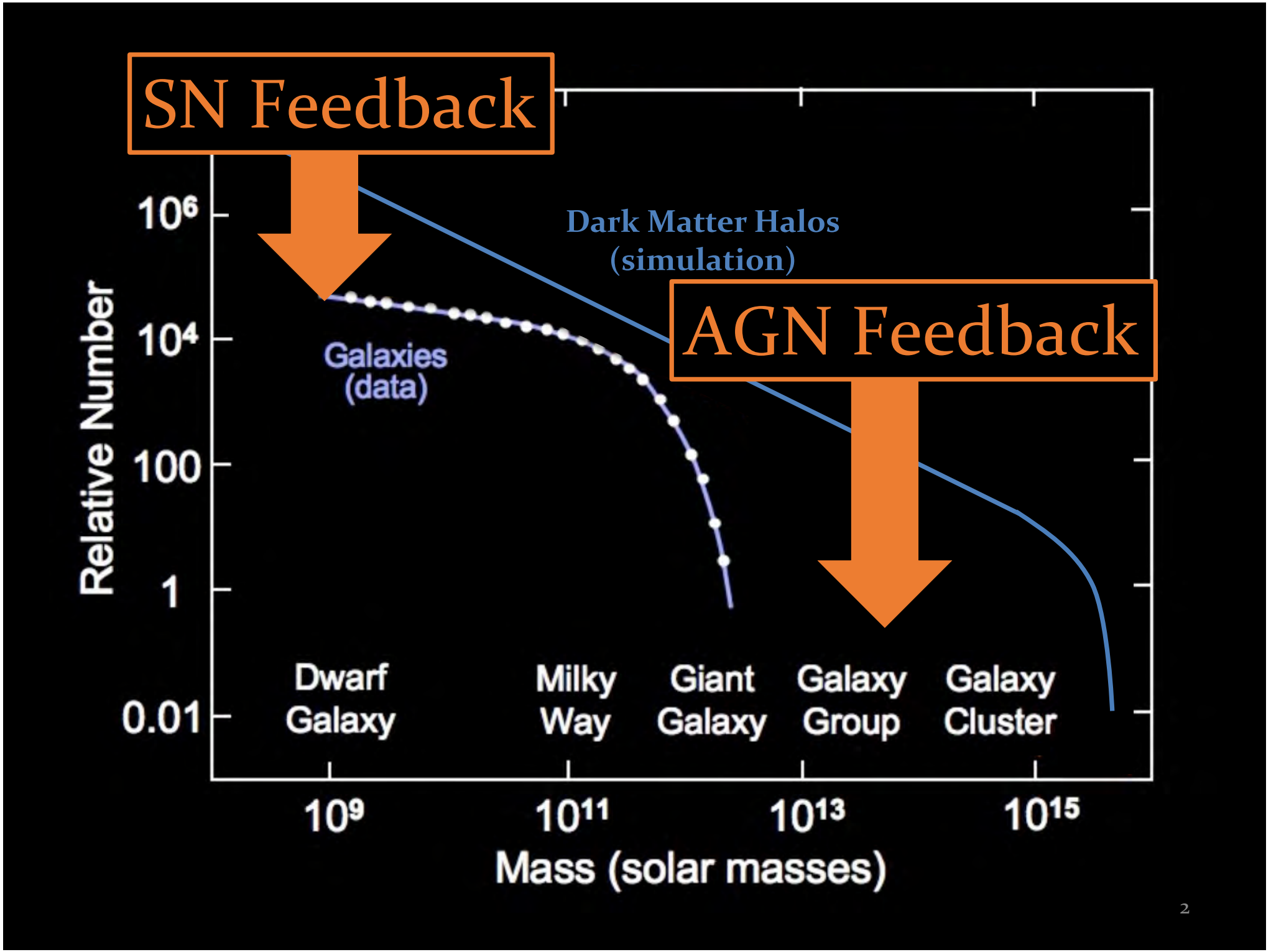
Cosmic Ray Feedback in the Universe – Fermi Bubbles and Odd Radio Circles



Hsiang-Yi Karen Yang (NTHU, Taiwan)

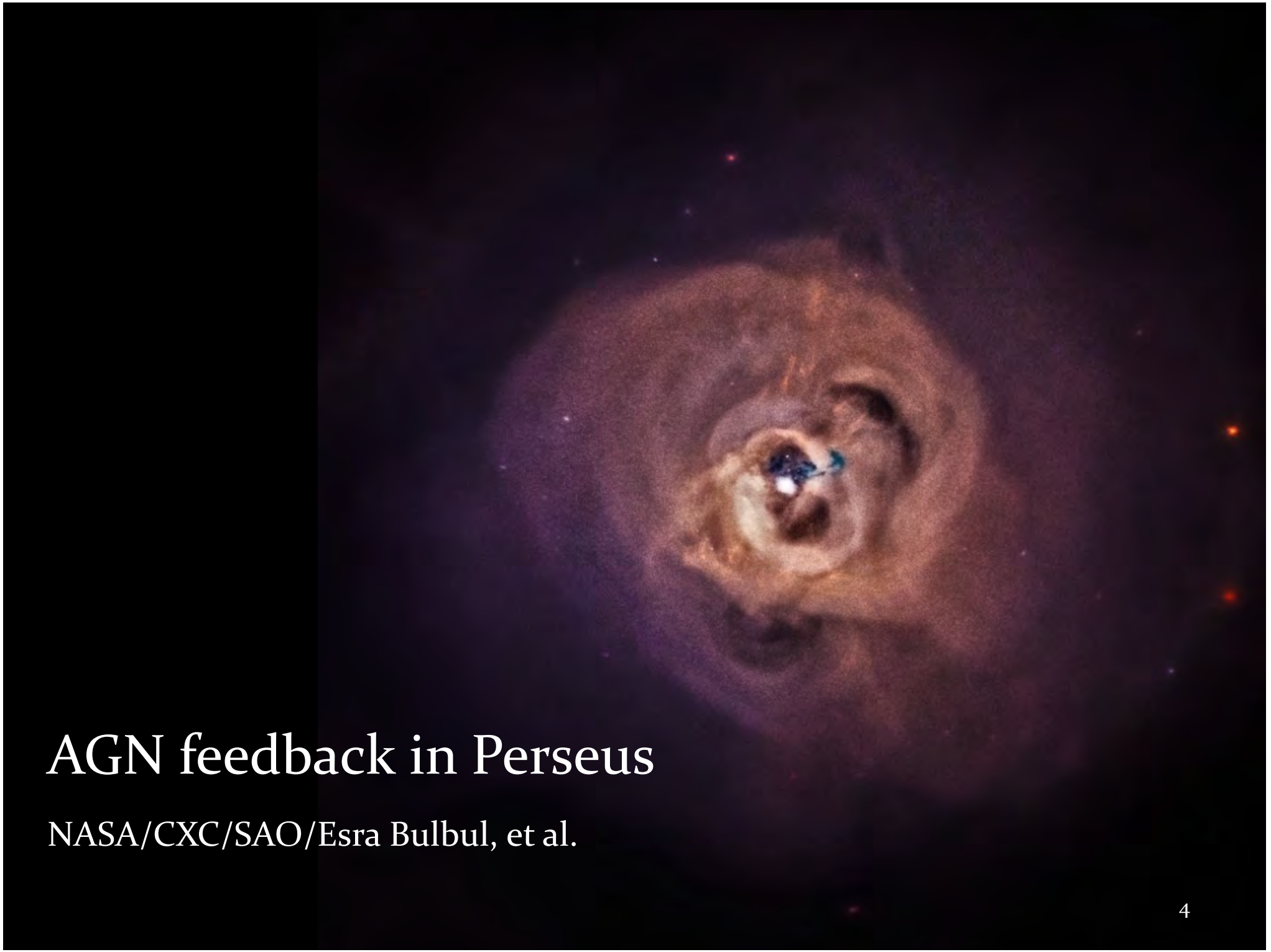
EAMA11 Meeting @ Niigata, Japan, 12/12/2025


SN Feedback
AGN Feedback
Dark Matter Halos
(simulation)
Galaxies
(data)
Relative Number
10⁶
10⁴
100
1
0.01
Dwarf
Galaxy
Milky
Way
Giant
Galaxy
Galaxy
Group
Galaxy
Cluster
10⁹
10¹¹
10¹³
10¹⁵
Mass (solar masses)



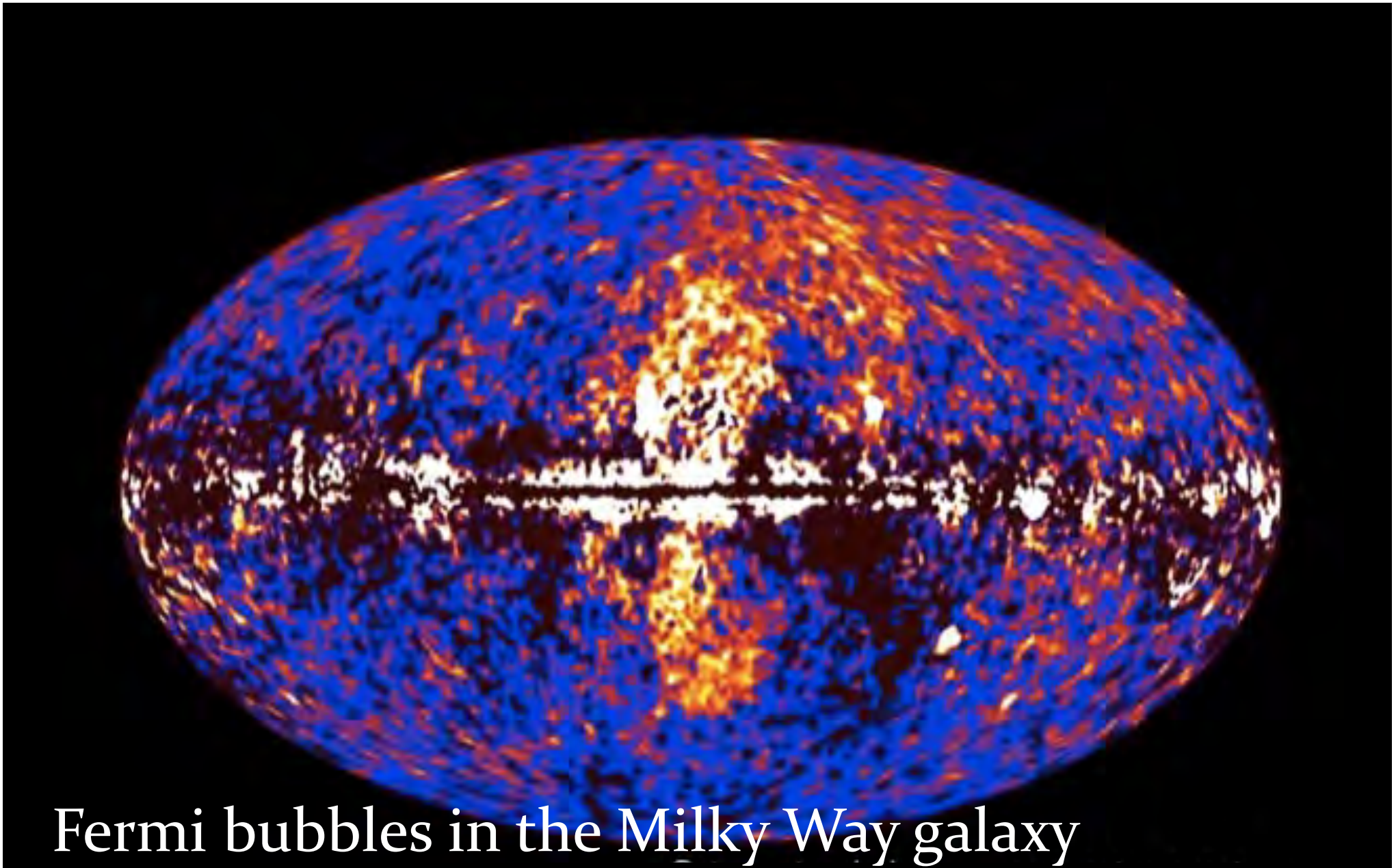
Starburst wind feedback in M82

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



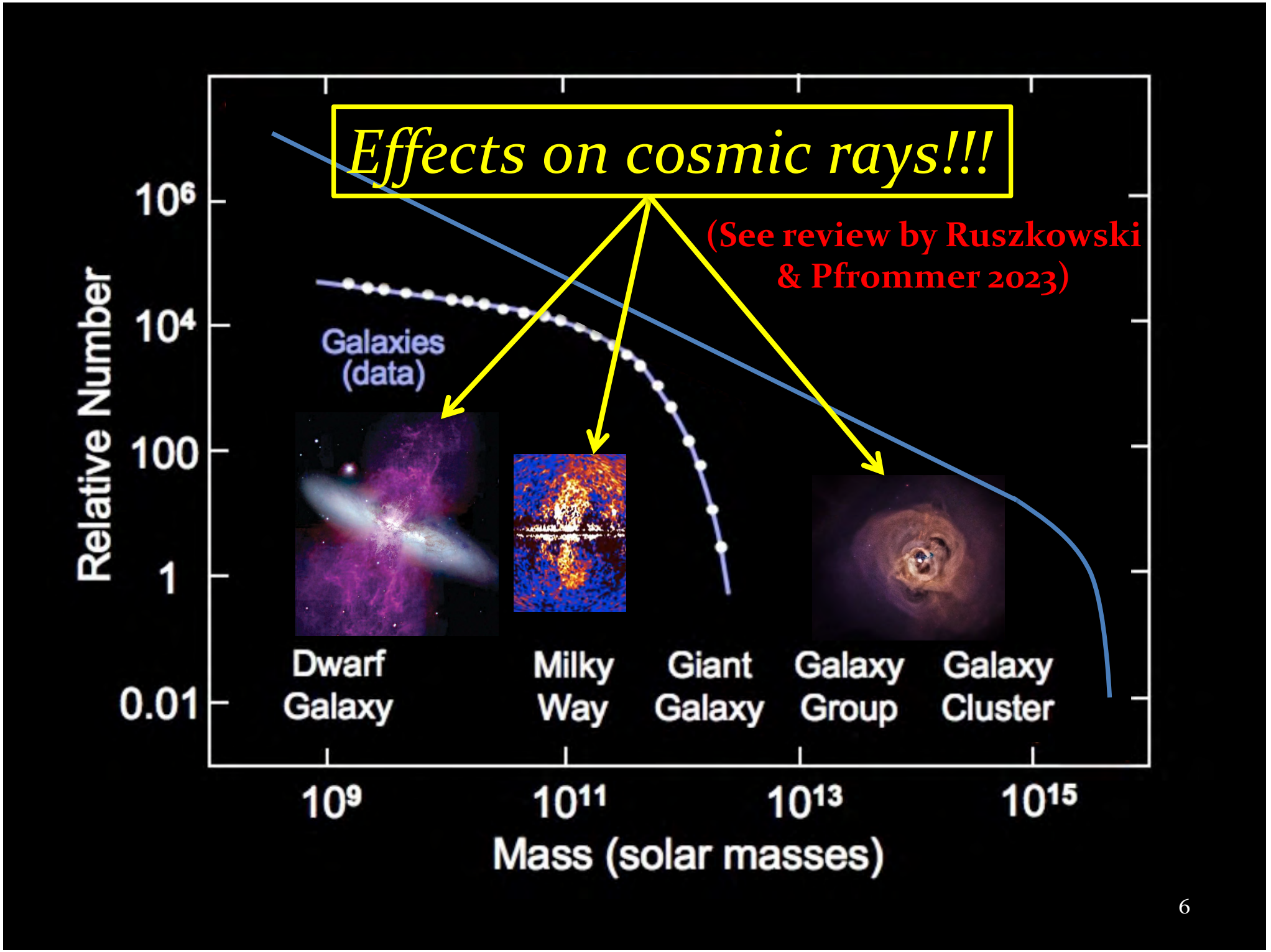
AGN feedback in Perseus

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

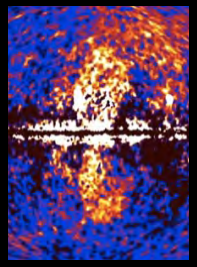


Fermi bubbles in the Milky Way galaxy

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


Effects on cosmic rays!!!
(See review by Ruszkowski & Pfrommer 2023)
Relative Number
10⁶
10⁴
100
1
0.01
Galaxies (data)
Dwarf Galaxy
Milky Way
Giant Galaxy
Galaxy Group
Galaxy Cluster
10⁹
10¹¹
10¹³
10¹⁵
Mass (solar masses)

Theme of my research group @ NTHU – ***CR feedback from galaxy to cluster scales***



❖ Fermi bubbles & analogs in other galaxies

-- Yang, Ruszkowski & Zweibel, 2022, Nature Astronomy, 6, 584

-- Owen & Yang, 2022a, MNRAS, 510, 5834

-- Owen & Yang, 2022b, MNRAS, stac2289

-- Tseng, Yang, Chen, Schive & Chiueh, 2024, ApJ in press

-- Lin & Yang, 2024, ApJ, 974, 269



❖ AGN feedback in galaxy clusters

-- Wang & Yang, 2022, MNRAS, 512, 5100

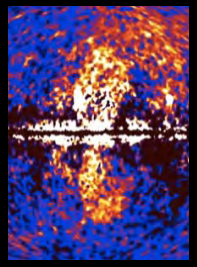
-- Lin, Yang & Owen, 2023, MNRAS, 520, 963

-- Li & Yang 2025, ApJ submitted (arXiv: 2511.23267)

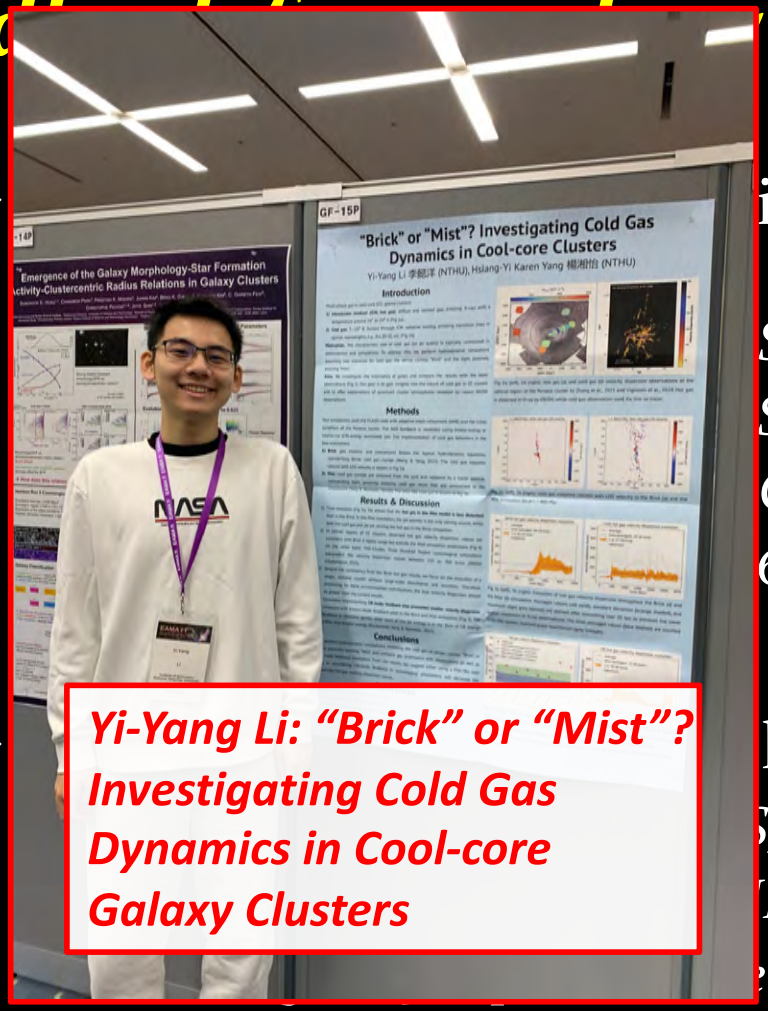
*-- Hsieh, Yang & ZuHone, to be submitted to MNRAS (**SM-10P**)*

*-- Li & Yang, in prep. (**GF-15P**)*

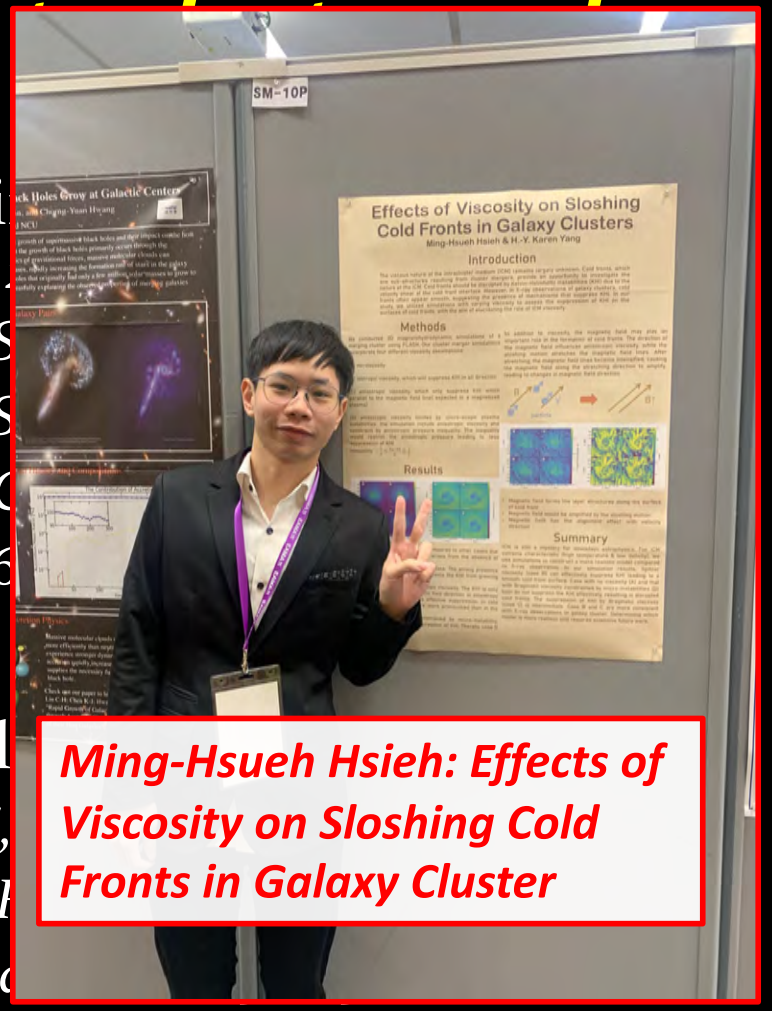
Theme of my research group @ NTHU – ***CR feed***







Yi-Yang Li: "Brick" or "Mist"? Investigating Cold Gas Dynamics in Cool-core Galaxy Clusters



Ming-Hsueh Hsieh: Effects of Viscosity on Sloshing Cold Fronts in Galaxy Cluster

*-- Hsieh, Yang & ZuHone, to be submitted to MNRAS (**SM-10P**)*

*-- Li & Yang, in prep. (**GF-15P**)*

Postdoctoral Position in Computational Astrophysics

More details on AAS Job Register
Due date: 1/5/2026

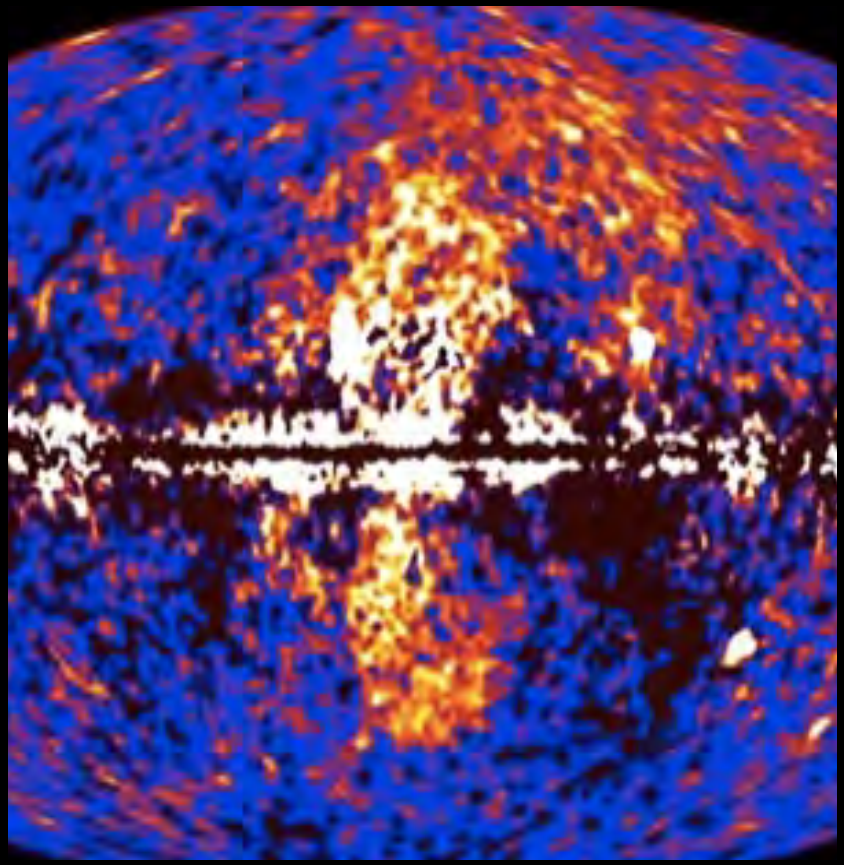
Job Summary

Category: Post-doctoral Positions and Fellowships
Institution: National Tsing Hua University
Department: Institute of Astronomy
Number of Positions Available: 1
Work Arrangement: In-Person

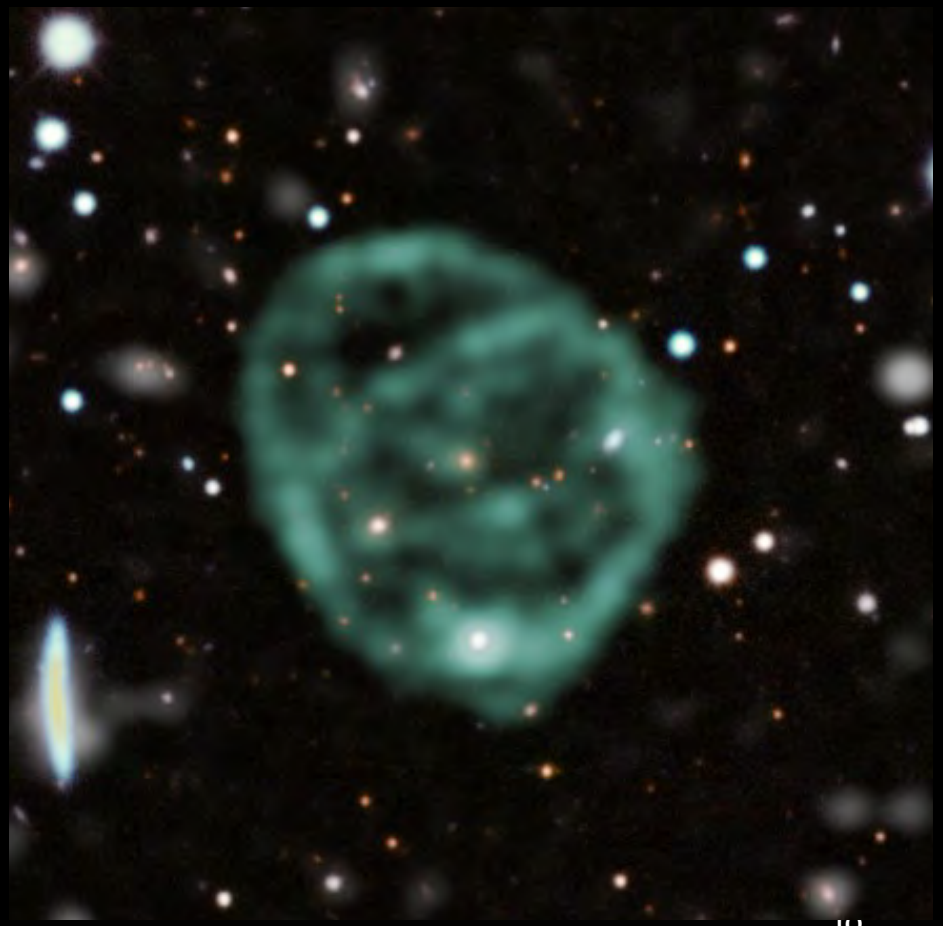


Two examples of CR feedback

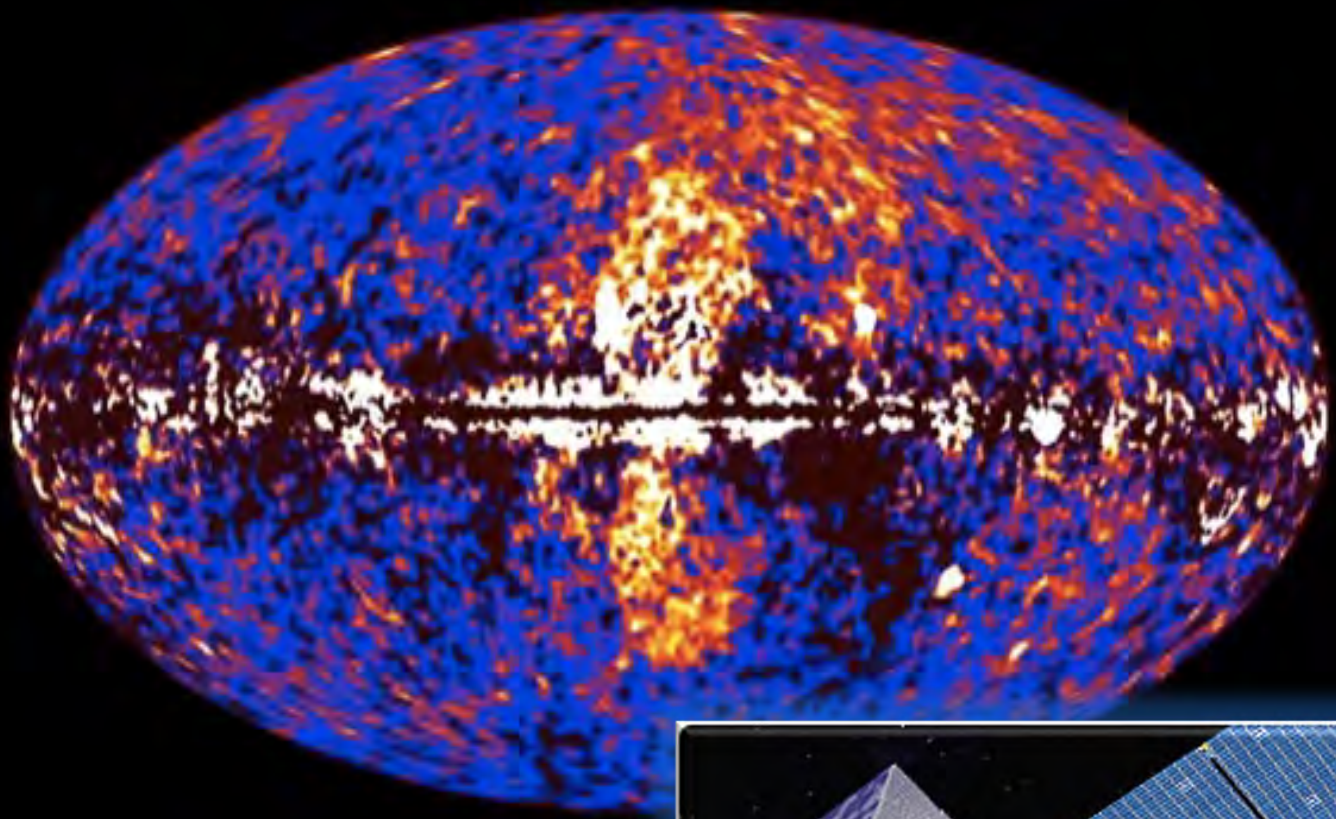
#1: Fermi/eRosita bubbles



#2: Odd radio circles (ORCs)

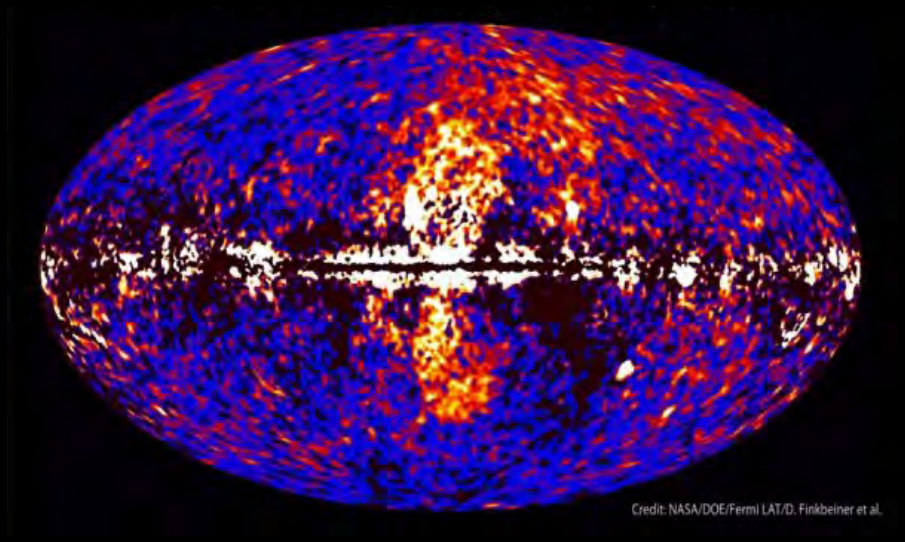


The Fermi bubbles (Su+ 2010)

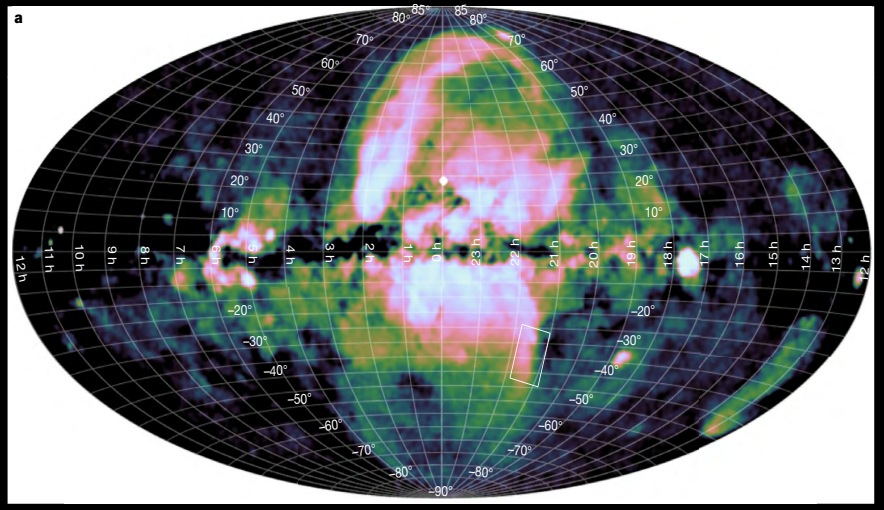




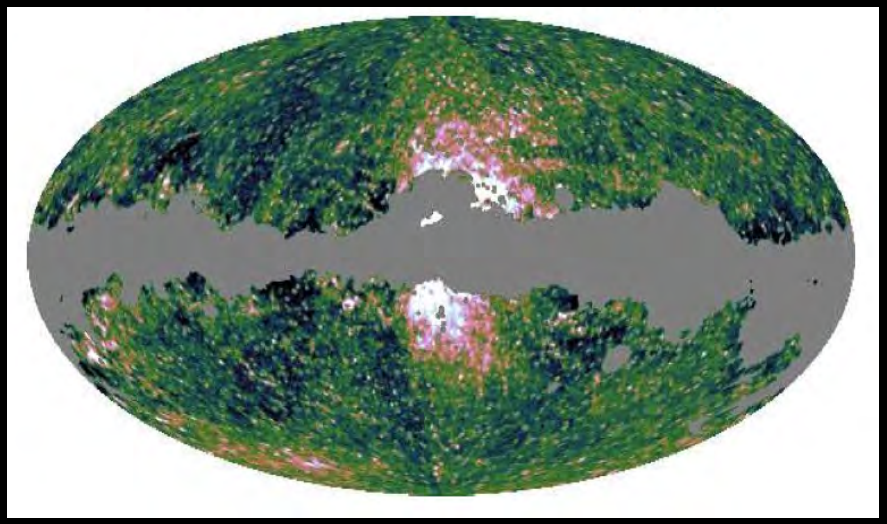
Fermi (Gamma-ray)



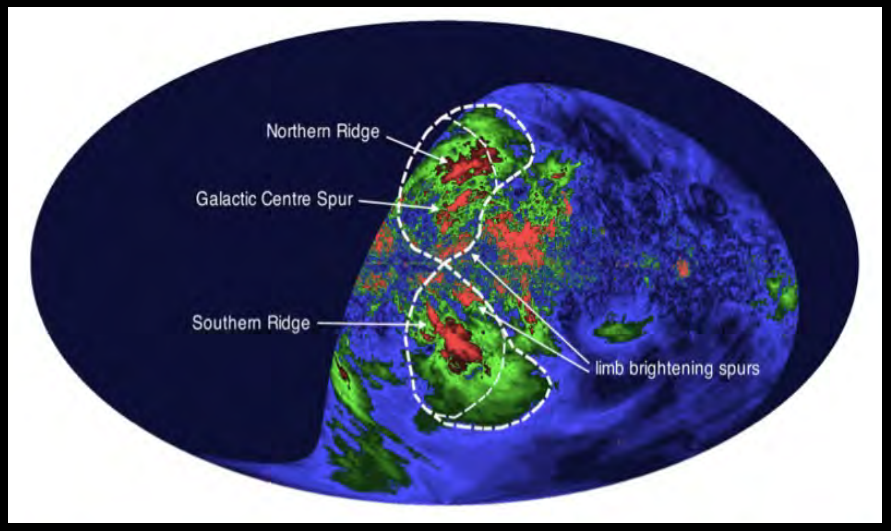
eRosita (X-ray)



WMAP & Planck (Microwave)

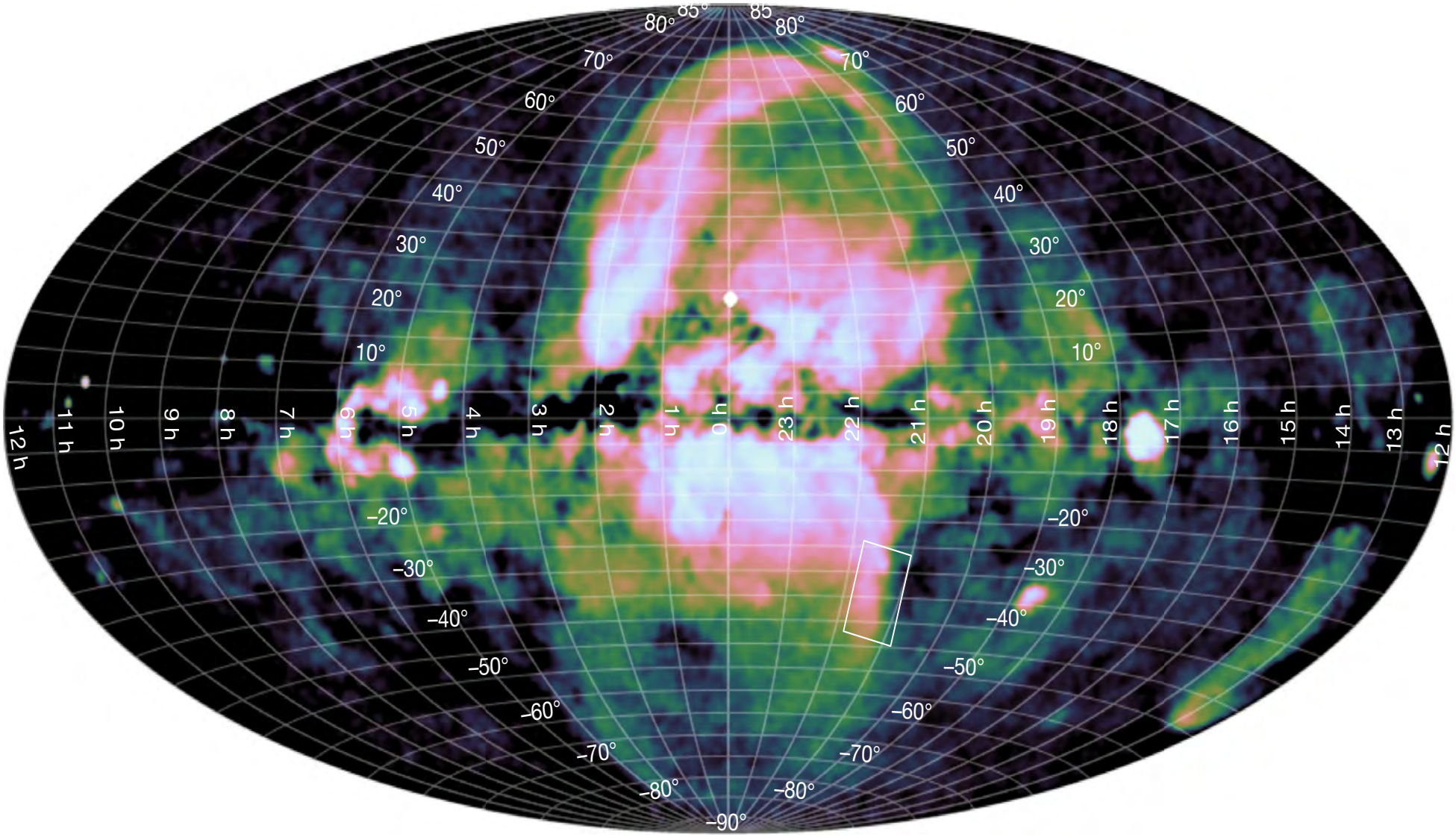


S-PASS (Polarization)



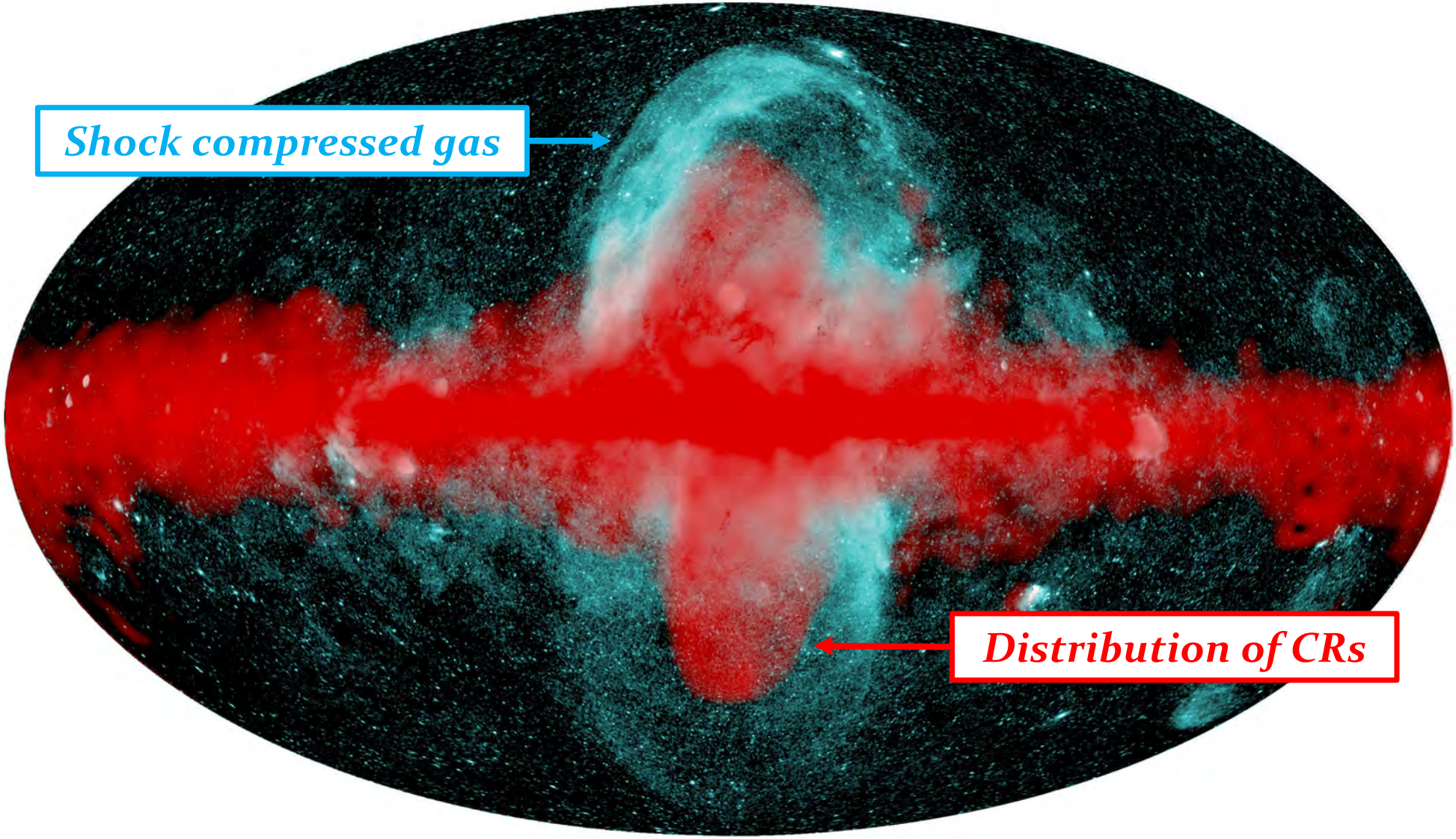
The eRosita bubbles (0.6-1.0 keV)

(Predehl et al., 2020, Nature, 588, 227)



X-ray map by *eRosita* + Gamma-ray by *Fermi*

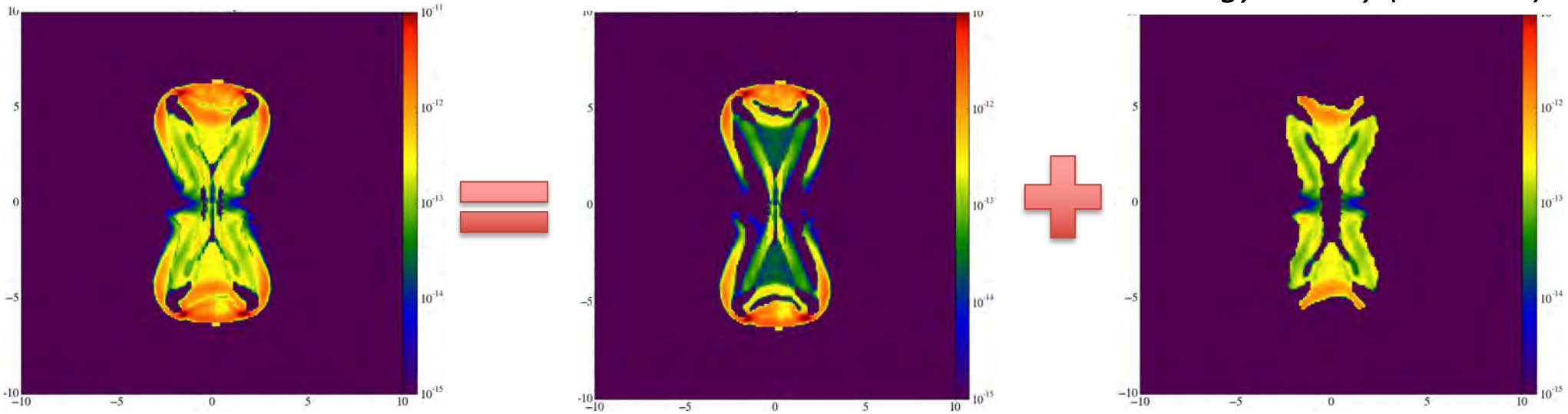
(Predehl et al., 2020, Nature, 588, 227)



Simulating formation of the Fermi/eROSITA bubbles driven by AGN jets

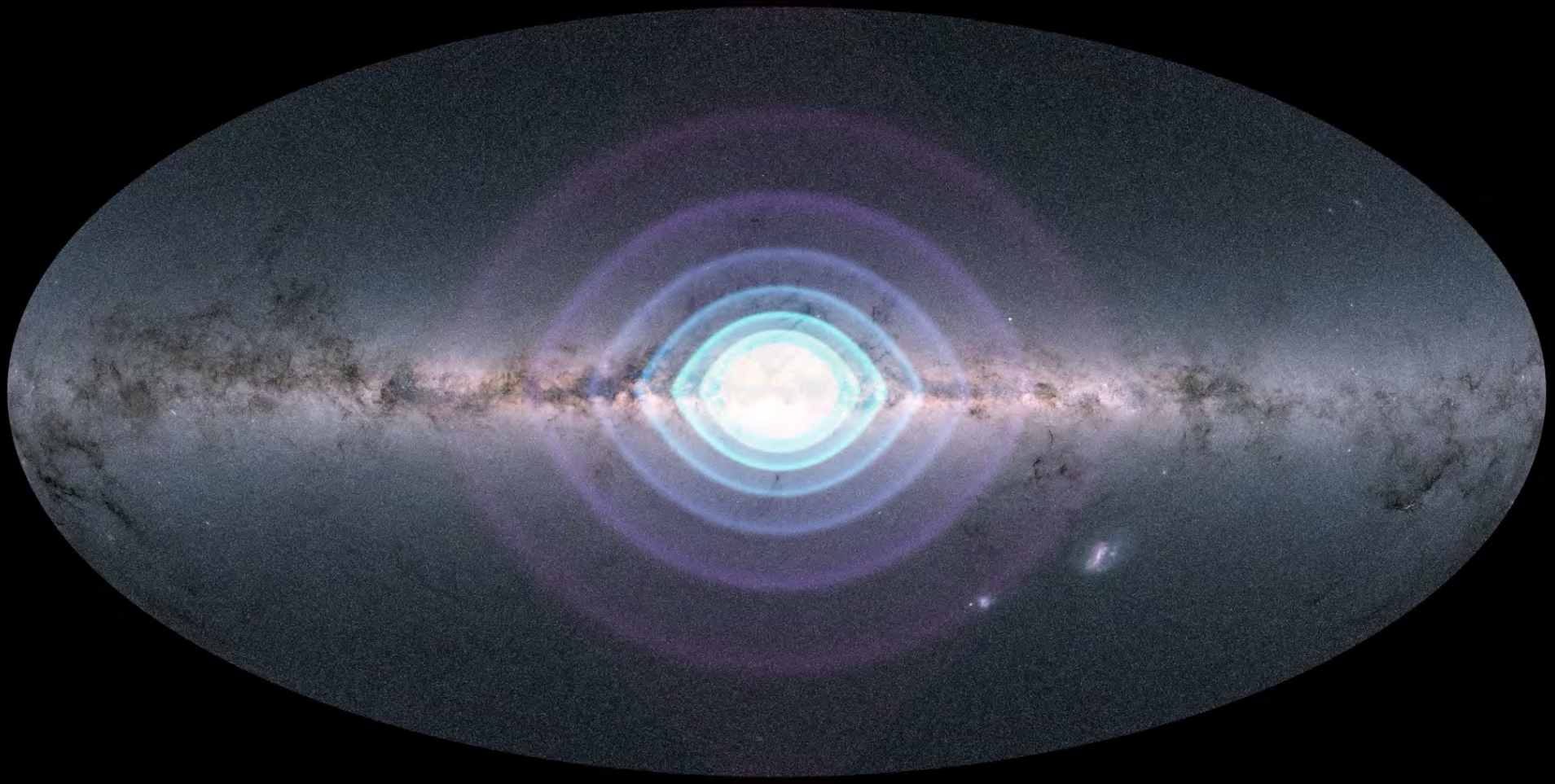
- Simulated using *MHD+CRSPEC* module in FLASH
- Injection spectrum: 10 GeV ~ 10 TeV
- IC & syn. cooling (due to Galactic radiation & B field)

Total CR energy density = *CR energy density (>10 GeV)* + *CR energy density (<10 GeV)*



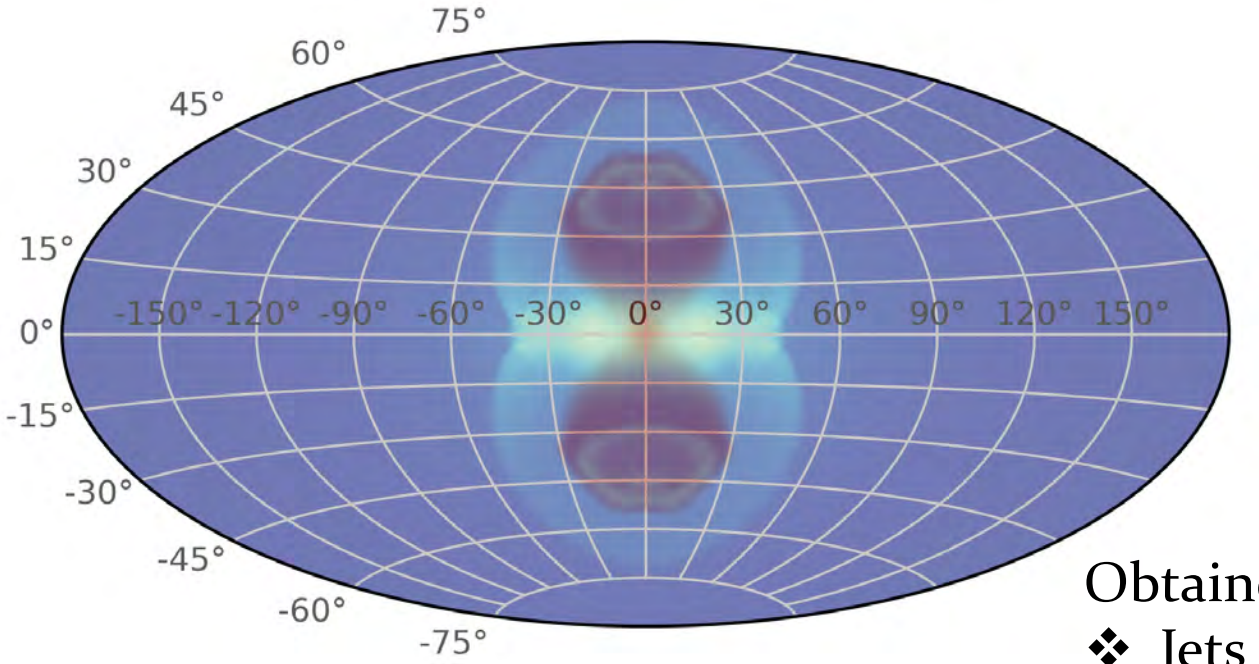
Yang & Ruszkowski (2017)

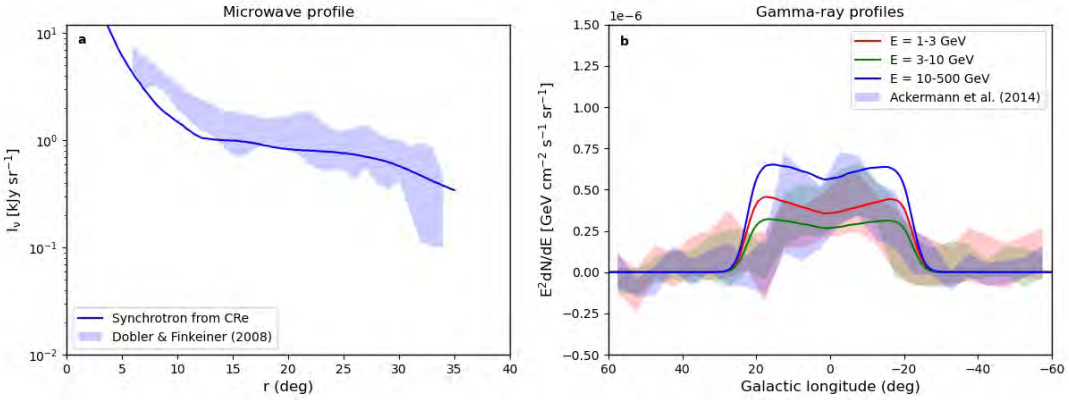
CR-MHD simulation of bubble formation by jets



Formation of the Fermi/eRosita bubbles by past jet activity from Sgr A*

(Yang, Ruszkowski, Zweibel, 2022, Nature Astronomy, 6, 584)





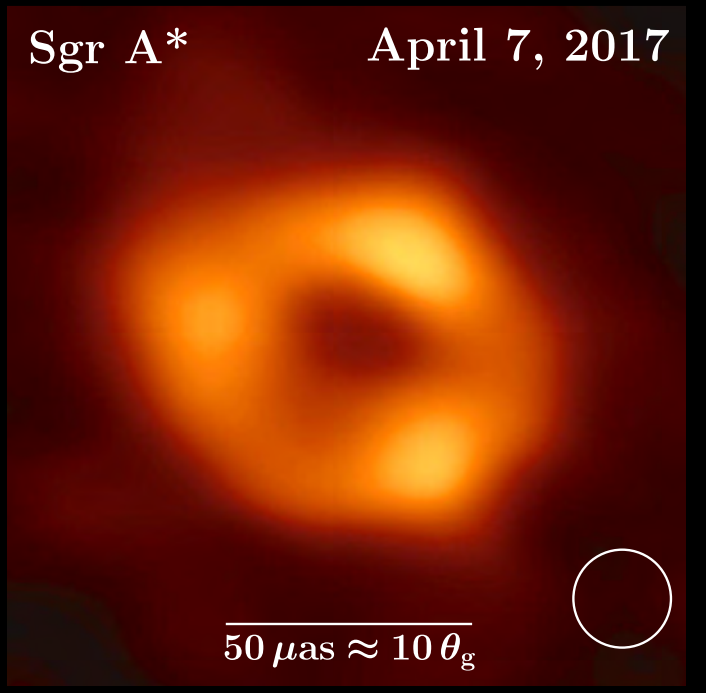
Obtained from the simulations:

- Jets occurred ***~2.6 Myr ago***
- Jets were active for 0.1 Myr
- Inferred ***Eddington ratio ~1-10%***

What about jet inclination?



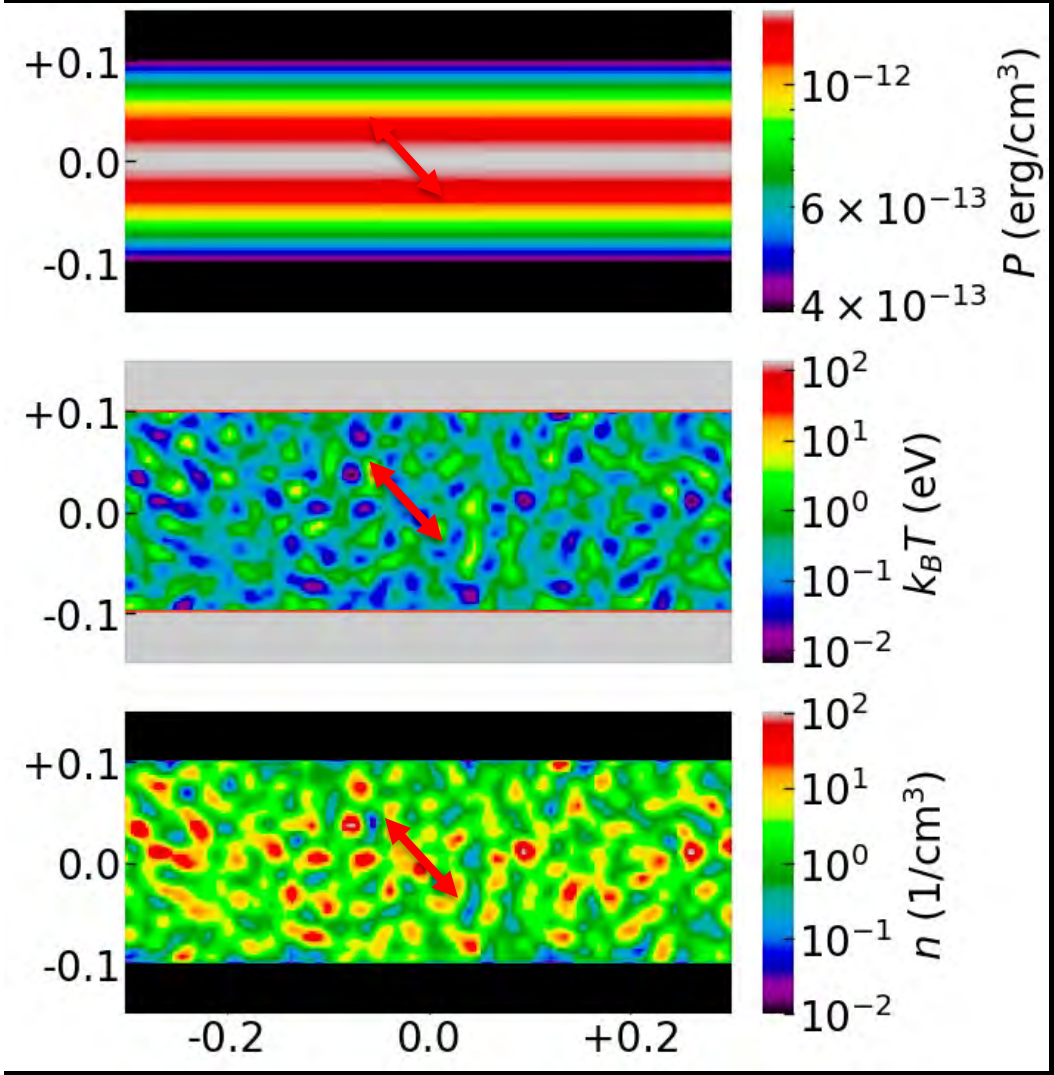
- AGN jets do not need to be perpendicular to the galactic disks



- Constraints from GRMHD simulations suggest that the spin axis of Sgr A* could be inclined (at the present day)

Can tilted jets produce symmetric Fermi/eRosita bubbles?

(Tseng, Yang, Chen, Schive & Chiueh, 2024, ApJ, 970, 146)

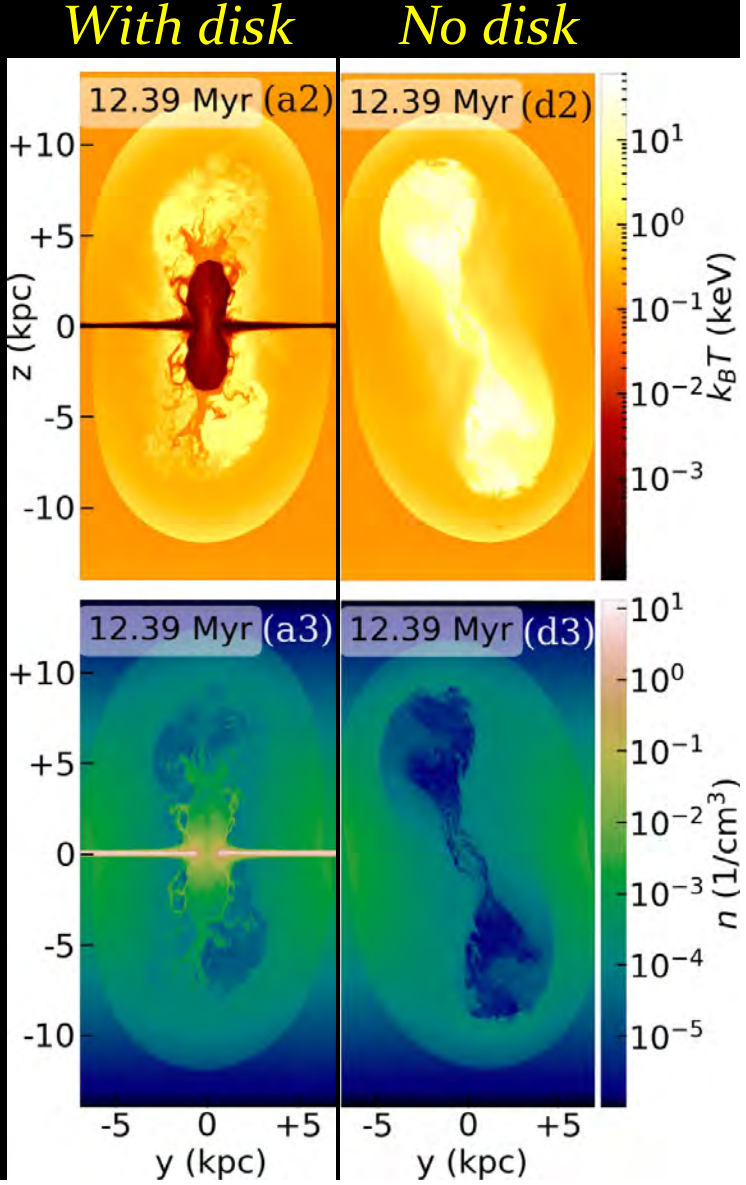


- 3D special-relativistic CR simulations using GAMER
- Tilted jets interacting with a clumpy galactic disk

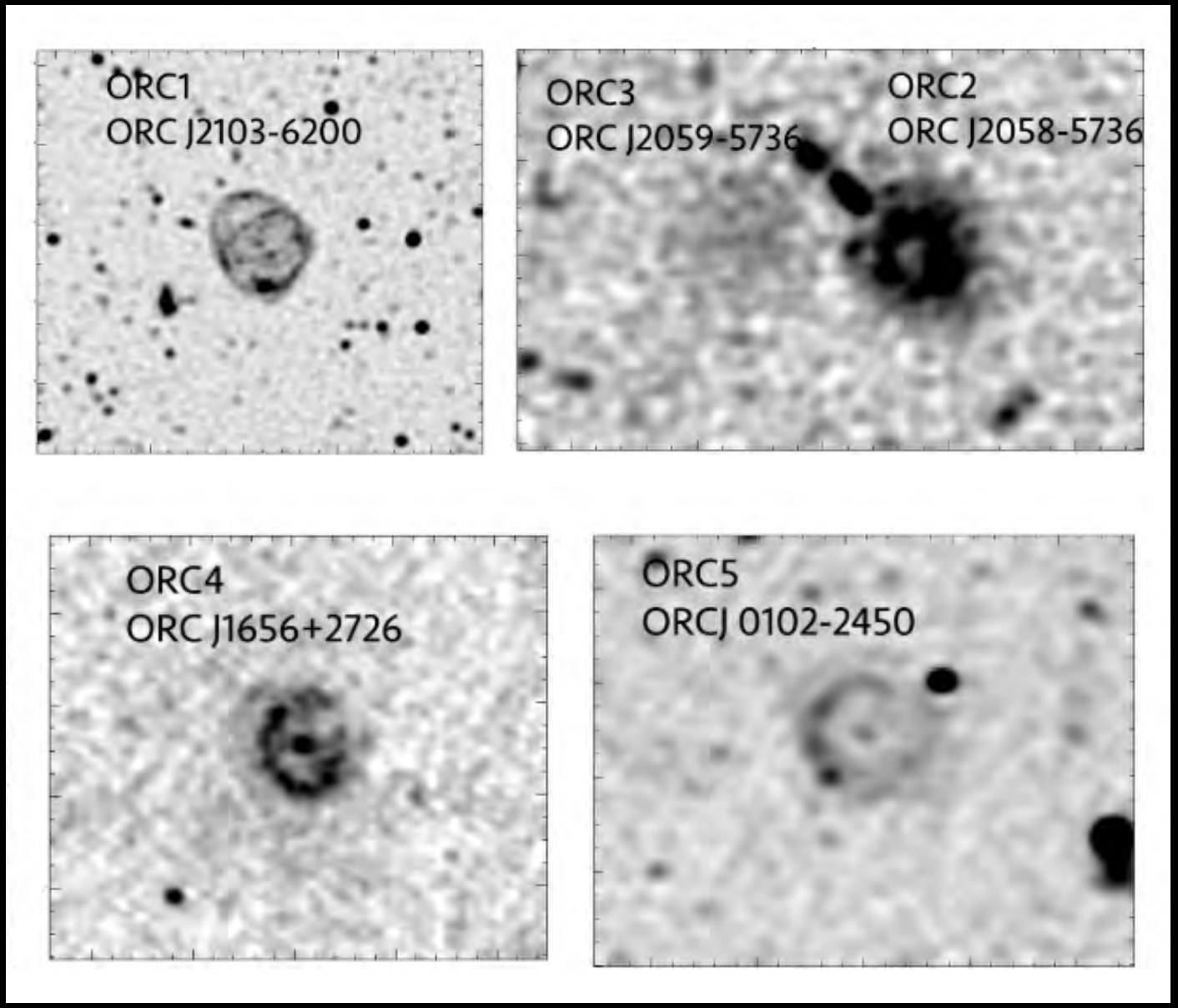
Can tilted jets produce symmetric Fermi/eRosita bubbles?

(Tseng, Yang, Chen, Schive & Chiueh, 2024, ApJ, 970, 146)

- Symmetric bubbles can be produced due to jet dissipation within the dense galactic disk
- ***Caveat***: 12.39 Myr is longer than cooling time of 500 GeV CRs => need CR re-acceleration



Odd radio circles (ORCs)



Norris et al. (2022)

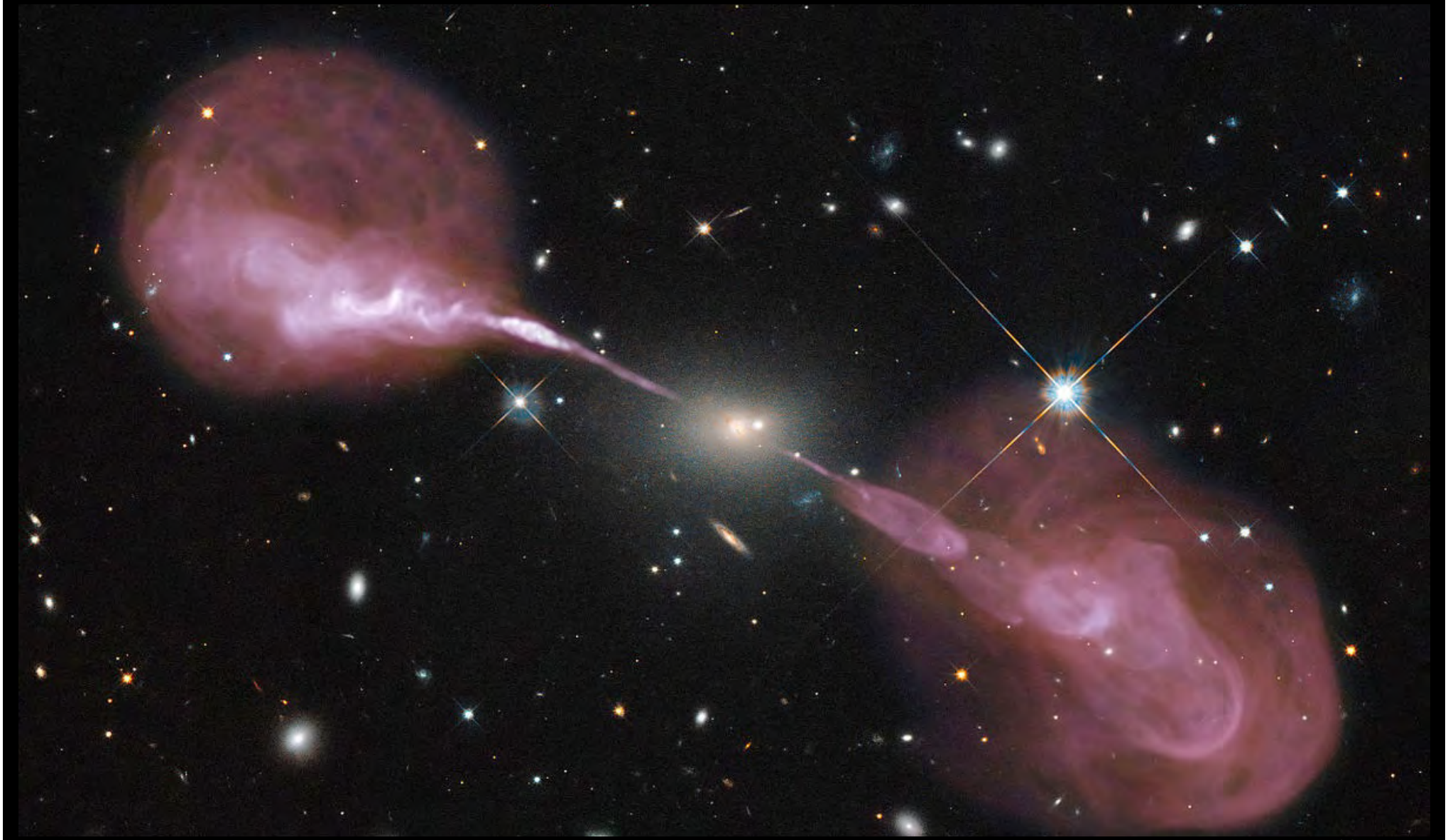
Odd radio circles (ORCs)

- Discovered in 2021 (~a dozen found so far)
- Faint, edge-brightened, and large (z~0.2-0.6, R~250kpc)
- Possible origin:
  - Star formation termination shock (Norris et al. 2022)
  - Shocks by galaxy mergers (Dolag et al. 2023)
  - Virial shocks around galaxies (Yamasaki et al. 2023)
  - End-on AGN jet-inflated bubbles



ORC1 (Norris et al. 2022)

Can AGN bubbles explain the ORCs?



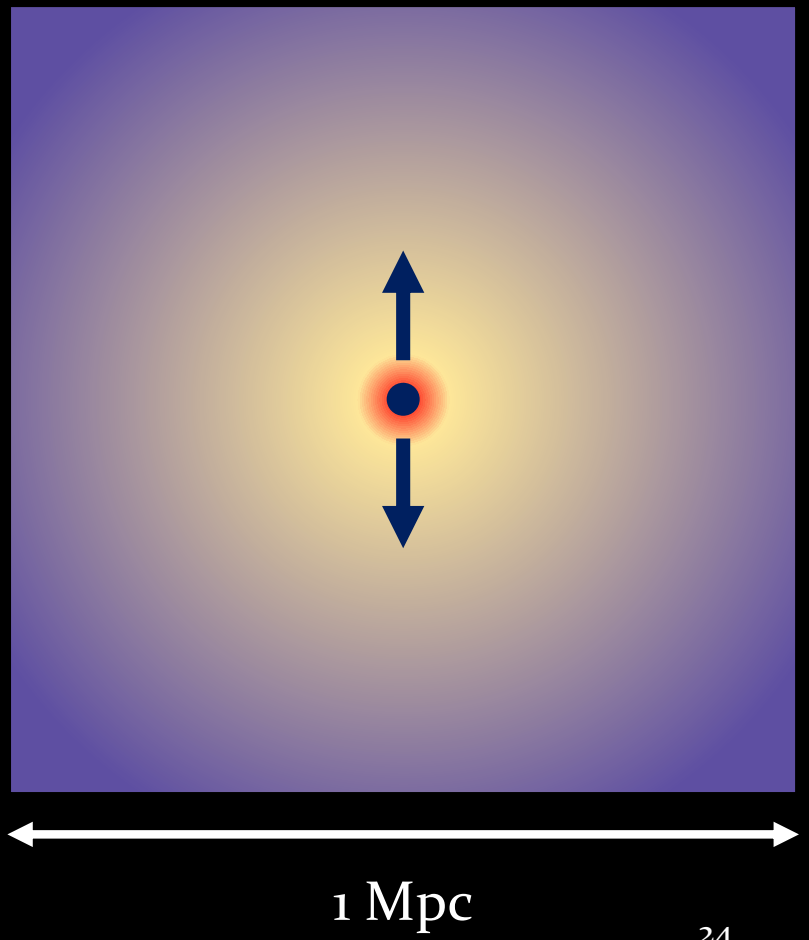
CR-MHD simulations of the ORCs

(Lin & Yang, ApJ, 974, 269)

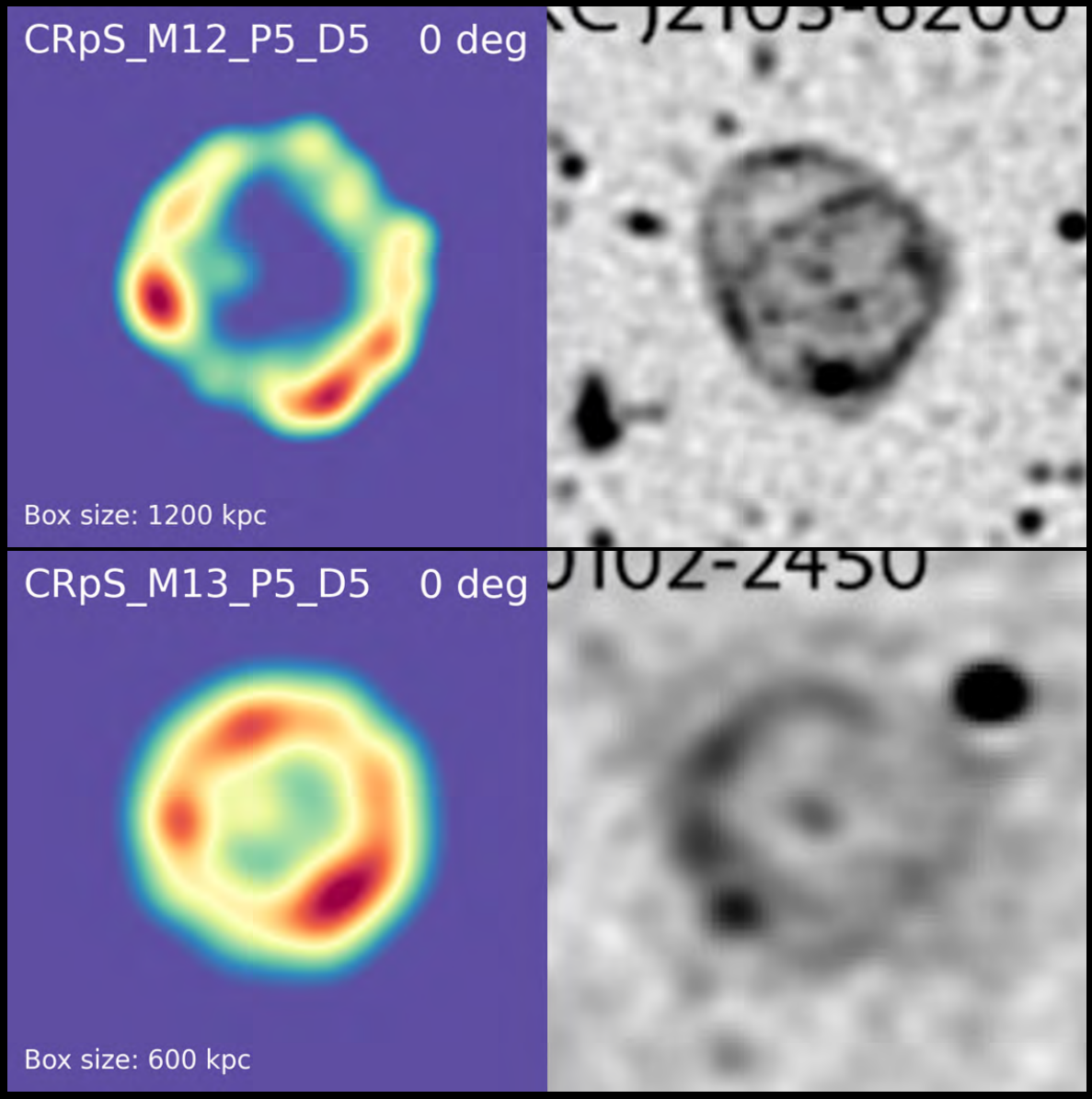


Yen-Hsing Lin
(NTHU->UCSD)

- FLASH code
- Box size: 1 Mpc, resolution: 0.5 kpc
- Gas within a low-mass halo
  (M_{vir}=8e12 ~ 8e13 M_{sun})
- ***CRp*** dominated jets
  (P_{jet}=2.5e46 erg/s, T_{jet}=50 Myr)
- Radio emission from synchrotron of secondary electrons generated via ***hadronic*** collisions



Results – ORCs reproduced!

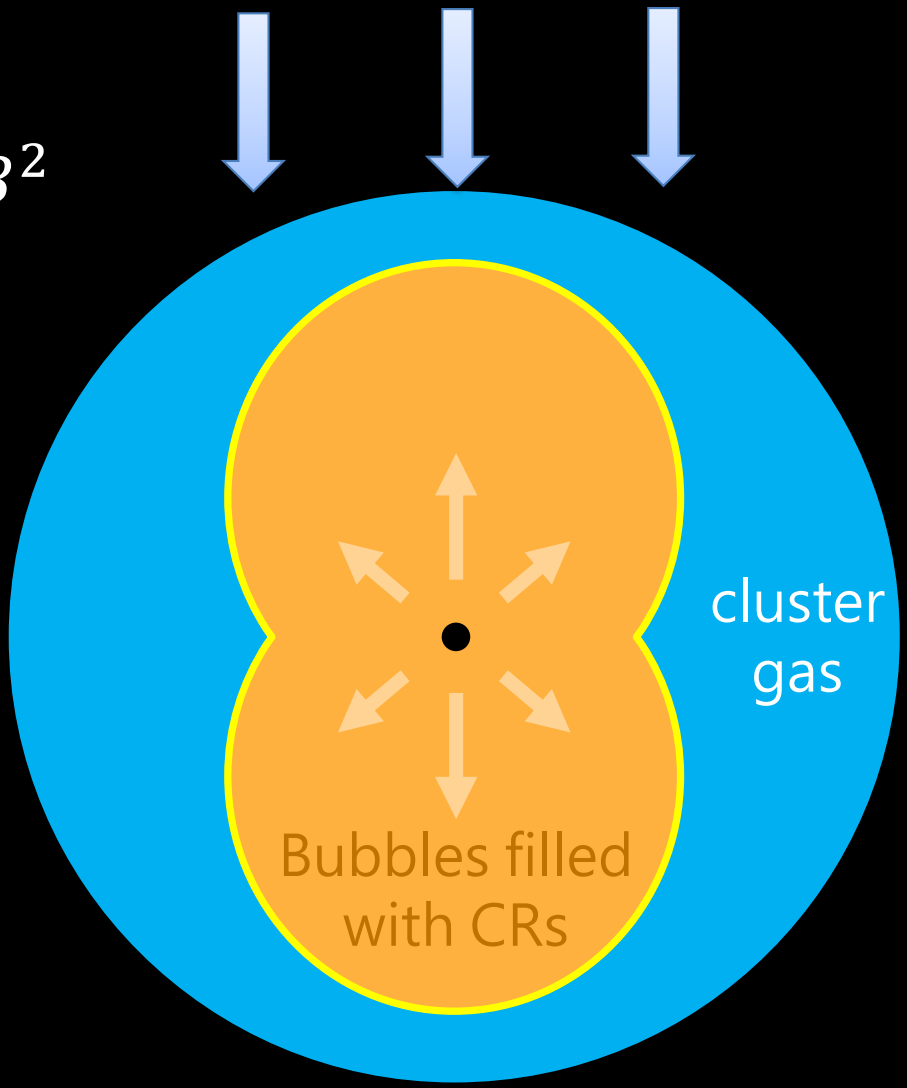


Lin & Yang (2024) Norris et al. (2022)

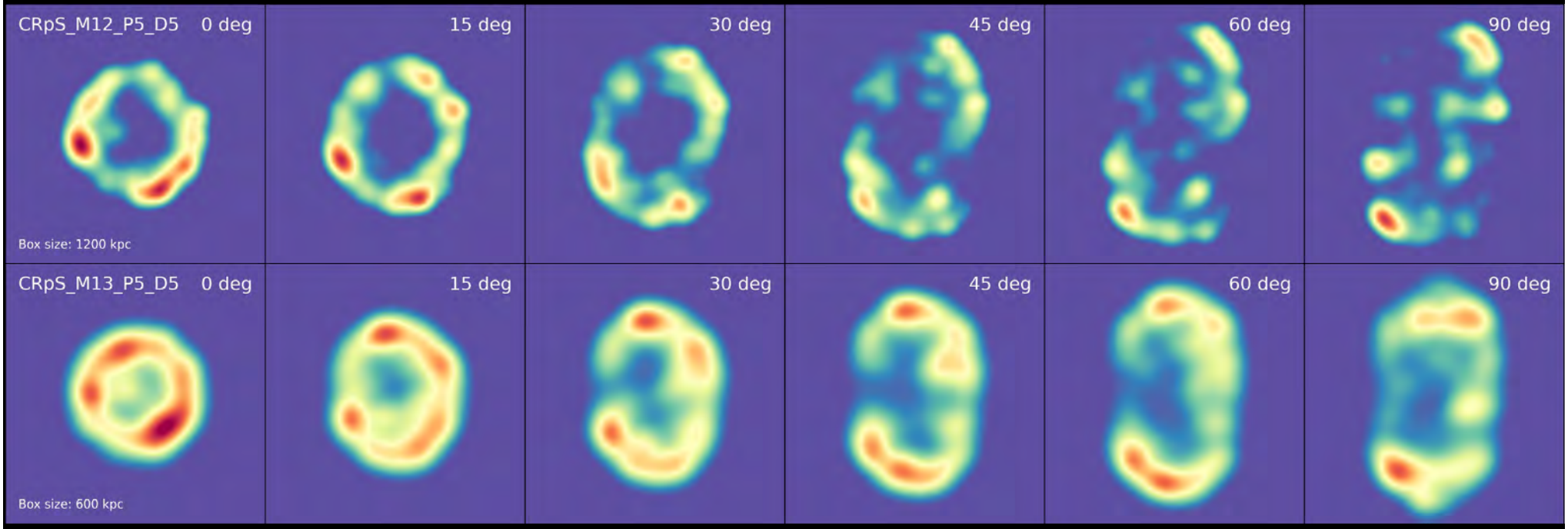
How to produce edge-brightened ORCs?

Radio emissivity: $\epsilon_{radio} \propto \boldsymbol{\rho e_{cr}} B^2$

→ highest at the bubble surface



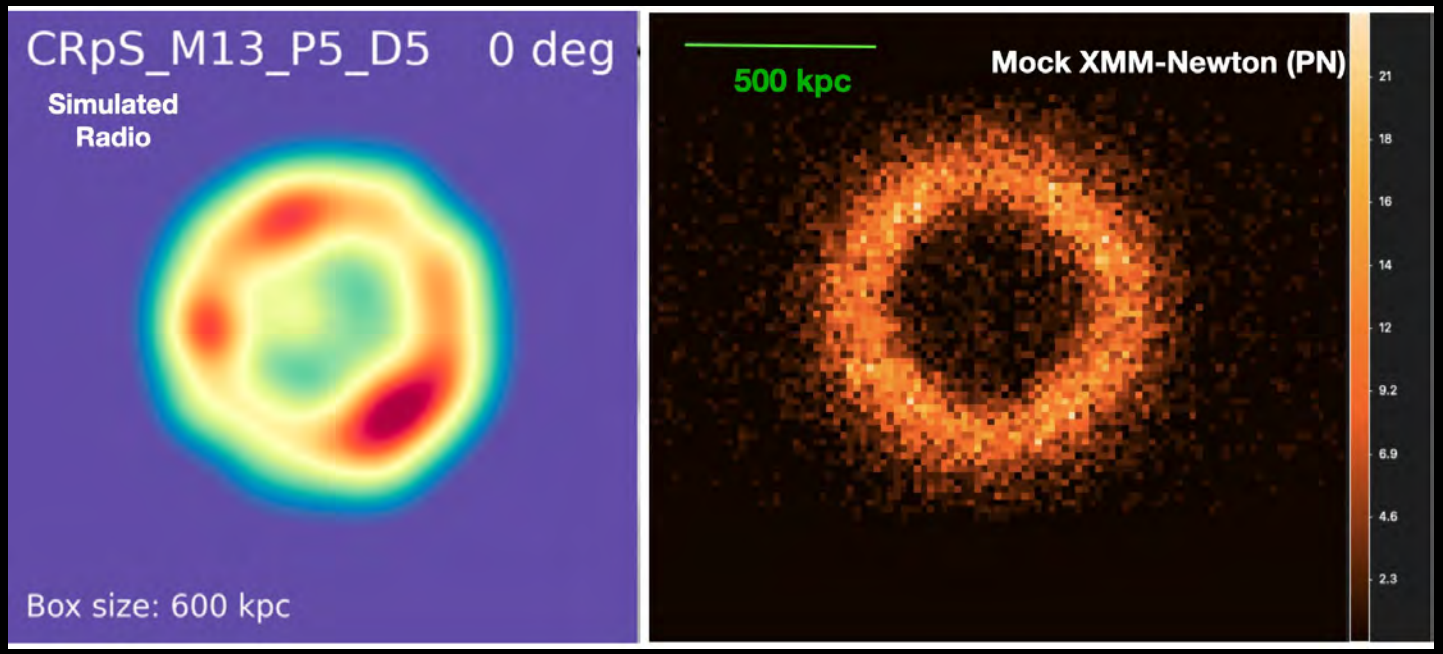
Dependence on viewing angles



end on ← → *side on*

- Shape similar to ORC1 up to θ ~ 30 degrees, relieving the requirement for perfect alignment

X-ray counterpart of ORCS?





Dr. Majidul Rahaman (NTHU)

- Our model predicts detectable X-ray emission from the shock compressed gas given long exposure times
- Our accepted proposals of ***MeerKAT, uGRMT, VLA and XMM-Newton*** observations will further unveil the origin of ORCs

Conclusions

- We've performed CR-MHD simulations to model the Fermi/eRosita bubbles and odd radio circles (ORCs)
- Fermi/eRosita bubbles are likely produced by past jet activity of Sgr A*. Both vertical and oblique jets are plausible
- End-on AGN bubbles is a plausible scenario for reproducing key features of the observed ORCs
- Understanding the Fermi/eRosita bubbles & ORCs could provide valuable information about CR feedback in the universe