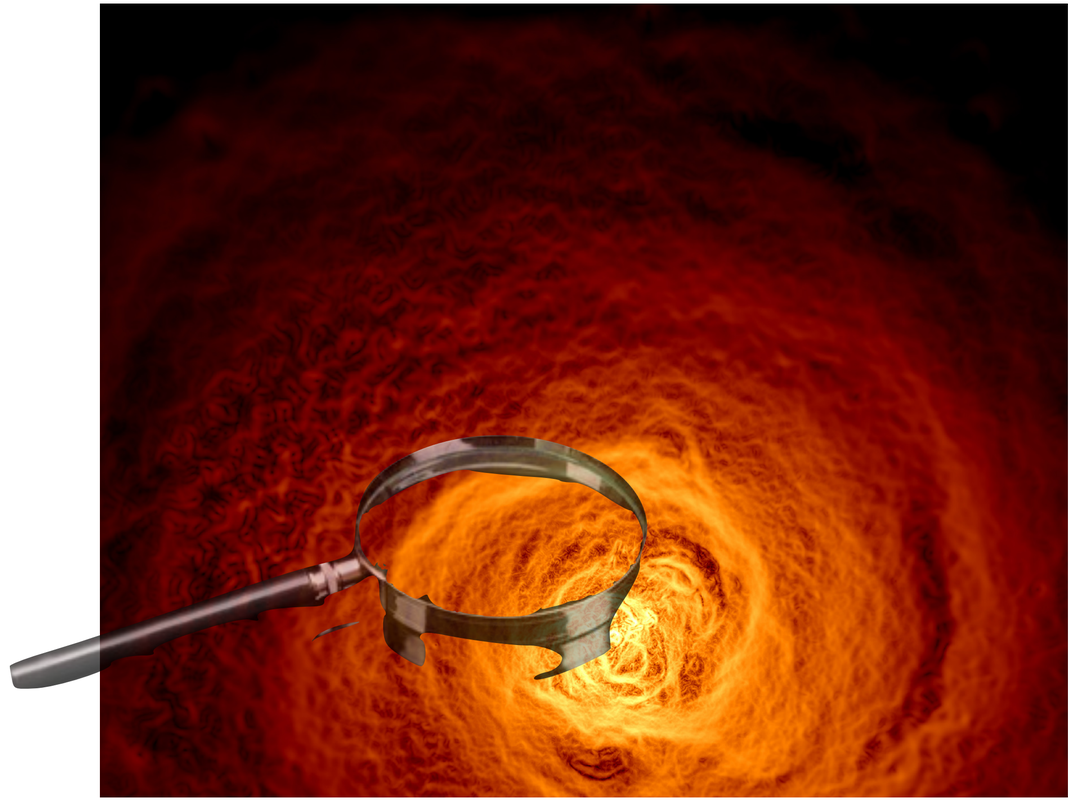
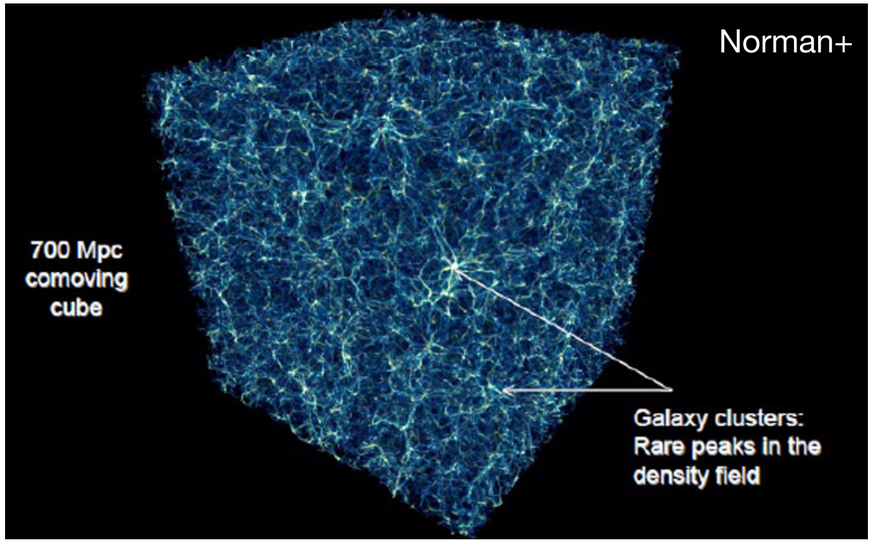
The problems of energy transport and its multi scale impact in the ICM

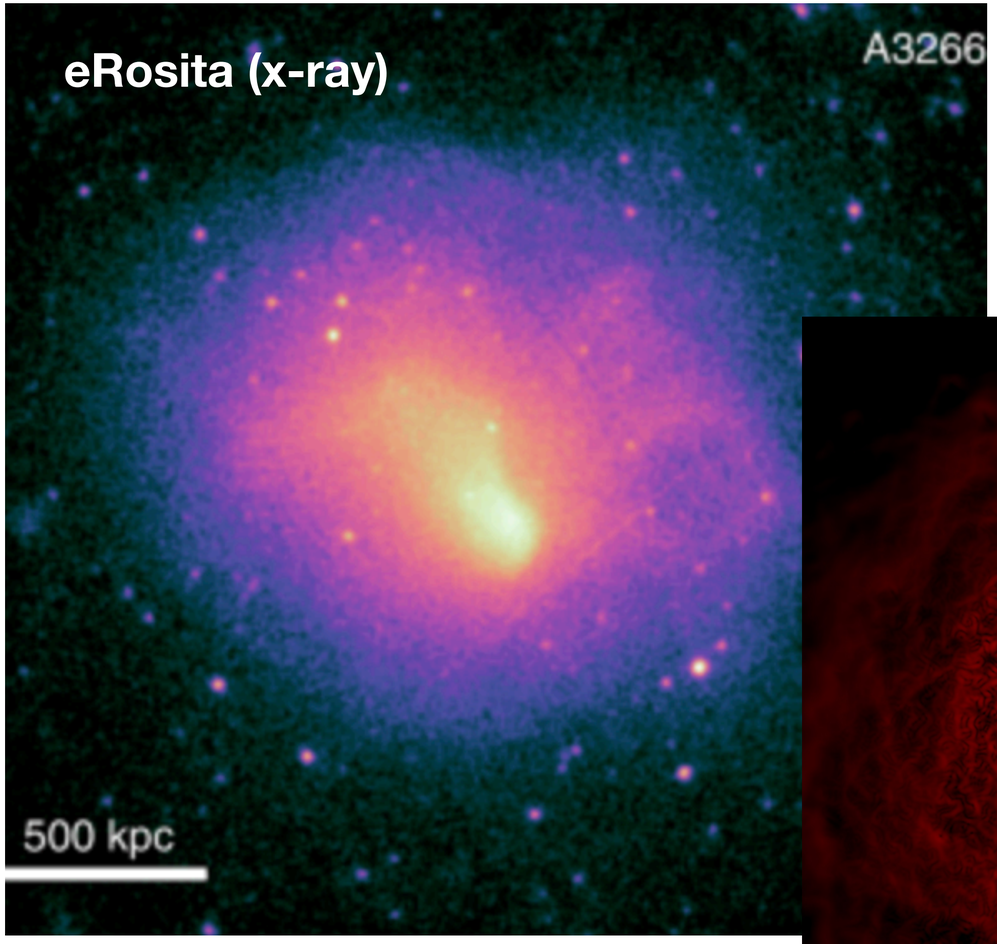


Prakriti PalChoudhury, IoA Cambridge

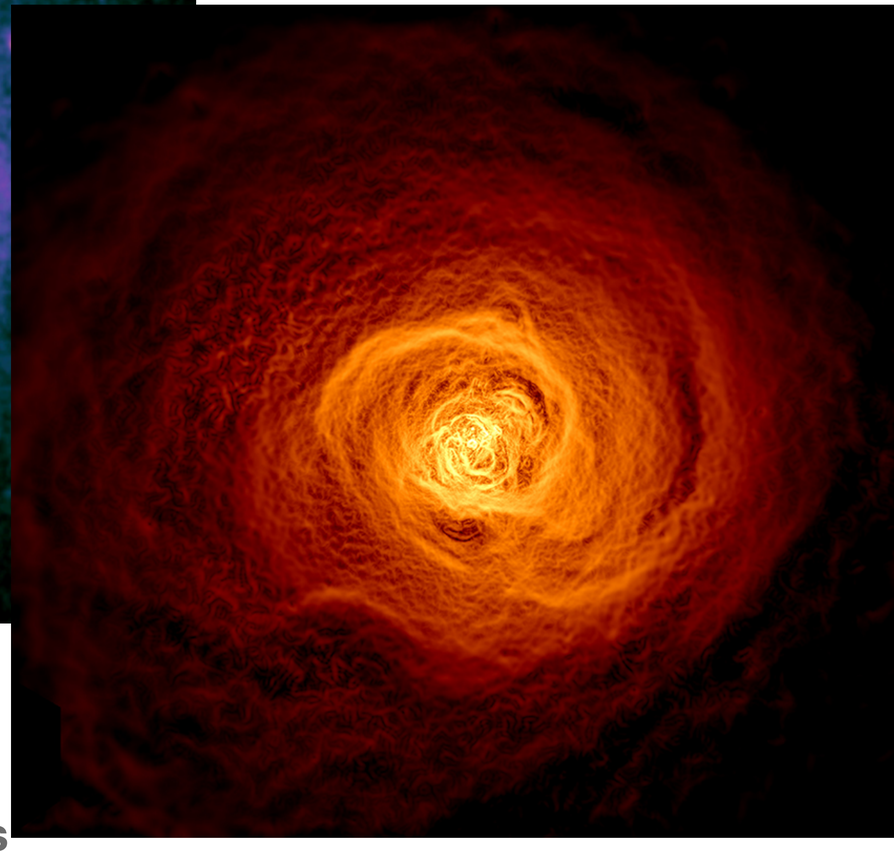
Copenhagen, August 2022

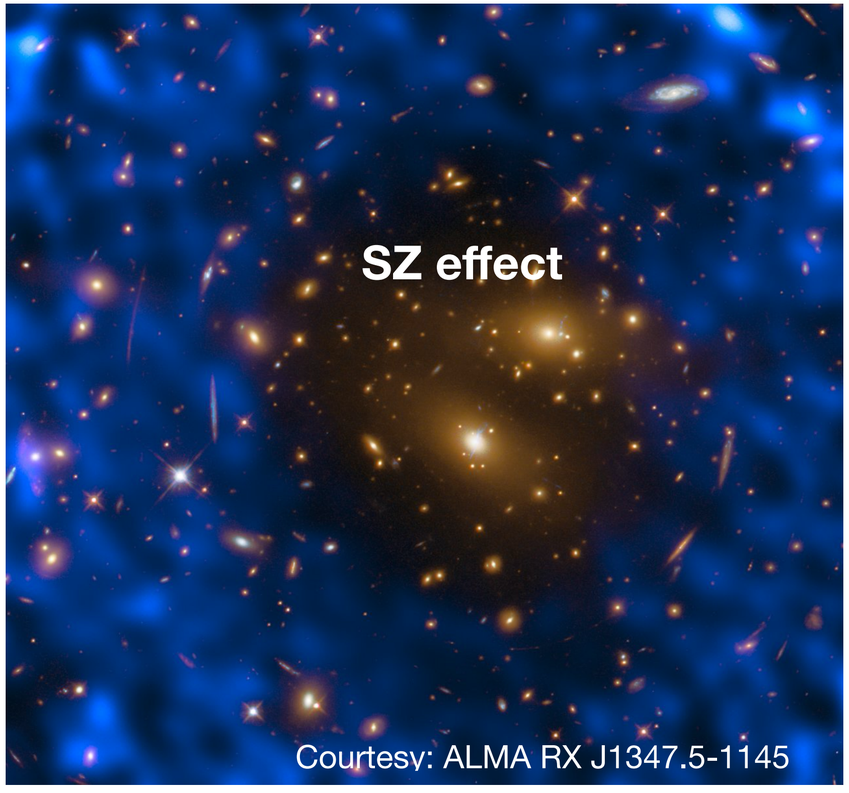
Sustained hot gas in clusters





Perseus at high res with good old Chandra





In near future Athena, AXIS
& in far future Lynx
will look for cluster hot gas across redshifts more extensively

How is the hot gas medium sustained?

Energy injection (mainly “feedback”)

Energy transport (by waves, g-modes, thermal conduction, may be CRs)

Energy dissipation (viscous) ⟶ thermalization

Simulations: Reynolds+2015 (inefficient g-mode driving), Bambic+Reynolds, Yang+Reynolds, Mohapatra+
Observations: Fabian+ (sound waves), Zhuravleva+, Li+ (density fluctuations, VSF, etc)

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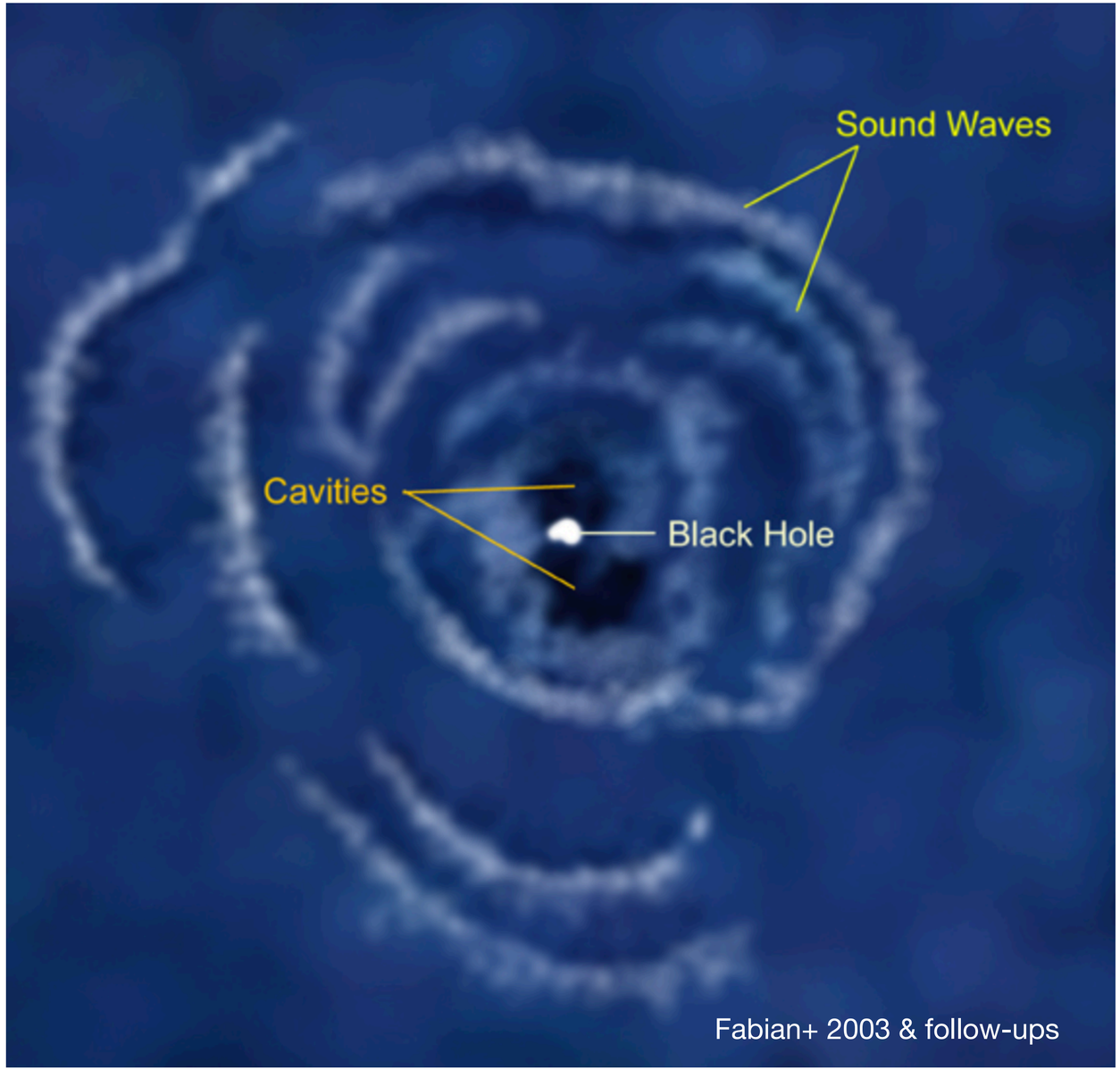
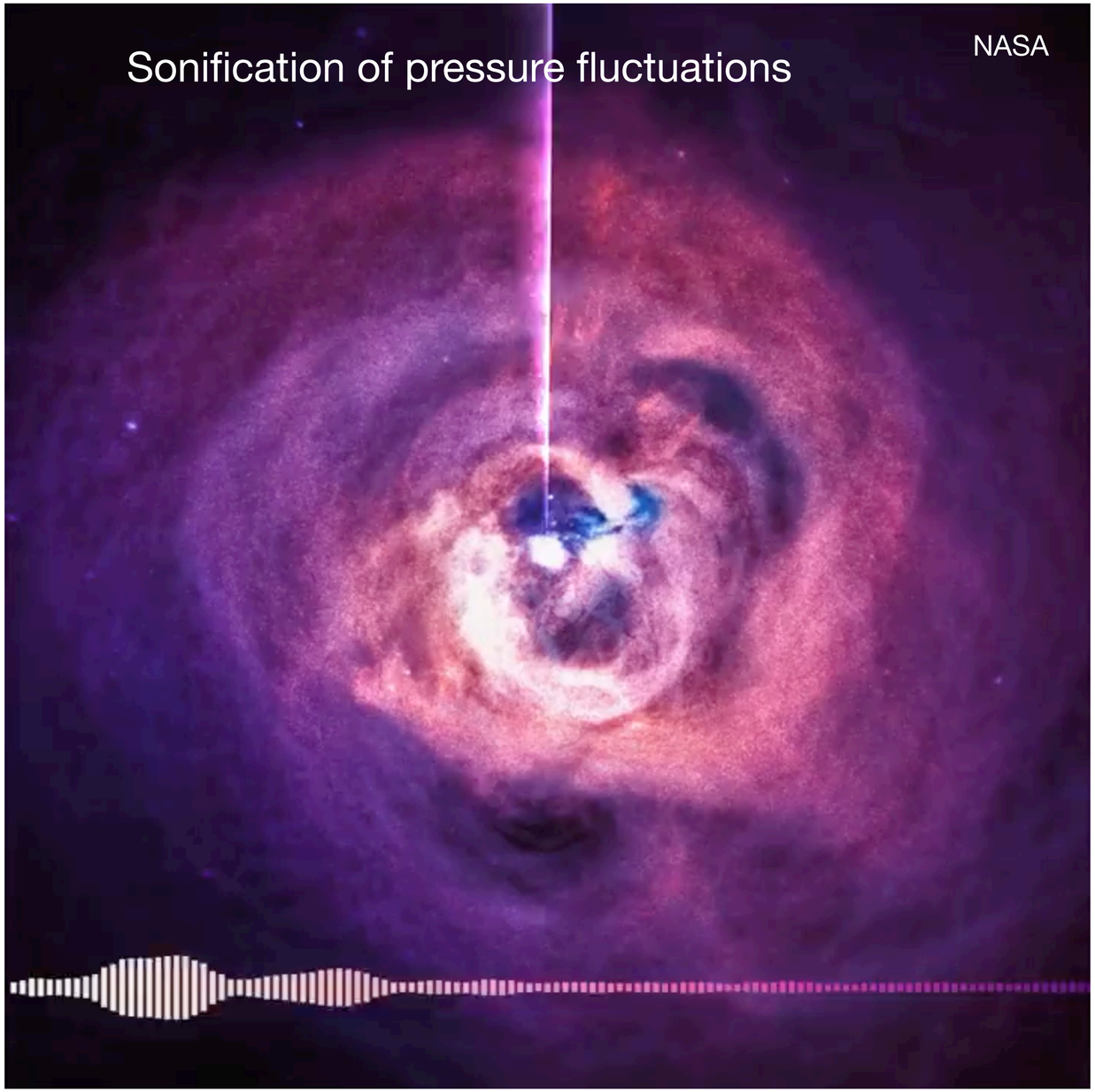
The gyro-scale physics of thermal conduction opens a Pandora’s box. I’ll briefly touch upon that.
Any viscous dissipation mentioned in this talk is suppressed Spitzer.

Sound waves in cluster : example Perseus





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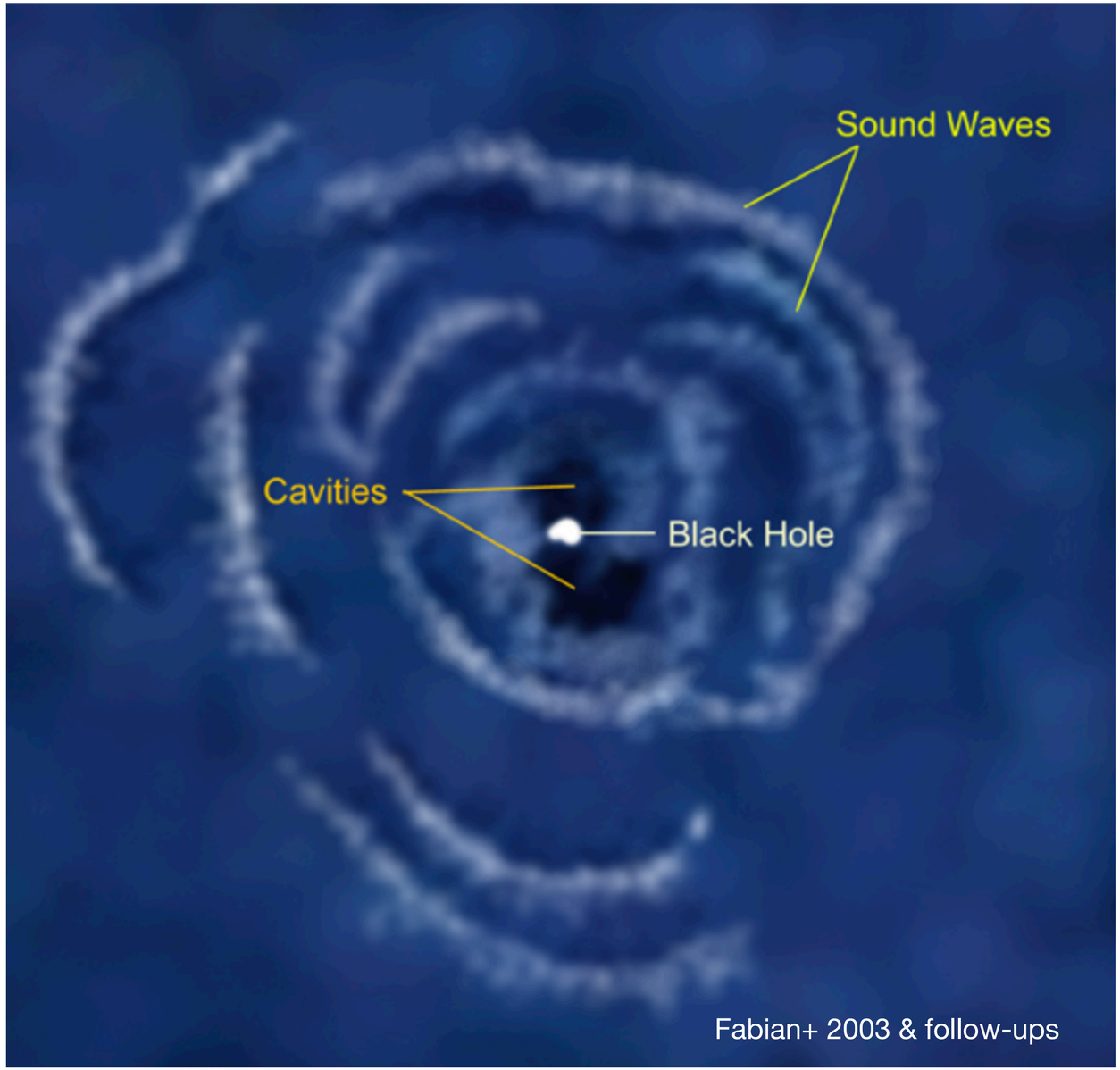
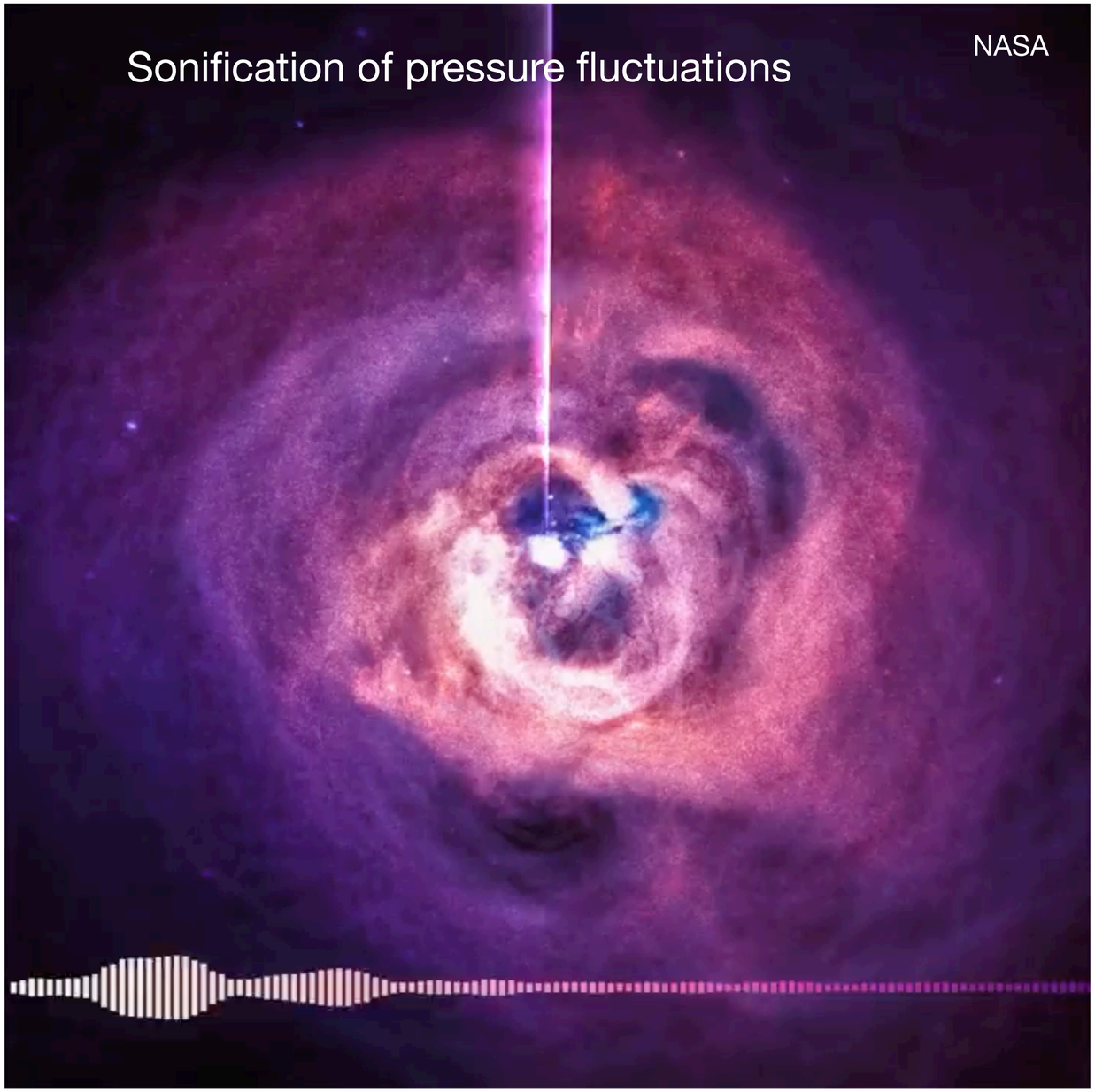
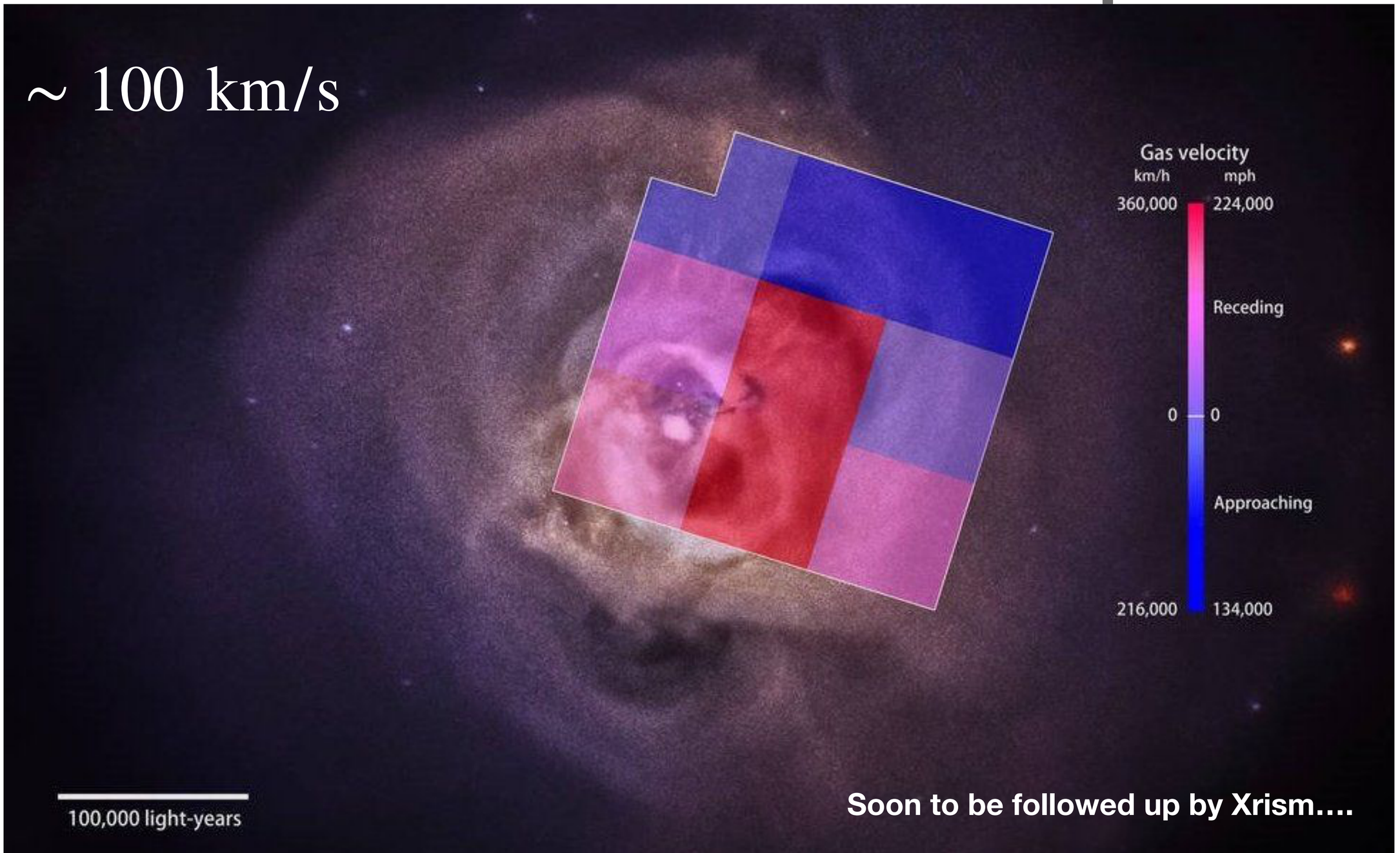
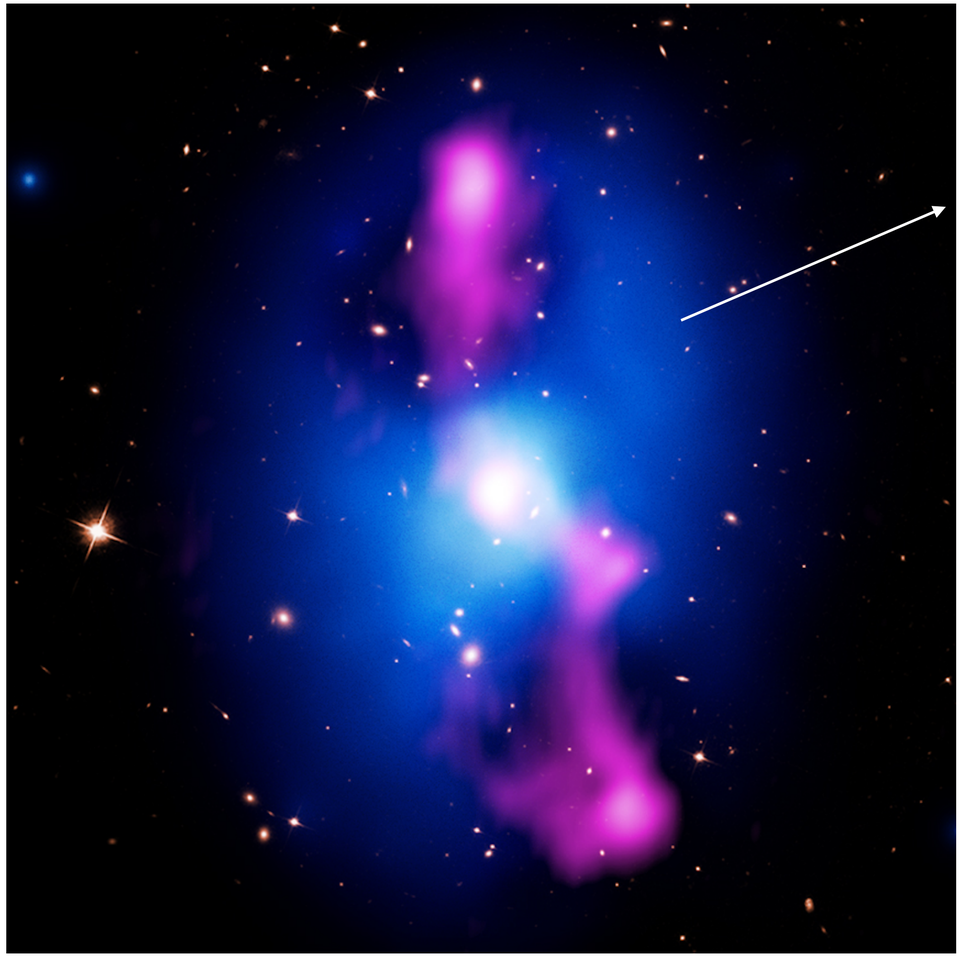




Turbulence in cluster cores: example Perseus

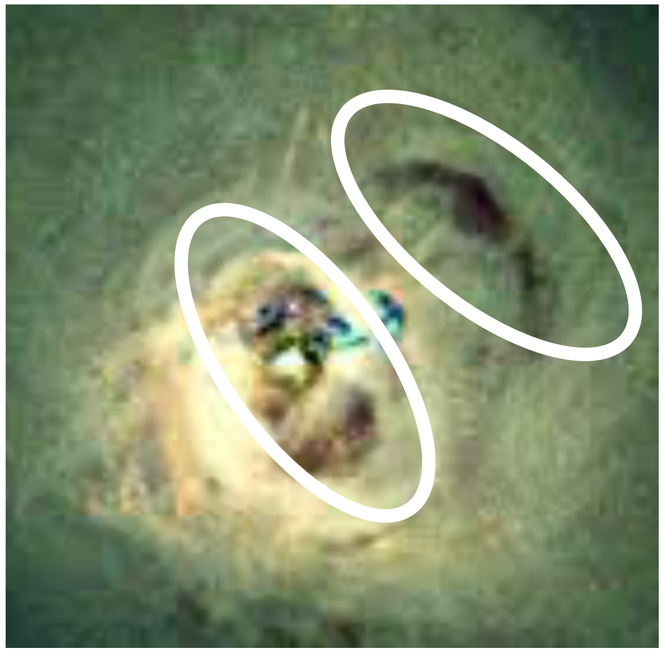


How to develop waves & turbulent cluster cores?



$$T \gtrsim 10^7\ K$$

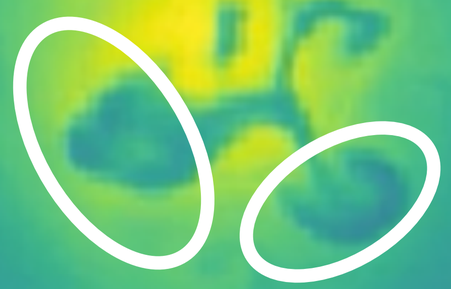
bremsstrahlung (blue)



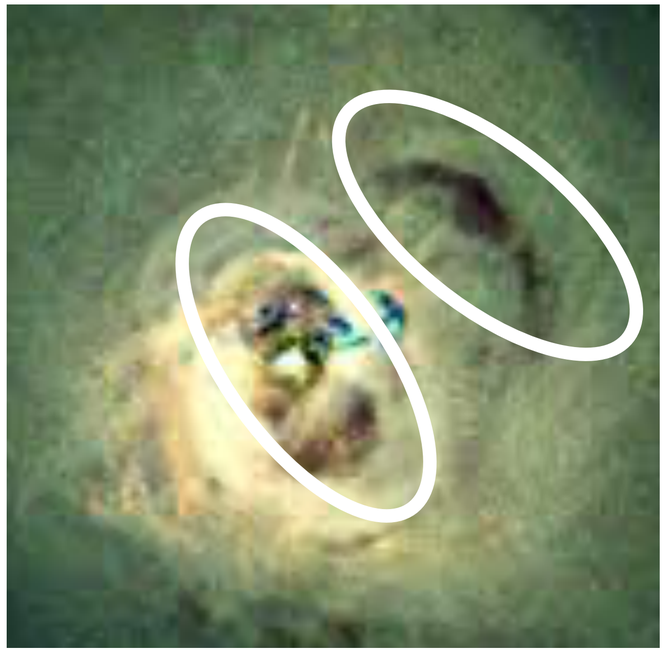
No “pure” cooling flow (stability)
Enough “total” energy available
to balance (mapped in radio, red)

How to develop waves & turbulent cluster cores?

3D Perseus-like ICM simulations (I used PLUTO v4.3)

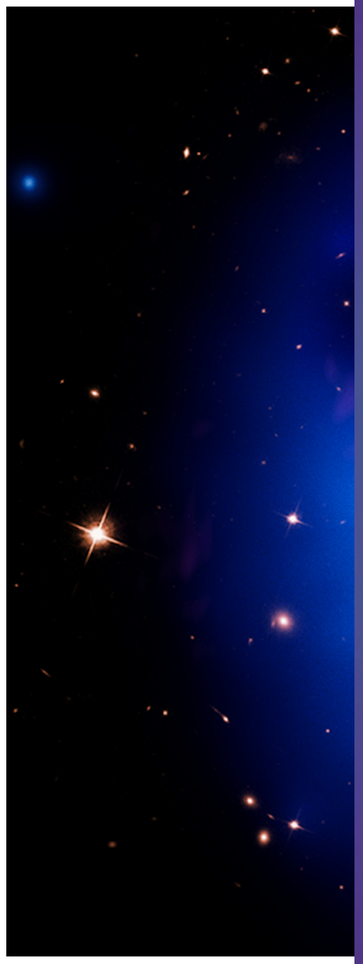


Low or moderately powered idealised radio(thermal) feedback
Radiative cooling
Suppressed isotropic viscosity
Recently tangled B



stability)
vailable
dio, red)

How to develop waves & turbulent cluster cores?



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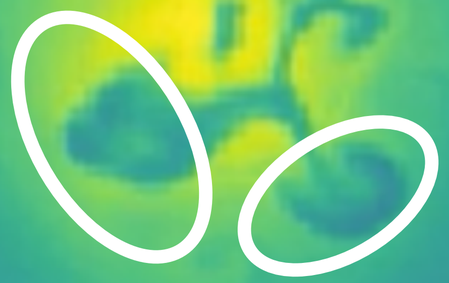

Low or moderately powered idealised radio(thermal) feedback
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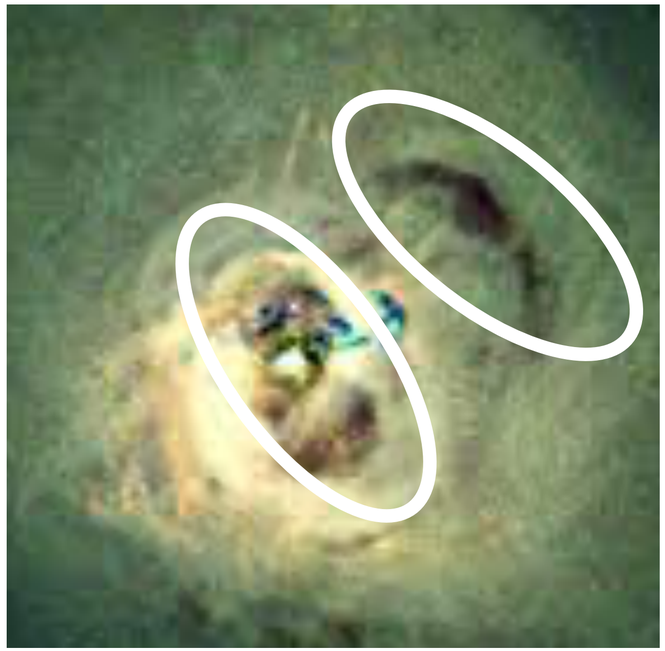


stability)
vailable
dio, red)

400 kpc 384^3

200 kpc

Double resolution than outer 256^3

Break down into compressible & incompressible

Helmholtz decomposition of 3D velocity cubes

$$V = V_{\text{compressible}} + V_{\text{incompressible}}$$

Curl-free

Divergence-free

$$\nabla \cdot V = \nabla^2 \phi_{\text{c}} \qquad V_{\text{compressible}} = \nabla \phi_{\text{c}}$$

$$\phi_{\text{c,FT}} = -i\mathbf{k} \cdot V_{\text{FT}} / k^2$$

How a central plane looks

Compressible

Incompressible

How a central plane looks

Compressible

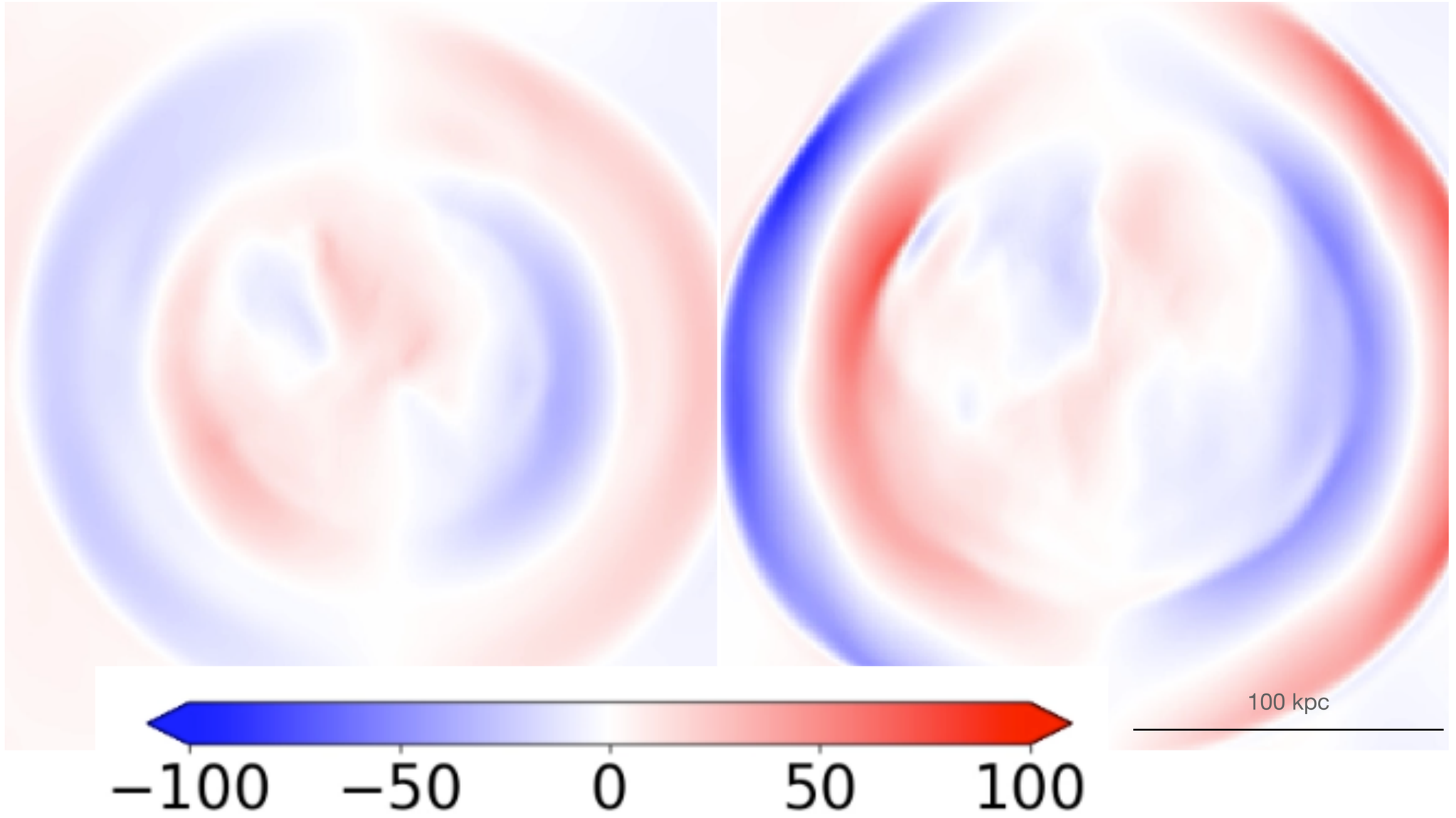
Incompressible

Low powered thermal feedback

$\sim 10^{44}\mathrm{erg\ s^{-1}}$

Moderately powered thermal feedback

$\sim 4 \times 10^{44}\mathrm{erg\ s^{-1}}$



Choudhury & Reynolds MNRAS 2022

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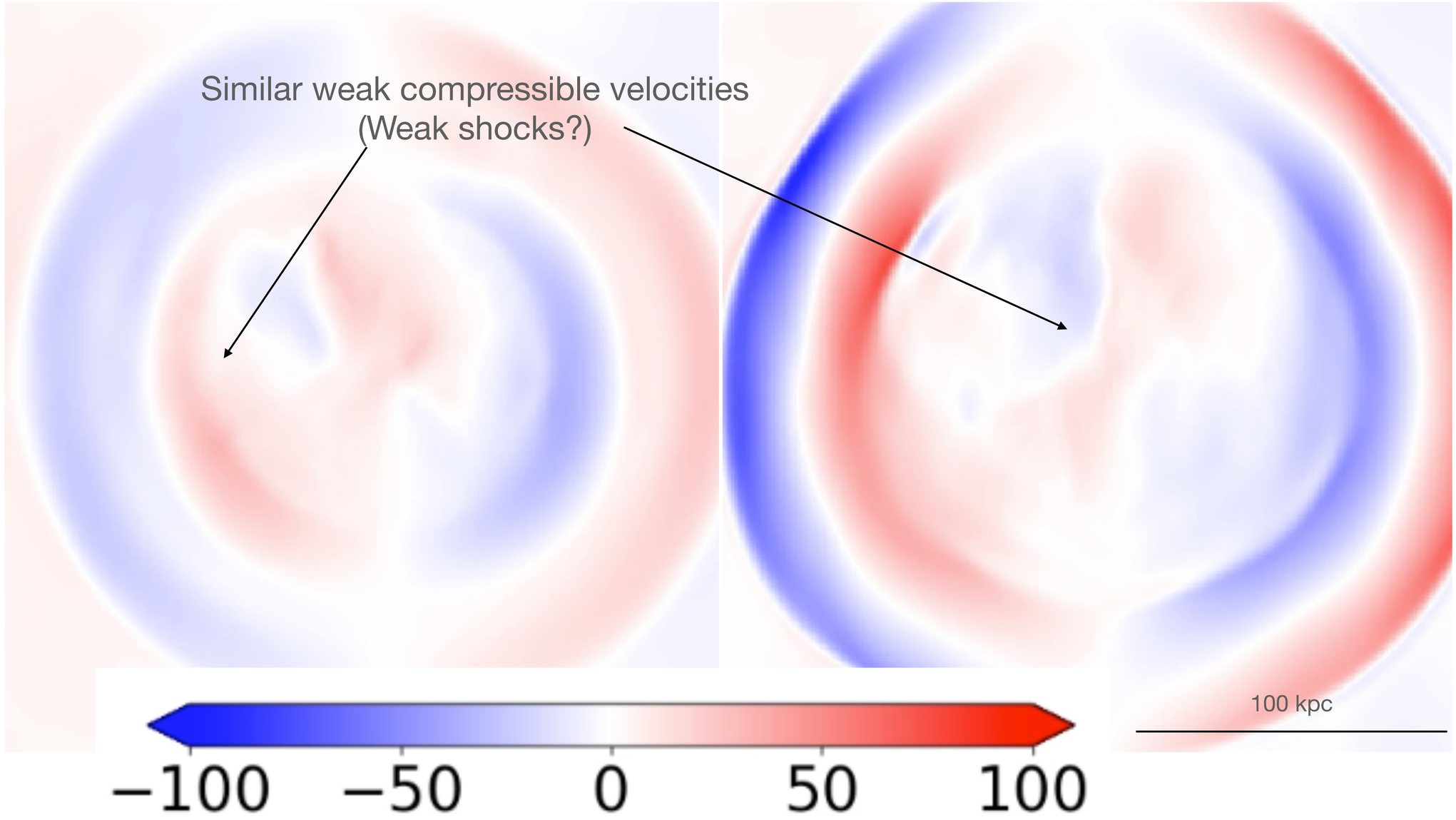

Choudhury & Reynolds MNRAS 2022

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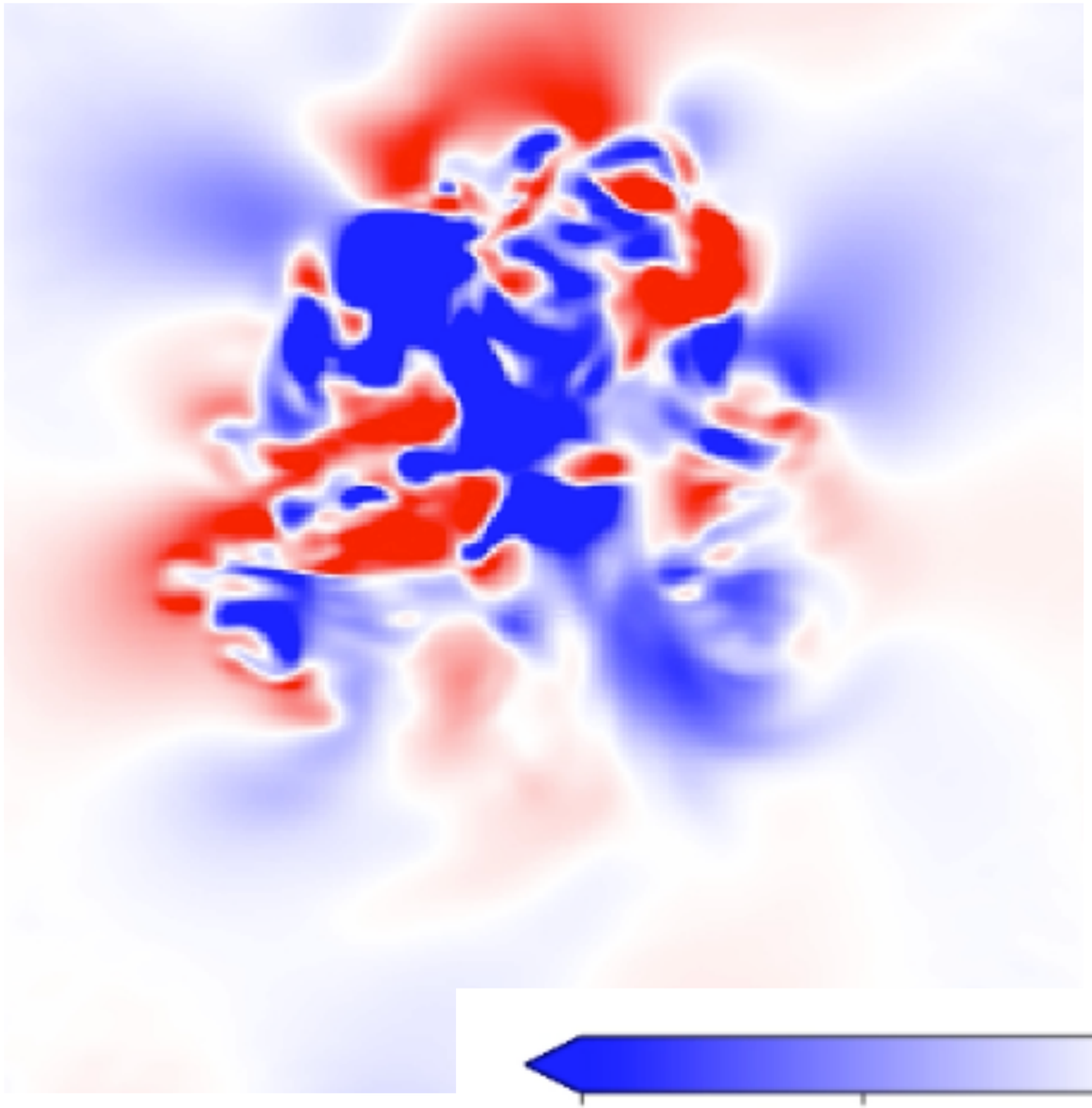
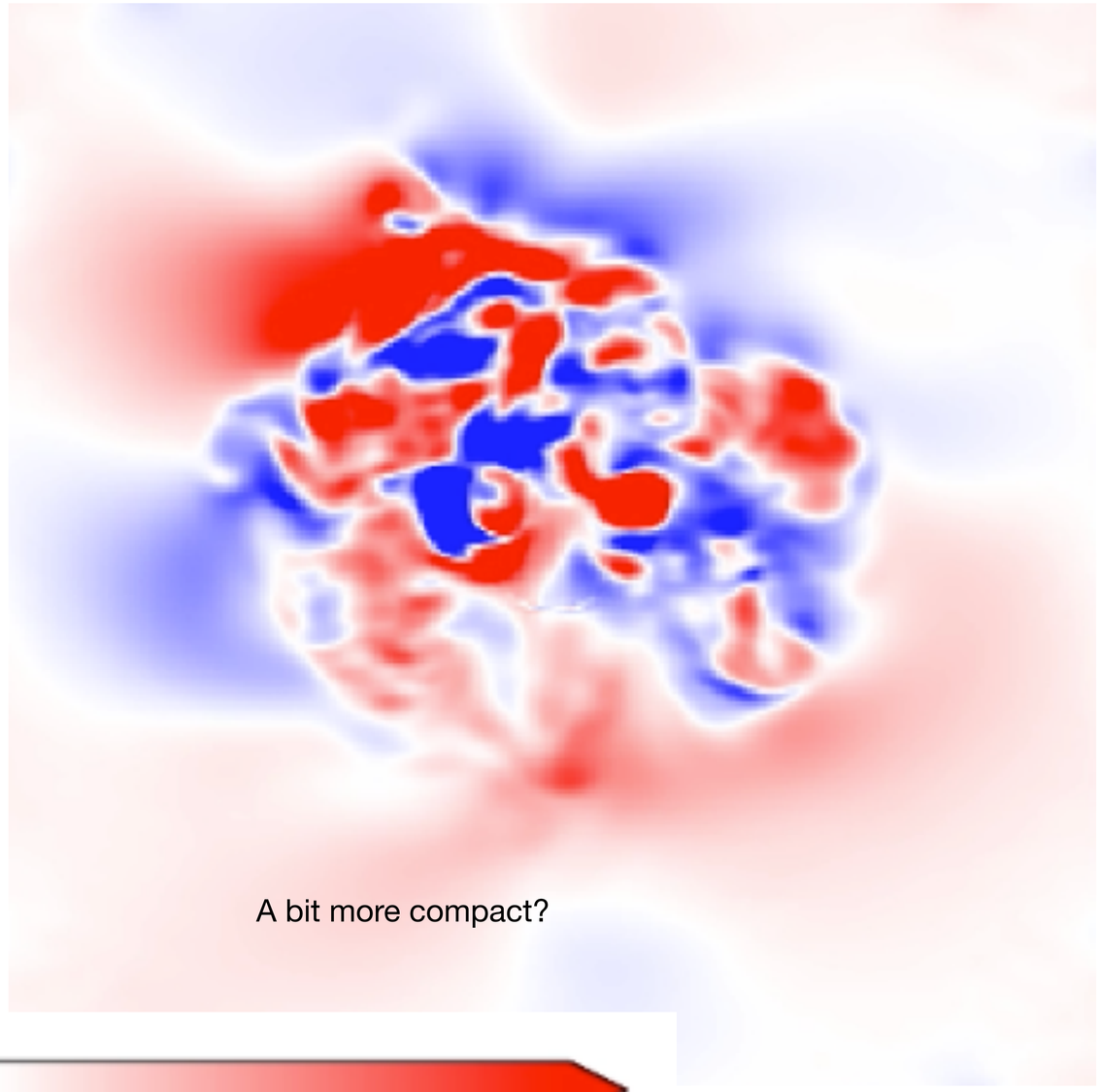
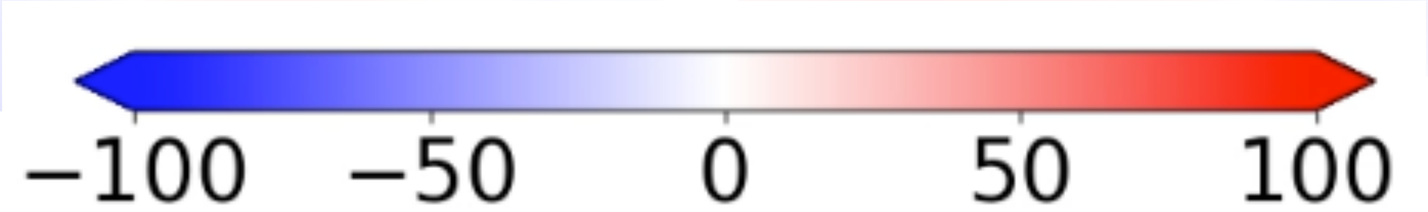
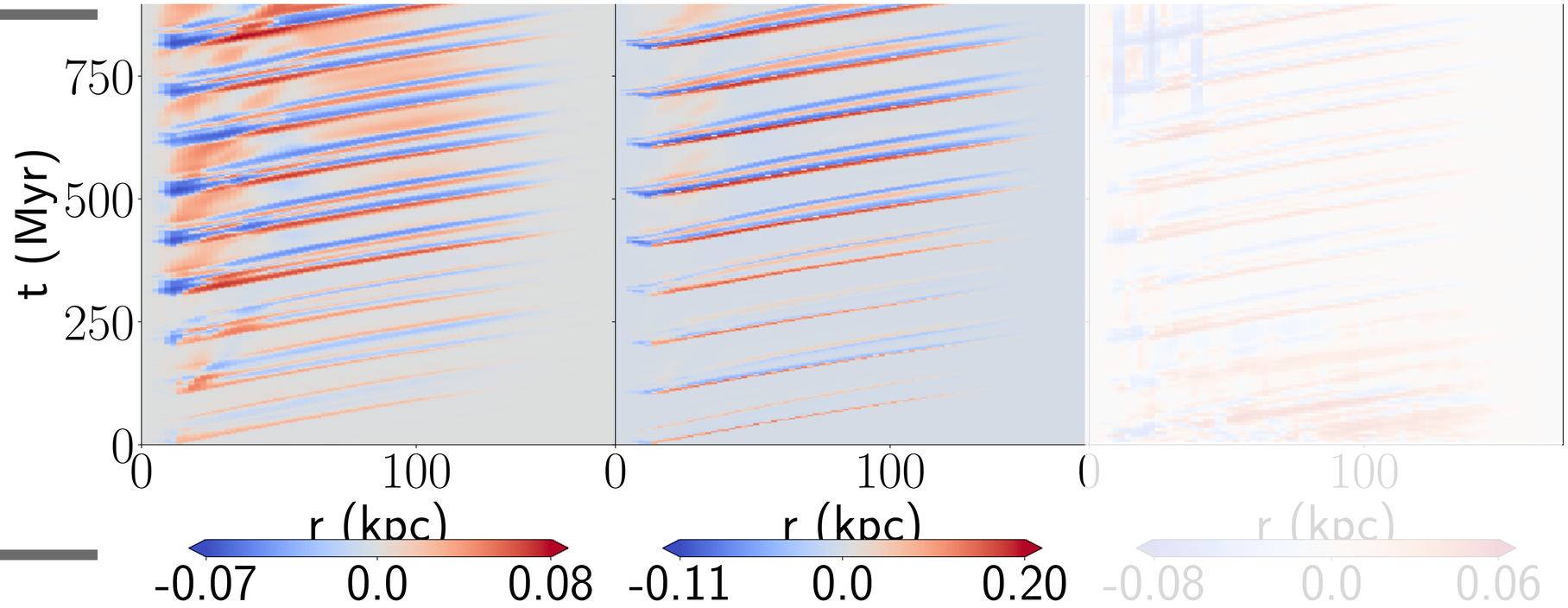




A bit more compact?



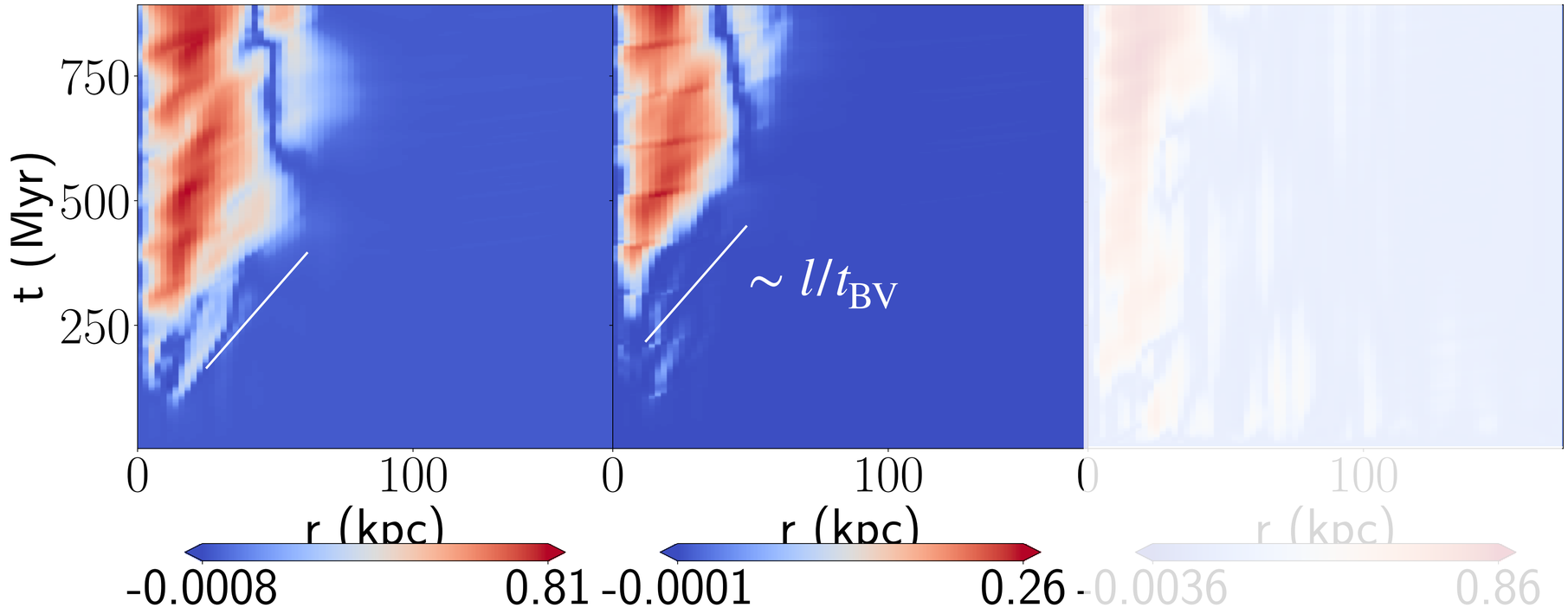
Choudhury & Reynolds
MNRAS 2022



Compressible
Flux

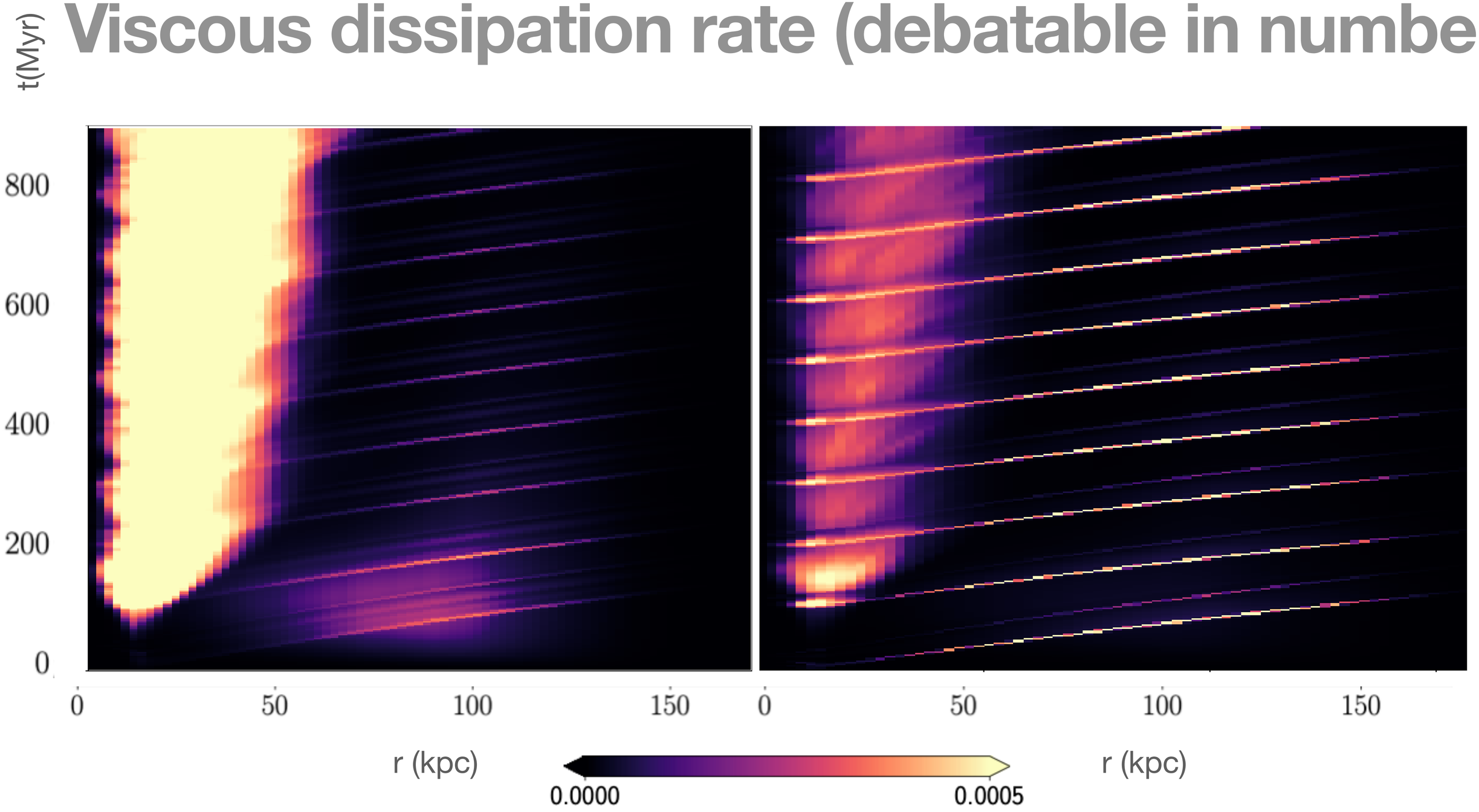
Mohapatra+
Wang+
Froude number
(Mateuzs' talk)

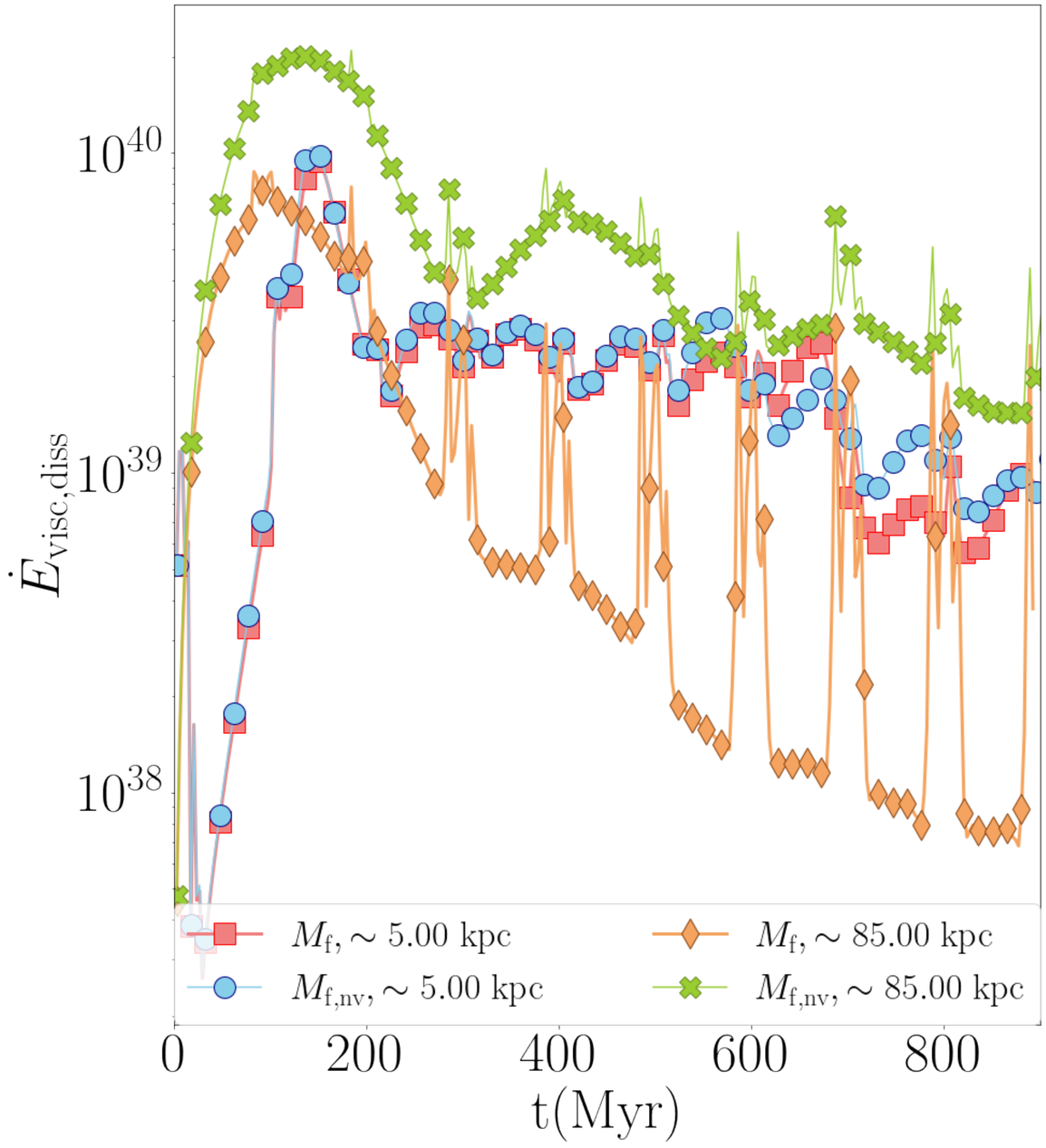
Fraction of incompressible
flux expected in IGWs
(Kumar & Goldreich)



preliminary

Viscous dissipation rate (debatable in number)





Which part is “more” physical?

Choudhury+2022 (appendix)

What is missing? Magnetic field, of course!

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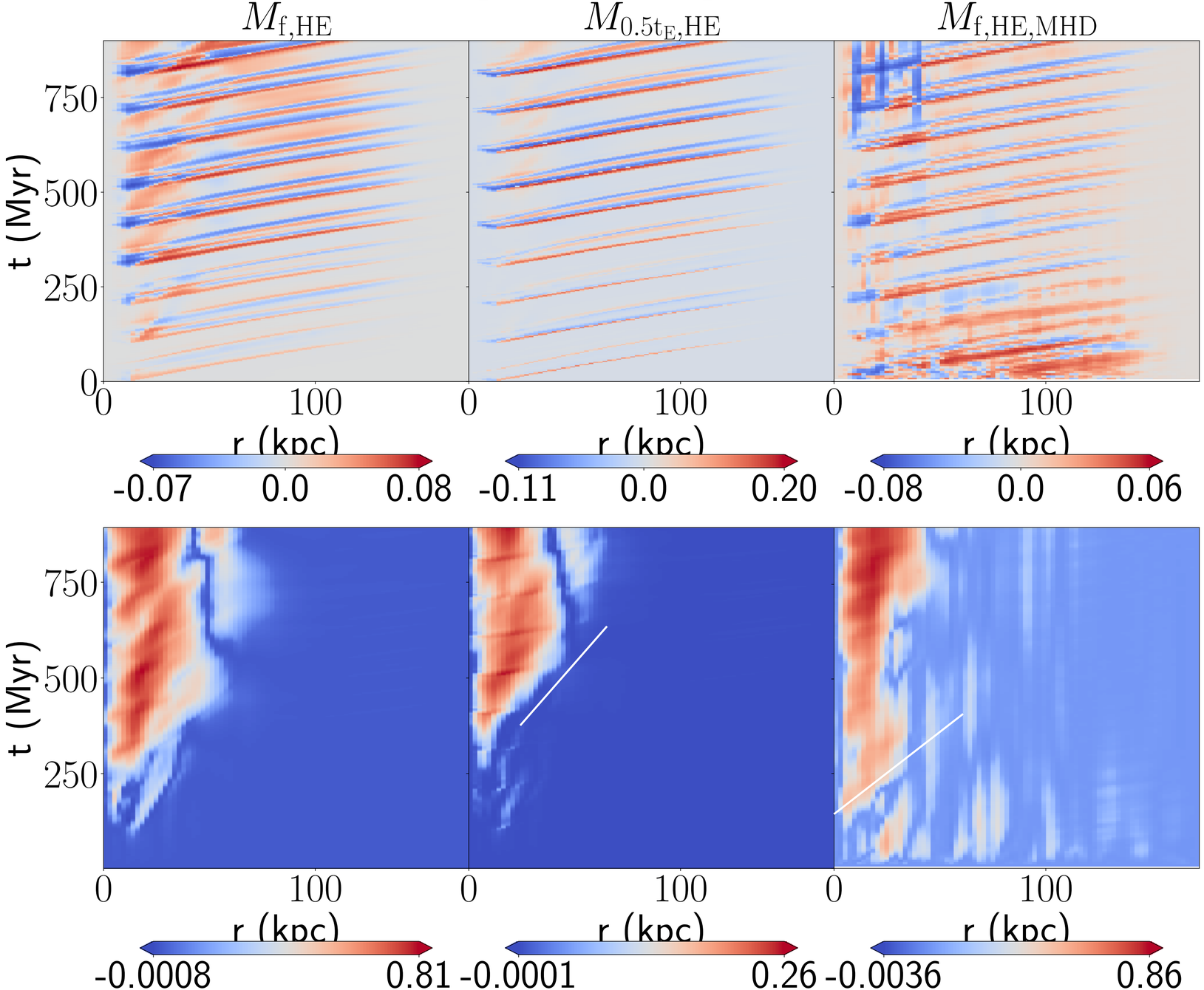

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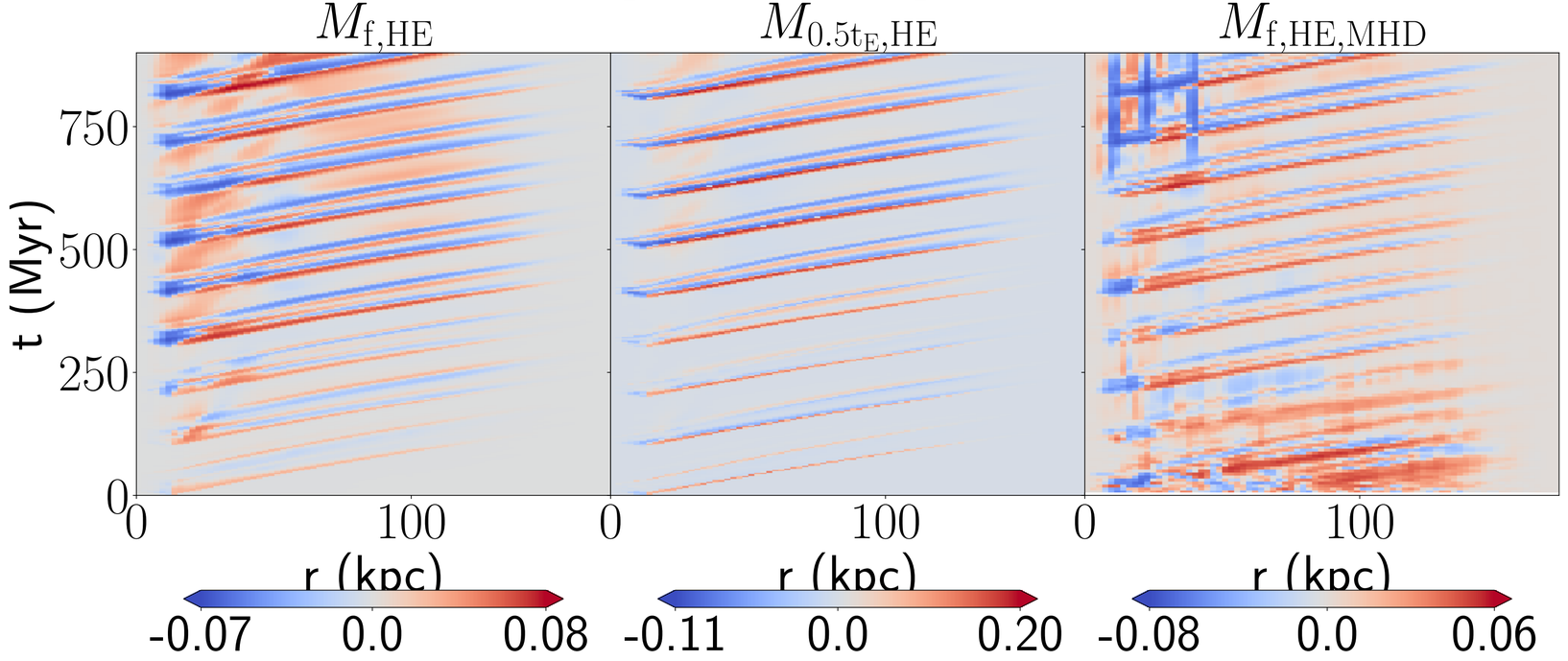

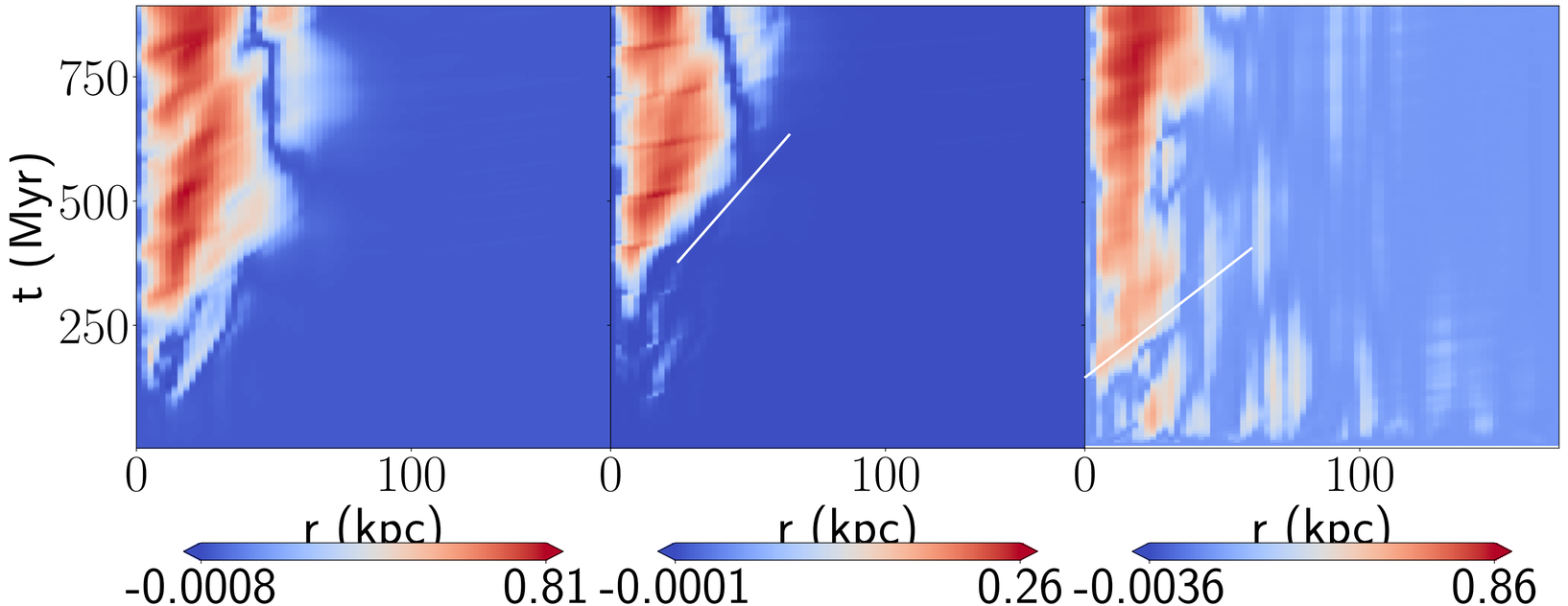

Magnetosonic?

Alfven-buoyancy?

preliminary

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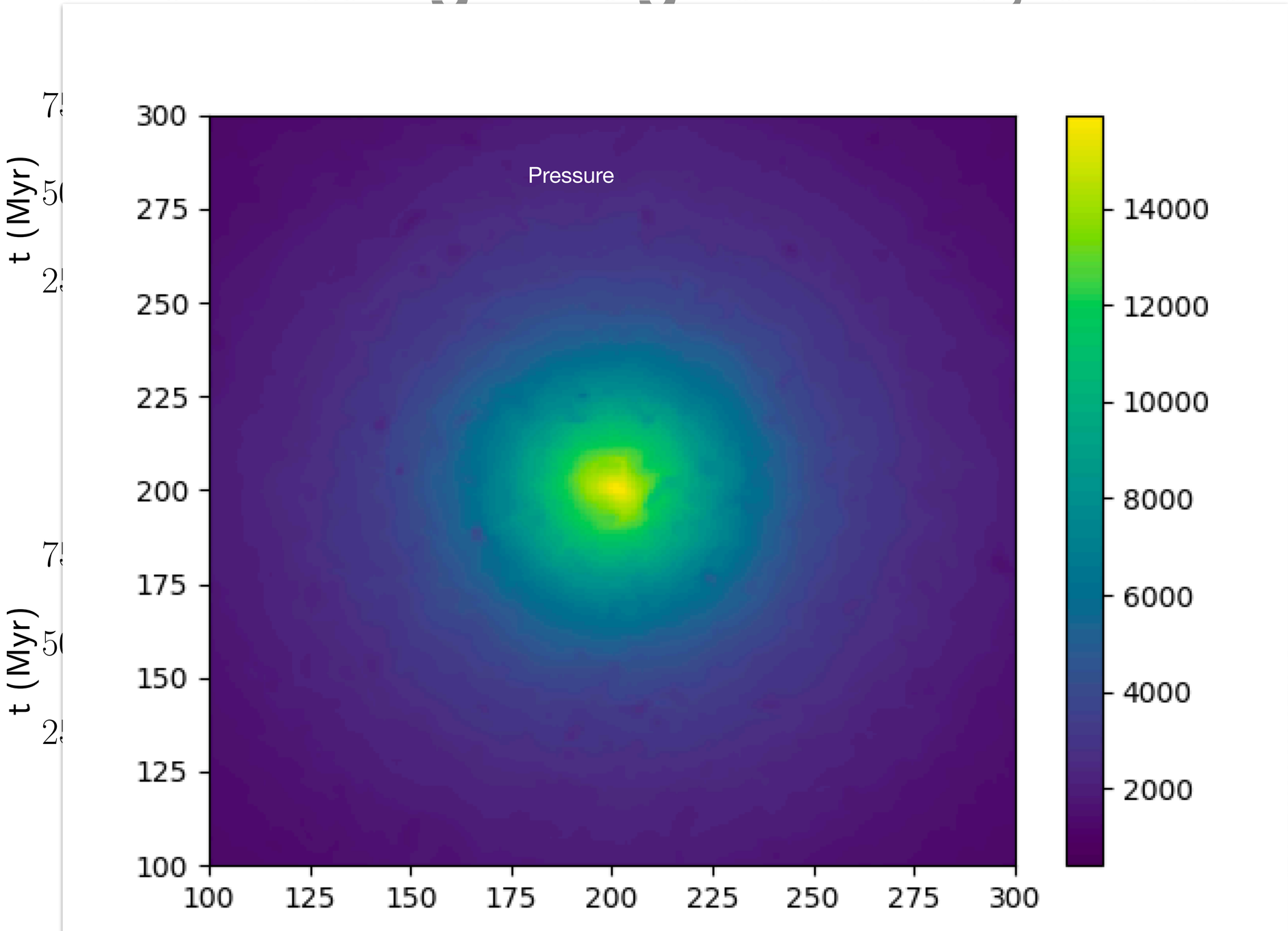

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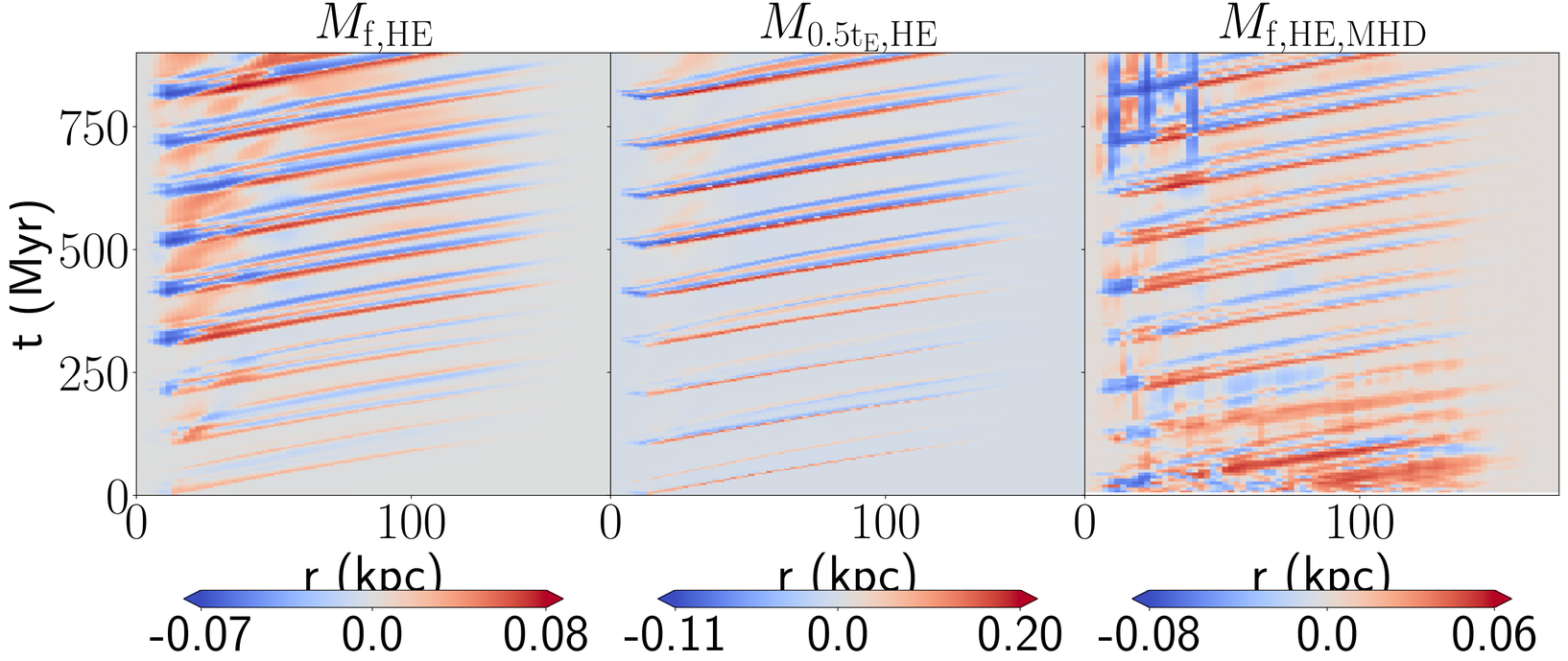
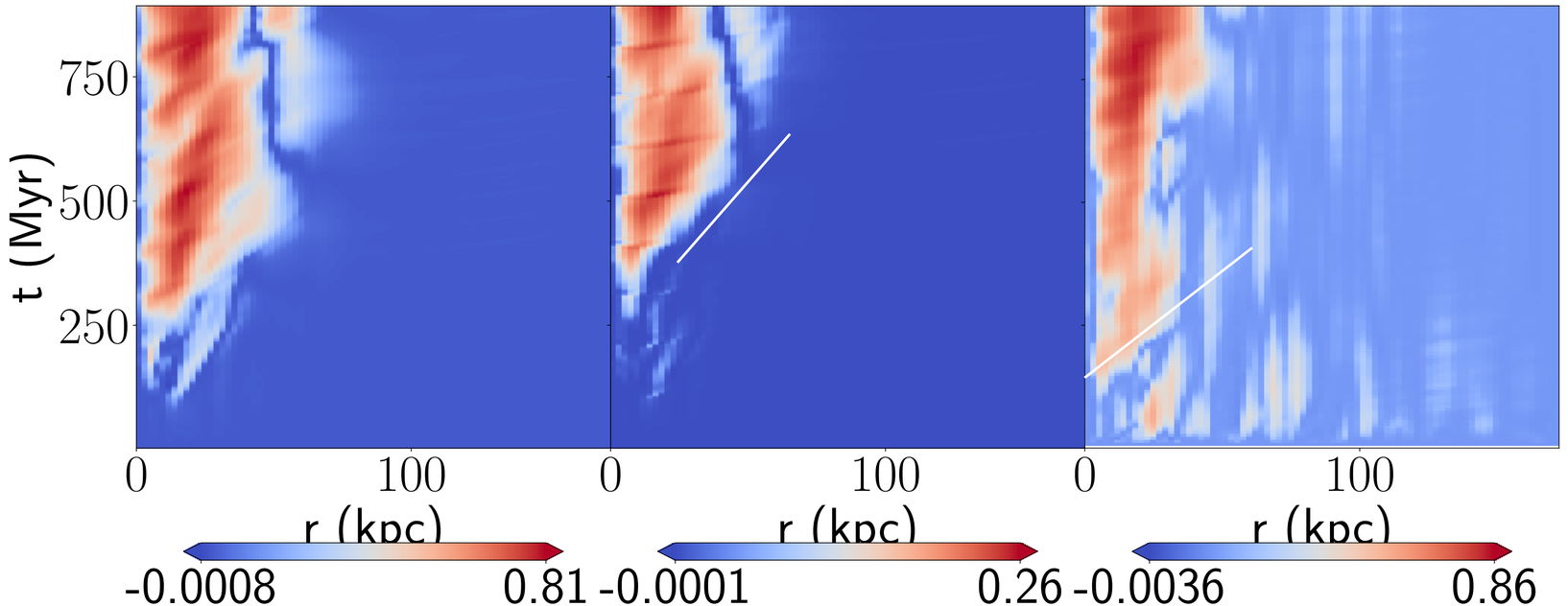


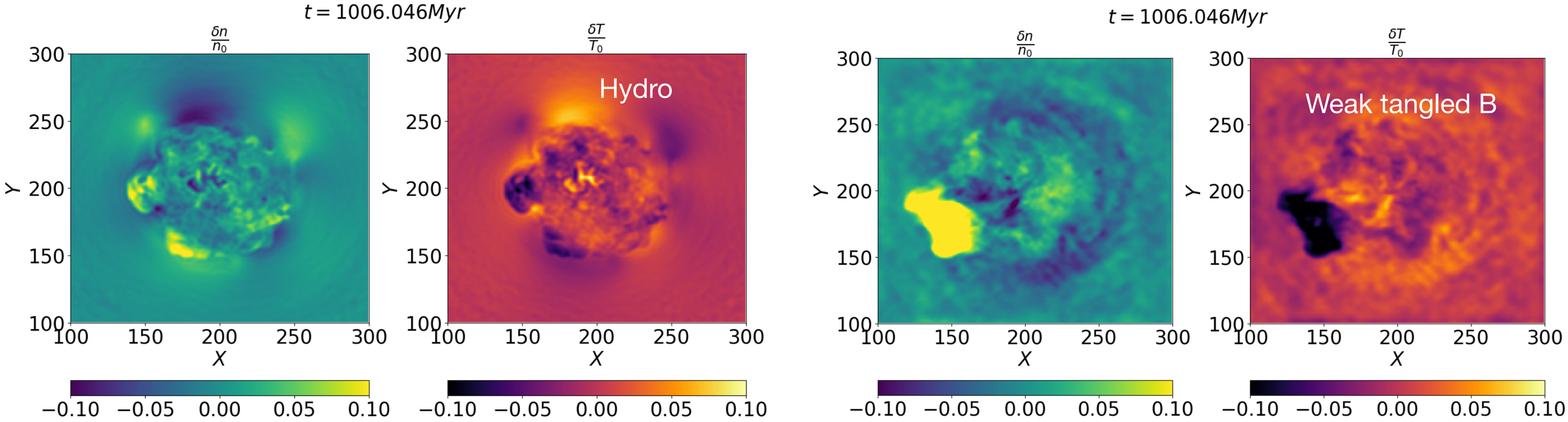


Magnetosonic?

Alfven-buoyancy?

preliminary

Complementary Q:
What's happening to cooler gas in my cluster? Is the turbulence dominated core bigger in presence of B?



Integrated emission weighted density and temperature

Magnetic field! But going smaller scales

Thermal conduction - really microscopic

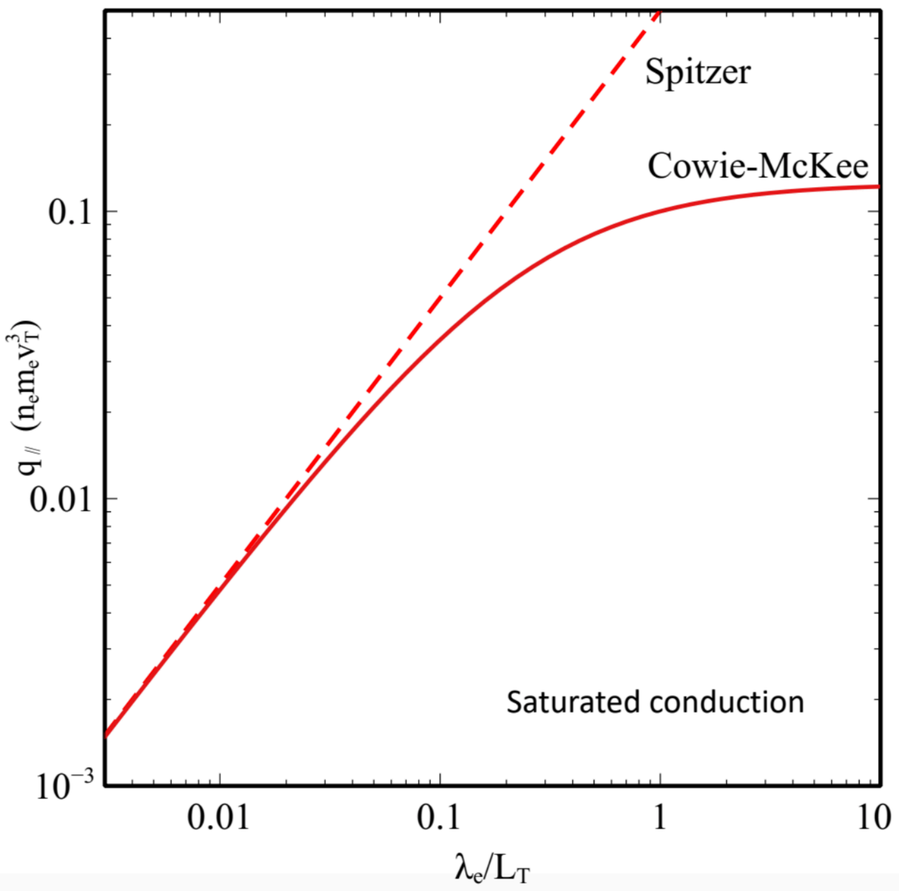
$$Q = -\kappa \nabla T$$

Collisional gas (Spitzer)

$$Q = -\kappa (\hat{b} \cdot \nabla T)\hat{b}$$

Collisional gas but with B (Braginskii); Suppression in cross-direction

collisional= small electron mean free path



T_h T_c L

Highly collisional

Clusters (weakly collisional)

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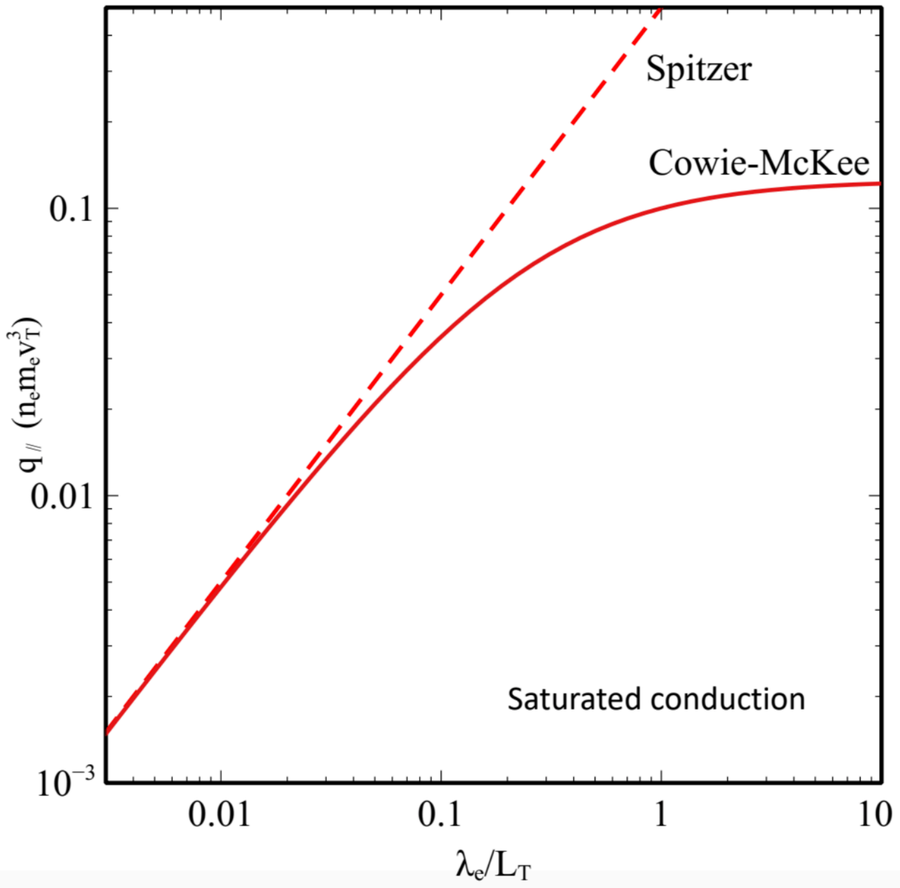
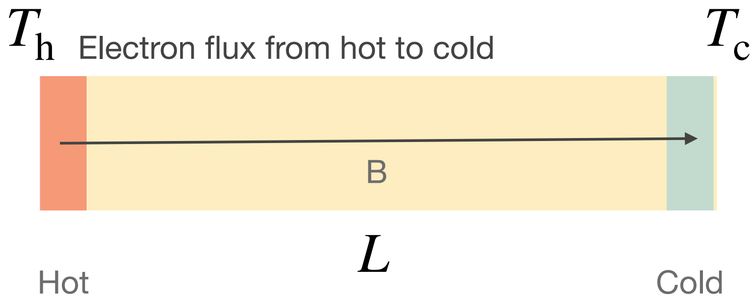
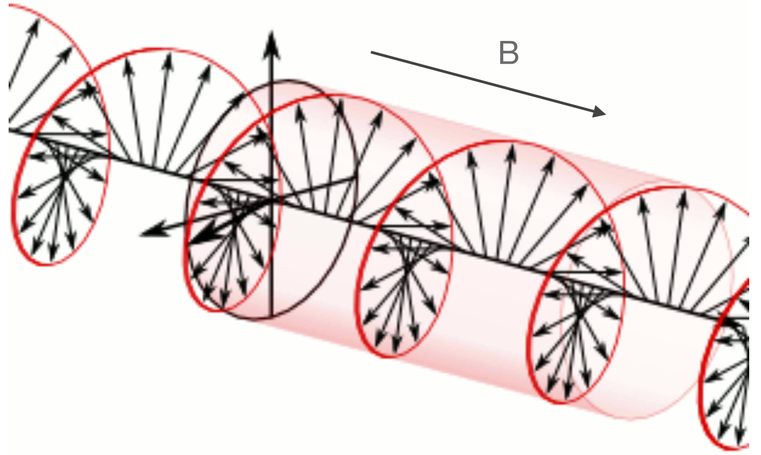


Highly collisional

Roberg-clarke+





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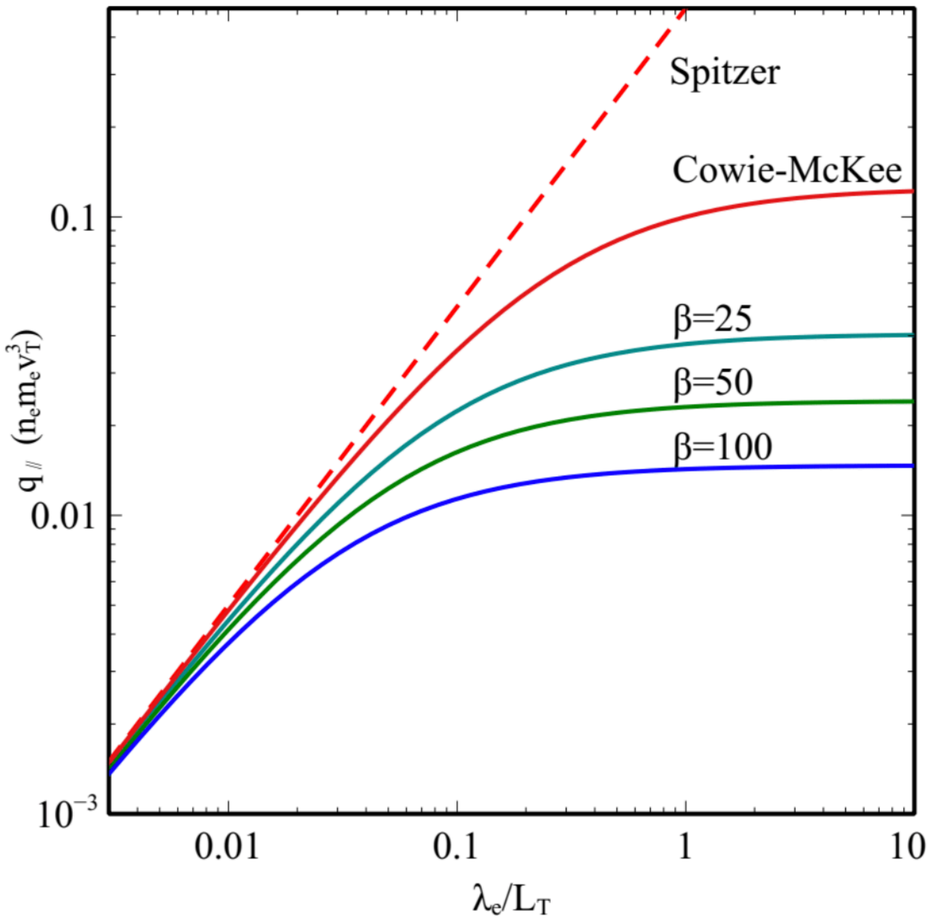

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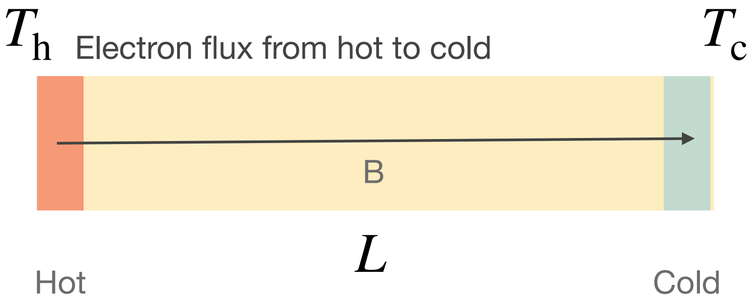
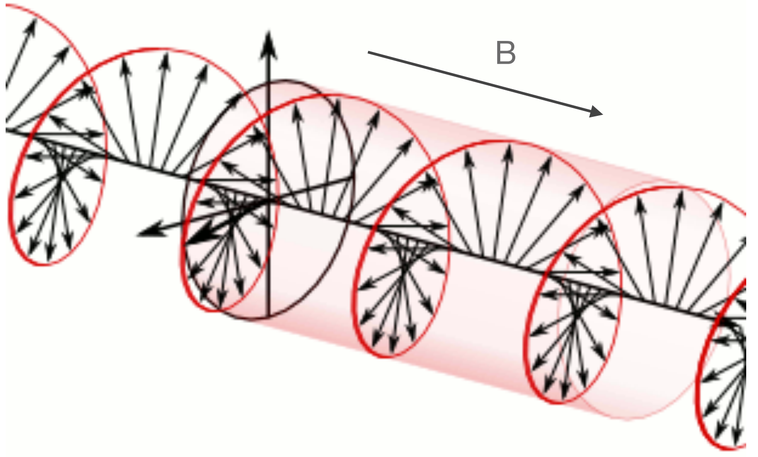
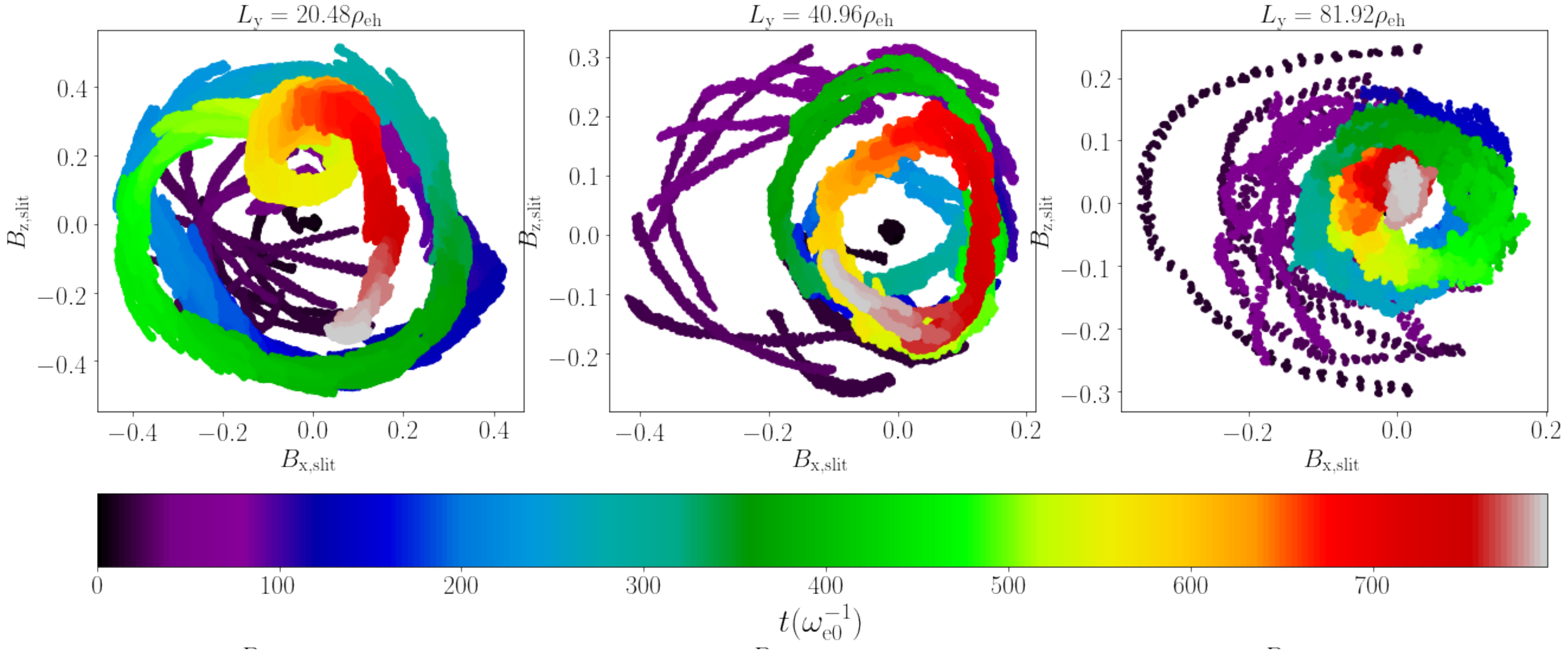




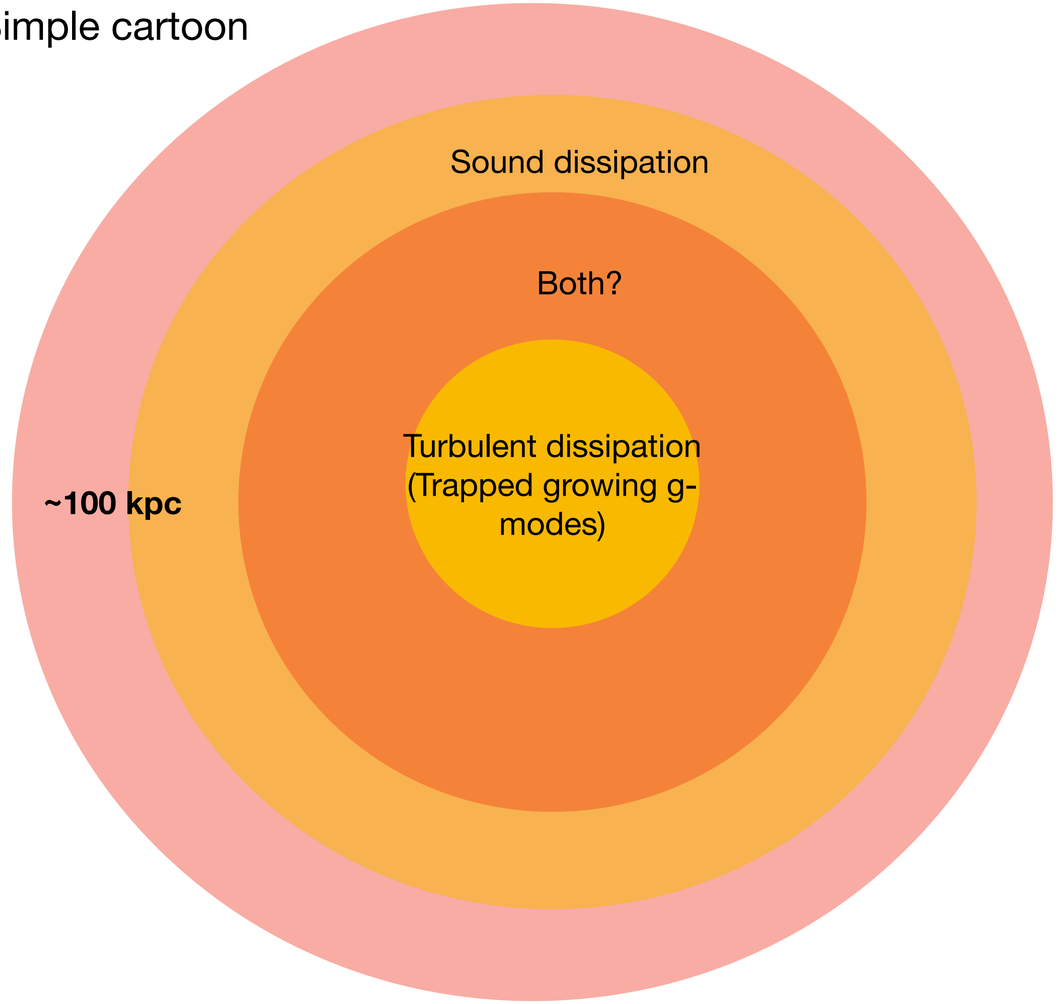
Does TC really get well suppressed for high beta & across larger length scales? (preliminary)

With Chris Reynolds, Jim Drake, Marc Swisdak

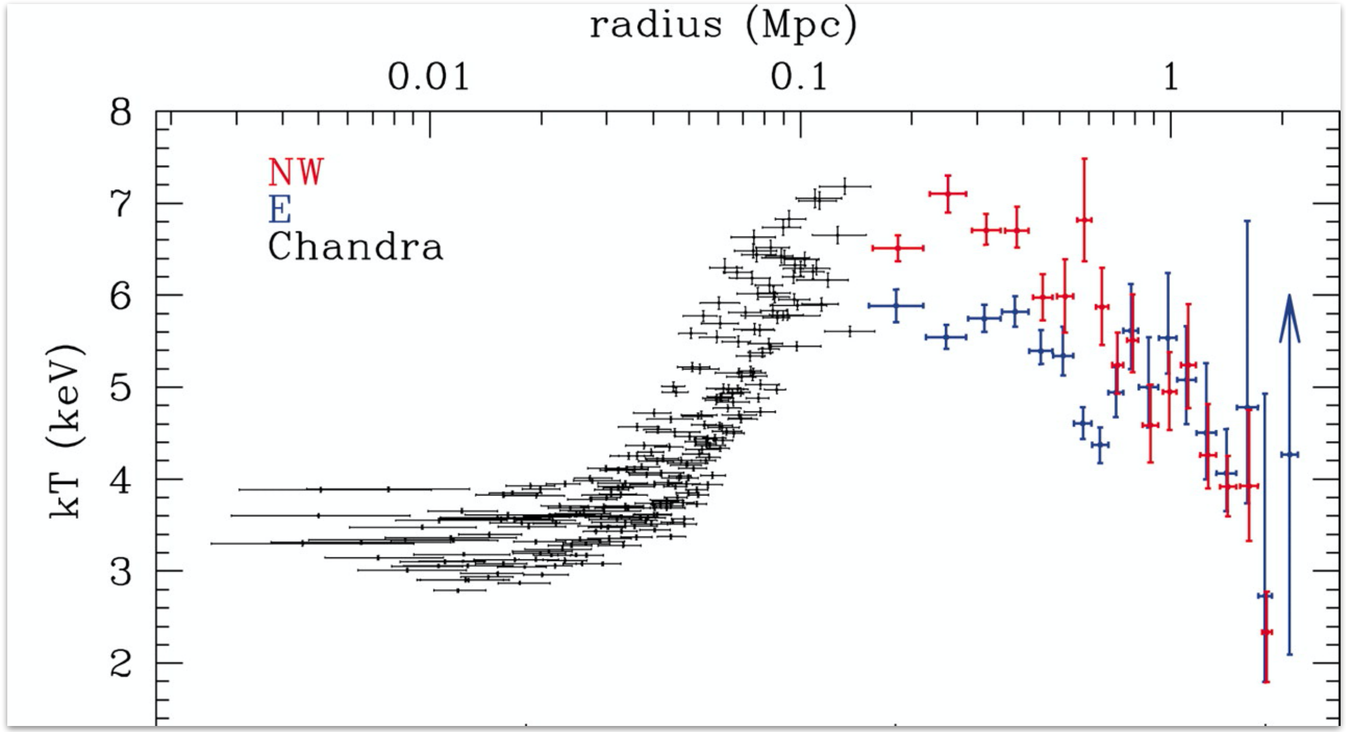


Summary so far on heating clusters

Simple cartoon



Perseus Cluster temperatures



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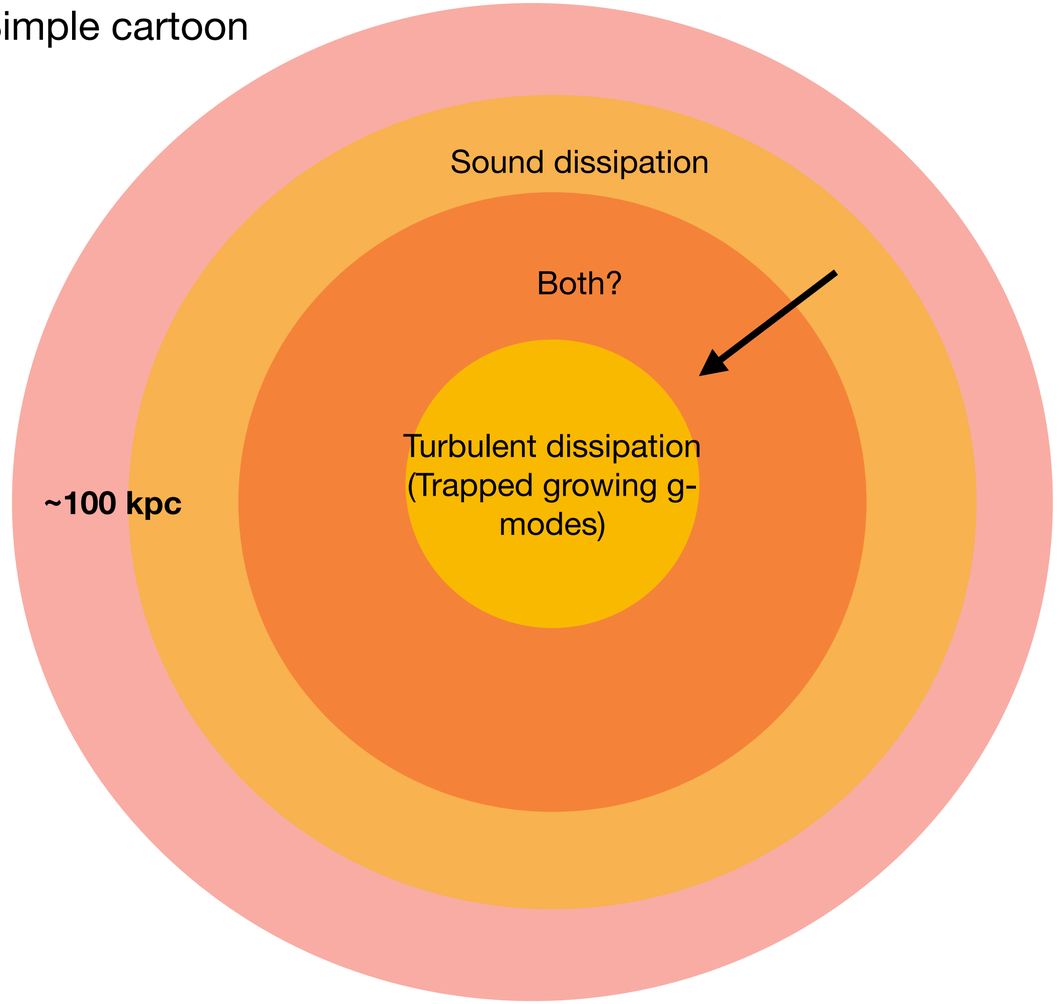
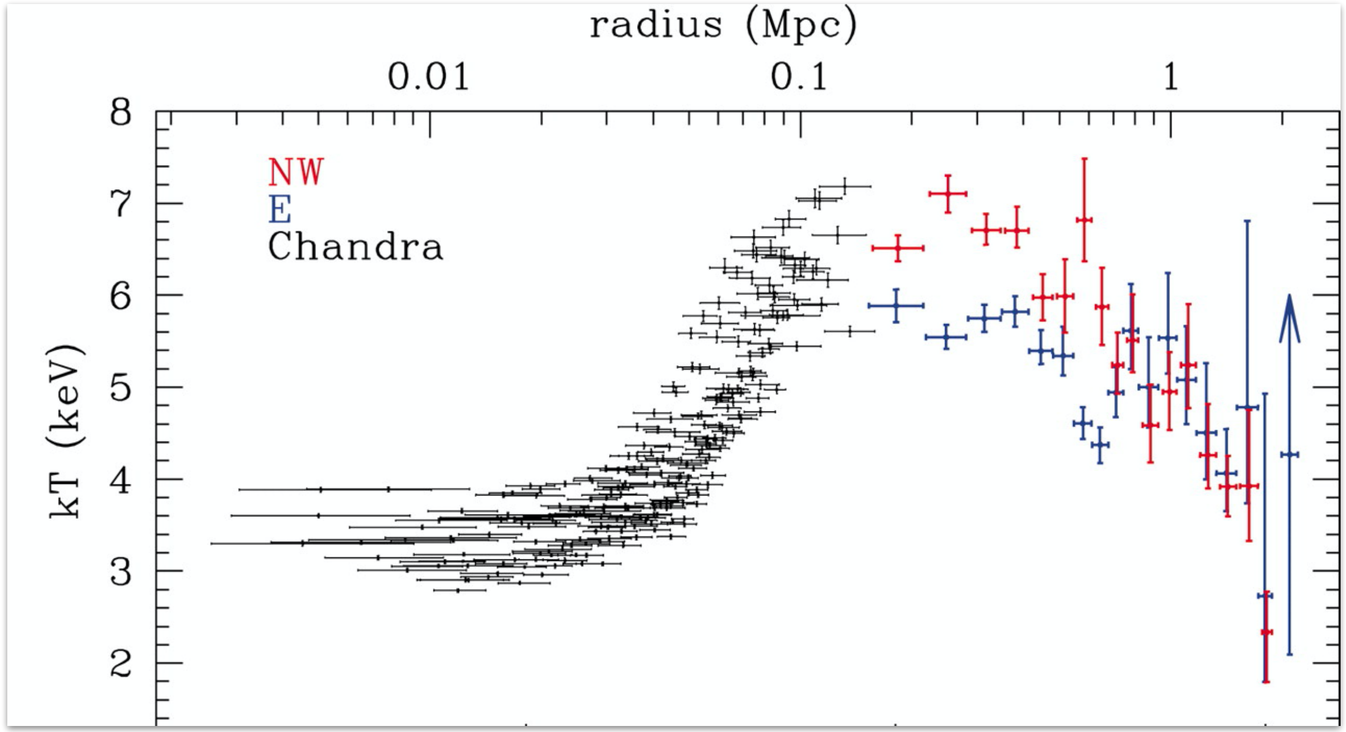


Perseus Cluster temperatures



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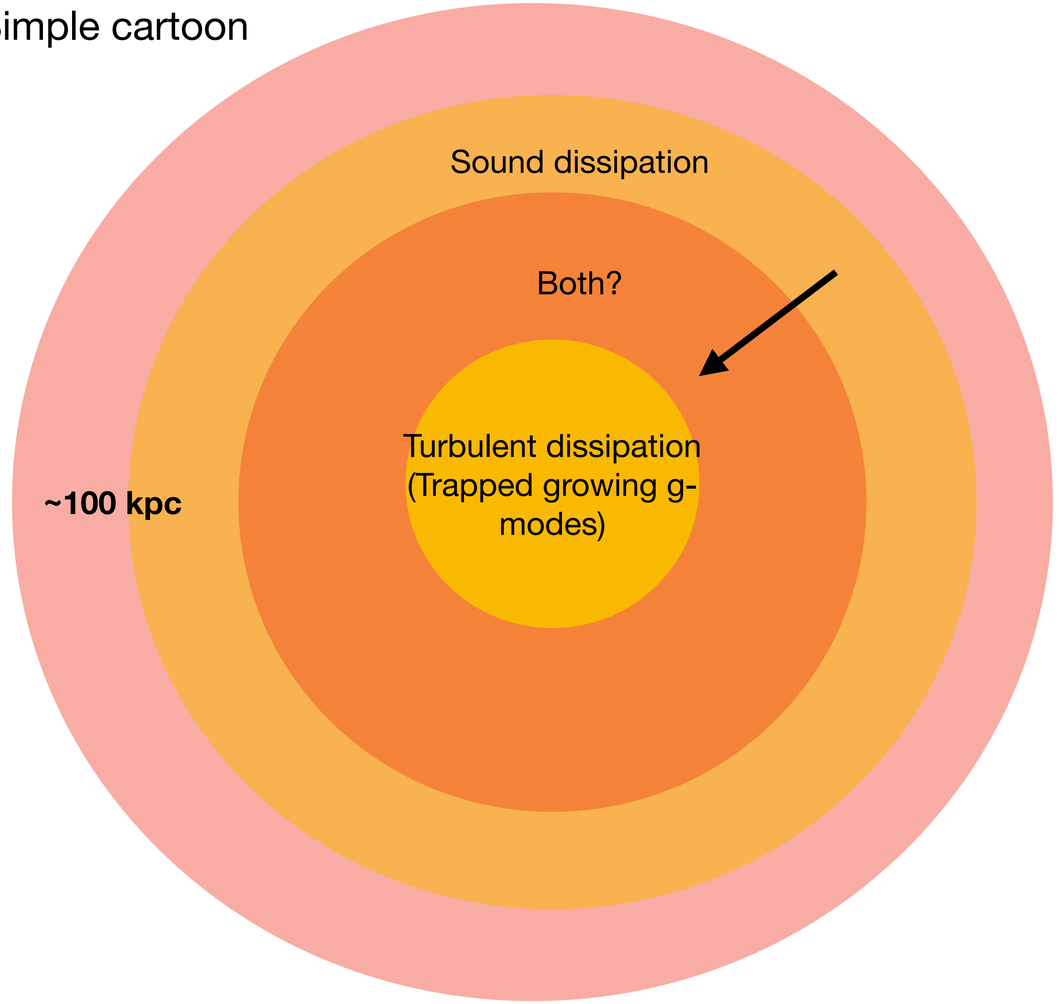

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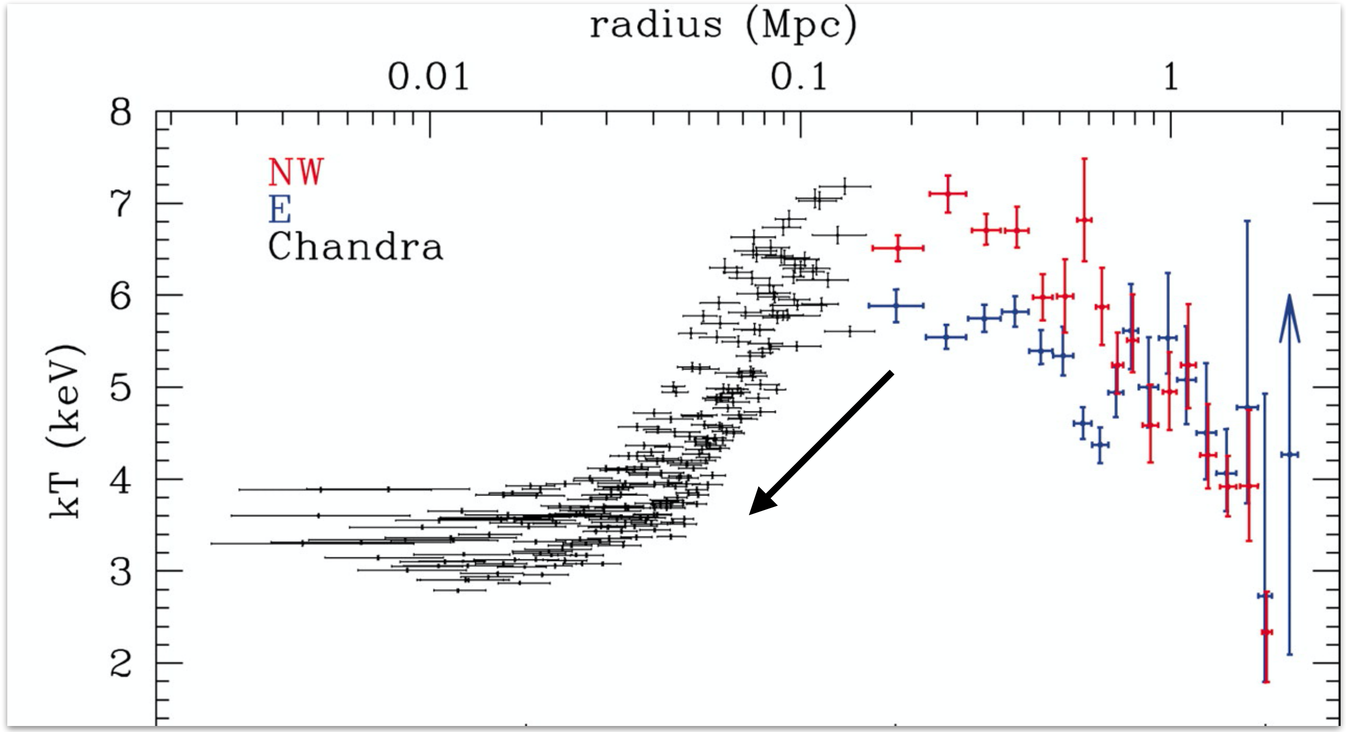

Summary so far on heating clusters

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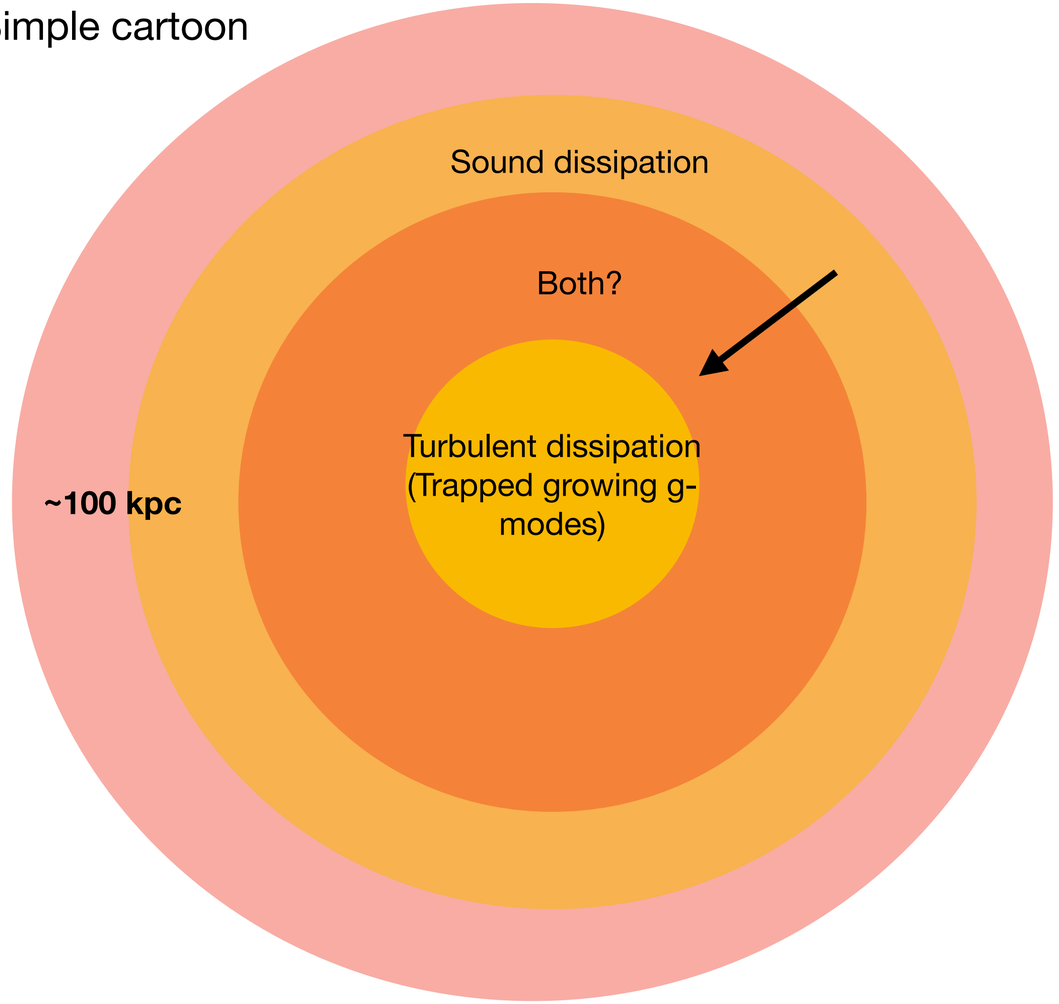

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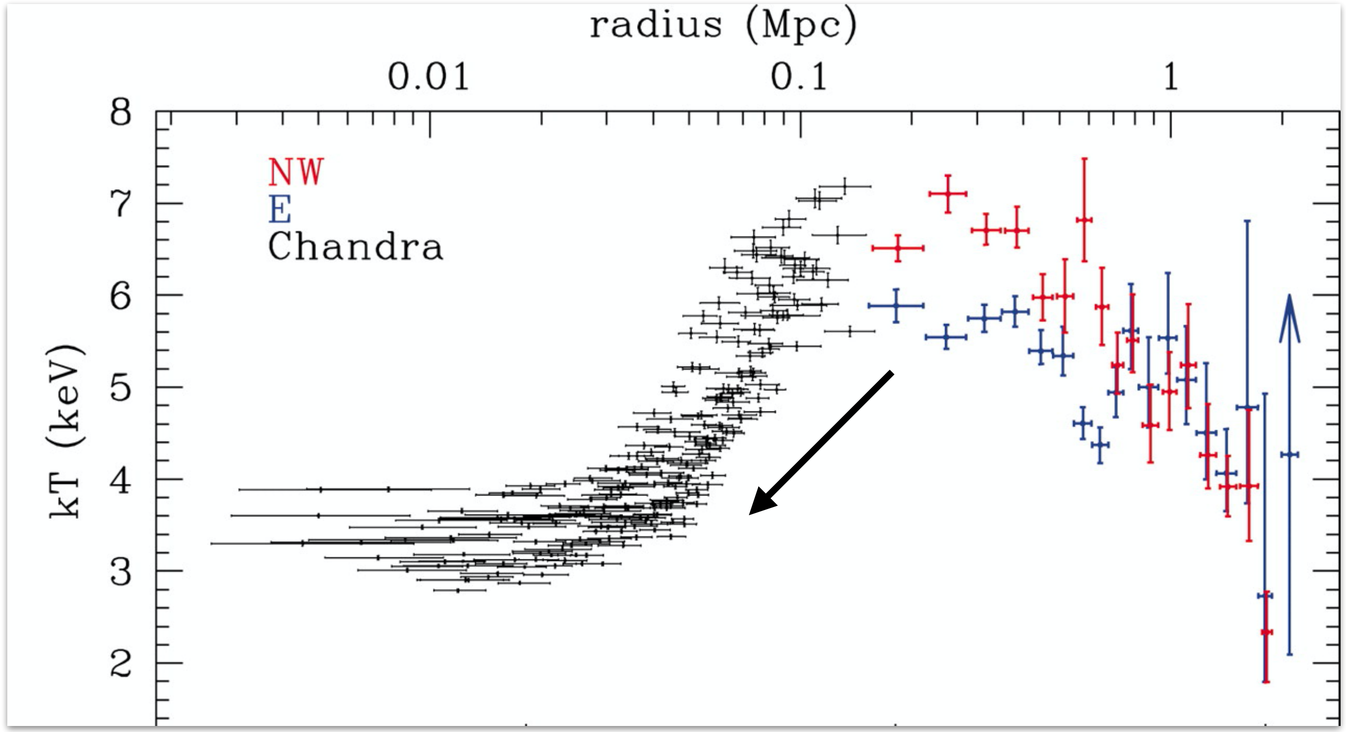
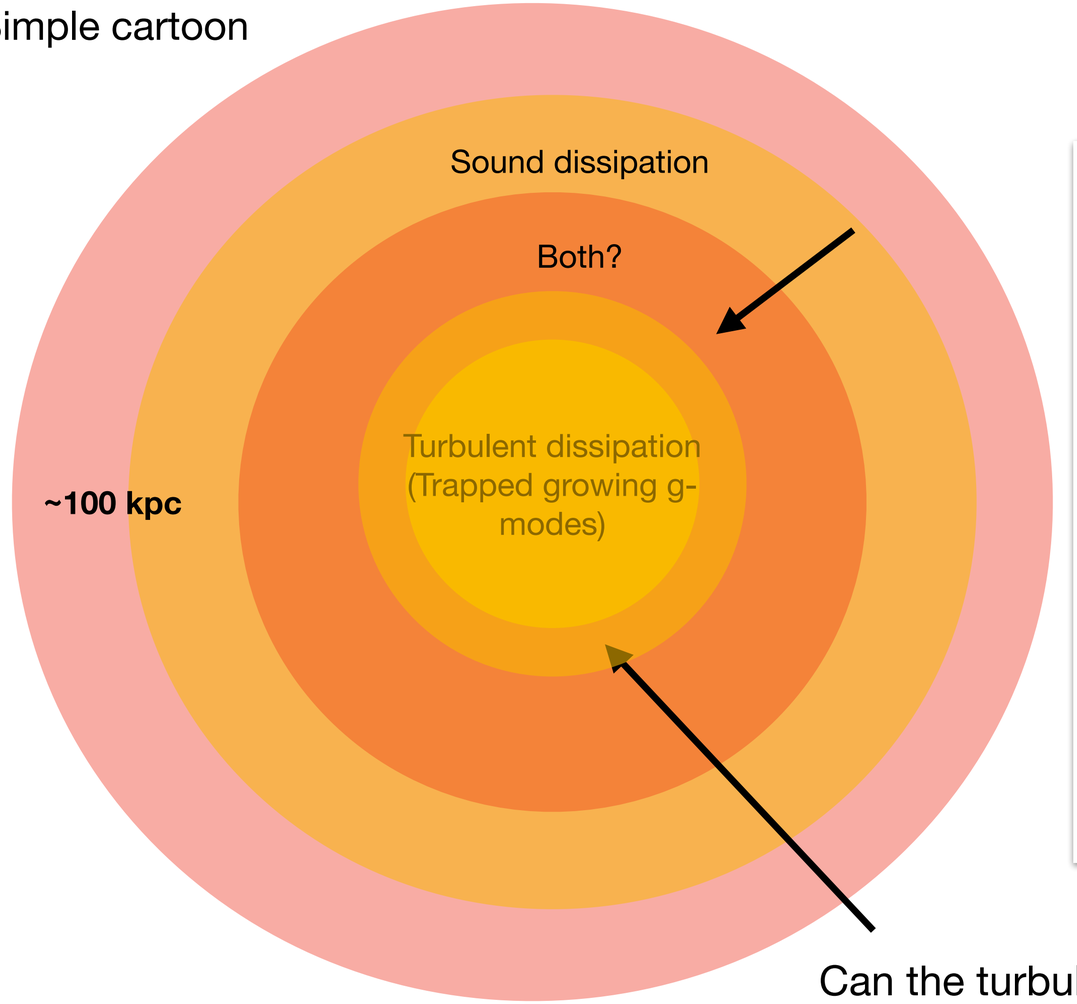


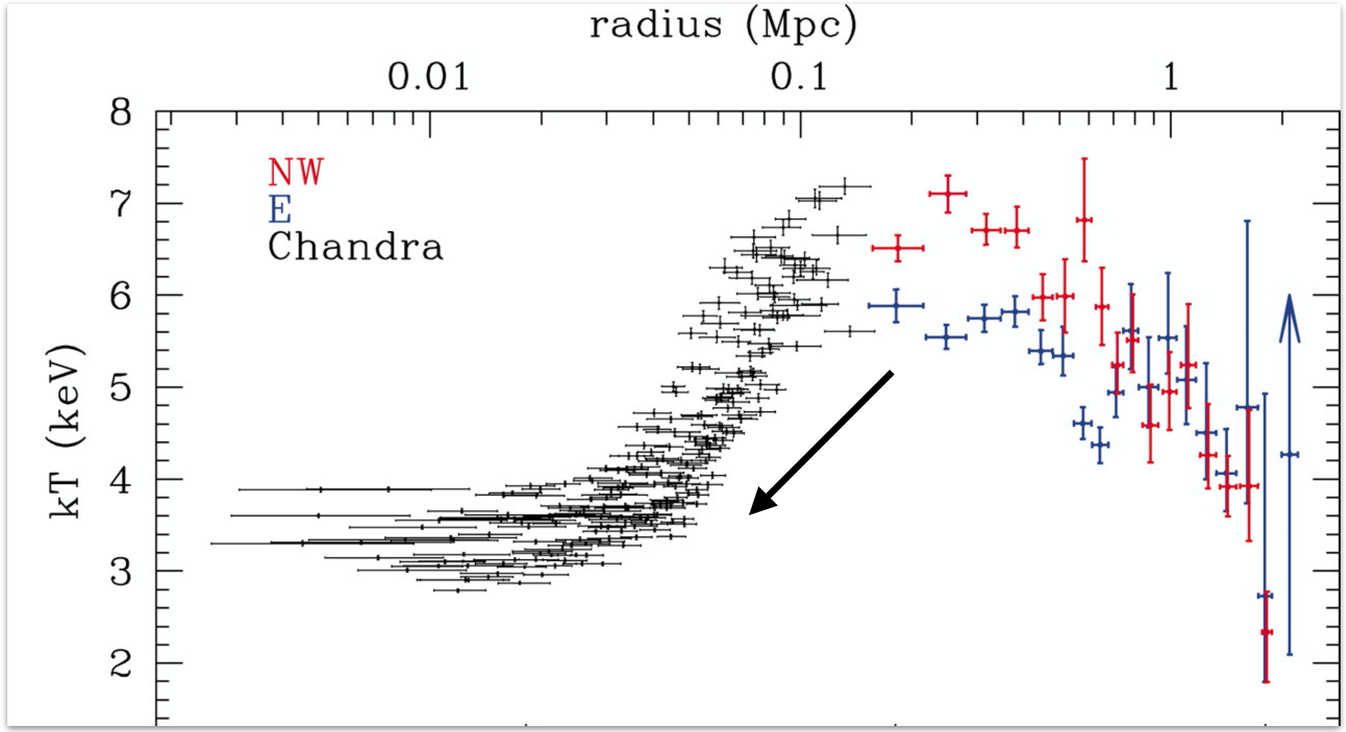
Is there a heat flux? Can suppression open up thermal instability at smaller scales?

Summary so far on heating clusters

Simple cartoon

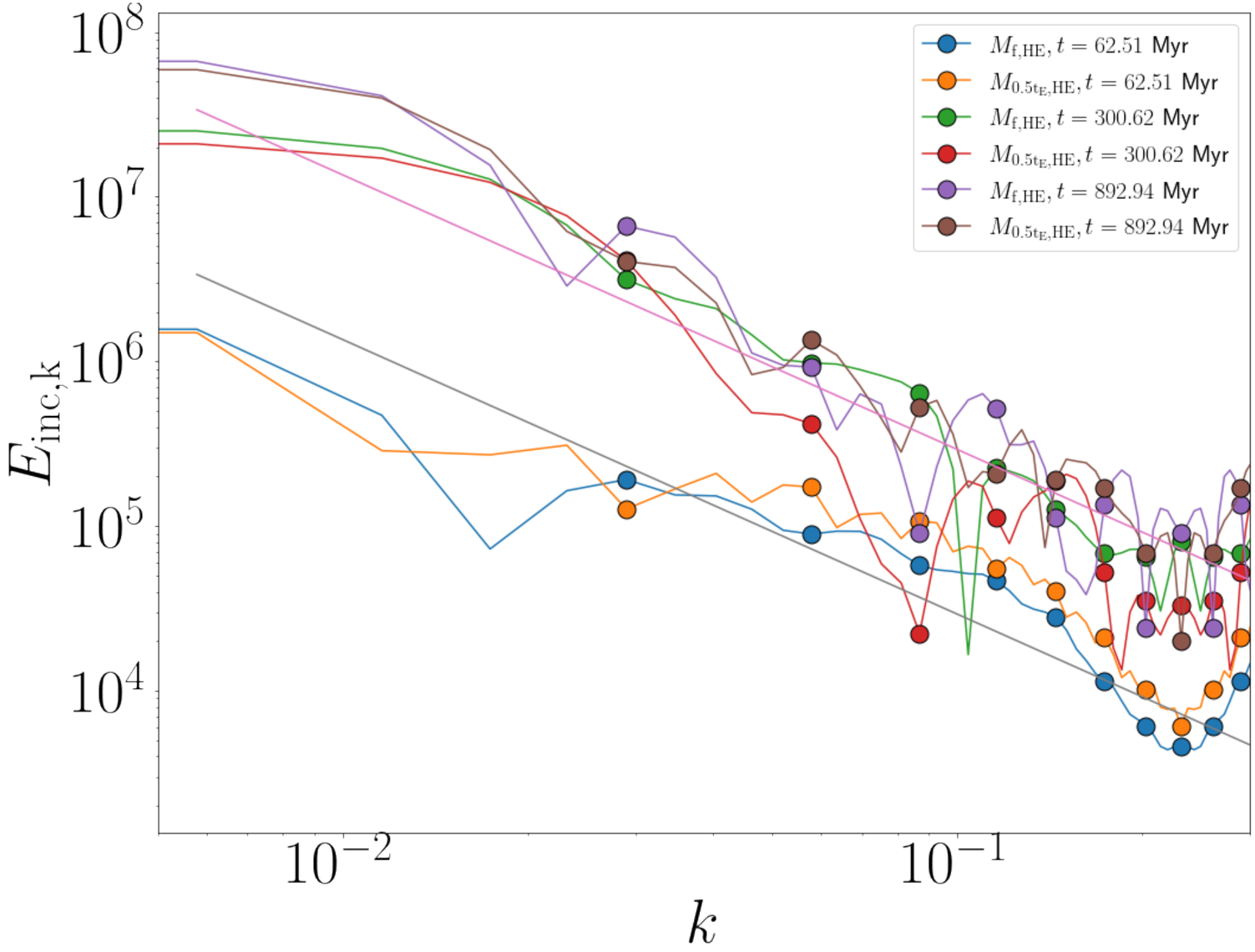


Perseus Cluster temperatures



Can the turbulent core be less confined in presence of B?

Is there a heat flux? Can suppression open up thermal instability at smaller scales?


10^8
10^7
10^6
10^5
10^4
$E_{\mathrm{inc,k}}$
10^{-2}
10^{-1}
k
$M_{\mathrm{f,HE}}, t = 62.51$ Myr
$M_{0.5\mathrm{t_E,HE}}, t = 62.51$ Myr
$M_{\mathrm{f,HE}}, t = 300.62$ Myr
$M_{0.5\mathrm{t_E,HE}}, t = 300.62$ Myr
$M_{\mathrm{f,HE}}, t = 892.94$ Myr
$M_{0.5\mathrm{t_E,HE}}, t = 892.94$ Myr