Probing Feedback Processes in Galaxy Formation with Simulations

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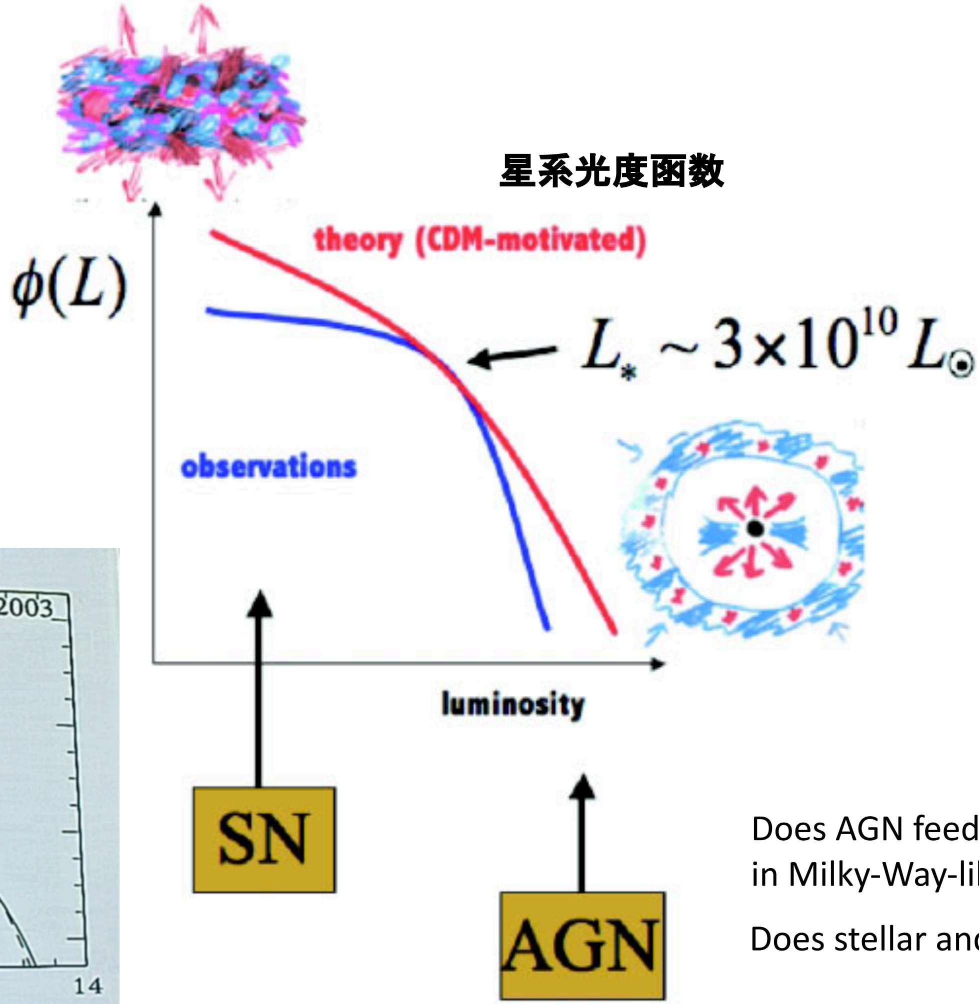
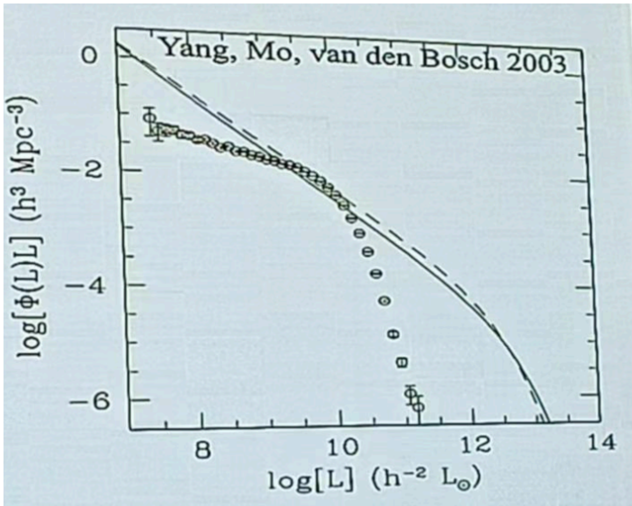
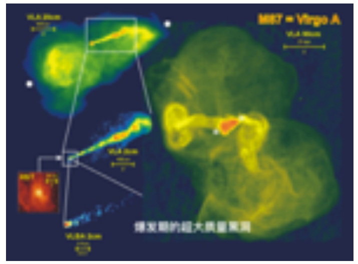
Stellar and AGN Feedback in Galaxy Formation

Stellar Feedback, M82







AGN Feedback, M87

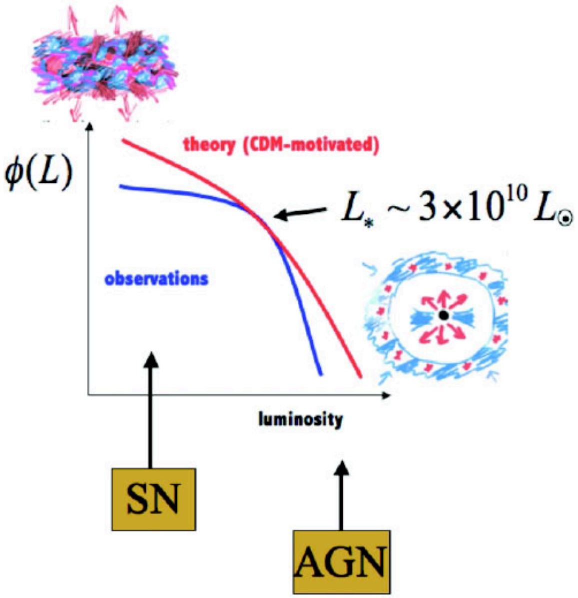
Does AGN feedback start to operate in Milky-Way-like L_* galaxies?

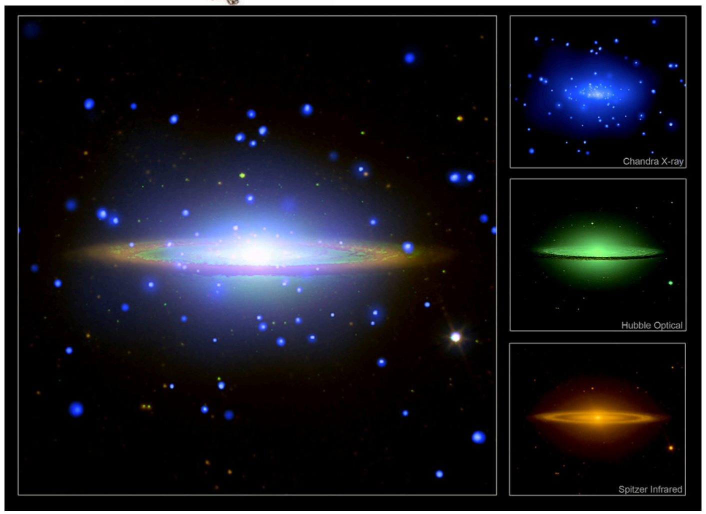
Does stellar and AGN feedback "collaborate" with each other?

Type Ia Supernova Feedback in the nearby quiescent galaxy M104

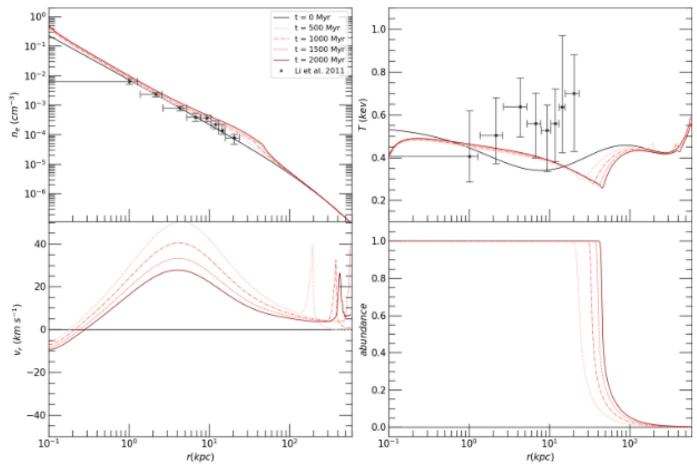
Wei Miao

Supernova Feedback in M104, the Sombrero Galaxy 草帽星系





Hot subsonic gaseous outflows due to feedback

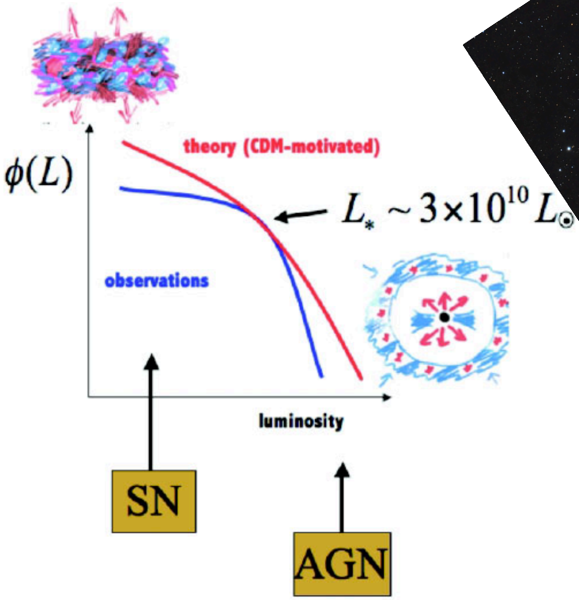


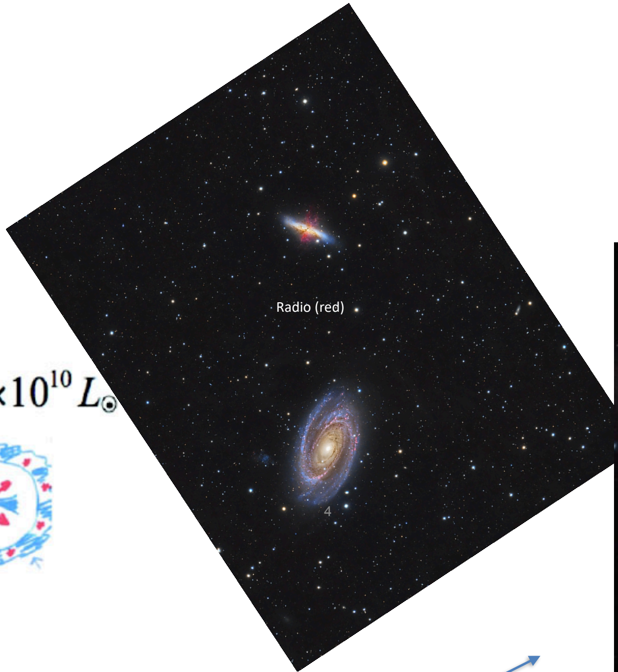
Miao & Guo, to be submitted soon

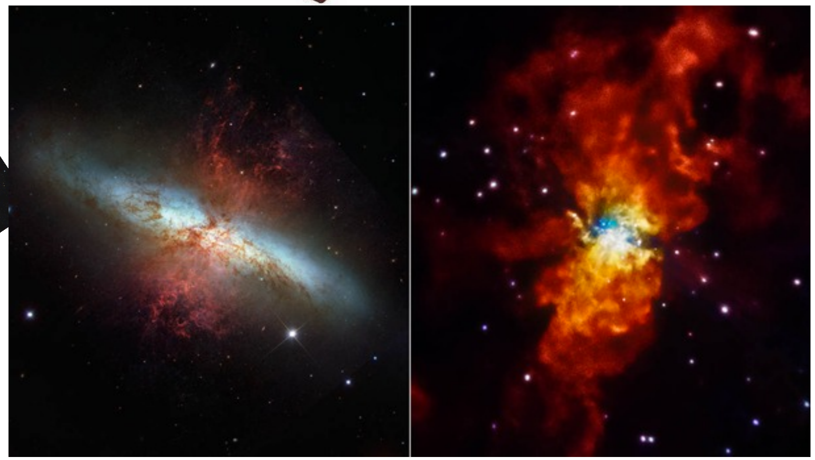
Type II Supernova Feedback in the nearby starburst galaxy M82

Yuezhen Ye

Supernova Feedback in M82, the Cigar Galaxy 雪茄星系







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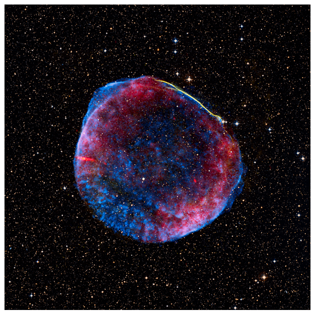


$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = q \,,$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = \rho \boldsymbol{f} - \nabla P - \nabla P_{\mathrm{C}} \,,$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\boldsymbol{v}] = Q - C + \rho \boldsymbol{v} \cdot \boldsymbol{f} + I \,,$$

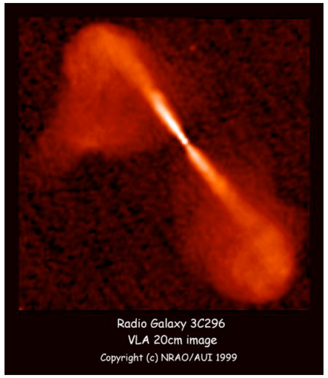
$$\frac{\partial \rho_{\mathrm{C}} E_{\mathrm{C}}}{\partial t} + \nabla \cdot [(\rho_{\mathrm{C}} E_{\mathrm{C}} + P_{\mathrm{C}})\boldsymbol{v}_{\mathrm{C}}] = Q_{\mathrm{C}} - I \,.$$

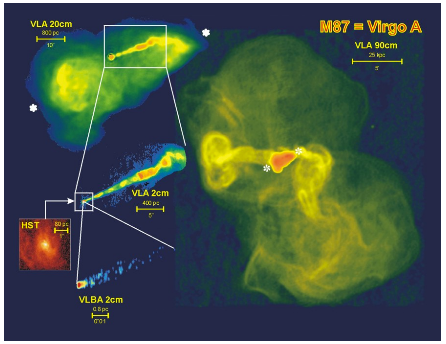
Quasar Mode and Jet Mode AGN Feedback

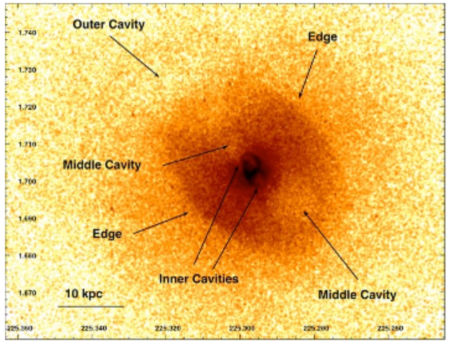
- quasar mode (radiative mode)

- Multi-phase quasar outflows (v ~ 1000 km/s ; Fabian 2012; Harrison et al 2018)
- No well-established correlation with star formation (even positive feedback in some systems)

- Jet Mode (Radio Mode)



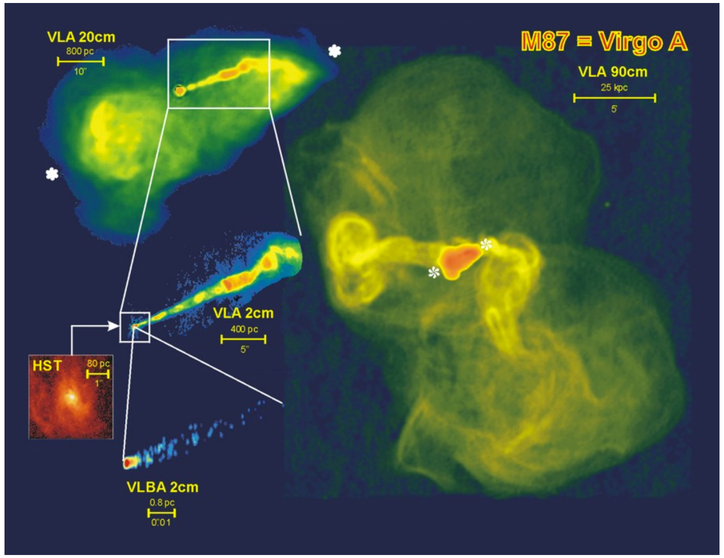


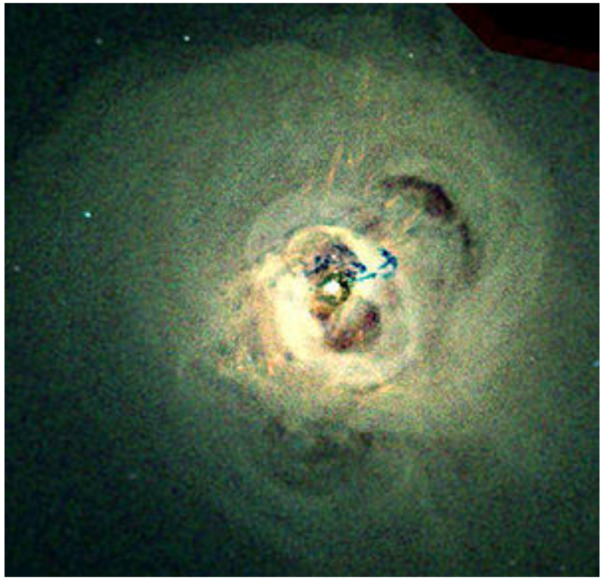


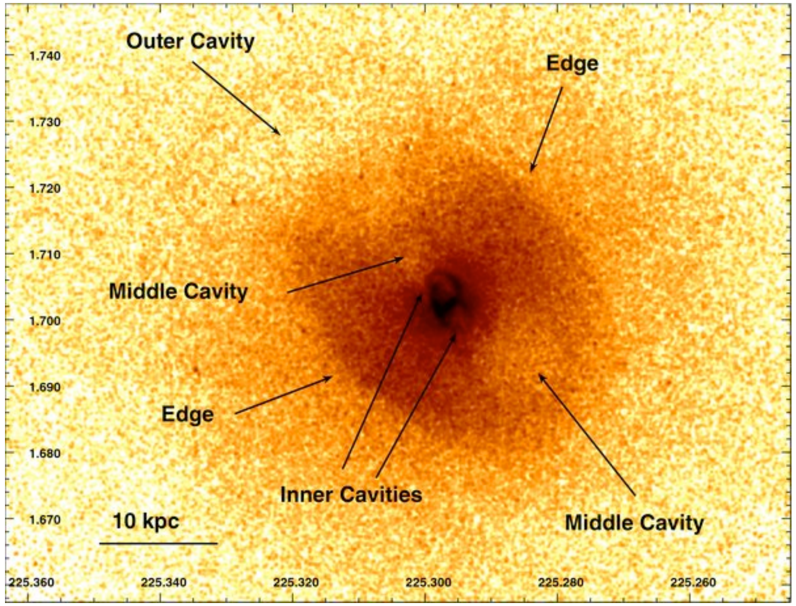
- Major evidence for negative AGN feedback, seen in galaxy clusters and groups
- What about lower-mass systems, e.g., L* galaxies? Does AGN feedback start to operate in them?

Jet-mode AGN Feedback in X-ray Galaxy Clusters

Radio lobes, X-ray cavities, weak shocks, sound waves …





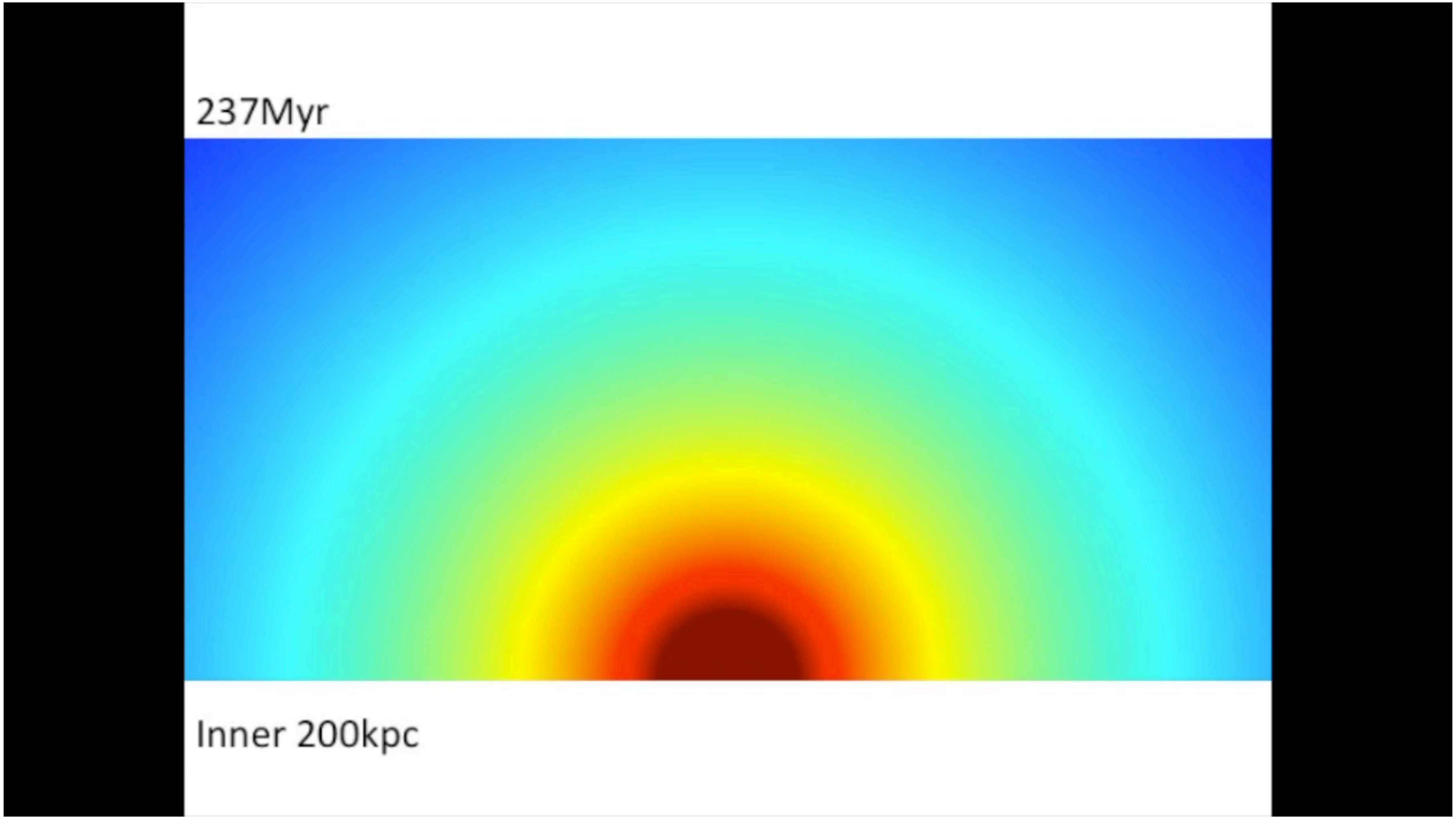


0.3-2 keV *Chandra* image of NGC 5813 (Randall+11)

X-ray image of the inner Perseus cluster

Jet-mode AGN feedback in Galaxy Clusters

(Guo et al 2018, MNRAS; Duan & Guo 2018 & 2020, ApJ; Guo 2020 ApJ; Duan & Guo 2023)



Jet Simulation

Guo et al 2018

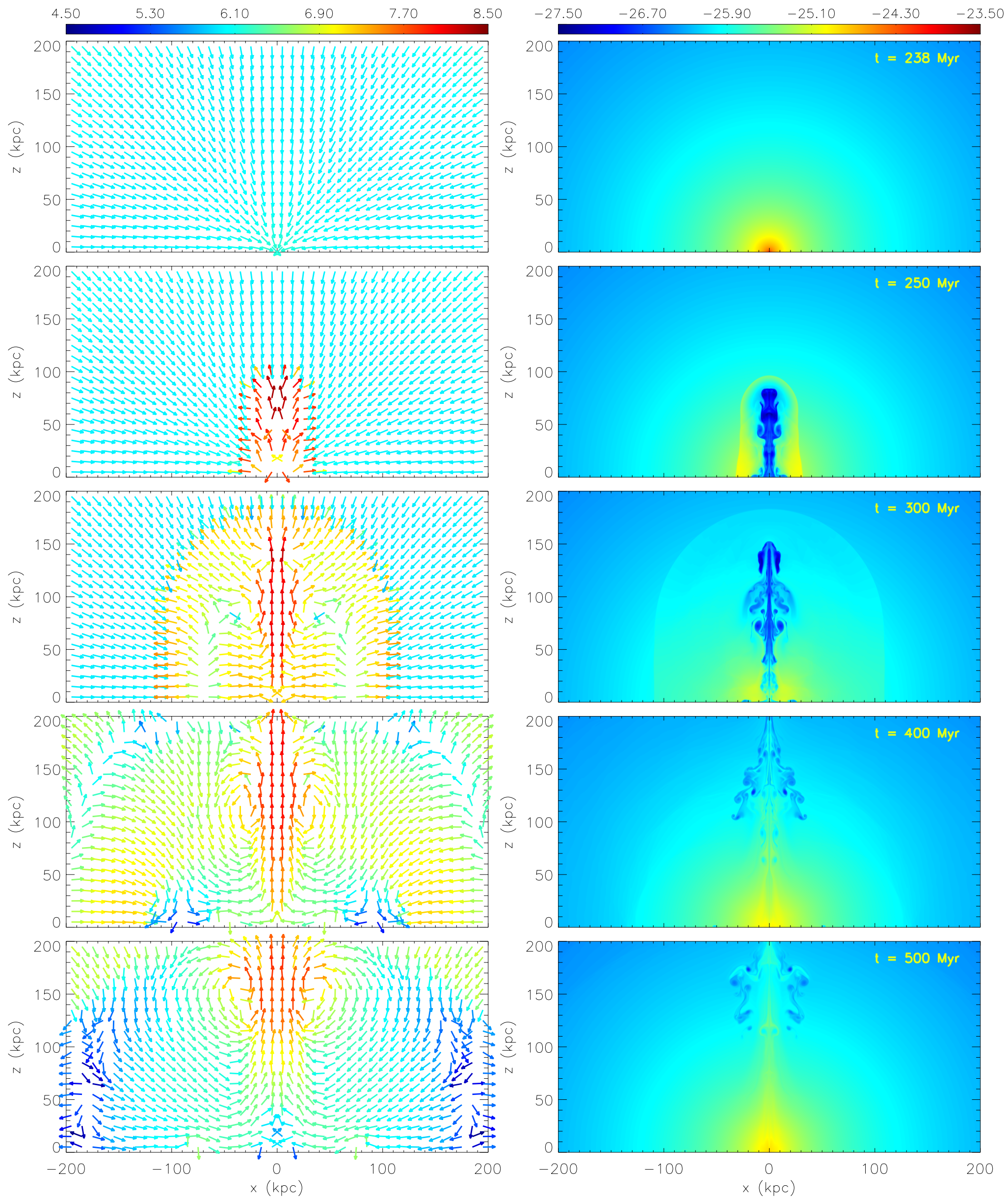
Hydrodymamic features:

Prominent radio lobes

Weak forward shock

cool core expansion

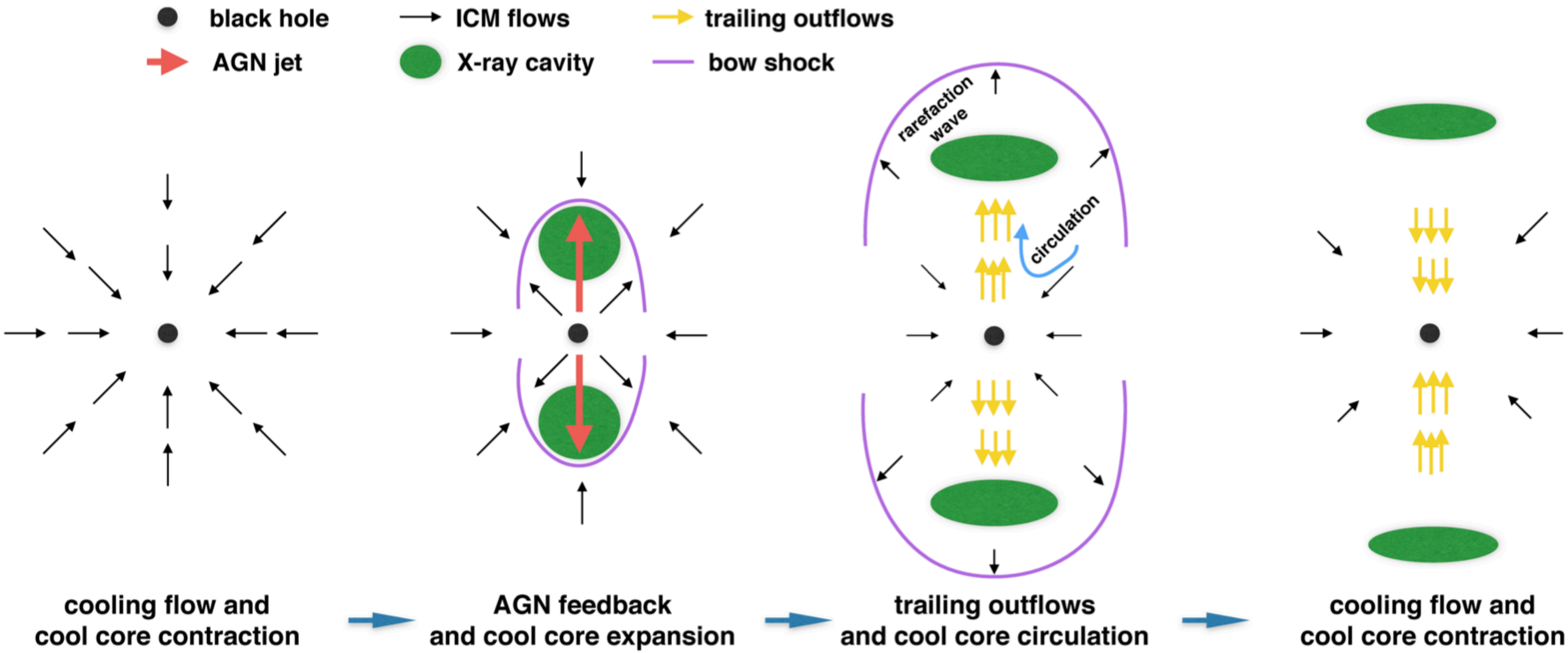
Wake flows behind radio lobes



Density Map

Jet Simulation in Galaxy Clusters

Guo et al 2018



wake flow in AGN feedback: metal-rich outflows and cold filaments

Duan & Guo 2018, 2023

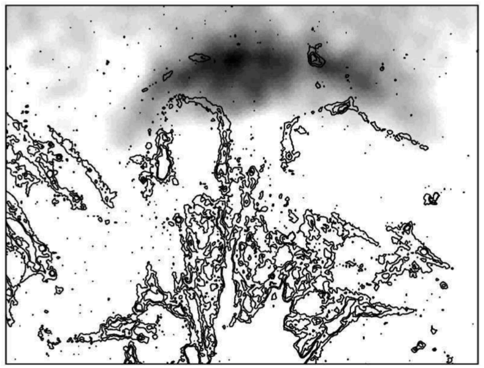
Hydrodymamic features:

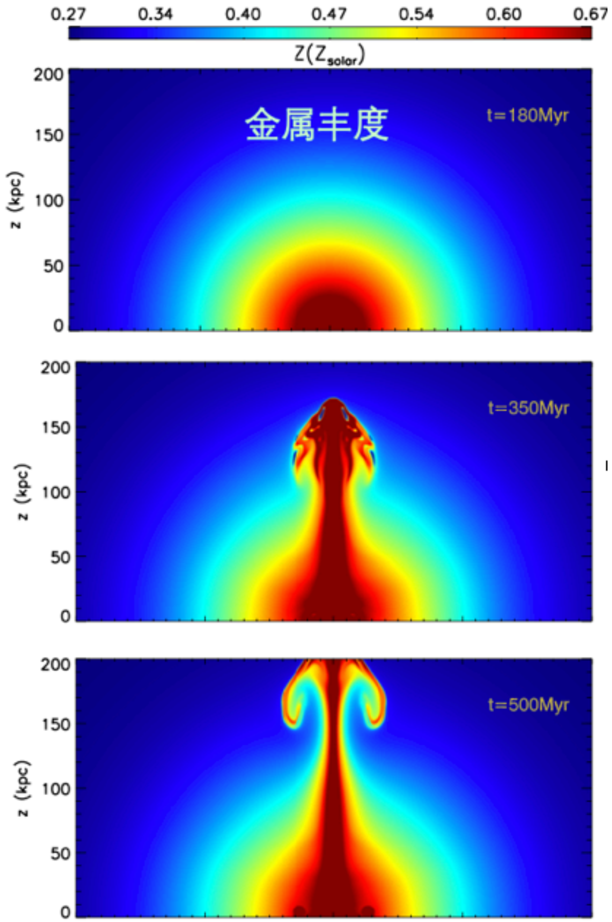
Prominent radio lobes

Weak forward shock

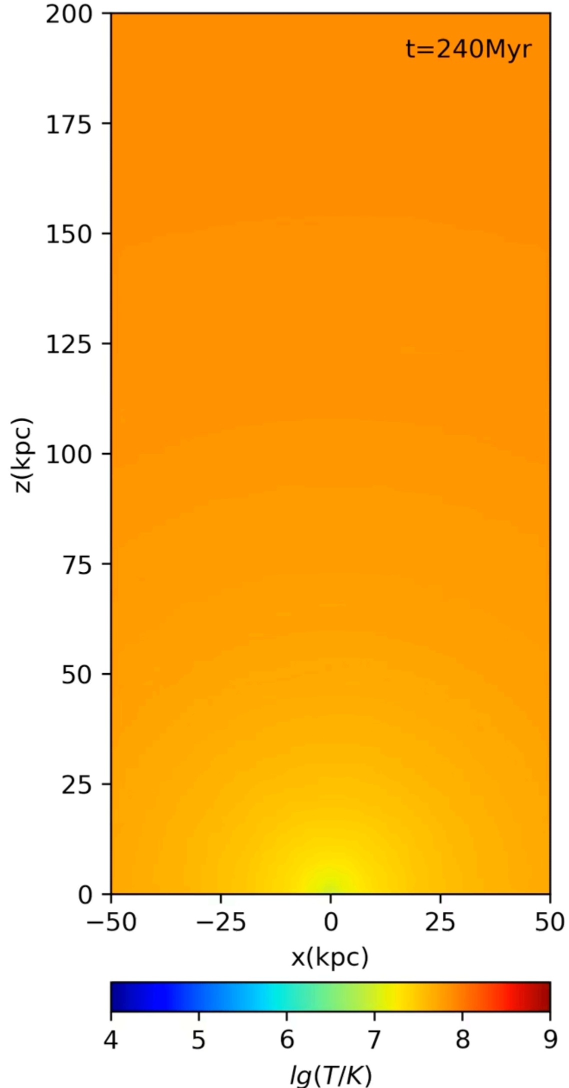
cool core expansion

Wake flows behind radio lobes



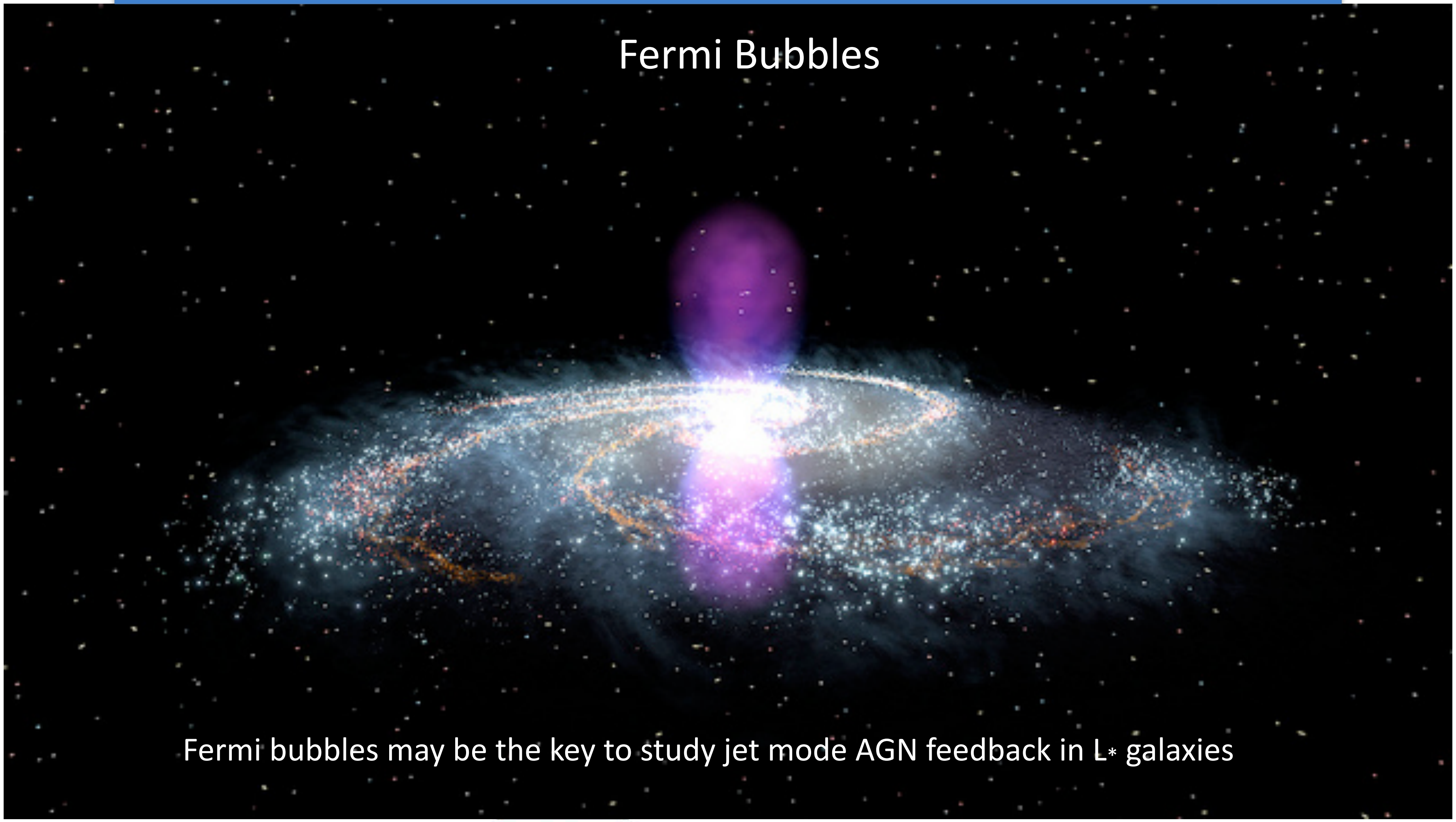


Metallicity distribution
metal-rich outflows uplifted by AGN bubbles



Temperature evolution
Formation of cold filaments below AGN bubbles

Jet Mode AGN Feedback in L_* Galaxies



Fermi Bubbles in Various Bands

GIANT GAMMA-RAY BUBBLES FROM *FERMI*-LAT: ACTIVE GALACTIC NUCLEUS ACTIVITY OR BIPOLAR GALACTIC WIND?

Meng Su[1], Tracy R. Slatyer[1,2], and Douglas P. Finkbeiner[1,2]
[1] Institute for Theory and Computation, Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, MS-51, Cambridge, MA 02138, USA; mengsu@cfa.harvard.edu
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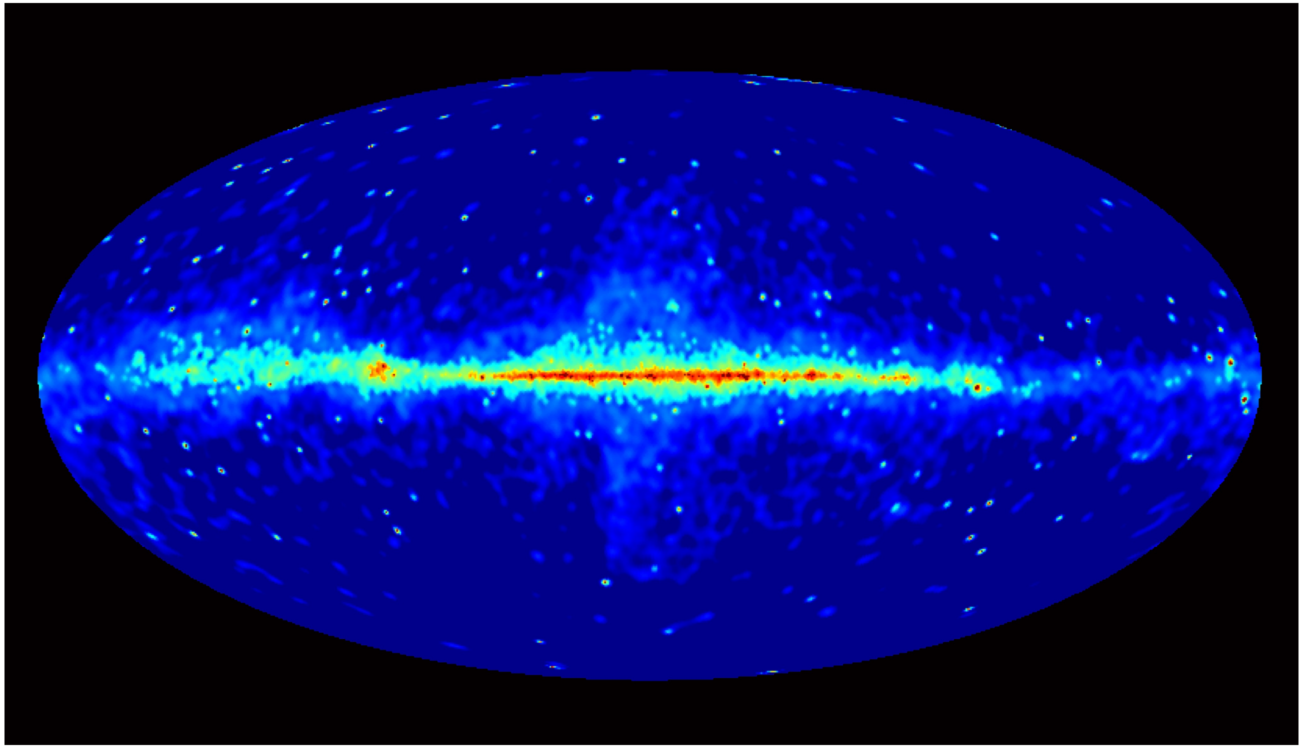
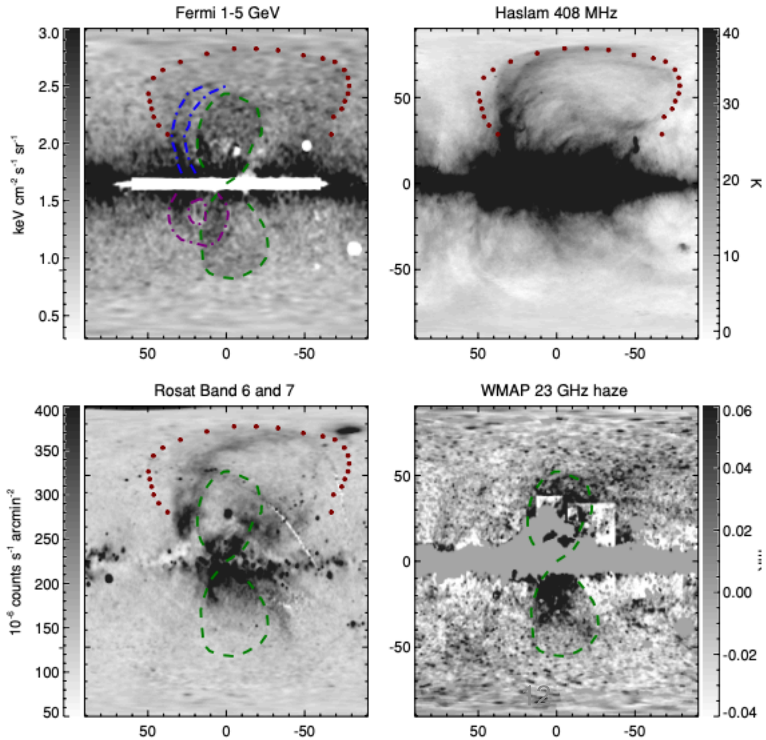
Received 2010 June 2; accepted 2010 September 23; published 2010 November 10

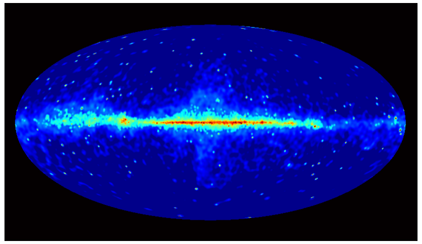
The All-sky Fermi View at E >10 GeV





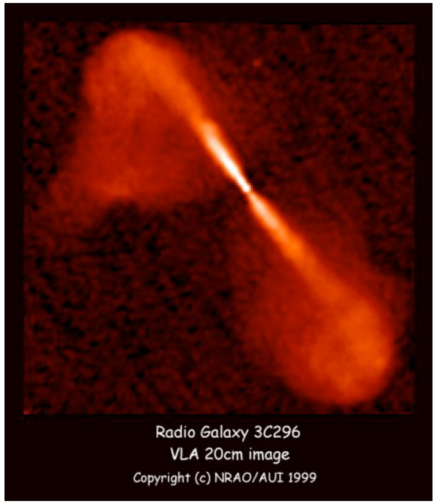
The Origin of the Fermi Bubbles

Galactic Feedback



Fermi bubbles, Milky Way Feedback?

Stellar Feedback; M82

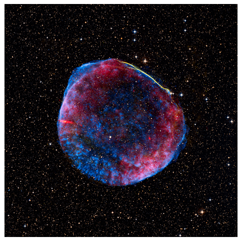


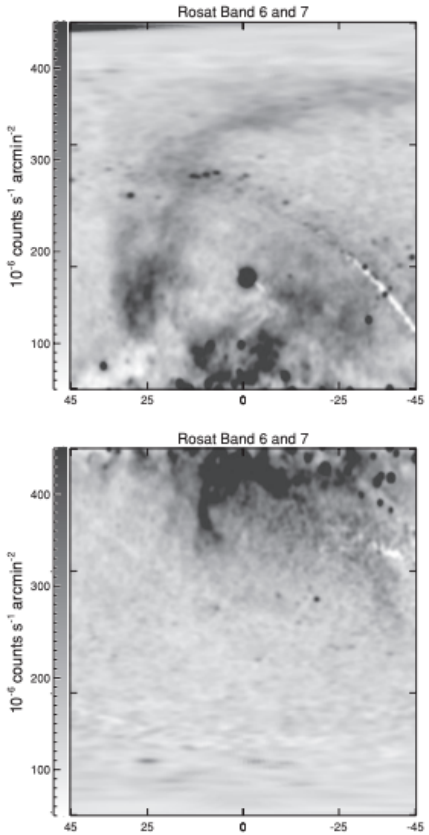
AGN Feedback; Radio Galaxy

The origin of the Fermi bubbles

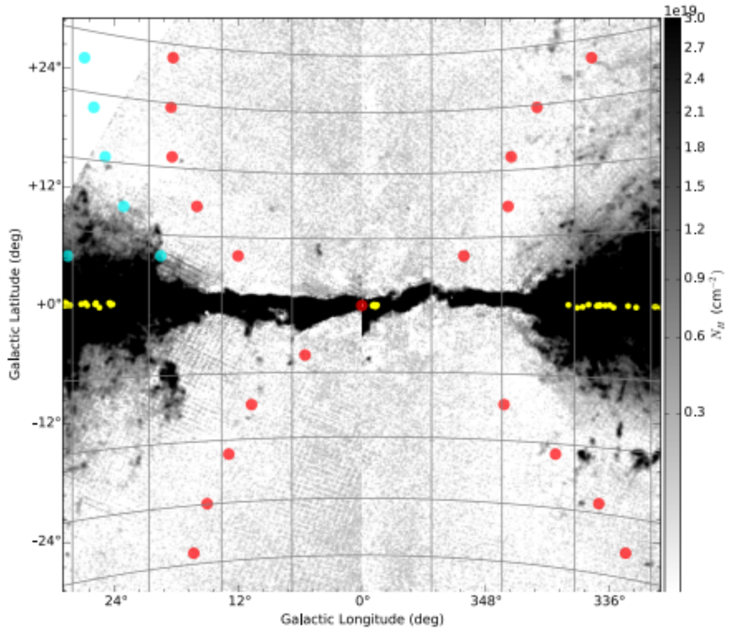
- Galactic winds from the Galactic Center? (Crocker & Aharonian 2011; etc)

M82 wind due to Type II SNe





ROSAT X-ray map

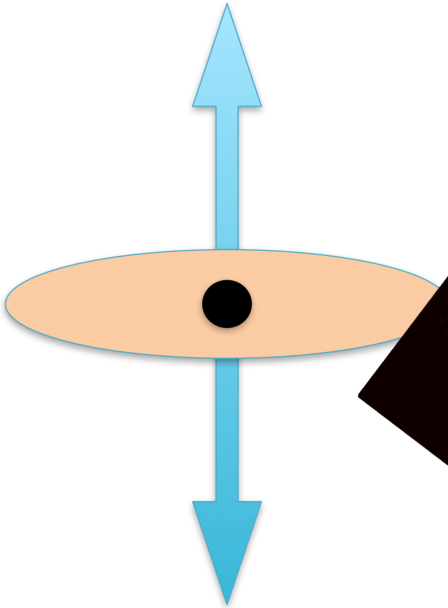


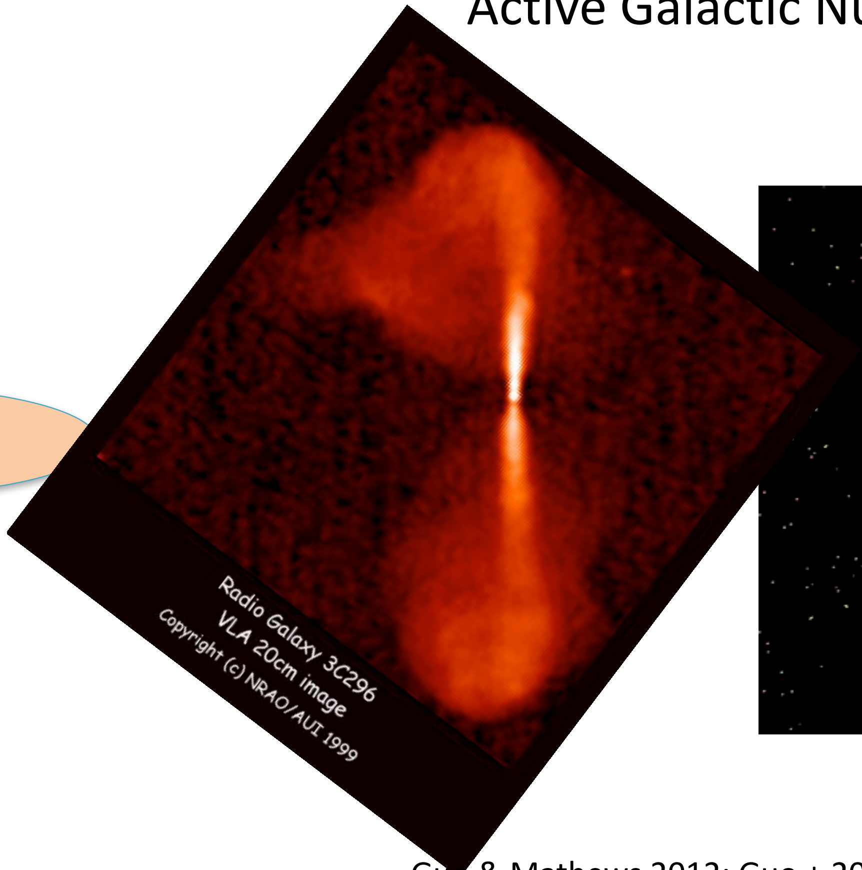
Lockman, McClure-Griffiths (2016)

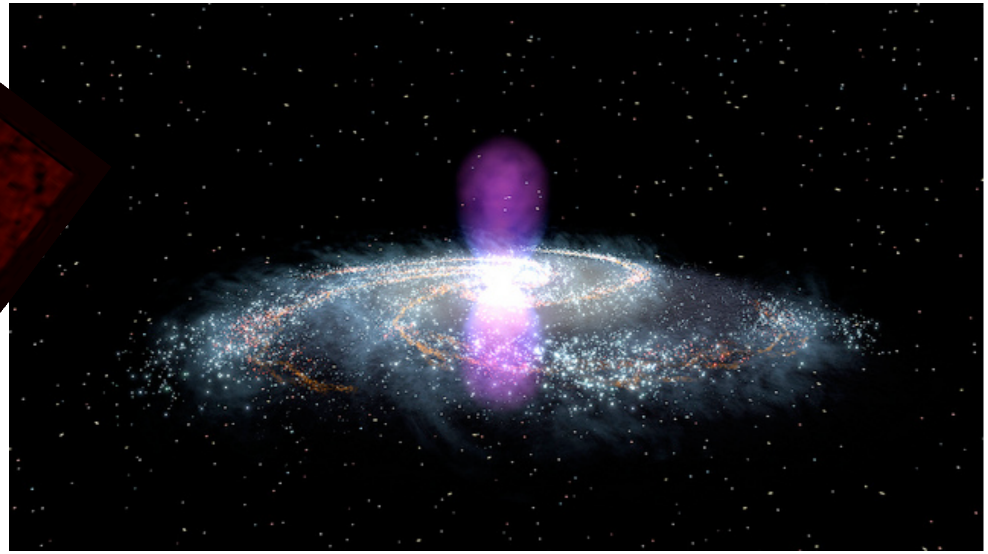
The AGN Jet Model of the Fermi Bubbles

Active Galactic Nucleus (AGN)

Bipolar Jets







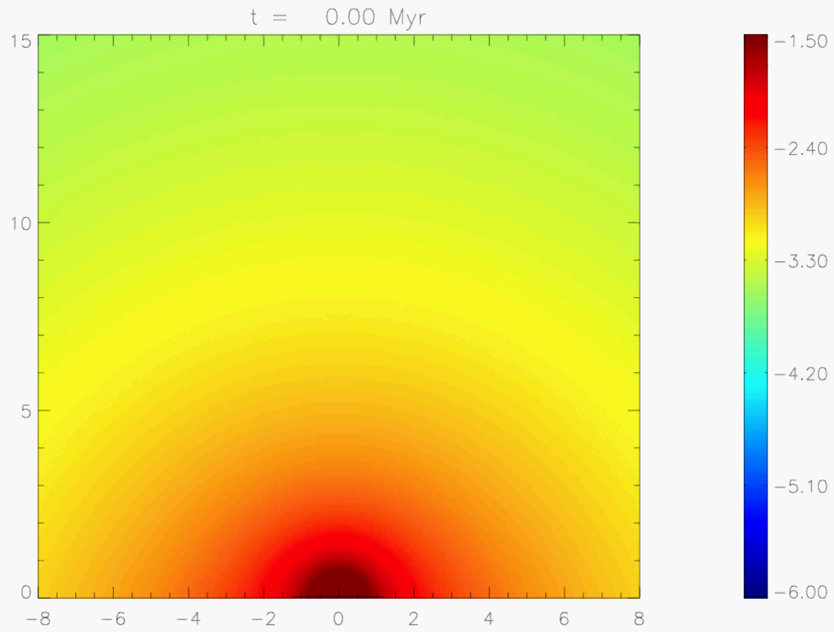
Fermi Bubbles

- Guo & Mathews 2012; Guo + 2012, ApJ; Guo 2017

other AGN models: Quasar outflow model, hot accretion flow - outflow model

Prediction： Forward Shock in the CGM

thermal gas density distribution



produce a forward shock and expansion of the inner gaseous halo

Guo & Mathews, ApJ， 2012a, 2012b

Fermi Bubbles： gamma-ray emission of Radio Lobes in the Milky Way?
eROSITA bubbles: shocked CGM bubbles of the Fermi bubble event?

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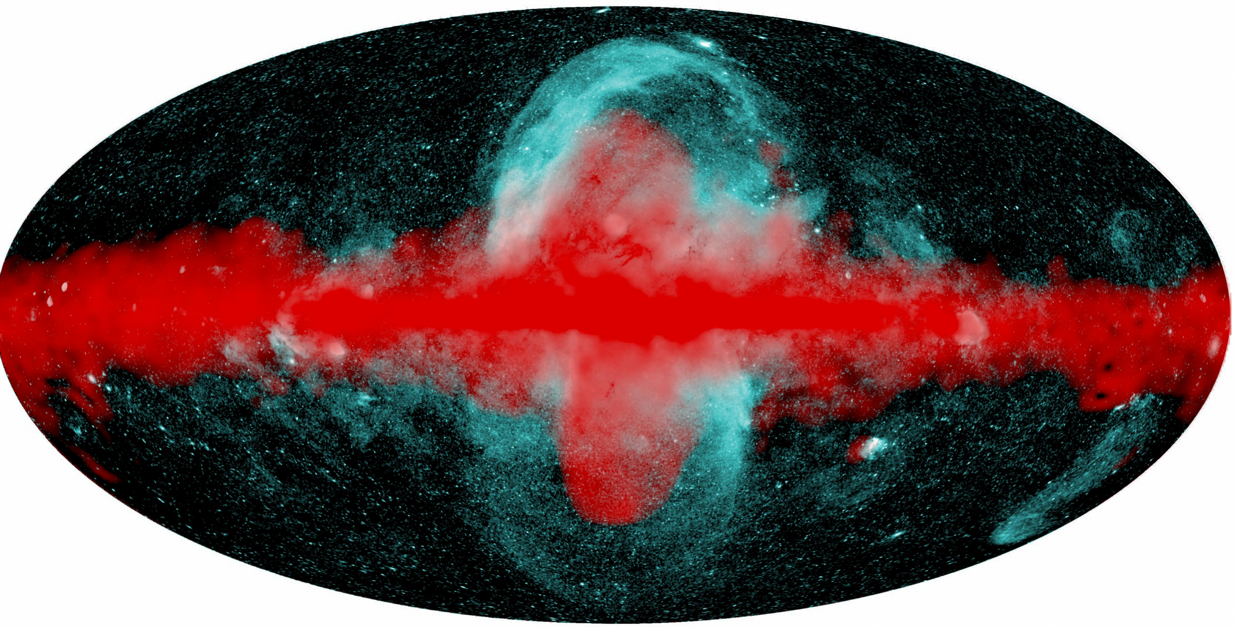
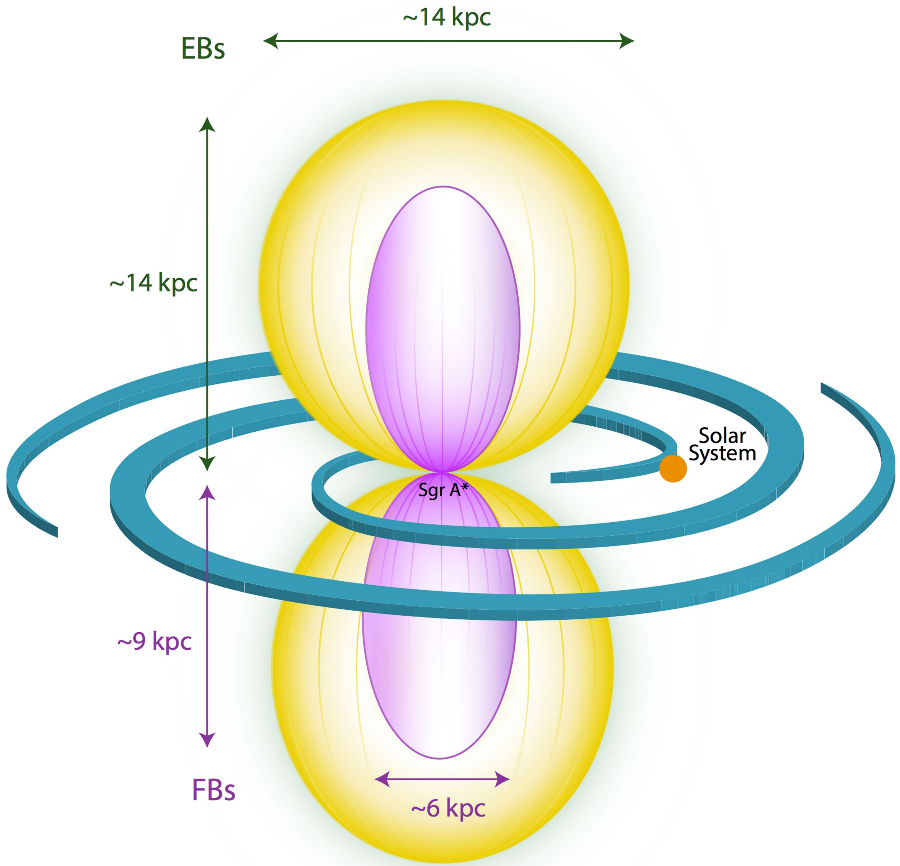
Article | Published: 09 December 2020

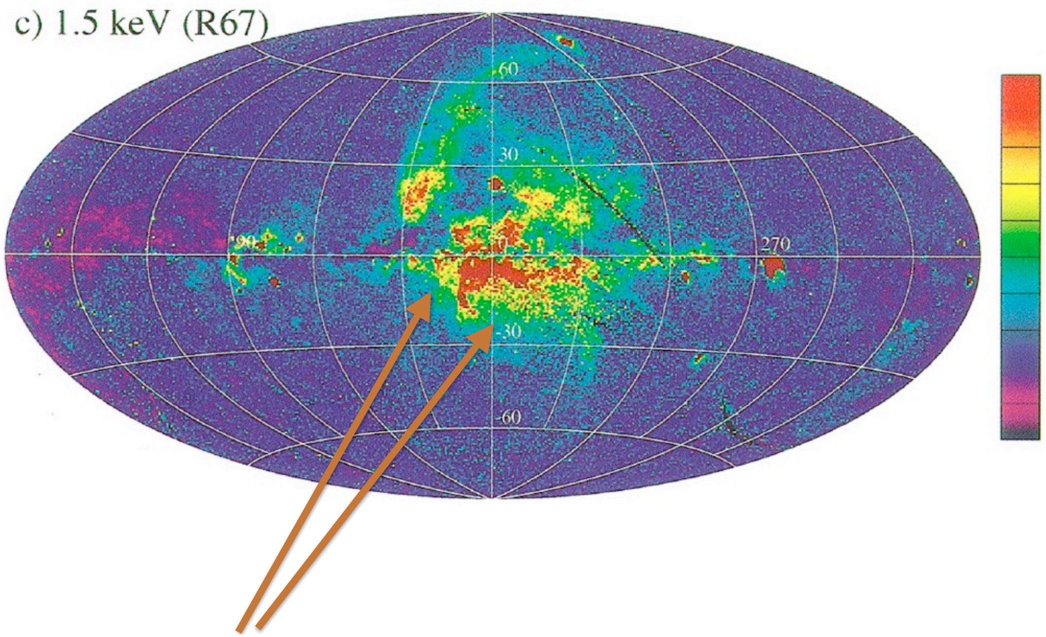
Detection of large-scale X-ray bubbles in the Milky Way halo



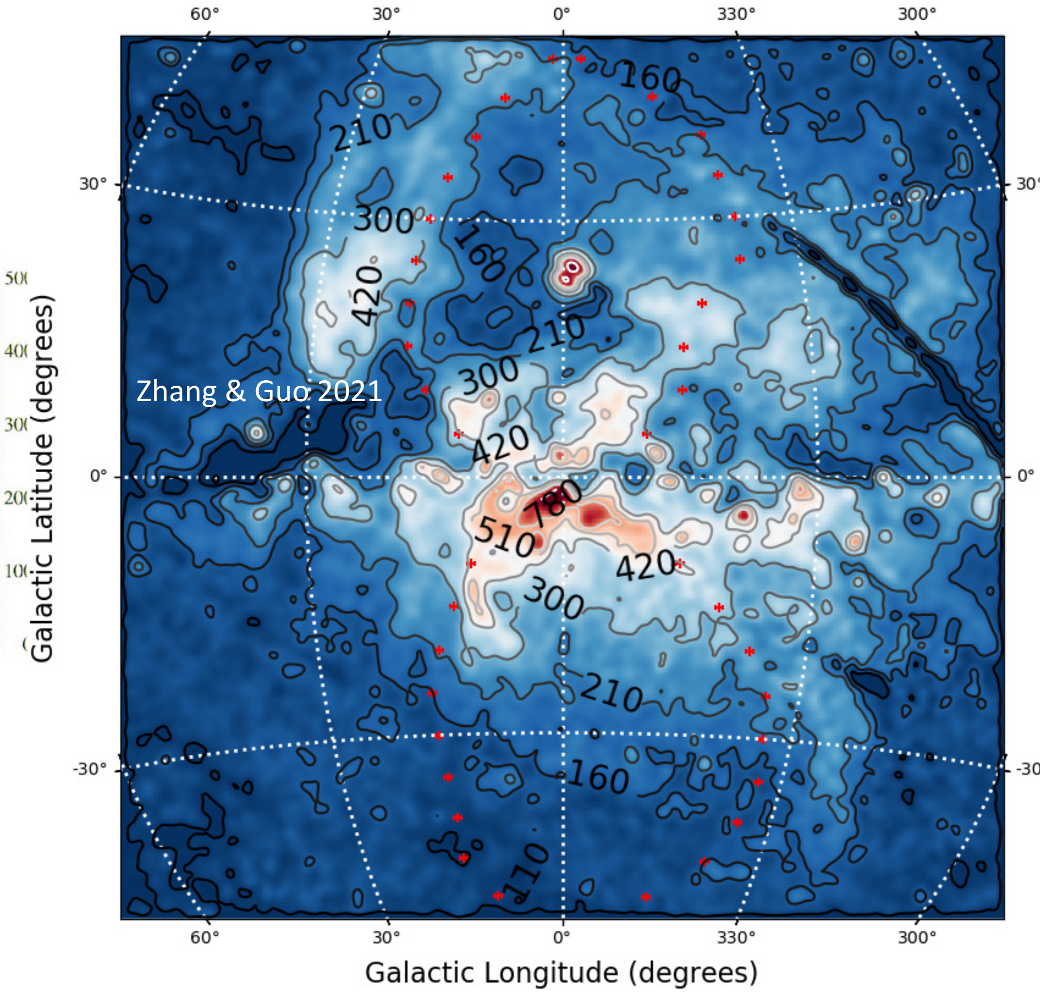
eROSITA Bubbles

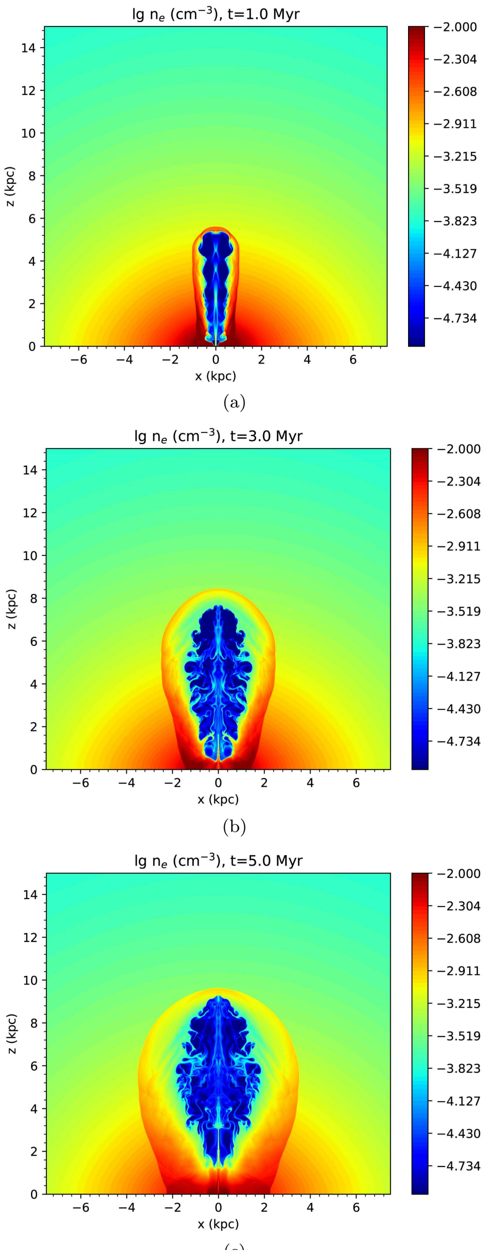


Where is the forward shock? 激波在哪里?



Central bipolar X-ray outflows with the same edges as Fermi bubbles





The Evolution of Fermi bubbles

张瑞玉

The energetics and age of the bubbles are constrained very well by the bubble morphology and the gas temperature within the bubbles!

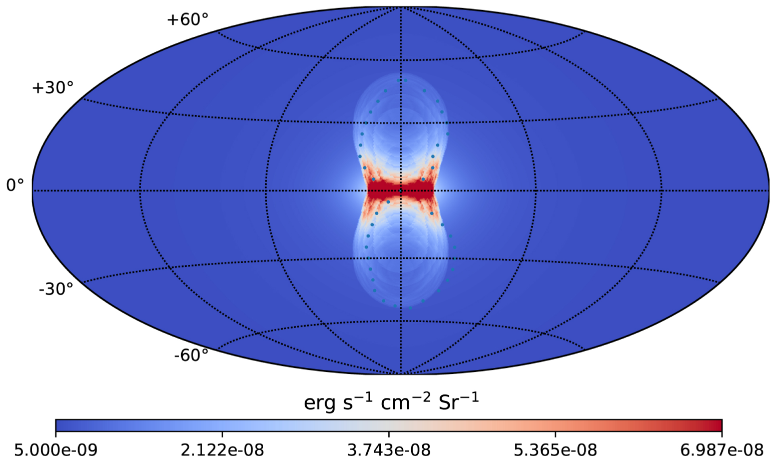


Figure 9. Synthetic X-ray (0.7–2 keV) surface brightness map in Galactic coordinates with a Hammer-Aitoff projection for run A at t = 5 Myr. The dots represent the edge of the observed Fermi bubbles.

Zhang & Guo, 2020

Properties of the Fermi bubbles in Our Model

single-jet Power: 3.42×10^{41} erg s^{-1}

Jet duration: 1 Myr

Current Fermi bubble age: 5 Myr

Total injected energy ~ 2 $\times 10^{55}$ erg

Eddington ratio: ~ 0.001, hot accretion mode

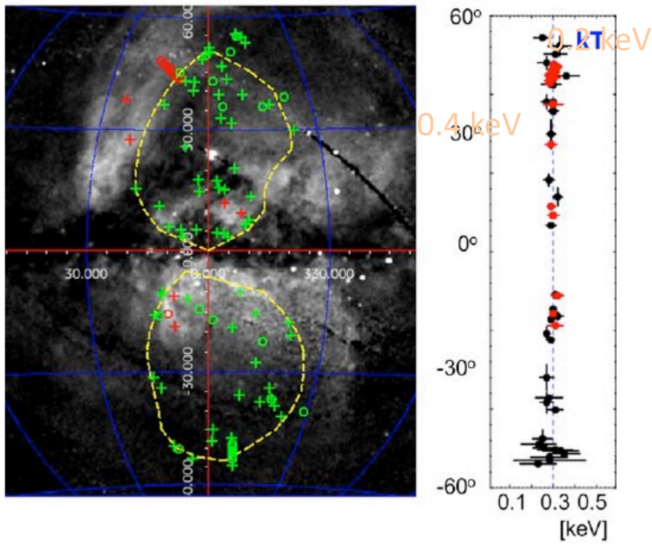
Sgr A* accretion rate ~ 0.0001 solar mass/yr

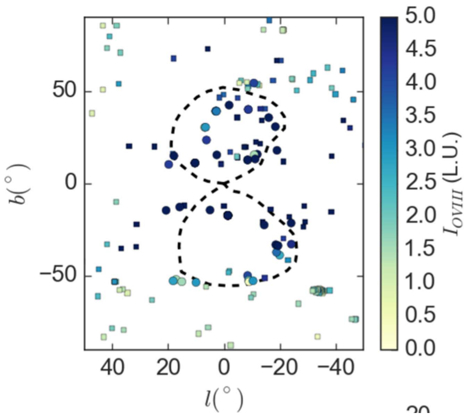
Consistent with Other Observations

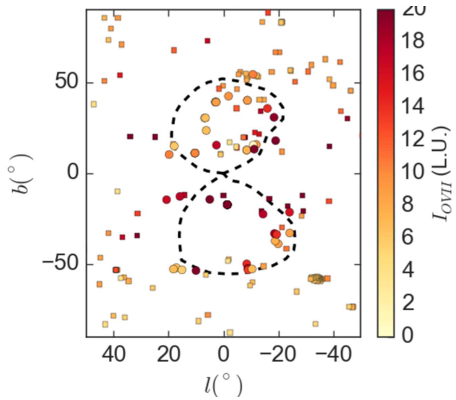
Miller et al.(2016) found the bubble temperature is kT~0.40 keV, gas density ~0.001 cm^{-3}

Bordoloi et al.(2017) found the bubble age is 5-9 Myr from UV absorption line studies of HVCs towards the bubbles.

Sgr A$*$ is orbited by over a hundred massive stars with ages ~ 6±2 Myr

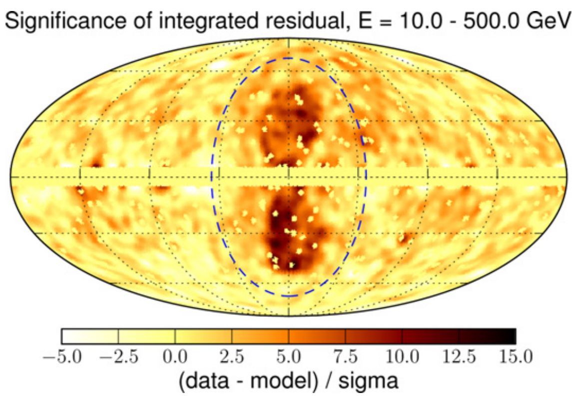


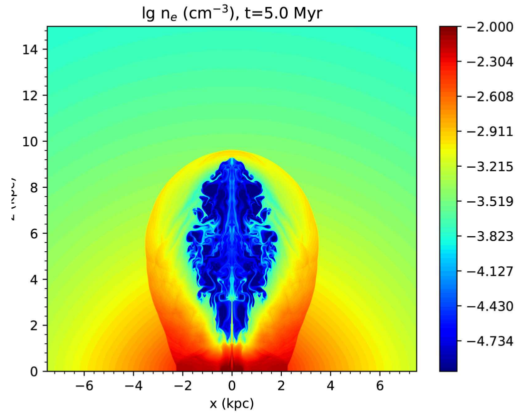




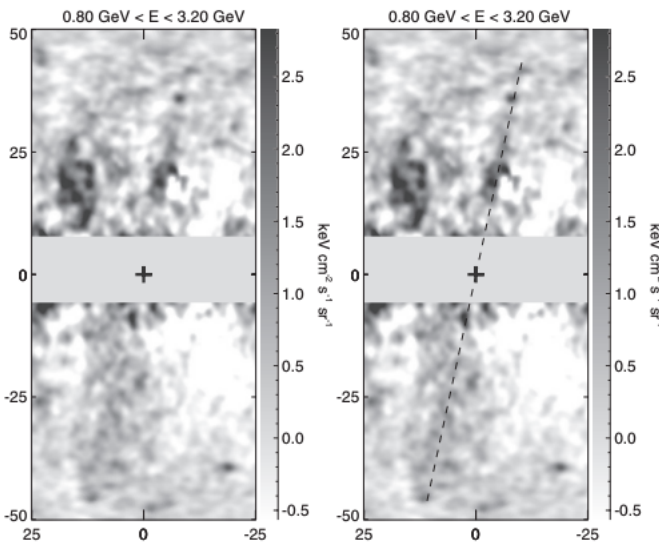
Miller et al.(2016)

Fermi Bubbles： Forward shock + (unseen) inner lobes



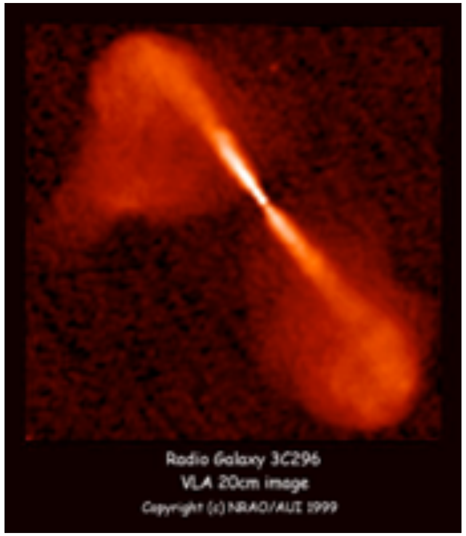


Su & Finkbeiner 2012



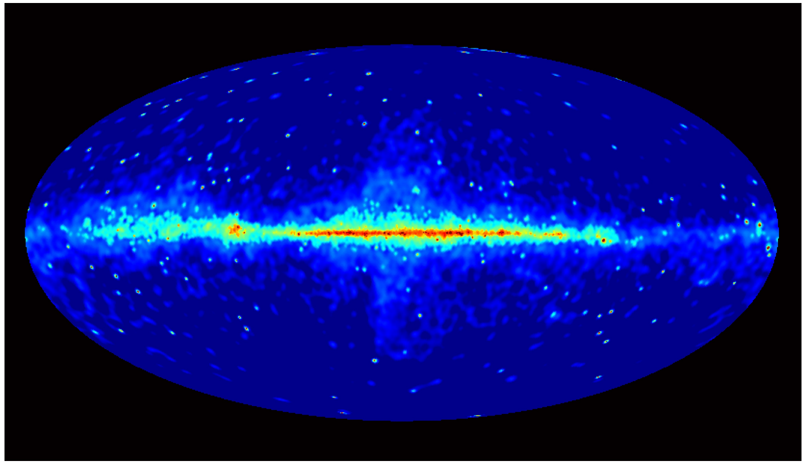
very weak evidence for inner ejecta lobes in gamma rays

Jet-mode AGN Feedback： galaxy clusters vs. L* galaxies



Jet mode AGN feedback in galaxy clusters:

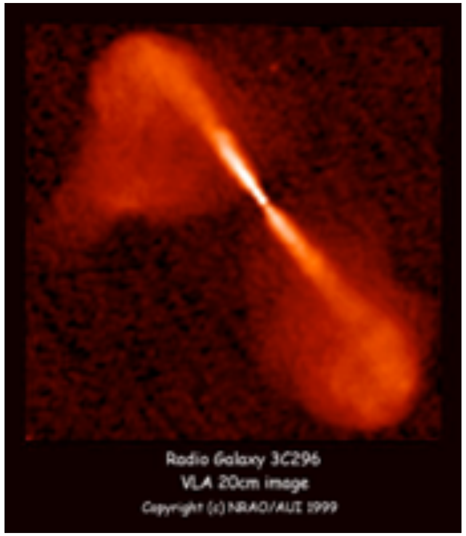
prominent radio lobes + weak shocks



Jet mode AGN feedback in L* galaxies:

(Weak or strong) inner ejecta bubbles + prominent shocked bubbles

A Comprehensive Picture of Jet-mode AGN Feedback
galaxy clusters vs. L* galaxies



Jet mode AGN feedback in galaxy clusters:
prominent radio lobes + weak shocks

Jet mode AGN feedback in L* galaxies:
(Weak or strong) inner ejecta bubbles
+ prominent shocked bubbles
(kpc-scale radio structures commonly found in local Seyfert galaxies)

Next: How do Fermi-bubble-like events affect the evolution of L* galaxies?