Turbulence, Stratification, B-fields in Hot halos

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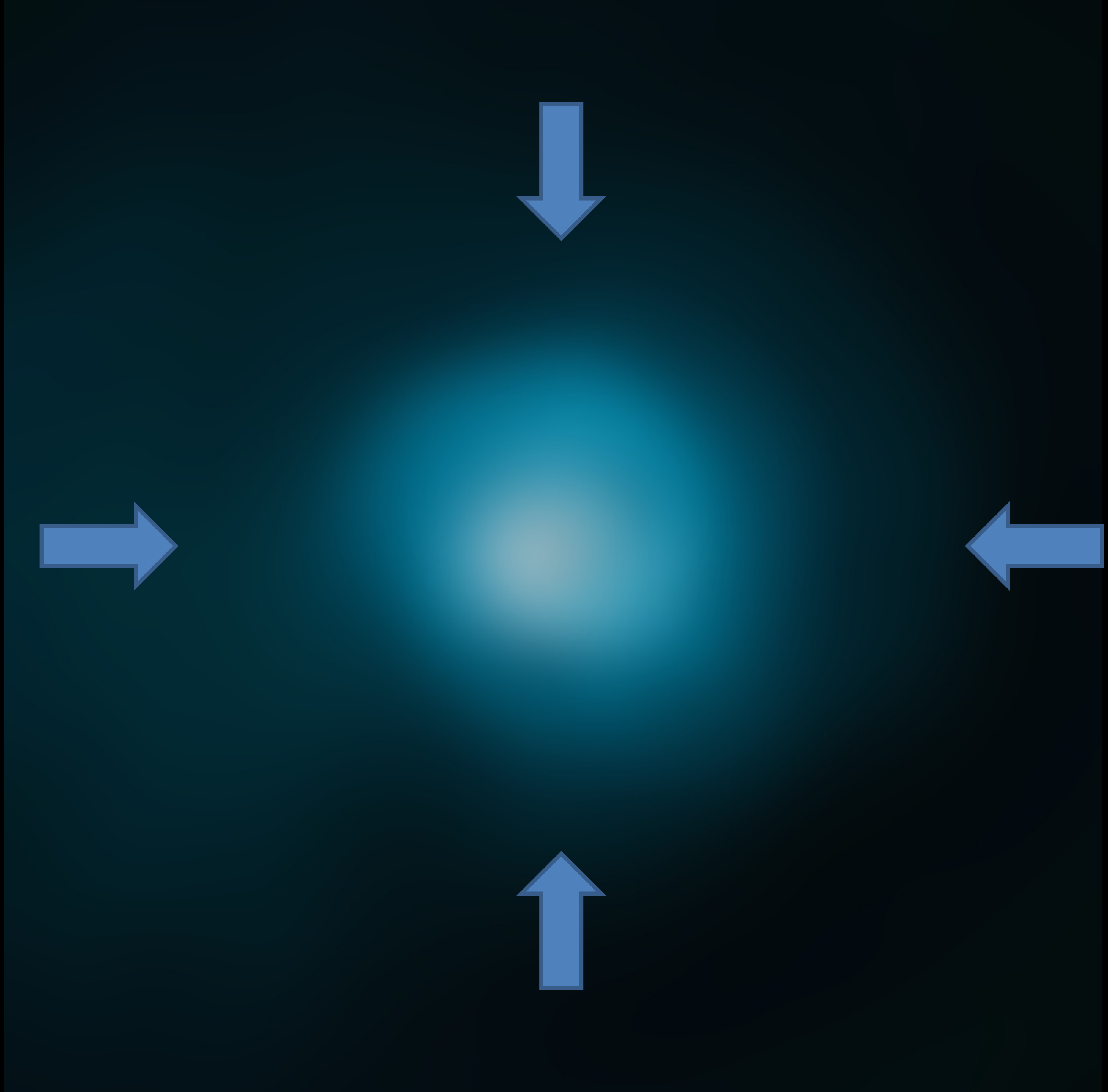
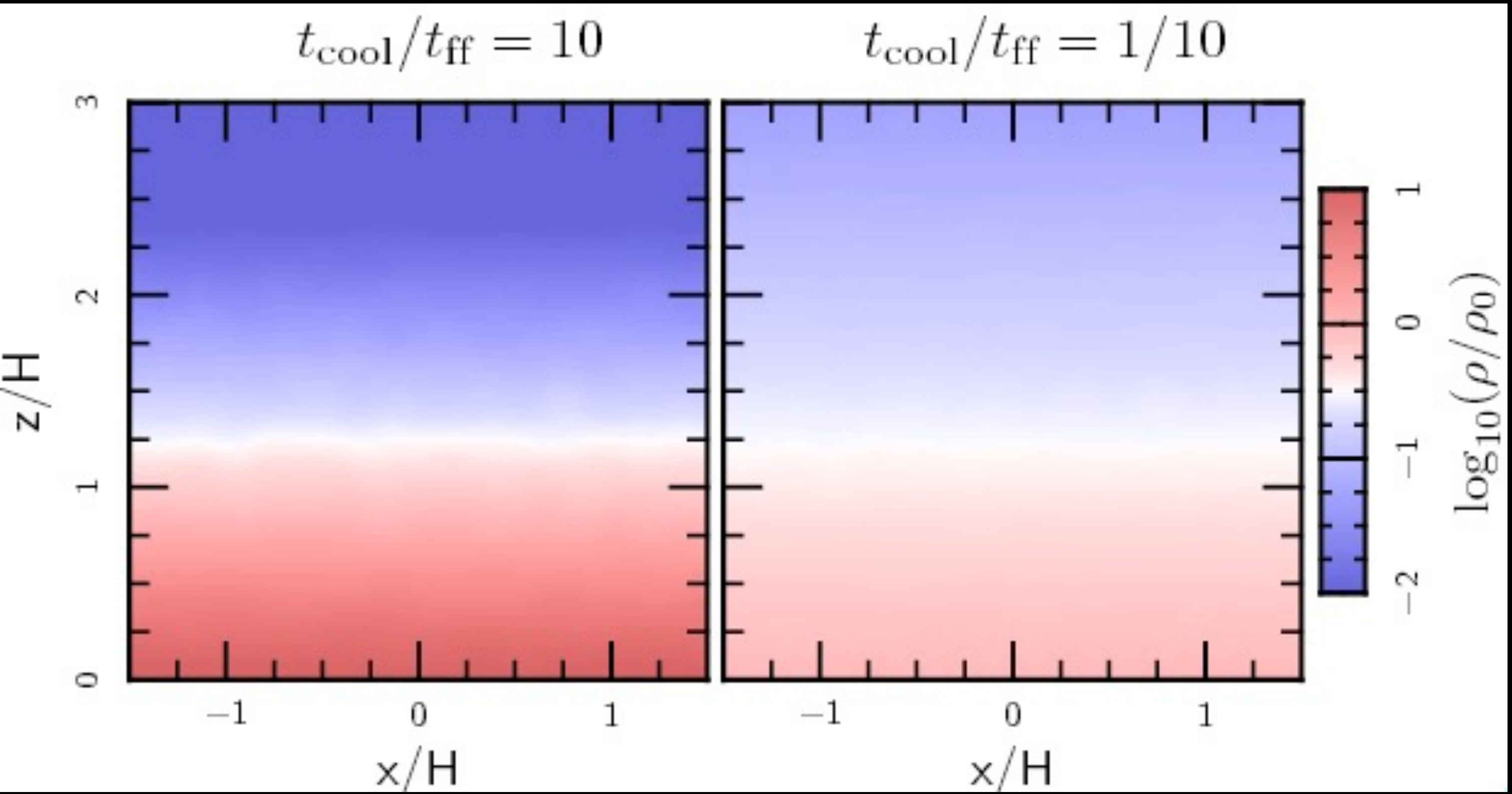
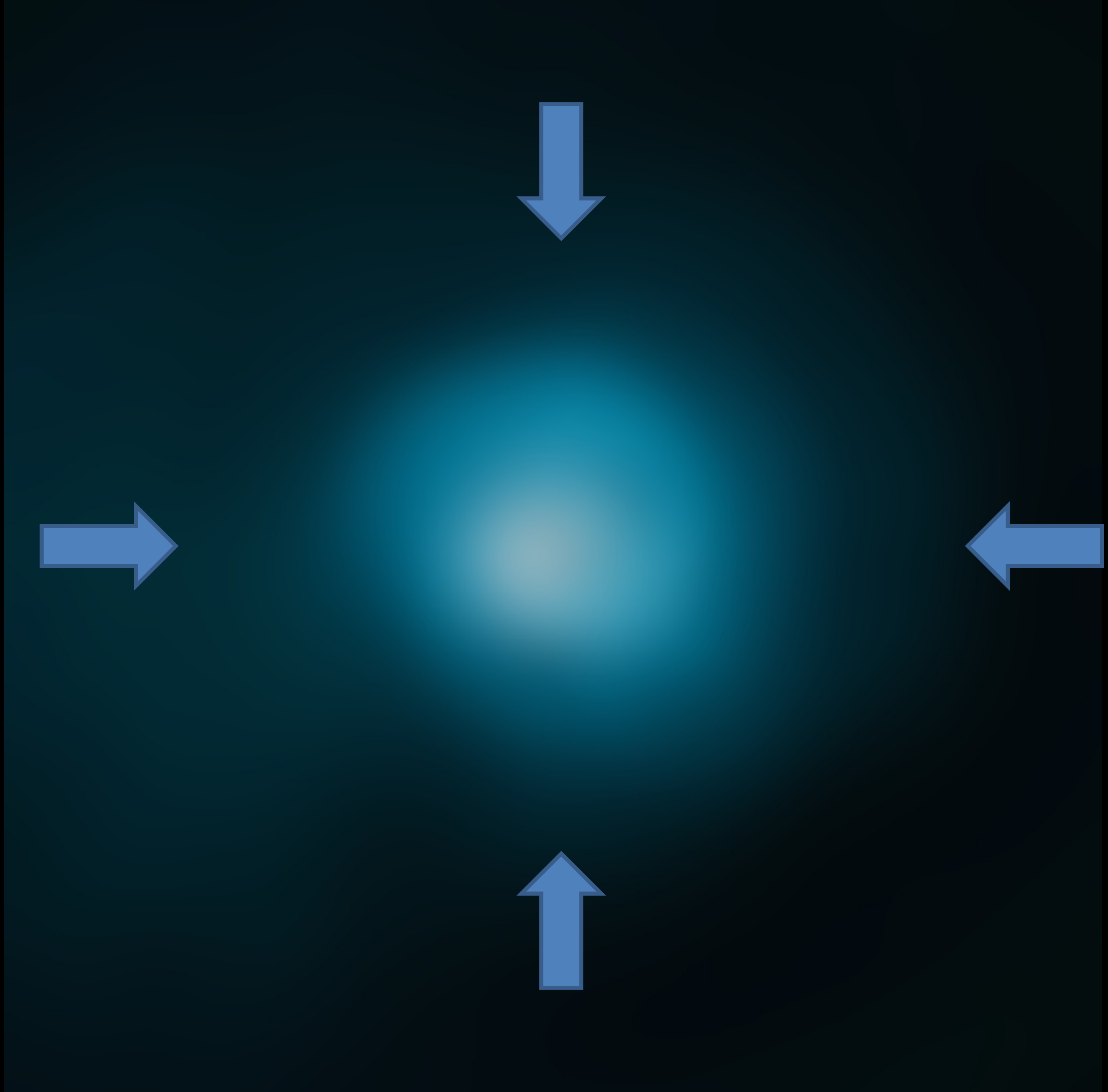
MPA Garching

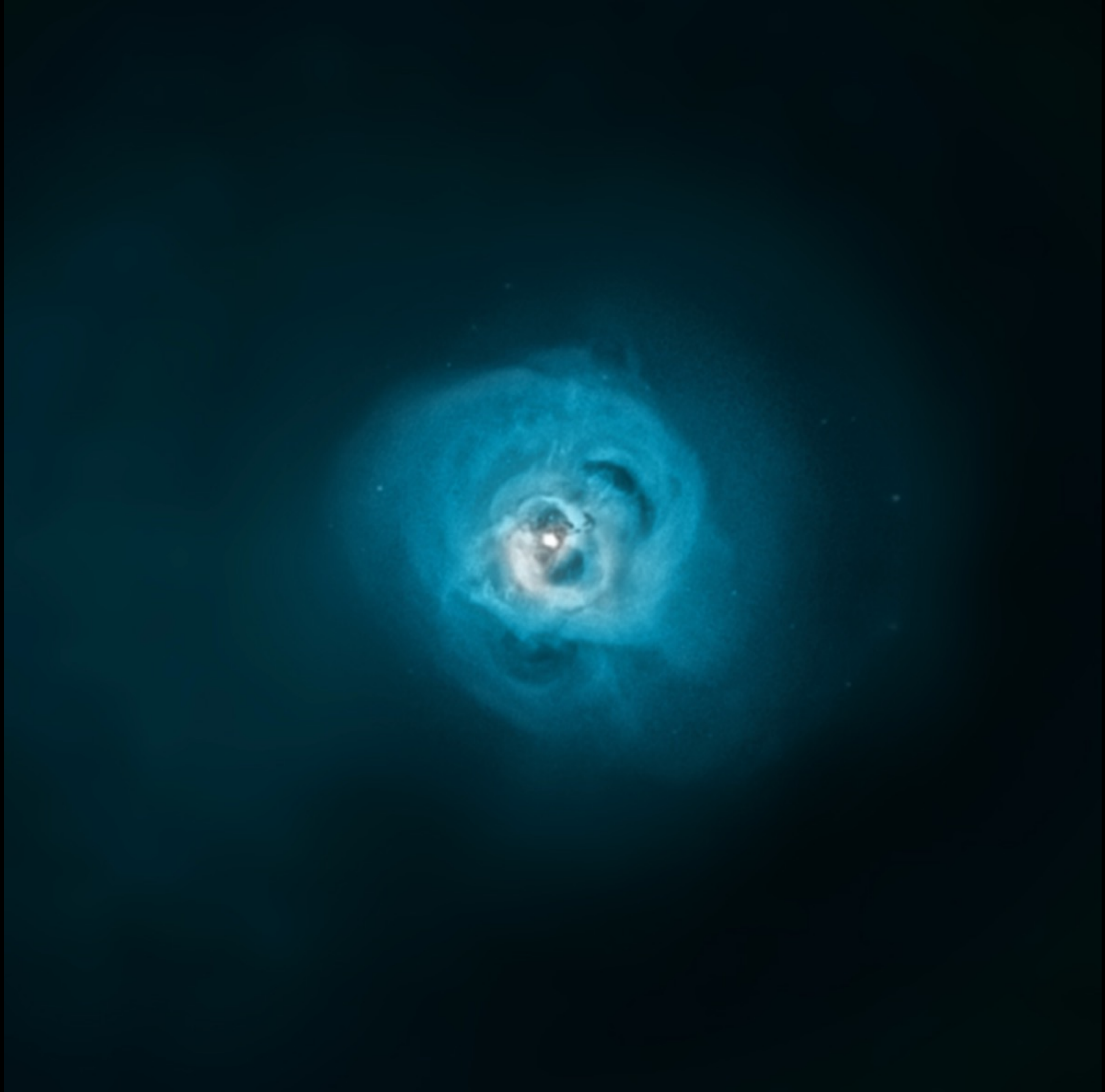


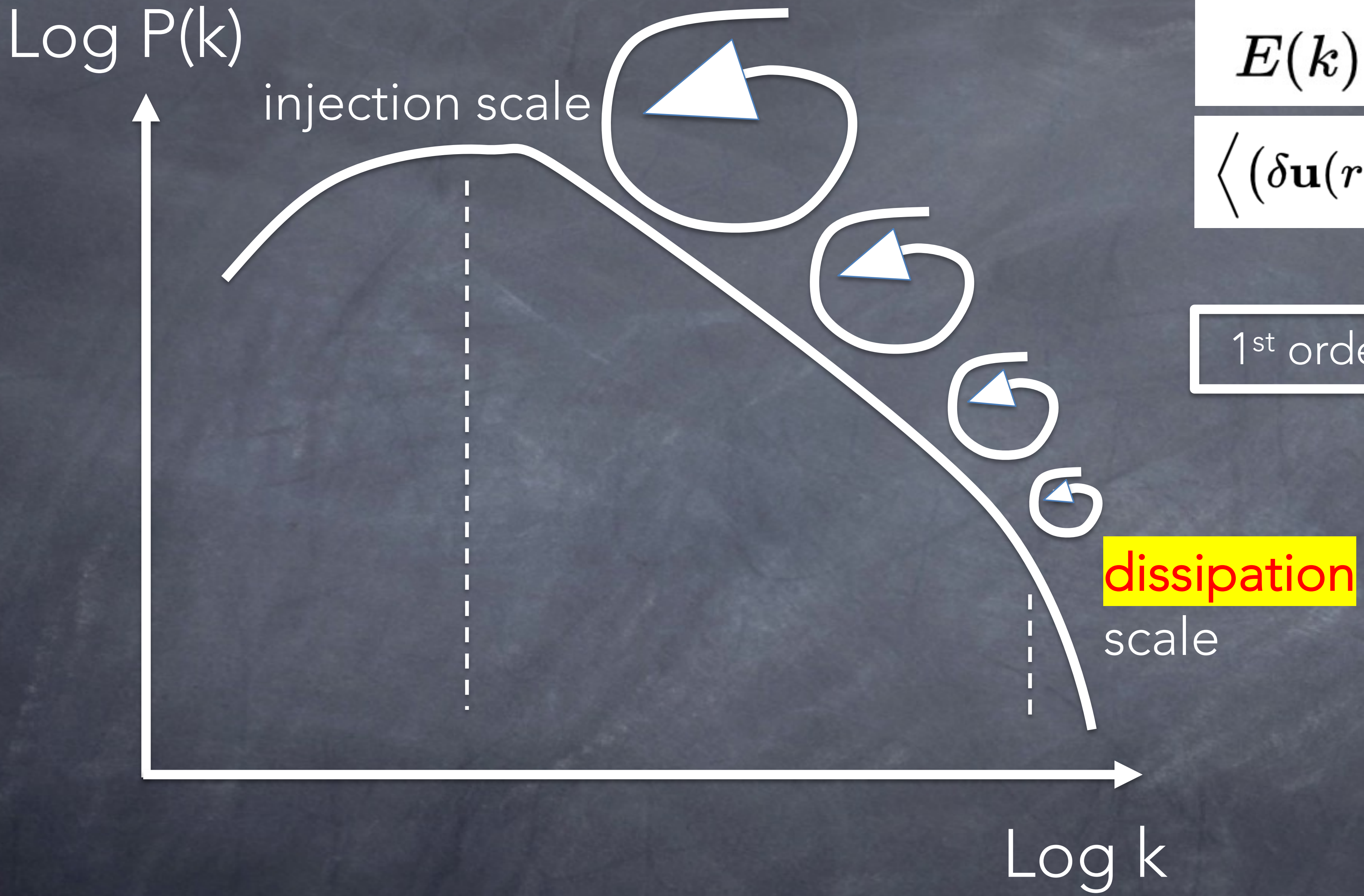
Precipitation & chaotic cold accreion



McCourt, Sharma, Quataert, Parrish 2012
Sharma, McCourt, Quataert, Parrish 2012
Gaspari, Ruszkowski, Sharma 2012
Sharma et al. 2012
Gaspari, Ruszkowski, Oh 2013
Voit, Bryan, O'Shea, Donahue 2015
Yang & Reynolds 2016a,b
Li, Ruszkowski, Bryan 2017
Li, Ruszkowski, Tremblay 2018
Choudhury et al. 2019
Butsky et al. 2020
Nelson et al. 2020





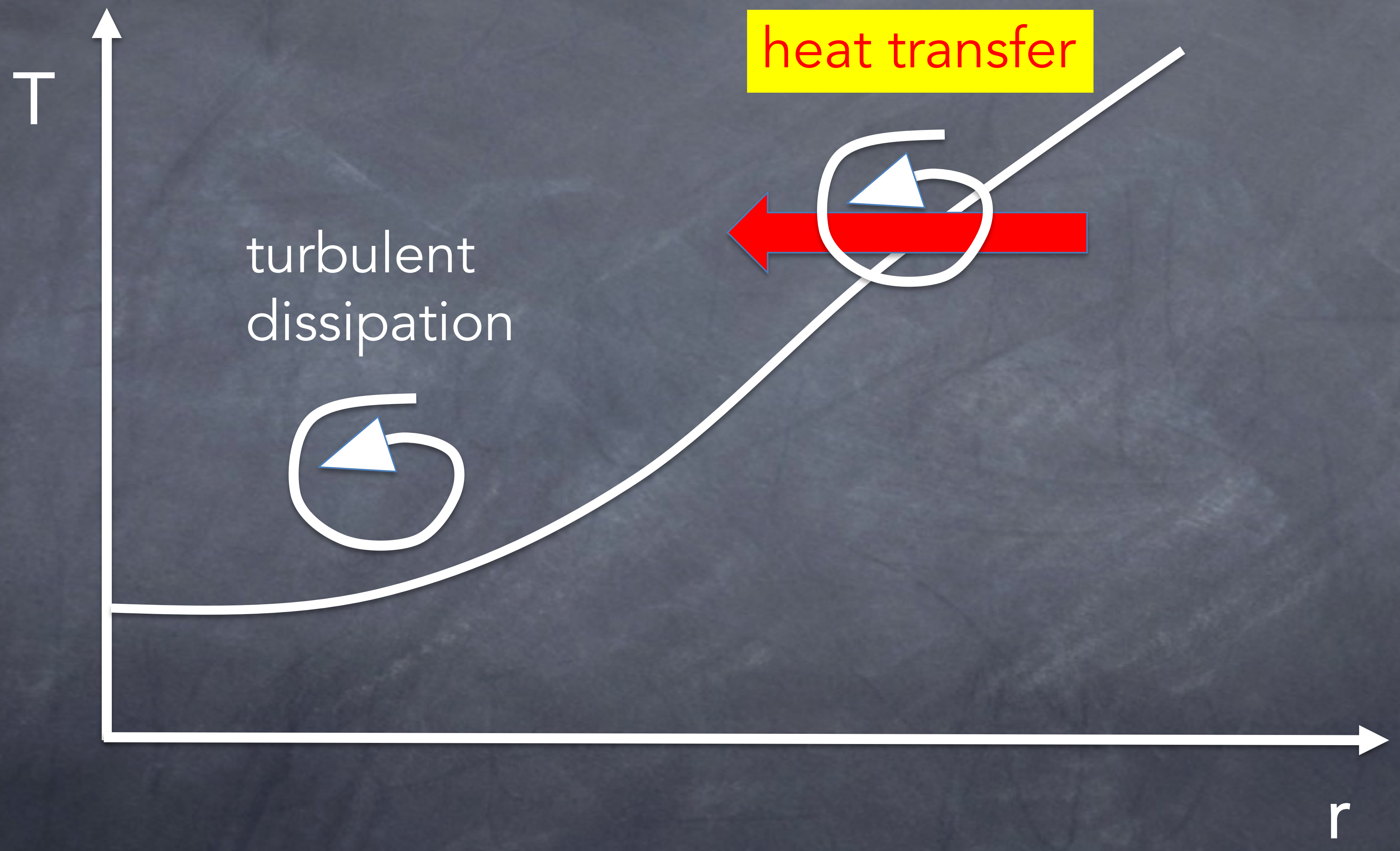


$$E(k) = K_0 \varepsilon^{\frac{2}{3}} k^{-\frac{5}{3}}$$

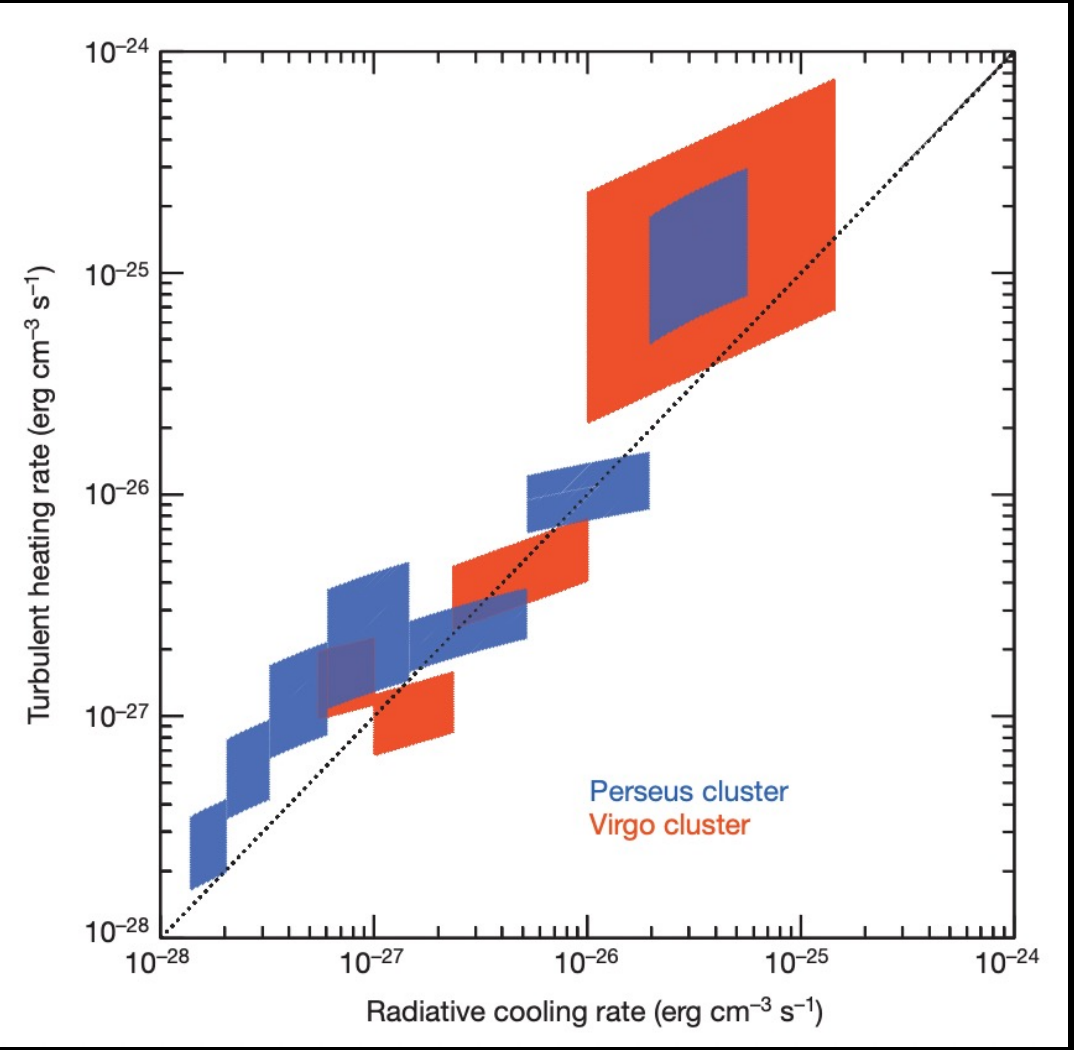
$$\left\langle (\delta \mathbf{u}(r))^n \right\rangle = C_n (\varepsilon r)^{\frac{n}{3}}$$

1st order VSF $\propto r^{1/3}$

Turbulent heating vs radiative losses



Turbulent heating rate

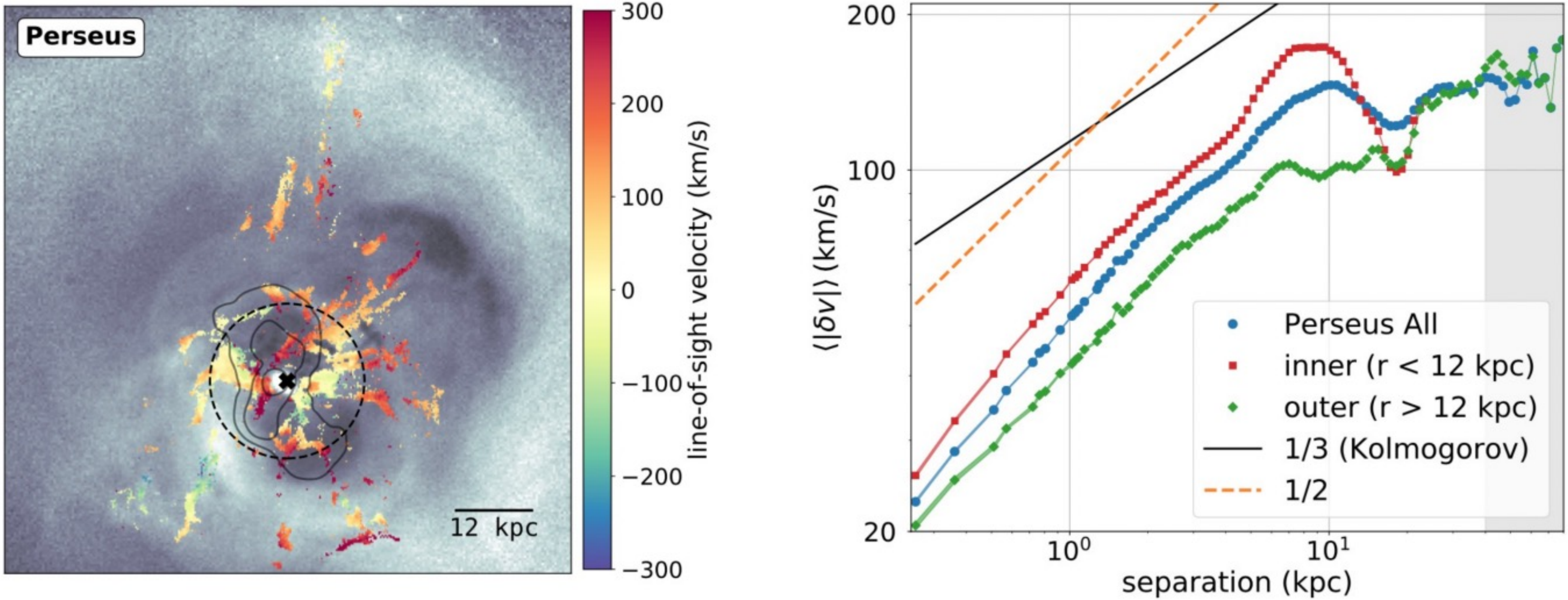


Zhuravleva et al. (2014)

$$\delta\rho_k/\rho_0 \approx \eta_1 V_{1,k}/c_s$$

- Measure density fluctuations
- Infer velocity fluctuations
- **Assume Kolmogorov spectrum**
- Infer dissipation rate

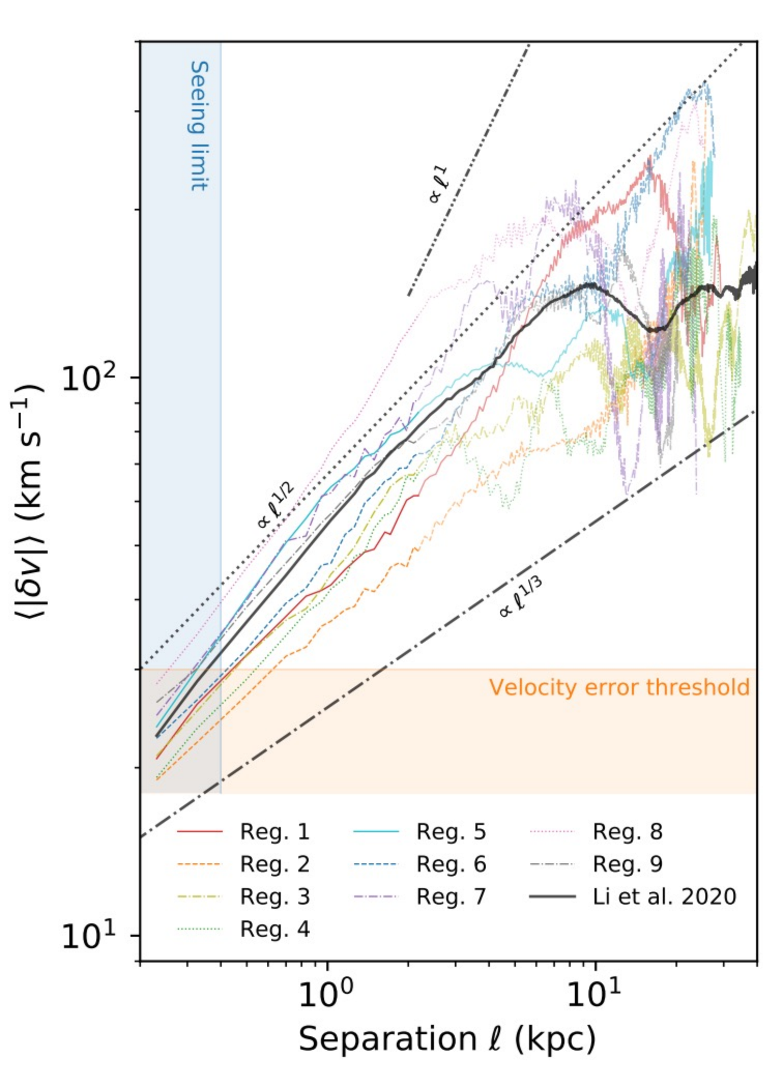
But is turbulence Kolmogorov?

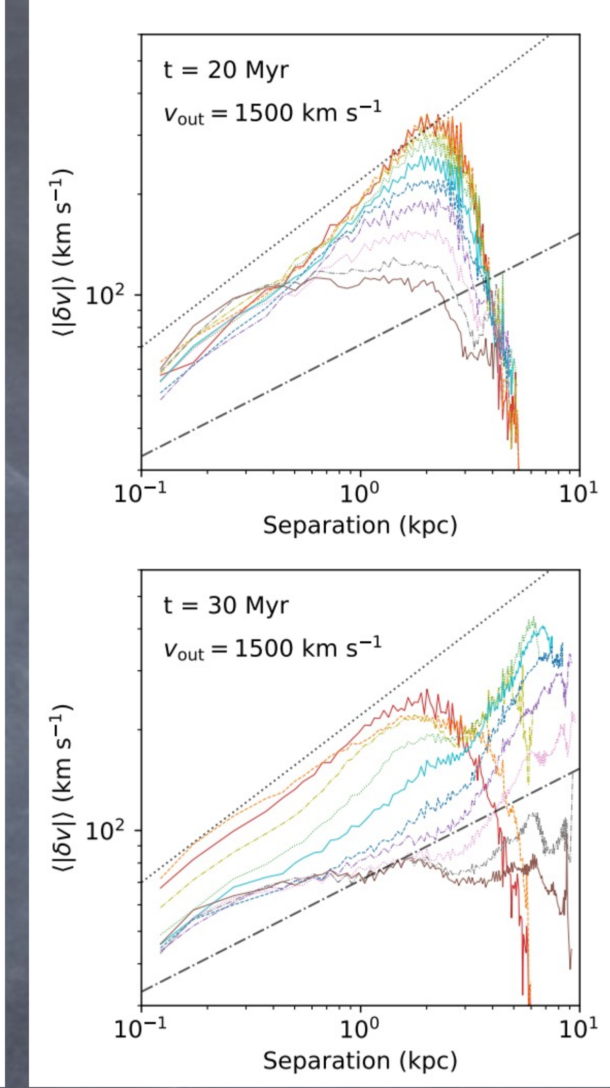


(discovered by) Li et al. (2020)

Possible explanations for non-Kolmogorov VSF

- Supersonic uplift (Hu et al. 2022)
- Kinetic turbulence in collisionless high-β plasma (Arzamasskiy et al. 2022)
- Gravity wave breaking (Mark Voit)
- Driving by AGN jets & precipitatation (Wang et al. 2021)

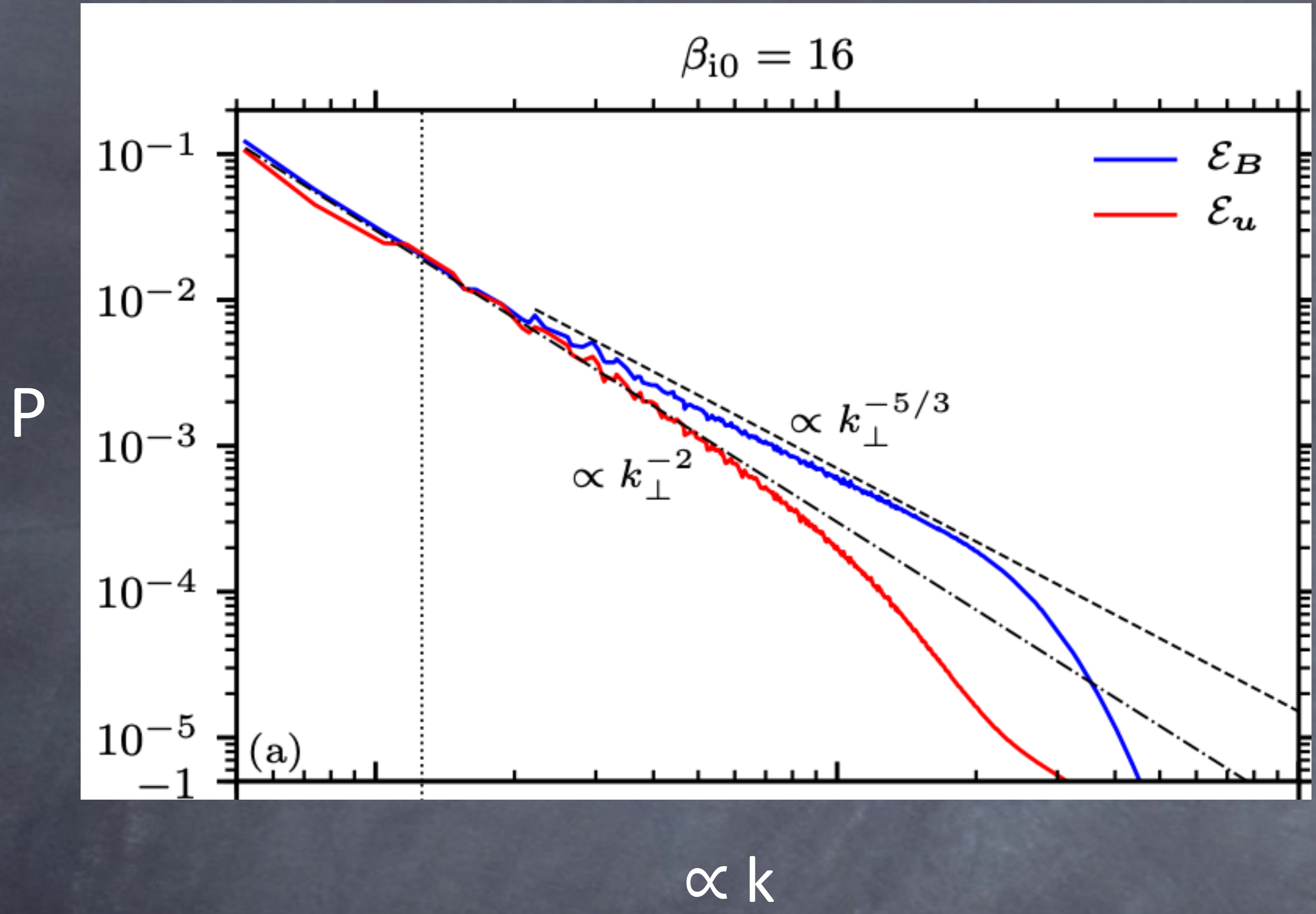




Supersonic turbulence generates VSF steeper than Kolmogorov

Hu et al. 2022: VSF flattens over time

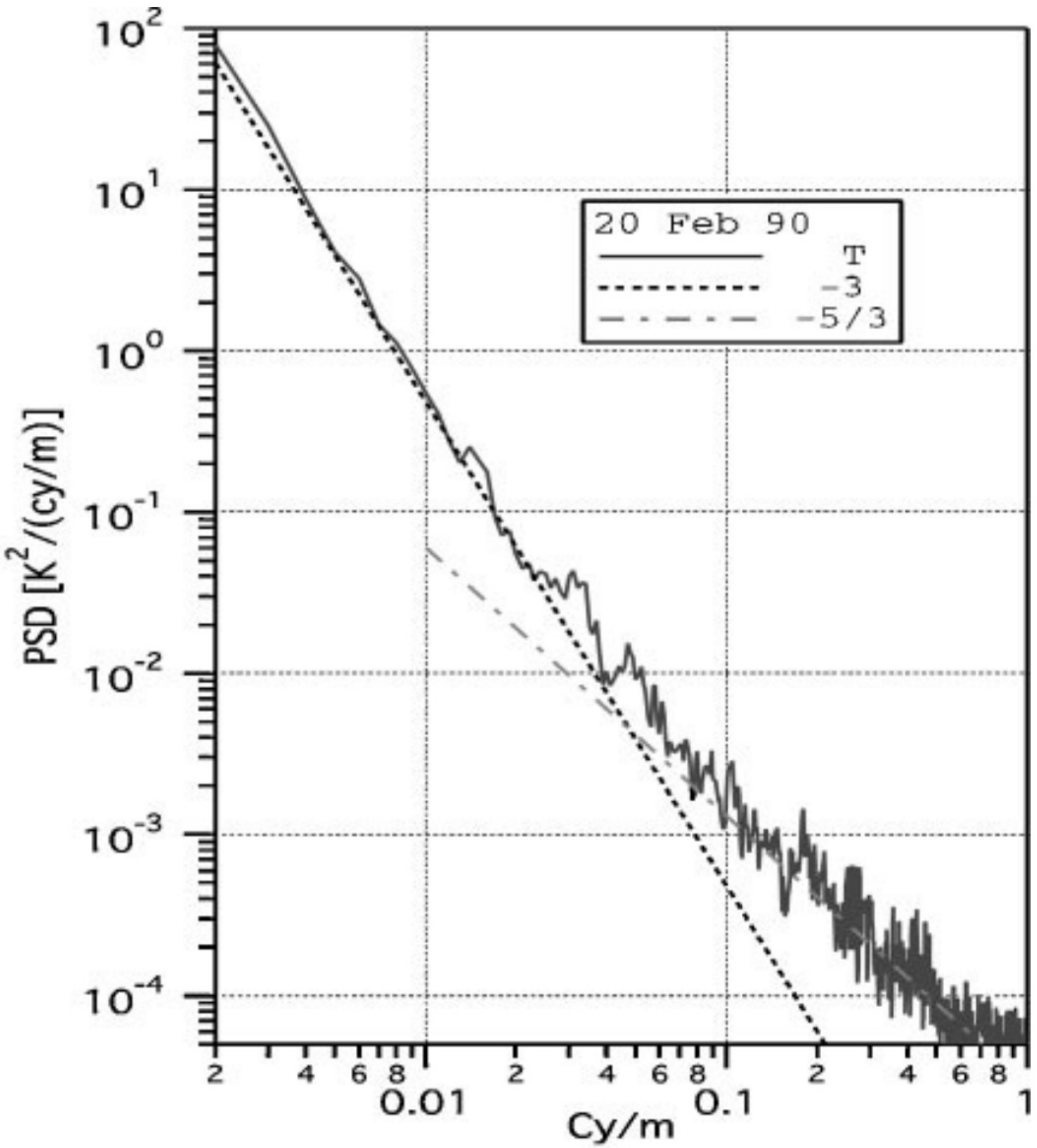
Hα filaments need to be short-lived to explain steep VSF slopes



Kinetic turbulence in collisionless high-β plasma

Arzamasskiy et al. (2022)

more negative P(k) slope → more positive VSF slope

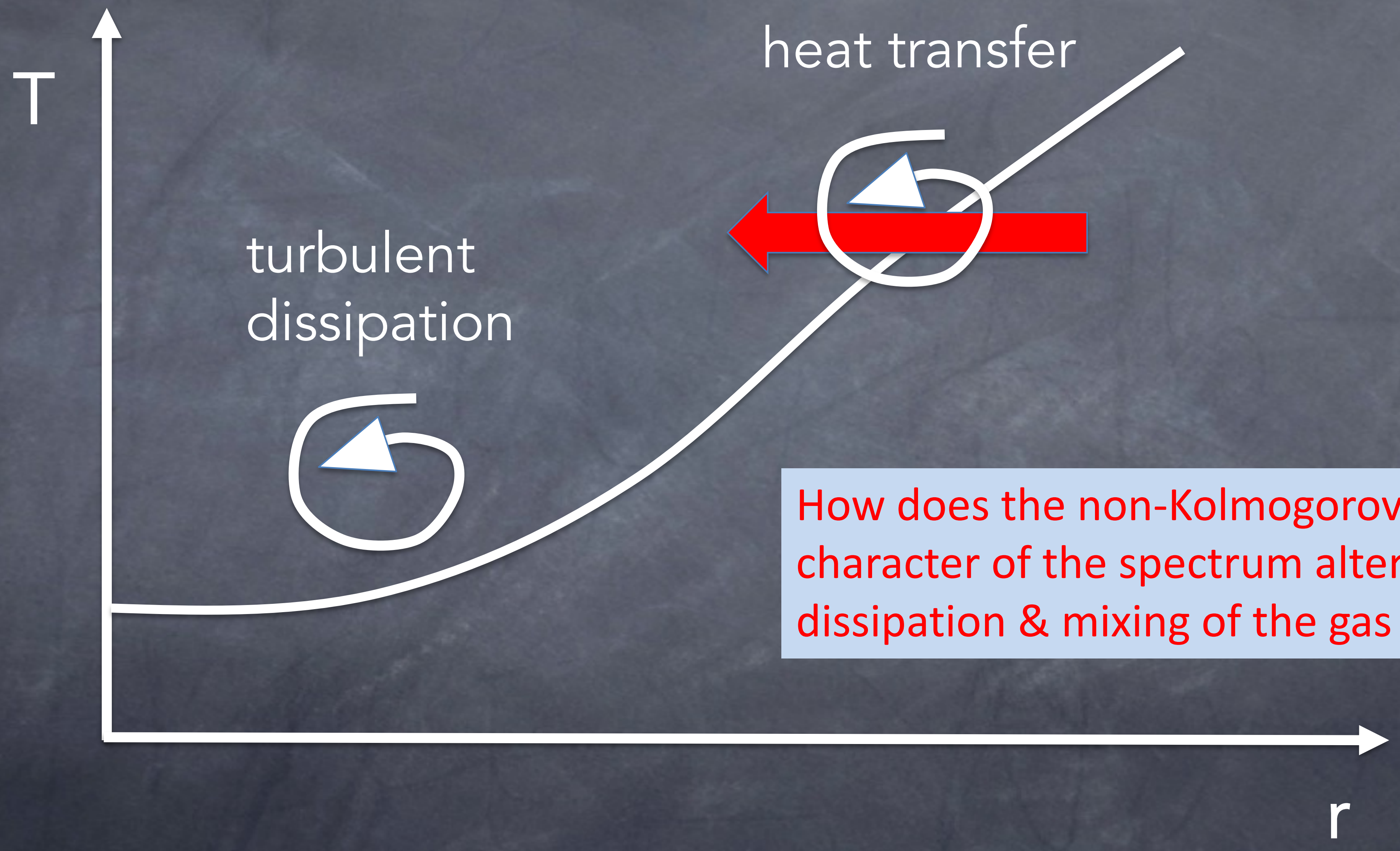


Atmospheric spectra showing:

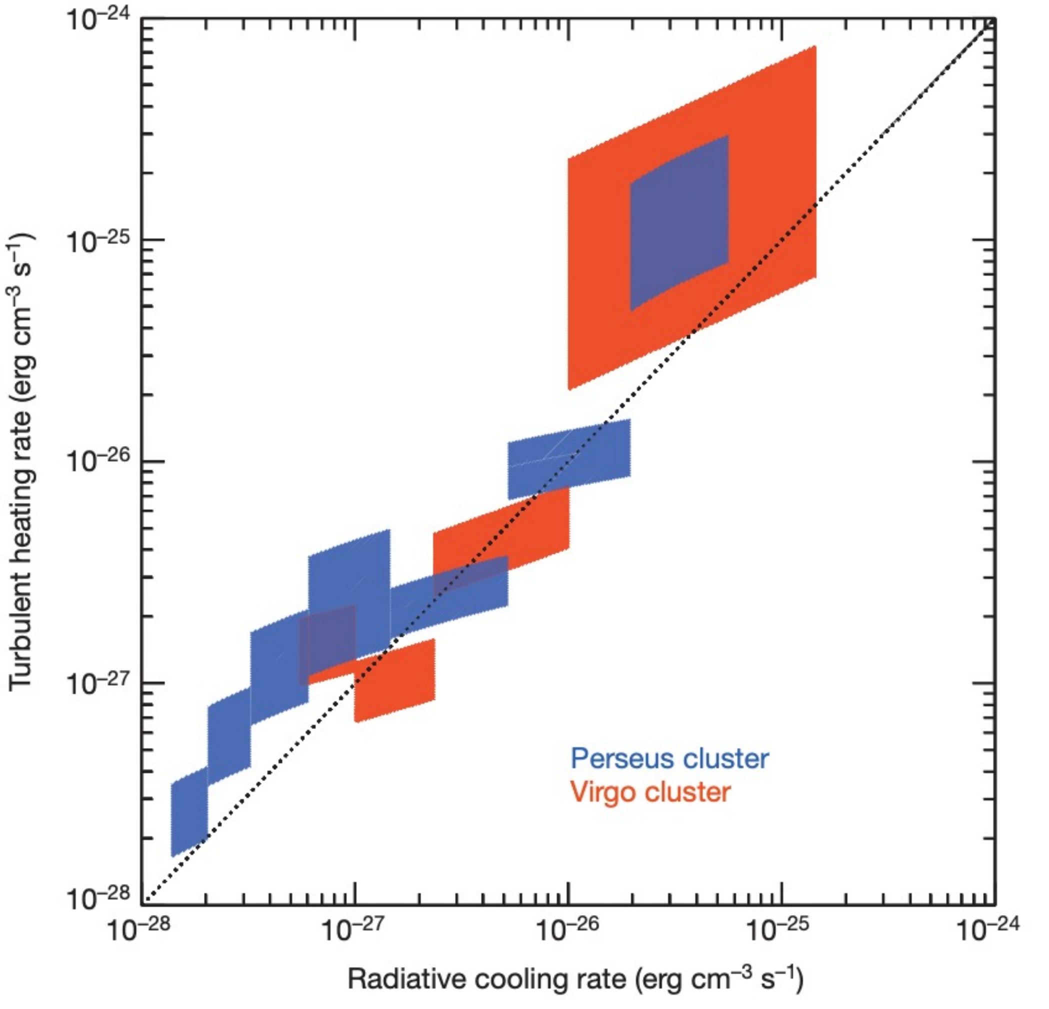
- k^−3
- Kolmogoroff k^−5/3 tail @ high k

Staquet & Sommeria (2002)

Turbulent heating vs radiative losses

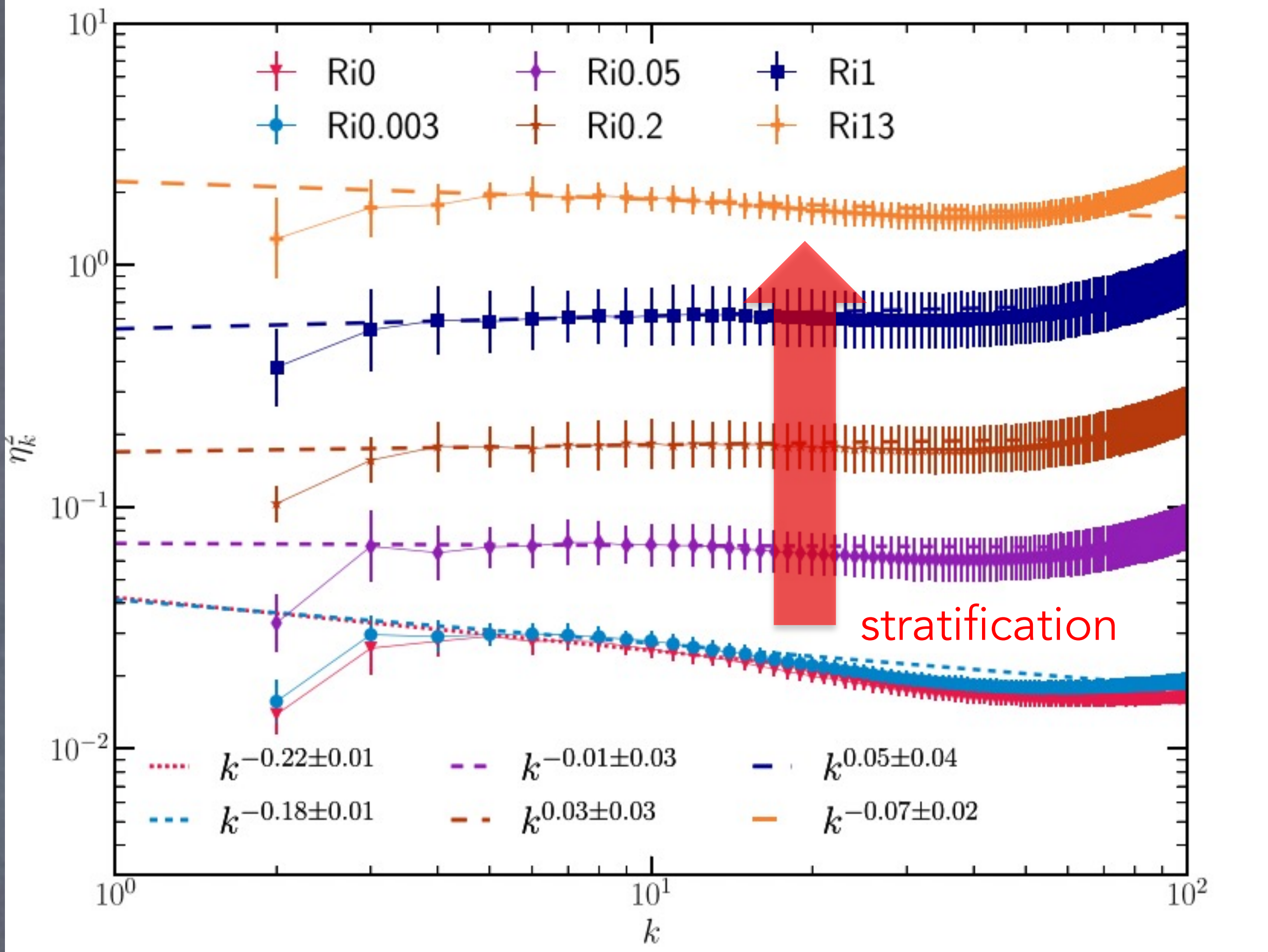


How does the non-Kolmogorov character of the spectrum alter the dissipation & mixing of the gas ?



$\delta\rho_k/\rho_0 \approx \eta_1 V_{1,k}/c_s$

Zhuravleva et al. (2014)



$\eta_k = (\delta\rho_k/\langle\rho\rangle)/(v_{1,k}/c_s) \approx \sqrt{3P(\bar{\rho}_k)/P(\mathcal{M}_k)}$

Mohapatra et al. (2020)

Turbulent heating

$$\epsilon \sim \frac{\langle v^2 \rangle}{\tau_{\rm cas}} \sim \frac{kE(k)}{\tau_{\rm cas}}$$

How does dissipation change when there is a preferred direction set by **g**?

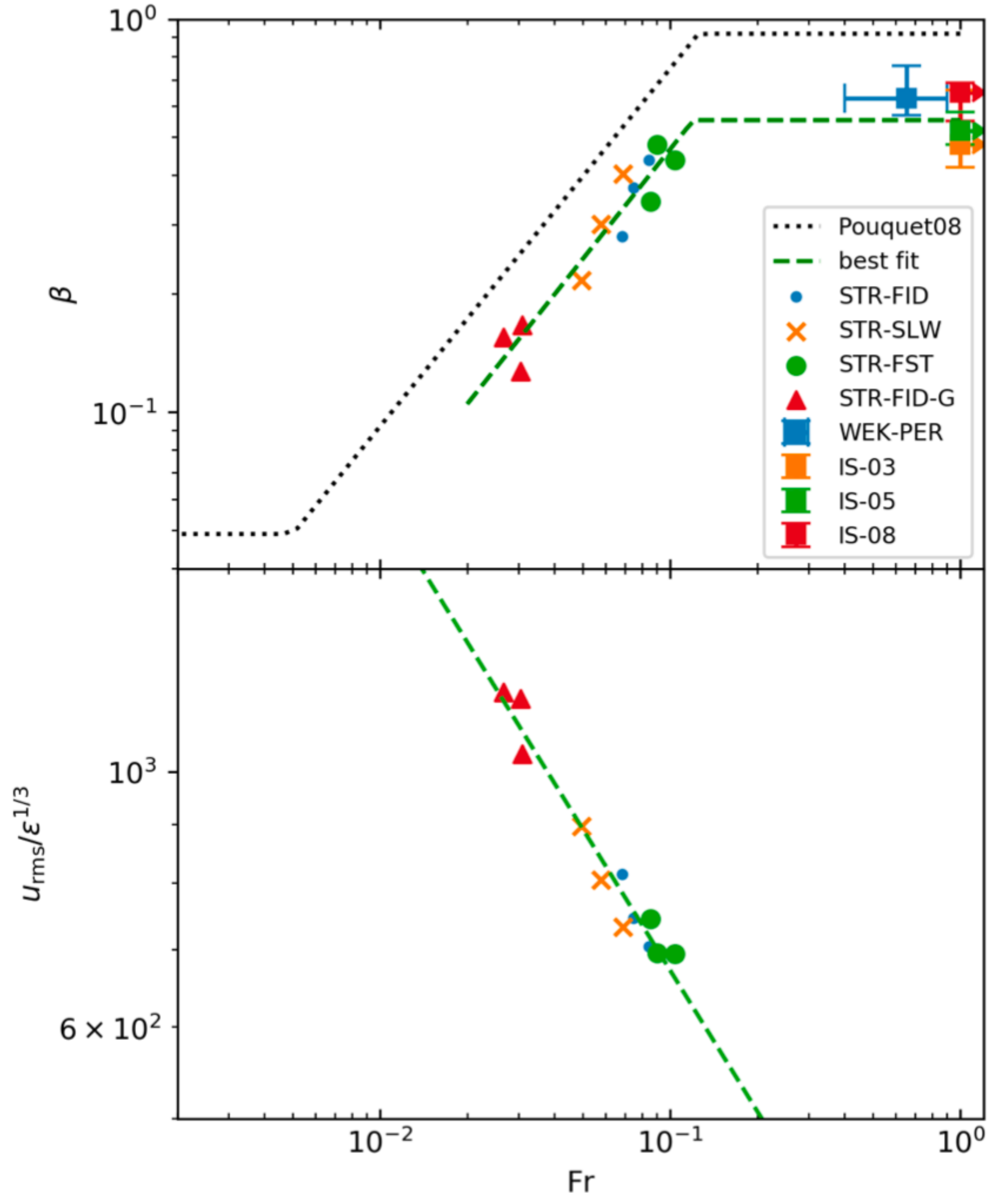
g → additional timescale in the problem ~ N^{-1} (N = Brunt-Väisälä frequency)

$\tau_{\rm NL} \ll N^{-1}$: Kolmogorov

$\tau_{\rm NL} \gg N^{-1}$: non-Kolmogorov; gravity waves important, anisotropic turbulence

$1 \gg \frac{\tau_{\rm NL}^{-1}}{N} \equiv Fr$ wave-turbulence interactions increase cascade times

$$\tau_{\rm cas} \sim \tau_{\rm NL}/{\rm Fr}$$



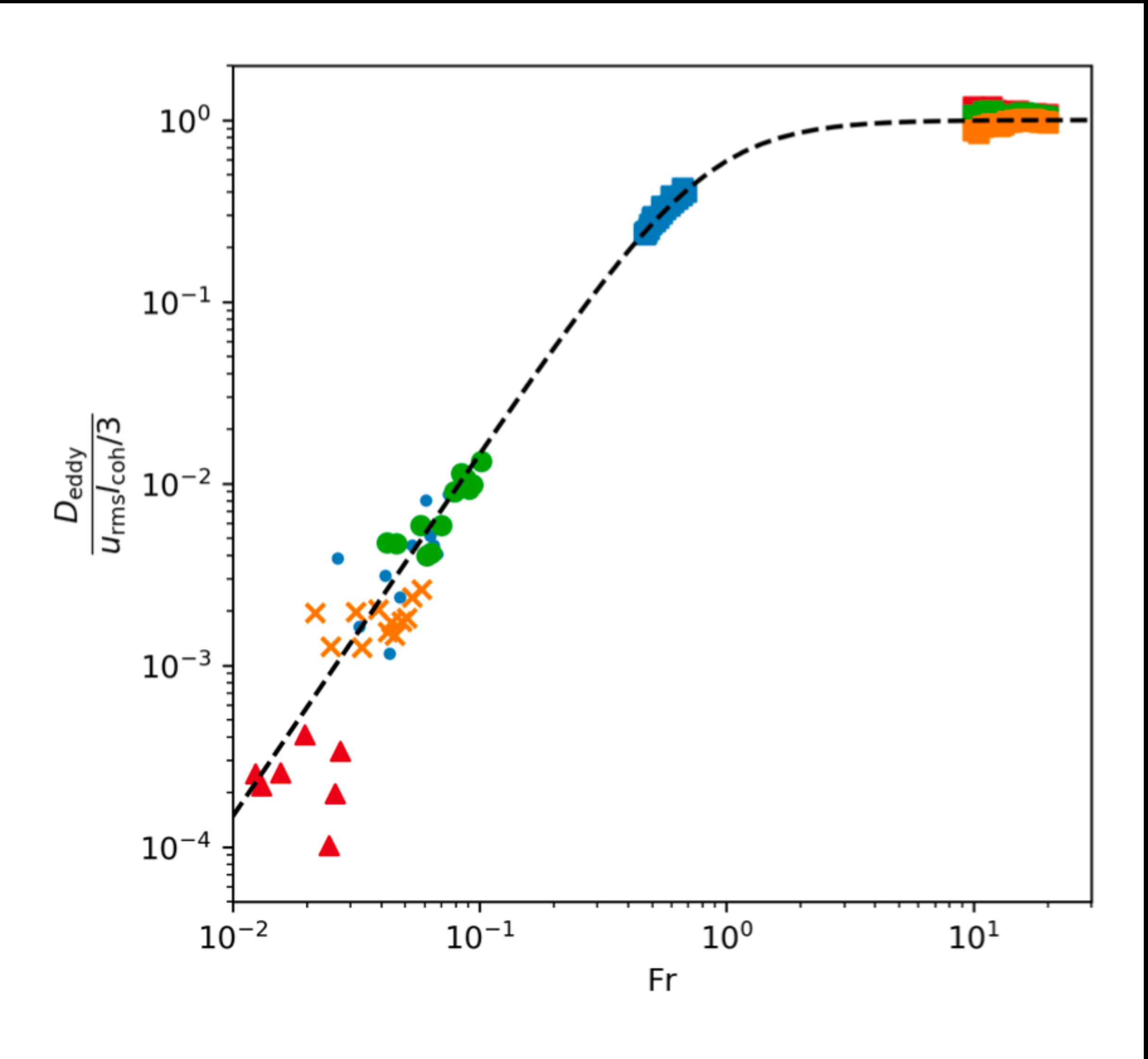
Wang, Oh, Ruszkowski (2022)

$$\epsilon \sim \epsilon_K \, \mathrm{Fr}$$

$$v \sim \left(\frac{\epsilon L}{\mathrm{Fr}}\right)^{1/3}$$

significantly higher turbulent velocities required to offset cooling OR

<u>other heating mechanisms are needed</u>



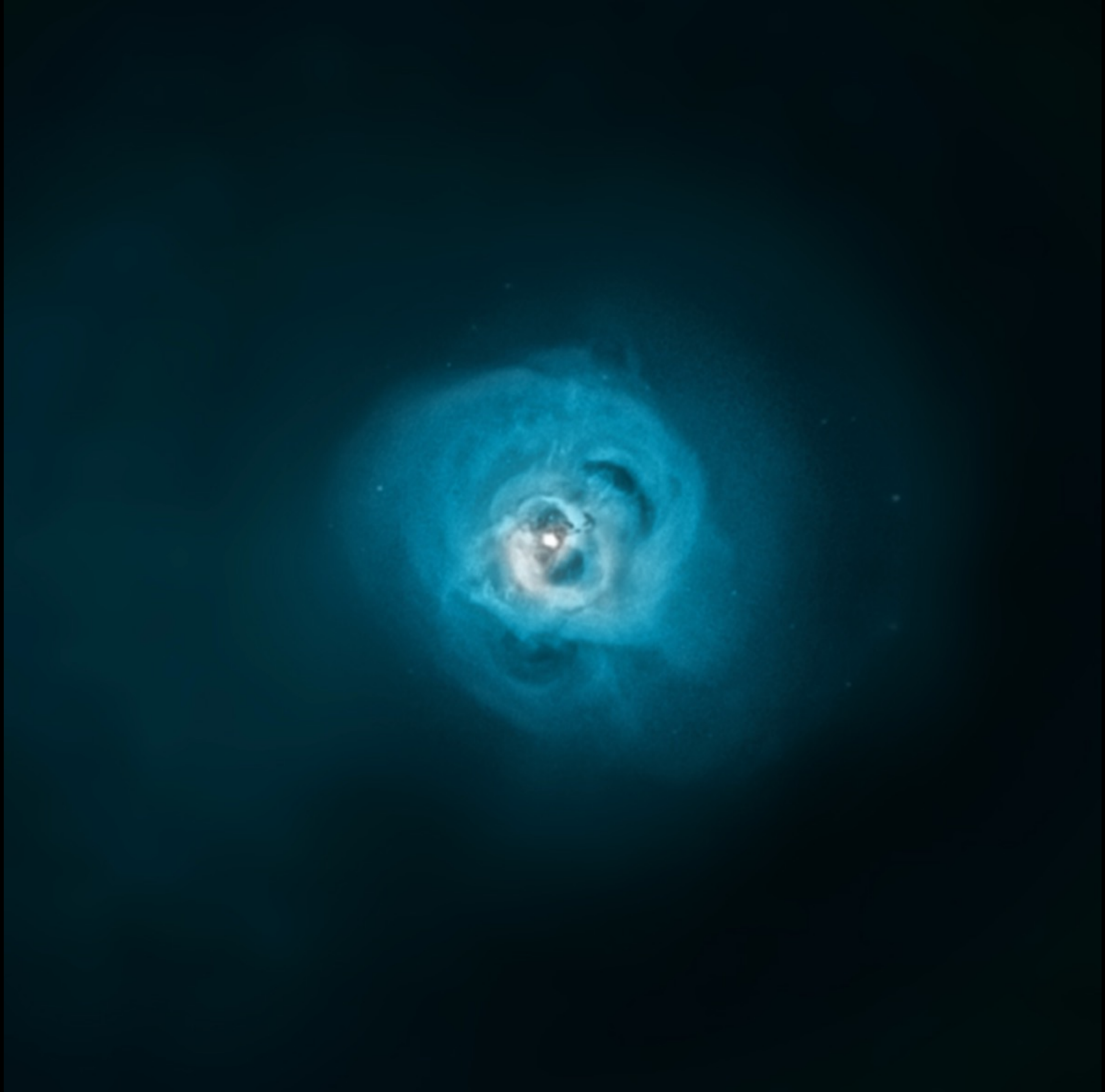
Wang, Oh, Ruszkowski (2022)

$$D_{\parallel} = c_0 \frac{uL}{1 + c_1 \mathrm{Fr}^{-2}}$$

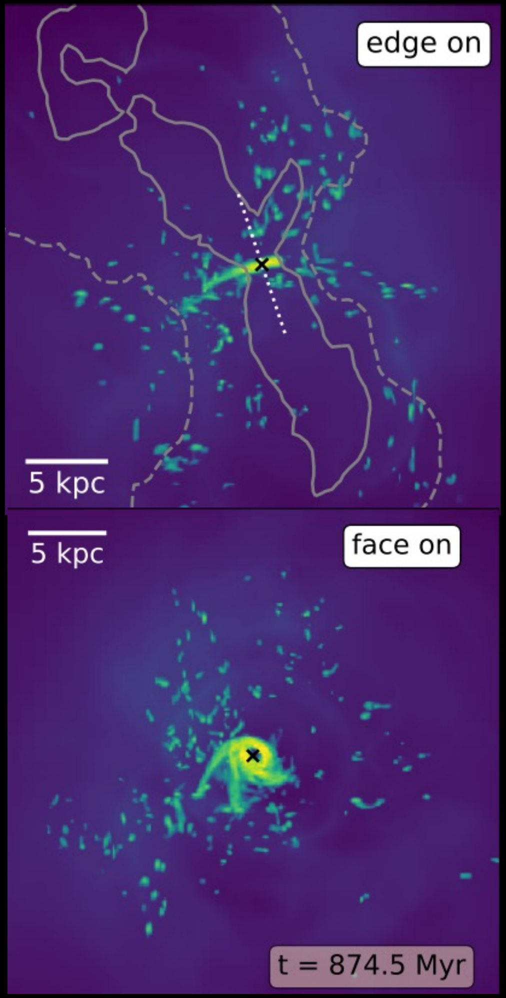
c1 is **16x larger** than the value calibrated in Weinstock (1981) for the conditions appropriate for the Earth's atmosphere

Heavily suppressed metal diffusion in hot halos

But what about magnetic fields?

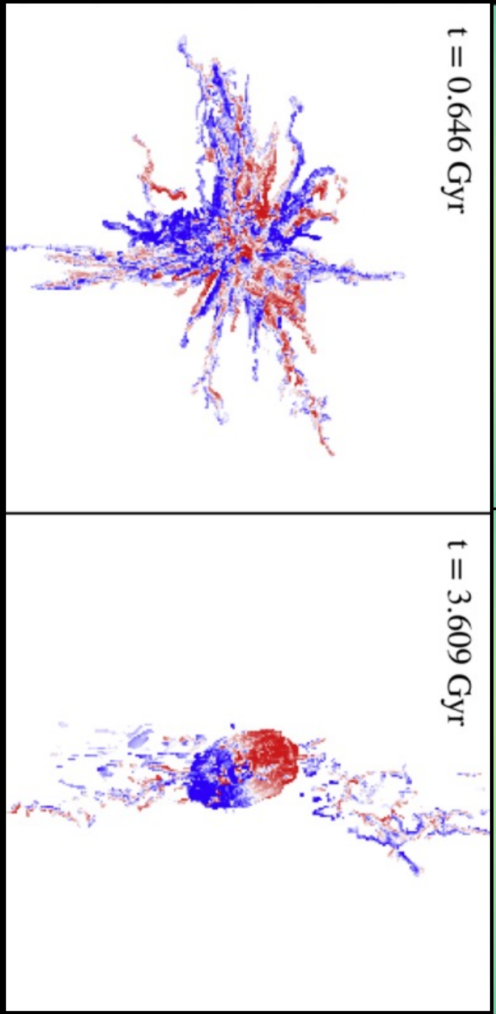


What physics are we missing?



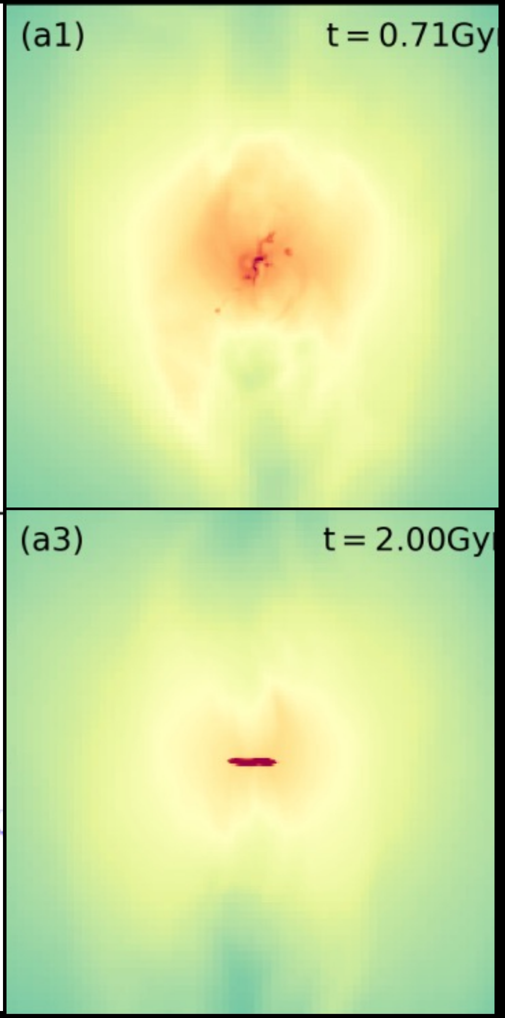
Beckmann et al. (2019)

RAMSES



Qiu et al. 2019

Enzo

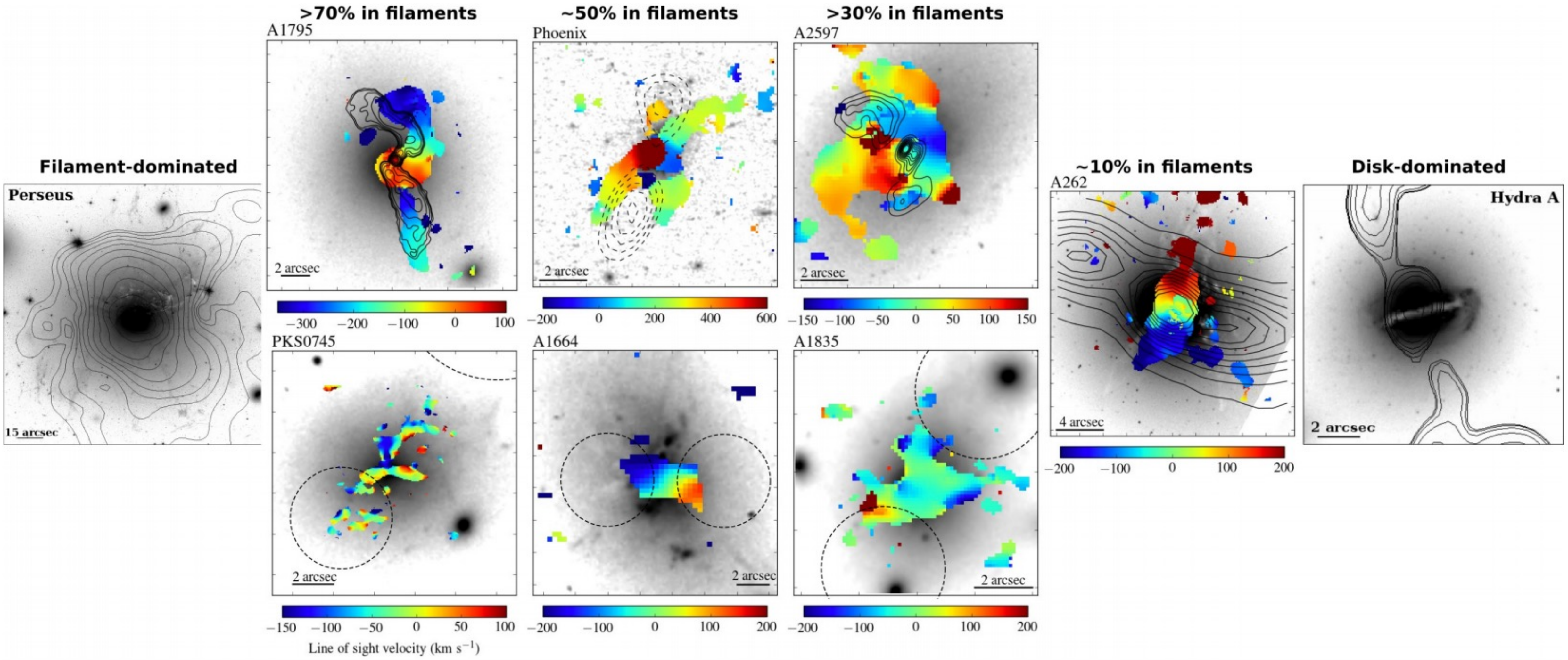


Wang, et al. 2020

FLASH

overly clumpy
massive disks

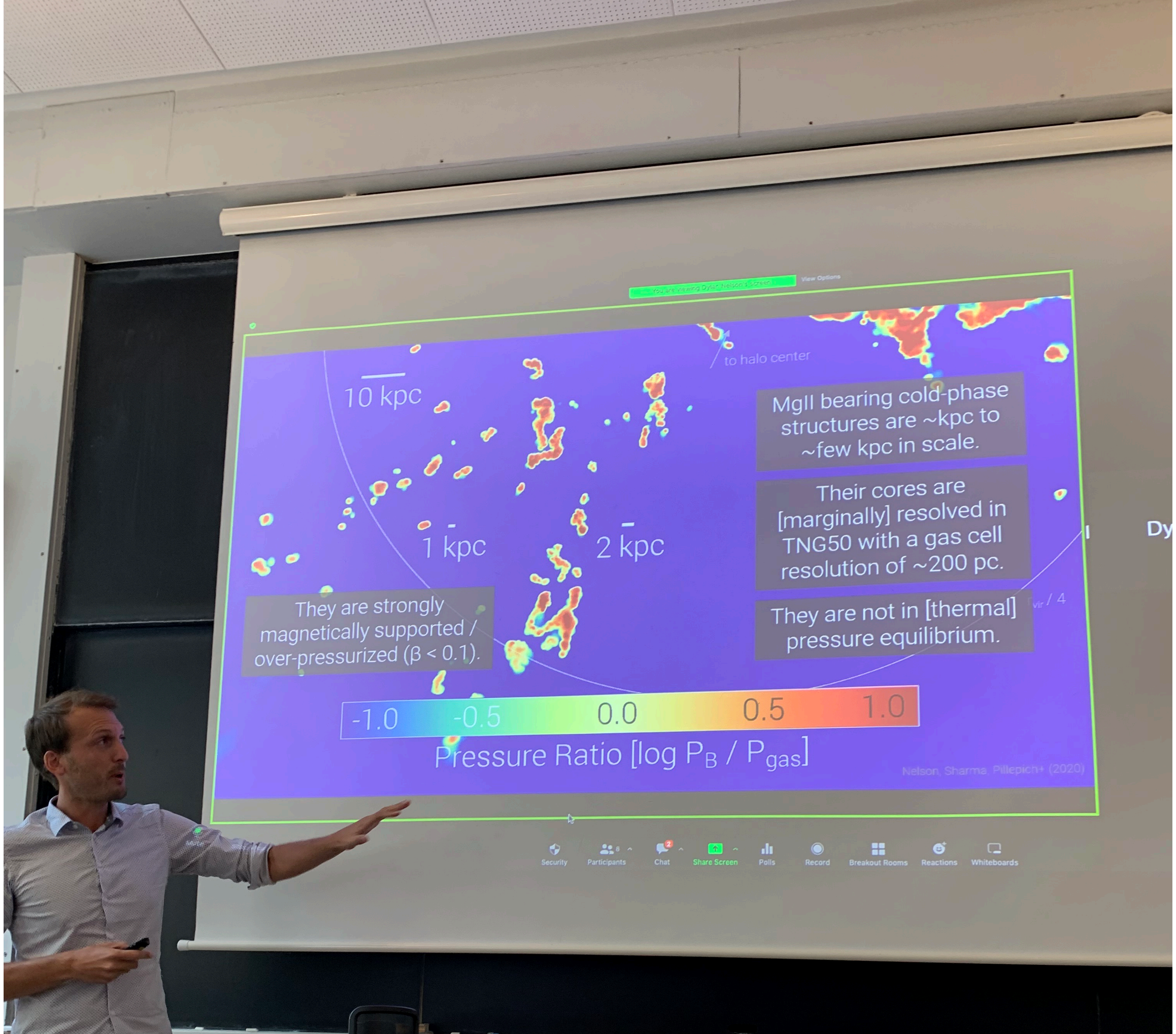
Li & Bryan 2014
Prasad, Sharma & Babul 2015
Eisenreich et al. 2017
Qiu et al. 2019
Beckmann et al. (2019)
Wang, Li, Ruszkowski 2019

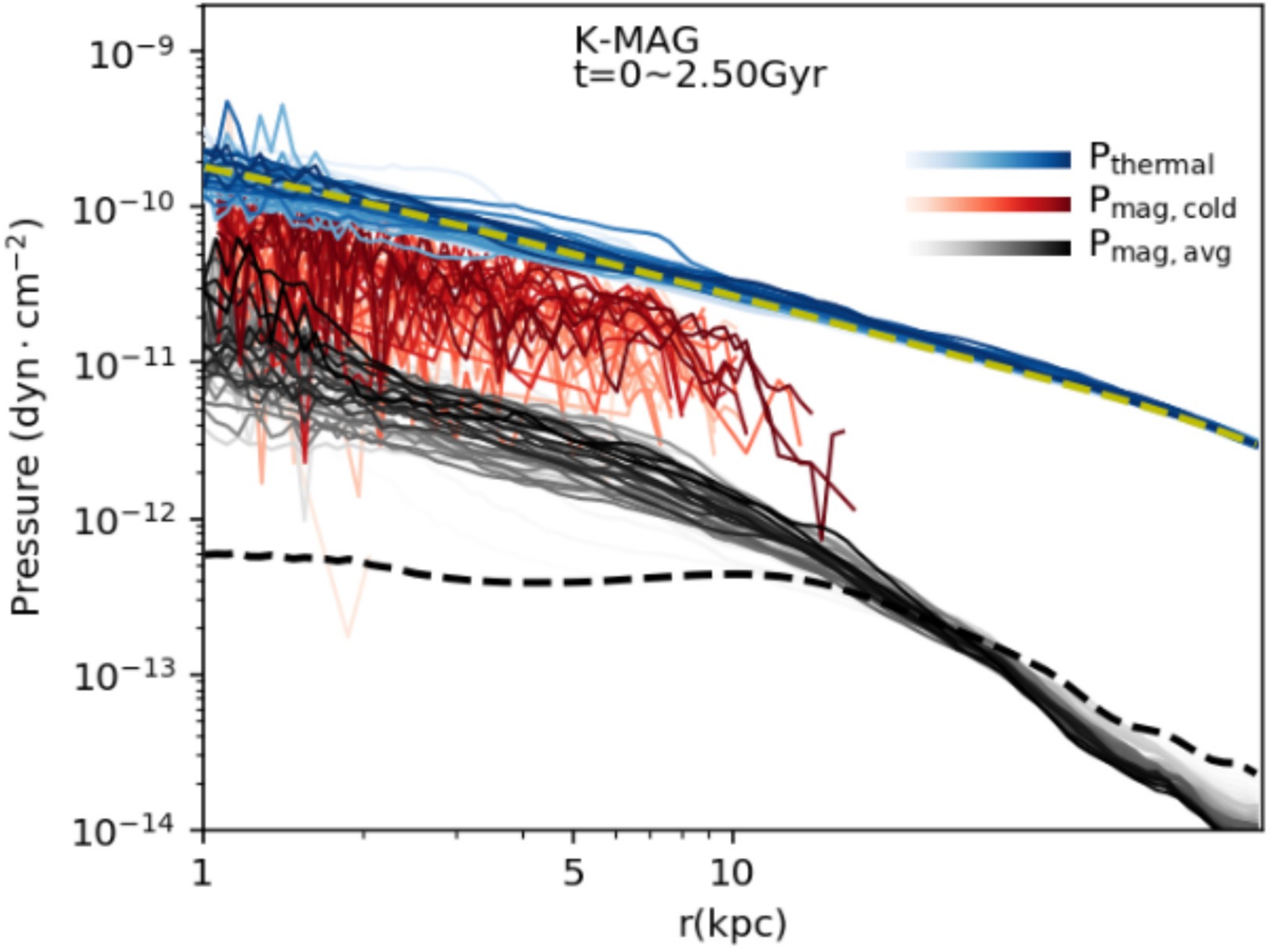


Russell at el. 2019


Earth to Scale

Dylan Nelson





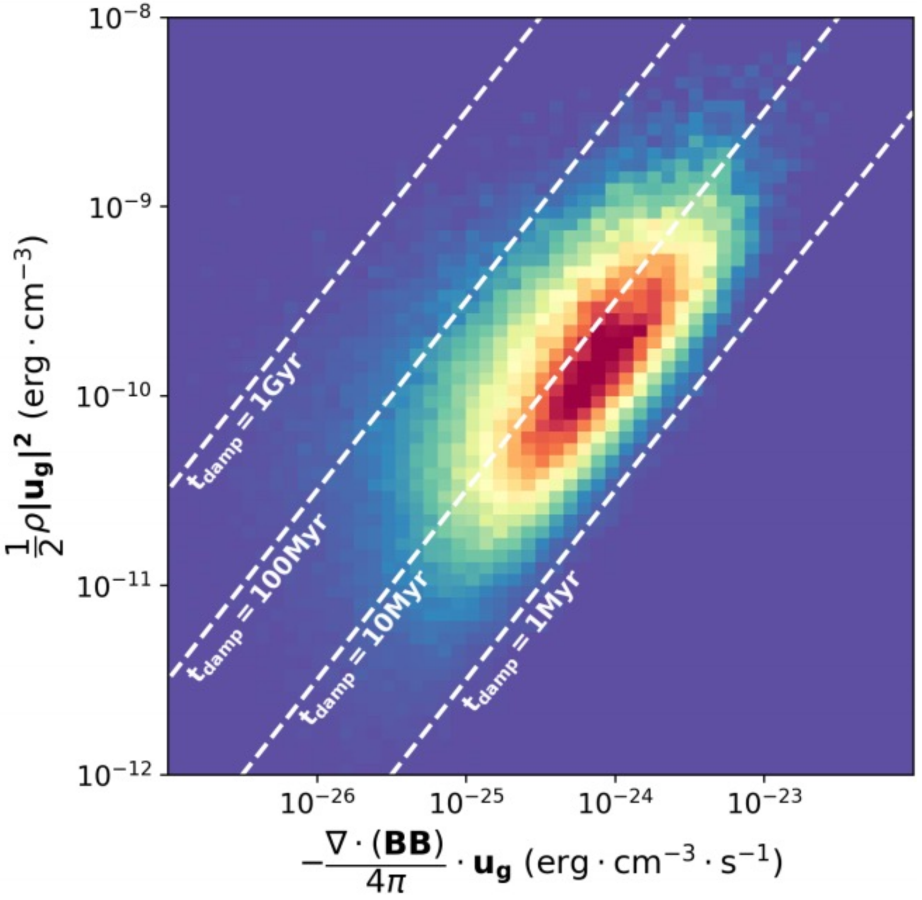
Magnetic pressure supported cold CGM phase

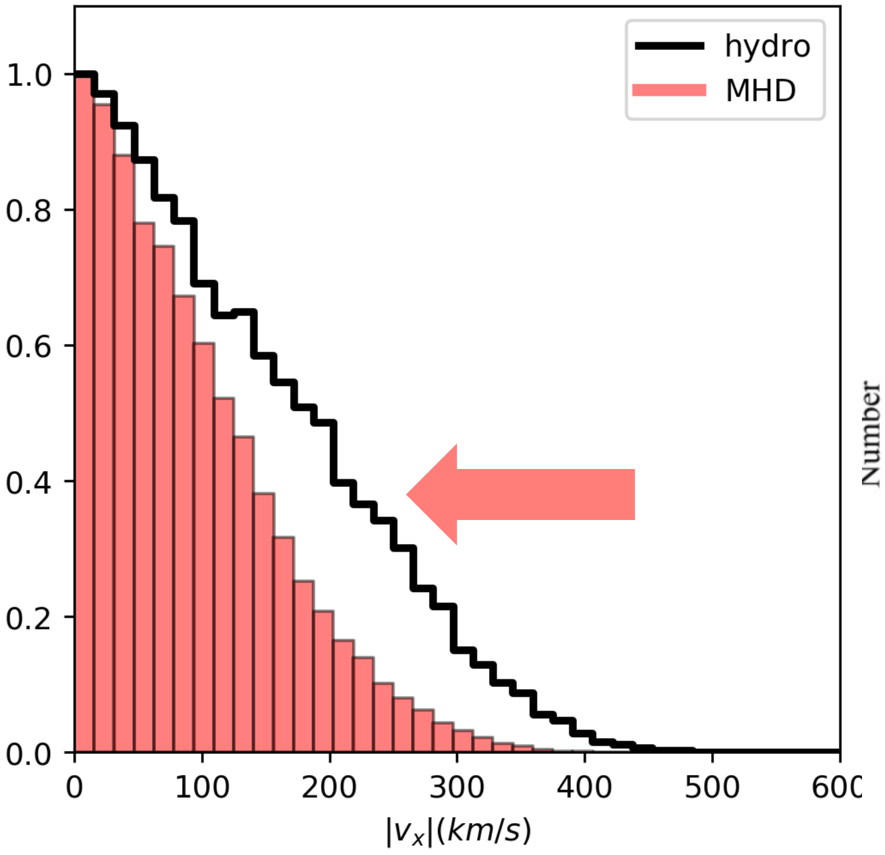
Wang et al. 2020
CR-MHD AGN feedback
in giant ellipticals

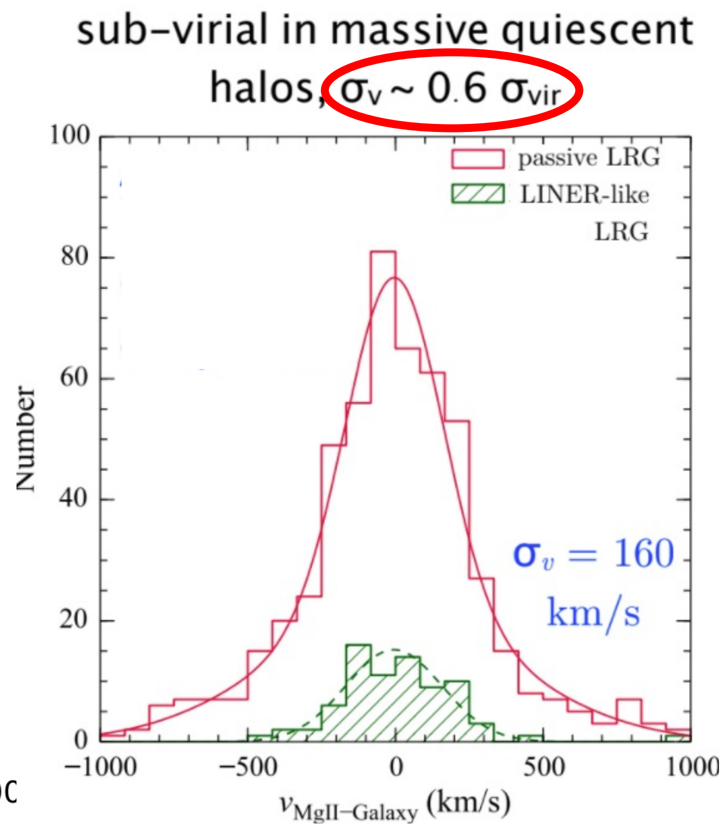
Ruszkowski et al. 2018
Cold gas filaments
heated by CRs???


B-field
Gravity
Magnetic tension

Clouds are not falling ballistically







Add B → disks disappear !!!

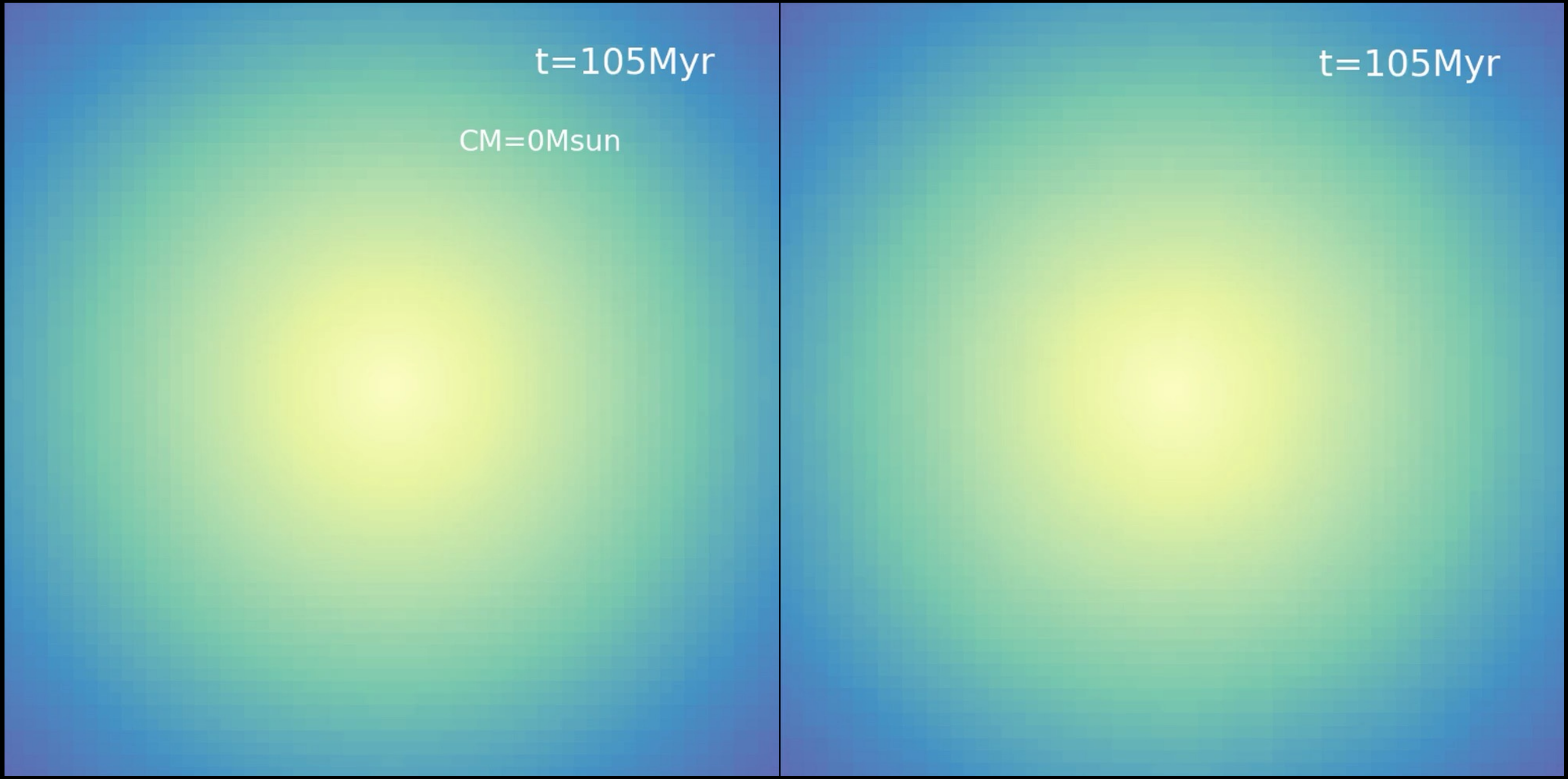
Wang, Ruszkowski, Yang 2020

see also
Li, Ruszkowski, Tremblay et al. 2018

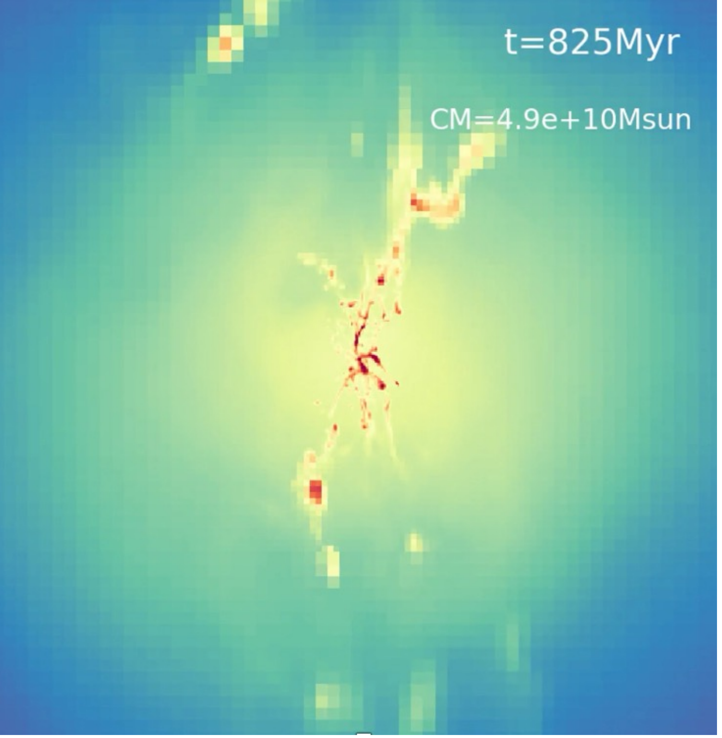
Huang et al. 2016, 2020
Zahedy et al. 2019

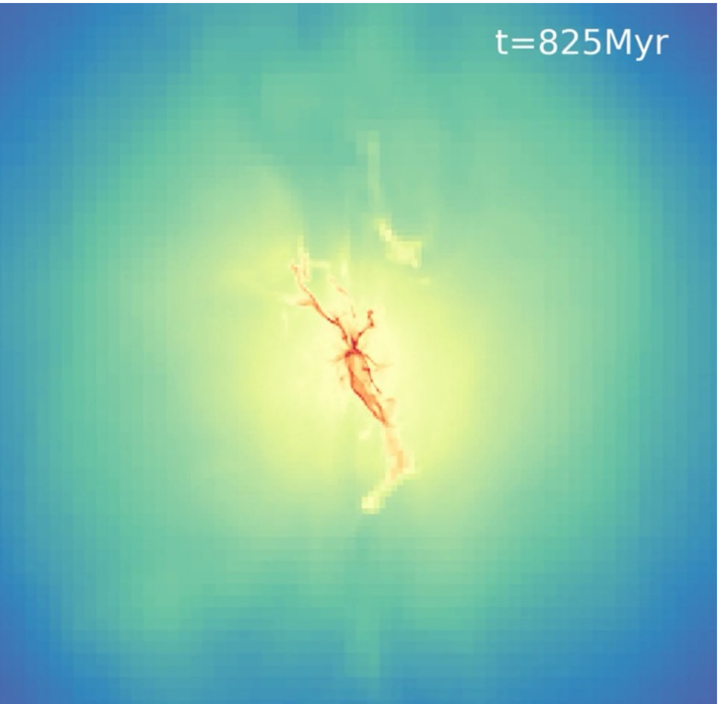
Voort et al. 2021
Ehlert et al. 2022

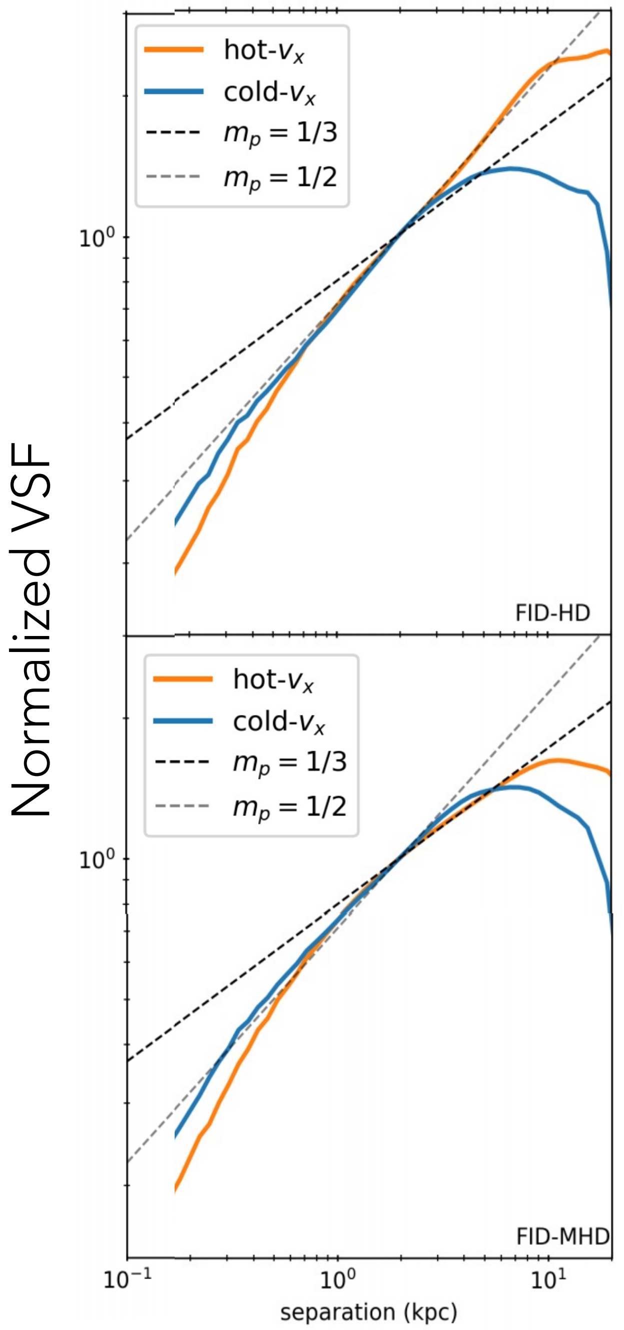
Hydro MHD



Wang, Ruszkowski, Pfrommer, Oh & Yang 2021







VSF has a non-Kolmogorov slope!

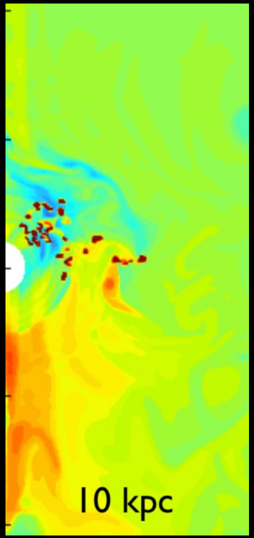
Wang, Ruszkowski, Pfrommer, Oh & Yang 2021

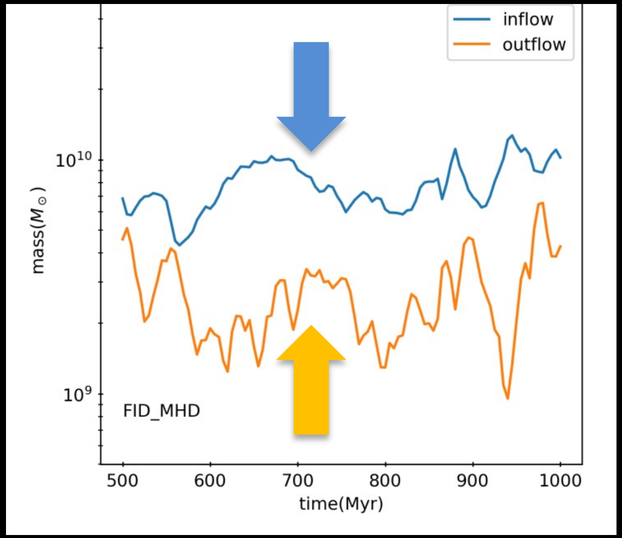
This has been observed

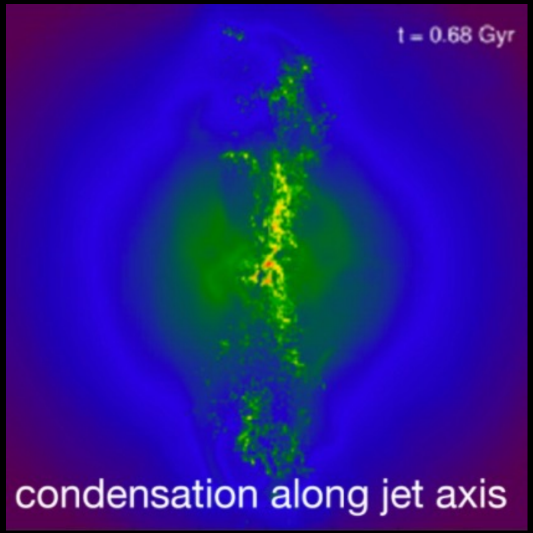
Li et al. 2020

Also seen in Earth's stratospheric spectra

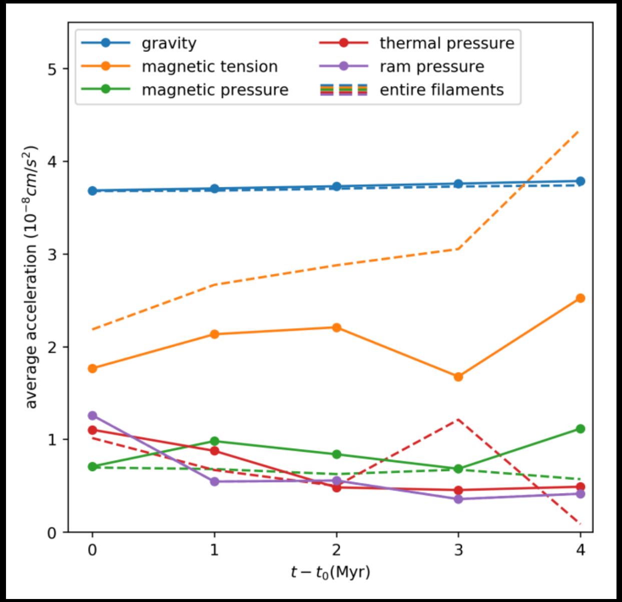
Sharma et al. 2012







Li & Bryan 2014

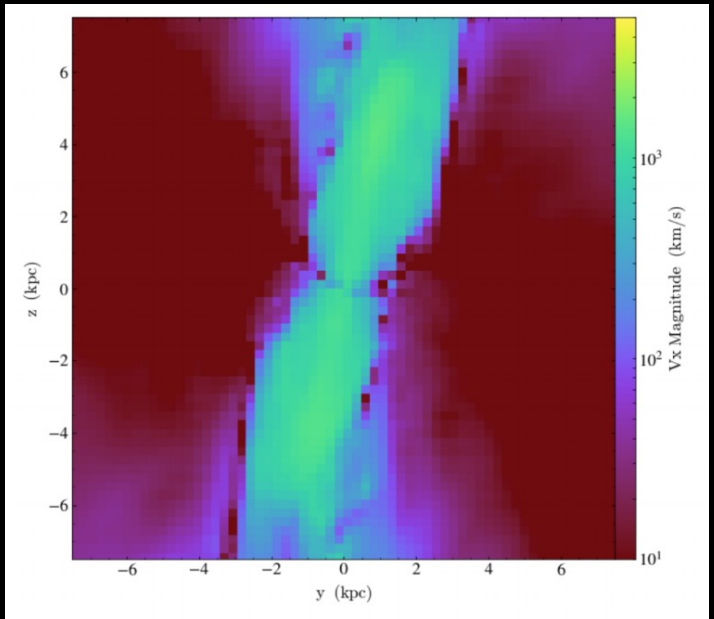


constant gravity

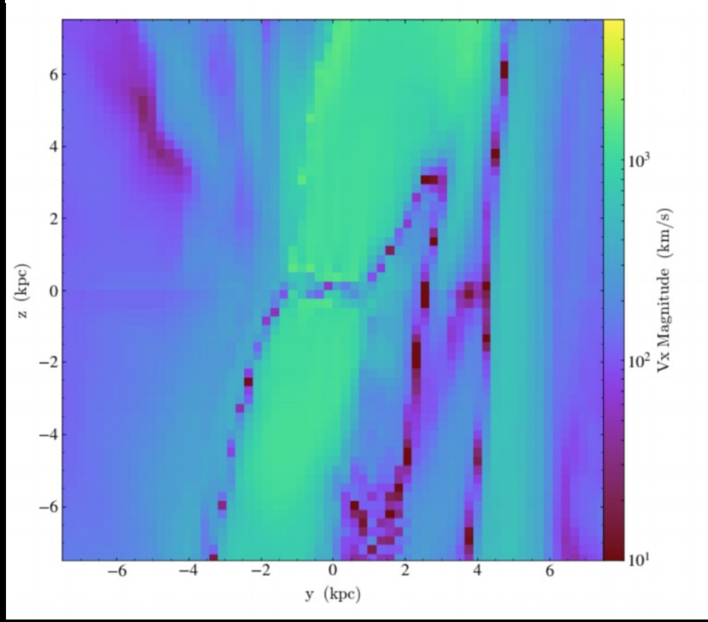
B-field forces

$$v \sim L^{1/2}$$

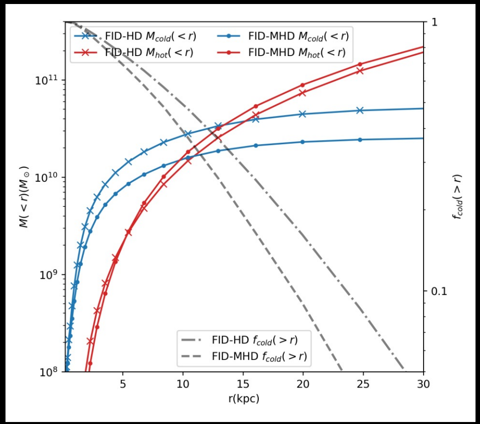
What drives turbulence in the hot phase?



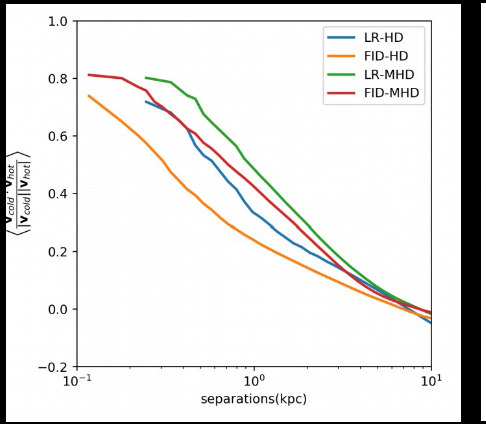
HD



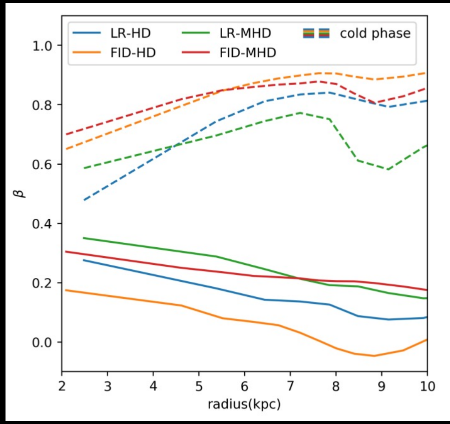
MHD



a lot of cold gas



spatial correlation of hot & cold phase



radially-biased velocity

Recall Nhut Truong's talk

- Hot gas is stirred by the black hole jet & precipitating clouds
- Hot & cold gas turbulence is non-Kolmogorov

Conclusions

Gravitationally stratified turbulence may be **non-Kolmogorov** & anisotropic

Turbulent dissipation may be **suppressed**

Turbulent mixing may be **suppressed**

Even **weak B-fields are important** for the CGM / ICM dynamics