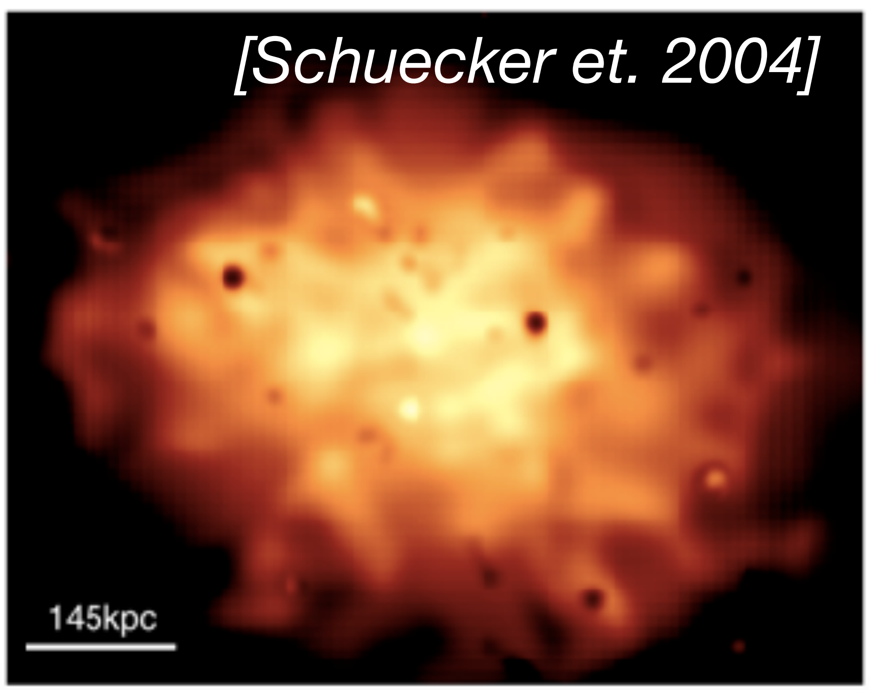
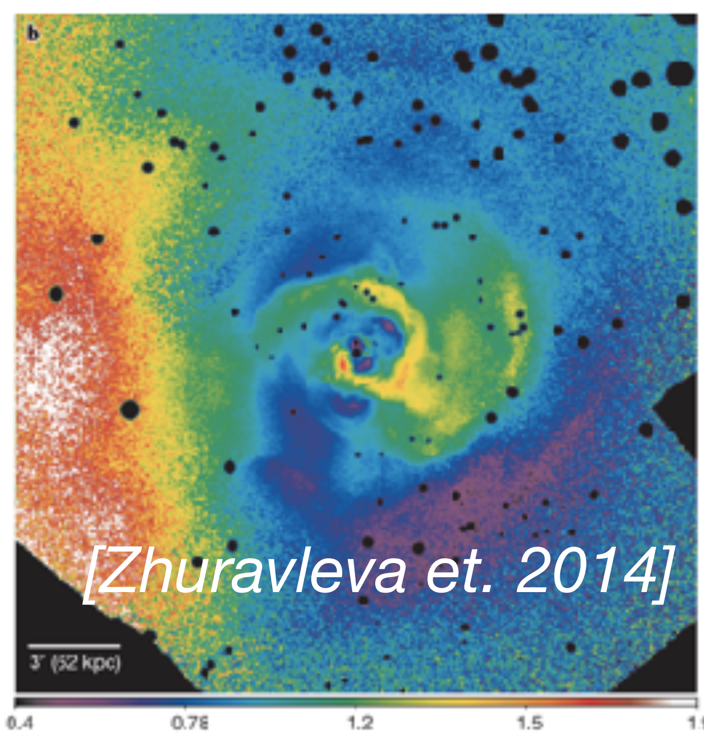
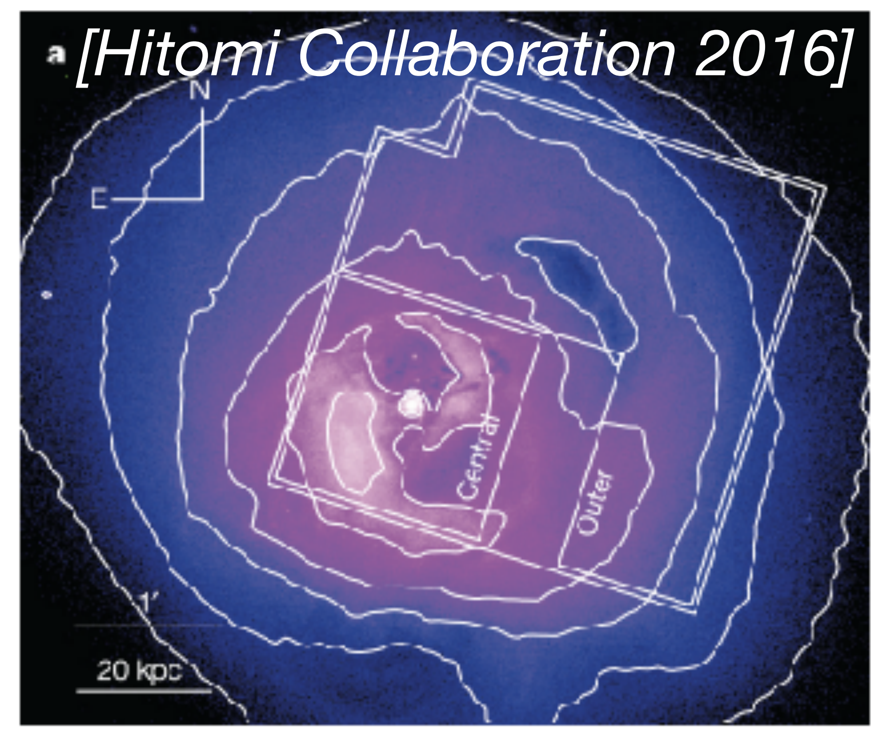
Turbulence in the ICM

Prateek Sharma, IISc Bangalore

ICM workshop, Garching, 09/09/2018







Systematics have really interesting physics!

Why study ICM turbulence?

- Turbulent support biases cluster mass estimates
- Turbulent heating in cool cores
- Constraints on ICM (high-β) plasma transport
- Implications on thermal instability & condensation, extrapolation to puzzling CGM observations (turbulent BLs, cloudlets, t_{cool}/t_{eddy},…)
- Convert SB (X-ray maps) & projected pressure fluctuations (resolved SZ maps) to v_t

Idealized simulations

Turbulence in the intracluster medium: simulations, observables & thermodynamics

arXiv:1810.00018

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Isotropic, homogeneous turbulence

To test scalings of density/pressure fluctuations with rms Mach number

ρ, P, v Power spectra: ρ/P spectra smaller by a factor of M^2 as compared to v

Turbulence with heating & cooling

TI leads to much larger density fluctuations

If cold gas condenses out of ICM, $t_{cool} < t_{mix}$

Constraints v_t & turbulent heating to be small

Idealized simulations

Turbulence in the intracluster medium: simulations, observables & thermodynamics

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Isotropic, homogeneous turbulence

ρ, ... by

Caveats:

ICM is gravitationally stratified
Turbulence can excite gravity waves
$\delta\rho_k/\rho \sim (v_k/c_s)/\sqrt{3}$

But Kolmogorov at small scales!

Turbulence with heating & cooling

T ... s

If ... ix

Co ... all

Caveats:

Cold gas may not condense from hot ICM
E.g., can be uplifted from the BCG
In this case, t_{cool} can be $\gg t_{mix}$
& turbulent heating can balance cooling

Turbulence simulations

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

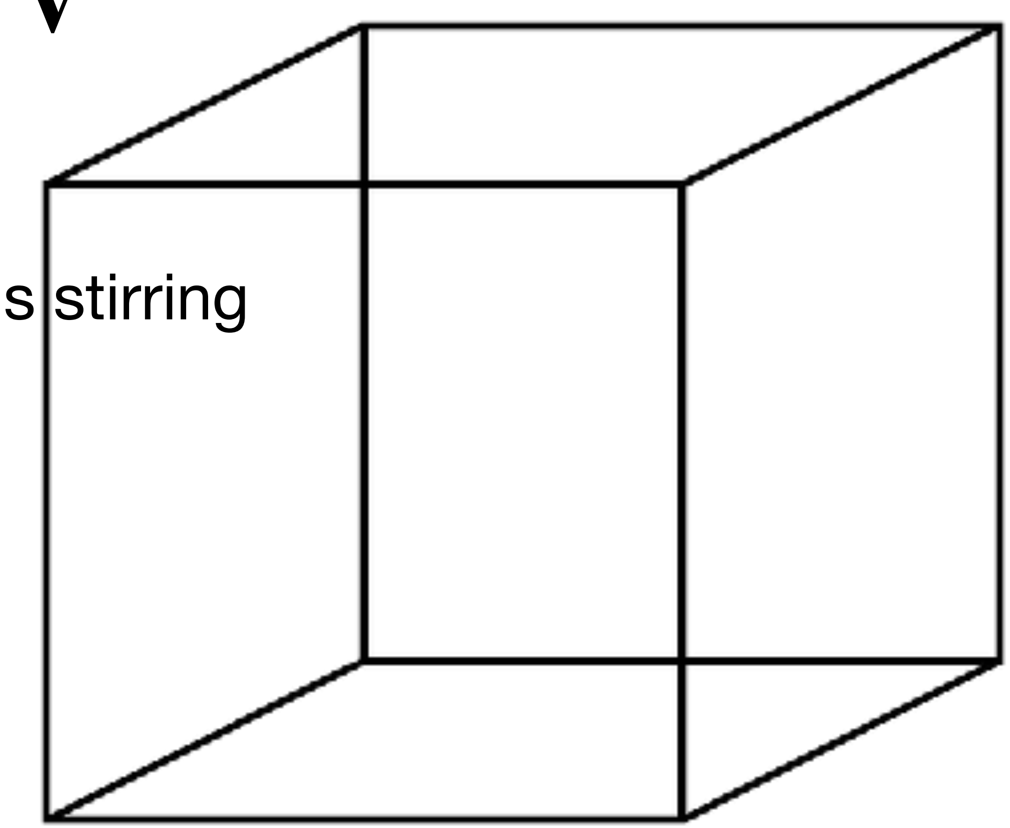
Solenoidal forcing at selected ks

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla P = \mathbf{F},$$

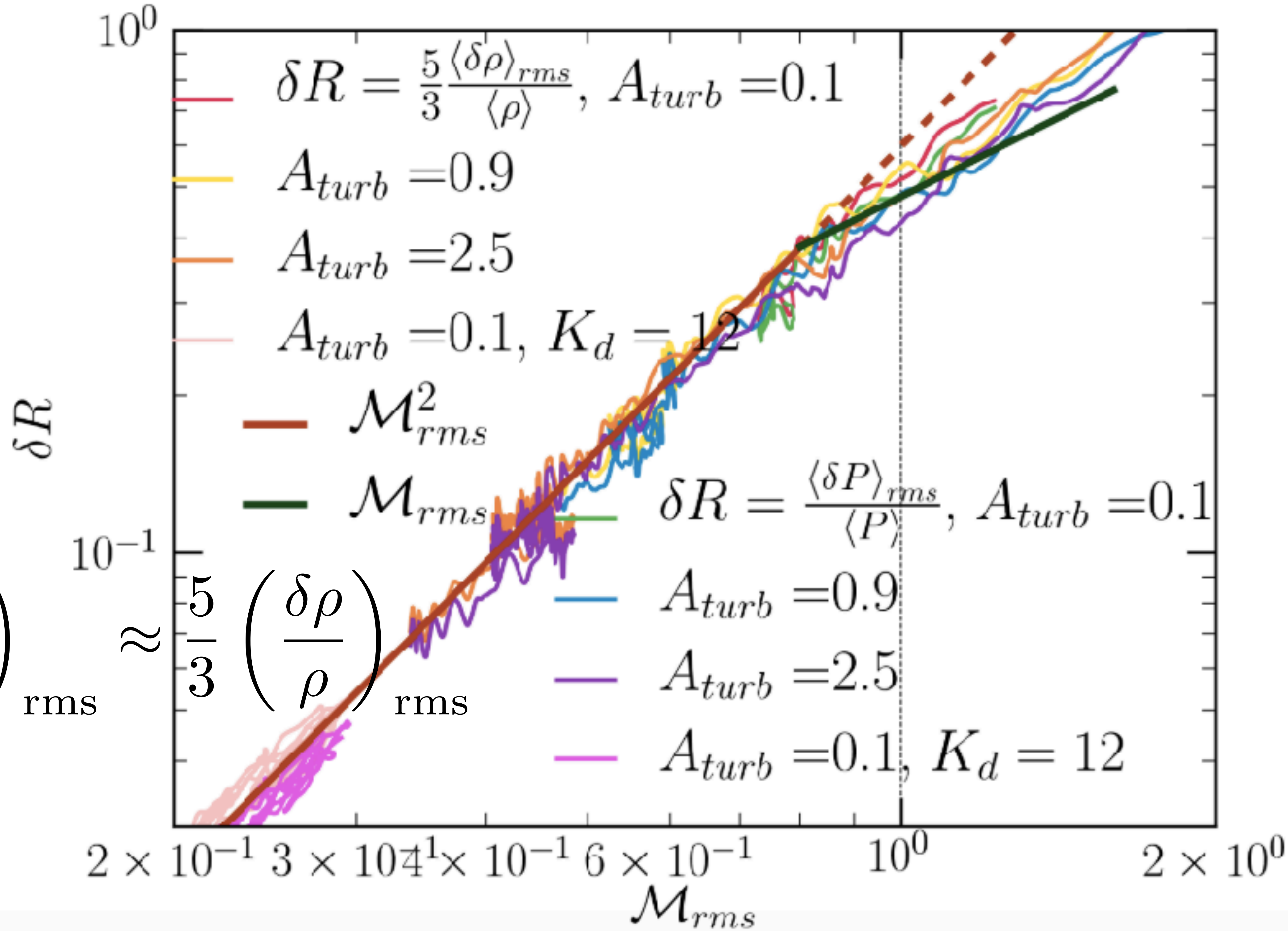
Power input by turbulent forcing heats the gas

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E + P)\mathbf{v}) = \mathbf{F} \cdot \mathbf{v}$$

3-D periodic box, isotropic/homogeneous stirring
Using PLUTO code
256^3, 512^3 simulations

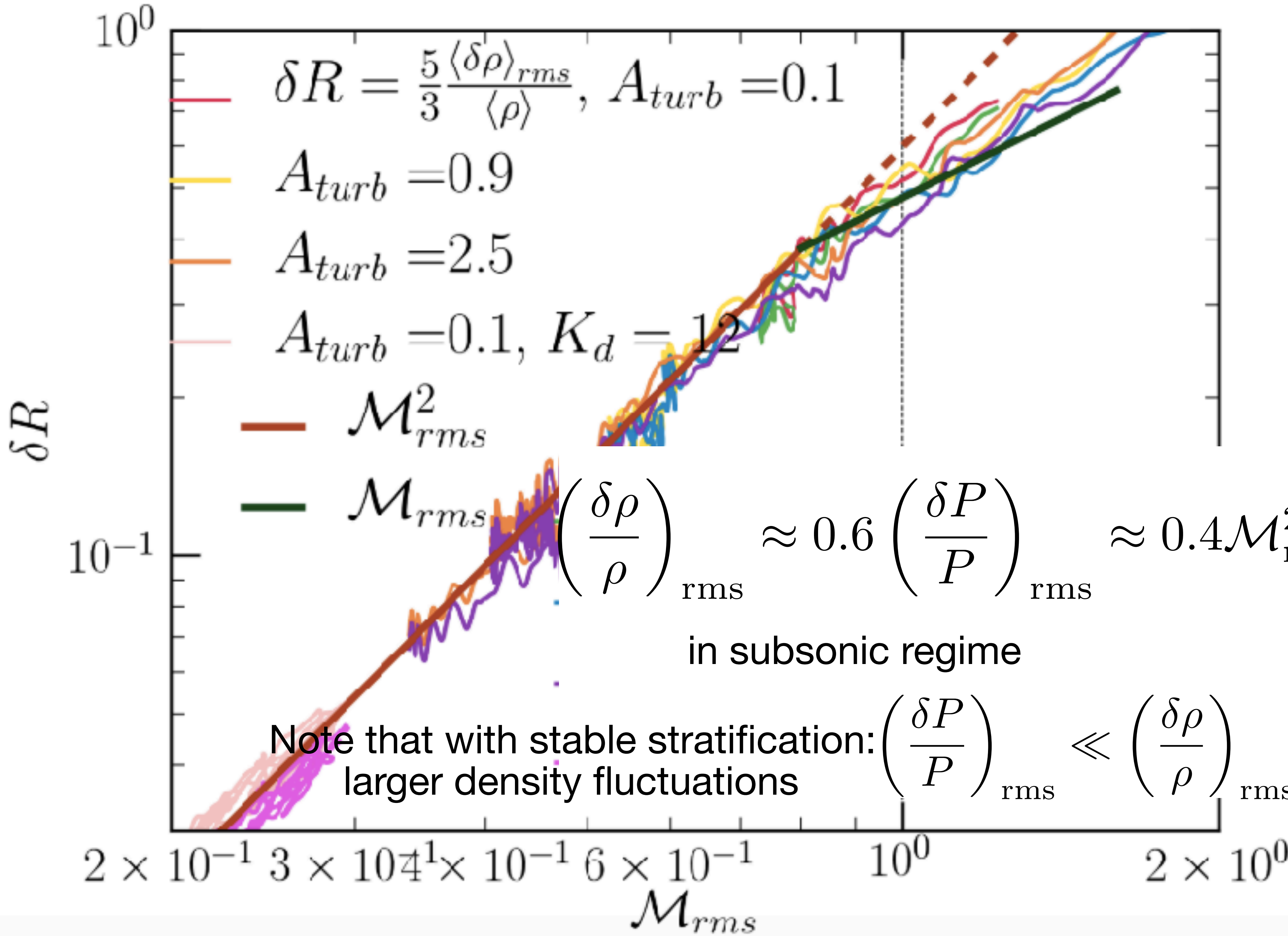


ρ/P fluctuations vs M



$$\left(\frac{\delta P}{P}\right)_{\mathrm{rms}} \approx \frac{5}{3}\left(\frac{\delta\rho}{\rho}\right)_{\mathrm{rms}}$$

ρ/P fluctuations vs M

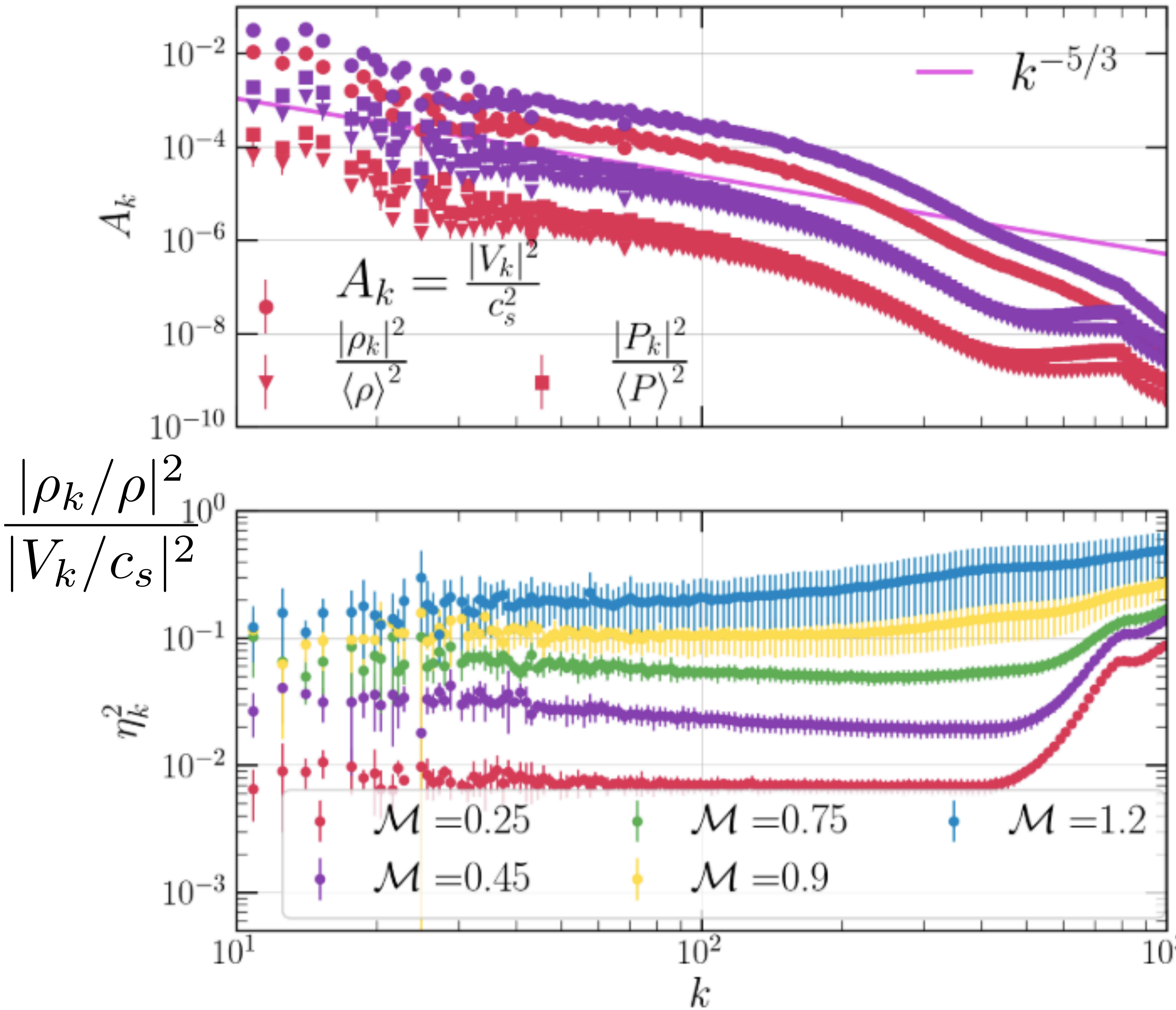


$$\left(\frac{\delta\rho}{\rho}\right)_{\rm rms} \approx 0.6\left(\frac{\delta P}{P}\right)_{\rm rms} \approx 0.4\mathcal{M}^2_{\rm rms}$$

in subsonic regime

Note that with stable stratification: larger density fluctuations $\left(\frac{\delta P}{P}\right)_{\rm rms} \ll \left(\frac{\delta\rho}{\rho}\right)_{\rm rms} \approx \frac{\mathcal{M}_{\rm rms}}{\sqrt{3}}$

Power spectra

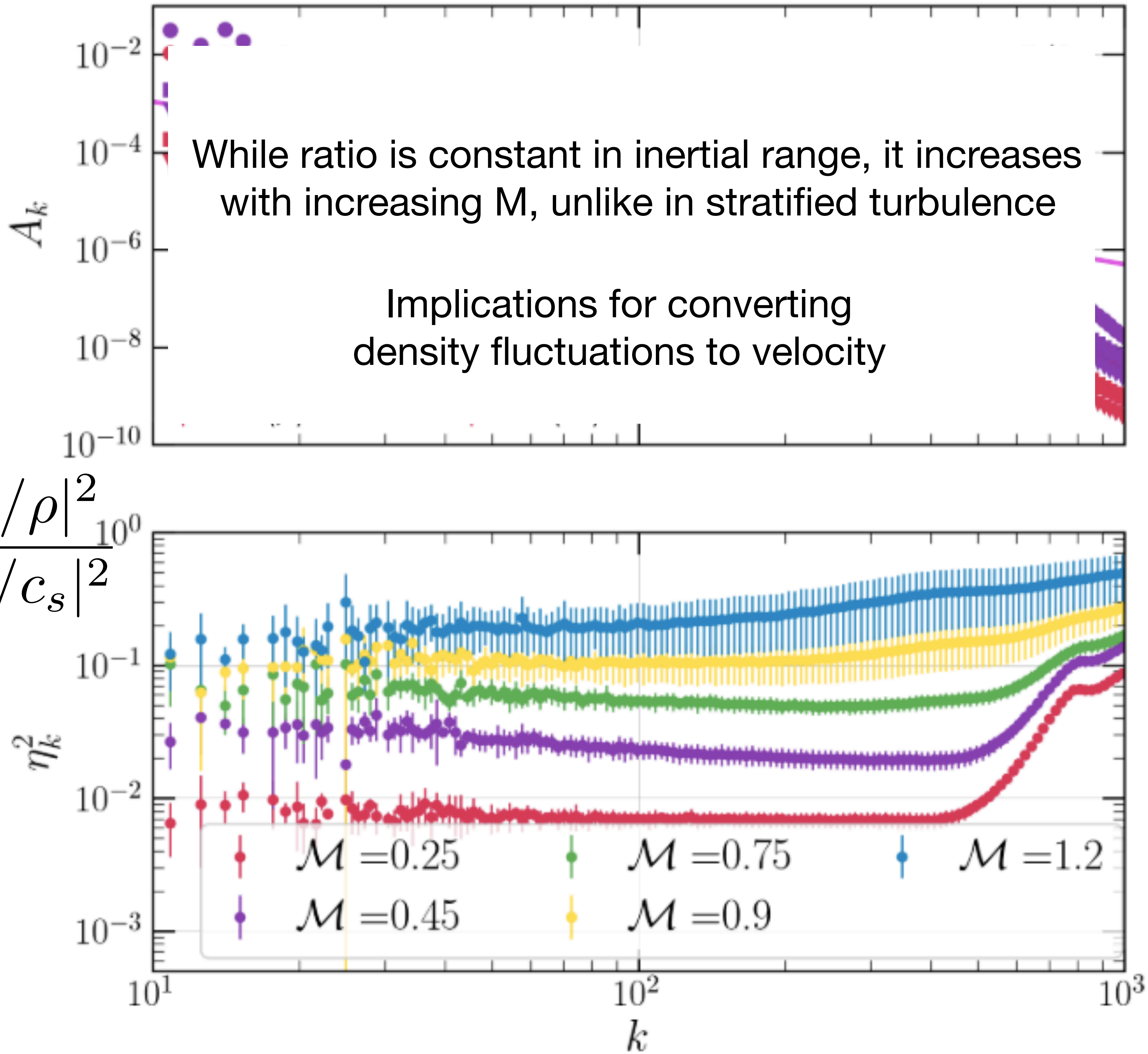


Power spectra

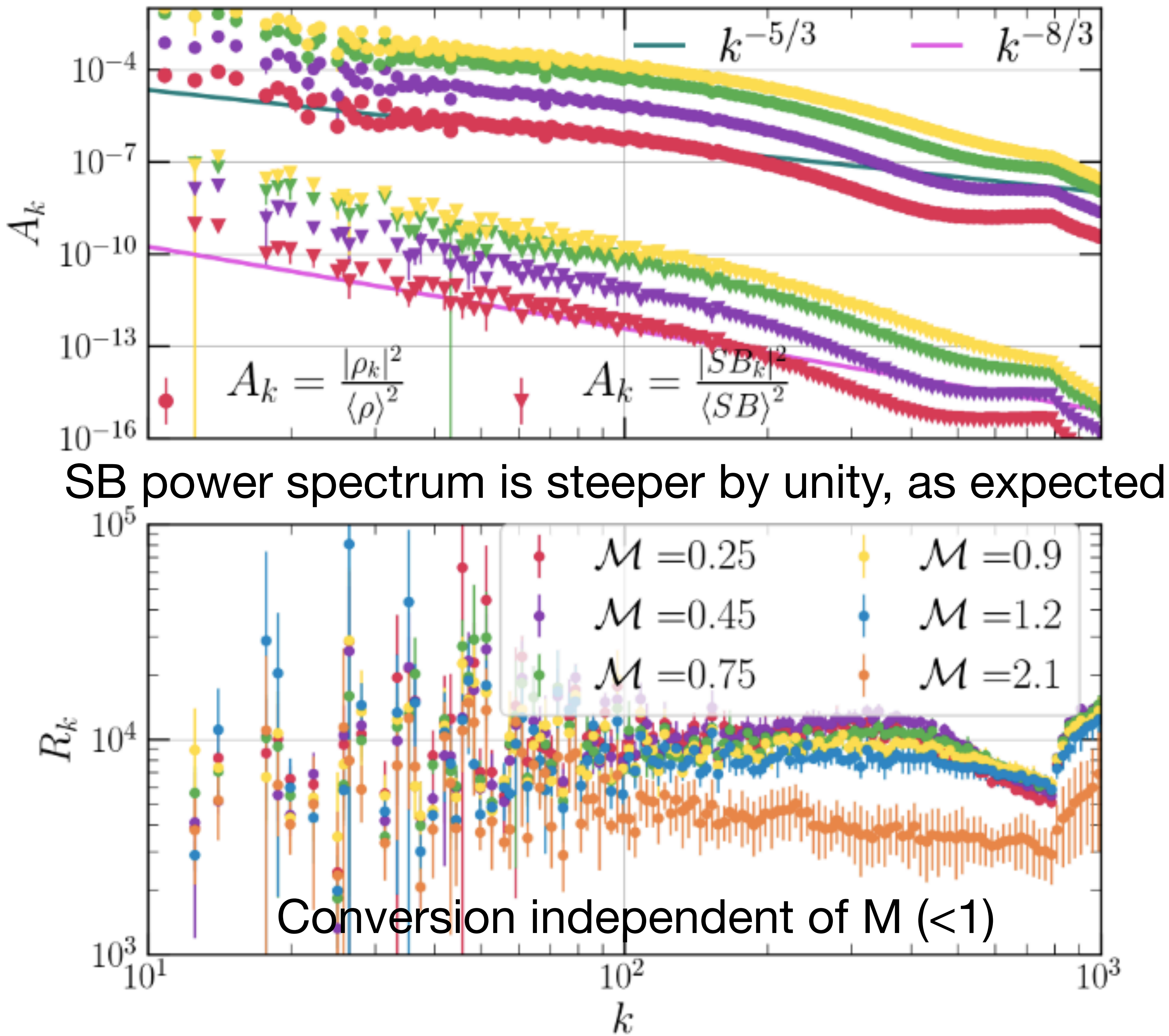
While ratio is constant in inertial range, it increases with increasing M, unlike in stratified turbulence

Implications for converting density fluctuations to velocity

$$\frac{|\rho_k/\rho|^2}{|V_k/c_s|^2}$$

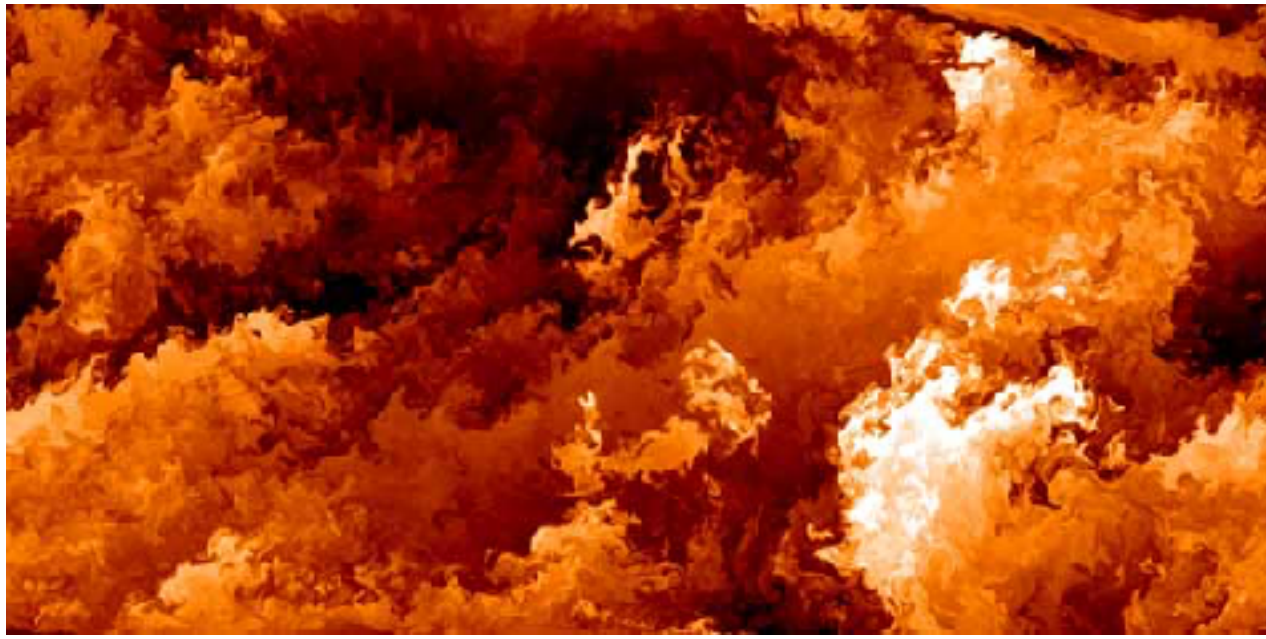


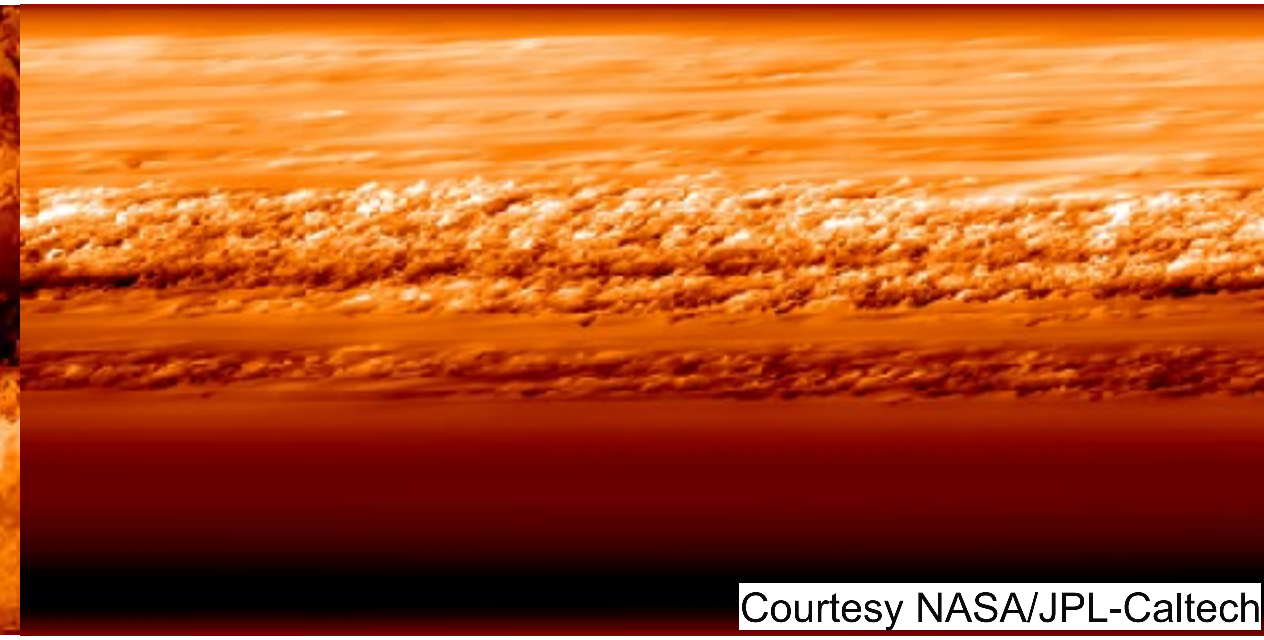
ρ/SB spectra



A_k
$k^{-5/3}$
$k^{-8/3}$
$A_k = \frac{|\rho_k|^2}{\langle\rho\rangle^2}$
$A_k = \frac{|SB_k|^2}{\langle SB\rangle^2}$
SB power spectrum is steeper by unity, as expected!
R_k
$\mathcal{M}$ =0.25
$\mathcal{M}$ =0.45
$\mathcal{M}$ =0.75
$\mathcal{M}$ =0.9
$\mathcal{M}$ =1.2
$\mathcal{M}$ =2.1
Conversion independent of M (<1)
k

Stably stratified turbulence





Spiral structures in ICM!

$$\mathrm{Ri}(l) = \mathrm{Fr}^{-2}(l) = \frac{N^2}{v^2(l)/l^2} = \frac{\frac{g}{\gamma}\frac{d}{d\ln r}\ln(p/\rho^\gamma)}{v^2(l)/l}$$

Anisotropy crucial for Ri>>1, not so much for the ICM that has a shallow entropy profile

$g\frac{d}{d\ln r}\ln T$ for magnetized plasmas, which is even shallower

Turbulence dominates at small scales.

Caveat for the present work: background stratification & gravity are ignored
Background gravity also suppresses multiphase condensation due to local TI

Turbulence, heating & cooling

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

Solenoidal forcing at selected ks

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla P = \mathbf{F},$$

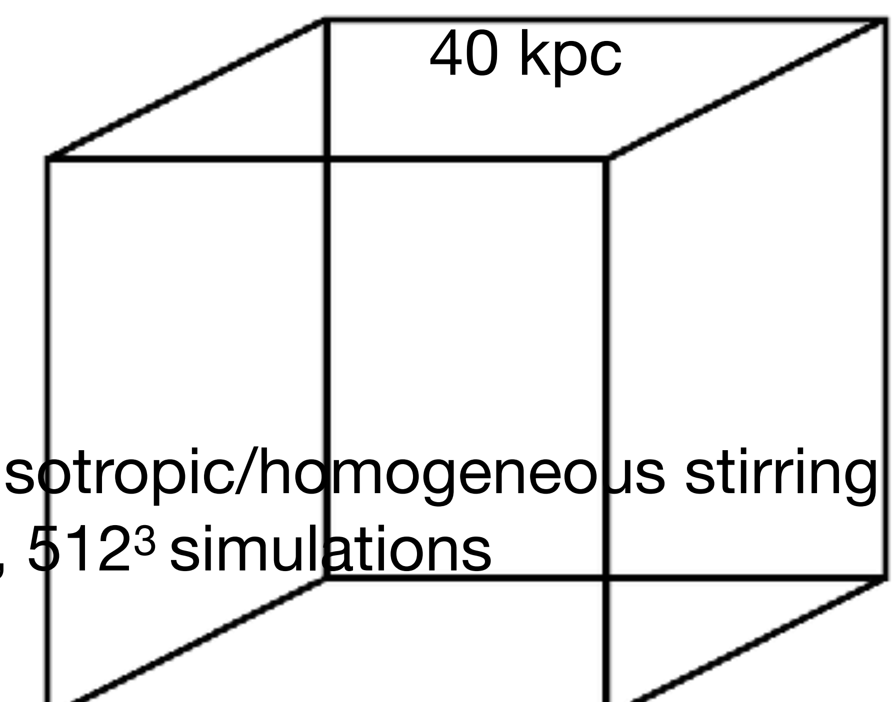
Power input by turbulent forcing $= f_{\rm turb} \langle \mathcal{L} \rangle$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E + P)\mathbf{v}) = \mathbf{F} \cdot \mathbf{v} + Q - \mathcal{L},$$

$= n_e n_i \Lambda[T]$ floor T=10^6 K

$(1 - f_{\rm turb}) \langle \mathcal{L} \rangle$
added as thermal energy

Imposed observed thermal balance



3-D periodic box, isotropic/homogeneous stirring
256^3, 512^3 simulations

K41 Estimates

thermal balance, driving at large scales

$$\dot{E}_{\rm turb} \sim \rho v_l^2/t_{{\rm mix},l} \approx \rho v_l^3/l \approx f_{\rm turb}\dot{E}_{\rm cool} = f_{\rm turb}U/t_{\rm cool}$$

$$t_{\rm cool}/t_{{\rm mix},L} \approx f_{\rm turb}U/2K \sim f_{\rm turb}\mathcal{M}_{\rm rms}^{-2}$$

If cold gas is to condense out of the hot phase, $t_{\rm cool} \lesssim t_{\rm mix}$

or, $\mathcal{M} \gtrsim 1$ for $f_{\rm turb} \sim 1$

For driving at small scales, an equivalent estimate is

$f_{\rm turb}(L/l)^2\mathcal{M}_{\rm rms}^{-2} < 1$ for $l > L$

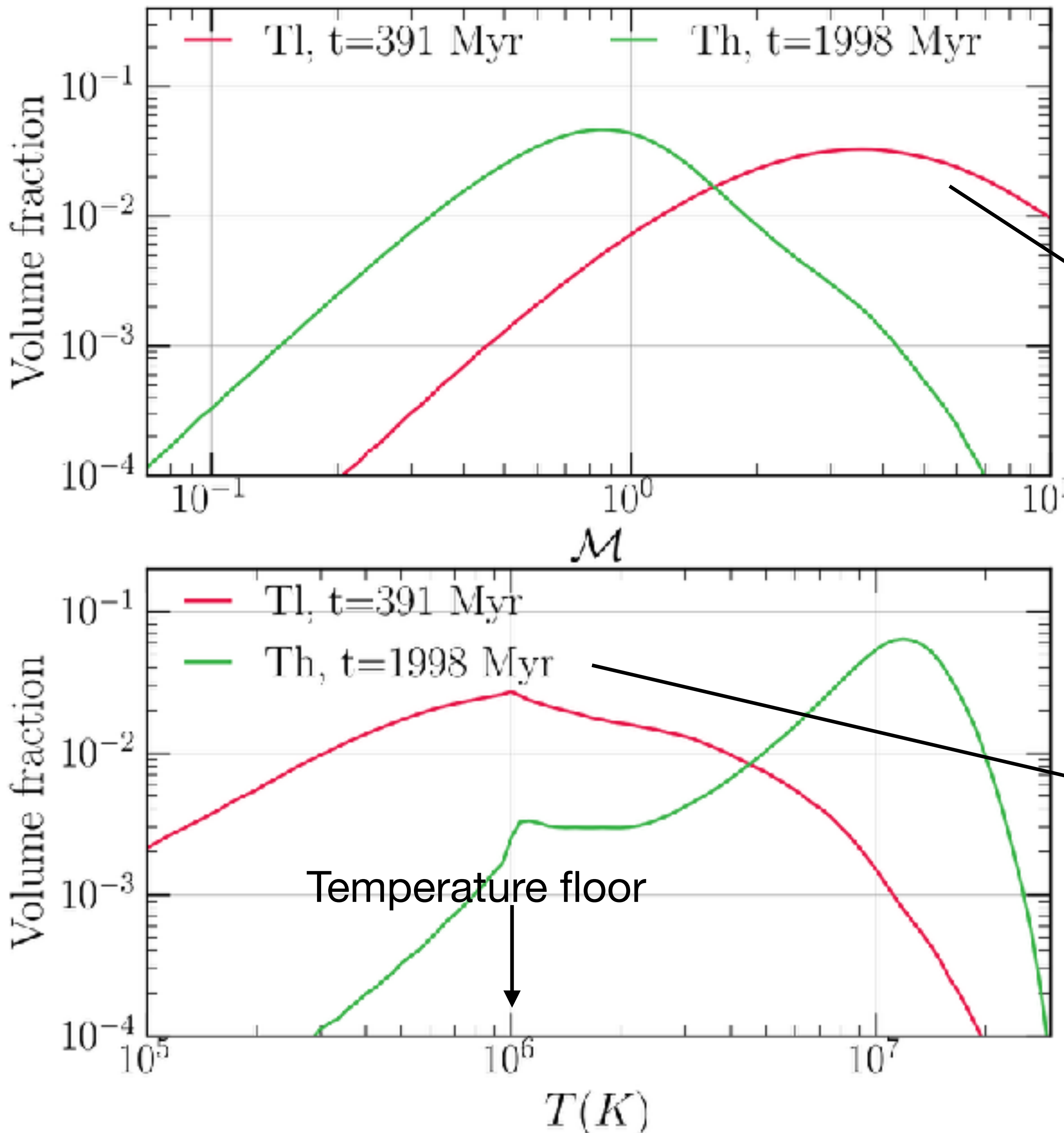
A smaller/reasonable $\mathcal{M}_{\rm rms}$ for small scale driving & smaller $f_{\rm turb}$

$t_{\rm cool}/t_{\rm mix} \gg 1$ Ok if most cold gas does not condense out but say is uplifted

$k = \sqrt{2}(2\pi/L)$

$k = 12(2\pi/L)$

LS & SS driving

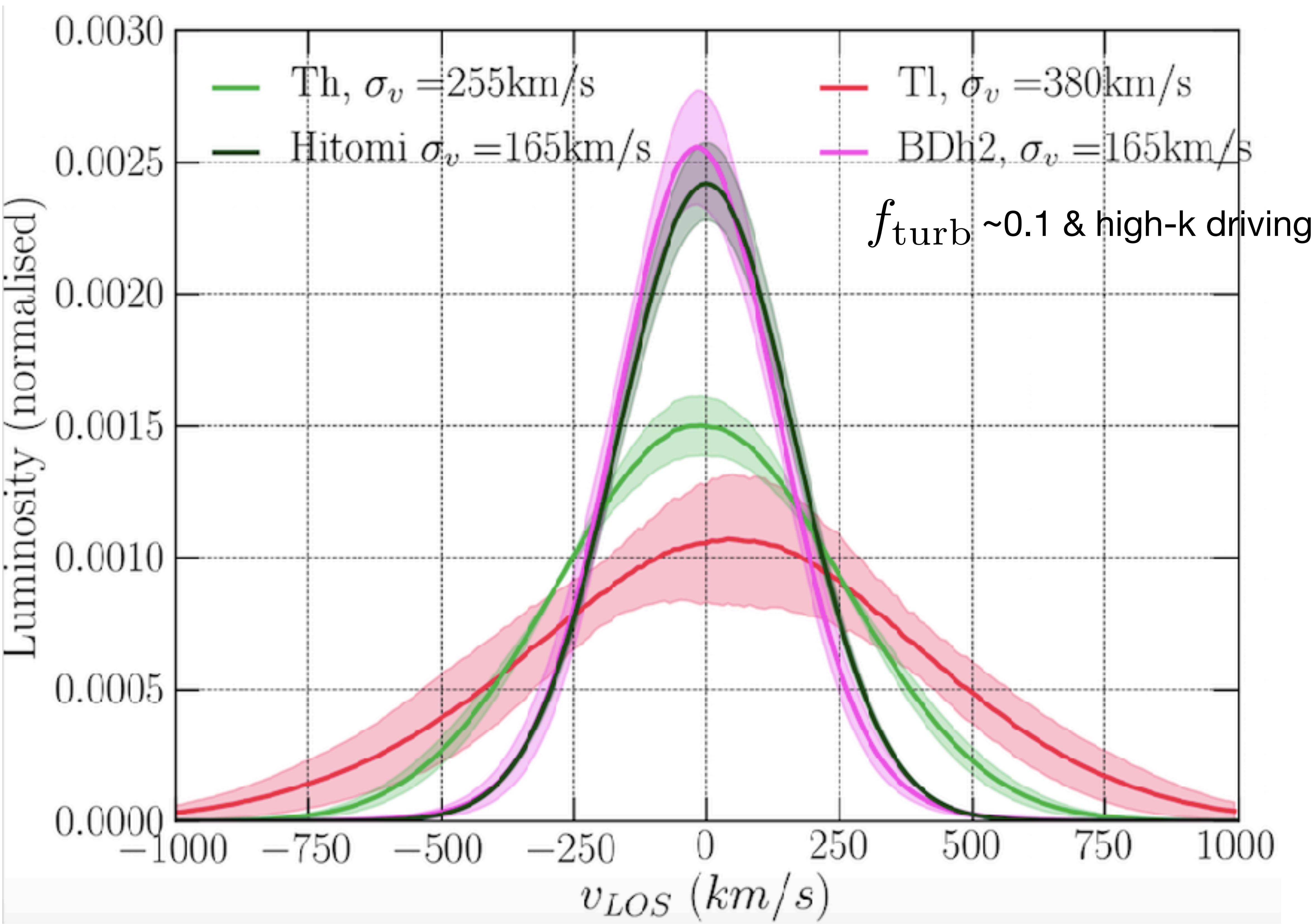


Supersonic Mach no. peak

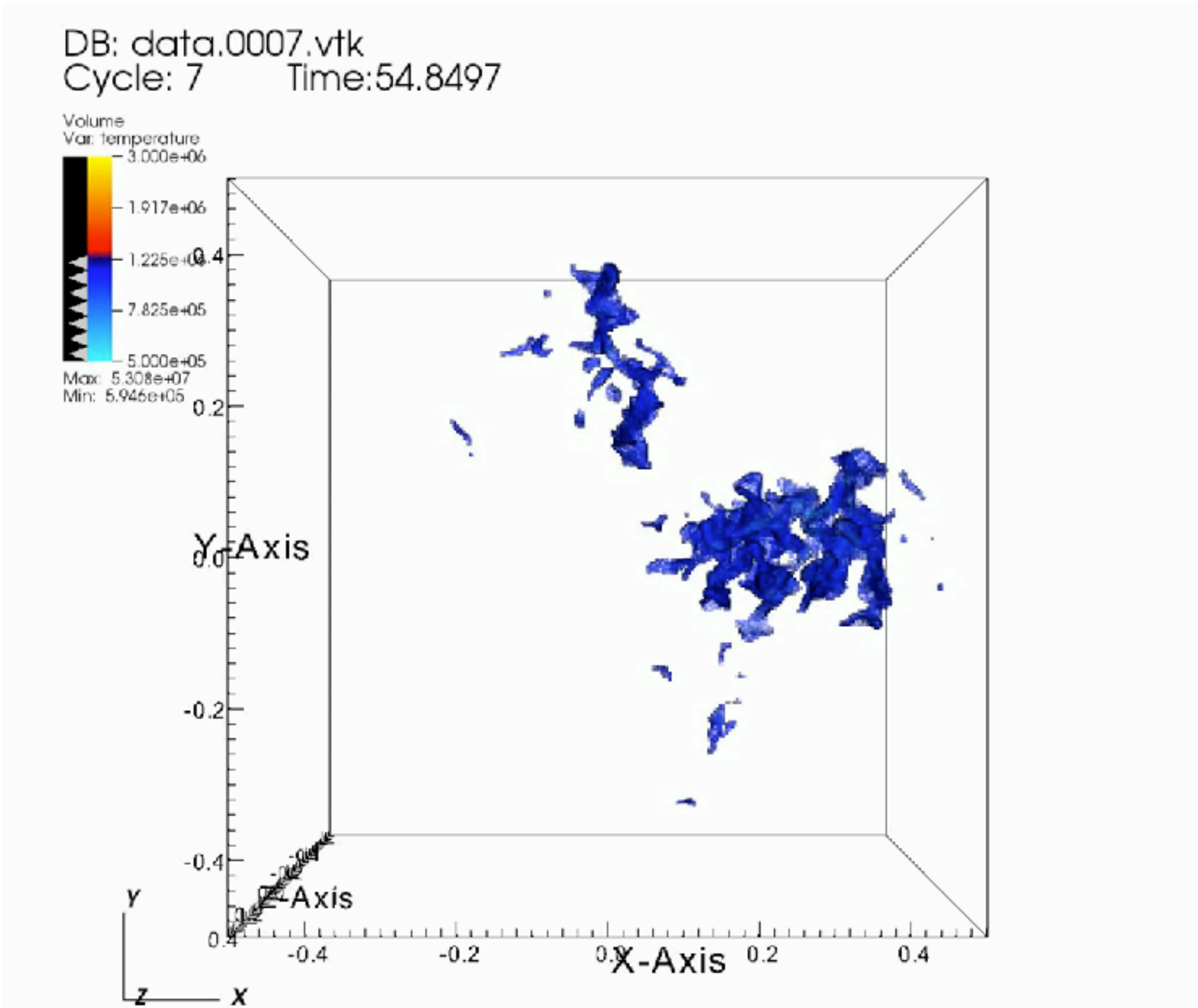
Condensation takes too long for SS driving, fast mixing

Very large velocities for both!

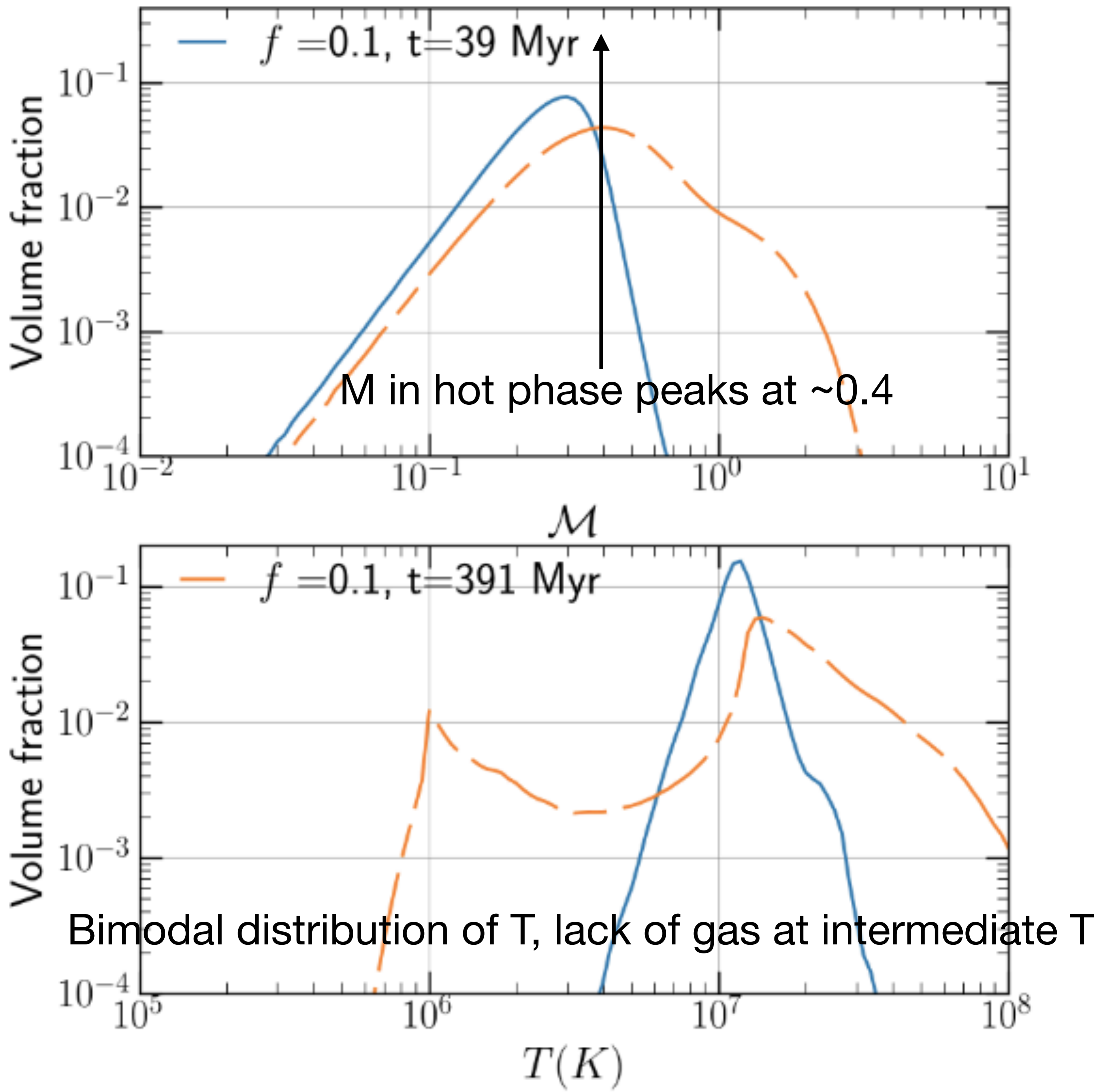
Adjusting $f_{\rm turb}$ to match Hitomi



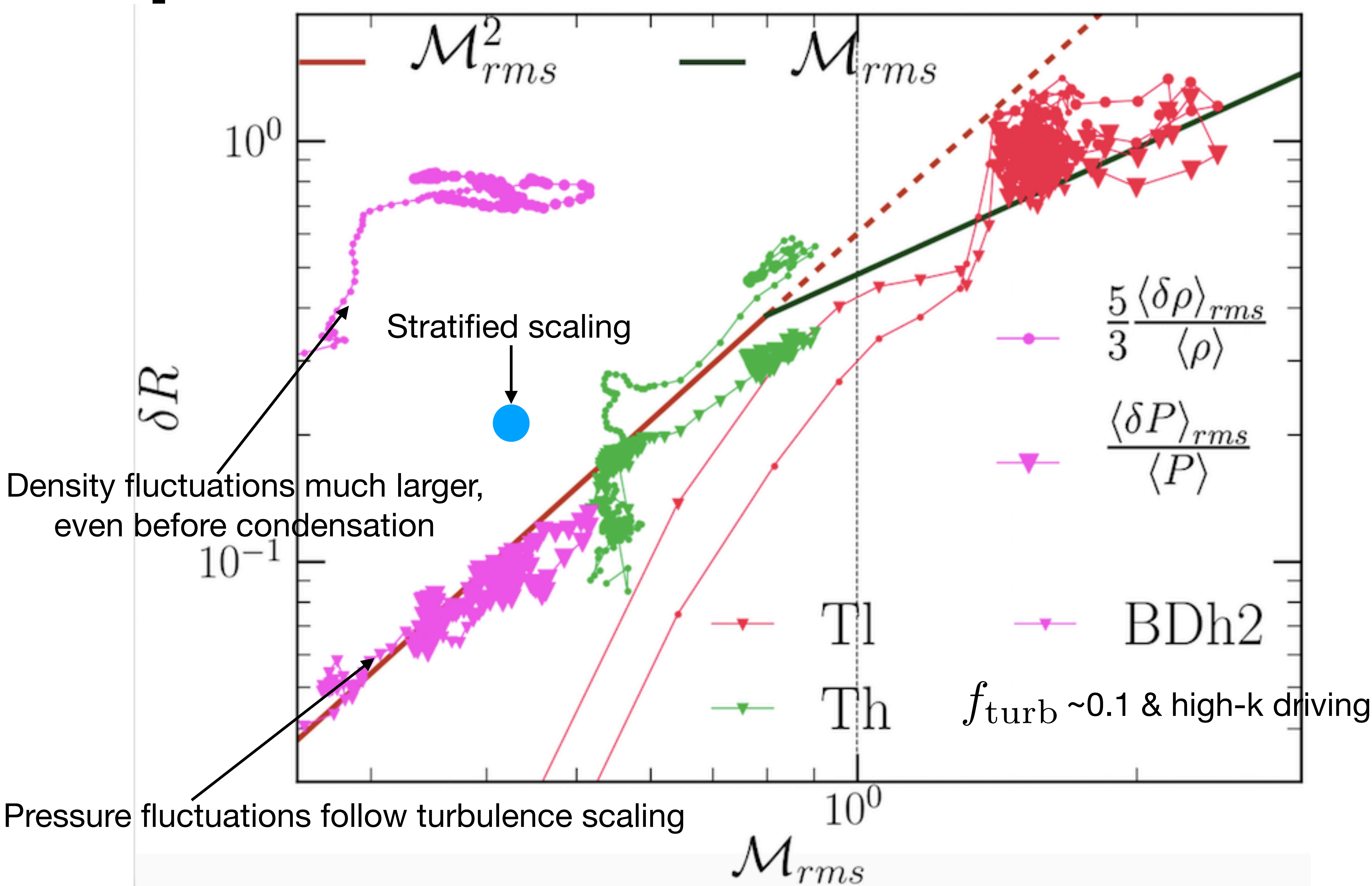
Condensation for $f_{\rm turb}$~0.1



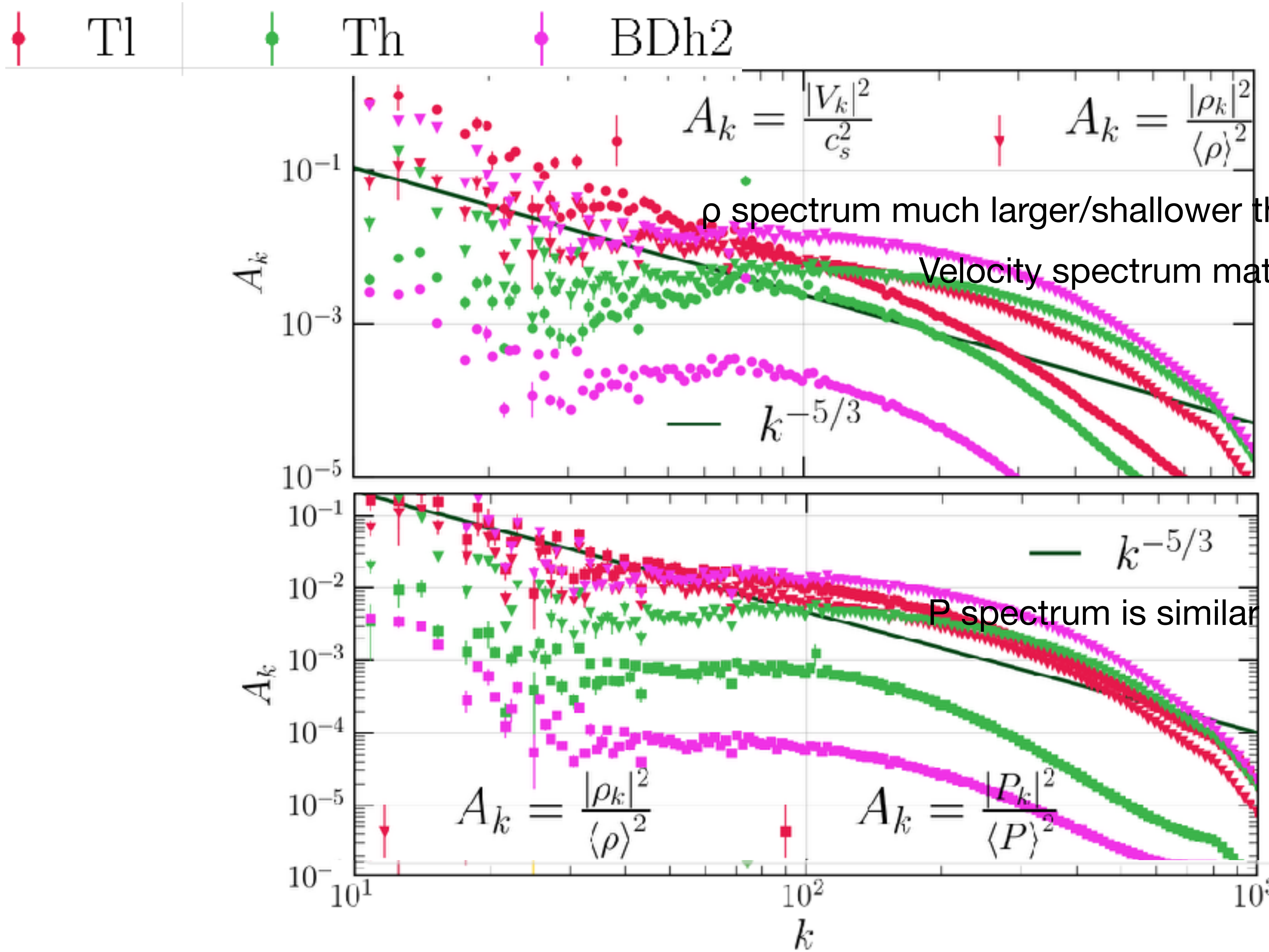
M, T PDF for $f_{\rm turb}$~0.1



ρ/P fluctuations vs M



Power spectra w htg/clg



ρ spectrum much larger/shallower than K41

Velocity spectrum matches K41

P spectrum is similar to velocity,

Conclusions

- cooling+heating can lead to large density fluctuations in CCs; TI must be accounted for in converting density fluctuations to v_{rms}
- M<1 implies that f_{turb}<<1 if cold gas is to condense out of the ICM
- $f_{\rm turb}$~0.1 to match Hitomi v_{LOS} in our setup
- Density power spectrum larger/shallower with htg/clg
- Role of **background stratification** in ρ-v_{rms} relation? t_{cool}/t_{ff}?
- Synergies w high resolution tSZ, X-ray and direct velocity measurements (Hitomi successor)
- MHD, plasma effects!

Thank You!