What do the world's largest simulations of cold phase interstellar medium turbulence tell us?

Luncheon Talk, Harvard University

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In collaboration: Amitava Bhattacharjee (Princeton), Christoph Federrath (ANU), Ralf Klessen (UH) & Salvatore Cielo (LRZ)

Beattie+2025 (*Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

Beattie & A. Bhattacharjee (*submitted PRL*). Scale-dependent alignment in compressible magnetohydrodynamic turbulence

The cold ISM: A supersonic laboratory for interesting nonlinear physics

- ~ 20% MW ISM gas is molecular hydrogen, organised into MCs (low-volume filling ~ 1-2%).

- cold, $T \sim 10\,K$, c_s is low (and $t_{\text{cool}} \ll t_{\text{nl}}$), **approximately isothermal**

- $\sigma_v/c_s = \mathcal{M} \sim 10$, **supersonic (compressible), $\text{Re} \sim 10^9$**

- $L \sim 10\,\text{pc} \implies \tau = L/\sigma_v \sim \mathcal{O}(\text{Myr})$

- $n \sim 10^3 - 10^{7+}$, **huge density contrasts.**

- **weakly bounded (not virialised) by their own self-gravity** $\alpha_{\text{vir}} = 2\,|E_{\text{kin}}|/|E_{\text{grav}}| > 2.$

- **threaded by dynamically important B fields, Ohmic $\text{Rm} \sim 10^{16}$.**

W3/W4/W5 MCs and star forming region complex.
ESA/Herschel/NASA/JPL-Caltech CC BY-SA 3.0 IGO; Acknowledgement: R. Hurt (JPL-Caltech).

Krumholz & McKee (2005); Federrath & Klessen (2012); Tritsis+(2016); Xu & Lazarian (2016); Soler & Hennebelle (2017); Squire & Hopkins (2017); Mocz & Burkhart (2018), Burkhart & Mocz (2018); Heyer+(2012); Tritsis+(2018); Hu+(2019); Heyer+(2020); Krumholz+(2020); Beattie & Federrath (2020); Beattie+(2020); Körtgen & Soler (2020); Skalidis & Tassis (2020); Federrath+(2021); Bukhart (2021); Barreto-Mota+(2021); Hopkins+(2022); Beattie+(2022); Fielding+(2022); Sampson+ (2022); Kriel+(2022); Galishnikova+(2022); Beattie+(2023)

The cold ISM: A supersonic laboratory for interesting nonlinear physics

- ~ 20% MW ISM gas is molecular hydrogen, organised into MCs (low-volume filling ~ 1-2%).
- cold, $T \sim 10\,K$, c_s is l... **isothermal**
- $\sigma_v/c_s = \mathcal{M} \sim 10$, **sup**
- $L \sim 10\,\mathrm{pc} \implies \tau =$
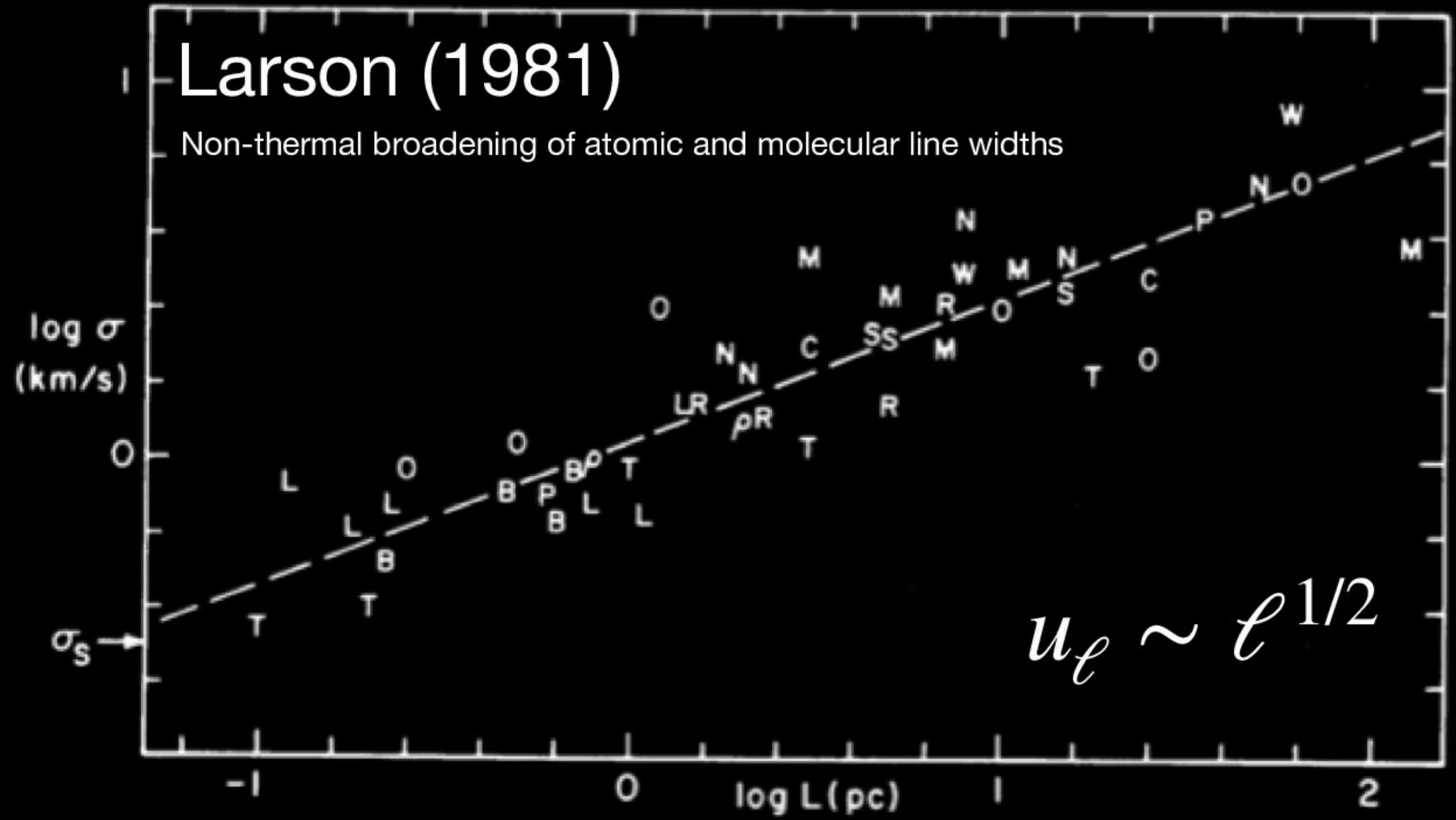- $n \sim 10^3 - 10^{7+}$, **huge**
- **weakly bounded (not** $\alpha_{\mathrm{vir}} = 2\,|E_{\mathrm{kin}}|/|E_{\mathrm{grav}}$
- **threaded by dynamic** $\underline{\mathrm{Rm} \sim 10^{16}}$.

Larson (1981)

Non-thermal broadening of atomic and molecular line widths

$\log \sigma$ (km/s)

$\log L\,(\mathrm{pc})$

$u_\ell \sim \ell^{1/2}$

Why should astrophysicists care — star formation?

Sink particle ∝ stellar IMF

Legend:
- N1 $(N_{sink} = 987) : \Gamma = -1.20^{+0.23}_{-0.27}$
- N2 $(N_{sink} = 926) : \Gamma = -3.07^{+0.67}_{-0.77}$
- Salpeter: $\Gamma = -1.35$

$$\mathscr{E}(k) \sim k^{-2}$$
$$\mathscr{E}(k) \sim k^{-1}$$

N_{sink} (vertical axis)

$m = M_{sink}/M_{cloud}$ (horizontal axis)
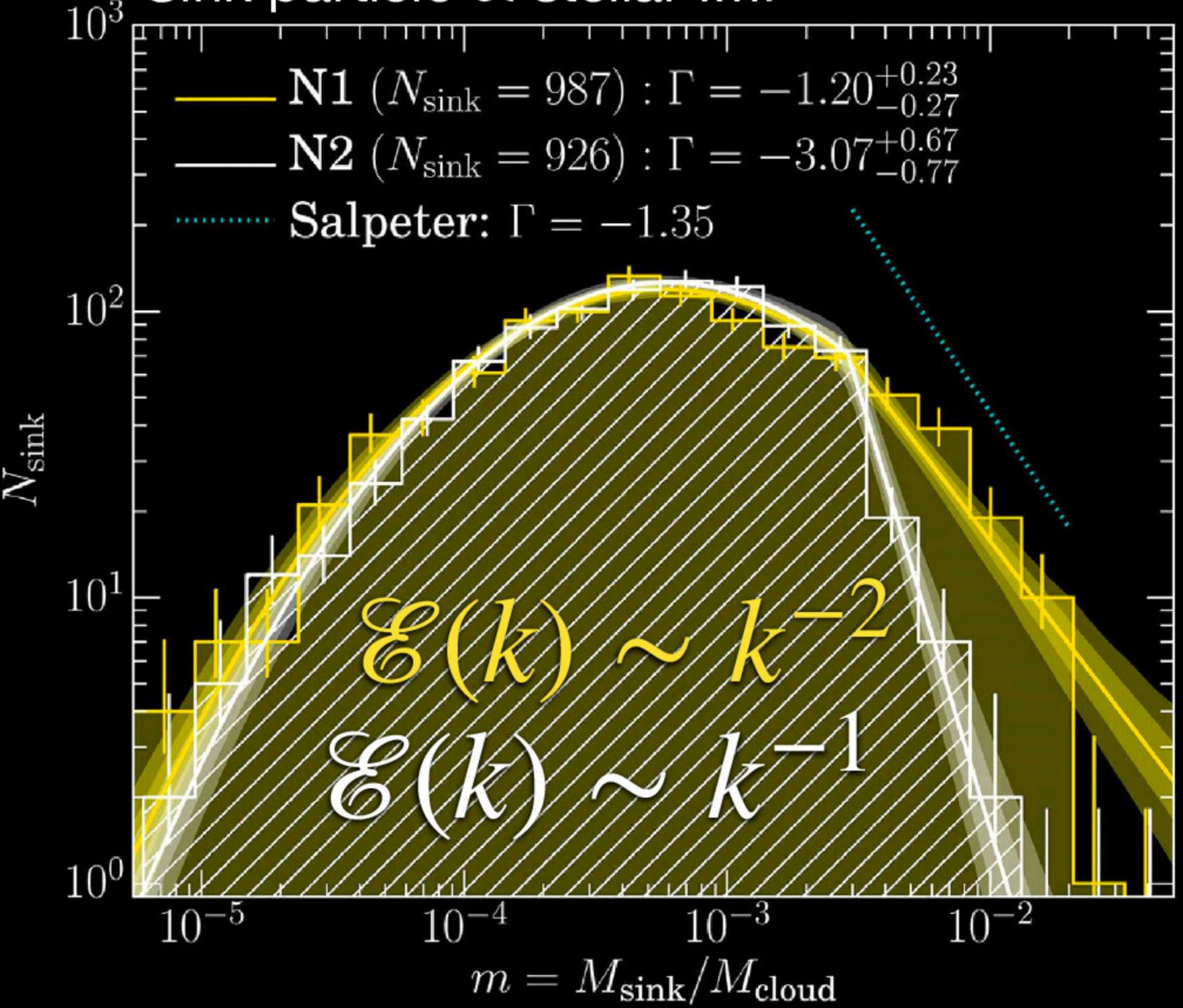
Nam, Federrath & Krumholz (2021)

$\delta u(\ell/L) > c_s$

ℓ_0

P_{therm}

$P_{turb} \propto 1/2 \nabla u^2$ $\ell_s \propto L \mathcal{M}^{-2}$

$\delta u(\ell_s/L) = c_s$
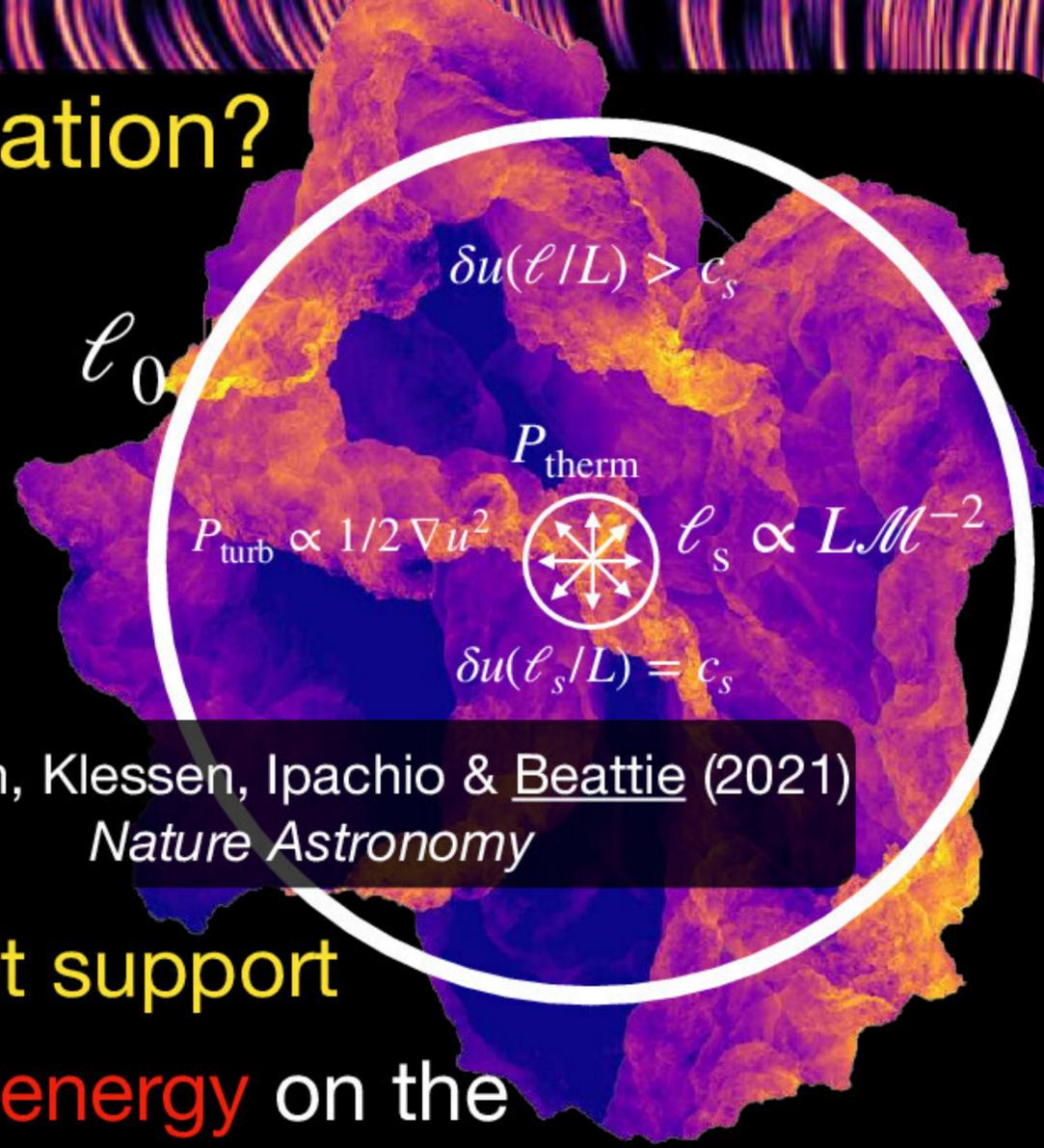
Federrath, Klessen, Ipachio & Beattie (2021)
Nature Astronomy

Turbulent support

More energy on the small-scales (more small-scale support) implies less high-mass stars formation
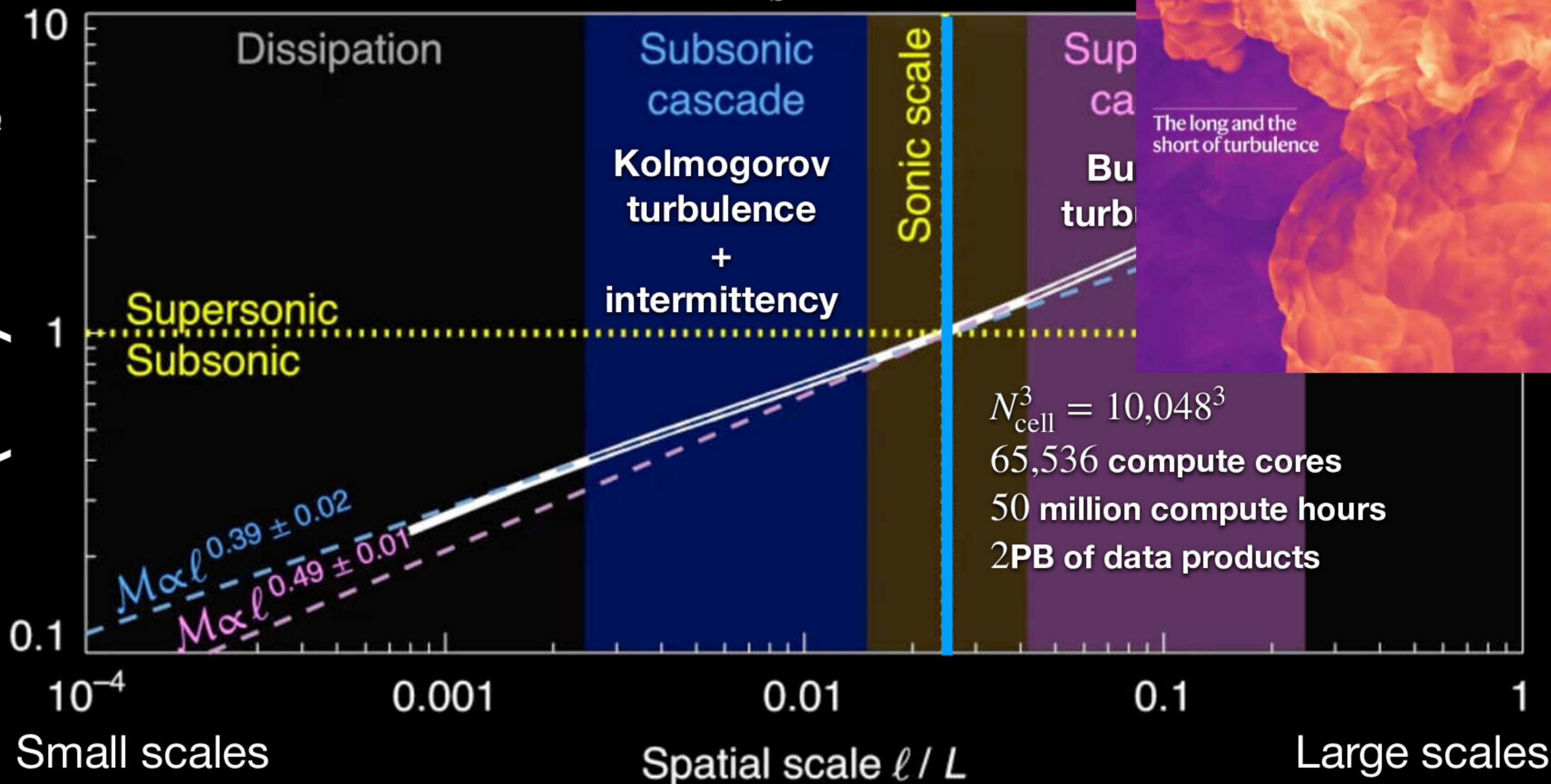
$$\mathbf{u} \cdot \nabla \otimes \mathbf{u} = \frac{1}{2} \nabla u^2 - \mathbf{u} \times \nabla \times \mathbf{u}$$

Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

The energy cascade in supersonic HD turbulence

Federrath, Klessen, Ipachio & Beattie (2021)
 Nature Astronomy
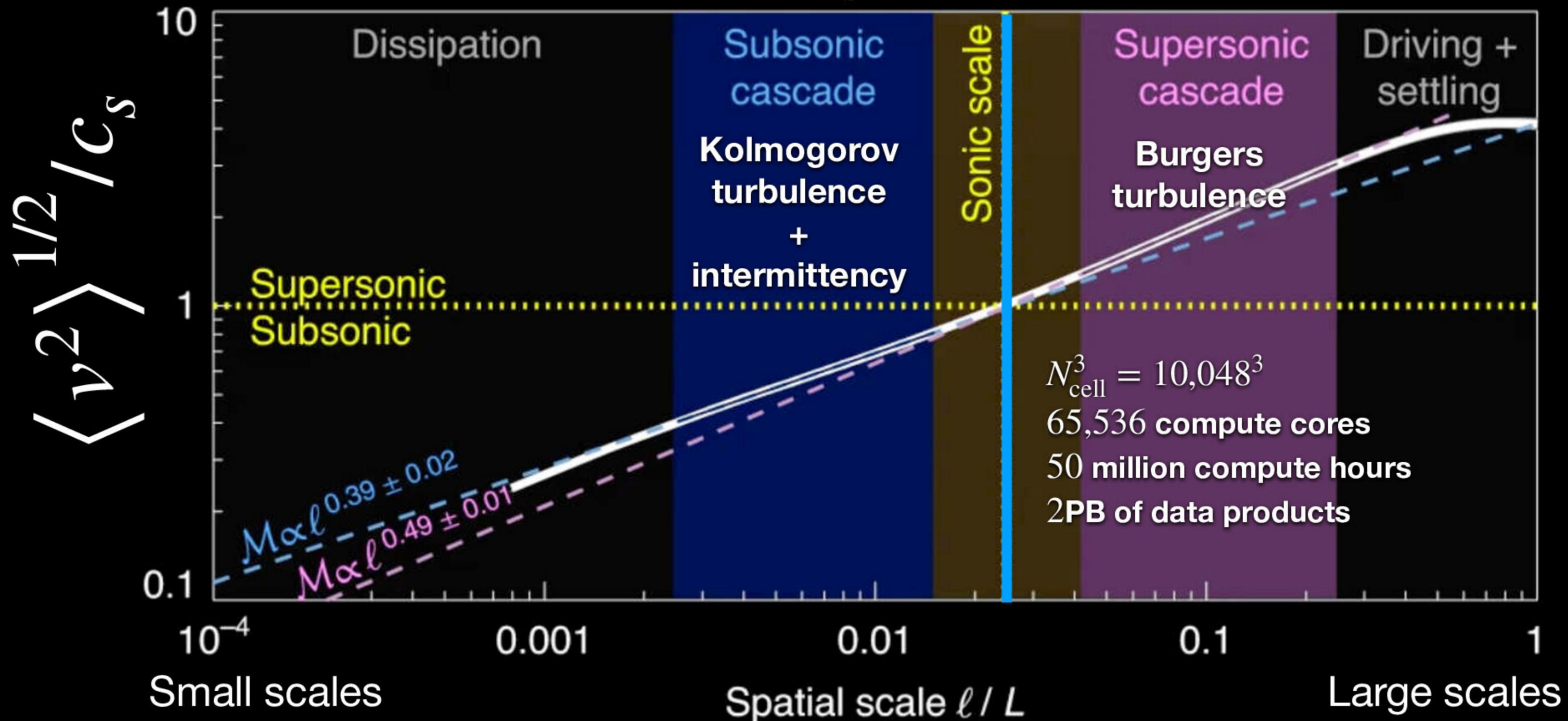

$$\ell_s \sim (0.1\,\mathrm{pc})^{-1}$$

Dissipation

Subsonic cascade

Sonic scale

Sup ca

Kolmogorov turbulence + intermittency

Bu turb

Supersonic
Subsonic

$M \propto \ell^{0.39 \pm 0.02}$
$M \propto \ell^{0.49 \pm 0.01}$

$N_{\mathrm{cell}}^3 = 10{,}048^3$
65,536 **compute cores**
50 **million compute hours**
2**PB of data products**

Small scales Spatial scale ℓ / L Large scales

The energy cascade in supersonic HD turbulence

$$\ell_s \sim (0.1\,\mathrm{pc})^{-1}$$
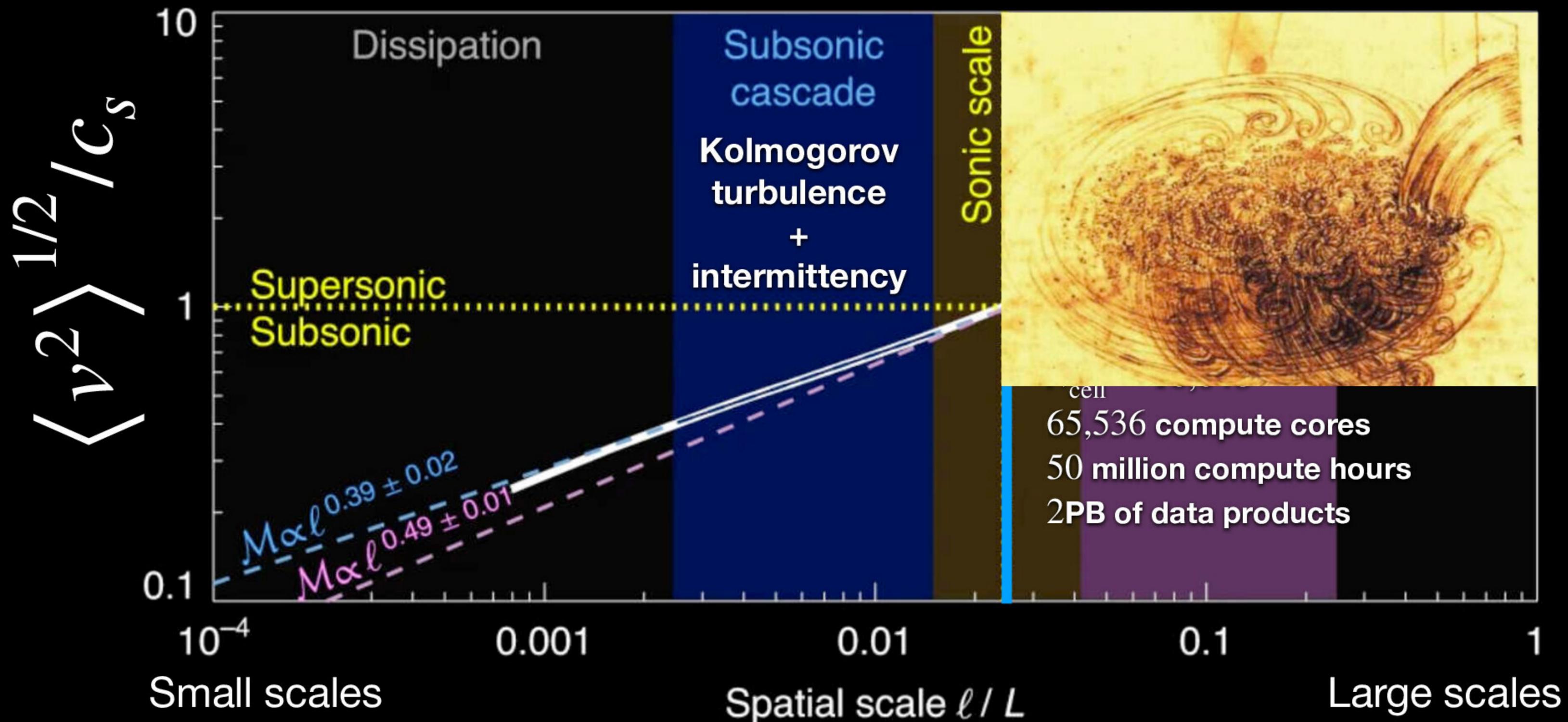
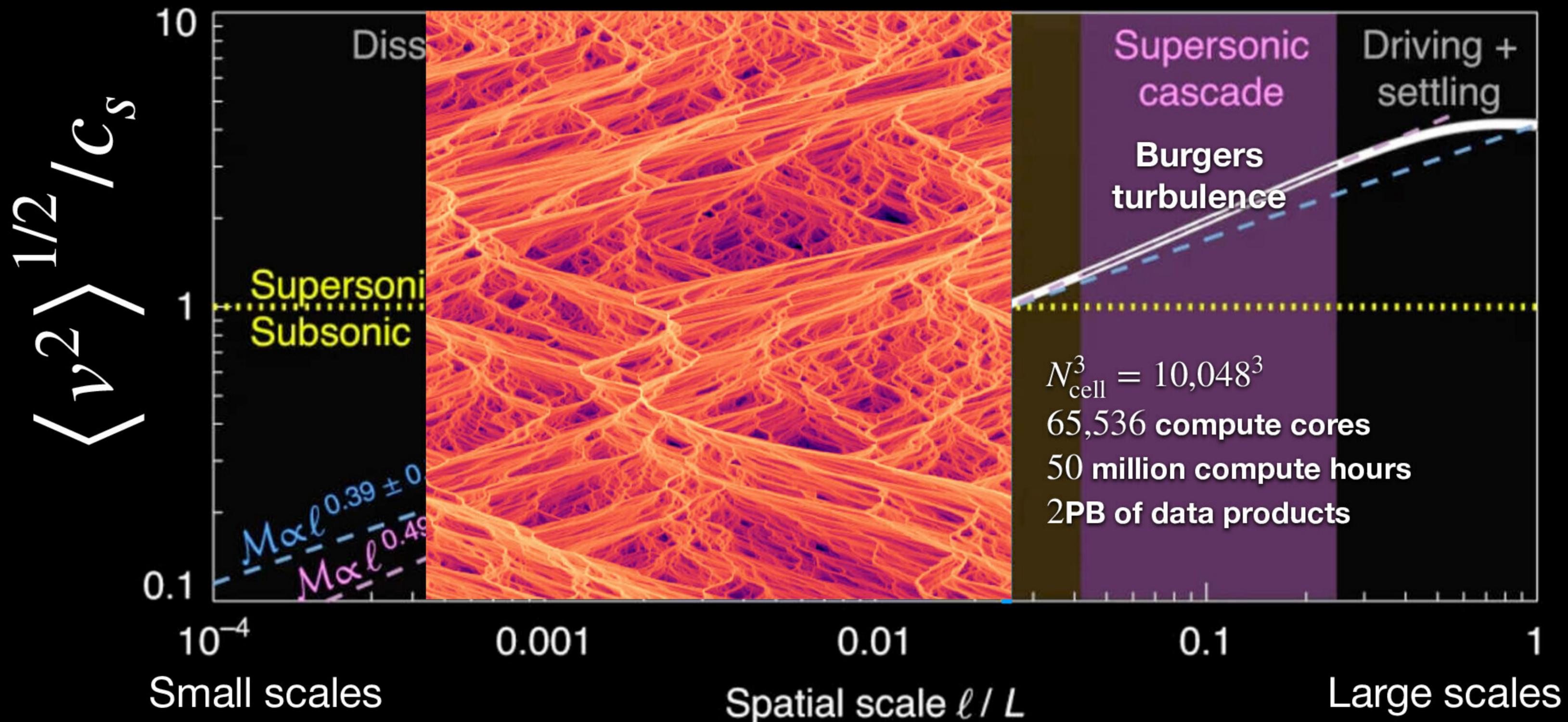# The energy cascade in supersonic HD turbulence

$$\mathscr{E}(k) \sim k^{-5/3}$$

The energy cascade in supersonic HD turbulence

Federrath, Klessen, Ipachio & Beattie (2021)
Nature Astronomy

$$\mathscr{E}(k) \sim k^{-2}$$

The energy cascade in supersonic HD turbulence

Subsonic cascade embedded in supersonic turbulence (not scale-free!)

Inconsistent with Boldyrev (2002): a single power law changed by shocks

Compressible turbulence asymptotically becomes incompressible turbulence at small-scales!
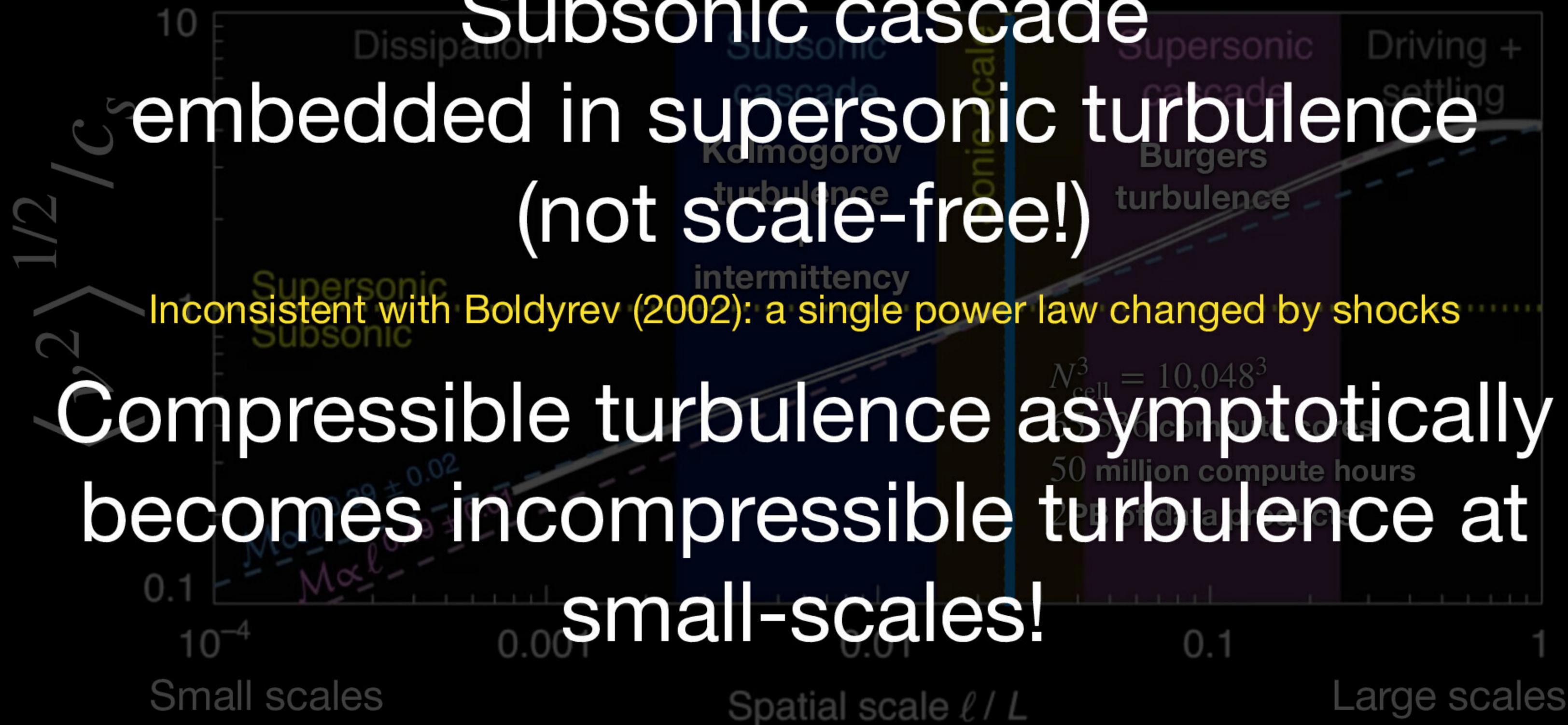
$L \sim \mathcal{O}(\mathrm{kpc})$

The Whirlpool Galaxy, 2017

The Whirlpool Galaxy, 2021

But what about magnetic fields?

Credit: NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA)

Credit: NASA, the SOFIA science team, A. Borlaff; NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA)
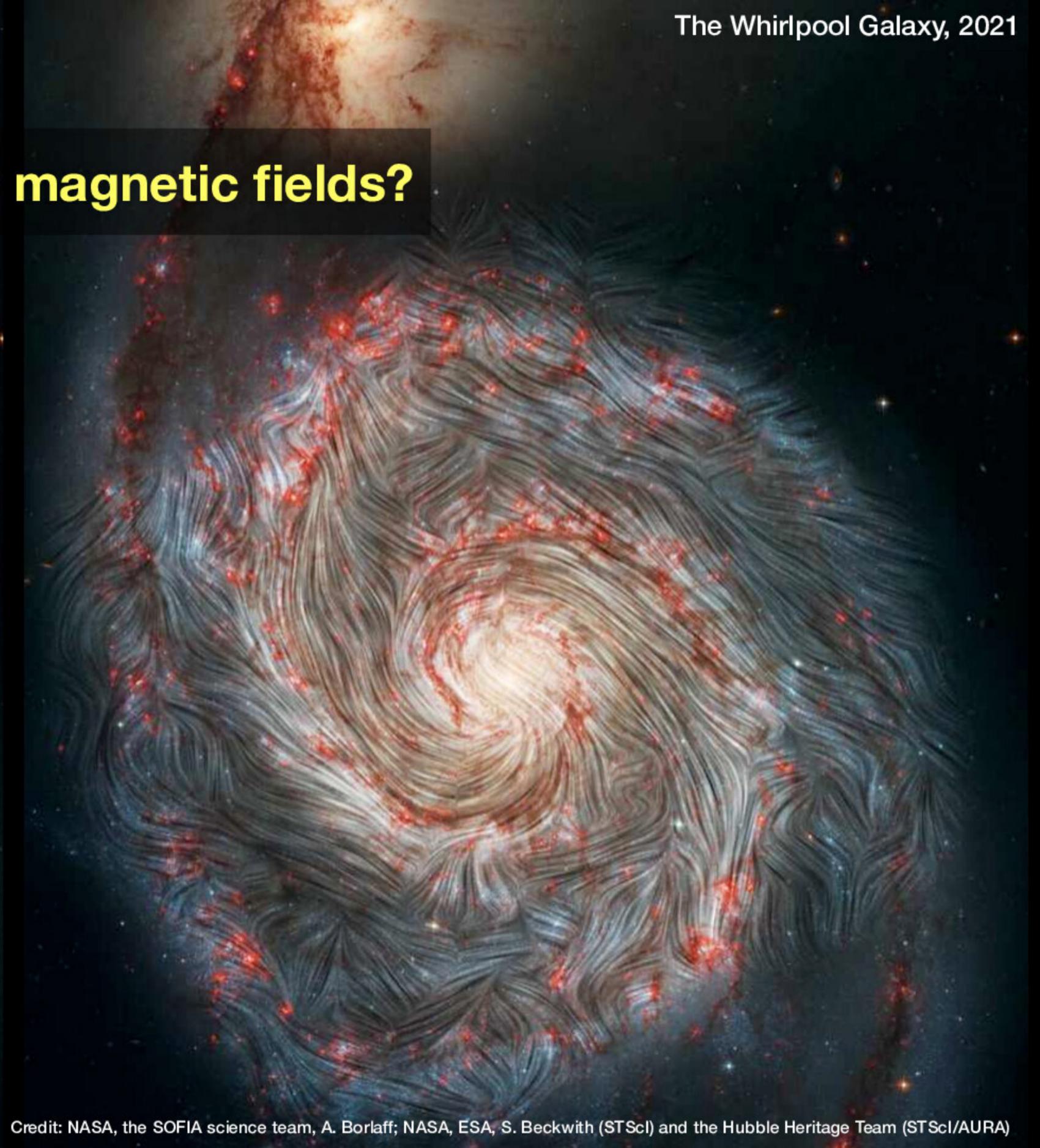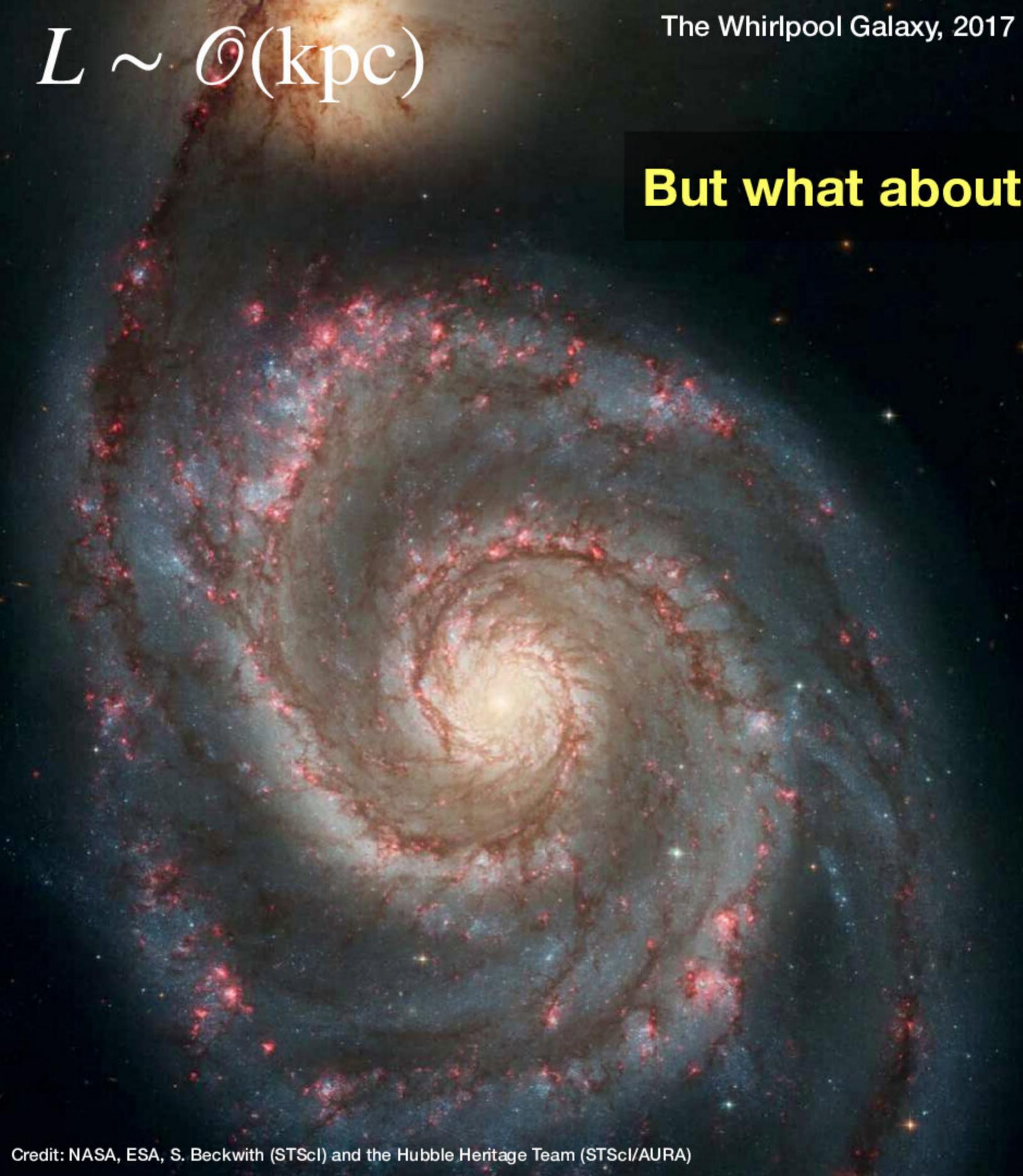
$L \sim \mathcal{O}(\mathrm{pc})$

Irreducible — add magnetic flux to the cascade on all scales

straight, strong fields ($\kappa \propto B^{-1/2}$; Schekochihin+2004) penetrating through Orion A

Orion A in infrared; ESA/Herschel/Planck; J. D. Soler, MPIA

$10,080^3$ magnetized supersonic turbulence simulation (cold ISM analogue)

Beattie, Federrath, Klessen, Cielo & Bhattacharjee

1. What is the scaling of the energy cascade in compressible MHD turbulence?
2. How are the characteristic scales organized in the compressible interstellar medium turbulence?
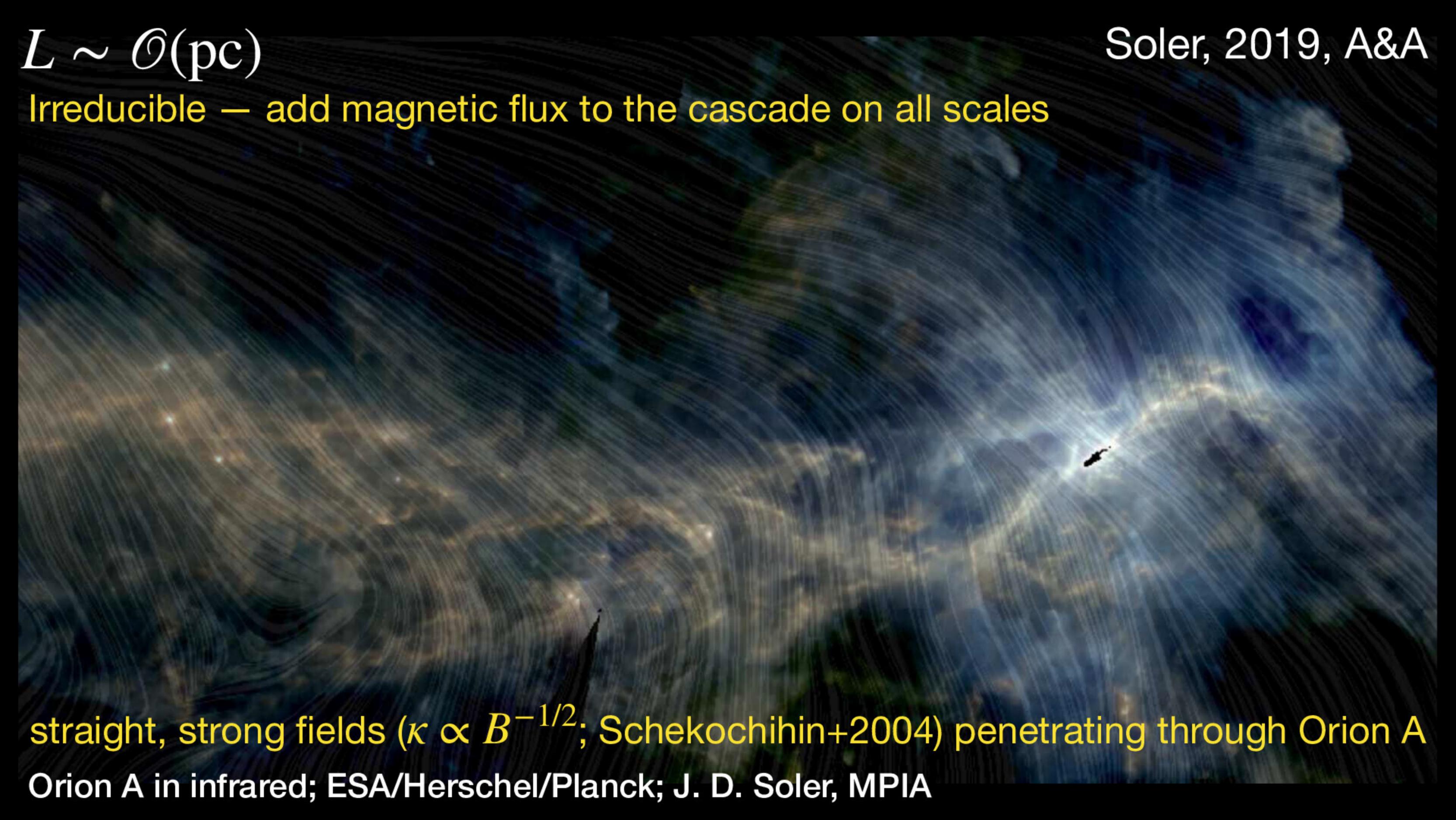3. What are the saturation physics of the turbulent dynamo?

PI of a three total 230<u>million core-hour</u> projects on superMUC-NG

ILES of compressible MHD turbulence

Turbulence: $\sigma_V/c_s \approx 4,\ \ell_0 = L/2$

Magnetic fields: $B = b_{\mathrm{turb}},\ \mathcal{M}_A \approx 2$

Three experiments for convergence tests:
- **LOW-RES:** $2,520^3$ (0.3Mcore-h, 8,640cores)
- **MID-RES:** $5,040^3$ (4.0Mcore-h, 34,560cores)
- **HIGH-RES:** $10,080^3$ (80.0Mcore-h, 148,240cores)

$3.45\mathrm{PB}$ **in data products** $\mathrm{Rm} \sim \mathrm{Re} \gtrsim 10^6,\quad \mathrm{Pm} \sim 1-2$

Broad Code details:

- Highly-modified version of finite volume code *FLASH*, second-order in space approximate Riemann (PPM) solver with framework outlined in Bouchut+2010, tested in *FLASH* in Waagen+2011.

- Ideal (ILES) compressible non-helical, isothermal MHD turbulence with finite correlation time (OU process; Federrath+2022).

DB: EXTREME_Turb_hdf5_plt_cnt_0100
Cycle: 118366   Time: 1.25

mag. field
gas density

Visualisation: Salvatore Cielo (VisIt)

$10,080^3$ magnetized supersonic turbulence simulation (cold ISM analogue)

Perfect weak scaling on SuperMUC-NG

Beattie, Federrath, Klessen, Ciel Bhattacharjee

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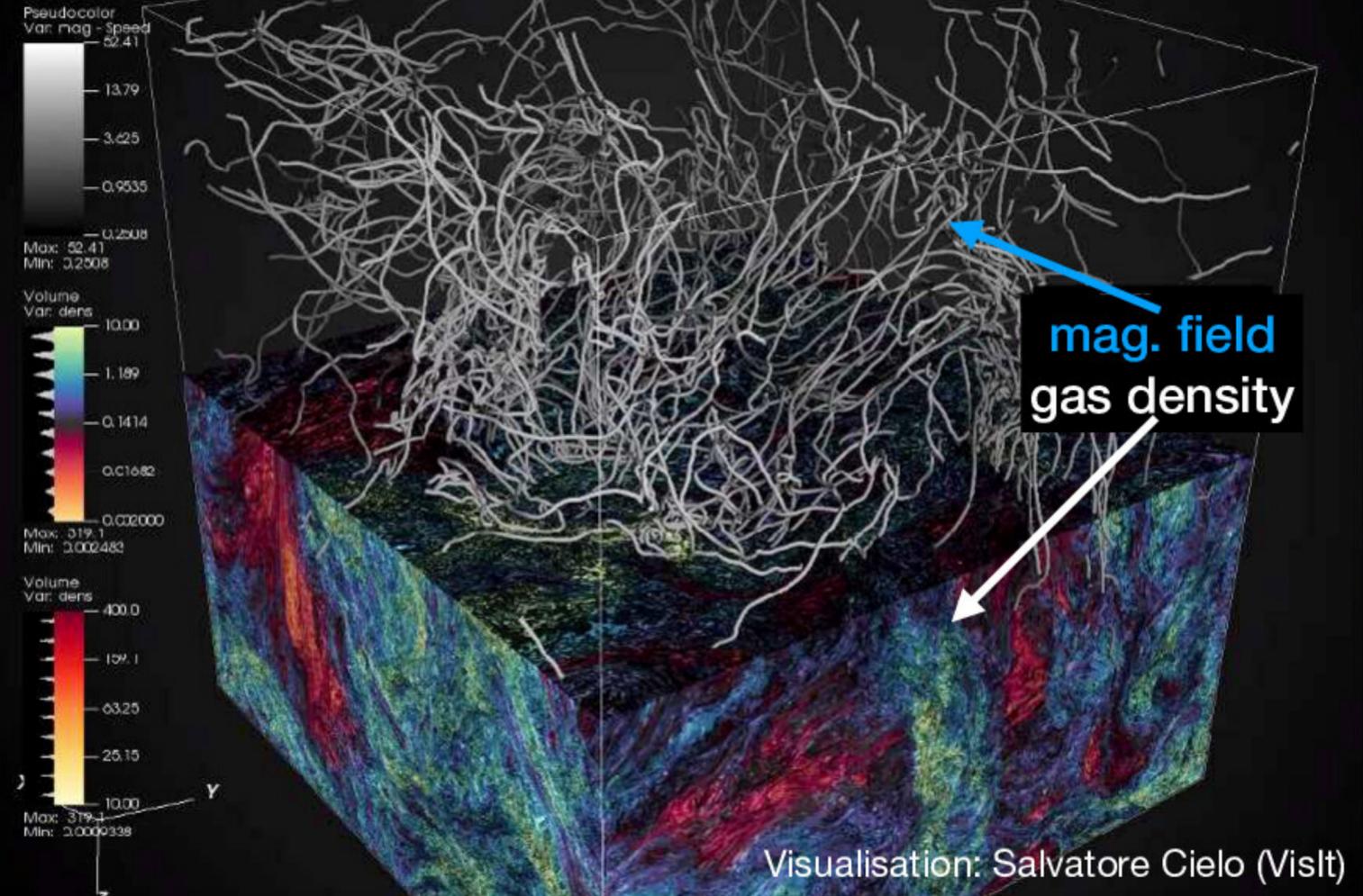
Three experiments for convergence tests:
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- **HIGH-RES:** $10,080^3$ (80.0Mcore-h, 14

3.45PB in data products $\quad Rm \sim Re \gtrsim 10^6,$

Number of compute cells

$10^8 \qquad 10^9 \qquad 10^{10} \qquad 10^{11} \qquad 10^{12}$

FLASH (v4, **our version**) on SuperMUC-NG

MHD turbulence (double-precision, public version)

Hybrid precision propagated throughout the entire code (factor 3ish)

full-machine

MHD turbulence (hybrid-precision, optimized)

HD turbulence (hybrid-precision, optimized)

Time/cell/step [micro sec]

$10 \qquad 100 \qquad 10^3 \qquad 10^4 \qquad 10^5 \qquad 10^6$

Number of compute cores

Max: 319.1
Min: 3.000338
10.00

Visualisation: Salvatore Cielo (VisIt)

Volume integral Quantities

$$\mathscr{M} = \left\langle \frac{u^2}{c_s^2} \right\rangle_{\mathscr{V}}^{1/2}$$

Interpolation to generate ICs for successively higher resolution experiments

Settling and *interpolate* to 5040^3

Settling and *interpolate* to 10080^3

$$t_{\mathrm{populate}} \sim \mathrm{Re}^{1/2} t_0$$

— 2520^3
— 5040^3
— 10080^3
⋯ $\langle \mathcal{M} \rangle_{5t_0} = 4.32 \pm 0.18$

$\mathscr{M}$

t/t_0

Beattie+ 2025 (*Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium
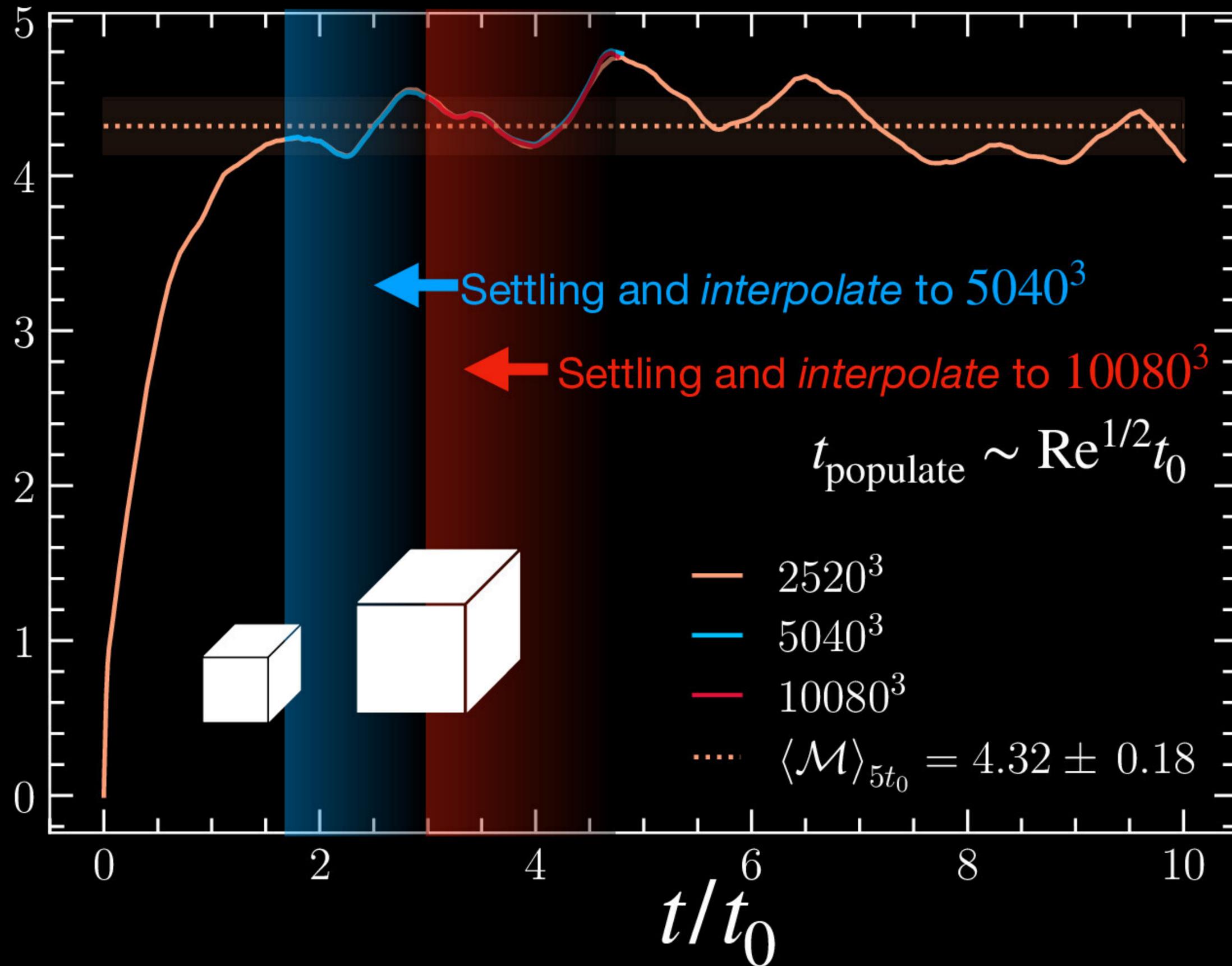
Volume integral Quantities

$$\mathscr{M}_A = \sqrt{\frac{E_{kin}}{E_{mag}}}$$

Interpolation to generate ICs for successively higher resolution experiments

$\beta \sim 1/2$

$\mathscr{M}_A$

Settling and *interpolate* to 5040^3

Settling and *interpolate* to $10,080^3$

HIGH-RES: $10,080^3$ (80.0Mcore-h, 148,240cores)

$0 < t/t_0 < 2$

t/t_0

—— 2520^3
—— 5040^3
—— 10080^3
······ $\langle \mathscr{M}_A \rangle_{5t_0} = 2.039 \pm 0.096$

compute | disk

Data dumps at 10x per correlation time for averages across the statistically steady state

Read out domain into HDF5 chunks, grouped by m nodes writing each chunk

Merge into single HDF5 file in post-processing (C++ mpi tool)

$10,080^3$

$10,080^3$

200 GB/sec

...

180 sec to write a 28 TB checkpoint file

Almost max. bandwidth for SuperMUC-NG scratch

C++ & FFTW backend
Power spectrum on 50,000 cores
Spectra in ~ 3mins
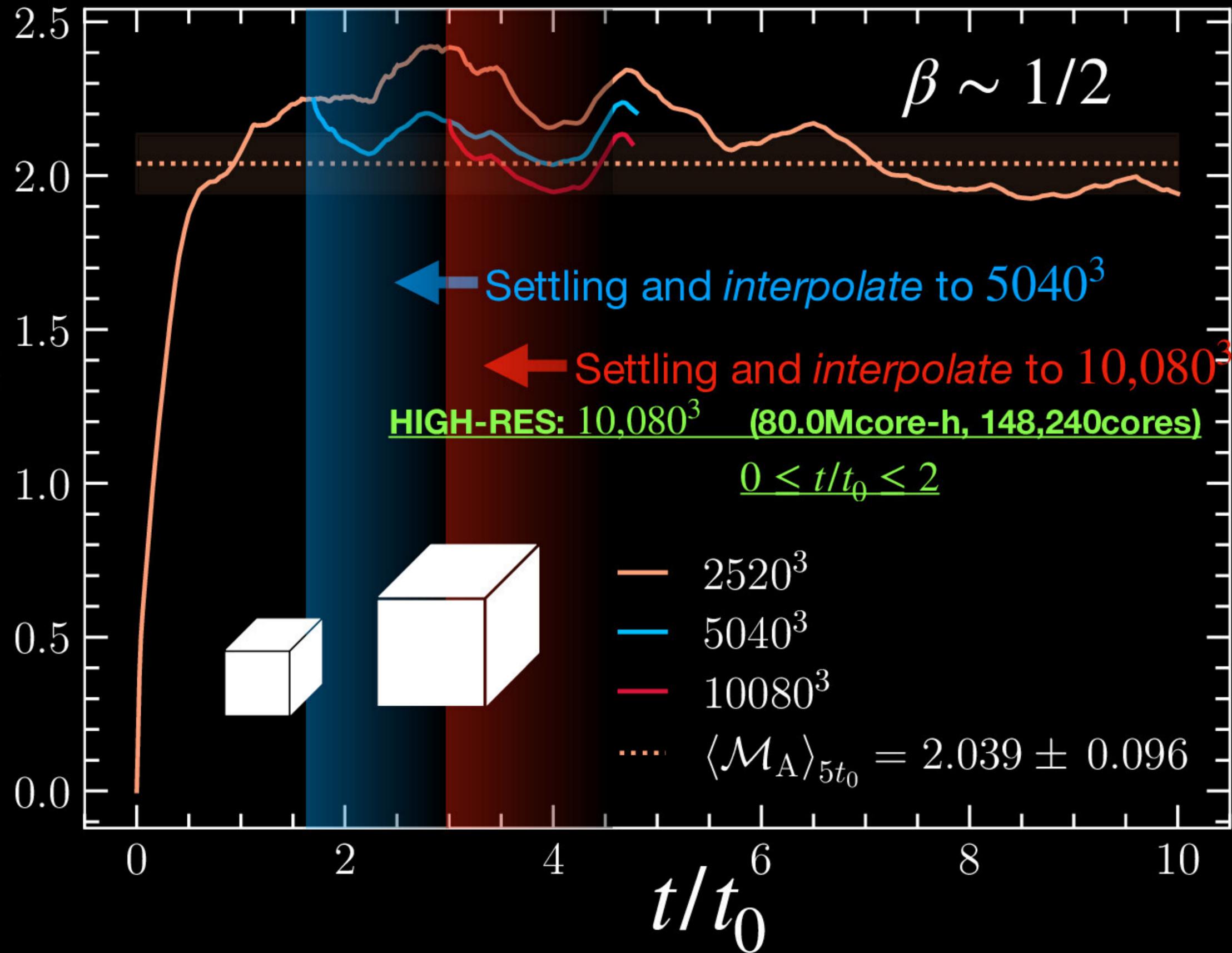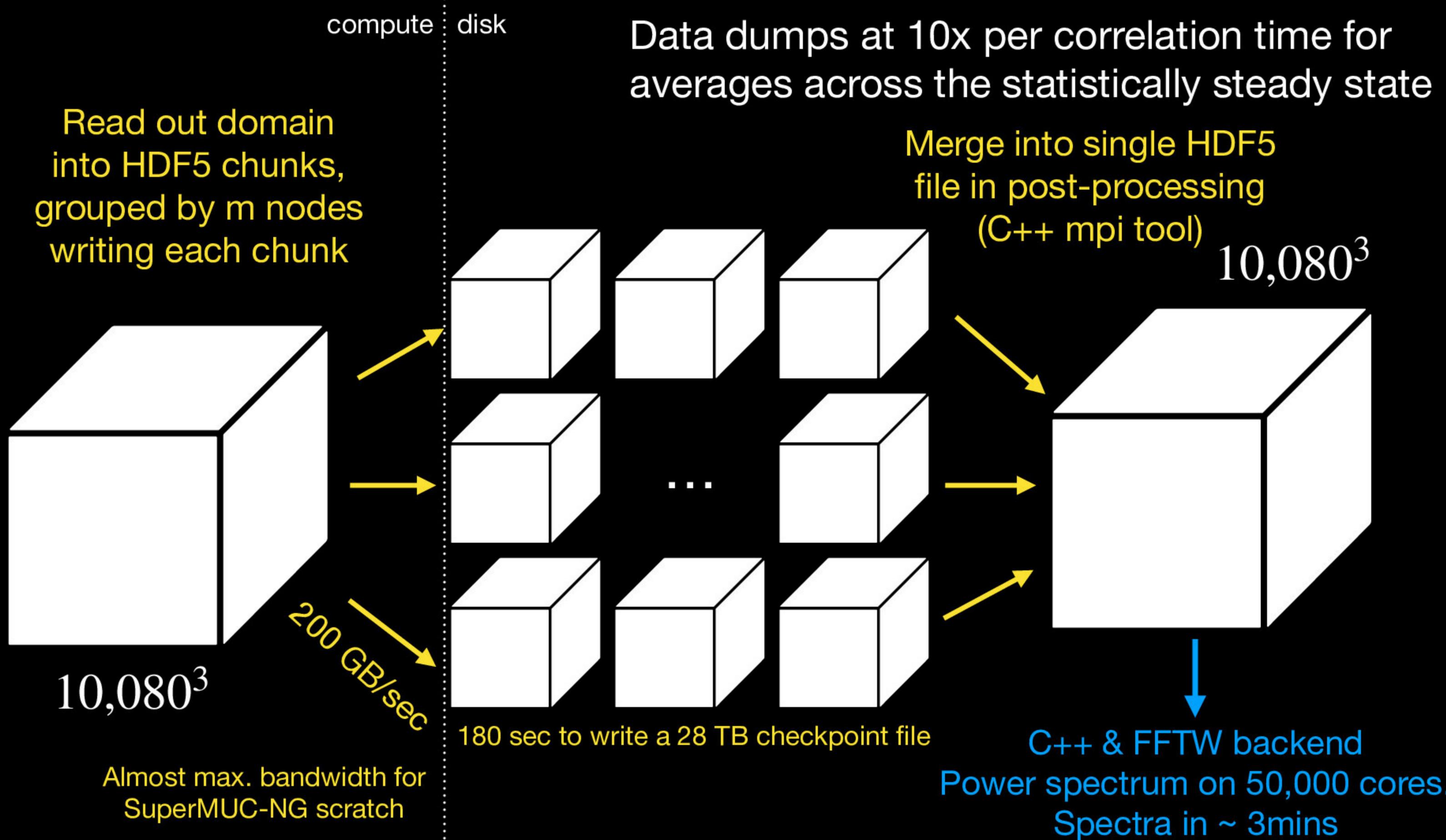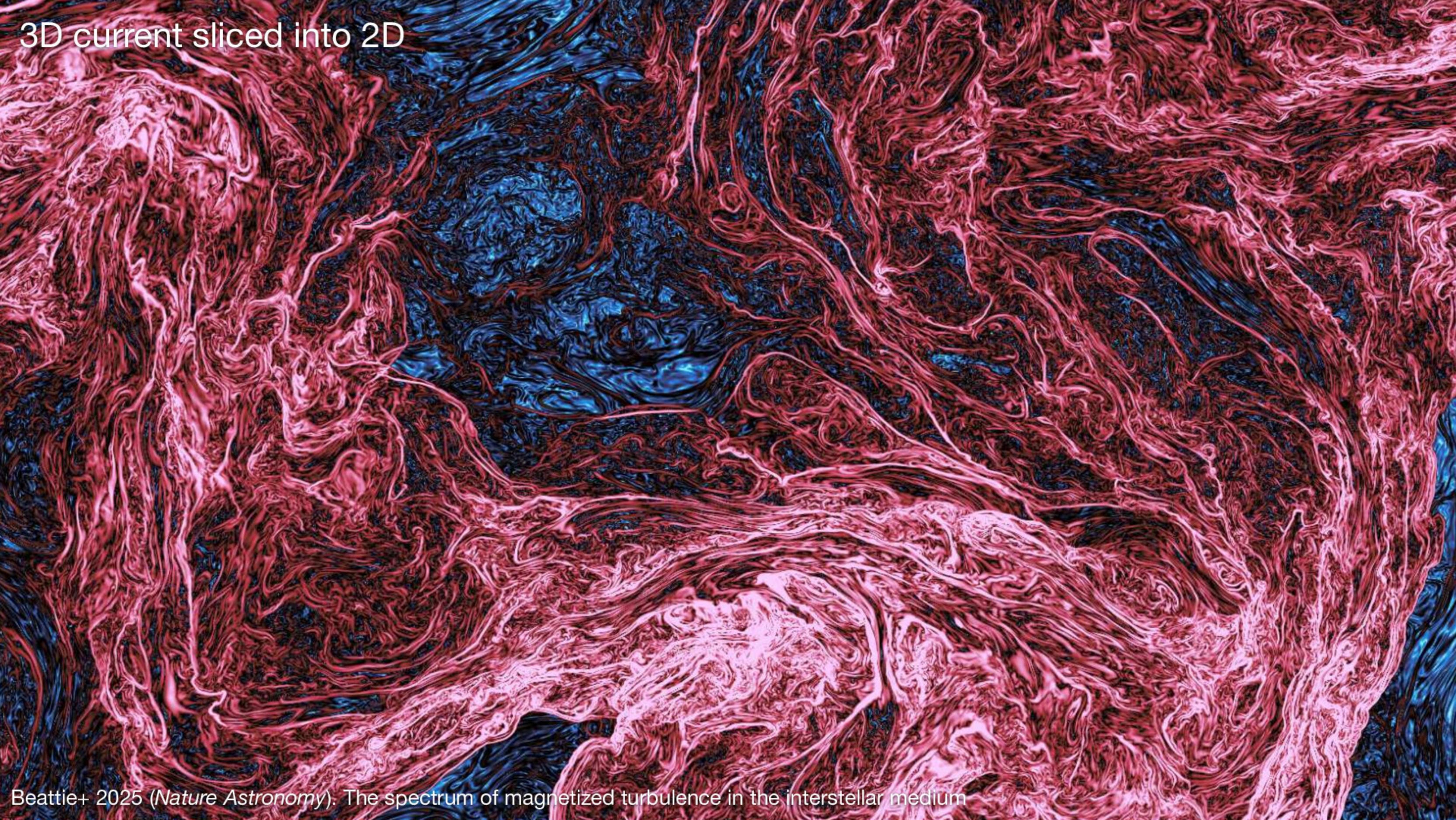
3D current sliced into 2D

Beattie+ 2025 (*Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

Two important scales — the sonic scale
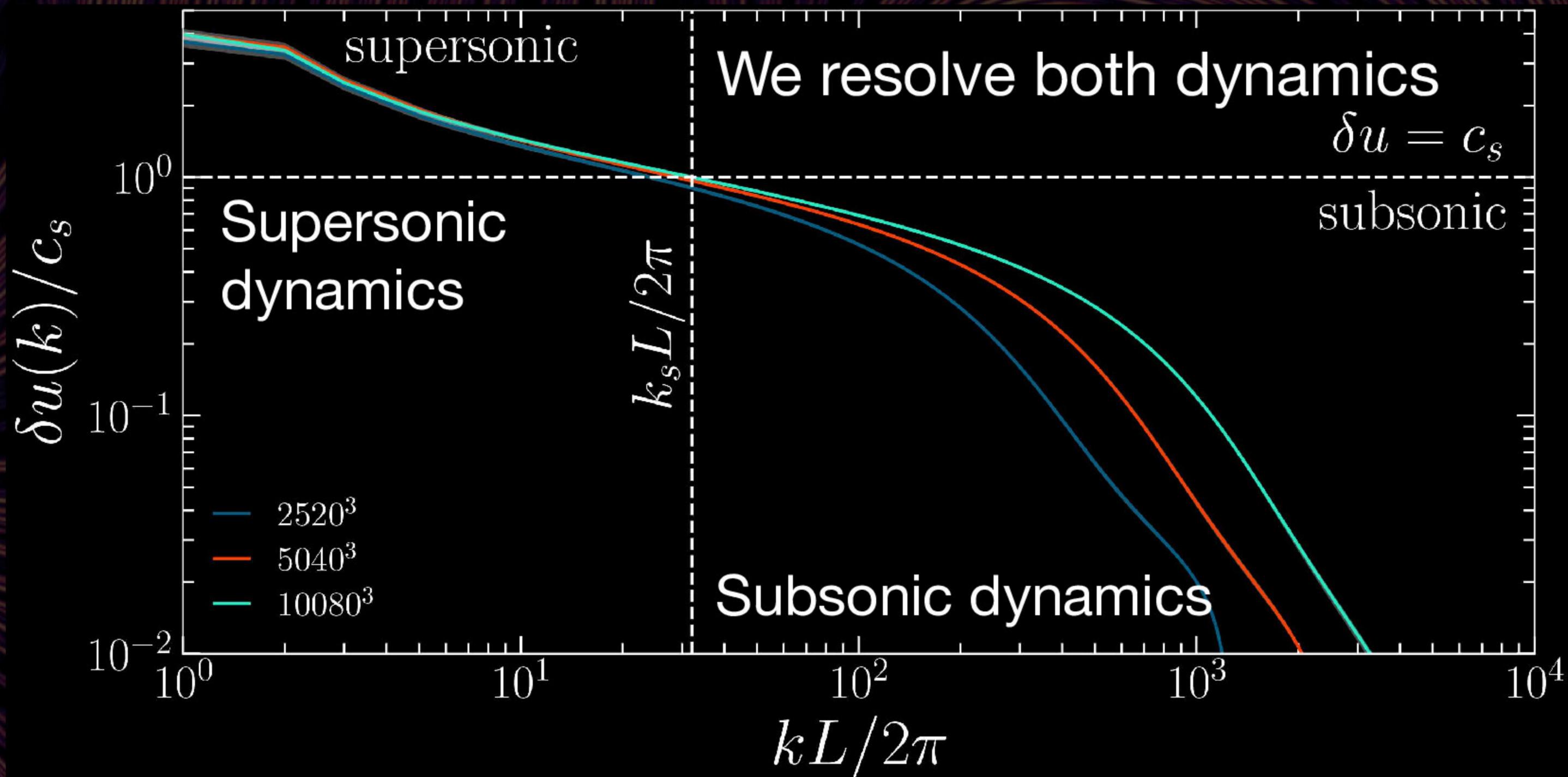
supersonic

We resolve both dynamics

$\delta u = c_s$

Supersonic dynamics

subsonic

$k_s L / 2\pi$

$\delta u(k) / c_s$

2520^3
5040^3
10080^3

Subsonic dynamics

$kL/2\pi$

Beattie+ 2025 (*Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

Two important scales
— the Alfven scale

sub-Alfvenic

k_{eq}

super-Alfvenic

Multiple regimes
in a single domain!

(f)

k_{s}

k_{eq}

$\mathcal{E}_{\text{mag}}(k) > \mathcal{E}_{\text{kin}}(k)$

$\mathcal{E}_{\text{mag}}(k) < \mathcal{E}_{\text{kin}}(k)$

Sonic-scale
maximizes
the energy
ratio

$\mathcal{E}_{\text{mag}}(k)/\mathcal{E}_{\text{kin}}(k)$

10^0

10^{-1}

10^{-2}

— 2,520^3
— 5,040^3
— 10,080^3

$k_* \longrightarrow$

10^0 10^1 10^2 10^3 10^4

$kL/2\pi$

Beattie+ 2025 (*Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

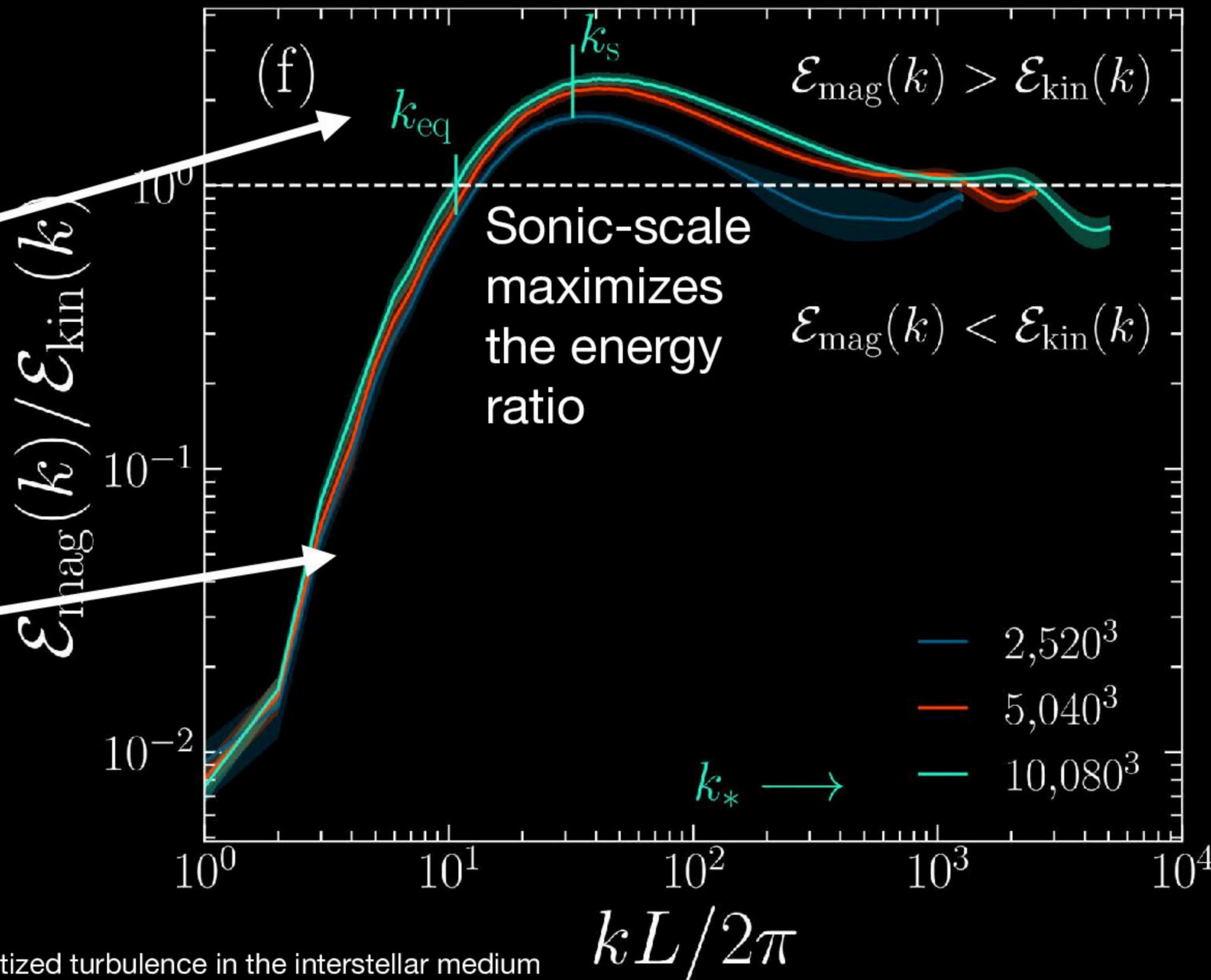Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

Energy spectra: the disparate lives of u and b fluctuations

(a) Kinetic energy spectrum $\mathcal{E}_{\rm kin}(k)/k^{-3/2}$ versus $kL/2\pi$ with marked scales $k_{\rm cor}^u$, $k_{\rm eq}$, $k_{\rm s}$, $k_{\rm u}^u$, and k_*. Reference slopes: $k^{-3/2}$ Boldyrev (2006); dynamical alignment, $k^{-5/3}$ Goldreich & Shridar (1995); Alfvénic, k^{-2} Burgers (1964); Shocks.

(b) Magnetic energy spectrum $\mathcal{E}_{\rm mag}(k)/k^{-9/5}$ versus $kL/2\pi$ with marked scales $k_{\rm s}$, $k_{\rm u}^b$, $k_{\rm eq}$, $k_{\rm cor}^b$, and k_*. Reference slopes: $k^{-3/2}$ Boldyrev (2006); dynamical alignment, $k^{-5/3}$ Goldreich & Shridar (1995); Alfvénic, $k^{-9/5}$ Fielding + (2023); empirical, $k^{-19/9}$ Galishnikova+ (2022); tearing, $k^{-11/5}$ Dong+ (2022); plasmoid instability.

Two power laws

One power law, only emerging at very high Rm

Beattie+ 2025 (*Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

Thanks, questions?

✉ **james.beattie@princeton.** 🐦 **@astro_magnetism**

Not enough time to talk about many more key results
- Ideas about the origin of alignment
- Other primitive variable / curl alignment structure function
- In situ current sheet and plasmoid development
- Comparison of density fluctuations with MMS data
- Turbulent dynamo saturation through alignment
- Comparisons with more global supernova-driven turbulence

The future is bright

- Next generation of $10,000^3$ simulations with large-scale field integrating now
- Moving to also have AthenaK capabilities to do GPU counterpart runs
- Pushing towards $20,000^3$ (500TB 3D dumps) to further explore asymptotic state