Fermi Bubbles:

MHD simulations of leptonic AGN jets

Mateusz **Ruszkowski**
University of Michigan, Ann Arbor

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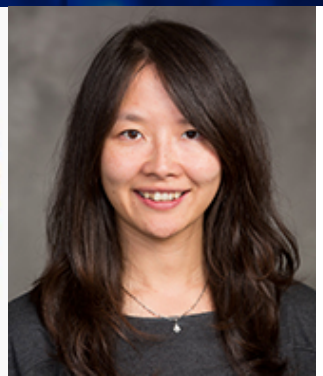
Karen **Yang**

Ellen **Zweibel**



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MHD simulations of leptonic AGN jets

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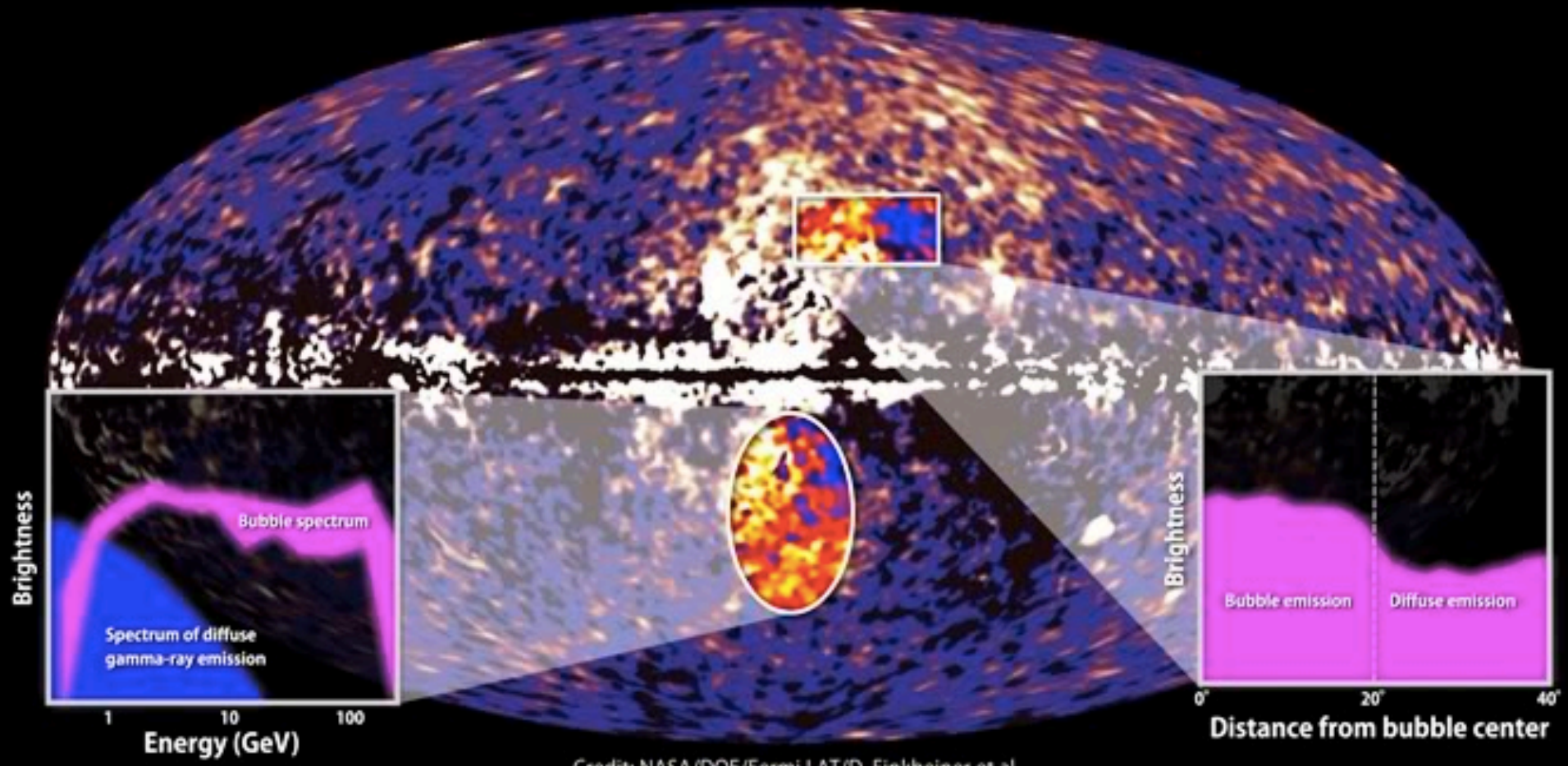
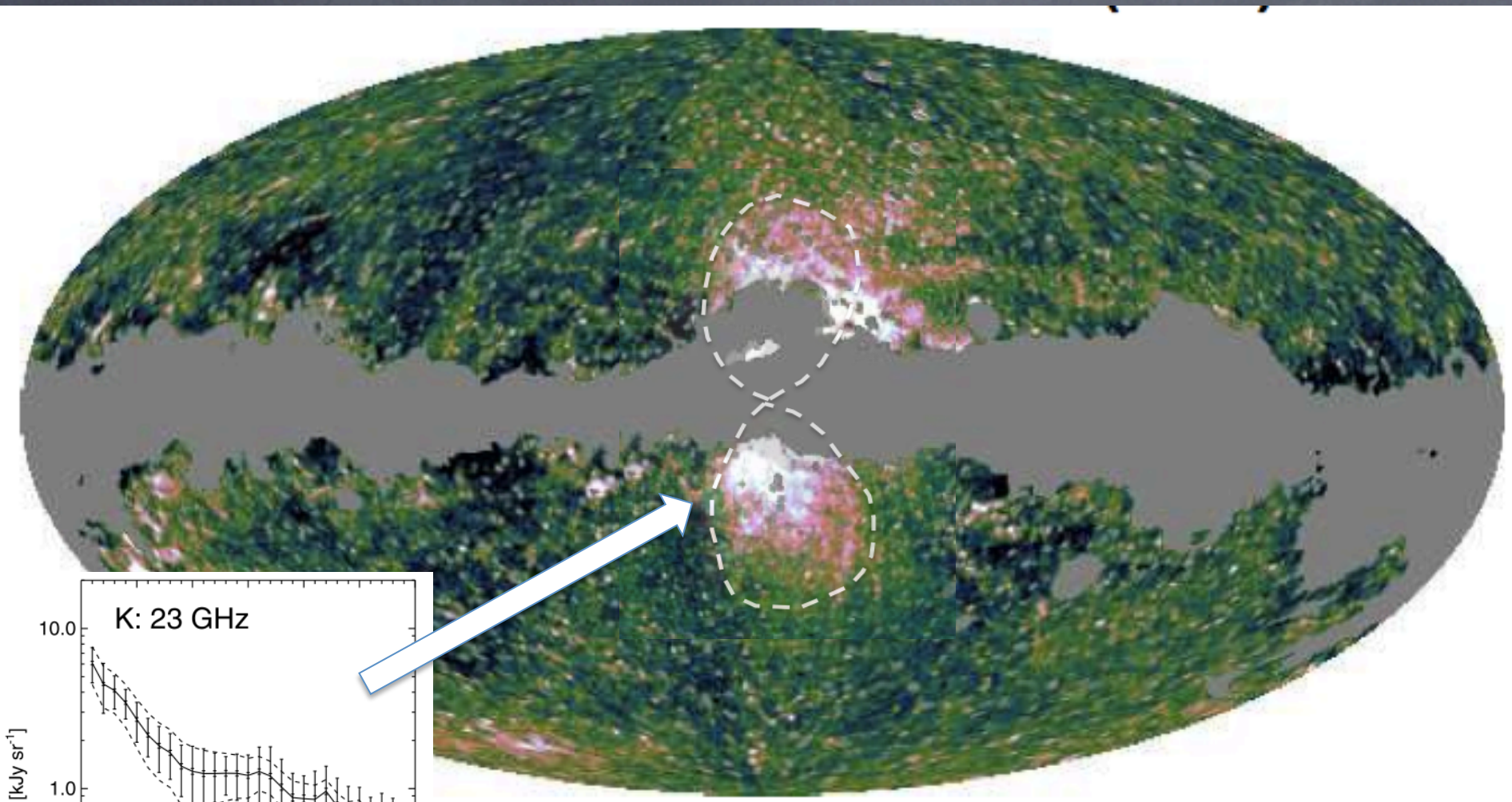
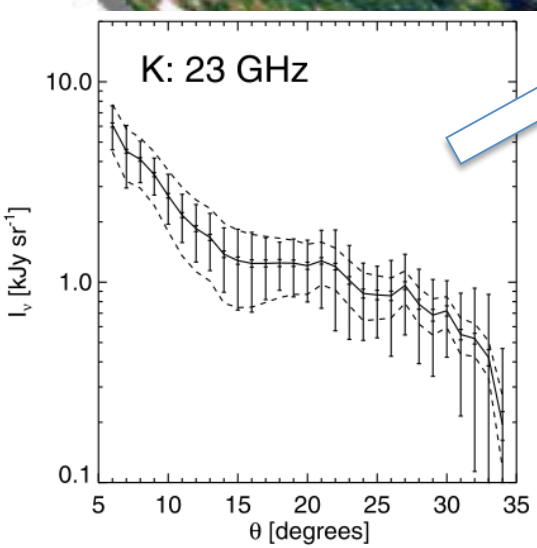
Bubbles show energetic spectrum and sharp edges



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

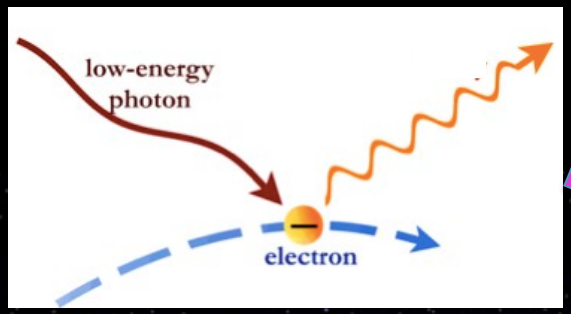
Haze emission

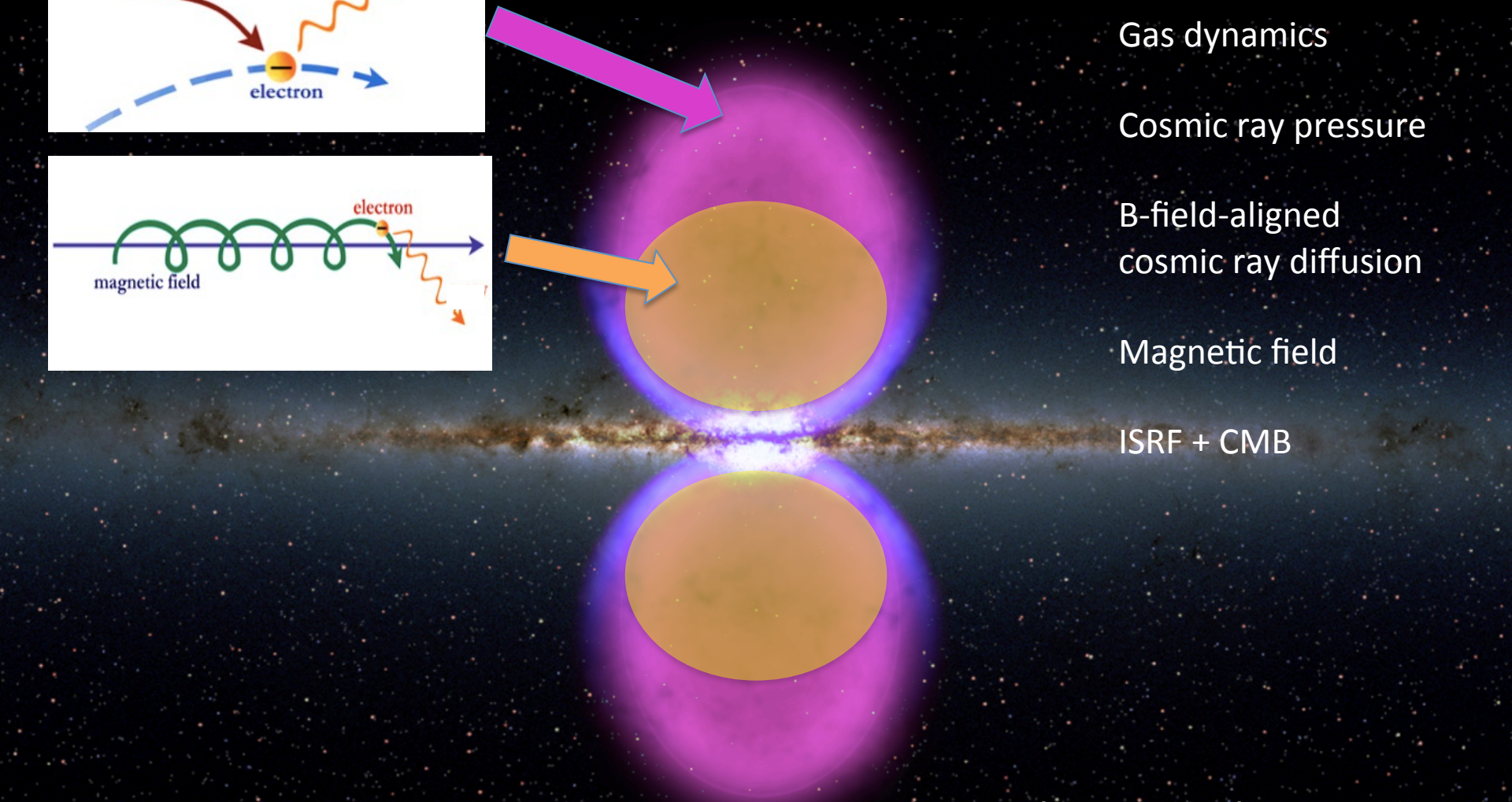




Finkbeiner 2004, Dobler 2008, *Planck* collab.

Simulations:





Gas dynamics

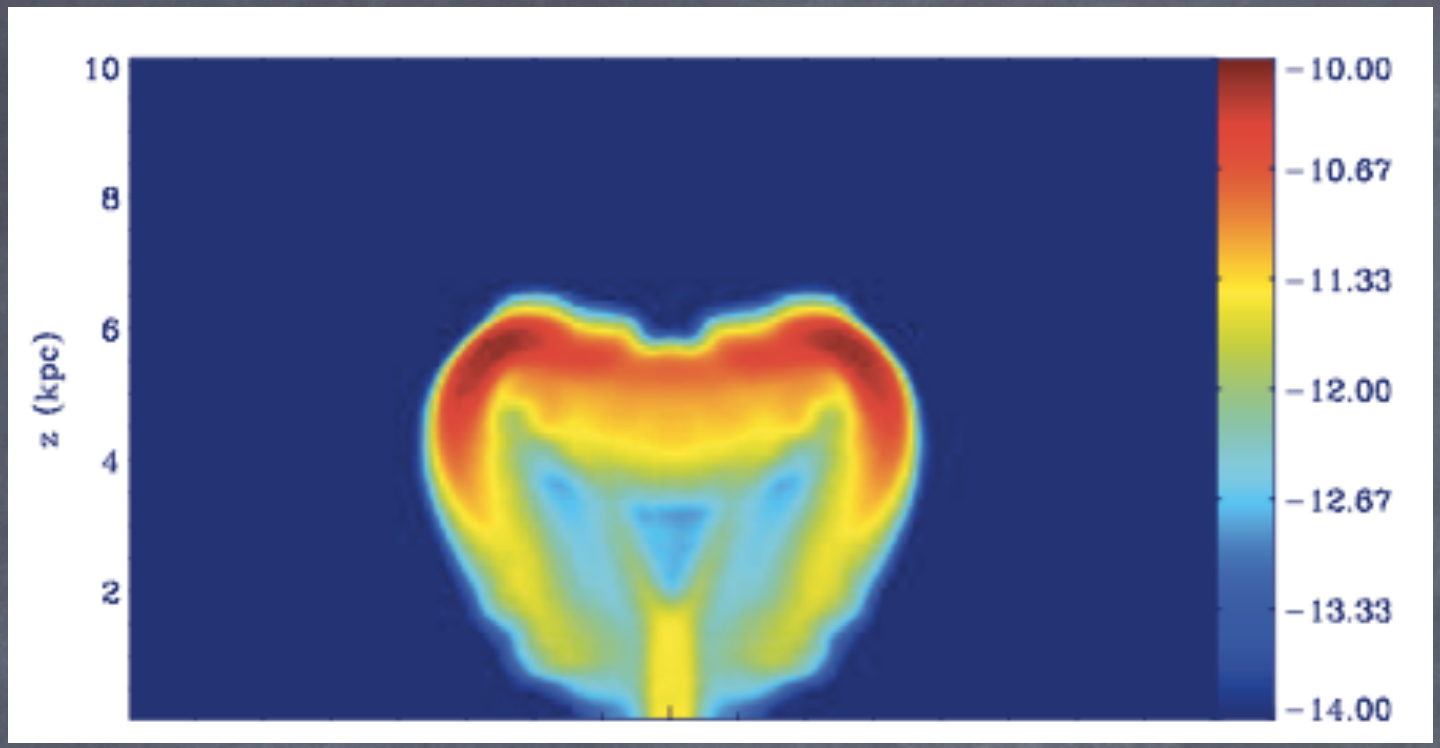
Cosmic ray pressure

B-field-aligned
cosmic ray diffusion

Magnetic field

ISRF + CMB

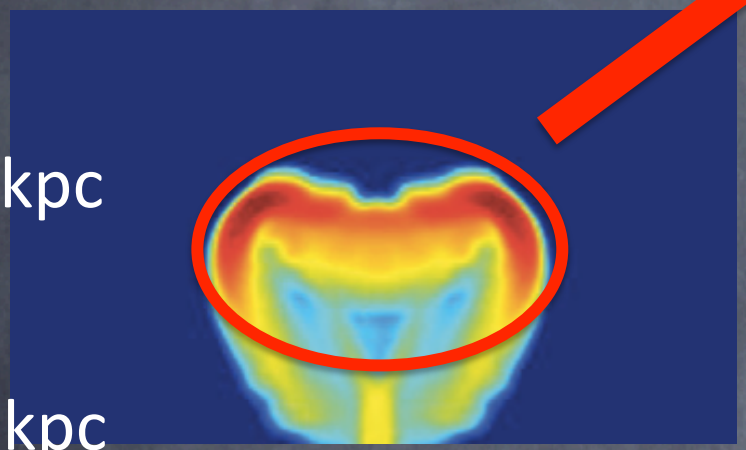
Yang, Ruszkowski, Zweibel 2013, MNRAS (in press)
Yang, Ruszkowski, Ricker, Lee, 2012, ApJ

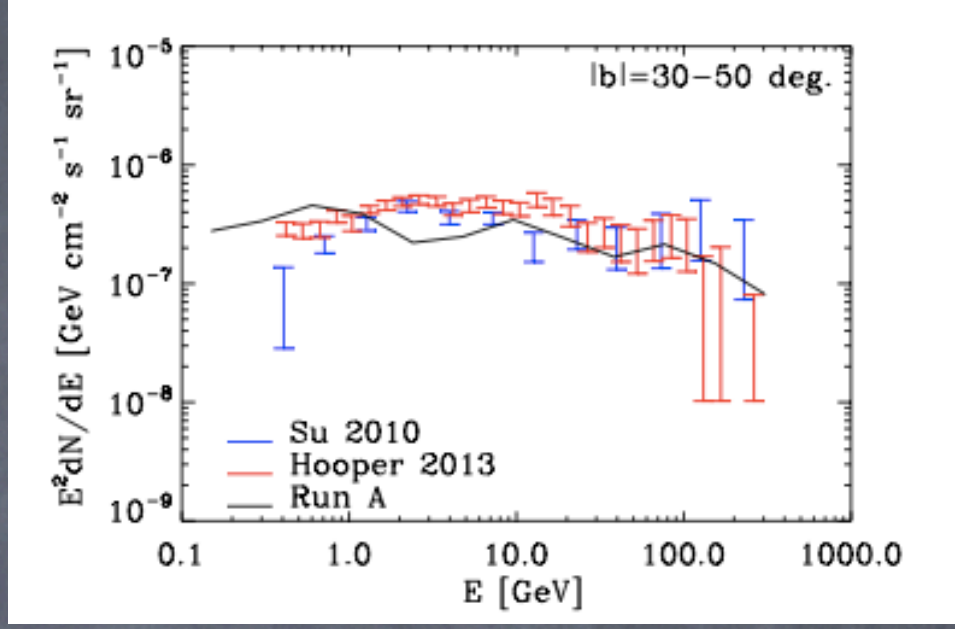


edge-enhanced CR distribution

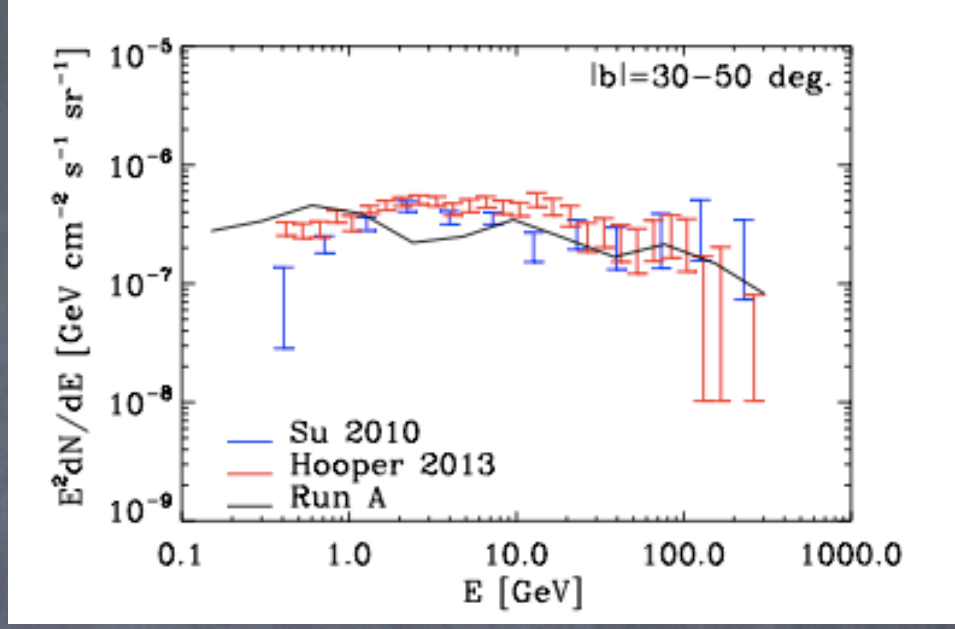
flat sky-projected gamma-ray distribution

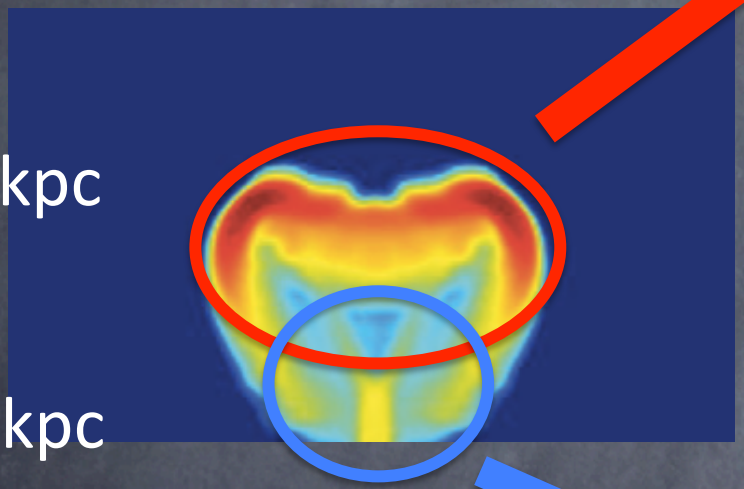
Gamma-ray spectrum

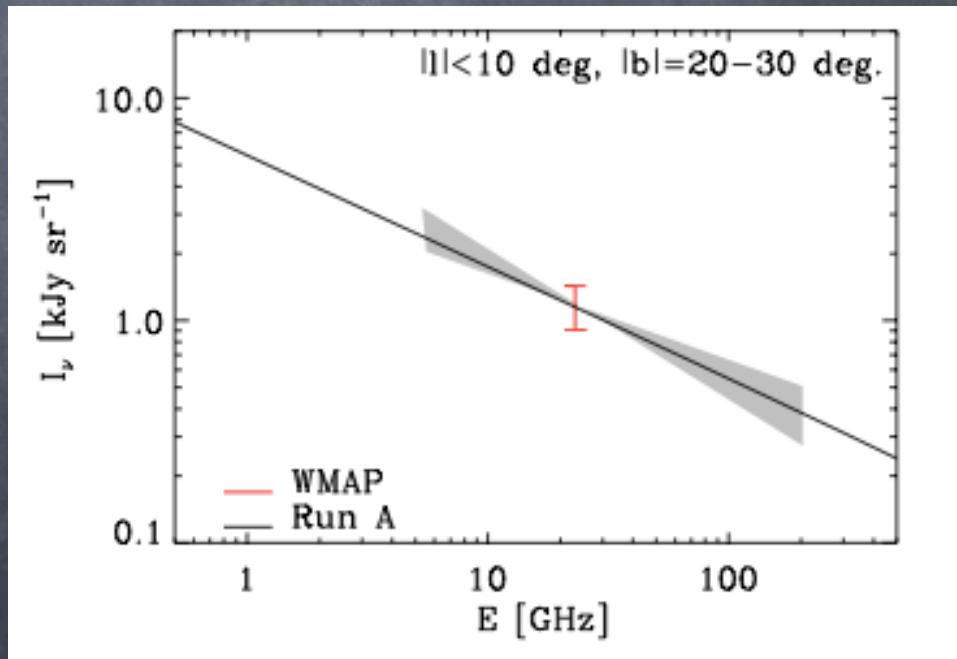




Gamma-ray spectrum



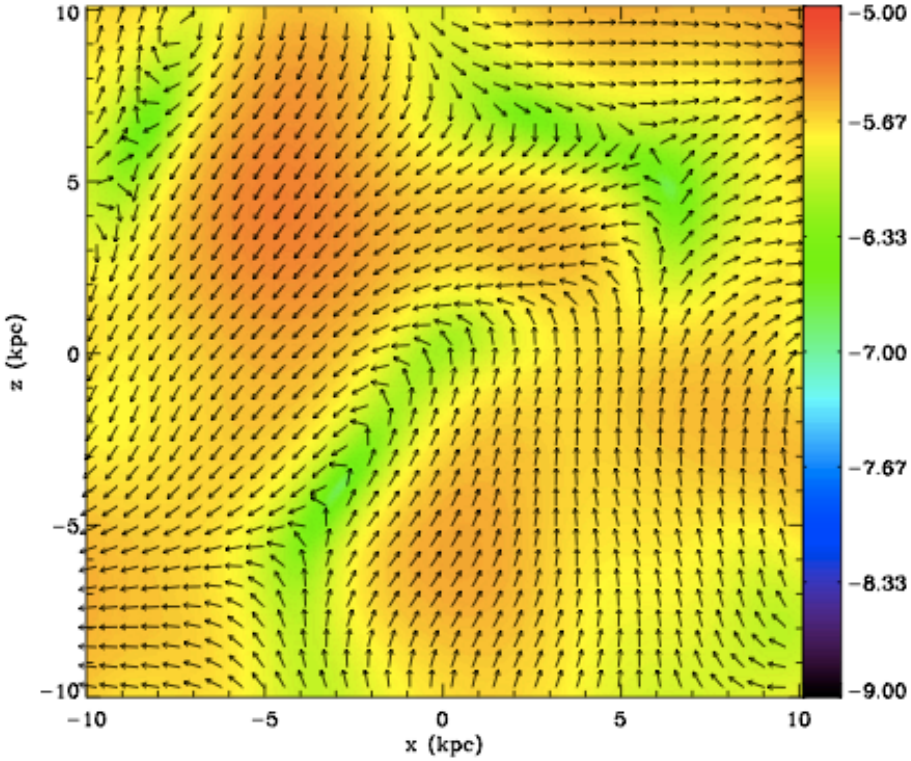


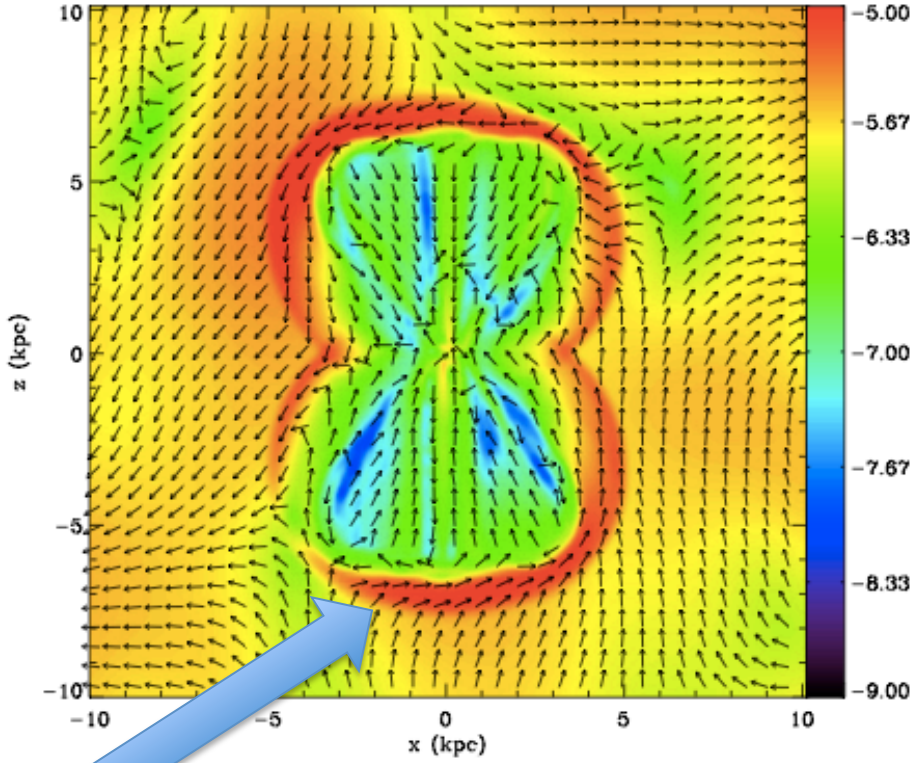


assuming GALPROP's

$$|B| = B_0 \exp(-z/z_0) \exp(-R/R_0)$$

Haze normalization/slope



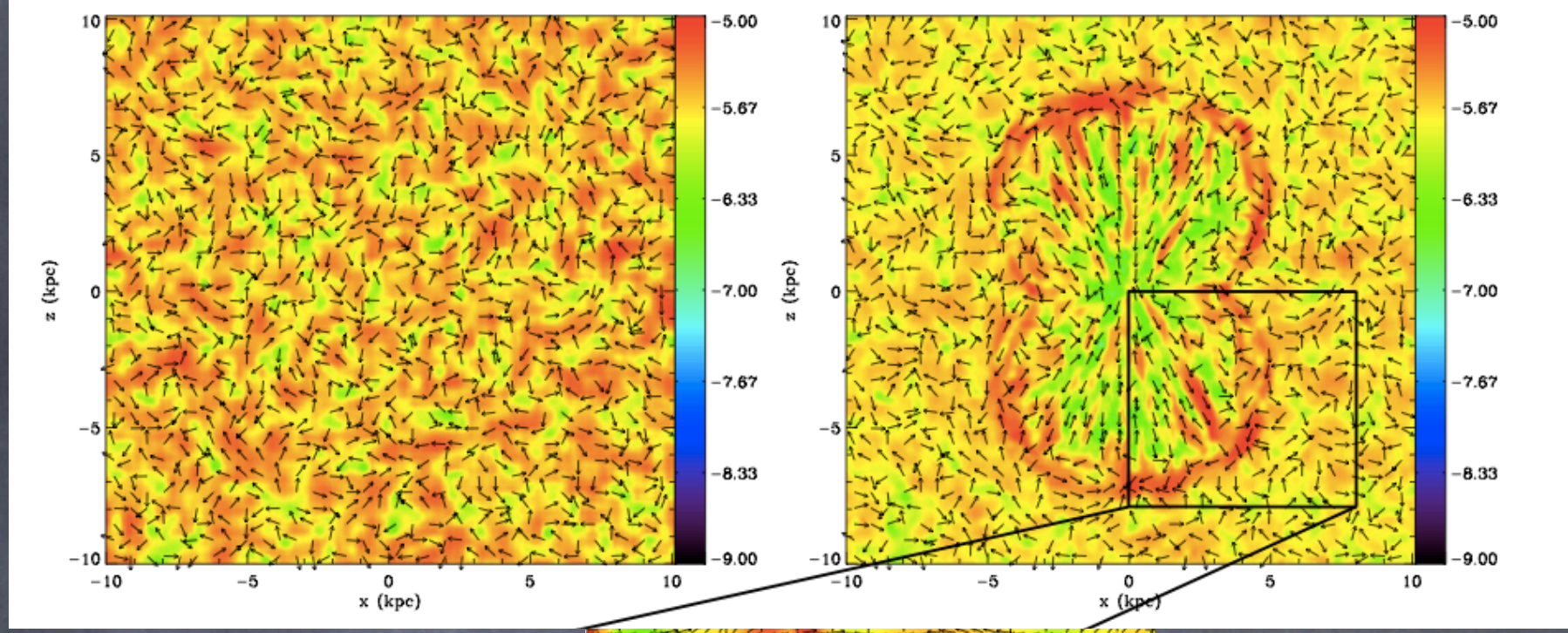


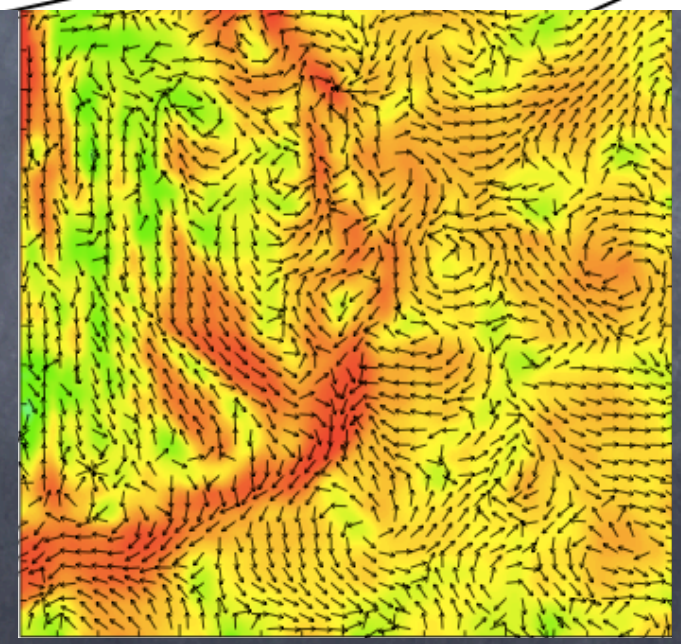
t=0

t ~ 1 Myr

Magnetic draping
sharp bubble edges in gammas

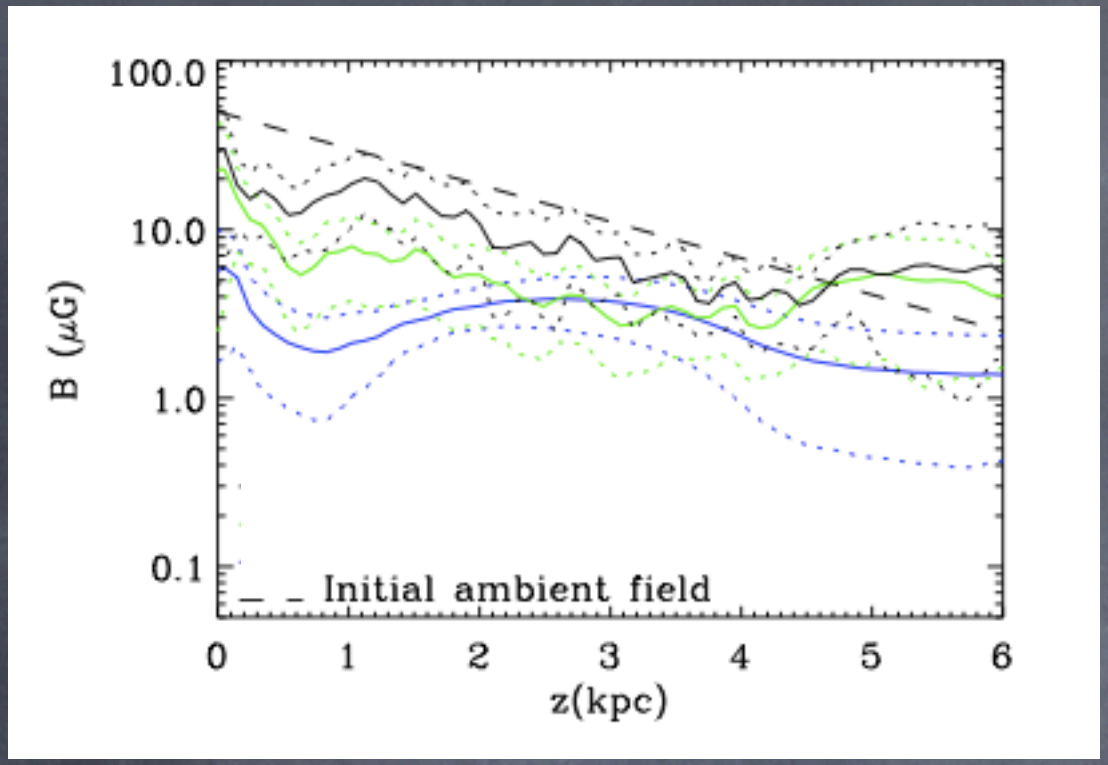
CRs in contact with ***weak*** B-field
(***weak*** synchrotron emission)



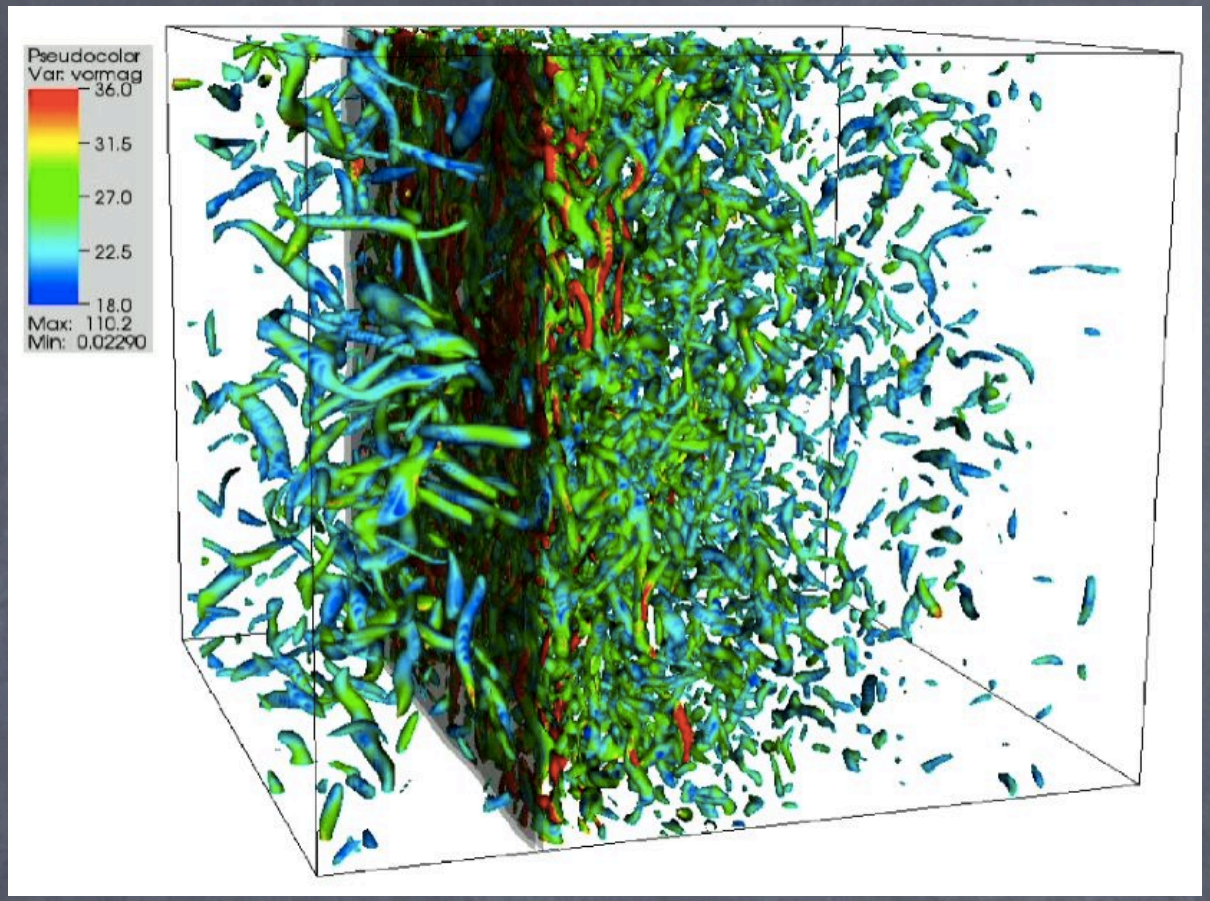


Partial magnetic draping:

- bubble edges *still* sharp
- seed fields enter the bubble



Coherence length > **Coherence length** > **Coherence length**



Vorticity magnitude

Larsson & Lele (2009)

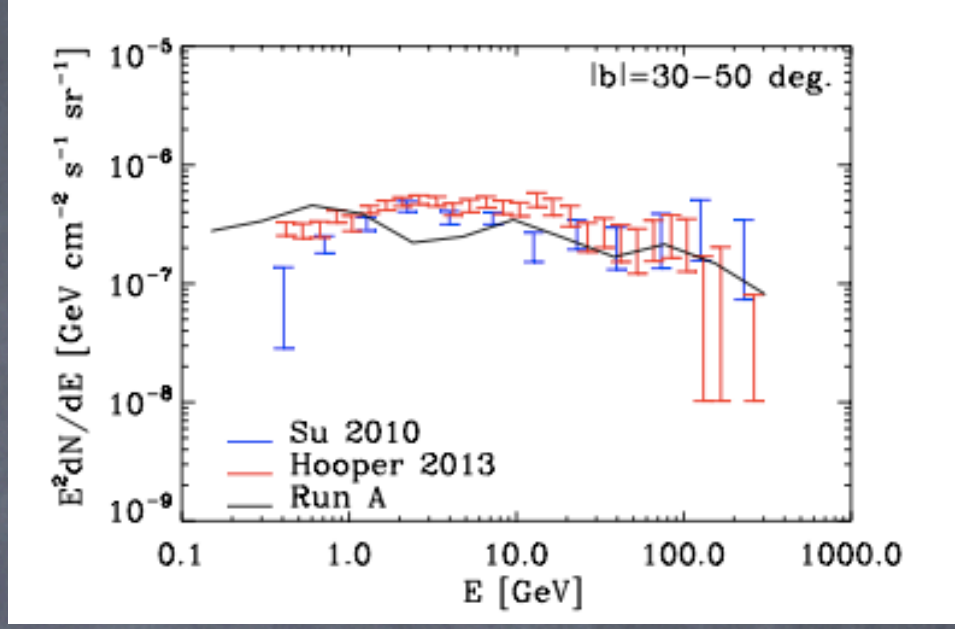
Ambient ISM B_{amb}

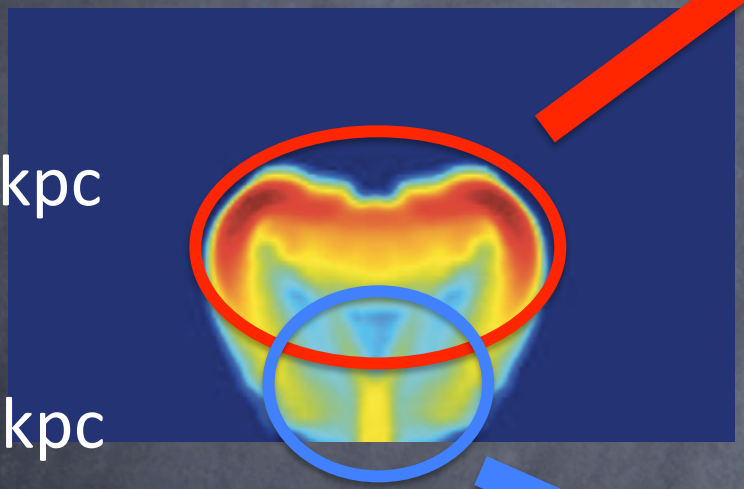
Shocked shell

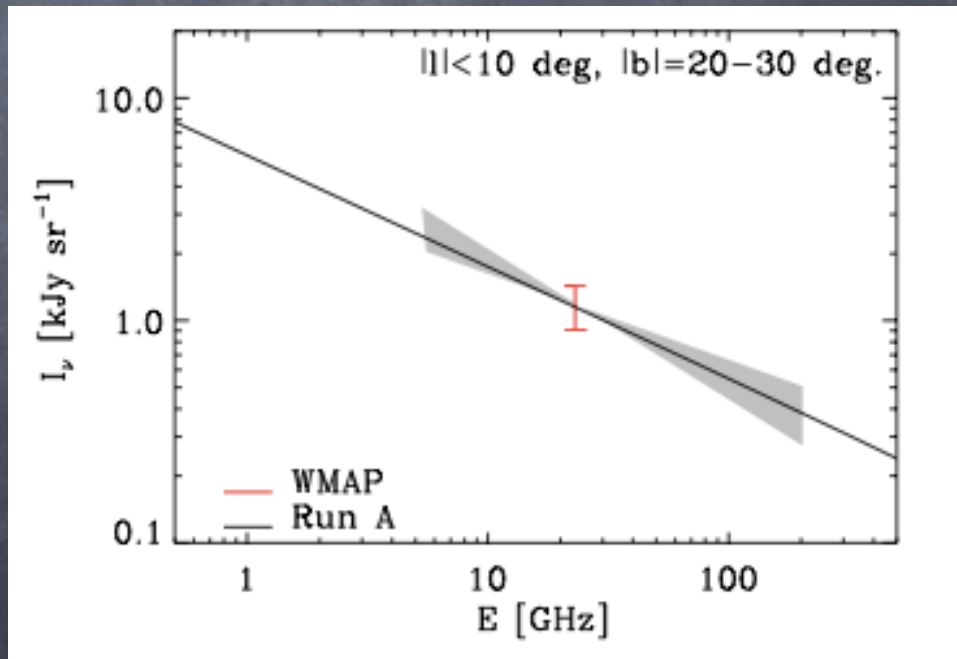
Bubble B_{bubb}

$$B_{bubb} \leq (\alpha r)^{1/2} B_{amb}$$

Gamma-ray spectrum







Haze normalization/slope

B-fields strong enough
to explain synchtrotron

BUT at low-z

$$\beta \sim \frac{P_B + P_{th} + P_{cr}}{P_B} \sim 1$$

CR & gas are displaced

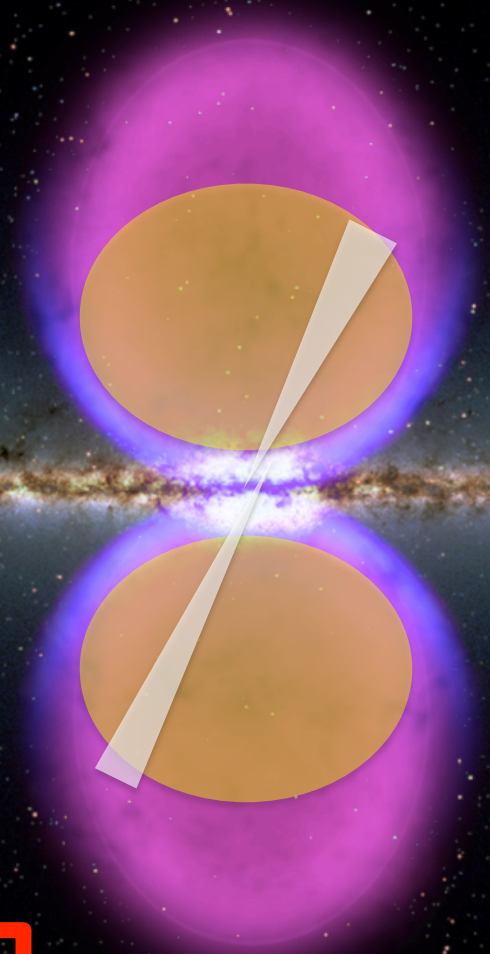
need CR replenishment
near the center

B-fields strong enough
to explain synchtrotron

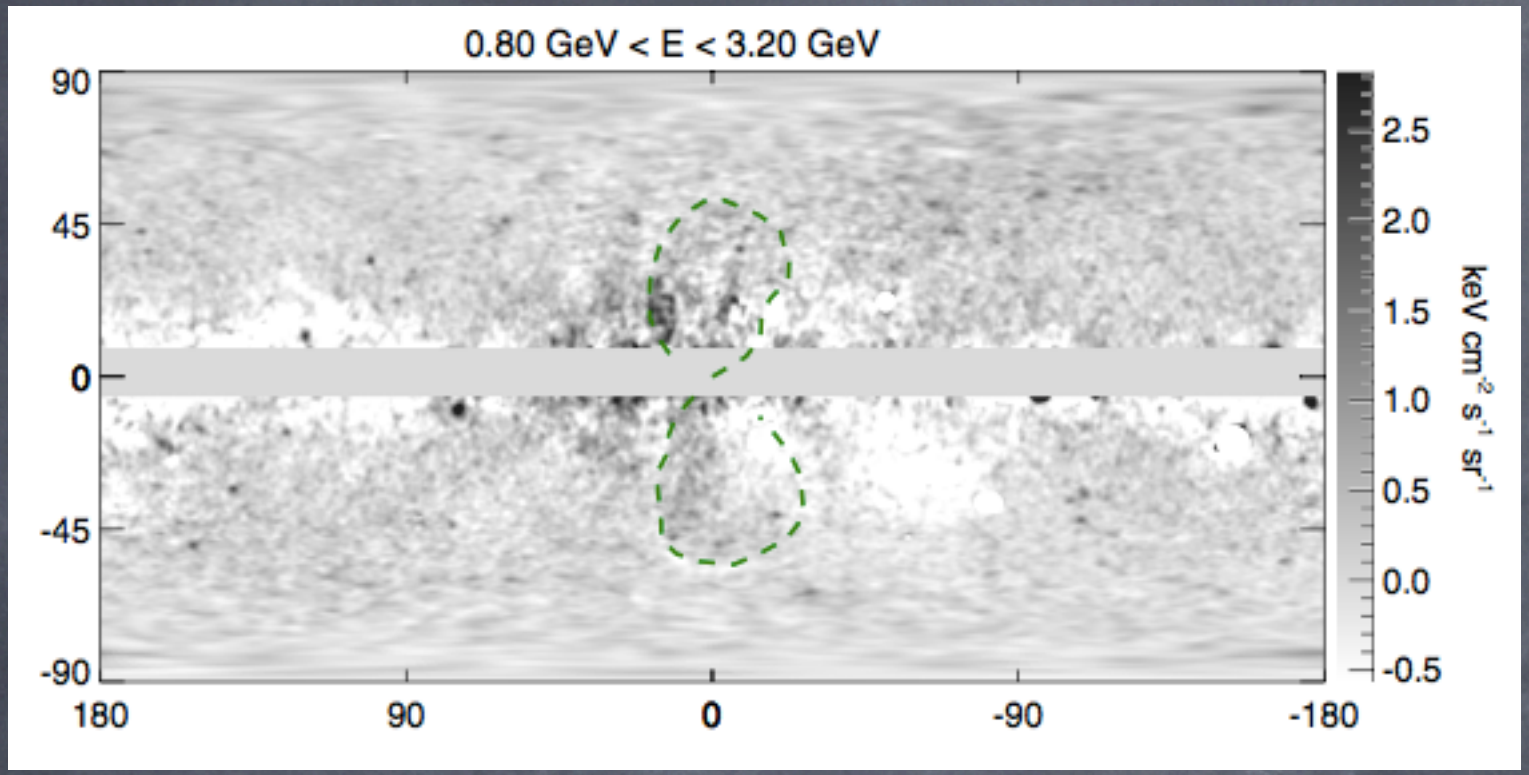
BUT at low-z

$$\beta \sim \frac{P_B + P_{th} + P_{cr}}{P_B} \sim 1$$

CR & gas are displaced



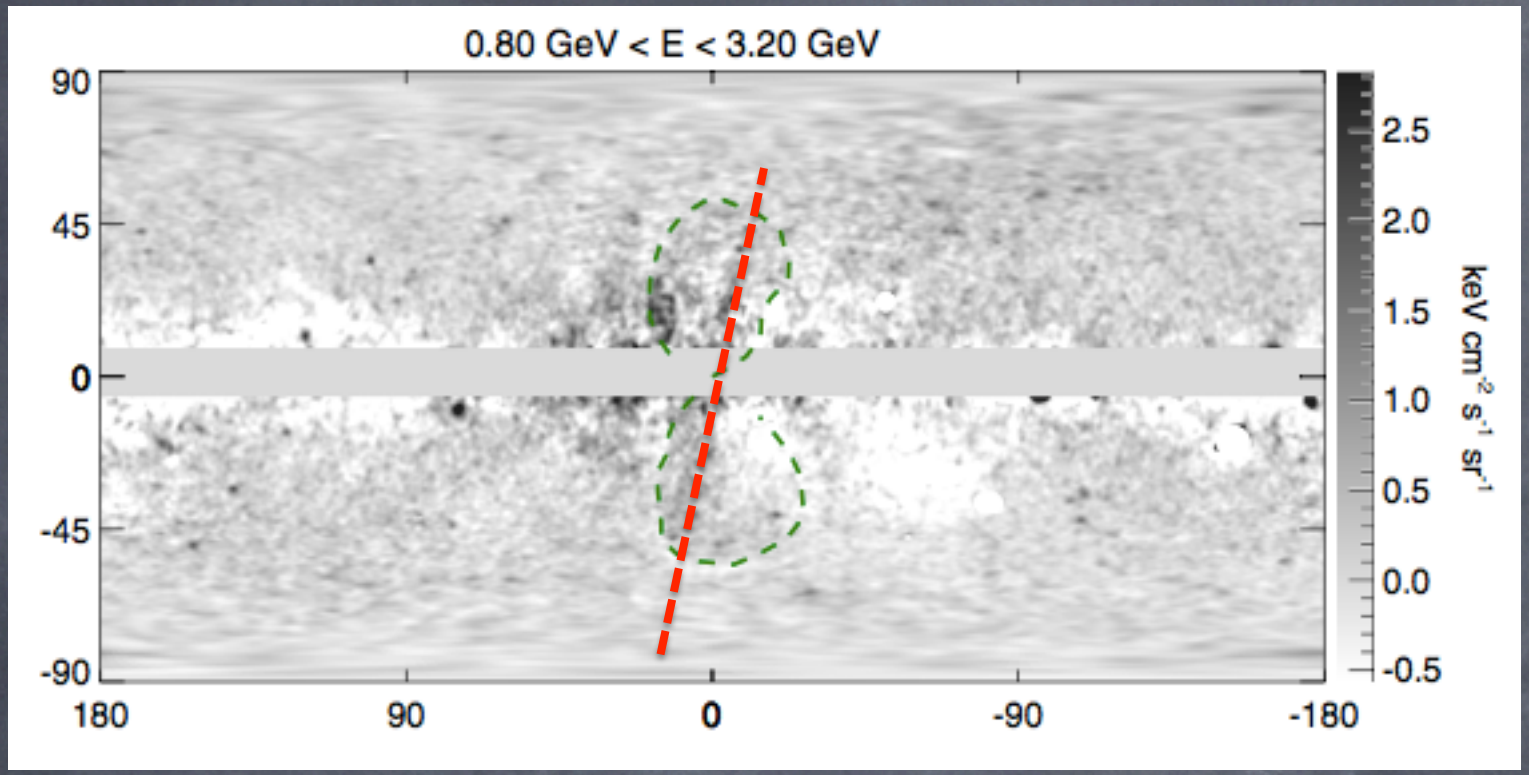
need CR replenishment
near the center



Su & Finkbeiner (2012)

See also: Li, Morris, Baganoff (2013) astro-ph posting yesterday

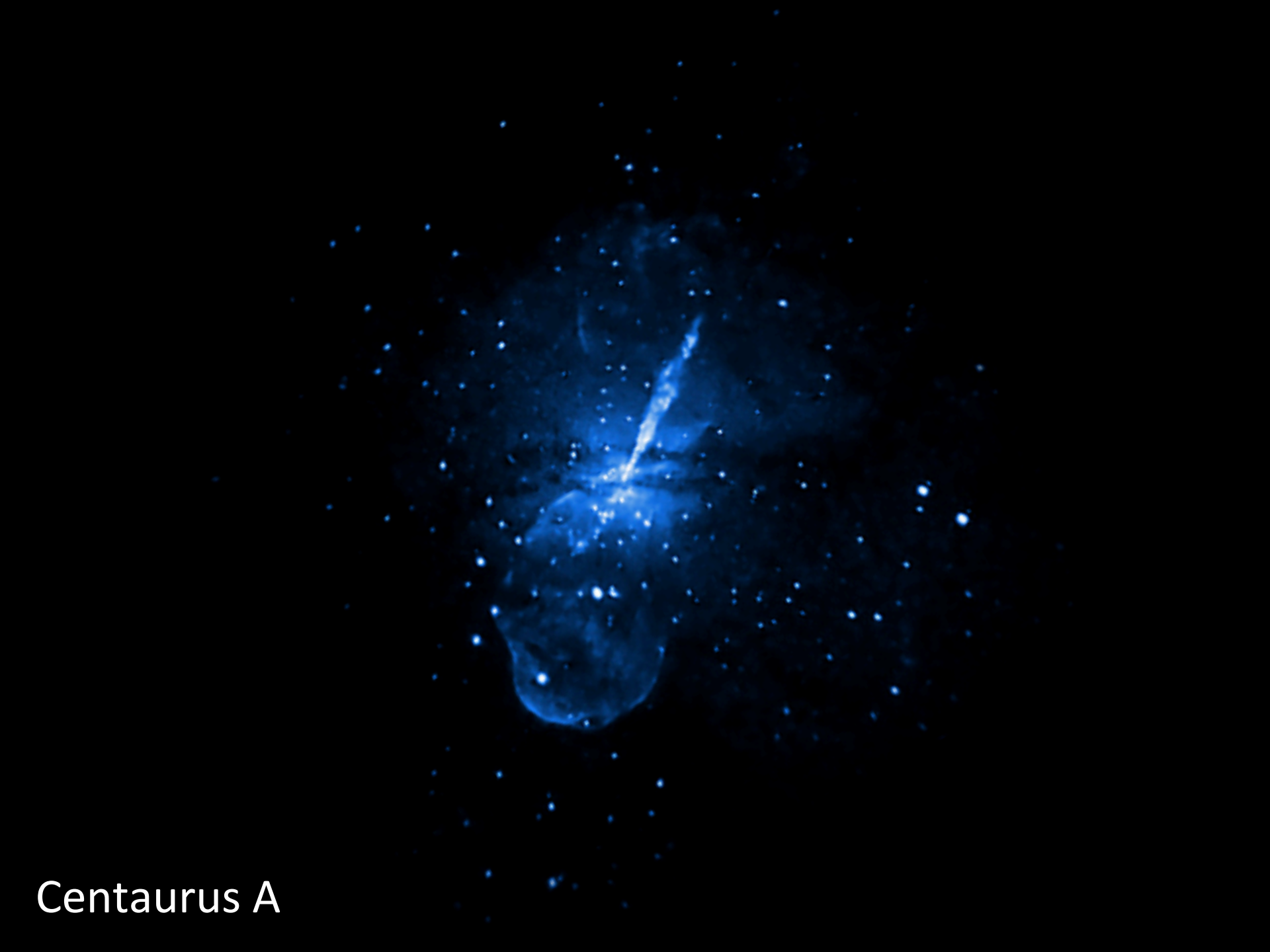
Sub-parsec X-ray Jet



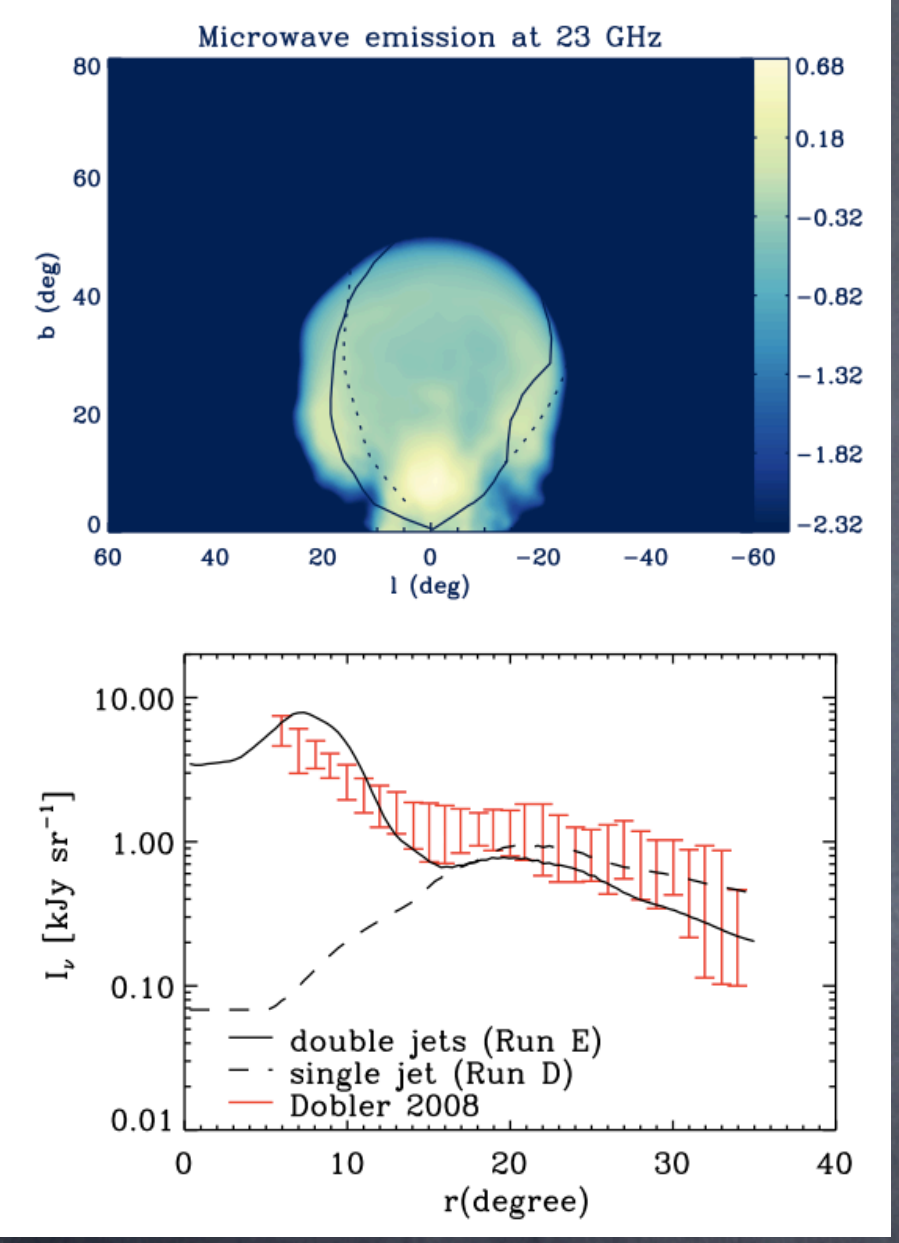
Su & Finkbeiner (2012)

See also: Li, Morris, Baganoff (2013) astro-ph posting yesterday

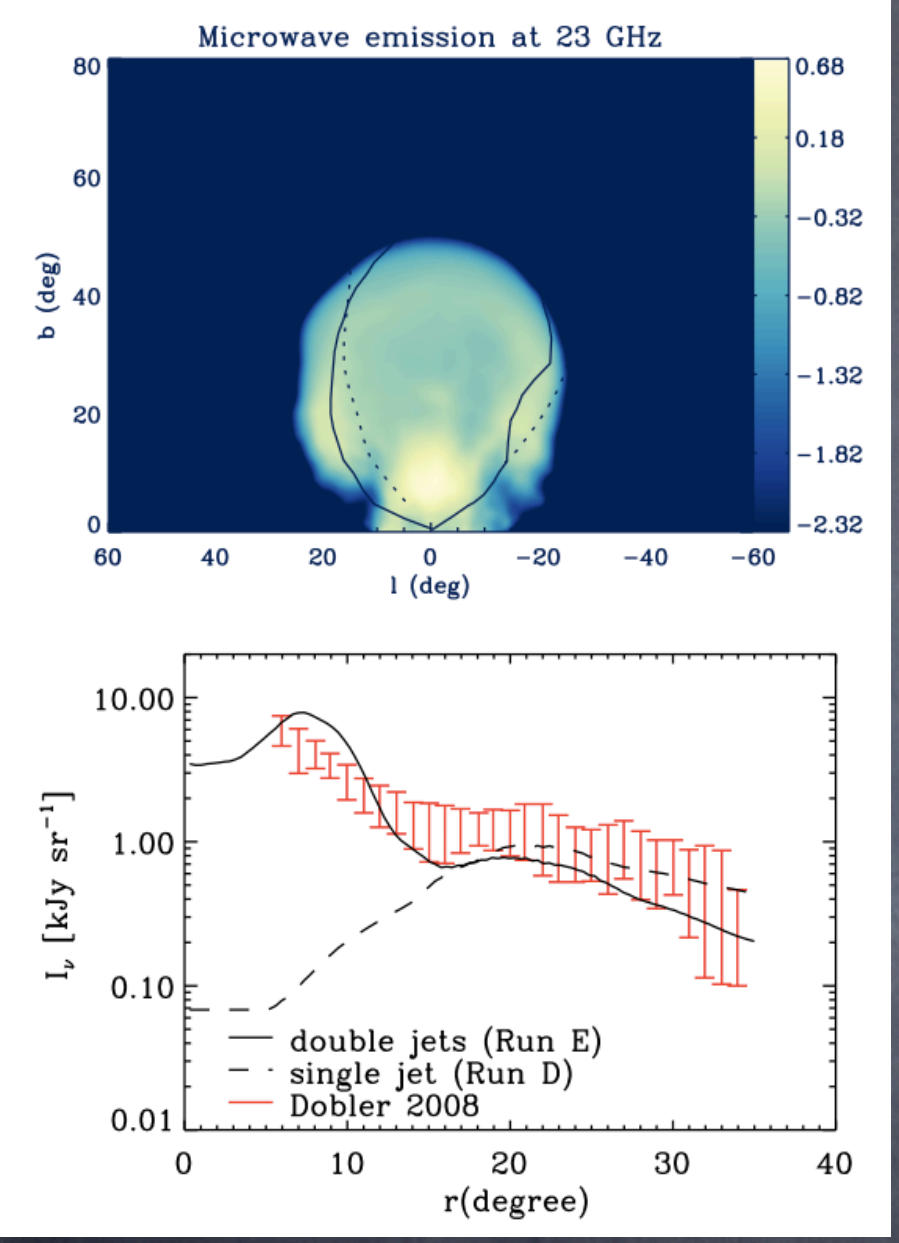
Sub-parsec X-ray Jet

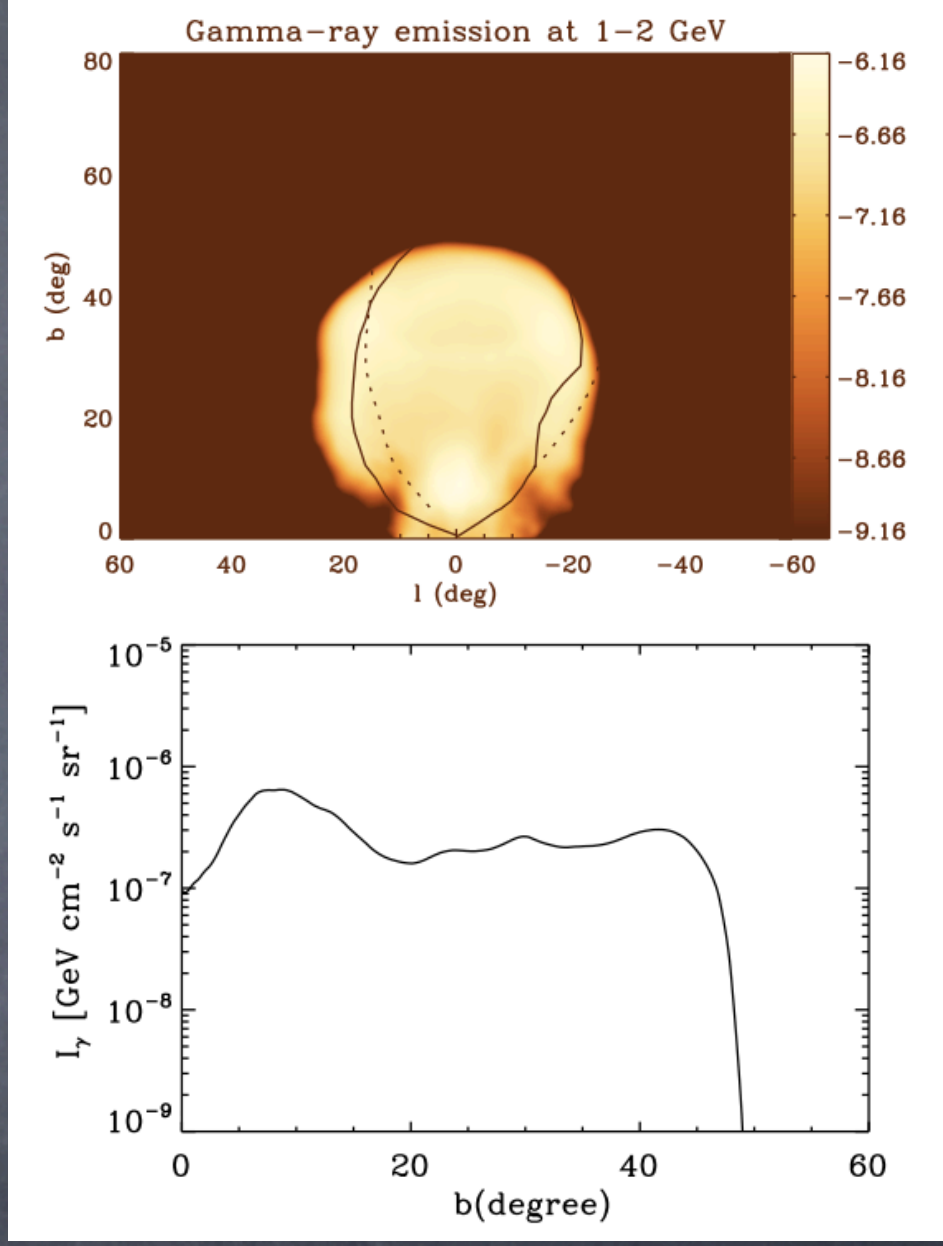


Centaurus A



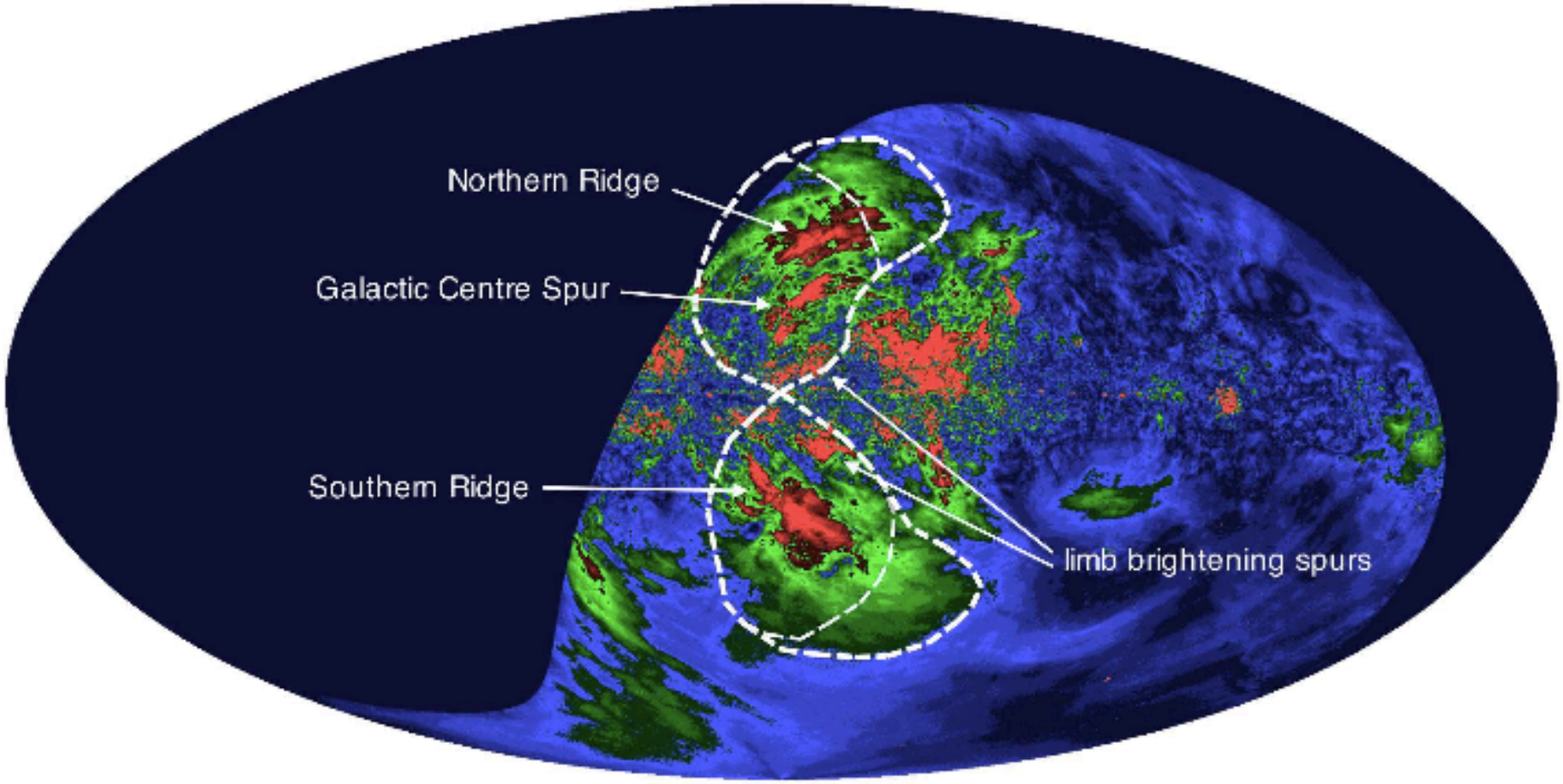
Haze profile matches data



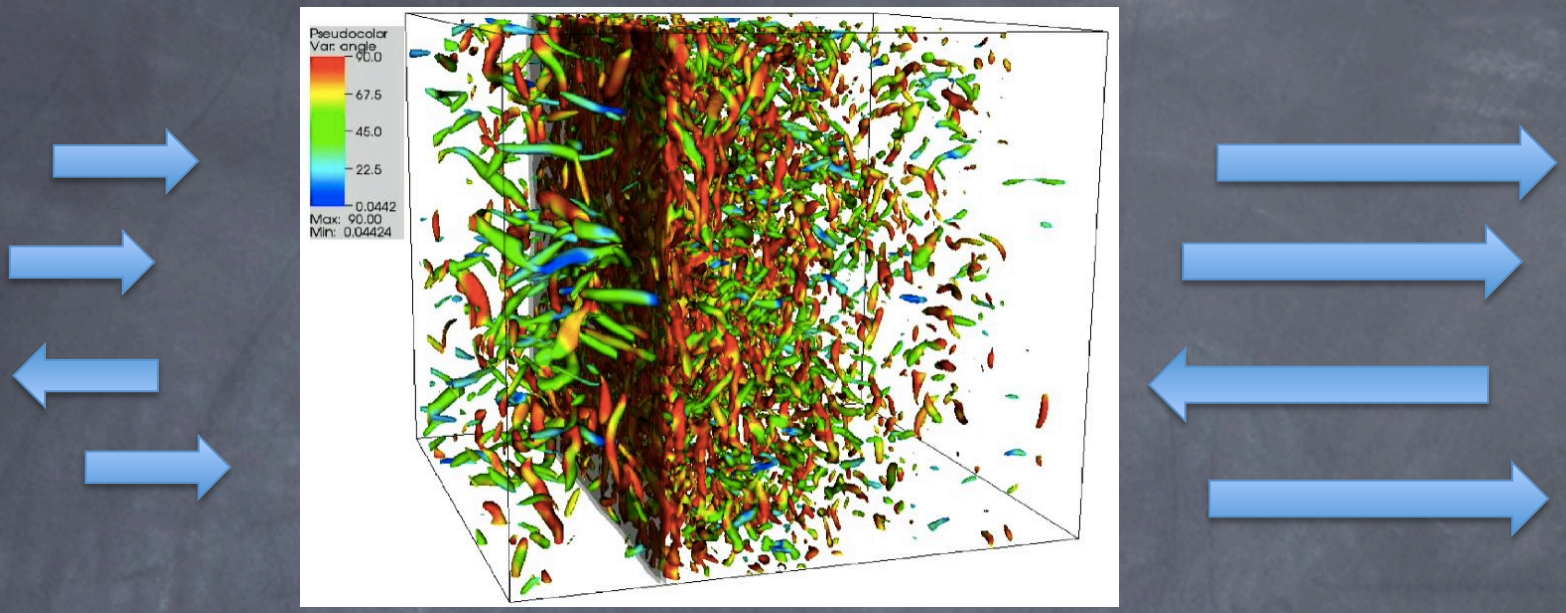


Haze profile matches data

Gamma-ray profile nearly flat as observed



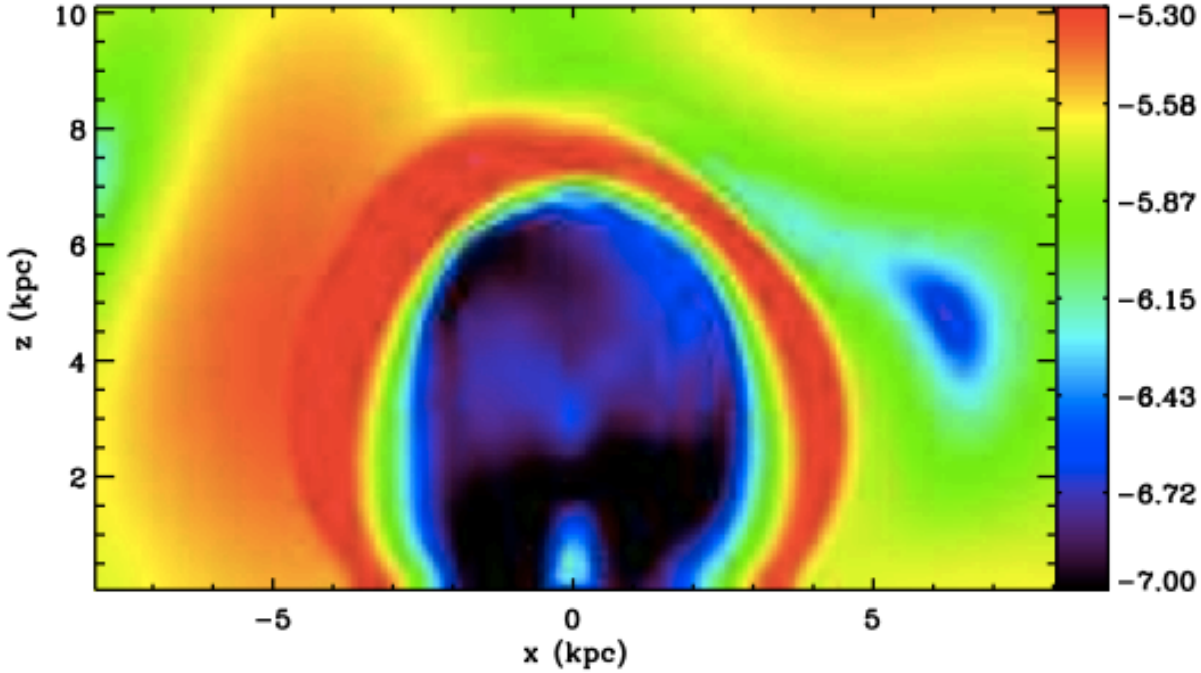
S-PASS data: Carretti, Crocker et al. (2013)

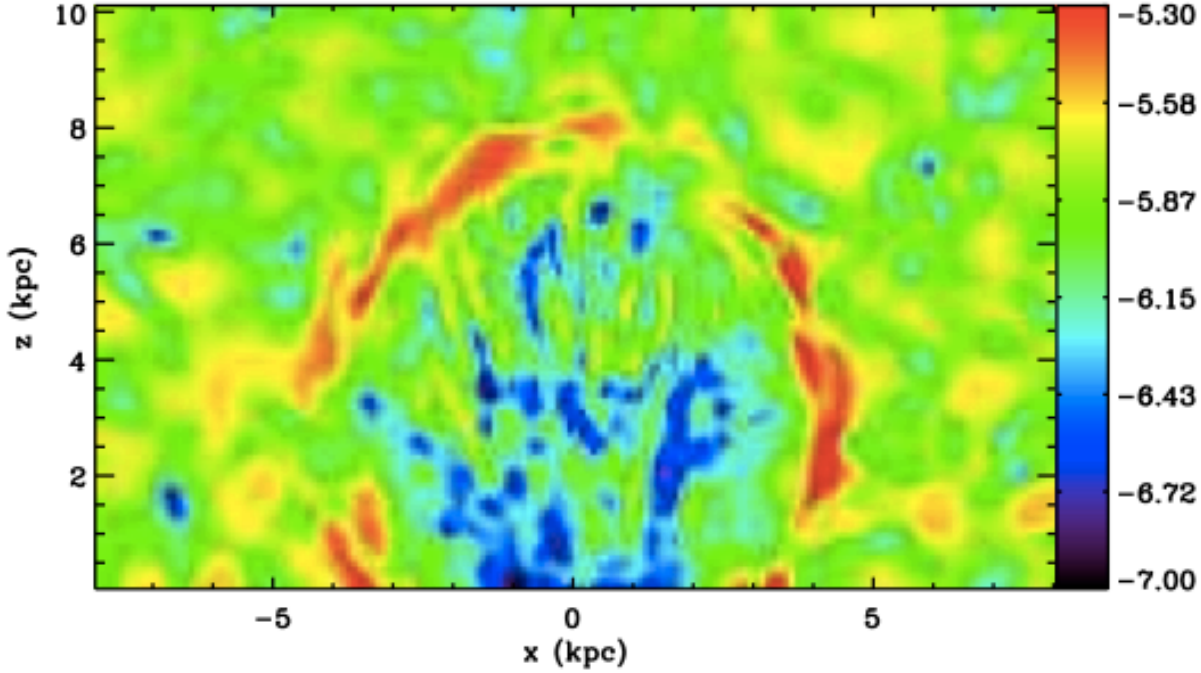


Angle between vorticity and x-axis:

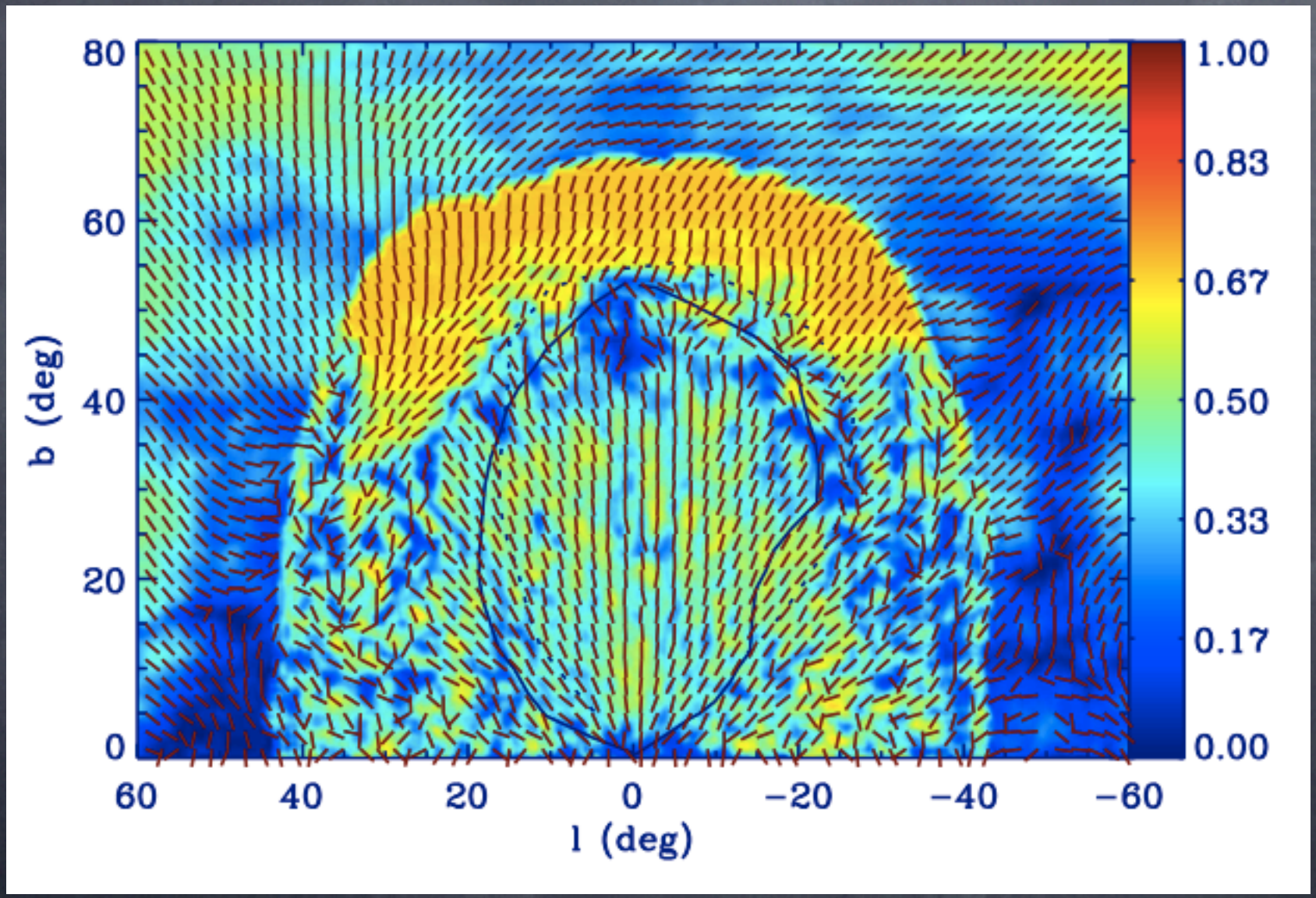
90 degrees   0 degrees

Larsson & Lele (2009)

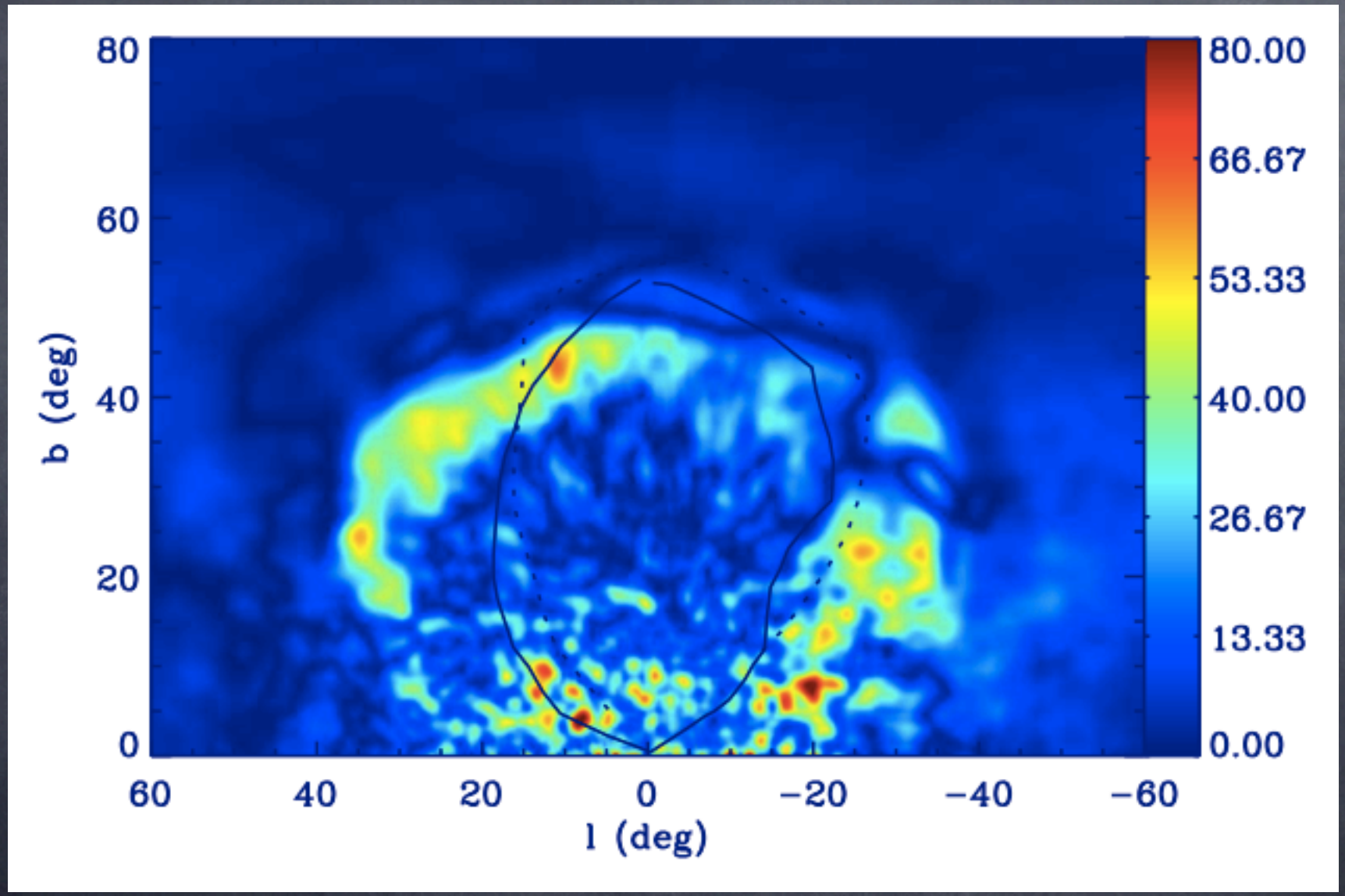

z (kpc)
x (kpc)
10
8
6
4
2
−5
0
5
−5.30
−5.58
−5.87
−6.15
−6.43
−6.72
−7.00


z (kpc)
x (kpc)
10
8
6
4
2
−5
0
5
−5.30
−5.58
−5.87
−6.15
−6.43
−6.72
−7.00

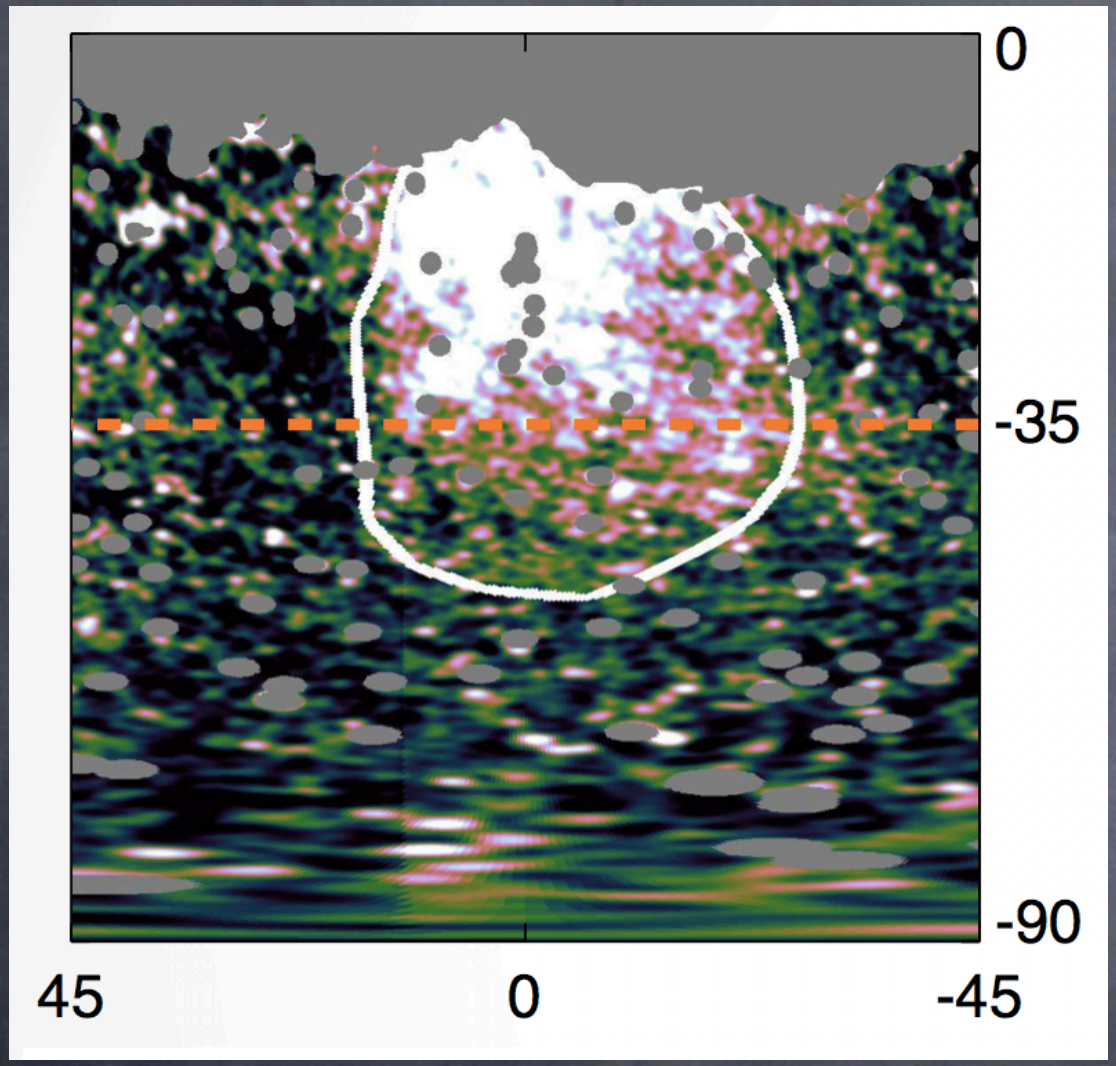
Polarization fraction and sky-projected B-field



Rotation measure map



Deficient Haze emission < -35 degrees



suppressed CR number density
(would contradict gamma map)

OR

suppressed B-field

Planck collaboration (2012)

2.3 GHz S-PASS data:

$$B_{\mathrm{eq}} \sim 6\mu G$$

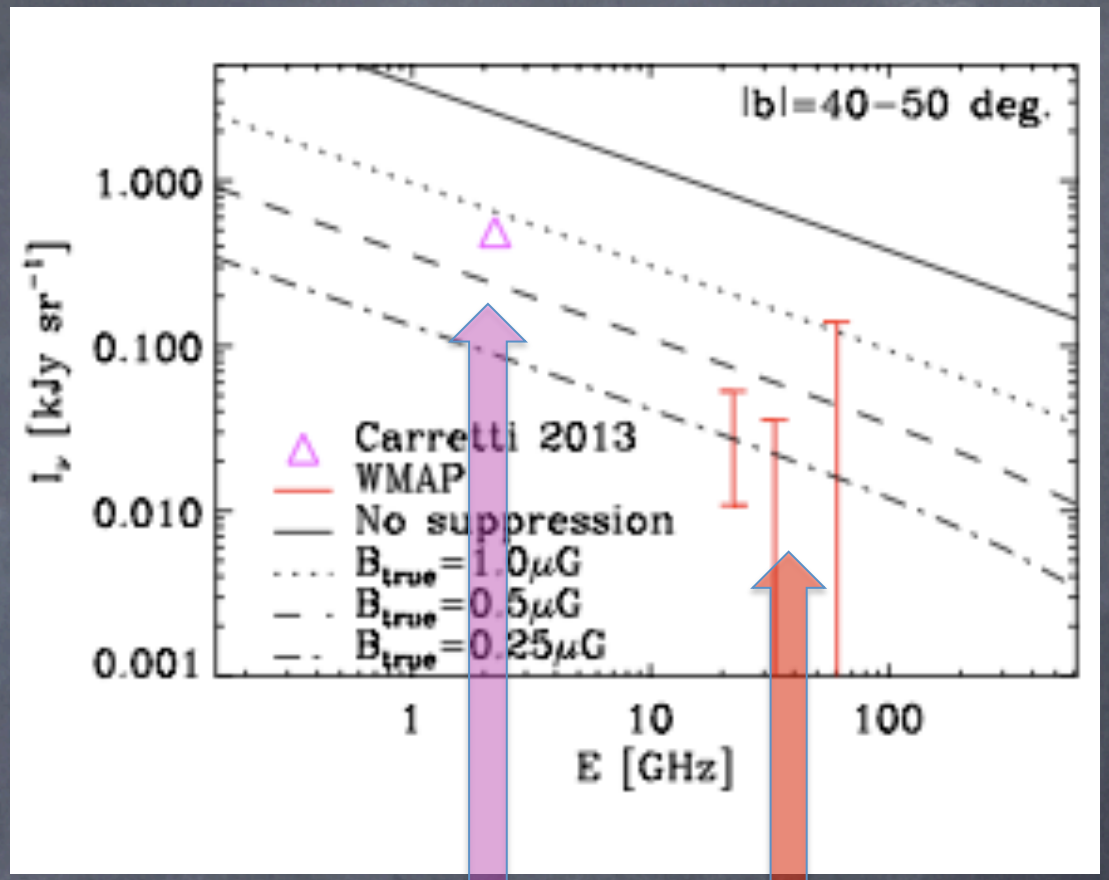
$$\frac{e_{\mathrm{cr}}}{e_{\mathrm{B}}} = \left(\frac{B_{\mathrm{true}}}{B_{\mathrm{eq}}}\right)^{-\frac{p+5}{2}}$$

Beck & Krause (2005)

$$e_{\mathrm{CRe}} \sim f_{\mathrm{e},\nu} e_{\mathrm{cr,sim}}$$

$$e_{\mathrm{CRp}}/e_{\mathrm{CRe}} = 100$$

$$B_{\mathrm{true}} \sim 2\mu G$$



If $e_{\mathrm{cr}} > e_{\mathrm{CR,sim}}$ → $B_{\mathrm{true}} < 2\mu G$

Bubble Composition

in the leptonic model:

same population of e-
explains WMAP and gamma

$$e_{\mathrm{CRe}} \sim f_{\mathrm{e}} e_{\mathrm{CR,sim}} \sim 5\mathrm{x}10^{-4} e_{\mathrm{CR,sim}}$$

$$k \equiv \frac{e_{\mathrm{CRp}}}{e_{\mathrm{CRe}}} \leq 200$$

$$e_{\mathrm{CRp}} \sim f_{\mathrm{p}} e_{\mathrm{CR,sim}} \leq 0.1 e_{\mathrm{CR,sim}}$$

Yang, Ruszkowski, Zweibel 2013
Yang, Ruszkowski, Ricker,Zewibel, Lee 2012
Guo, Mathews 2012
Guo, Mathews, Dobler, Oh 2012

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in the hadronic model
one would need

$$e_{\mathrm{CRp}} \sim f_{\mathrm{p}} e_{\mathrm{CR,sim}} \sim e_{\mathrm{CR,sim}}$$

$$e_{\mathrm{2nd\ e\text{-},cumul}} \sim 5\mathrm{x}10^{-4} e_{\mathrm{CR,\ sim}}$$

Yang, Ruszkowski, Zweibel 2013
Crocker & Aharonian 2011
Guo, Mathews 2012
Guo, Mathews, Dobler, Oh 2012

Key Points

- Same population of CR e-
  simultaneously explains Fermi gamma and WMAP emission

- Our simulations require second jet
  (in agreement with Su & Finkbeiner 2012)

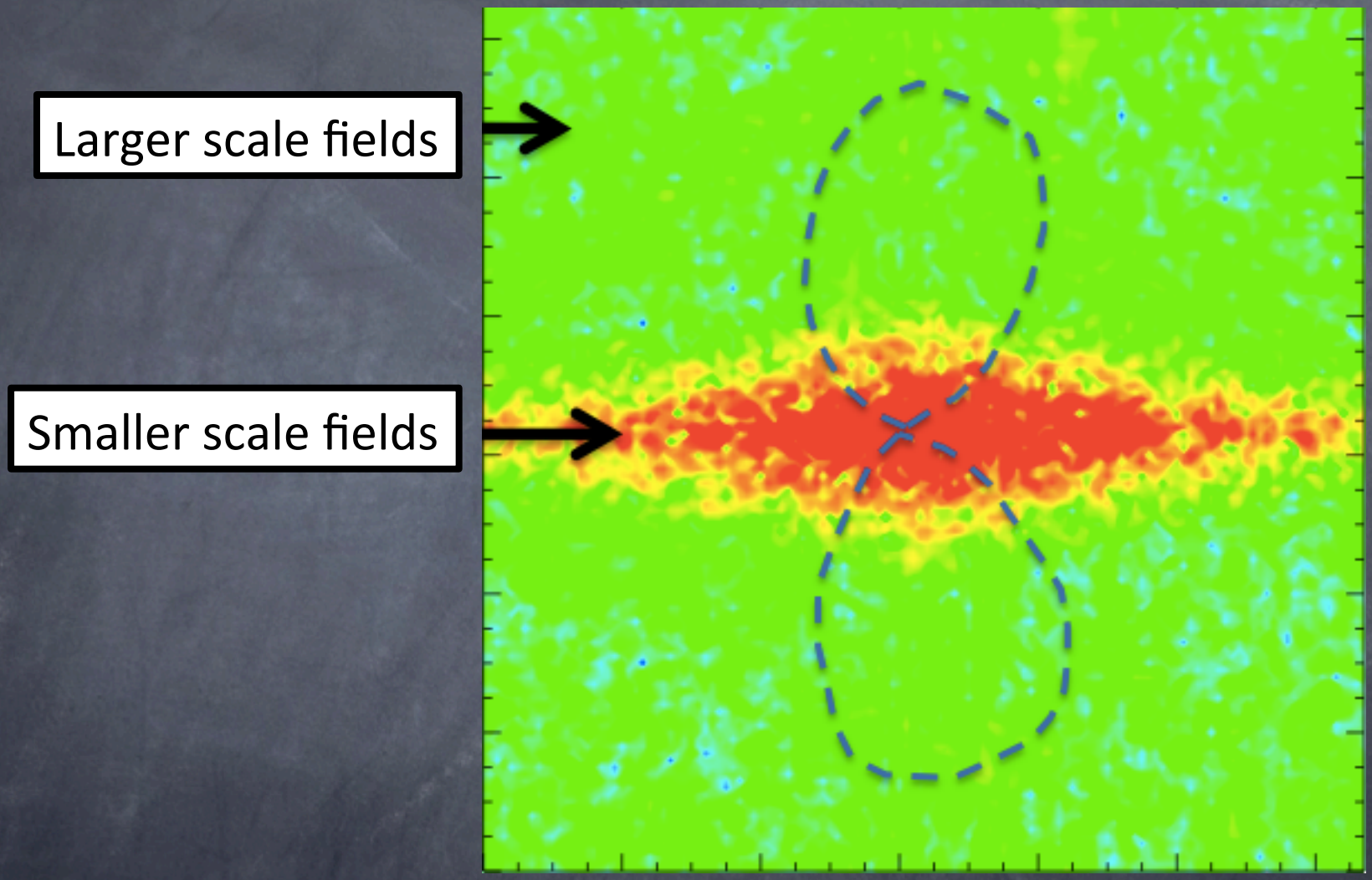
- B-field amplification inside Fermi bubbles can be efficient
  (consistent with WMAP emission & S-PASS polarization data)

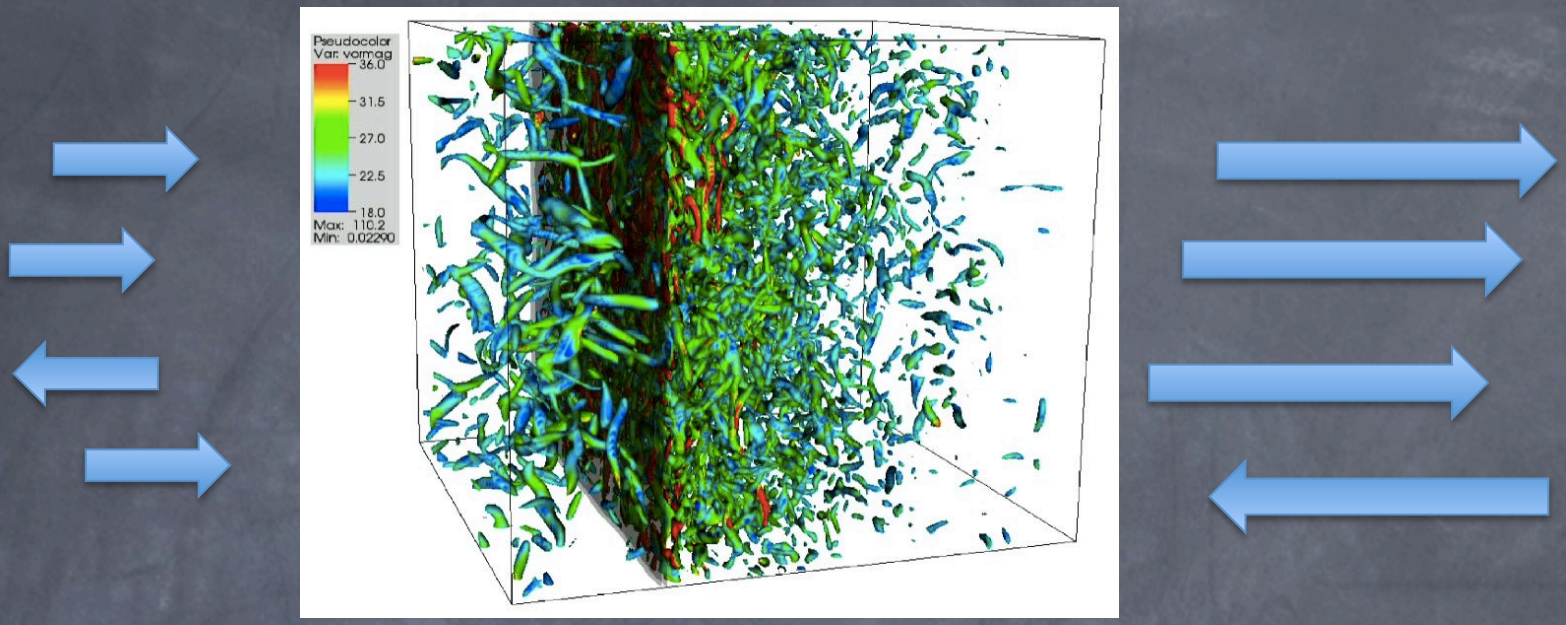
- Multiwavelength data allow us to an look inside the bubbles
  (leptonic model suggests weak CR pressure support)

- A separate low-energy CR population required
  to explain S-PASS emission; in agreement with Carretti et al. 2013

AAS - Job Register

Postdoctoral Position in Theoretical Astrophysics - JRID45794


Larger scale fields
Smaller scale fields



Vorticity magnitude

Larsson & Lele (2009)

Ambient ISM $e_{\mathrm{B,am}} \sim e_{\mathrm{turb,am}}$

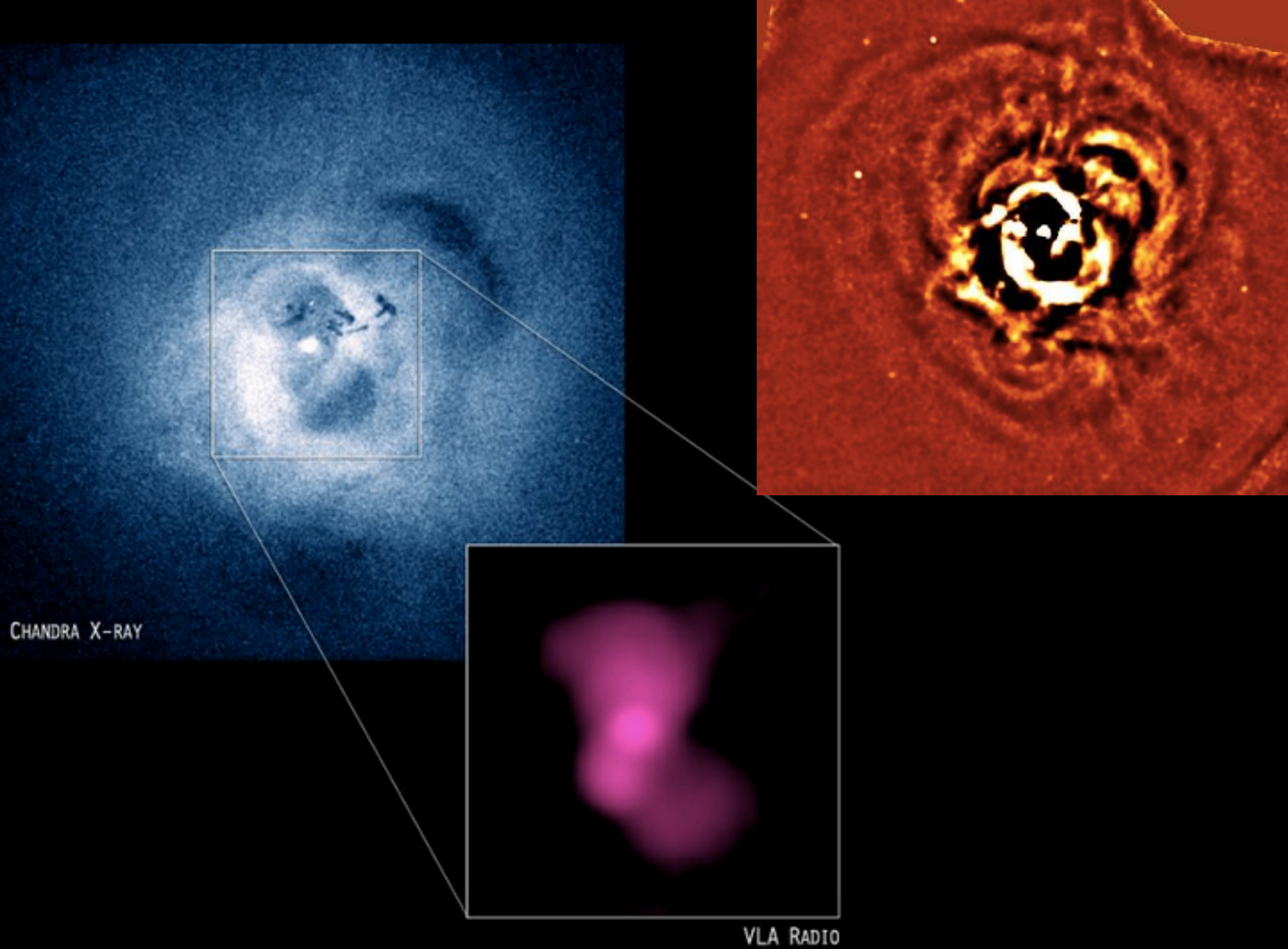
Shocked shell $e_{\mathrm{turb,sh}}$

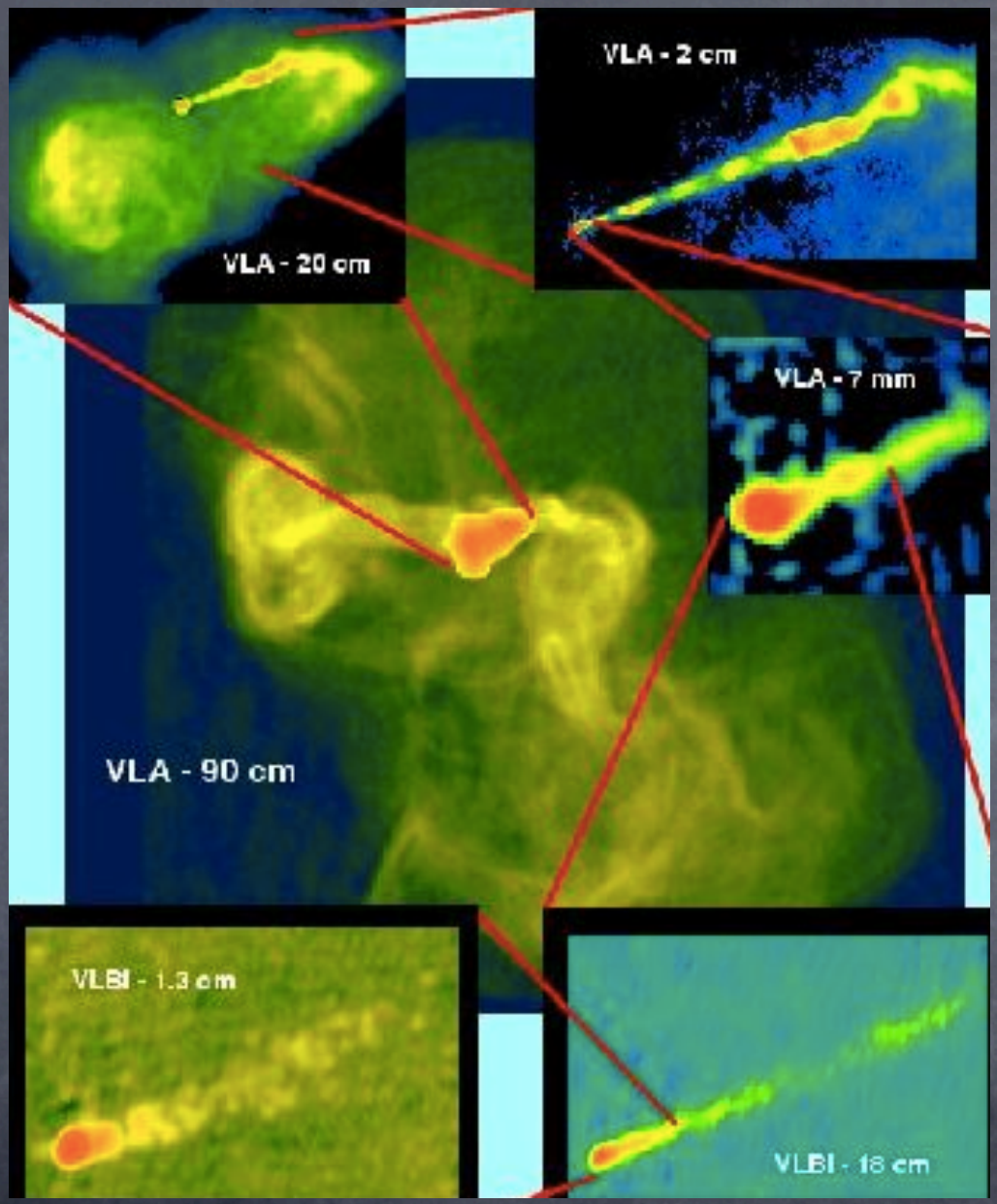
Bubble $e_{\mathrm{B,bub}} \sim e_{\mathrm{turb,bub}}$

$$e_{\mathrm{turb,bub}} \lesssim e_{\mathrm{turb,sh}} = 0.5\rho_{\mathrm{sh}}\sigma_{\mathrm{sh}}^2$$

$$0.5(r\rho_{\mathrm{amb}})(\alpha\sigma_{\mathrm{amb}}^2) = \alpha r e_{\mathrm{turb,amb}}$$

$$B_{bubb} \leq (\alpha r)^{1/2} B_{amb}$$

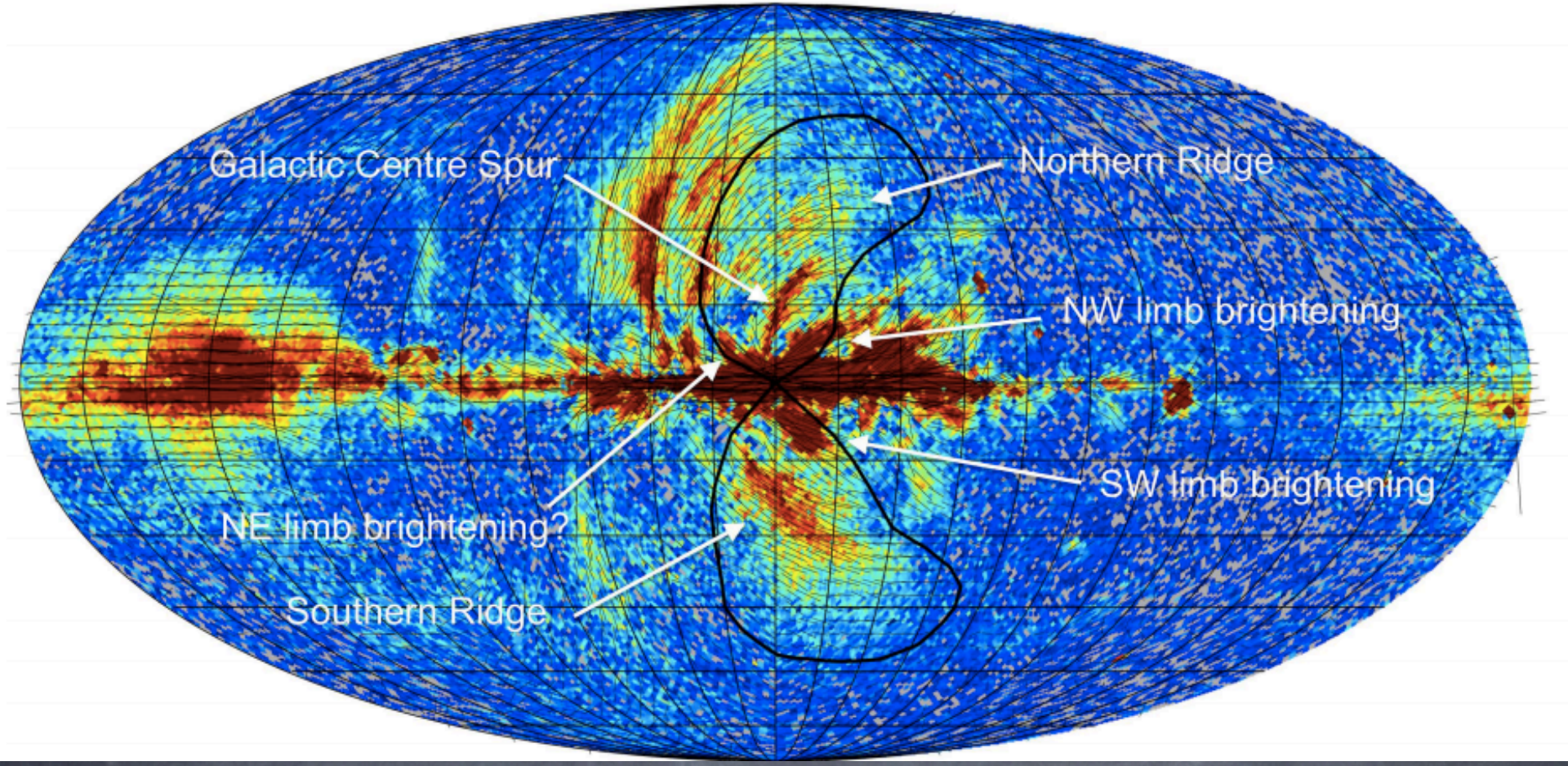

CHANDRA X-RAY
VLA RADIO

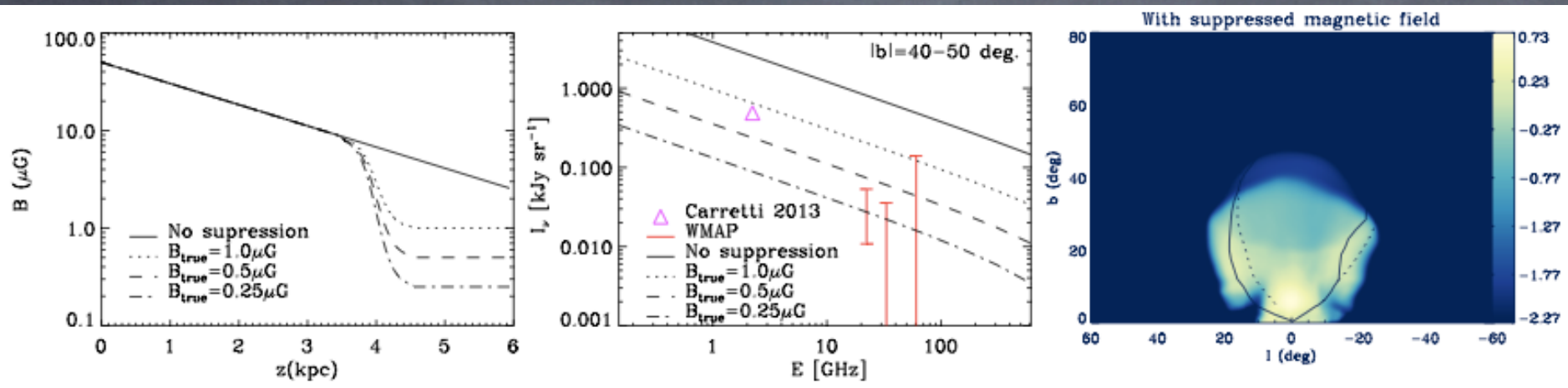


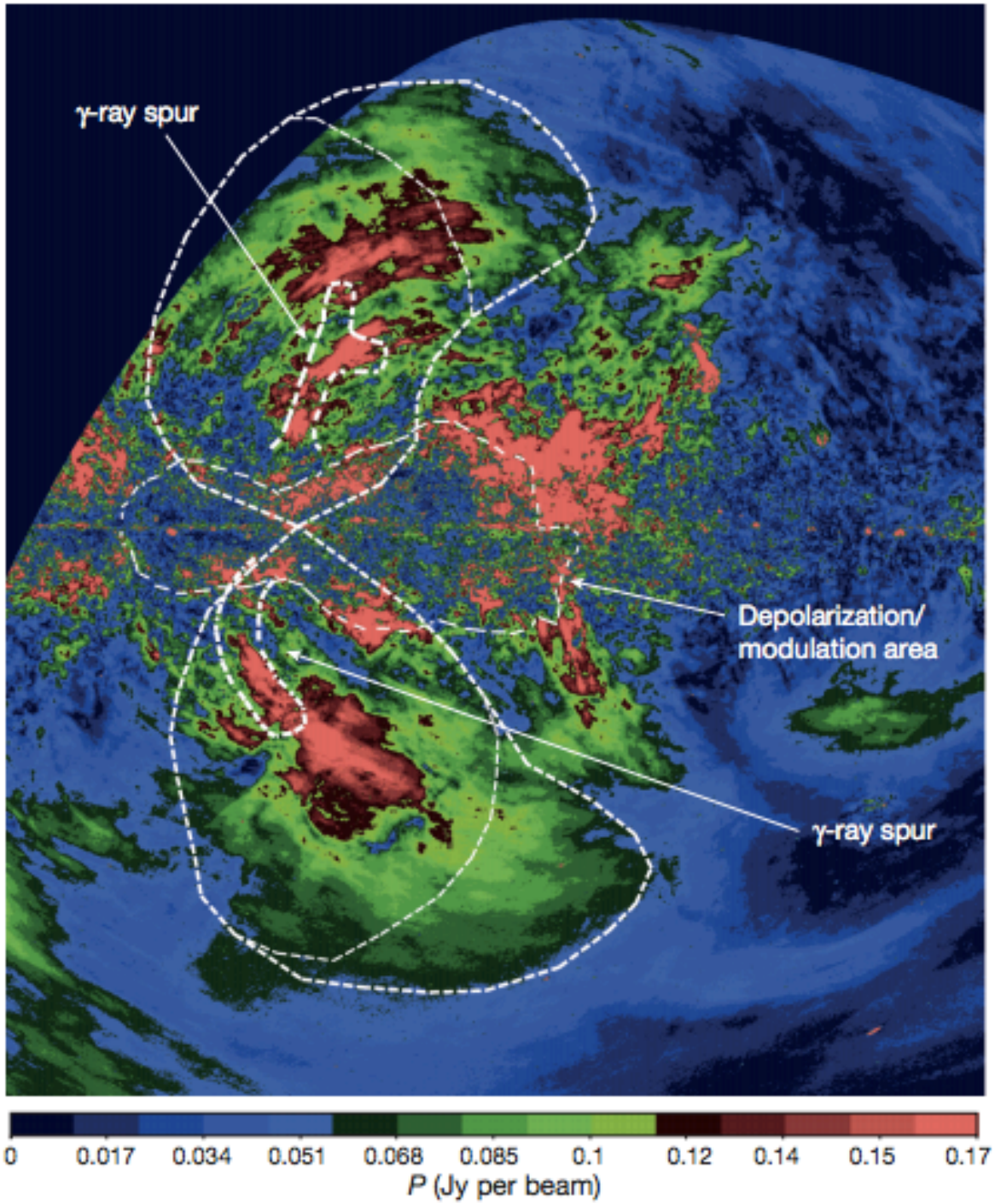
Owen (NRAO), Biretta (STScI)

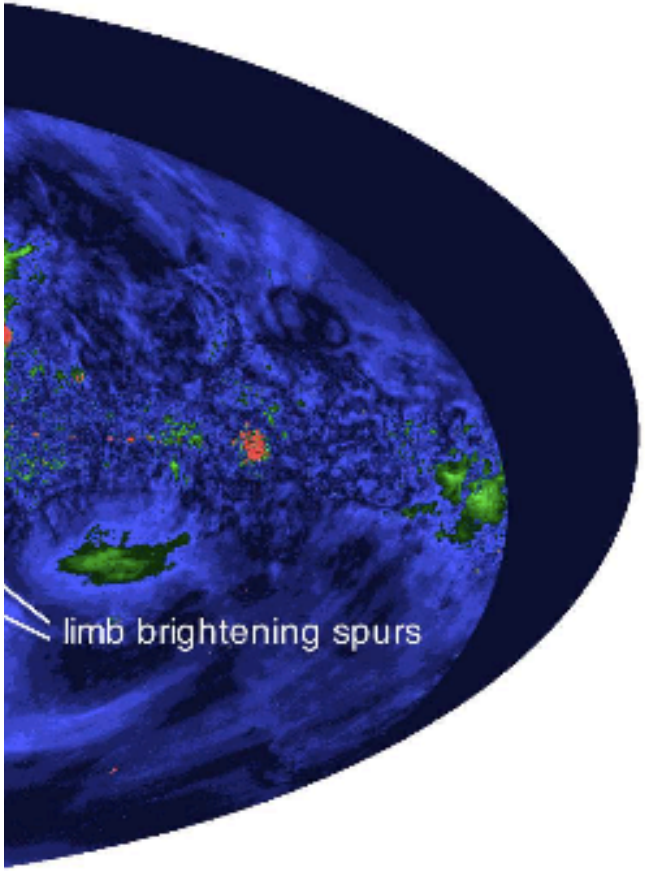
very early in the bubble evolution
only for the most energetic particles in the CR energy spectrum

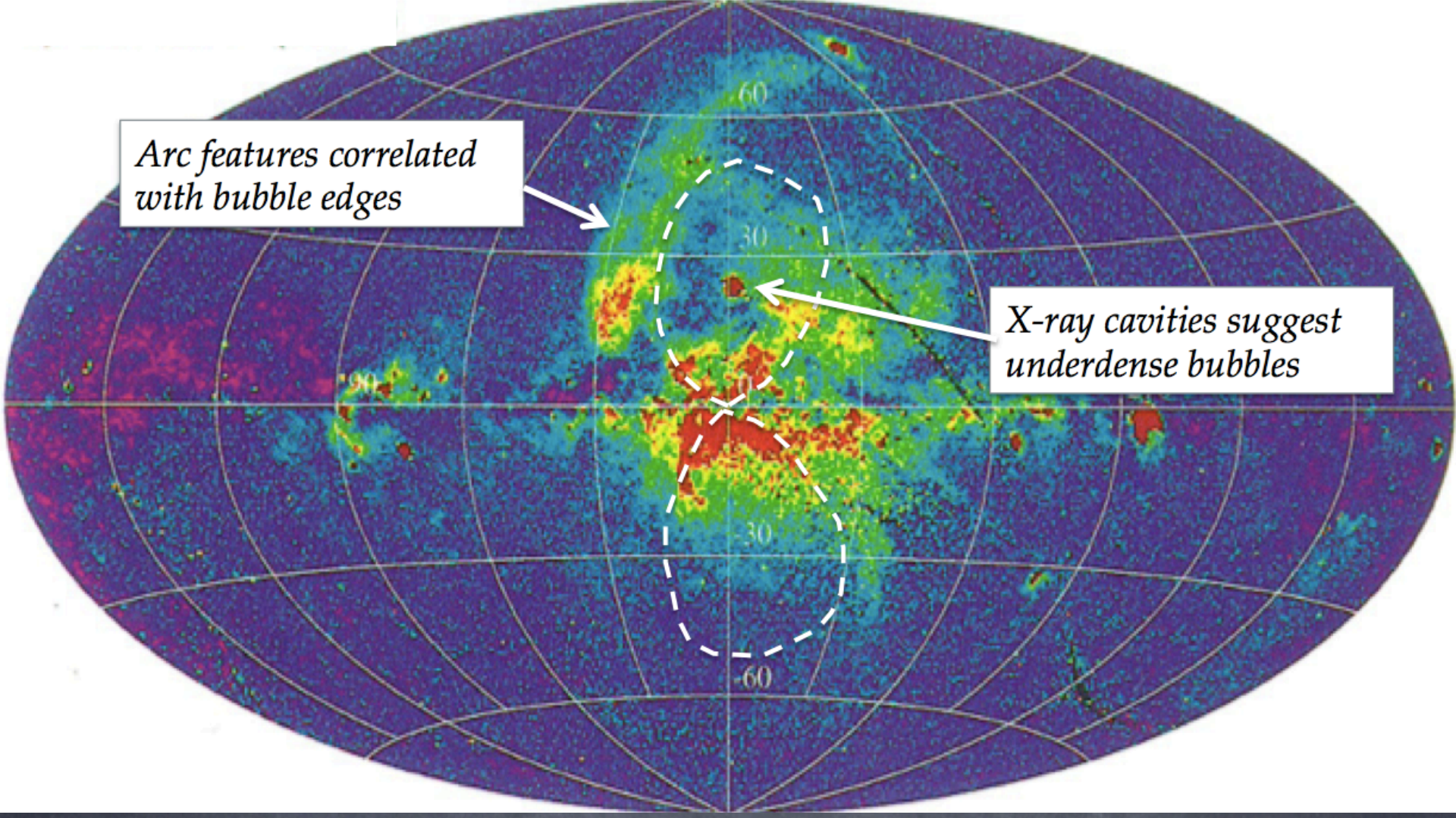
$$\min(t_{\mathrm{IC}}, t_{\mathrm{synch}}) > t_{dyn}$$ for $$t < 0.1\mathrm{Myr} << t_{\mathrm{Fermi}}$$


Galactic Centre Spur
Northern Ridge
NW limb brightening
SW limb brightening
NE limb brightening?
Southern Ridge


100.0
10.0
1.0
0.1
B (μG)
0
1
2
3
4
5
6
z(kpc)
No supression
B_true=1.0μG
B_true=0.5μG
B_true=0.25μG
|b|=40−50 deg.
1.000
0.100
0.010
0.001
I_ν [kJy sr^-1]
1
10
100
E [GHz]
Carretti 2013
WMAP
No suppression
B_true=1.0μG
B_true=0.5μG
B_true=0.25μG
With suppressed magnetic field
80
60
40
20
0
b (deg)
60
40
20
0
−20
−40
−60
l (deg)
0.73
0.23
−0.27
−0.77
−1.27
−1.77
−2.27


γ-ray spur
Depolarization/
modulation area
γ-ray spur
0
0.017
0.034
0.051
0.068
0.085
0.1
0.12
0.14
0.15
0.17
P (Jy per beam)


limb brightening spurs


Arc features correlated with bubble edges
X-ray cavities suggest underdense bubbles
60
30
-30
-60

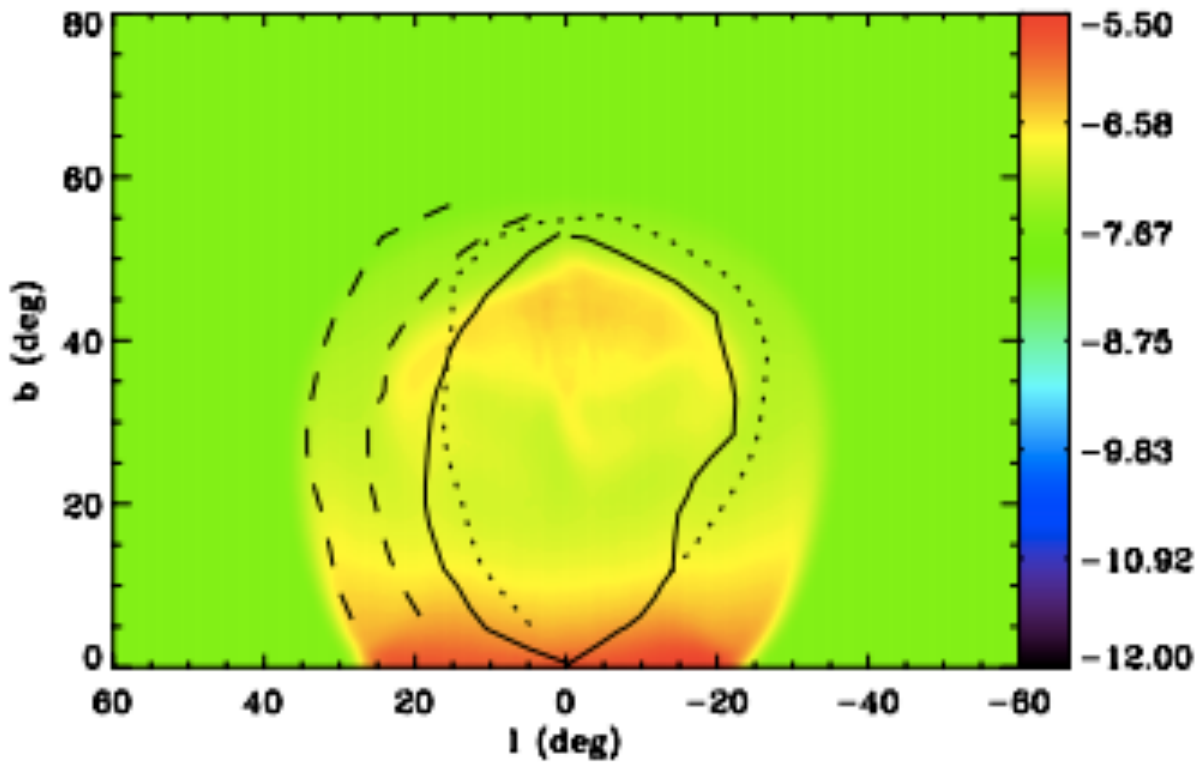


Figure 6. Simulated X-ray map at 1.5 keV (see the text for definition) for the same run as Figure 5. The solid and dotted lines show the surfaces of the observed northern and southern *Fermi* bubbles, respectively. The dashed lines are the inner and outer northern arcs observed by the *ROSAT* X-ray satellite.

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