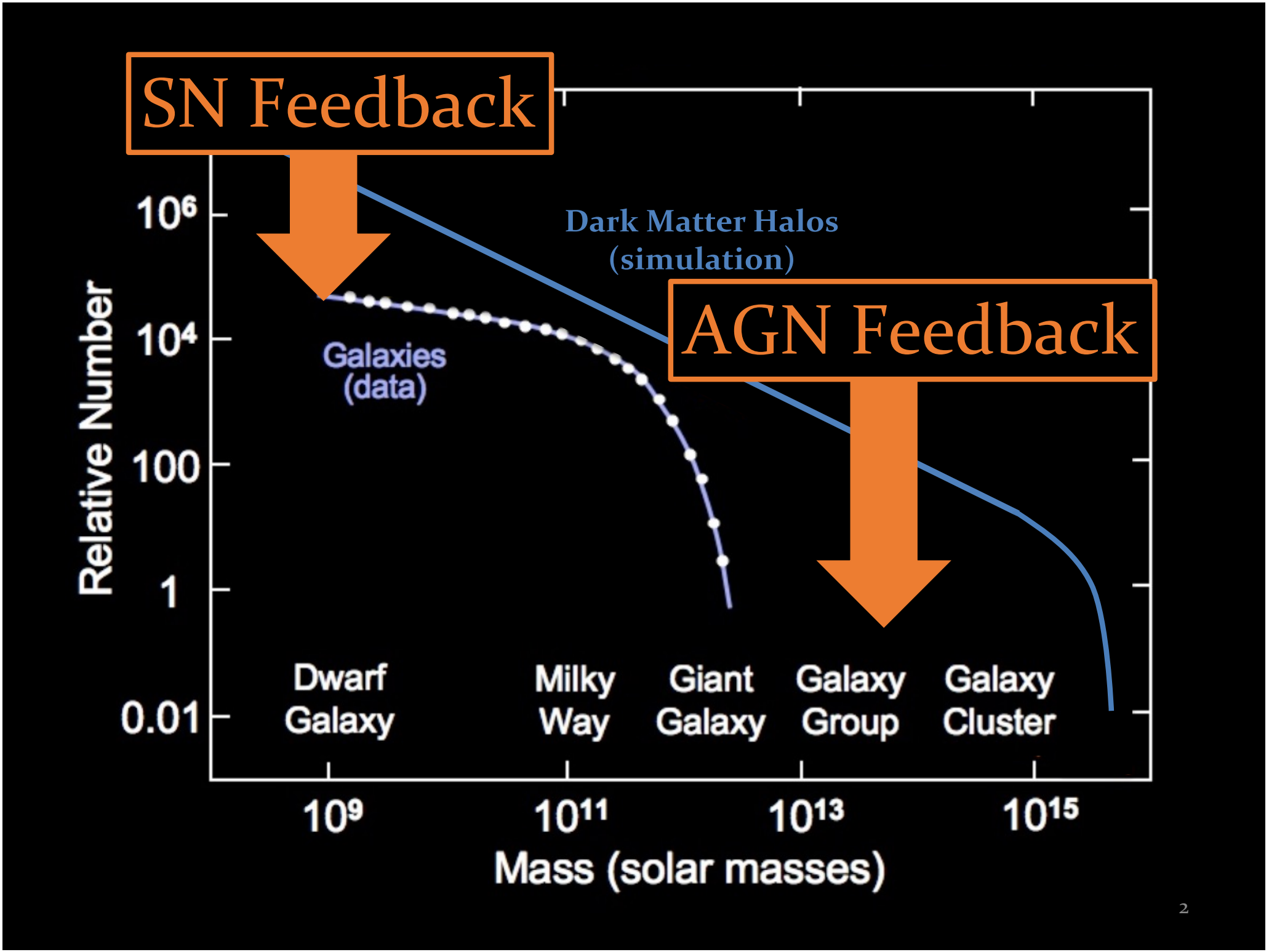
Cosmic Ray Feedback in the Universe – Fermi Bubbles and Odd Radio Circles

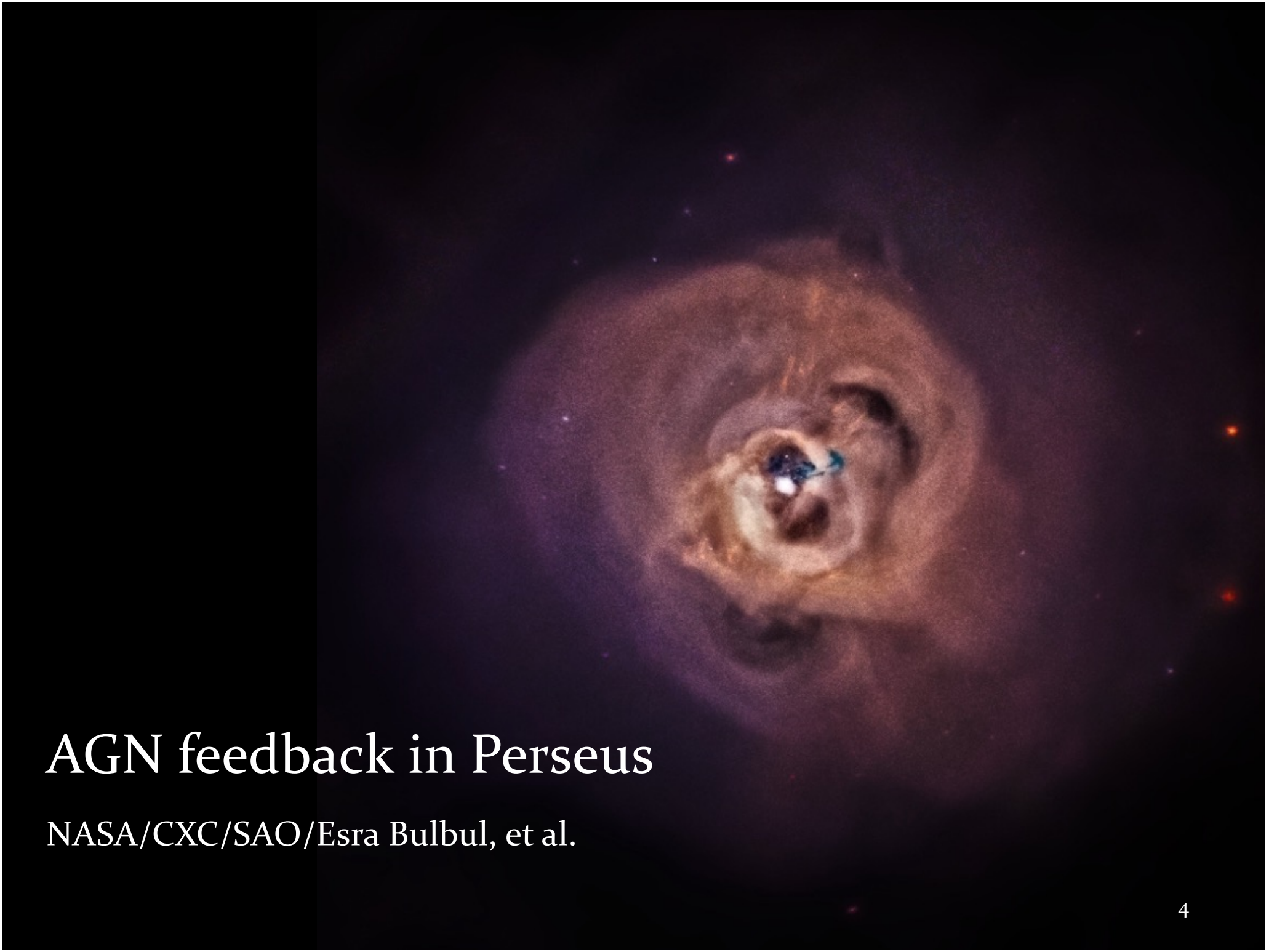
Hsiang-Yi Karen Yang (NTHU)

AIP Thinkshop @ Potsdam, 7/14/2025


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)

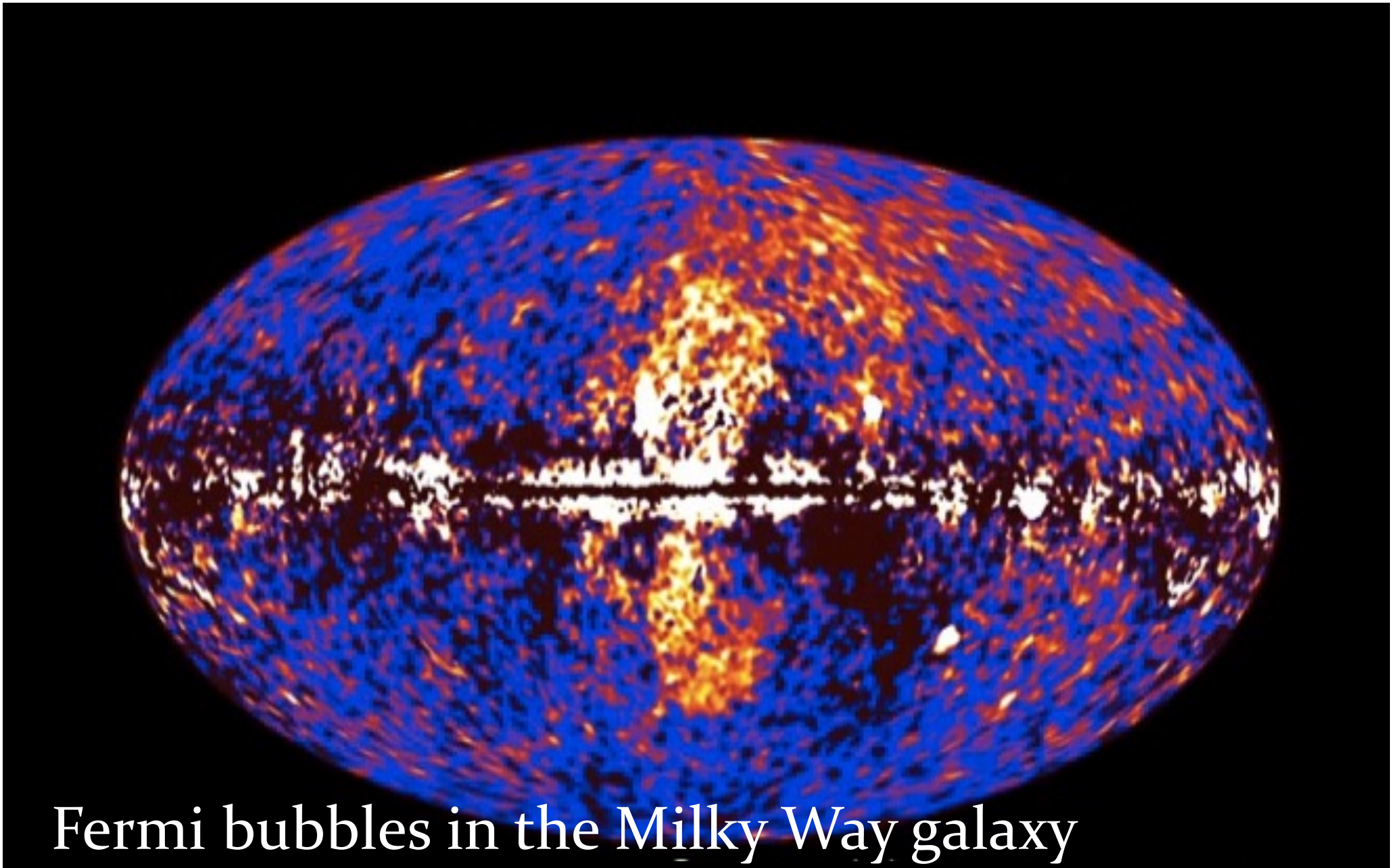
Starburst wind feedback in M82

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



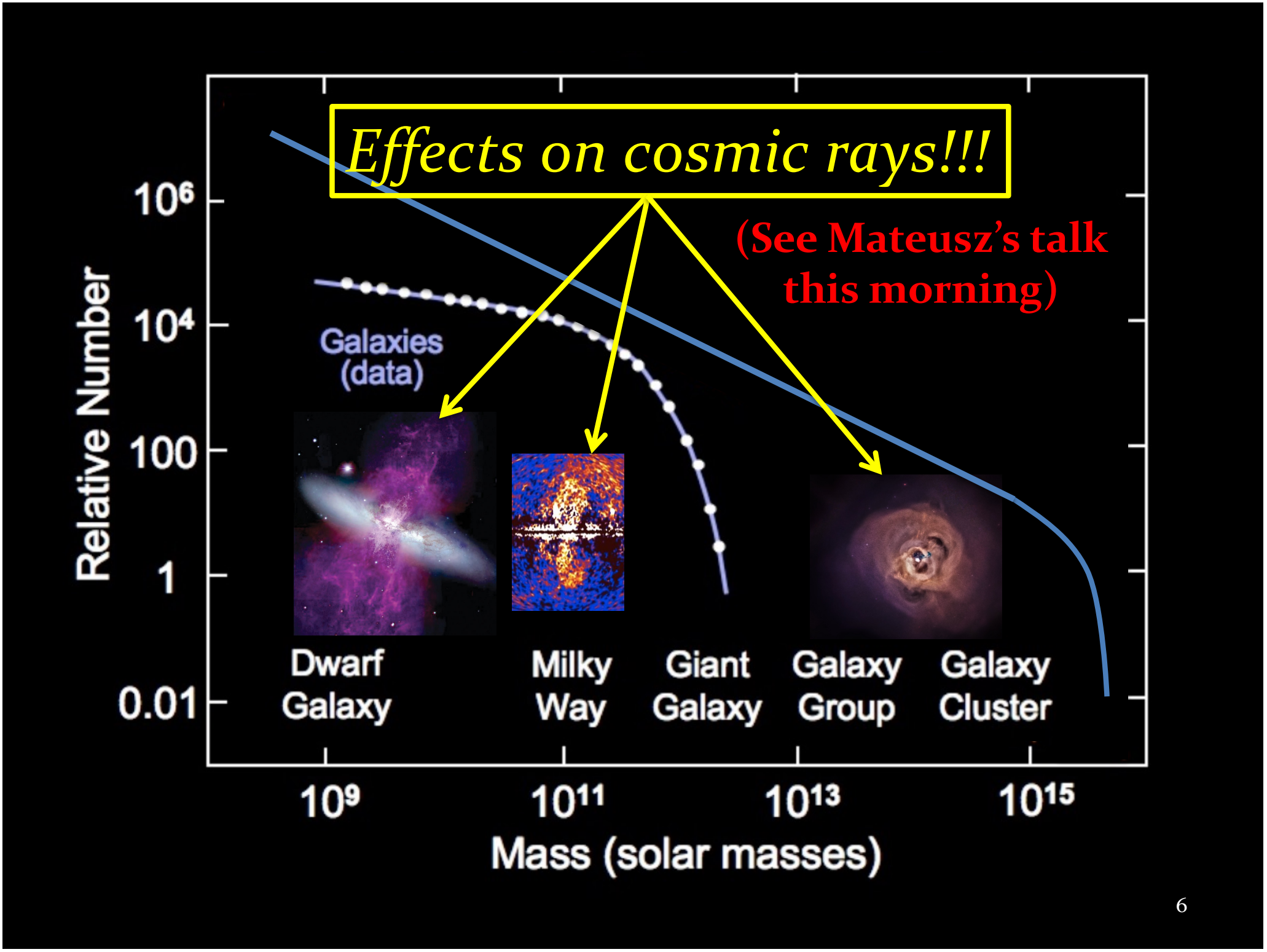
AGN feedback in Perseus

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



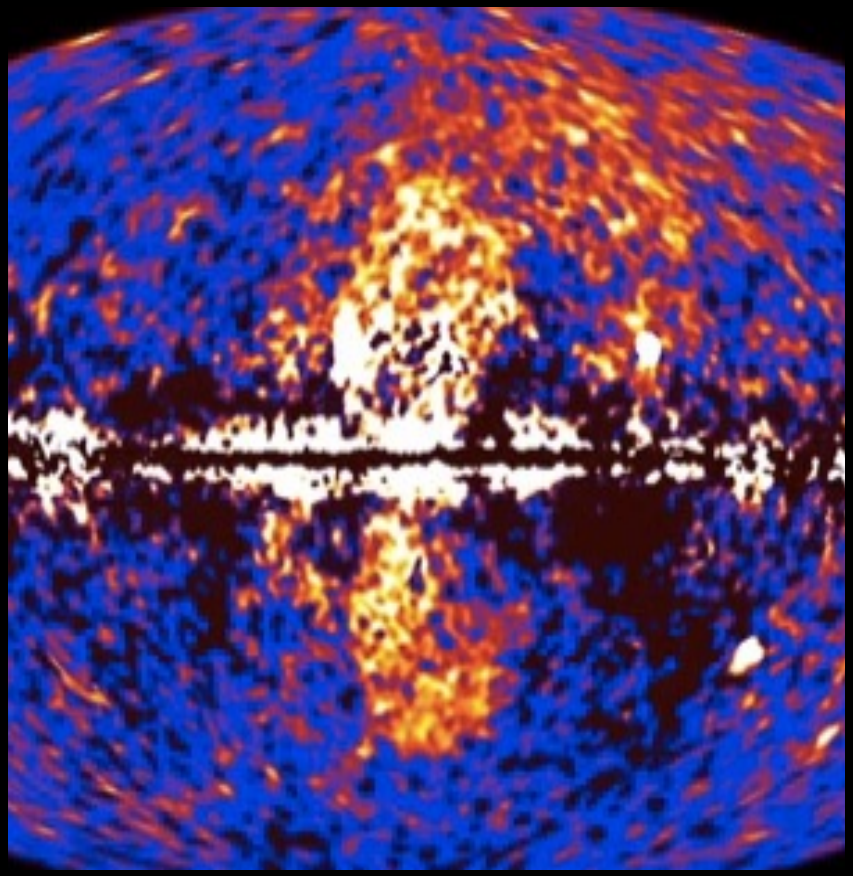
Fermi bubbles in the Milky Way galaxy

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


Effects on cosmic rays!!!
(See Mateusz's talk this morning)
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)

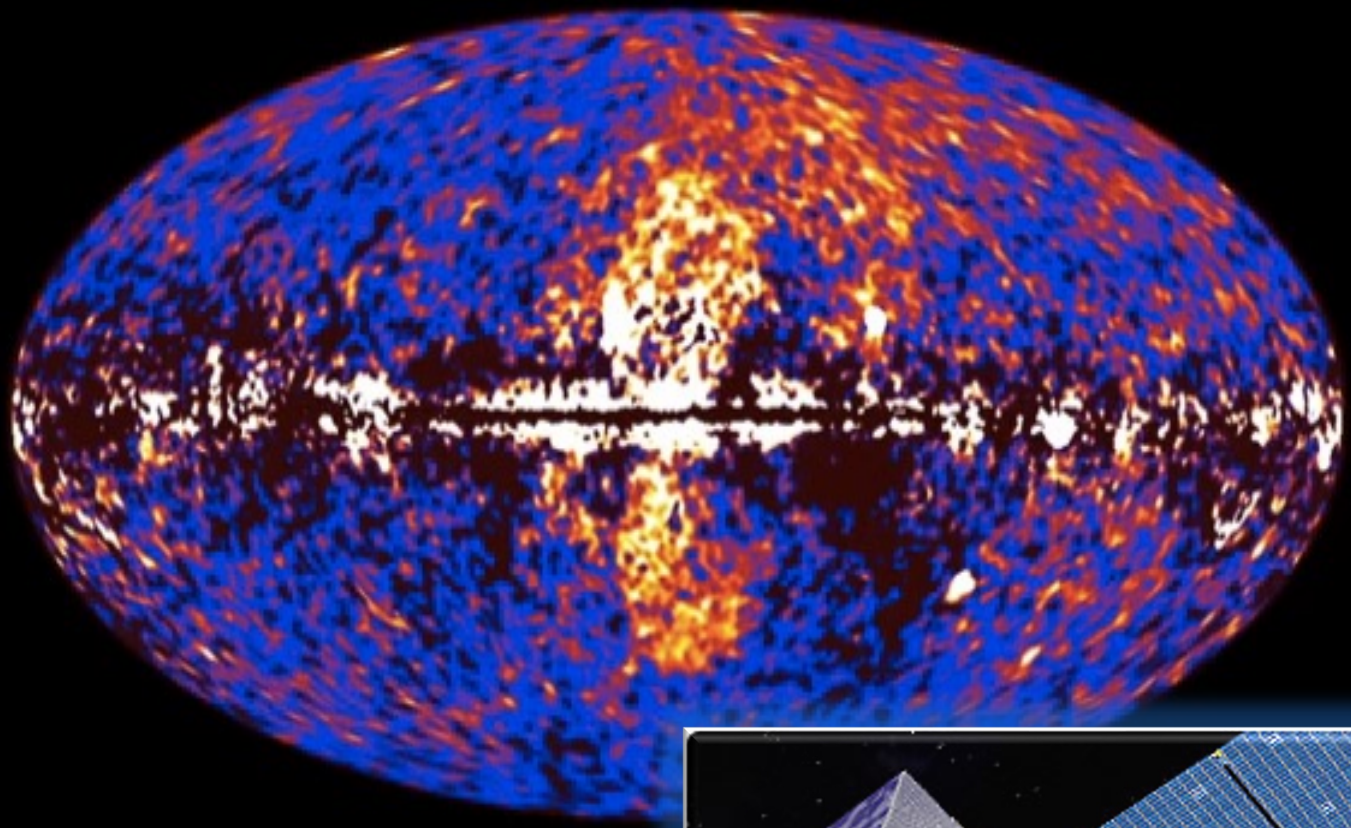
Two examples of CR feedback

#1: Fermi/eRosita bubbles

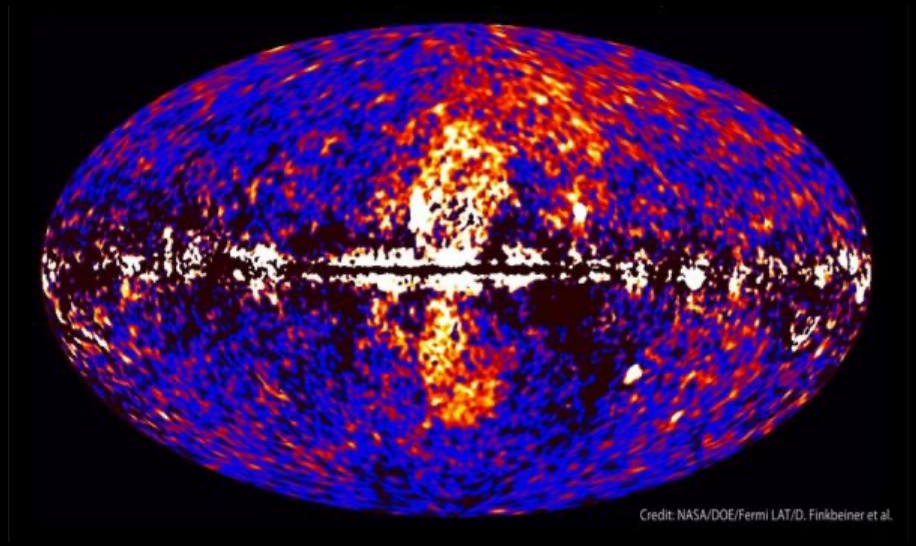


#2: Odd radio circles (ORCs)

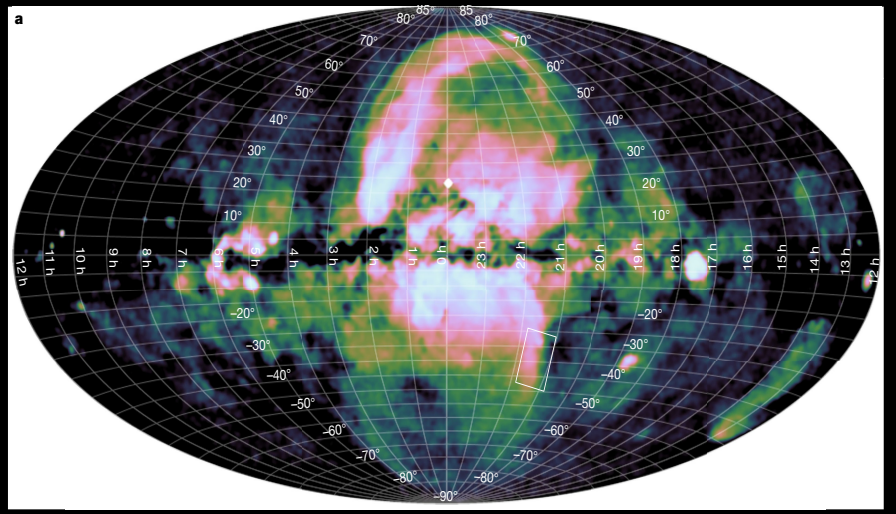
The Fermi bubbles (Su+ 2010)



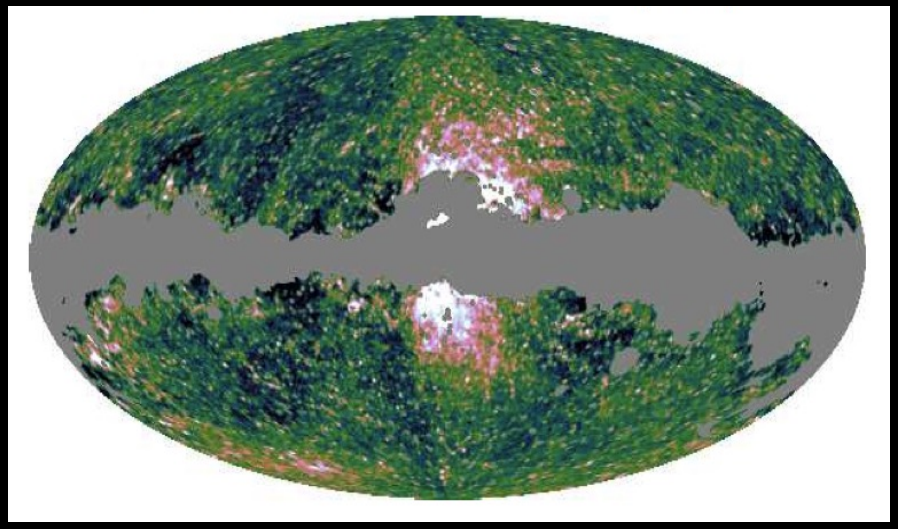
Fermi (Gamma-ray)



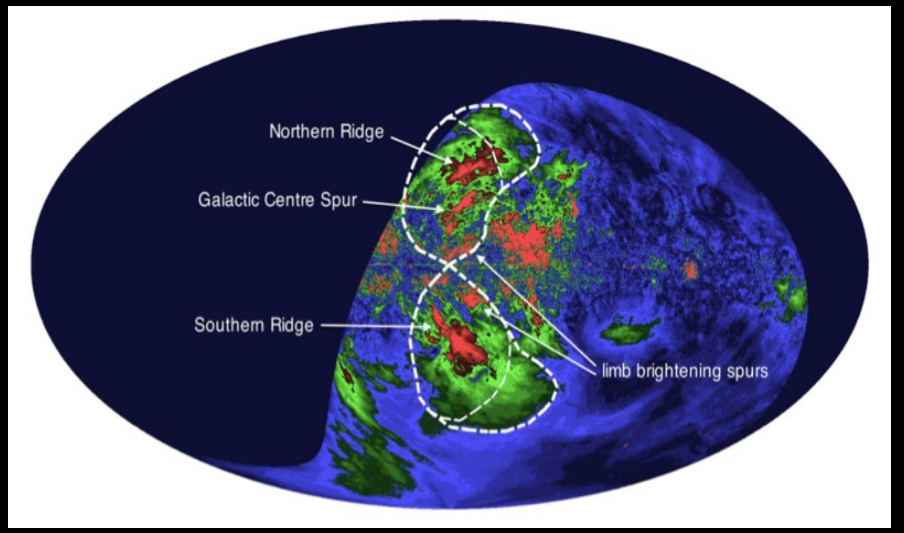
eRosita (X-ray)



WMAP & Planck (Microwave)

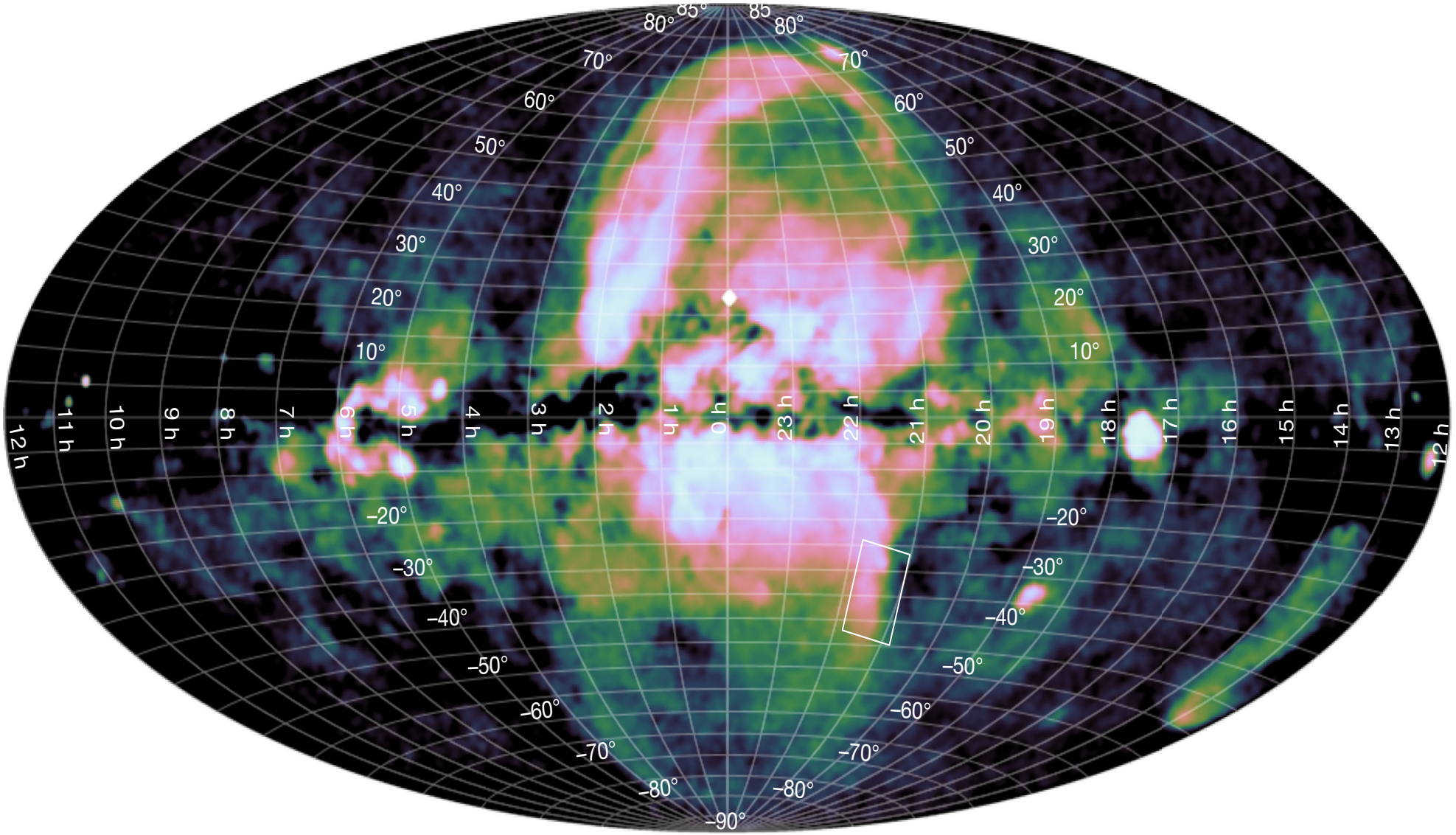


S-PASS (Polarization)



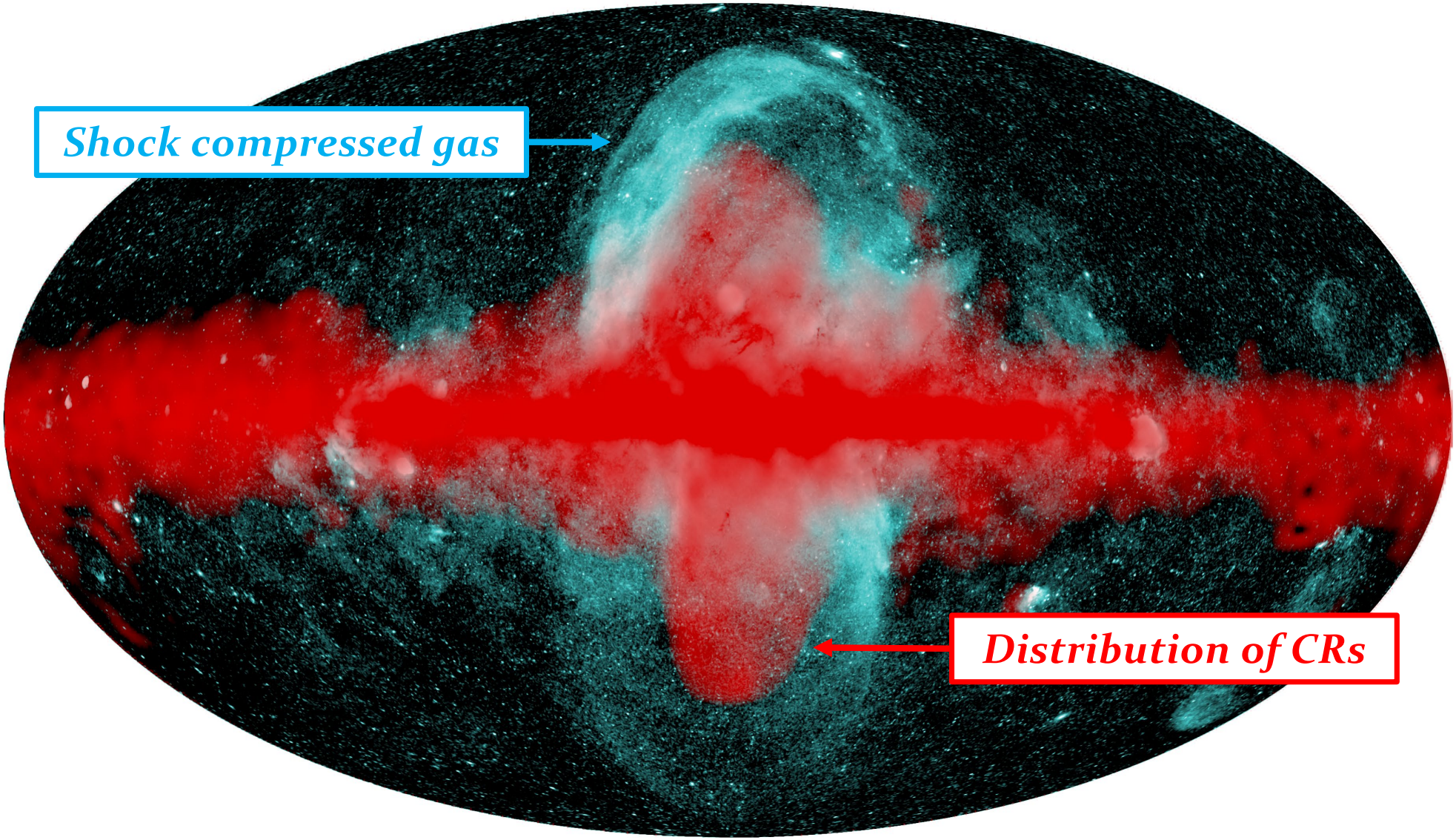
The eRosita bubbles (0.6-1.0 keV)

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



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

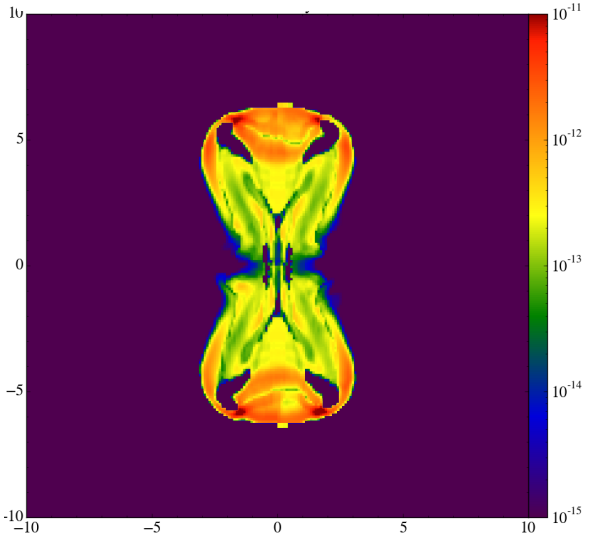
(Predehl et al., 2020, Nature, 588, 227)



Simulating the *Fermi* bubble spectrum

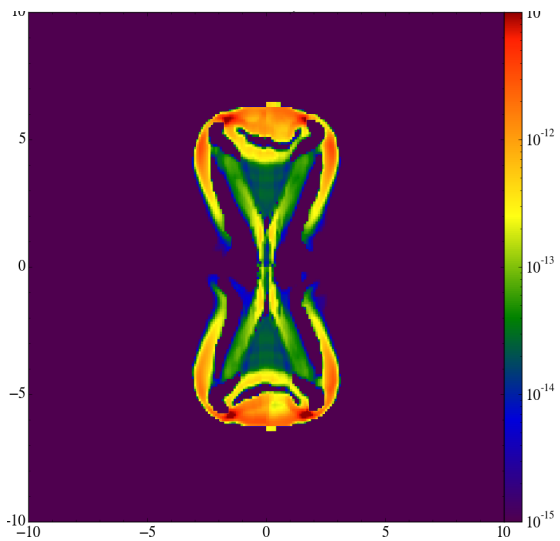
- Implemented *MHD+CRSPEC* module in FLASH
- Injection spectrum: 10 GeV ~ 10 TeV
- IC & syn. cooling (due to Galactic radiation & B field)

Total CR energy density



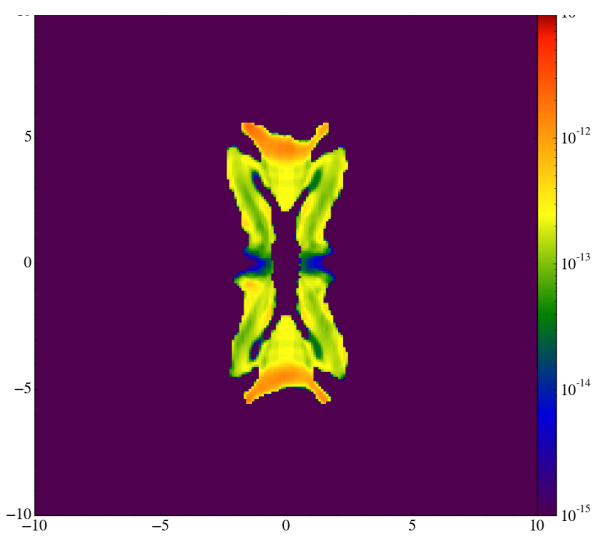
=

CR energy density (>10 GeV)



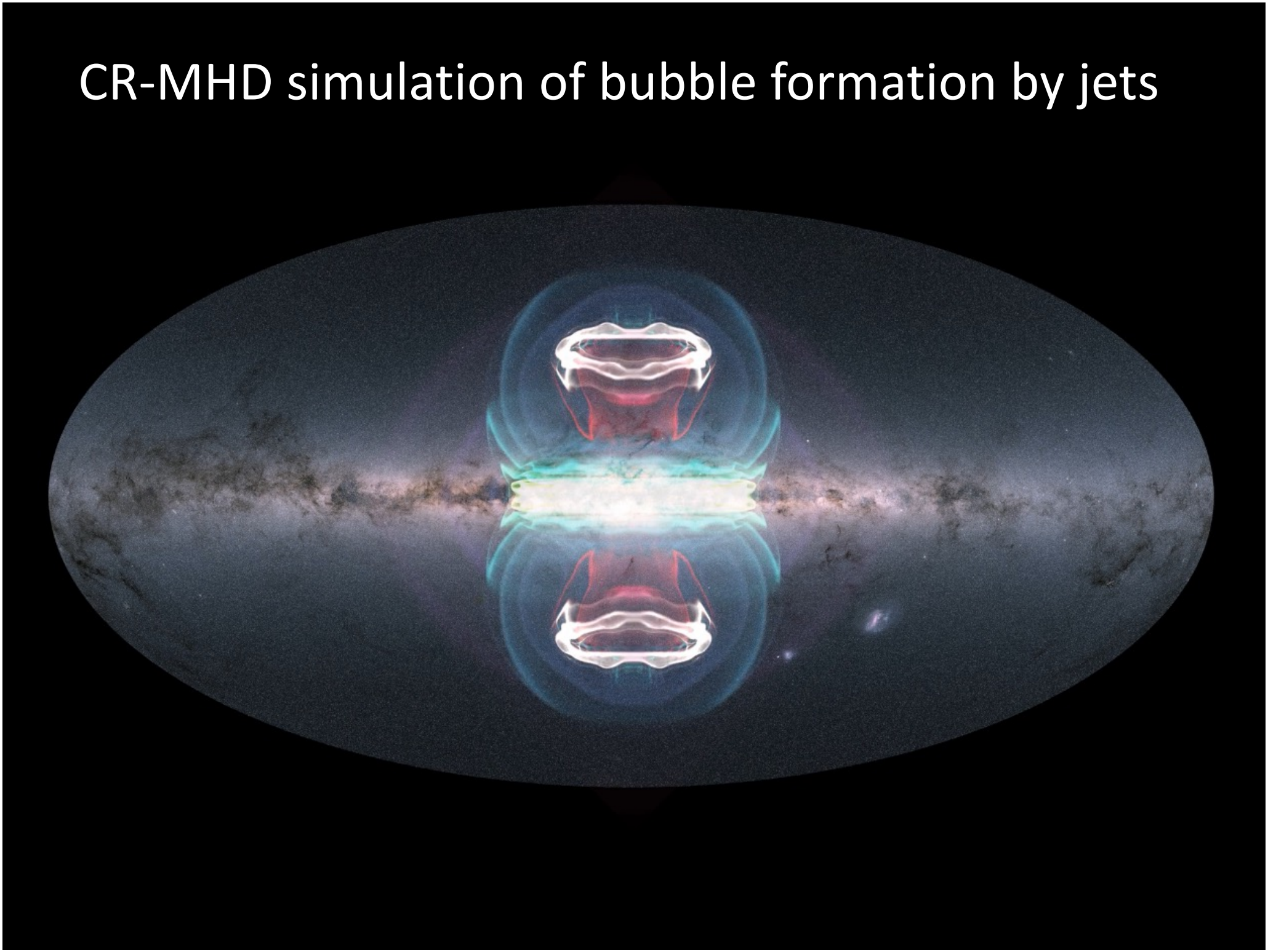
+

CR energy density (<10 GeV)



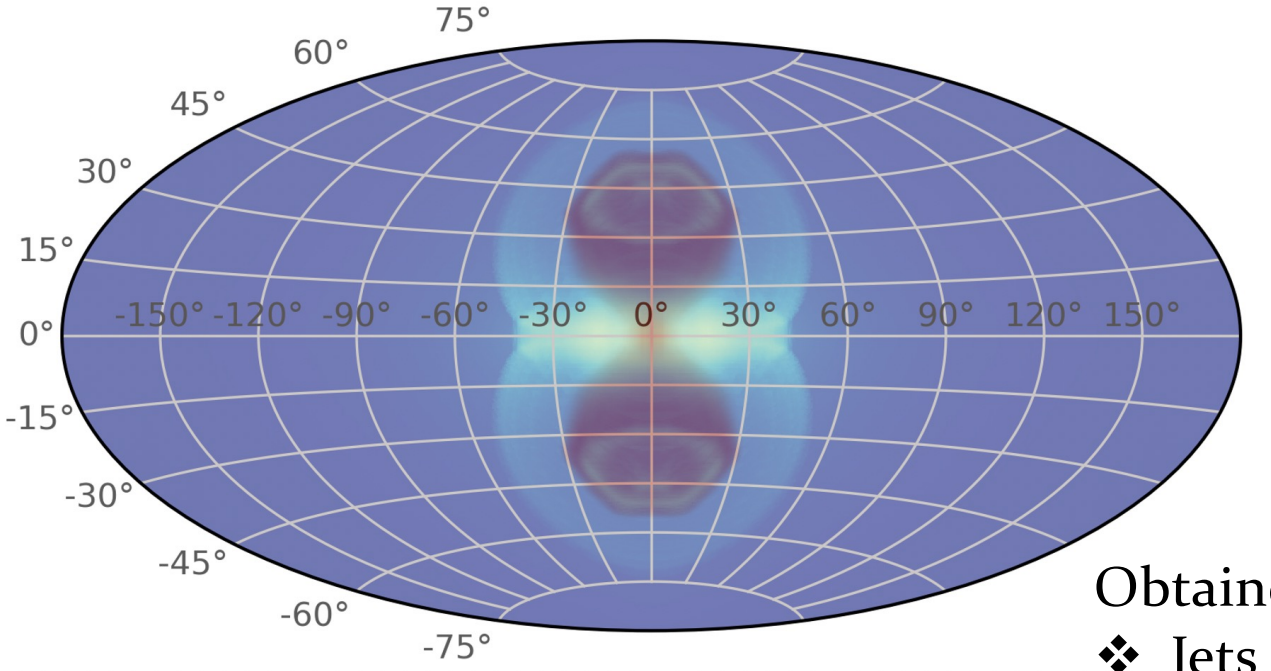
Yang & Ruszkowski (2017)

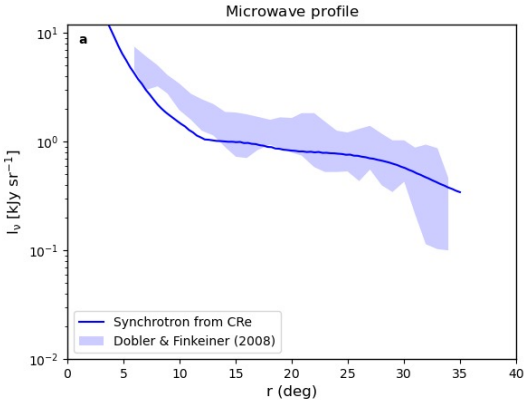
CR-MHD simulation of bubble formation by jets

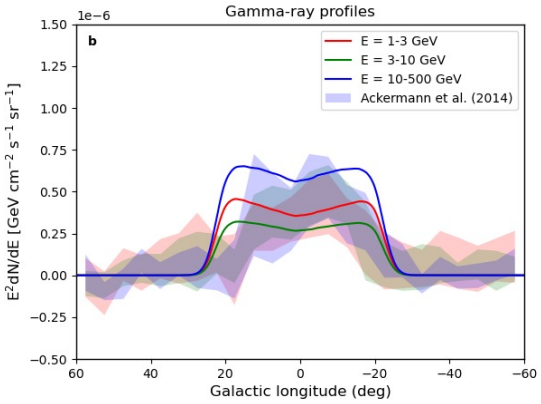


Formation of the Fermi/eRosita bubbles by past jet activity from Sgr A*

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





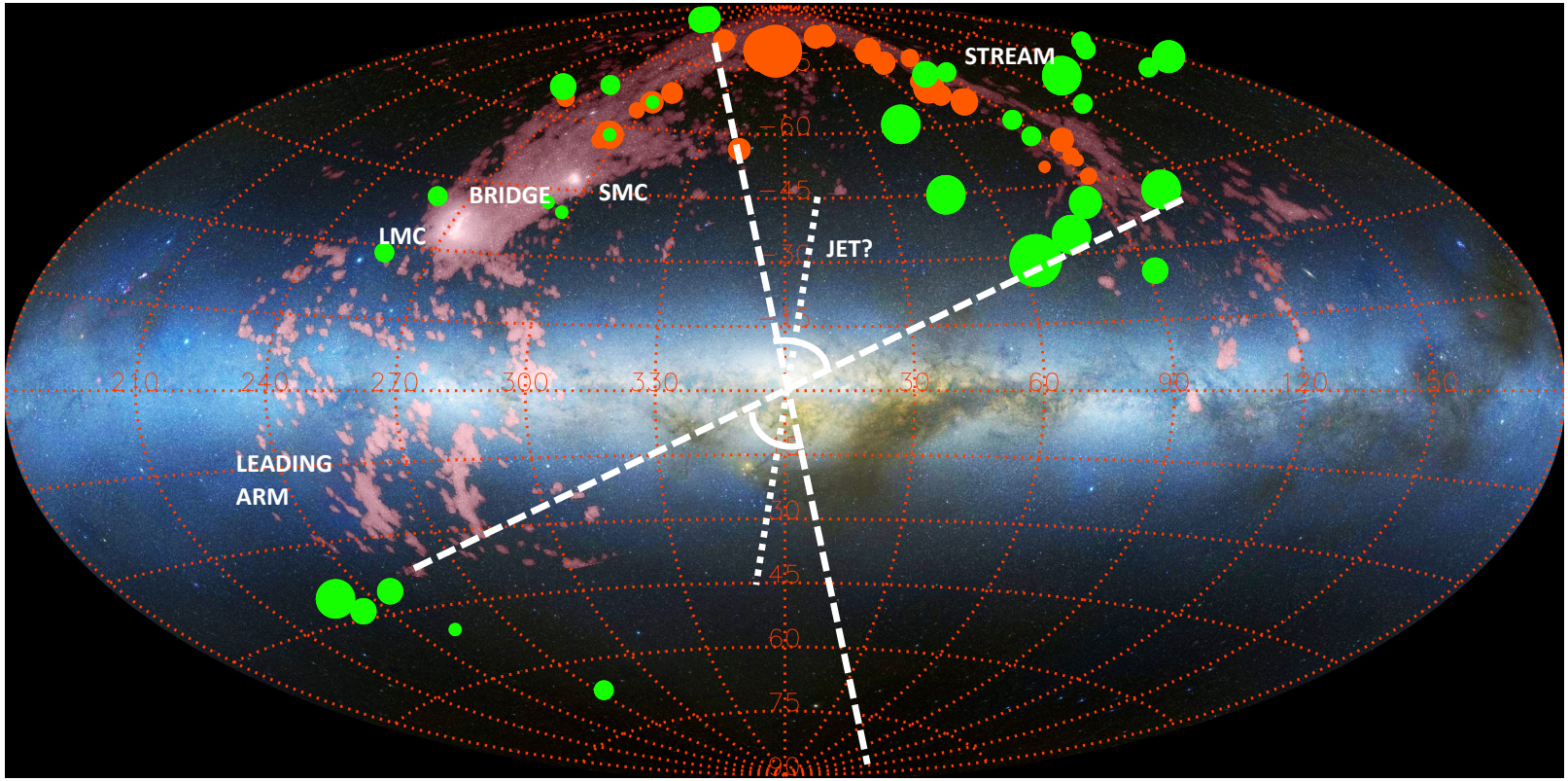


Obtained from the simulations:

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

Ionization cone in the Magellanic Stream

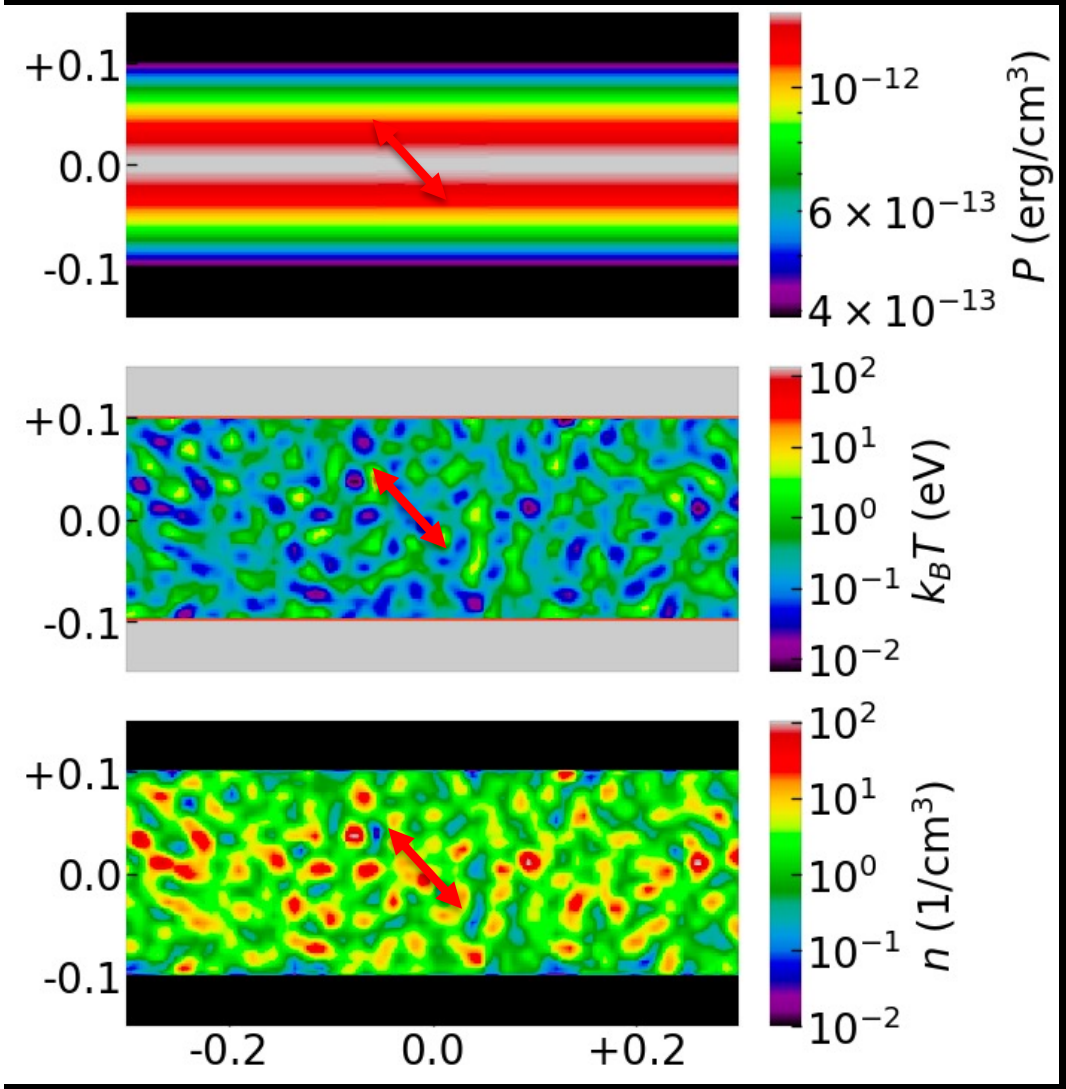
(Bland-Hawthorn et al. 2013, 2019)



- Enhanced Ha, CIV/CII, Si IV/Si II suggest past Seyfert flare activity
- Inferred ***Eddington ratio ~ 1-10%***
- Inferred ***age ~ 3.5 +- 1 Myr***

Can tilted jets produce symmetric Fermi/eRosita bubbles?

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

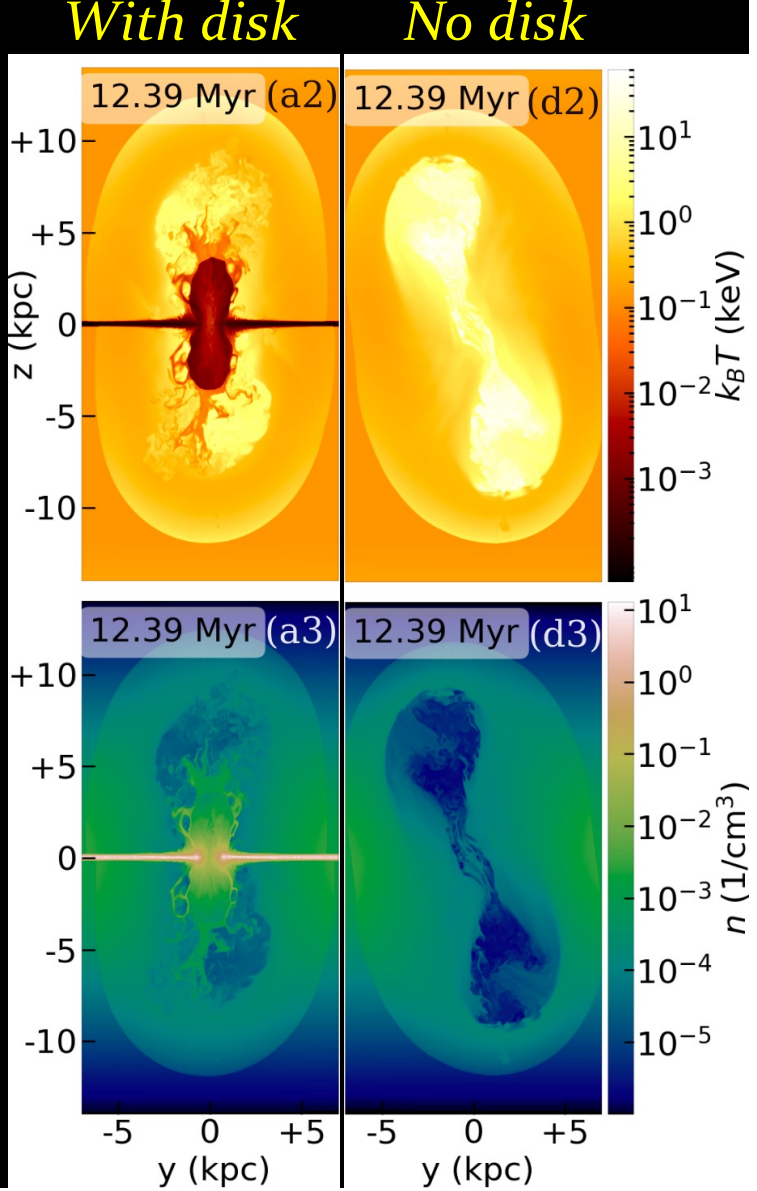


- 3D special-relativistic CR simulations using GAMER
- Tilted jets interacting with a clumpy galactic disk

Can tilted jets produce symmetric Fermi/eRosita bubbles?

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

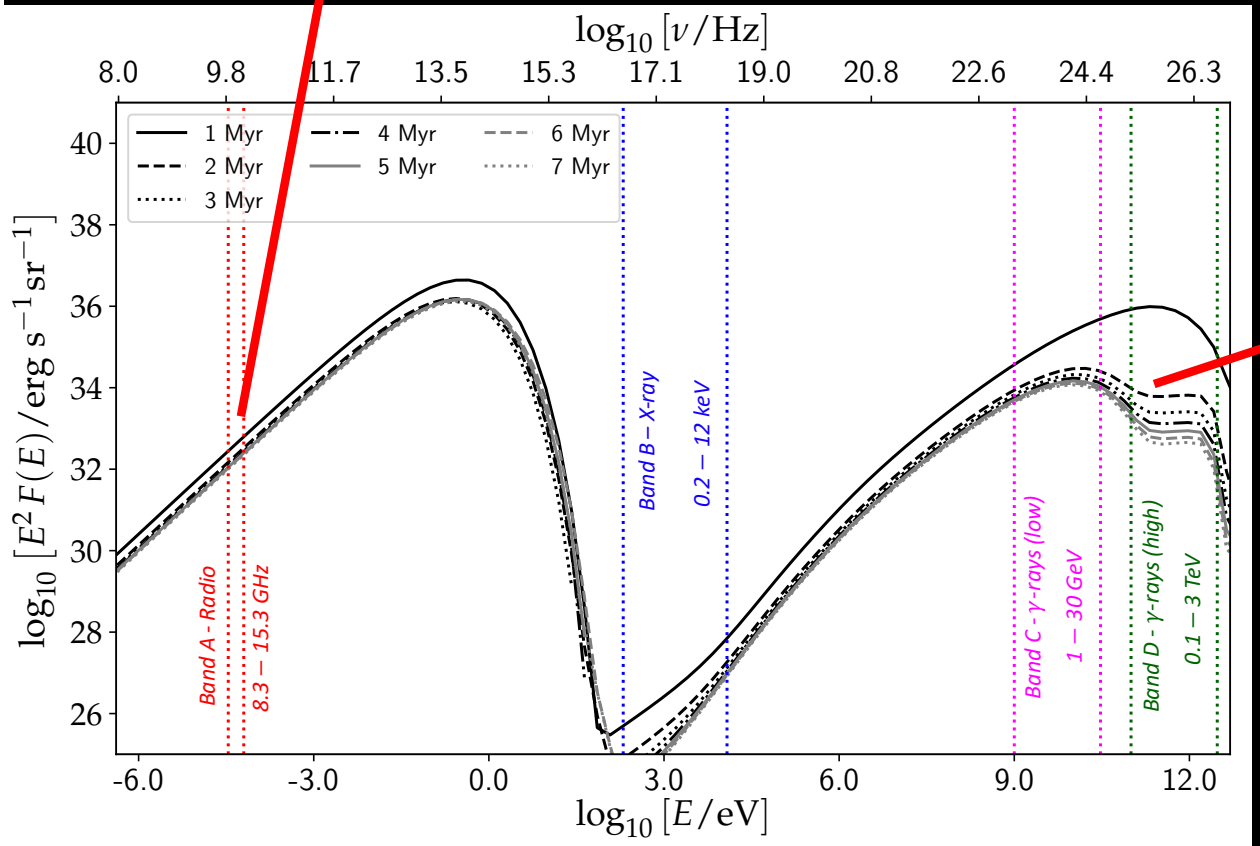
- Symmetric bubbles can be produced due to jet dissipation within the dense galactic disk
- ***Caveat***: 12.39 Myr is longer than cooling time of 500 GeV CRs => need CR re-acceleration



Can we observe FB analogs in nearby galaxies?

(***Leptonic***: Owen & Yang 2022a; ***Hadronic***: Owen & Yang 2022b)

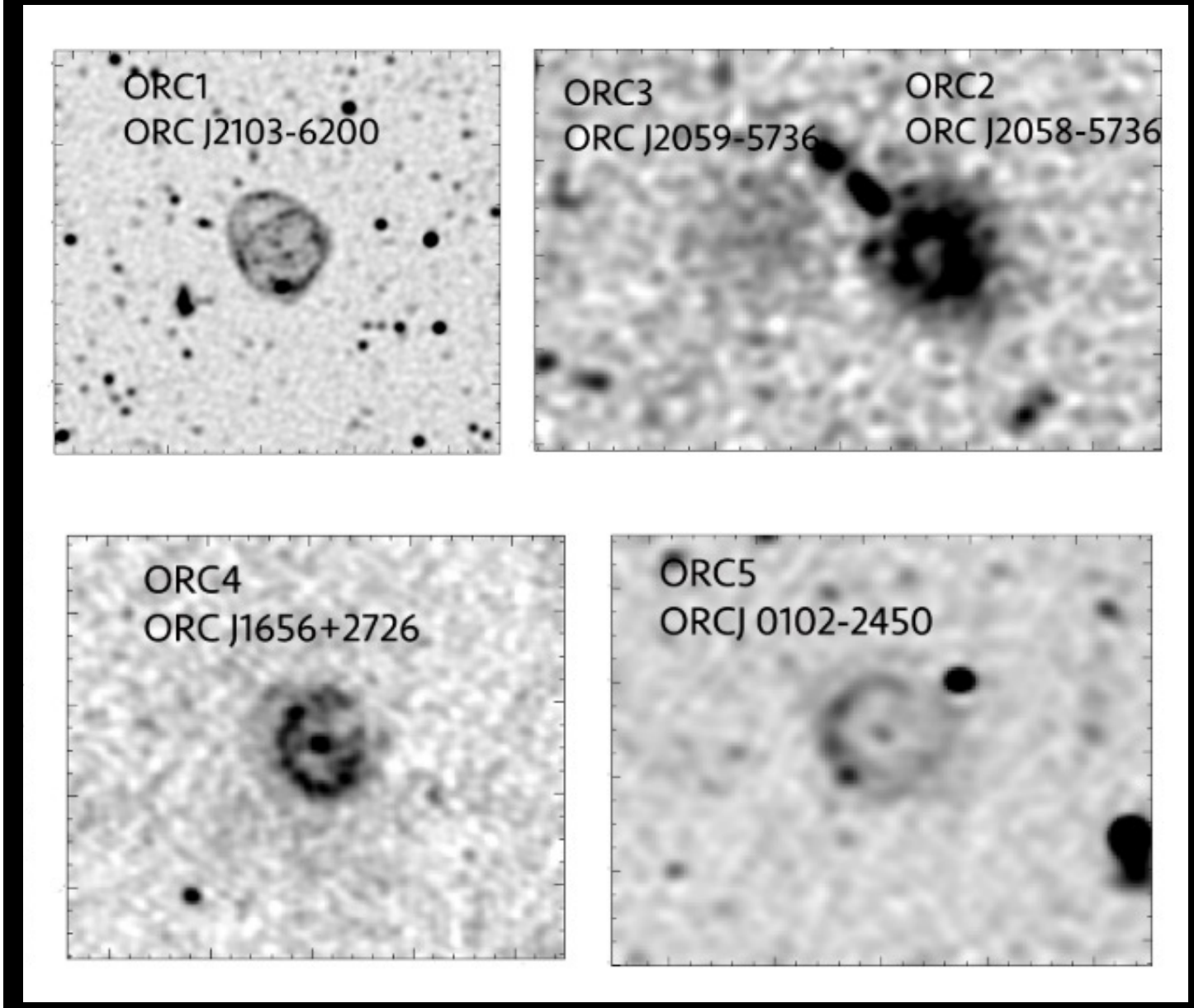
- ❖ *Radio emission drops relatively slowly*
- ❖ *A few dozens may be observable by SKA*



- ❖ *GeV & TeV emission die out quickly*
- ❖ *Only a few observable by CTA*

predicted leptonic spectra (Owen & KY 2022a)

Odd radio circles (ORCs)



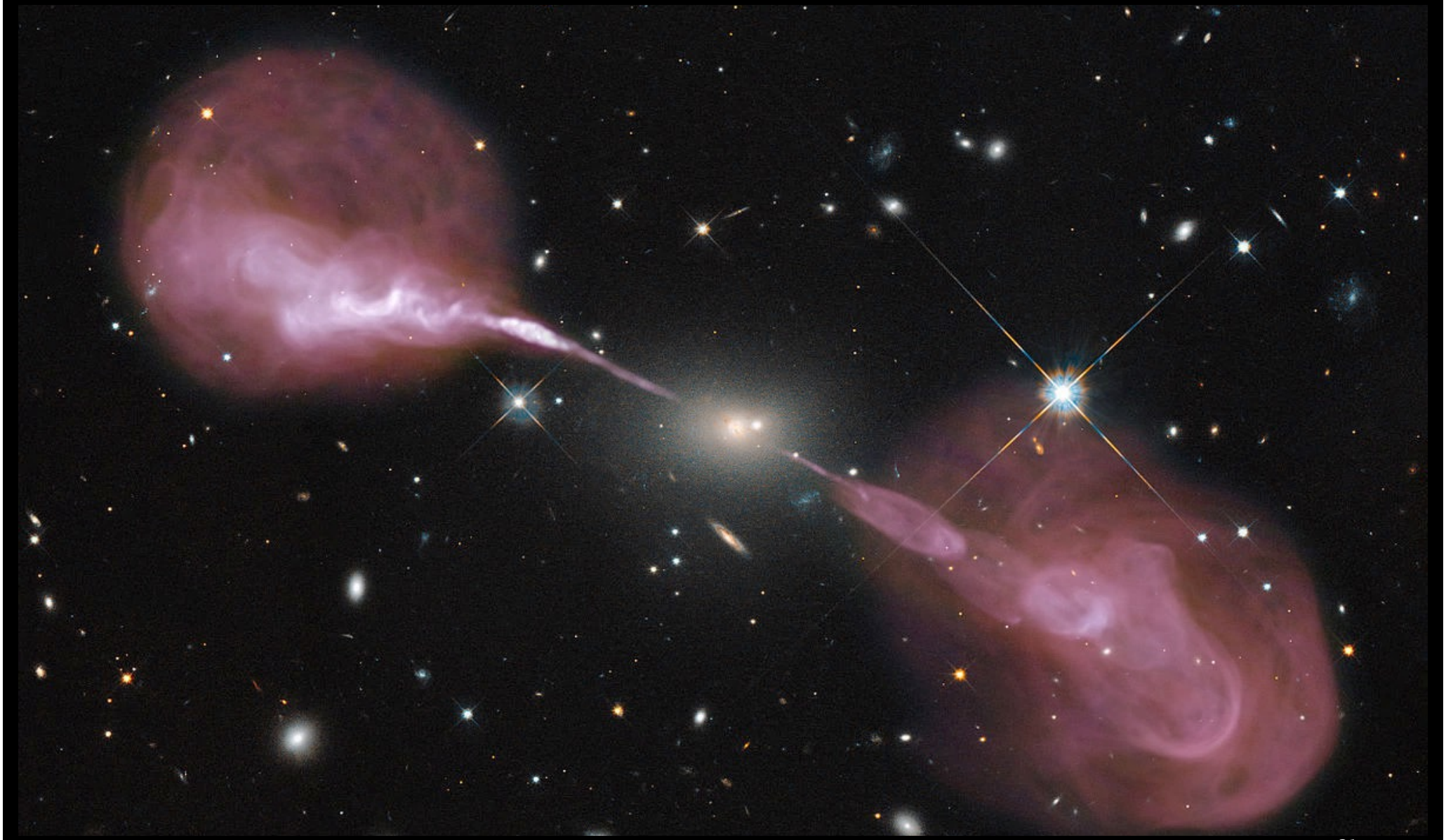
Norris et al. (2022)

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

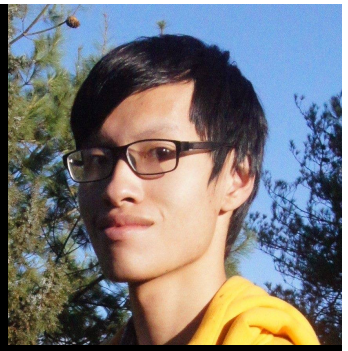
ORC1 (Norris et al. 2022)

Can AGN bubbles explain the ORCs?



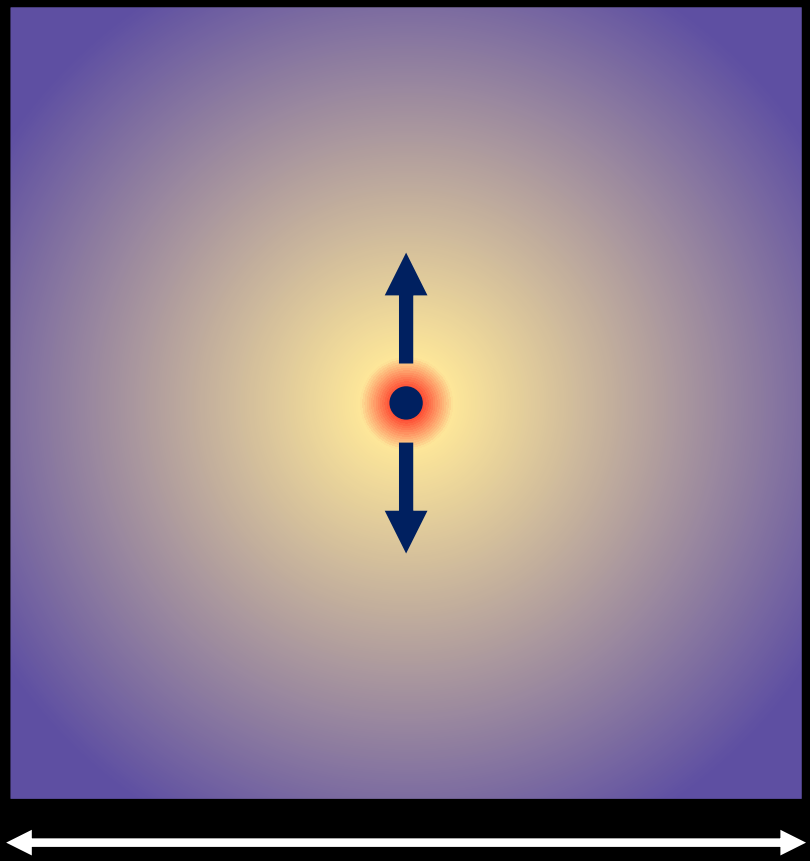
CR-MHD simulations of the ORCs

(Lin & Yang, ApJ, 974, 269)

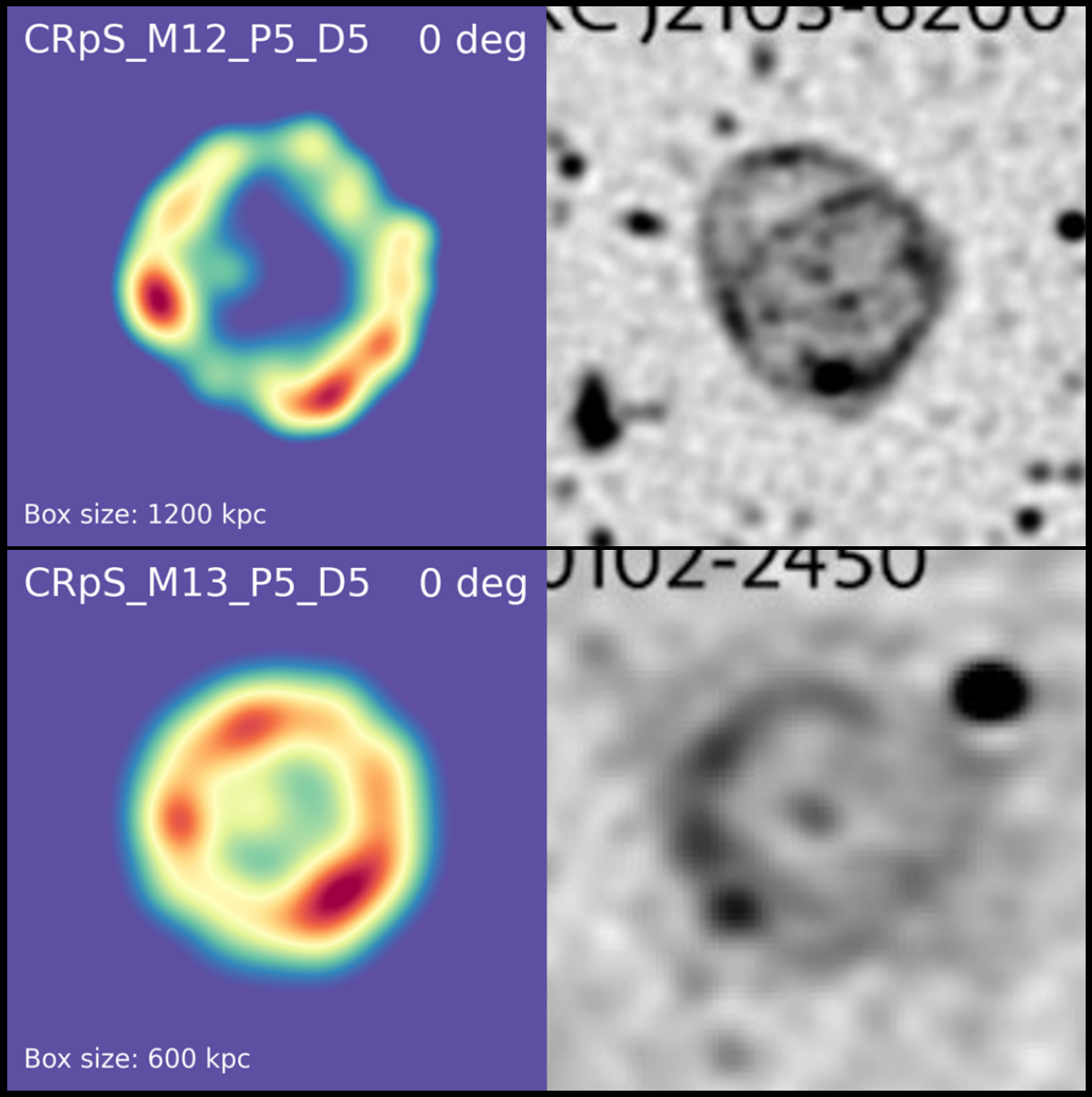


Yen-Hsing Lin
(NTHU->UCSD)

- 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!

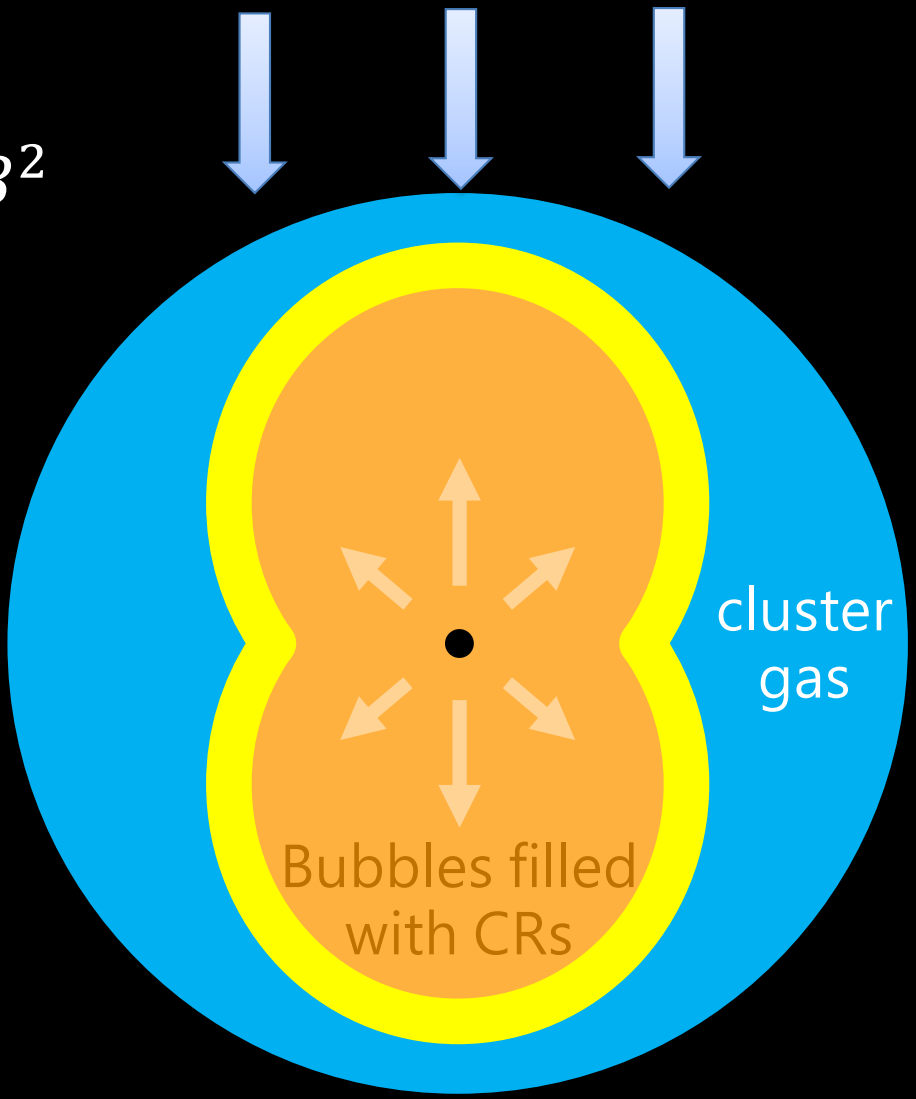


Lin & Yang (2024) Norris et al. (2022)

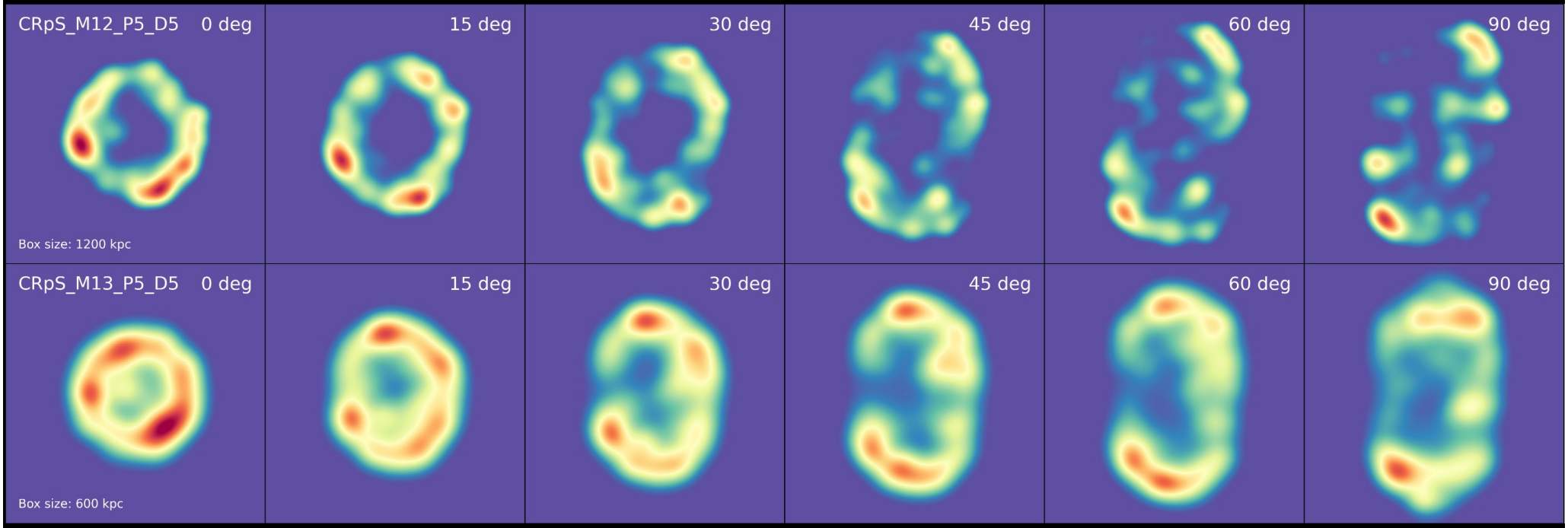
How to produce edge-brightened ORCs?

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

→ highest at the bubble surface



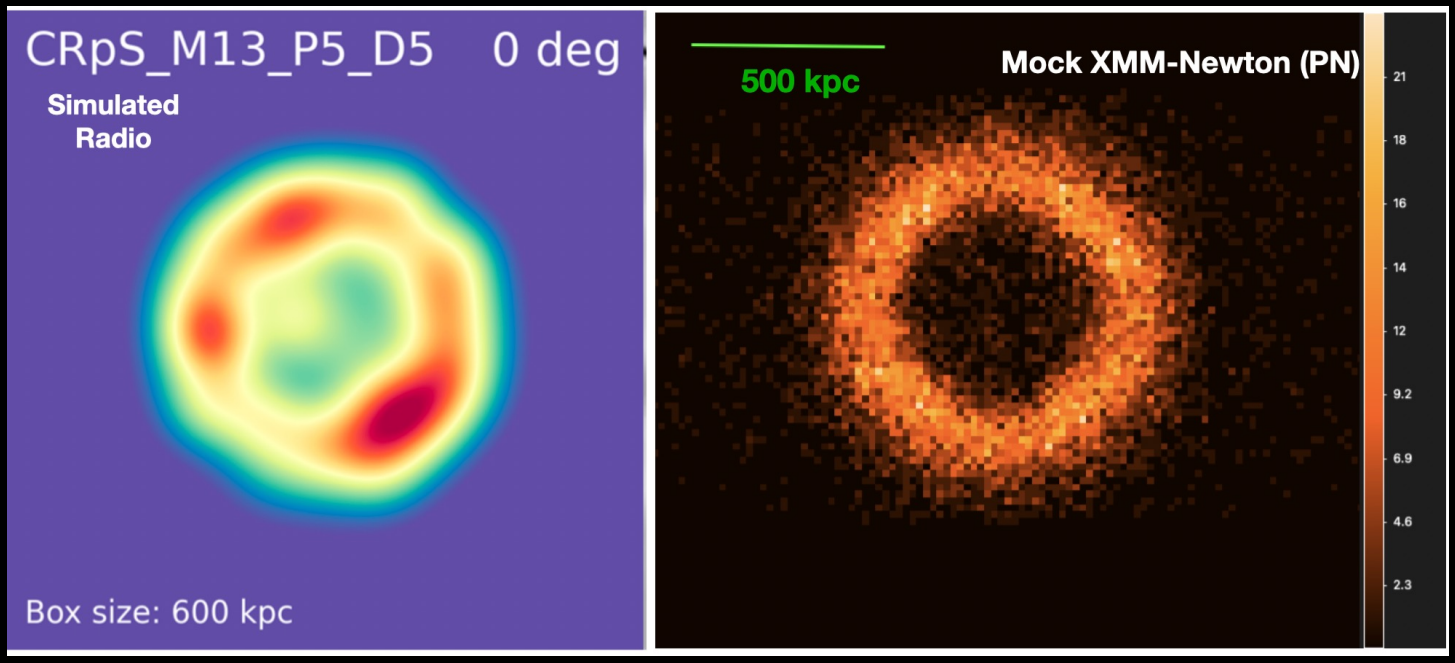
Dependence on viewing angles



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 AGN feedback & galaxy evolution