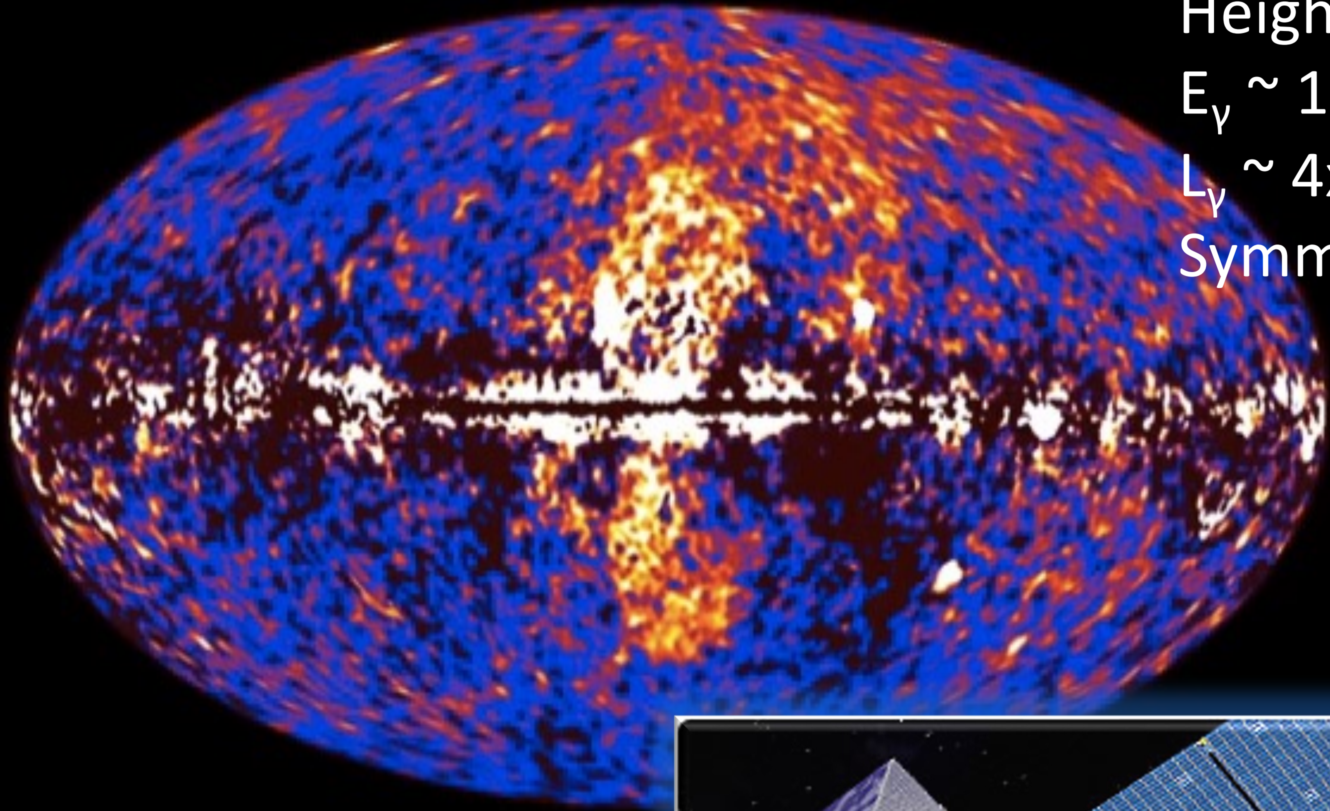
Unveiling the Origin of the Fermi/eRosita Bubbles

Hsiang-Yi Karen Yang
National Tsing Hua University (NTHU), Taiwan

Collaborators: Mateusz Ruszkowski (U Mich), Ellen Zweibel (UW-Madison)

Highlight talk at ECRS
July 29, 2022

The *Fermi* bubbles (Su+ 2010)



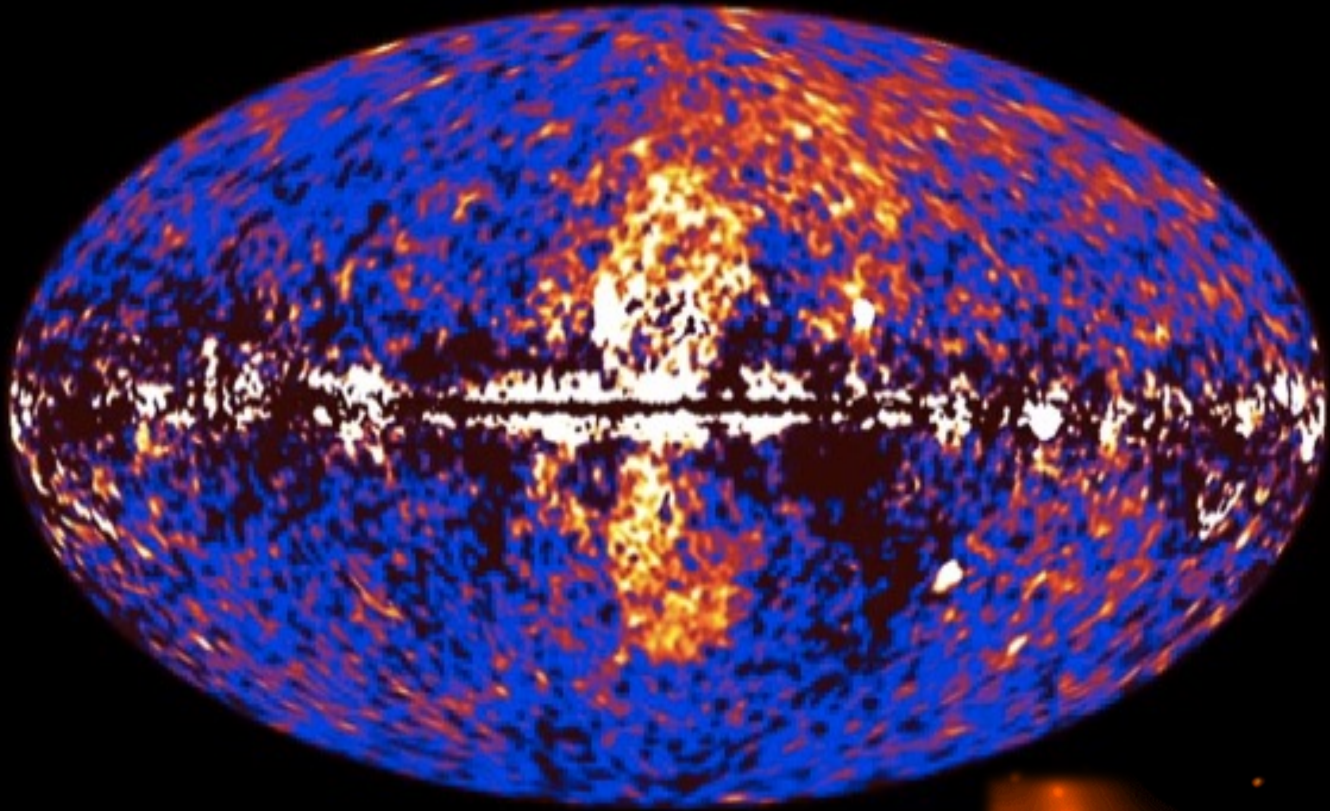
Height: ~50 deg (~10kpc)

E_γ ~ 1-100 GeV

L_γ ~ 4×10^{37} erg/s

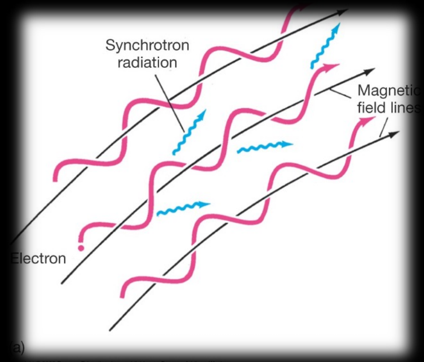
Symmetric about the GC

The *Fermi* bubbles (Su+ 2010)

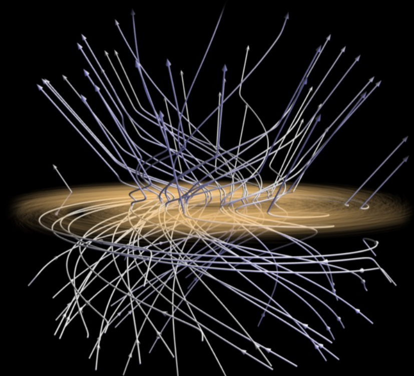


AGN jets (Cen A)

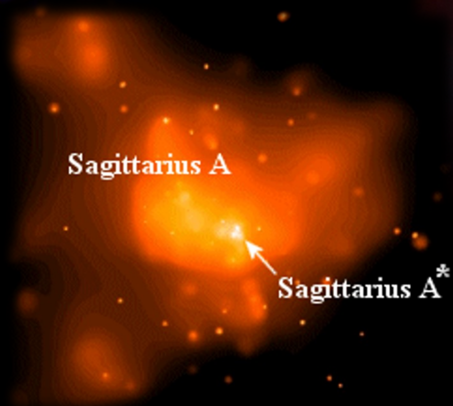
Starburst winds (M82)



CR transport

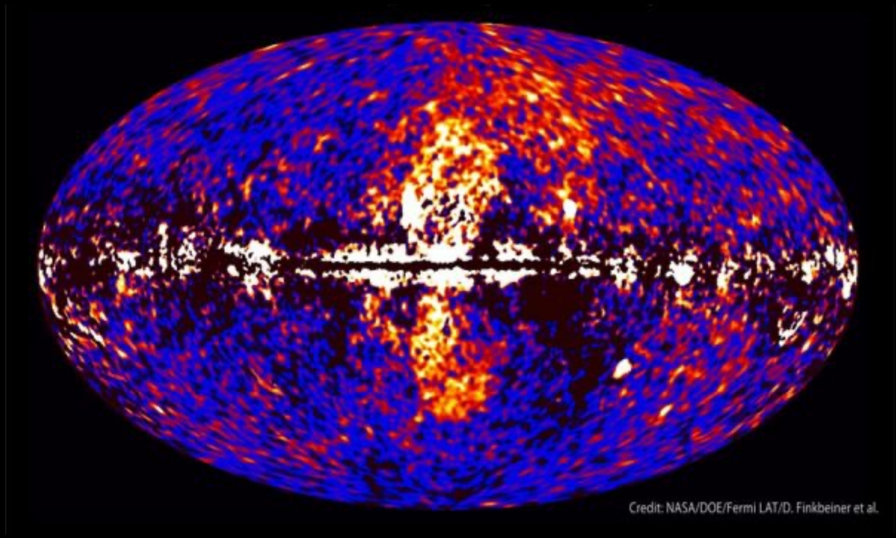


Galactic B field

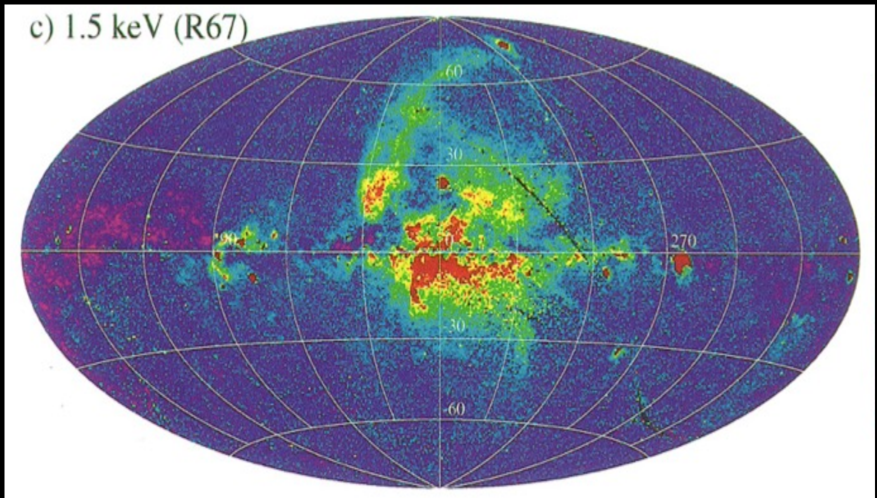


GC activity

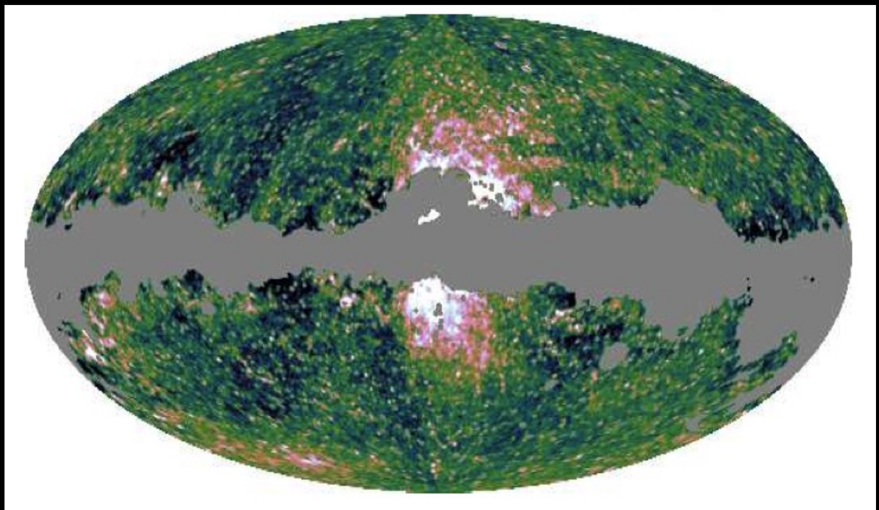
Fermi (Gamma-ray)



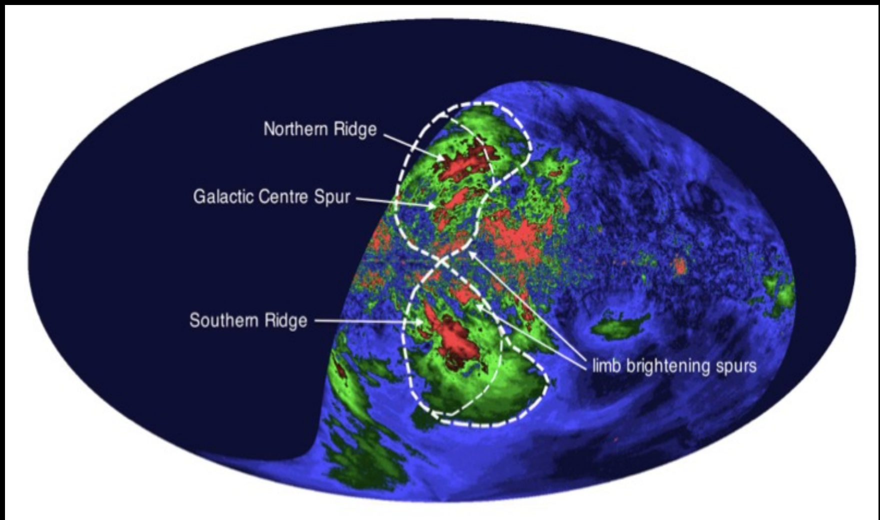
ROSAT (X-ray)



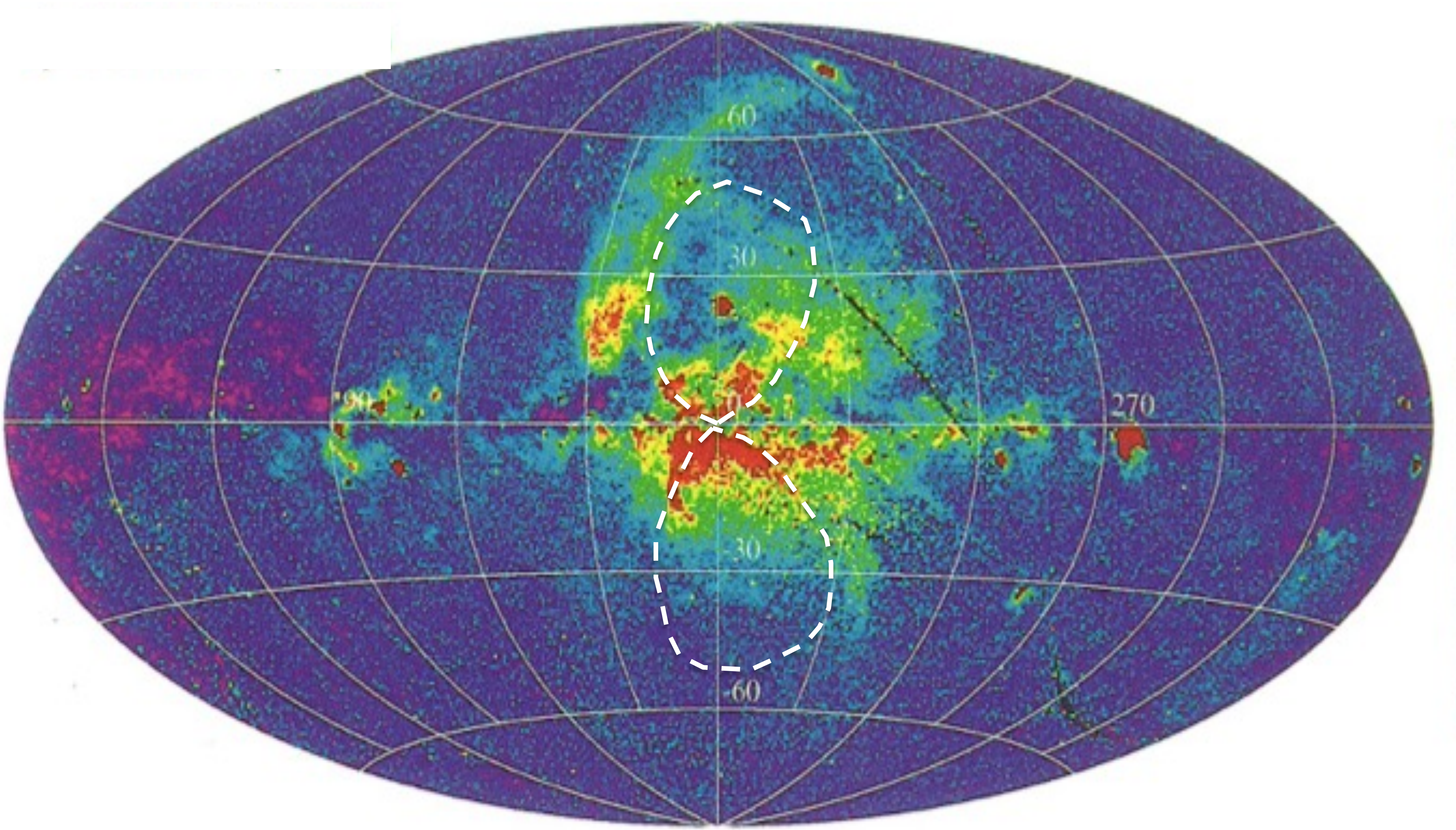
WMAP & Planck (Microwave)



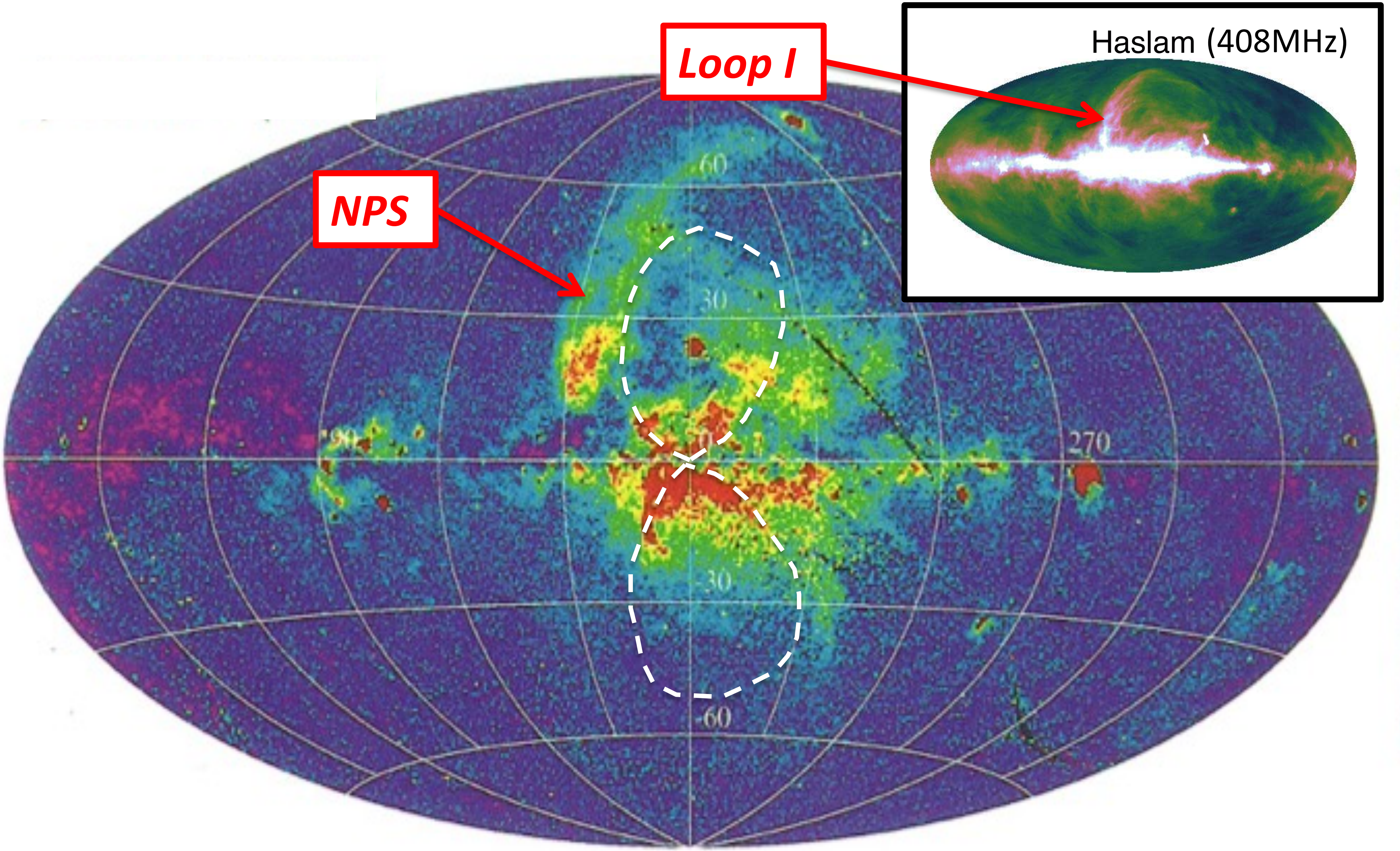
S-PASS (Polarization)



X-ray map at 1.5 keV by *ROSAT* (Snowden+ 1997)

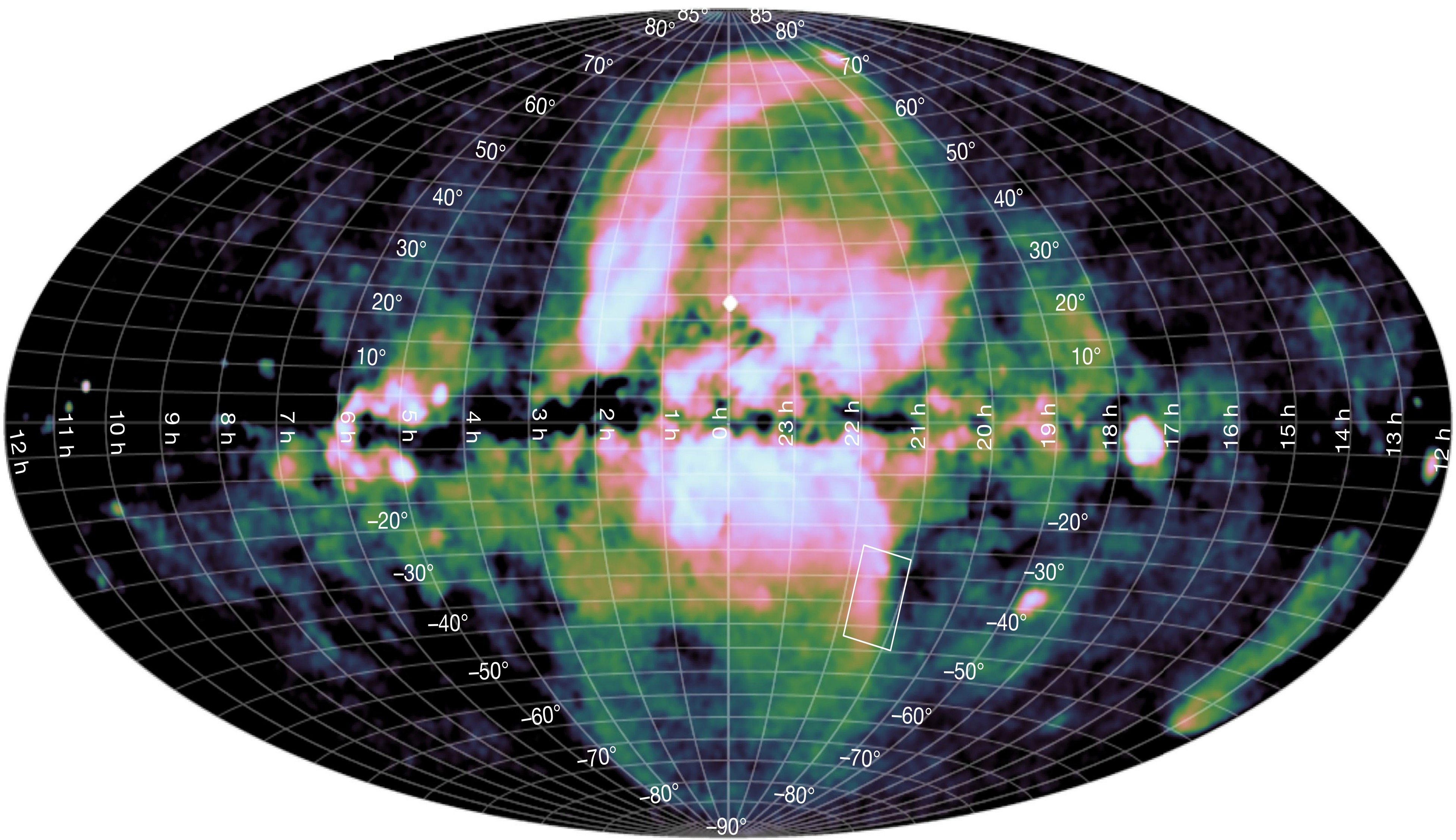


X-ray map at 1.5 keV by *ROSAT* (Snowden+ 1997)



The eRosita bubbles (0.6-1.0 keV)

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

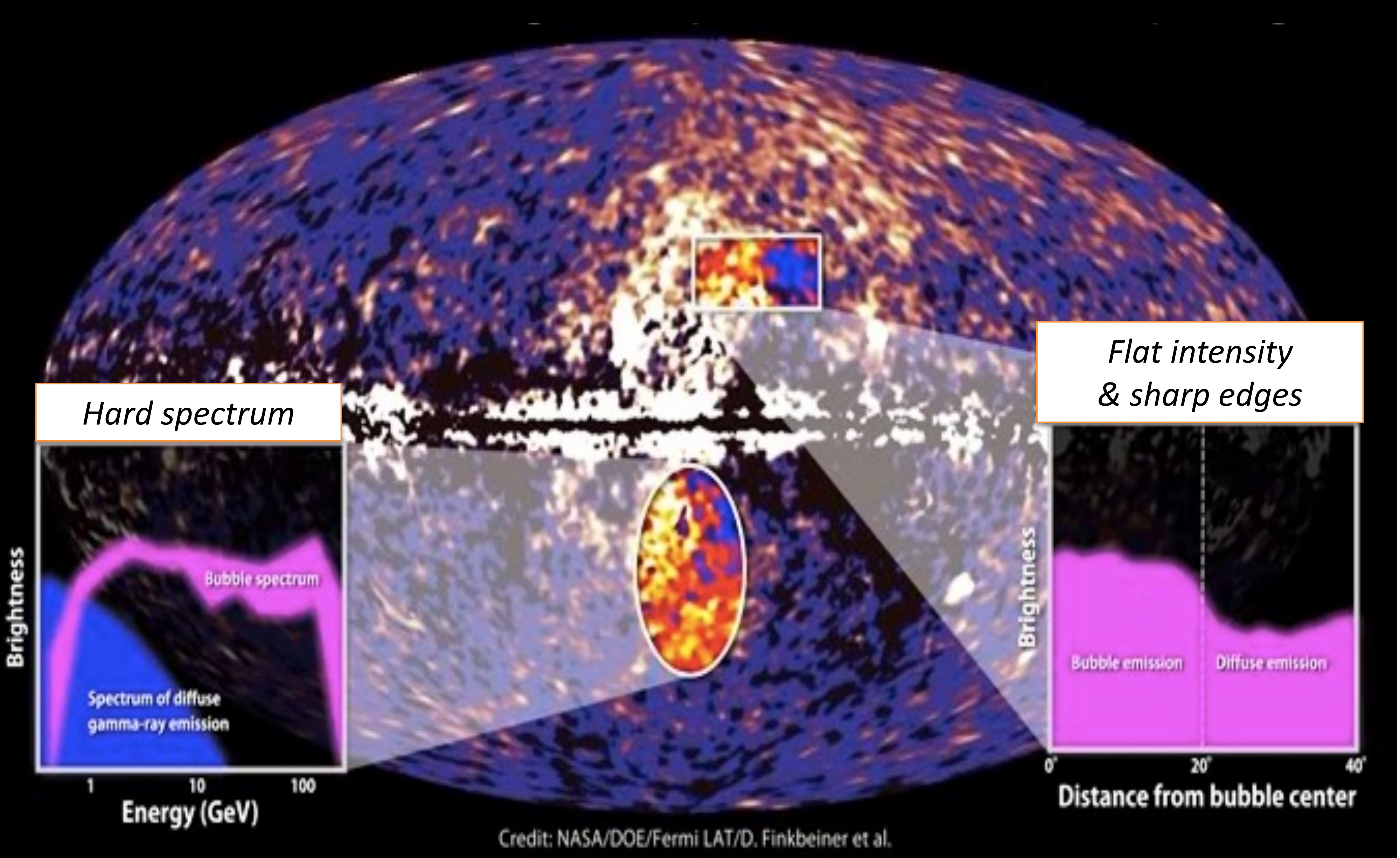


Outline

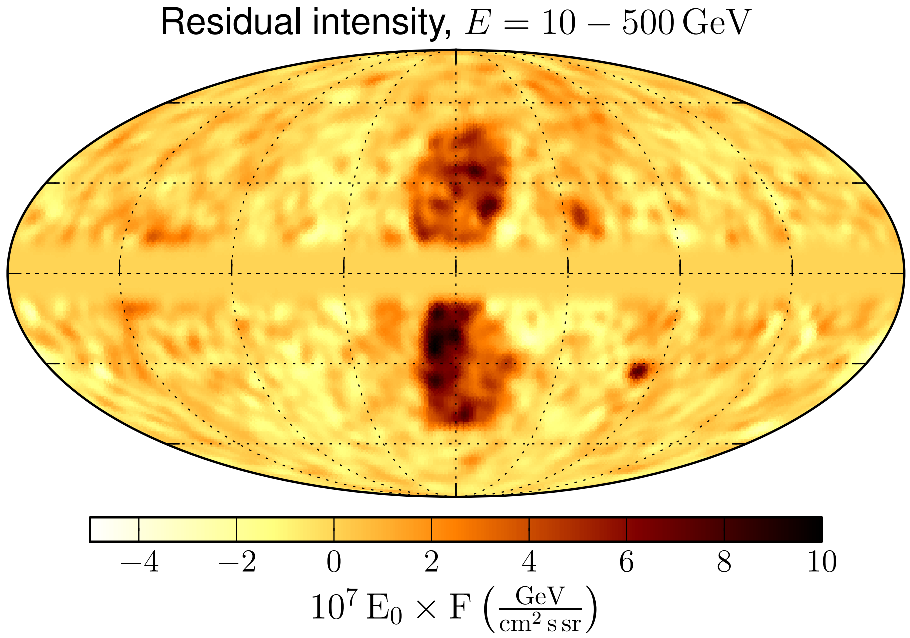
- What do we know about the Fermi bubbles ***observationally***?
- What do we know about the Fermi bubbles ***theoretically***?
- What does the new ***eRosita*** data tell us about the origin of the bubbles?

Multi-messenger observations

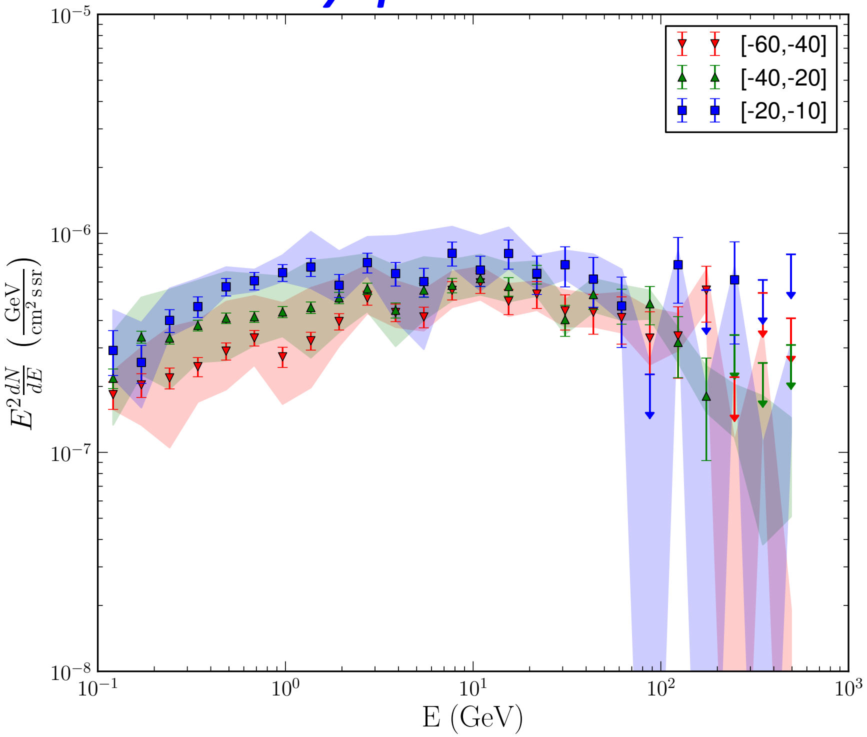
Gamma-ray bubbles by *Fermi* (Su+ 2010)



Gamma-ray bubbles by *Fermi – 50 months* (Ackermann+ 2014)



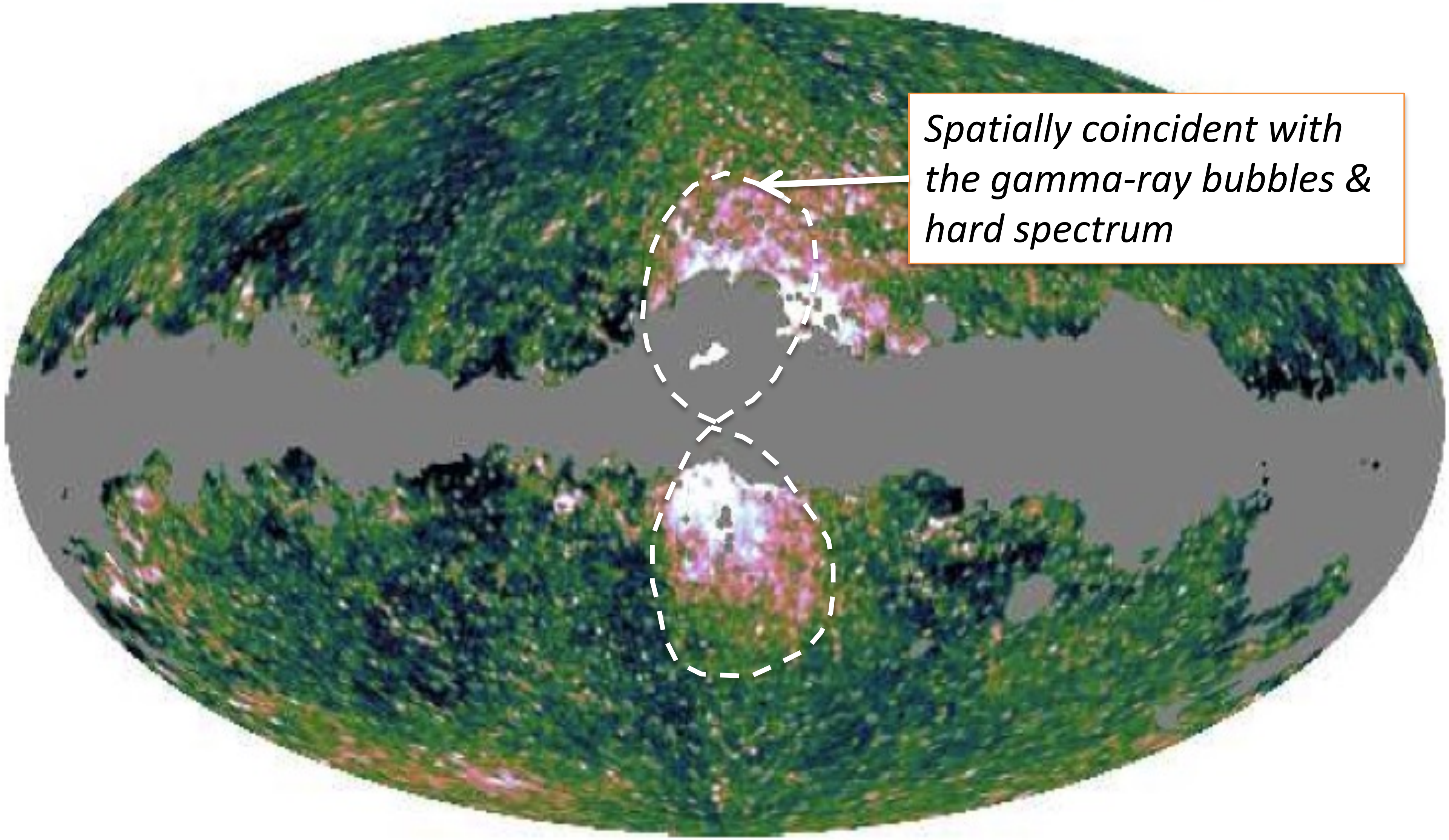
Gamma-ray spectrum with latitudes



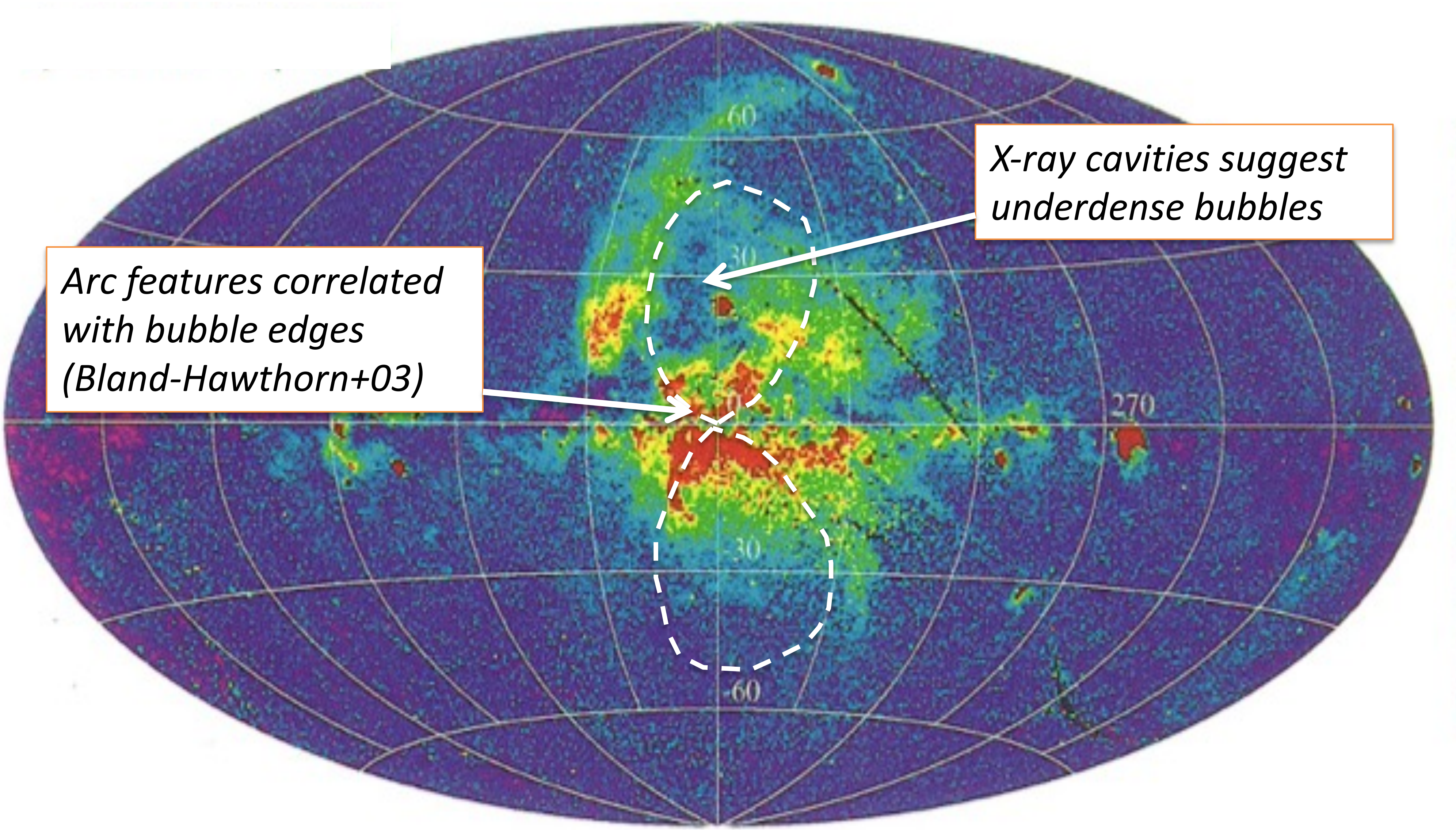
- ❖ Spatially uniform hard spectrum with spectral index of -2
- ❖ High-E cutoff at ~110 GeV

Microwave haze by *WMAP & Planck*

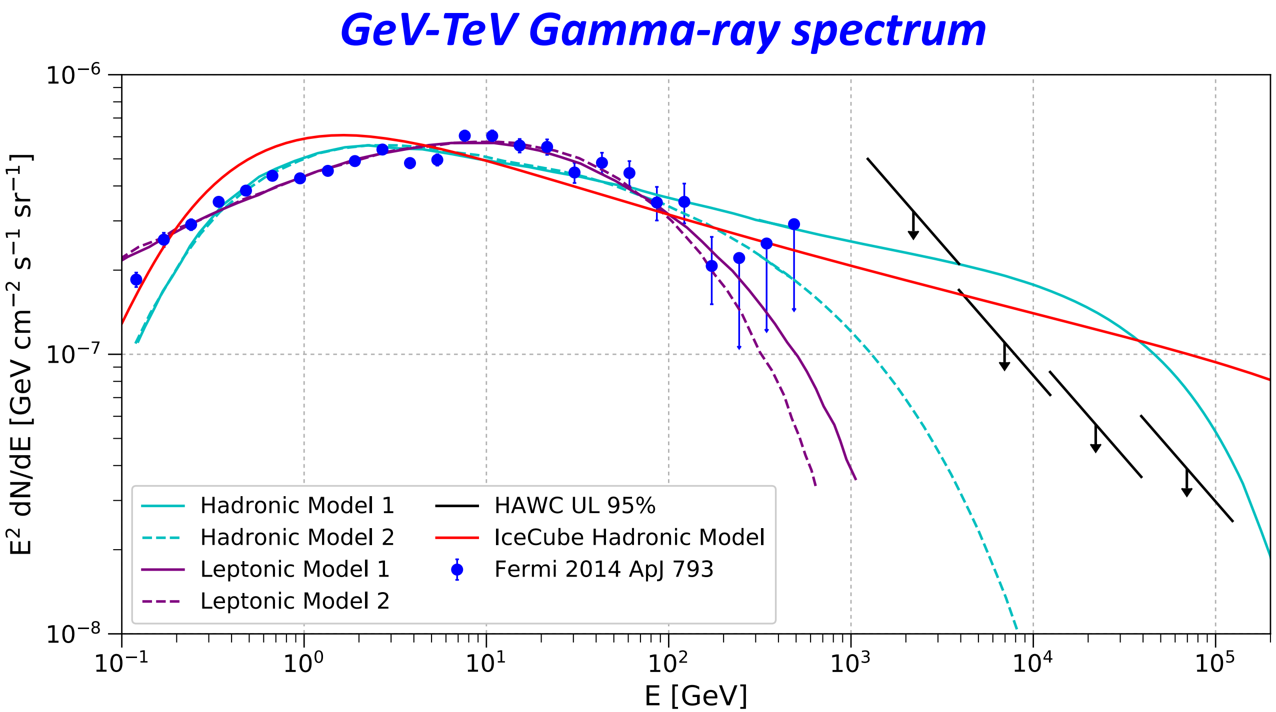
(Finkbeiner 2004, Dobler+ 2008; Planck Collaboration 2012)

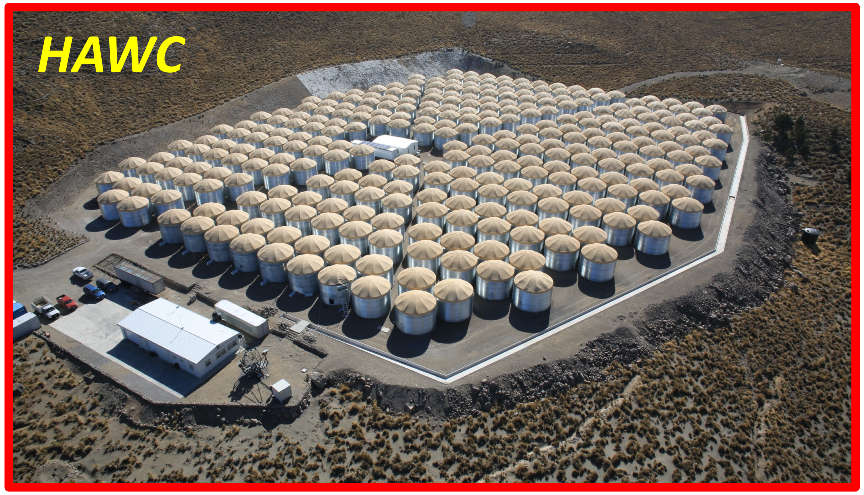


X-ray map at 1.5 keV by *ROSAT* (Snowden+ 1997)



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

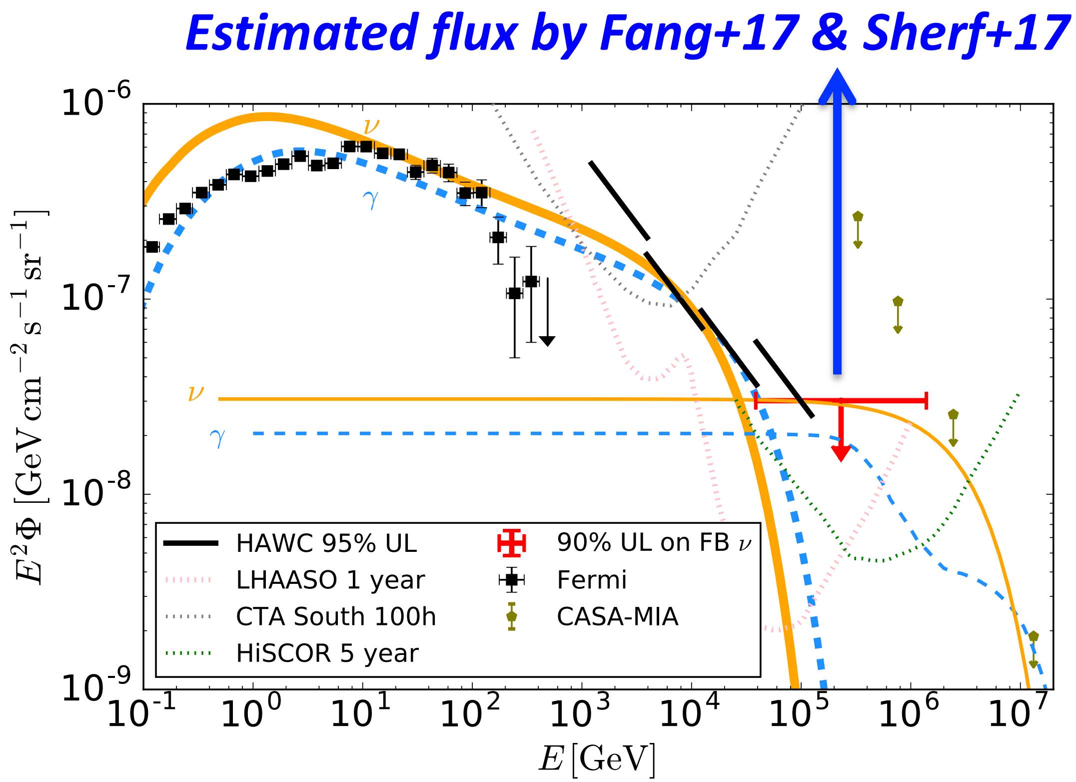




- Upper limits above 1 TeV
- ***Purely hadronic models extending to PeV ranges disfavored***

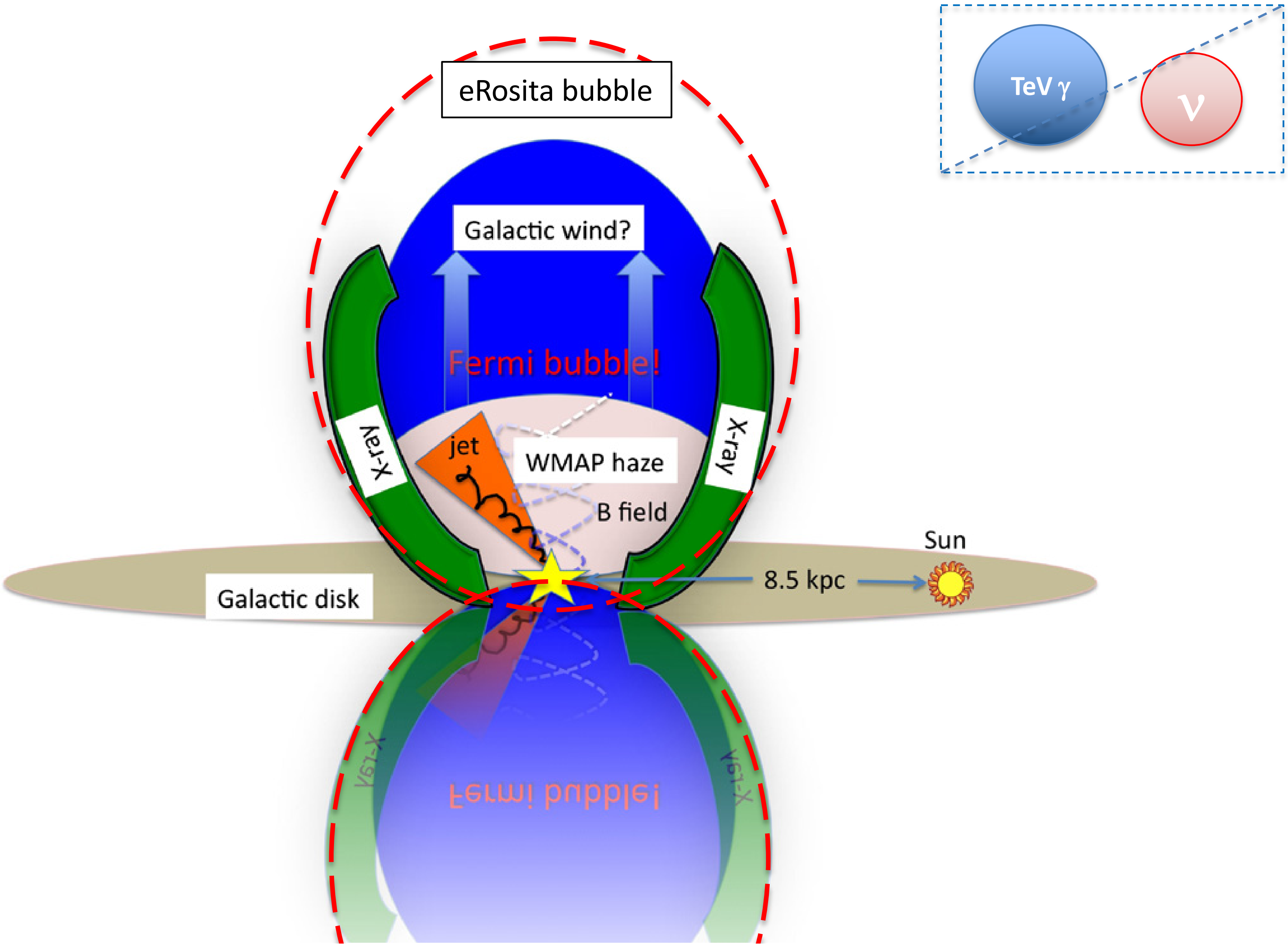
Neutrino events near the Fermi bubbles by *IceCube*

(Lunardini+ 2014, 2015, Ahlers+ 2014, 2016, Taylor+ 2014, Aartsen+ 2015, Fang+ 2017, Sherf+ 2017, IceCube Collaboration 2020)



- No FB neutrinos detected
- Purely hadronic models disfavored, though hybrid models are still allowed

A schematic view



Origin?

What is the origin of the bubbles?

(see review by KY, Ruszkowski & Zweibel 2018)

What is the origin of the bubbles?

(see review by KY, Ruszkowski & Zweibel 2018)

Q1: What are the emission mechanisms?

- ❖ Leptonic (CRe)
- ❖ Hadronic (CRp)

What is the origin of the bubbles?

(see review by KY, Ruszkowski & Zweibel 2018)

Q1: What are the emission mechanisms?

- ❖ Leptonic (CRe)
- ❖ Hadronic (CRp)

Q2: What activity at the GC triggers the event?

- ❖ Nuclear star formation (NSF)
- ❖ Active galactic nucleus (AGN)

What is the origin of the bubbles?

(see review by KY, Ruszkowski & Zweibel 2018)

Q1: What are the emission mechanisms?

- ❖ Leptonic (CRe)
- ❖ Hadronic (CRp)

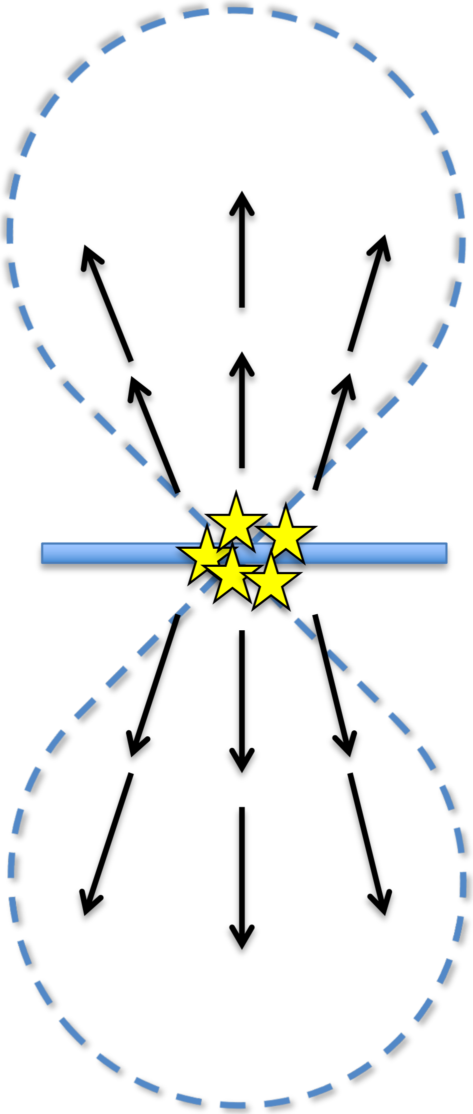
Q2: What activity at the GC triggers the event?

- ❖ Nuclear star formation (NSF)
- ❖ Active galactic nucleus (AGN)

Q3: Where are the CRs produced?

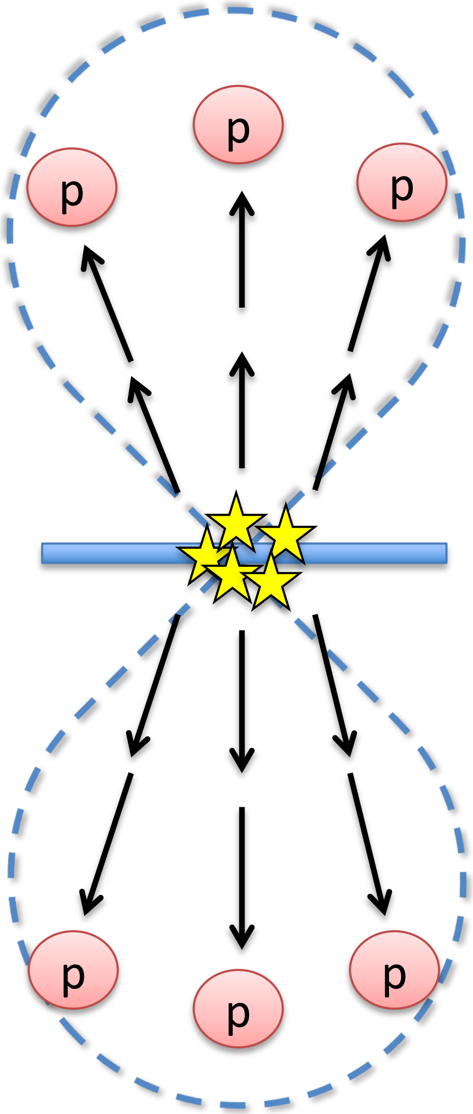
- ❖ Transported from GC
- ❖ In-situ acceleration (shocks or turbulence)

Theoretical Models



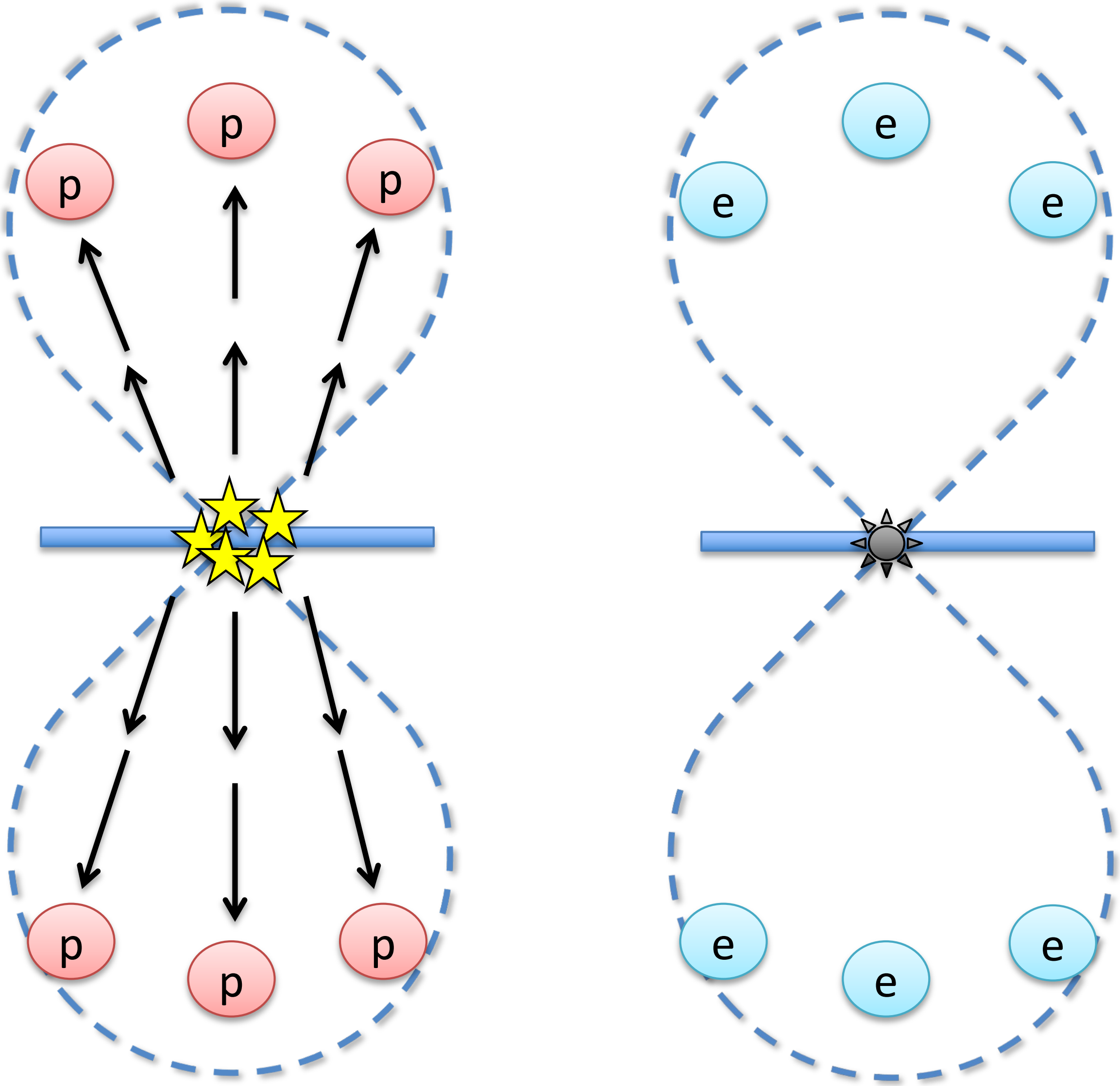
Theoretical Models

I. Hadronic winds



Theoretical Models

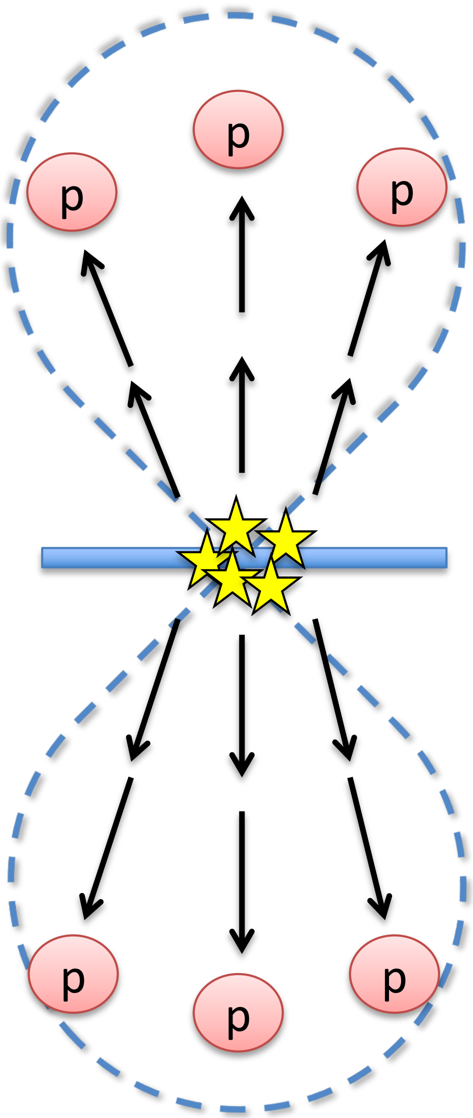
I. Hadronic winds

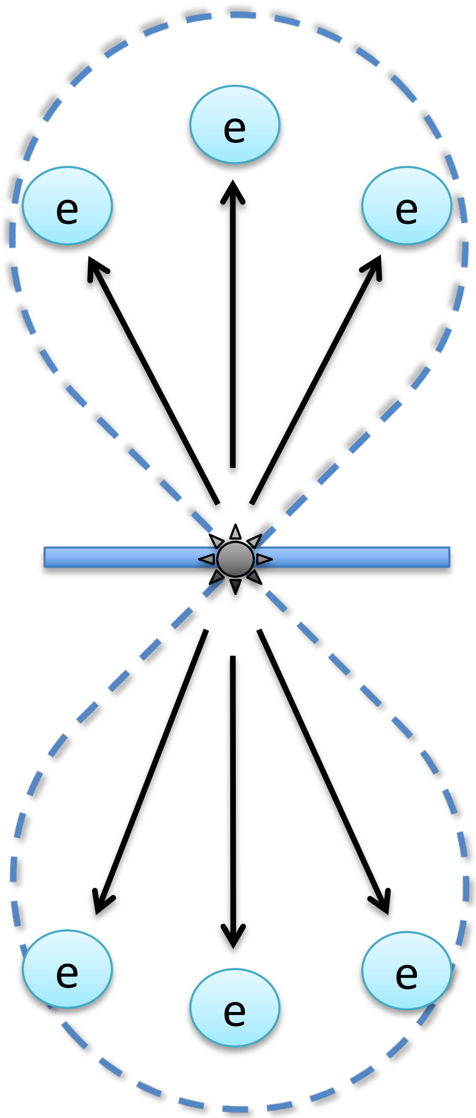


Theoretical Models

I. Hadronic winds

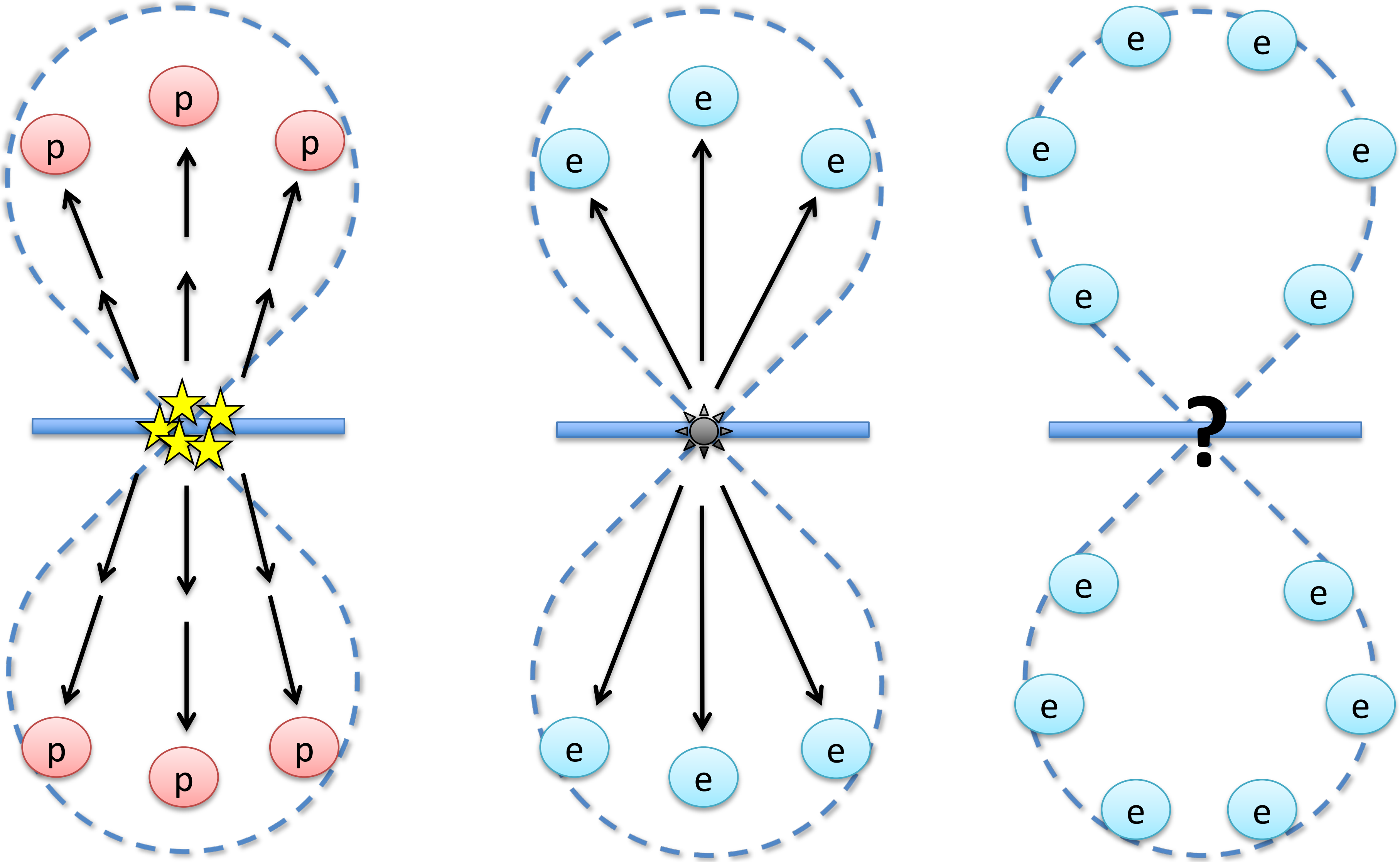
II. Leptonic jets



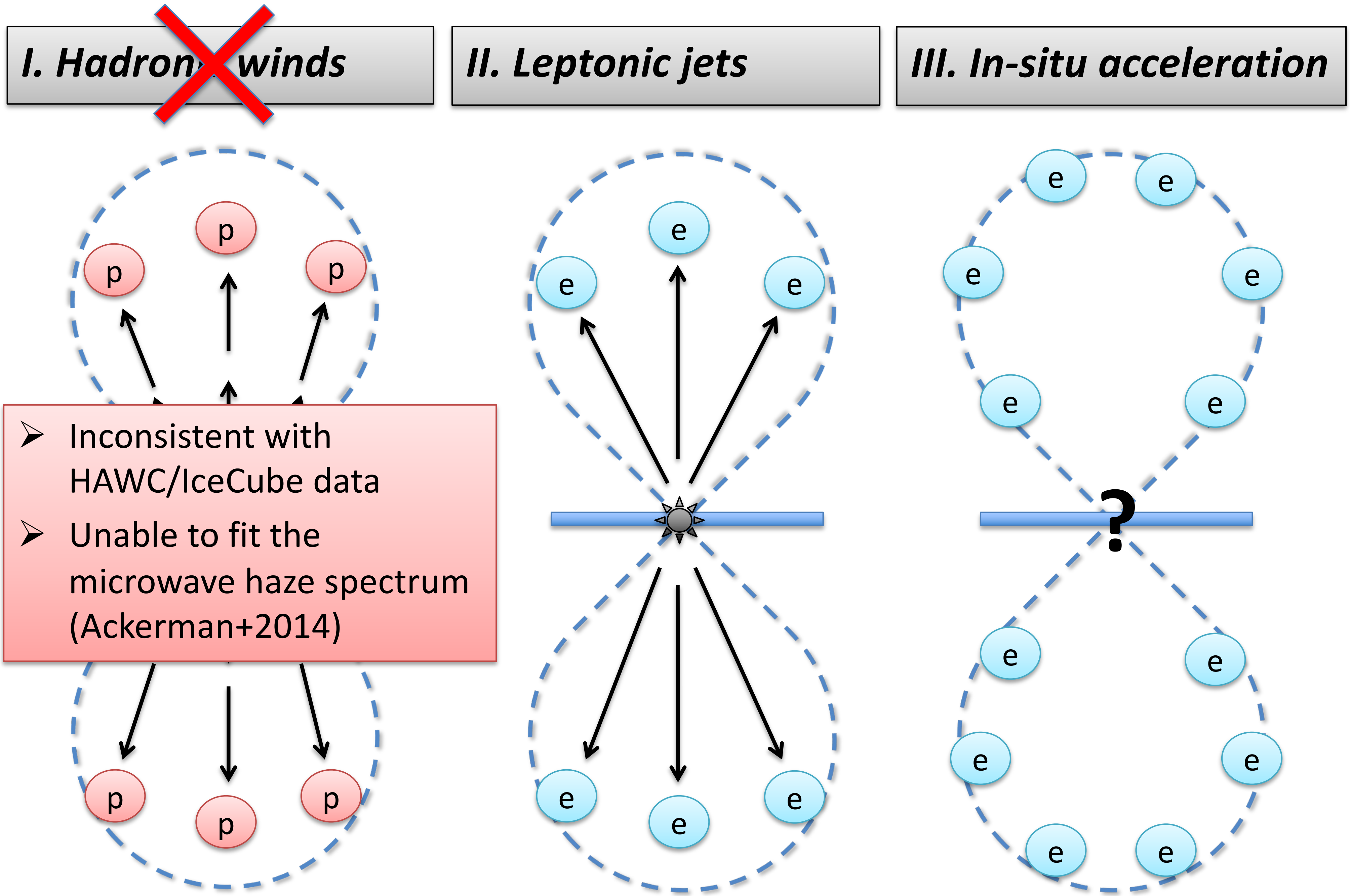


Theoretical Models

I. Hadronic winds | ***II. Leptonic jets*** | ***III. In-situ acceleration***

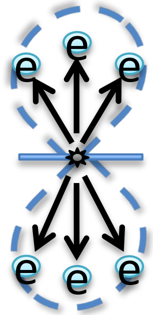


Theoretical Models



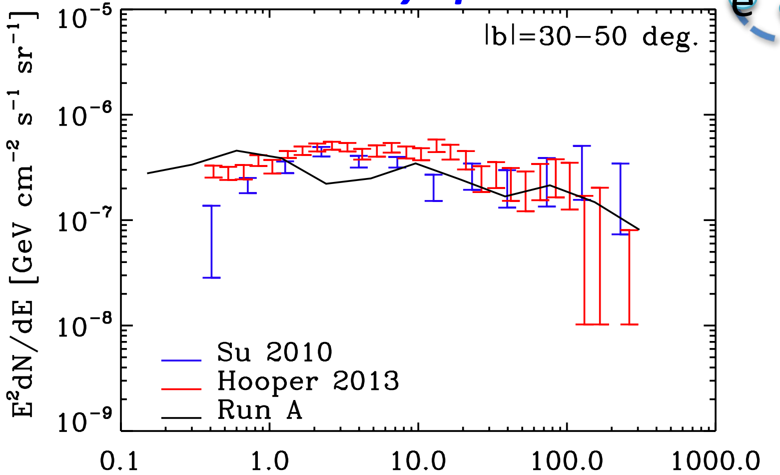
II. *Leptonic jet* models

(Guo+ 2011, 2012, KY+ 2012, 2013, 2017, Barkov+ 2013)

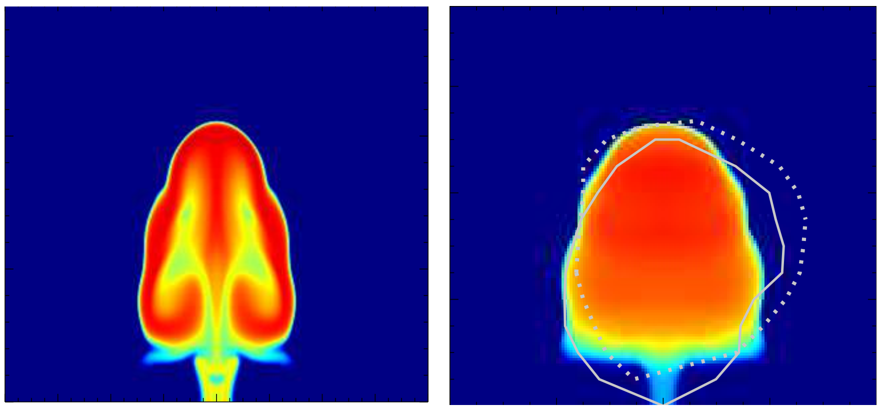


- AGN jets of speed ~thousands to 10^4 km/s
- Bubble ages ~few Myr
- Bubble and haze produced by same CRe

Gamma-ray spectrum

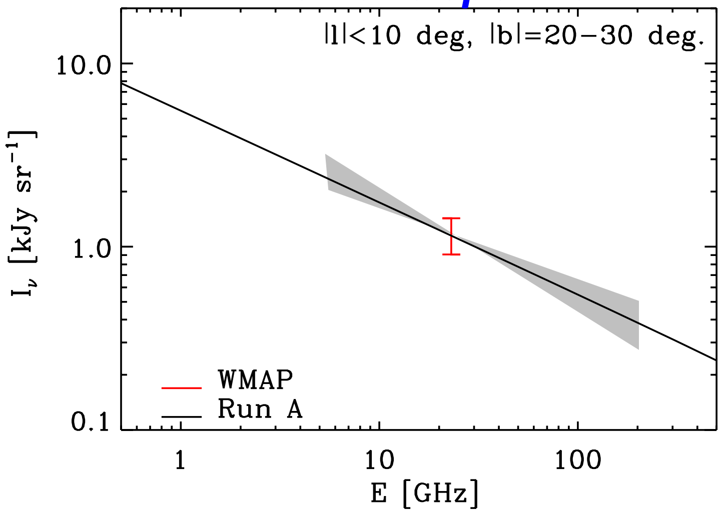


CR energy density ***Projected CR energy density***



2D hydro (Guo+ 2012)

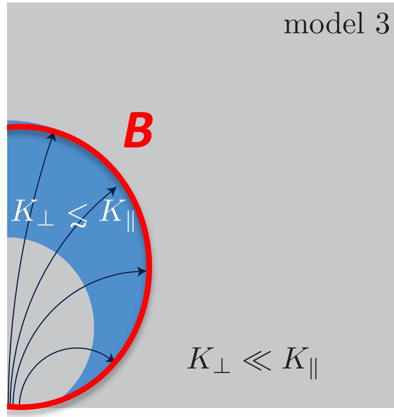
Microwave spectrum

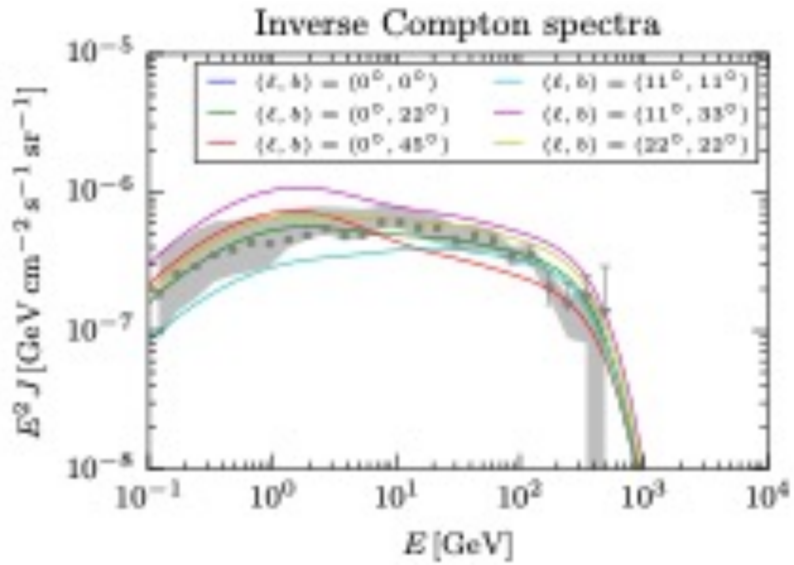


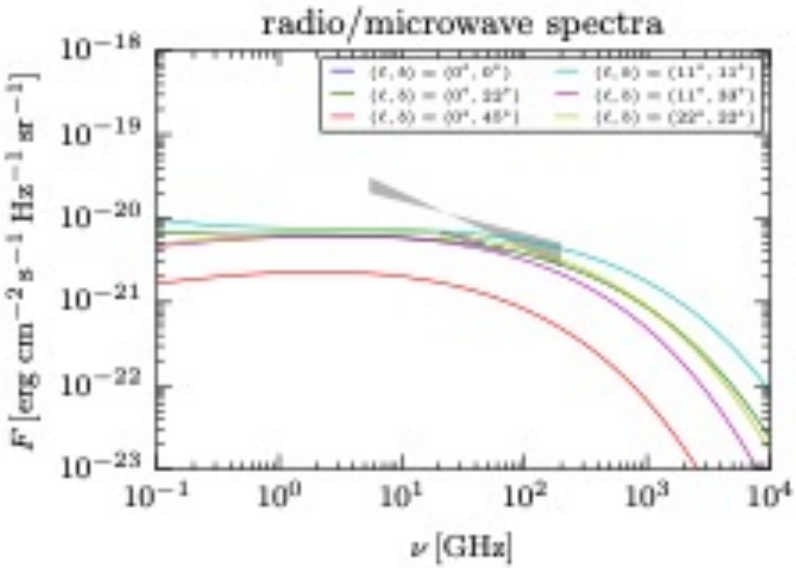
3D MHD (KY+ 2013)

III. In-situ acceleration models
(Mertsch+2018)

Assumed B &
CR diffusion





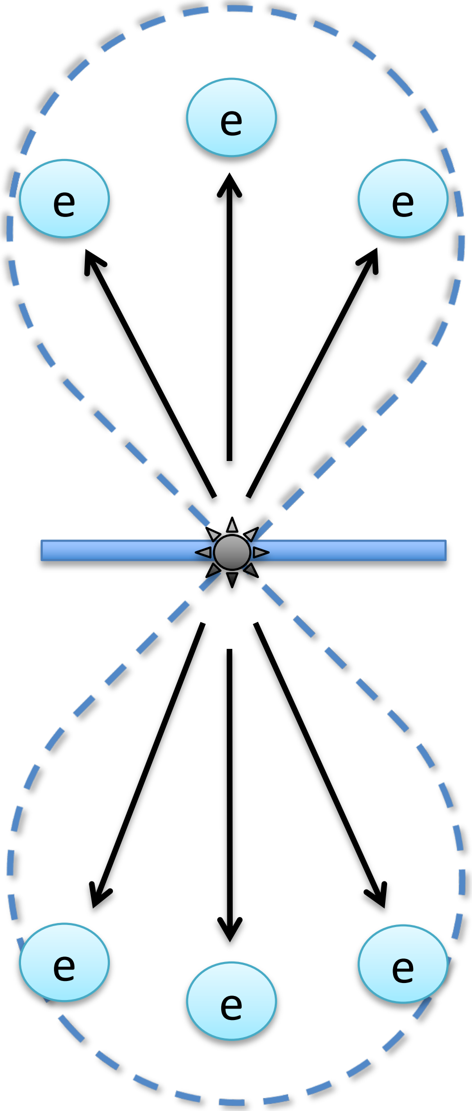


- Event: AGN/NSF/un-specified
- Assume CRe are injected at the shock and accelerated by turbulence in the shock downstream
- Spatially uniform gamma-ray spectrum & haze reproduced

Leptonic jets or in-situ acceleration?

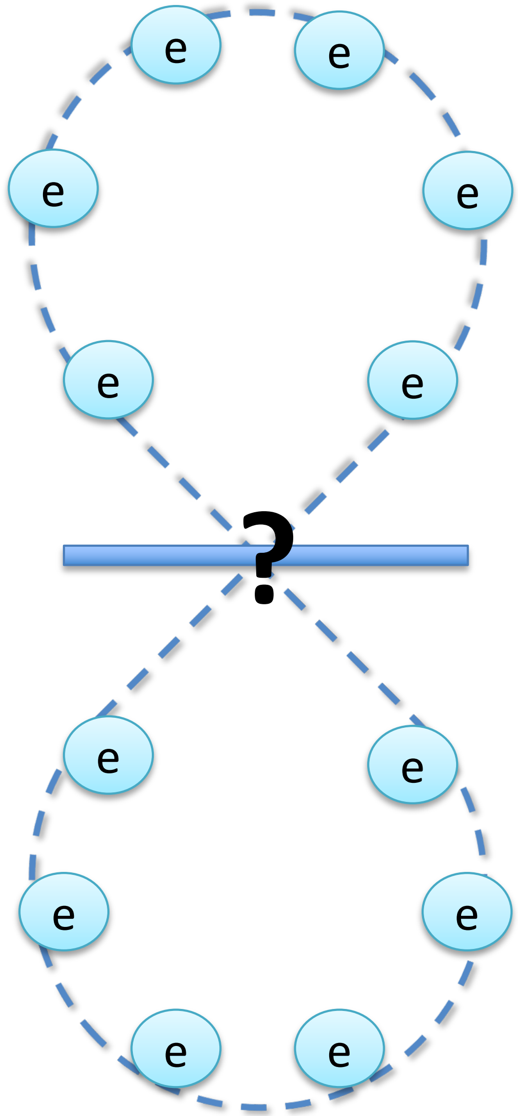
Theoretical Models

II. Leptonic jets



vs.

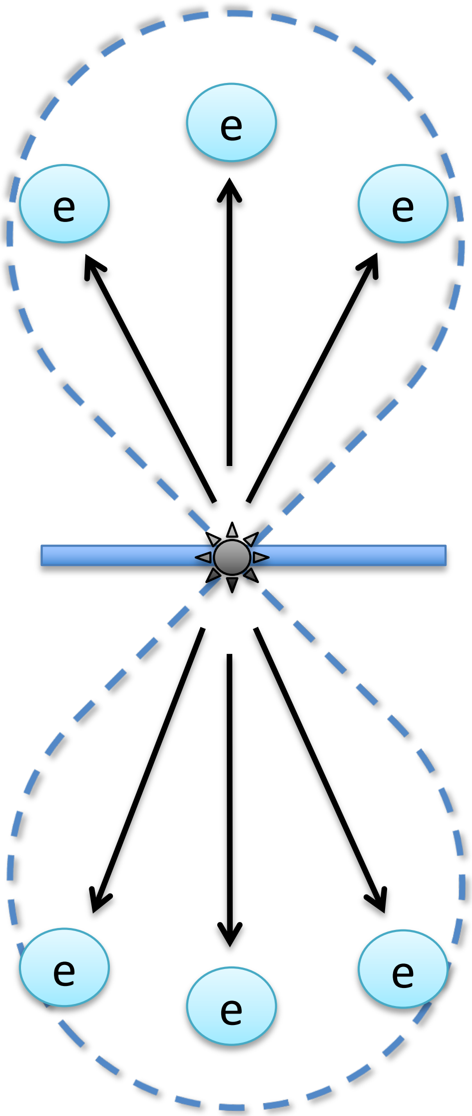
III. In-situ acceleration



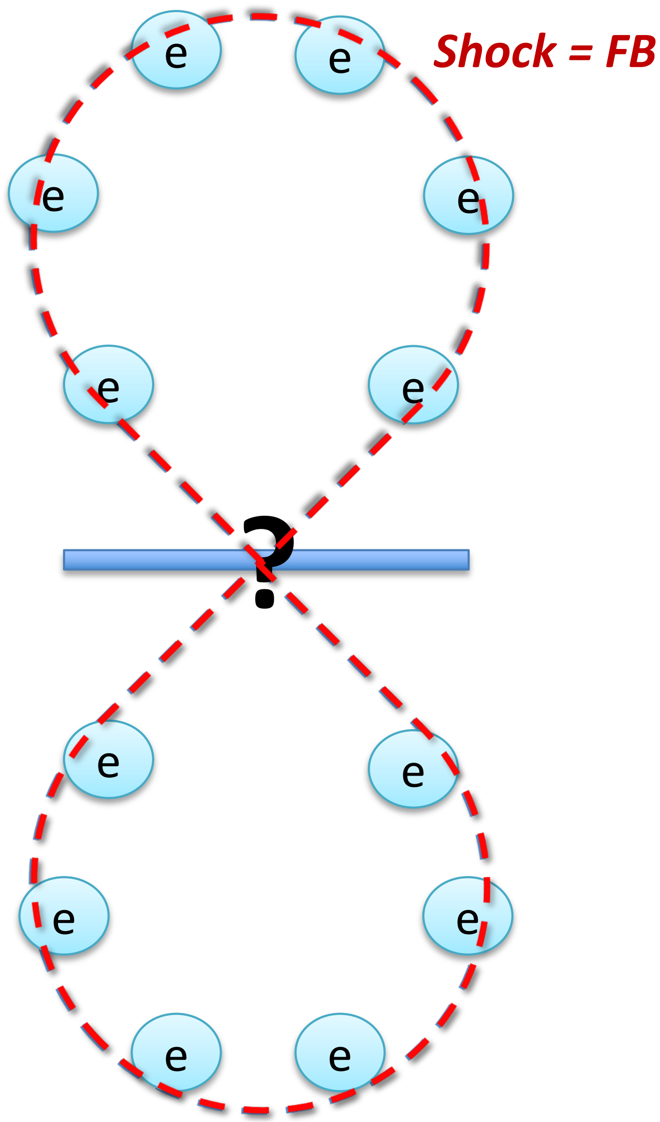
Theoretical Models

II. Leptonic jets

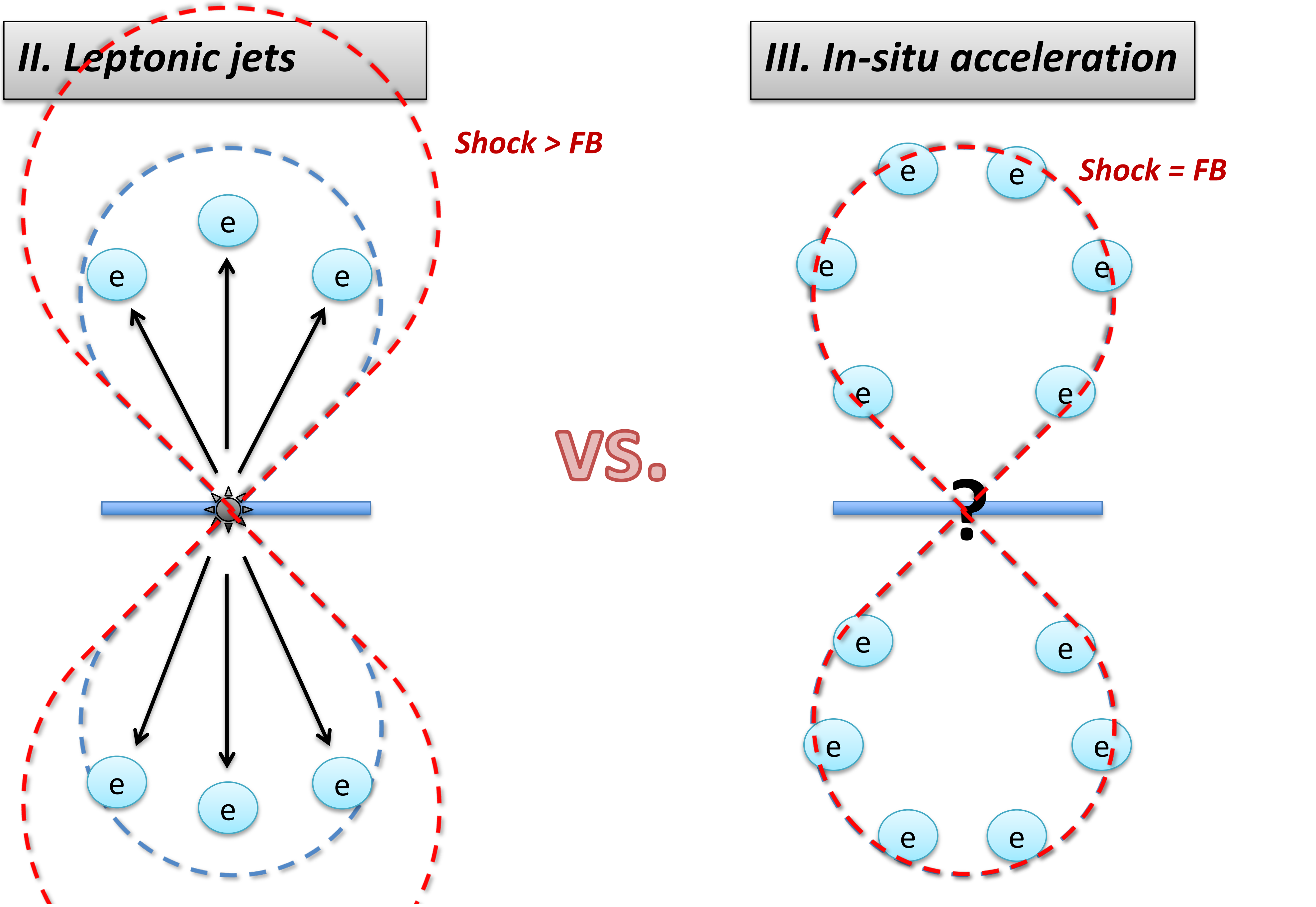
III. In-situ acceleration



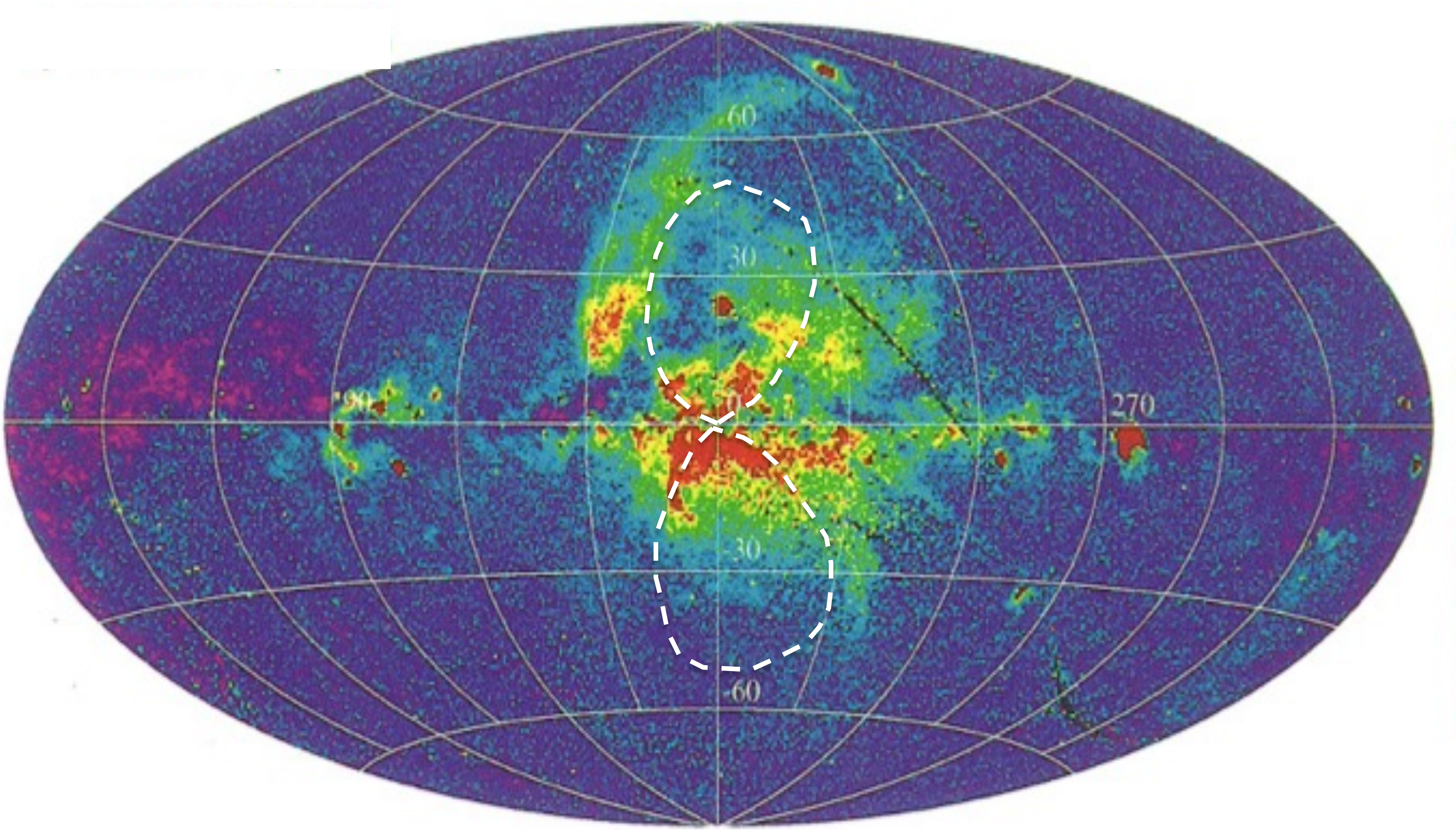
VS.



Theoretical Models

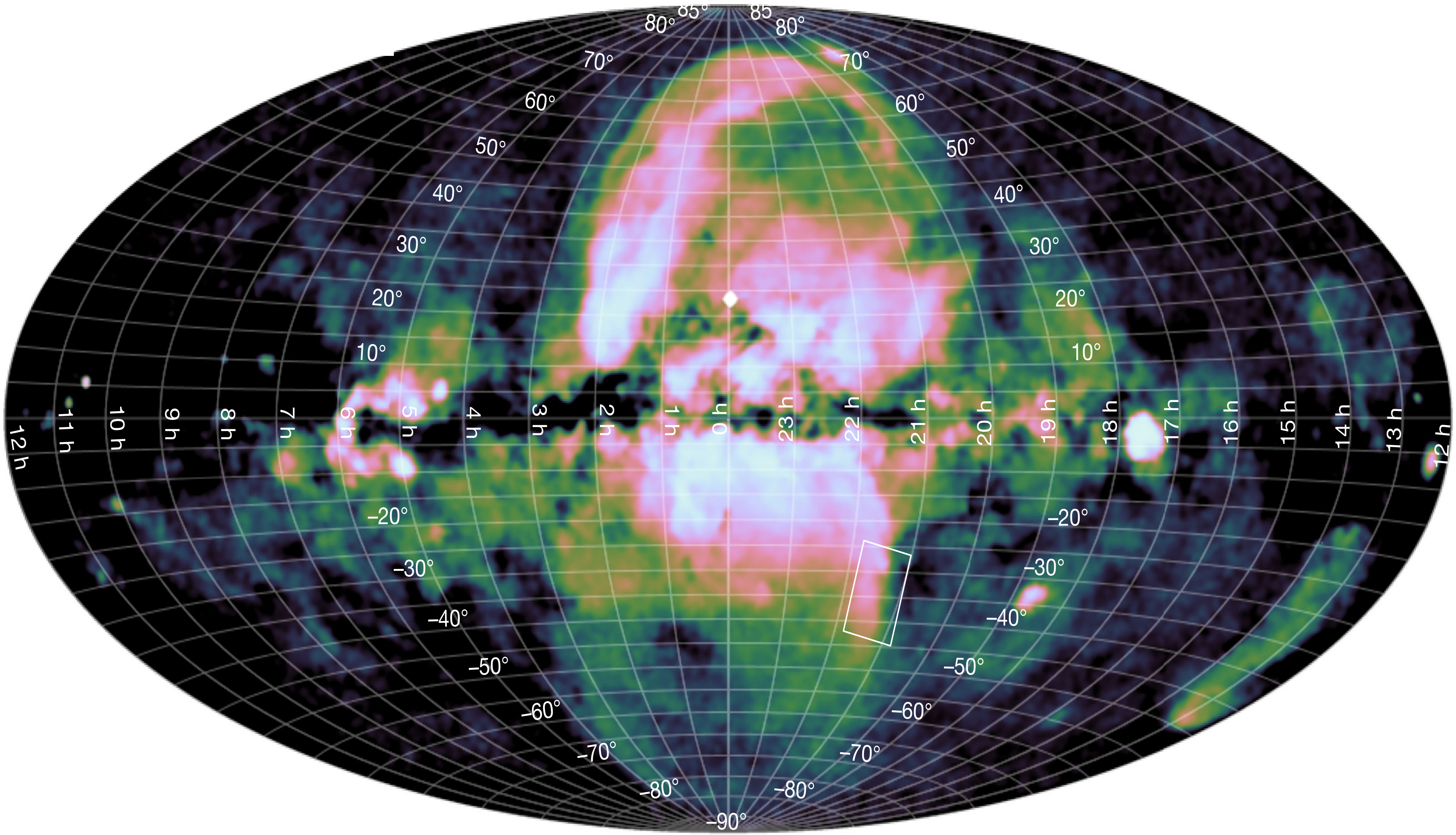


X-ray map at 1.5 keV by *ROSAT* (Snowden+ 1997)



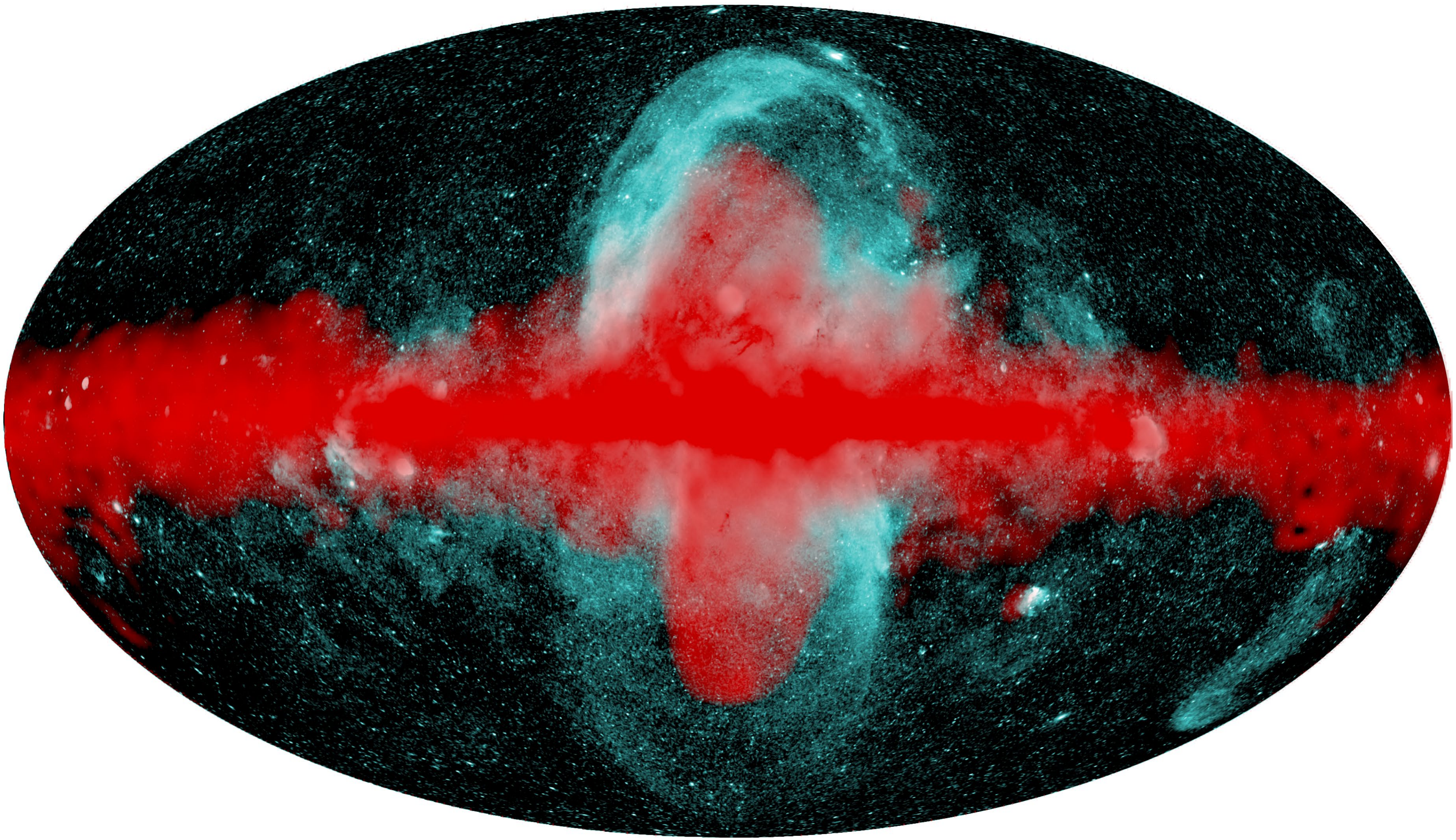
X-ray map at 0.6-1.0 keV by *eRosita*

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



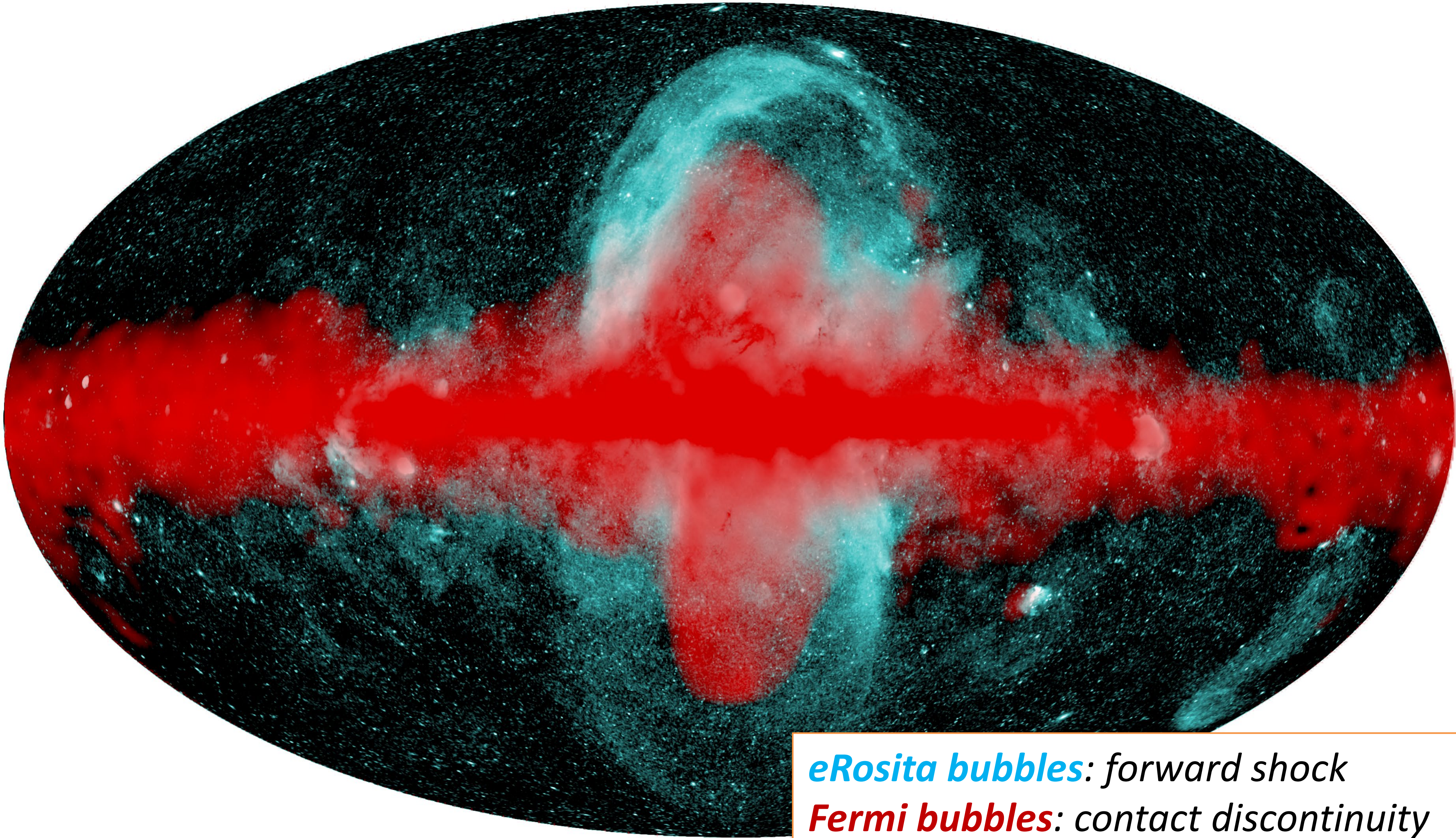
X-ray map at 0.6-1.0 keV by *eRosita* + Gamma-ray by *Fermi*

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



X-ray map at 0.6-1.0 keV by *eRosita* + Gamma-ray by *Fermi*

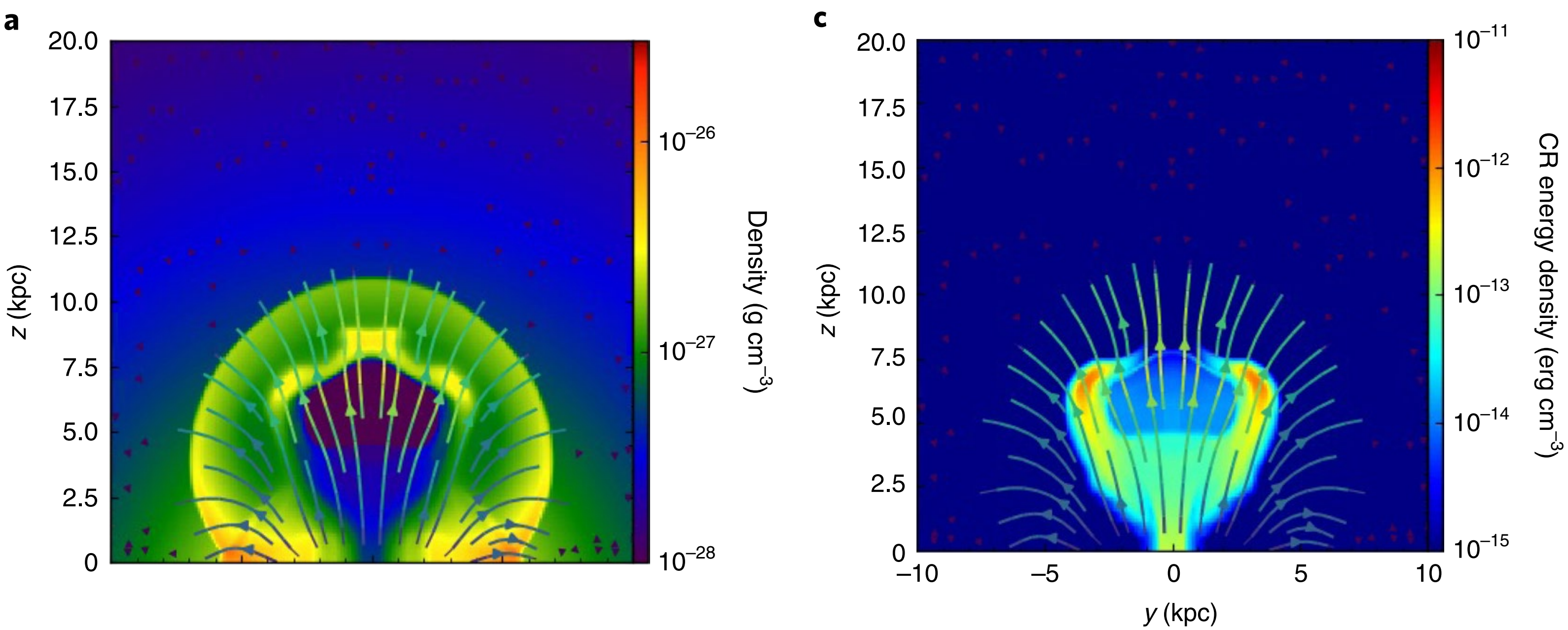
(Predehl et al., 2020, Nature, 588, 227)



eRosita bubbles*: forward shock*
Fermi bubbles*: contact discontinuity*
They are not the same!!

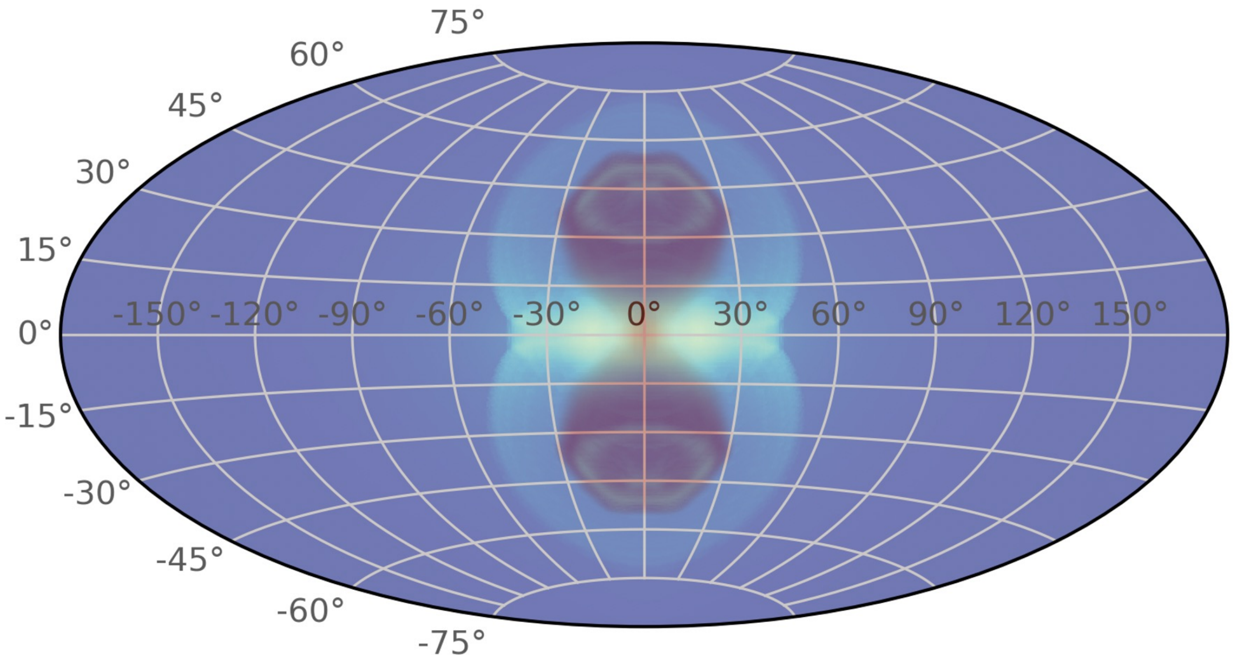
Simulating the *Fermi* bubble spectrum

- Implemented ***MHD+CRSPEC*** module in FLASH
- Injection spectrum: 10 GeV ~ 10 TeV
- IC & syn. cooling (due to Galactic radiation & B field)
- X-ray from Bremsstrahlung of thermal gas; gamma-ray/microwave from leptonic CRs

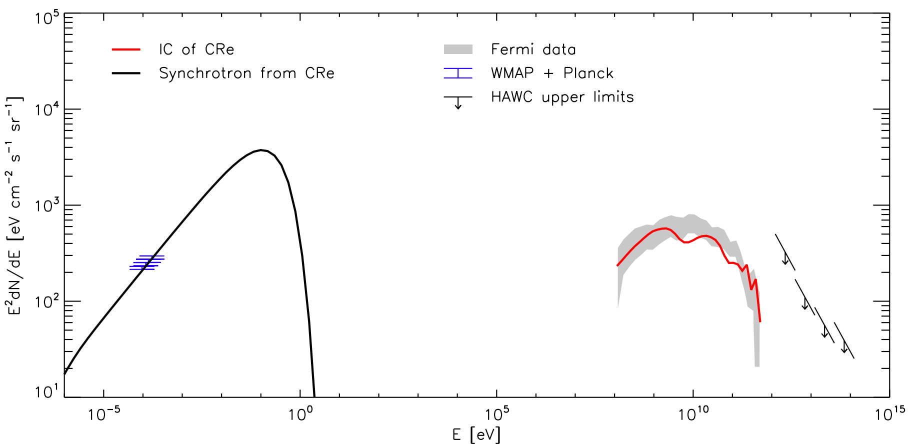


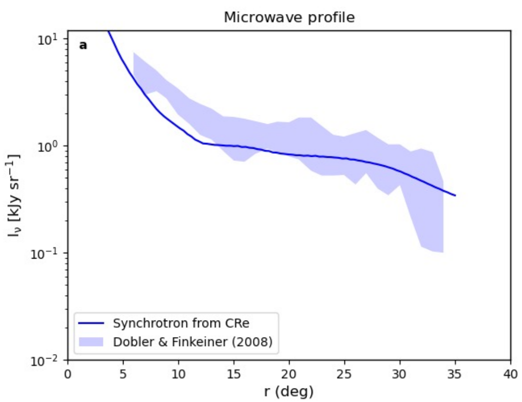
All X-ray/gamma/microwave data are matched!

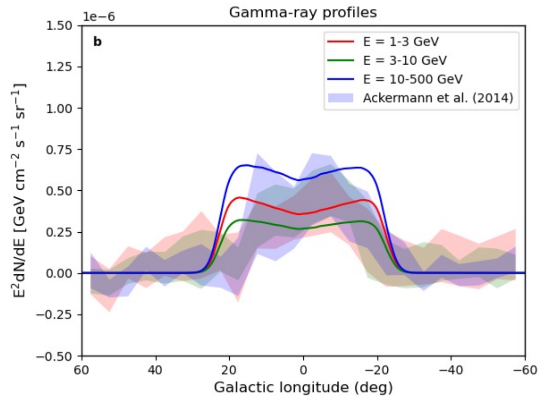
Yang et al. (2022), Nature Astronomy (http://arxiv.org/abs/2203.02526)



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







Fermi and eROSITA bubbles as relics of the past activity of the Galaxy's central black hole

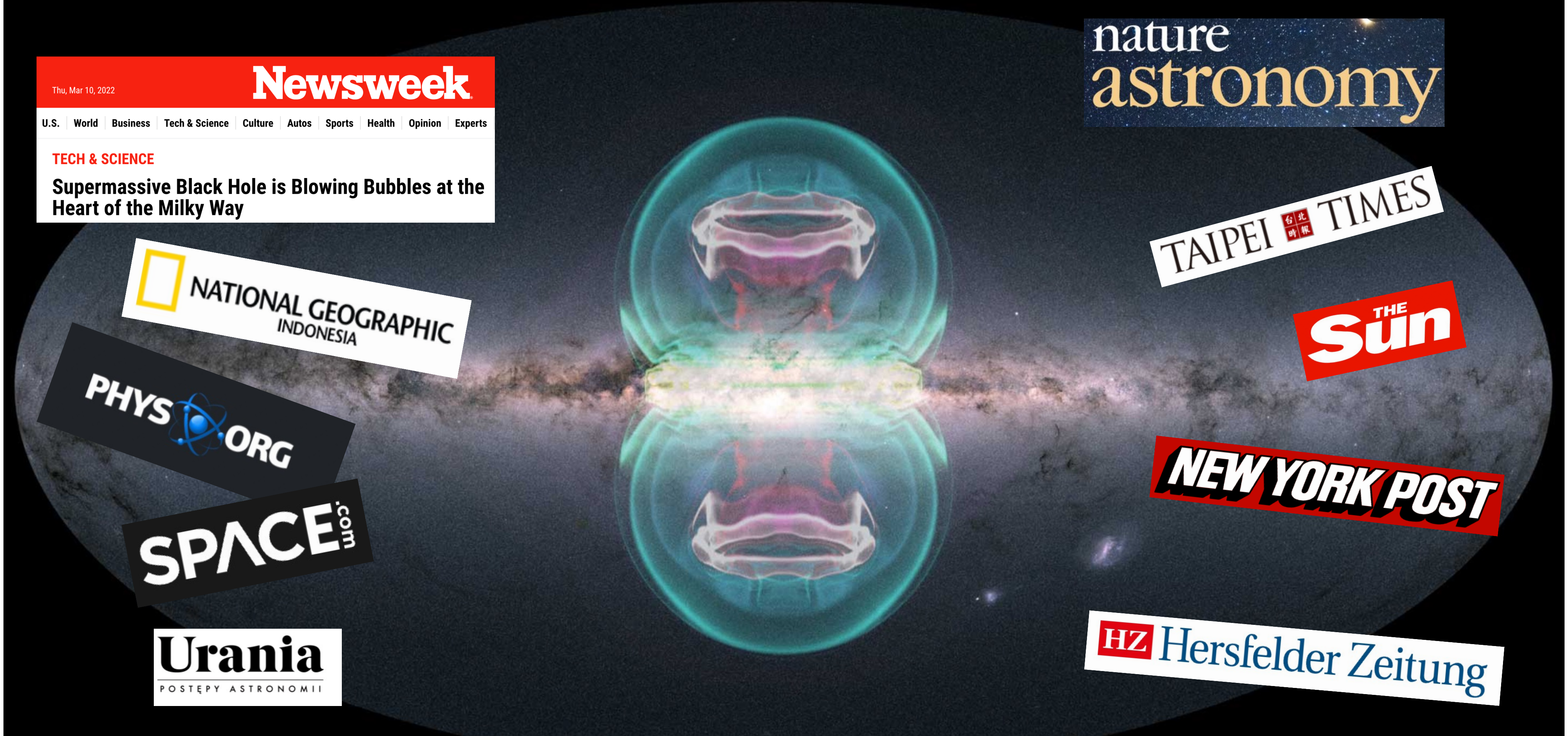
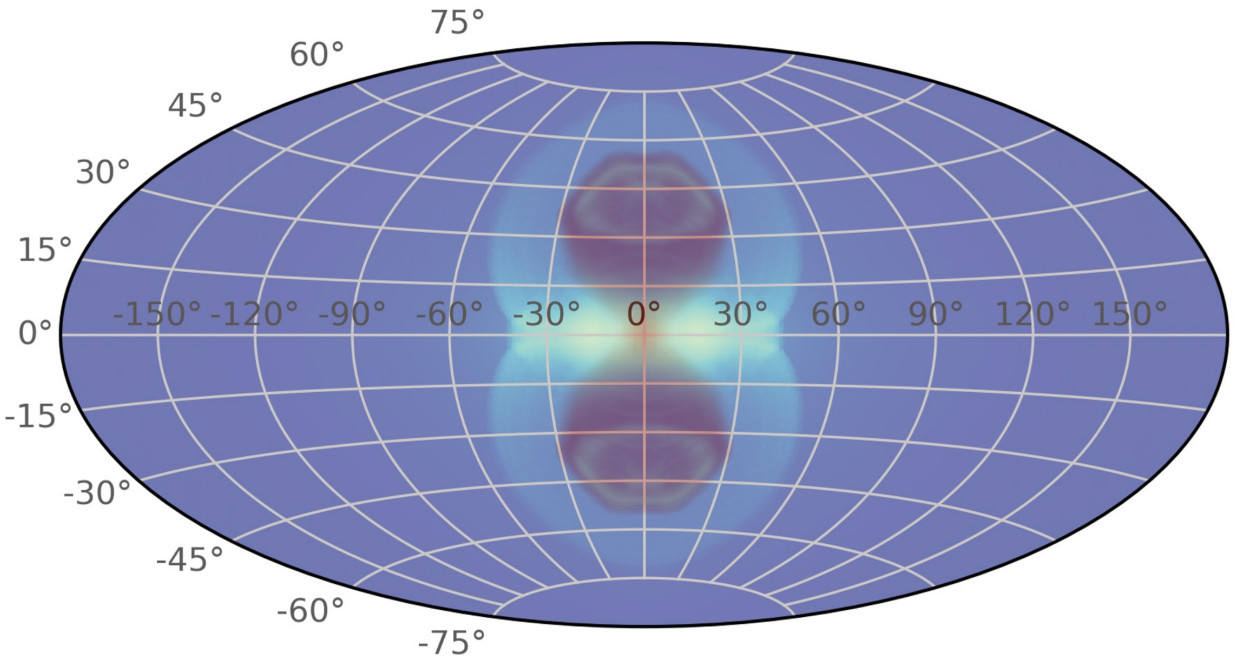


Image credits: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO, NASA

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

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

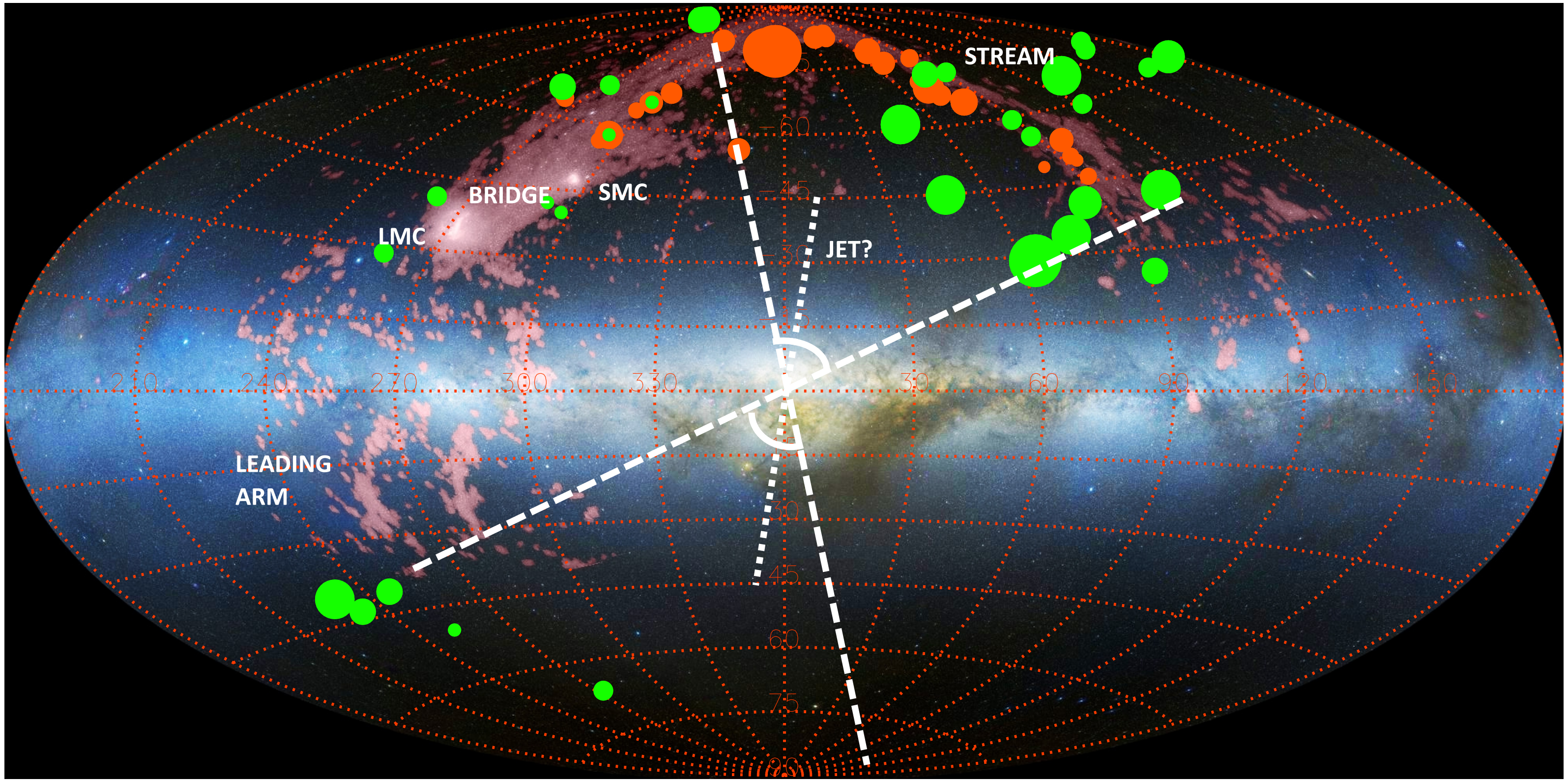


What we've learned from the simulations:

- 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***

Summary

- The multi-wavelength observations of the Fermi/eRosita bubbles are likely caused by a single outburst of jet activity of Sgr A*

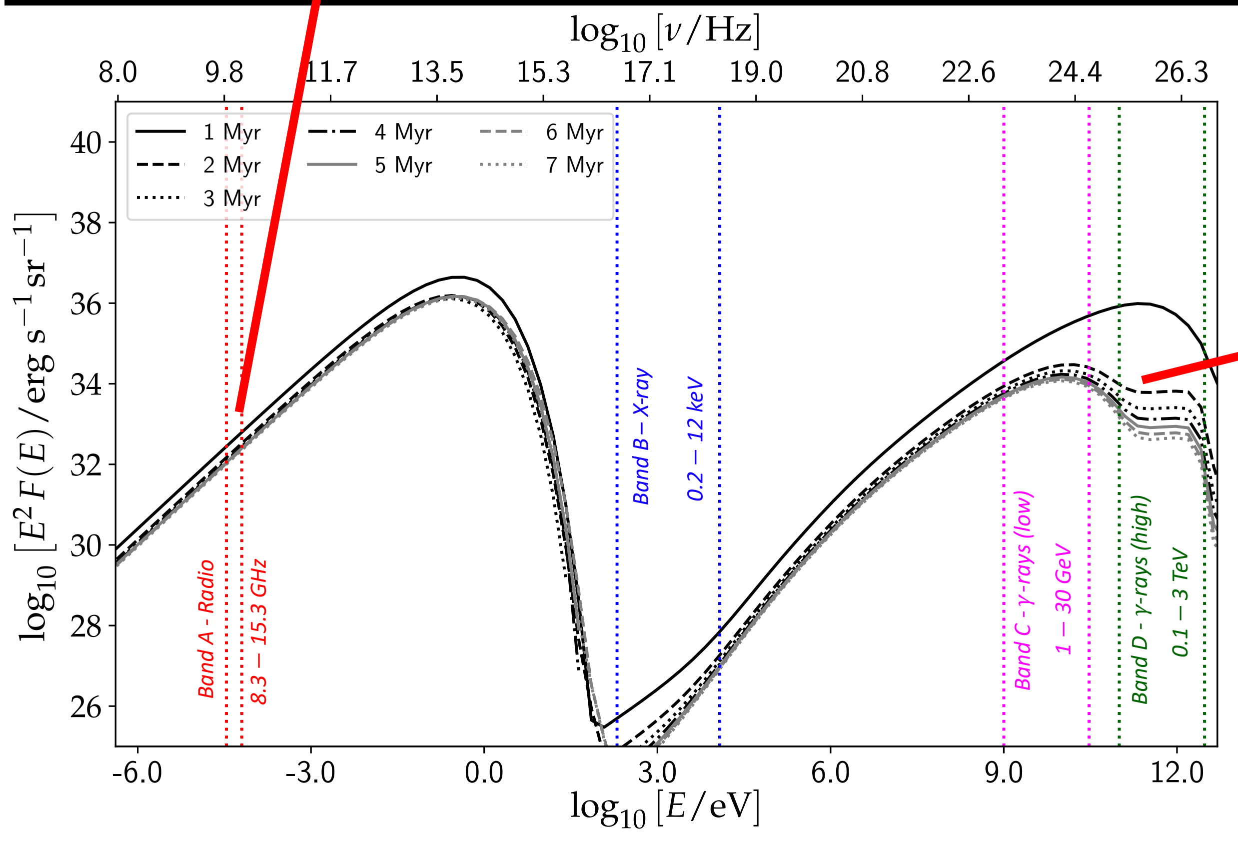
- The inferred age of ~2.6 Myr and Eddington ratio ~1-10% are consistent with enhanced ionization in the Magellanic Stream, pointing to a Seyfert-flare activity of Sgr A*

Multi-wavelength leptonic emission from aging galaxy bubbles

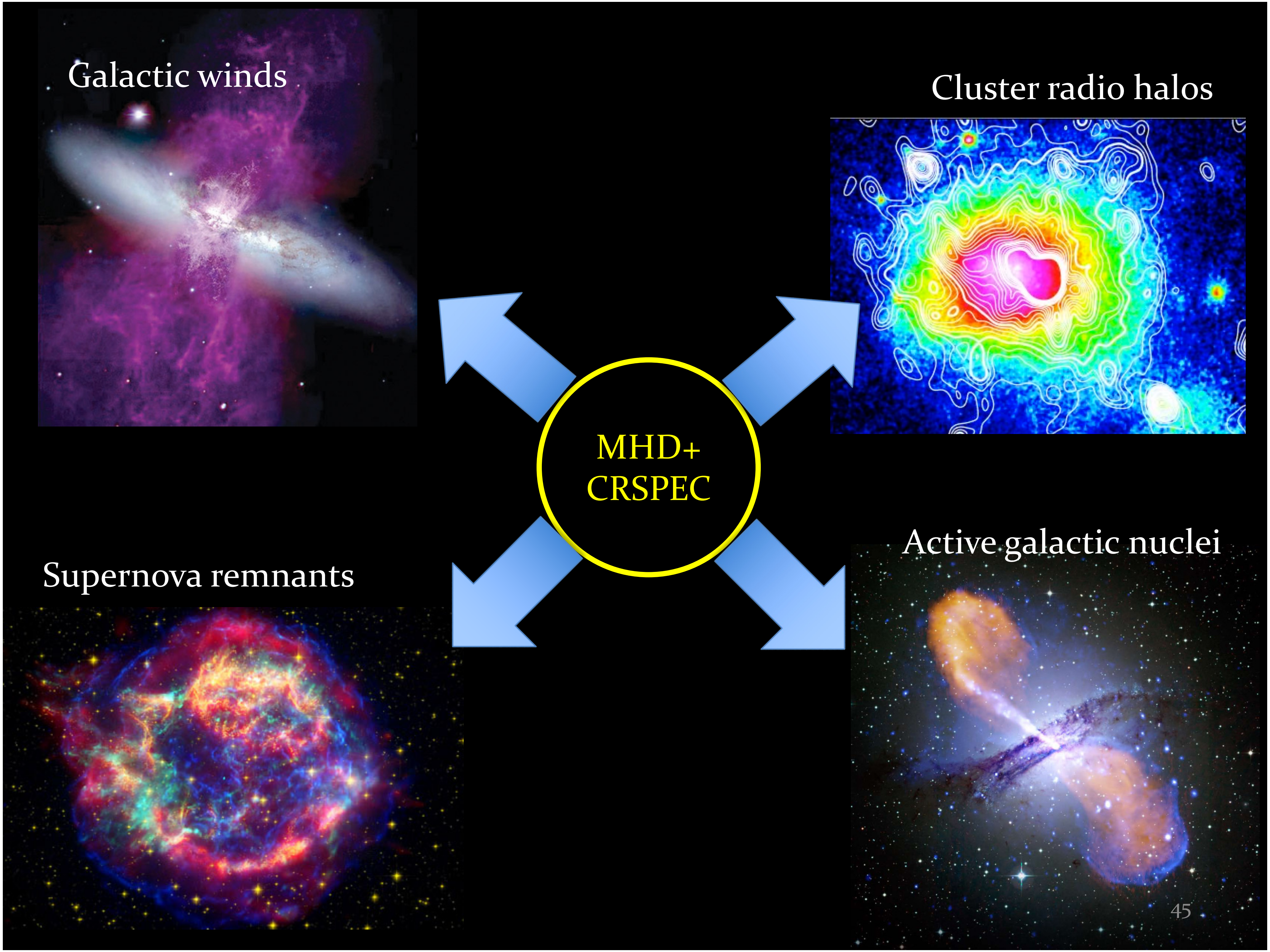
(Owen & Yang, 2022, MNRAS, 510, 5834)

Ellis Owen
(CICA Fellow, NTHU)

- ❖ *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*


Galactic winds
Cluster radio halos
MHD+
CRSPEC
Supernova remnants
Active galactic nuclei