Micro- Vs Macro Transport

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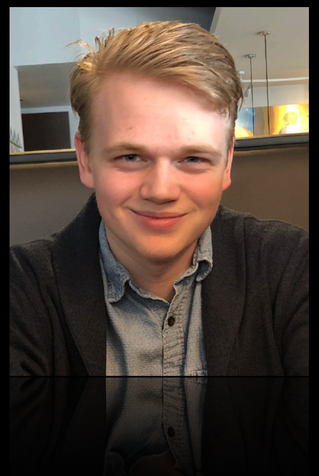
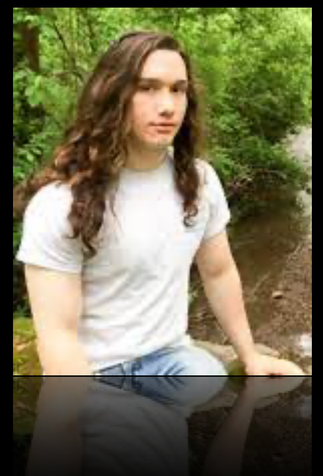
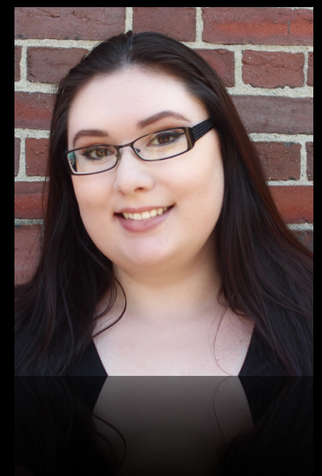
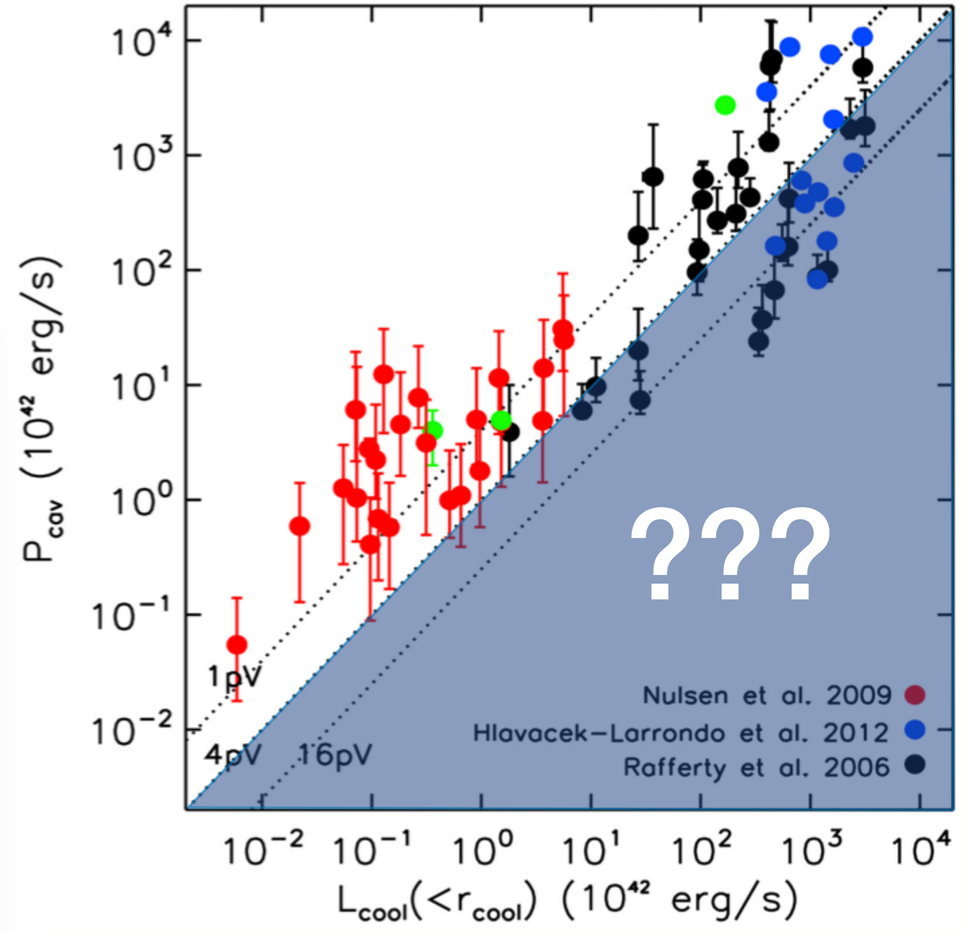
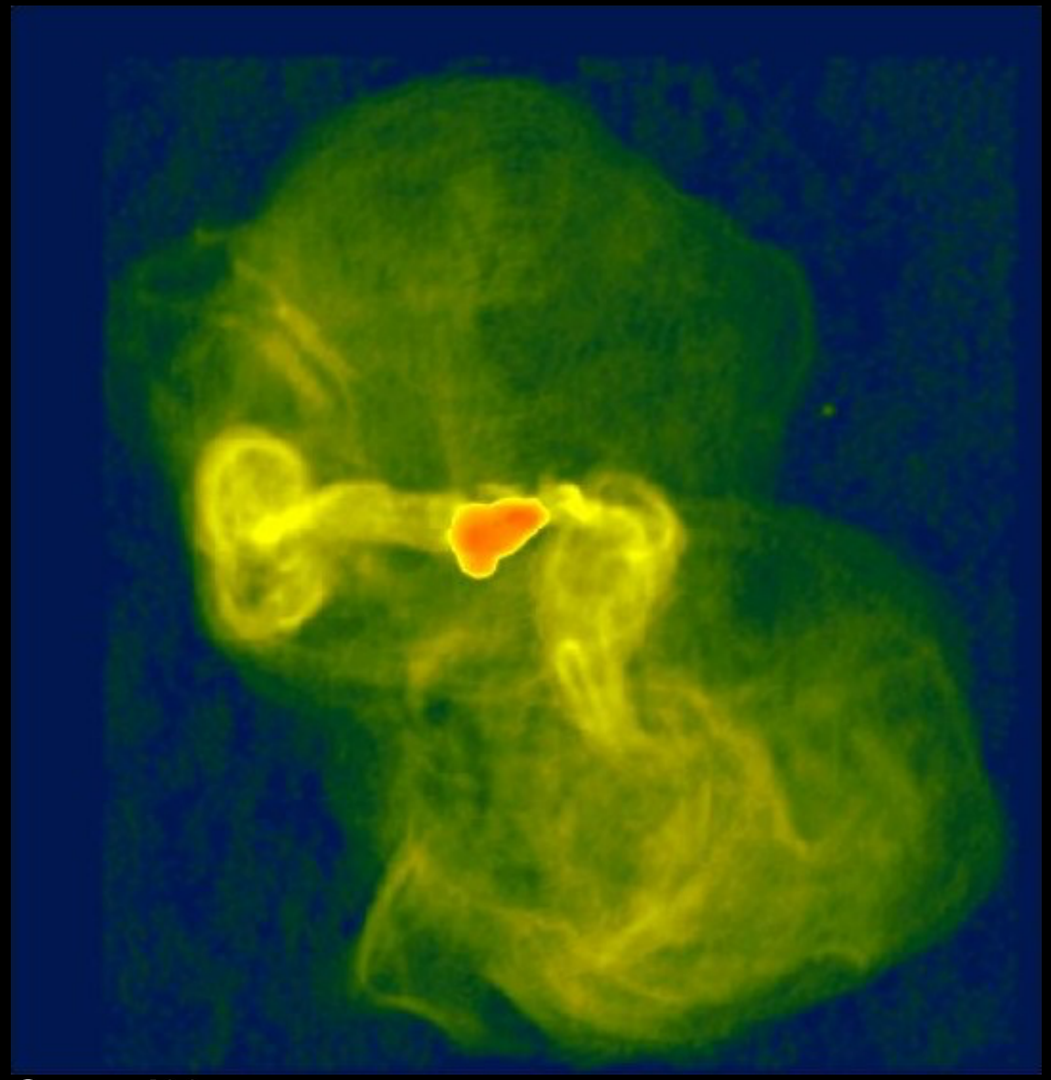





Feedback Efficiency

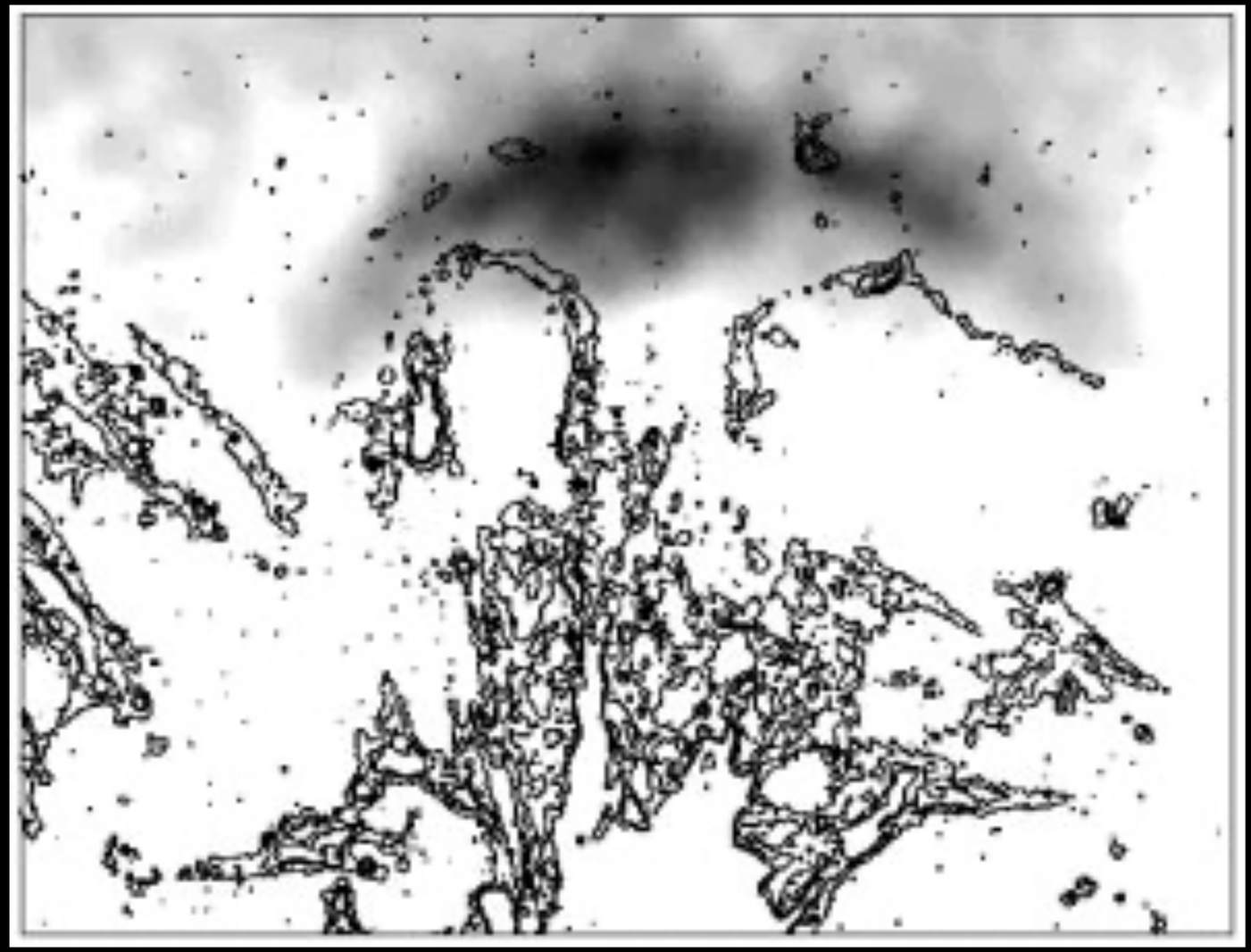


Rafferty+'06, Hlavacec-Larrondo+'12

Macroscopic Transport



Owen+’00



Fabian+’03

Microscopic Transport

ROSAT, Churazov+'03

Early models of conductive heating:

- Global conduction models (e.g., Zakamska+'03)
- Double heating models (e.g., Ruszkowski+'02, Brüggen '03)

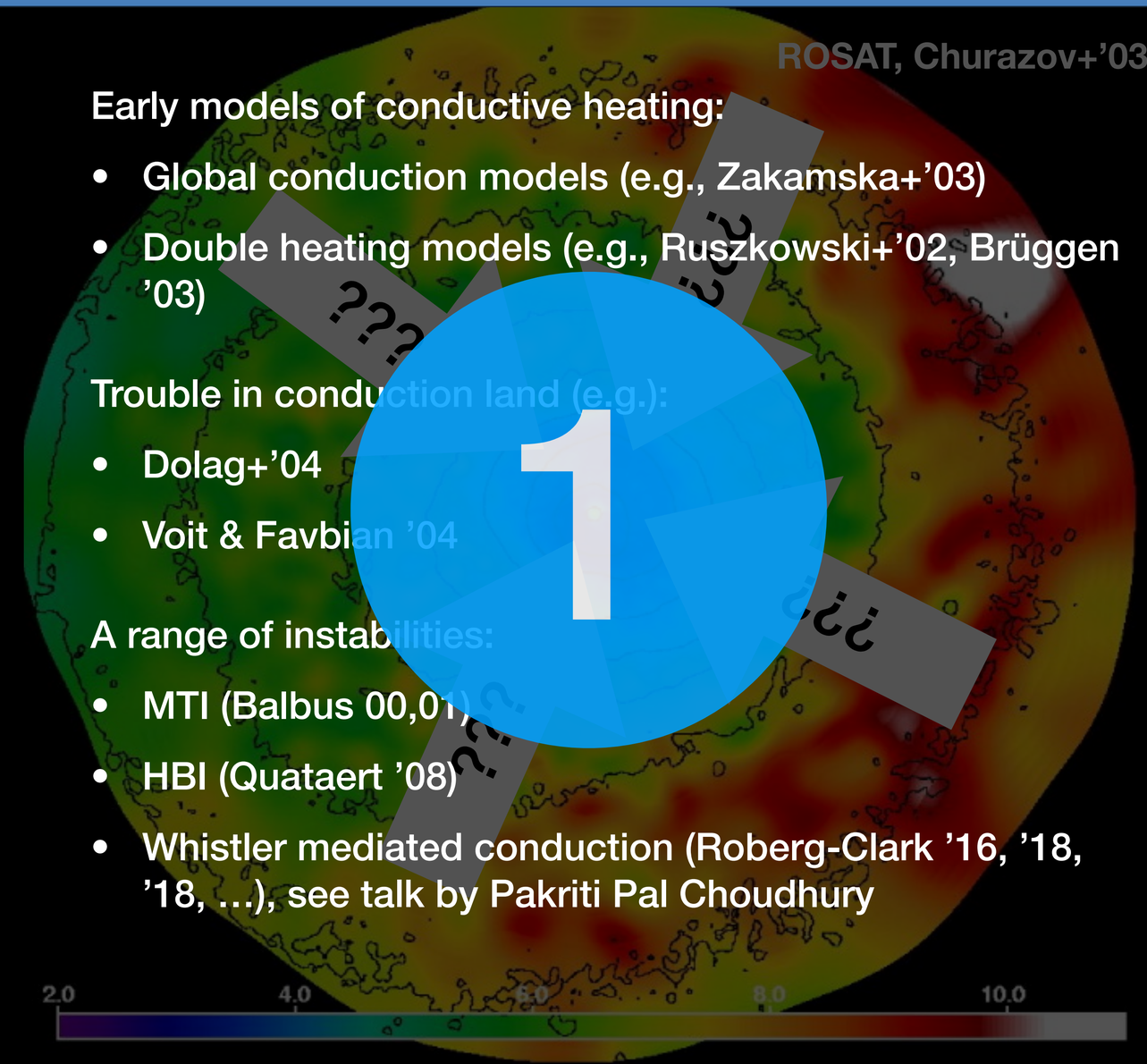
Trouble in conduction land (e.g.):

- Dolag+'04
- Voit & Favbian '04

A range of instabilities:

- MTI (Balbus 00,01)
- HBI (Quataert '08)
- Whistler mediated conduction (Roberg-Clark '16, '18, '18, …), see talk by Pakriti Pal Choudhury

1



VLA, Pedlar+'90

Radio Mini-Halos:

- Common in cool core clusters (e.g., Pedlar+'90, Giovannini+'99)
- Unrelated to radio halos in NCC

Difficulty:

- Cooling time ~ few100 Myrs
- Requires replenishment

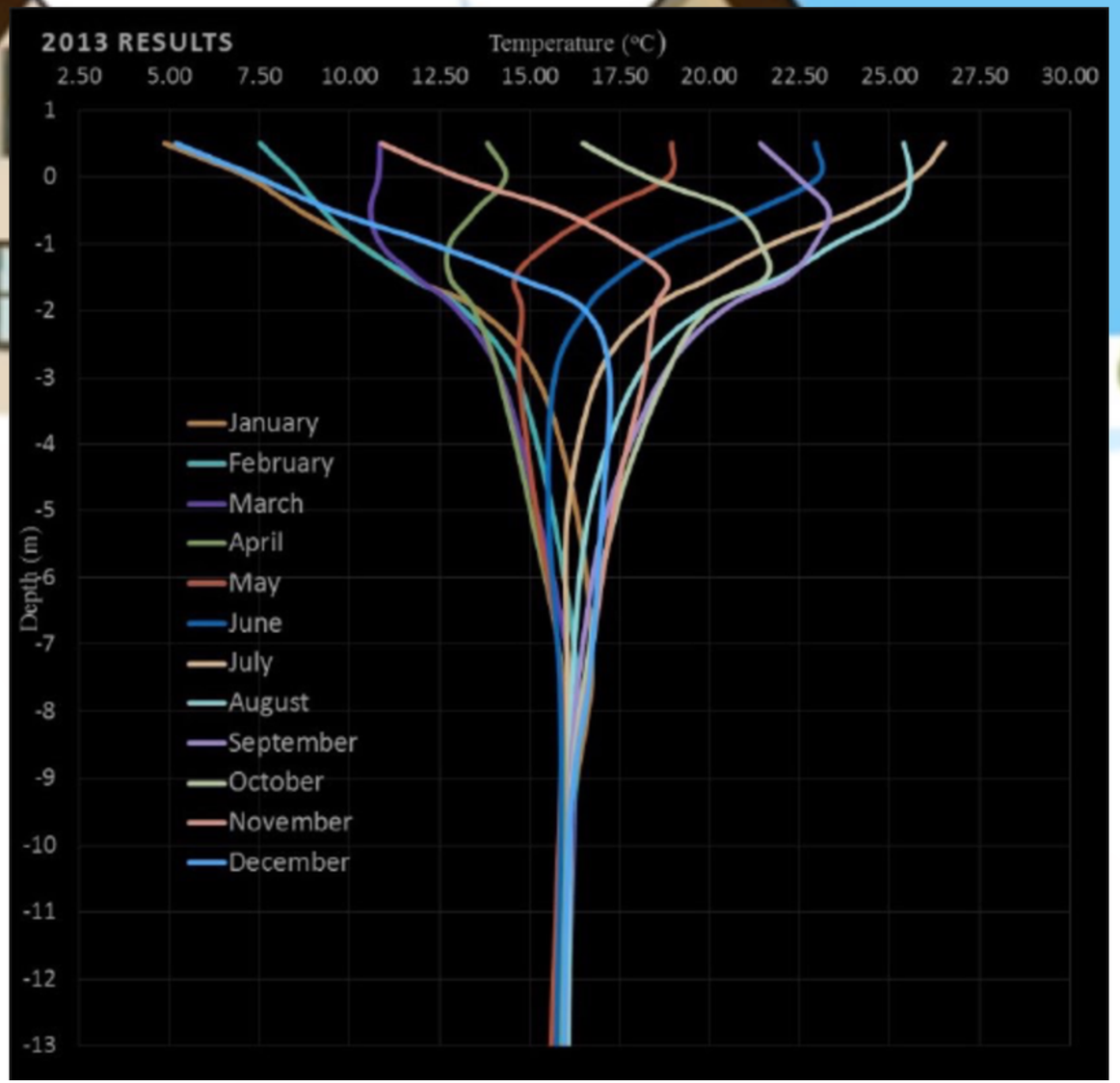
Possible relation to BCG AGN not fully understood

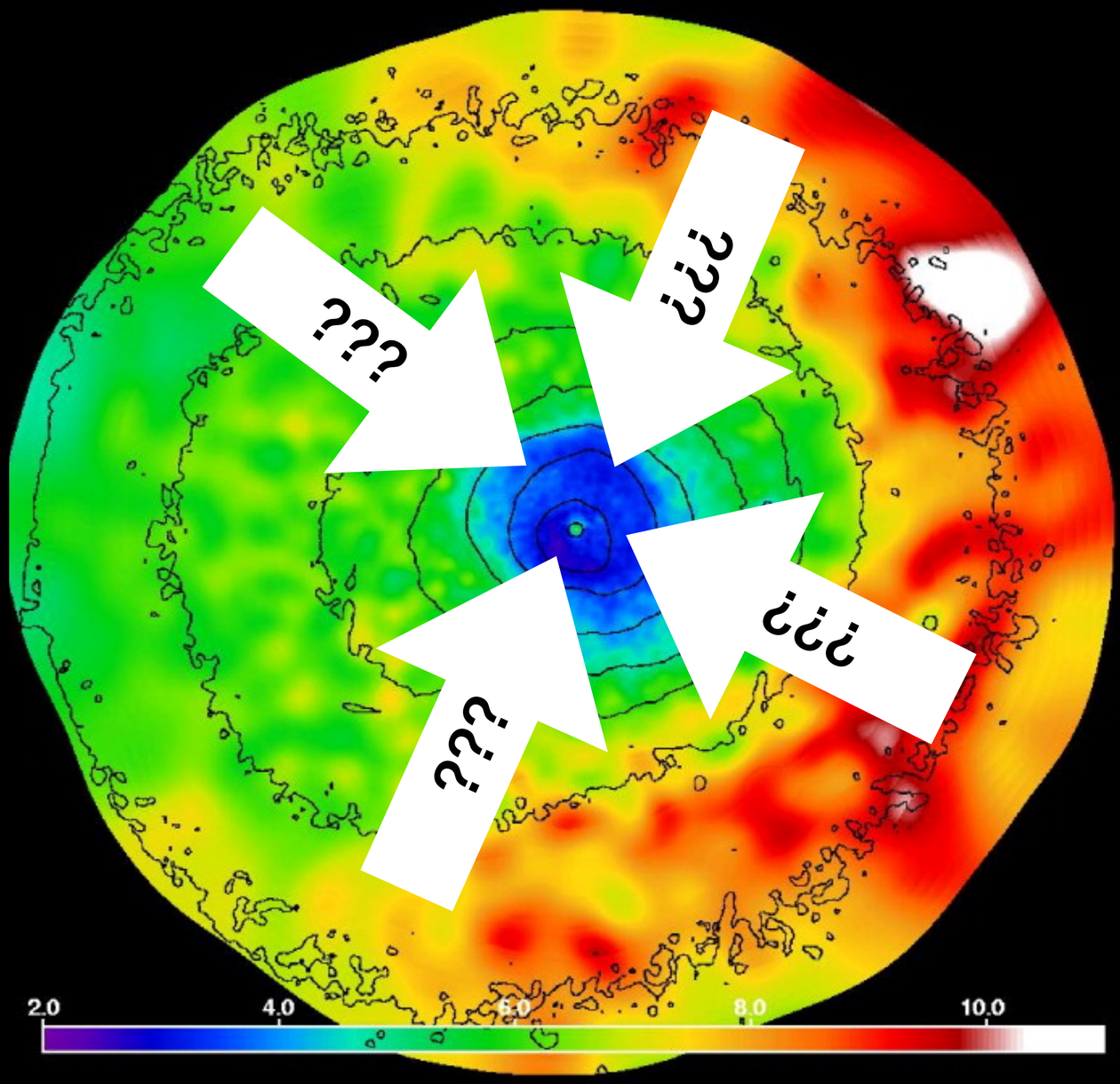
- e.g. Richard-Laferriere+'20, Gendron-Marsolais+'20

Alternatives:

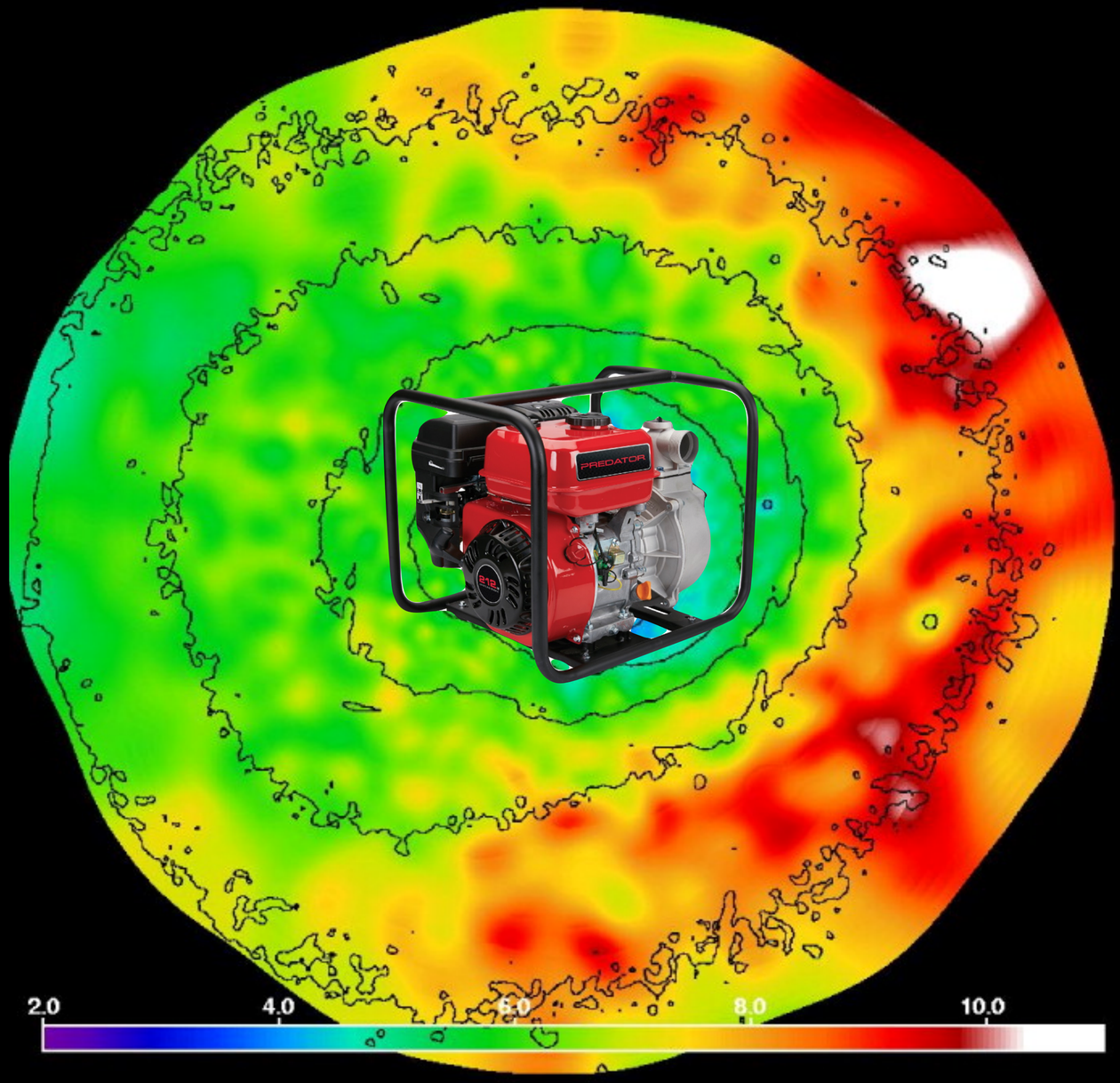
- Turbulent acceleration (e.g., Gitti+'02,'04)
- Cosmic Rays (e.g., Pfrommer+'04)

2


2013 RESULTS
Temperature (°C)
2.50
5.00
7.50
10.00
12.50
15.00
17.50
20.00
22.50
25.00
27.50
30.00
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
Depth (m)
January
February
March
April
May
June
July
August
September
October
November
December



Churazov+'03



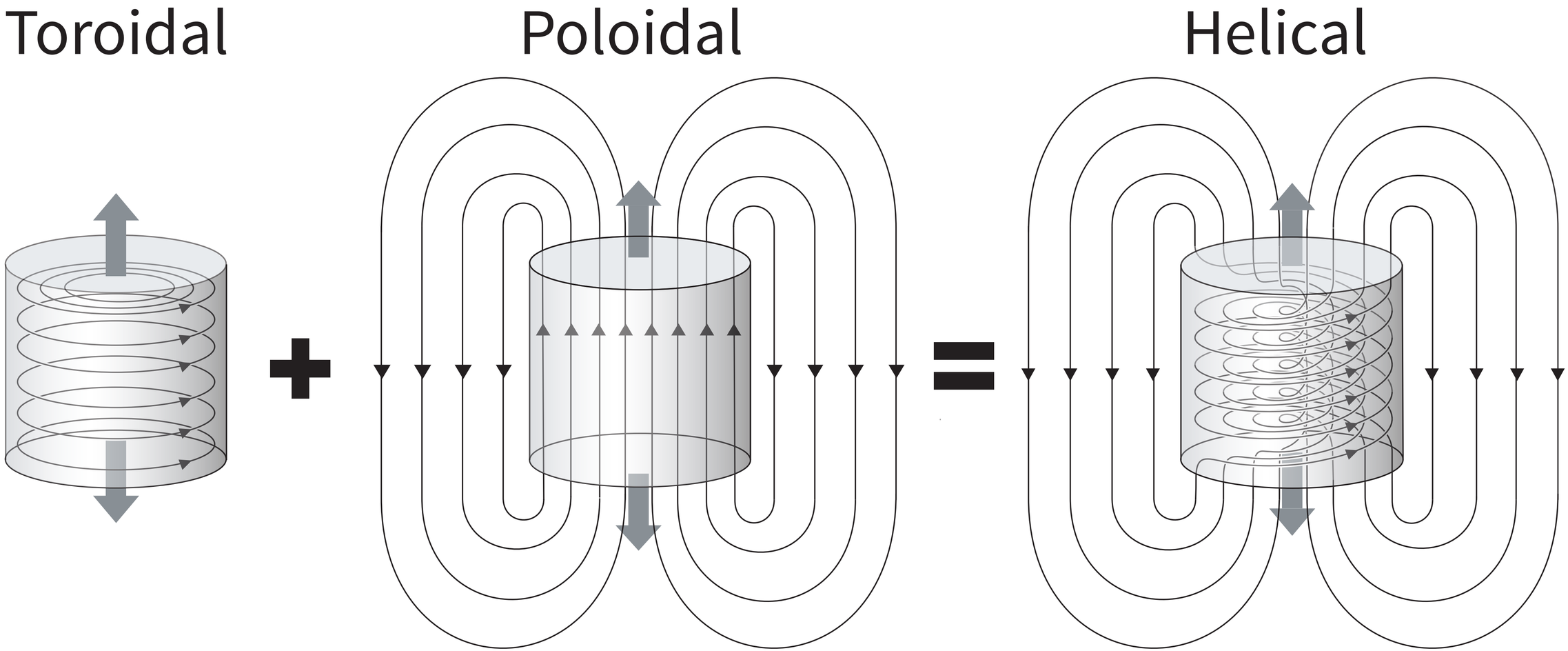
Churazov+’03

Ideal MHD simulations

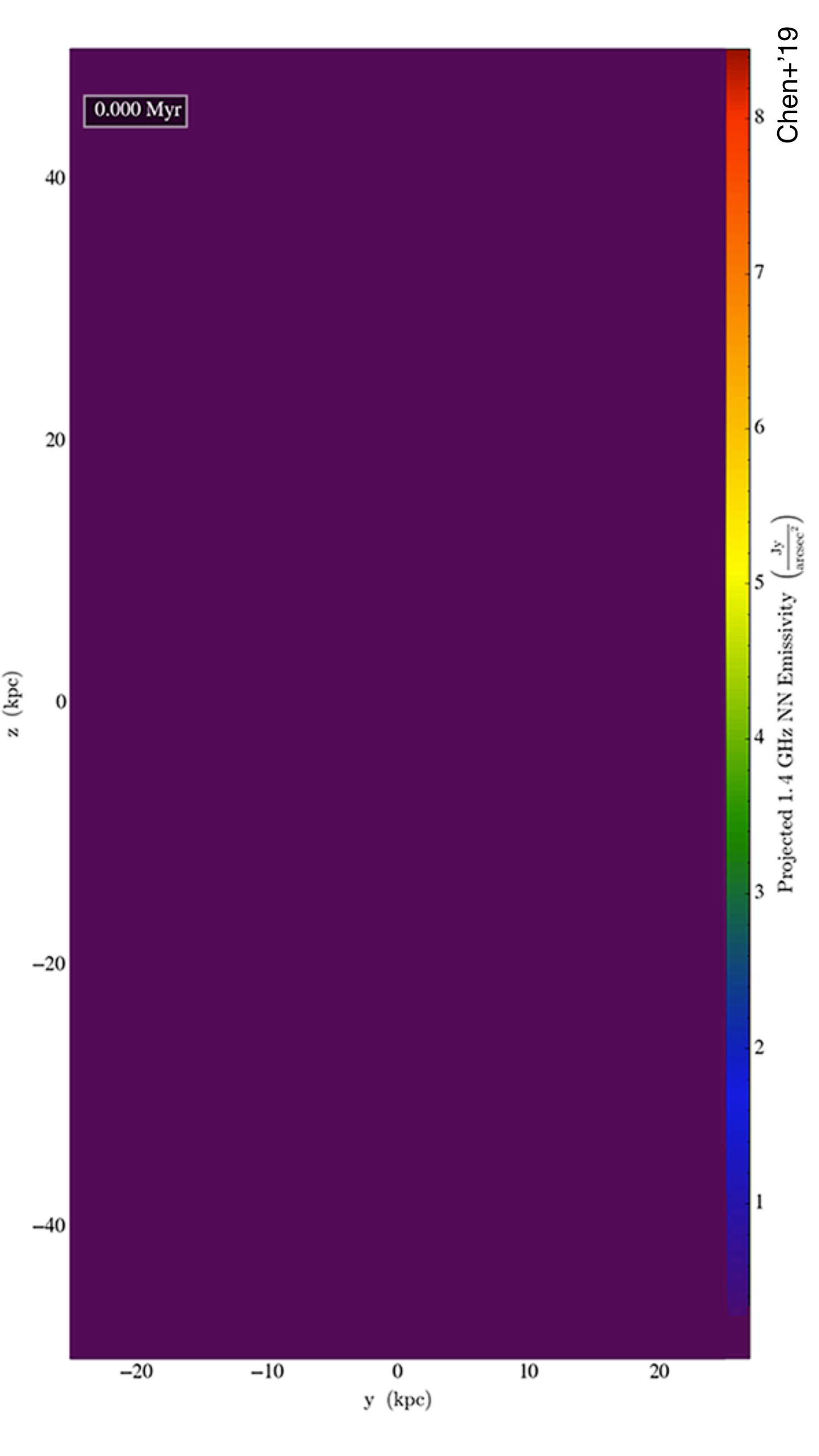
- FLASH 4.6, AMR
- Single shot injection at 10^{45} ergs/s for 10 Myrs
- β=1
- v=0.1c to 0.2c, Mach 10 to 5, respectively (kinetic)
- Lagrangian tracer particles (ICM and non-thermal)
- Implicit solution to transport equation
- Cylindrical nozzle, smallest cell size 30pc
- Perseus Cluster adopted from Zhuravleva+'15
- Dentist drill jitter

Chen+'19, '22, Heinrich+'21, Ilan+'22

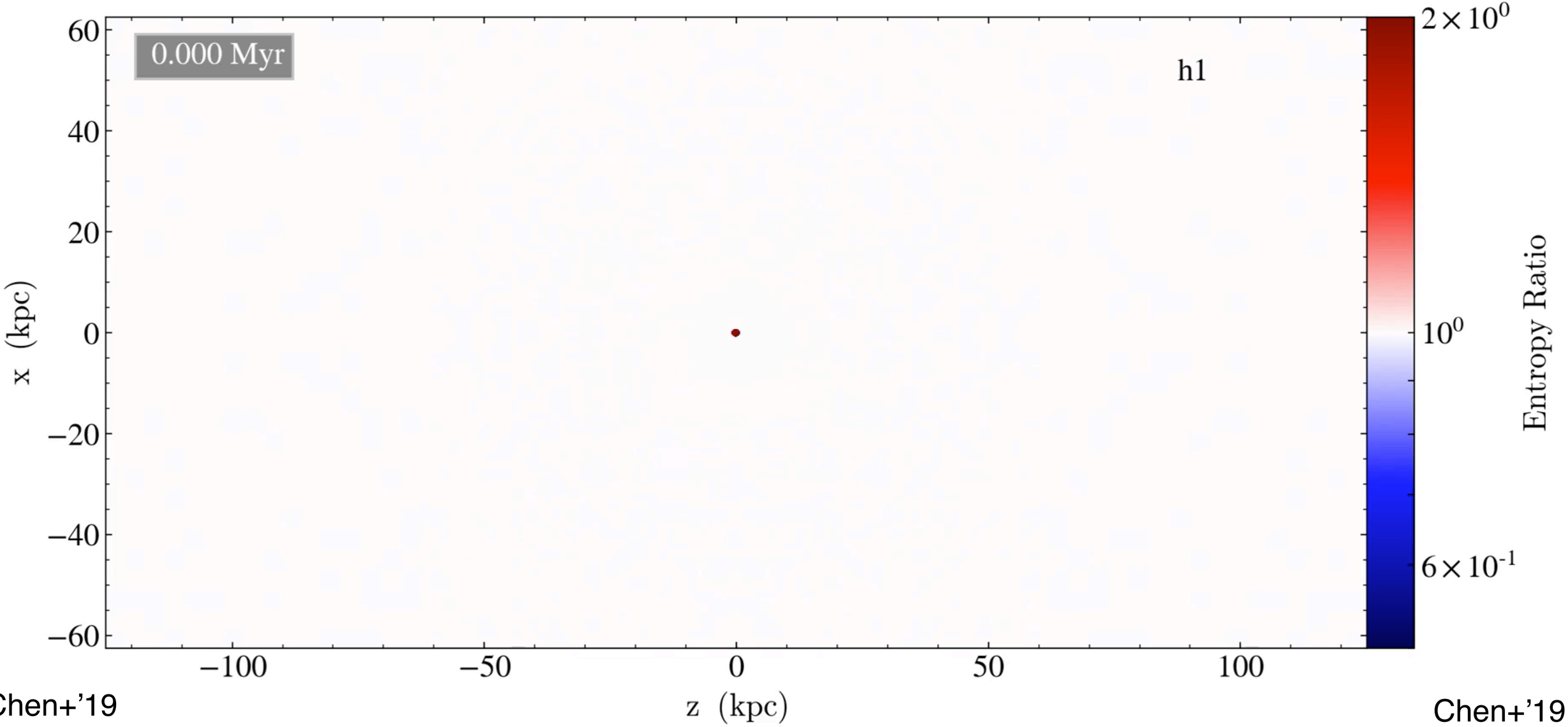
Magnetic Topology



Chen+’19, ‘22, Heinrich+’21, Ilan+’22


0.000 Myr
40
20
0
−20
−40
z (kpc)
−20
−10
0
10
20
y (kpc)
8
7
6
5
4
3
2
1
Projected 1.4 GHz NN Emissivity $\left(\frac{\text{Jy}}{\text{arcsec}^2}\right)$
Chen+'19

Jets: A Cosmic Heat Pump



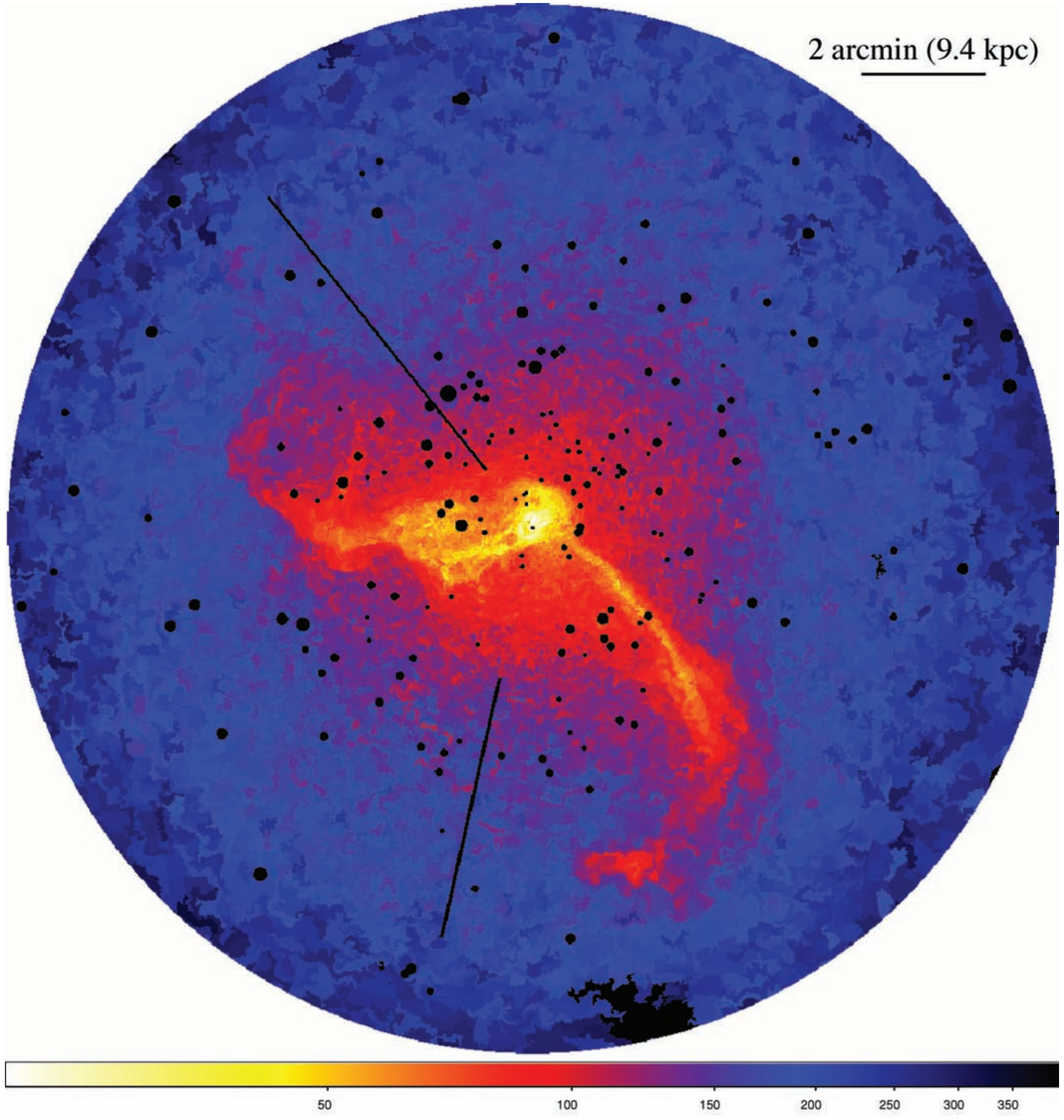
Chen+'19

Chen+'19

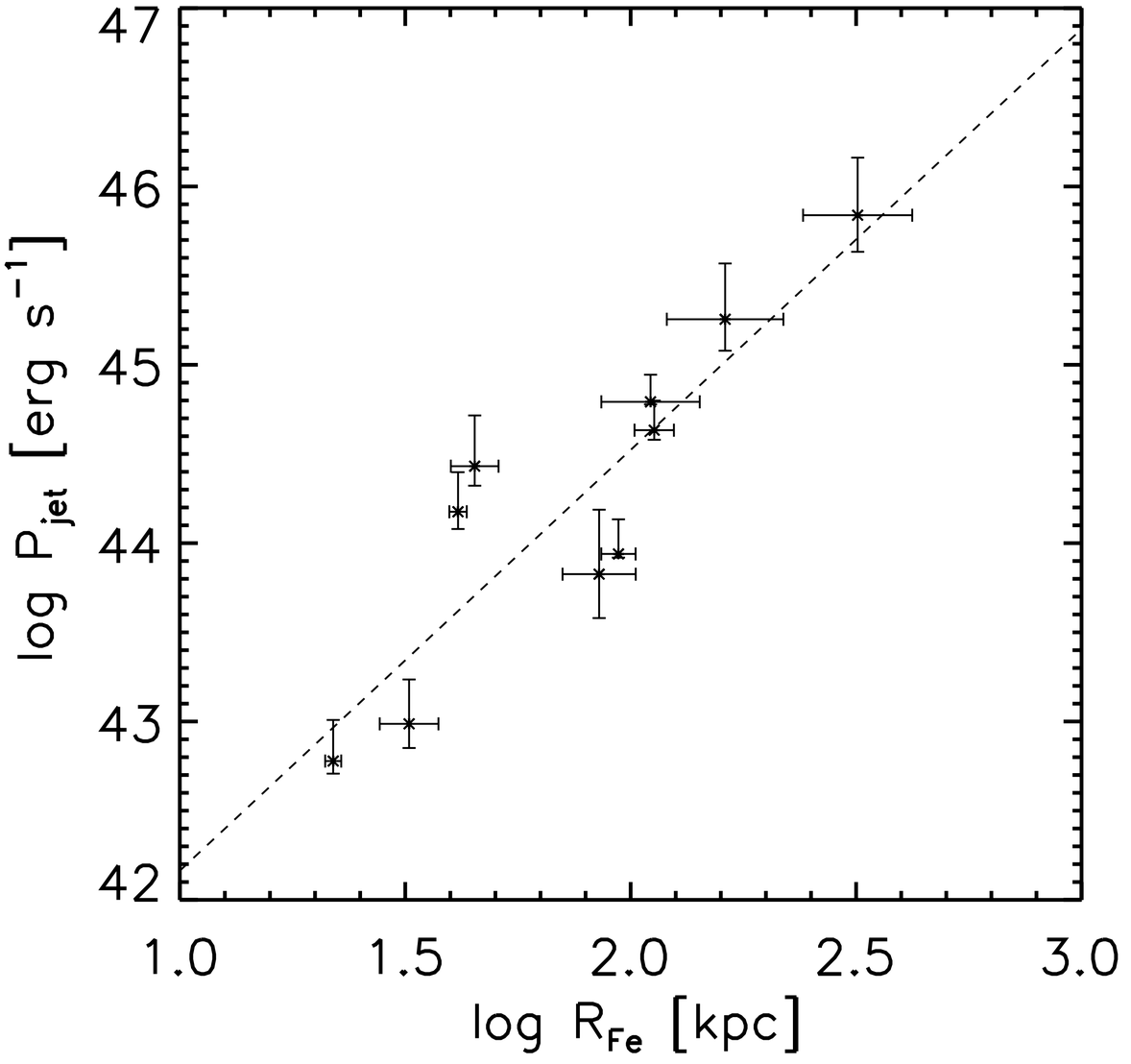
Chen+’19

Macroscopic Transport

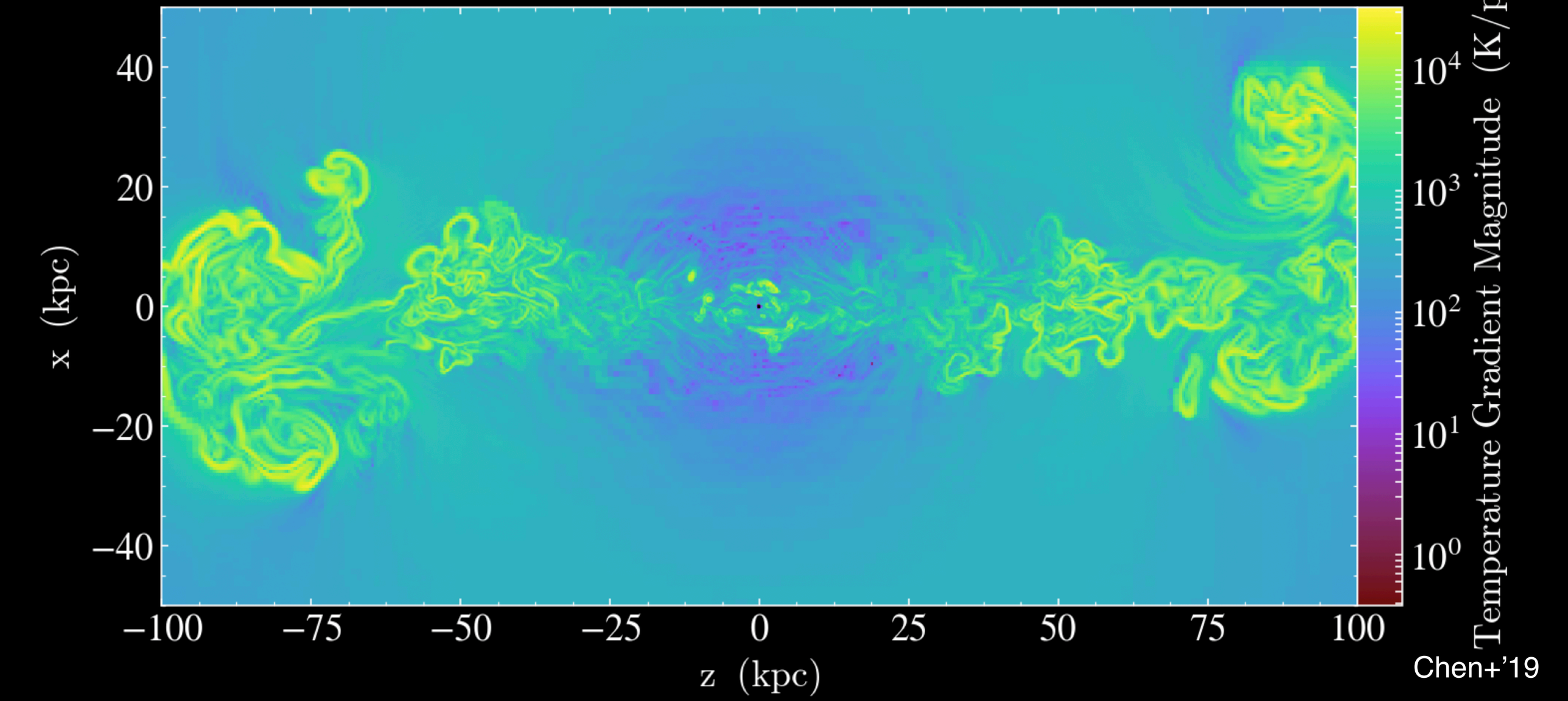
Million+'10



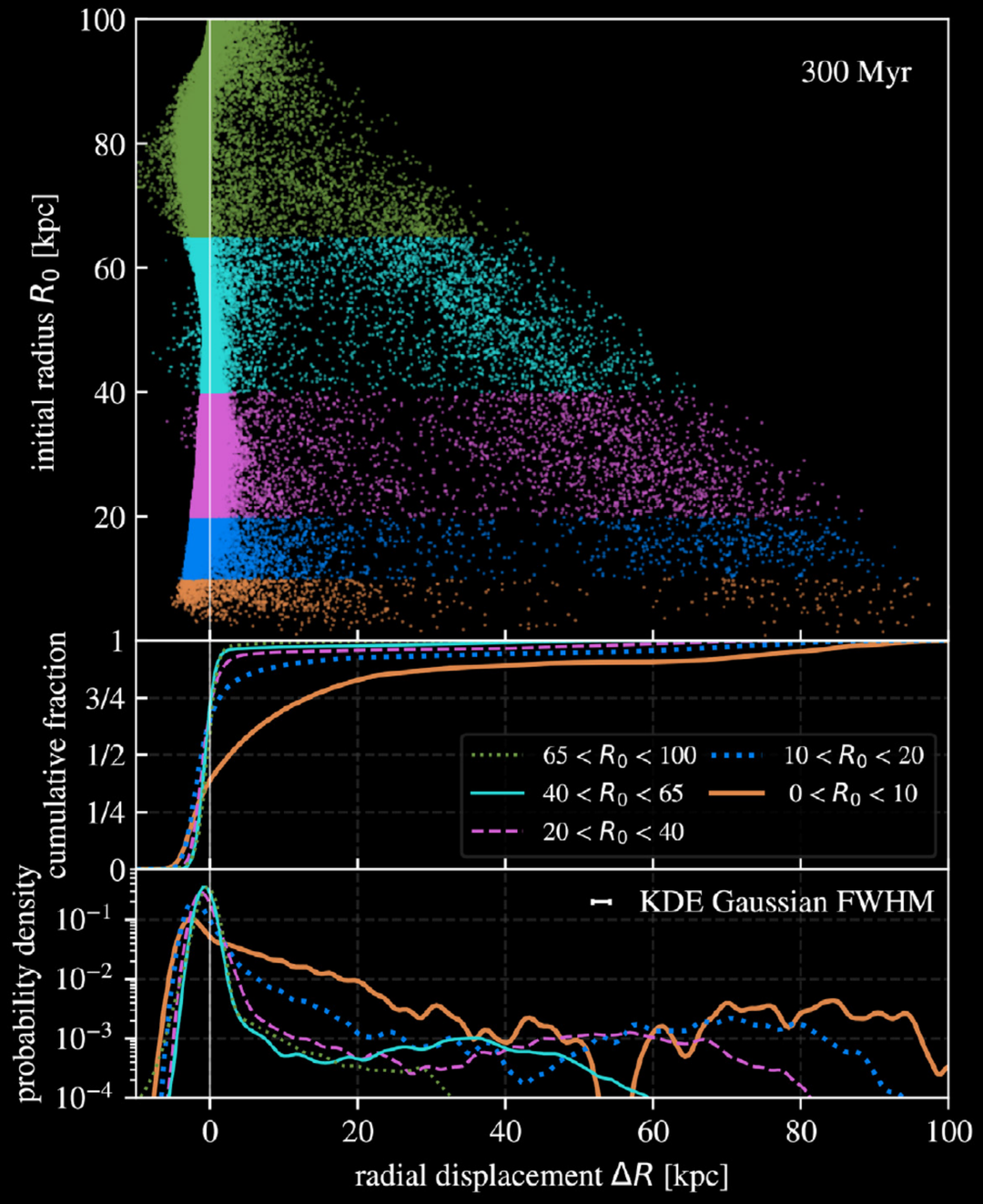
Kirkpatrick+'11

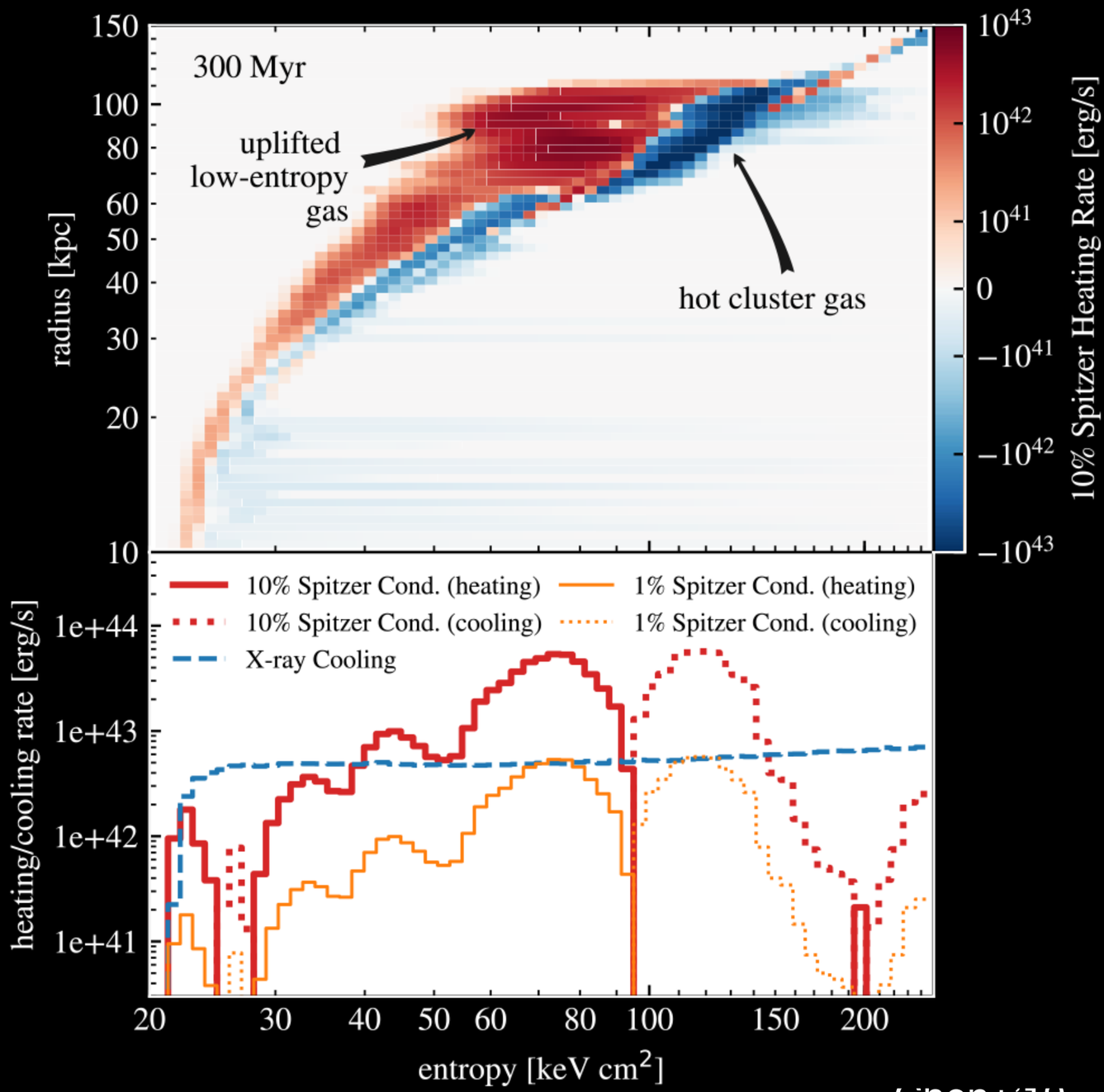


$$\frac{\partial \epsilon}{\partial t} \equiv \nabla \mathbf{Q} \equiv -\nabla \kappa \cdot \nabla T - \kappa \Delta T$$

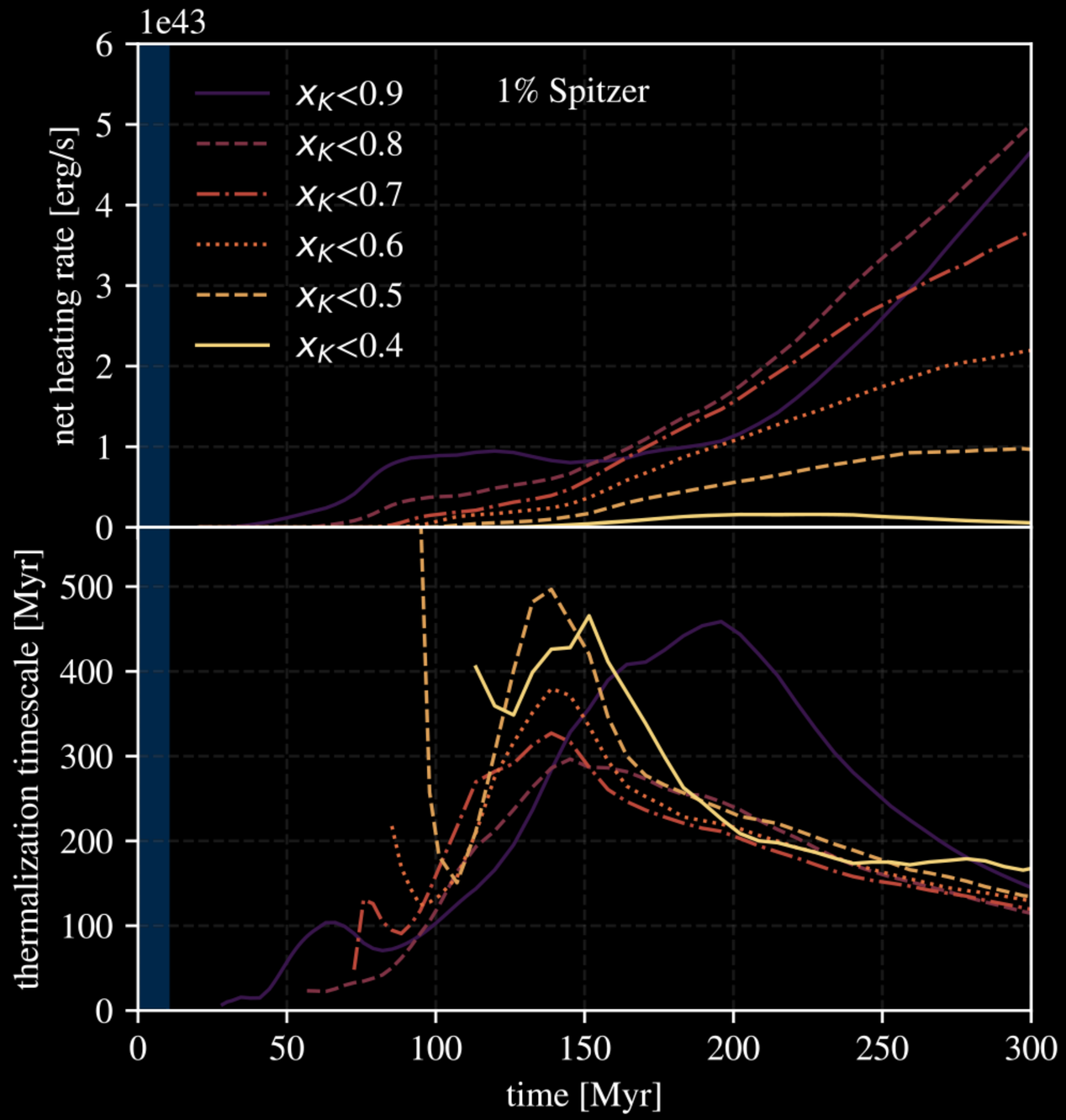


Chen+'19


300 Myr
initial radius R_0 [kpc]
cumulative fraction
probability density
$65 < R_0 < 100$
$40 < R_0 < 65$
$20 < R_0 < 40$
$10 < R_0 < 20$
$0 < R_0 < 10$
KDE Gaussian FWHM
radial displacement ΔR [kpc]

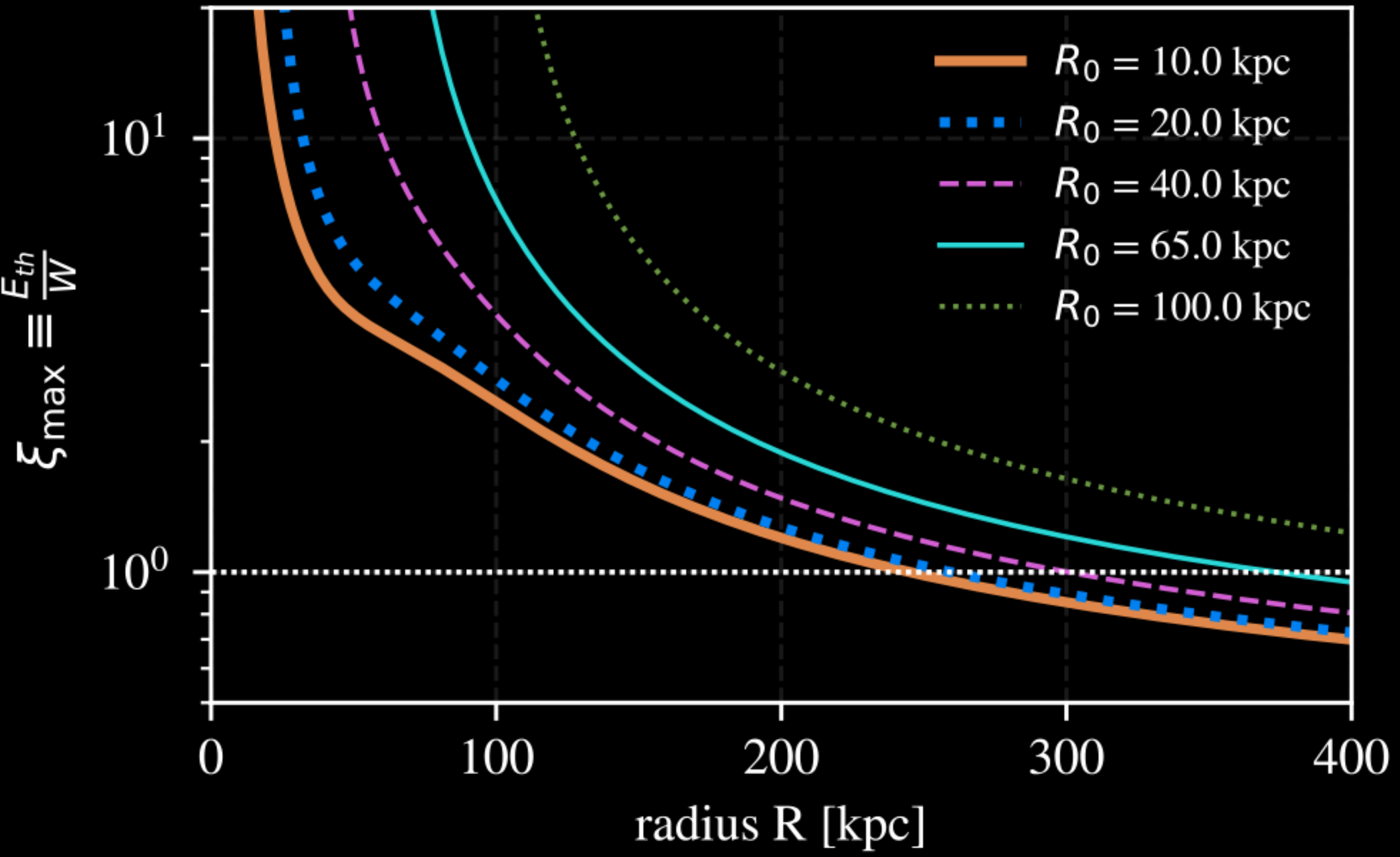

300 Myr
uplifted
low-entropy
gas
hot cluster gas
radius [kpc]
10% Spitzer Heating Rate [erg/s]
10% Spitzer Cond. (heating)
10% Spitzer Cond. (cooling)
X-ray Cooling
1% Spitzer Cond. (heating)
1% Spitzer Cond. (cooling)
heating/cooling rate [erg/s]
entropy [keV cm^2]

Chen+'19

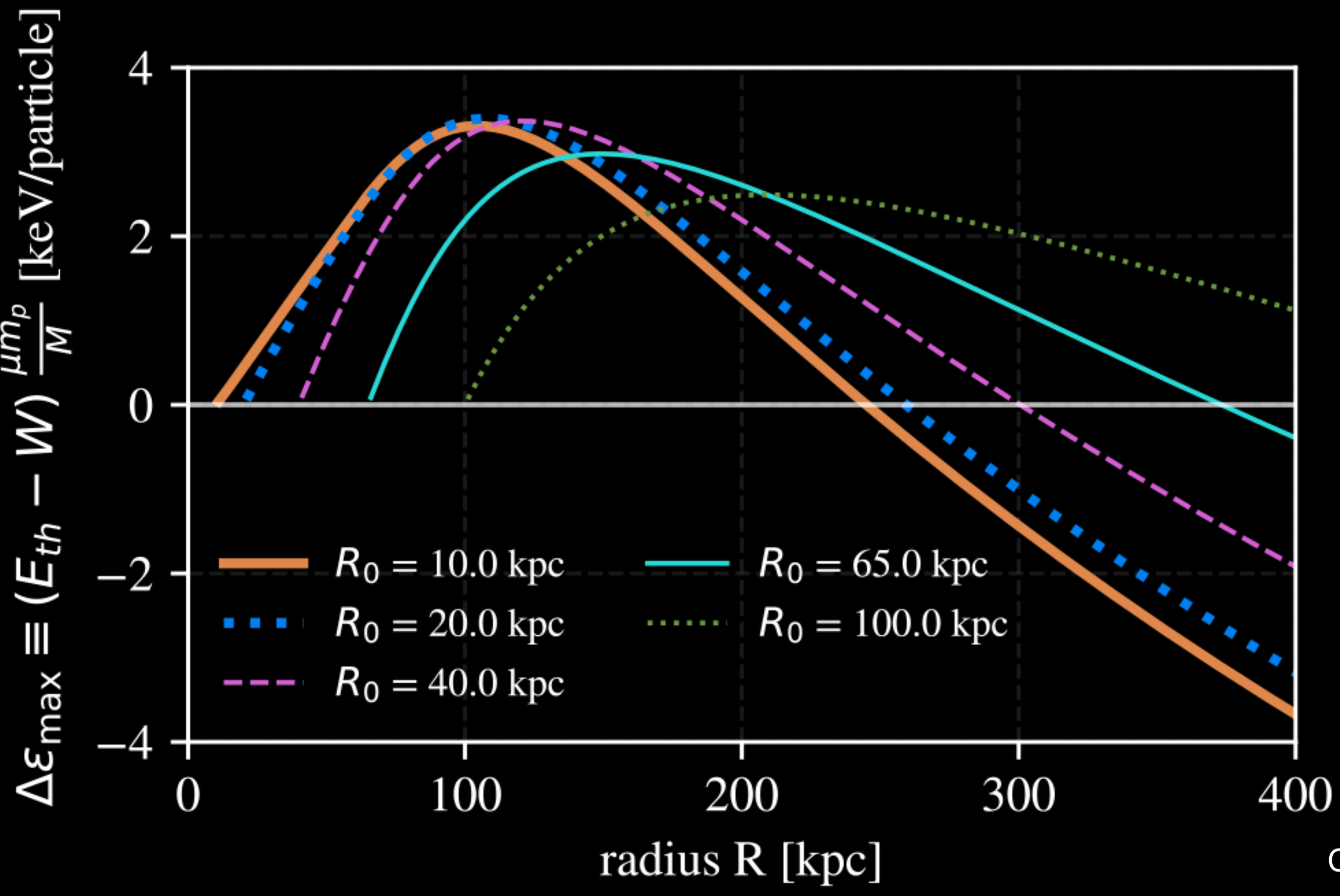


Thermalization Time

Chen+'19

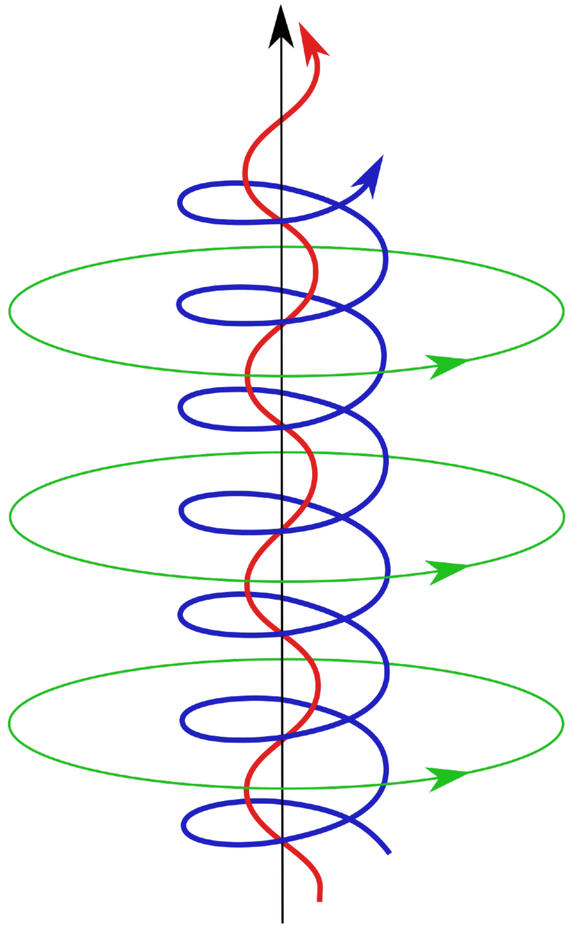

$R_0 = 10.0$ kpc
$R_0 = 20.0$ kpc
$R_0 = 40.0$ kpc
$R_0 = 65.0$ kpc
$R_0 = 100.0$ kpc
$\xi_{max} \equiv \frac{E_{th}}{W}$
10^1
10^0
0
100
200
300
400
radius R [kpc]

Chen+'19


$\Delta\varepsilon_{max} \equiv (E_{th} - W)\frac{\mu m_p}{M}$ [keV/particle]
4
2
0
−2
−4
0
100
200
300
400
radius R [kpc]
$R_0 = 10.0$ kpc
$R_0 = 20.0$ kpc
$R_0 = 40.0$ kpc
$R_0 = 65.0$ kpc
$R_0 = 100.0$ kpc

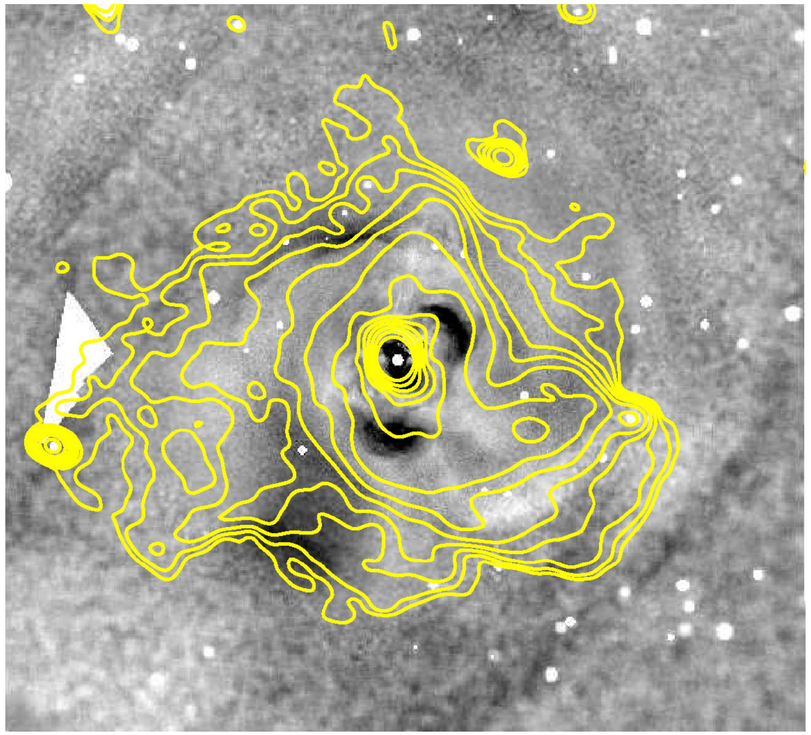
Chen+'19

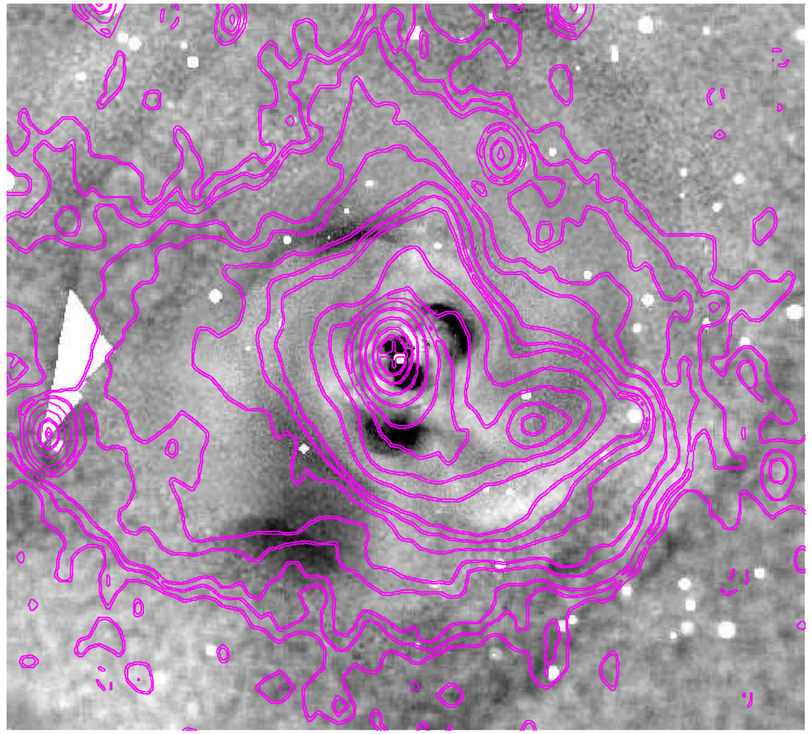
- The heat pump effect can substantially increase the efficiency of black hole feedback
- This is gentle heating
- If macroscopic mixing is efficient, it will complement the effect
- Next up: Simulations with proper anisotropic conduction, whistler-mediated conduction



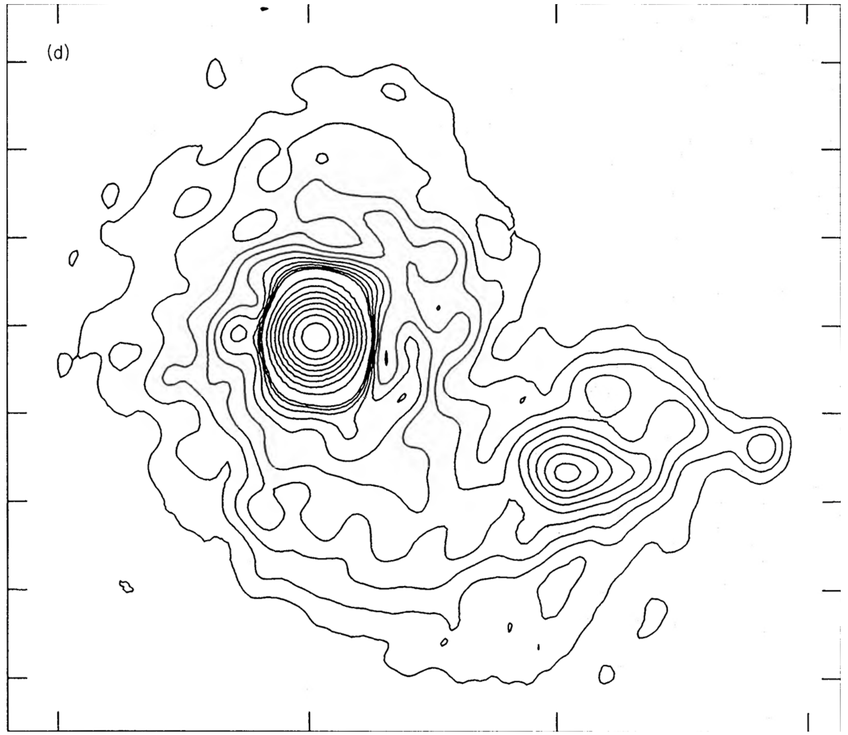
Chen+’19

Radio Mini Halos



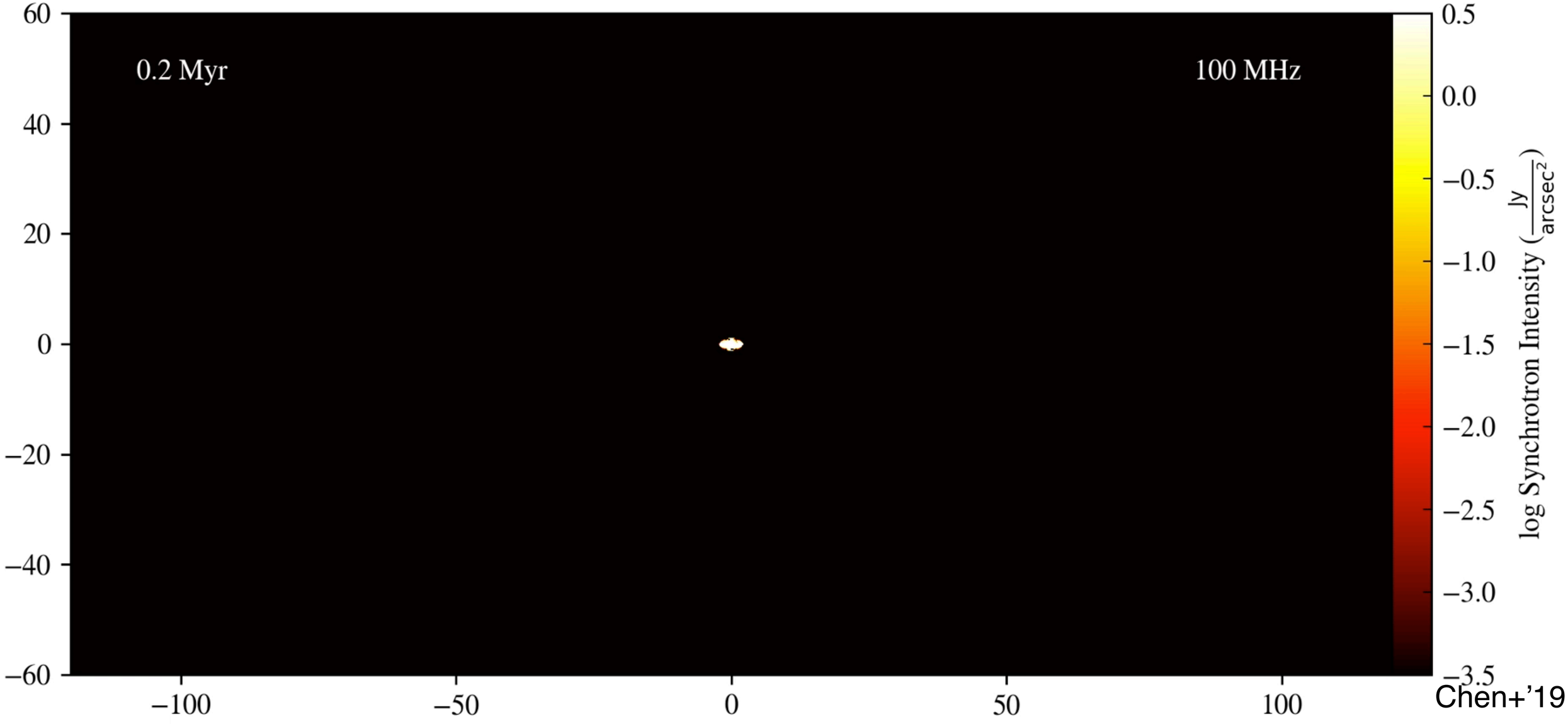


Gendron-Marsolais+’17



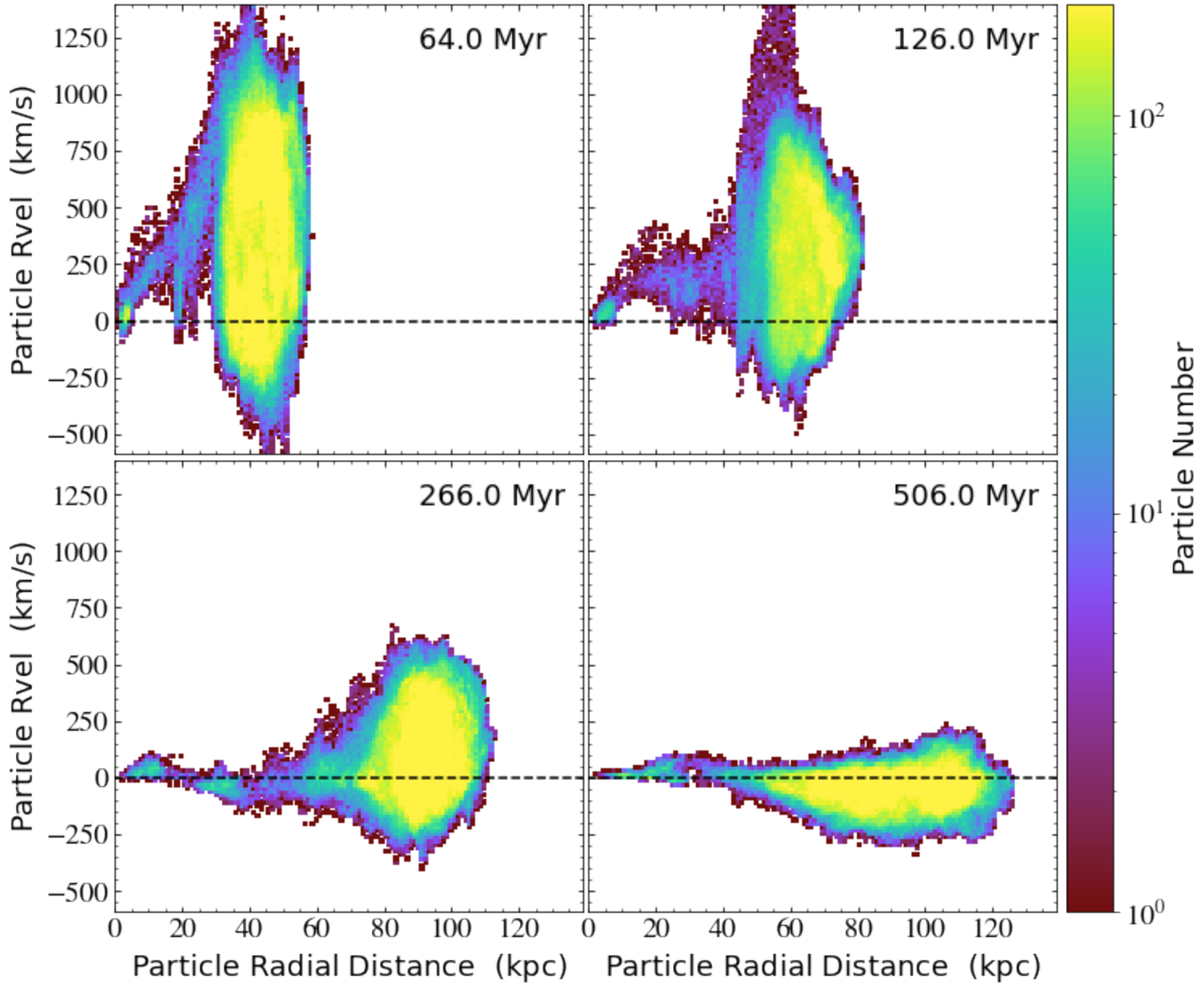
Pedlar+’90

Synchrotron Intensity



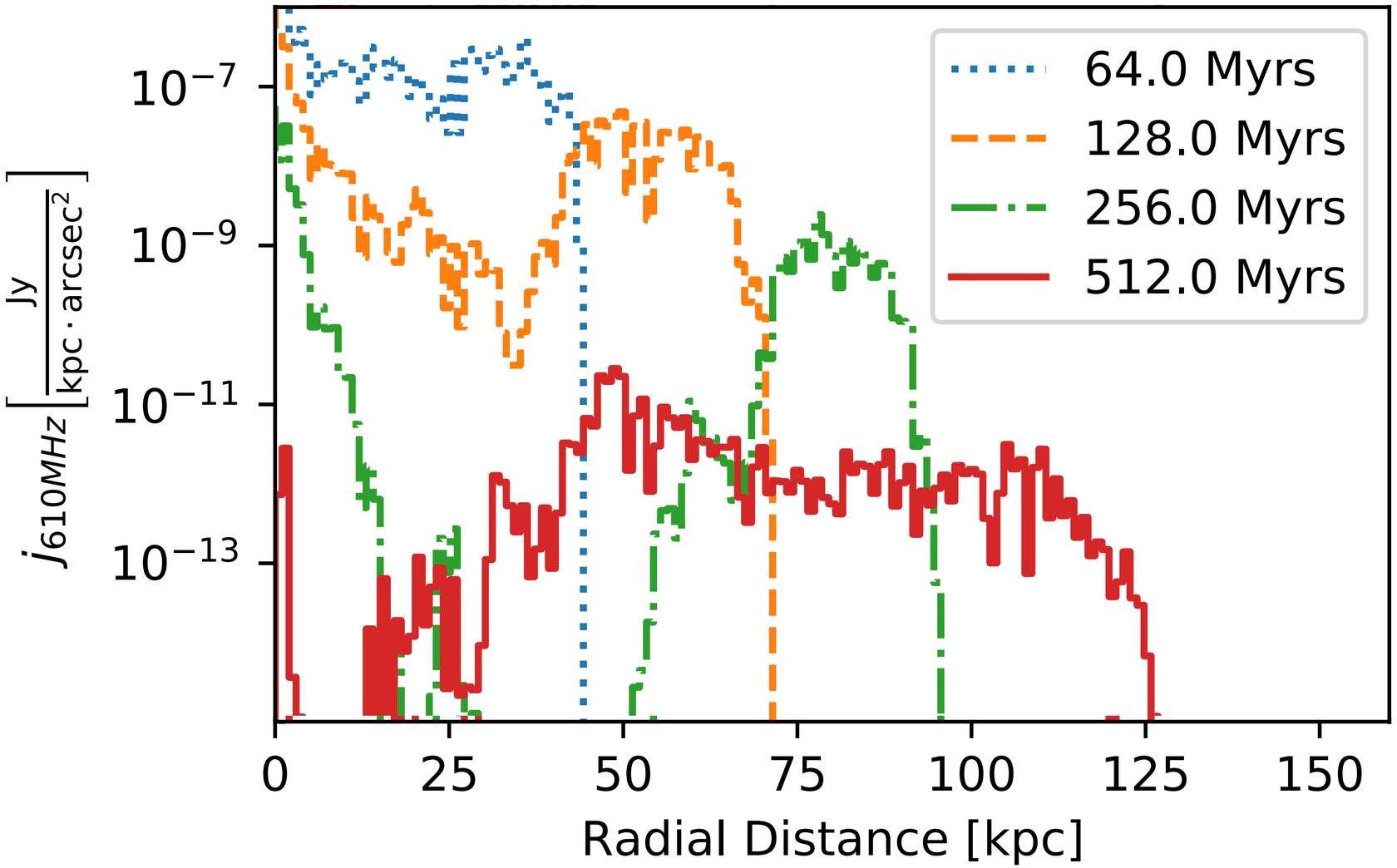
Chen+'19

Cluster Downdrafts



Ilan+22, tbs

Emission Coefficient



Ilan+22, tbs

Summary

- Jets can uplift substantial amounts of cold gas.
- The close thermal contact between low and high entropy ICM can vastly increase conductive heating, acting as a heat pump.
- The conductive heating time can be shorter than the dynamical time even for conduction rates as low as 0.01 Spitzer.
- The heating efficiency can exceed 100% and deposit energy gently.
- The reverse process (downdraft) can drag non-thermal plasma that was stored ar high altitude and low B-field back into the cluster center, where it re-ignites.
- With sufficiently high jet duty cycle, this downdraft effect may contribute to mini halos in clusters like Perseus.