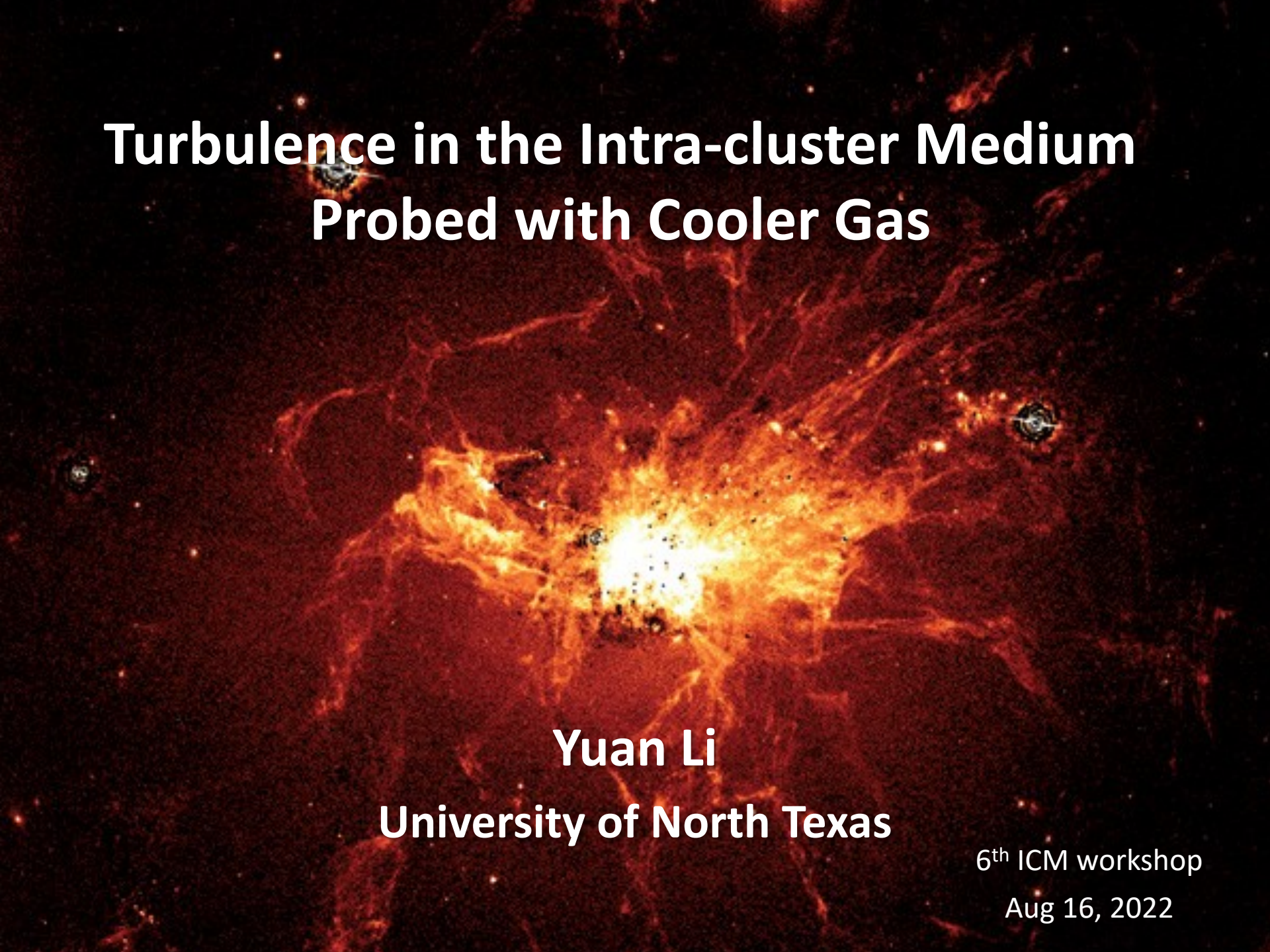


Turbulence in the Intra-cluster Medium Probed with Cooler Gas

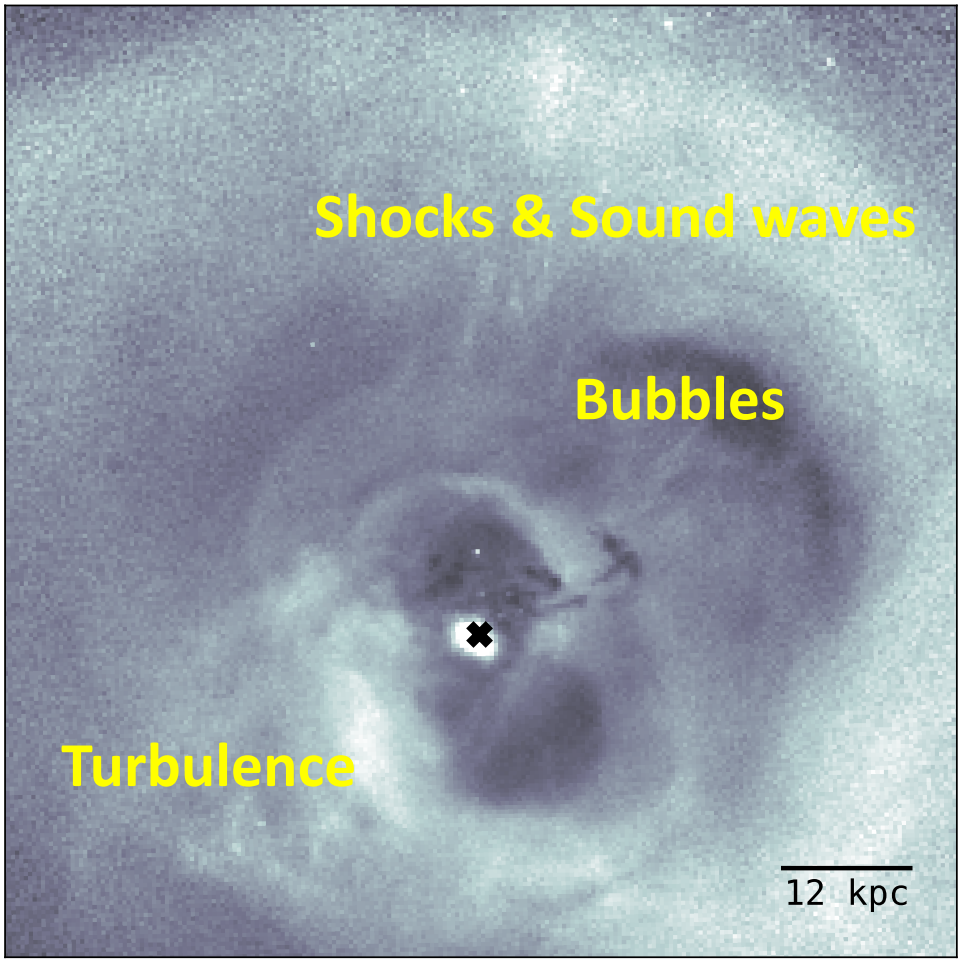
Yuan Li

University of North Texas

6th ICM workshop

Aug 16, 2022

How Do Black Holes Feed Back?



Chandra X-ray image of the Perseus Core

Turbulent Heating

Little turbulence found in numerical simulations:

Reynolds+2015

Yang&Reynolds2016

Li+2017

Hillel&Soker2017

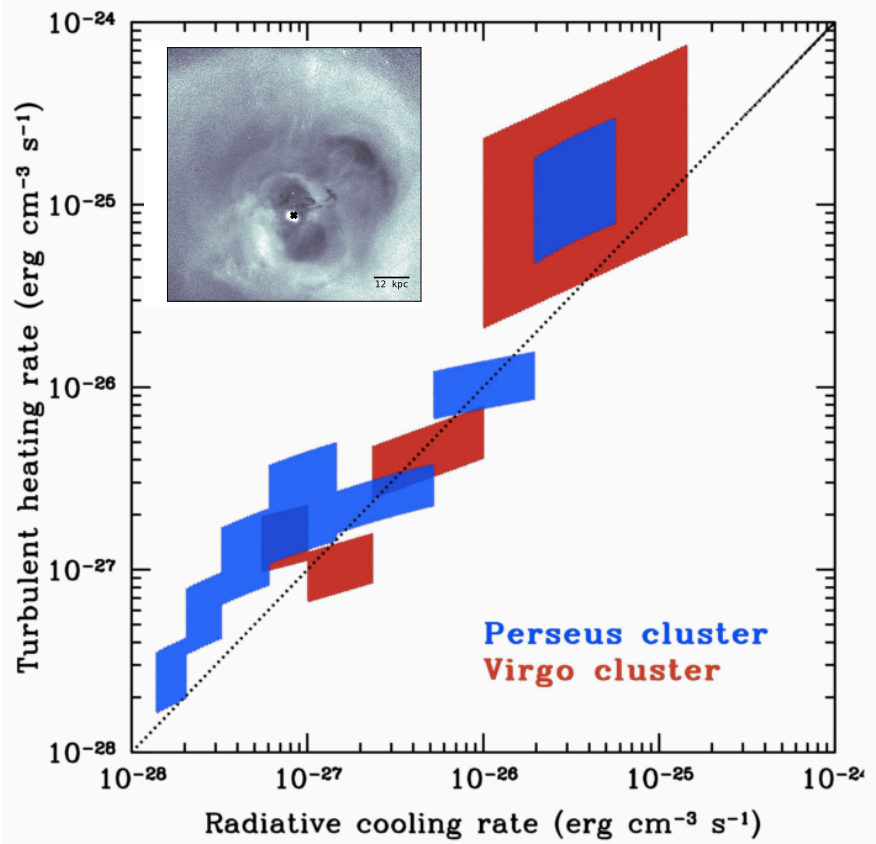
Martizzi+2018

Bombic&Reynolds2019

…

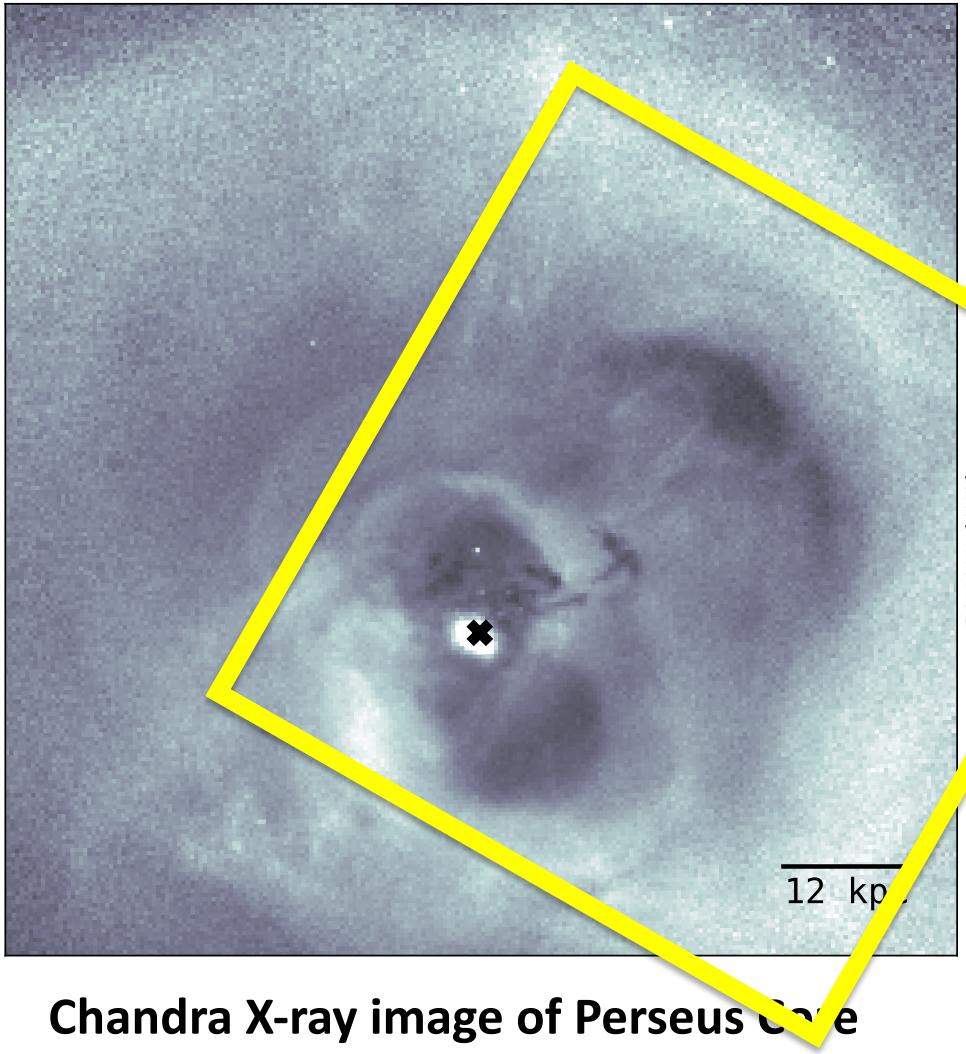
Shock waves, sound waves, adiabatic processes and mixing are more important than turbulent dissipation

Lots of turbulence inferred from X-ray surface brightness fluctuations



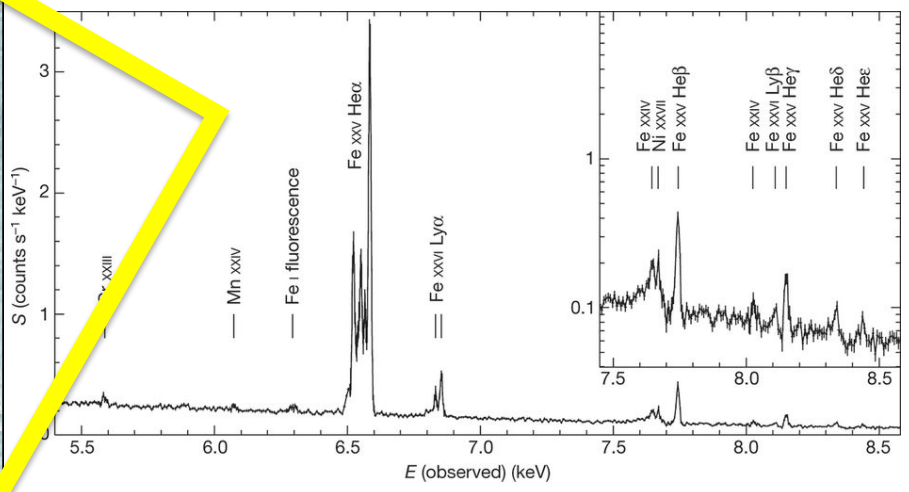
Zhuravleva+2014, Nature

Measuring Turbulence(?) in the Hot ICM



Chandra X-ray image of Perseus Cluster

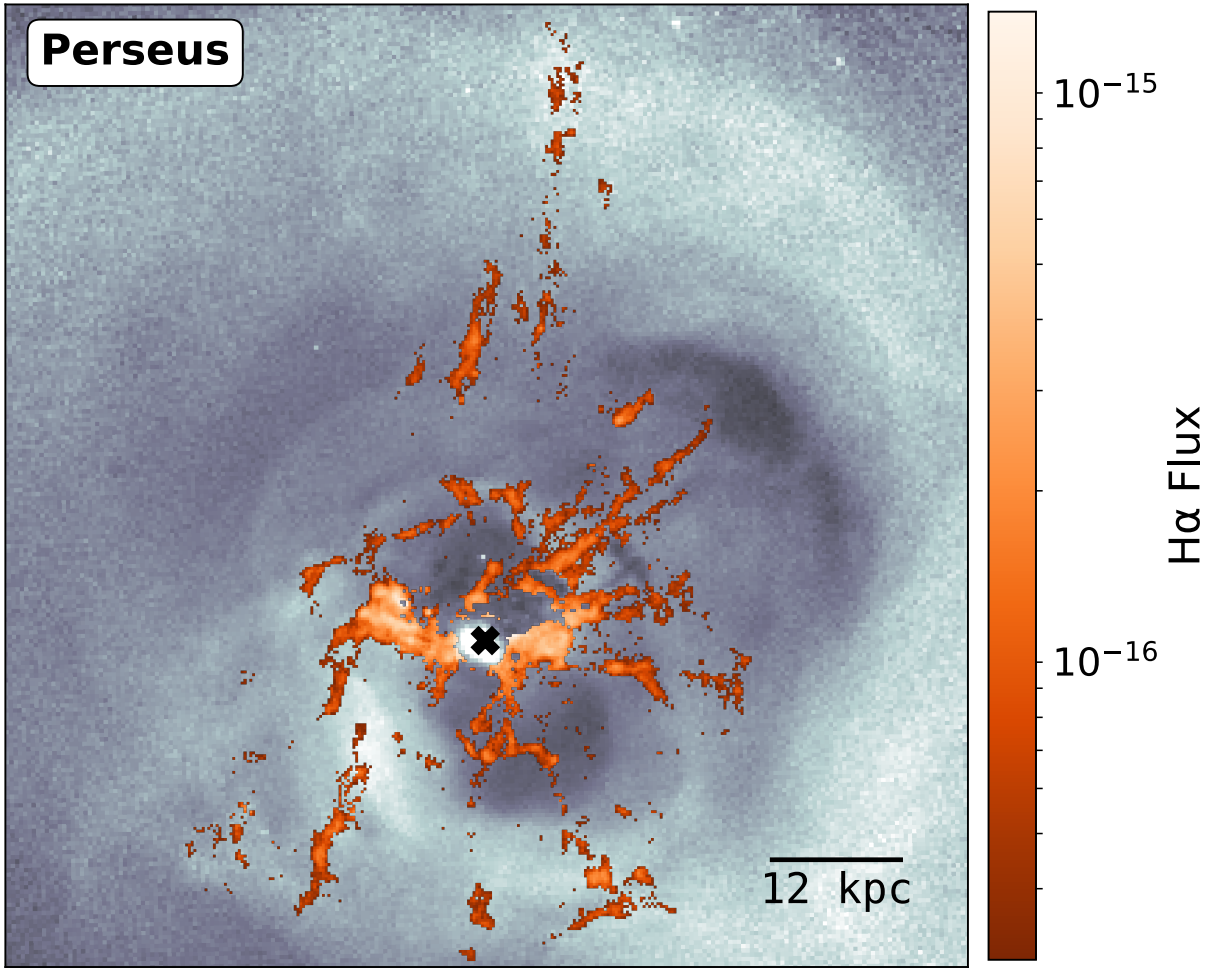
Hitomi line broadening => line-of-sight velocity dispersion ~ 164 km/s, consistent with Zhuravleva+2014



Aharonian+2016

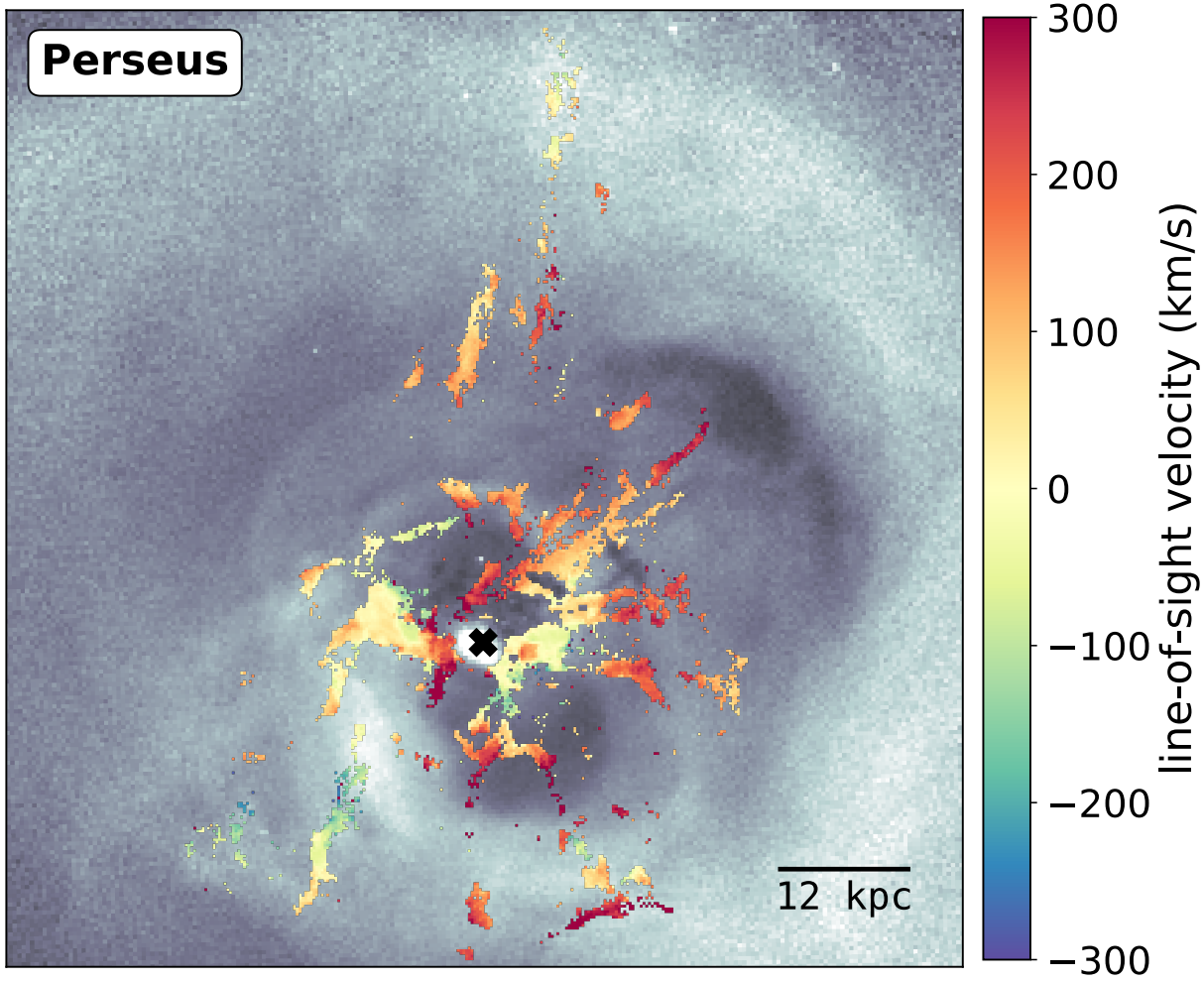
The ICM is Multiphase

X-ray: >10^7K
Optical Hα: 10^4K
ALMA CO: <100 K



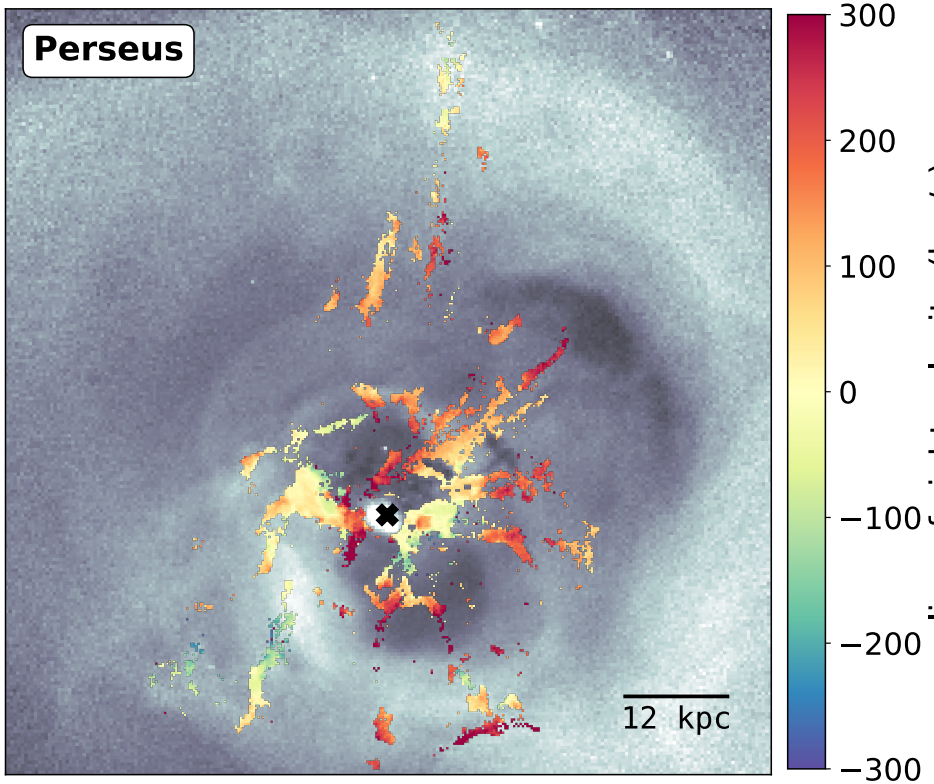
Cold filaments observed by CFHT (Gendron-Marsolais+2018)

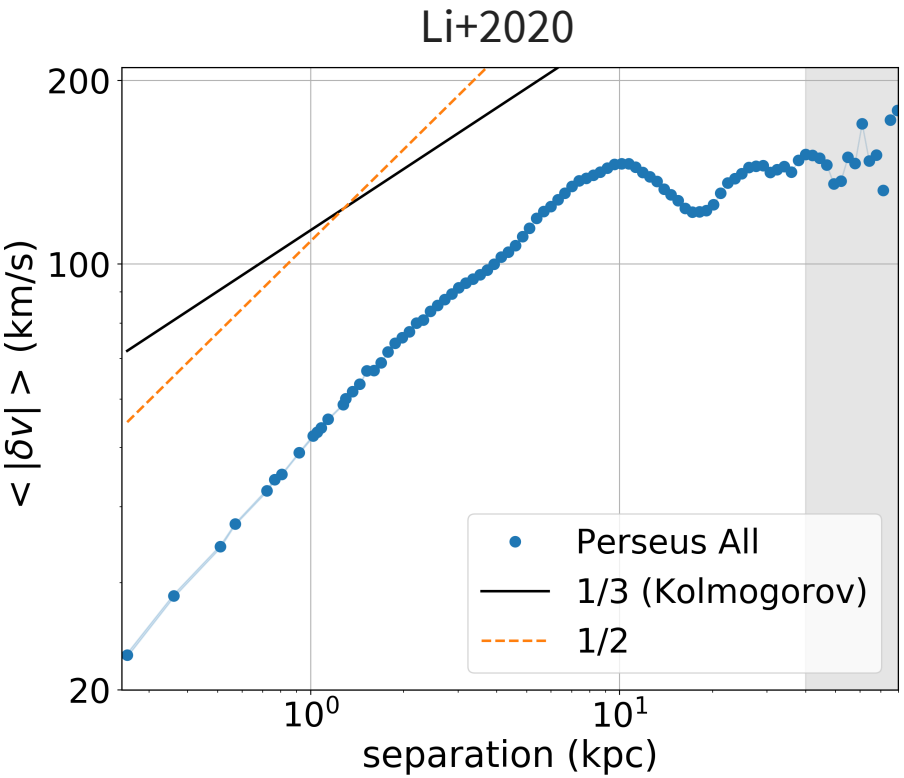
The Motions of the Filaments Appear Random=>Turbulence?



Cold filaments observed by CFHT (Gendron-Marsolais+2018)

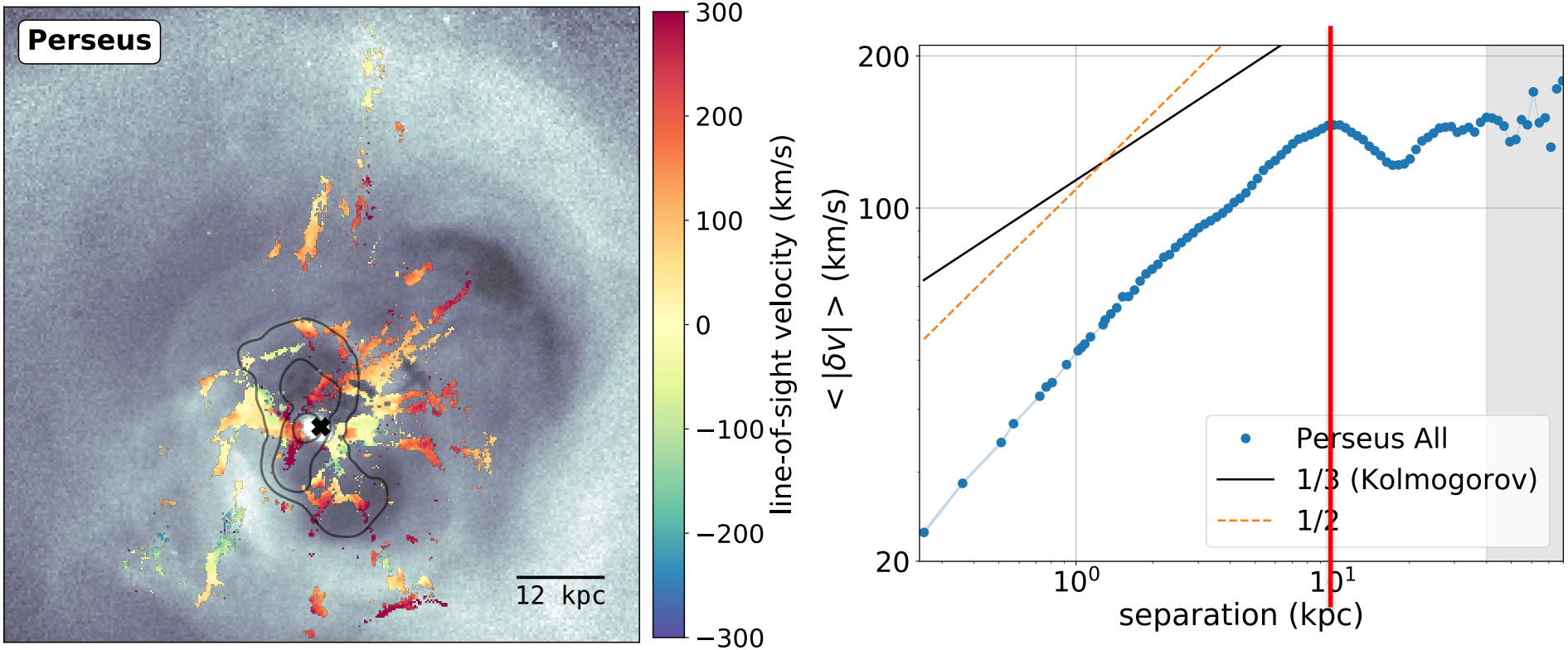
The Velocity Structure Function of Perseus Filaments





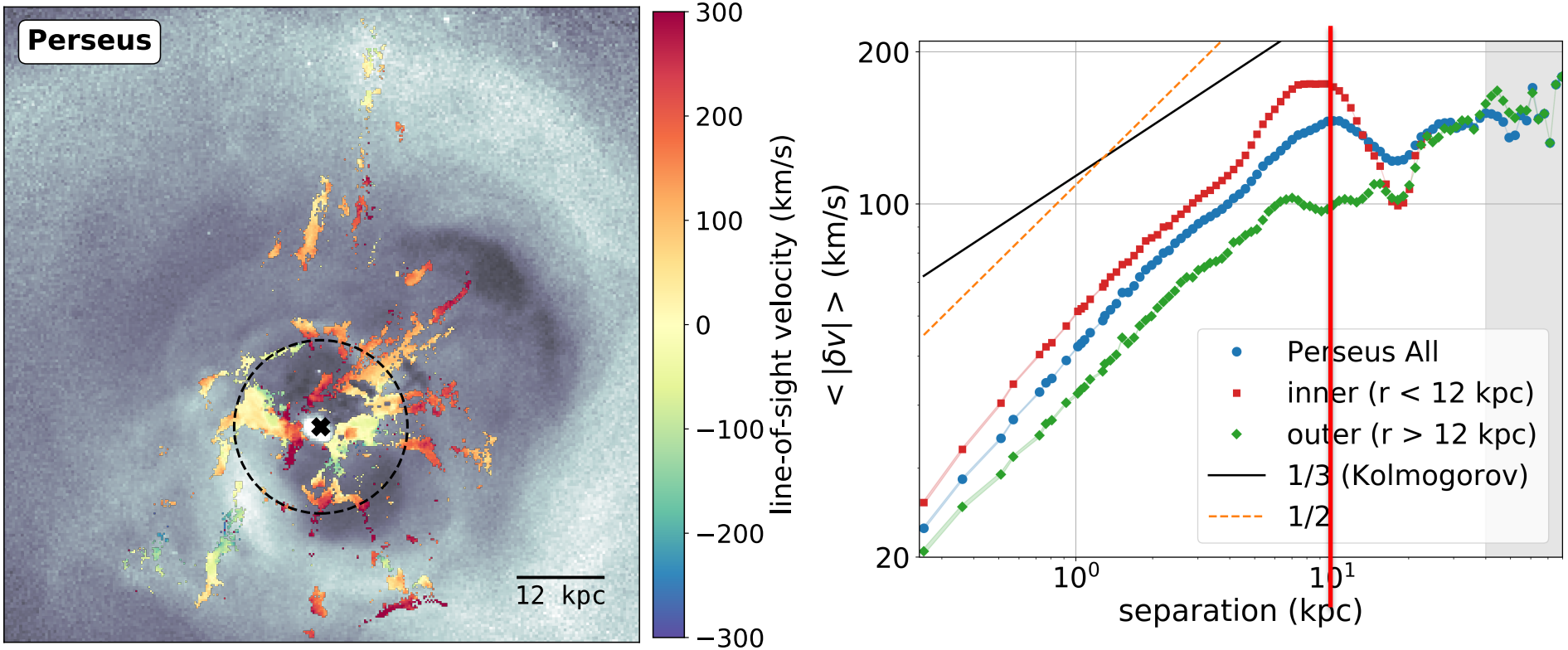
Big whorls have little whorls
Which feed on their velocity,
And little whorls have lesser whorls
And so on to viscosity. -Lewis Fry Richardson

The Velocity Structure Function of Perseus Filaments



Sizes of the X-ray Bubbles = The inferred driving scales of turbulence

The Velocity Structure Function of Perseus Filaments



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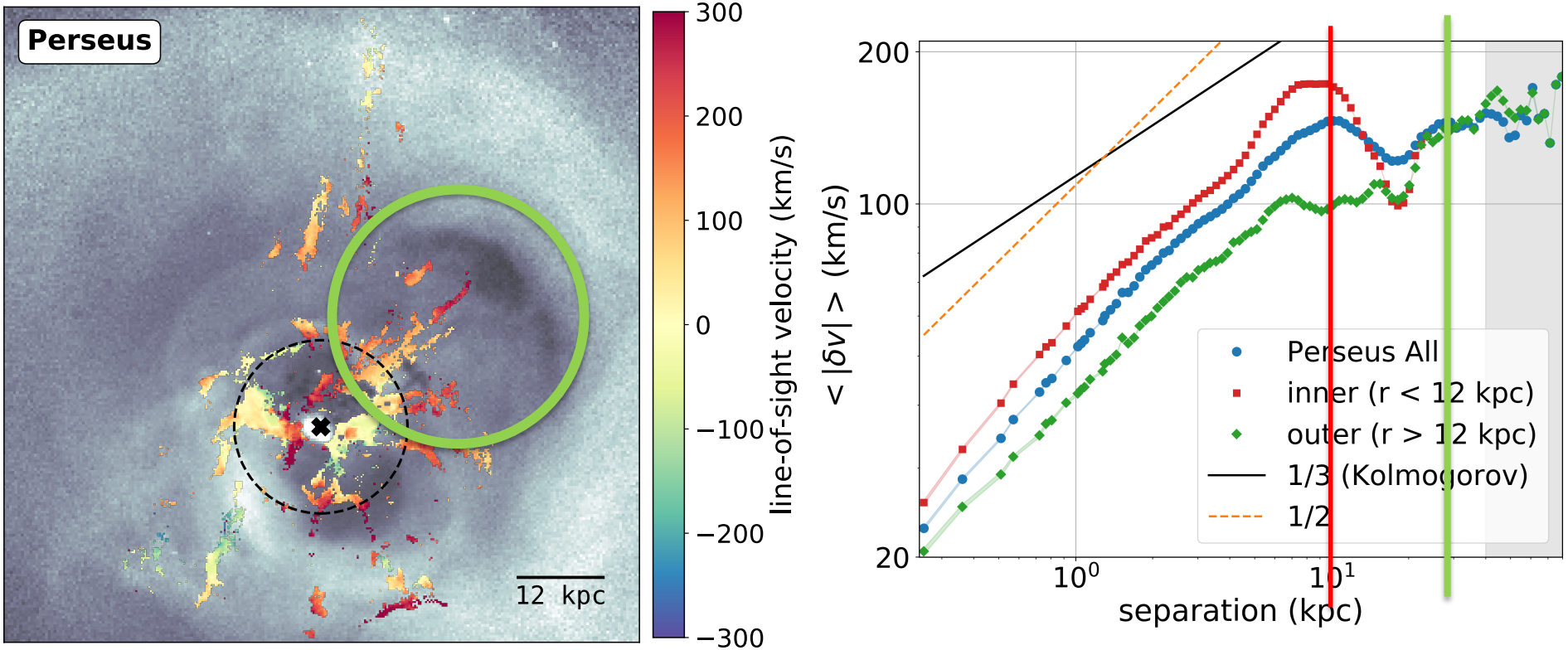
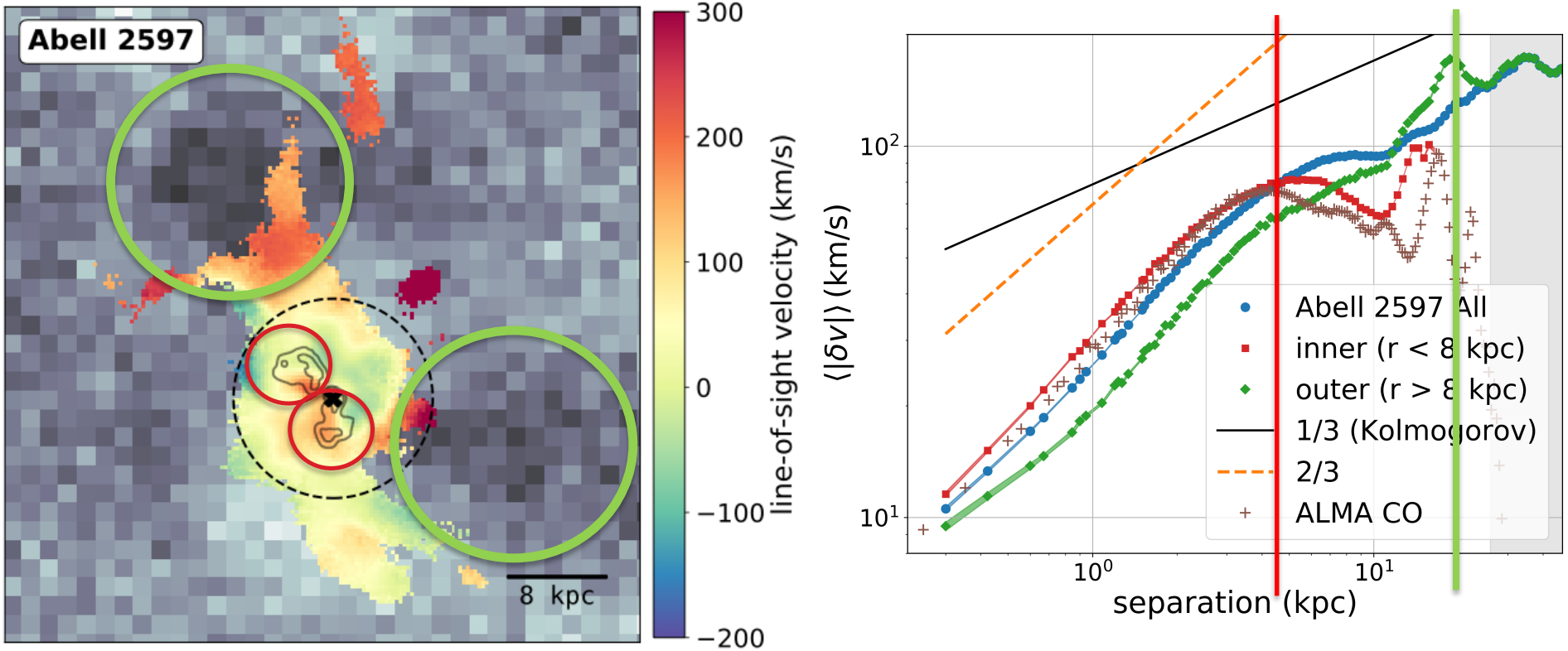


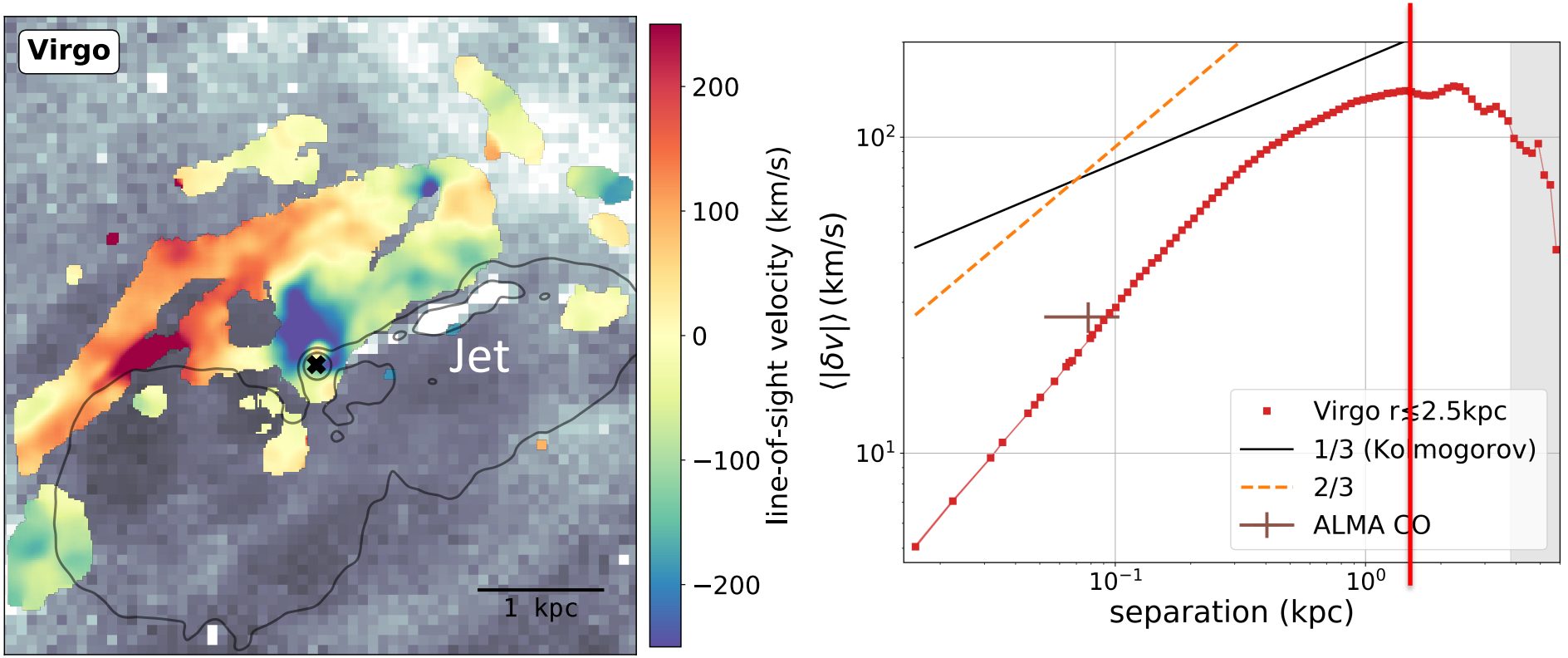
Sizes of the X-ray Bubbles = The inferred driving scales of turbulence

The Velocity Structure Function of Abell 2597 Filaments



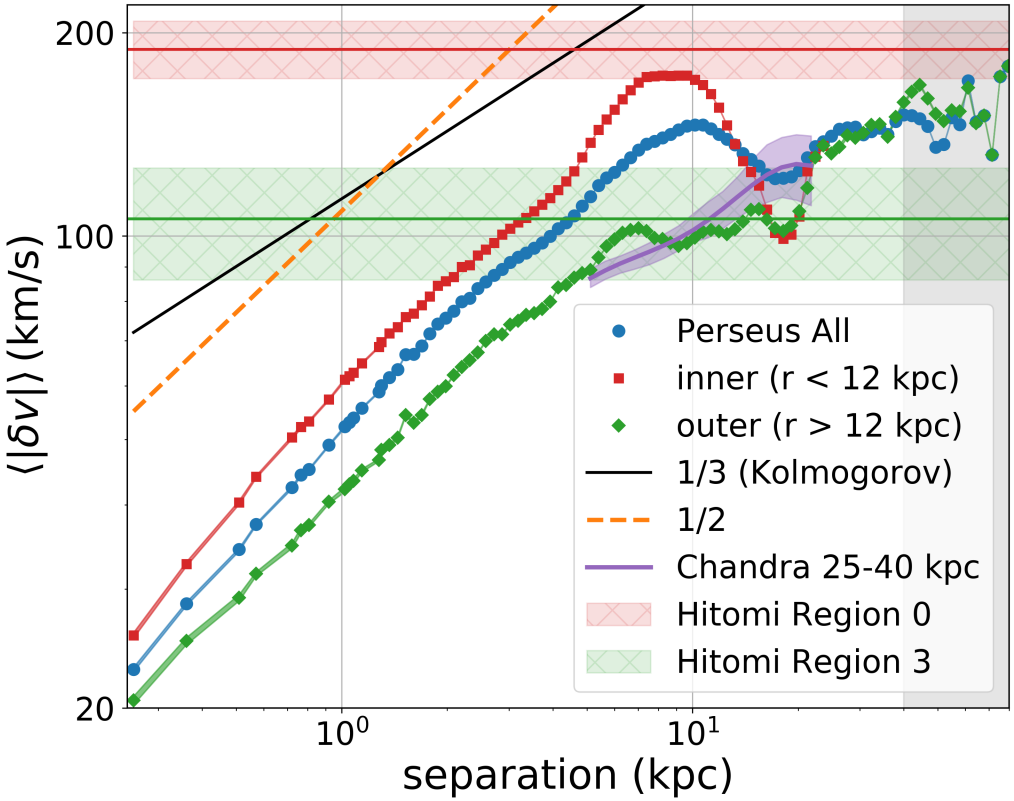
Sizes of the X-ray Bubbles = The inferred driving scales of turbulence

The Velocity Structure Function of Virgo Filaments



Sizes of the X-ray Bubbles = The inferred driving scales of turbulence

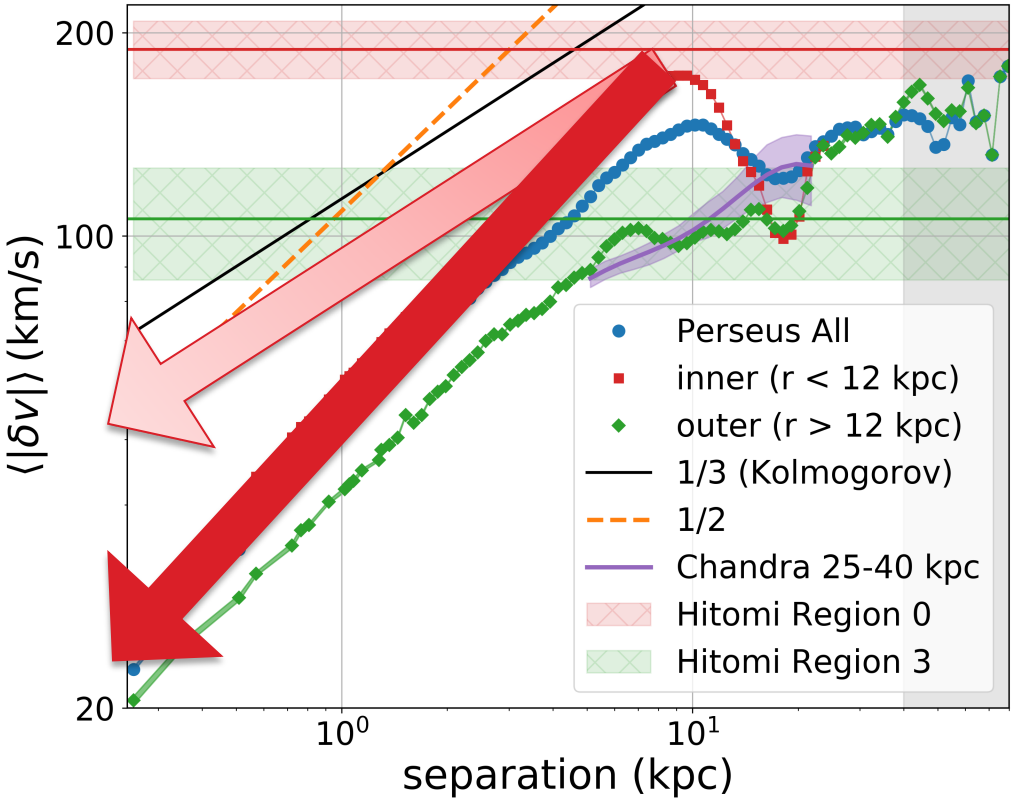
Comparison with X-ray Measurements



Excellent agreement near the driving scale!

Cool filaments are good tracers of the hot ICM (?)

Comparison with X-ray Measurements



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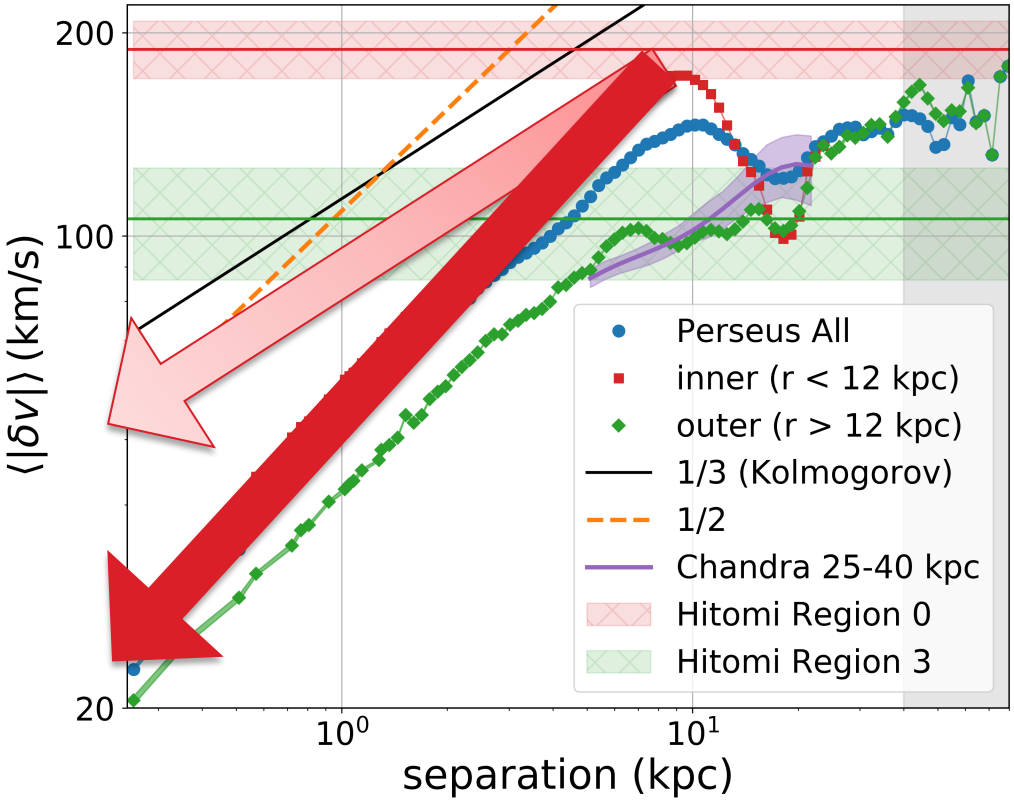
However, the dissipation rate on small scales is smaller than the previous estimation based on classical Kolmogorov turbulence.

Comparison with X-ray Measurements



The missing Kolmogorov Problem?

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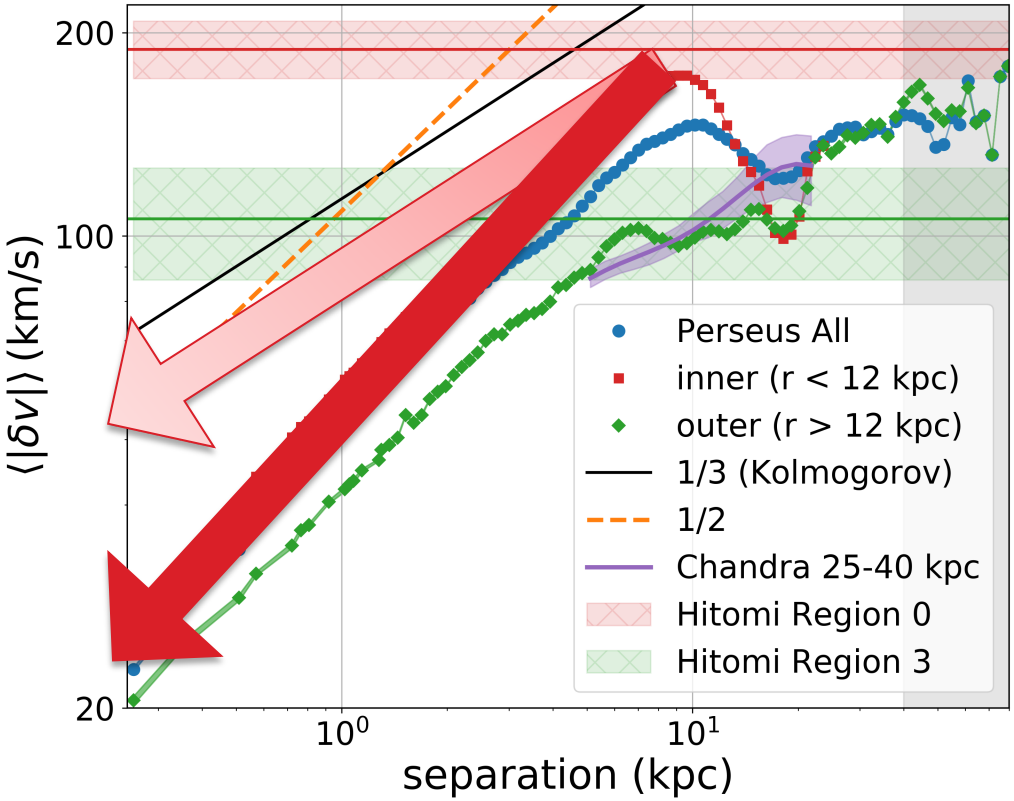
Comparison with X-ray Measurements

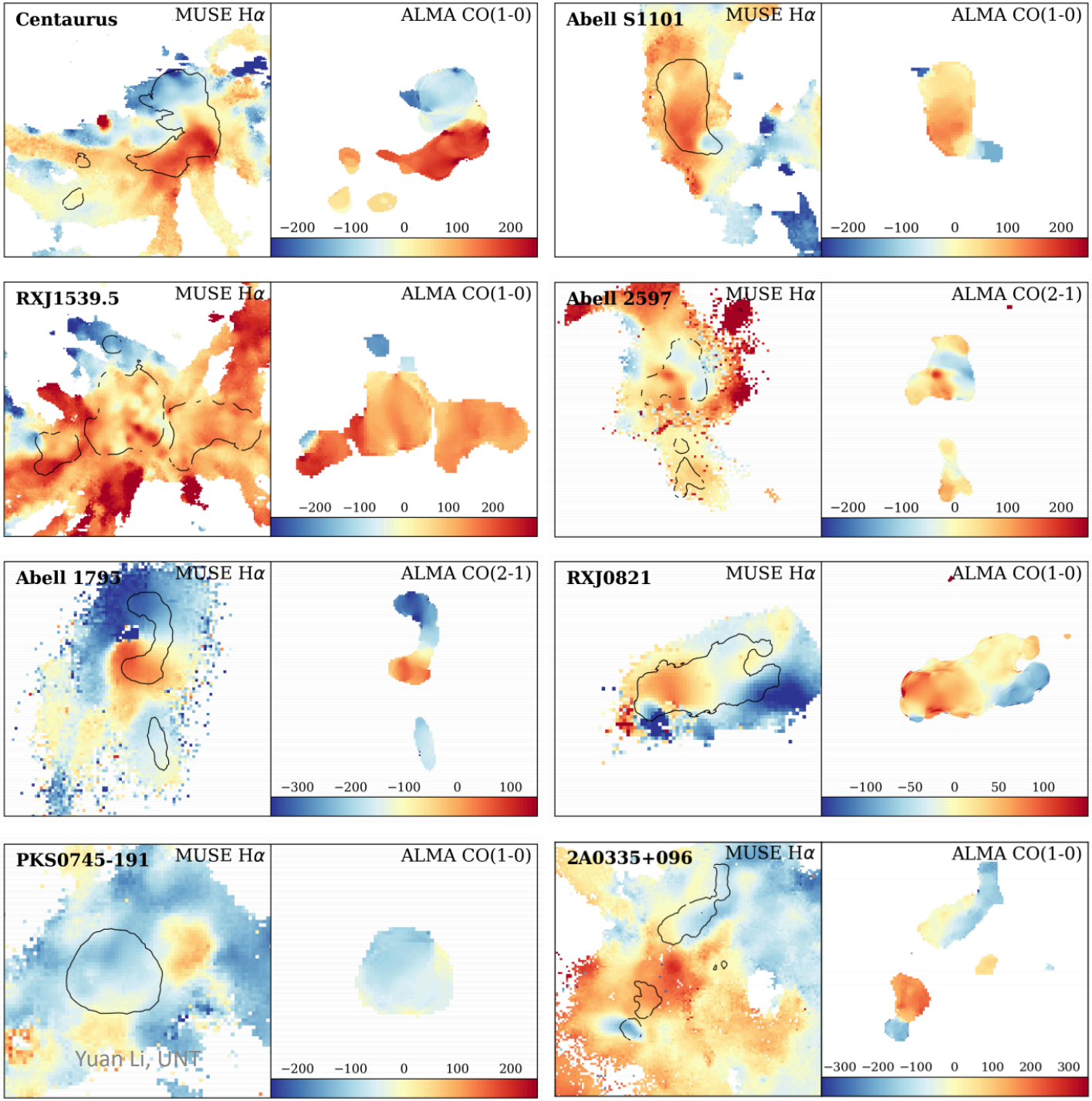


Everything changes on short timescales (shorter than eddy turnover time):
driving-scale, strength, volume filling factor, etc.

Black Holes Are Bad Drivers of Turbulence

Chaos is generated only locally!

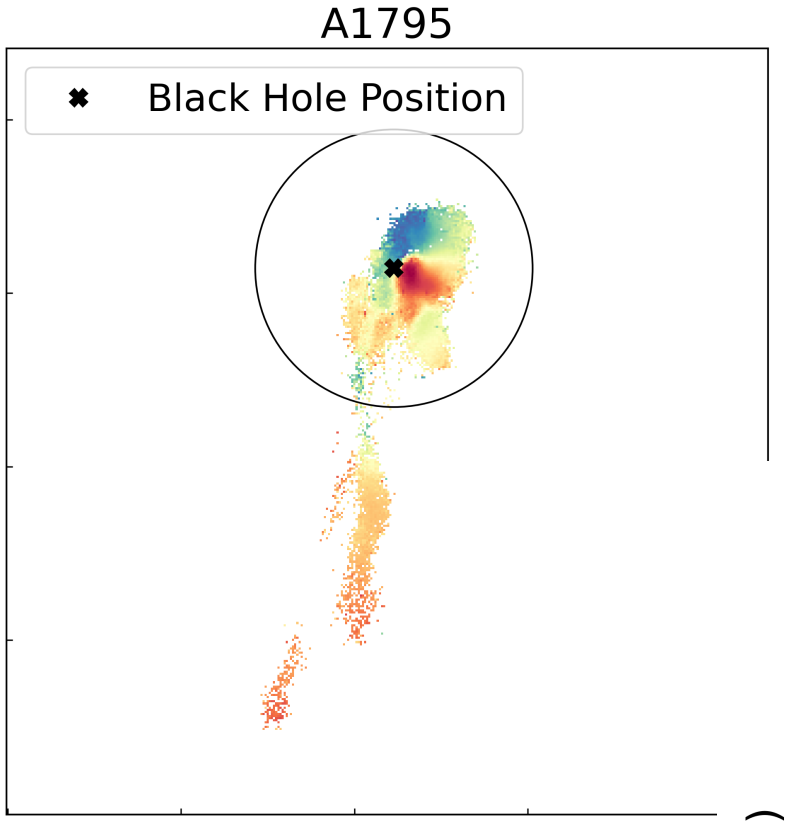
Other possibilities:
Magnetic fields, gravity waves, plasma instabilities, etc.

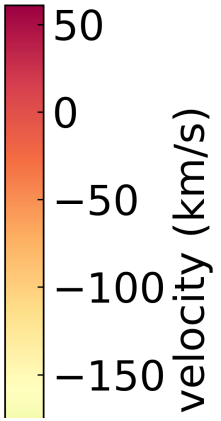


More data!

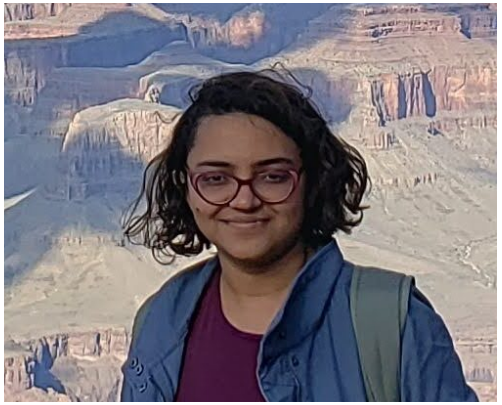
Valeria Olivares (UKY)

Olivares+2019

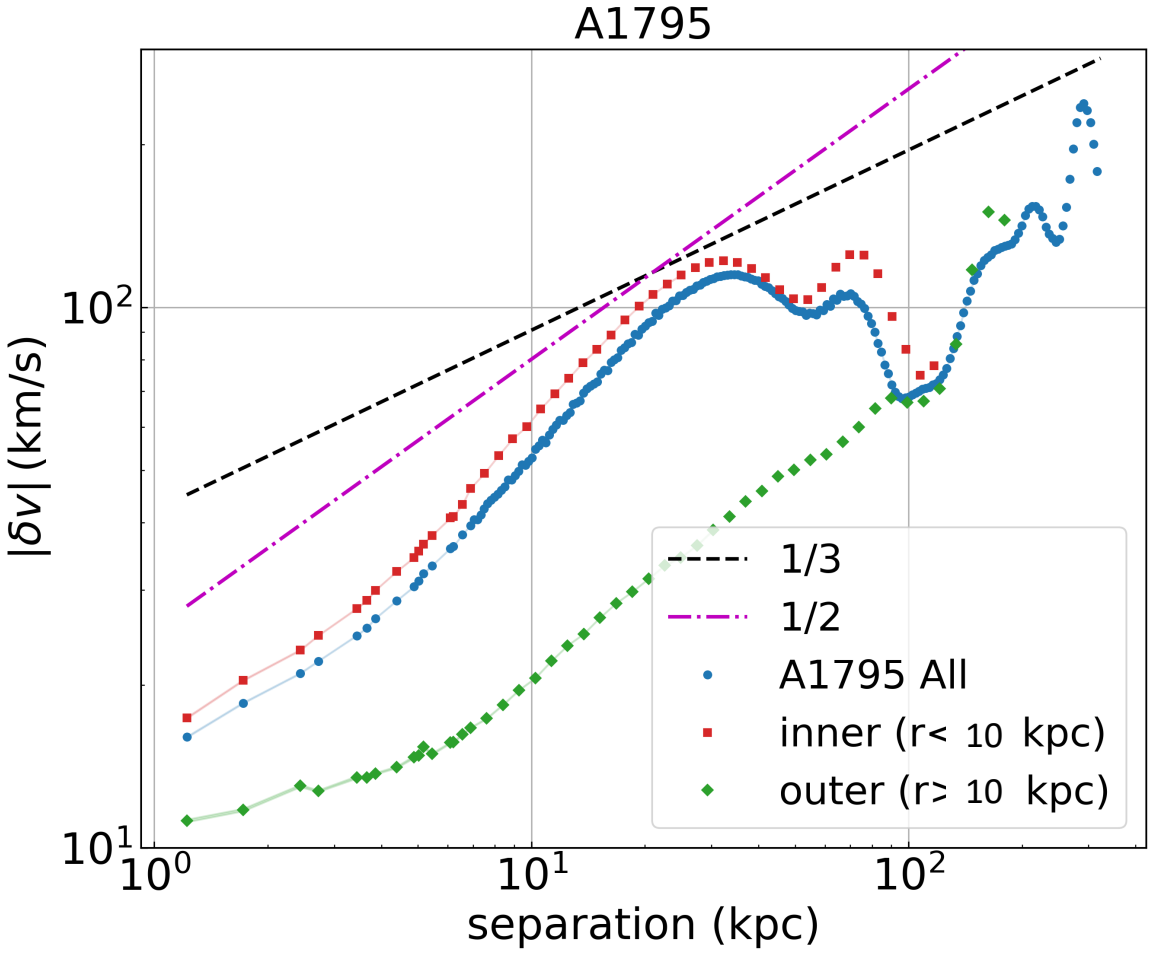




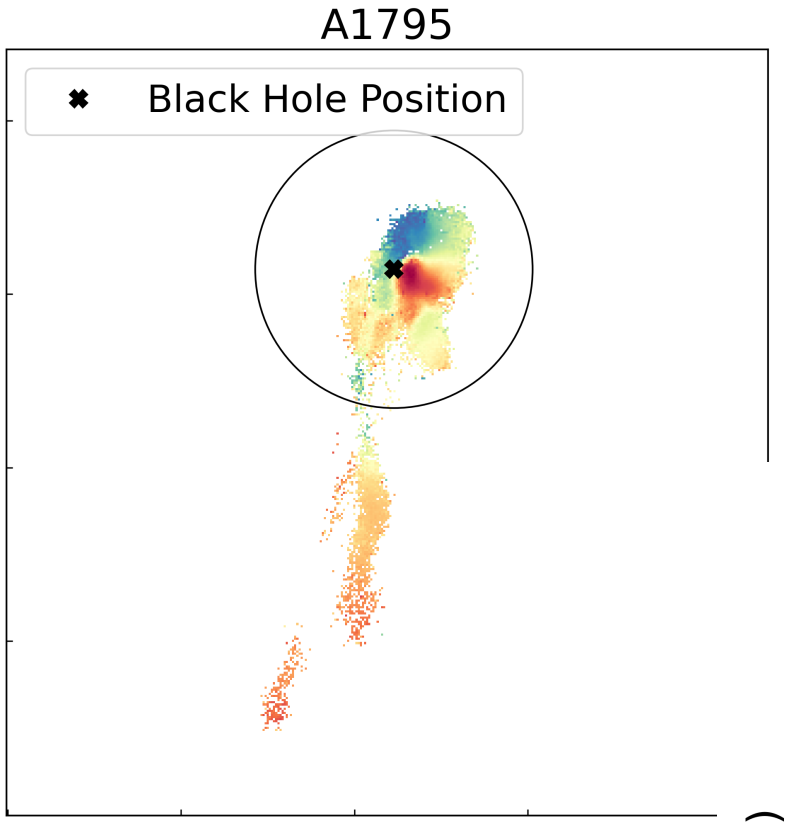
PRELIMINARY



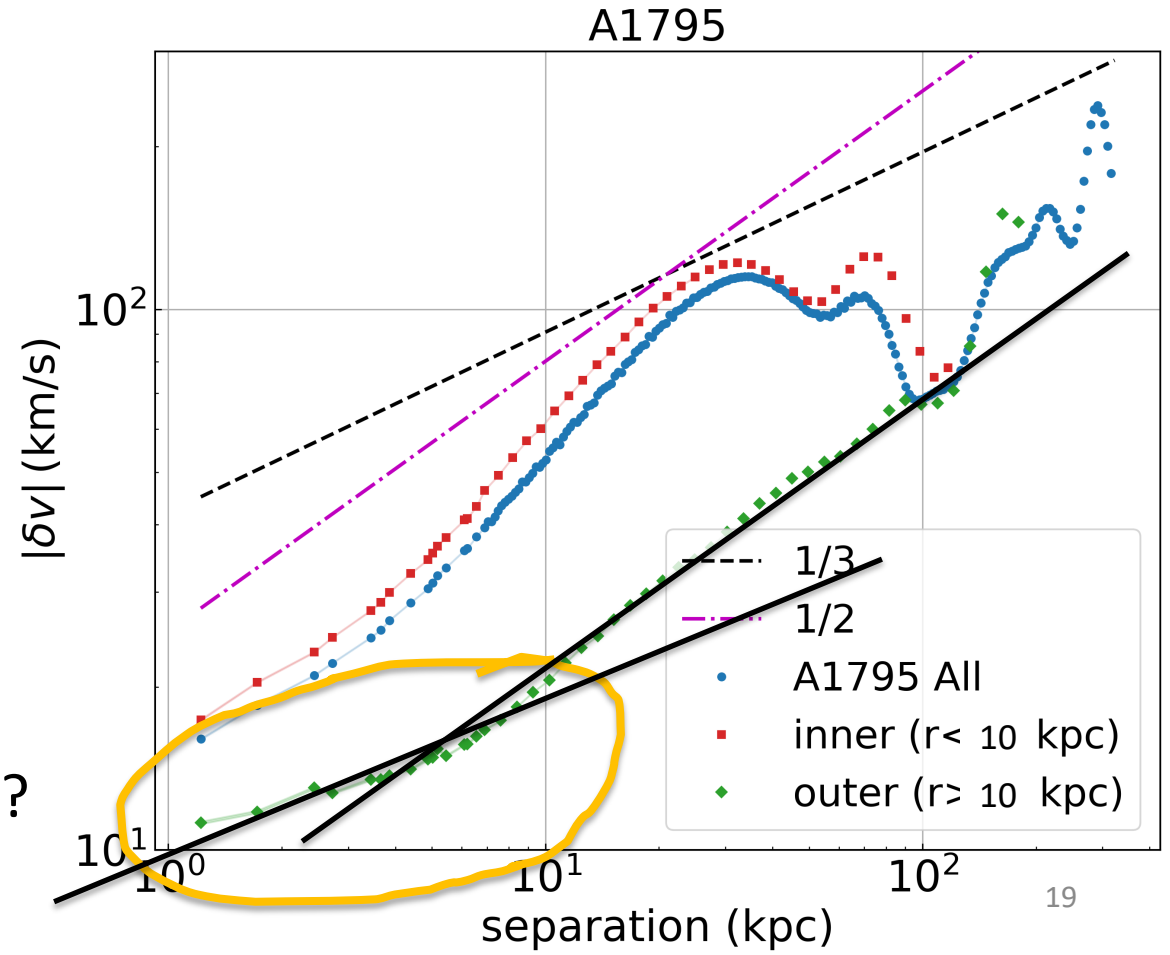
Shalini Ganguly (UNT)



Yuan Li, UNT

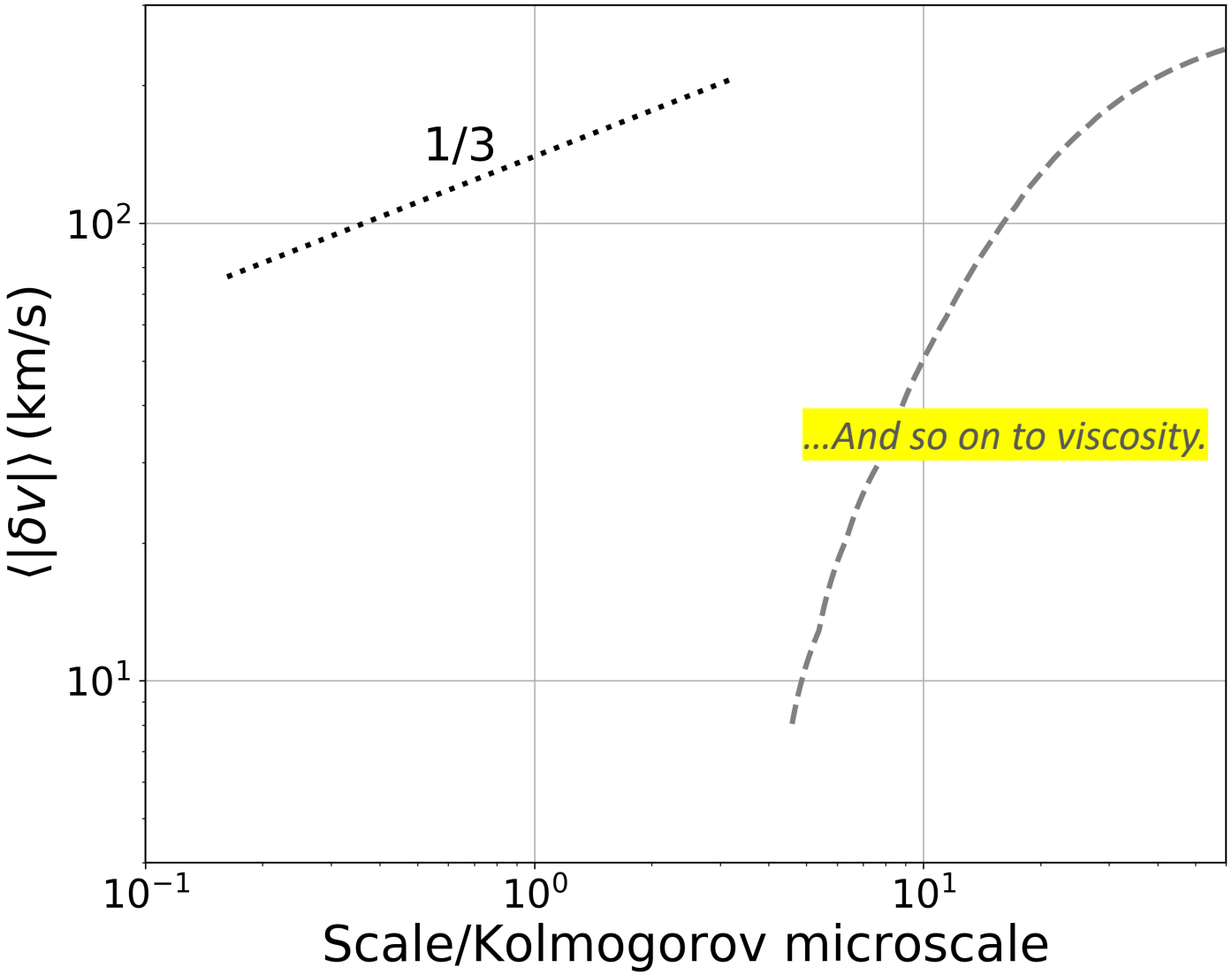


PRELIMINARY

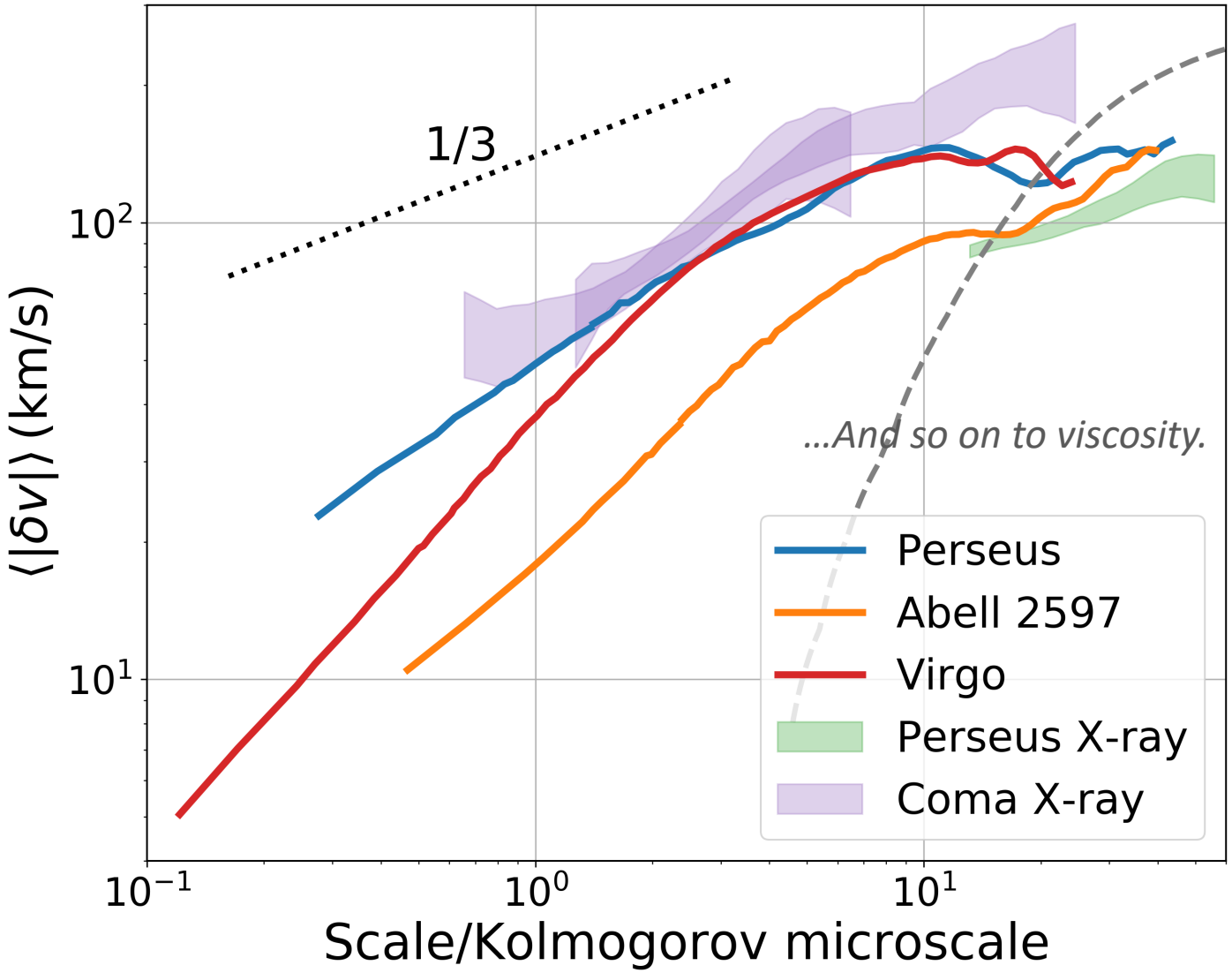


Is this the missing Kolmogorov turbulence?

Turbulence near electron mean free path: Probing Microscale Plasma Physics



Turbulence near electron mean free path: Probing Microscale Plasma Physics

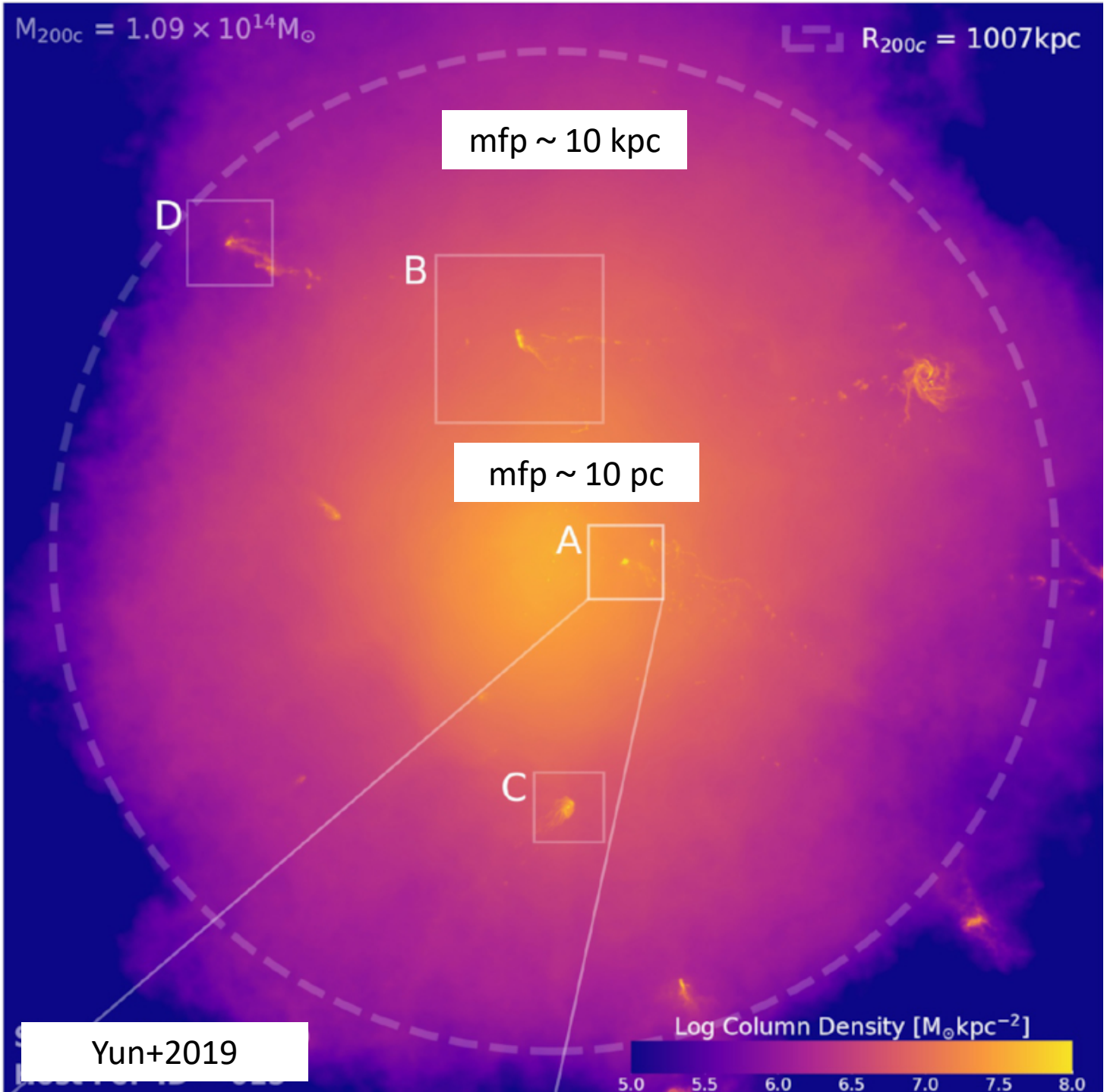


X-ray from Zhuravleva+2019

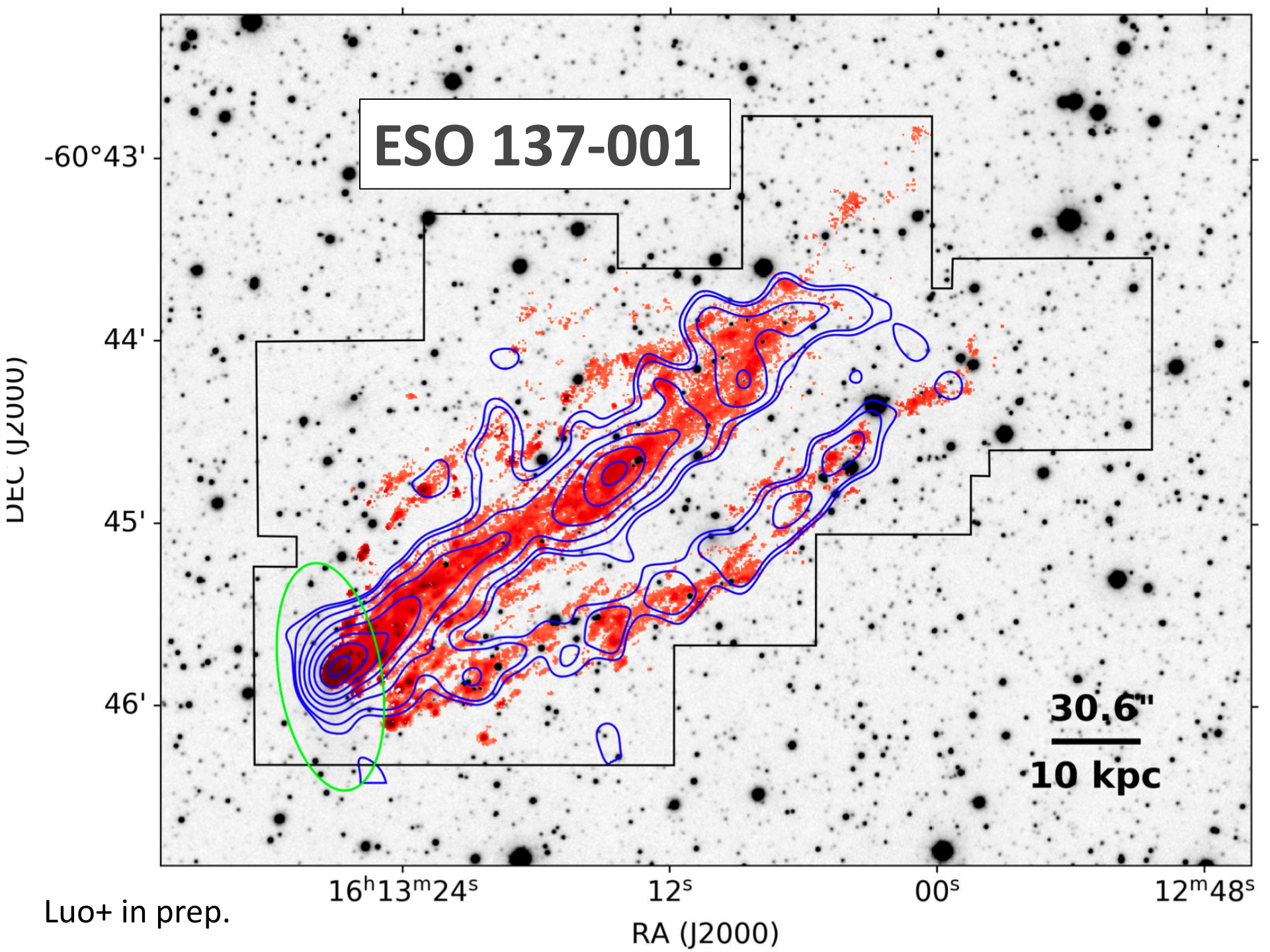
inferred from surface brightness fluctuations

12-day-long Chandra observations of Coma

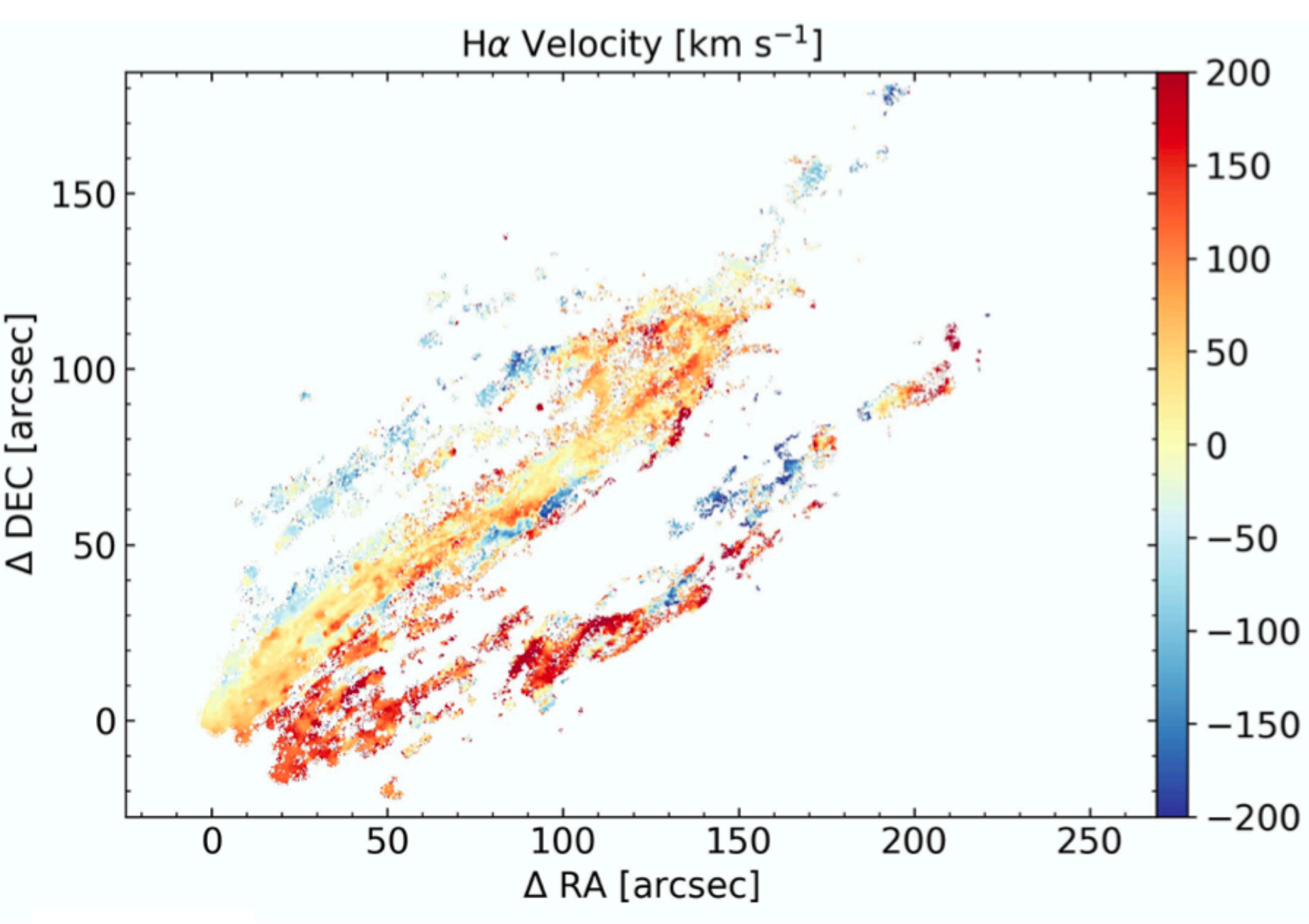
Optical/ALMA: Much cheaper!


$M_{200c} = 1.09 \times 10^{14} M_\odot$
$R_{200c} = 1007$kpc
mfp ~ 10 kpc
D
B
mfp ~ 10 pc
A
C
Log Column Density [$M_\odot$kpc^{-2}]
5.0
5.5
6.0
6.5
7.0
7.5
8.0

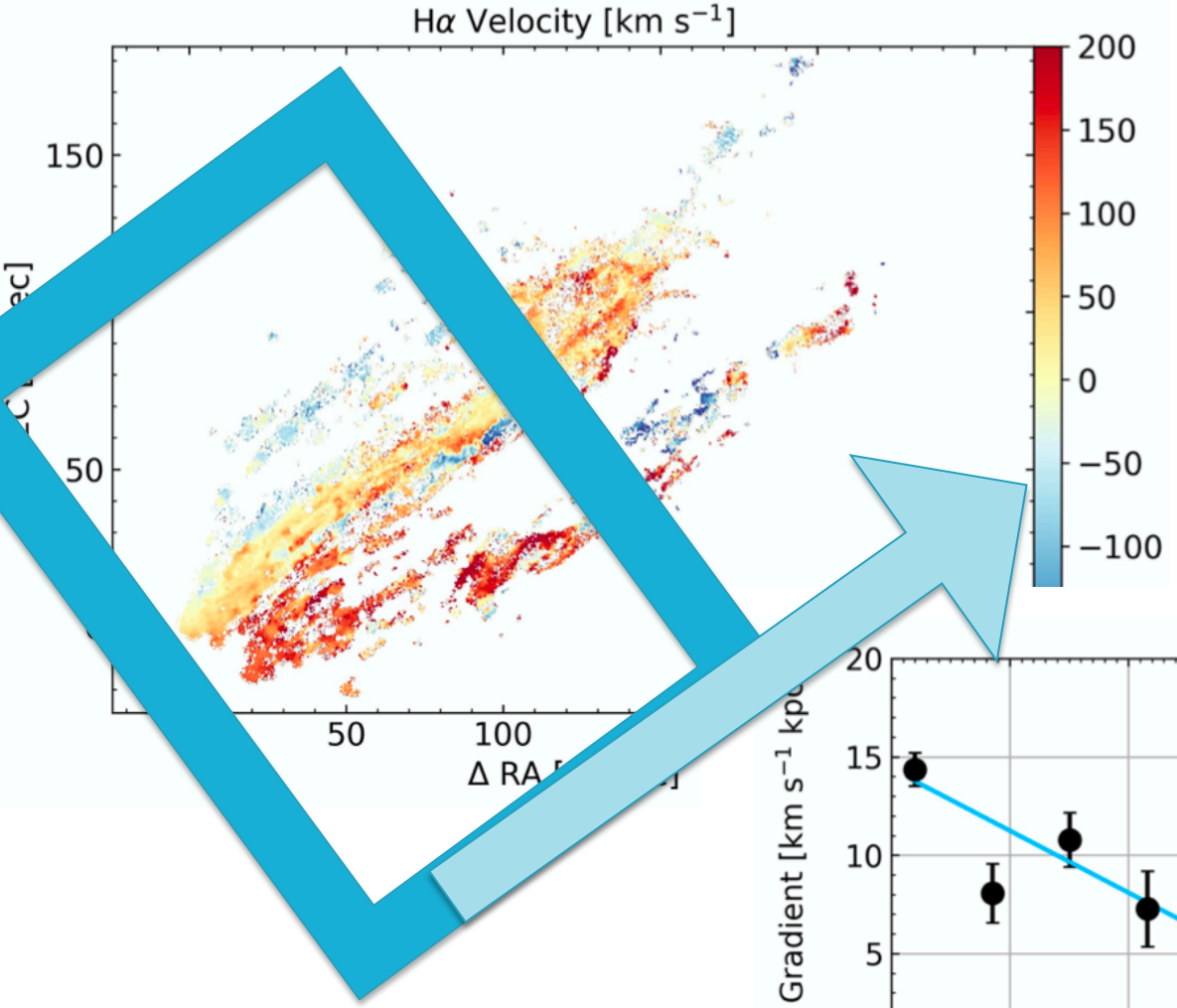
Yun+2019


ESO 137-001
-60°43'
44'
45'
46'
DEC (J2000)
16h13m24s
12s
00s
12m48s
RA (J2000)
30.6"
10 kpc

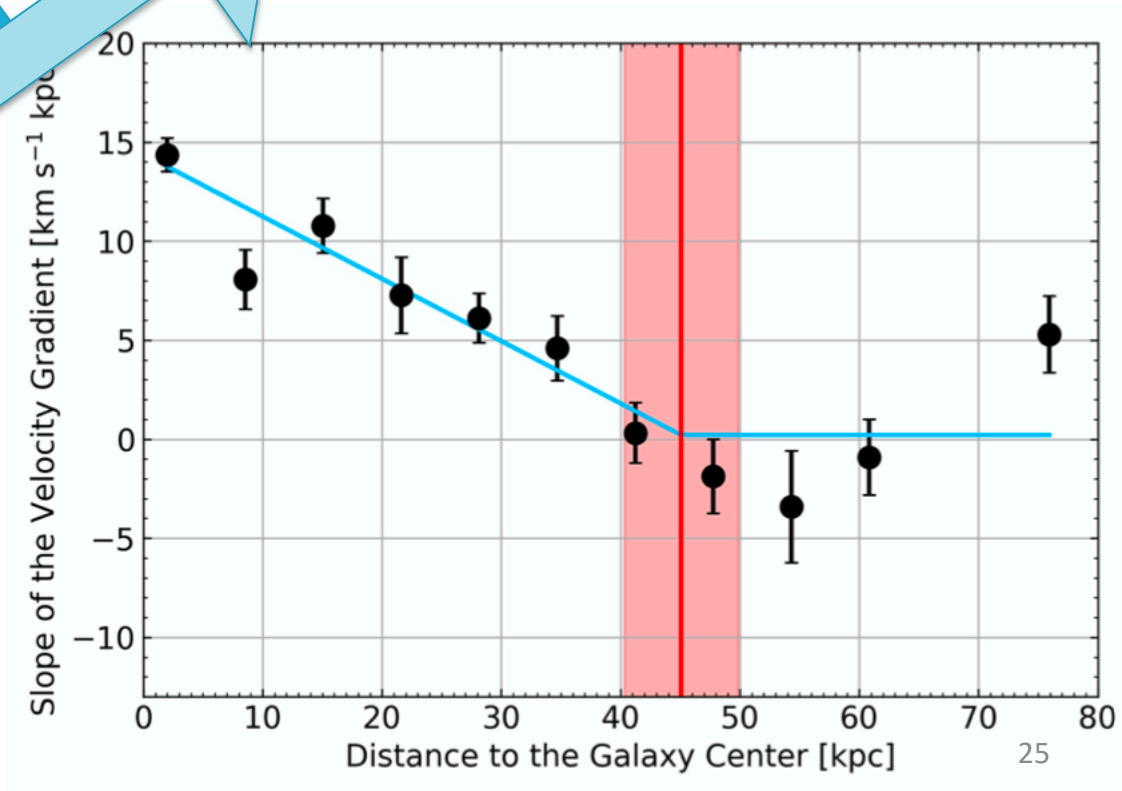
Luo+ in prep.


Hα Velocity [km s^{-1}]
Δ DEC [arcsec]
Δ RA [arcsec]
0
50
100
150
200
250
200
150
100
50
0
−50
−100
−150
−200

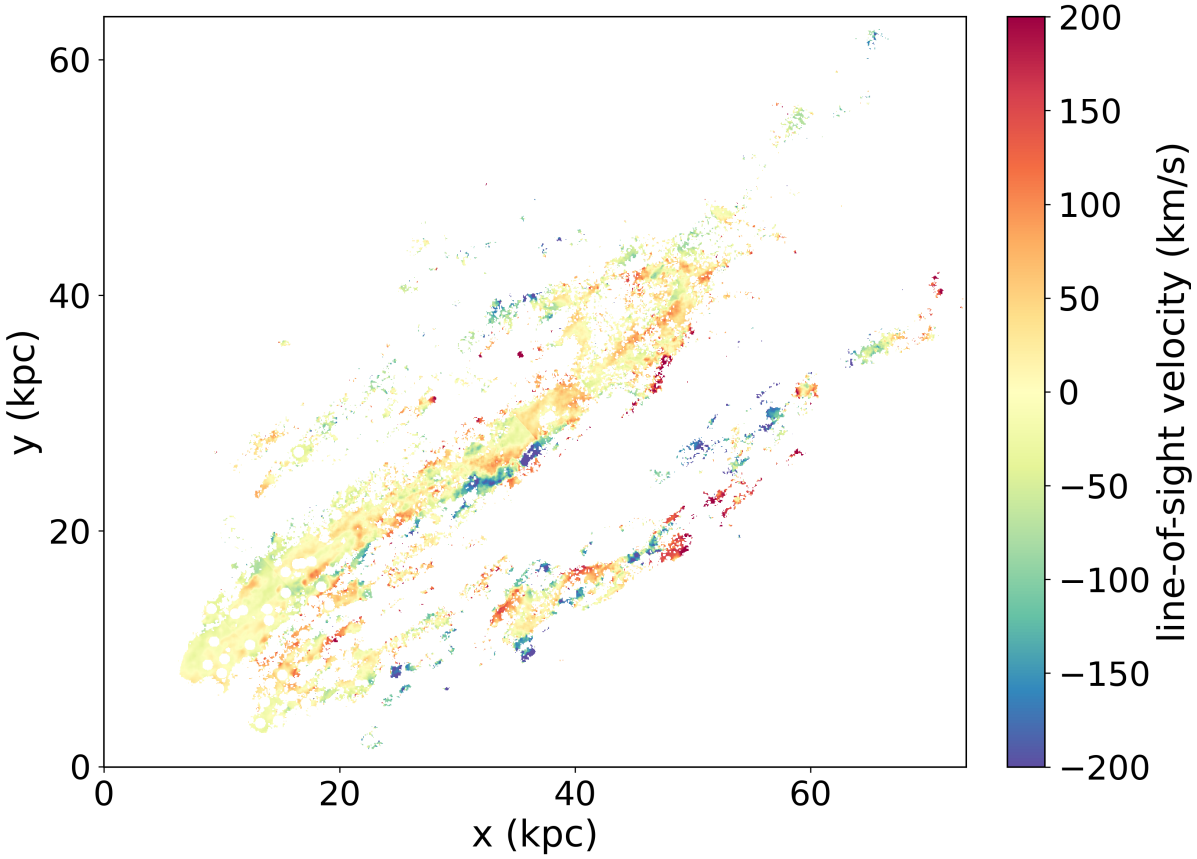
Luo+ in prep.



Rongxin Luo (UAH)



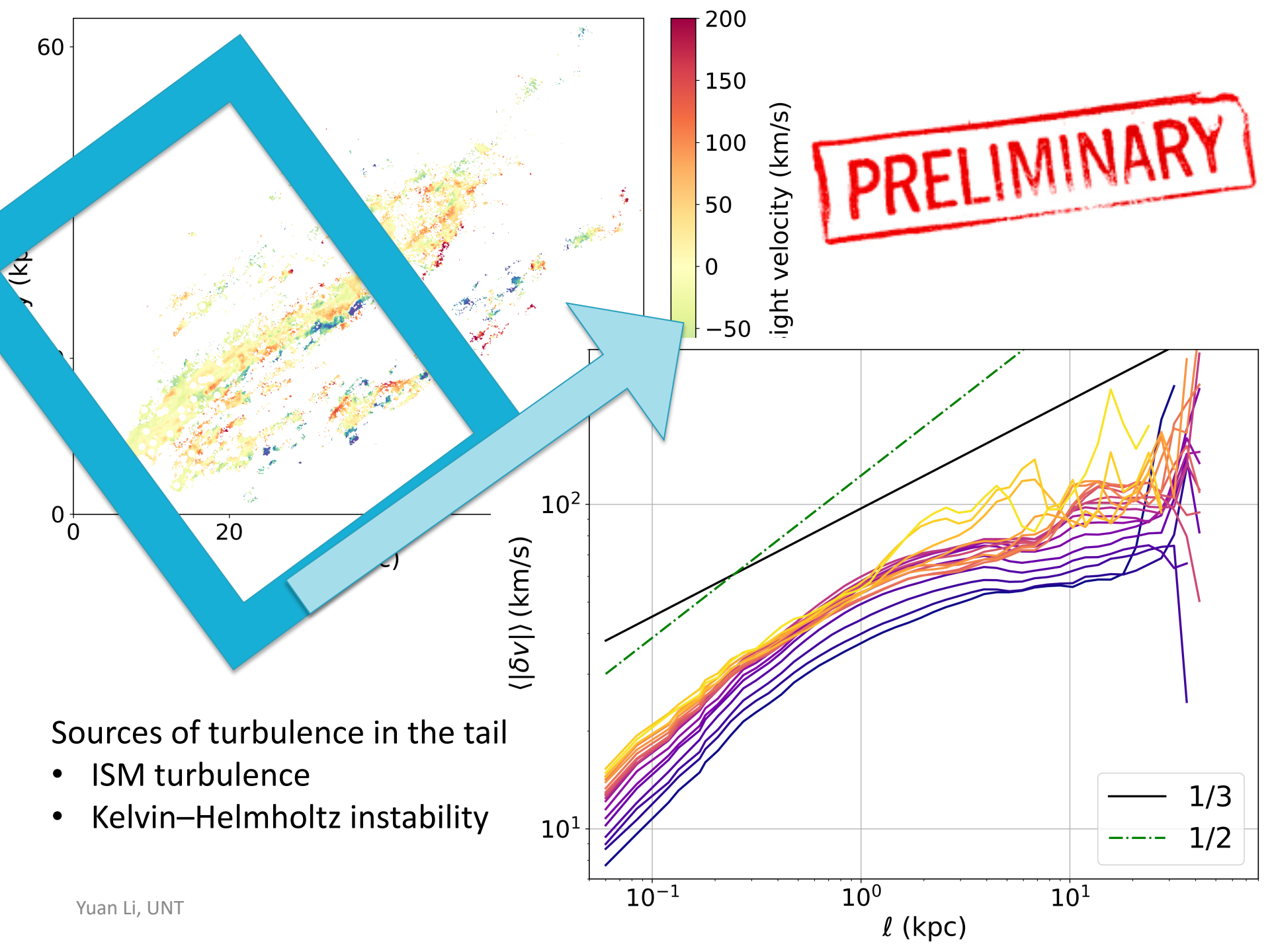
Luo+ in prep.



PRELIMINARY

Sources of turbulence in the tail

- ISM turbulence
- Kelvin–Helmholtz instability



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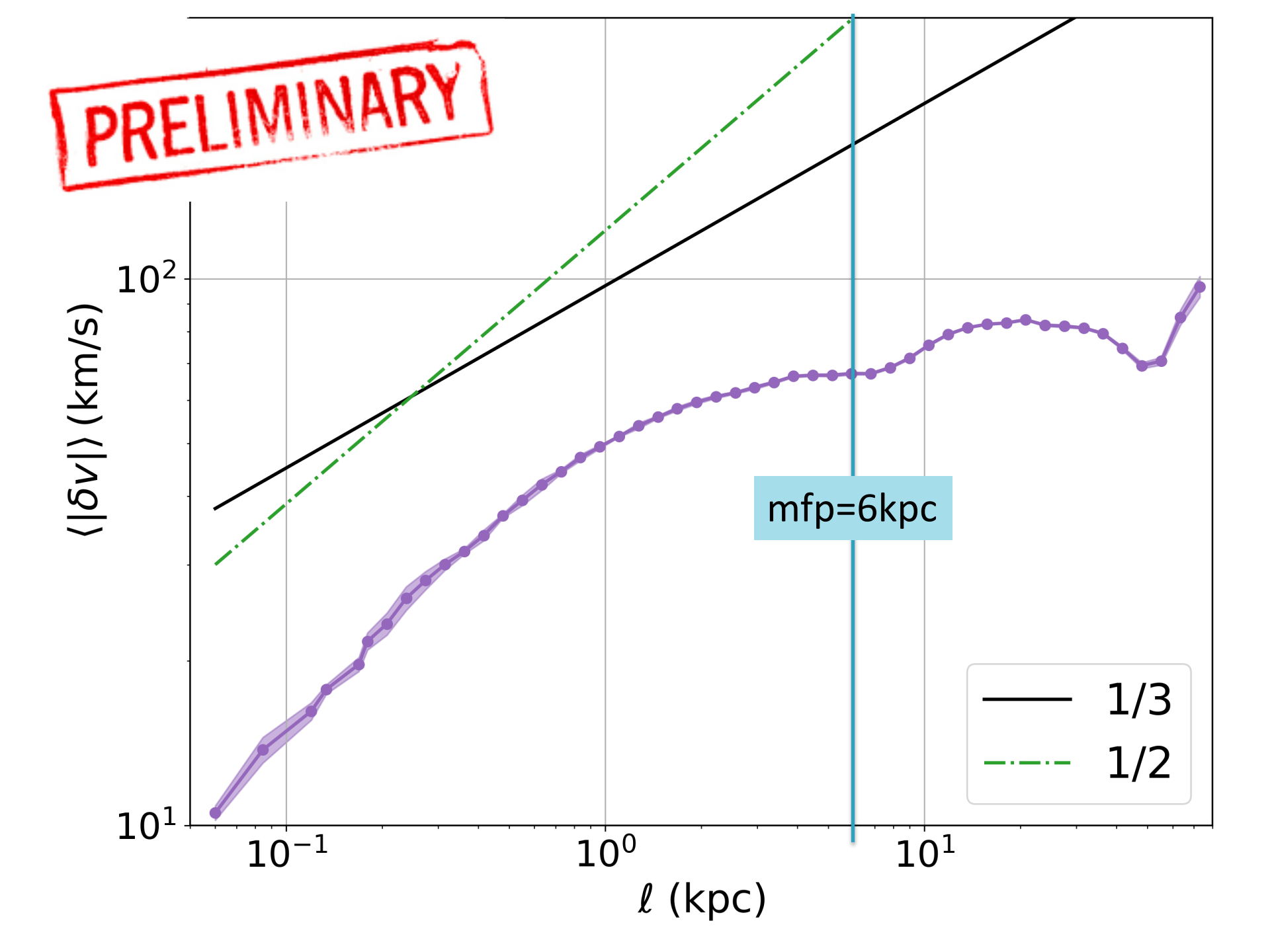
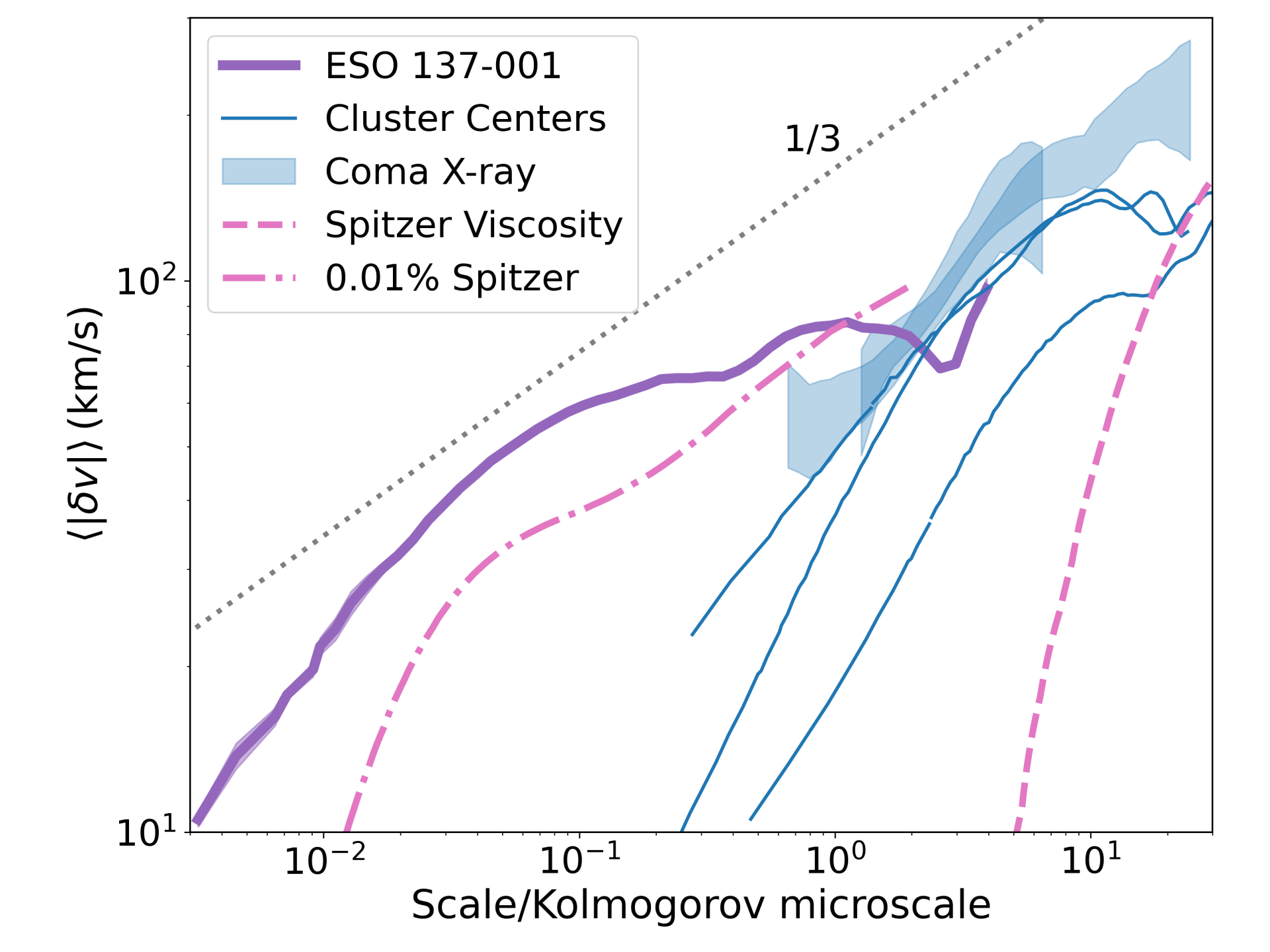

PRELIMINARY
10^2
10^1
$\langle|\delta v|\rangle$ (km/s)
10^{-1}
10^0
10^1
ℓ (kpc)
mfp=6kpc
1/3
1/2


ESO 137-001
Cluster Centers
Coma X-ray
Spitzer Viscosity
0.01% Spitzer
1/3
10^2
10^1
$\langle|\delta v|\rangle$ (km/s)
10^{-2}
10^{-1}
10^0
10^1
Scale/Kolmogorov microscale

Summary

- In the intracluster medium (ICM) all phases appear turbulent (?) and appear well-coupled (?). Cold gas may be used as a tracer of the hot plasma (?).
- SMBH feedback is the main driver of turbulence in cluster centers, but turbulent dissipation may be a subdominant heating mechanism (?).
- Isotropic viscosity is suppressed in the ICM. Turbulence probed with jellyfish tails suggests ICM viscosity is less than 0.01% Spitzer.