# Magnetohydrodynamics turbulence simulations as testing ground for PUNCH

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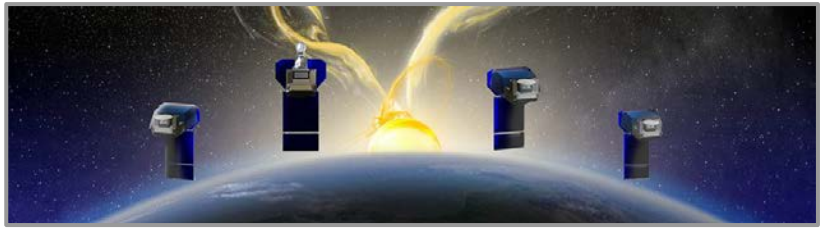
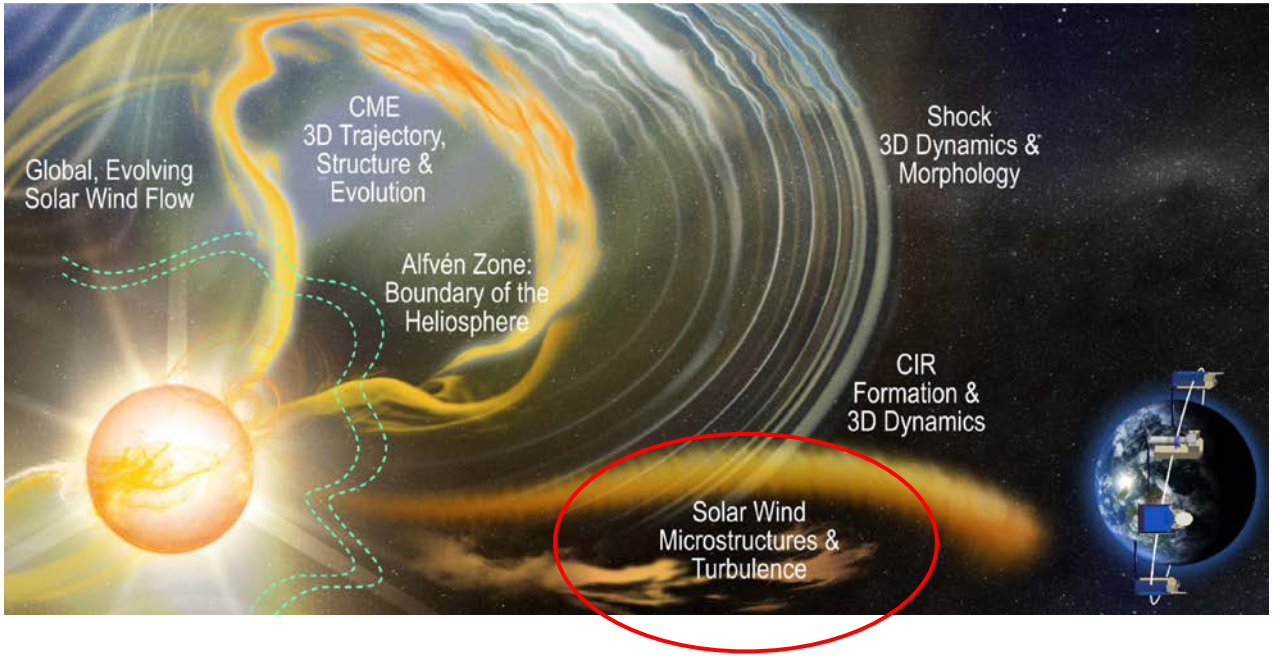
[4]Southwest Research Institute, Boulder, US-CO



# Punch science objectives



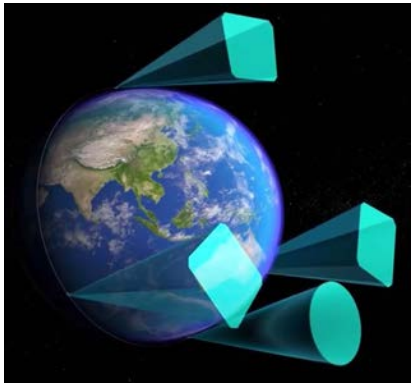

1. **Understand how coronal structures become the ambient solar wind.**
2. Understand the evolution of transient structures (such as CMEs) in the young solar wind.

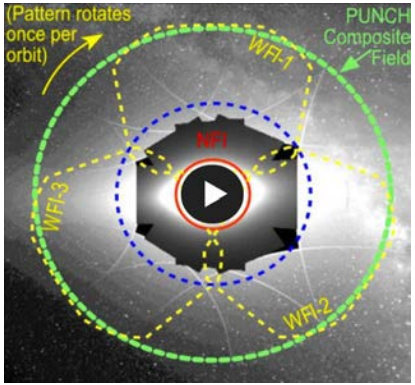
I. Slow solar wind near Earth is dominated by fluctuations of unknown origin.
   - Do they form mainly from turbulence in the solar wind?
   - Or is the slow solar wind intrinsically intermittent from its origins?

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





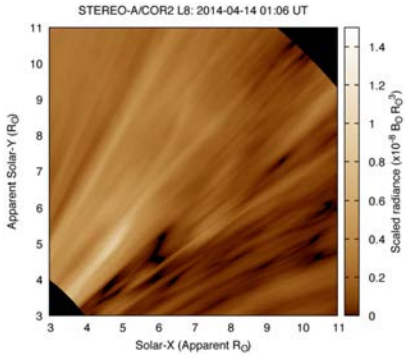

- Narrow Field Imager (NFI) 6 $R_\odot$ - 32 $R_\odot$
  Resolution: 0.67 arcmin ~ 0.04 $R_\odot$ ~ 28 Mm
- Wide Field Imagers (WFI) 20 $R_\odot$ - 180 $R_\odot$
  Resolution: 1.33 arcmin ~ 0.08 $R_\odot$ ~ 56 Mm
- 4-min cadence observations – longer than the crossing time of a 140 Mm structure

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

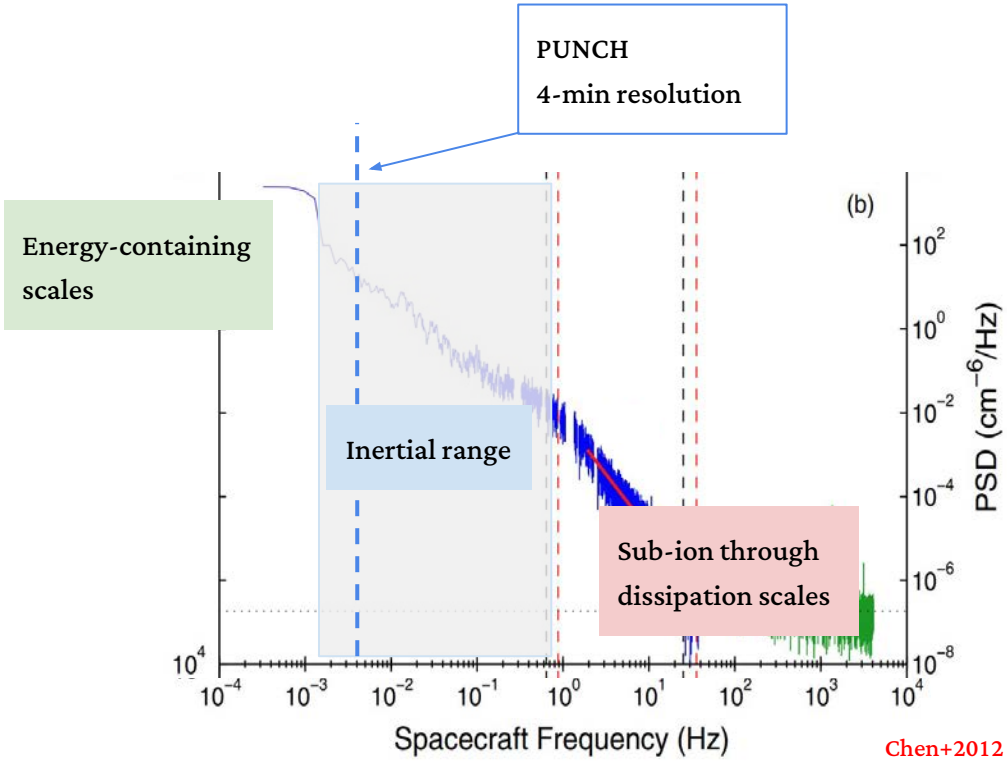
1. **Understand how coronal structures become the ambient solar wind.**

# Observations in the inertial range

PUNCH will provide observations in the inertial range



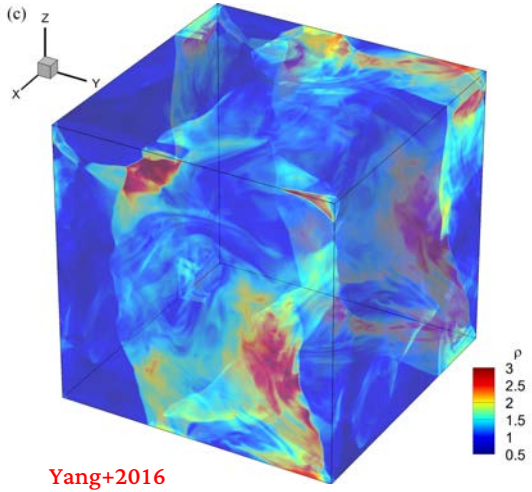

DeForest+2018




Chen+2012

e- density, Artemis @ 1AU

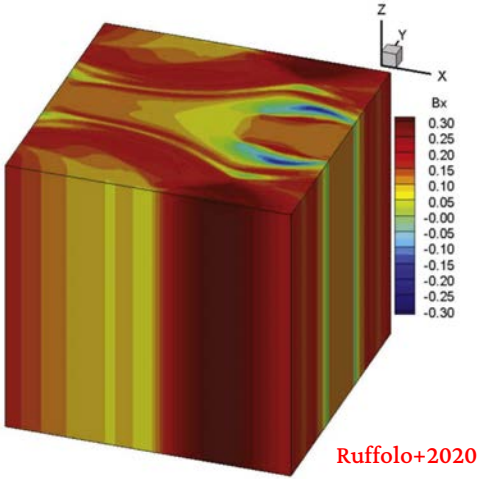
# Simulation campaign



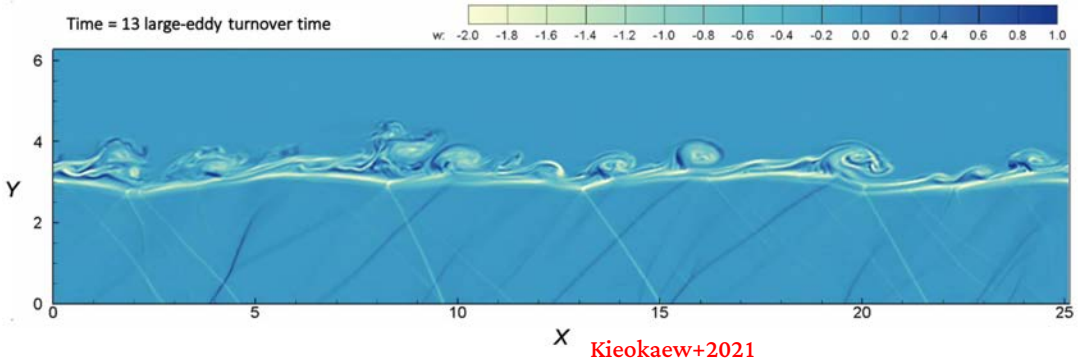

Yang+2016

Several MHD simulations:

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

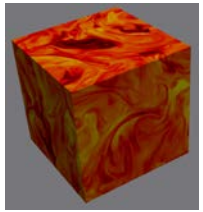


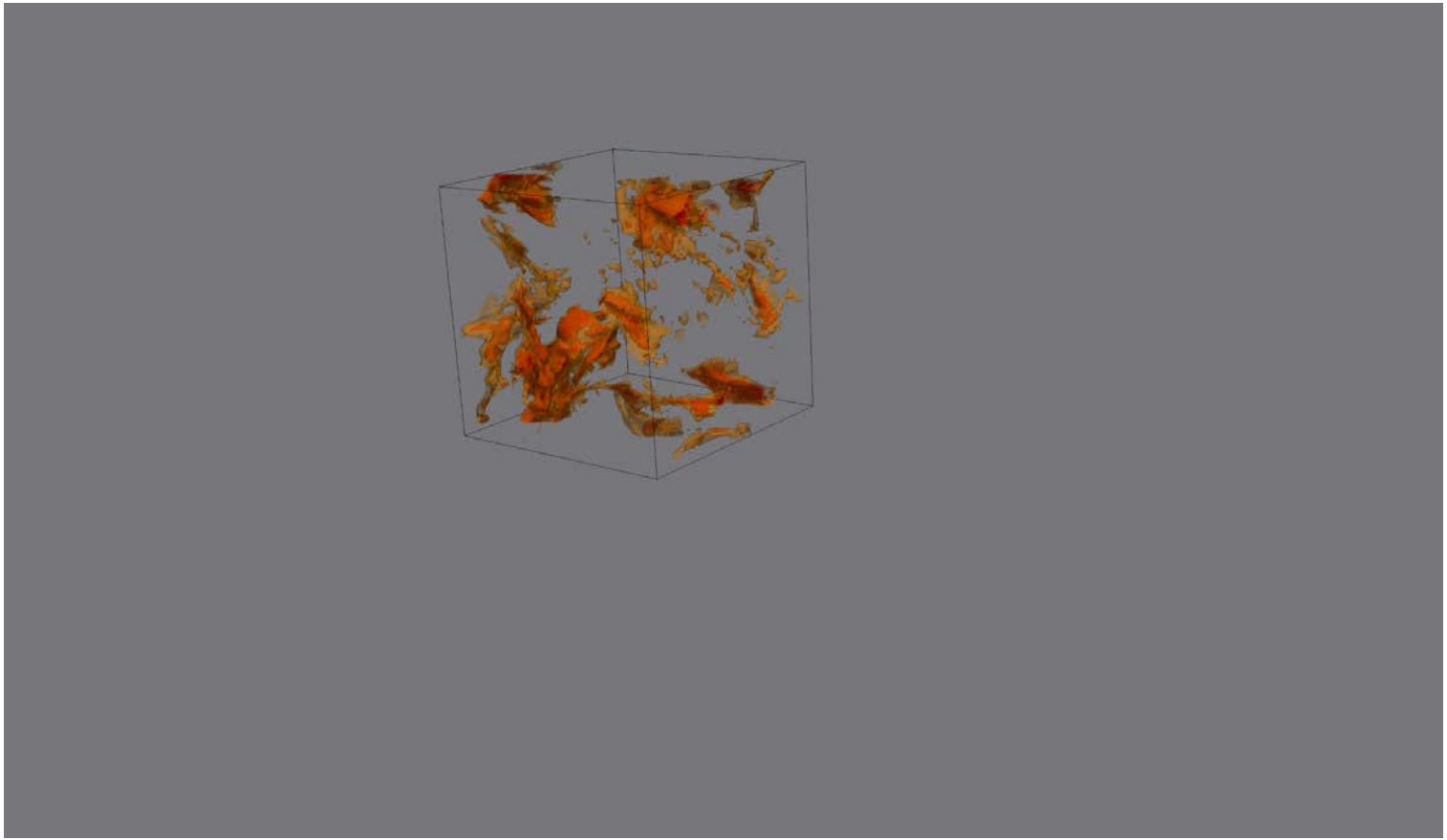

Ruffolo+2020




Kieokaew+2021

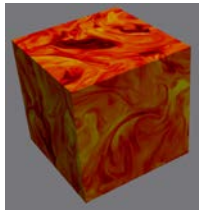
# Rubik's heliosphere

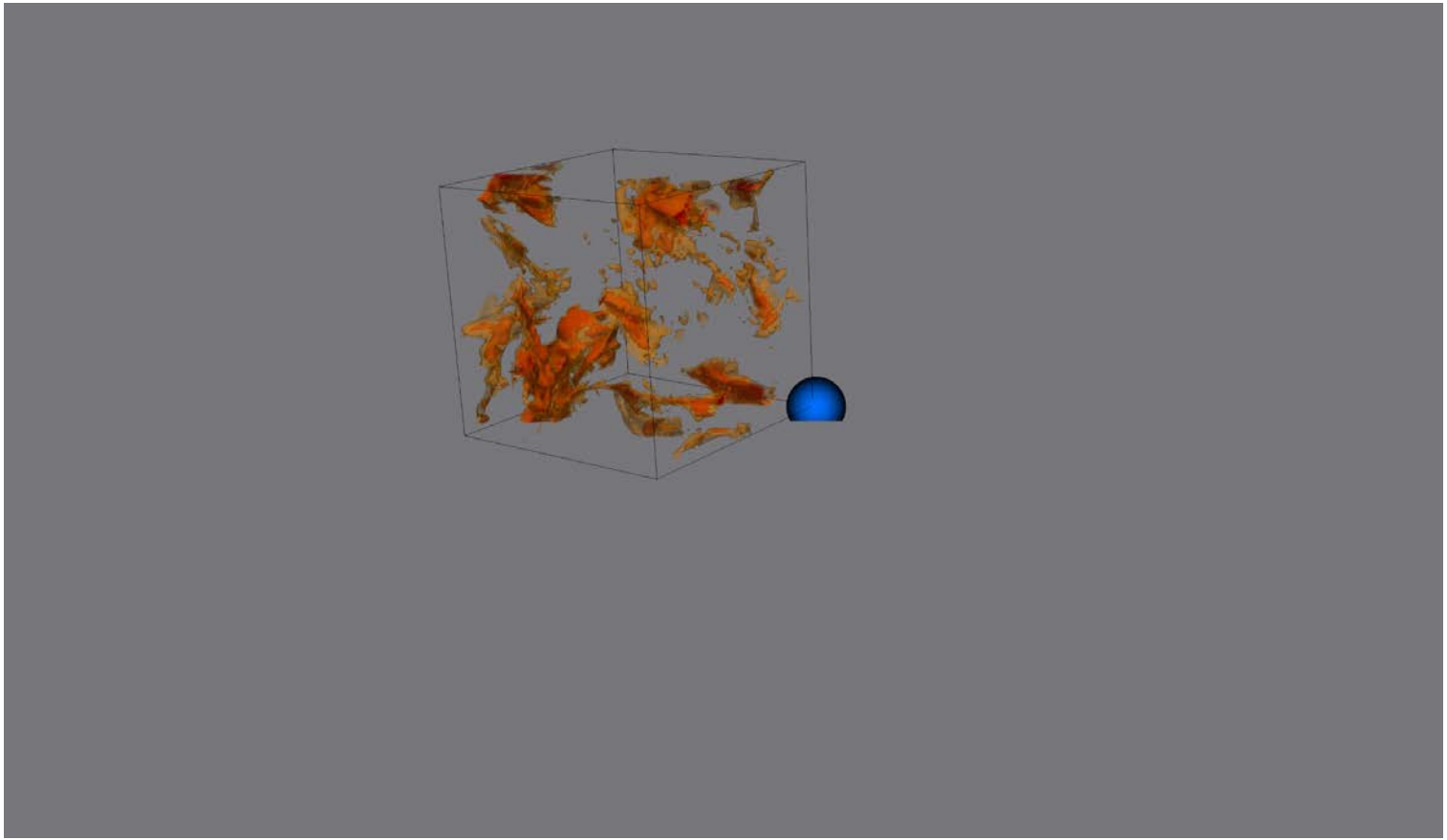




Pecora+ in prep

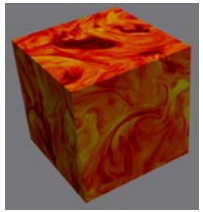
# Rubik's heliosphere

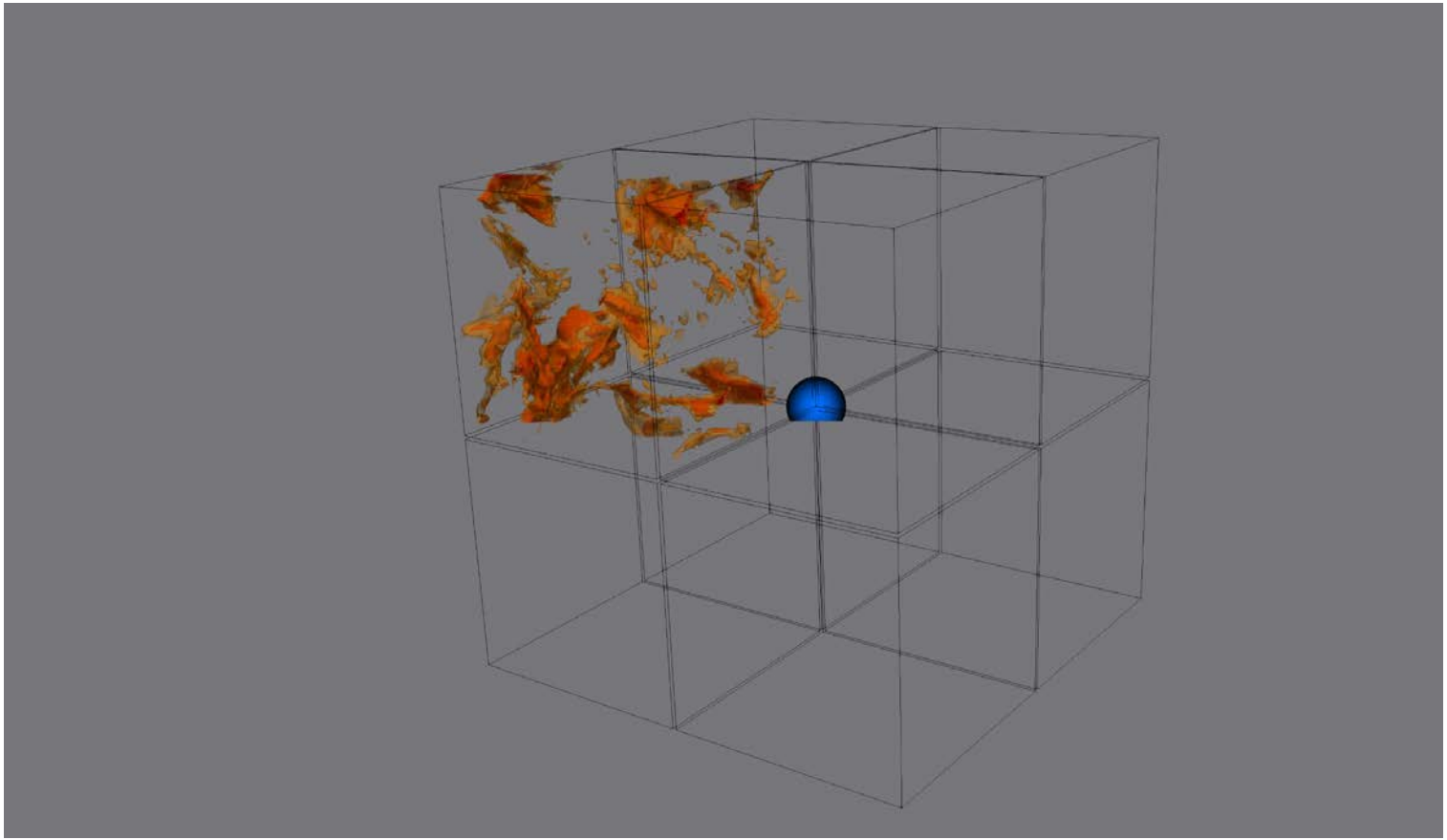




Pecora+ in prep

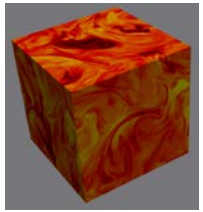
# Rubik's heliosphere

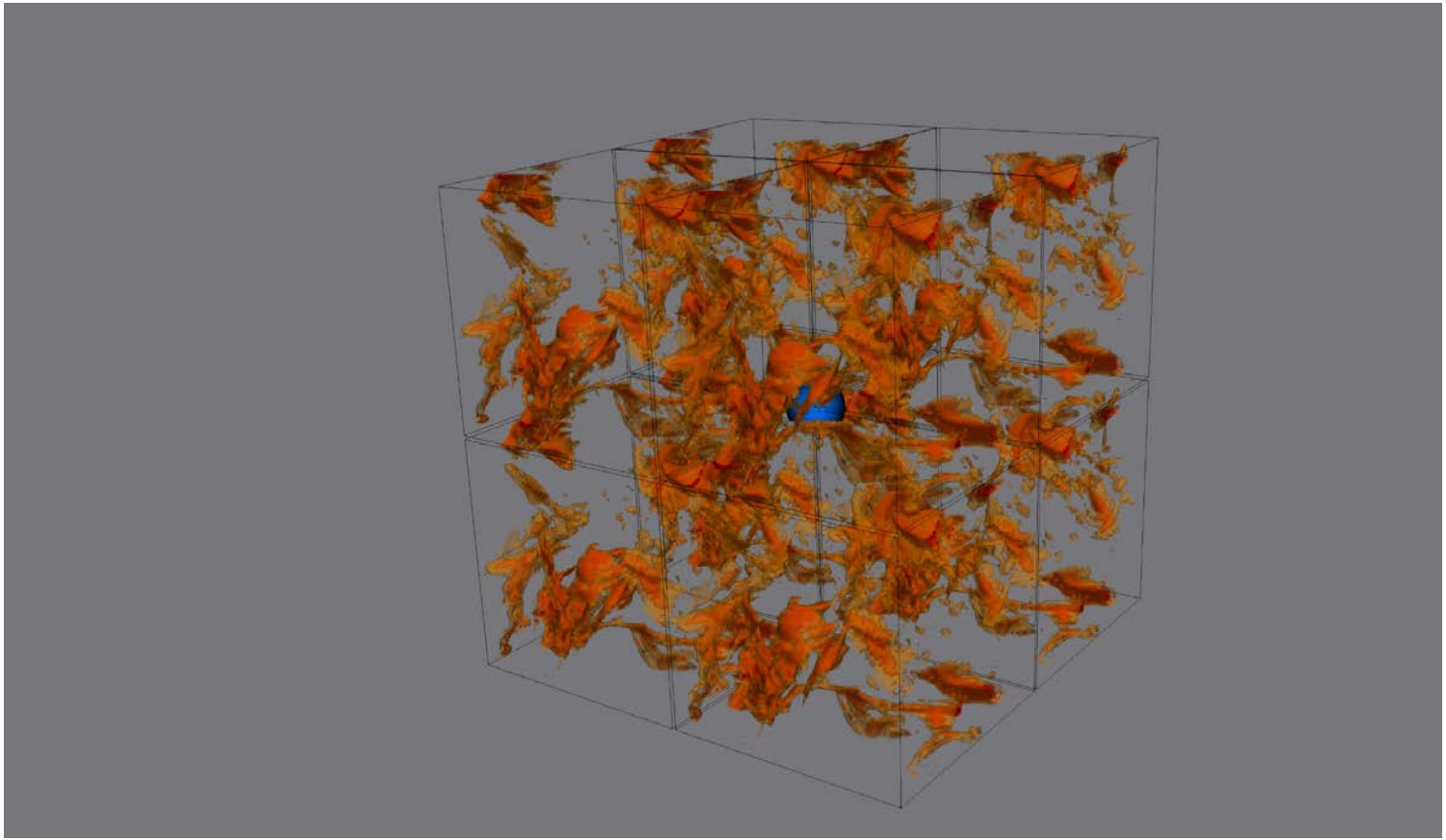




Pecora+ in prep

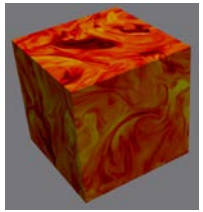
# Rubik's heliosphere

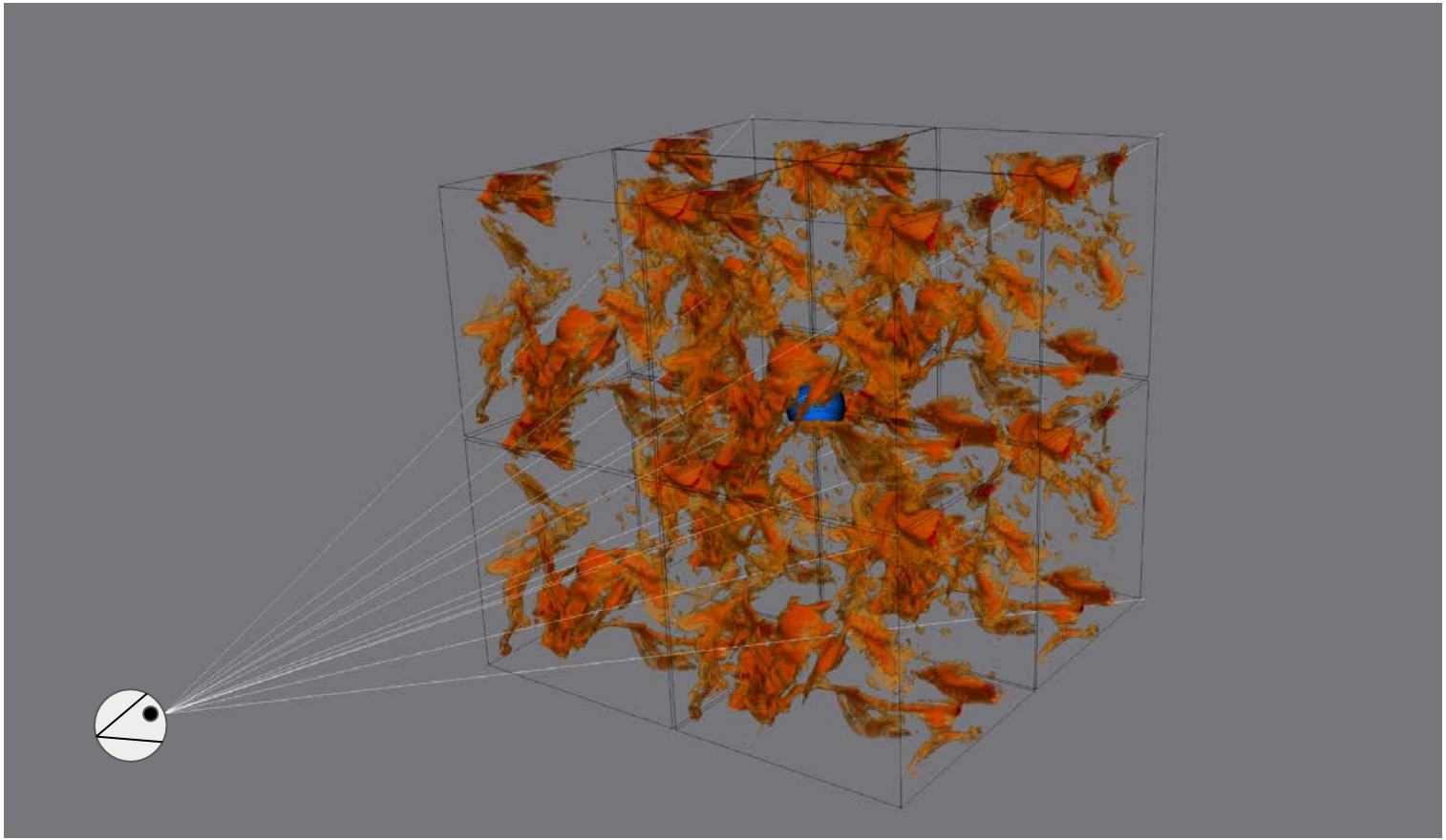




Pecora+ in prep

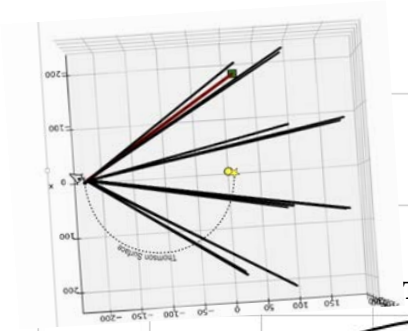
# Rubik's heliosphere





Pecora+ in prep

# Forward modeling



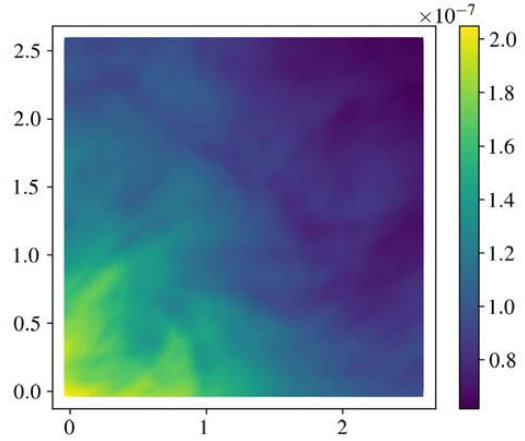
Thomson's surface

Far FOV

Mid FOV

Near FOV






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

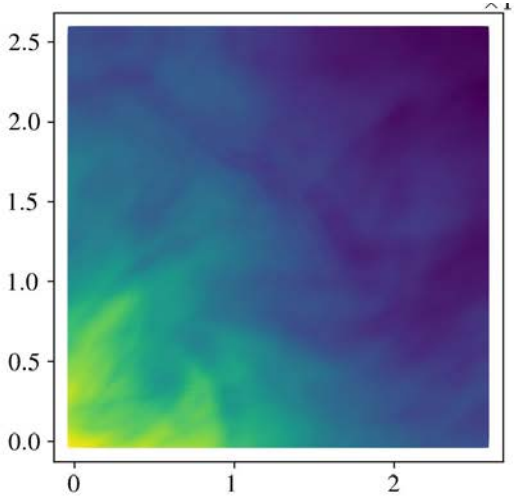
**FORWARD tool**

**3d sampling** Gibson+2016

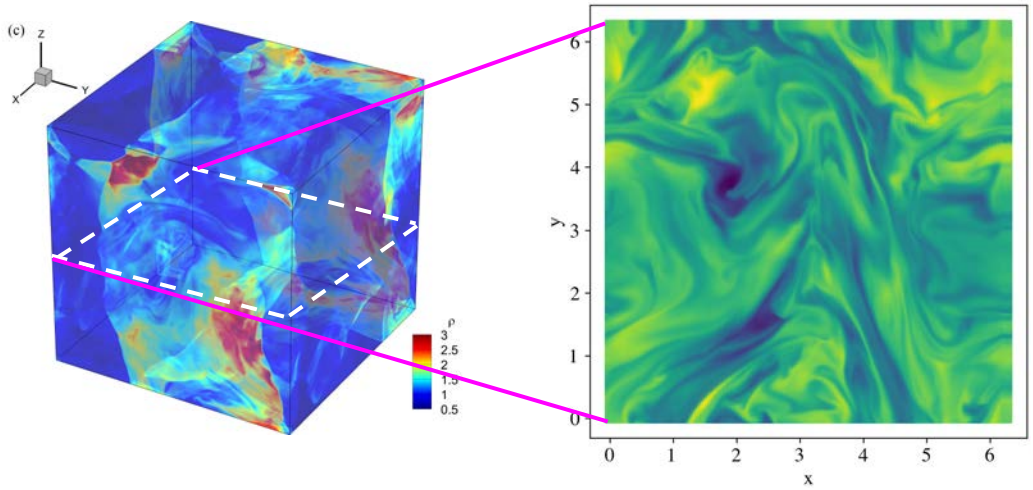
# Not 1-to-1 comparison!

Forward-generated images include:

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




PUNCH-like image



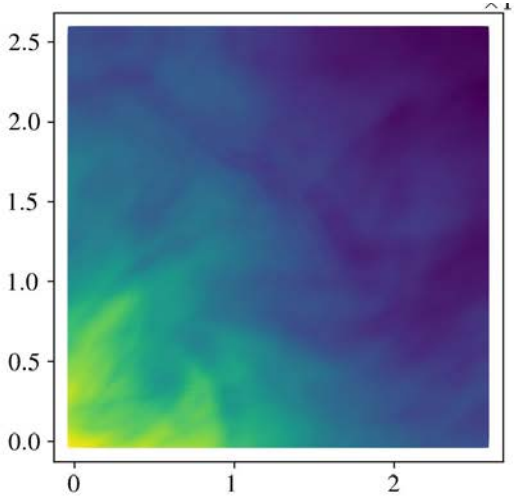

Simulation –

One 2D plane

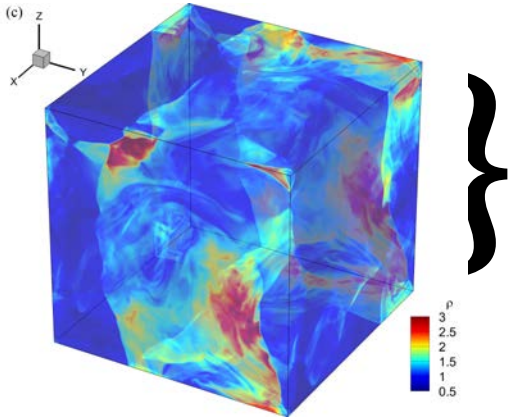
# Not 1-to-1 comparison!

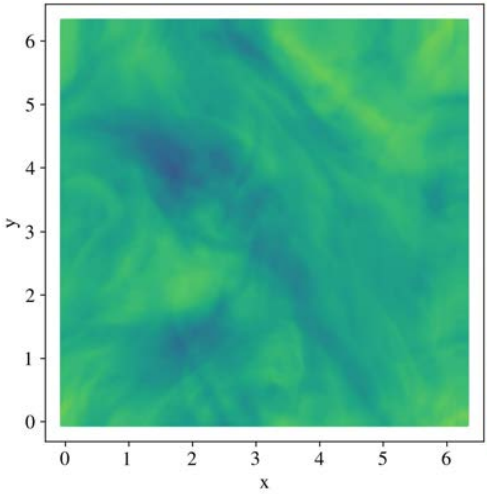
Forward-generated images include:

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




PUNCH-like image



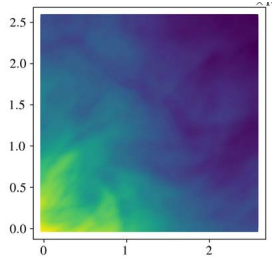

Simulation –

Integrated density

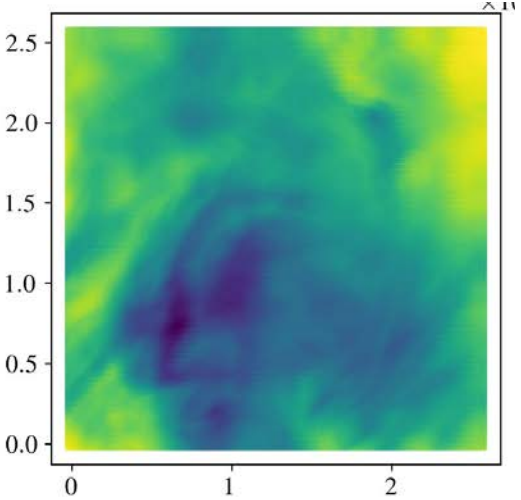
# Not 1-to-1 correspondence!

Forward-generated images include:

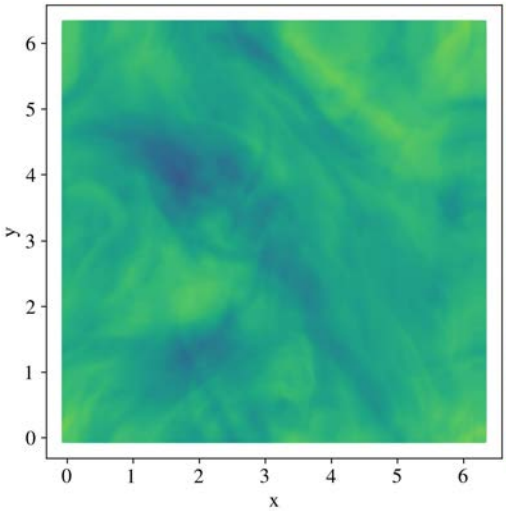
- ~~Effects from integration along LOS (smearing of structures)~~
- ~~Radial trend due to scattering function~~

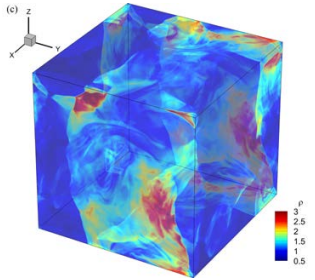



**PUNCH – detrended**




**Simulation – integrated**



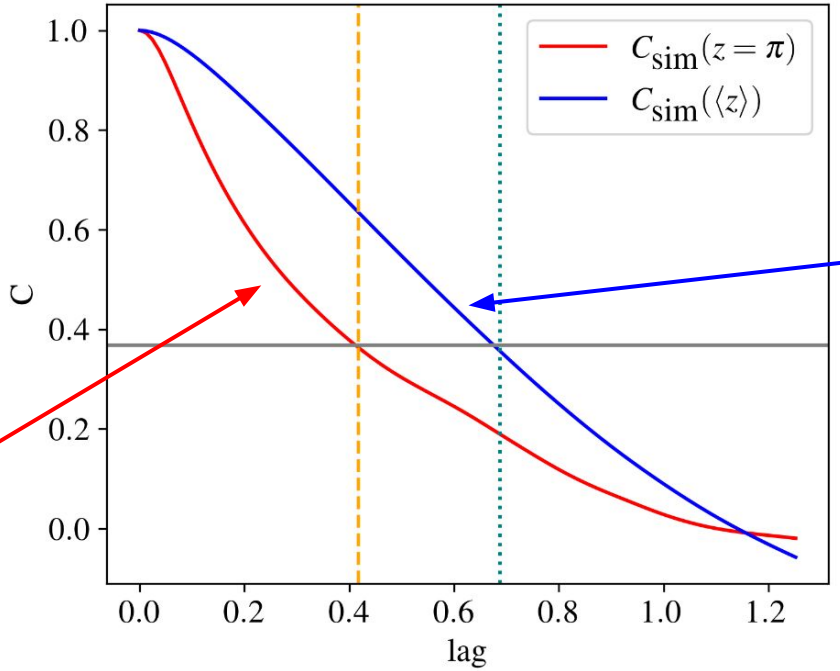



**Not the same, but same spectral properties!**

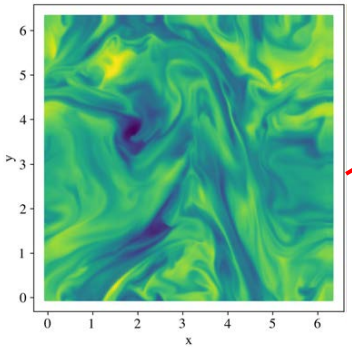
# Effect of LOS integration on correlation scale

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

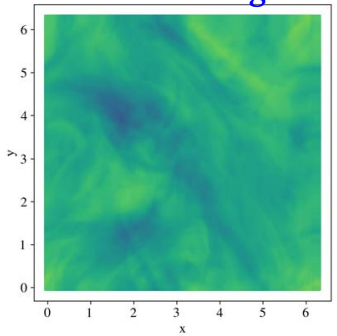
- Integrated fields decorrelate more slowly
- Absence of small-scale structures




Simulation 2D plane



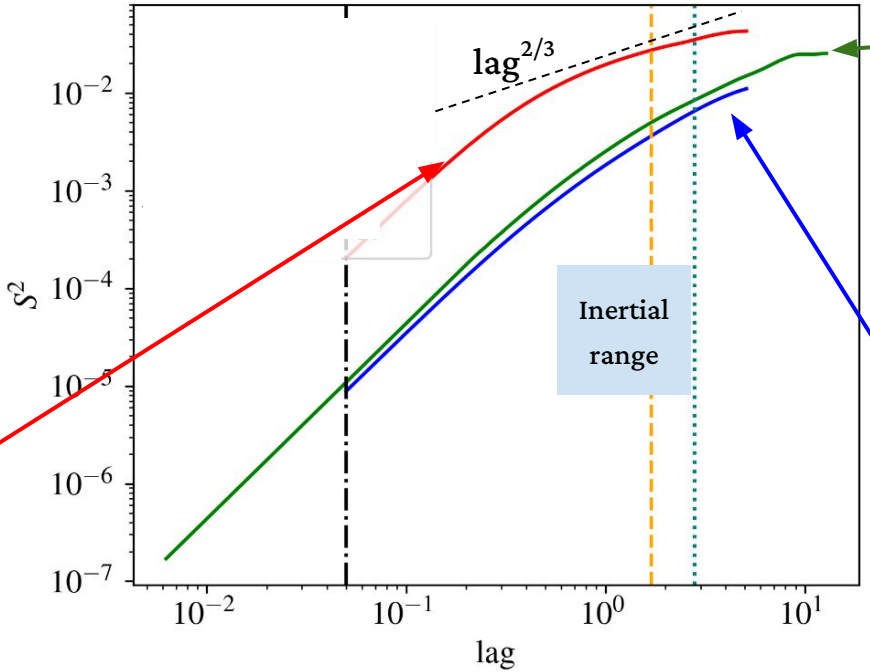

Simulation – integrated



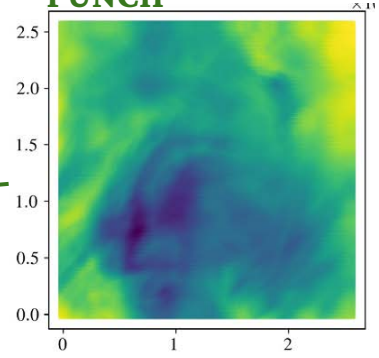
# Second-order structure function

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

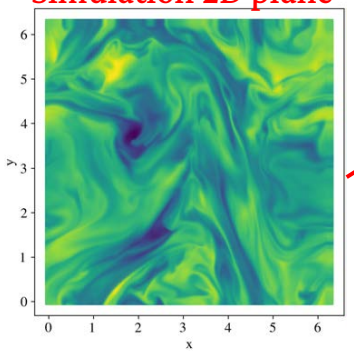
- **Simulation 2D plane** has the expected scaling from turbulence theory
- **PUNCH** and **integrated sim** have the same scaling



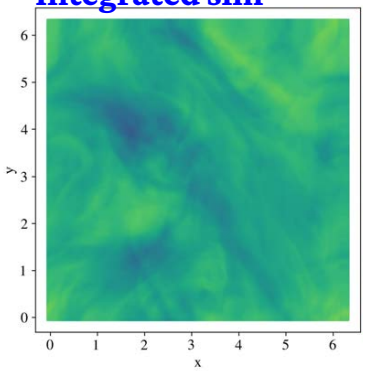

PUNCH



Simulation 2D plane

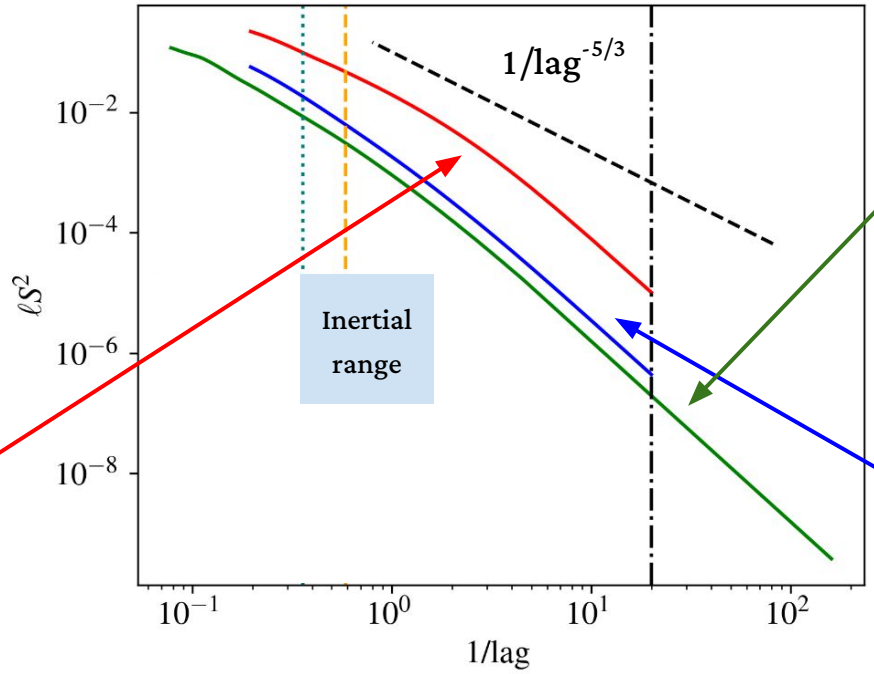


Integrated sim

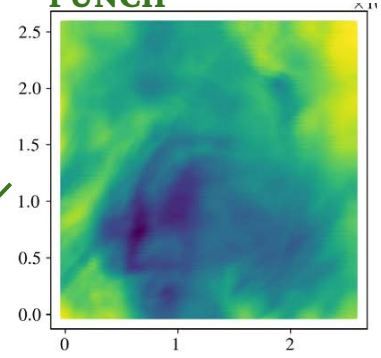


# Equivalent power spectra

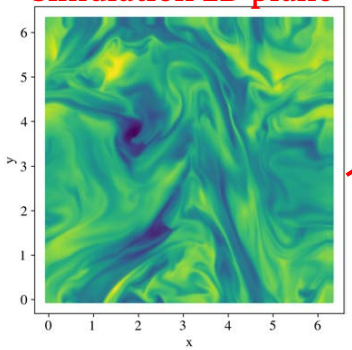
- **Simulation 2D plane** has the expected scaling from turbulence theory
- **PUNCH** and **integrated sim** have the same scaling



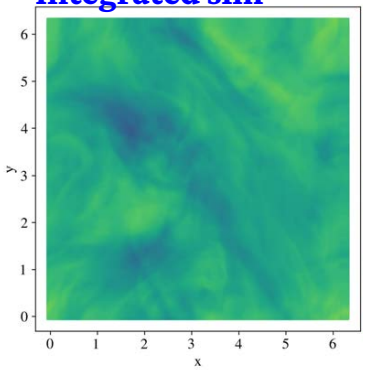

PUNCH



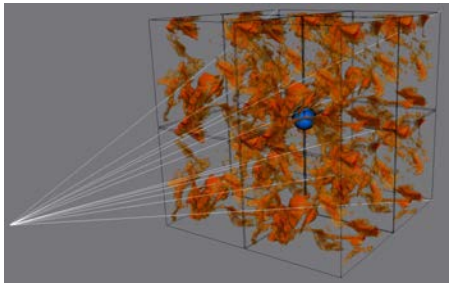
Simulation 2D plane



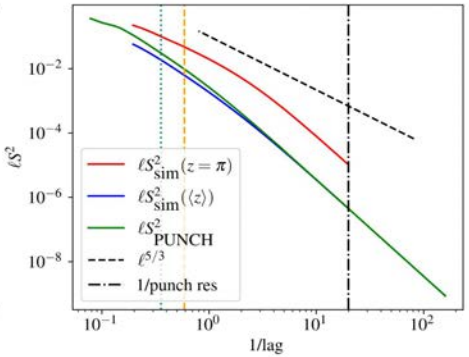
Integrated sim



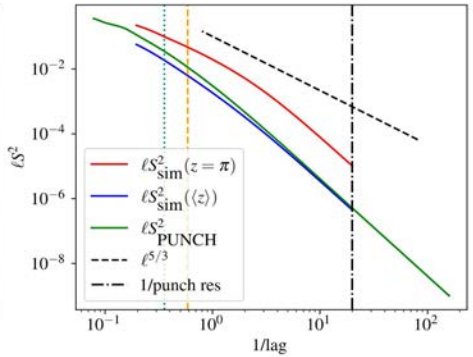
# Effects of Rubik's cube dimensionality



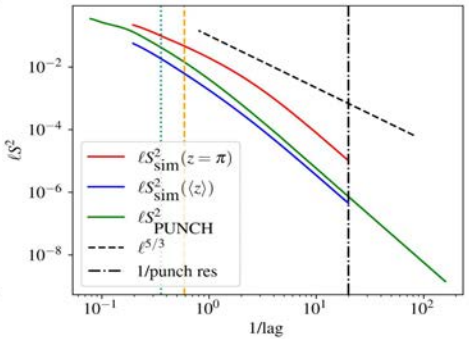
1 cube



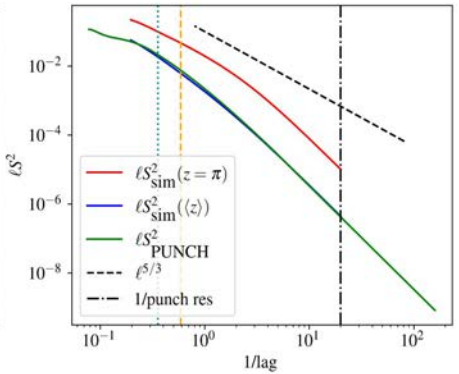

2 cubes




4 cubes



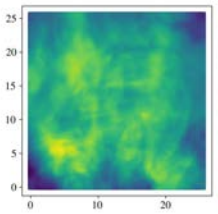

8 cubes

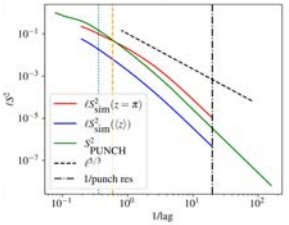


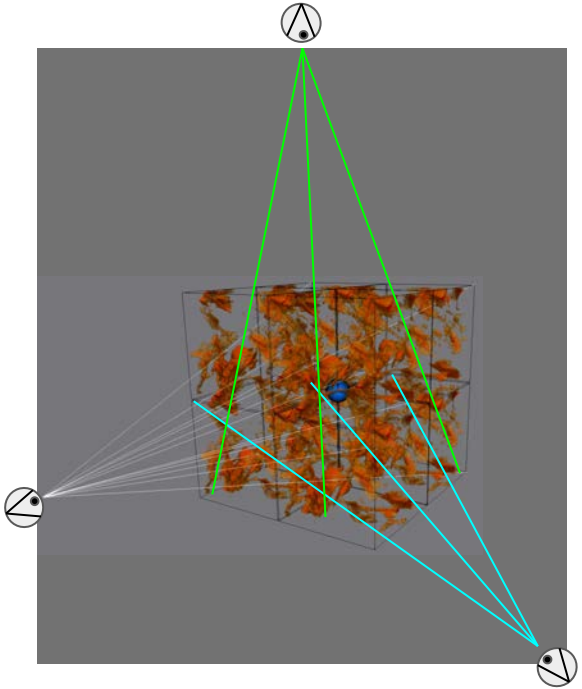

- Scaling of **PUNCH** and **integrated sim** does not change
- Periodicity may bias results

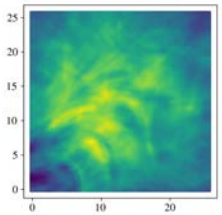
# Changing observer direction

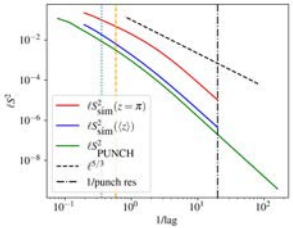
- Scaling of **PUNCH** and **integrated sim** does not change (as expected from isotropic turbulence)

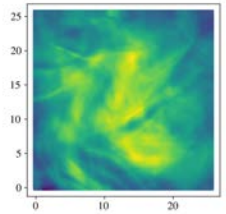


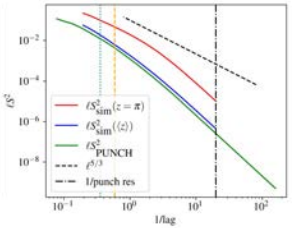








# Conclusions

- 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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