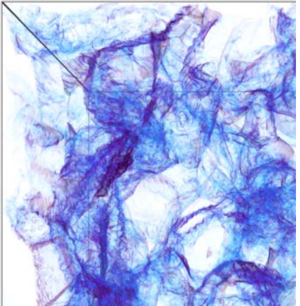


Self-Gravitating Supersonic MHD Turbulence

GTP Workshop on MHD LES, Session VI

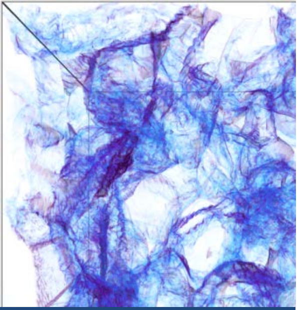
INSTITUT FÜR ASTROPHYSIK GÖTTINGEN

Wolfram Schmidt

with thanks to

Ann Almgren, Harald Braun, Jörg Büchner Jan F. Engels, Christoph Federrath, Muhammad Latif, Emanuel Lévêque, Jens Niemeyer, Dominik Schleicher

and **CRC 963, GWDG, HLRN, yt-project**



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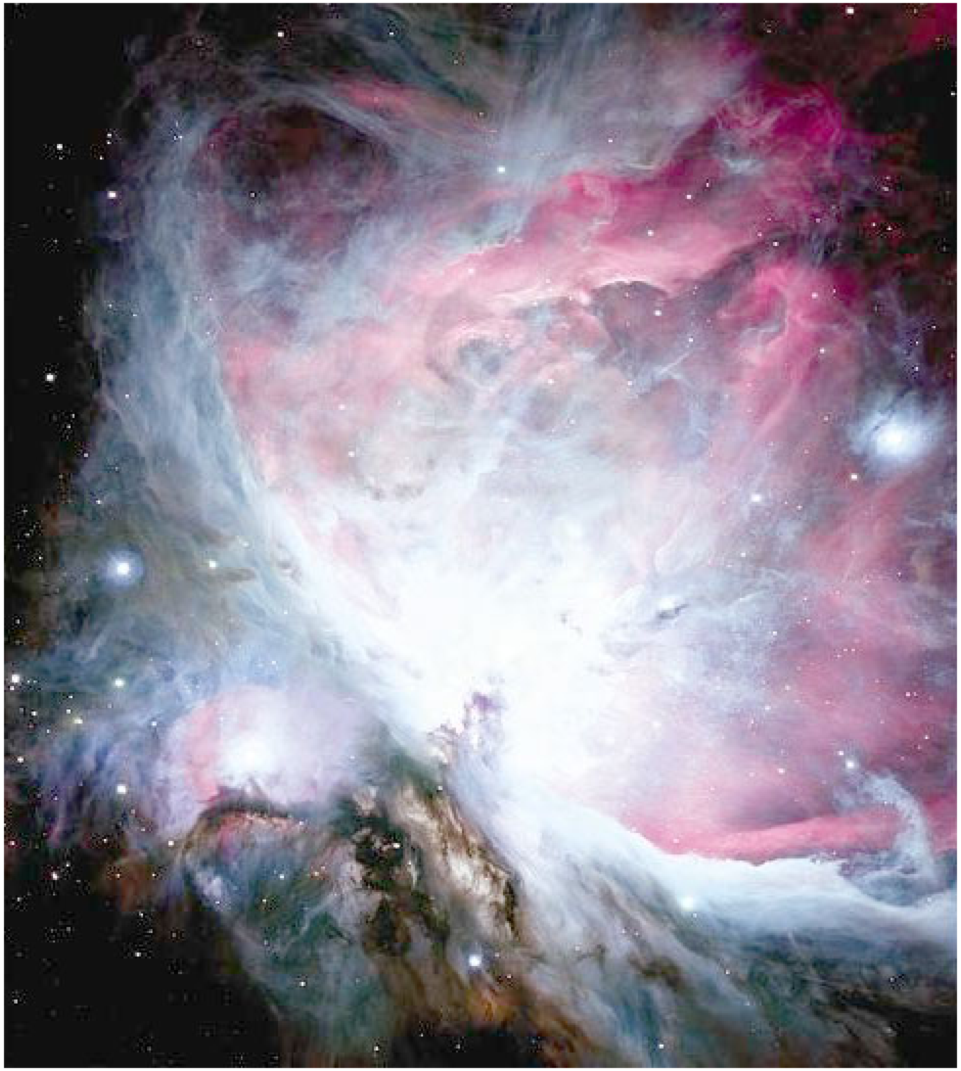
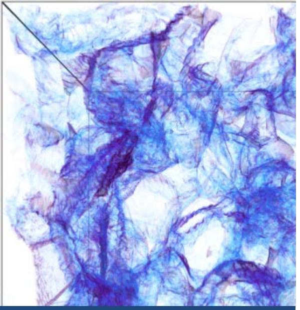
Application I: Star-Forming Clouds





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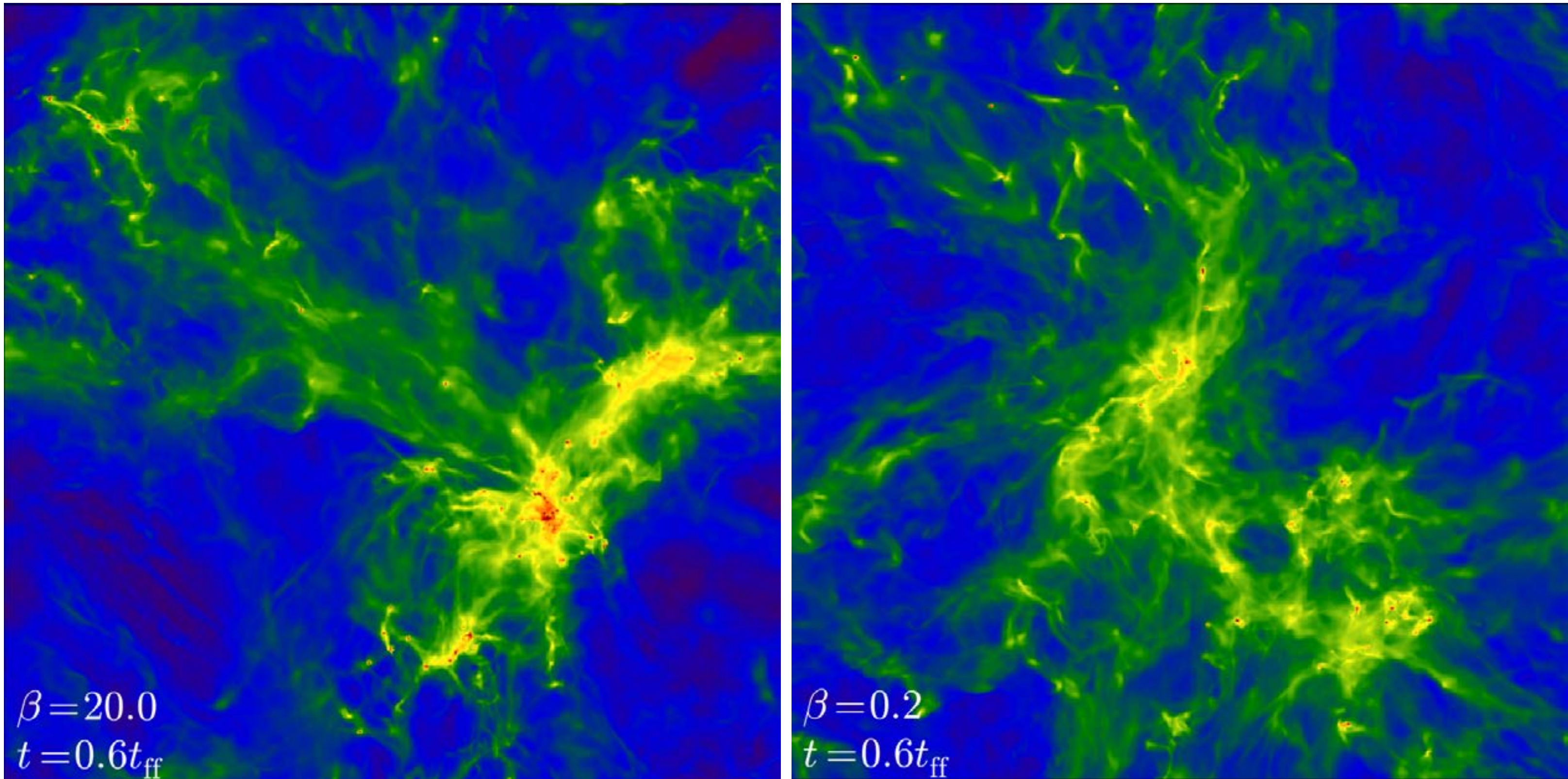
ILES of Forced MHD

Collins et al. (2012):

- AMR simulation (4 levels, 16 cells per Jeans length)
- PLM (Li et al. 2008), CT method, $\mathrm{Ma}_{\mathrm{rms}} \approx 9$



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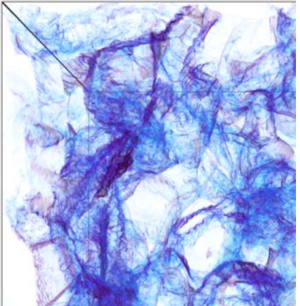
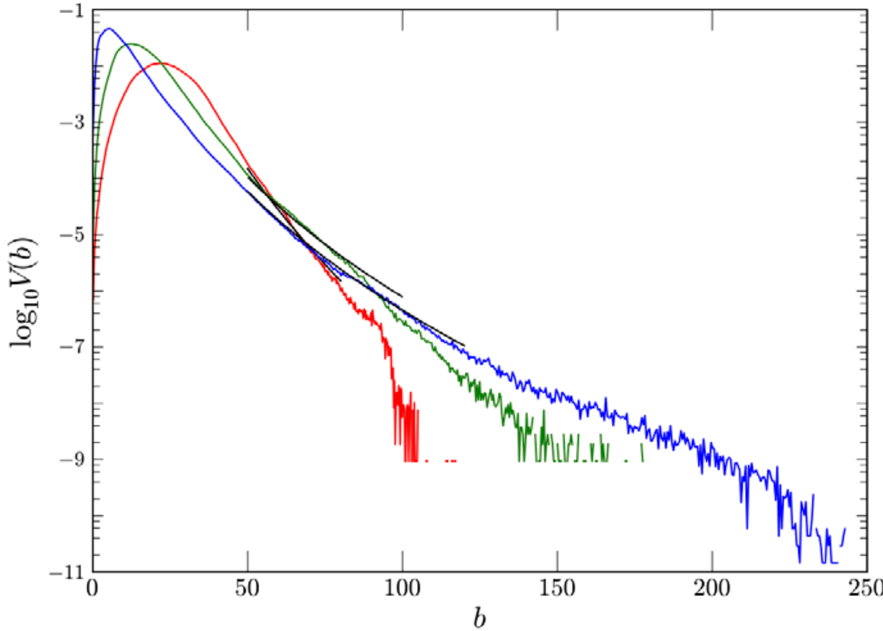




Magnetic field PDFs:

– field fluctuation b

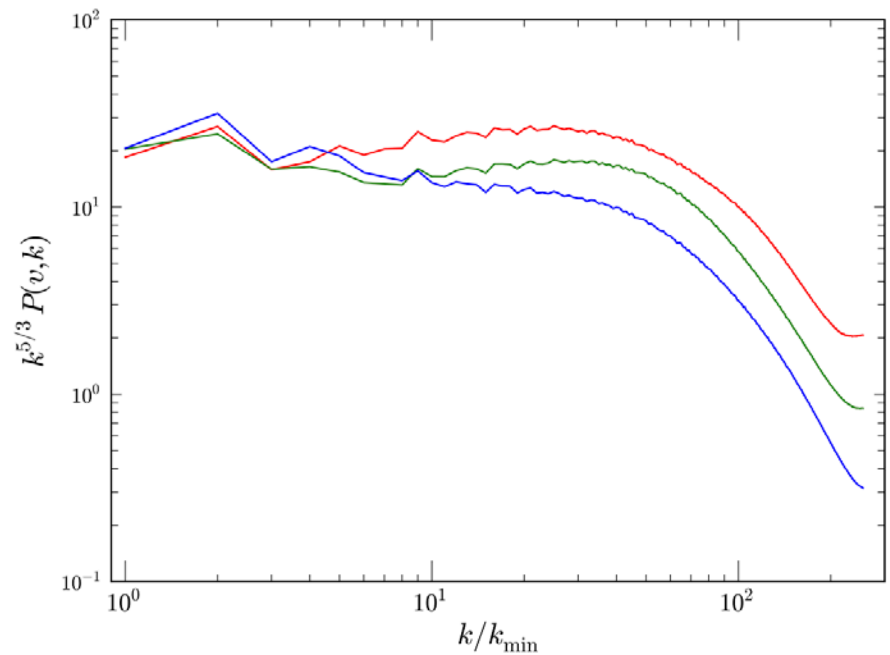
– peaks given by β_0

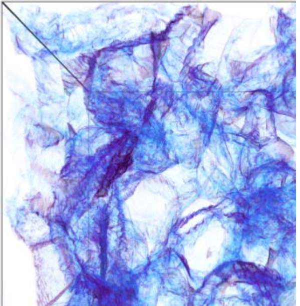
– widest tail for weakest field

Velocity power spectra:

– no evolution due to gravity

– Steeper slope for lower β_0





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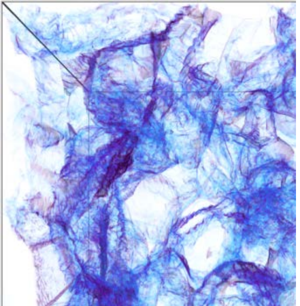
Local Magnetic Field Amplification

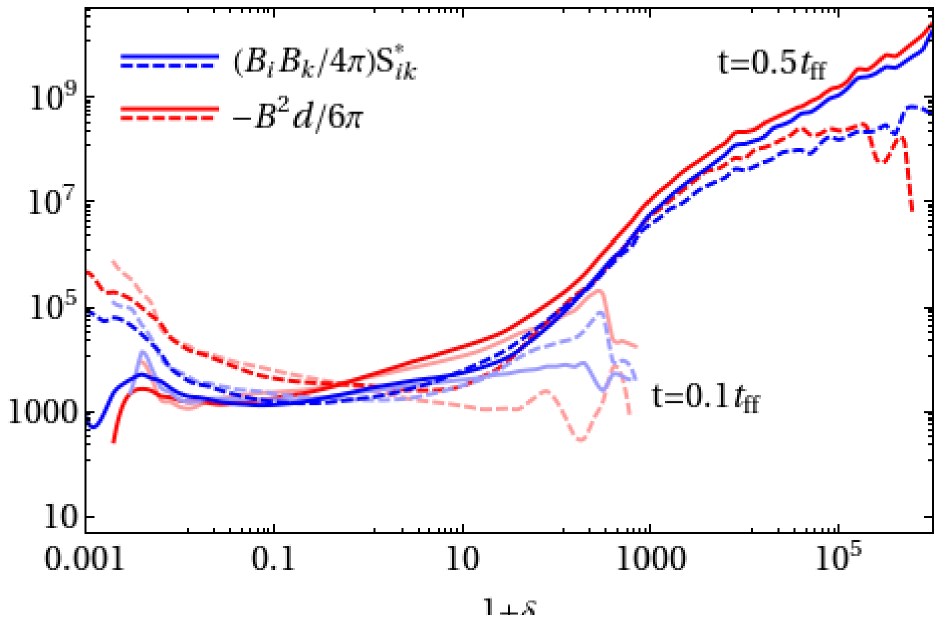
- PDE for the **magnetic pressure** follows from compressible induction equation (ideal MHD):

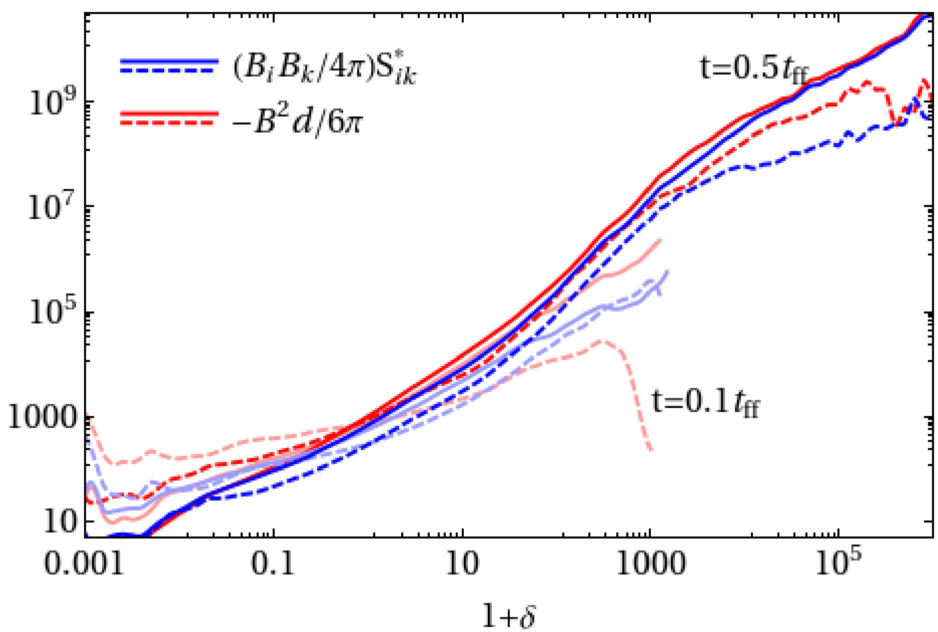
$$\frac{\mathrm{D}}{\mathrm{D}t}\left(\frac{B^2}{8\pi}\right)=\frac{1}{4\pi}\left(B_i B_k S^*_{ik}-\frac{2}{3}B^2 d\right)$$

- Two contributions:
  - Amplification by **shear** (dynamo action)
  - Gravitational and shock **compression**
- Can be positive or negative
  - Compute averages of positive and negative contributions for given overdensity $\rho/\rho_0 = 1+\delta$



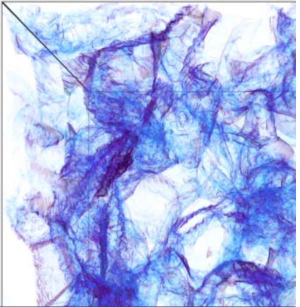
$\beta \approx$ 0.034 and 0.21 (WS, Collins, Kritsuk 2013)





Magnetic field amplification:

- initially saturation
- balance between shear-induced and compressive amplification
- stronger effect for higher β
- net amplification at high densities (collapsing gas)



Application II: The First Stars in the Universe

- **Direct collapse scenario**:
  - dark matter halos of mass $\sim 10^7 M_{sun}$
  - fragmentation due to atomic gas cooling
  - collapse produces prestellar cores ($1000 M_{sun}$)
- Might lead to the formation of seed black holes that can grow to **supermassive BHs**
- **Deep zoom-in simulations** with Enzo (Latif, Schleicher, WS, and Niemeyer 2013):
  - 27 levels of refinement
  - follows collapse down to 0.25 AU
  - MHD runs
  - HD runs: comparison LES to ILES

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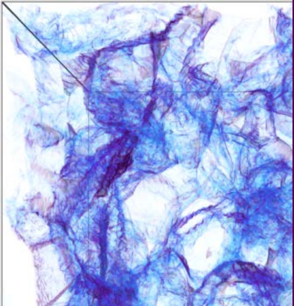

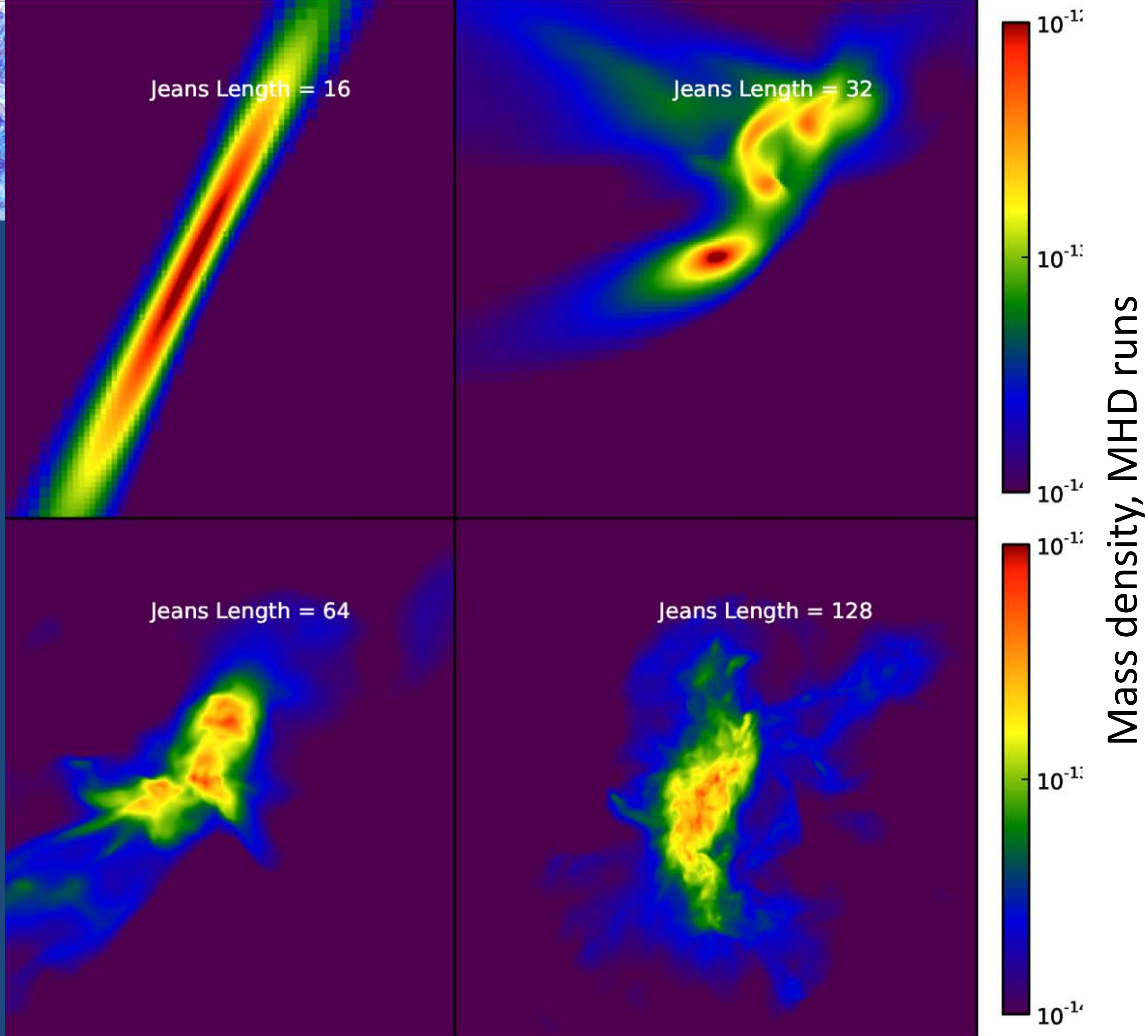

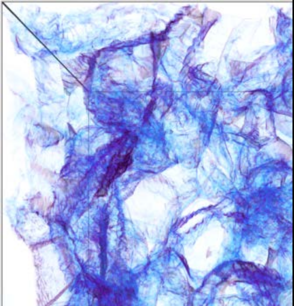

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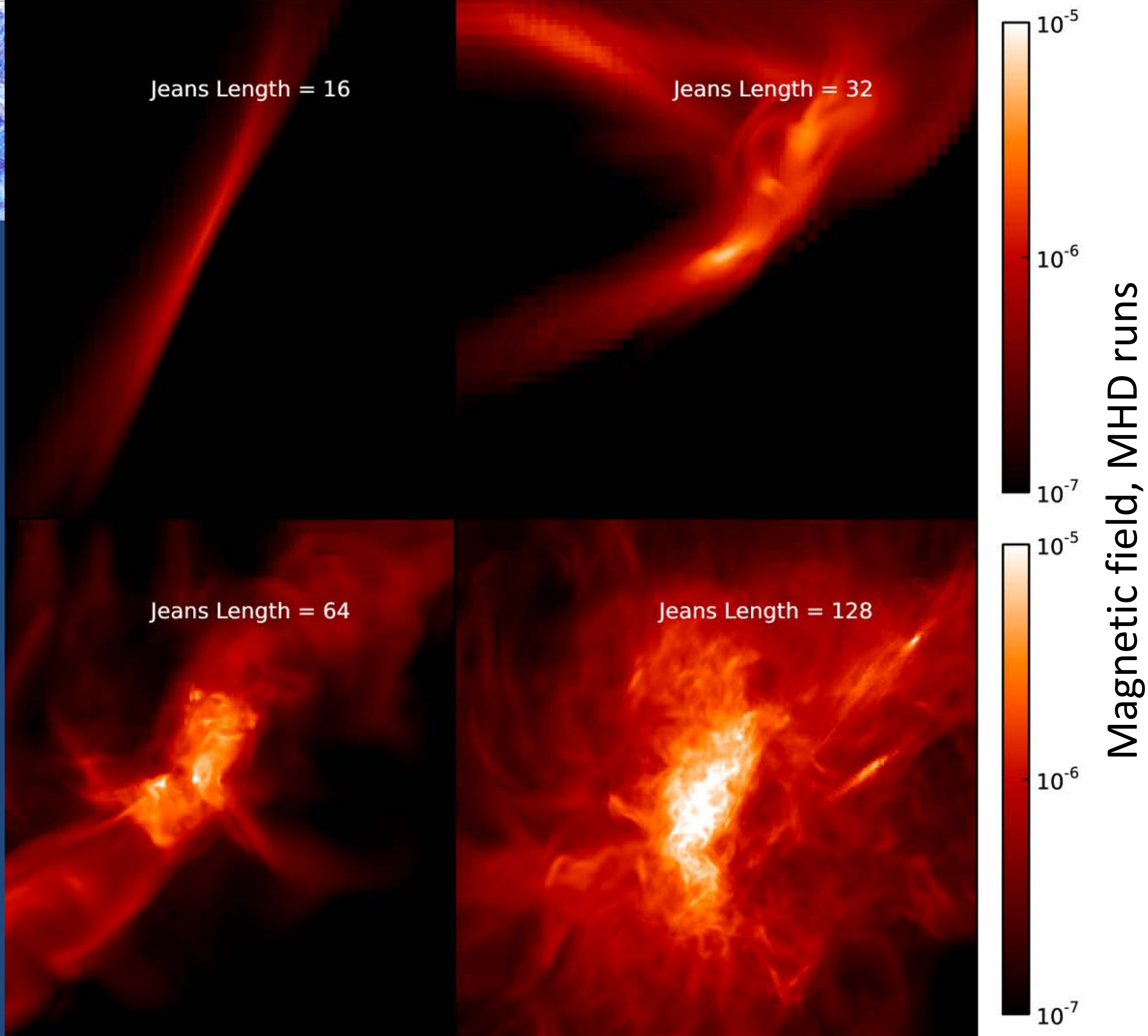
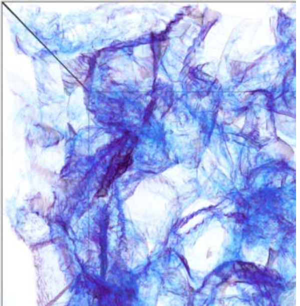
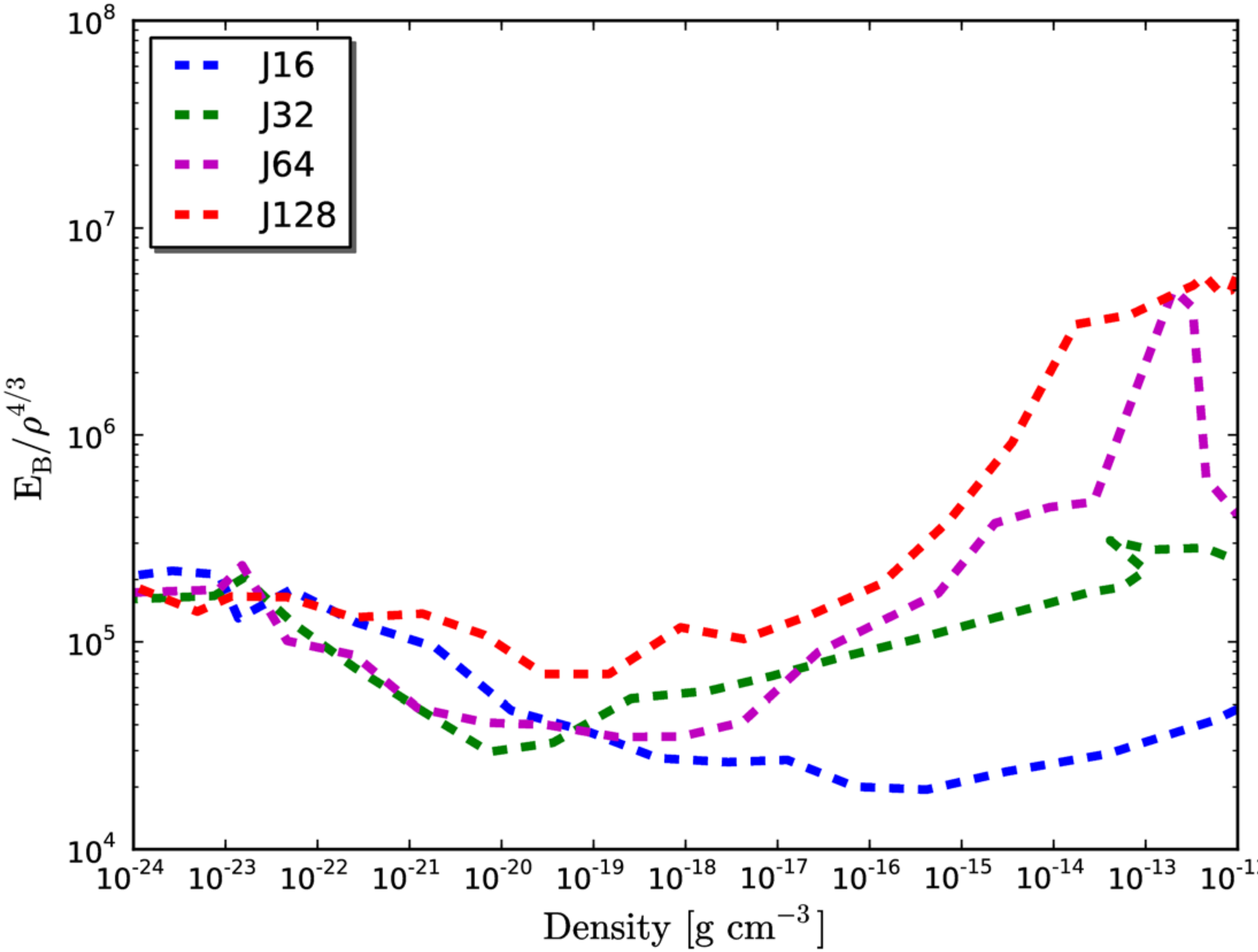


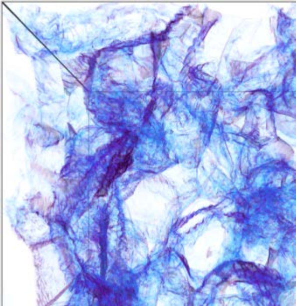




Magnetic field amplification:

– no amplification at low resolution

– Amplification at high densiteis for $\geq$ 64 cells per λ_J



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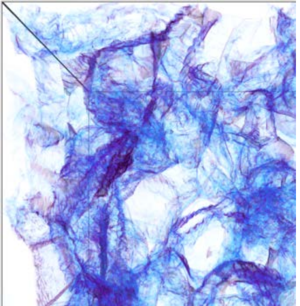
What's going on here?

- Turbulence is **driven by self-gravity** of the gas
- Energy injection on length scales $l \geq \lambda_{\mathrm{J}}$
- We barely touch the turbulent cascade in these simulations – would need $\Delta \ll \lambda_{\mathrm{J}}$
- **Growth rate** of B due to dynamo can be estimated by (Schober et al. 2012):

$$1/\tau_B \sim \frac{V}{\lambda_{\mathrm{J}}} \mathrm{Re}^{1/2} \sim \frac{V}{\lambda_{\mathrm{J}}} \left(\frac{\lambda_{\mathrm{J}}}{l_{\mathrm{K}}} \right)^{2/3}$$

- But in ILES that do not resolve the physical dissipation scale, the dynamo is driven from the **smallest resolved length scales** $l \sim \Delta \gg l_{\mathrm{K}}$



Subgrid Scale Model for Hydrodynamical Turbulence

- Based on Germano (1992) decomposition
- A priori tests of closure for compressible turbulence (Schmidt et al. 2006, 2011)

$$\frac{\partial}{\partial t}\rho + \nabla\cdot(\mathbf{u}\rho) = 0$$

$$\frac{\partial}{\partial t}(\rho\mathbf{u}) + \nabla\cdot(\rho\mathbf{u}\otimes\mathbf{u}) = -\nabla\underbrace{\left(P+\frac{2}{3}\rho K\right)}_{\text{eff. pressure}} + \underbrace{\nabla\cdot\boldsymbol{\tau}^{*}_{\text{sgs}}}_{\text{nondiag. stresses}} + \rho(\mathbf{g}+\mathbf{f}_{\text{ext}})$$

$$\frac{\partial}{\partial t}\rho E + \nabla\cdot(\rho\mathbf{u}E) = -\nabla\cdot\left[\mathbf{u}\left(P+\frac{2}{3}\rho K\right)\right] + \nabla\cdot(\mathbf{u}\cdot\boldsymbol{\tau}^{*}_{\text{sgs}}) + \rho\mathbf{u}\cdot(\mathbf{g}+\mathbf{f}_{\text{ext}}) \underbrace{-\Lambda+\Gamma}_{\text{radiative}} \underbrace{-\Sigma+\rho\epsilon}_{\text{turbulent}}$$

$$\frac{\partial}{\partial t}\rho K + \nabla\cdot(\rho\mathbf{u}K) = \mathfrak{D} + \Sigma - \rho\epsilon$$

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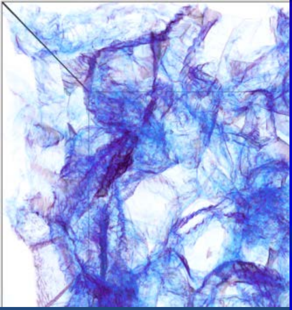

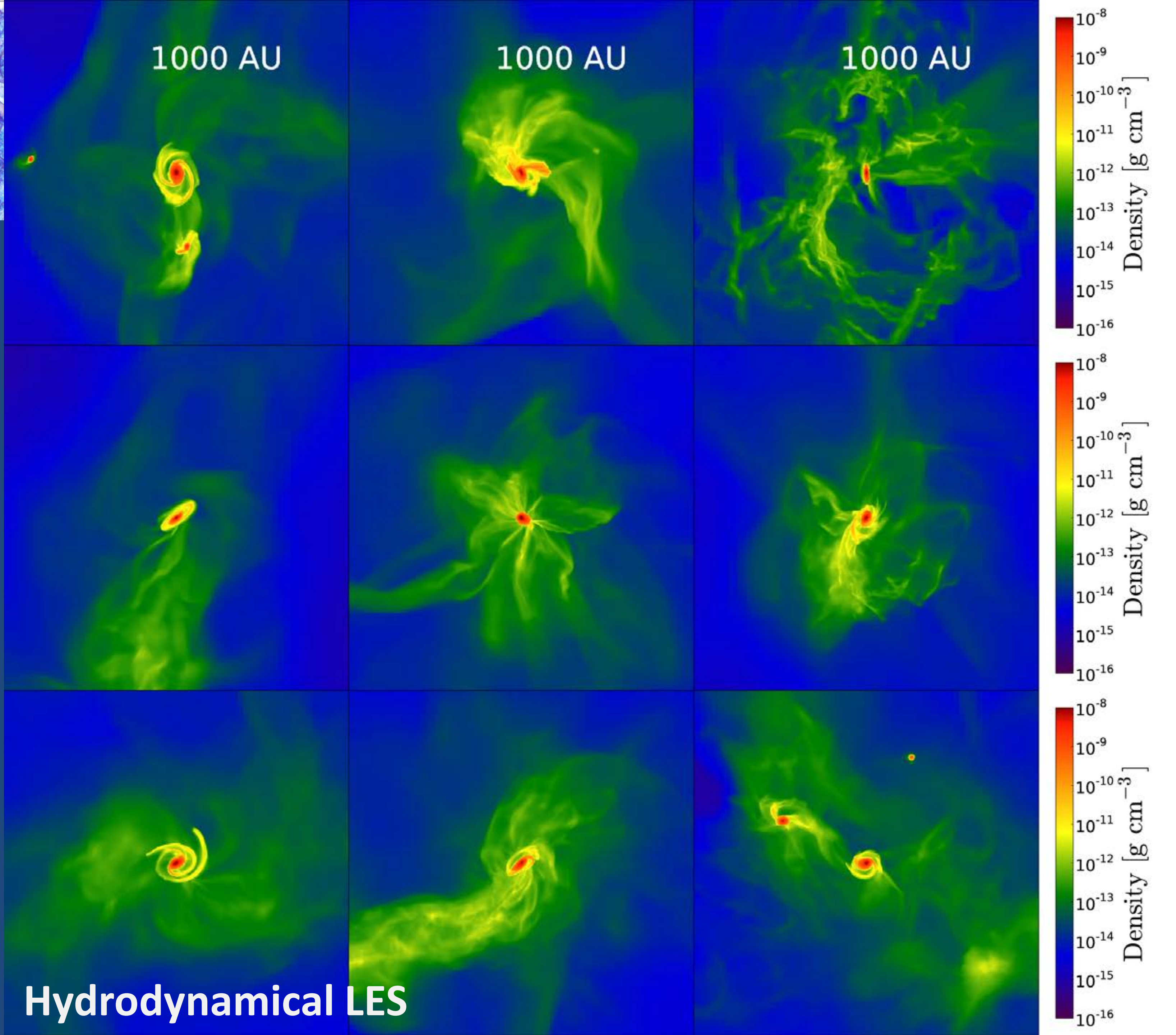

Hydrodynamical LES

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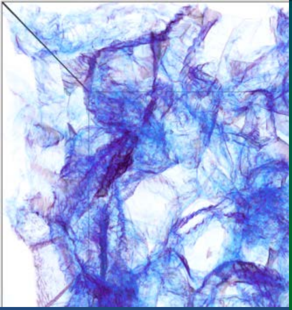
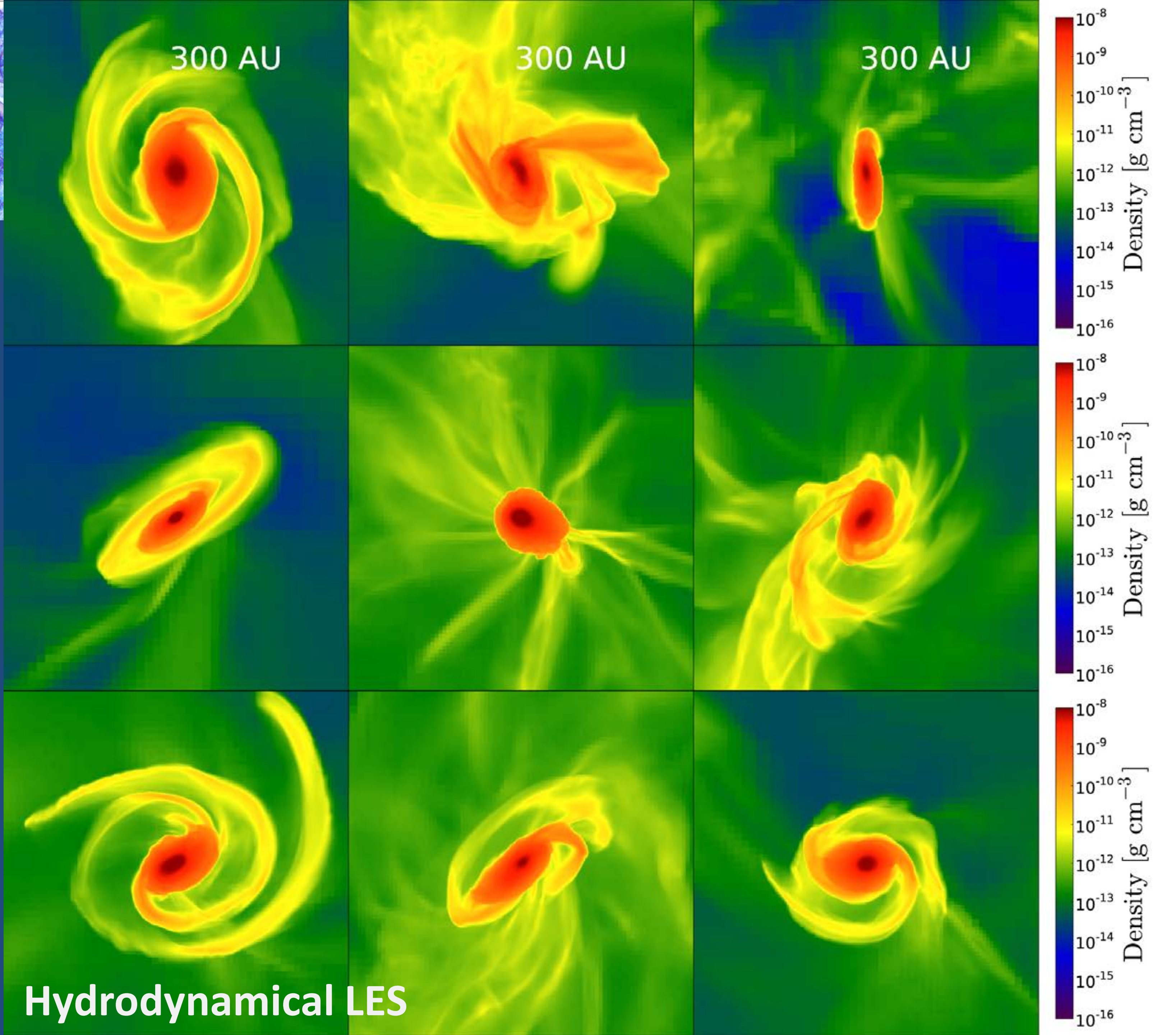


Hydrodynamical LES



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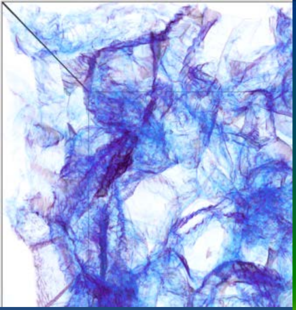
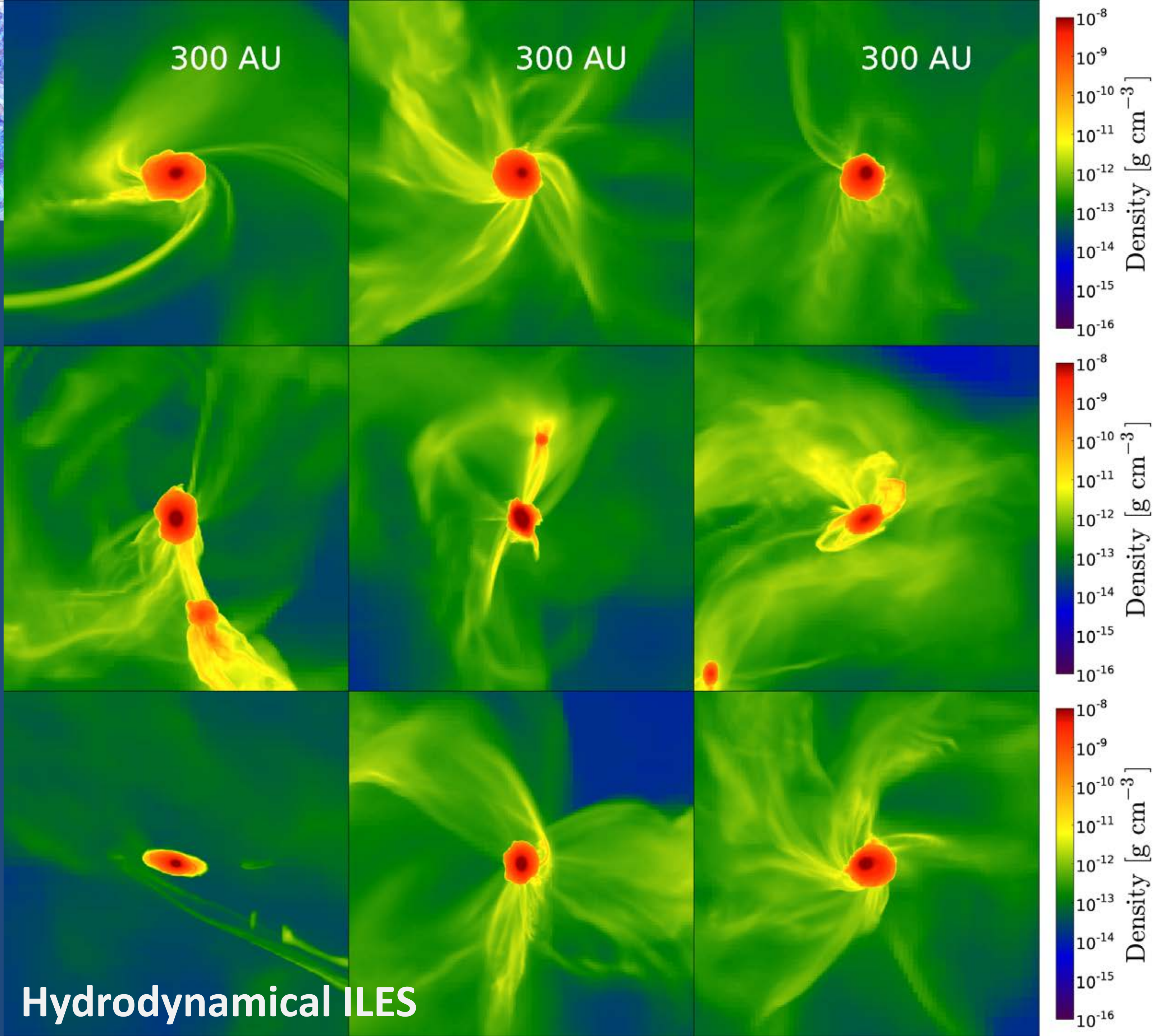
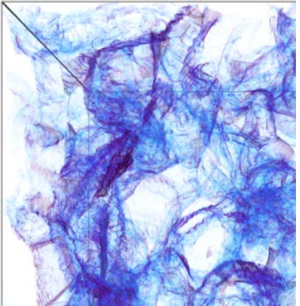




Hydrodynamical ILES



ILES vs LES

	ILES	LES
diffusivity (SGS)	$\nu_{\mathrm{num}} = \nu_{\mathrm{turb}}$?	e.g. $\nu_{\mathrm{sgs}} = C_\nu \Delta K^{1/2}$
dissipation	instantaneous (kin. energy to heat)	intermediate reservoir ρK
turbulent pressure (SGS)	none	$P_{\mathrm{sgs}} = \frac{2}{3}\rho K$
dynamo	increases with $1/\Delta$	closure for $\alpha \boldsymbol{B}$
AMR	numerical cooling/heating	energy bookkeeping ($\frac{1}{2}\rho u^2 \leftrightarrow \rho K$)

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