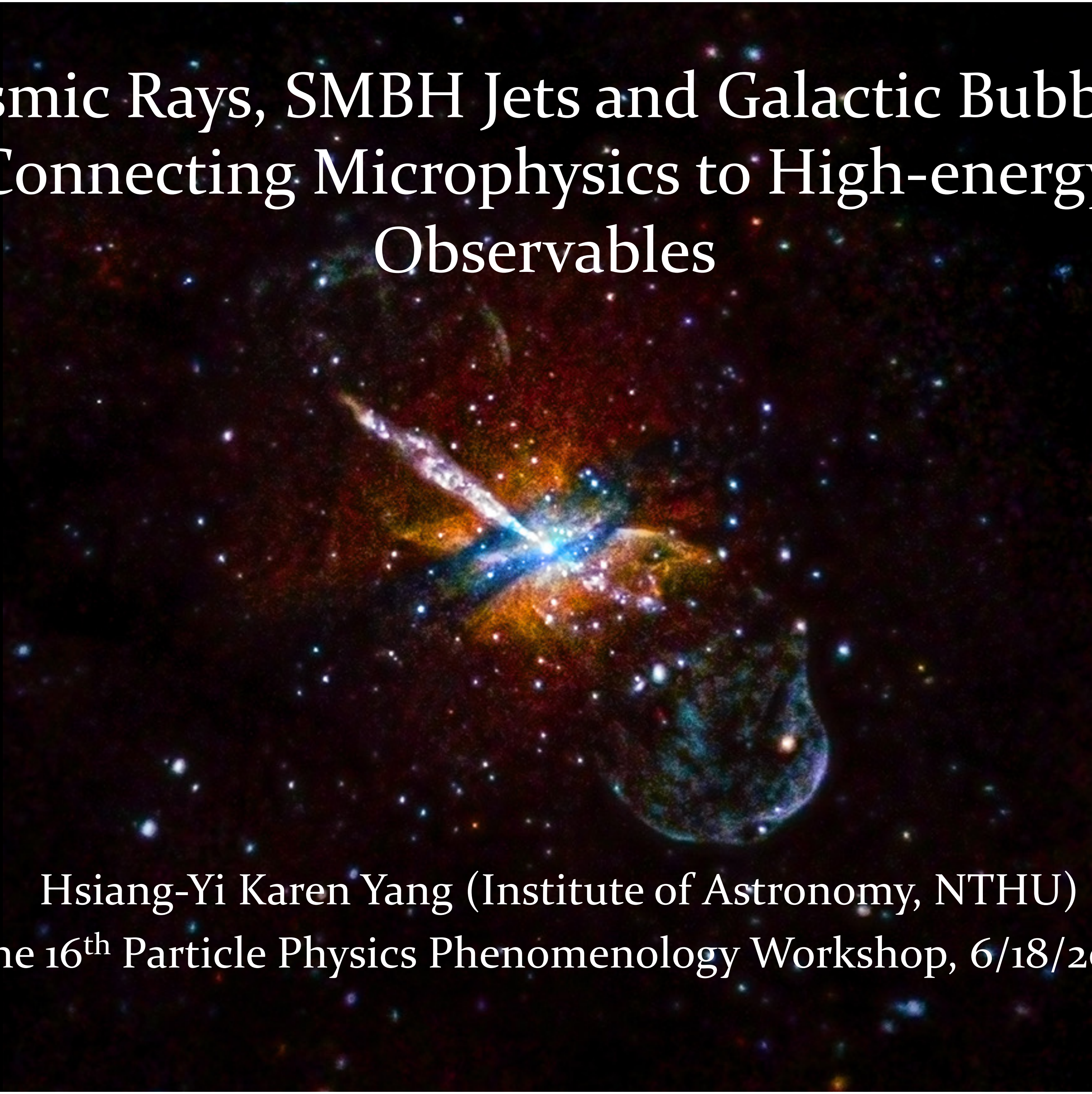
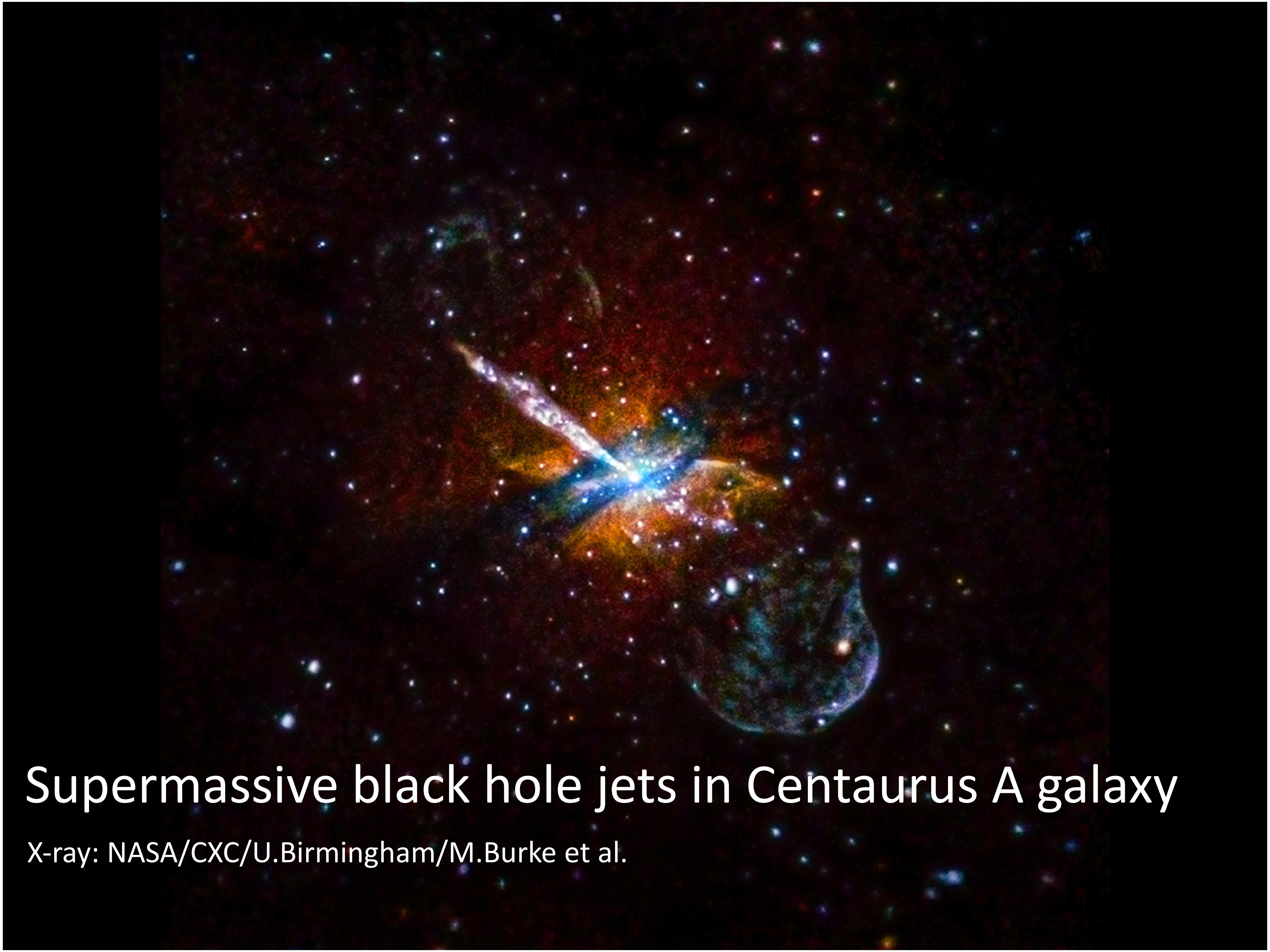
Cosmic Rays, SMBH Jets and Galactic Bubbles: Connecting Microphysics to High-energy Observables



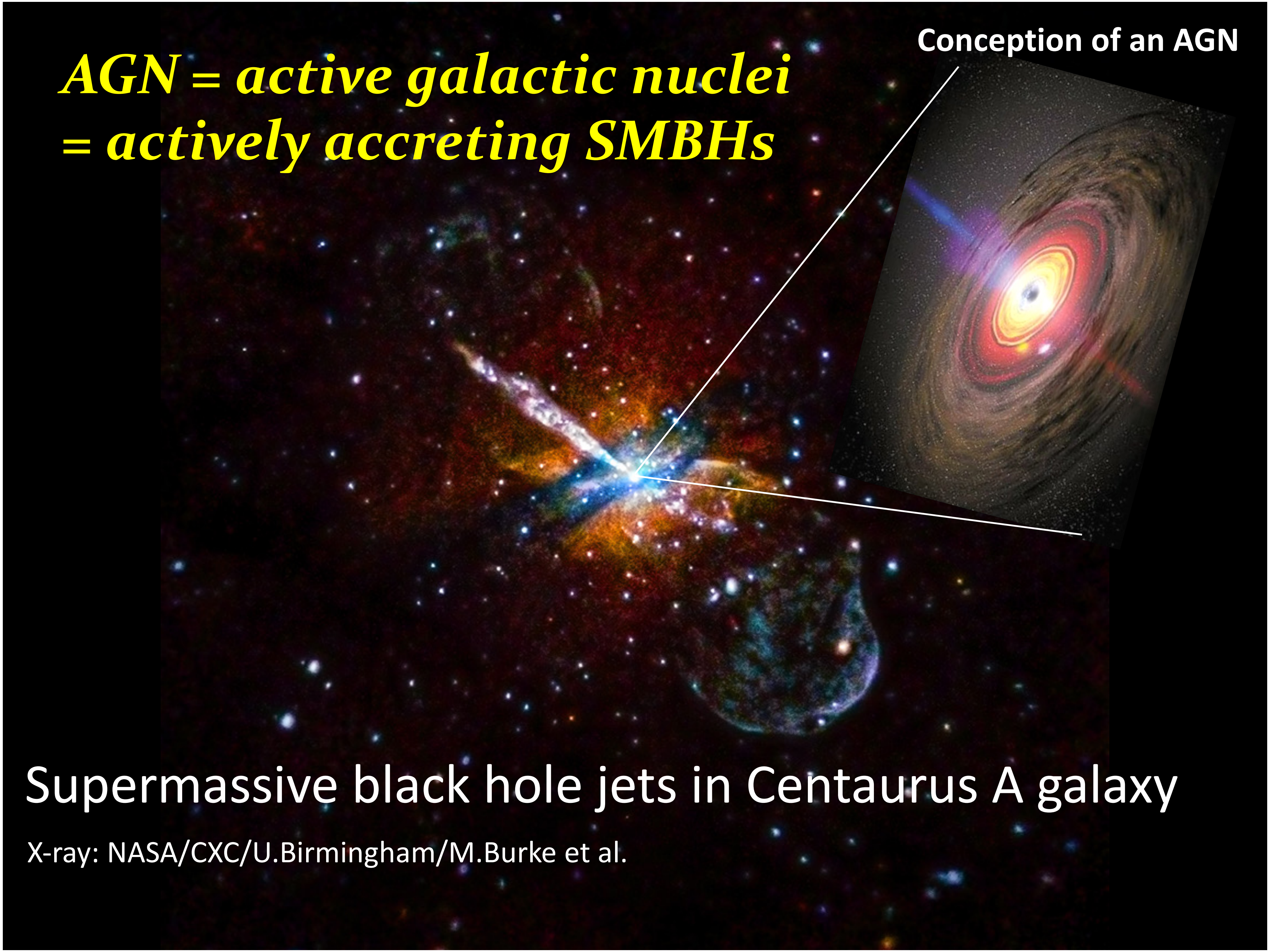
Hsiang-Yi Karen Yang (Institute of Astronomy, NTHU)

The 16th Particle Physics Phenomenology Workshop, 6/18/2026



Supermassive black hole jets in Centaurus A galaxy

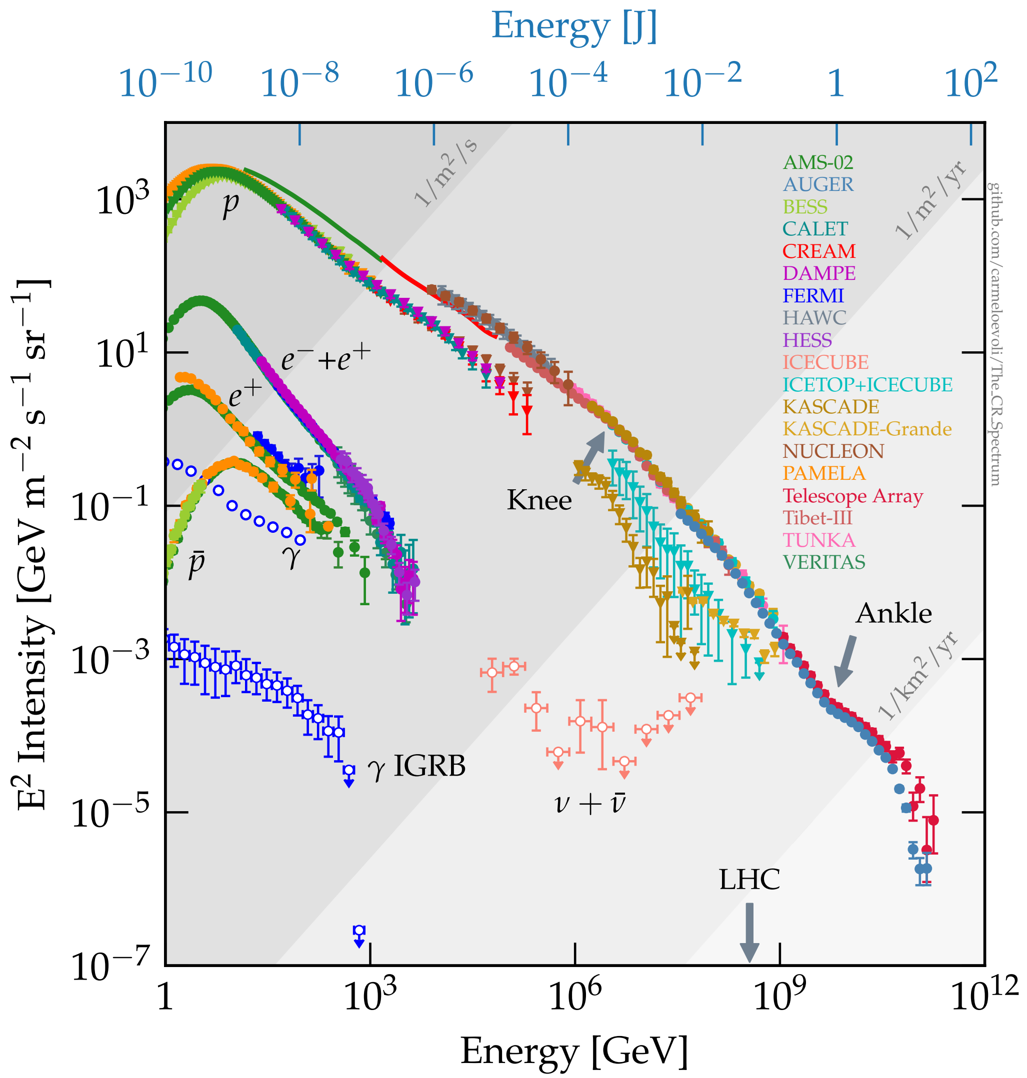
X-ray: NASA/CXC/U.Birmingham/M.Burke et al.


AGN = active galactic nuclei
= actively accreting SMBHs
Conception of an AGN
Supermassive black hole jets in Centaurus A galaxy
X-ray: NASA/CXC/U.Birmingham/M.Burke et al.

Outline

- Introduction – importance of ***cosmic rays (CRs)*** in astrophysics
- How to model CRs in MHD simulations
- Physical origin of the ***Fermi bubbles*** ***& open questions***
- Physical origin of the ***odd radio circles (ORCs)*** ***& open questions***
- Conclusions

Physical origin of cosmic rays (CRs)



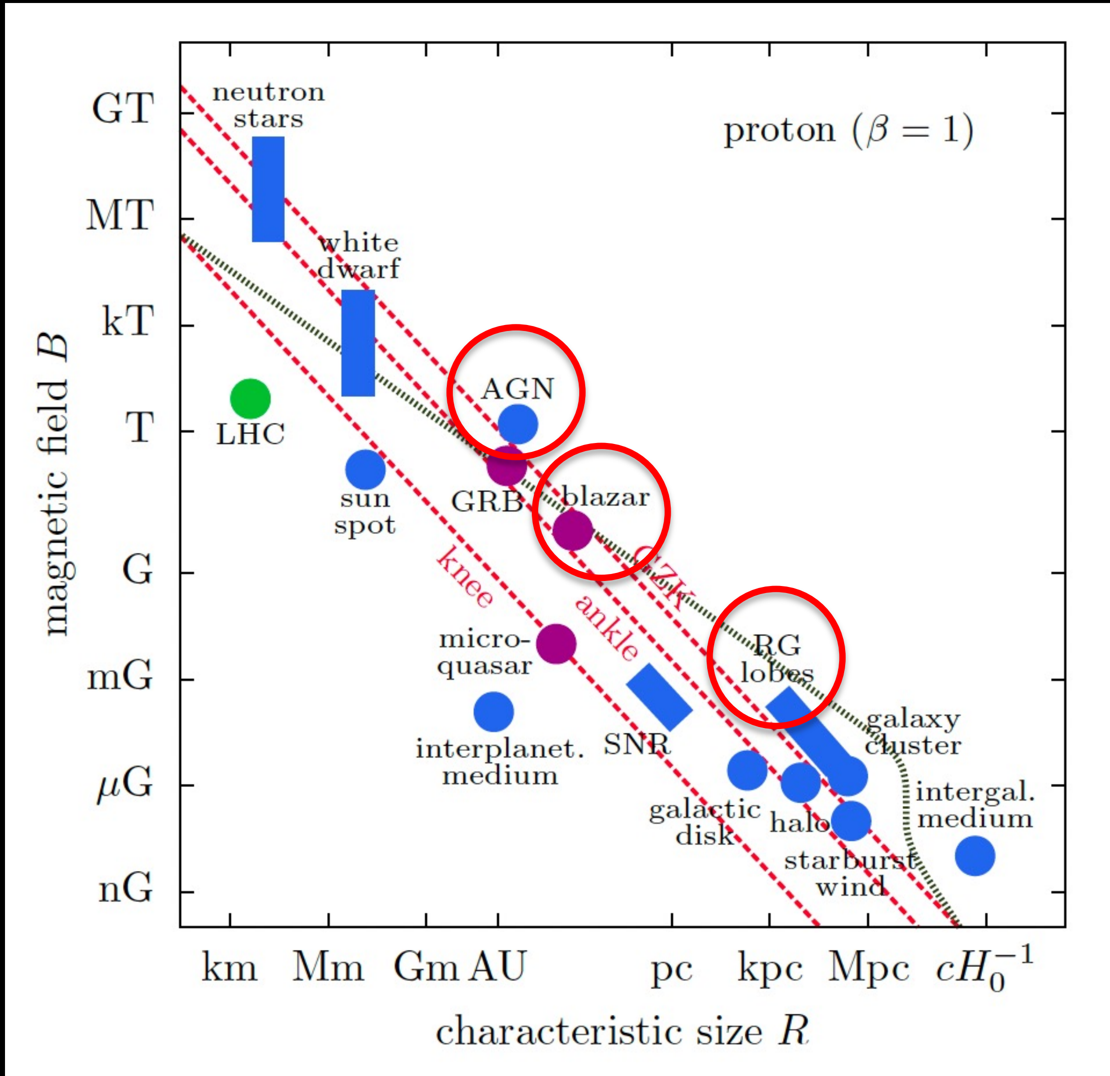
❖ Below the ***knee*** ($E < 10^6$ GeV):
- -- Spectral index ~ -2.7
- -- Galactic supernova remnant
- -- Diffusive shock acceleration

❖ For 10^6 GeV < E < 10^{10} GeV:
- -- Spectral index ~ -3.1
- -- Transition from Galactic to extragalactic

❖ Above the ***ankle*** ($E > 10^{10}$ GeV)
- -- Extragalactic origin

Evoli (2025)

Physical origin of cosmic rays (CRs)



- Hillas criterion:

$$R \geq r_g = \frac{E}{qB}$$

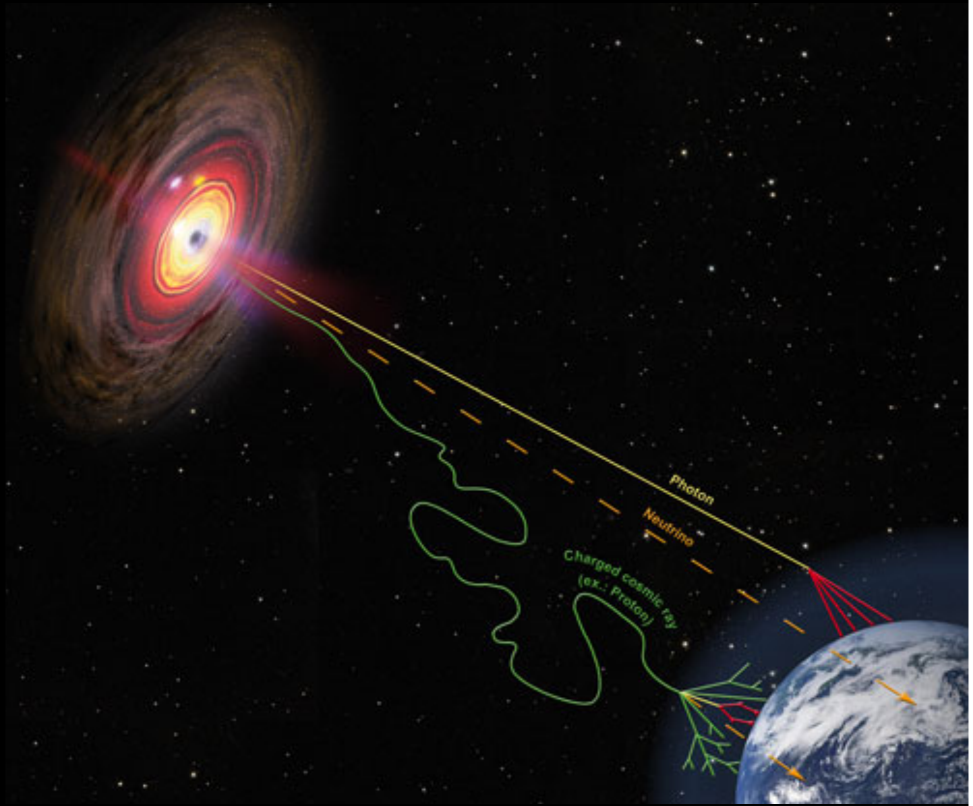
$$\Longrightarrow E_{max} = qBR$$

SMBH jets/lobes are important sources of CRs!!

IceCube Collaboration (2017)

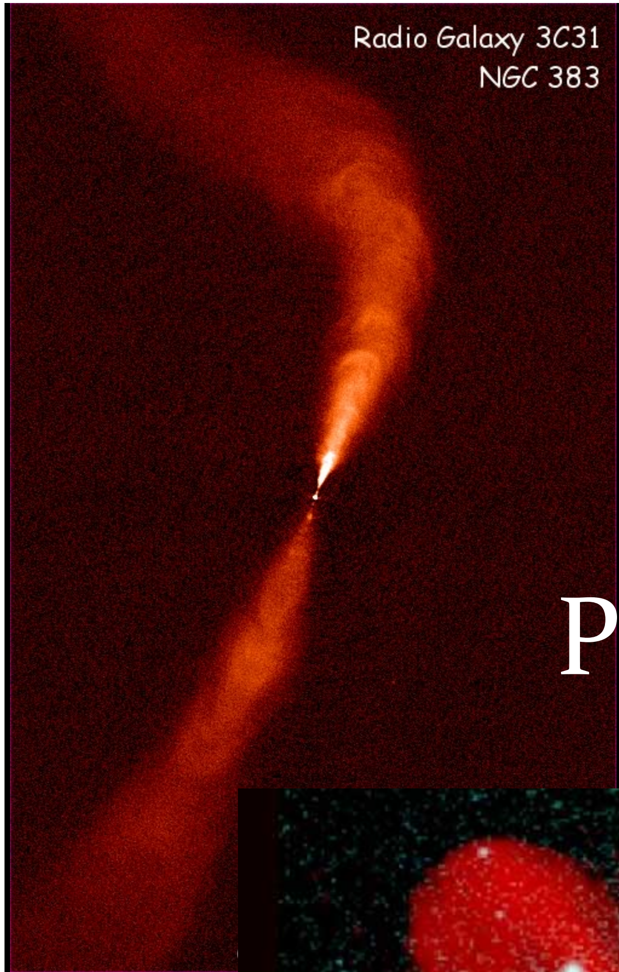
SMBH jets could be sources of high energy neutrinos

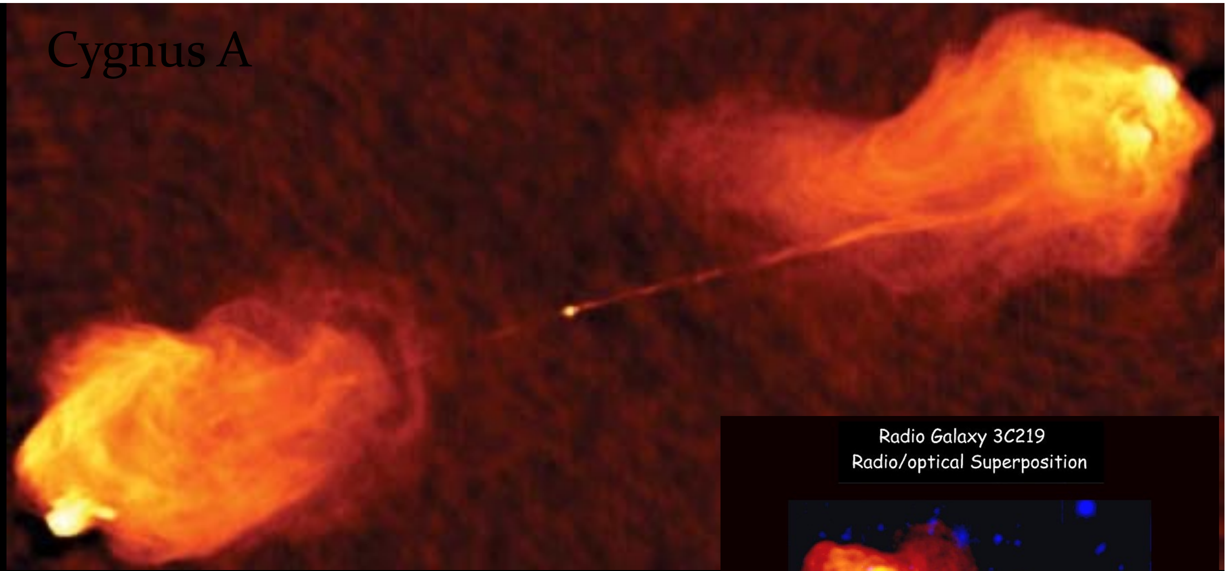
- One neutrino event with 290 TeV coincident with ***blazar*** TXS 0506+056 (IceCube+2017)
- Flares detected in gamma-ray/X-ray/optical/radio
- Strong evidence that SMBH jets are one of the sources of high energy neutrinos

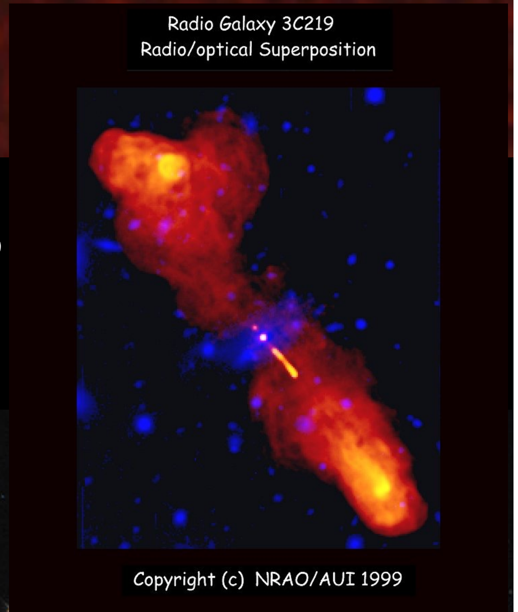


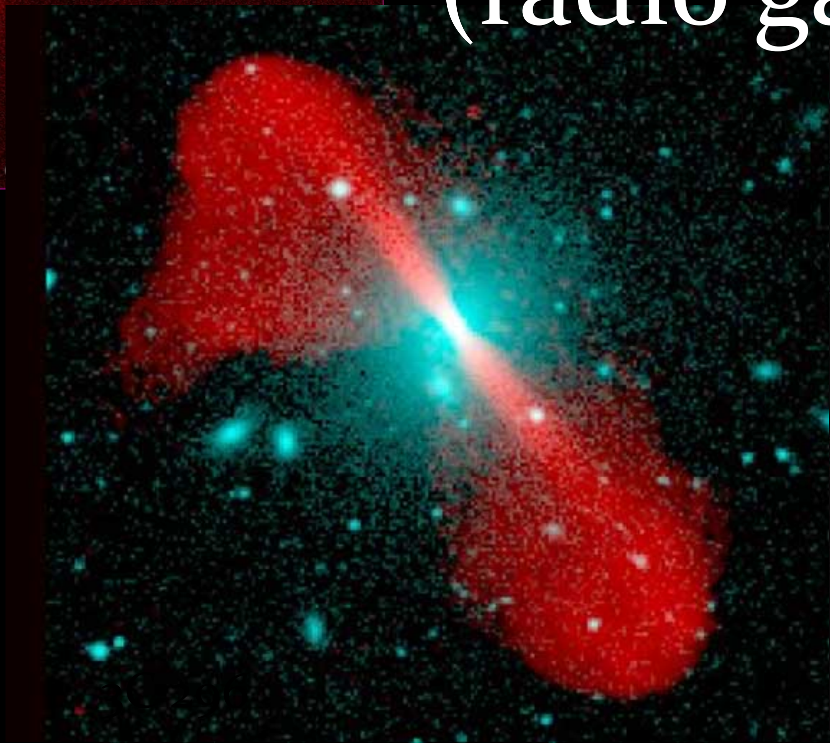
See J. Beacom's lectures

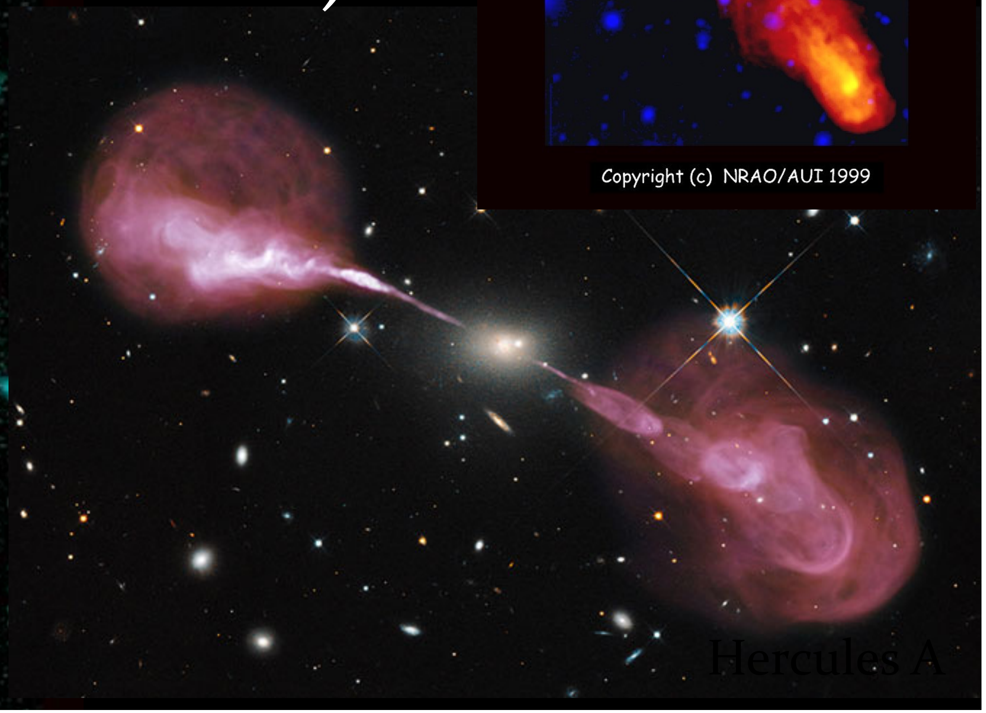
Powerful SMBH jets (radio galaxies)





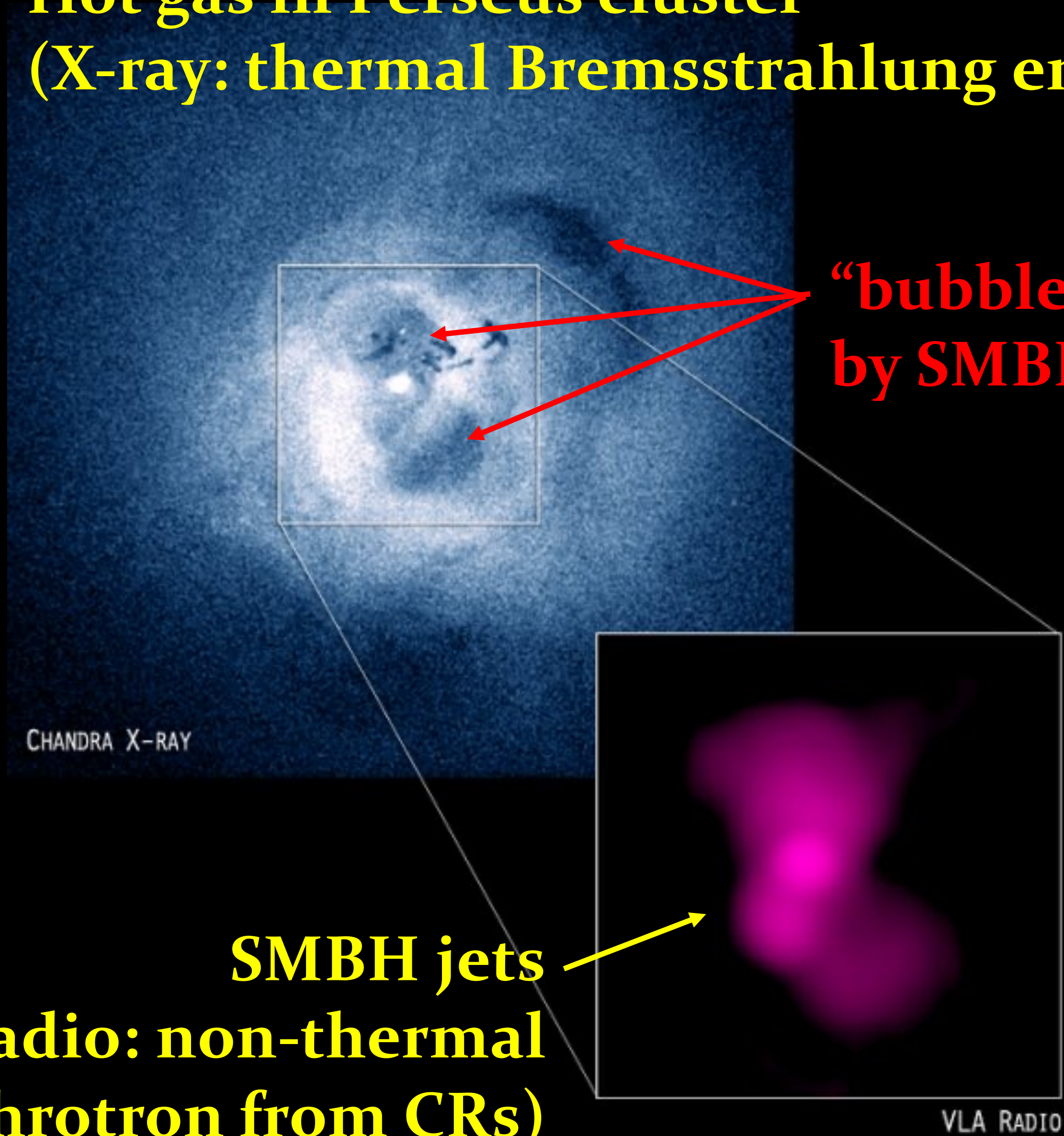






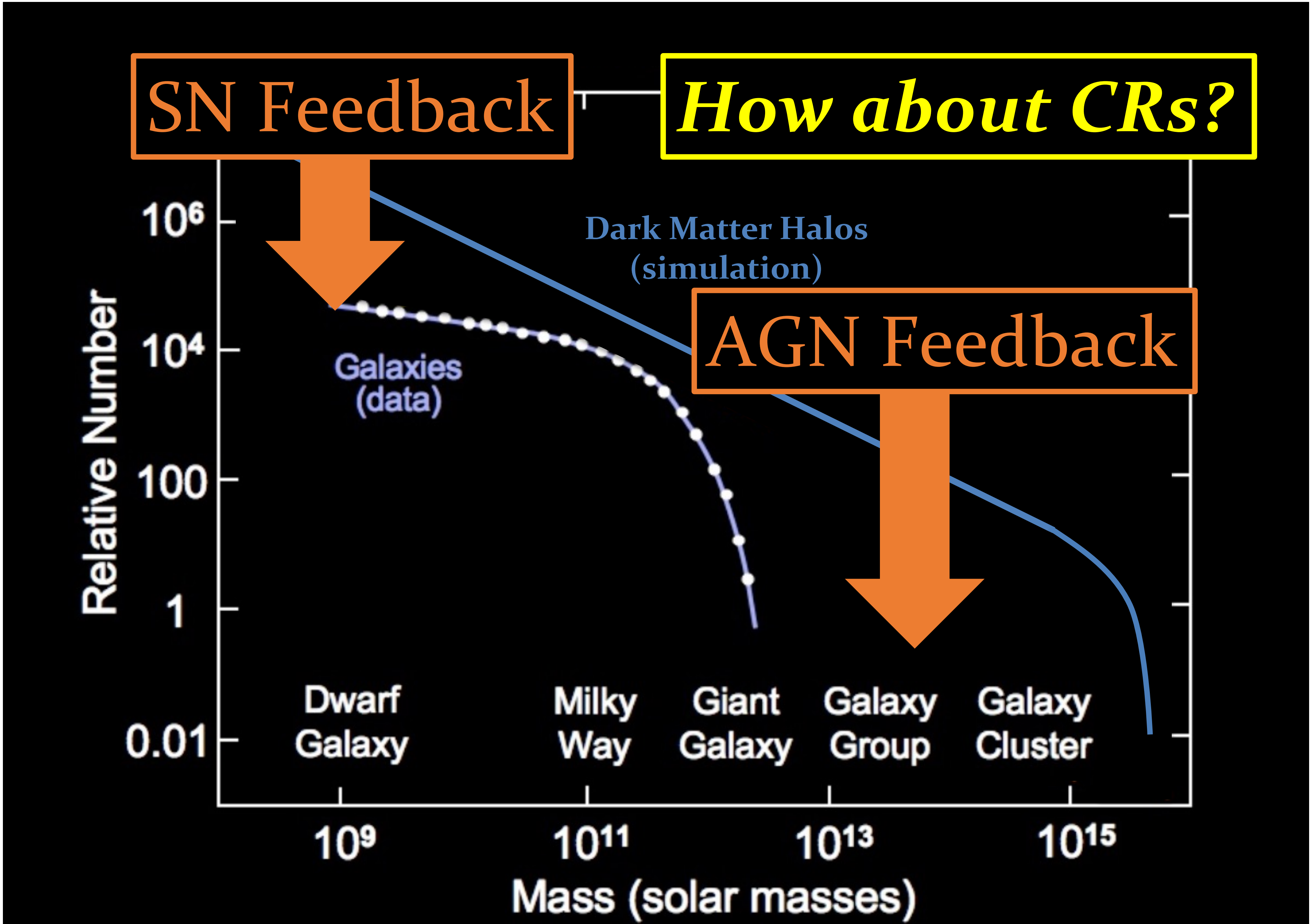
Influence of AGN Feedback

Hot gas in Perseus cluster
(X-ray: thermal Bremsstrahlung emission)



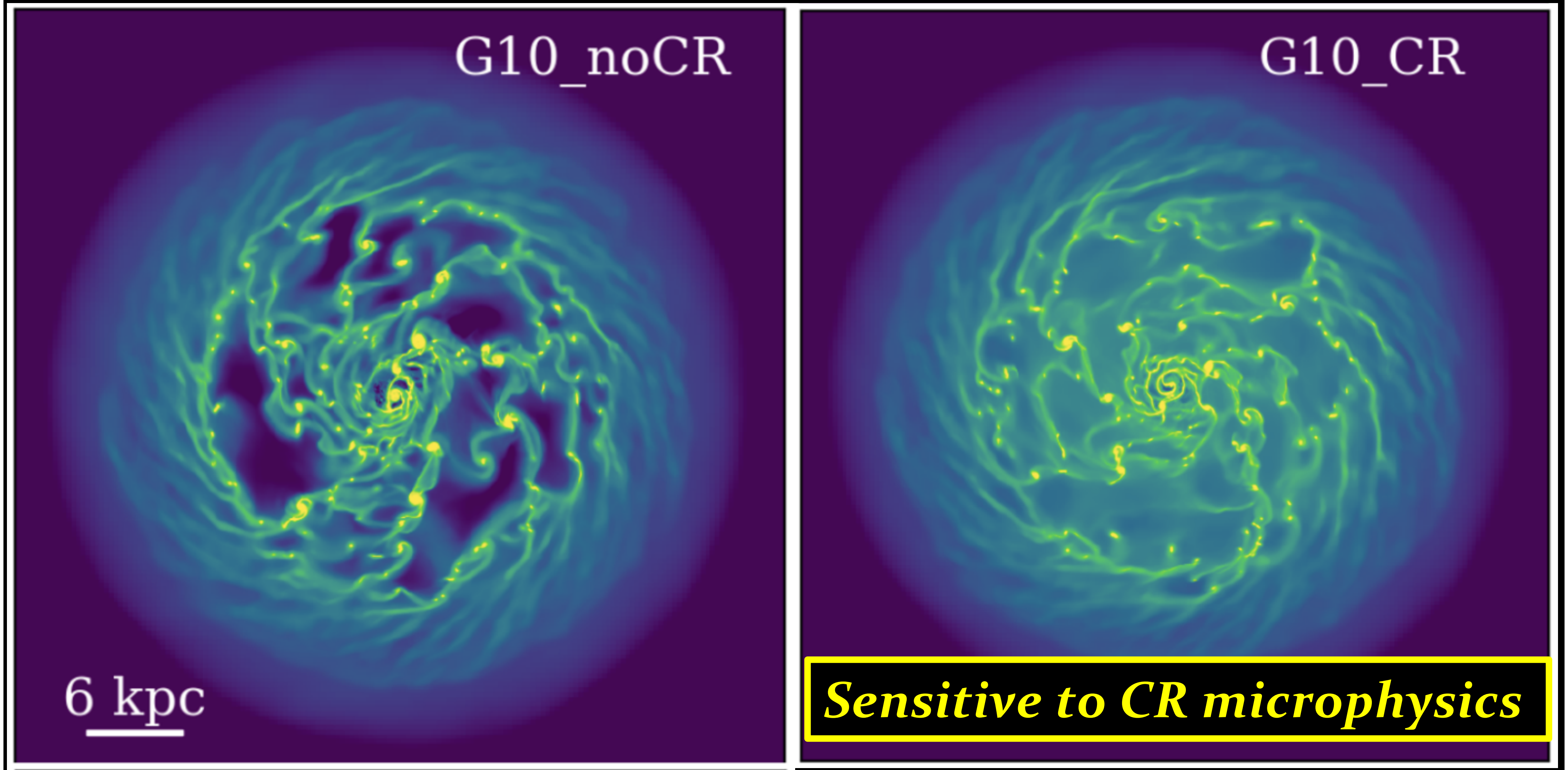
"bubbles" inflated by SMBH jets

SMBH jets
(radio: non-thermal synchrotron from CRs)



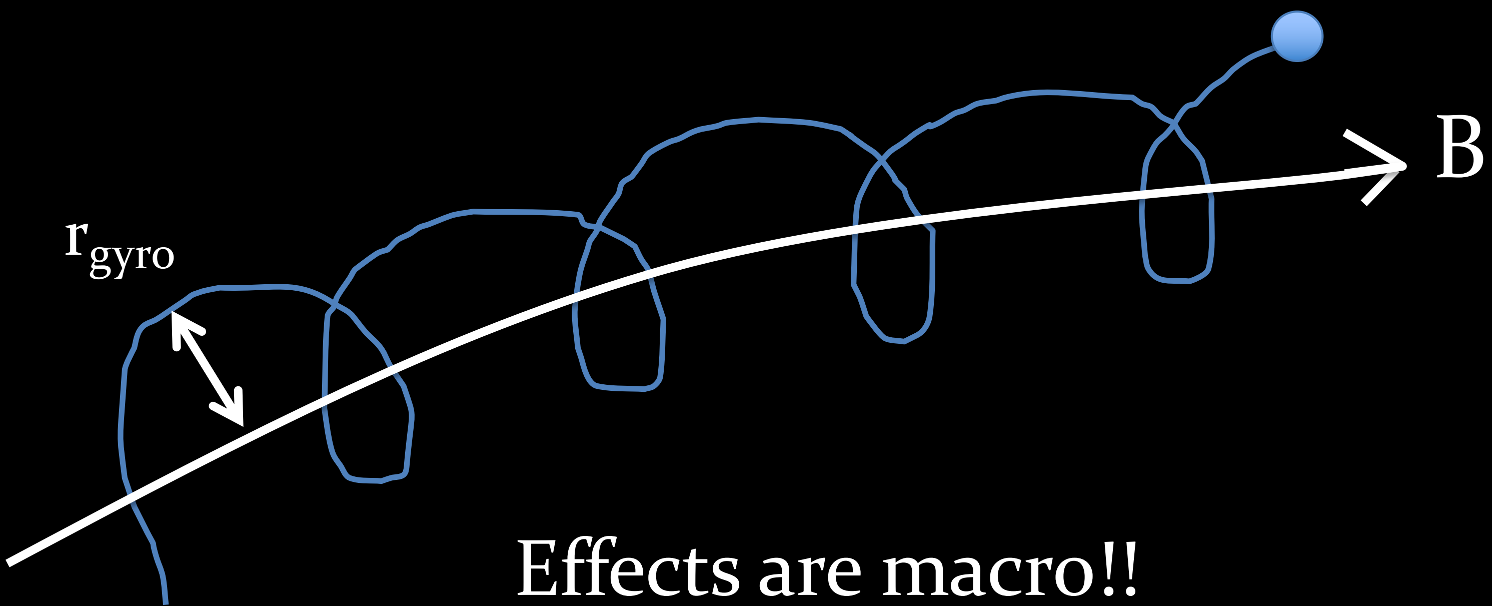
SN Feedback
How about CRs?
Dark Matter Halos
(simulation)
AGN Feedback
Galaxies
(data)
Relative Number
10⁶
10⁴
100
1
0.01
Dwarf Galaxy
Milky Way
Giant Galaxy
Galaxy Group
Galaxy Cluster
10⁹
10¹¹
10¹³
10¹⁵
Mass (solar masses)

Effects of *CRs* on simulated galaxies



Farcy+2020

The “microphysics”?



Effects are macro!!

-- Affect *CR propagation*

-- Transport is *anisotropic*

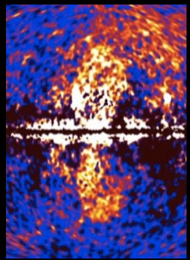
-- Transport speed governed by *plasma physics*

Scales are micro:

$r_{gyro} << L$

Particle-in-cell (PIC) simulations

Theme of my research group @ NTHU –
CR effects 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, 970, 146*
  - -- *Lin & Yang, 2024, ApJ, 974, 269*

- AGN feedback in galaxy clusters
  - -- *Wang & Yang, 2022, MNRAS, 512, 5100*
  - -- *Lin, Yang & Owen, 2023, MNRAS, 520, 963*
  - -- *Chen et al. 2026, ApJ, 999, 197*
  - -- *Tsai & Yang, 2026, MNRAS, 548, 1*
  - -- *Li & Yang 2025, ApJ submitted (arXiv: 2511.23267)*

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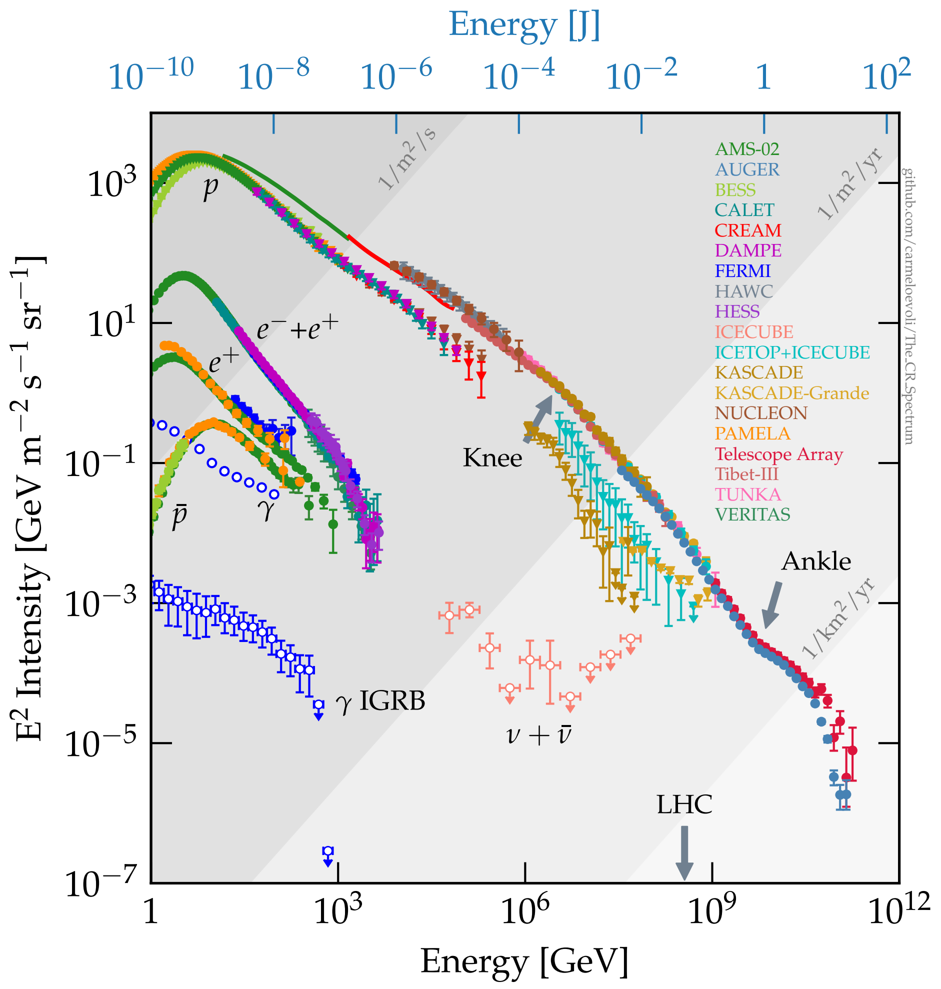
Properties of CRs in the Galaxy



- Power-law from GeV to 10^{20} eV
- Mostly CR protons ($n_i/n_e \sim$ 50-100)
- <E> ~ 3 GeV
- $U_{CR} \sim 1$ eV cm^{-3} ~ $U_B \sim U_{rad} \sim U_{th}$

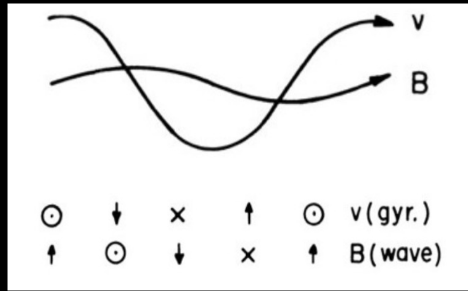
=> ***dynamically important***

- Very isotropic

=> ***well-scattered by B fields*** ($\lambda_{mfp} \sim 1$ pc)

Self-confinement picture of CR transport

- Gyro-resonance scattering: $k_{||} \sim \frac{1}{\mu r_L}$



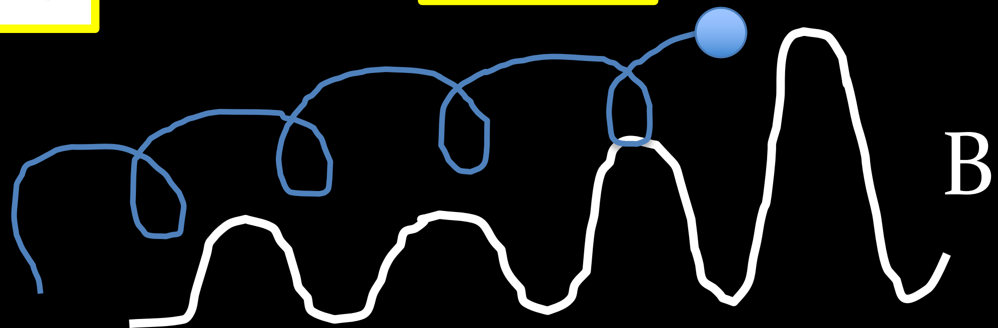
F = v x B

- Streaming instability (Kulsrud & Pearce, 1969):
  Anisotropy => wave growth => enhanced scattering

$$\Gamma_{CR}(k_{||}) \sim \Omega_0 \frac{n_{CR}(>\gamma)}{n_i}\left(\frac{v_D}{v_A} - 1\right)$$

$v_D > v_A$

- Marginal stability: $v_D \sim v_A$



CR-MHD framework

(see reviews by Zweibel 2013, 2017)

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 **Heating via waves**

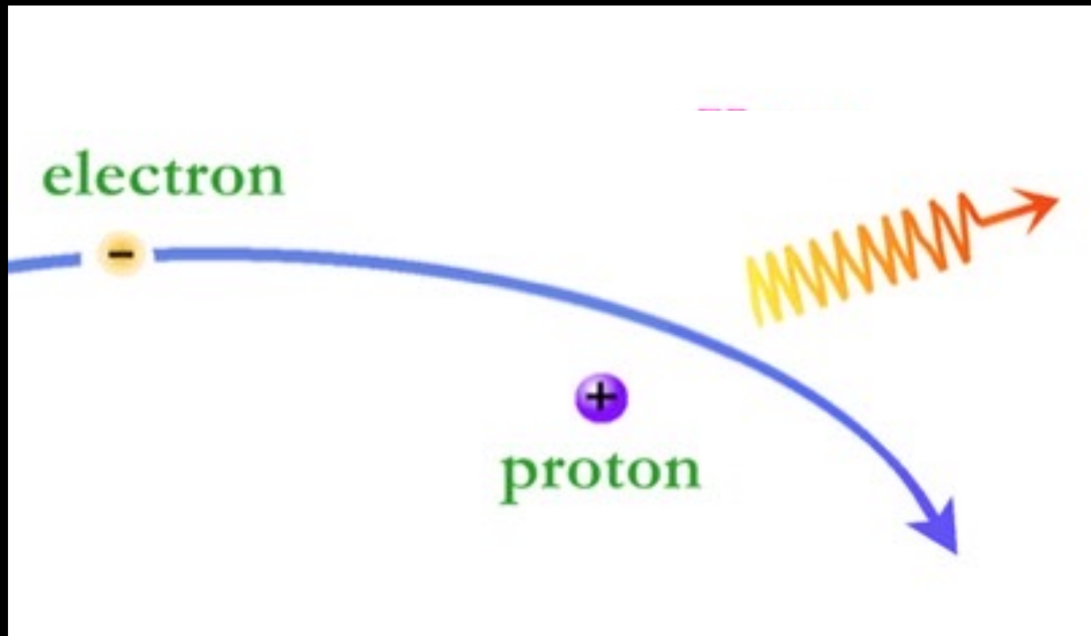
$$\boldsymbol{F} = (e_{\mathrm{CR}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{A}}, \ \ \kappa_{\parallel} \sim v^2/\nu$$

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

****Add-on: CRSPEC (Yang+17)***

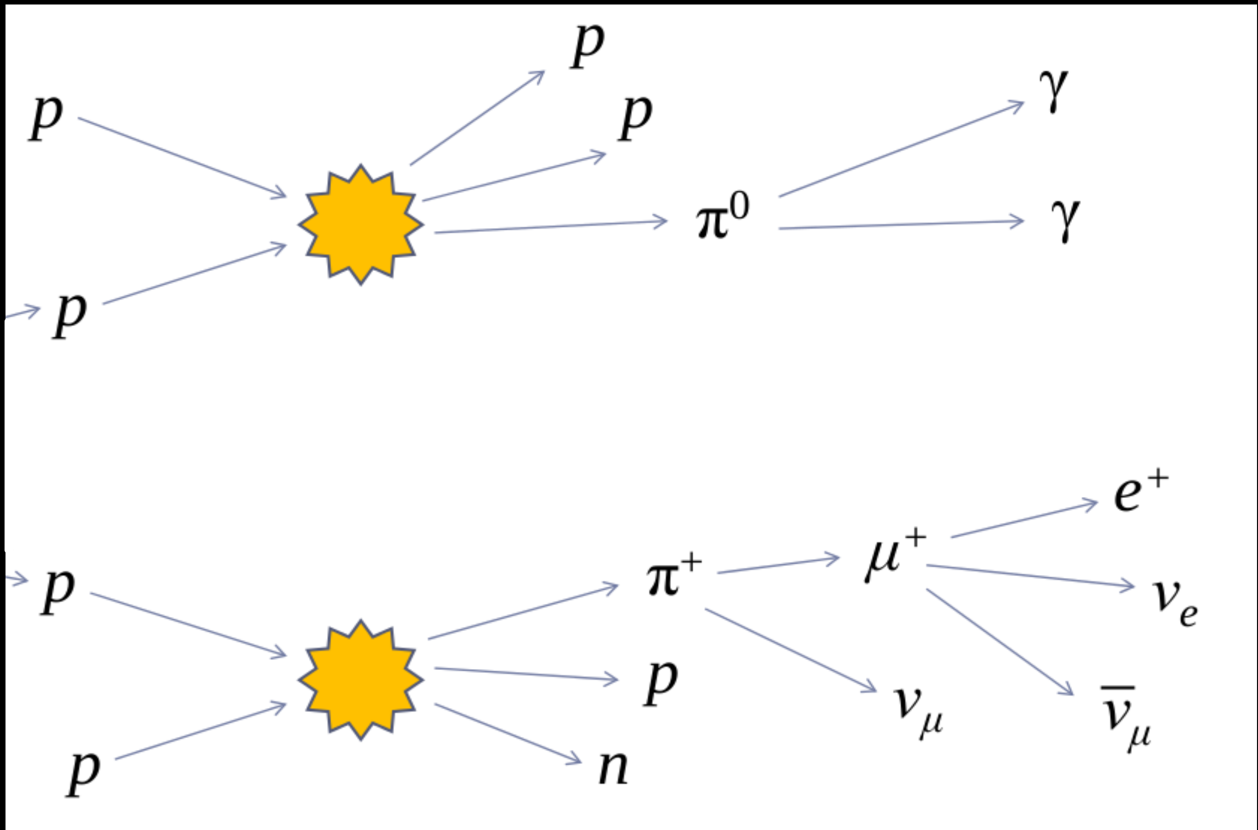
Thermal Bremsstrahlung emission by the gas

- Also called free-free emission
- Emitted by hot ionized gas in galaxies ($T \sim 10^6$K) and galaxy clusters ($T \sim 10^7$K)
- Observable in X-rays



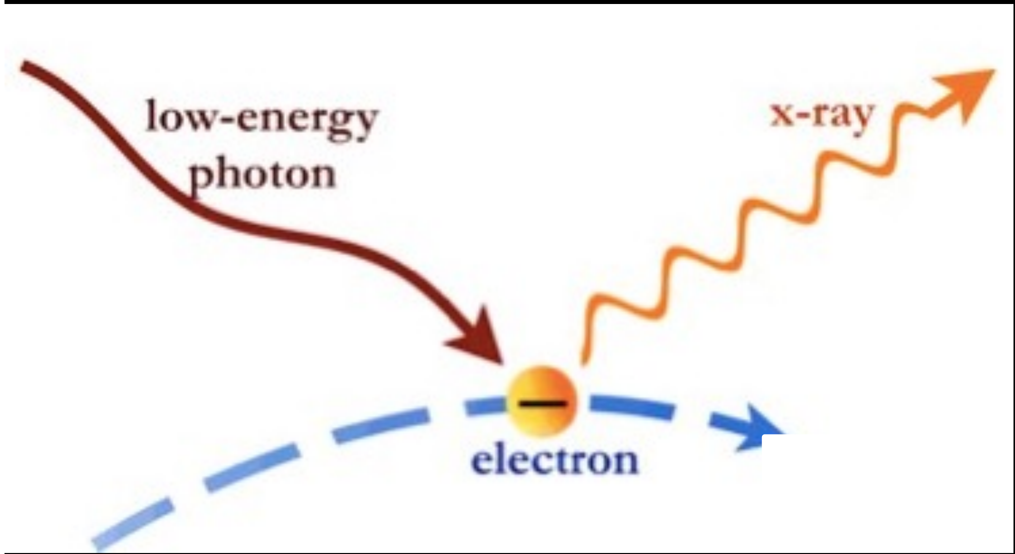
Non-thermal emission by CRp

- ***Hadronic process*** – inelastic collisions between CRp and thermal nuclei in the galactic medium
- Producing gamma rays, neutrinos, and synchrotron from secondary e- & e+



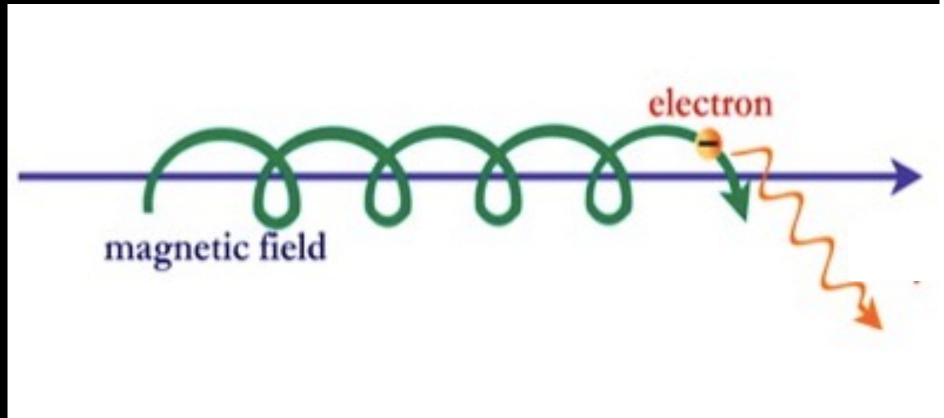
Non-thermal/leptonic emission by CRe

Inverse Compton (IC) scattering

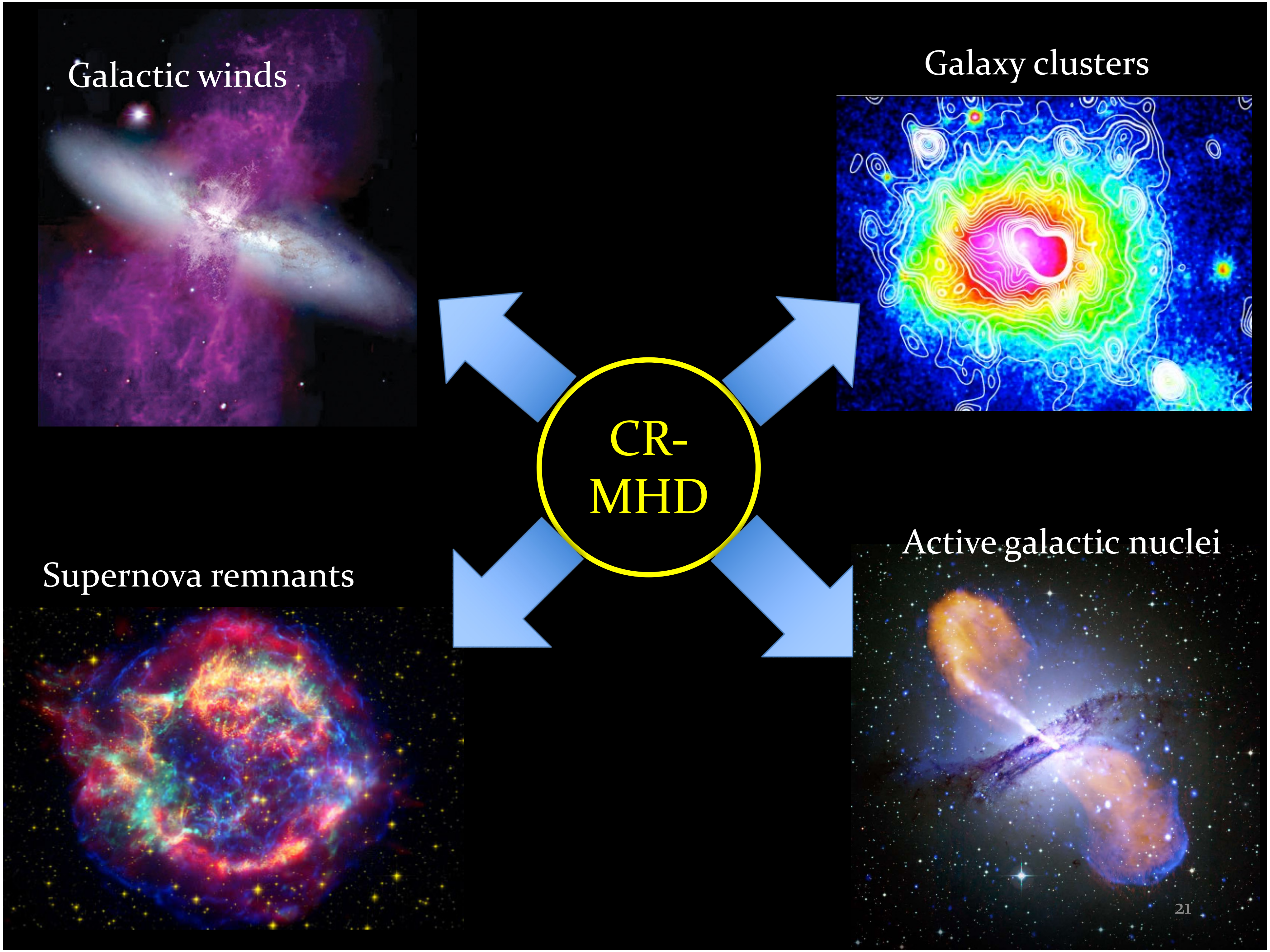


Observable in X-ray to gamma rays

Synchrotron radiation



Observable in radio up to X-ray


Galactic winds
Galaxy clusters
CR-
MHD
Supernova remnants
Active galactic nuclei
21

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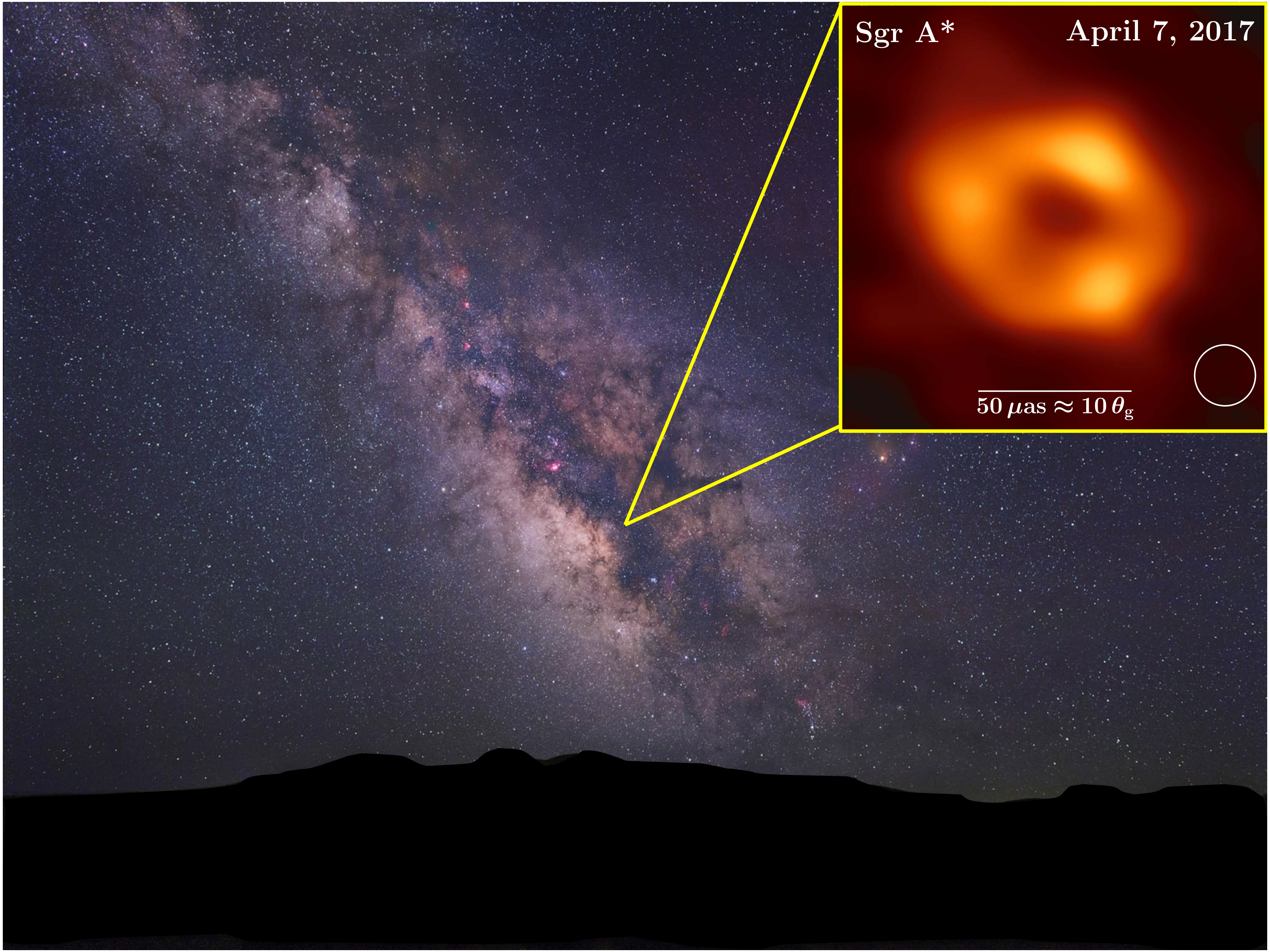
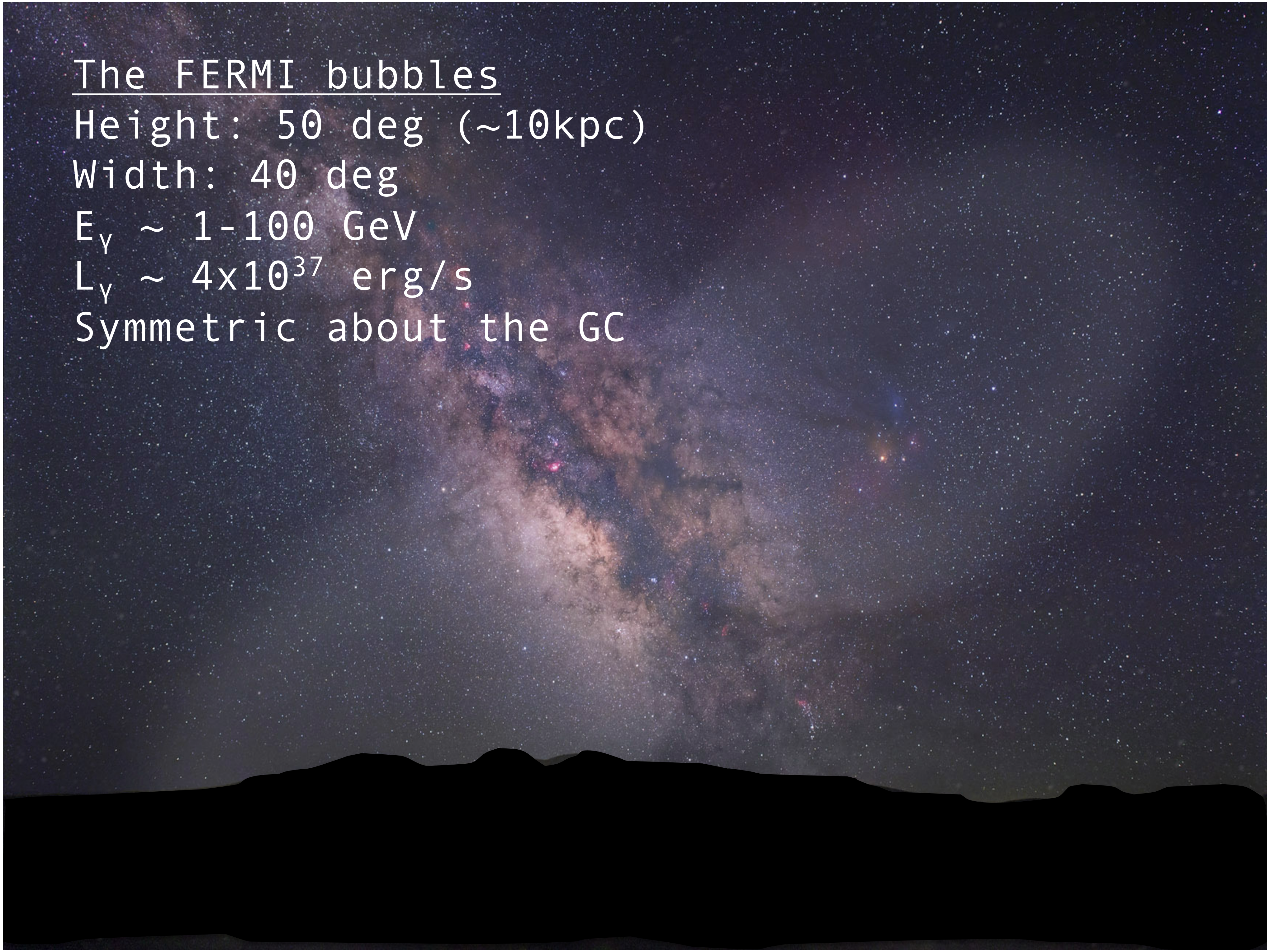


Sgr A*
April 7, 2017
50 μas ≈ 10 θ_g


The FERMI bubbles
Height: 50 deg (~10kpc)
Width: 40 deg
E_γ ~ 1-100 GeV
L_γ ~ $4x10^{37}$ erg/s
Symmetric about the GC

The FERMI bubbles

Height: 50 deg (~10kpc)

Width: 40 deg

$E_\gamma \sim$ 1-100 GeV

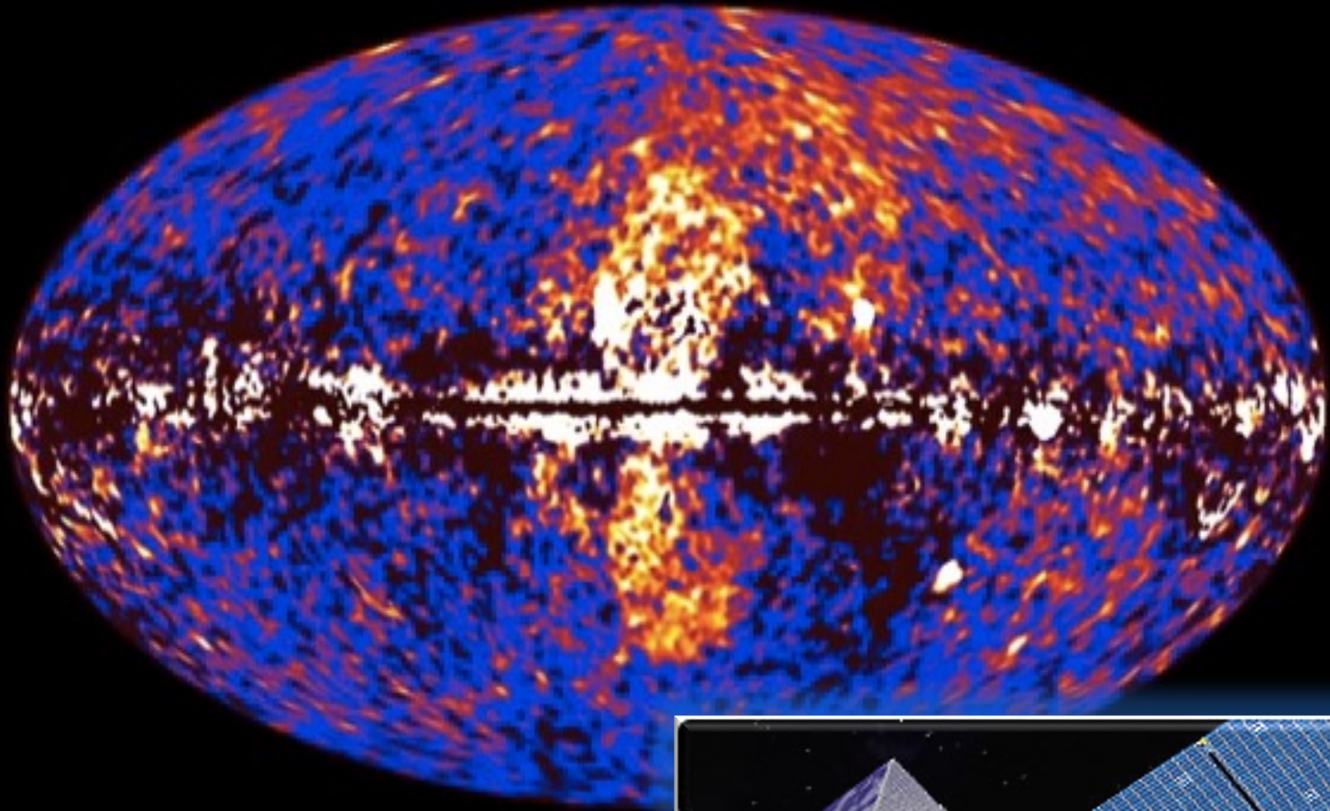
$L_\gamma \sim 4\times10^{37}$ erg/s

Symmetric about the GC

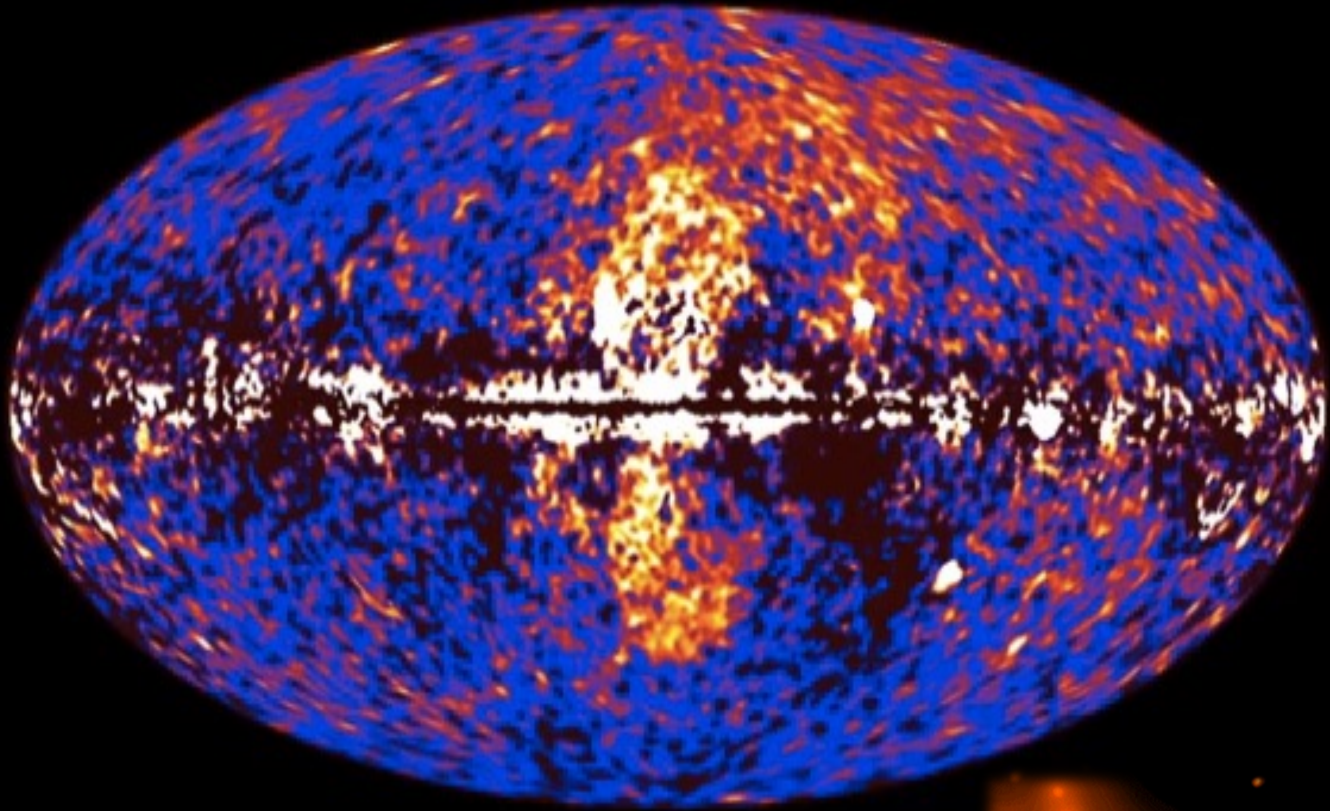
SMBH jets (Cen A)

Starburst winds (M82)

The Fermi bubbles (Su+ 2010)

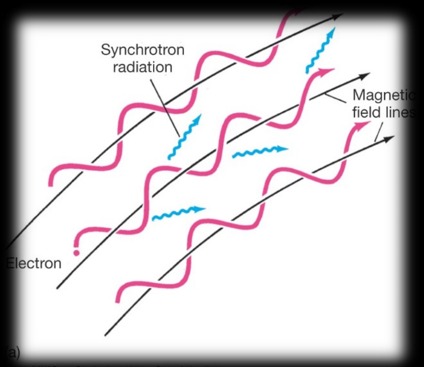


The *Fermi* bubbles (Su+ 2010)

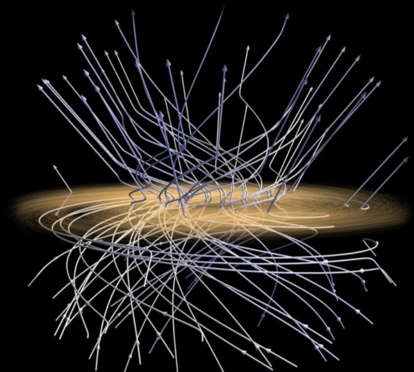


SMBH jets (Cen A)

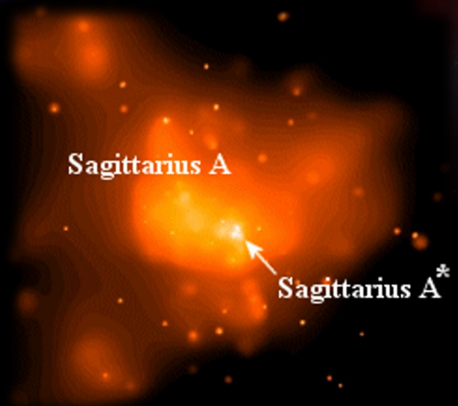
Starburst winds (M82)



CR transport

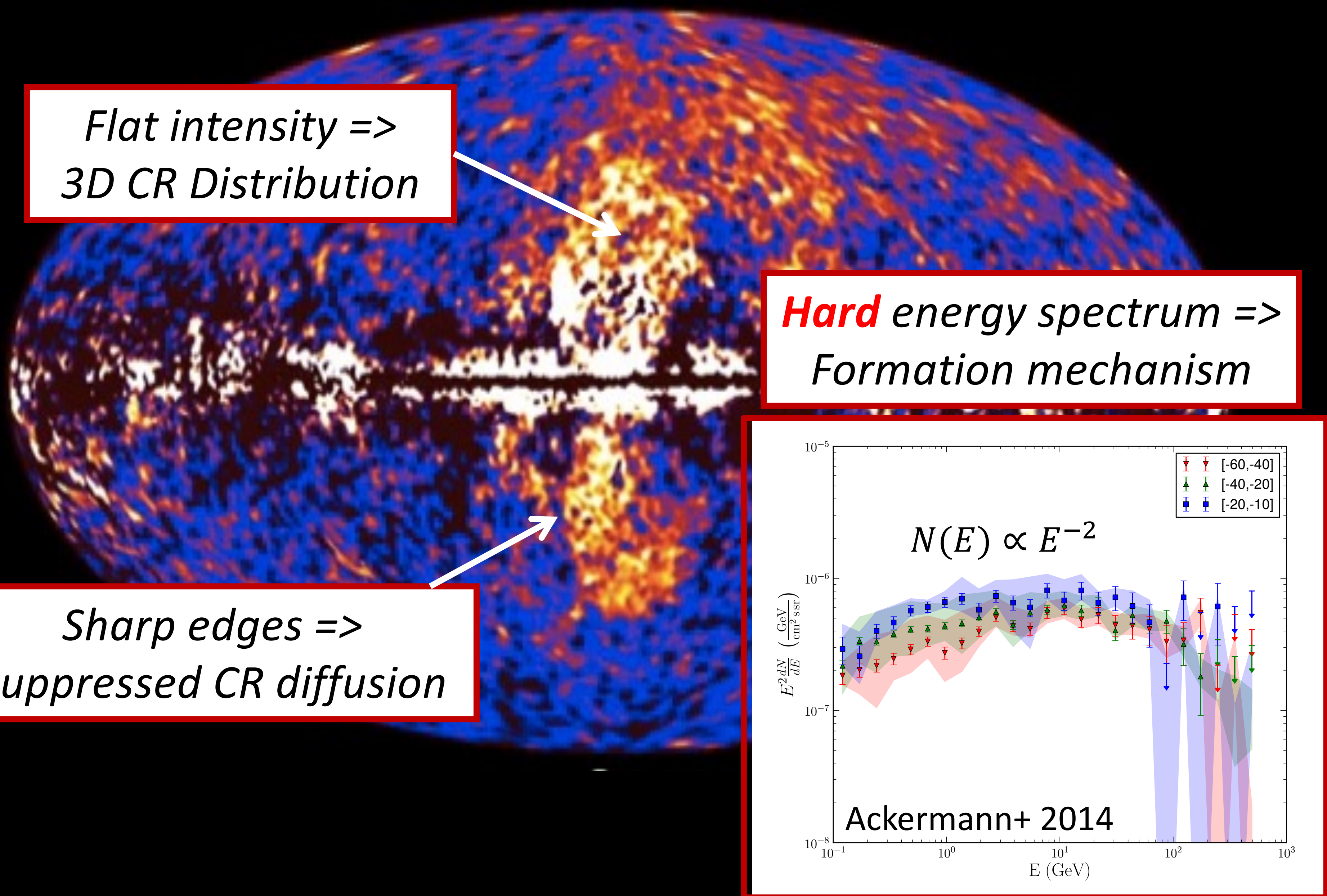


Galactic B field

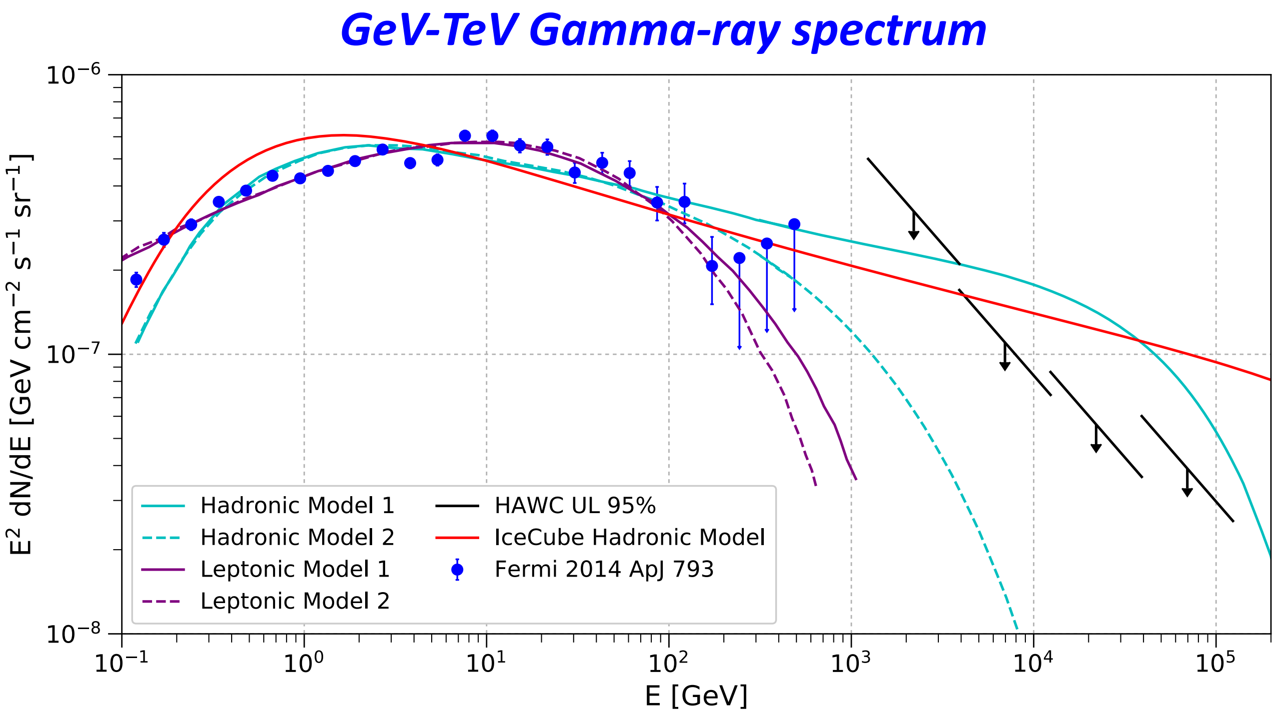


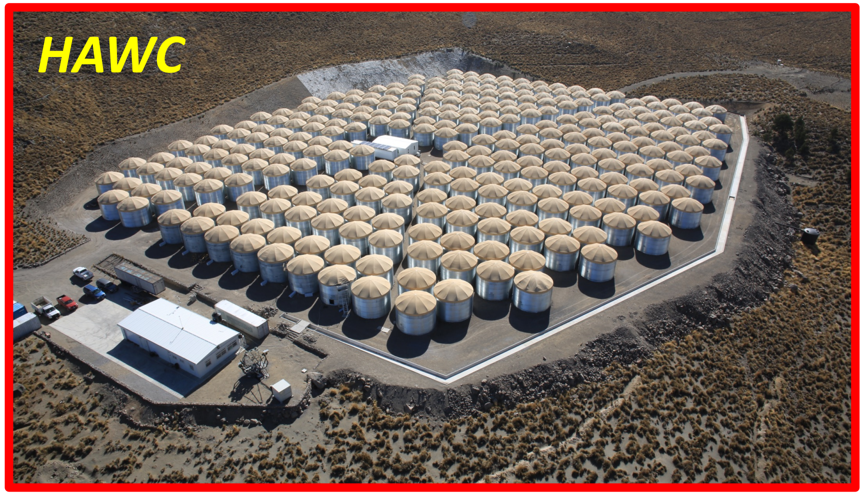
GC activity

Gamma-ray bubbles by *Fermi* (Su 2010)



TeV gamma-ray non-detection by *HAWC* (Abeysekara+ 2017)

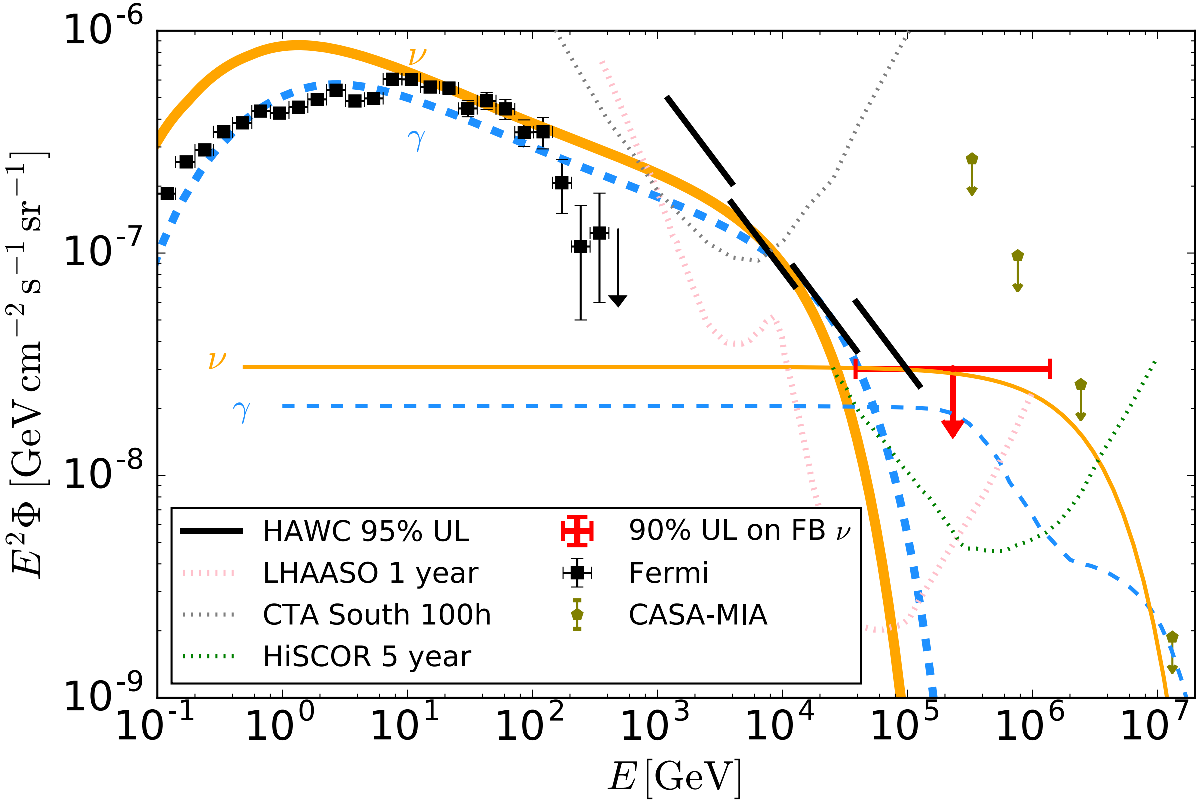




- Upper limits in the 1-100 TeV range
- ***Purely hadronic models disfavored***

Neutrino events near the Fermi bubbles by *IceCube*

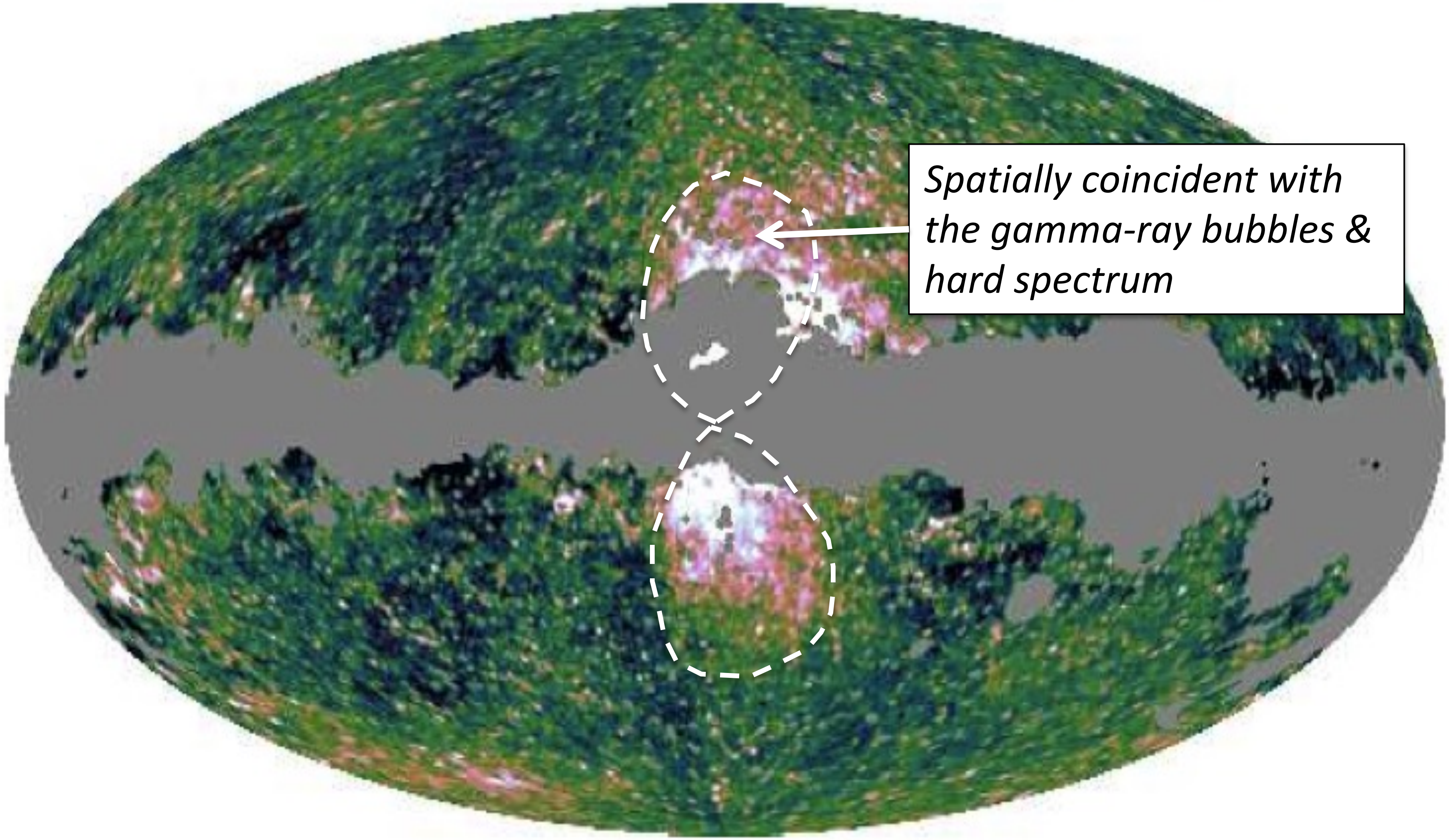
(Fang+ 2017, Sherf+ 2017)



- ❖ No FB neutrinos detected
- ❖ Purely hadronic models disfavored

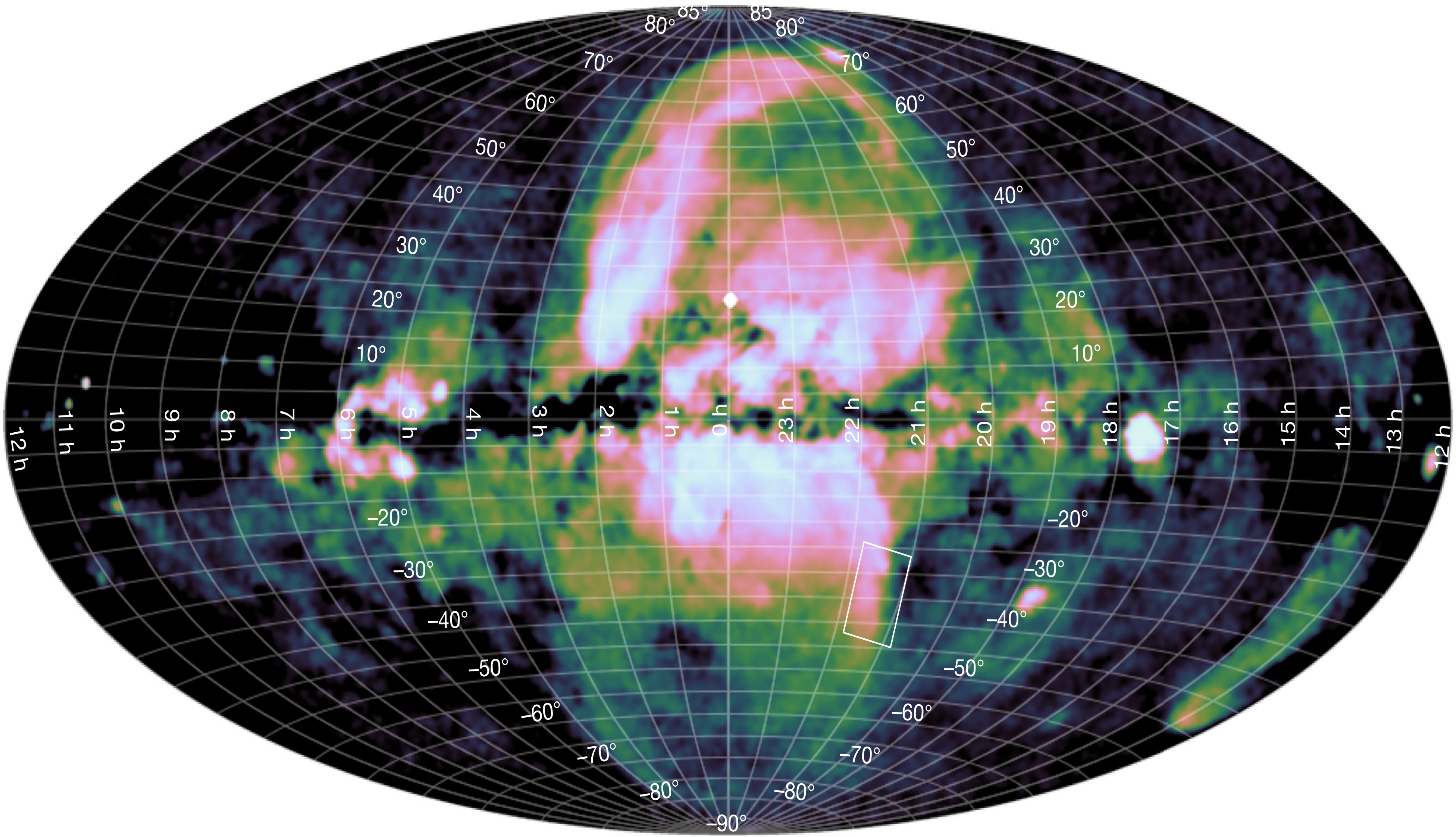
Microwave haze by *WMAP & Planck*

(Finkbeiner 2004, Dobler+ 2008; Planck Collaboration 2012)



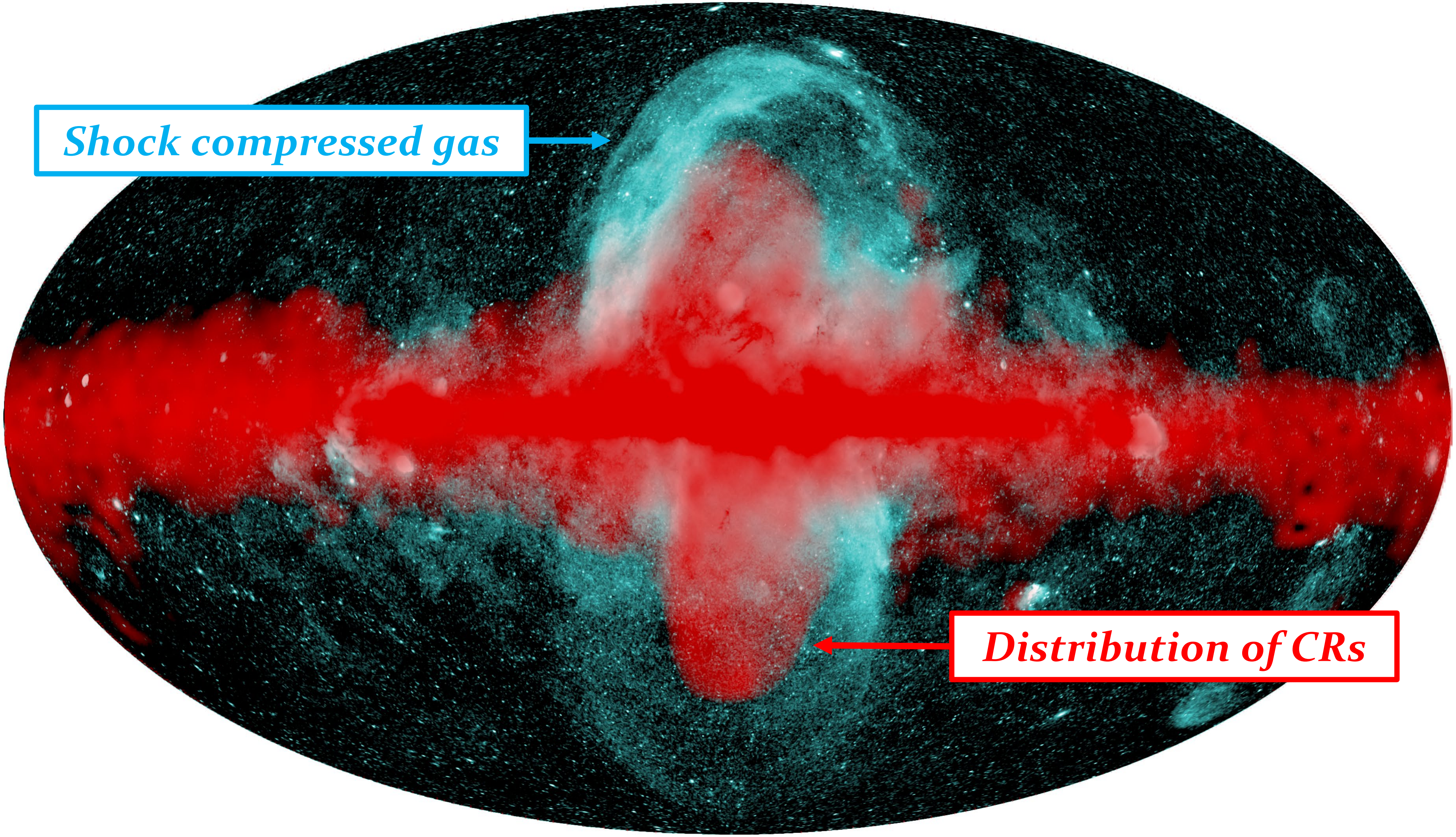
The eRosita bubbles (0.6-1.0 keV)

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



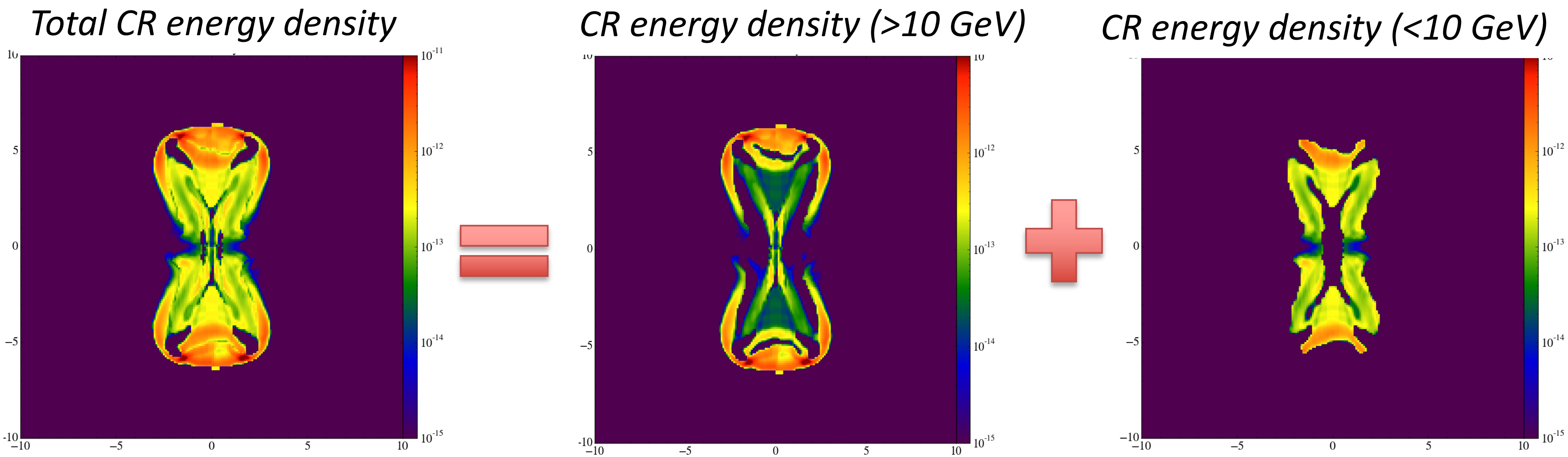
X-ray map by *eRosita* + Gamma-ray by *Fermi*

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



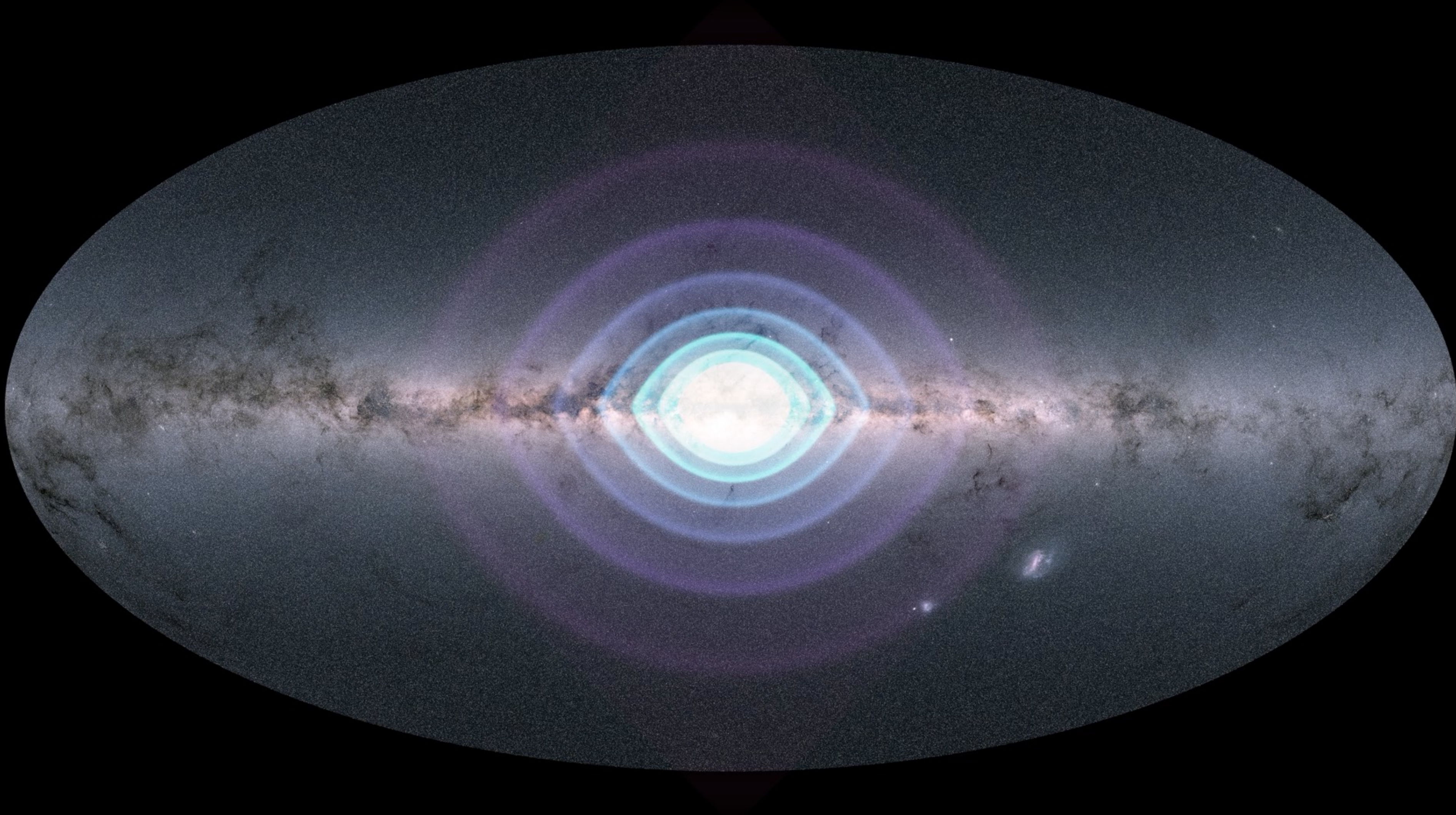
Simulating the *Fermi* bubble spectrum

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



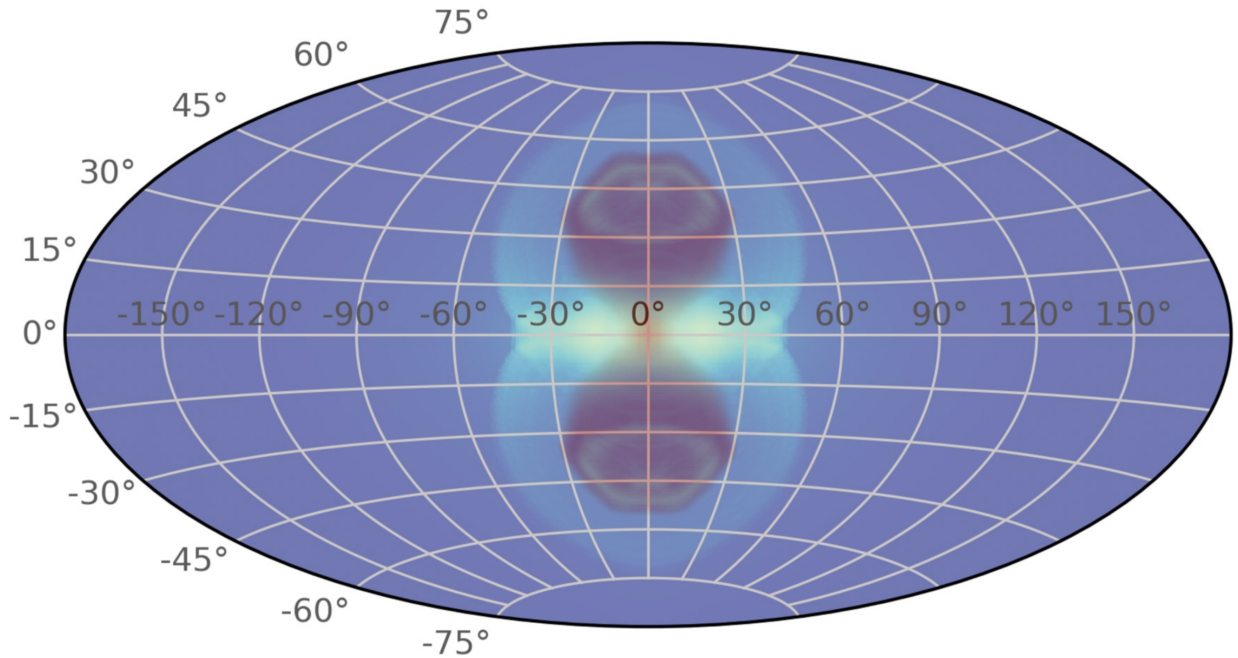
Yang & Ruszkowski (2017)

Simulation of bubble formation by SMBH jets

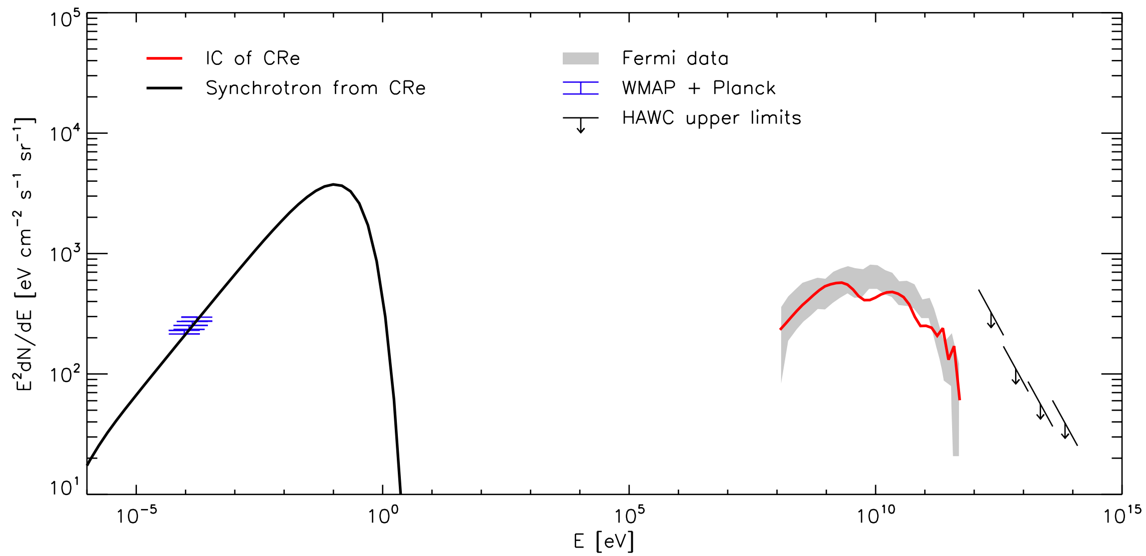


All X-ray/gamma/microwave data are matched!

KY et al. (2022), Nature Astronomy, 6, 584 (http://arxiv.org/abs/2203.02526)



"Fermi/eRosita bubbles as relics of past activity of the Galactic black hole"

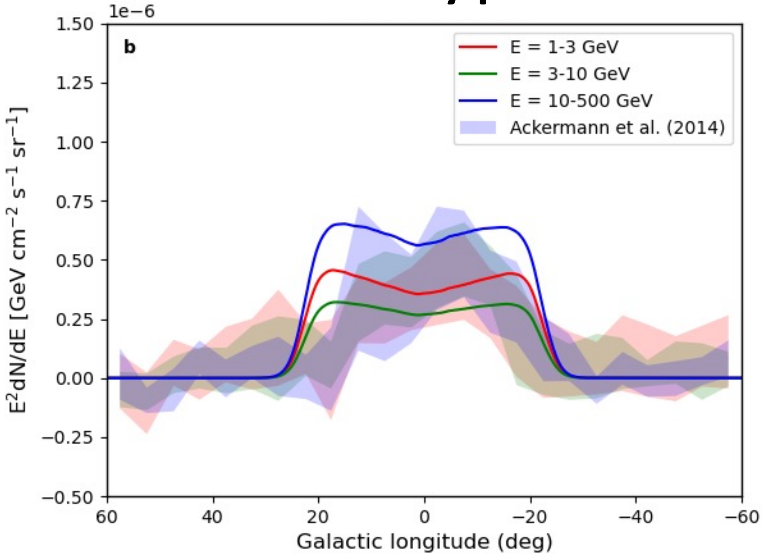


- Multi-wavelength spectra consistent with ***leptonic*** emission
- Jets occurred ***~2.6 Myr ago***
- Jets were active for 0.1 Myr
- Inferred accreted mass ~$10^{3\text{-}4}$ M_{sun}

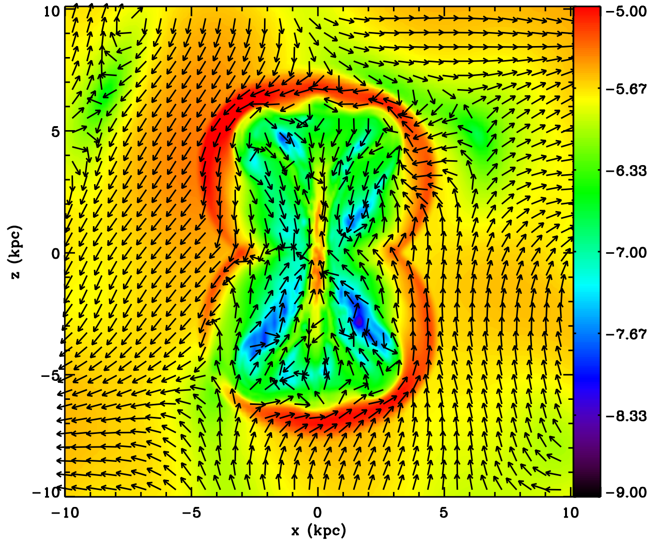
Magnetic draping + anisotropic CR diffusion

=> ***sharp bubble edges***

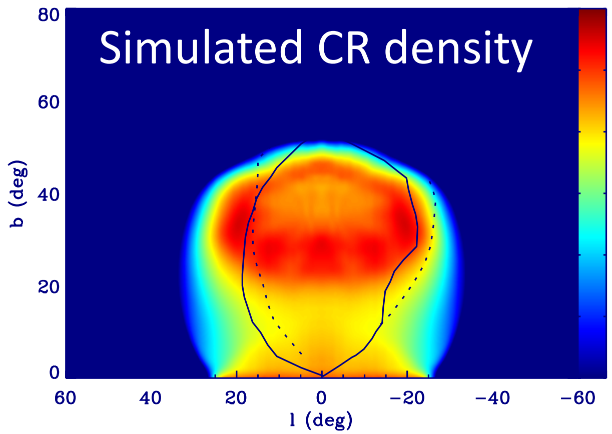
Gamma-ray profile



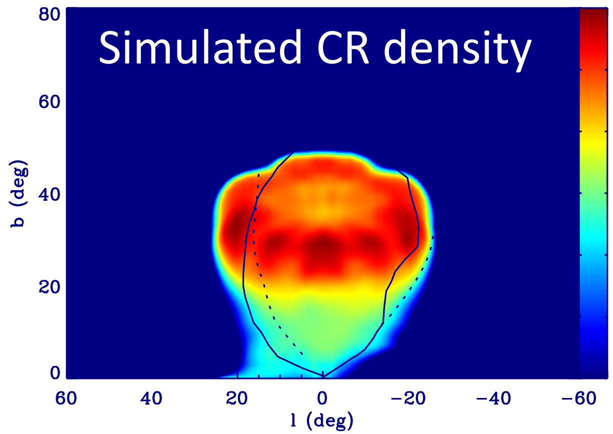
Magnetic draping effect



Isotropic CR diffusion

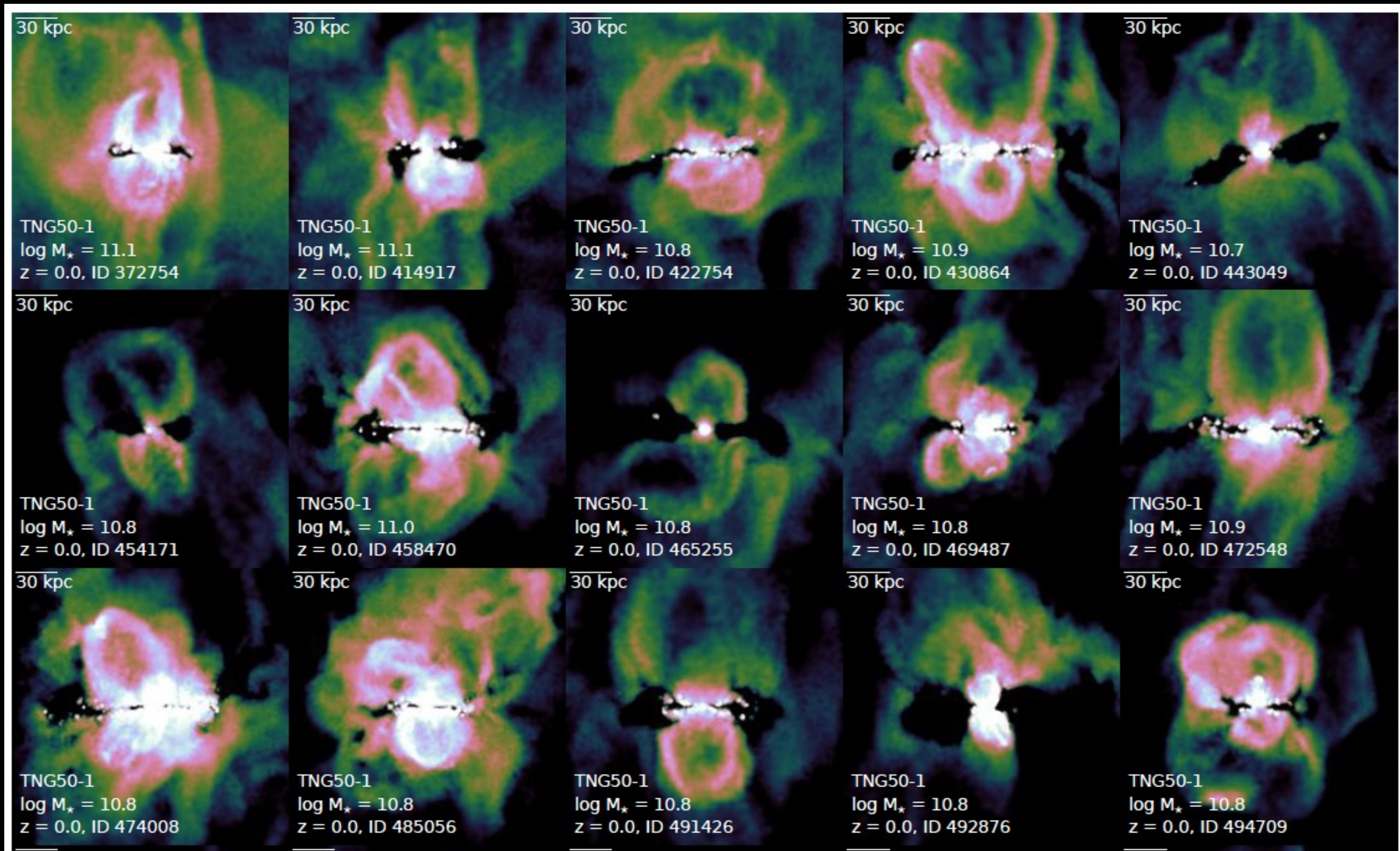


Anisotropic CR diffusion



Galactic bubbles should be ubiquitous
(Pillepich et al. 2021)

- Cosmological simulations found that 2/3 of MW-analogues show bubble-like structures driven by SMBH activities



Open questions

- What event triggered the SMBH activity a few Myr ago?
- Current modeling of Galactic CR propagation (e.g., leaky box, GALPROP) assume isotropic CR diffusion and some magnetic field geometry

=> Given that simulations predict complex structures (outflows, bubbles) and anisotropic CR transport, how do these influence results of previous models?

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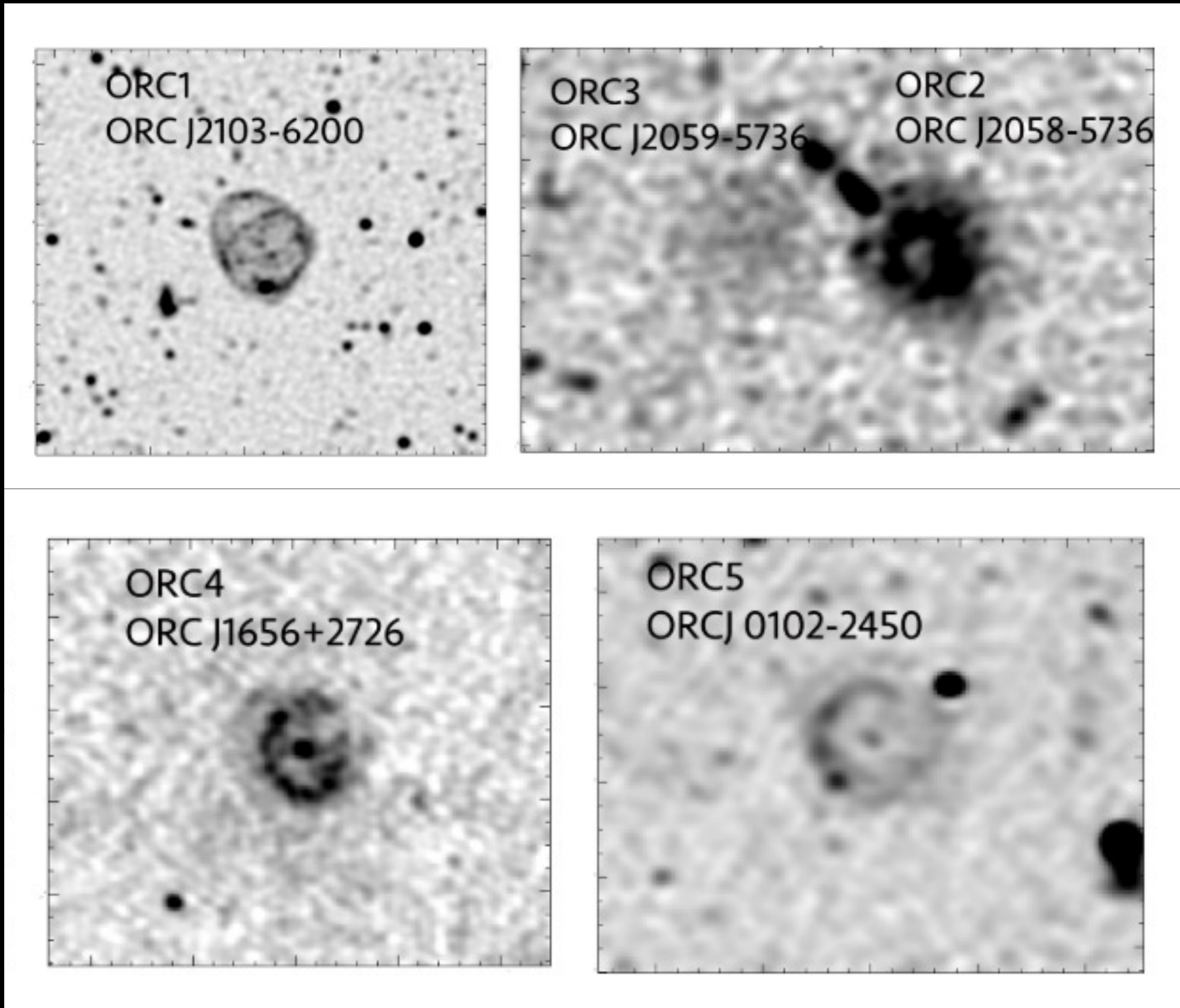
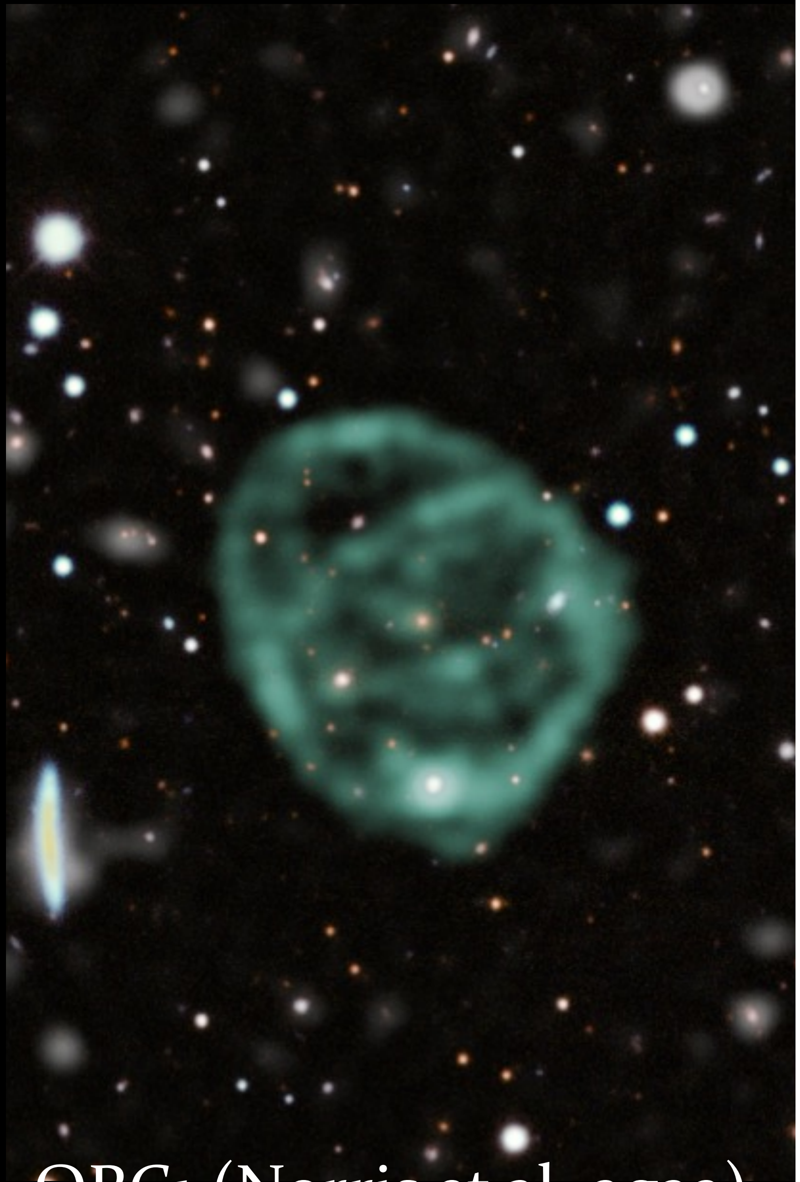
Odd radio circles (ORCs)



Norris et al. (2022)

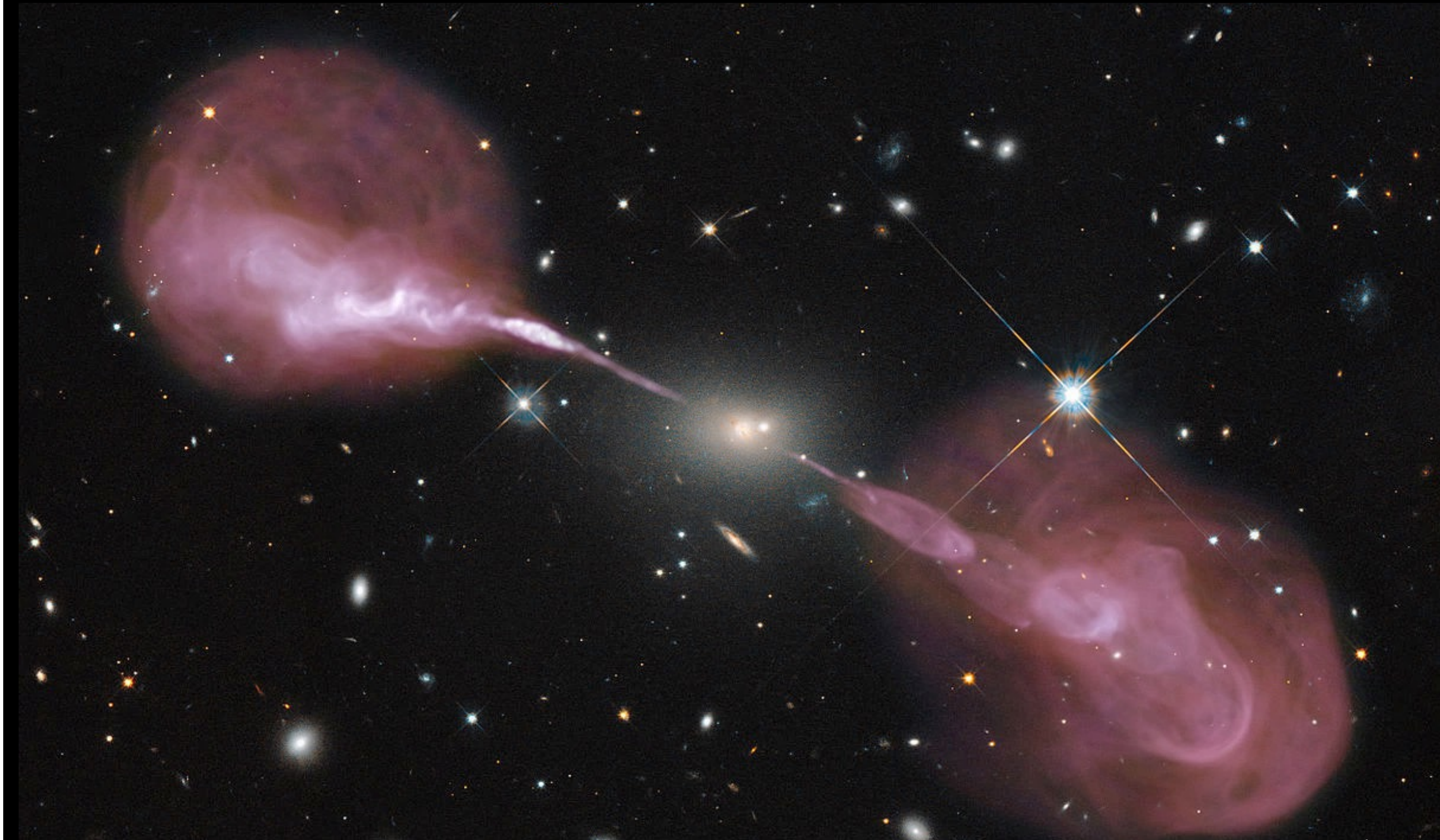
Odd radio circles (ORCs)

- Discovered in 2021 (~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)
  - End-on SMBH jet-inflated bubbles



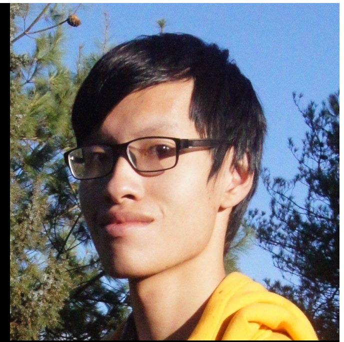
ORC1 (Norris et al. 2022)

Can AGN bubbles explain the ORCs?



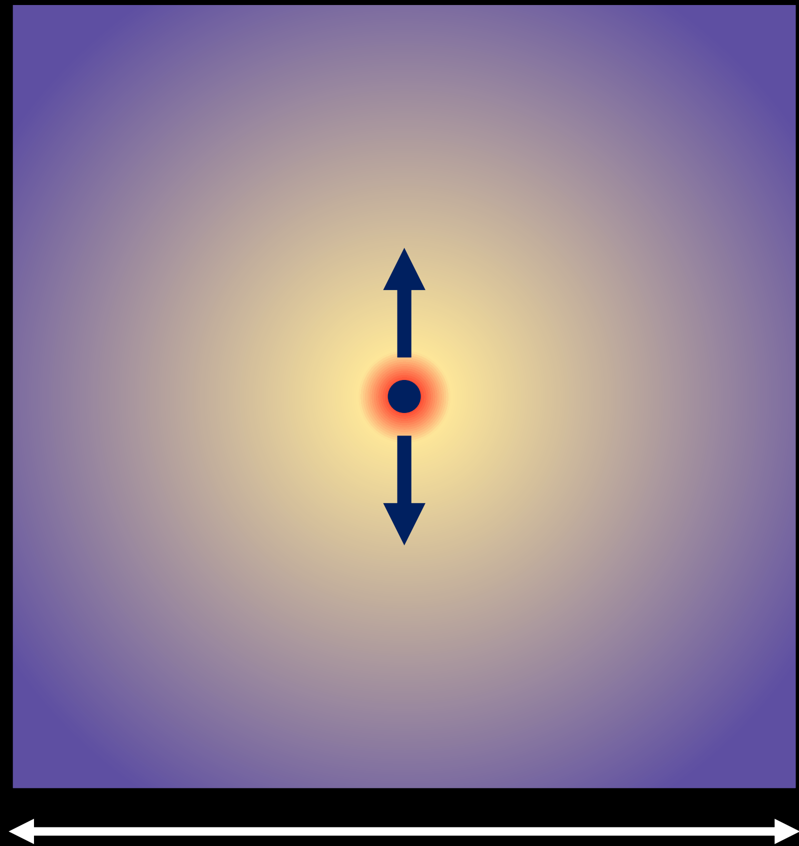
CR-MHD simulations of the ORCs

(Lin & Yang, 2024, ApJ, 974, 269)



Yen-Hsing Lin
(NTHU -> UCSD)

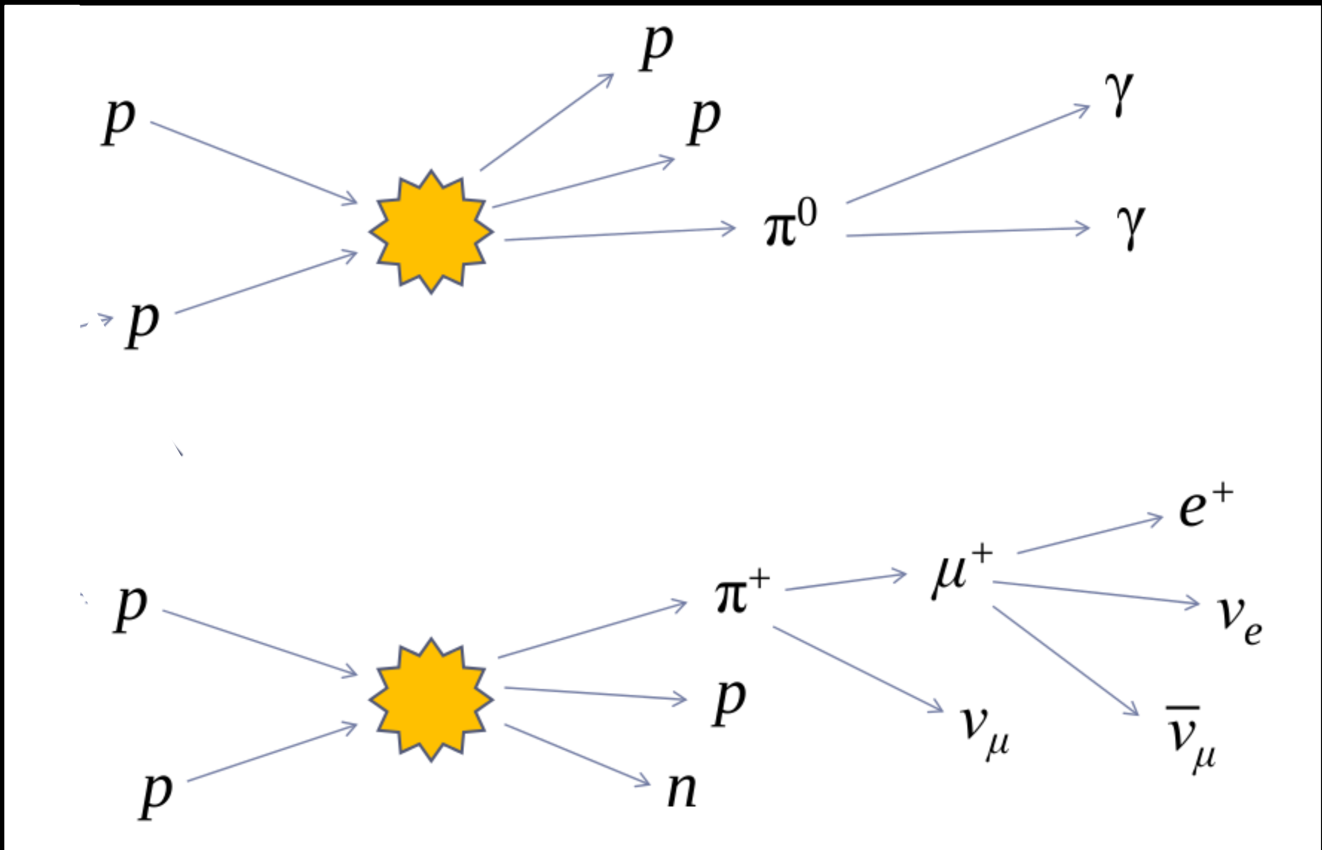
- FLASH code with AMR
- Box size: 1 Mpc, resolution: 0.5 kpc
- Gas within a galaxy group (M_{vir}=8e12 ~ 8e13 M_{sun})
- CR proton (CRp) dominated jets (P_{jet}=2.5e46 erg/s, T_{jet}=50 Myr)
- Radio image: integrated synchrotron emissivity



1 Mpc

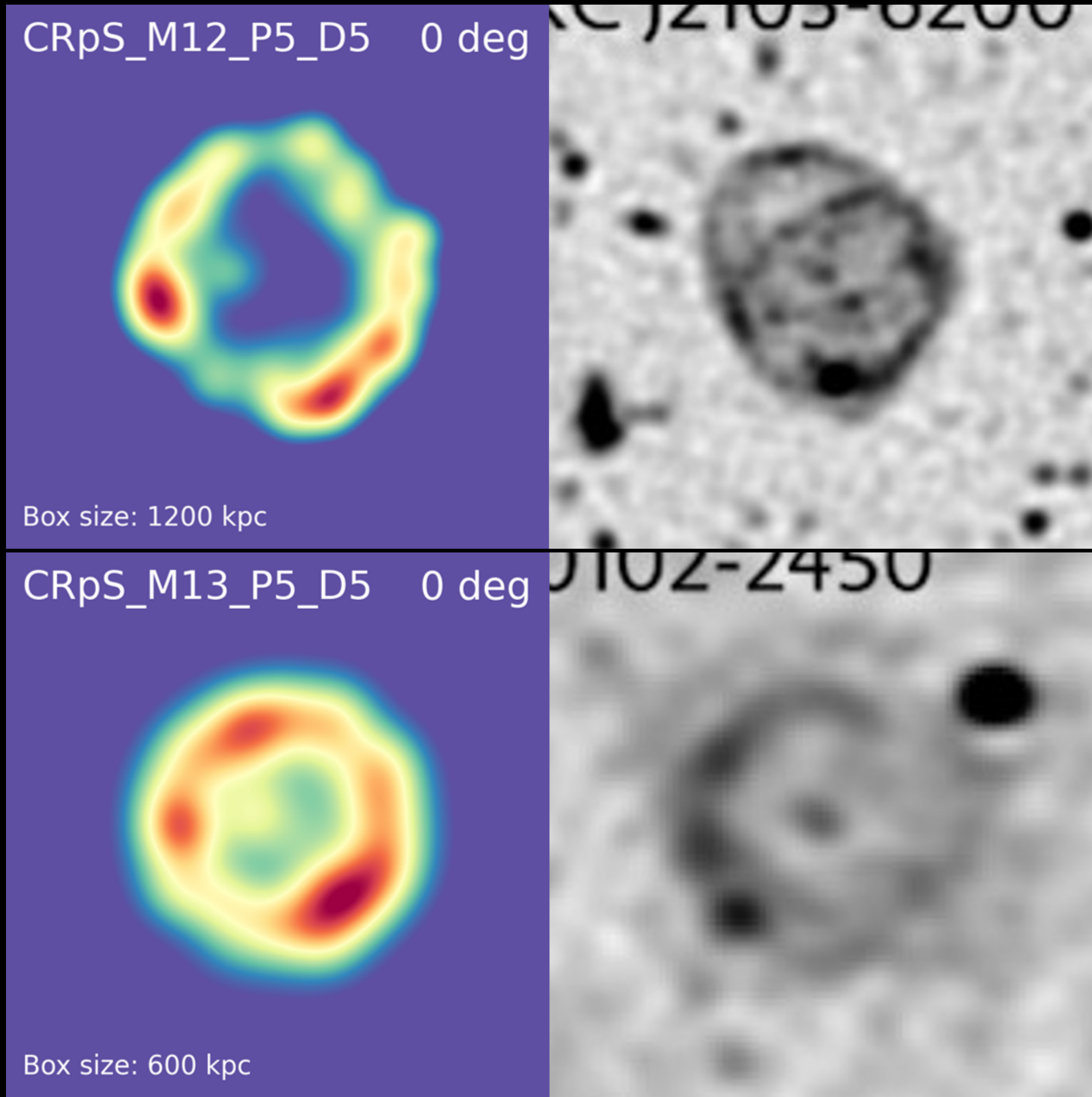
Where does the radio emission come from?

- ***Hadronic collisions*** between CRp and protons in the ambient medium



Secondary e- & e+
=> Radio synchrotron

Results – ORCs reproduced!



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

Open questions

- How to connect the ORCs into the standard picture of galaxy evolution? How are they related to typical radio galaxies? (Li & Yang, 2026, ApJL submitted)
- Our model predicts that the ORC emission originates from ***hadronic*** collisions, implying that ORCs are potential sources of cosmic ***neutrinos***!

Summary

- Understanding CRs is crucial for particle astrophysics; however, there remain large uncertainties regarding their microscopic transport processes

- CR-MHD simulations are powerful tools for modeling the thermal & non-thermal emission of various astrophysical objects

- The Fermi bubbles are likely generated by past jet activity of Sgr A*. Such bubbles should be common in MW-like galaxies. Galaxy models should include more realistic B field & CR transport

- We showed that end-on AGN bubbles could explain key features of the observed ORCs. Due to hadronic collisions, ORCs may be potential sources of cosmic neutrinos