Dissipation in Turbulent Circumgalactic Environments

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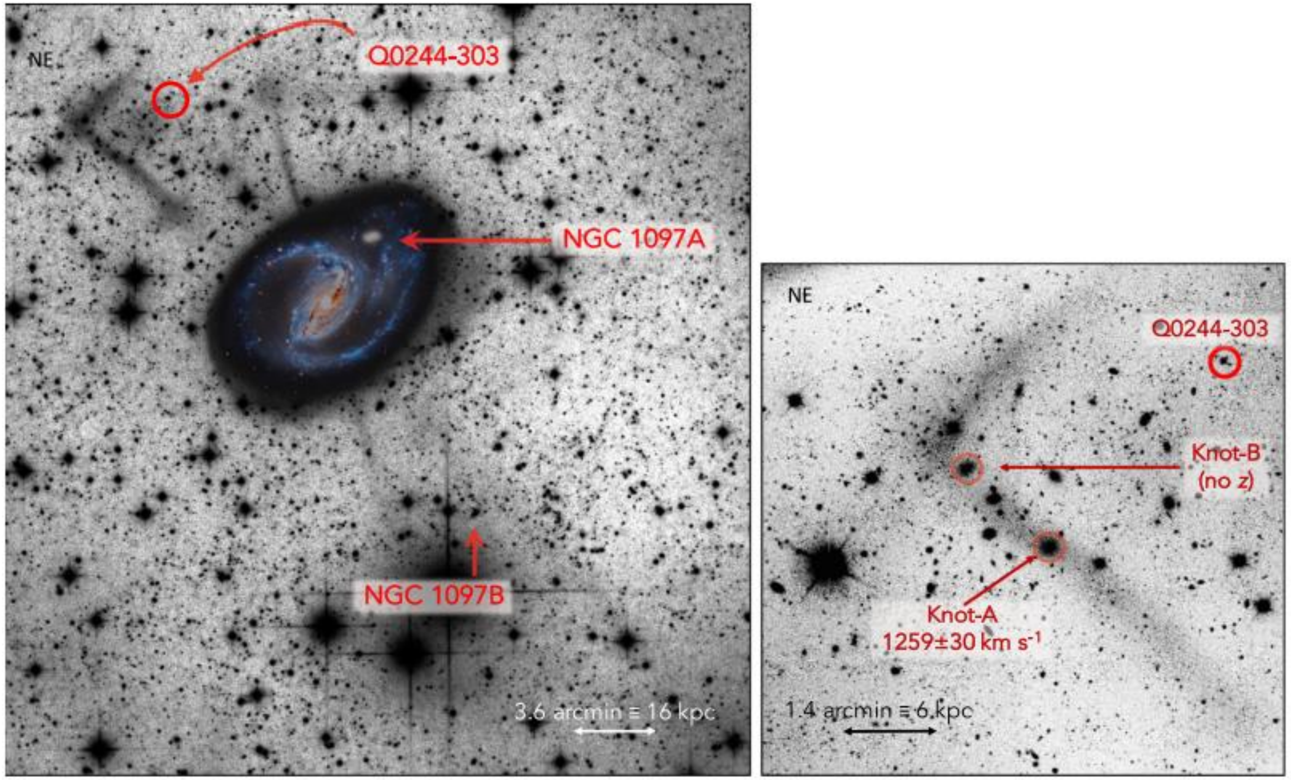
Motivation

- Turbulence driven by gravitational sources (inflows/accretion onto the disc)
- Development of subgrid models to be used in cosmological sims
- Characterization of adiabatic, compressible turbulence (deviates slightly from Kolmogorov theory)



Bowen et al. 2016

Setup

- “Shaking” a periodic box, and then letting the box rest
- Box is 256^3 pc, representing some region within the CGM
- Code used is KRATOS (Wang et al. in prep)
  - GPU code
- Parameter space:
  - Z (metallicity, units of solar metallicity)
  - N (number density, units of /cc)
  - $\dot{\epsilon}_i$ (turbulent energy injection rate, cgs units of erg/cc/s)

Setup cont. - Shaking

- “Uniform” shaking of a periodic box
- Random acceleration applied to each cell uniformly at each timestep

For turbulence injection we follow an approach similar to the one outlined by Mac Low (1999). The entire box is uniformly perturbed uniformly by an acceleration vector along a direction $\hat{a}$ drawn from a spherically uniform distribution at every timestep. While Mac Low (1999) draw their perturbations δv from sampling a range of k up to $|k| = 8$ in Fourier space from a Gaussian random field determined by a specific power spectrum (in this case $k^6 \exp -8k/k_{\rm pk}$ as used in Stone et al. (1998)), we draw our range of k from uniform random distribution in a box in Fourier space from $(-k_m, -k_m, -k_m)$ to (k_m, k_m, k_m), where in our simulations $k_m = \frac{2\pi n_m}{L}$ and $n_m = 1$. By only driving turbulence at the source range, our method does not presuppose an expected power spectrum such that any resulting power spectrum is self-consistent and unbiased. Additionally, since the amplitude of δv has no k dependence, we assume a uniform and time-variable amplitude across the entire box.

The turbulence energy injection rate is computed as

$$\dot{\epsilon} = A\left[(\langle\rho\rangle L^3)^{-1}\Delta t \sum_i m_i \vec{v}_i \cdot \hat{a}\right] \qquad (1)$$

Setup cont. - Physics

- Compressible and adiabatic gas
- Extrapolated standard cooling curve (Sutherland and Dopita, 1993)
- No self-gravity (neglected, since Jean’s length >> box size for CGM environments)

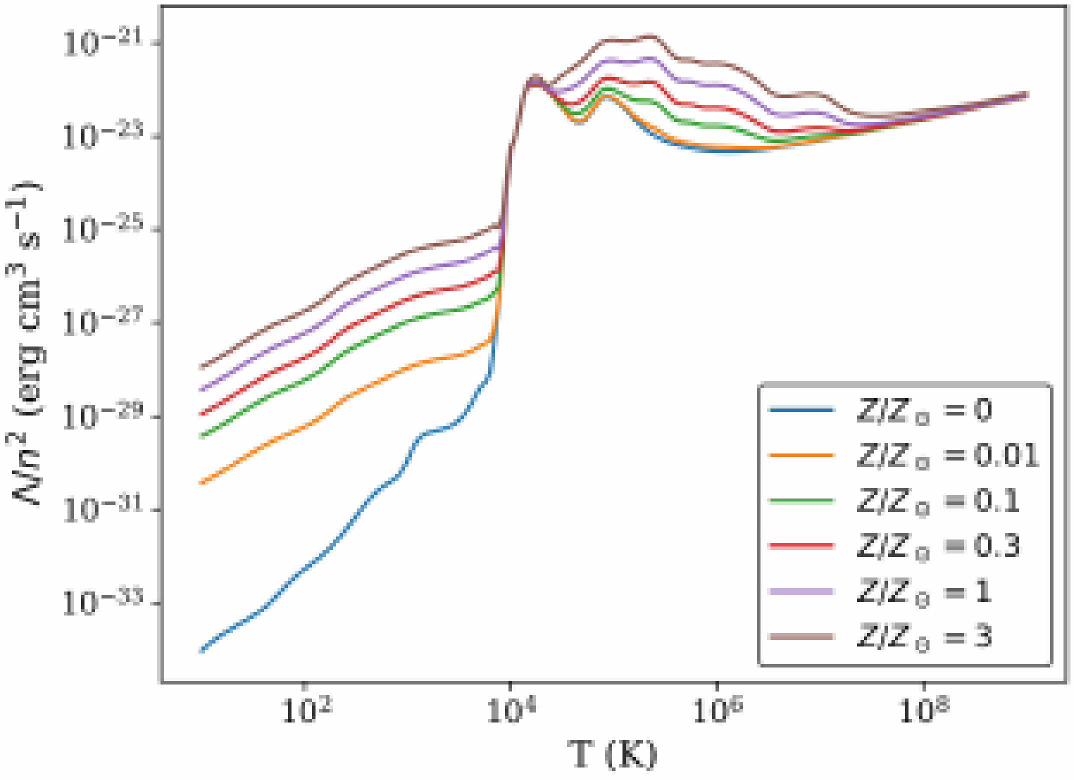


Figure 1. The cooling curves used for our runs. The interpolated and extrapolated curves are computed as $\Lambda(Z/Z_\odot)/n^2 = \Lambda(0)/n^2 + (Z/Z_\odot)(\Lambda(1)/n^2 - \Lambda(0)/n^2)$.

Results

- 1) Two dissipation epochs
- 2) Scaling relations
- 3) Energy Dissipation Timescales
- 4) Structural Dissipation

1) Two dissipation epochs

- Two distinct regimes:
  - Supersonic turbulence -> fast turbulence decay into slow thermal decay
  - Subsonic “turbulence’ -> slow thermal decay only

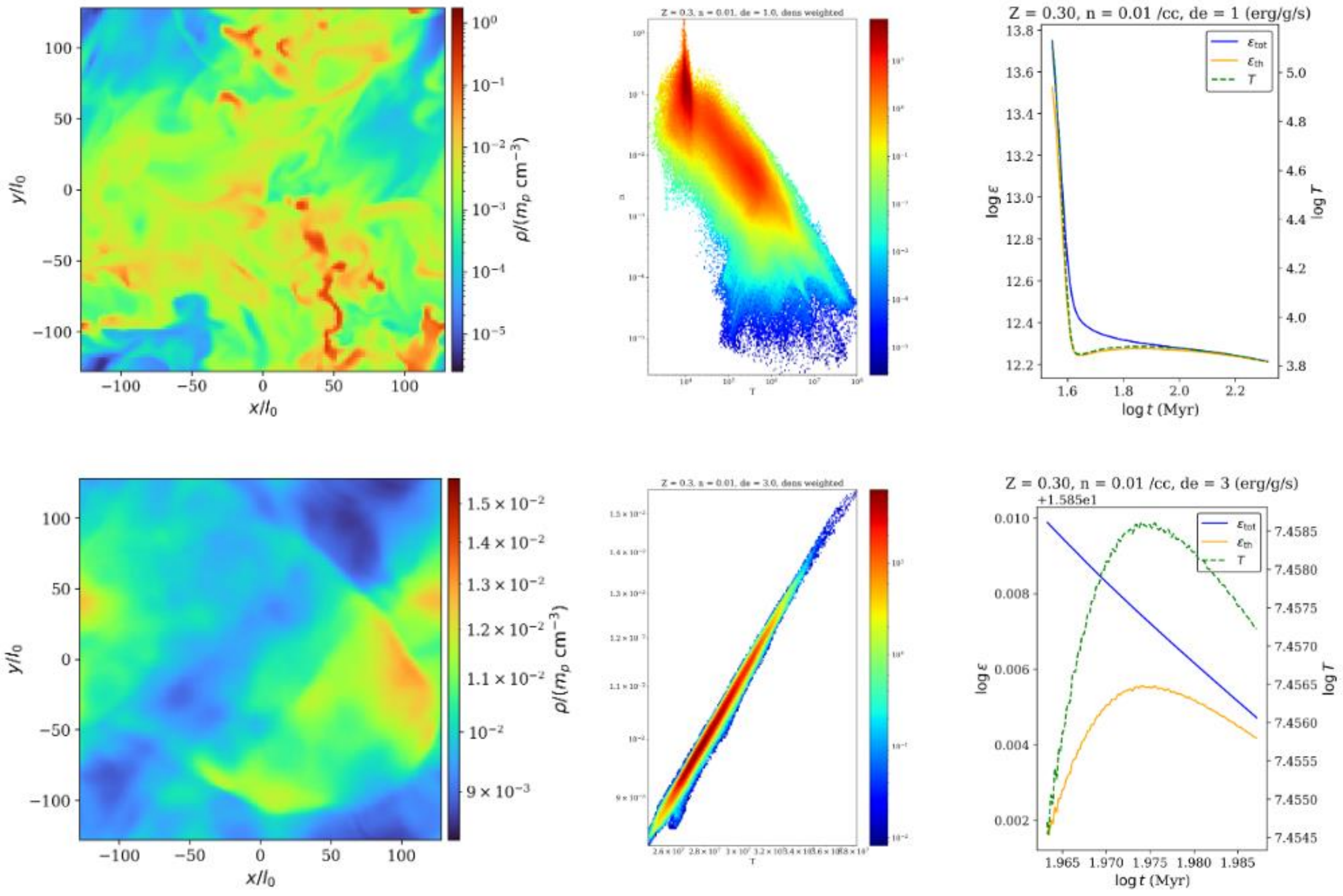


Figure 6. A comparison between two runs with parameters representative of the CGM. In both cases, $Z = 0.3Z_\odot$ and $n_h = 10^{-2}$, with the top and bottom rows representing de $= 1$ ergs^{-1}cm^{-3} and de $= 3$ ergs^{-1}cm^{-3} respectively. The left column shows density slice plots at $z = 0$, the middle column the mass-weighted density-temperature phase plots, and the right column the specific total and thermal energies and the mass-averaged temperature over time.

Lu, Wang and Cen, in prep

1) Two dissipation epochs

- Clear bimodality between subsonic and supersonic regimes
- Results from distinct "stable points" on the cooling curve during the turbulence driving epoch

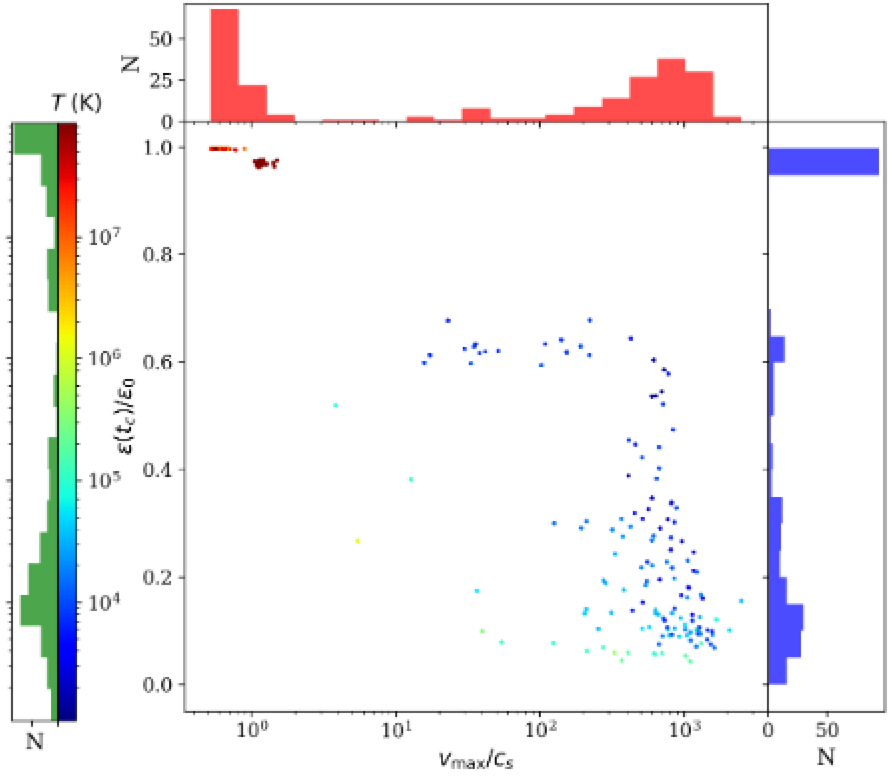


Figure 2. A scatter plot plotting the maximum mach number vs the crossing time fractional energy decay. Each point represents one of our runs. $v_{\max}$ is computed from the cell with the highest velocity and c_s is computed from the mass-averaged temperature of the entire box. t_c represents one mass-averaged crossing time $\langle t_{\rm cross}\rangle = \ell/\langle v\rangle$ computed using the initial mass-averaged velocity $\langle v\rangle = \frac{1}{M_{\rm box}}\sum \rho_i V_i|\vec{v}_i|$ computed from the initial state. The color of each point denotes the box's initial mass-averaged temperature, and the green histogram along the colorbar shows the distribution of mass-averaged initial temperatures

Lu, Wang and Cen, in prep

1) Two dissipation epochs

- Energy lost after a single crossing timescale
- High de results in faster thermal decay but not kinetic decay
- Suggests energy cascading timescale << decay timescales

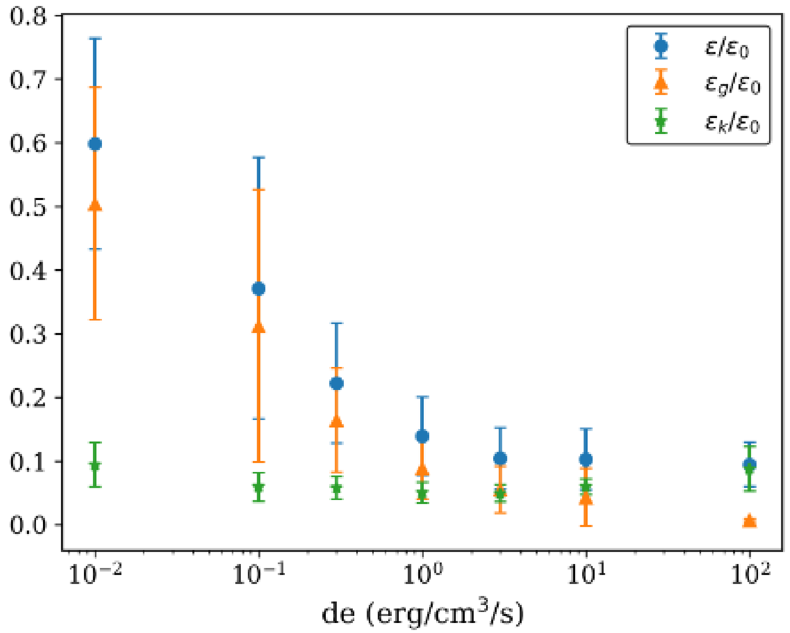
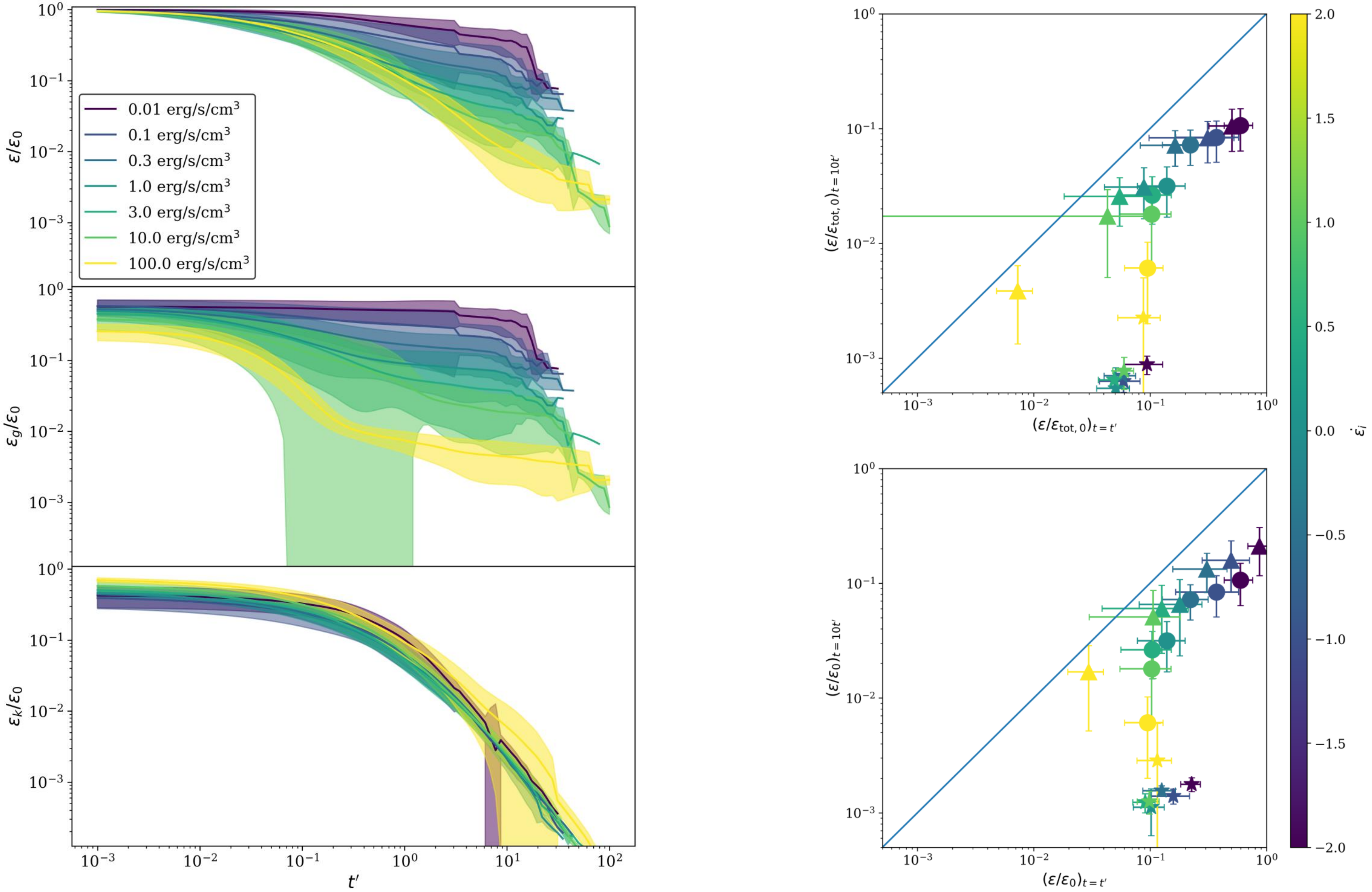


Figure 5. The total, thermal and kinetic energy ratios at $t' = 1$, as a function of de. The definitions of all variables and the error bars can be referred to in Figure 4.

Lu, Wang and Cen, in prep

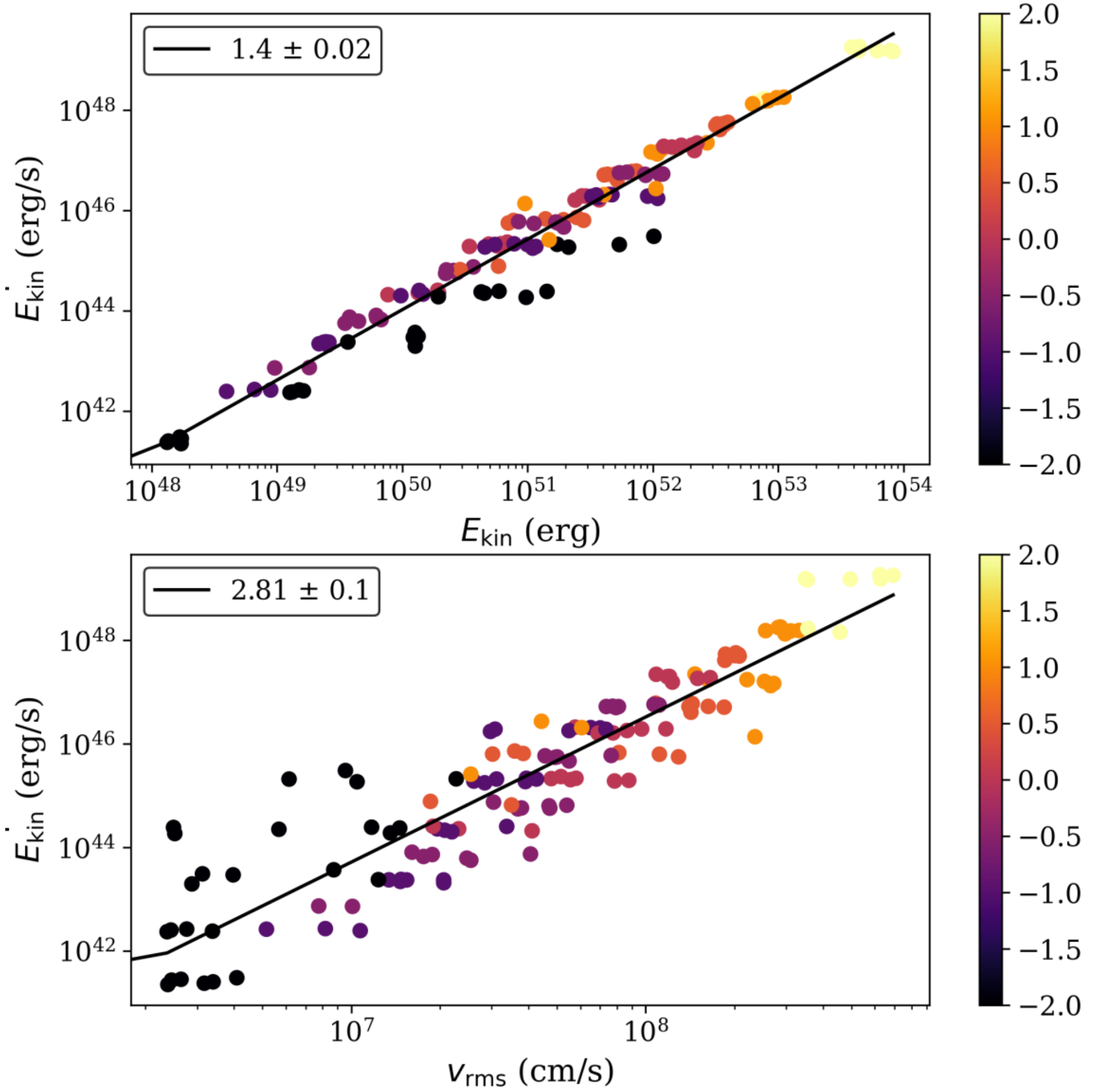


0.01 erg/s/cm^3
0.1 erg/s/cm^3
0.3 erg/s/cm^3
1.0 erg/s/cm^3
3.0 erg/s/cm^3
10.0 erg/s/cm^3
100.0 erg/s/cm^3
$\varepsilon/\varepsilon_0$
$\varepsilon_g/\varepsilon_0$
$\varepsilon_k/\varepsilon_0$
t'
$(\varepsilon/\varepsilon_{\mathrm{tot},0})_{t=10t'}$
$(\varepsilon/\varepsilon_{\mathrm{tot},0})_{t=t'}$
$(\varepsilon/\varepsilon_0)_{t=10t'}$
$(\varepsilon/\varepsilon_0)_{t=t'}$
$\dot{\varepsilon_i}$

2) Scaling Relations

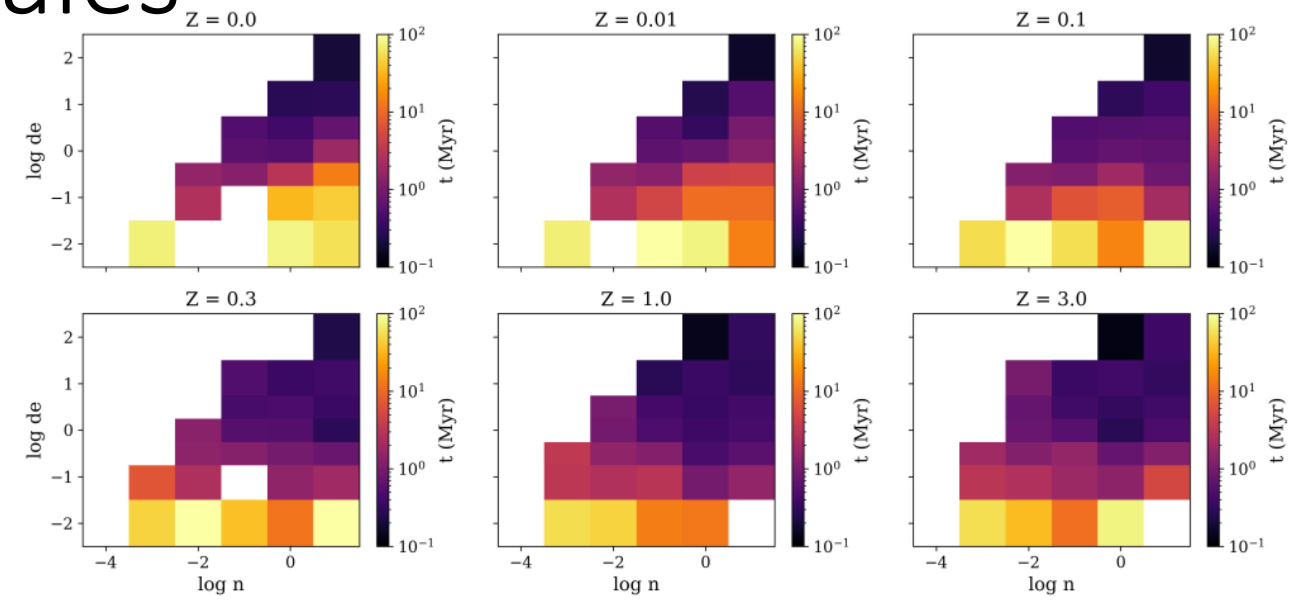
- For isothermal compressible turbulence (Mac Low, 1998):
  - $\dot{E}_{kin} \sim E_{kin}^{\frac{3}{2}}$
  - $\dot{E}_{kin} \sim v_{rms}^{3}$

- Adiabatic EoS + cooling results in slightly different scaling relations

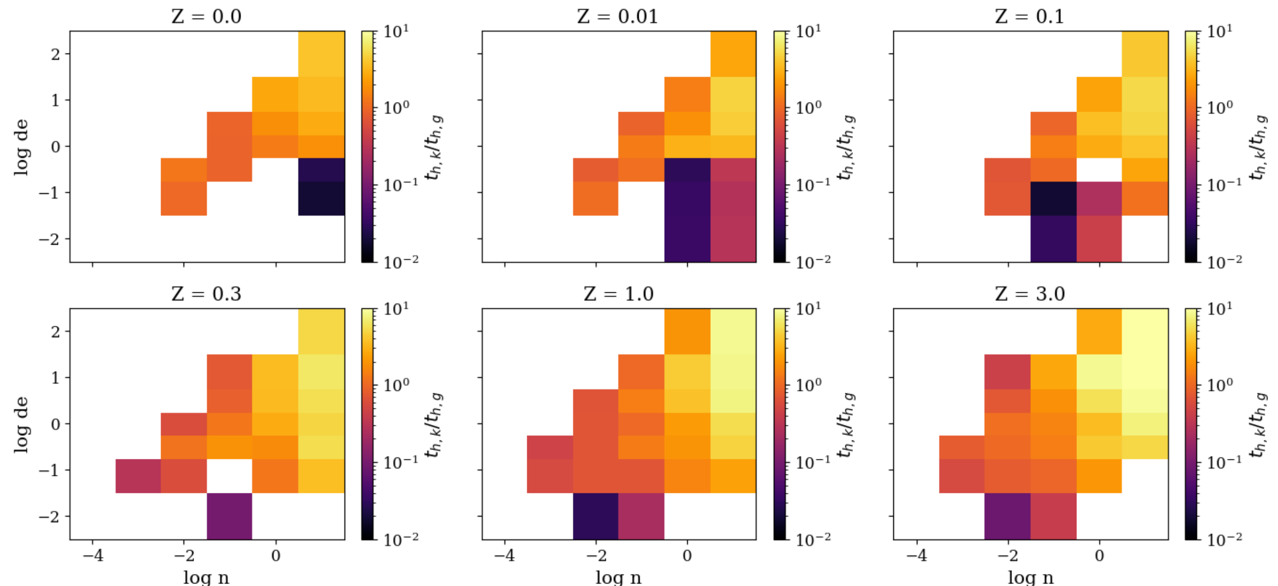


3) Dissipation Timescales

- Total energy dissipation timescale primarily varies with turbulent injection rate

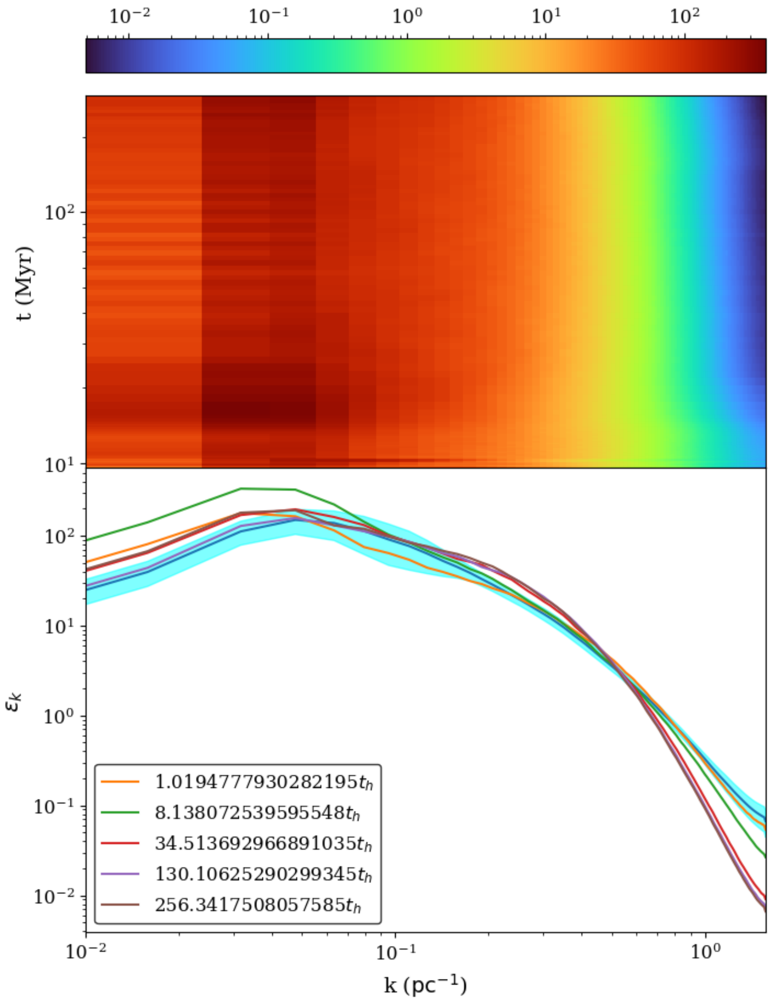


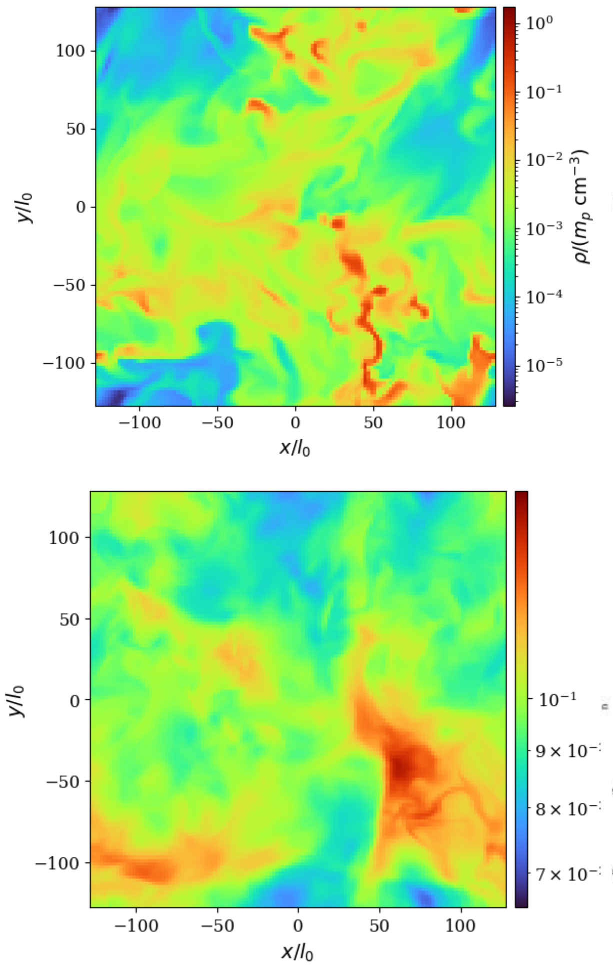
- Thermal dissipation dominates high turb energy, kinetic dissipation low turb energy

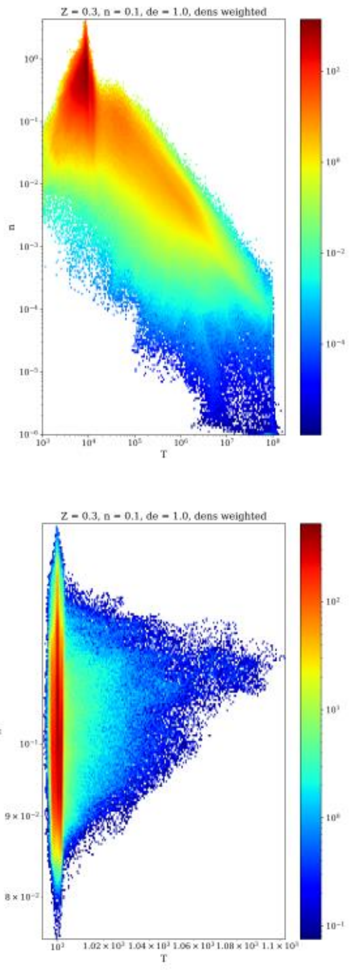


4) Structural dissipation

Z = 0.3, n = 0.1, de = 1





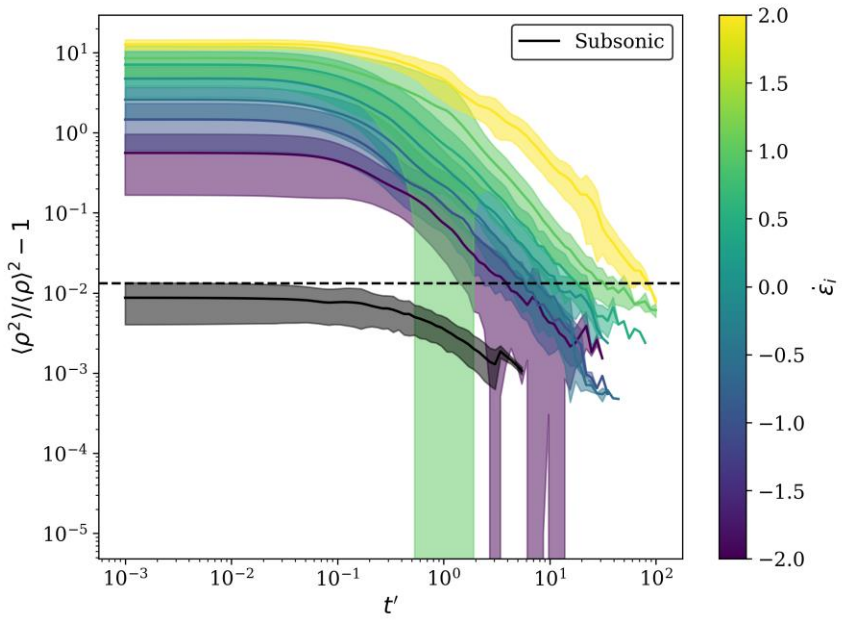


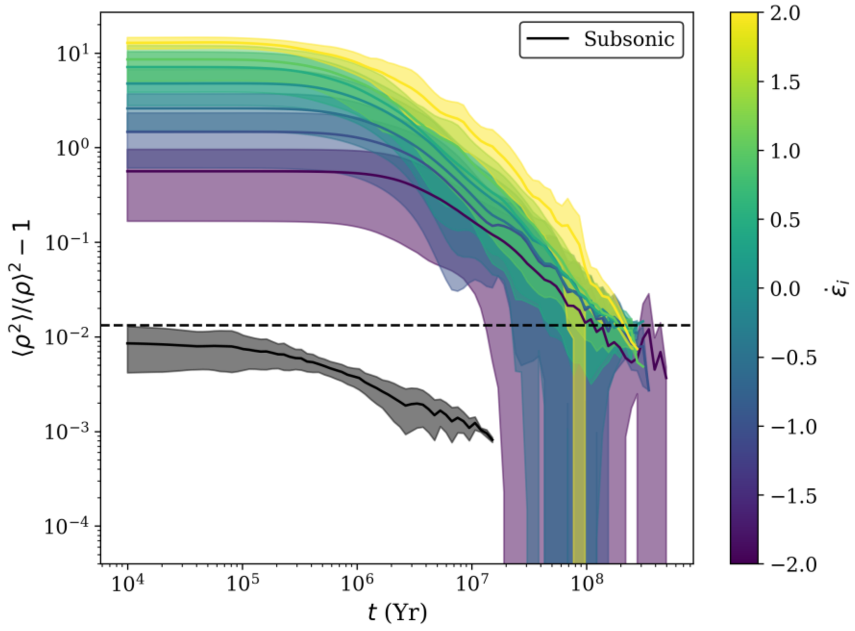
- Drop-off in the power spectrum at high k (small scales)
- Gas becomes highly uniform

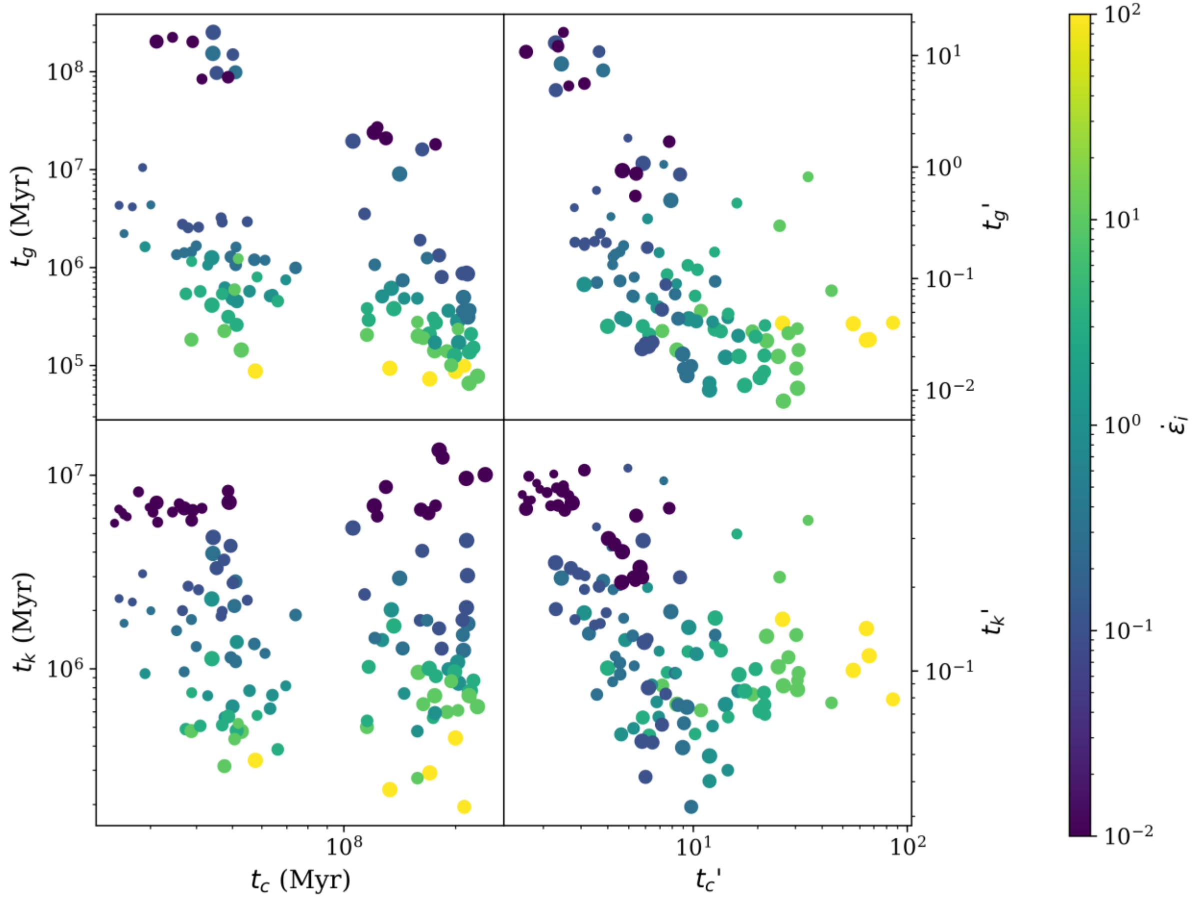
4) Structural Dissipation - cont

- Clumping factor scales with turb energy injection rate

- Time to dissipate = time it takes to reach dotted black line
  - Represents 5σ from the average clumping factor of all subsonic runs
  - Approximately all around 1E8 Yrs, independent of turb energy injection rate

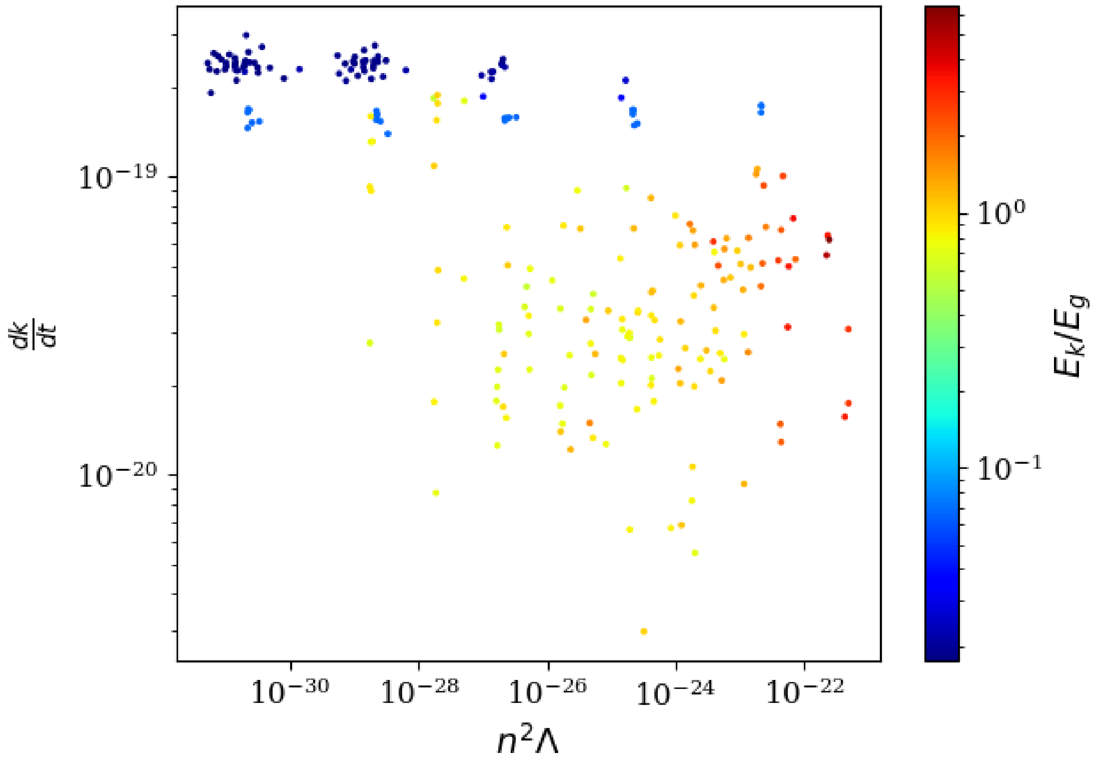


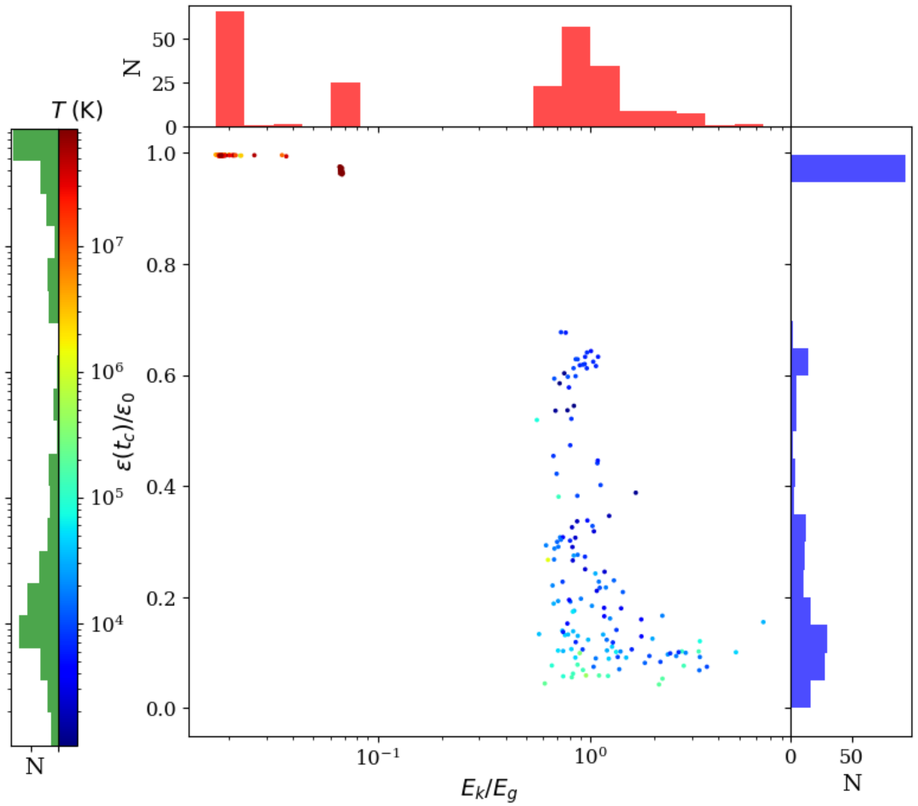



t_g (Myr)
t_k (Myr)
t_c (Myr)
t_c'
t_g'
t_k'
$\dot{\varepsilon}_i$
10^8
10^7
10^6
10^5
10^1
10^0
10^{-1}
10^{-2}
10^2

Conclusions

- 1) Two dissipation epochs
  - Supersonic turbulence – rapid + thermal
  - Subsonic turbulence – thermal only
- 2) Scaling relations
  - 14/5 power law instead of 3 (compared to Mac Low 1999, who used compressible isothermal EoS)
- 3) Energy Dissipation Timescales
  - Thermal dissipation couples more strongly to turb energy injection rate
  - Implies a very rapid energy crossing timescale (cascade from turbulence kinetic to thermal very fast)
- 4) Structural Dissipation
  - Dissipates all within approximately the same timescale





- $E(k) = C\left(\frac{dk}{dt}\right)^{\frac{2}{3}} k^{-\frac{5}{3}}$