OBS vs SIM

Comparing ISM observations and simulations beyond gaussian features

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ENS | PSL

École Doctorale d'Astronomie & Astrophysique d'île-de-France

LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

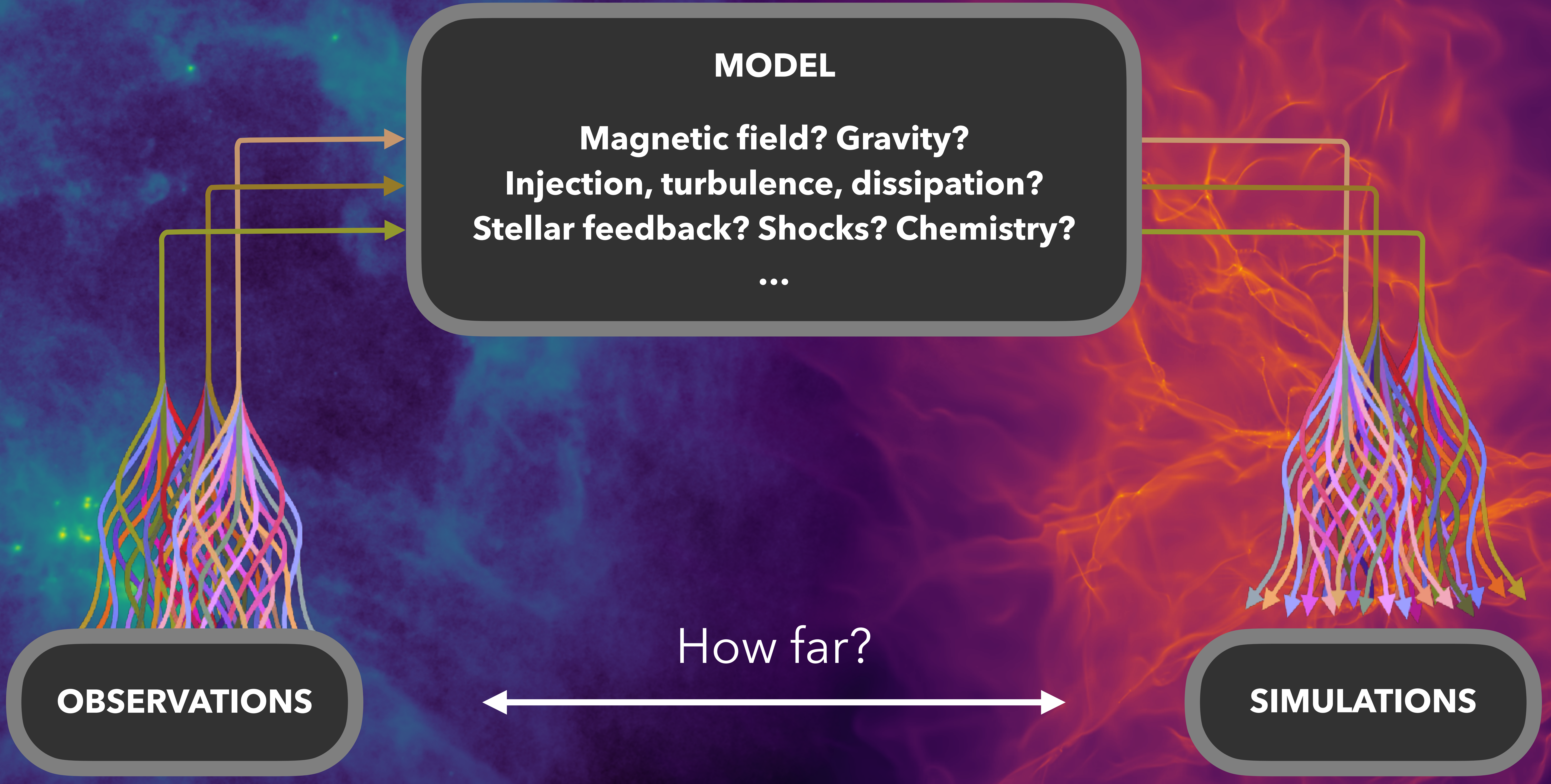
pcmi

PERSEUS – *Herschel* Gould Belt Survey 2010

ORION – Galactica Sim. Database – *Ntormousi & Hennebelle 2019*

INTRODUCTION

THE ISM COMPLEXITY



WHY IS NONLINEARITY A HURDLE?

Nonlinear dynamics

↓

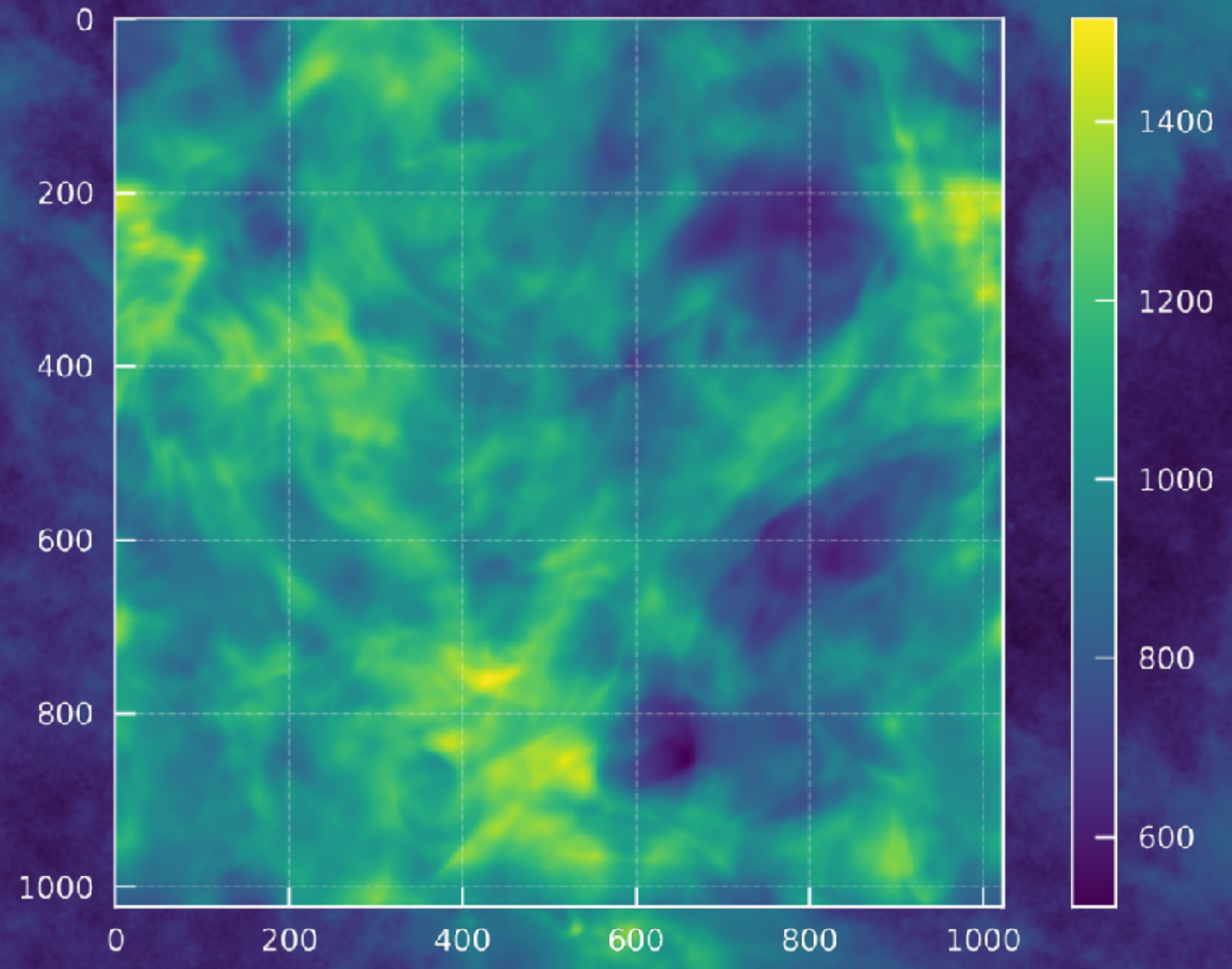
Coupling between scales

↓

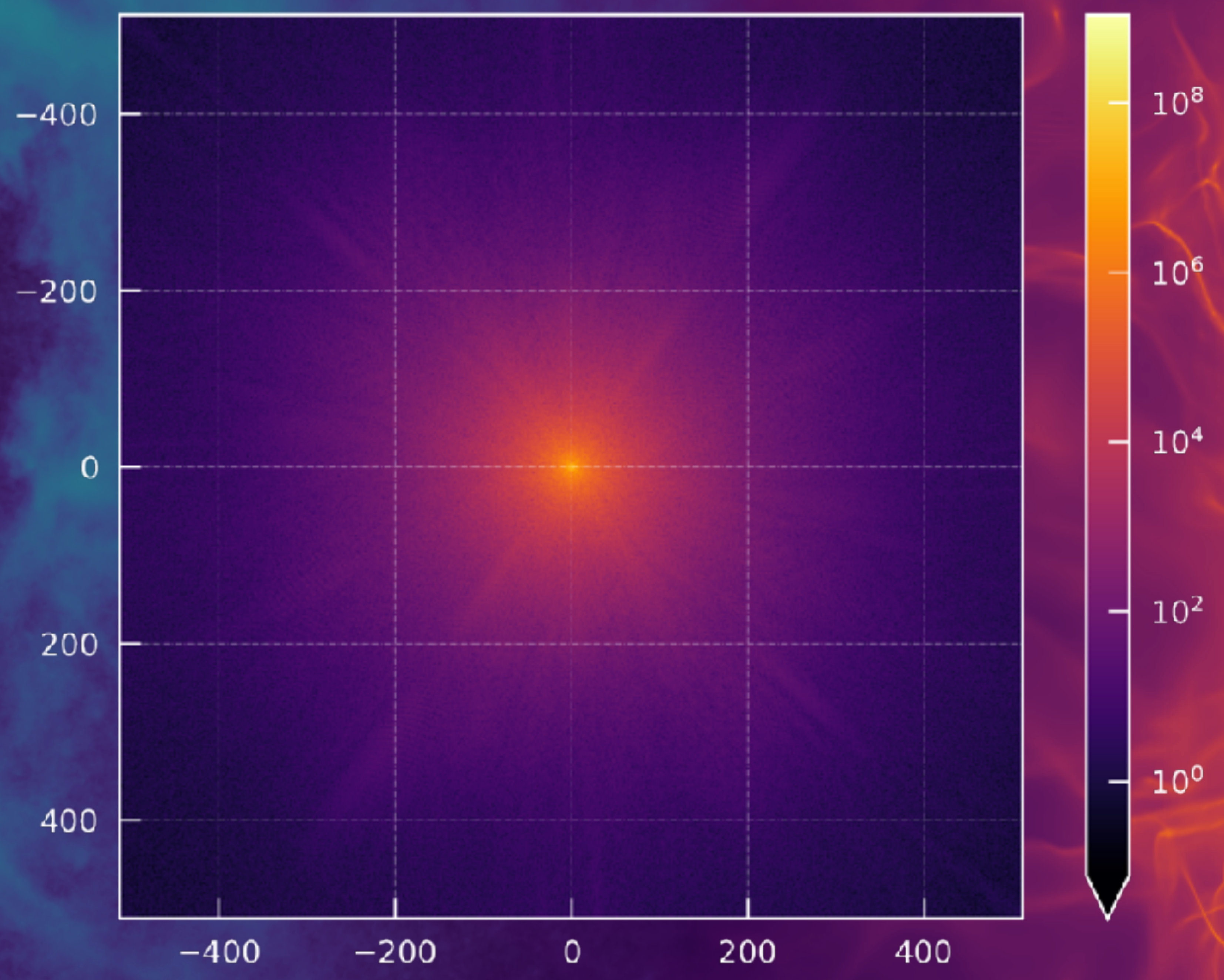
Coherent non-Gaussian structures

WHY IS NONLINEARITY A HURDLE?

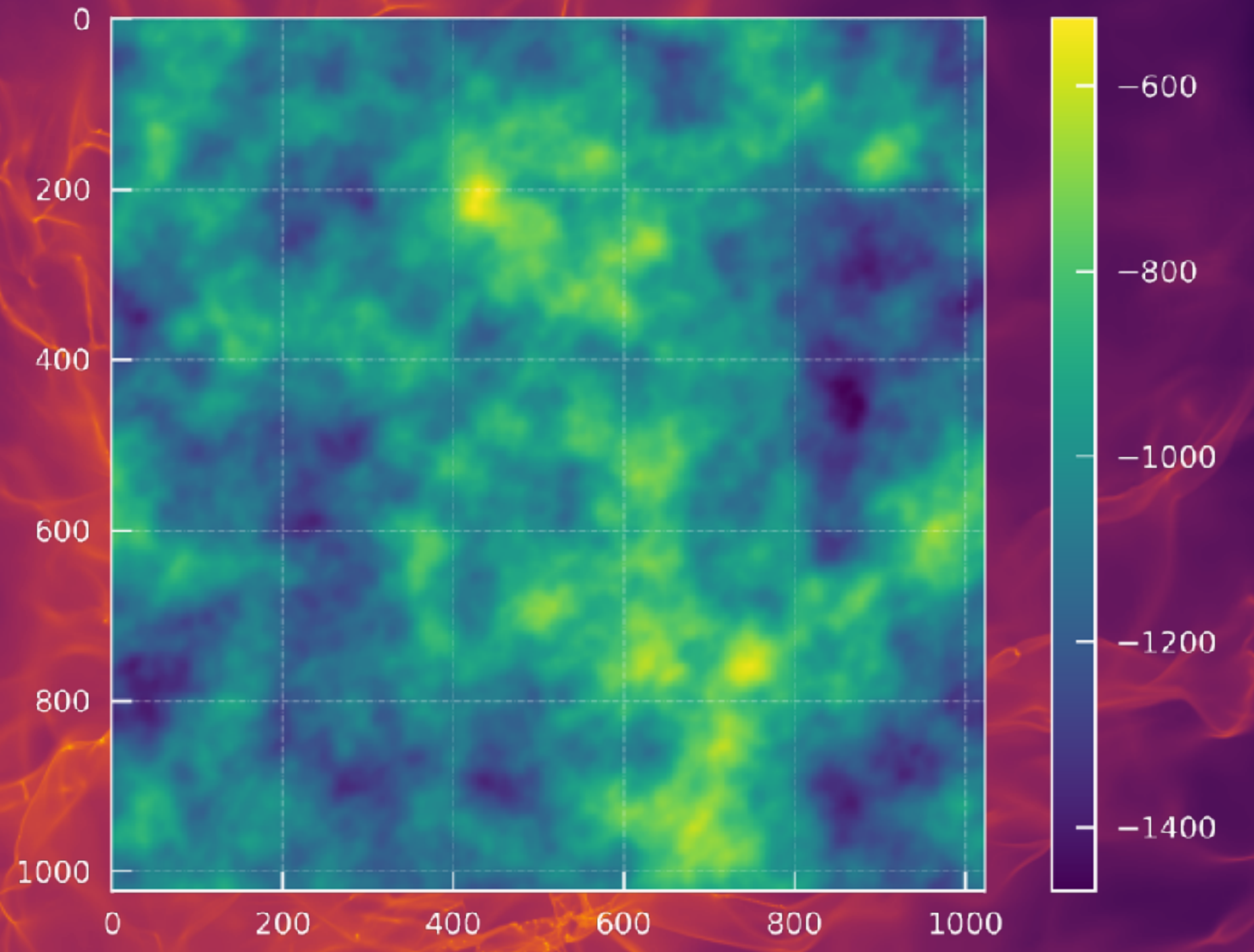
Ok but what if we use nevertheless gaussian stats.?



Coherent



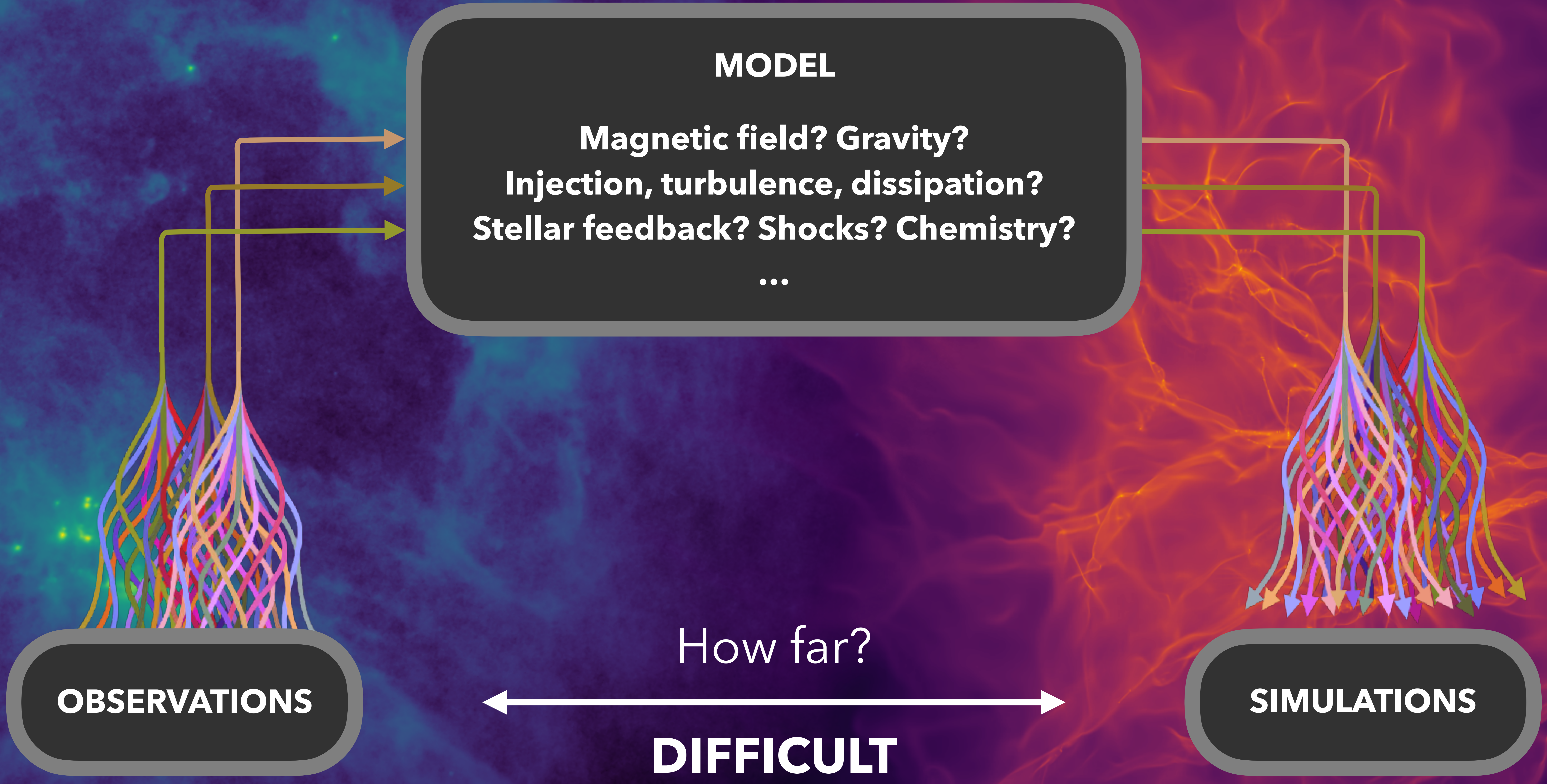
Fourier modulus



Gaussian

Strong degeneracies

THE ISM COMPLEXITY



TOOLS

WHERE IS COHERENT INFORMATION?

LIMITS OF THE FOURIER MODULUS

$$\left|\hat{I}(\vec{k})\right| = \left\|\hat{I} \cdot \delta_{\vec{k}}\right\|_2 = \left\|I \star e^{i\vec{k}\cdot\vec{x}}\right\|_2$$

What is lost during this operation?

The **phase**!

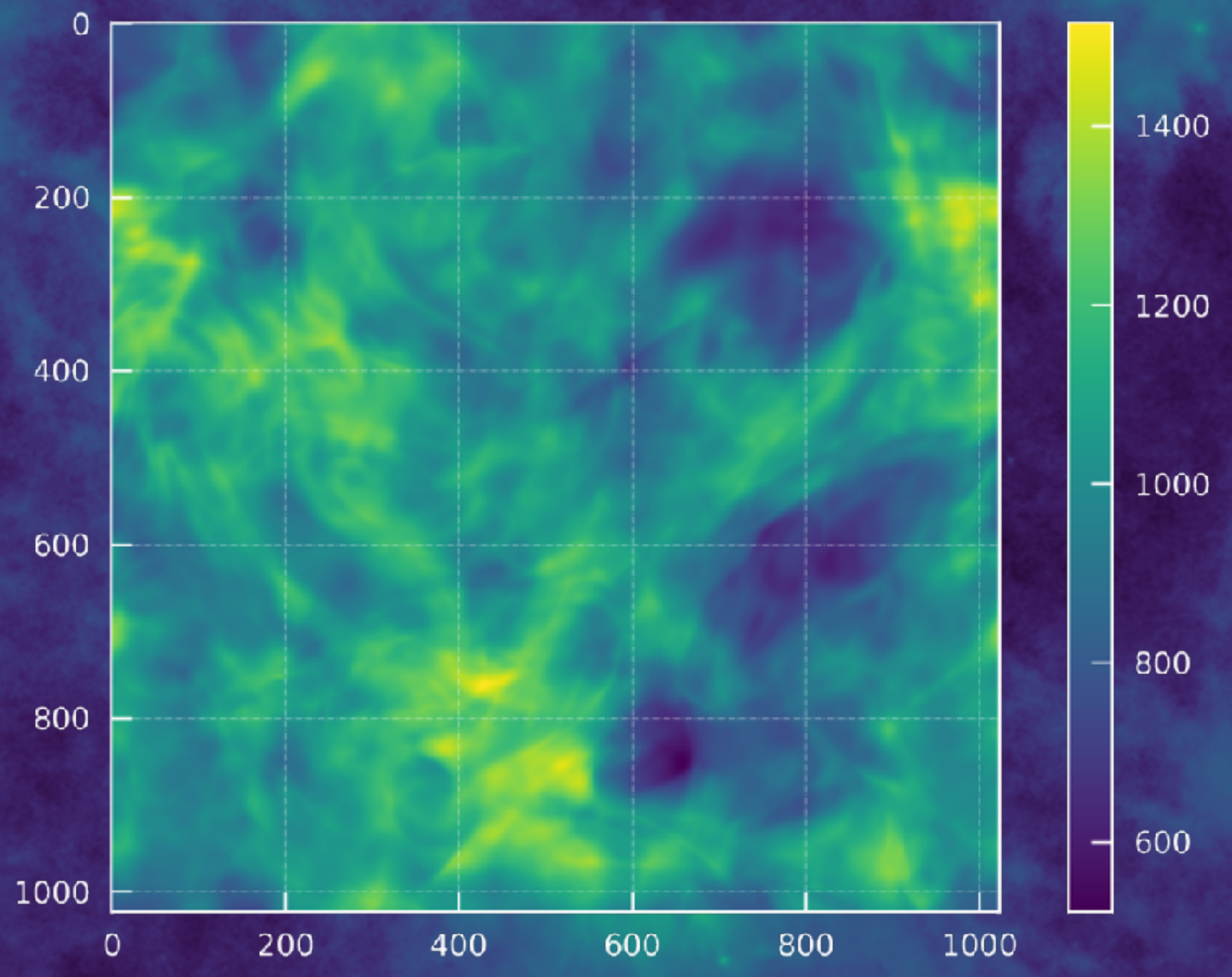
coherent structure $\Longrightarrow$ constructive interferences

$\Longrightarrow$ phase coherence between scales

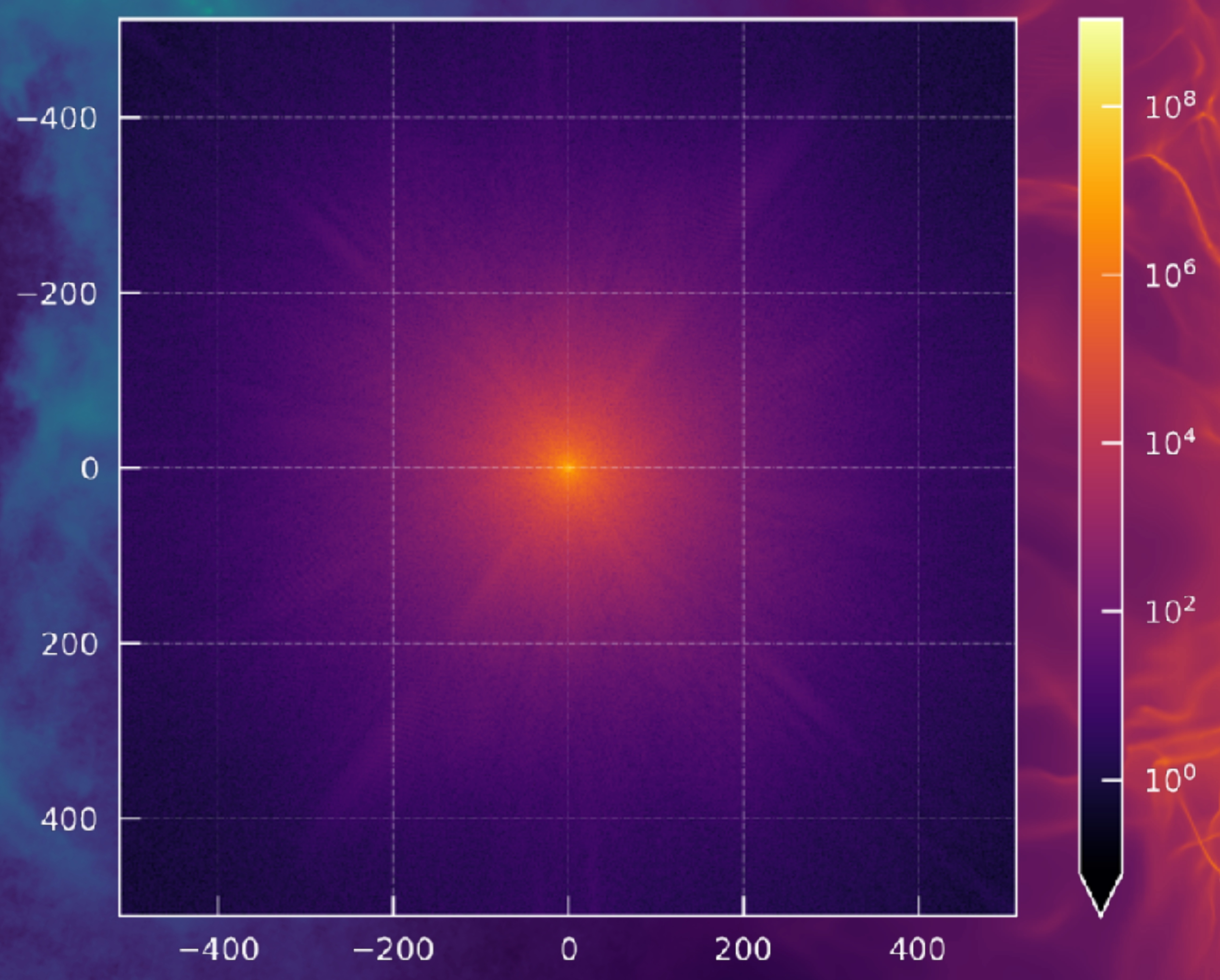
$\Longrightarrow$ scale interactions

WHERE IS COHERENT INFORMATION?

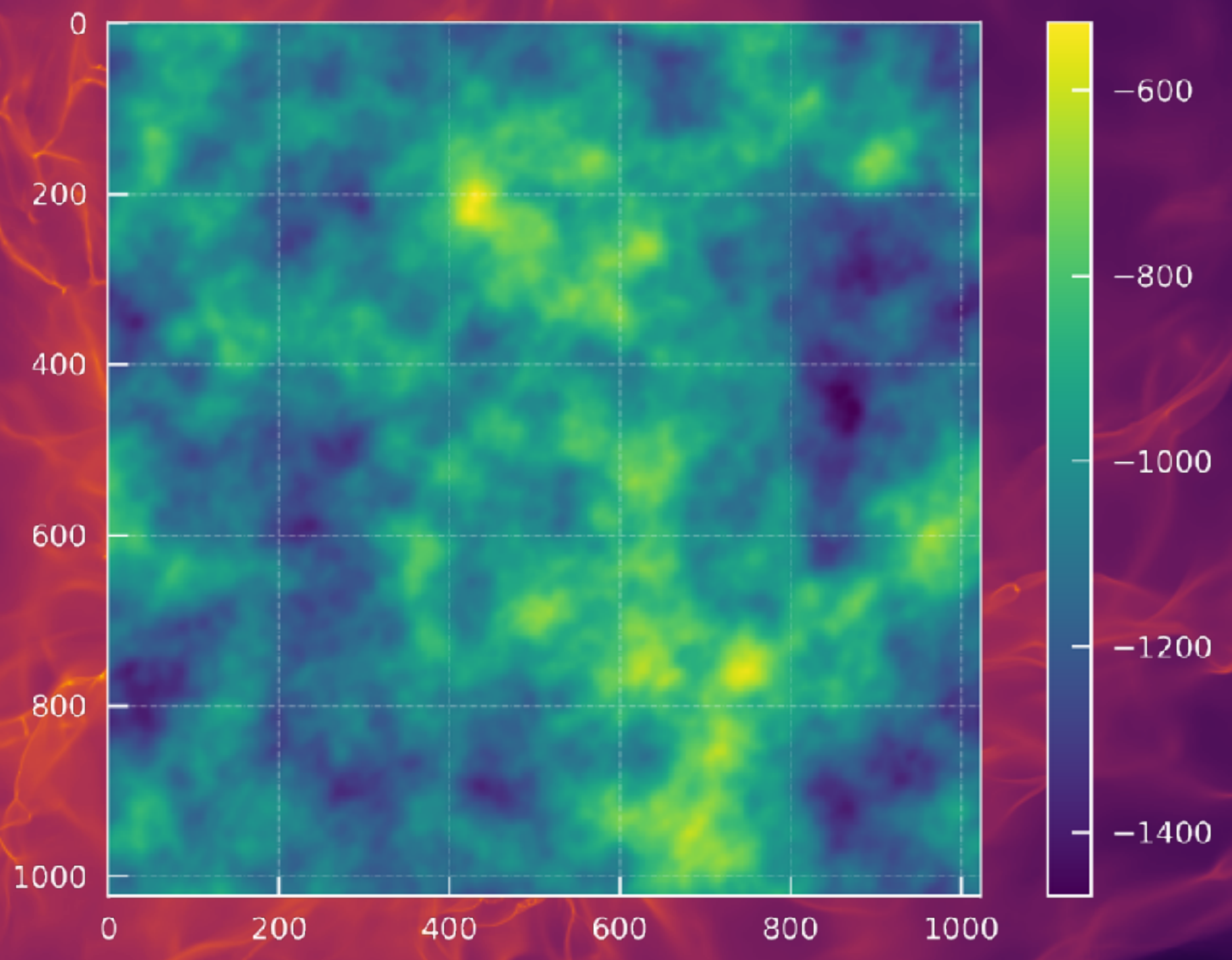
LIMITS OF THE FOURIER MODULUS



Coherent



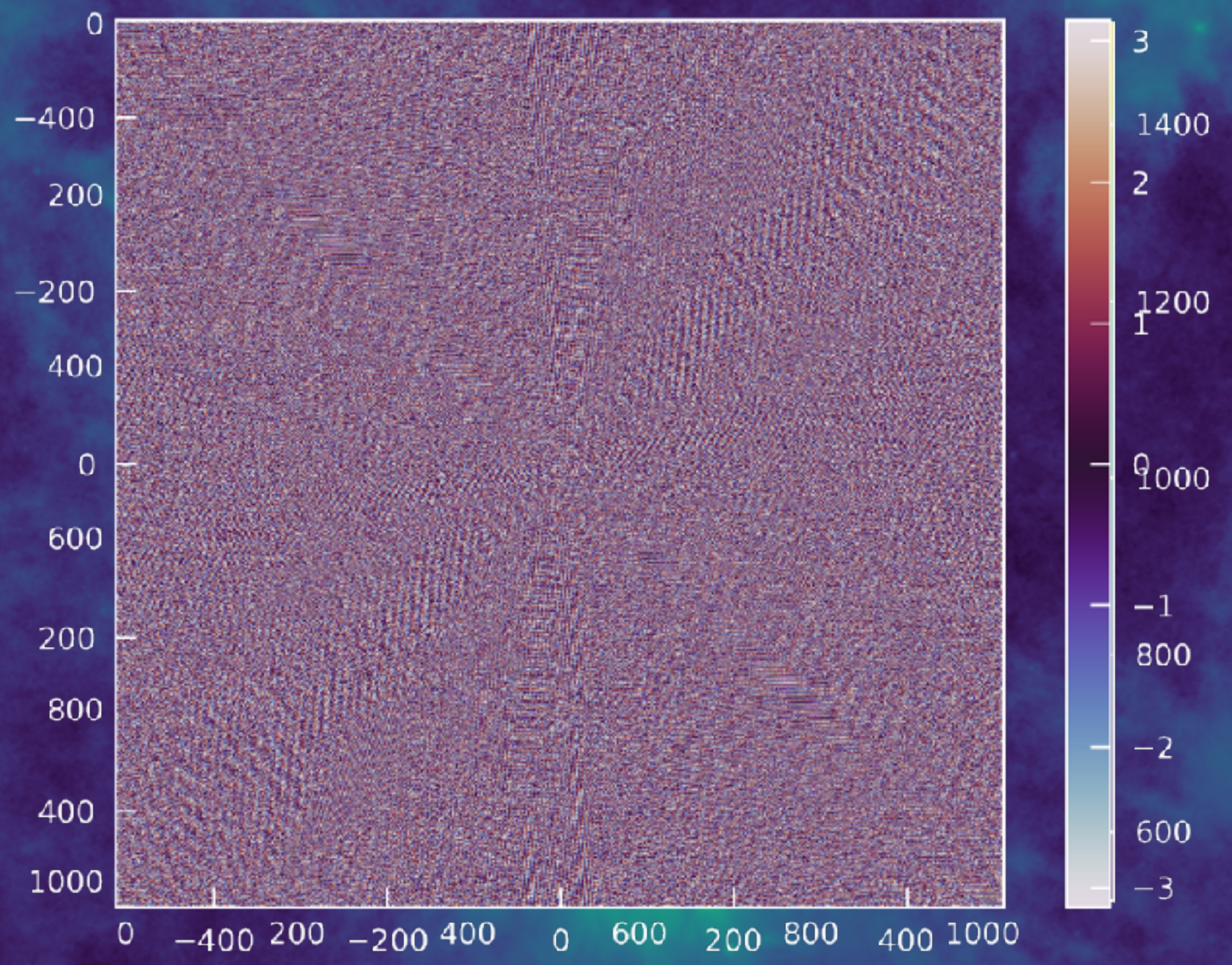
Fourier modulus



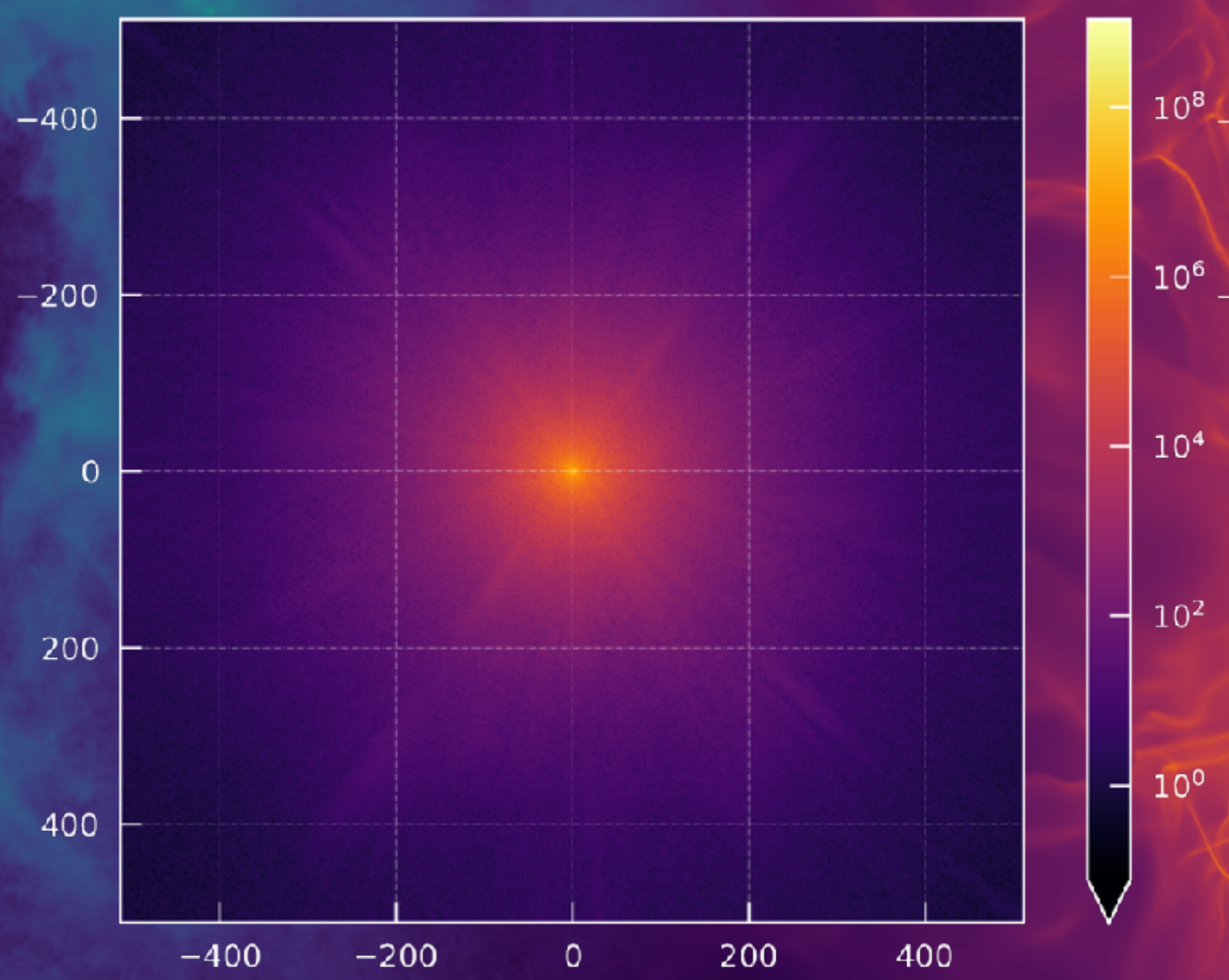
Gaussian

WHERE IS COHERENT INFORMATION?

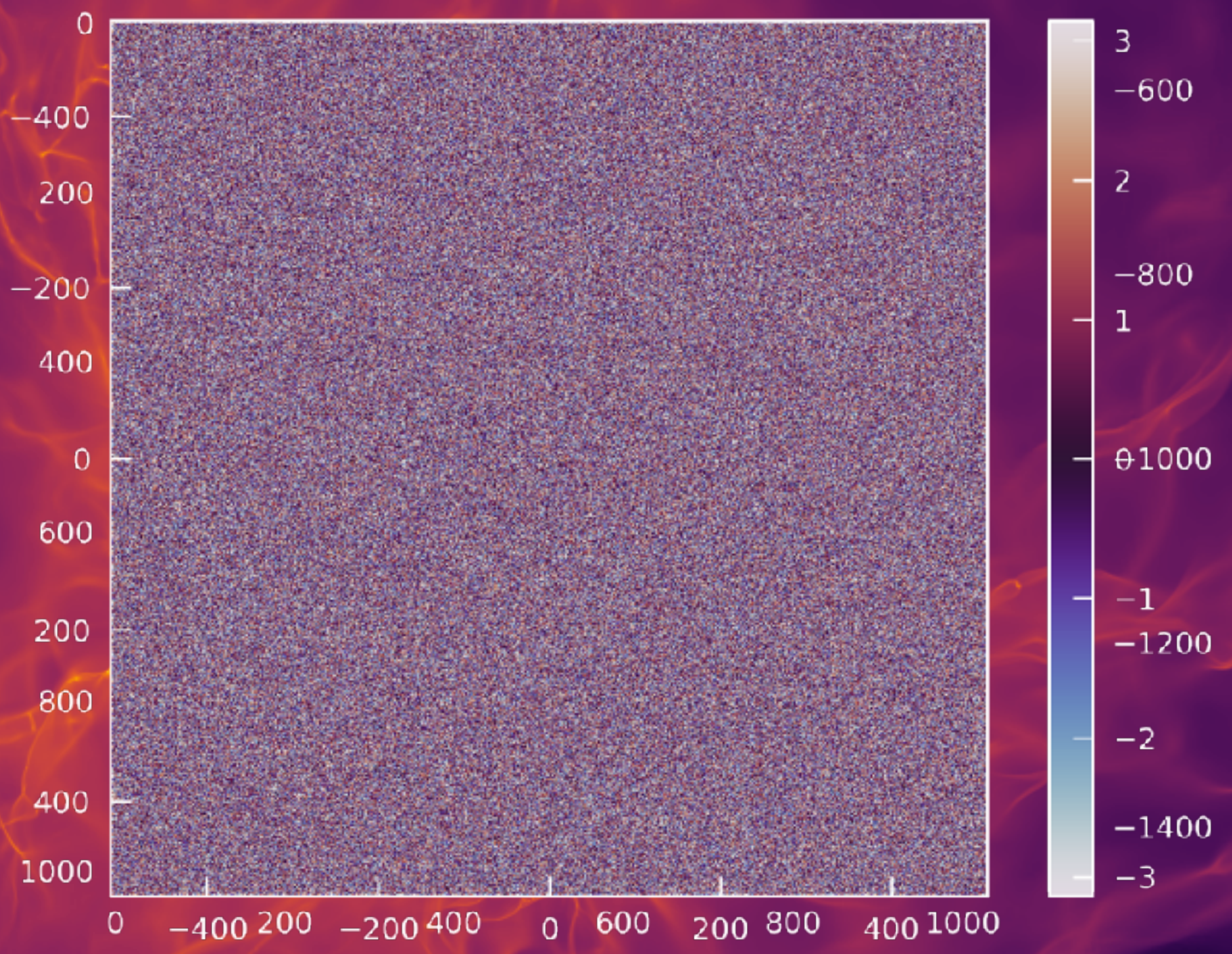
LIMITS OF THE FOURIER MODULUS



Coherent phase



Fourier modulus



Gaussian phase

WHY IS NONLINEARITY A HURDLE?

Nonlinear dynamics

↓

Coupling between scales

↓ ↑

Coherent non-Gaussian structures

HOW TO CATCH SCALE INTERACTIONS?

one scale $\vec{k}$ only $\quad \left|\hat{I}(\vec{k})\right| = \left\|\hat{I} \cdot \delta_{\vec{k}}\right\|_2 = \left\|I \star e^{i\vec{k}\cdot\vec{x}}\right\|_2$

two scales $\vec{k}_1 \neq \vec{k}_2 \quad \left\|I \star e^{i\vec{k}_1\cdot\vec{x}} \star e^{i\vec{k}_2\cdot\vec{x}}\right\|_2 \longrightarrow$ 0 just like $\langle \cos(x), \cos(2x) \rangle$

Idea: apply a **nonlinearity**

WHY IS NONLINEARITY A HURDLE?

Nonlinear dynamics → Coupling between scales → Nonlinear summary stats.

Coupling between scales ⇅ Coherent non-Gaussian structures

Nonlinear dynamics

Nonlinear summary stats.

Coupling between scales

Coherent non-Gaussian structures

HOW TO CATCH SCALE INTERACTIONS?

THE WAVELET SCATTERING TRANSFORM *(Mallat+, 2010+)*

$$\left\| I \star e^{i \vec{k}_1 \cdot \vec{x}} \star e^{i \vec{k}_2 \cdot \vec{x}} \right\|_2$$

↓

Apply a **nonlinearity**

$$\left\| \left| I \star e^{i \vec{k}_1 \cdot \vec{x}} \right| \star e^{i \vec{k}_2 \cdot \vec{x}} \right\|_2$$

↓

Stability & sparsity

$$\left\| \left| I \star \psi_{j_1,\theta_1} \right| \star \psi_{j_2,\theta_2} \right\|_2$$

↓

$$\boxed{\left\| \left| I \star \psi_{j_1,\theta_1} \right| \star \psi_{j_2,\theta_2} \right\|_1}$$

HOW TO CATCH SCALE INTERACTIONS?

THE REDUCED WAVELET SCATTERING TRANSFORM *(Allys+, 2019)*

$$\left\| \left| I \star \psi_{j_1,\theta_1} \right| \star \psi_{j_2,\theta_2} \right\|_1$$

↓

$$\log_2\left[S_2(j_1,\theta_1,j_2,\theta_2)\right] = \hat{S}_2^{iso1}(j_1,j_2) + \hat{S}_2^{iso2}(j_1,j_2)\cdot\cos\left[2\left(\theta_2-\theta_1\right)\right] + \ldots$$

Fully isotropic scale interaction

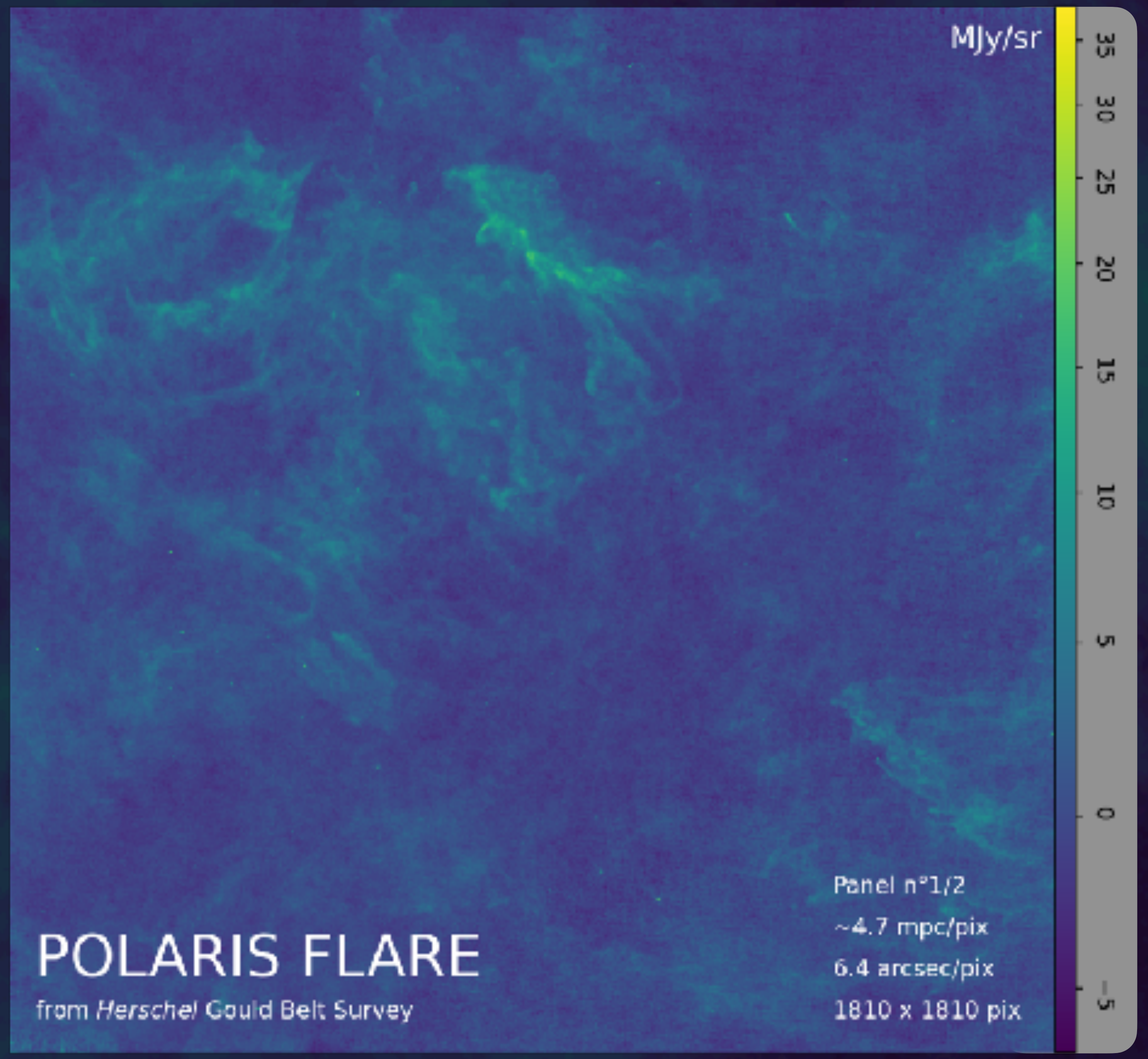
dependance on scales alignment

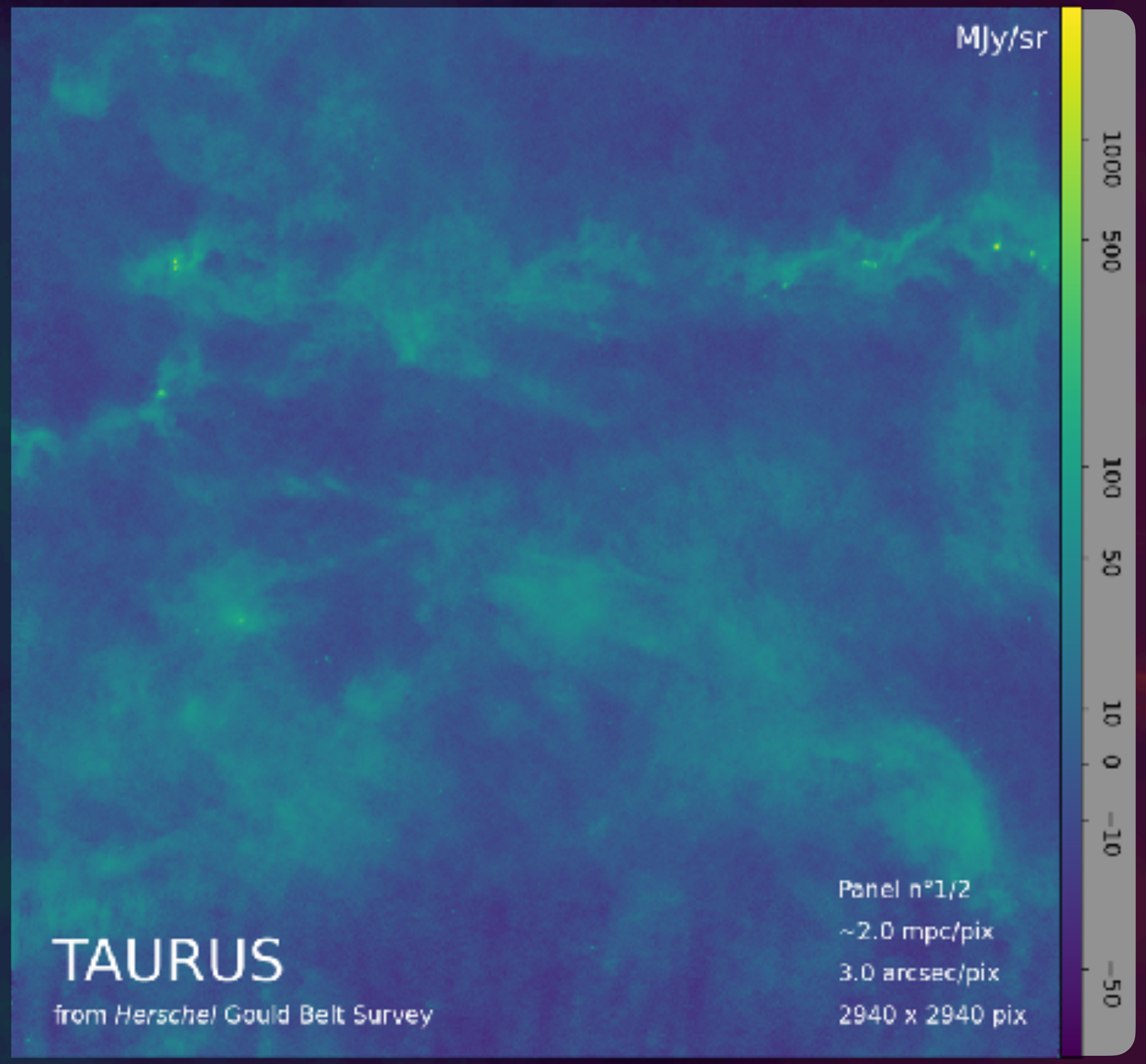
- basically a filament detector

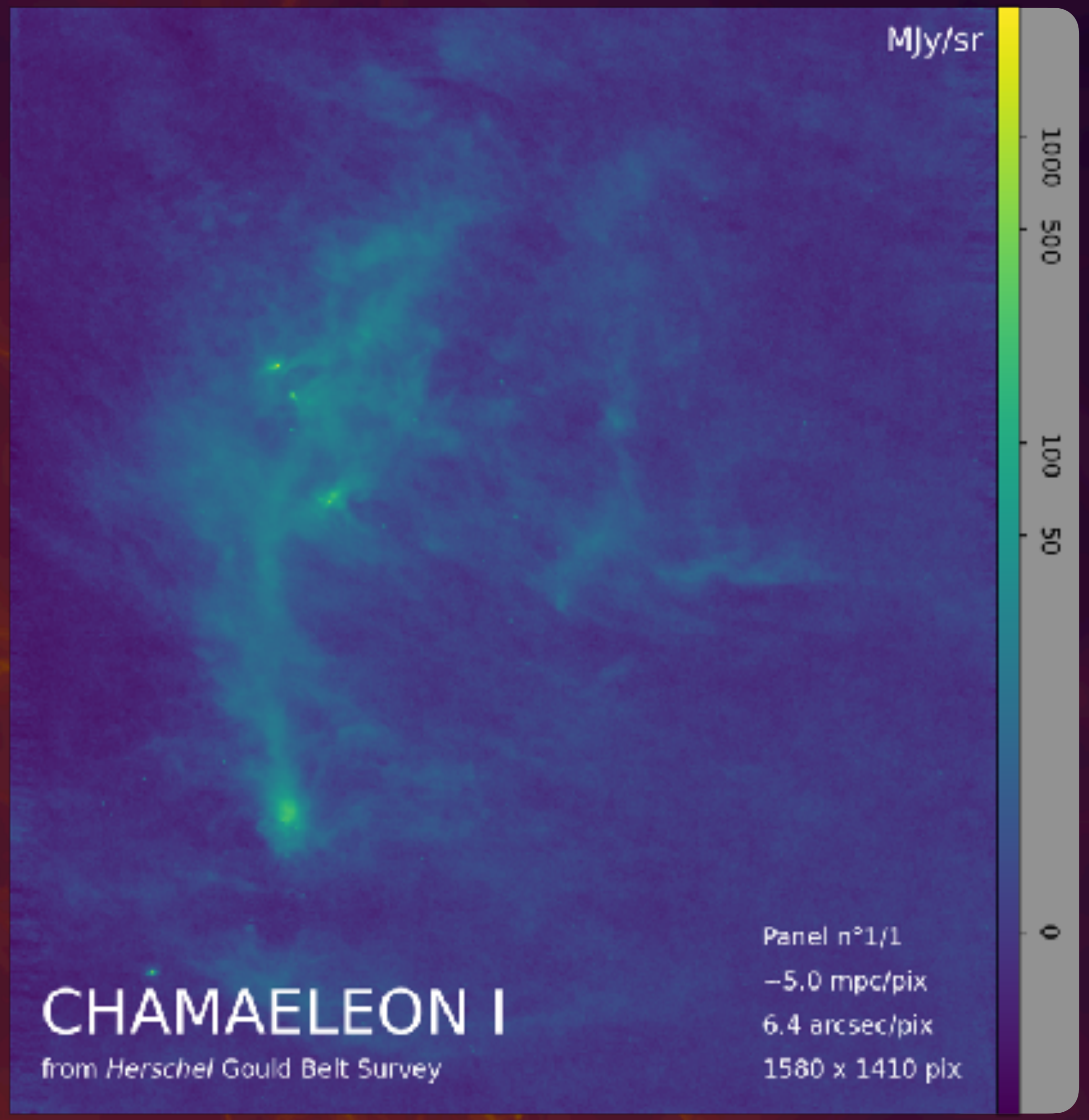
APPLICATION

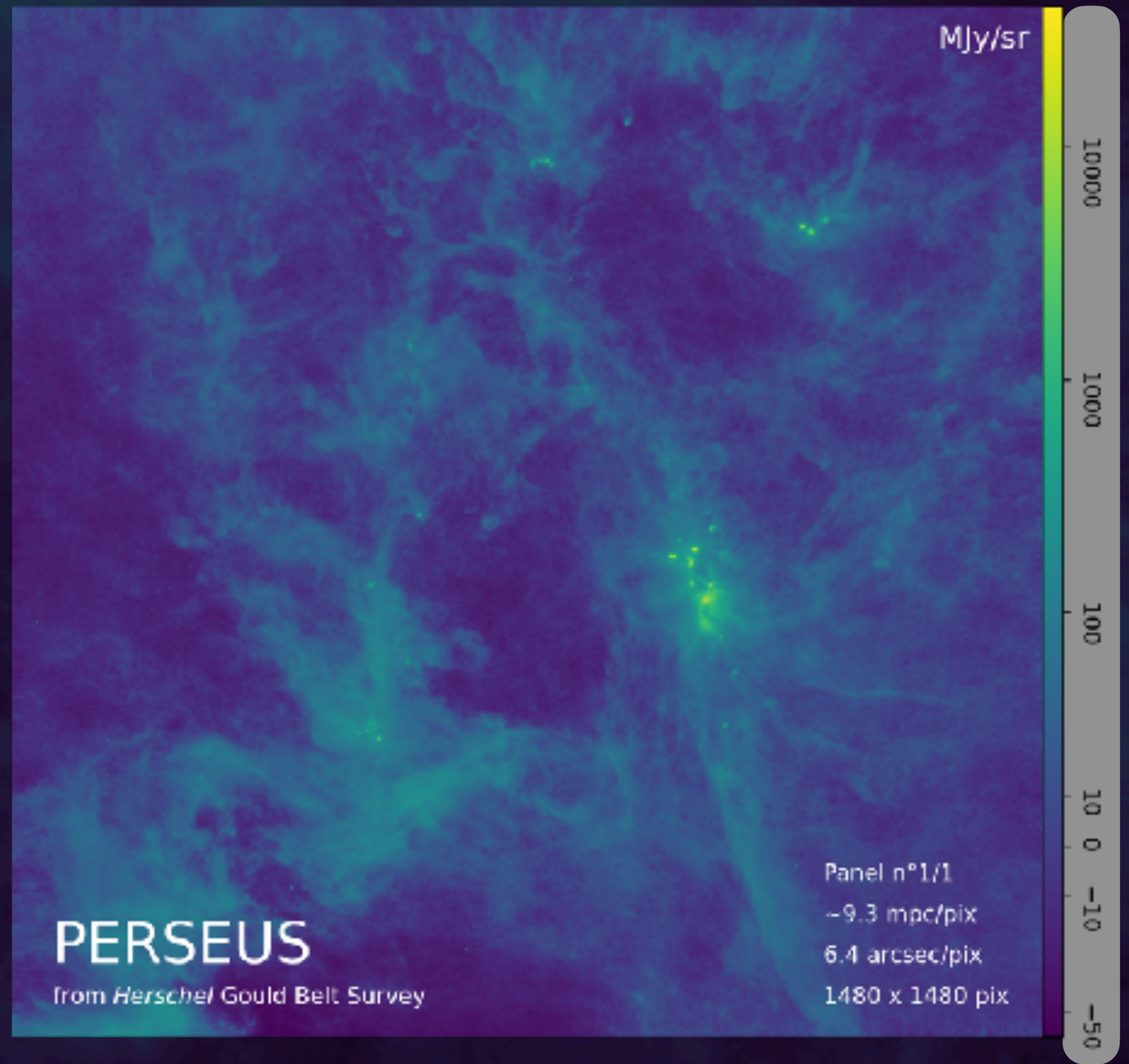
OBSERVATIONAL DATA

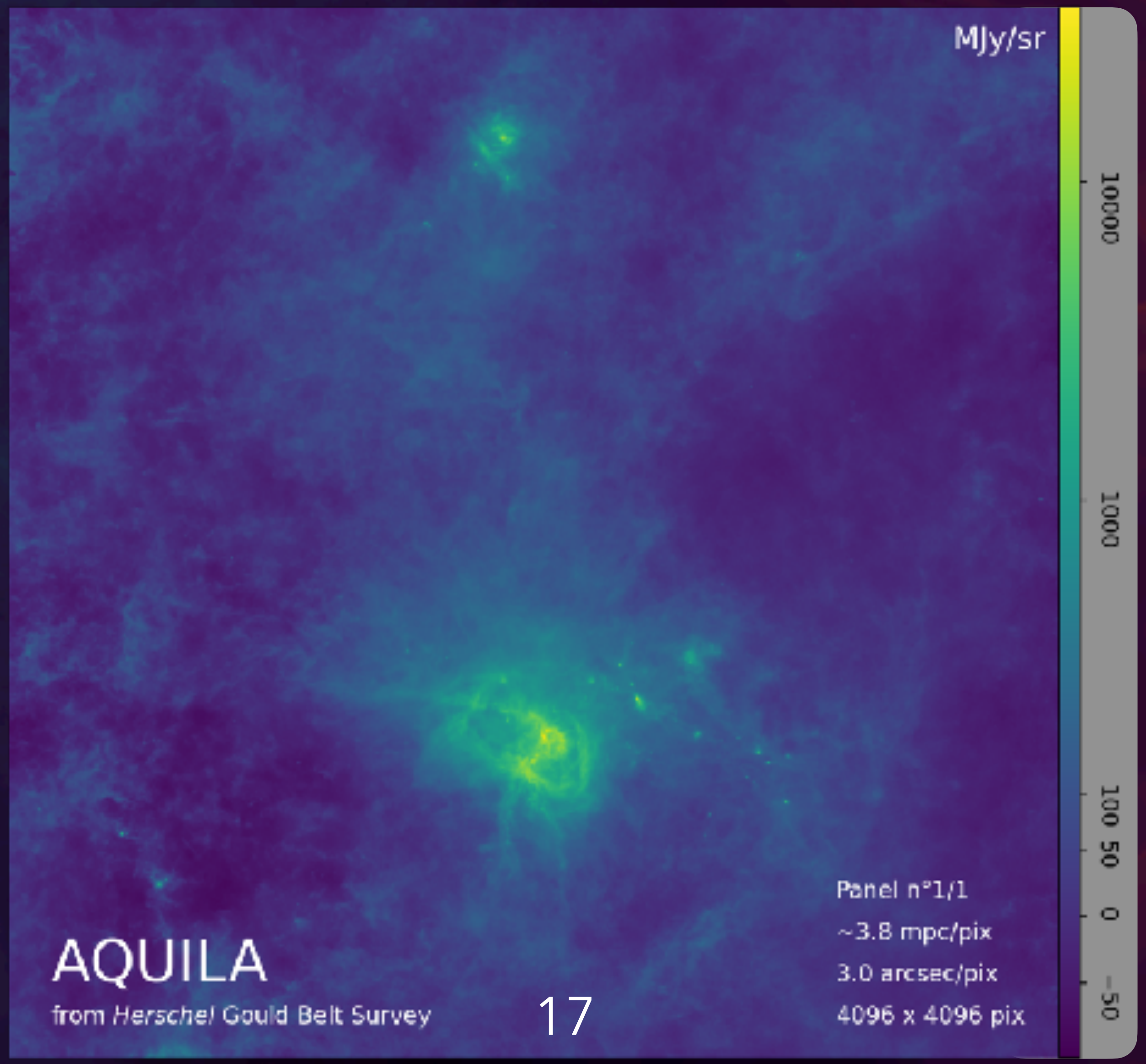
Herschel: PACS detector at 160 μm, ~13″ res., + estimated col. density

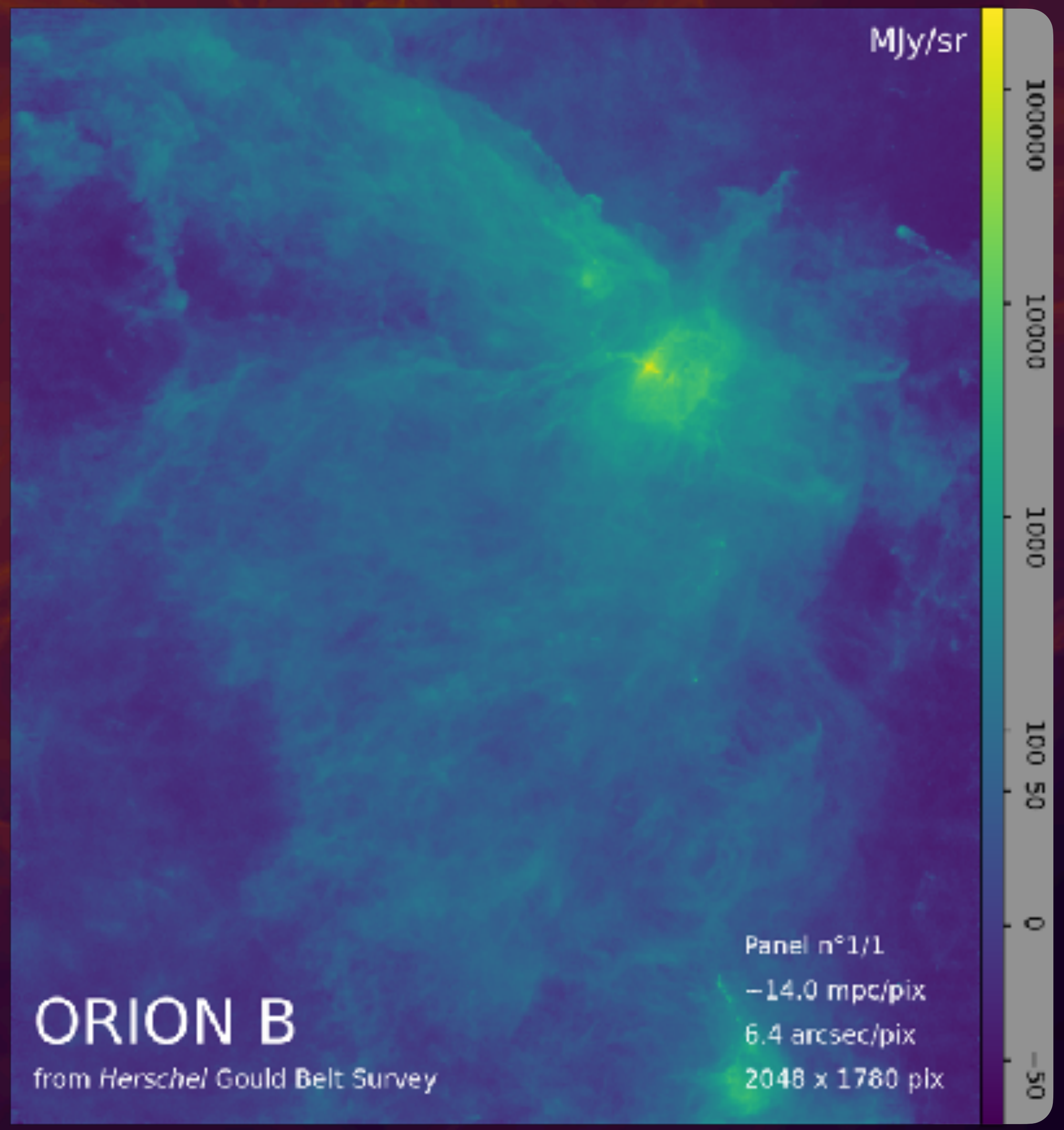




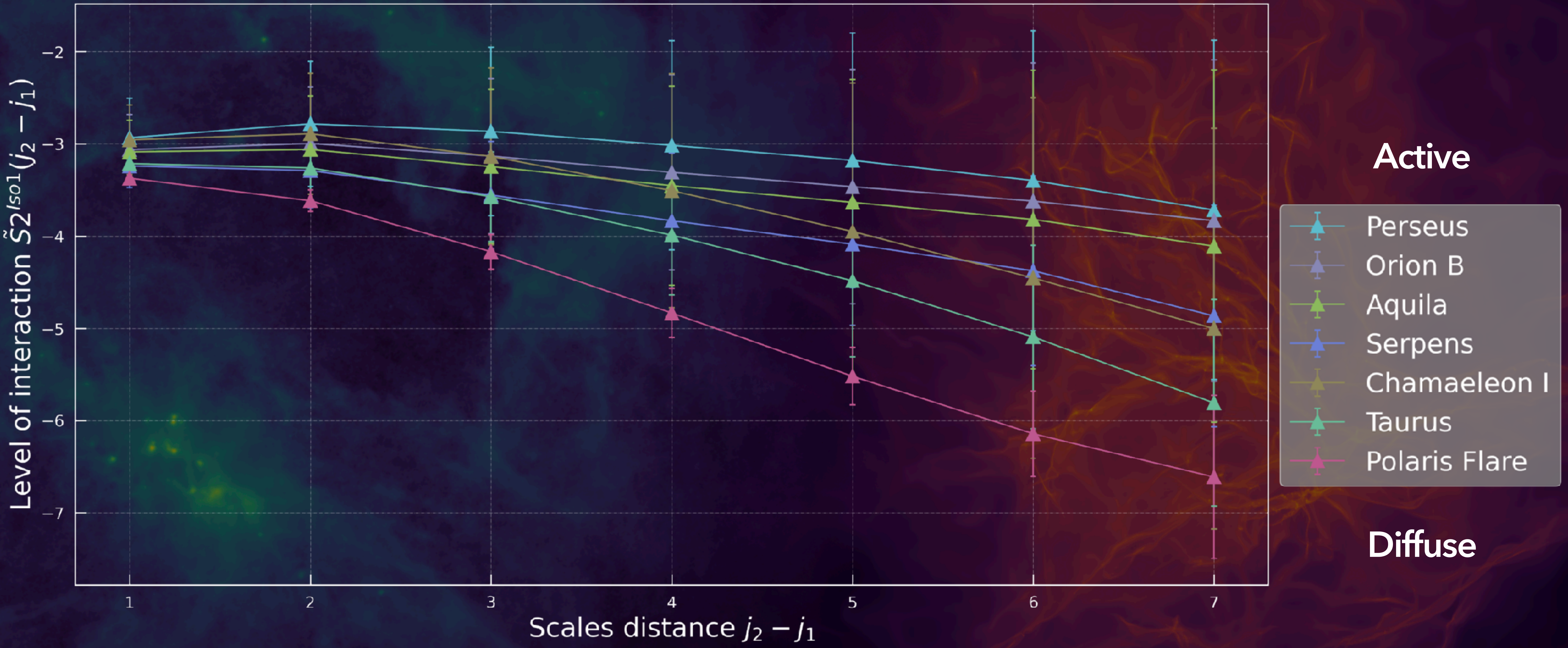








CAN WE RETRIEVE THIS DIFFUSE/ACTIVE SIGNATURE?

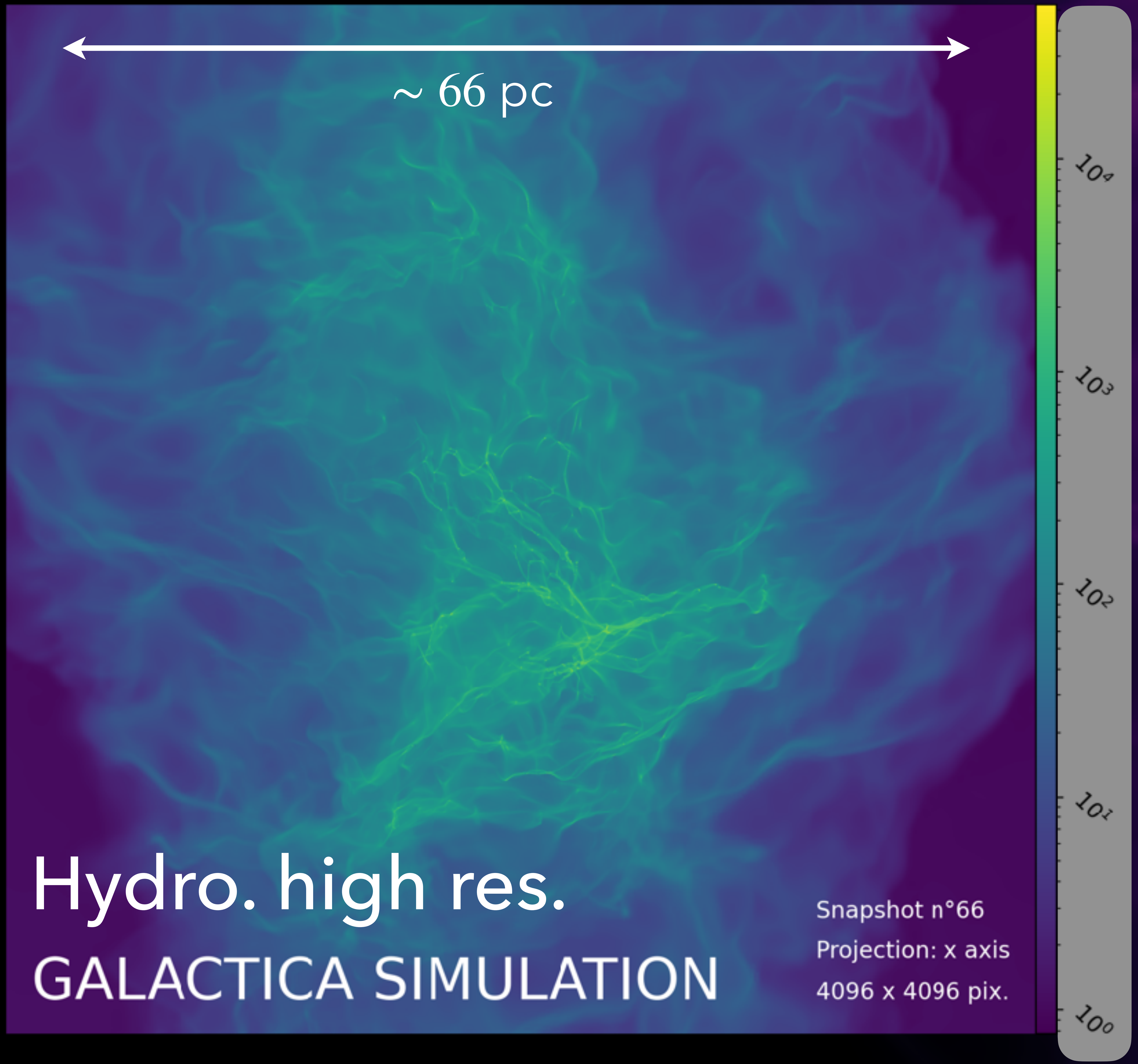


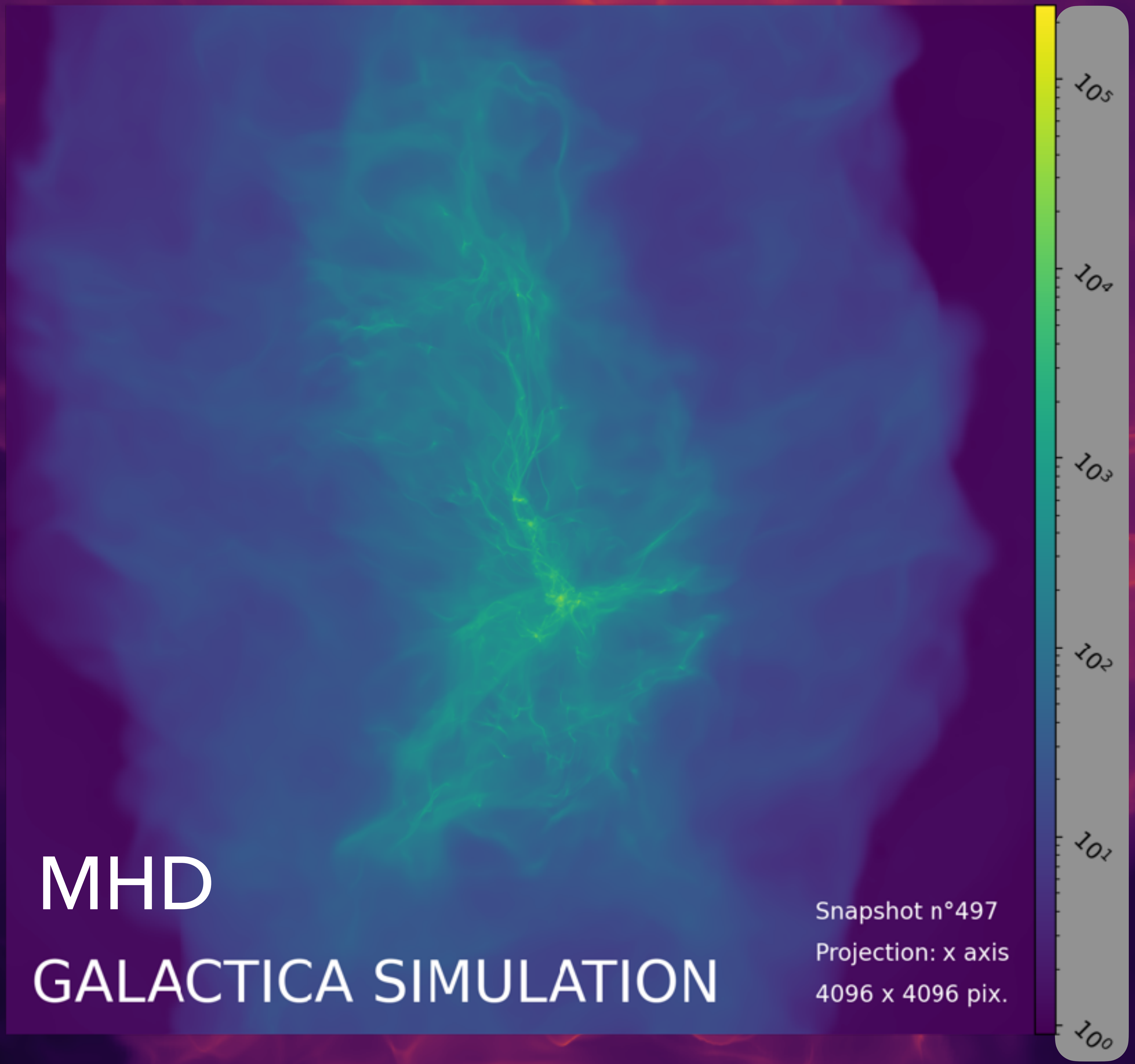
Active

Diffuse

DENSE SIMULATION DATA

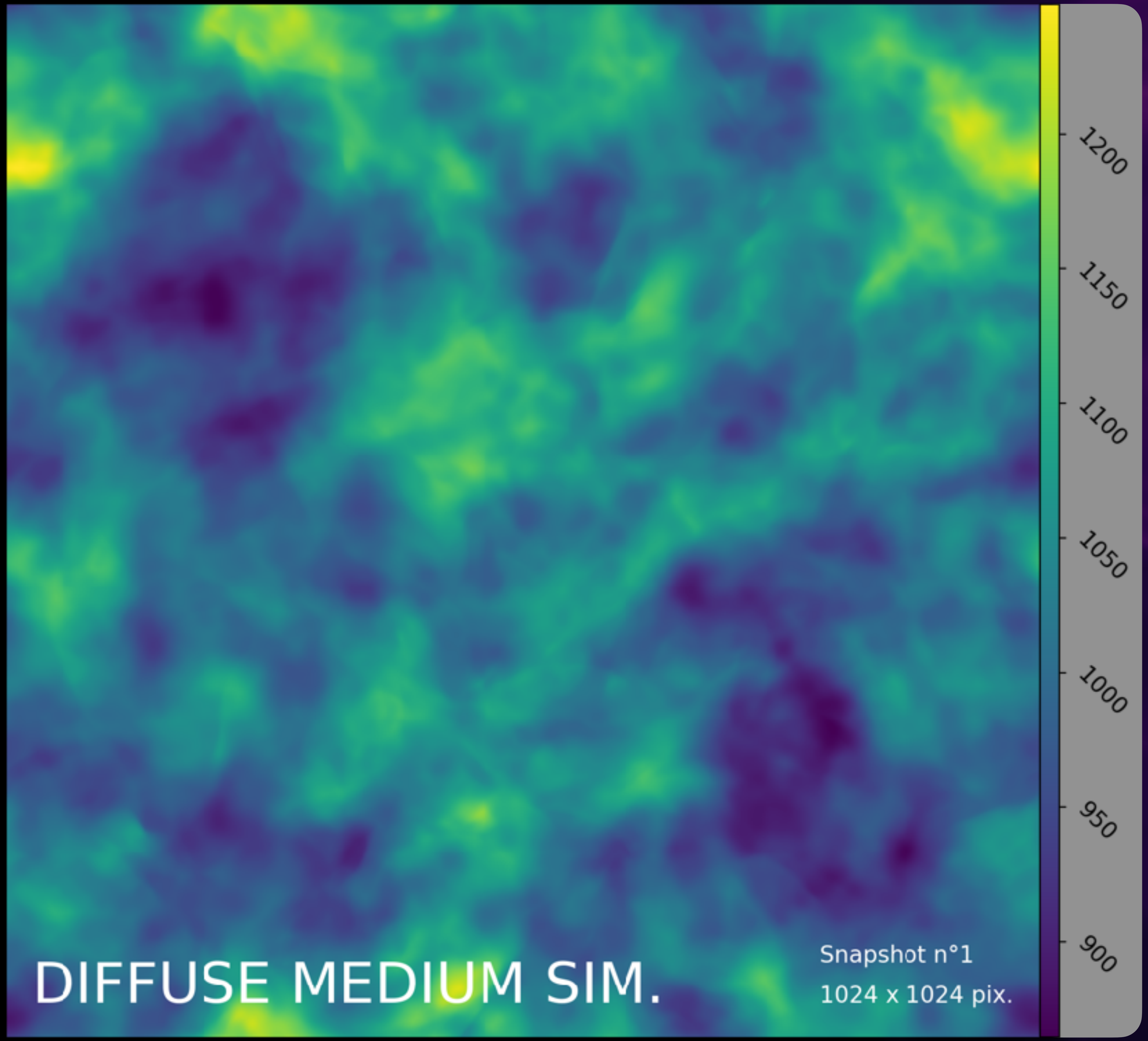
Orion Cloud – Ntormousi & Hennebelle 2019 – Galactica database | gravitational collapse & star form. | AMR

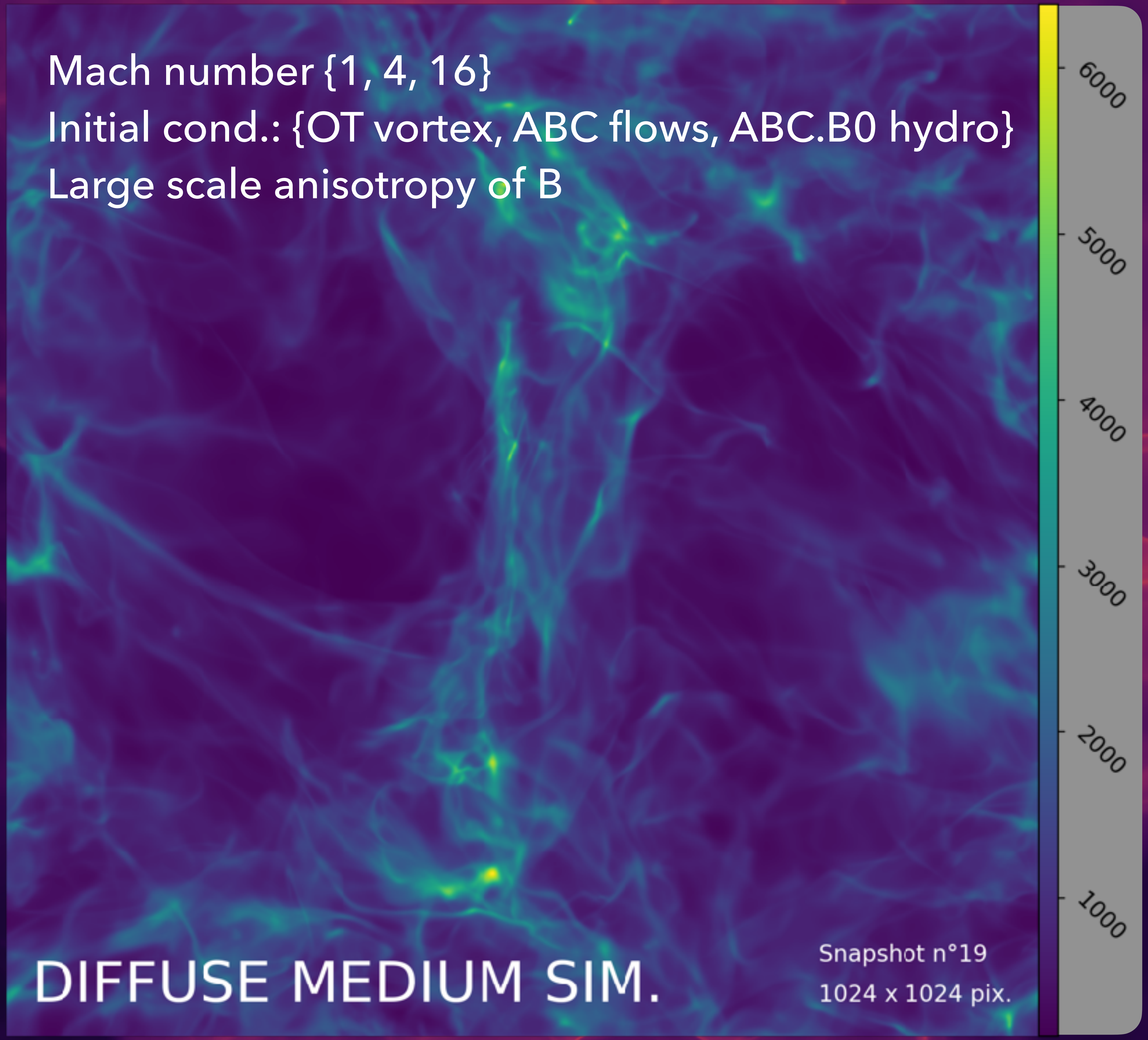




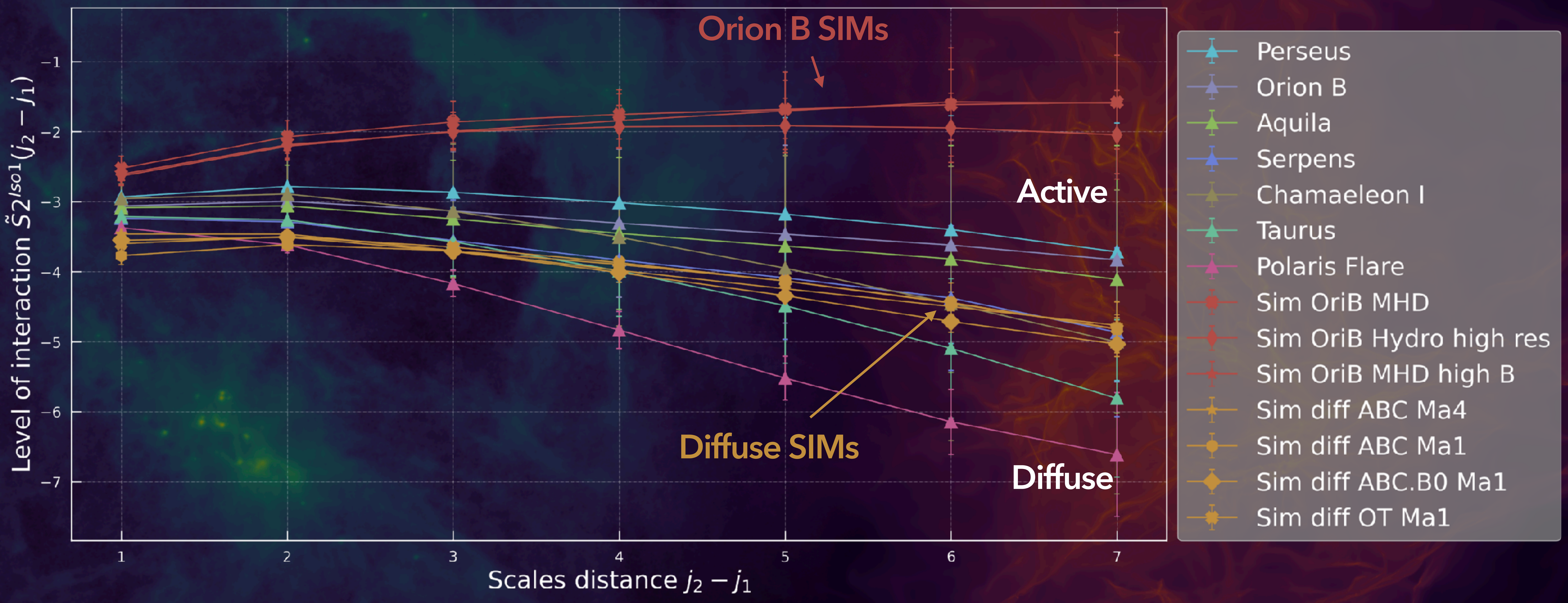
DIFFUSE SIMULATION DATA

P. Lesaffre – MHD Diffuse ISM | strongly mag. | PBC | dimensionless



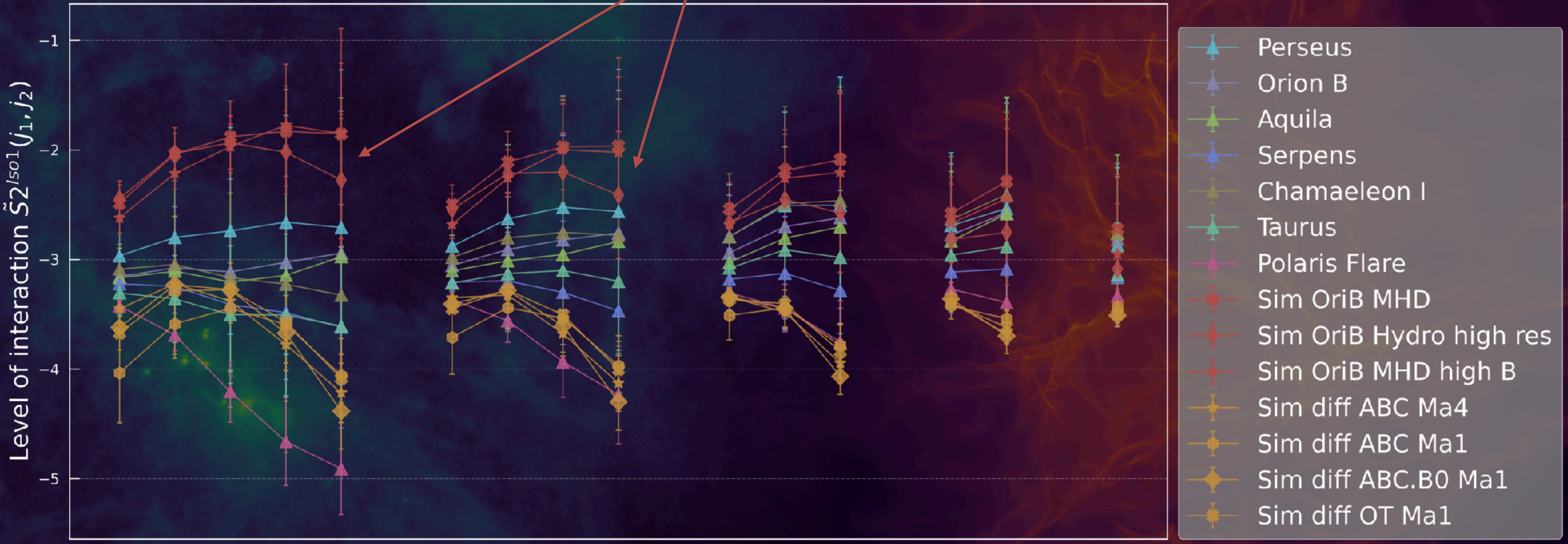


COMPARISON WITH SIMULATIONS



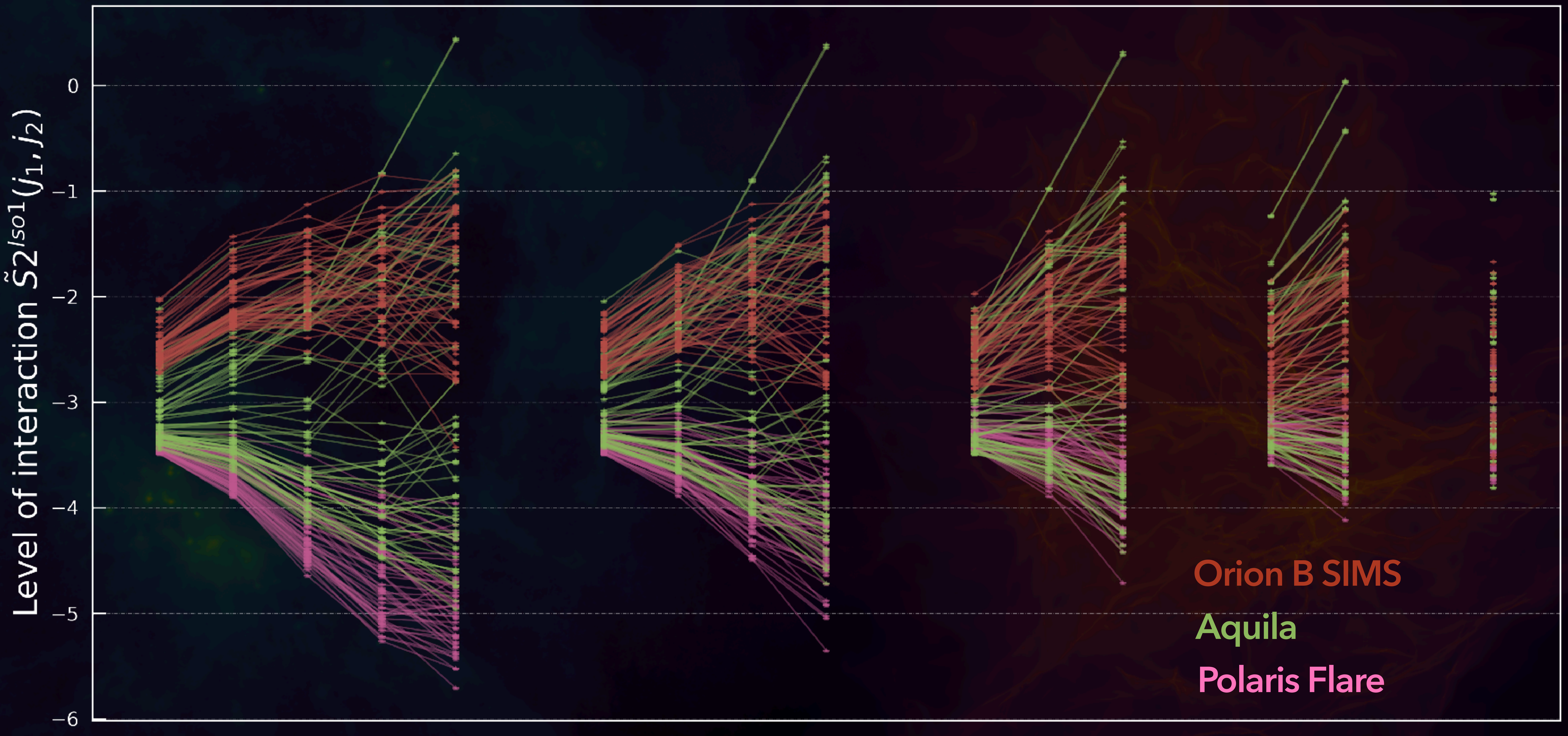
COMPARISON WITH SIMULATIONS

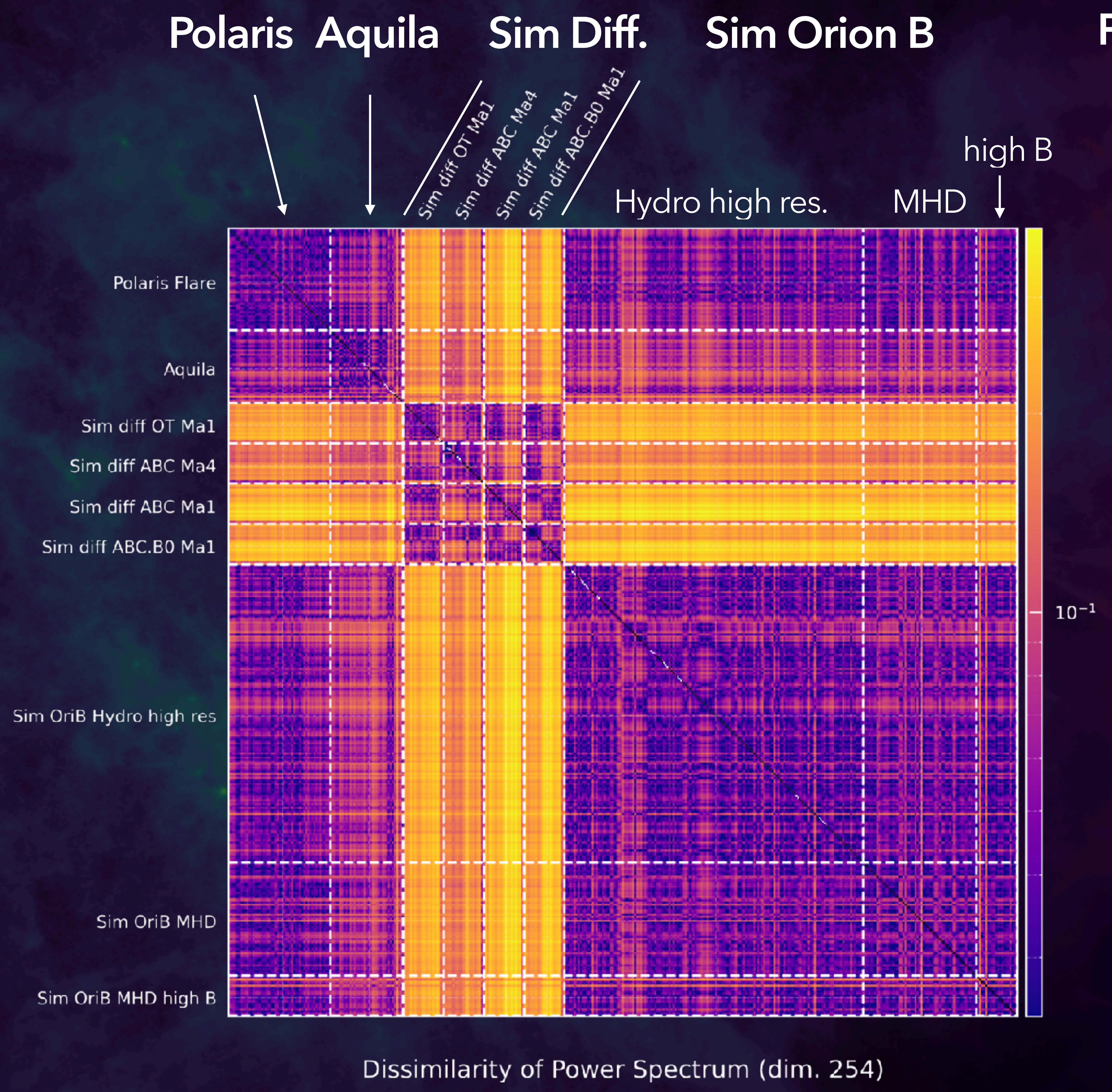
Pure hydro (♦) ≠ MHD (✖) and MHD high B (★)

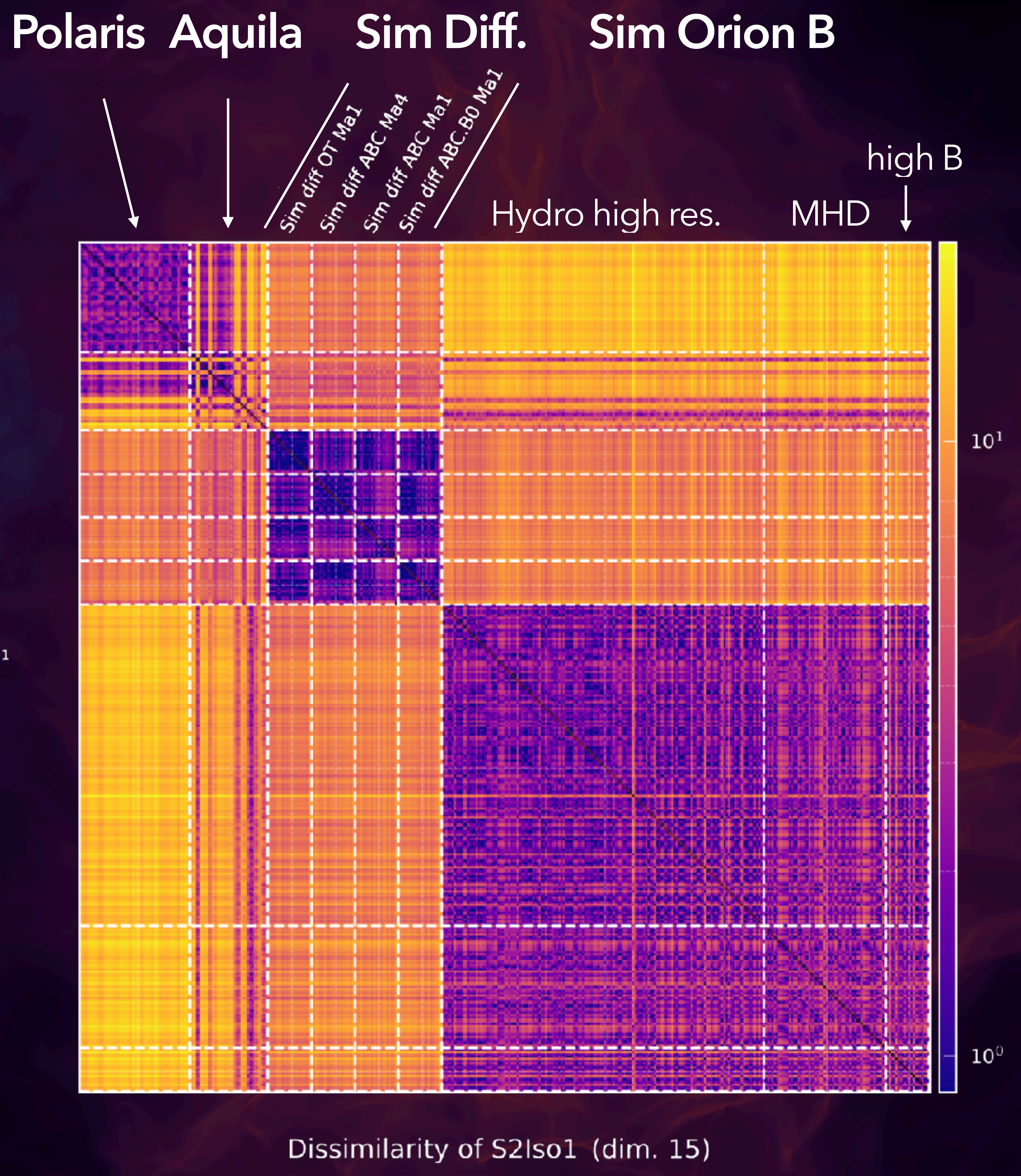


COMPARISON WITH SIMULATIONS

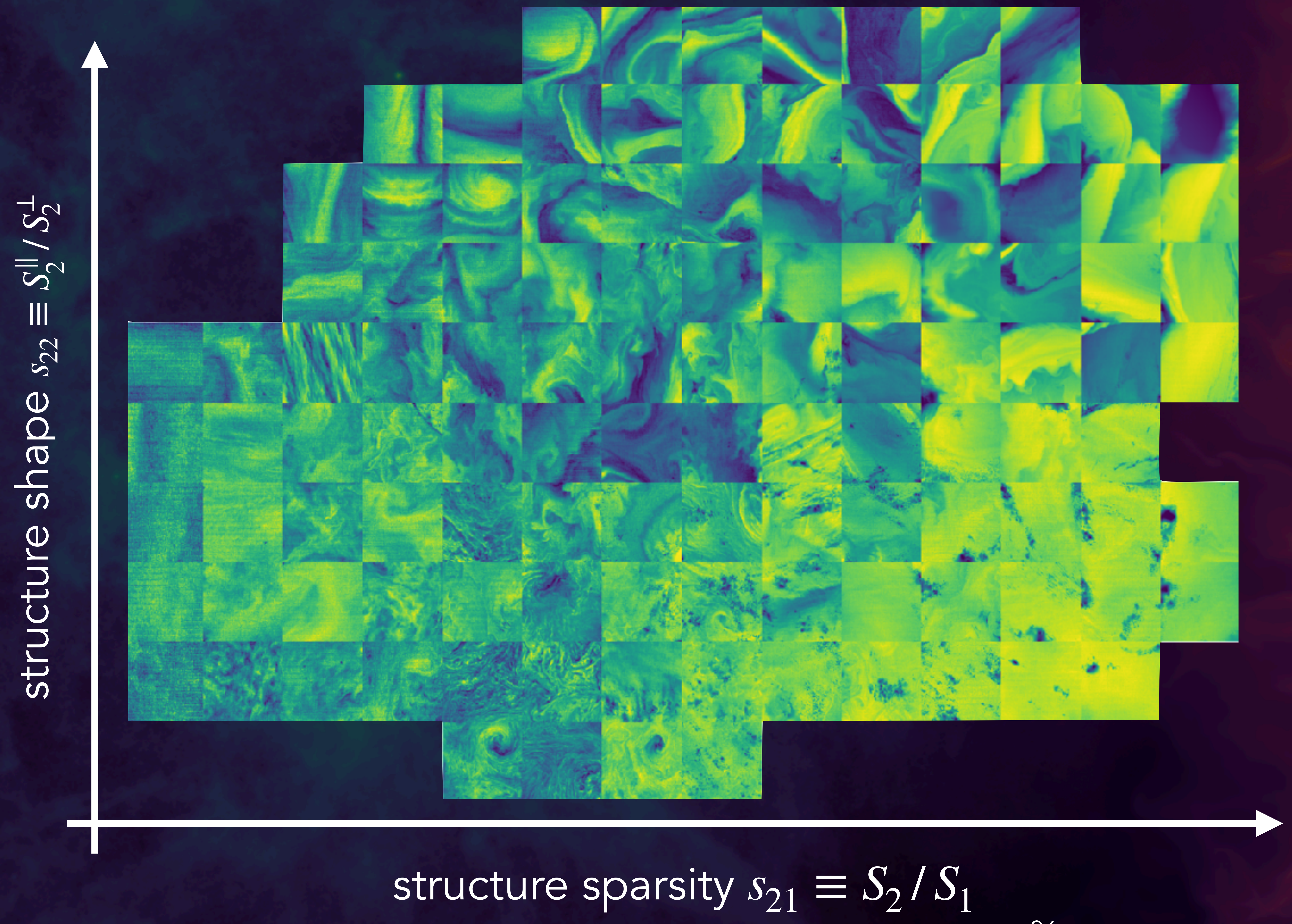
ANALYSIS OF THE STATS DISPERSION




Polaris
Aquila
Sim Diff.
Sim Orion B
Sim diff OT Ma1
Sim diff ABC Ma4
Sim diff ABC Ma1
Sim diff ABC.B0 Ma1
Hydro high res.
MHD
high B
Polaris Flare
Aquila
Sim diff OT Ma1
Sim diff ABC Ma4
Sim diff ABC Ma1
Sim diff ABC.B0 Ma1
Sim OriB Hydro high res
Sim OriB MHD
Sim OriB MHD high B
10^{-1}
Dissimilarity of Power Spectrum (dim. 254)


Polaris
Aquila
Sim Diff.
Sim Orion B
Sim diff OT Ma1
Sim diff ABC Ma4
Sim diff ABC Ma1
Sim diff ABC.B0 Ma1
Hydro high res.
MHD
high B
10^{1}
10^{0}
Dissimilarity of S2Iso1 (dim. 15)

EXAMPLE OF TEXTURE MAPPING



Cheng & Ménard, 2021

Sea temperature fields

CONCLUSION

- The nonlinear ISM dynamics generates **nonGaussian structures**
  - the Power Spectrum is far to fully describe them (degeneracies)
- The RWST are powerful **non-Gaussian summary** statistics
  - breaks power spectrum degeneracies
  - stability & reduces drastically the dimension (≤ 100 coefficients)
- The dispersion of the stats. is of importance to build a comparison
  - simple unsupervised techniques (PCA) already show interesting structures
  - identify a few numbers of relevant & interpretable features for low dim mapping (in progress)

THANKS!

Pablo RICHARD - 24/10/2022