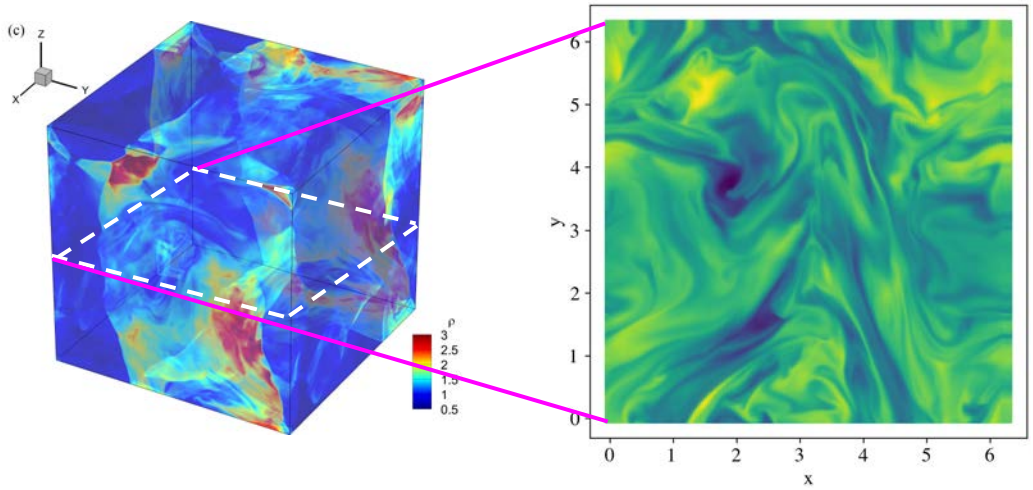
3d sampling Gibson+2016

PUNCH-like image from "Rubik's heliosphere" through Forward modeling

Not 1-to-1 comparison!

Forward-generated images include:

- Effects from integration along LOS (smearing of structures)
- Radial trend due to scattering function



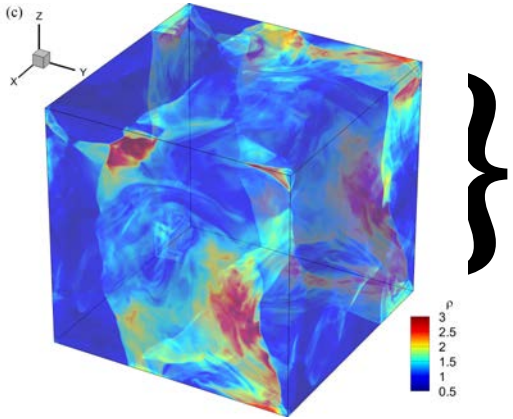
PUNCH-like image

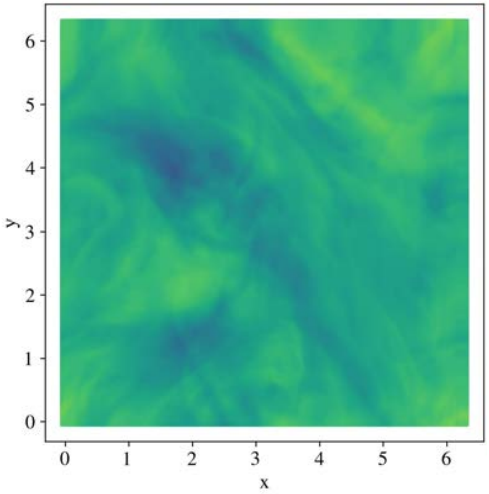
Simulation – One 2D plane

Not 1-to-1 comparison!

Forward-generated images include:

- ~~Effects from integration along LOS (smearing of structures)~~
- Radial trend due to scattering function





PUNCH-like image

Simulation – Integrated density

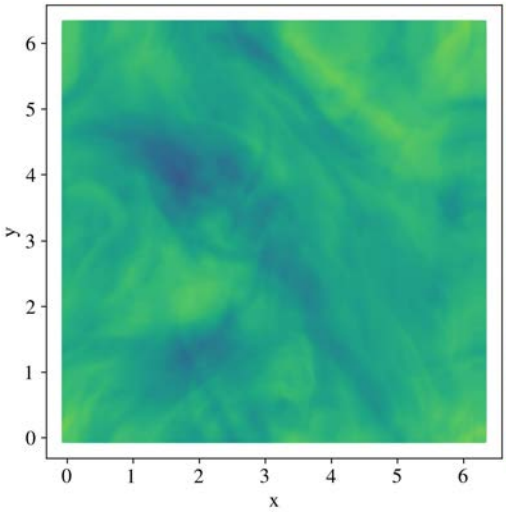
Not 1-to-1 correspondence!

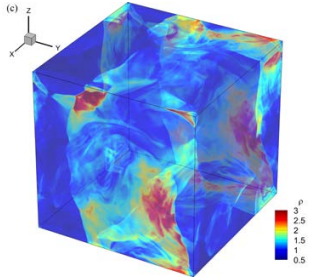
Forward-generated images include:

- ~~Effects from integration along LOS (smearing of structures)~~
- ~~Radial trend due to scattering function~~

PUNCH – detrended

Simulation – integrated



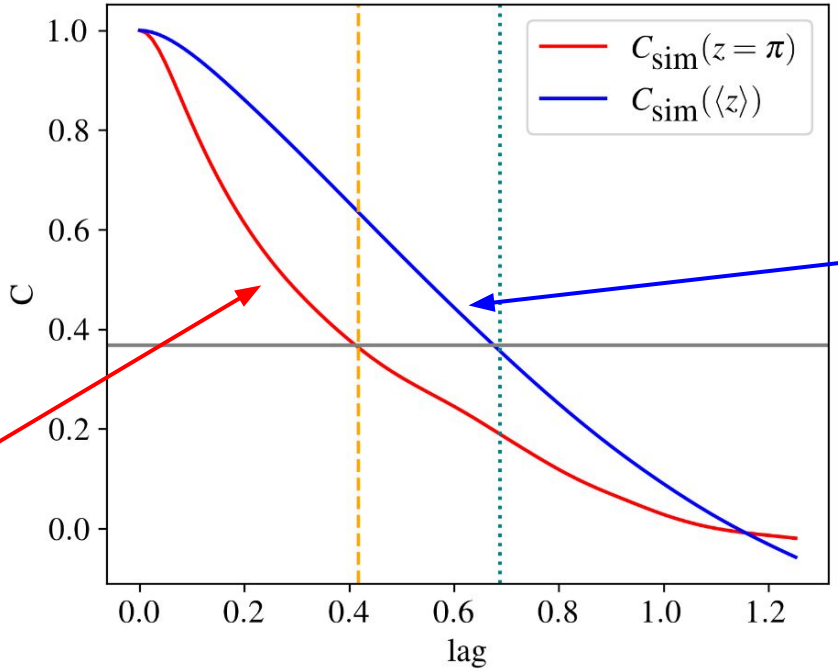


Not the same, but same spectral properties!

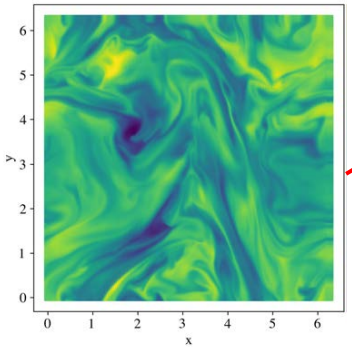
Effect of LOS integration on correlation scale

$$C(\boldsymbol{\ell}) = \langle f(\boldsymbol{x}) f(\boldsymbol{x} + \boldsymbol{\ell}) \rangle_{\boldsymbol{x}}$$

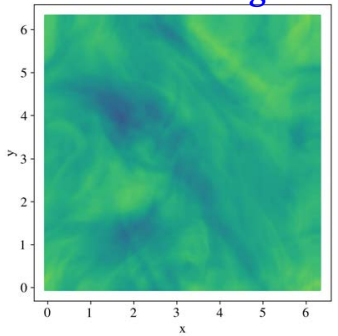
- Integrated fields decorrelate more slowly
- Absence of small-scale structures



Simulation 2D plane



Simulation – integrated

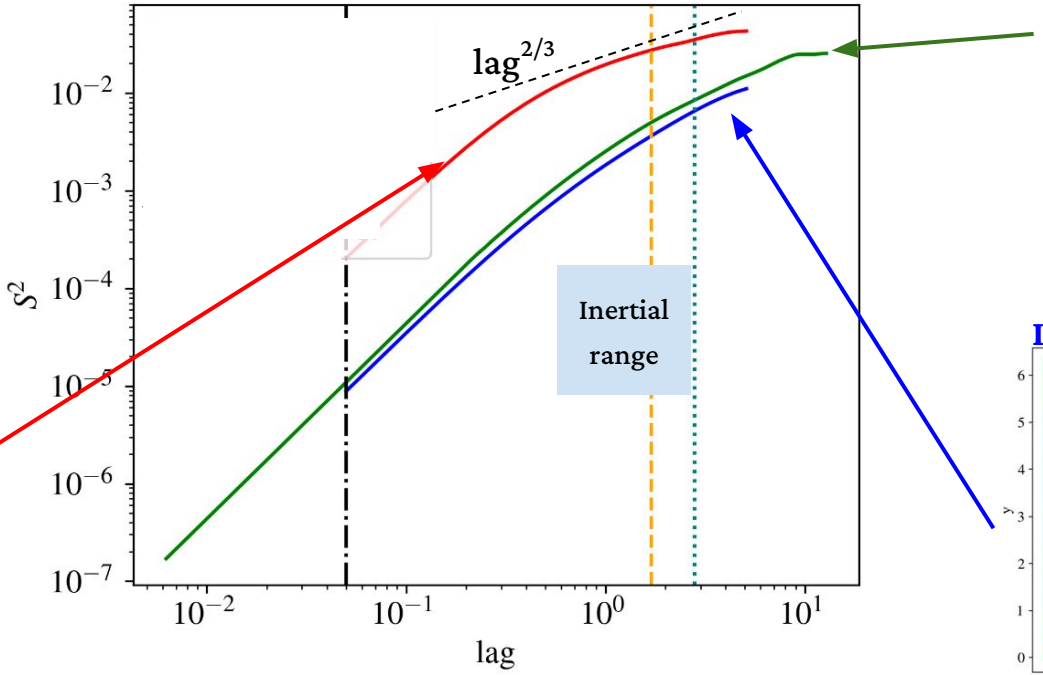


Second-order structure function

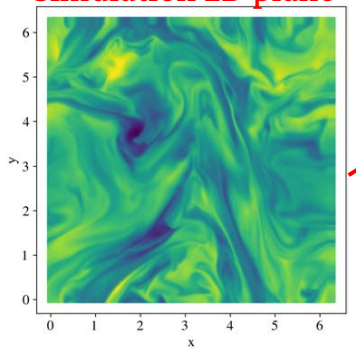
PUNCH

$$S^2(\boldsymbol{\ell}) = \langle |f(\boldsymbol{x}) - f(\boldsymbol{x}+\boldsymbol{\ell})|^2 \rangle_{\boldsymbol{x}}$$

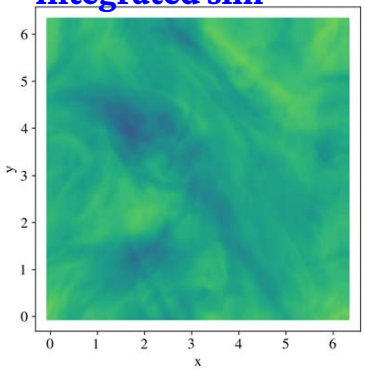
- **Simulation 2D plane** has the expected scaling from turbulence theory
- **PUNCH** and **integrated sim** have the same scaling



Simulation 2D plane



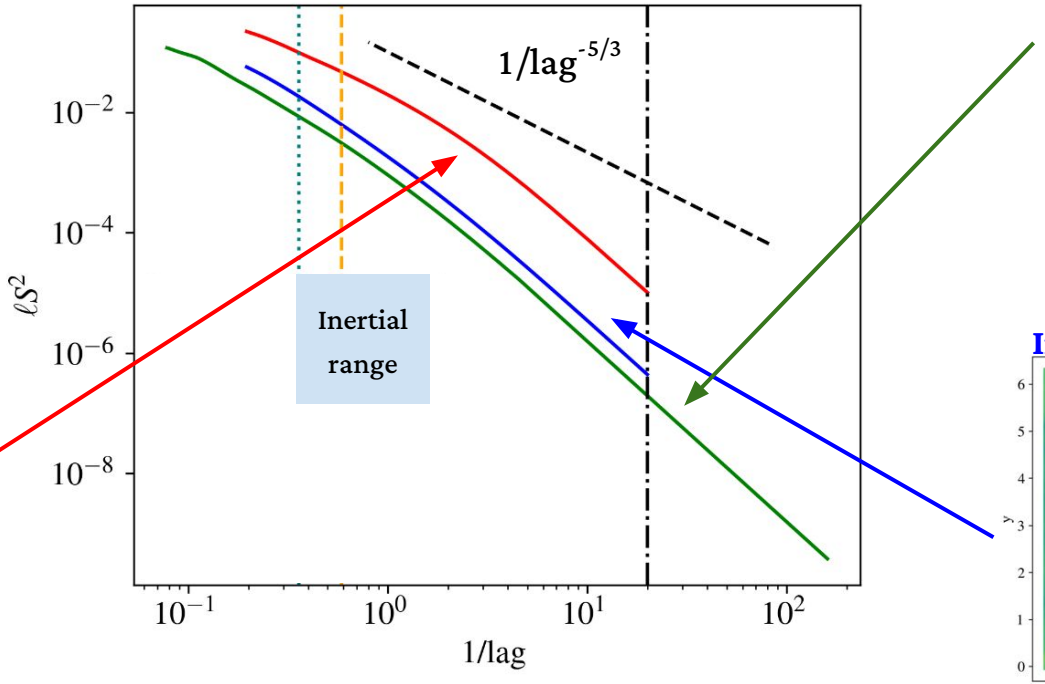
Integrated sim



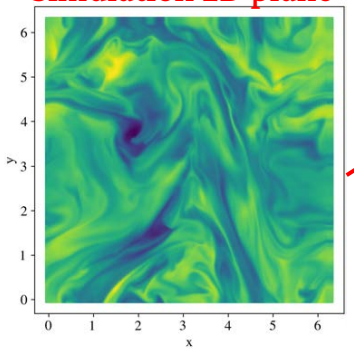
Equivalent power spectra

PUNCH

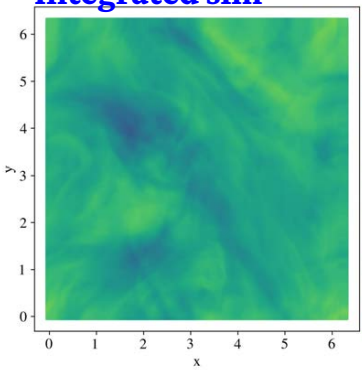
- **Simulation 2D plane** has the expected scaling from turbulence theory
- **PUNCH** and **integrated sim** have the same scaling



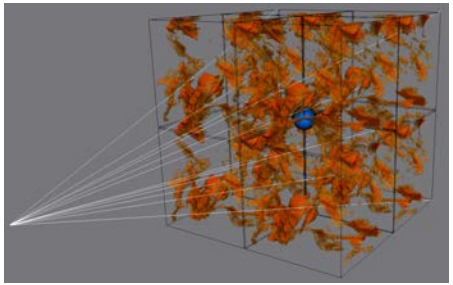
Simulation 2D plane



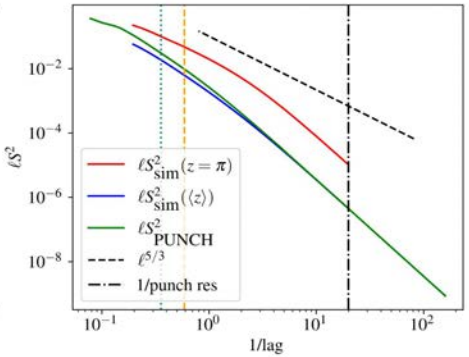
Integrated sim



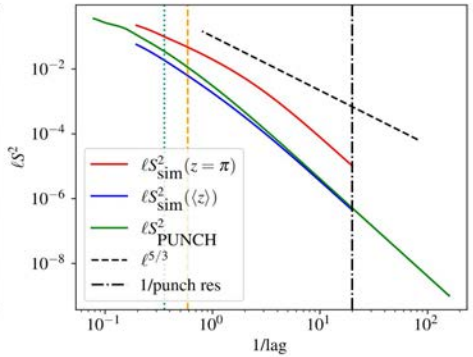
Effects of Rubik's cube dimensionality



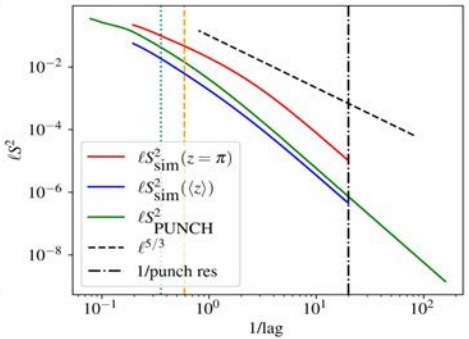
1 cube



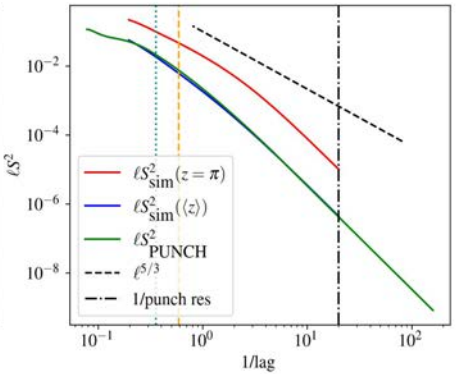
2 cubes



4 cubes



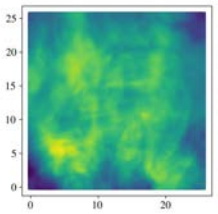
8 cubes

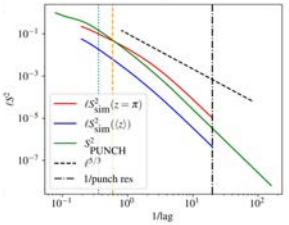


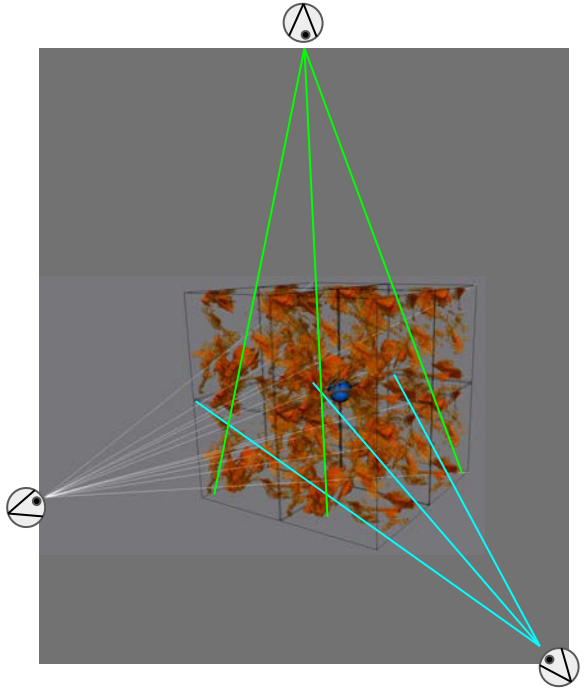
- Scaling of **PUNCH** and **integrated sim** does not change
- Periodicity may bias results

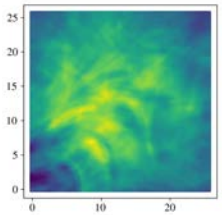
Changing observer direction

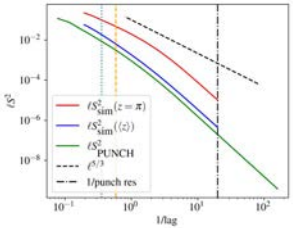
- Scaling of **PUNCH** and **integrated sim** does not change (as expected from isotropic turbulence)

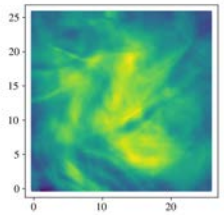


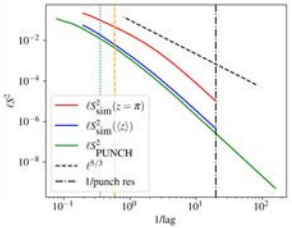












Conclusions

- Simulations can be used to create a tunable Rubik's cube corona/heliosphere
- Several caveats need to be taken into account:
  - Actual resolution (now x5)
  - averaging
  - trends
  - density falloff
- LOS integration modifies “usual” turbulence scalings.

- Use different simulations
- Investigate time evolution
- Anisotropies
- …

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