Theoretical Modeling of the Fermi Bubbles

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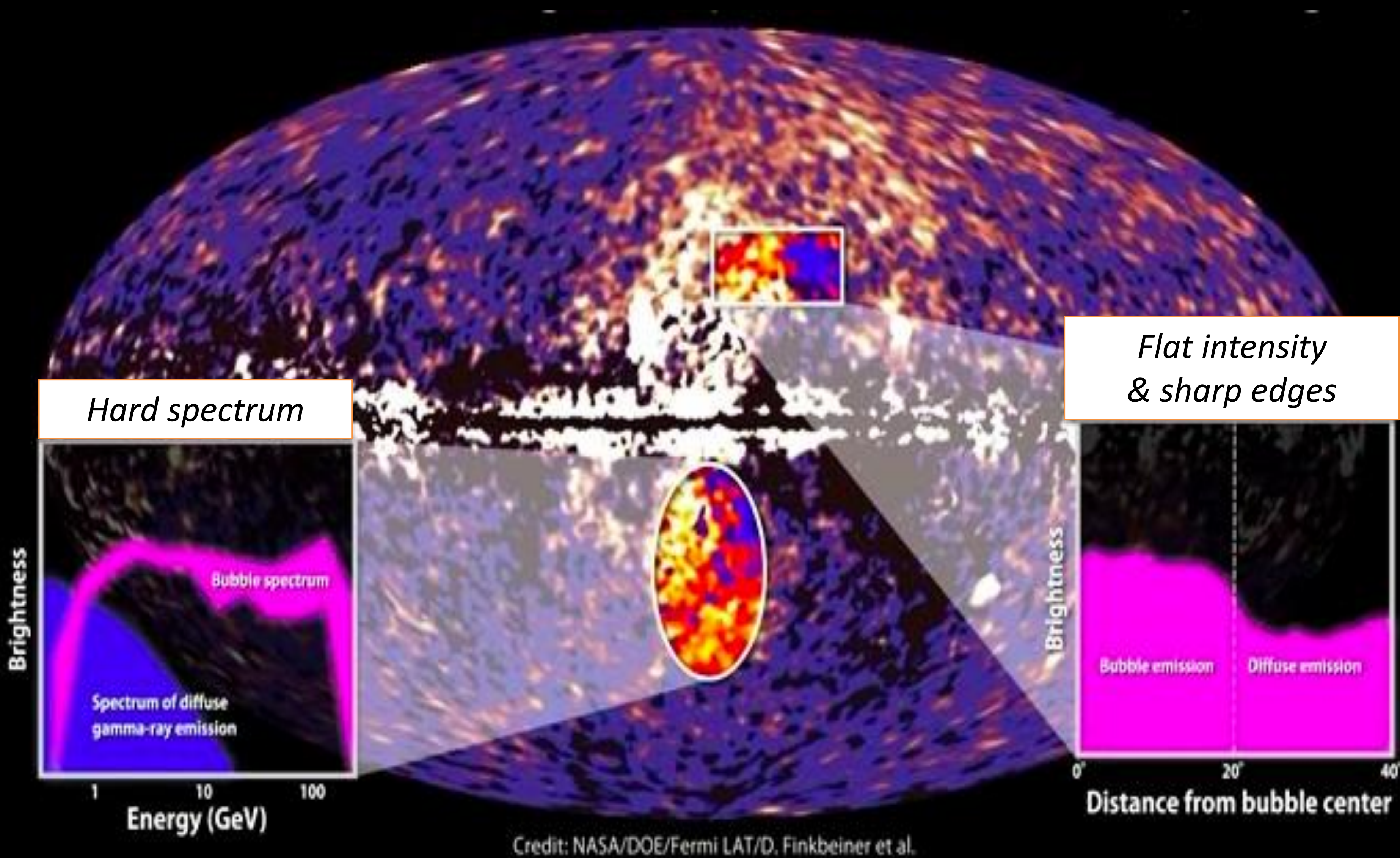
Three elephants in the gamma-ray sky
Oct. 23, 2017

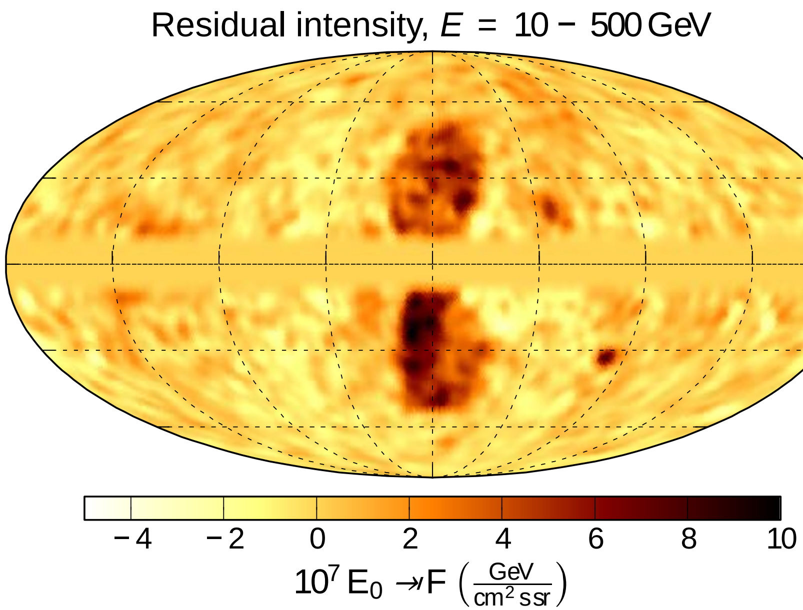
Observational Constraints
(see talks by Slatyer, Inoue and others)

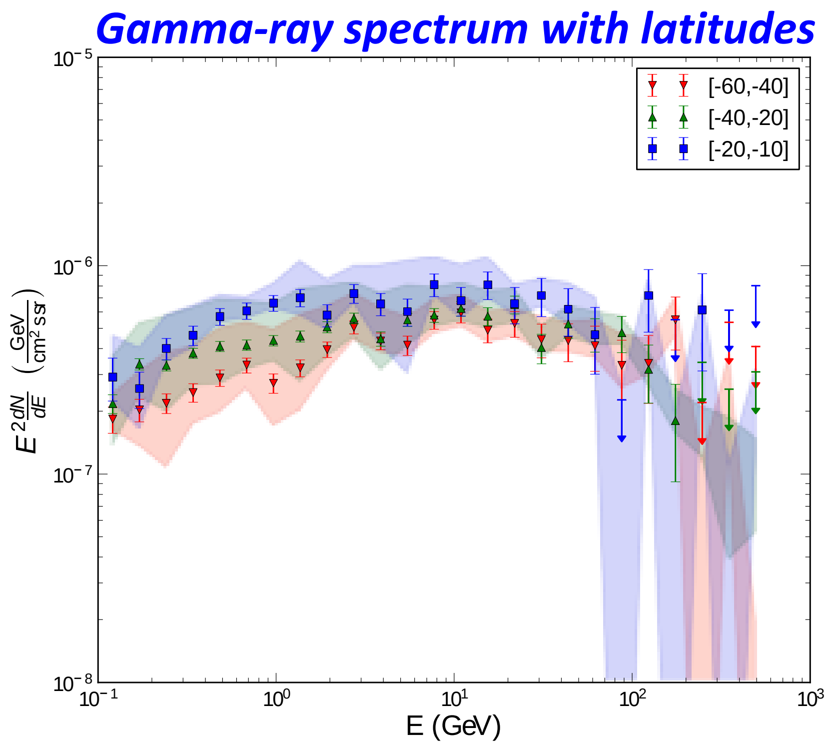
Gamma-ray bubbles by *Fermi* (Su+ 2010)



Gamma-ray bubbles by *Fermi – 50+ months*

(Ackermann+ 2014, see also Hooper & Slatyer 2013, Yang+ 2014, Narayanan & Slatyer 2016, Keshet & Gurwich 2016, 2017)

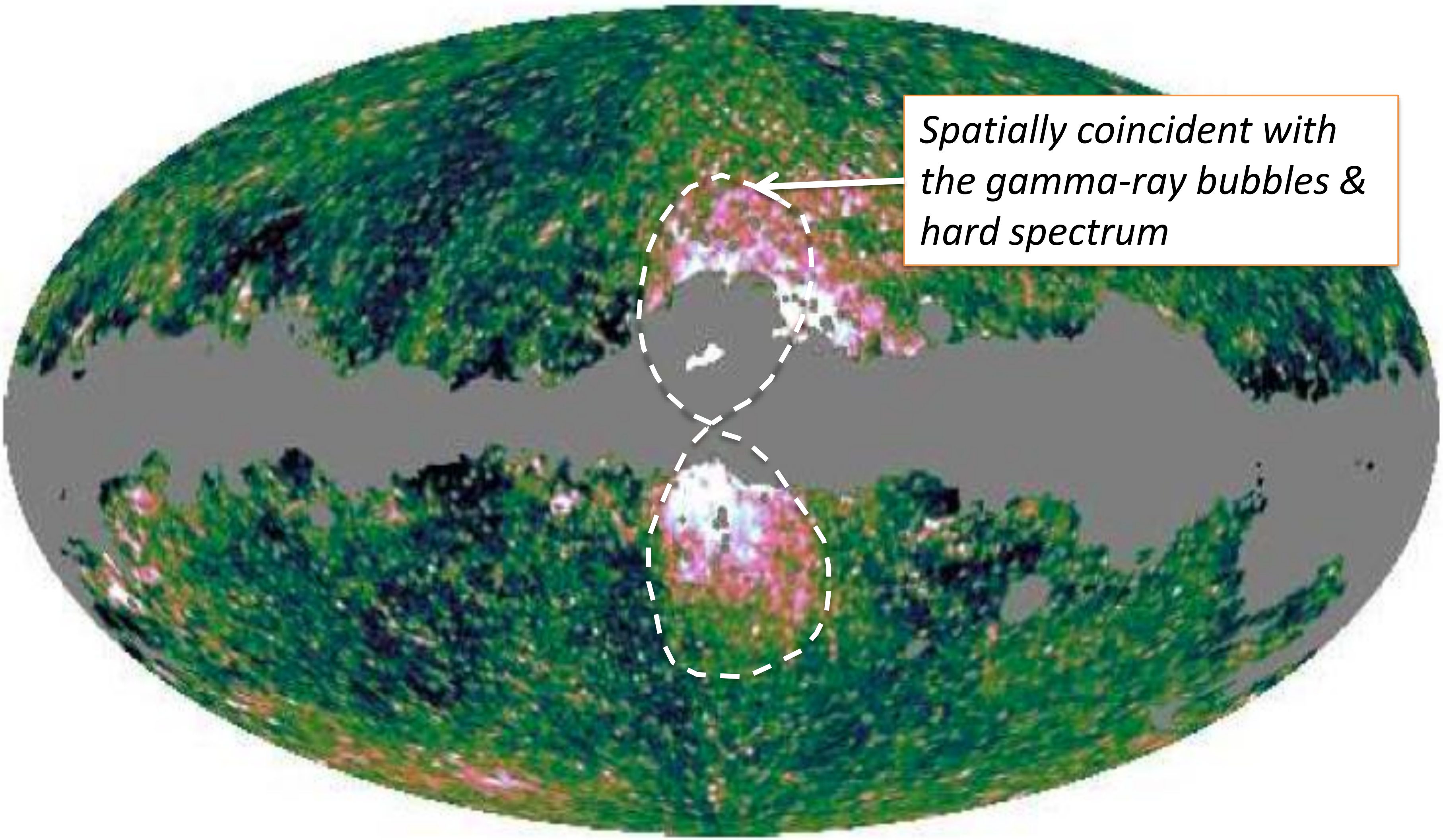




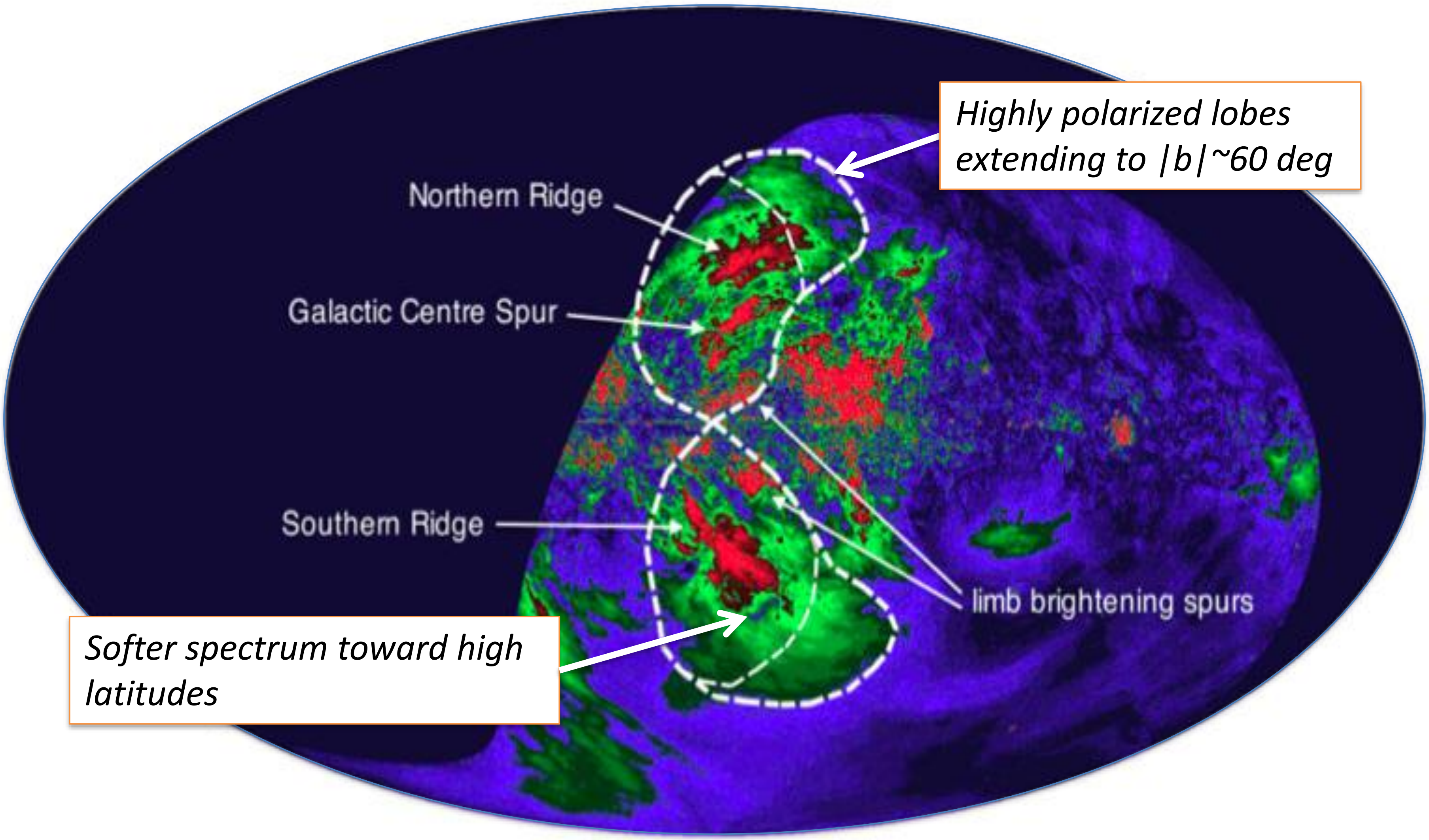
- Edge width ~ 3.4 deg
- Substructures: SE cocoon confirmed, no 2nd jet
- Spatially uniform hard spectrum
- High-E cutoff at ~110 GeV

Microwave haze by *WMAP & Planck*

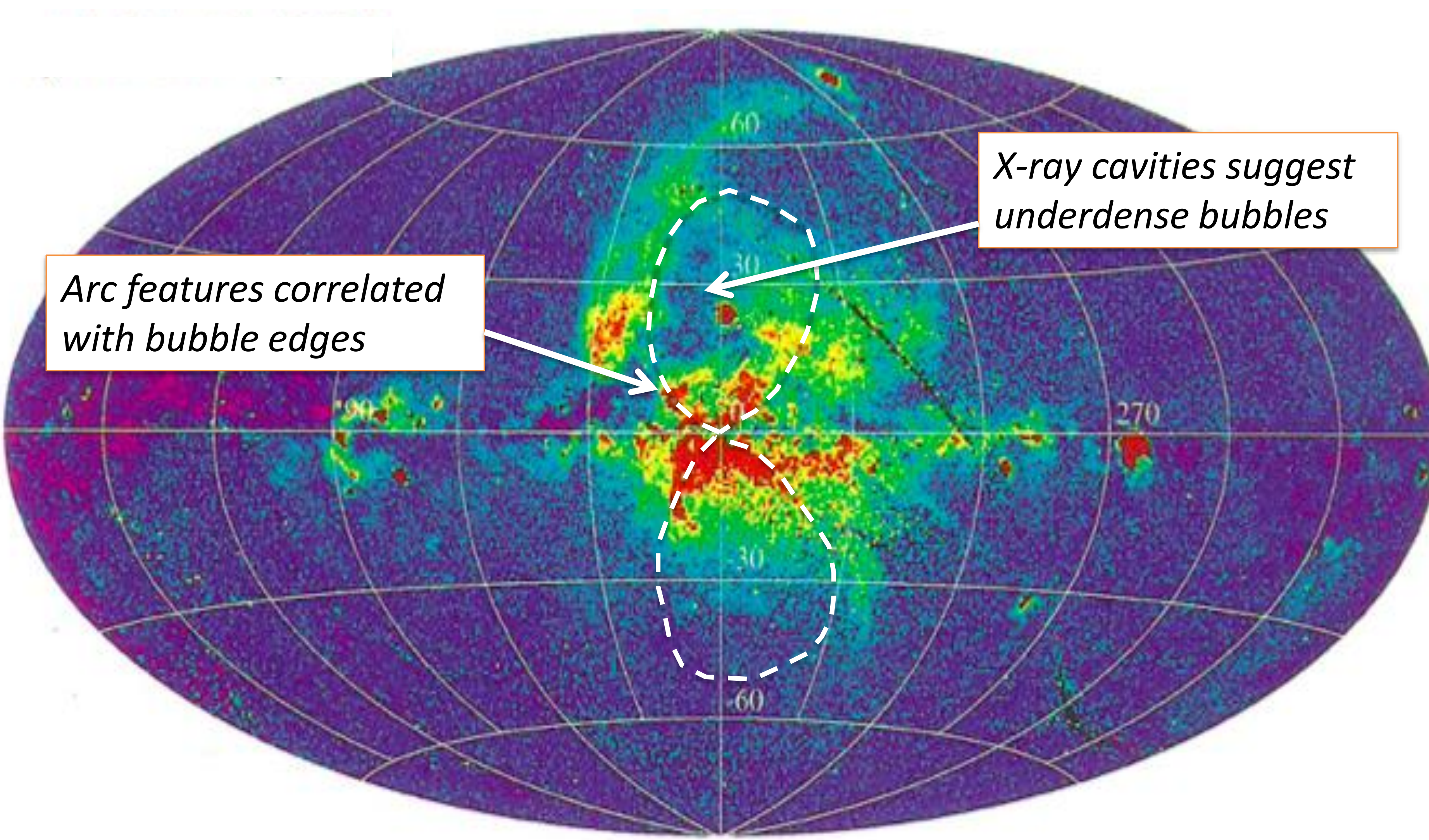
(Finkbeiner 2004, Dobler+ 2008; Planck Collaboration 2012)



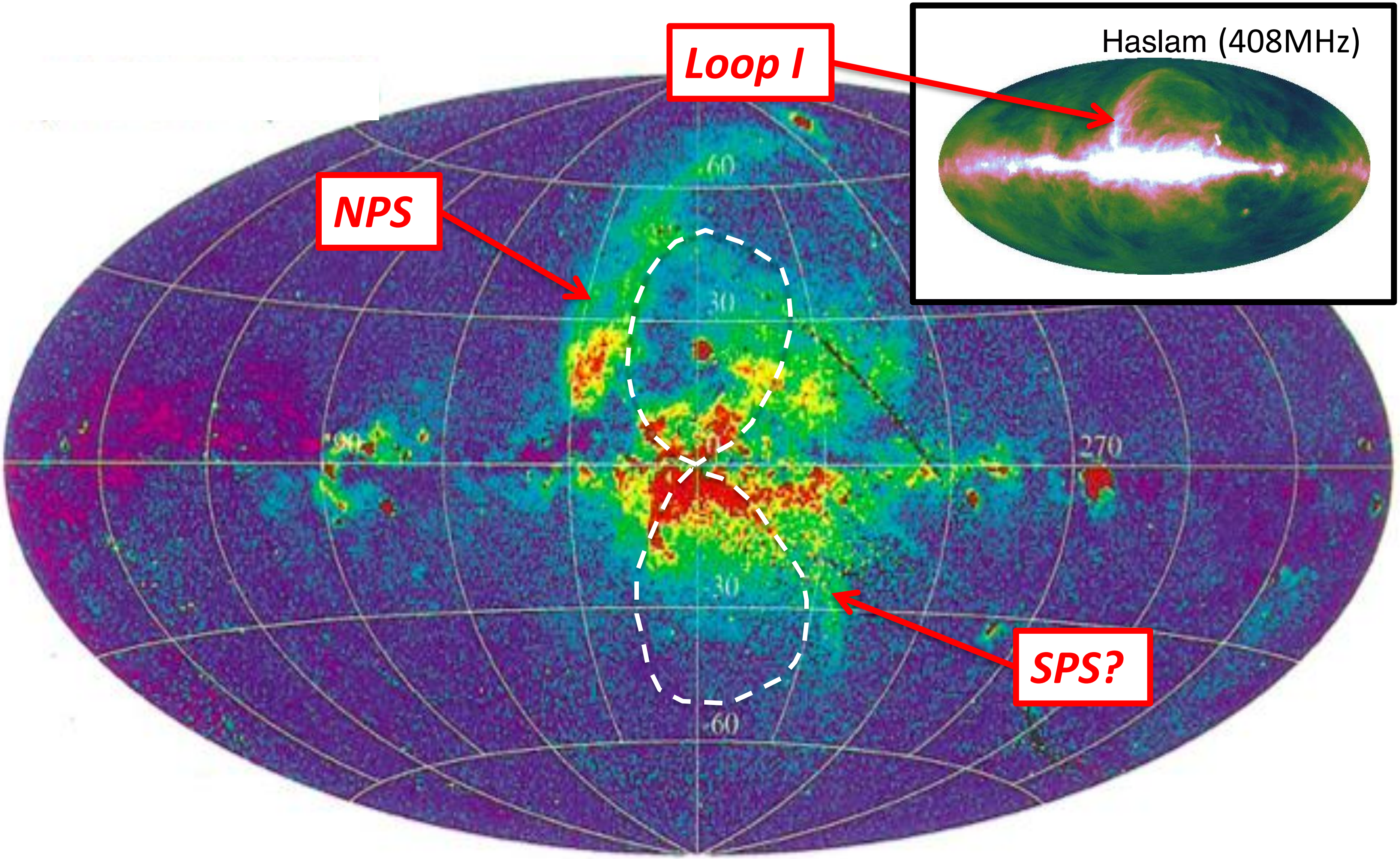
Polarized lobes at 2.3 GHz by *S-PASS* (Carretti+ 2013)



X-ray map by *ROSAT* (Snowden+ 1997, see talk by Shchekinov)



X-ray map by *ROSAT* (Snowden+ 1997, see talk by Shchekinov)



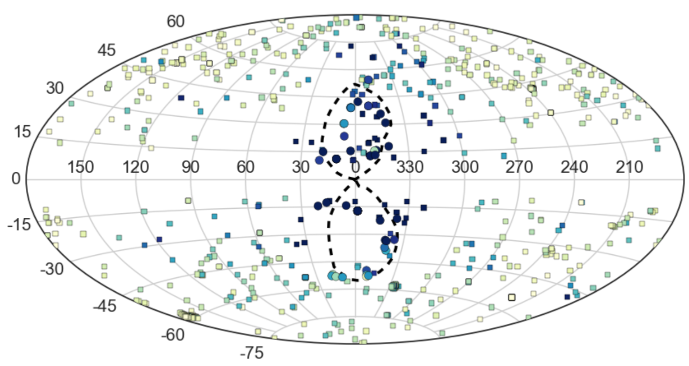
Kinematics of halo gas by *X-ray and UV studies*

v ~ 200 - 300 km/s:

- X-ray temperature (Kataoka+ 2013)
- Line broadening along 3C 273 (Fang+ 2014)
- OVIII/OVII ratio (Sarkar+ 2016)

v >~ 500 - 1300 km/s:

- UV line shifts (Fox+ 2015, Bordoloi+ 2017)
- OVIII/OVII ratio (Miller & Bregman 2016)

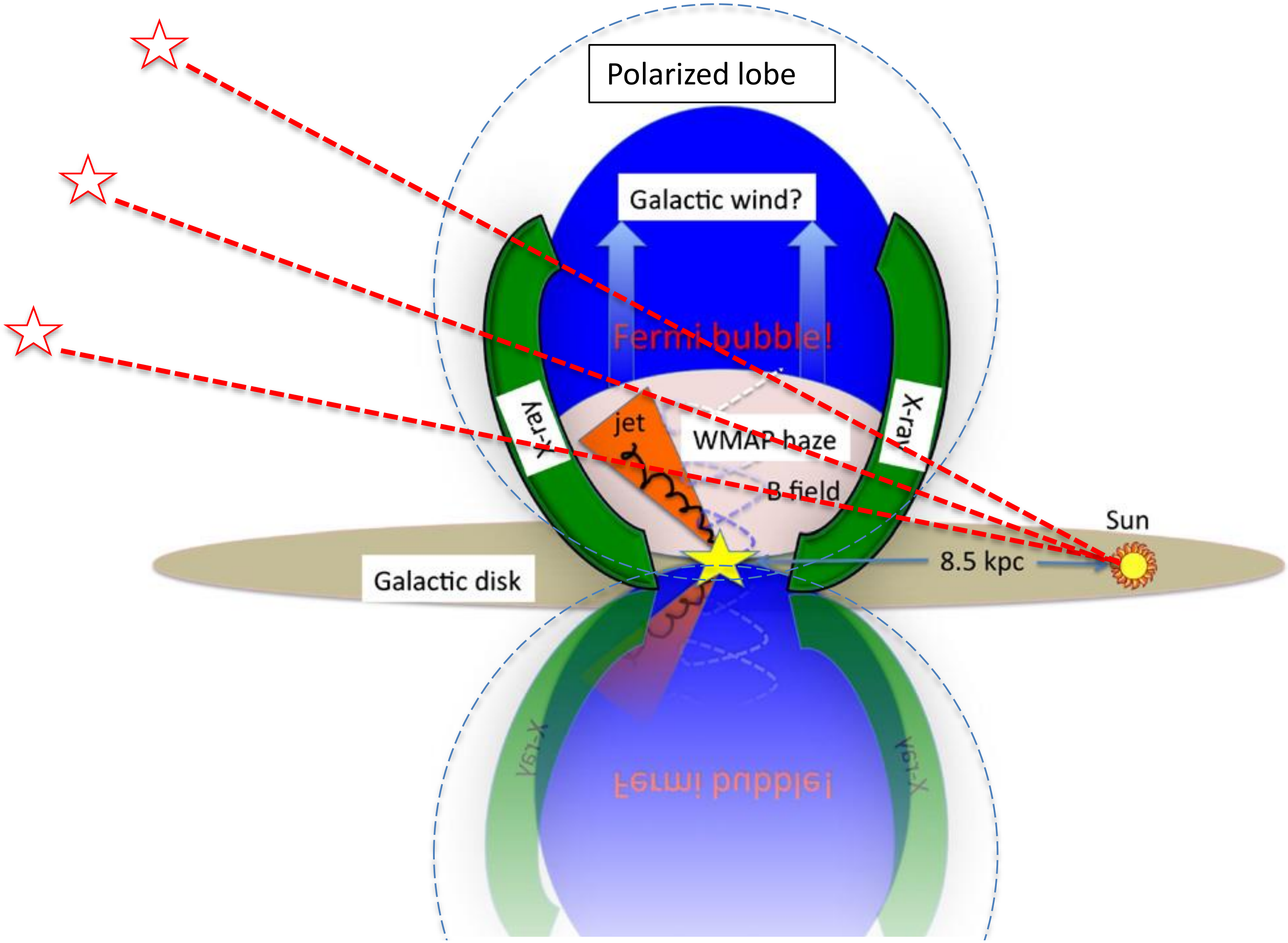


Miller & Bregman 2016

Things to caution:

- ***Structure of Galactic halo is complex (Kataoka+ 2015)***
- ***Confusion/misinterpretation due to foreground/background projections***
- ***Assumptions about outflow geometry and injection patterns***
- ***Short timescale for e-p equilibration***
- ***X-ray and UV probe different phases of the halo gas***

A schematic view



Blind men’s perceptions of an elephant

Any theoretical model has to be tested against ALL observed data!!!

Origin?

What is the origin of the bubbles?

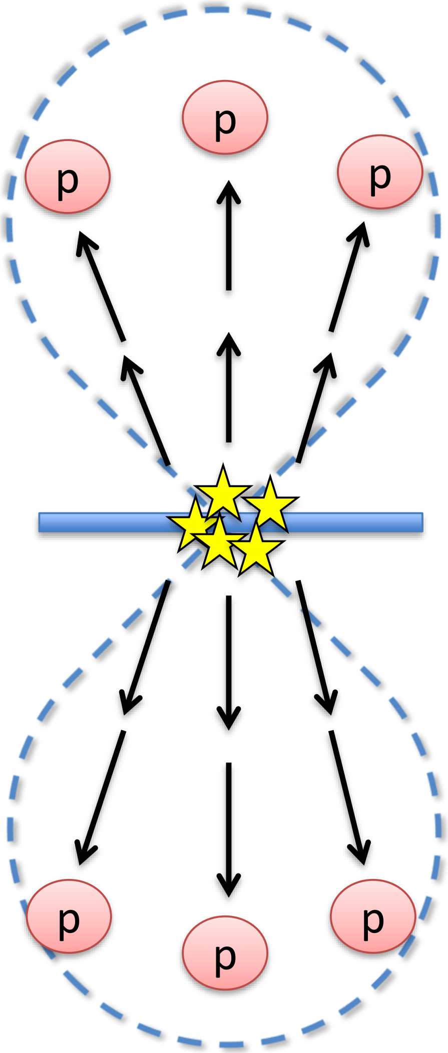
- ***What are the emission mechanisms?***
- Leptonic (CRe)
- Hadronic (CRp)

- ***What activity at the GC triggers the event?***
- Nuclear star formation (NSF)
- Active galactic nucleus (AGN)

- ***Where are the CRs produced?***
- Transported from GC (jets or winds)
- In-situ acceleration (shocks or turbulence)

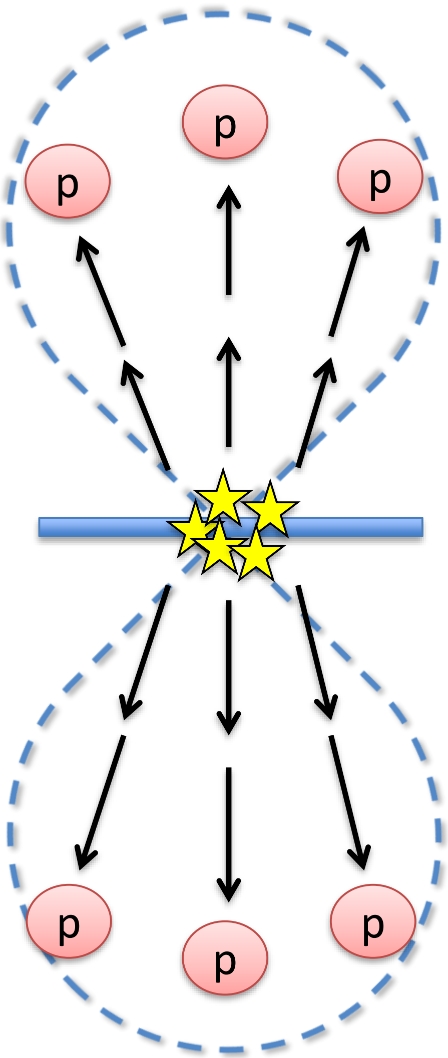
Theoretical Models

I. Hadronic winds

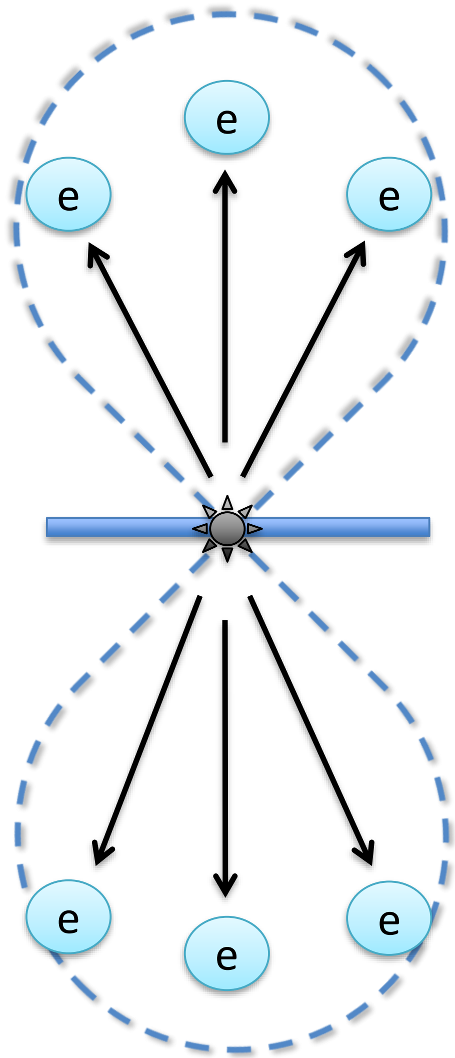


Theoretical Models

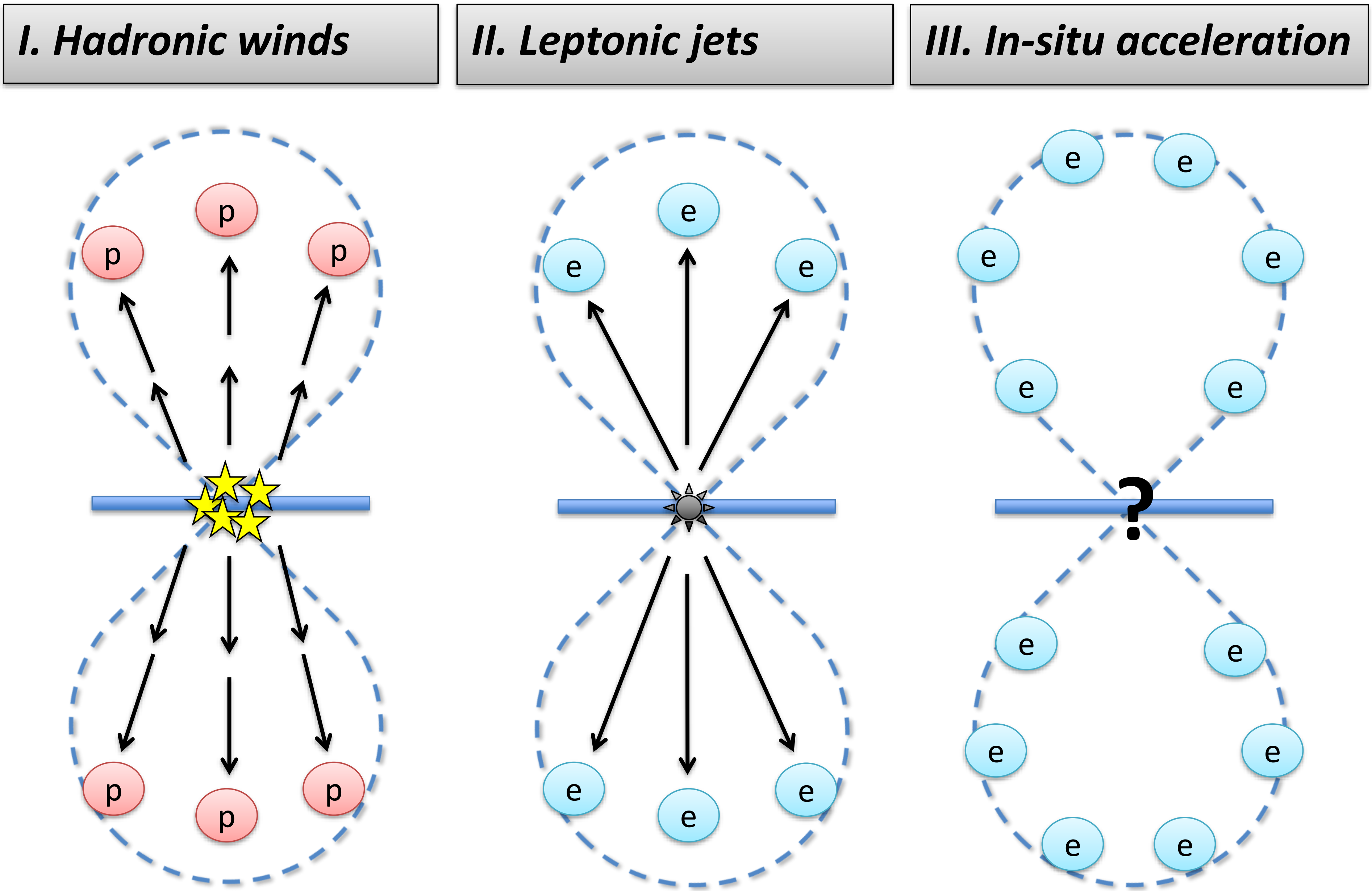
I. Hadronic winds



II. Leptonic jets

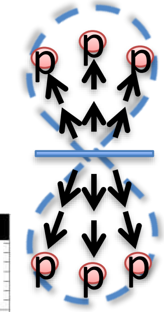


Theoretical Models



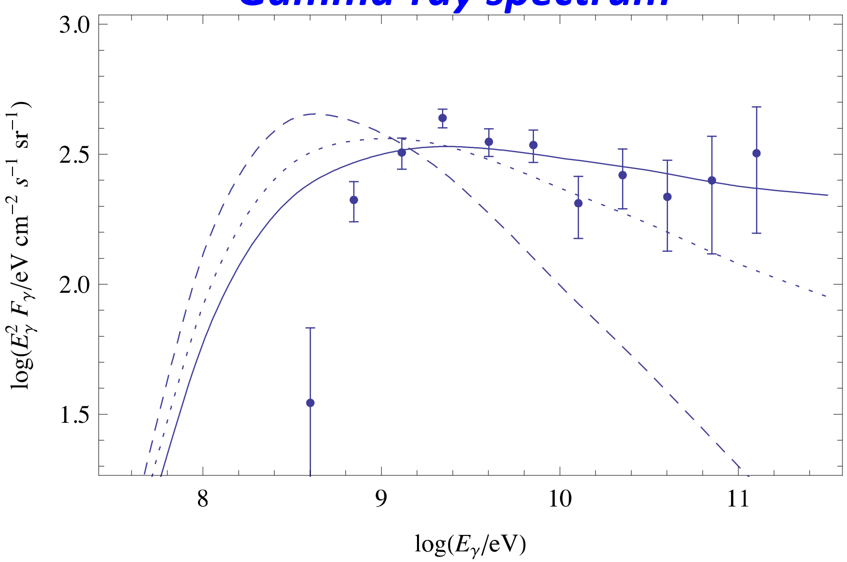
I. *Hadronic wind* models

(Crocker+ 2011, 2013, 2015, Thoudam+ 2013, Mou+ 2014, 2015, Cheng+ 2015)



- Wind speed ~ hundreds to 10^3 km/s
- Collimation by CMZ
- Event: NSF (Crocker+) or AGN winds (Mou+)

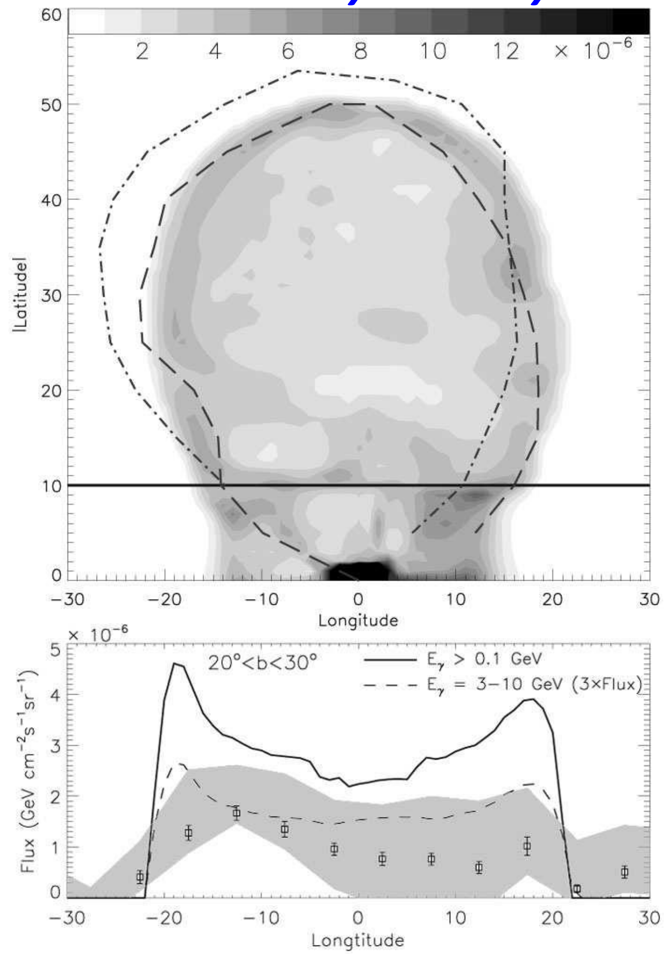
Gamma-ray spectrum



Mass injection rate ~ 0.1 Msun/yr

Steady state, t > few x 100 Myr (Crocker+)

Gamma-ray intensity



Eddington ratio ~ 1%

Transient, t ~ 10 Myr (Mou+ 2015)

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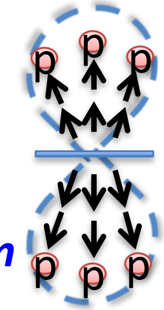
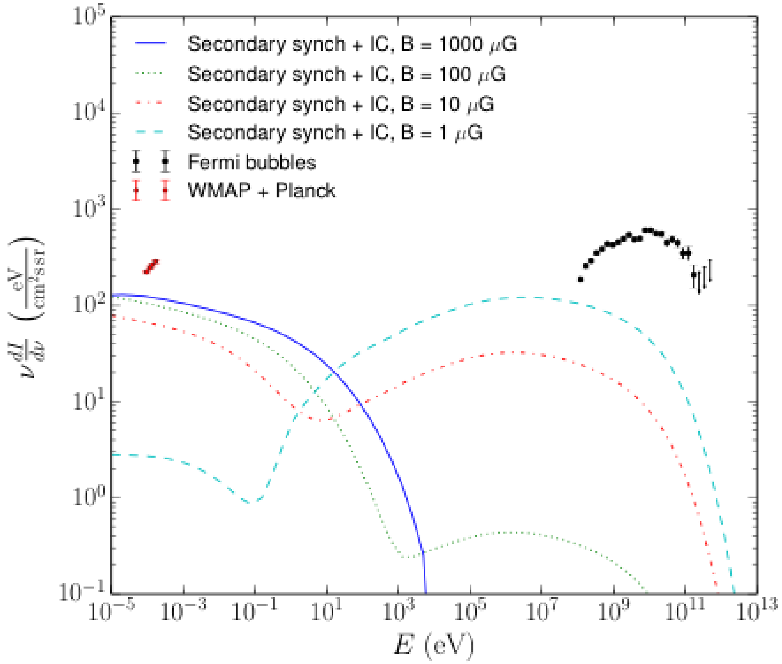
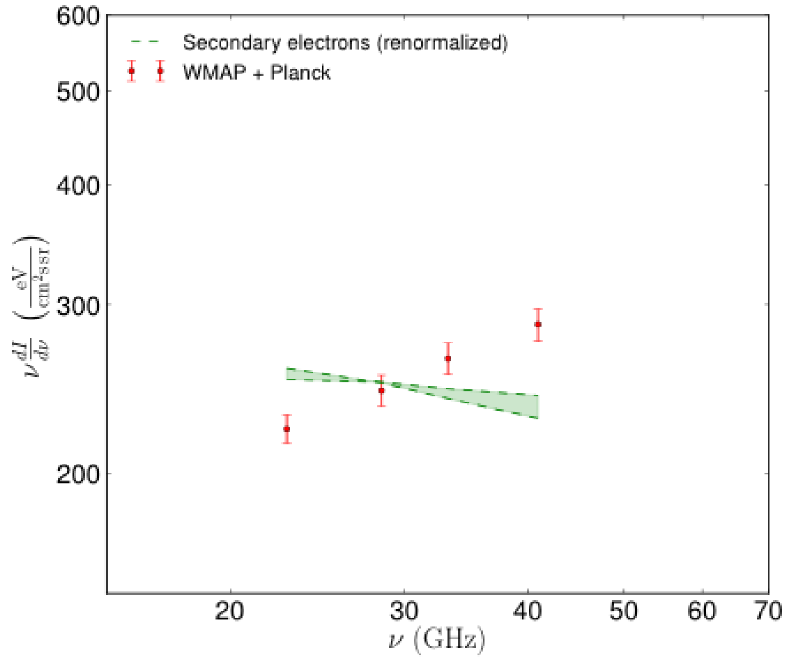
(Crocker+ 2011, 2013, 2015, Thoudam+ 2013, Mou+ 2014, 2015, Cheng+ 2015)



Gamma-ray and microwave spectrum



Renormalized microwave spectrum

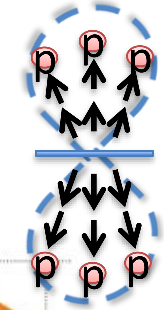


Ackermann+ 2014

- ➢ Secondary leptons fail to reproduce microwave haze
- ➢ Require another population of primary CRe

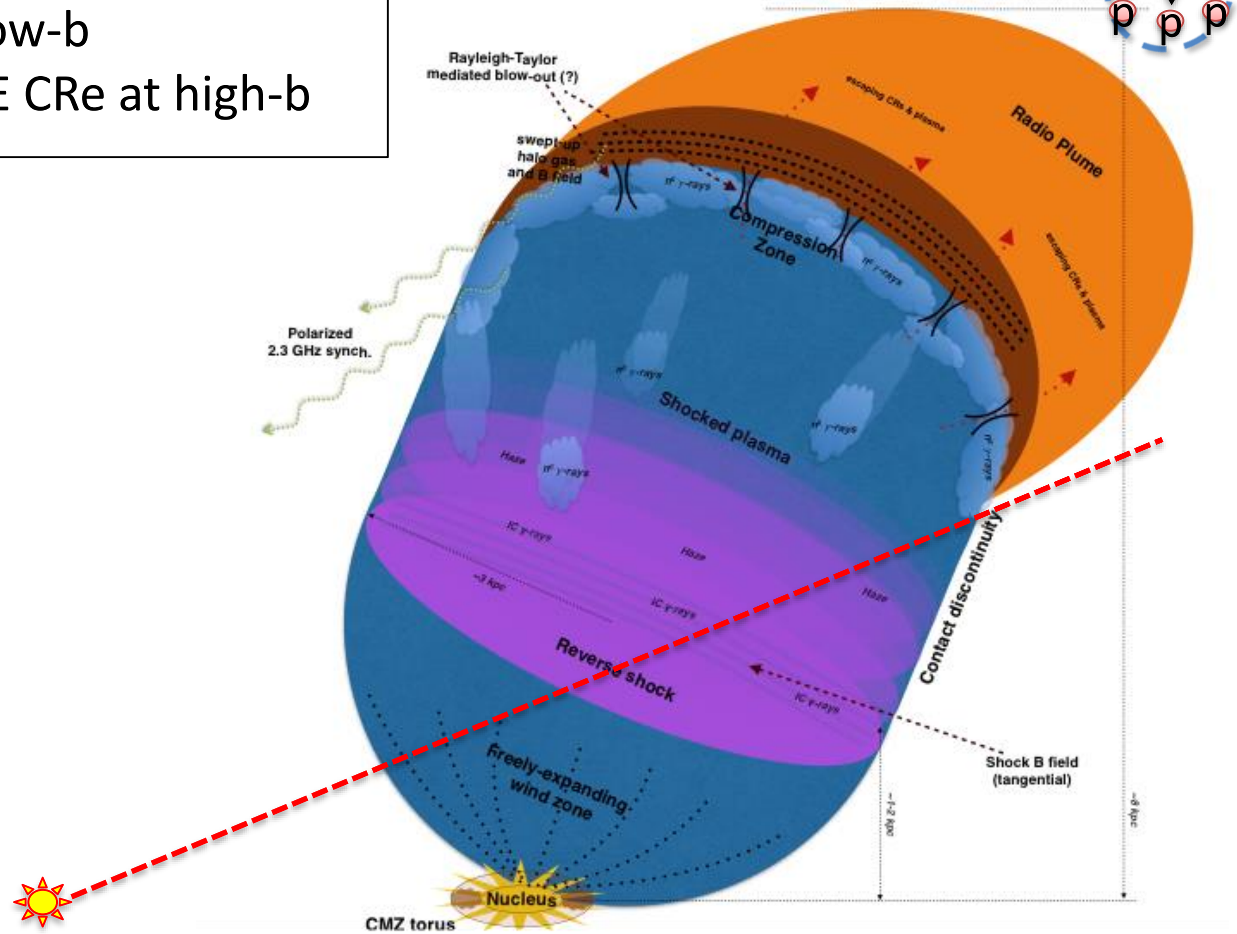
I. *Hadronic wind* models

(Crocker+ 2011, 2013, 2015, Thoudam+ 2013, Mou+ 2014, 2015, Cheng+ 2015)



- Giant reverse shocks supply primary CRe
- Haze by high-E CRe at low-b
- Polarized lobes by low-E CRe at high-b

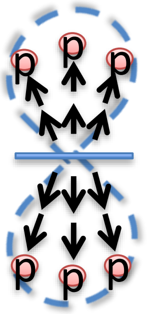
Projections?



Crocker+ 2015

I. ***Purely hadronic*** *wind* models

(Crocker+ 2011, 2013, Thoudam+ 2013, Mou+ 2014, 2015, Cheng+ 2015)



- Hard spectrum is naturally preserved

- Microwave haze is nontrivial to reproduce

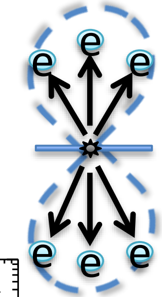
Hybrid *wind* model (Crocker+ 2015)

- Gamma-ray bubbles, microwave haze, and polarized lobes explained

- Effects of LOS projections
- High-E cutoff not typically expected

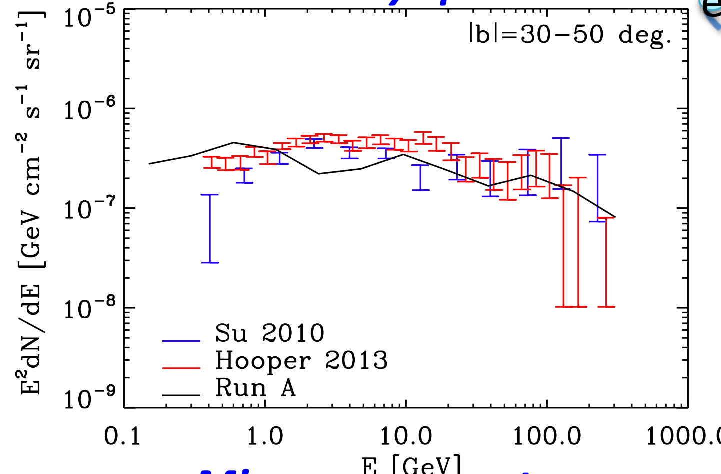
II. *Leptonic jet* models

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

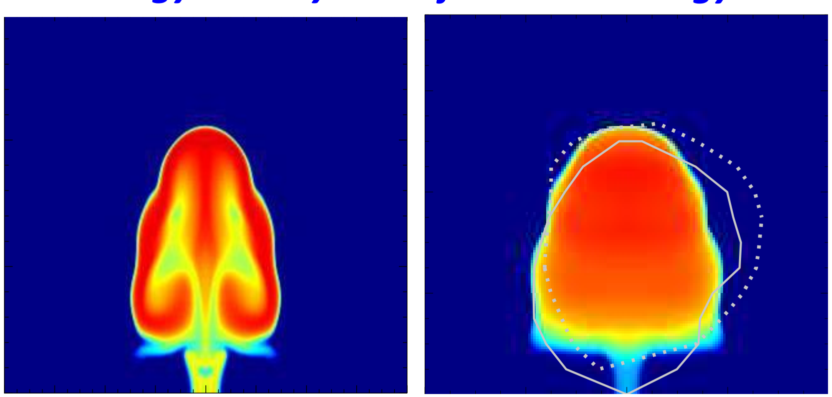


- AGN jets of speed ~thousands to 10^4 km/s
- Bubble ages <~few Myr
- Bubble and haze produced by same CRe

Gamma-ray spectrum

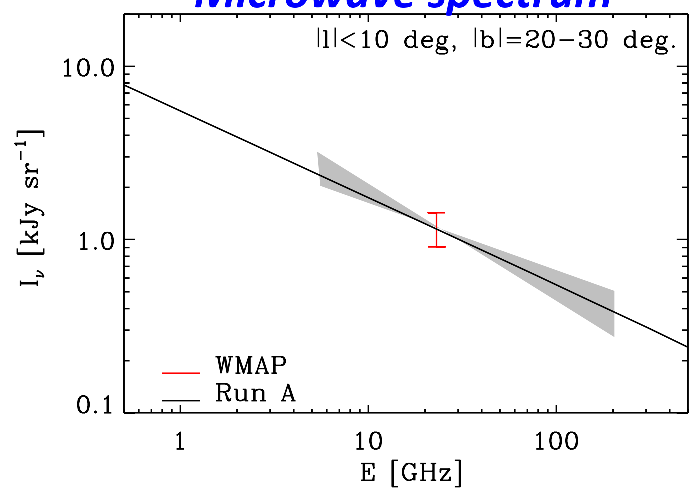


CR energy density ***Projected CR energy density***



2D hydro (Guo+ 2012)

Microwave spectrum



3D MHD (KY+ 2013)

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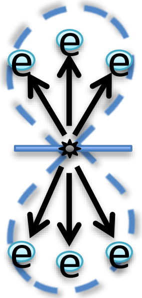
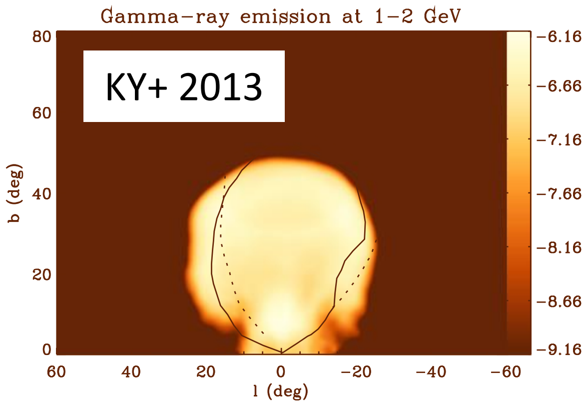
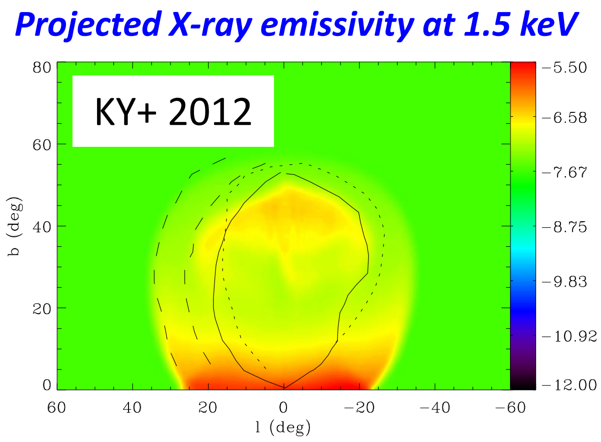
(Guo+ 2011, 2012, KY+ 2012, 2013, 2017, Barkov+ 2013)



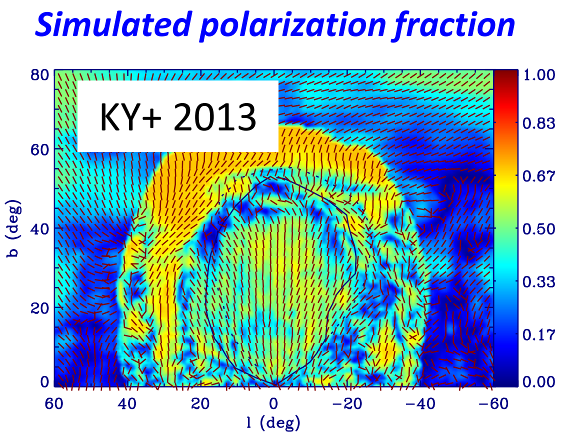
- Consistent with gamma-ray, X-ray, and polarization properties



- ✓ Morphology
- ✓ Smooth surface
- ✓ Flat intensity
- ✓ Sharp edges



- ✓ Shock location coincident with NPS



- ✓ High polarization fractions

II. *Leptonic jet* models

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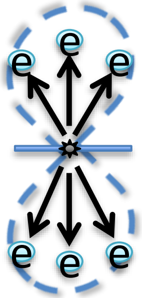
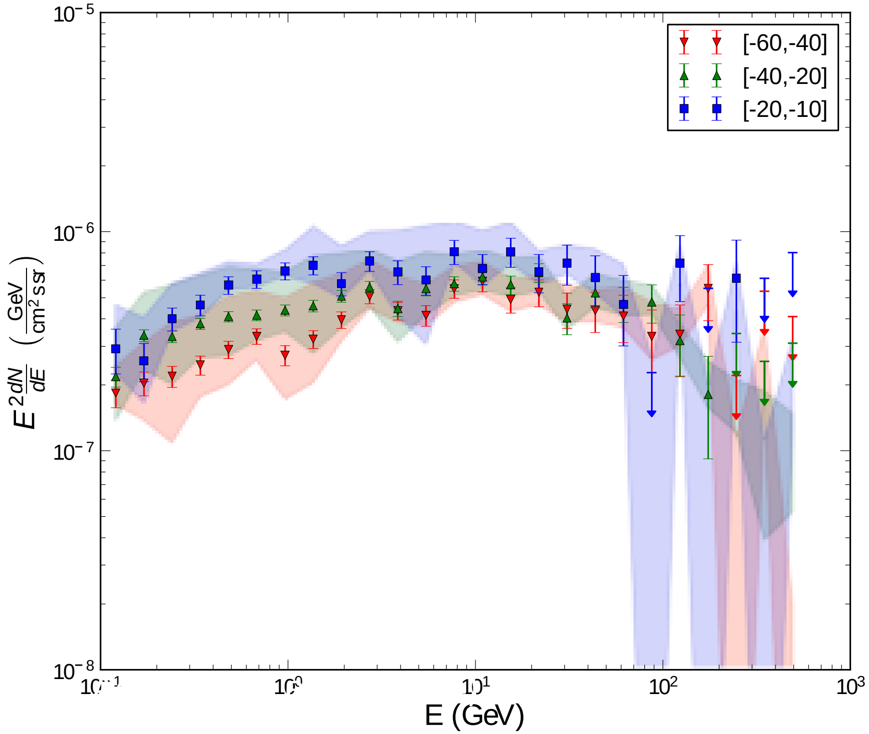


Why is the gamma-ray spectrum so spatially uniform?

Gamma-ray spectrum of the south bubble



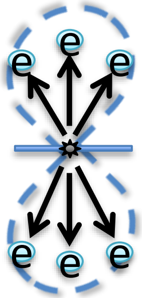
- Amplitude (flat intensity)?
- Overall shape is uniform?

$$\langle E_\gamma \rangle = (4/3)\gamma^2 \langle E_{\rm ph} \rangle.$$

- High energy cutoff ~ 110 GeV?

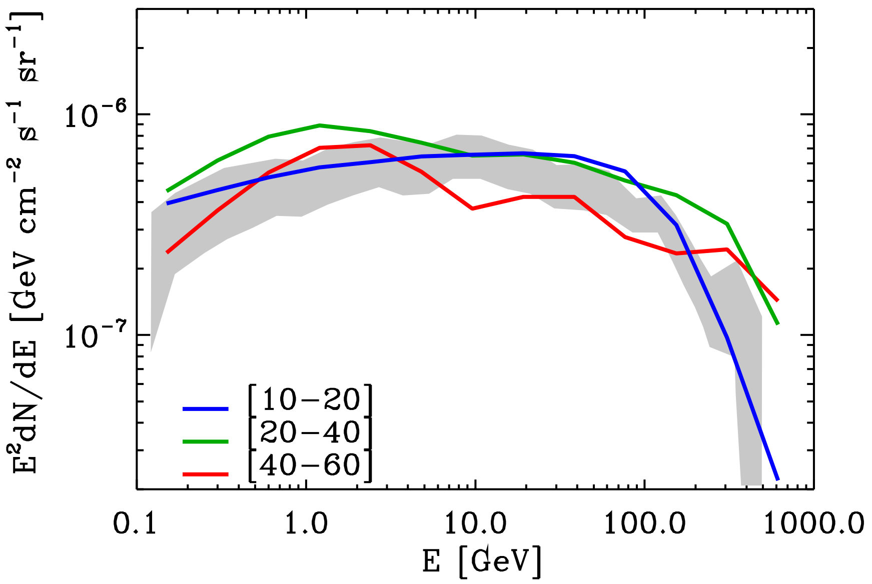
II. *Leptonic jet* models

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



- Spatially uniform spectra reproduced (KY & Ruszkowski 2017)

Simulated gamma-ray spectra



II. *Leptonic jet* models

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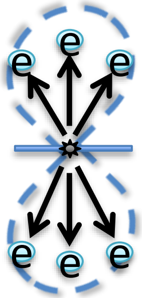

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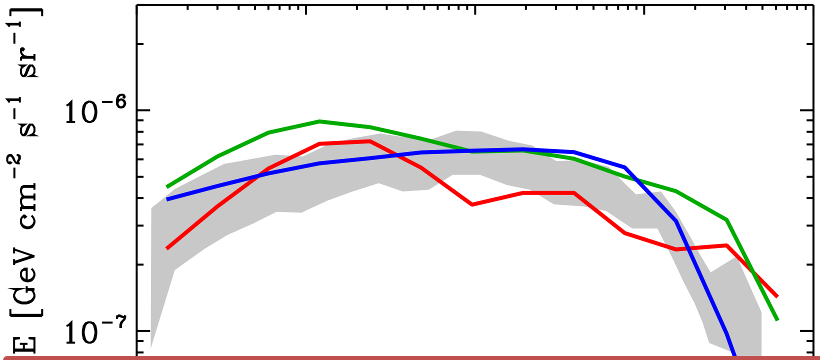
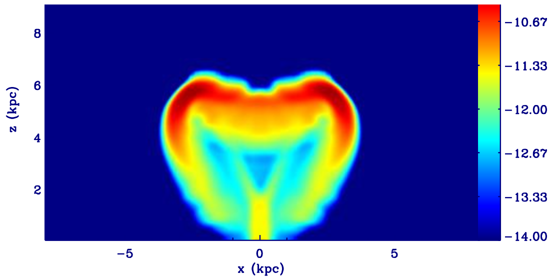


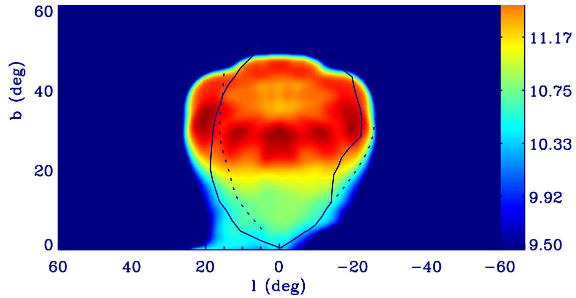
- ***Amplitudes (flat intensity):***
3D edge-brightened CR distribution from jet compression

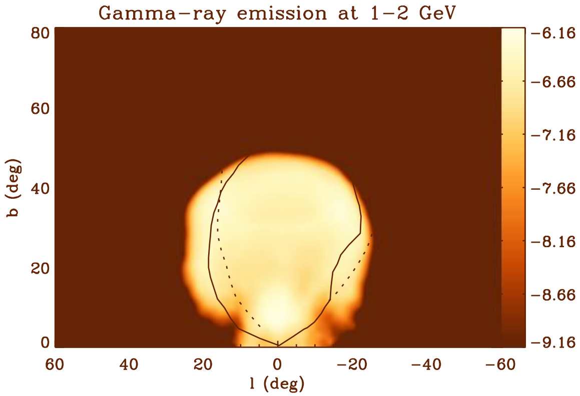
Slice of CR energy density



KY+ 2012

Projected CR energy density

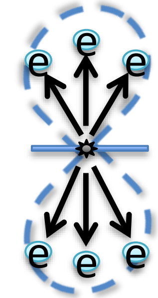




KY+ 2013

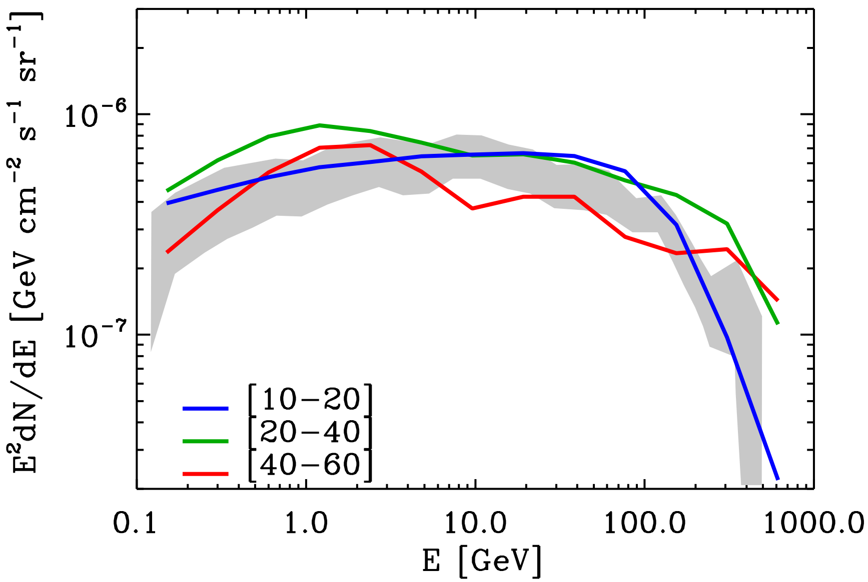
II. *Leptonic jet* models

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



- Spatially uniform spectra reproduced (KY & Ruszkowski 2017)

Simulated gamma-ray spectra

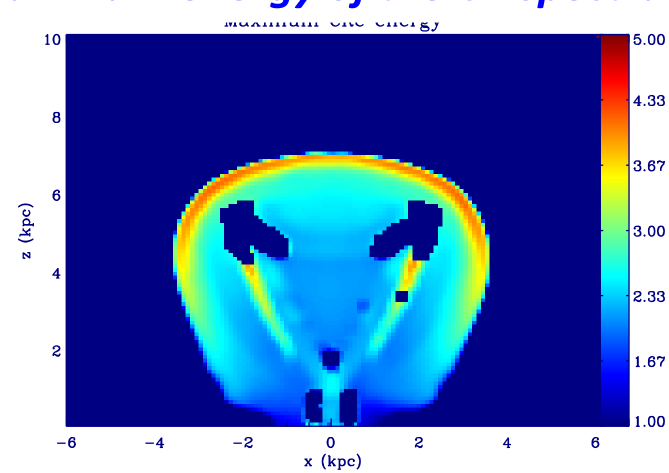


Recall: $\langle E_\gamma \rangle = (4/3)\gamma^2 \langle E_{\rm ph} \rangle.$

- ***Overall shape:***

Slight gradient of Emax compensates for gradient in Eph

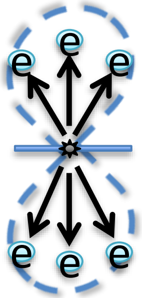
Maximum energy of the CR spectrum



KY & Ruszkowski 2017

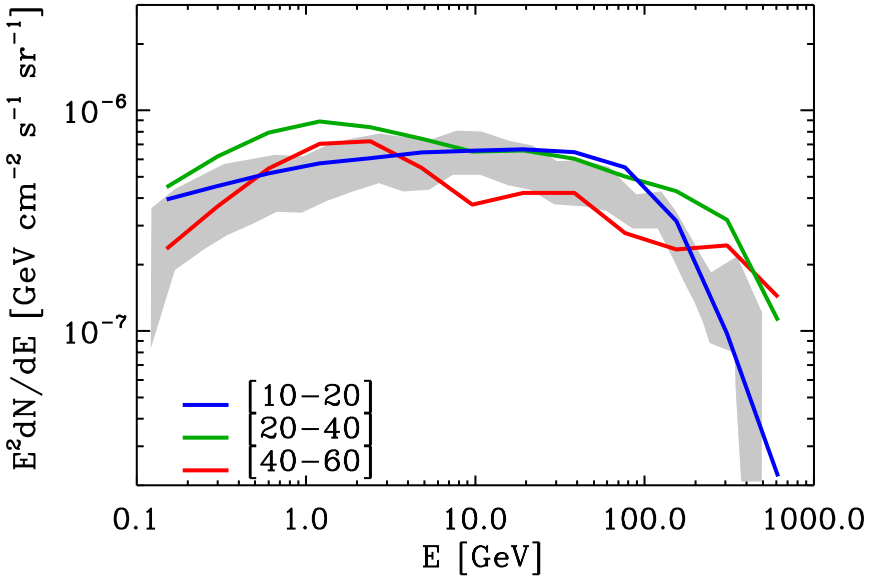
II. *Leptonic jet* models

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



➢ Spatially uniform spectra reproduced (KY & Ruszkowski 2017)

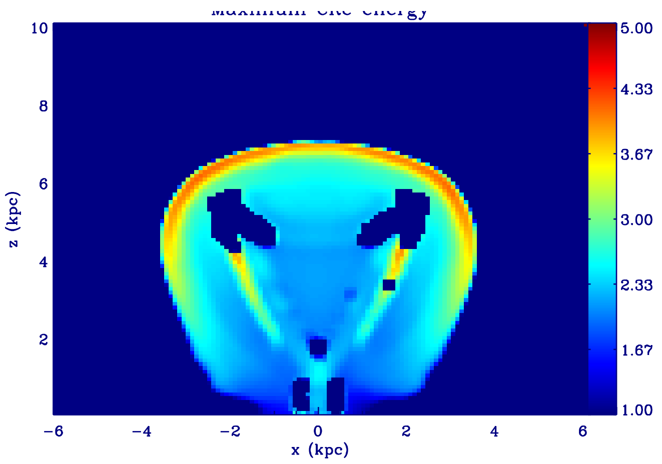
Simulated gamma-ray spectra



➢ ***High-energy cutoff:***

fast cooling near GC and fast advection by jets

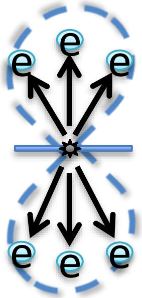
Maximum energy of the CR spectrum



KY & Ruszkowski 2017

II. *Leptonic jet* models

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

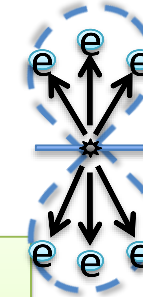


- Satisfy age constraint
- Simultaneously explain the microwave haze
- 3D spatial and spectral CR distribution consistent with spatially uniform gamma-ray spectrum

- Require Eddington ratio ~ 10%

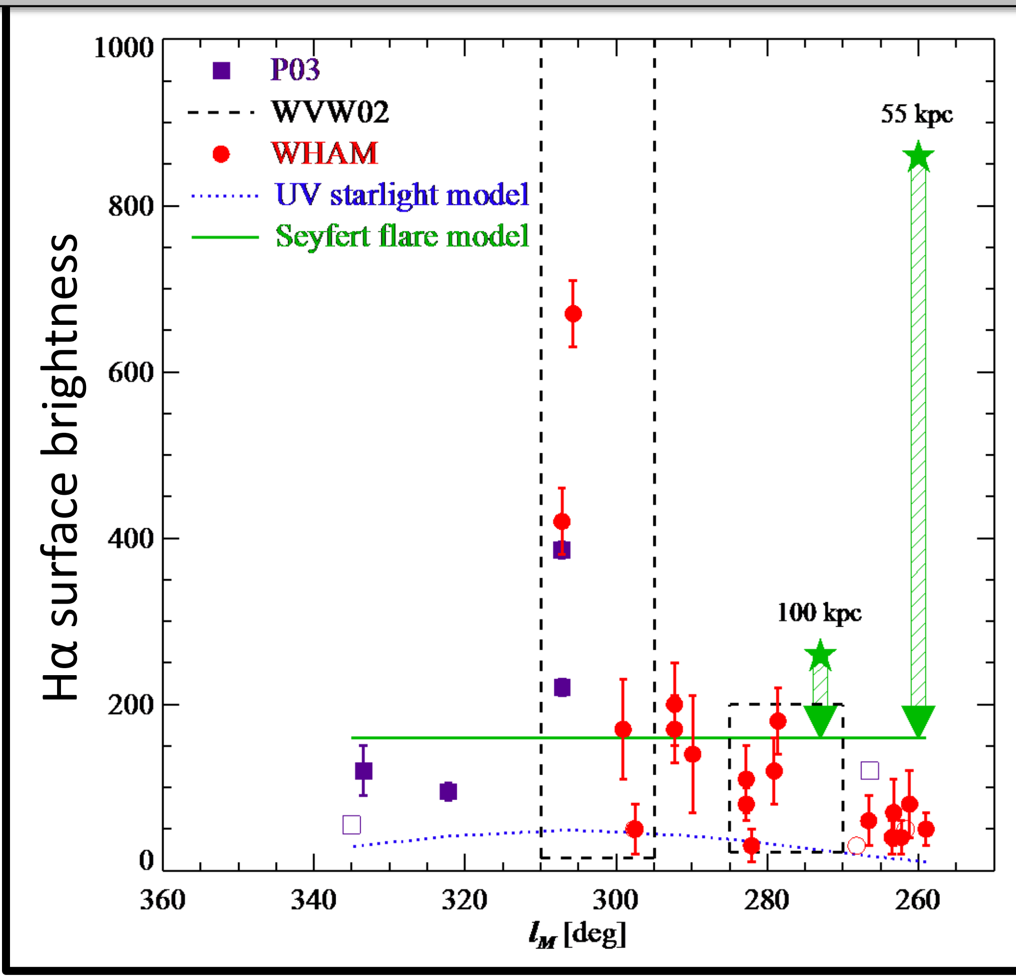
II. *Leptonic jet* models

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

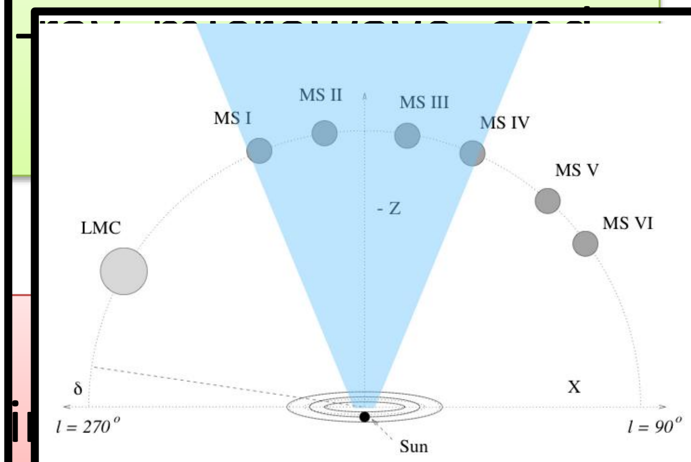


Enhanced Hα in MS requires

Eddington ratio ~ 3-30% and t~1-3Myr

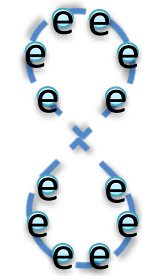


Bland-Hawthorn+ 2013



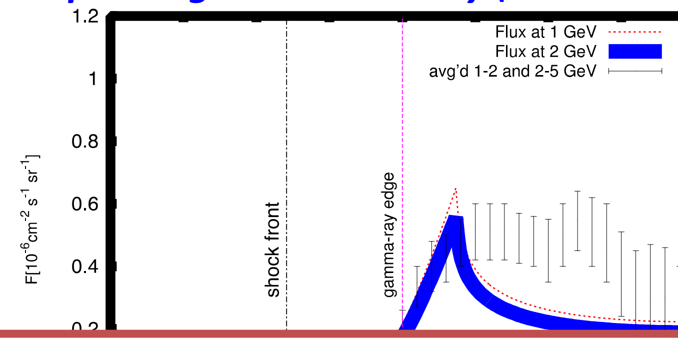
III. *In-situ acceleration* models

(Mertsch+ 2011, Cheng+ 2011, 2015, Zubovas+ 2012, Lacki 2013, Fujita+ 2013, 2014, Sasaki+ 2015, Sarkar+ 2015)

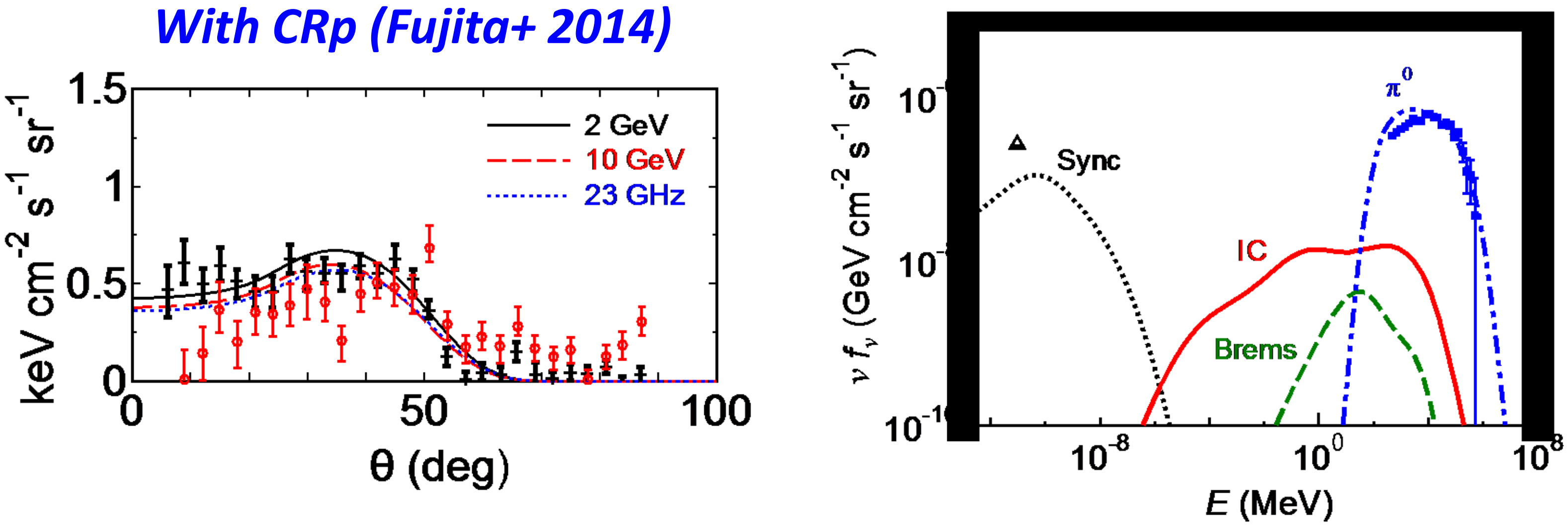


- CRe by shocks or turbulence near bubble edges
- Event: AGN/NSF/TDE/un-specified
- Flat intensity nontrivial to reproduce

Leptonic gamma intensity (Sasaki+ 2015)



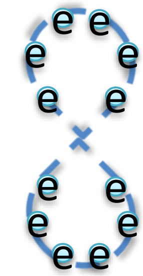
With CRp (Fujita+ 2014)



Fits the flat intensity but not the microwave haze

III. *In-situ acceleration* models

(Mertsch+ 2011, Cheng+ 2011, 2015, Zubovas+ 2012, Lacki 2013, Fujita+ 2013, 2014, Sasaki+ 2015, Sarkar+ 2015)



With efficiently escaped CRe (Sasaki+ 2015)

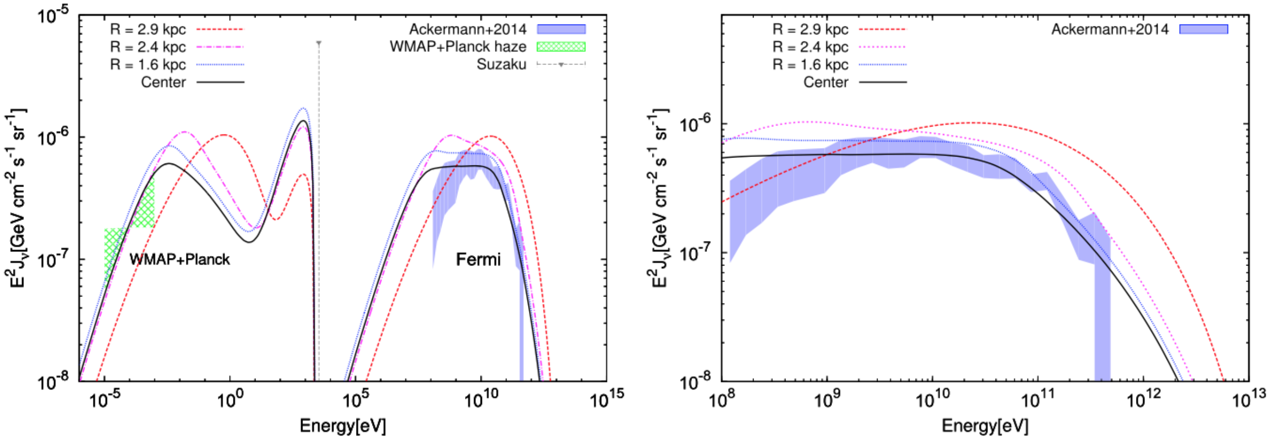
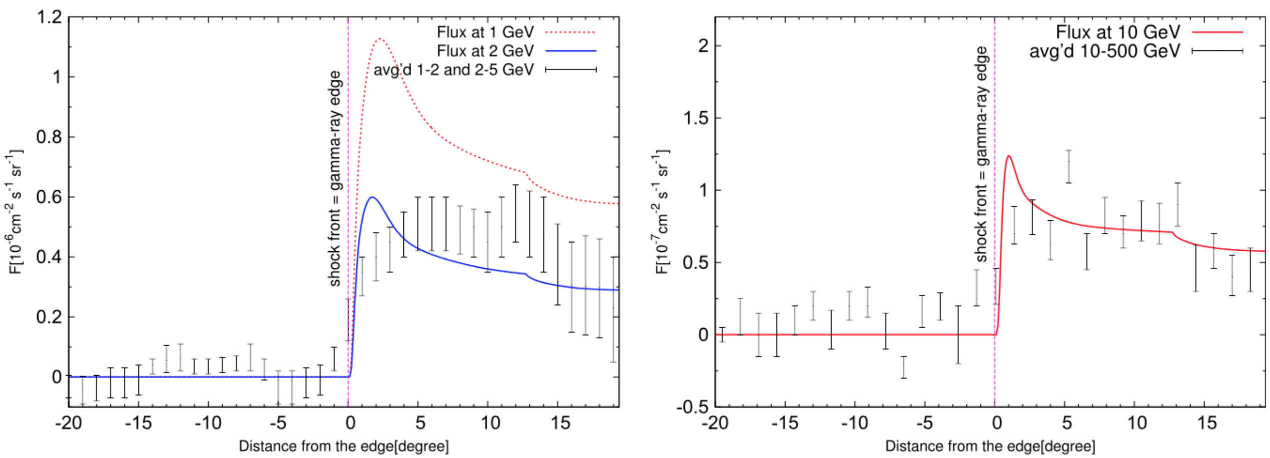


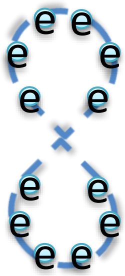
Figure 10. Same as Figure 4, but for the EfE model.



Spatially dependent ISRF and LOS projections?

III. *In-situ acceleration* models

(Mertsch+ 2011, Cheng+ 2011, 2015, Zubovas+ 2012, Lacki 2013, Fujita+ 2013, 2014, Sasaki+ 2015, Sarkar+ 2015)

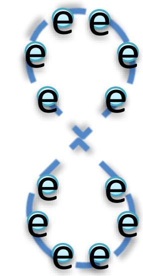


- Free from age constraint
- Sharp edges naturally explained

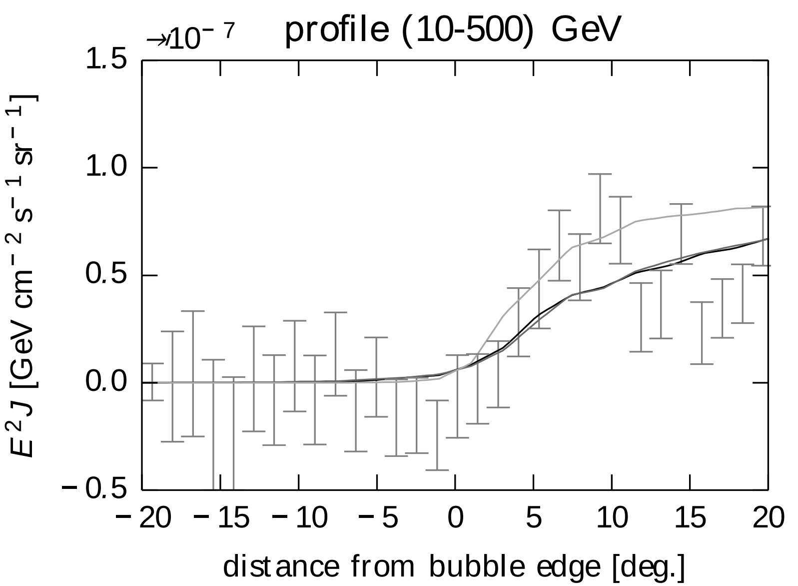
- Require more complex models to reproduce flat intensity and microwave haze
- Bubble geometry, spatial variation of ISRF, and LOS projections need to be examined

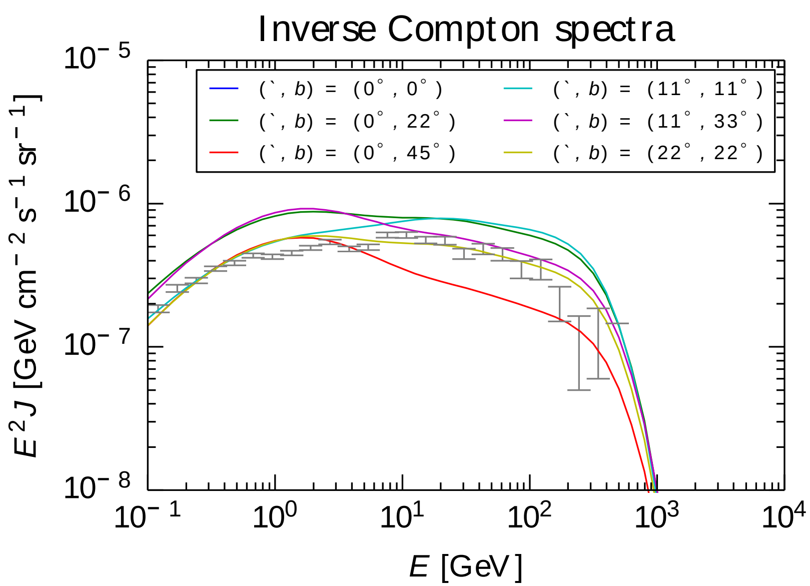
III. *In-situ acceleration* models

(Mertsch+ 2011, Cheng+ 2011, 2015, Zubovas+ 2012, Lacki 2013, Fujita+ 2013, 2014, Sasaki+ 2015, Sarkar+ 2015)



- Free from age constraint
- Sharp edges naturally explained





With realistic geometry (Mertsch+ in prep.)

Literature	Feature	Gamma spectrum	Haze spectrum	3D projections	Assumptions	Gamma morphology	Gamma smooth surface	Gamma sharp edges	Gamma flat intensity	X-ray arcs	Kinematcis from X-ray	Kinematics from UV lines	Polarized lobes
A. HADRONIC TRANSPORT													
Crocker 2011, Cheng 2015a	NSF	Green	Red		Orange	Yellow			Green	Orange			
Thoudam 2013	Galactic CR	Green			Orange			Green	Green	Orange			Orange
Crocker 2013	NSF	Green	Red		Green	Yellow			Orange	Yellow			
Mou 2014, 2015	AGN	Green	Orange	Green	Green	Green	Green	Green	Green	Green	Green	Orange	
Crocker 2015	NSF	Green	Yellow		Green	Yellow			Orange	Yellow	Green	Orange	Green
B. LEPTONIC TRANSPORT													
Guo 2011, 2012	AGN	Green	Green	Green	Yellow	Green	Green	Yellow	Green	Green			
Yang 2012, 2013	AGN	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Orange	Yellow	Green
Barkov 2013	AGN		[illegible]	[illegible]	Yellow	[illegible]	[illegible]	[illegible]	[illegible]	Yellow	Orange	Yellow	Green
C. IN-SITU ACCELERATION													
By Turbulence													
Mertsch 2011	CRe/Unk	Green	Red		Orange		Orange	Green	Yellow	Green			
Cheng 2015b	CRe/TDE	Green	Green		Orange		Orange	Green	Red	Green			
Sasaki 2015	CRe/Unk	Green	Green		Orange		Orange	Green	Red	Green			
By Shocks													
Cheng 2011	CRe/TDE	Green	Green		Orange				Red	Green			
Fujita 2013	CRp/Unk	Green			Orange			Green	Yellow	Green			
Lacki 2013	CRe/SF	Green			Green				Orange	Green			
Fujita 2014	CRp&e/Unk	Green	Yellow	Yellow	Orange			Green	Green	Green			
Un-specified													
Zubovas 2012	CRe/AGN				Orange	Green	Green	Orange					
Sarkar 2015	CRe/NSF	Yellow	Yellow	Green	Orange	Orange	Green	Orange	Green	Green	Green	Orange	Orange

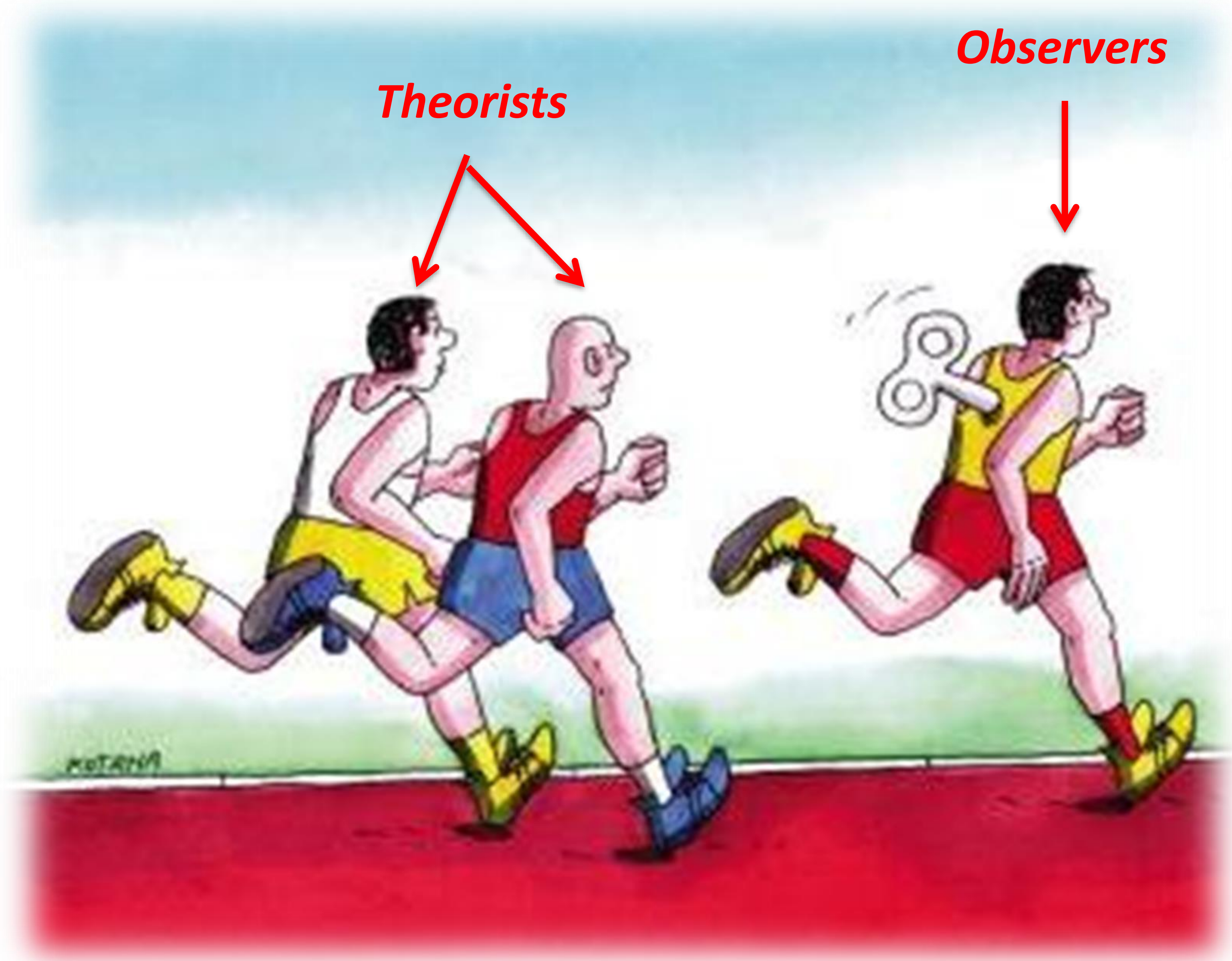
3D projections

Xray & UV lines

Green	Consistent
Yellow	Somewhat consistent
Orange	Potentially concerning
Red	Inconsistent

1. ***No model is perfect***
2. ***Some are ruled out***
3. ***Blanks remain to be filled***

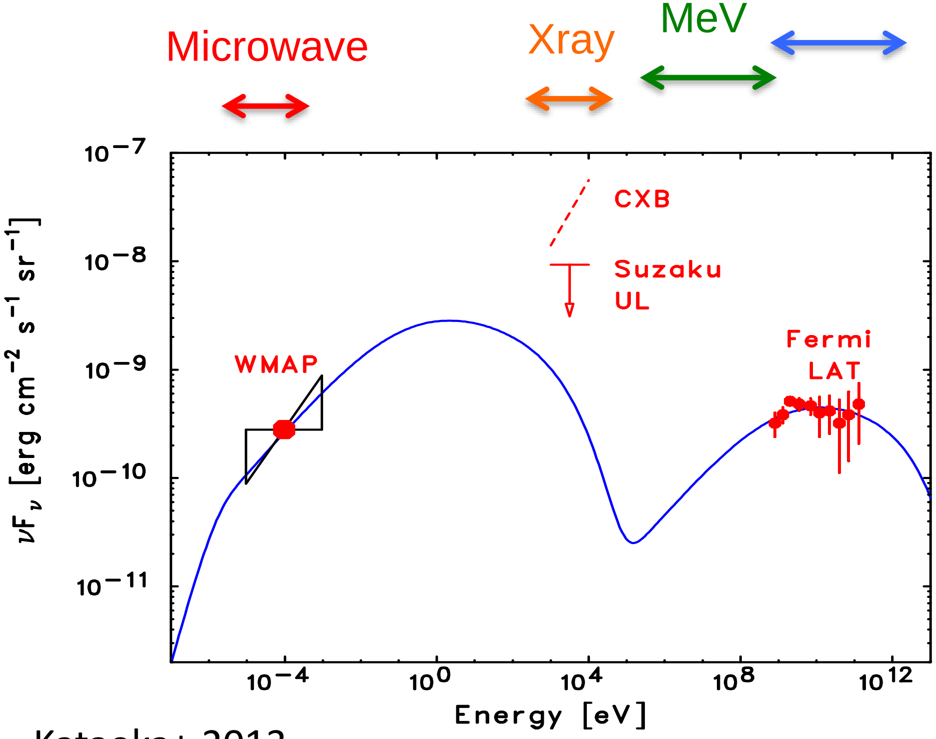
Future


Theorists
Observers

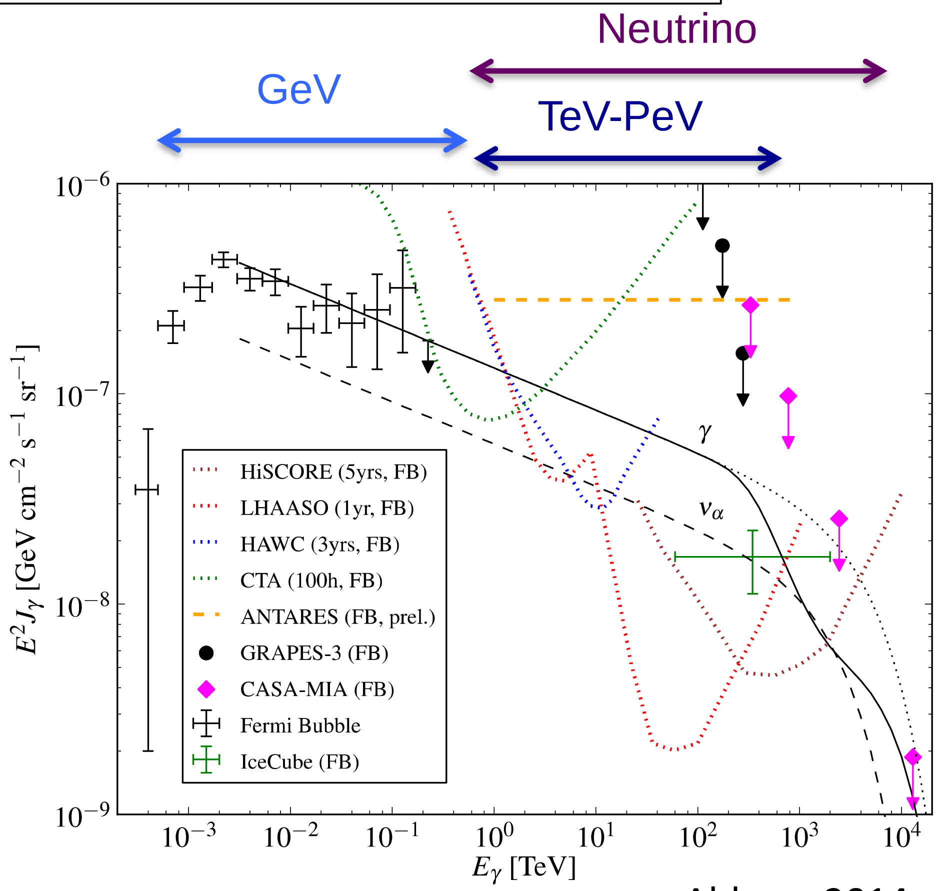
Multi-messenger observations

- ***Microwave***: Planck
- ***X-ray***: eRosita, MAXI
- ***MeV***: PANGU, CT, ASTROGAM, PolSTAR
- ***GeV***: Fermi, DAMPE
- ***TeV-PeV***: CTA, HAWC, LHAASO, HiSCORE
- ***Neutrino***: ICECUBE, ANTARES

Leptonic or Hadronic?



Kataoka+ 2013

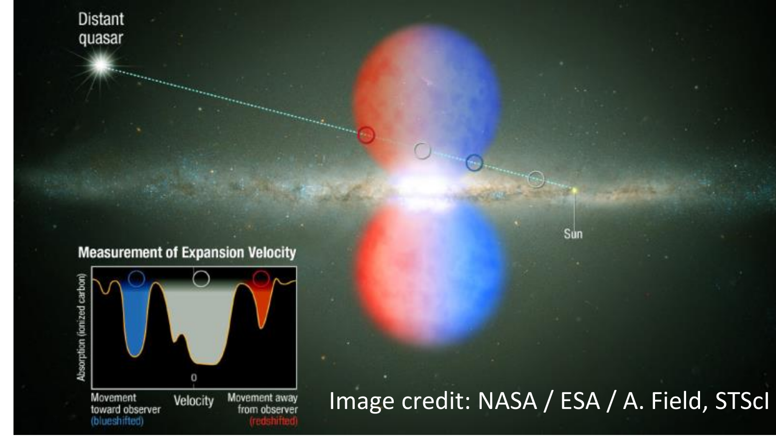


Ahlers+ 2014

Pointed observations

❖ ***UV/X-ray lines***: HST, Suzaka, XARM

=> Temperature, kinematics, metallicity



NSF or AGN?

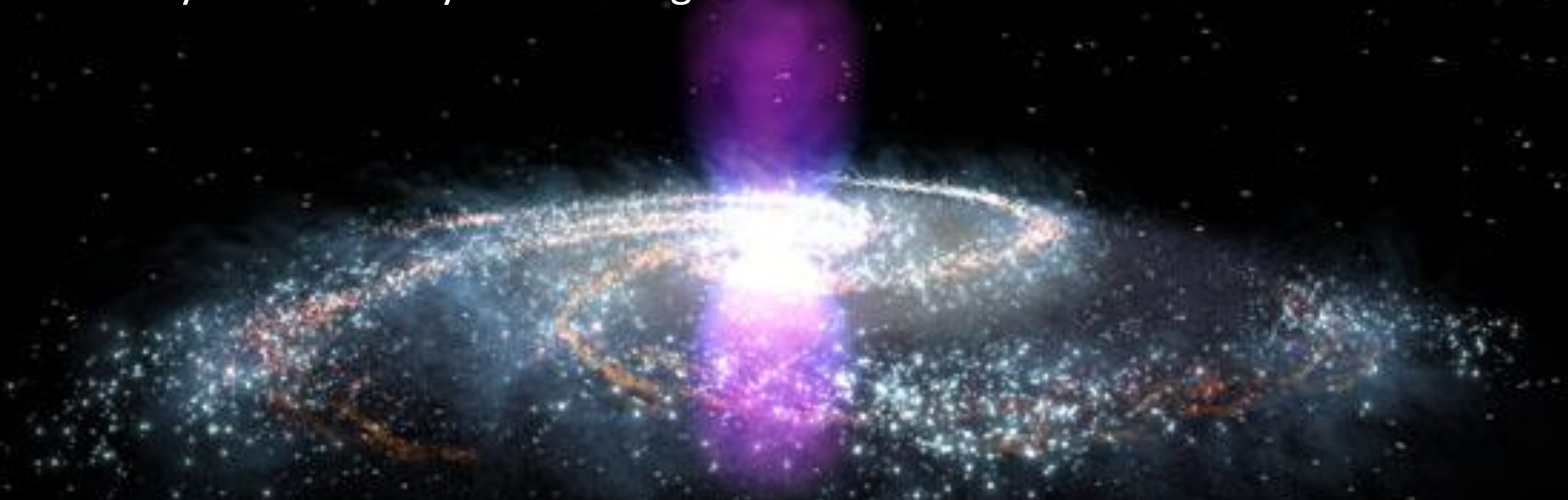
Inoue+ 2015

Table 1. Model Parameters for Metal-Enriched Outflows

Origin	Star formation		AGN wind	AGN wind
Emission	Leptonic	Hadronic	Leptonic	Hadronic
Reference	Lacki (2014)	Crocker et al. (2014)	Mou et al. (2014)	Zubovas et al. (2011)
SFR $[M_\odot/\mathrm{yr}]$	0.1	0.1	-	-
IMF model	Salpeter (1955)	Kroupa (2001)	-	-
IMF ranges	0.1-100 $M_\odot$	0.08-150 $M_\odot$	-	-
$\dot{M}_{out}$ $[M_\odot/\mathrm{yr}]$	0.02	0.1	0.02	0.08[a]
β	2.0	6.3	-[b]	-[b]
$Z_{FB}/Z_\odot$	5.3[c]	2.2[c]	1.0[c]	0.45[d]
$X_{Fe,FB}/X_{Fe,\odot}$	2.3[c]	1.3[c]	1.0[c]	0.45[d]
[O/Fe]	0.49[c]	0.30[c]	0.0[c]	0.0[d]
[Ne/Fe]	0.58[c]	0.38[c]	0.0[c]	0.0[d]

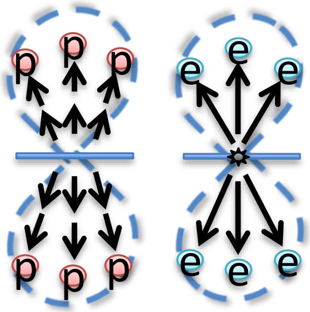
Summary

- The multi-messenger observations of the Fermi bubbles will continue to bring new insights into the bubble formation
- These data will put stringent constraints on theoretical models
- The Fermi bubbles are excellent laboratories for understanding feedback activity in our Galaxy and other galaxies

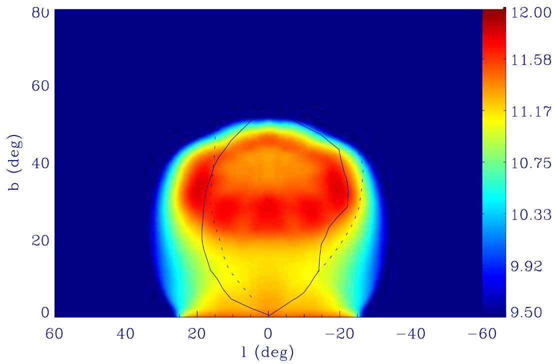


Mechanisms for other features

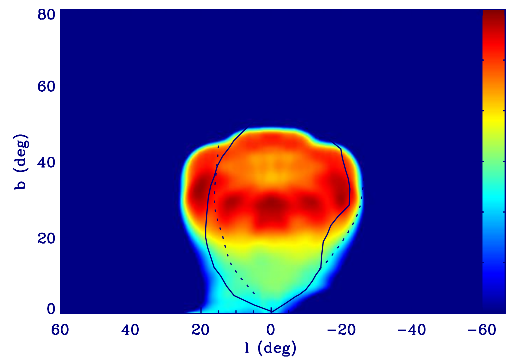
Sharp edges of the gamma-ray bubbles (KY+ 2012)



With isotropic diffusion



Suppressed diffusion



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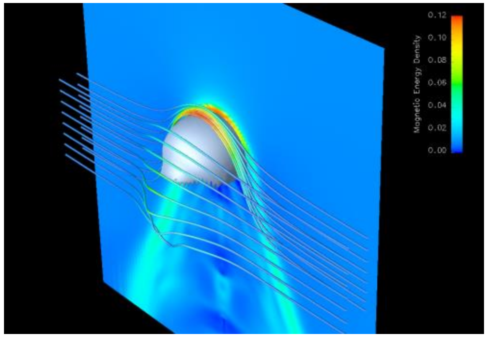
Magnetic draping

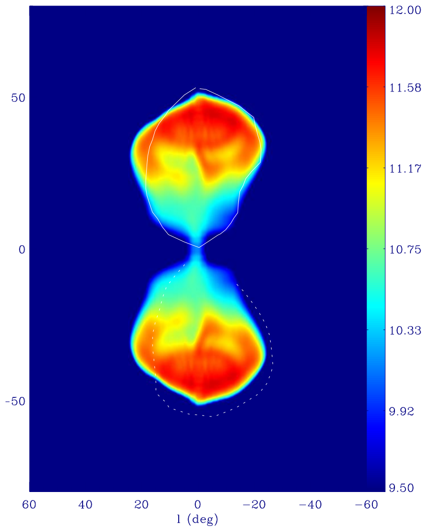


Dursi & Pfrommer (2008)

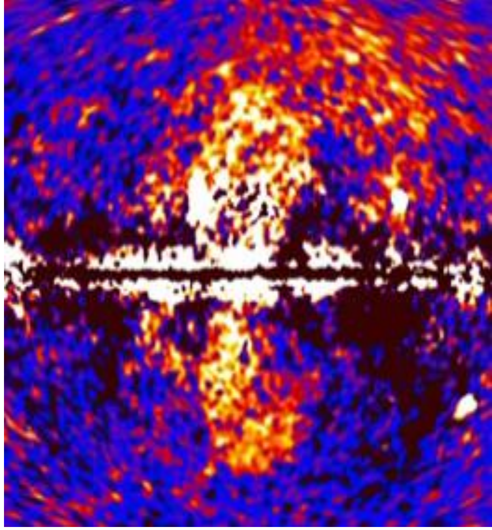
+

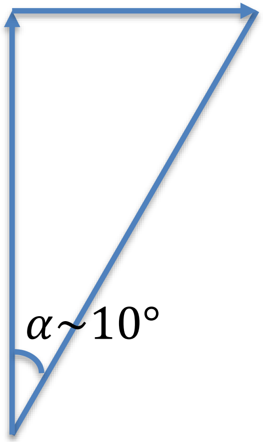
Anisotropic CR diffusion

Slight tilt of the gamma-ray bubbles



Ram pressure of AGN jets requires fast transverse winds, e.g., from SN explosion for 0.1 Myr from 0.5 pc away (KY+ 2012)

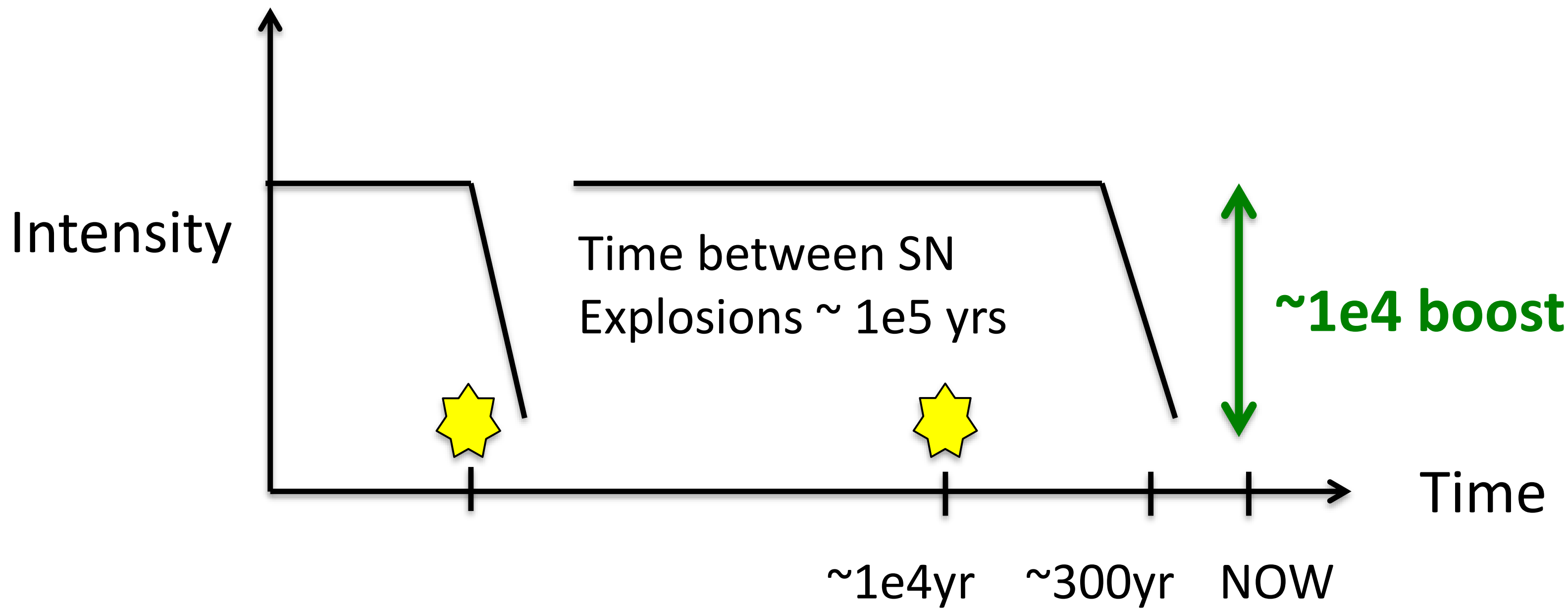




Ram pressure of NSF winds requires only gentle transverse winds, e.g., from the movement of MW in the Local Group (Crocker+ 2015)

$$\tan \alpha = \frac{P_{ram,\perp}}{P_{ram,\parallel}} \cong 0.2$$

Active past of Sgr A (Totani 2006)*



-- X-ray reflection nebula (e.g. Murakami+2001)
-- Ionized halo around SgrA* (Maeda+2002)
-- Galactic Center Lobe (Bland-Hawthorn+2003)
-- Expanding Molecular Ring (Kaifu+1972)
-- North Polar Spur (Sofue 2000)

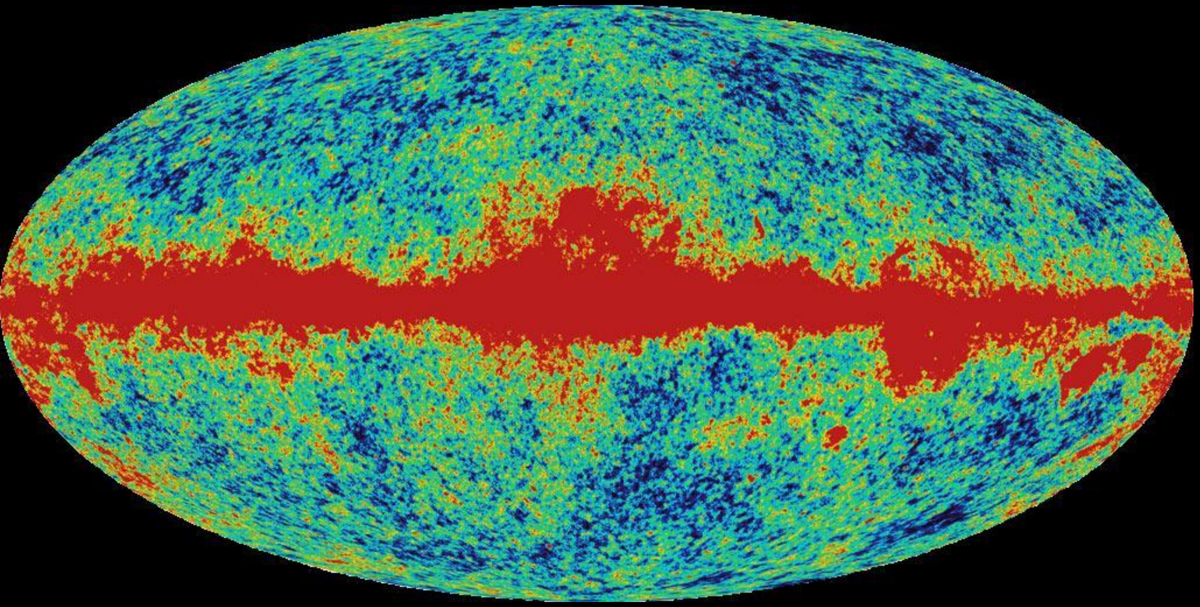
Fermi Gamma-ray Space Telescope

Science: diffuse gamma-ray sky, AGN, SNR, GRB, DM…

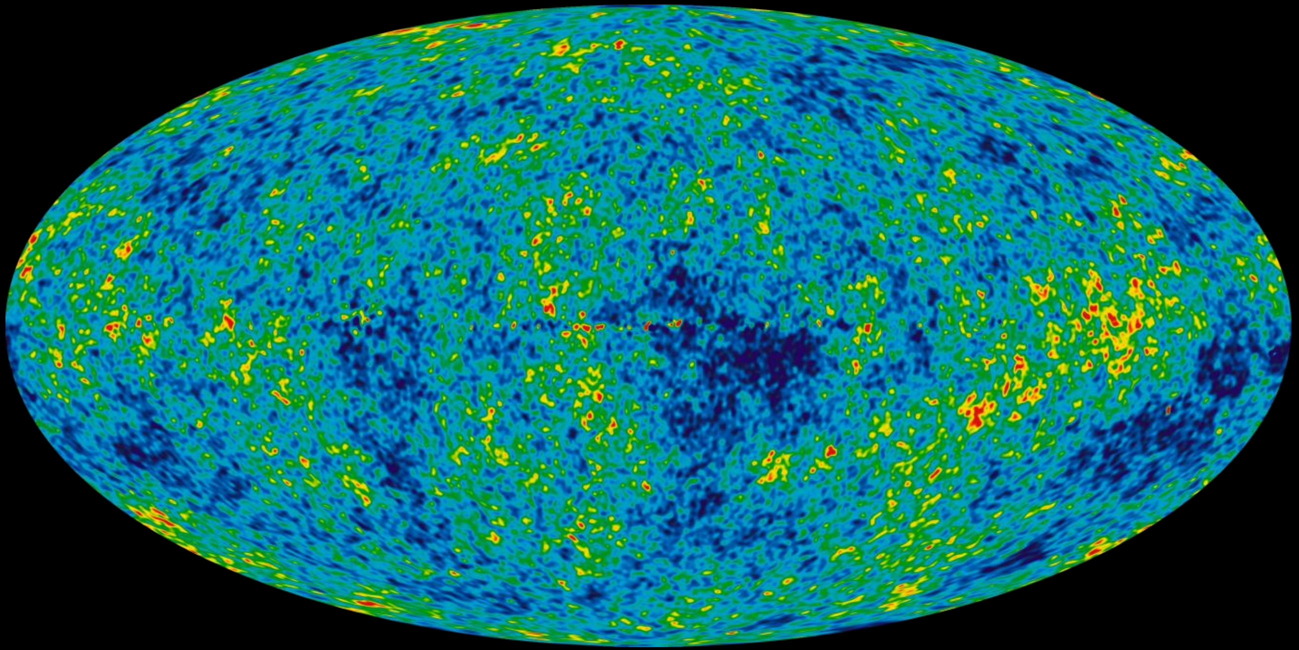
LAT Specifications & Performance

Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area [1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution [2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution [3]	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination [4]	< 0.5'	15'
Point Source Sensitivity [5]	$< 6 \times 10^{-9}$ cm^{-2} s^{-1}	$\sim 10^{-7}$ cm^{-2} s^{-1}

Discovery

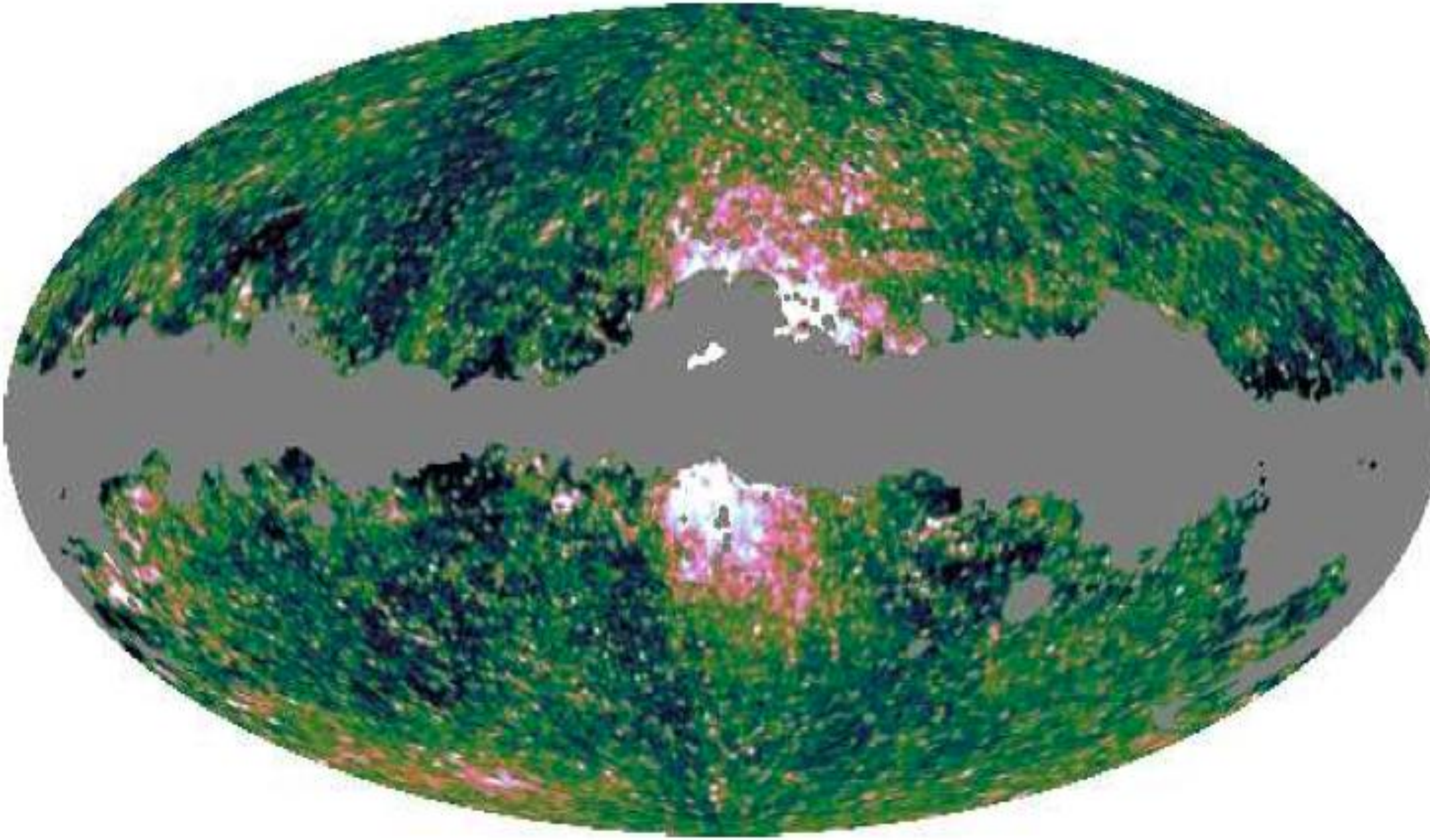


Wilkinson Microwave Anisotropy Probe (WMAP, 2001)

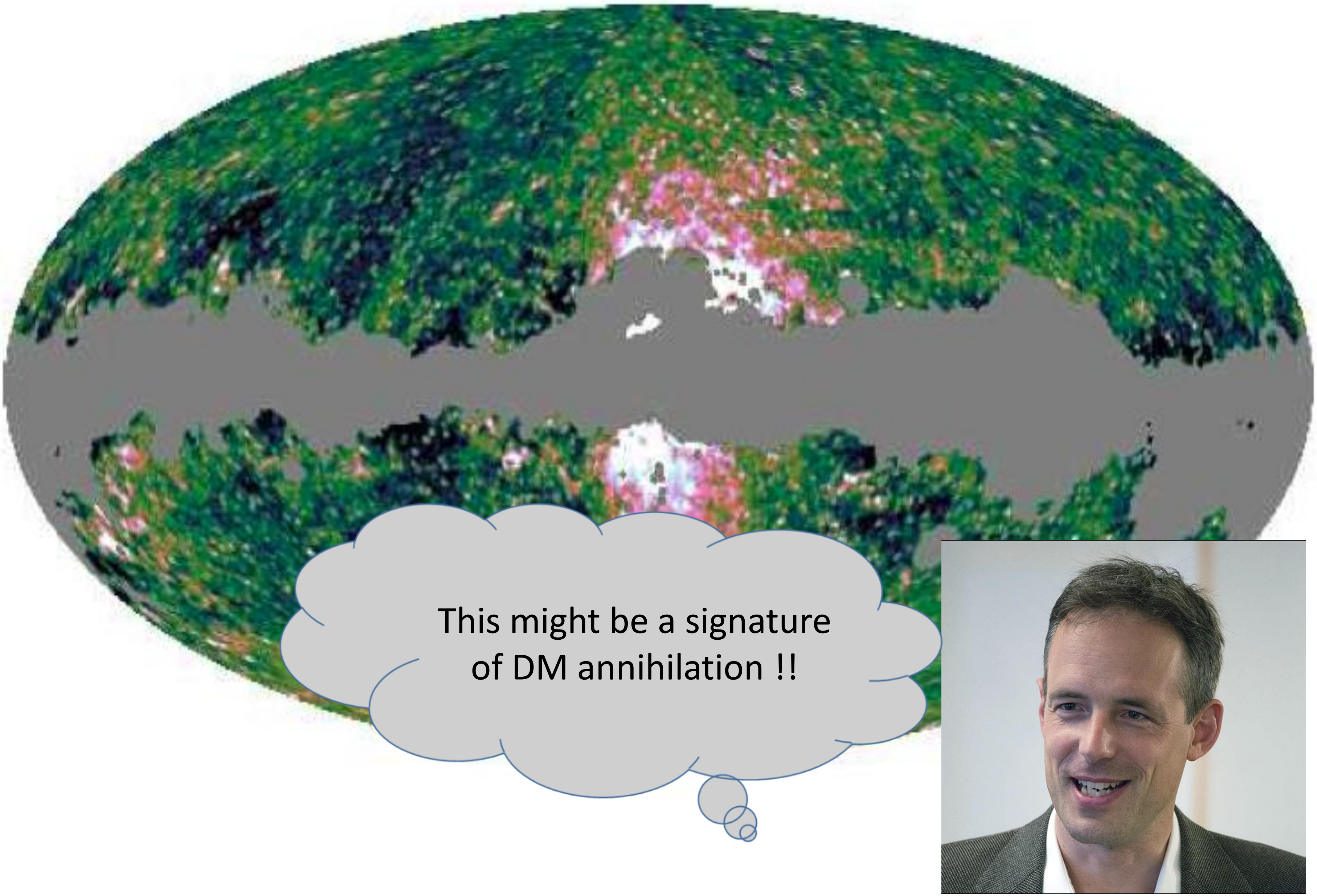


Cosmic Microwave Background (CMB)

The *WMAP haze* *(Finkbeiner 2004)*

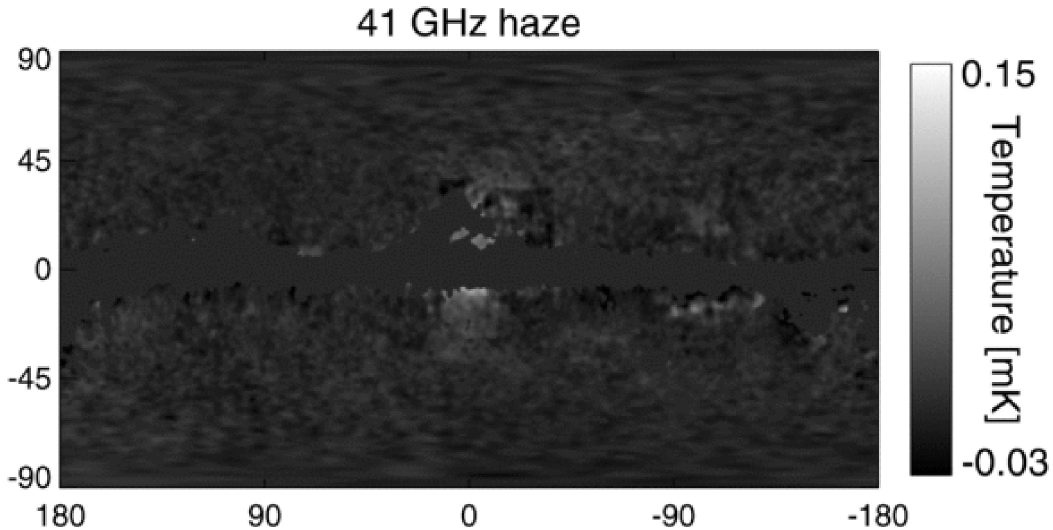


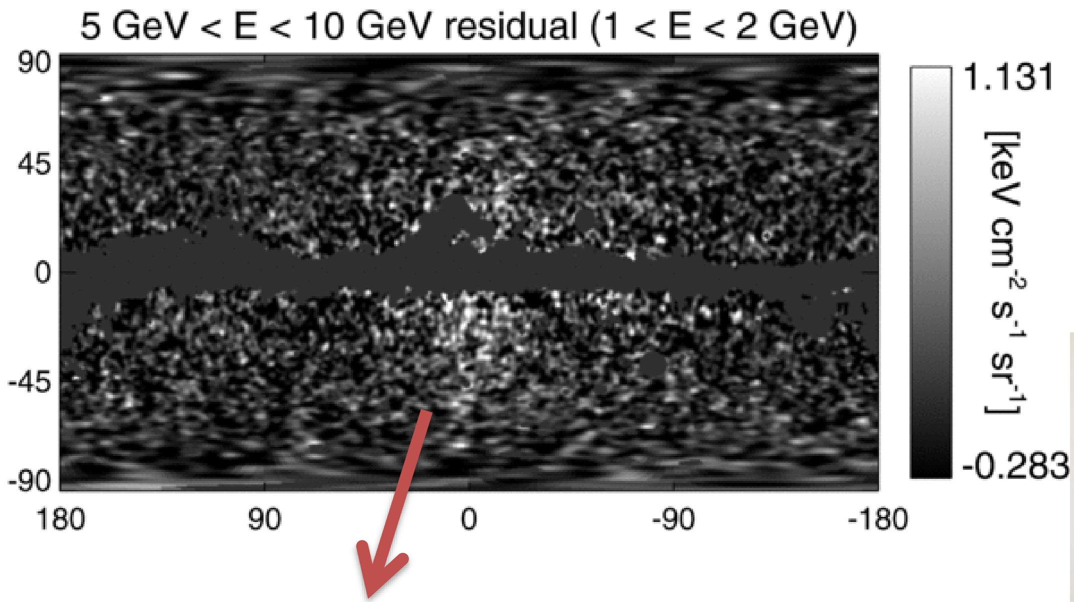
The *WMAP haze* *(Finkbeiner 2004)*



This might be a signature of DM annihilation !!

D. Finkbeiner

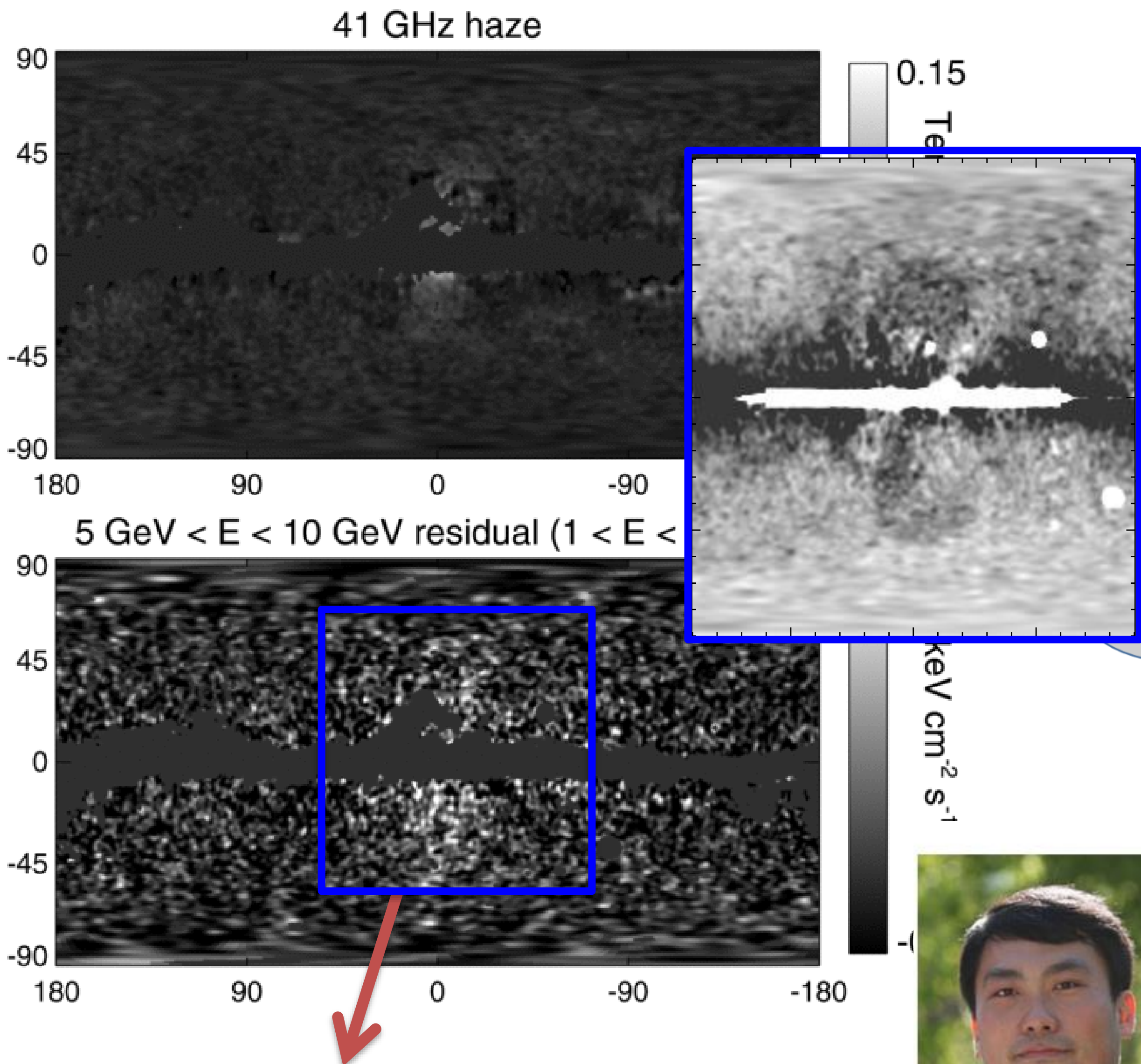




Fermi haze *(Dobler+ 2010)*

G. Dobler

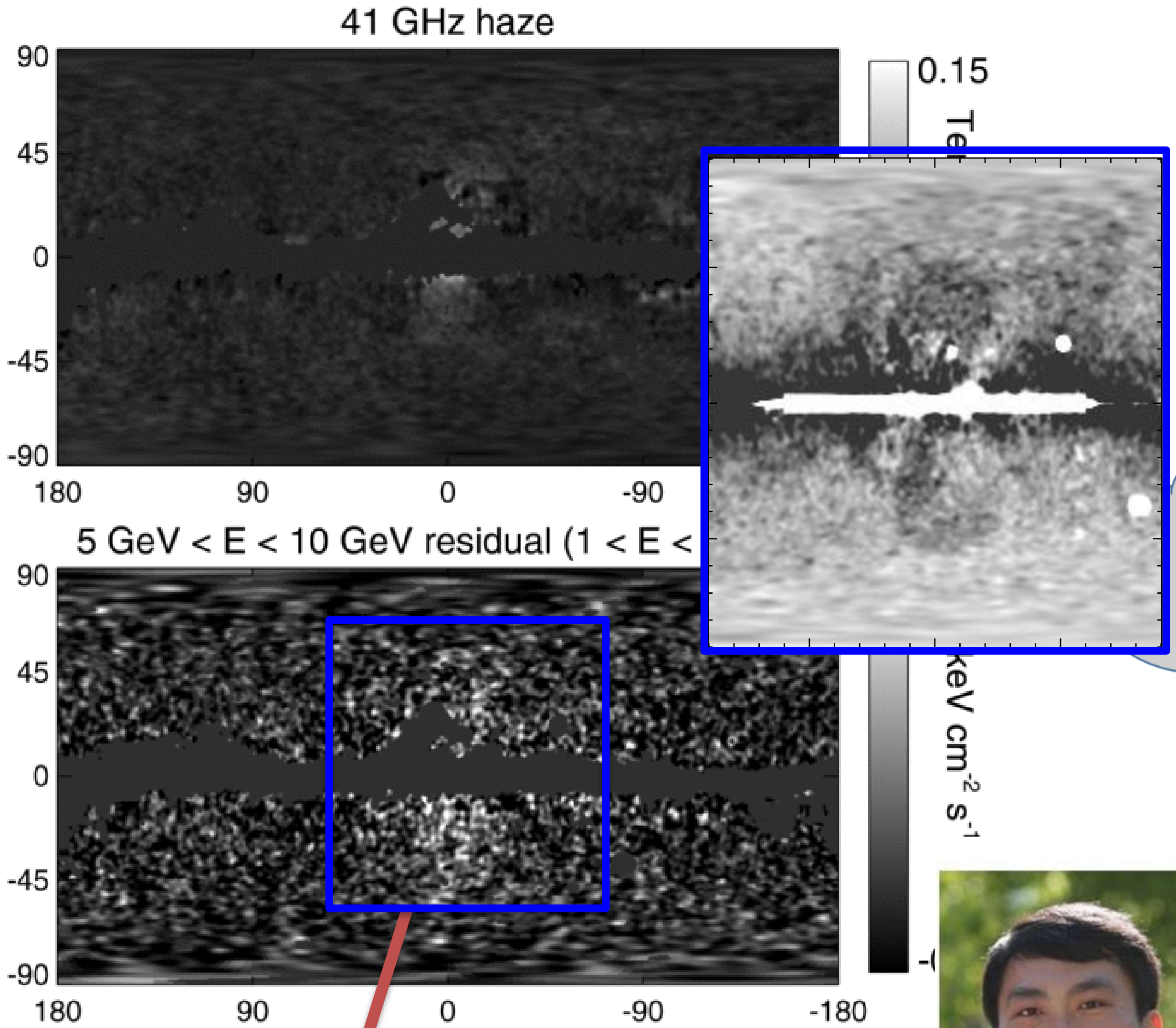
D. Finkbeiner



Fermi haze *(Dobler+ 2010)*

Wait… it has an edge!!!

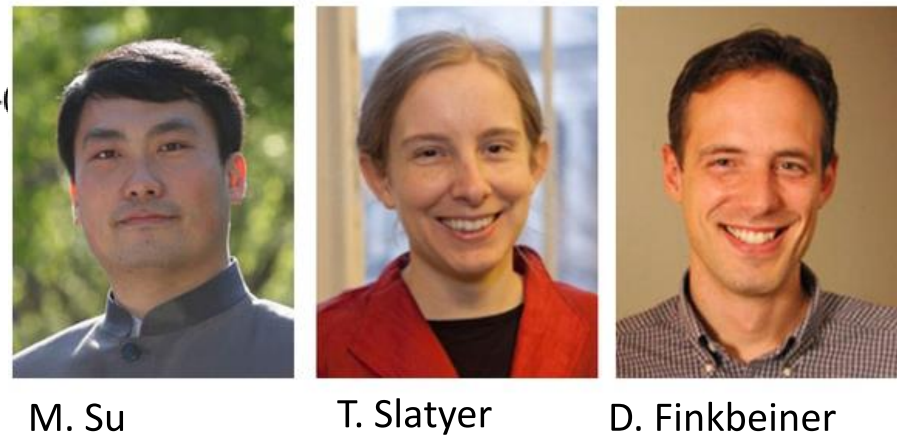
M. Su   T. Slatyer   D. Finkbeiner



Wait... it has an edge!!!

Fermi ~~*haze*~~ *(Dobler+ 2010)*

bubbles (Su+ 2010)



Energetics for the AGN jet model

- P_{jet} ~ 1e44 erg/s, E_{jet}~1e57 erg

- $M_{dot} = 2P_{jet}/(0.1c^2)$ ~ 0.04 M_{sun}/yr ~ 10% M_{dot_edd}

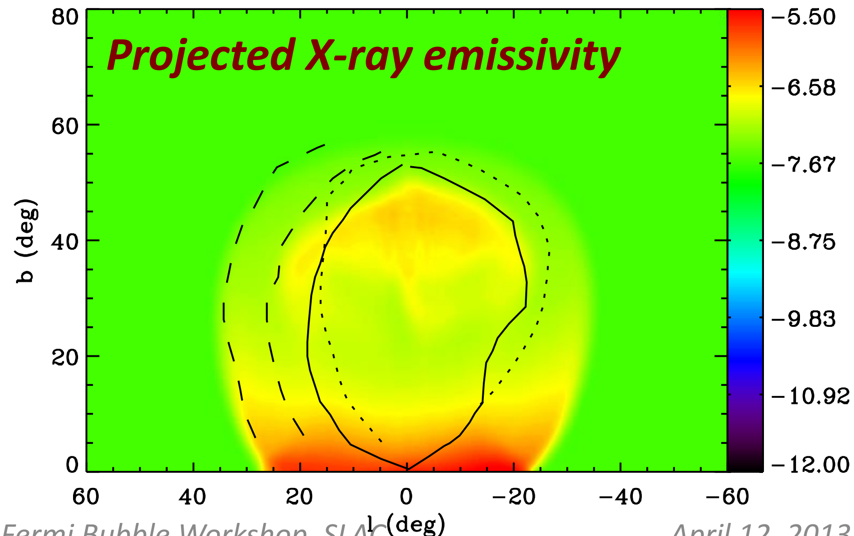
- $M_{acc} = M_{dot}*t_{jet}$ ~ 1e4 M_{sun}

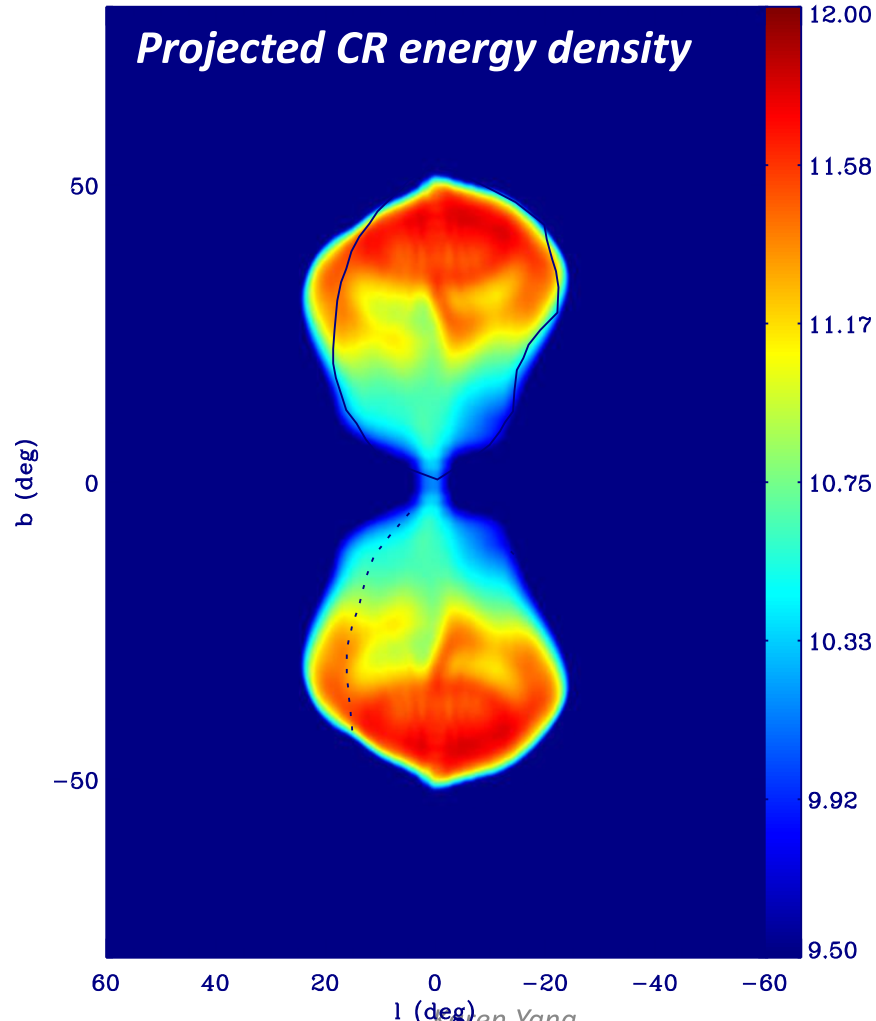
Observed Fermi Bubble Energetics

- E^2dN/dE = 3e-7 GeV cm^{-2} s^{-1} sr^{-1} from 1-100 GeV
- 1.4e-6 GeV cm^{-2} s^{-1} sr^{-1} across energy
- Flux = 1.13e-6 GeV cm^{-2} s^{-1} (0.808 sr)
- Total gamma-ray power = 2.5e40 GeV s^{-1} = 4e37 erg s^{-1}
  (~5% total Galactic gamma-ray luminosity)

Slight bends of the Fermi bubbles

- *Not*: Ram pressure from IGM, jet precession, BH motion
- Both jets tilted to the *east* by 10^o for t < 3e4yr, possibly due to SN ram pressure
- *Shock location matches outer X-ray arcs*



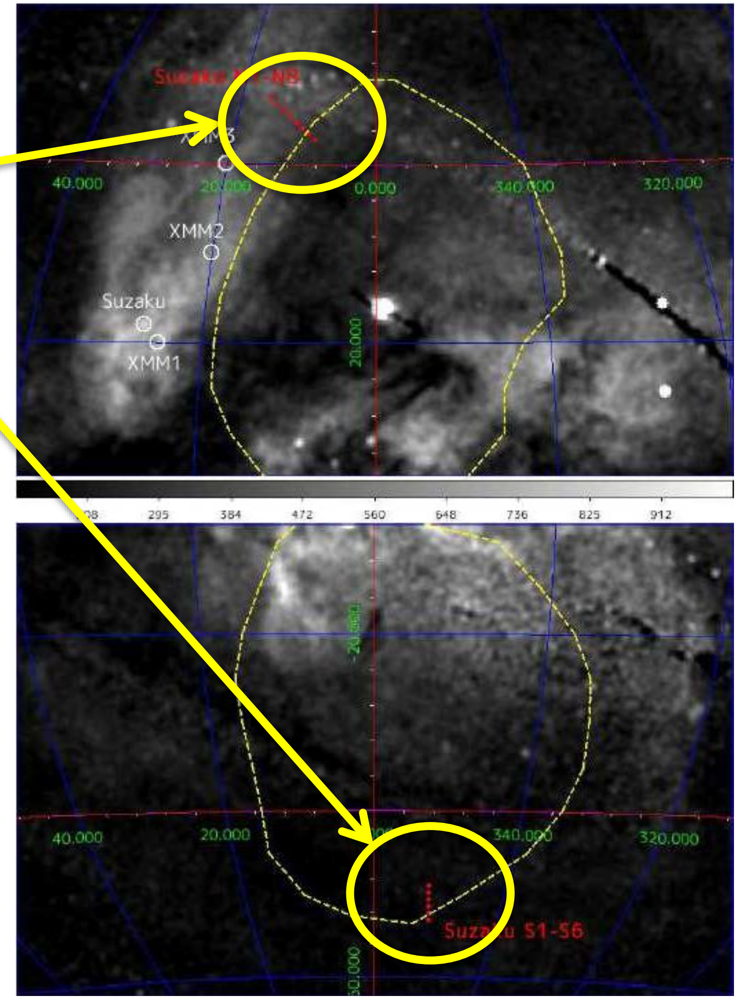


X-ray pointed observations by *Suzaku*

(Kotaoka+ 2013, Tahara+ 2015, Kotaoka+ 2015)

Bubble edges:

- ❖ EM decreases within bubbles
- ❖ No T jump, T~0.3keV
- ❖ Infer Mach~1.5, v~300km/s

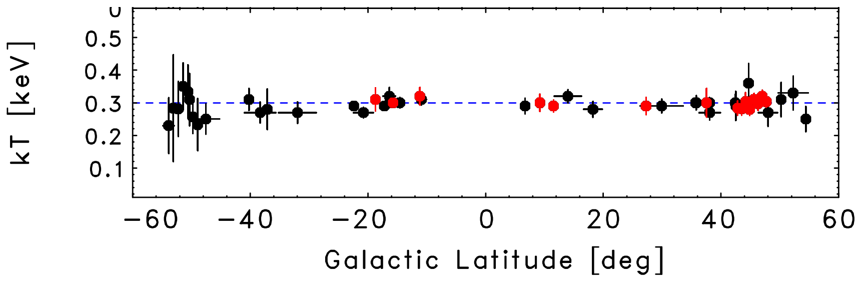


Kataoka+ 2013

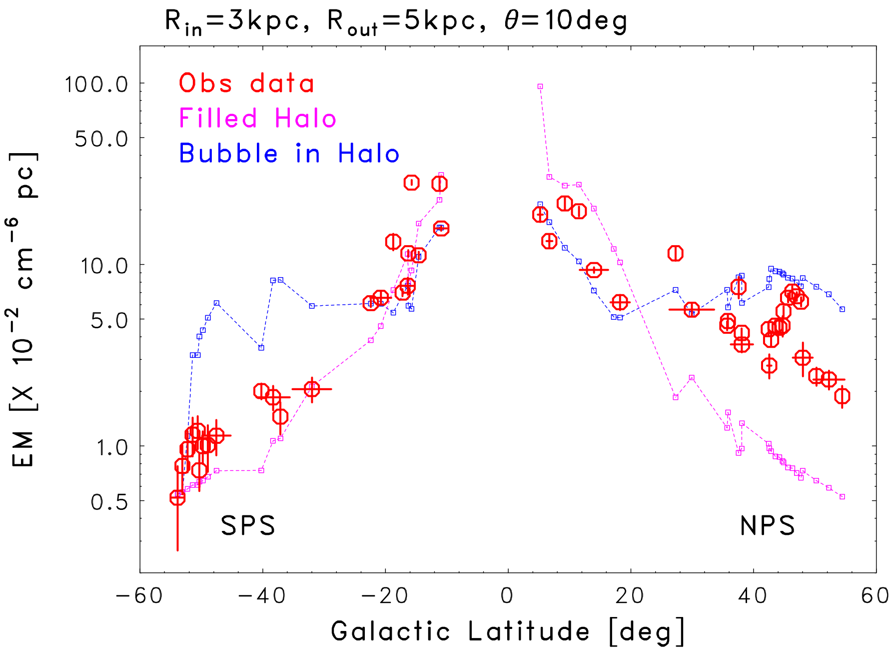
X-ray pointed observations by *Suzaku*

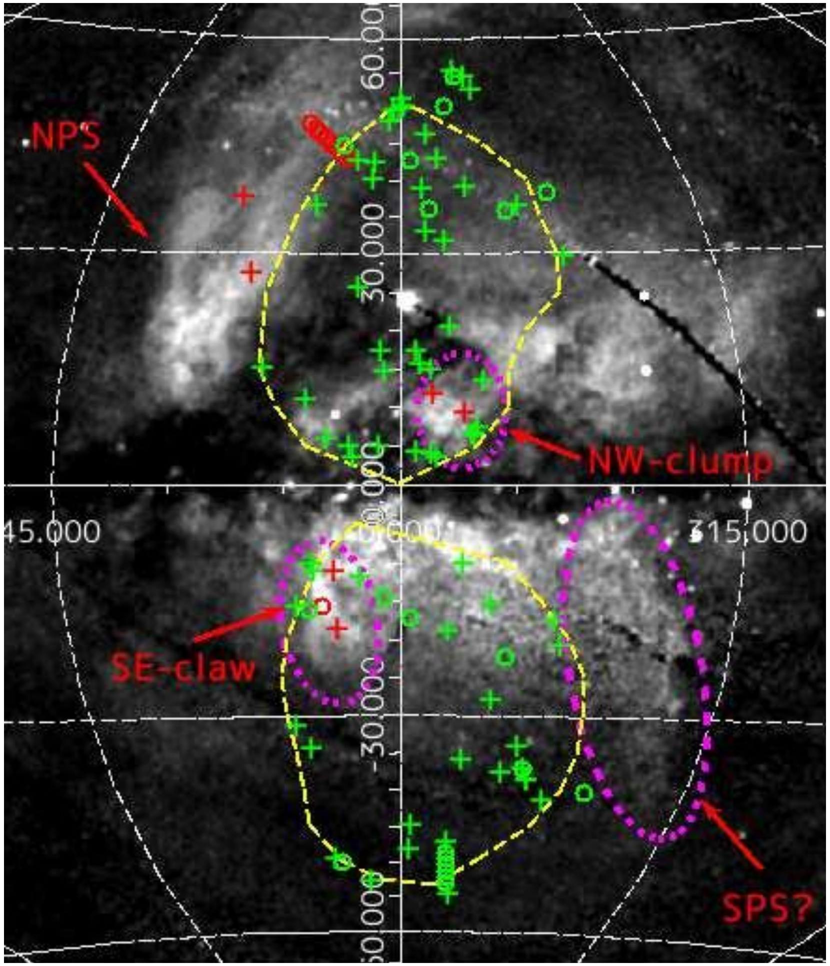
(Kotaoka+ 2013, Tahara+ 2015, Kotaoka+ 2015)

T~0.3keV across the bubbles



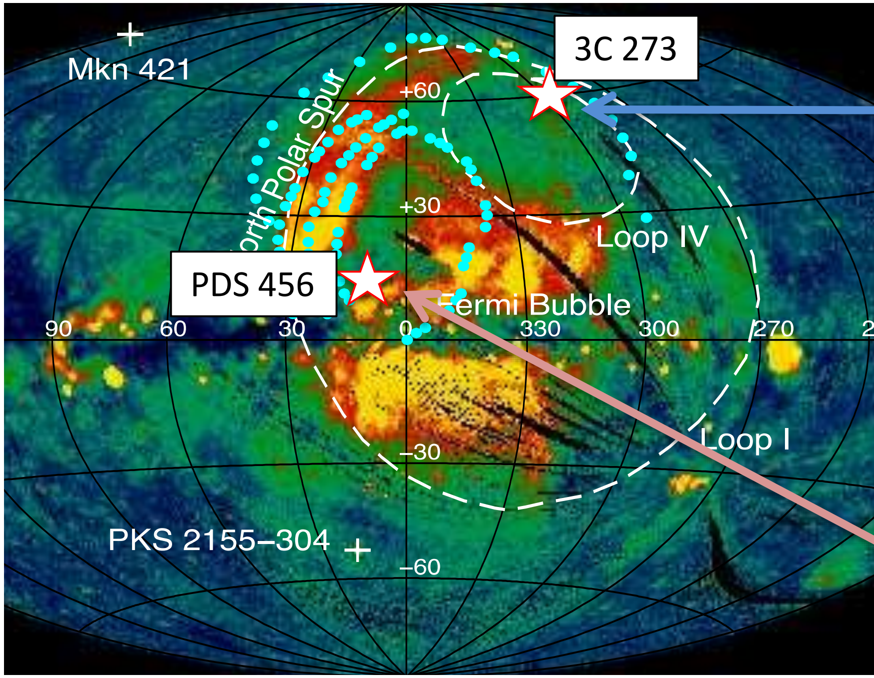
Asymmetric EM w.r.t Galactic plane





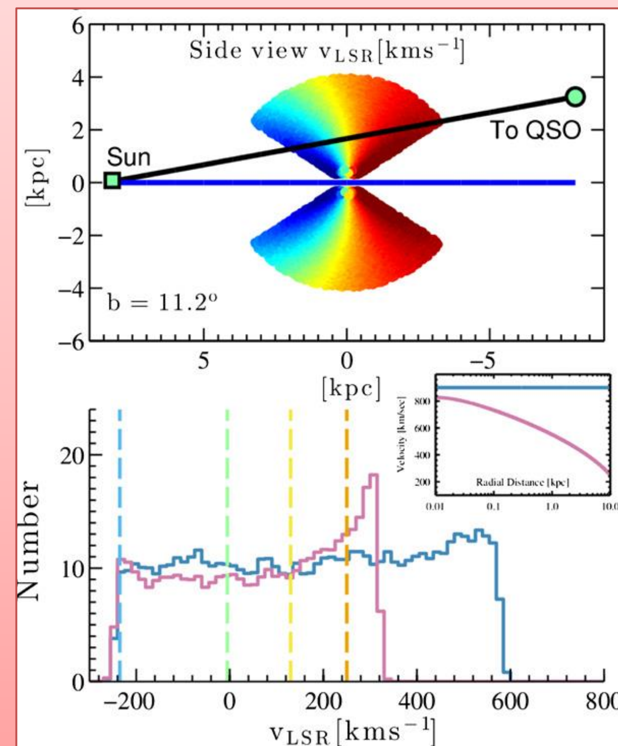
Kataoka+ 2015

Kinematics using X-ray and UV absorption lines

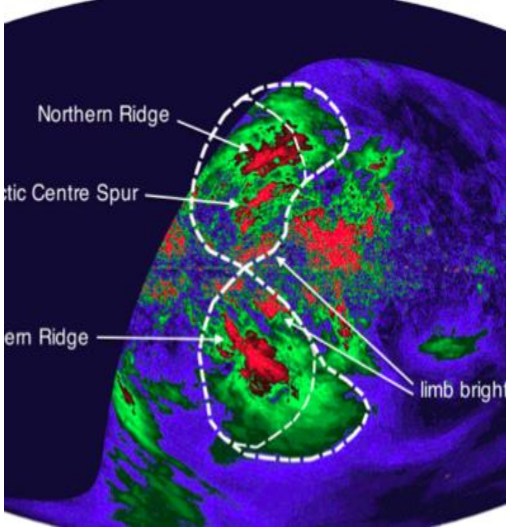


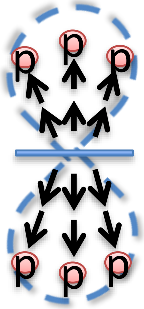
Nonthermal broadening:
v~200-300km/s (Fang+2014)

Line shifts: v=-235 and +250 km/s
Assuming biconical outflow:
v>~900km/s (Fox+2015)

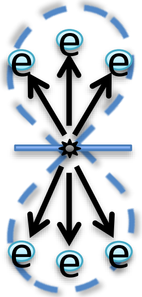


Polarized lobes observed by *S-PASS*





Ridges: energetics from B, velocities from cooling time, and geometry from disk rotation consistent with NSF winds
Lobes: several starbursts or AGN activity (Caretti+ 2013)



Inside: linear B amplified by elongated eddies behind shocks
Outside: magnetic draping (KY+ 2013)

Simulated polarization fractions