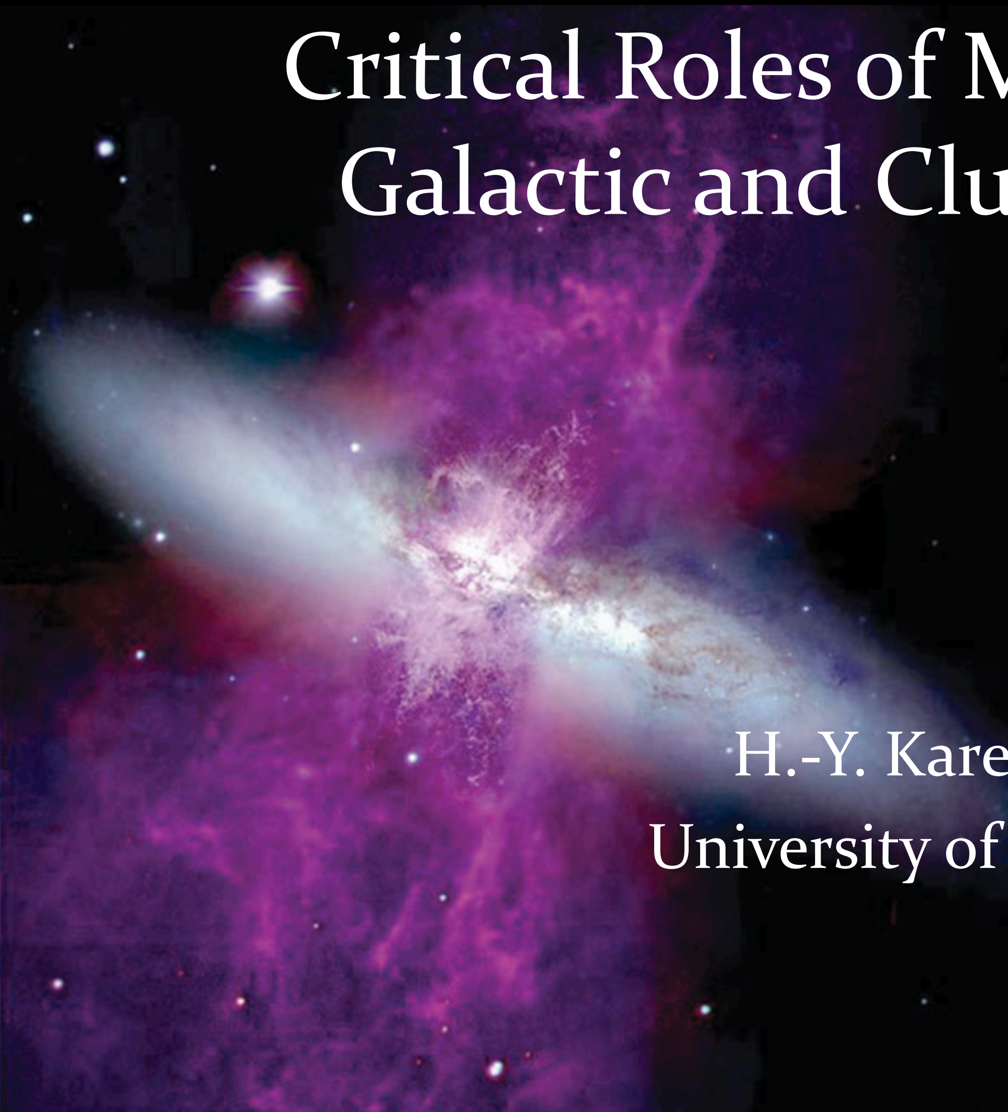
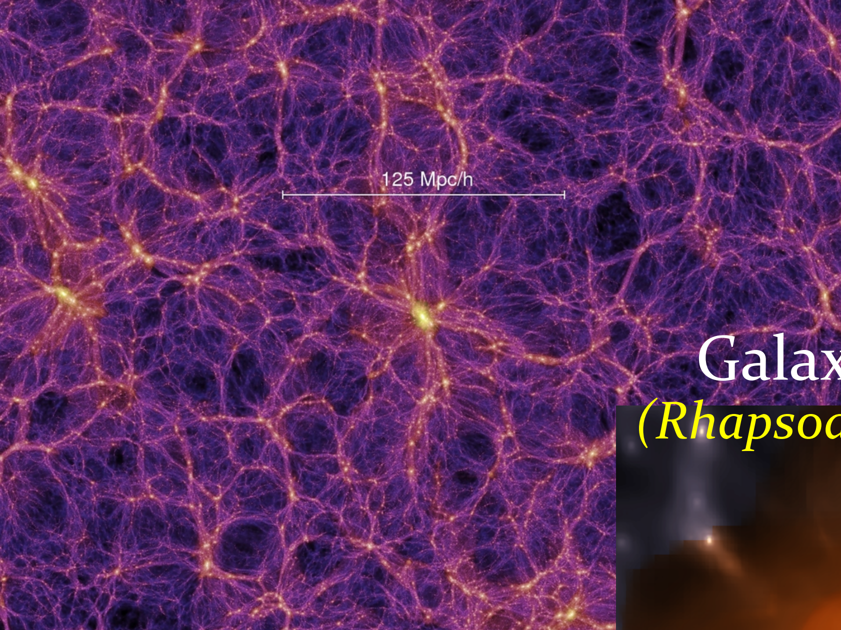
# Critical Roles of Microphysics on Galactic and Cluster Feedback



H.-Y. Karen Yang
University of Maryland

Sep. 11, 2019

KITP Astroplasma Conference




Large Scale Structure

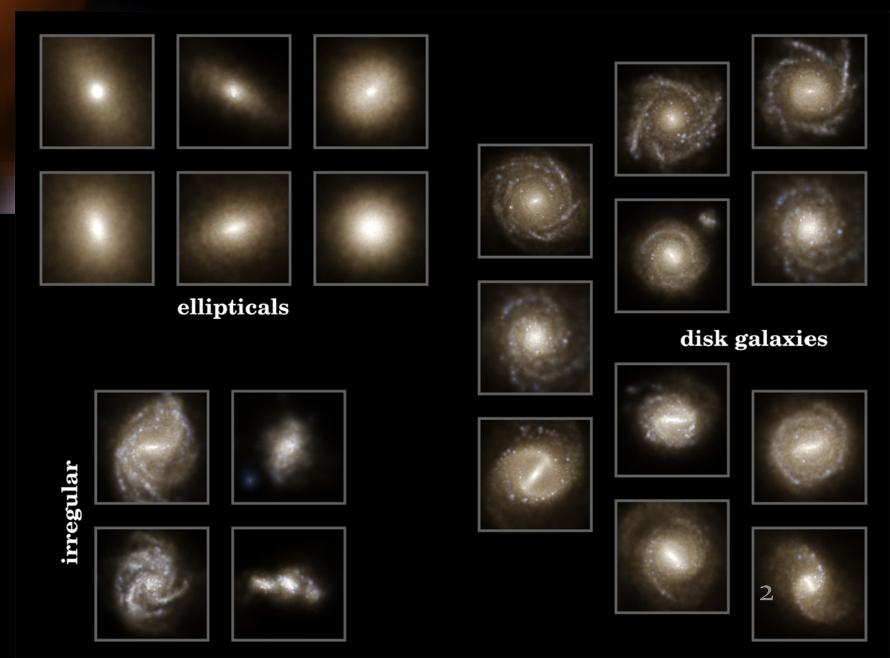
*(Millennium: DM only)*

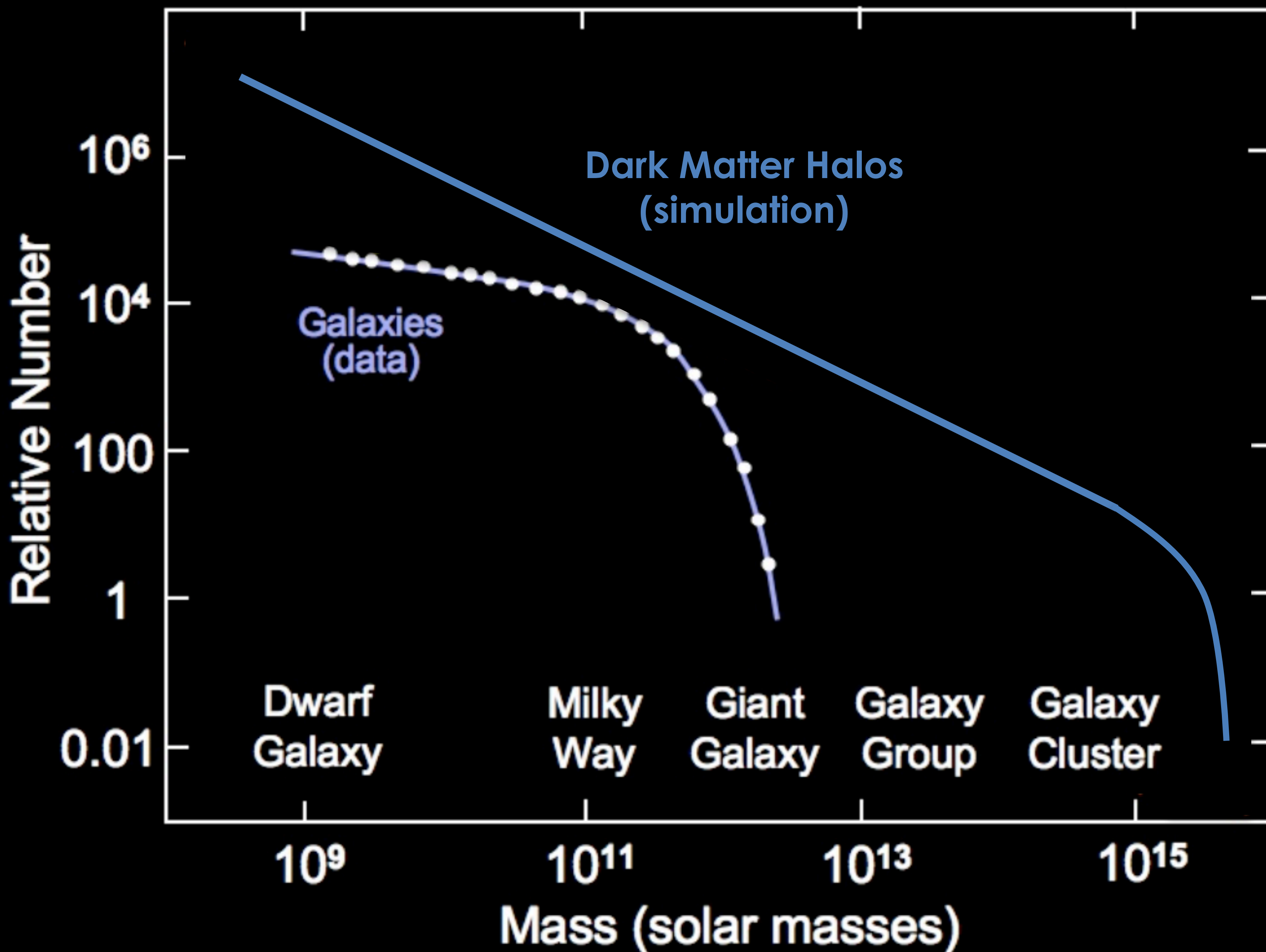
Galaxy Clusters

*(Rhapsody-G: DM+hydro)*

*(Illustris: DM+hydro)*

Galaxies

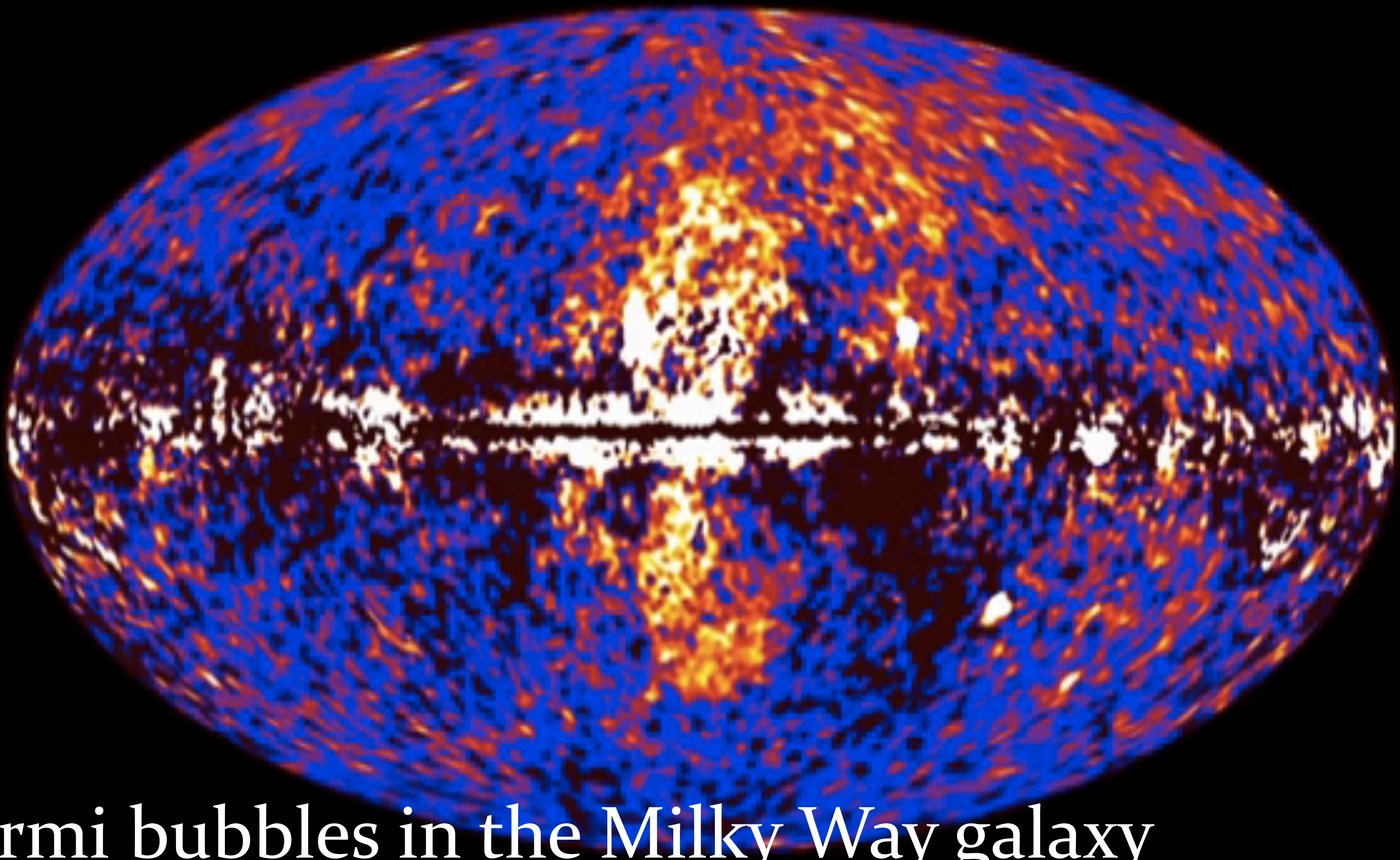




Dark Matter Halos
(simulation)
Galaxies
(data)
Relative Number
10^6
10^4
100
1
0.01
Dwarf Galaxy
Milky Way
Giant Galaxy
Galaxy Group
Galaxy Cluster
10^9
10^11
10^13
10^15
Mass (solar masses)

# Starburst wind feedback in M82

M. Westmoquette, J. Gallagher, L. Smith,
WIYN/NSF, NASA/ESA

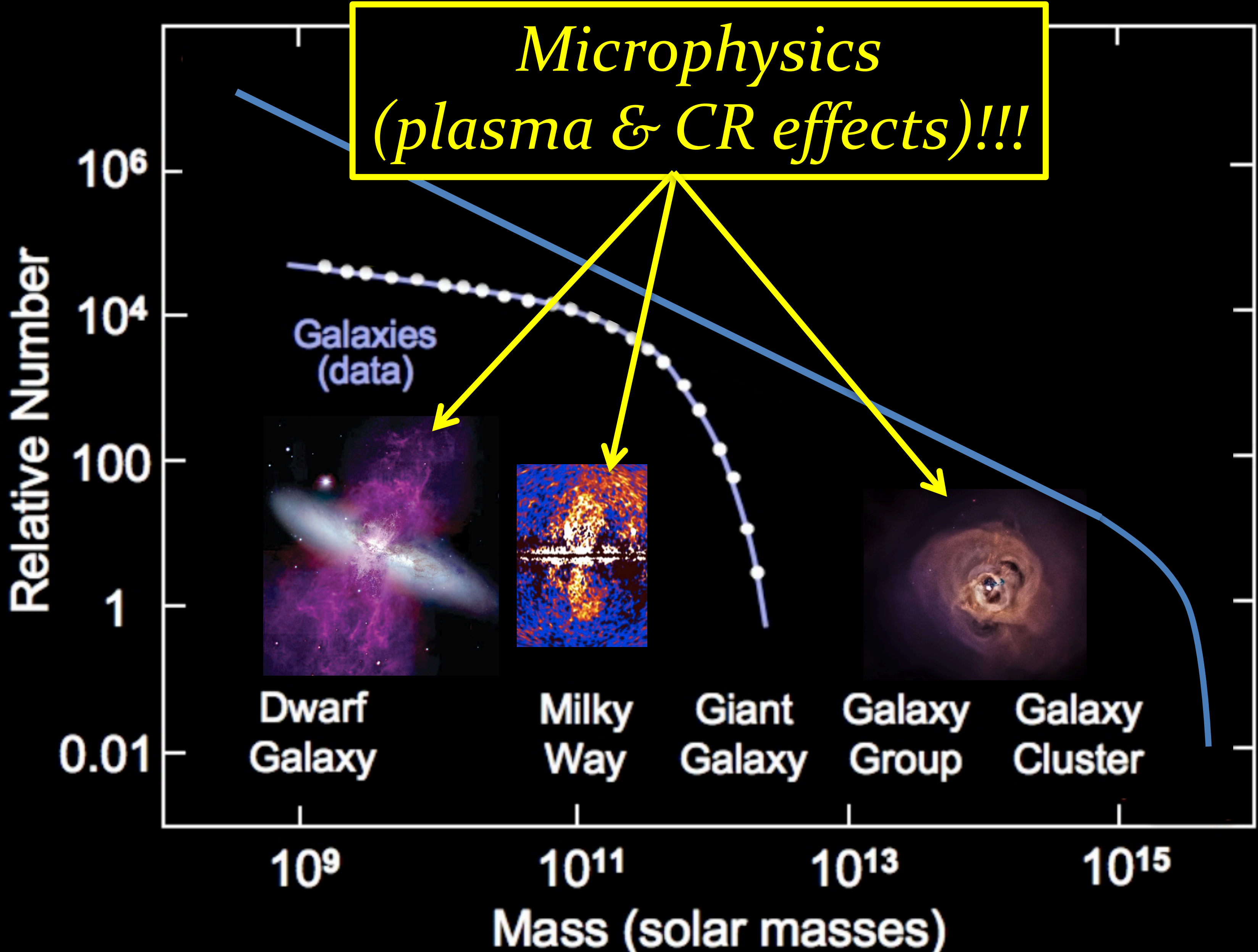


# Fermi bubbles in the Milky Way galaxy

NASA/DOE/Fermi LAT/Su et al. 2010

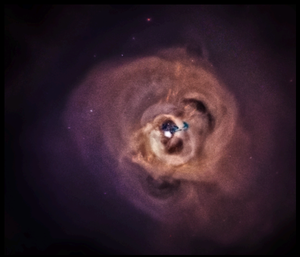
# AGN feedback in Perseus

NASA/CXC/SAO/Esra Bulbul, et al.



Microphysics
(plasma & CR effects)!!!
Relative Number
10^6
10^4
100
1
0.01
Galaxies
(data)
Dwarf
Galaxy
Milky
Way
Giant
Galaxy
Galaxy
Group
Galaxy
Cluster
10^9
10^11
10^13
10^15
Mass (solar masses)

# This talk…

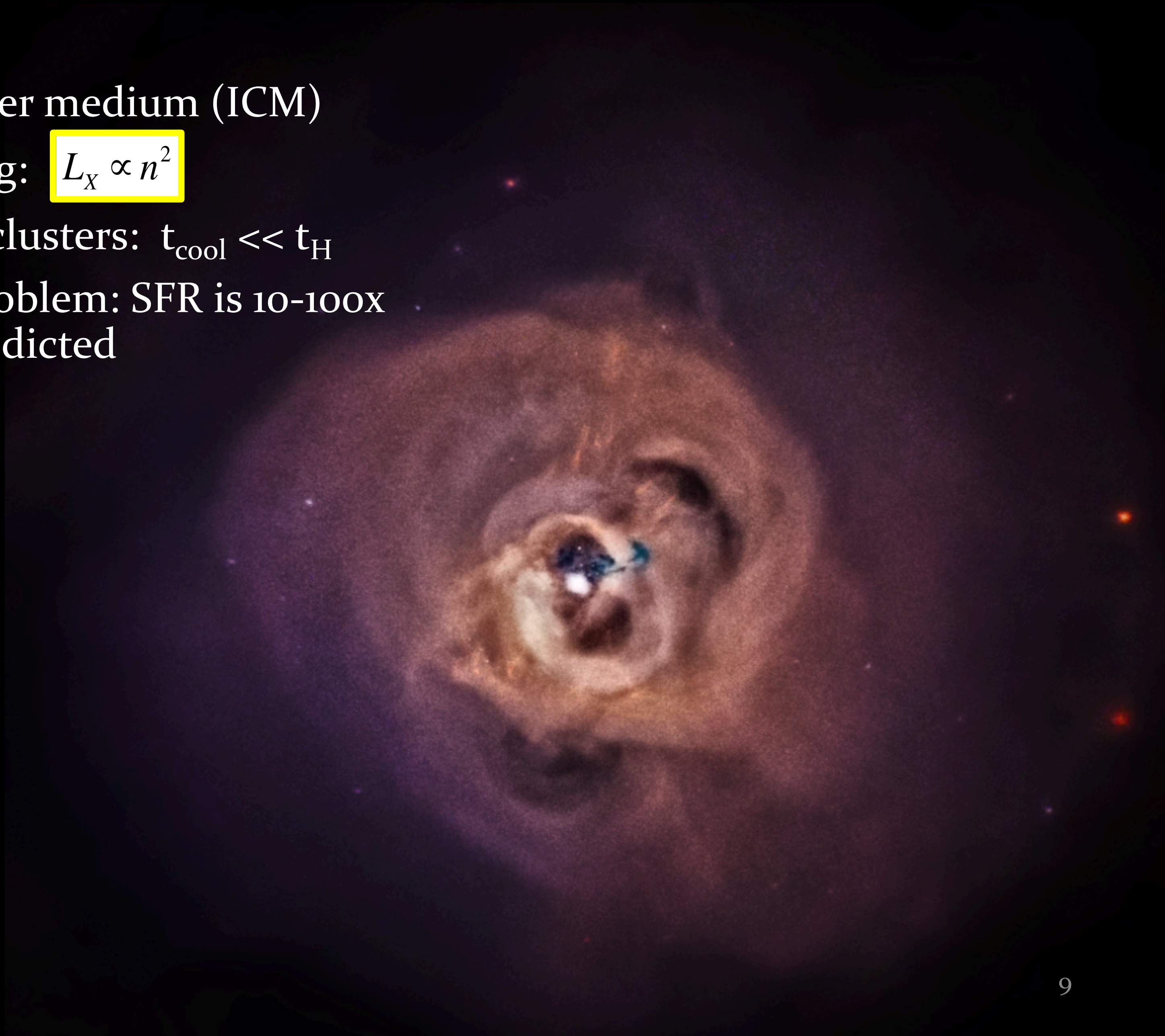


- ❖ Intro – the "cooling-flow problem" & hydrodynamic AGN feedback
- ❖ What about the microphysics?

- ❖ Effects of CR transport on galactic winds
- ❖ Concluding remarks & open questions

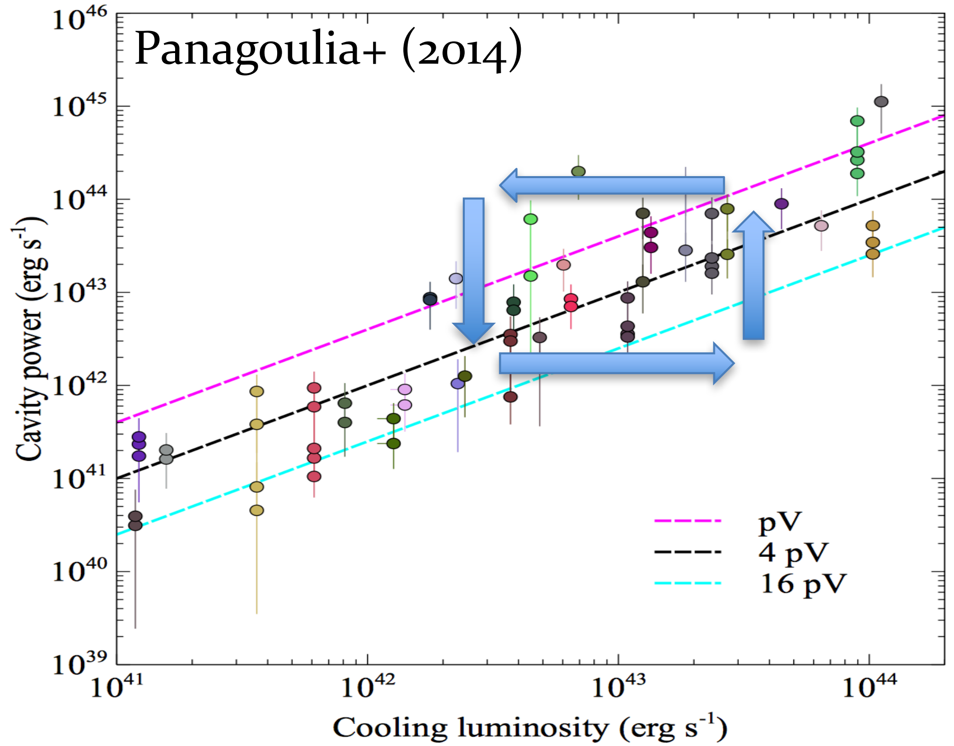
# Perseus cluster

- X-ray: intracluster medium (ICM)
- Radiative cooling: $L_X \propto n^2$
- Cool-core (CC) clusters: $t_{cool} << t_H$
- Cooling-flow problem: SFR is 10-100x smaller than predicted

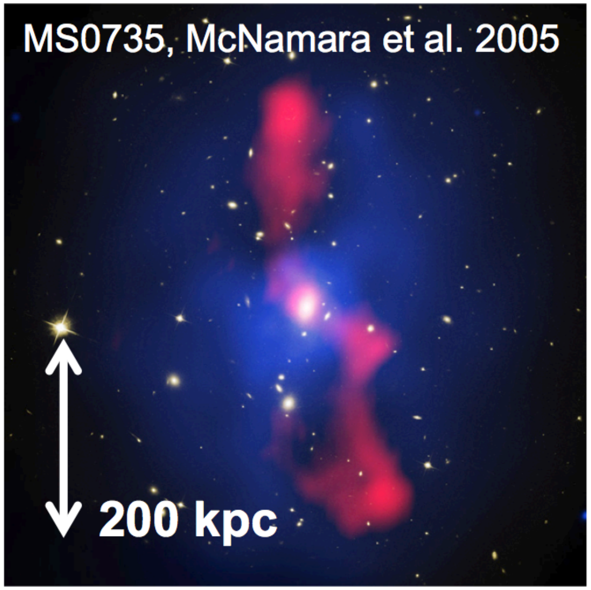


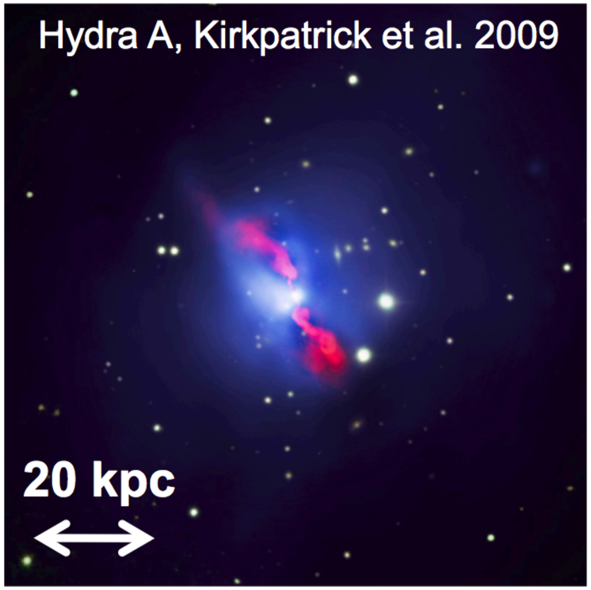
# AGN Feedback

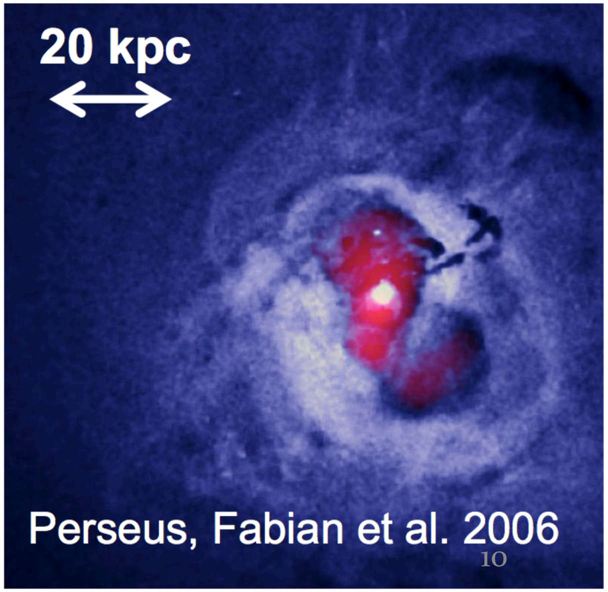
- Radio bubbles
- $P_{cav} \sim L_{cool}$



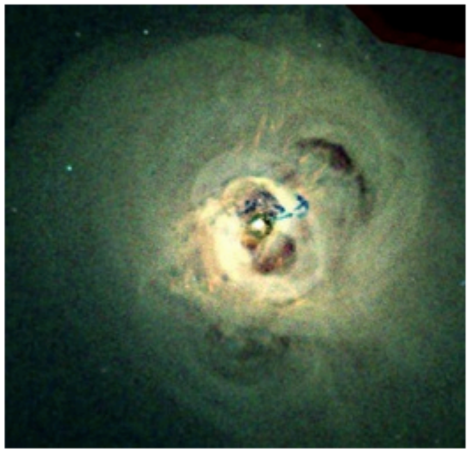

Courtesy of J.Hlavacek-Larrondo



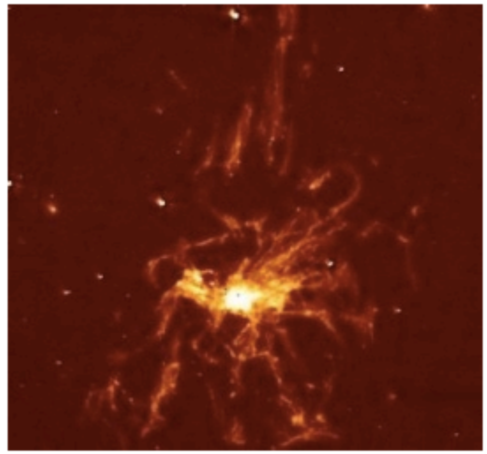



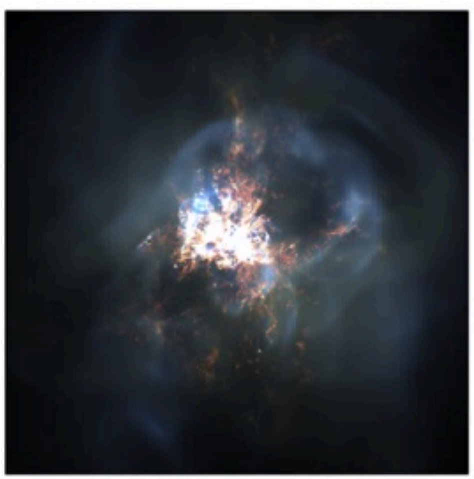
# Success of hydrodynamic AGN simulations



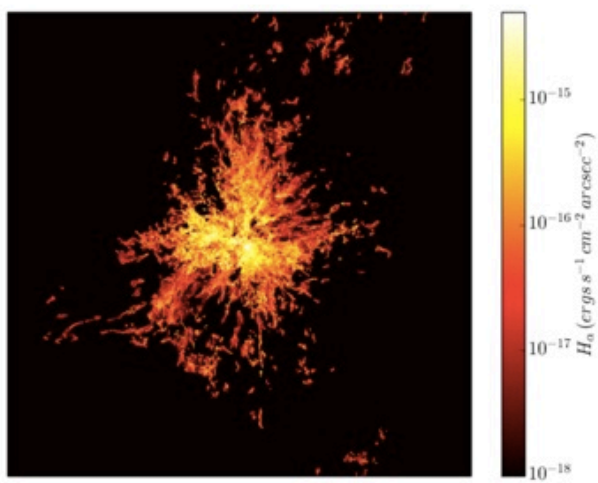
X-ray observations of Perseus



Hα observations of Perseus



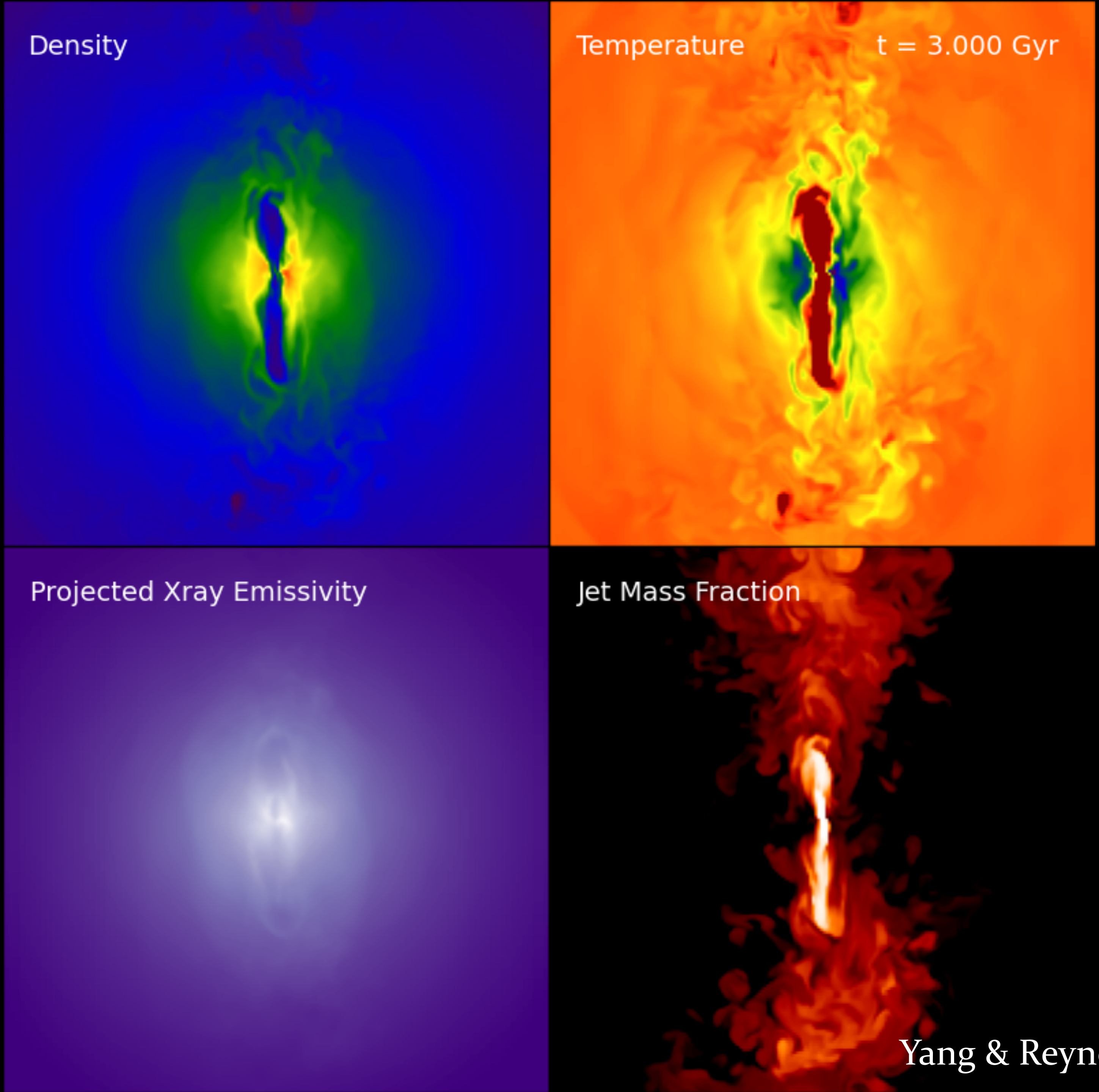
Synthetic X-ray composite image of the central 50 kpc region




Synthetic Hα map

- Cold gas accretion
- Kinetic-energy-dominated Jets
- Self-regulated

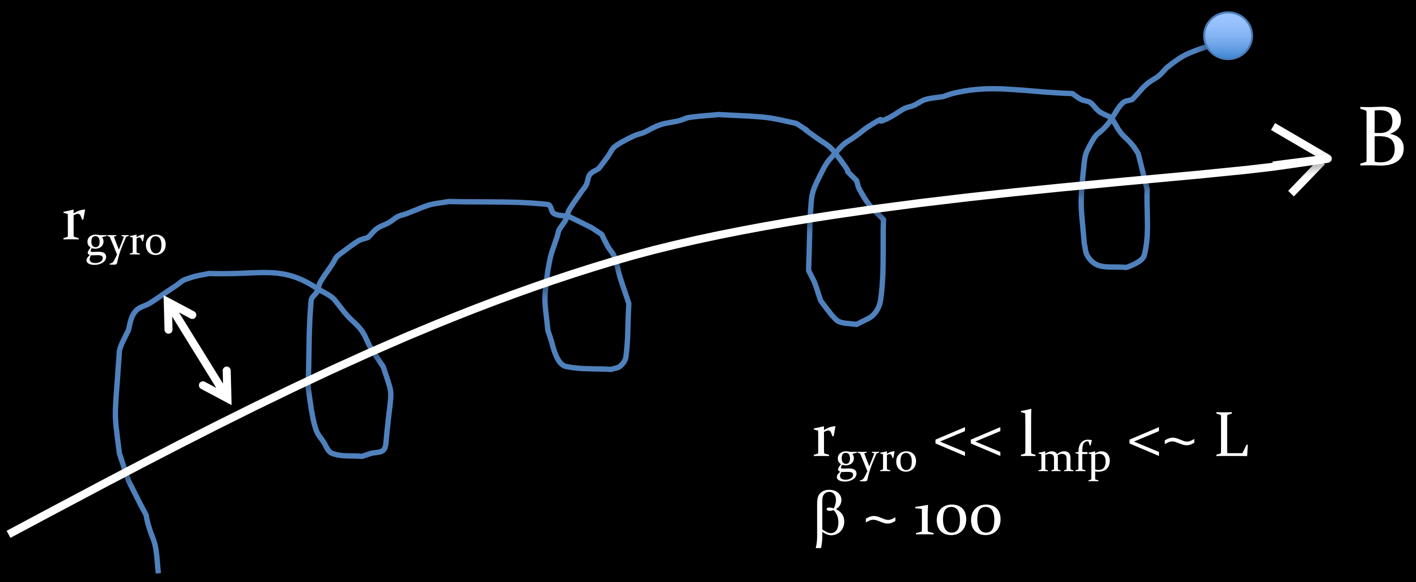
Gaspari et al. (2011, 2012)
Li et al. (2014, 2015)
Prasad et al. (2015)
Yang & Reynolds (2016ab)
Meece et al. (2017)
Martizzi et al. (2018)




Yang & Reynolds (2016b)

# Microphysics to worry about

1. Thermal conduction -- ***anisotropic***
2. Viscosity -- ***anisotropic***
3. Cosmic rays – ***anisotropic***

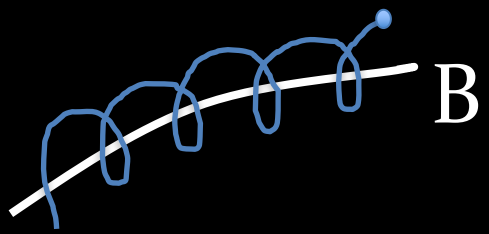


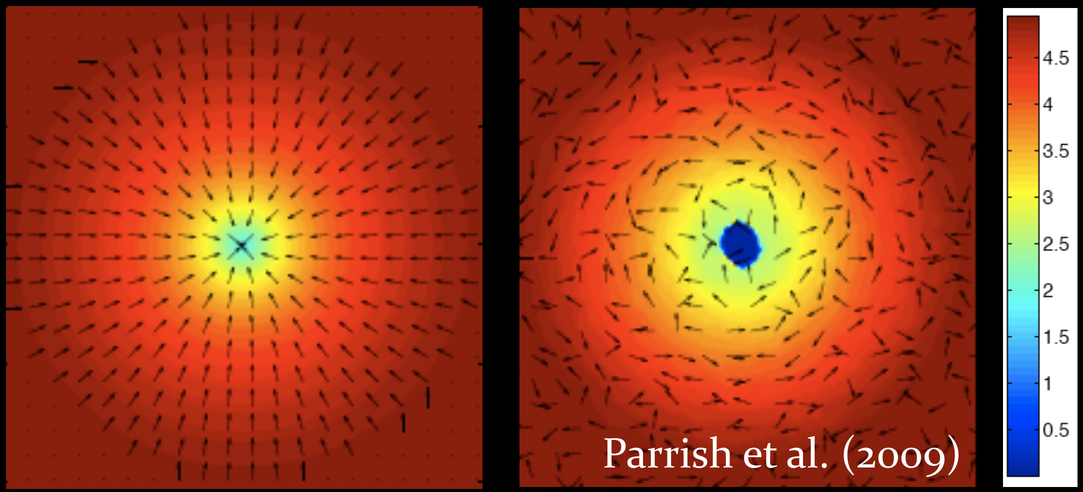

$r_{gyro} << l_{mfp} <\sim L$

$\beta \sim 100$

# Q1. Roles of thermal conduction?

- ❖ Conductive heating from cluster outskirts
- ❖ Anisotropic conduction -> HBI (Quataert 2007)
- ❖ Final B azimuthal, shut off conduction



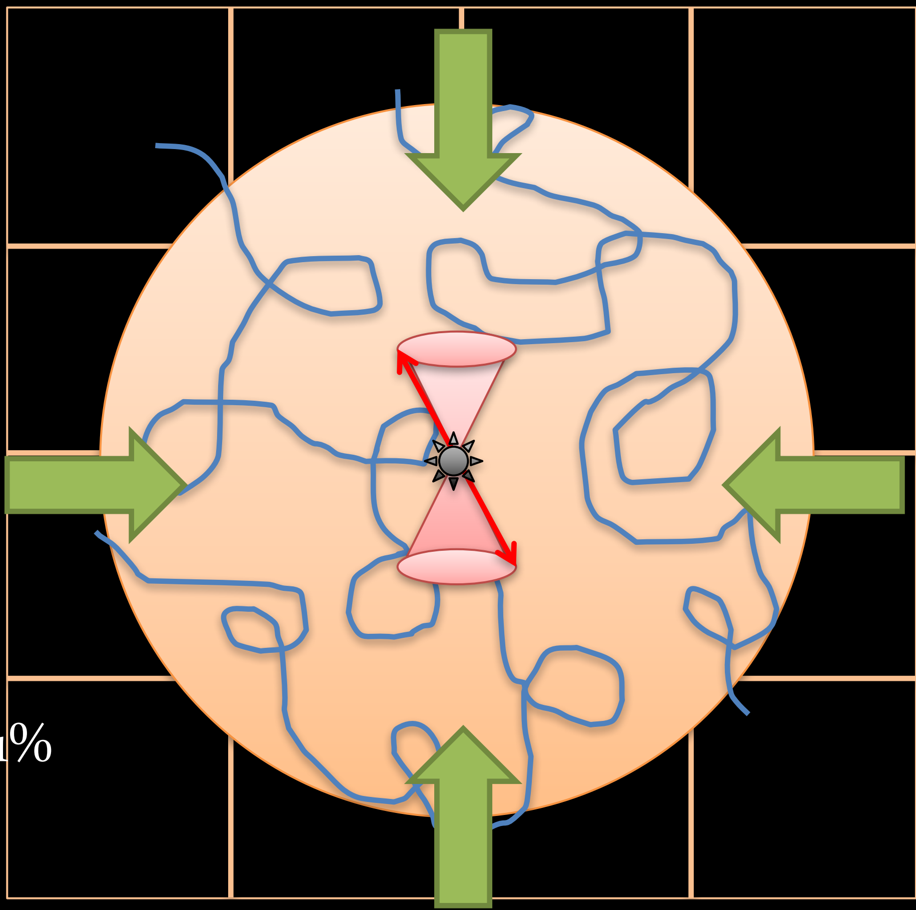

Parrish et al. (2009)

or

??

# Simulation setup

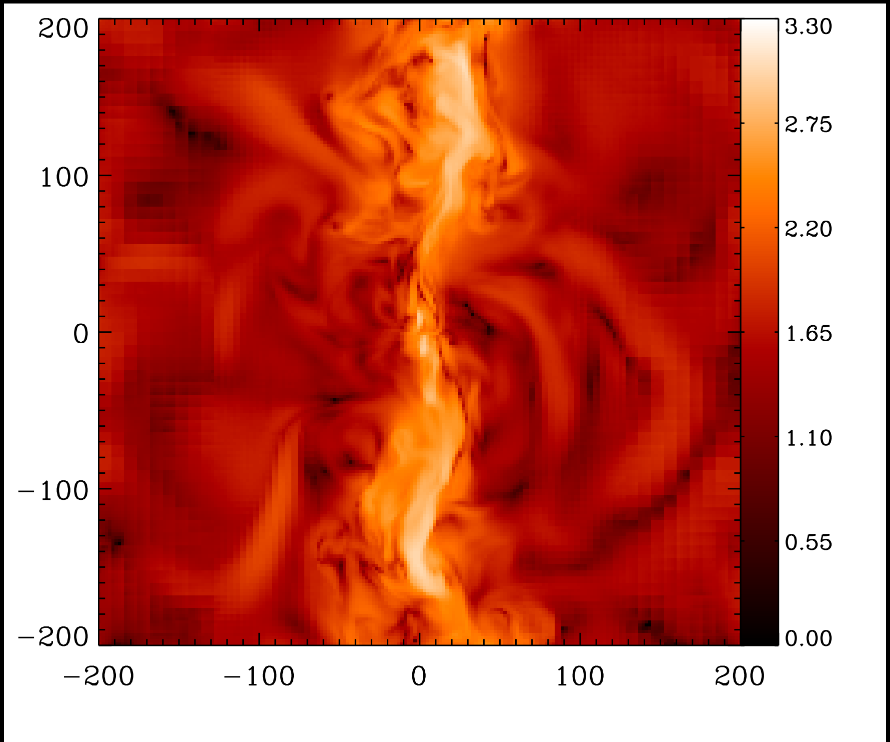
(Yang & Reynolds, 2016a)



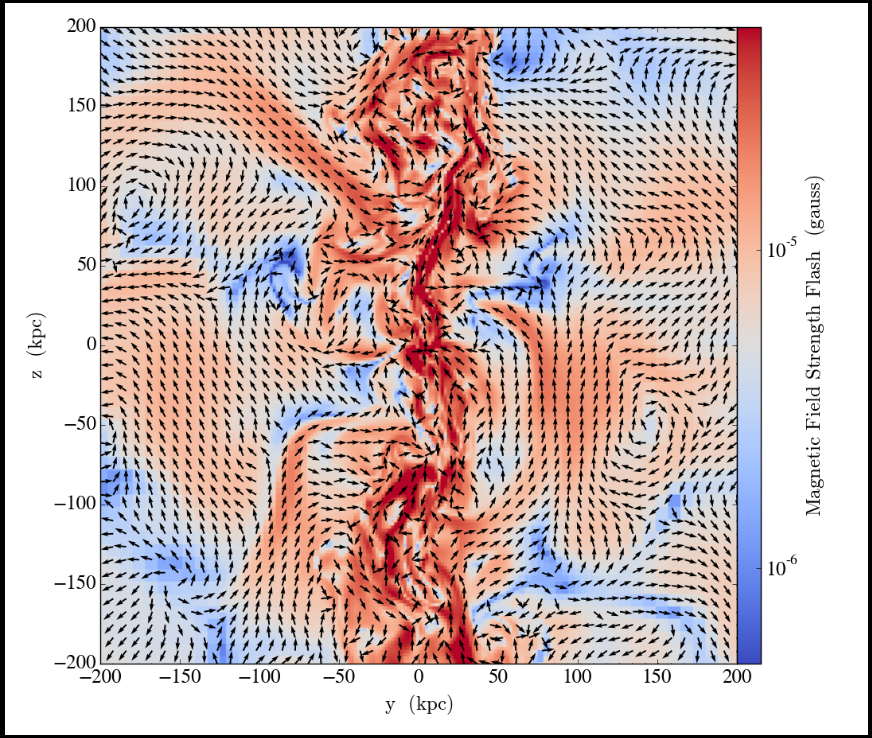
- *FLASH* code with AMR
- Perseus, $r_c$~100kpc
- Tangled B field with β ~ 100
- Radiative cooling
- Full Spitzer conductivity along B
- AGN feedback (Yang et al. 2012):
  -- accretion of cold gas (T<5e5K)
  -- kinetic jet feedback, efficiency = 0.1%
  -- jet precession

# AGN counteracts HBI (Yang & Reynolds 2016a)

*Turbulent velocity*



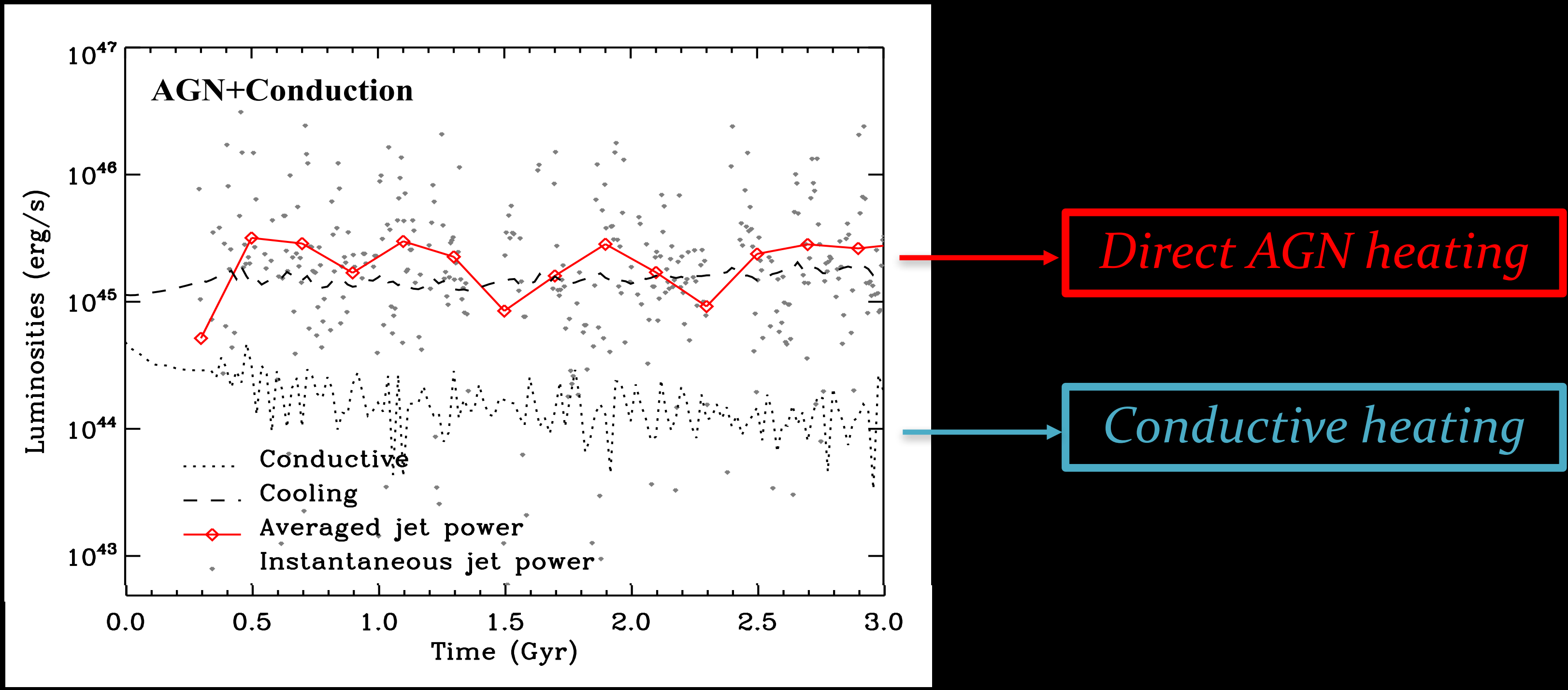

*B field*




- *AGN-driven turbulence randomizes field lines*
- *Effective Spitzer fraction $f_{sp} \sim 1/3$*

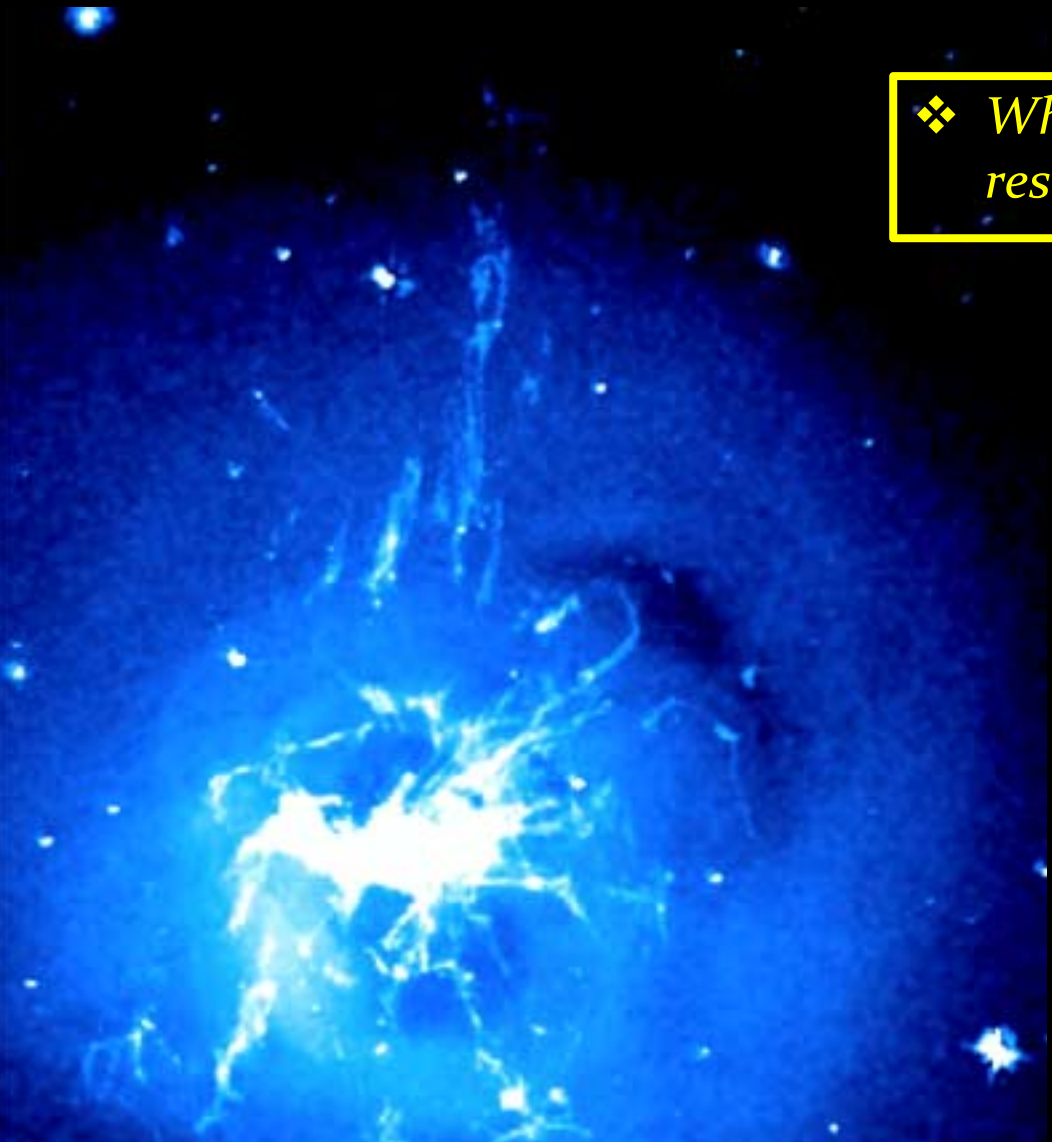
# Conductive heating < AGN heating

## (Yang & Reynolds 2016a, Kannon+2017)

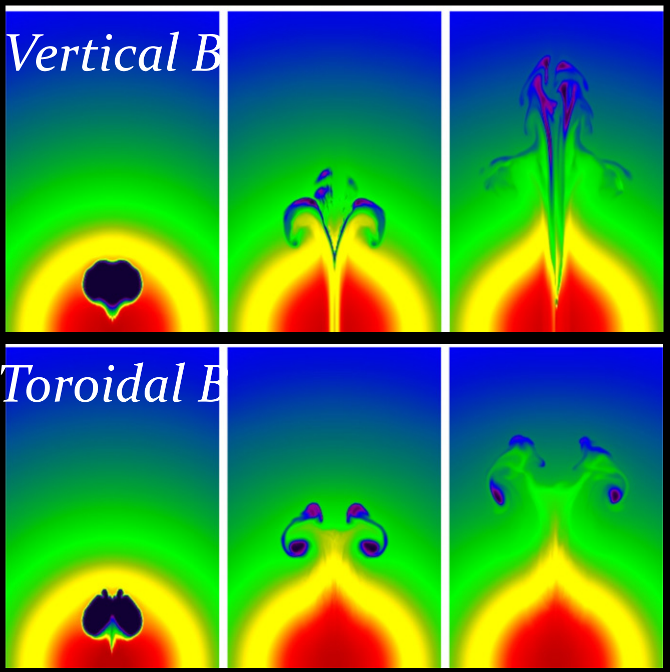



- *Conductive heating ~ 10-50% of cooling losses (upper limits)*
- *PIC simulations show large suppression (Roberg-Clark et al. 2016, 2018, Komarov et al. 2016, 2018) but indept. of grad(T)!?*

# Q2. Roles of viscosity?
## (Reynolds+05, Dong & Stone 09, Guo 15)



- *When including anisotropic viscosity, results depend on B geometry*



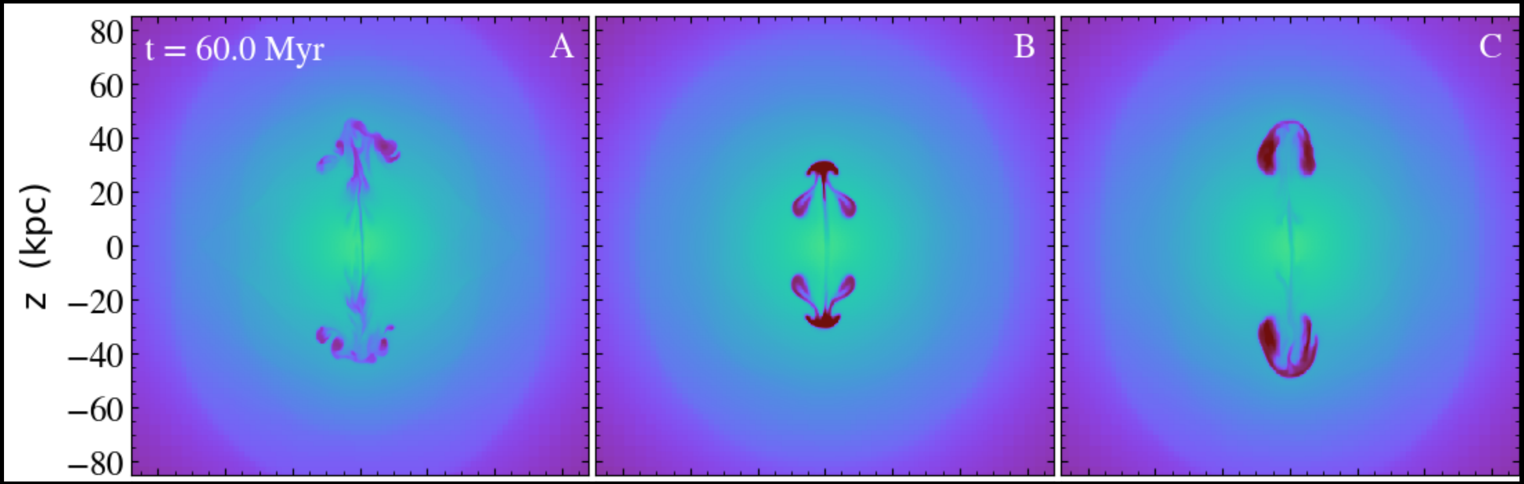

Dong & Stone (2009)

# Simulations with ***jets*** and ***tangled B***

(Kingsland et al., 2019, ApJL accepted, arXiv: 1909.01339)

Matthew Kingsland (UMD)

*Inviscid MHD* | *Isotropic viscosity* | *Full Braginskii viscosity*




- *Magnetic tension alone not enough for jet-inflated bubbles*
- *Full Braginskii viscosity in tangled field is similar to isotropic viscosity*

# Braginskii-MHD equations

(Braginskii 1965, Schekochihin et al. 2005, Kunz et al. 2014; also see J. Squire's and M. Kunz's talks)

Viscosity stress tensor: $\mathbf{\Pi}_{\rm aniso} = -3\mu\left(\boldsymbol{bb} - \frac{1}{3}\boldsymbol{I}\right)\left(\boldsymbol{bb} - \frac{1}{3}\boldsymbol{I}\right) : \nabla\boldsymbol{v},$

Pressure anisotropy: $p_\perp - p_\parallel = 0.96\frac{p_{\rm i}}{\nu_{\rm ii}}\frac{d}{dt}\ln\frac{B^3}{\rho^2} = 3\mu\left(\boldsymbol{bb} - \frac{1}{3}\mathsf{I}\right) : \nabla\boldsymbol{v}$

Stability condition: $-\frac{2}{\beta} \lesssim \Delta_p \equiv \frac{p_\perp - p_\parallel}{p} \lesssim \frac{1}{\beta}$

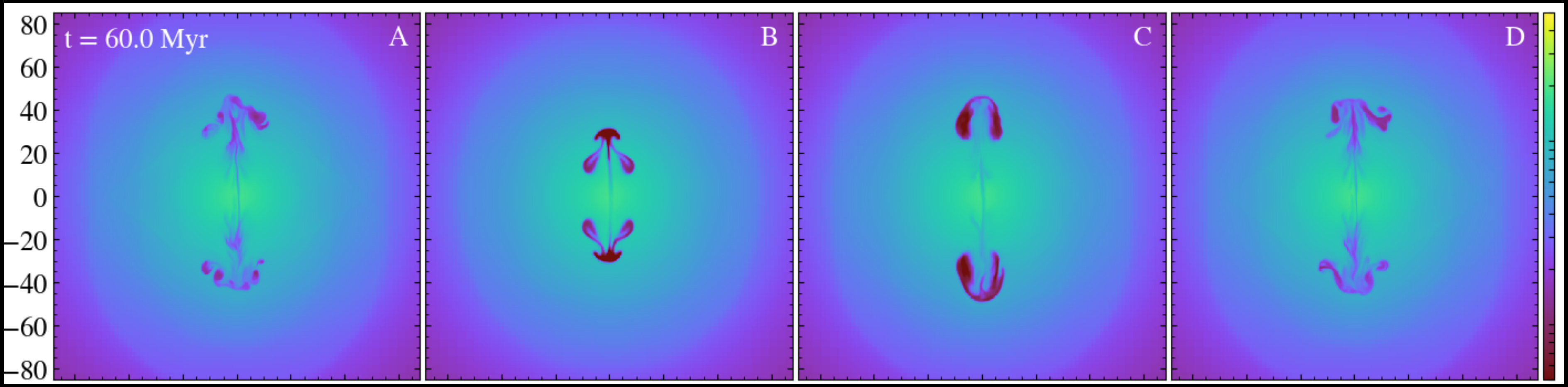
Firehose unstable if $\Delta_p < -2/\beta$

Mirror unstable if $\Delta_p > 1/\beta$

# Simulations with ***jets*** and ***tangled B***

(Kingsland et al., 2019, ApJL accepted, arXiv: 1909.01339)

*Inviscid MHD* | *Isotropic viscosity* | *Full Braginskii viscosity* | *Microinstability-limited Braginskii viscosity*




- *Microinstabilities dramatically limited pressure anisotropies and viscosity*
- *Bubbles deformed just as in the inviscid case!!*

# Simulations with ***jets*** and ***tangled B***

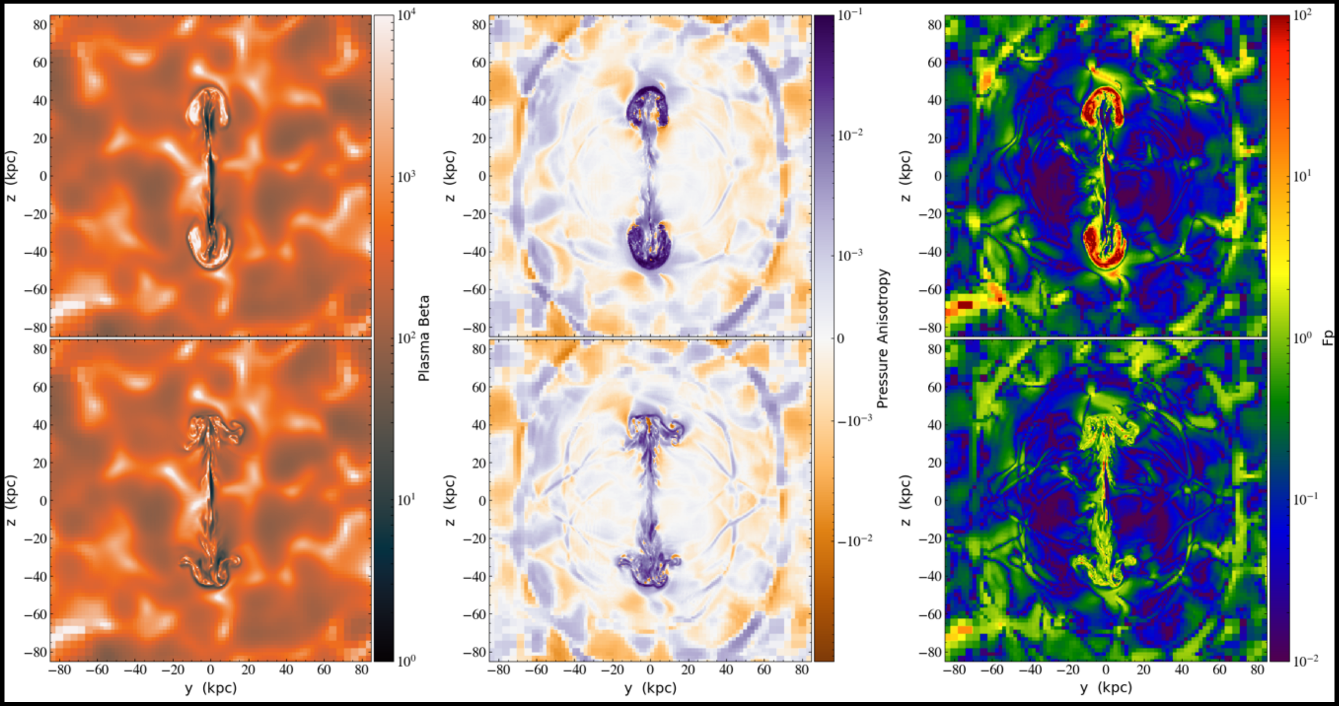
(Kingsland et al., 2019, ApJL accepted, arXiv: 1909.01339)

*Plasma β* | $\Delta_p$ | $f_p = \Delta_p/(1/\beta)$

*Full Braginskii*

*Microinstability -limited Braginskii*

$$-\frac{2}{\beta} \lesssim \Delta_p \equiv \frac{p_\perp - p_\parallel}{p} \lesssim \frac{1}{\beta}$$



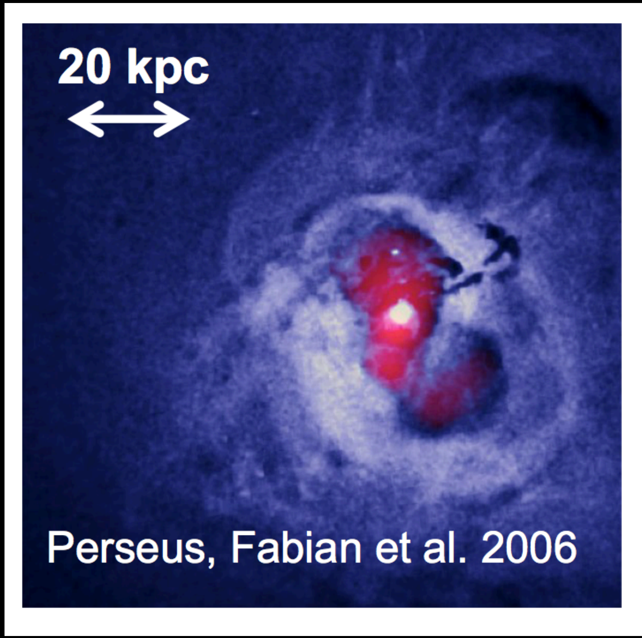

- If unsuppressed, plasma β ~ $10^4$, $f_p$ ~ 100 within bubbles
- Microinstability provides a factor of ~100 suppression of viscosity

# Q3: Effects of CRs?

$$P_{tot} = P_B + P_{CRe} + P_{CRp} + P_{th}$$

$$P_{tot} >> P_B + P_{CRe}$$ (Dunn et al., 2004, 2005)

=> $P_{th}$ or $P_{CRp}$ *dominates*



# CR hydrodynamics

(see reviews by Zweibel 2013, 2017;
also E. Zweibel's and C. Pfrommer's talks)

CRs stream down pressure gradient with $v_A$:

$$\boldsymbol{v}_s = -\mathrm{sgn}(\hat{\boldsymbol{b}} \cdot \nabla e_{\mathrm{CR}})\boldsymbol{v}_{\mathrm{A}}$$

$$\frac{\partial(\varrho \boldsymbol{u})}{\partial t} = [\ldots] - \nabla P_{\mathrm{CR}}$$

**Momemtum transfer via pressure gradient**

$$\frac{\partial e_{CR}}{\partial t} = [\ldots] - \nabla \cdot \boldsymbol{F} + \nabla \cdot (\boldsymbol{\kappa} \cdot \nabla e_{\mathrm{CR}}) - H_{\mathrm{CR}}$$

**Streaming and diffusion** **CR Heating**

$$\boldsymbol{F} = (e_{\mathrm{CR}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{A}}, \;\; \kappa_{\|} \sim v^2/\nu$$

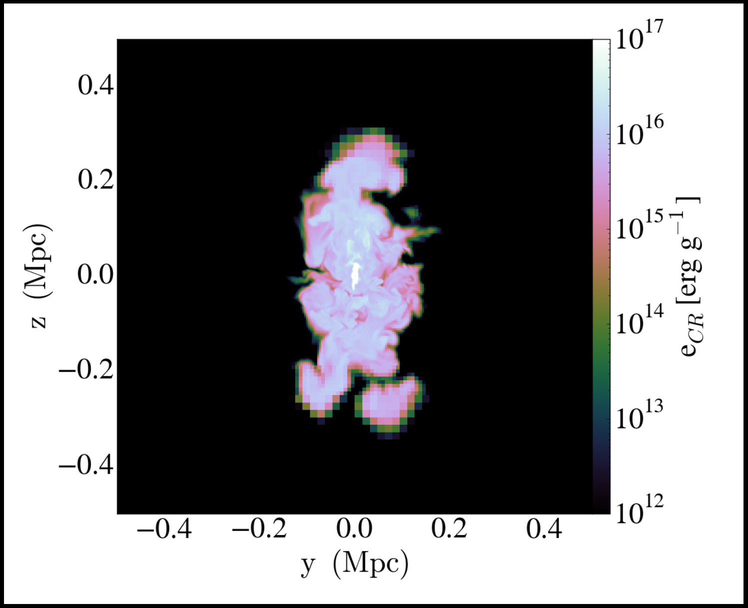
$$H_{CR} = -v_A \cdot \nabla P_{CR}$$

For alternative algorithms to simulate streaming, see Jiang & Oh (2018), Thomos & Pfrommer (2018)

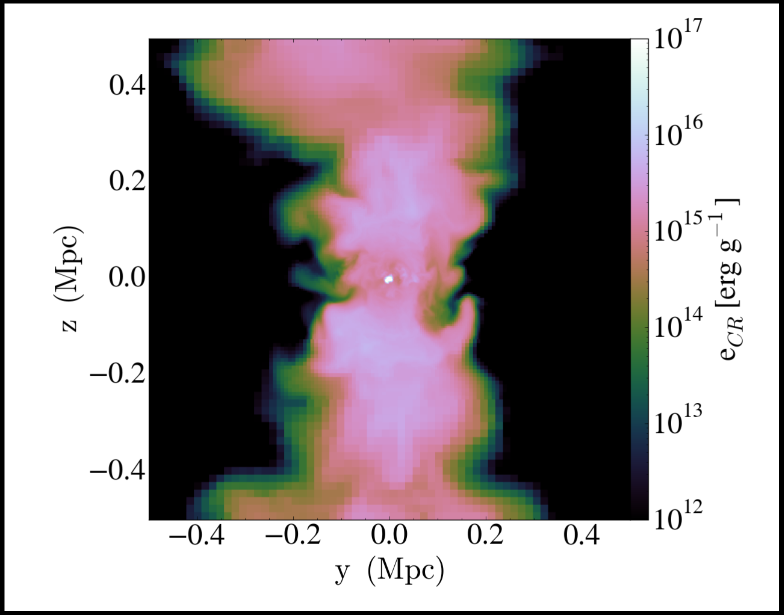
# AGN heating by CR-dominated jets

(Ruszkowski, Yang & Reynolds, 2017; see also Yang et al. 2019)

*No streaming*



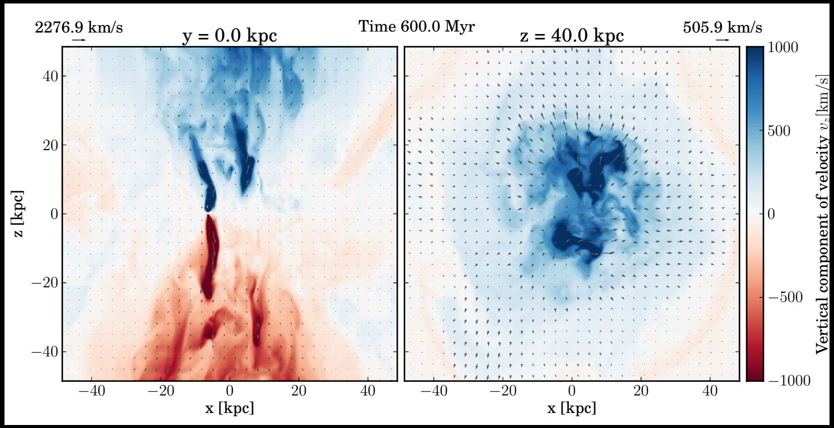

*With streaming*



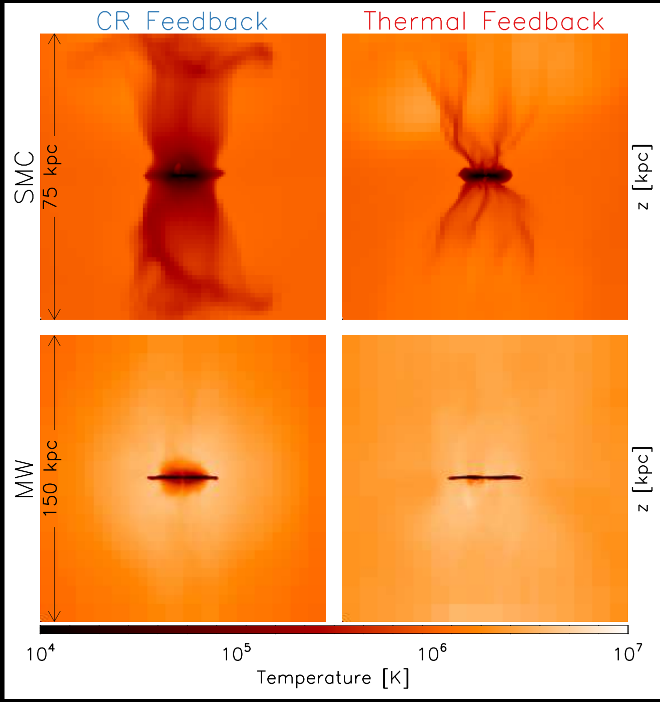

- *CRs stream outside bubbles*
- *Heating by Coulomb, hadronic, and streaming -> self-regulation*

# Galactic wind feedback

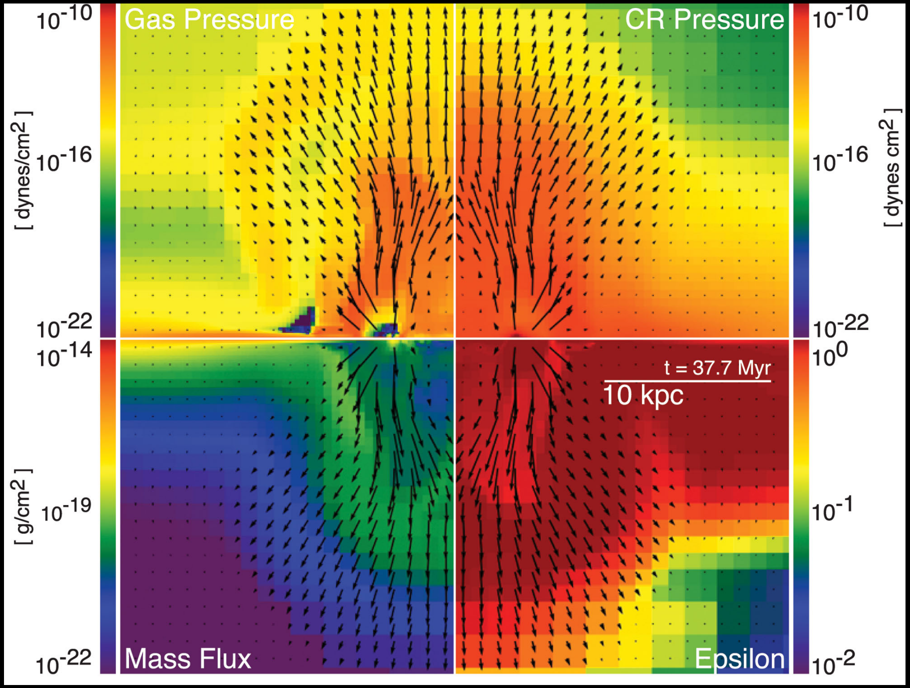
# CRs can drive galactic winds




Hanasz+13



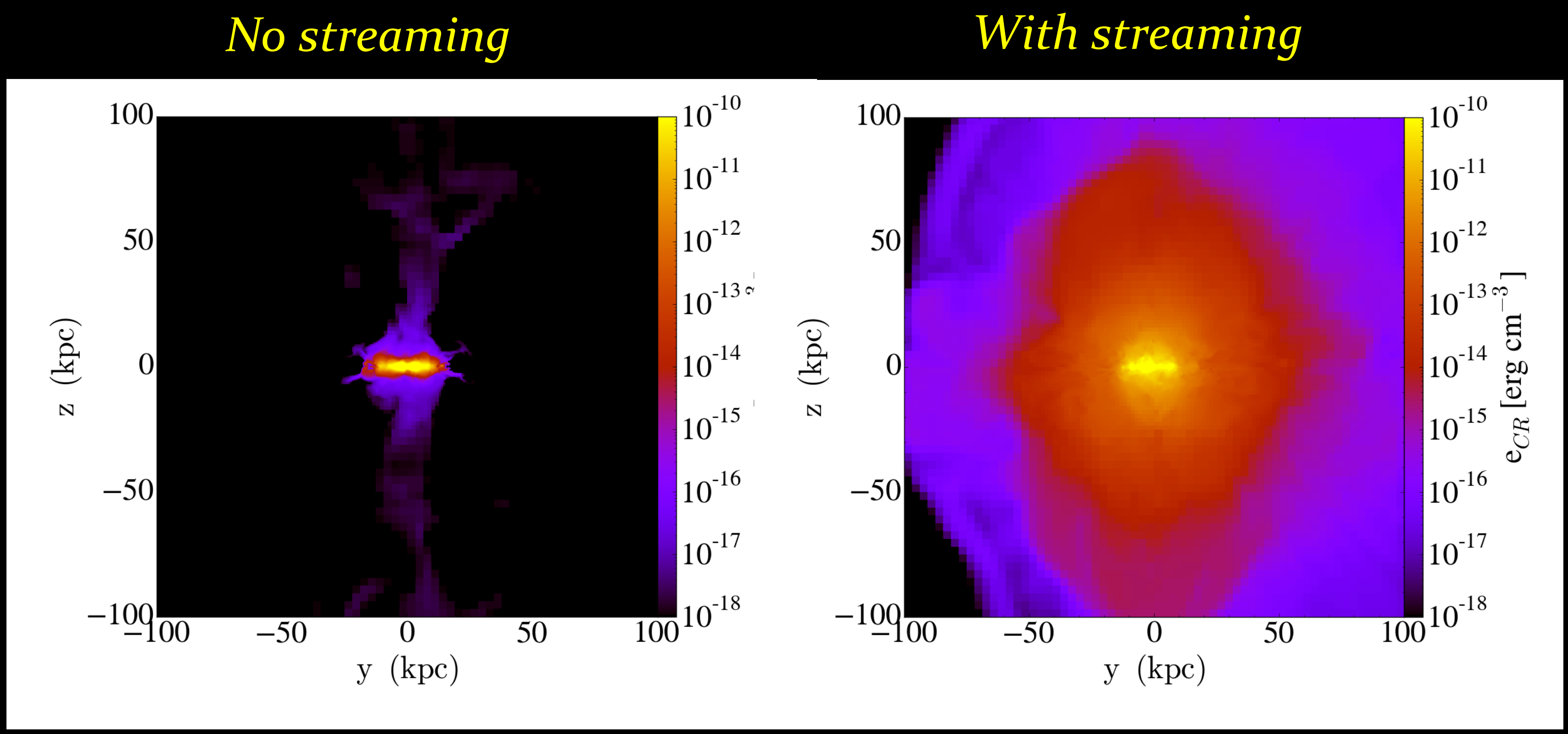

Booth+13




Salem+14

# No transport, no wind

(Ruszkowski, Yang & Zweibel, 2017)



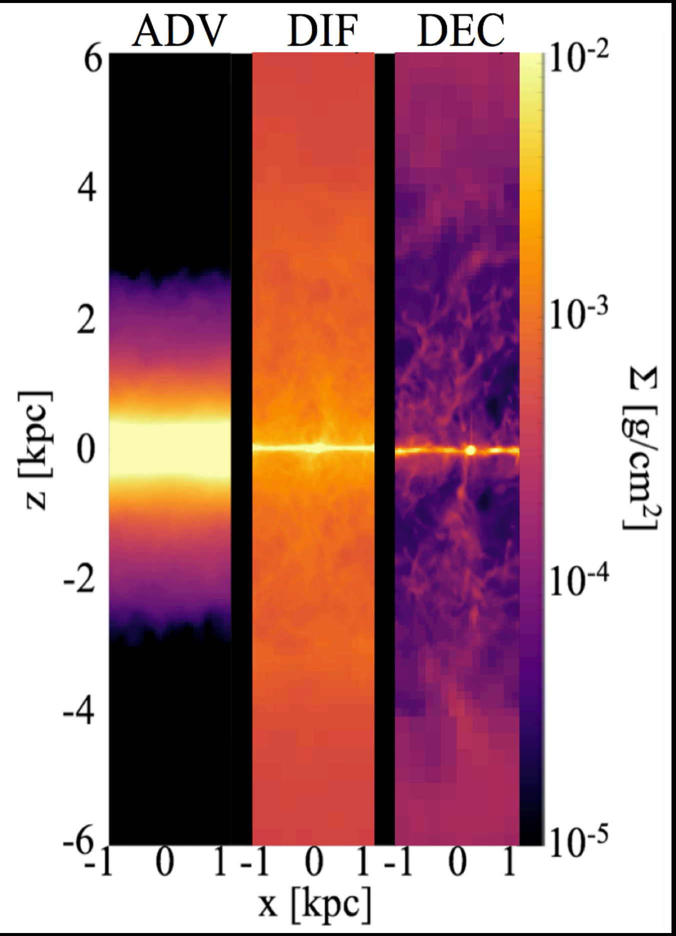

❖ *Mass loading factor and SFRs depend on transport speed!*

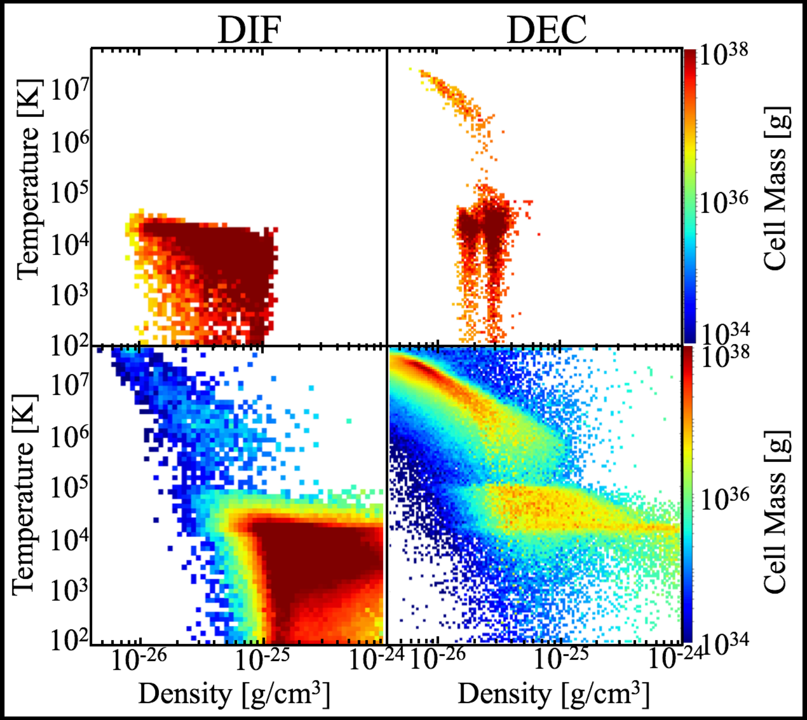
See also Uhlig+2012, Booth+2013, Hanasz+2013, Salem & Bryan 2014, Pfrommer+2016, Pakmor+2016

# Effects of decoupling on galactic winds

(Farber, Ruszkowski, Yang & Zweibel, 2018)

Ryan Farber
(Michigan)



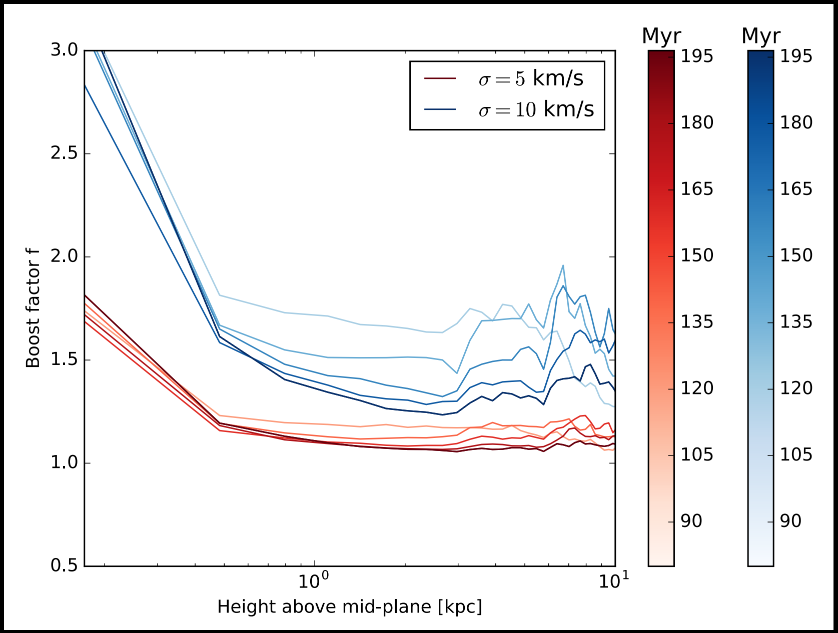

❖ *Winds are less dense and hotter with decoupling*

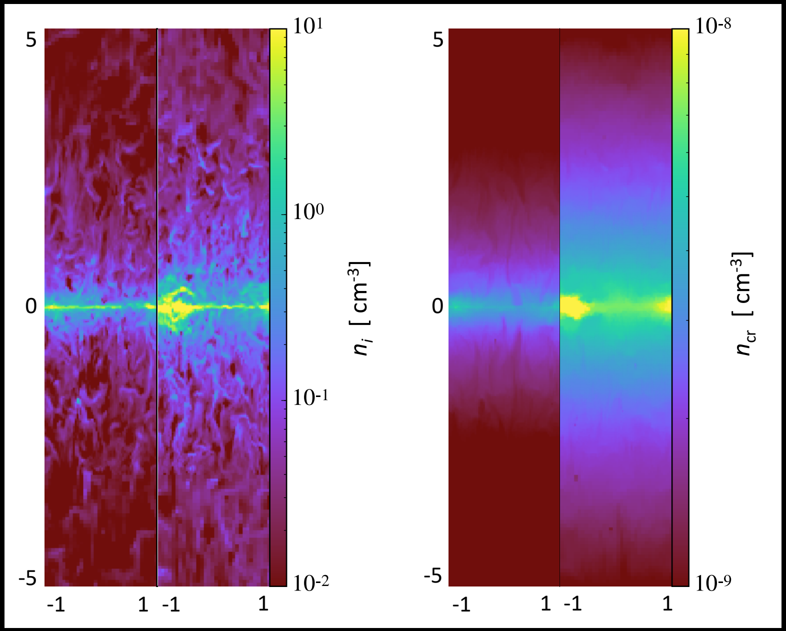
# Effects of turbulent damping on winds

(Holguin et al., 2019, accepted ***TODAY***, arXiv: 1807.05494)

Paco Holguin
(Michigan)

- *Streaming speed self-consistently computed by balancing wave growth and turbulent damping (Lazarian 2016)*



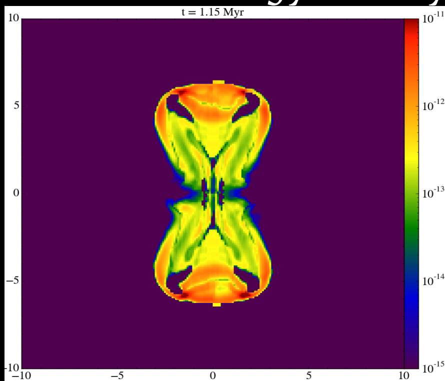

- *Streaming speed is mildly super-Alfvenic close to disk*

- *Gas and CR distributions more extended w/ damping*

# Simulating Fermi Bubbles with CR spectral evolution

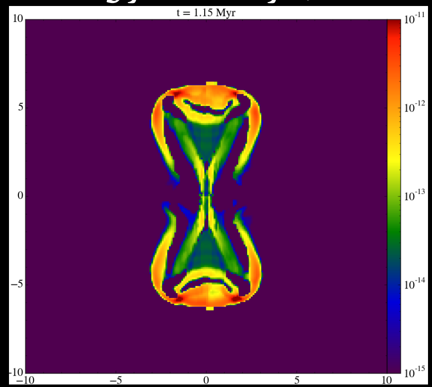
(Yang & Ruszkowski 2017)

*Total CR energy density*



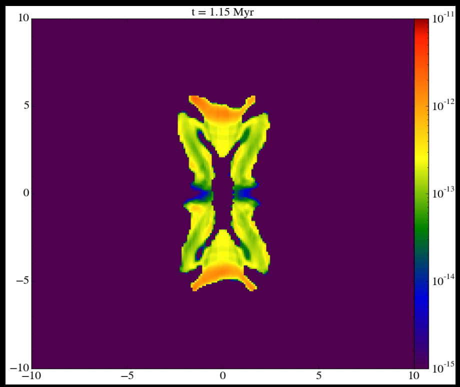

=

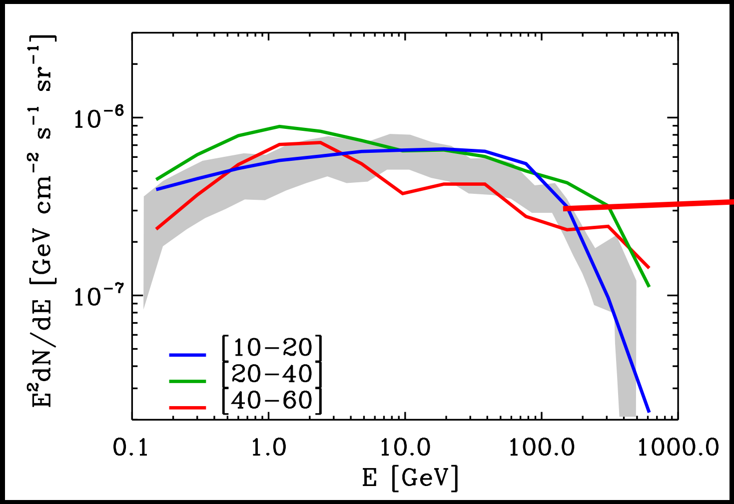
*CR energy density (>10 GeV)*




+

*CR energy density (<10 GeV)*




*Simulated gamma-ray spectra in good agreement with data*

# Roles of microphysics in feedback -- summary

- ***AGN feedback in clusters:***

  -- HBI and conductive heating are likely limited

  -- Braginskii viscosity limited by microinstabilities cannot preserve AGN bubbles

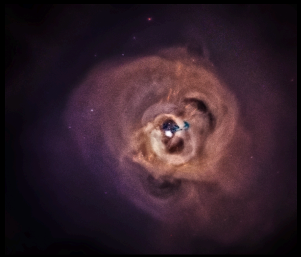
  -- CR transport is needed for CR-jet feedback

- ***Galactic wind feedback:***

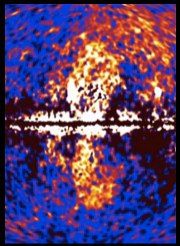
  -- Details of CR transport are crucial for predicting properties of winds and galaxies

- ***Progress requires iterative multi-scale simulations & comparisons with data***

# References



- AGN feedback in clusters & microphysics
  - -- *Kingsland, Yang, Reynolds, Zuhone, 2019, ApJL accepted (arXiv: 1909.01339)*
  - -- *Yang, Gaspari, Marlow, 2019, ApJ, 871, 1*
  - -- *Ruszkowski, Yang & Reynolds, 2017, ApJ, 844, 13*
  - -- *Yang & Reynolds, 2016b, ApJ, 829, 90*
  - -- *Yang & Reynolds, 2016a, ApJ, 818, 181*
  - -- *Yang, Sutter & Ricker, 2012, MNRAS 427, 1614*



- Fermi bubbles & microphysics
  - -- *Yang, Ruszkowski, Zweibel, 2018, Galaxies, 6, 29*
  - -- *Yang & Ruszkowski, 2017, ApJ, 850, 2*
  - -- *Yang, Ruszkowski & Zweibel, 2013, MNRAS, 436, 2734*
  - -- *Yang et al. 2012, ApJ, 761, 185*

- Galactic winds & microphysics
  - -- *Holguin, Yang et al., 2019, MNRAS accepted (arXiv: 1807.05494)*
  - -- *Farber, Ruszkowski, Yang & Zweibel, 2018, ApJ, 856, 112*
  - -- *Ruszkowski, Yang & Zweibel, 2017, ApJ, 834, 208*