What is the Origin of the Fermi Bubbles?

H.-Y. Karen Yang

Einstein Fellow

University of Maryland and JSI

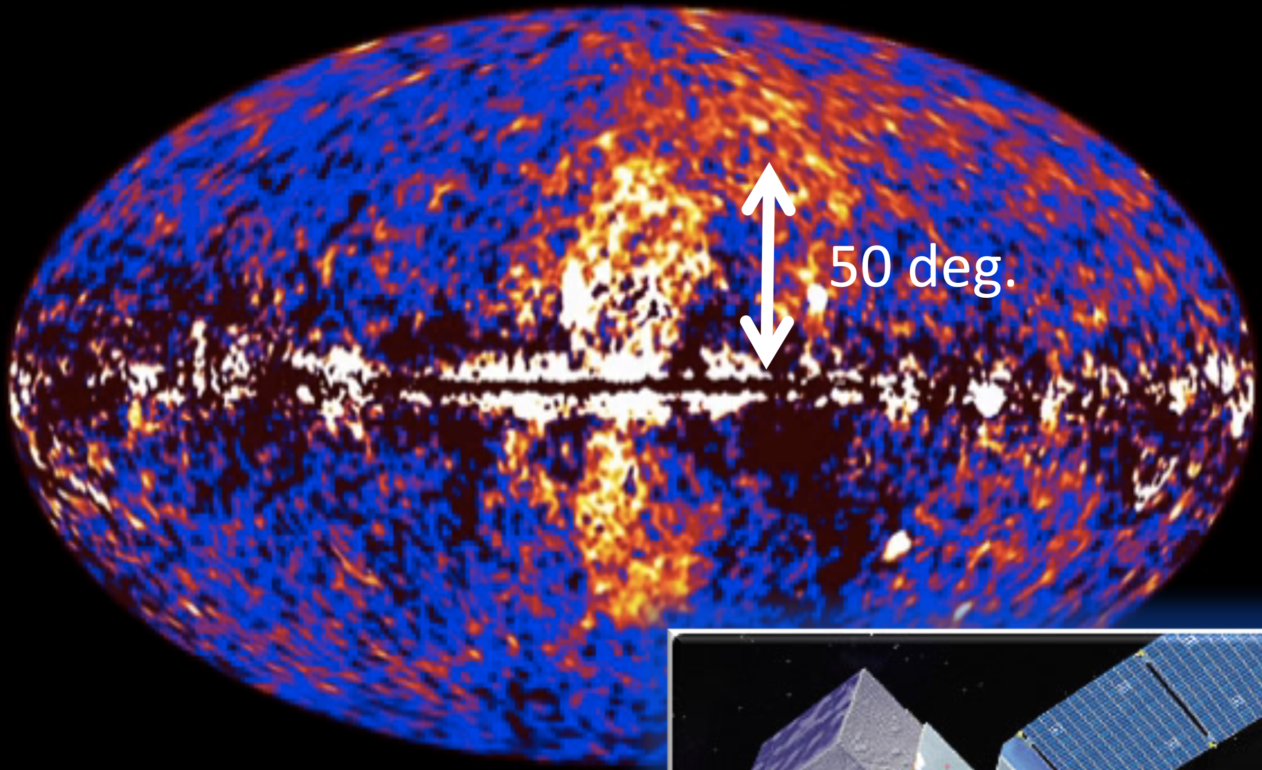
Yang & Ruszkowski, 2017, ApJ submitted (arXiv://1706.05025)

What I proposed three years ago…

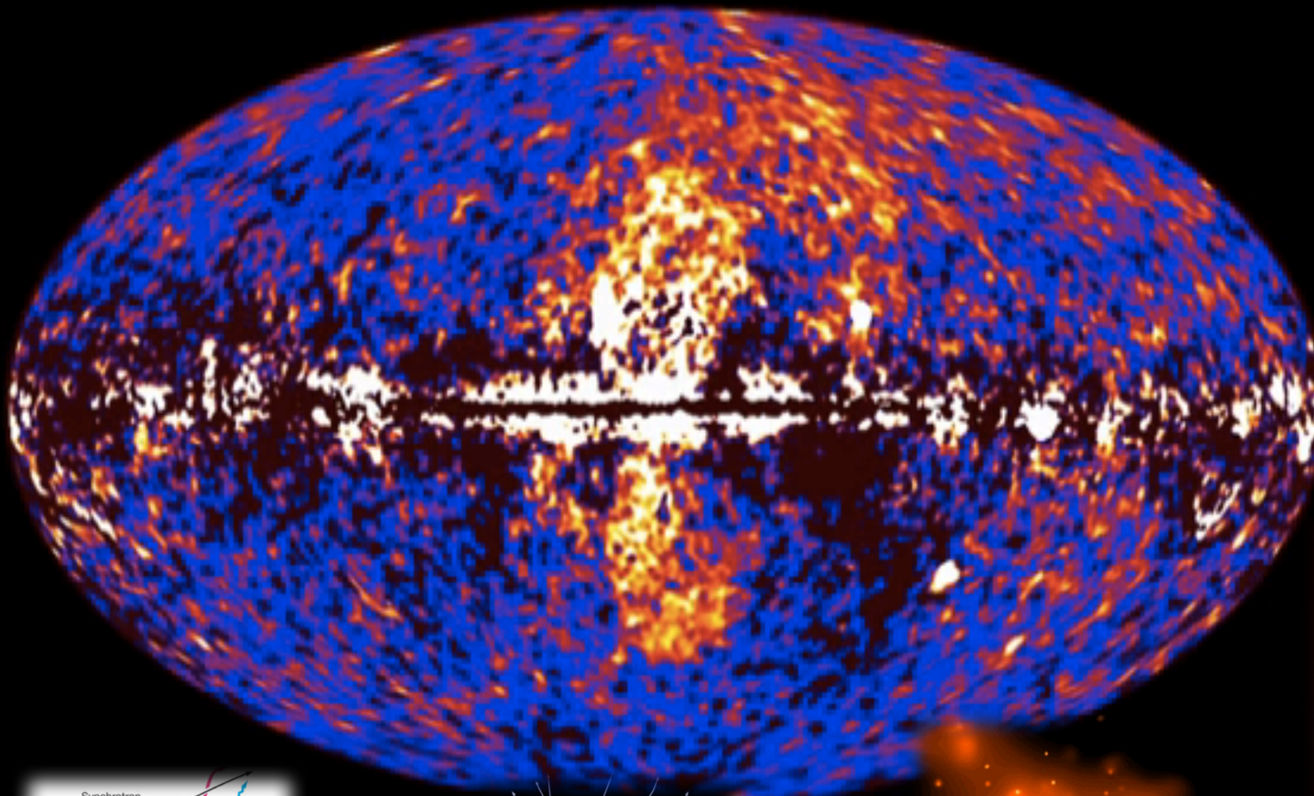
1 Proposed Research

I propose to investigate the physical origin of the *Fermi* bubbles, one of the most important discoveries of the *Fermi Gamma-ray Space Telescope*, using three-dimensional (3D) magnetohydrodynamic (MHD) simulations including relevant cosmic-ray (CR) physics. This study will discover the most important physical mechanisms responsible for the spatially uniform hard spectrum of the observed bubbles. I will constrain the compositions and spectra of CR particles within the bubbles,

The *Fermi* bubbles (Su et al. 2010)

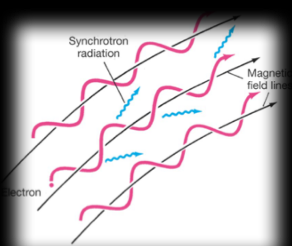


The *Fermi* bubbles (Su et al. 2010)

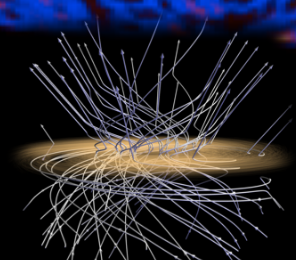


AGN jets

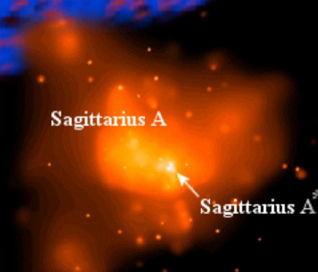
Starburst winds



CR transport

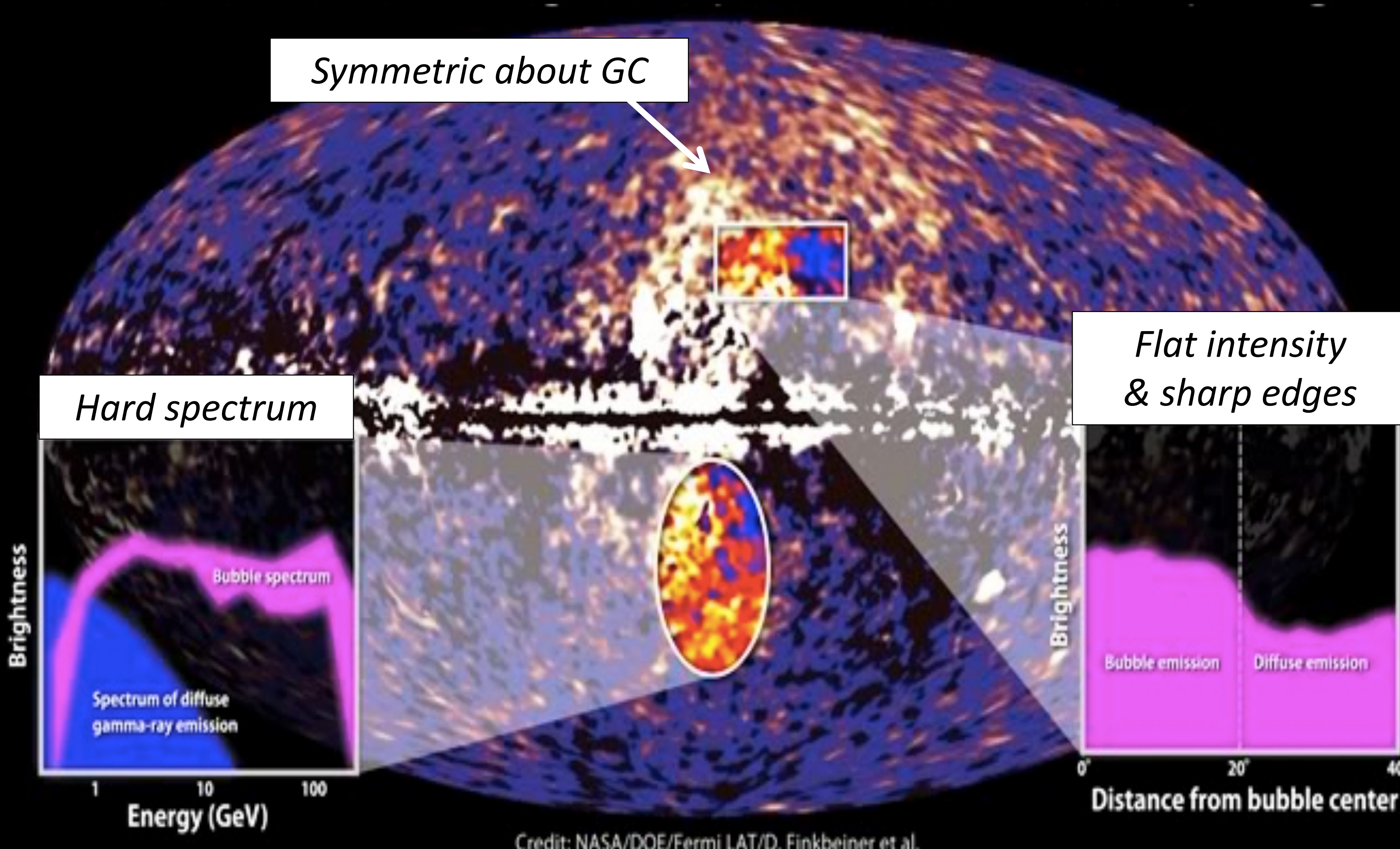


Galactic B field



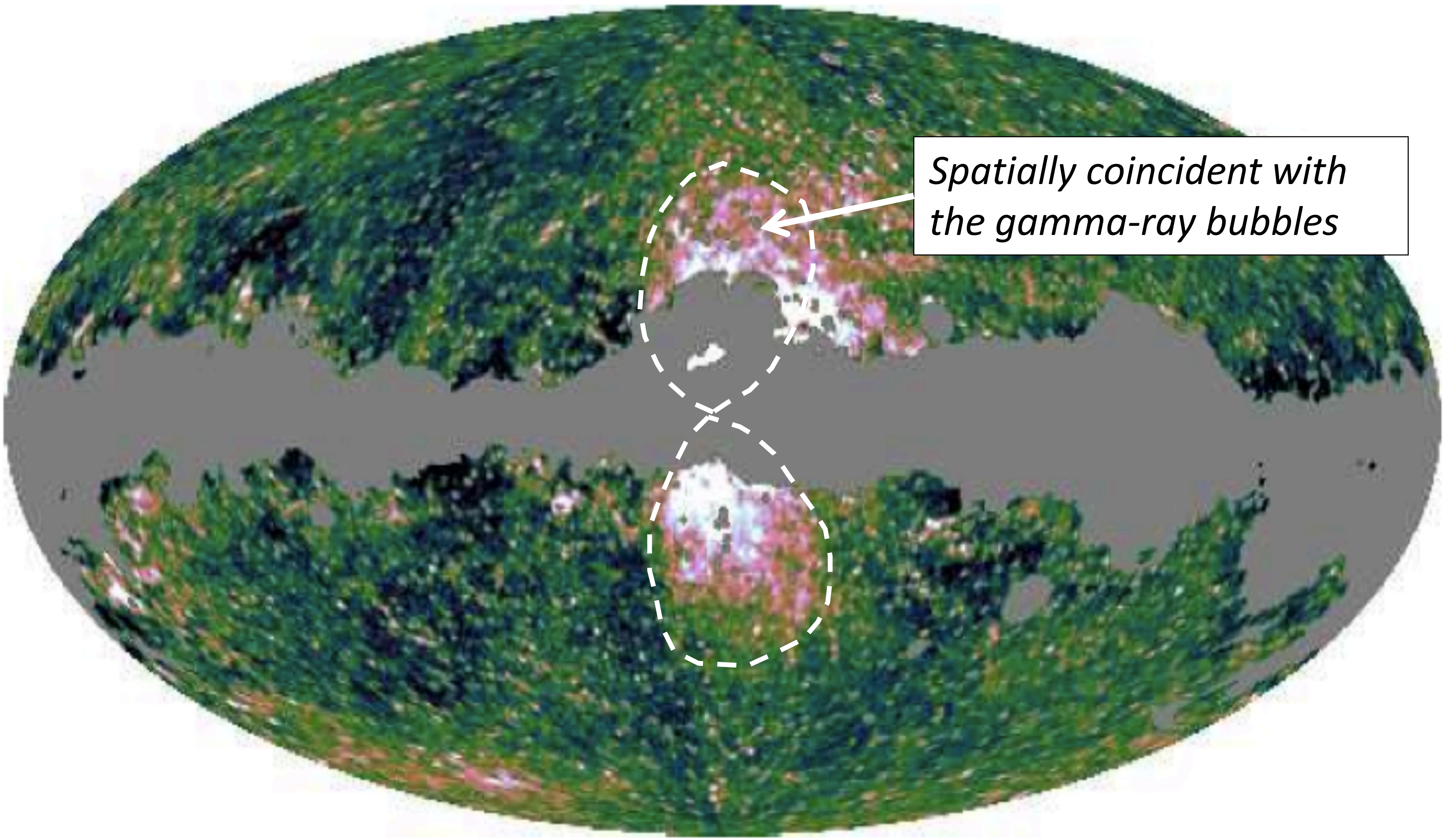
GC activity

The *Fermi* bubbles (Su et al. 2010)

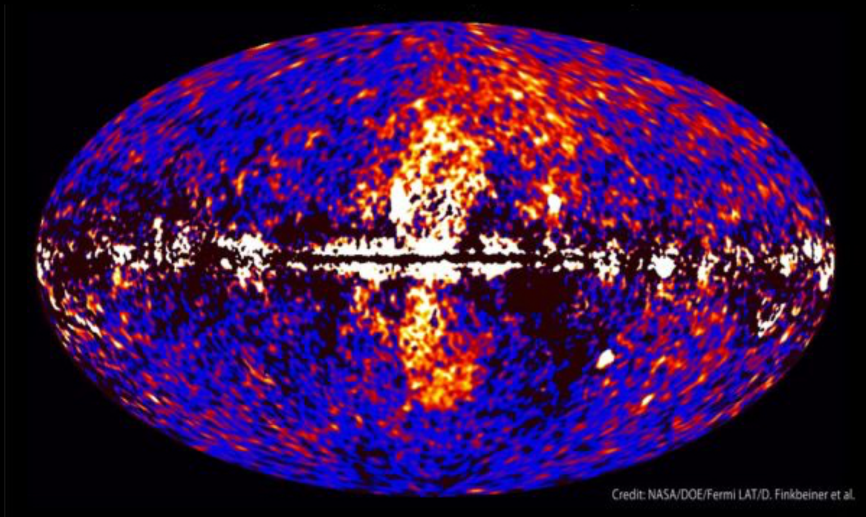


Microwave haze by *WMAP & Planck*

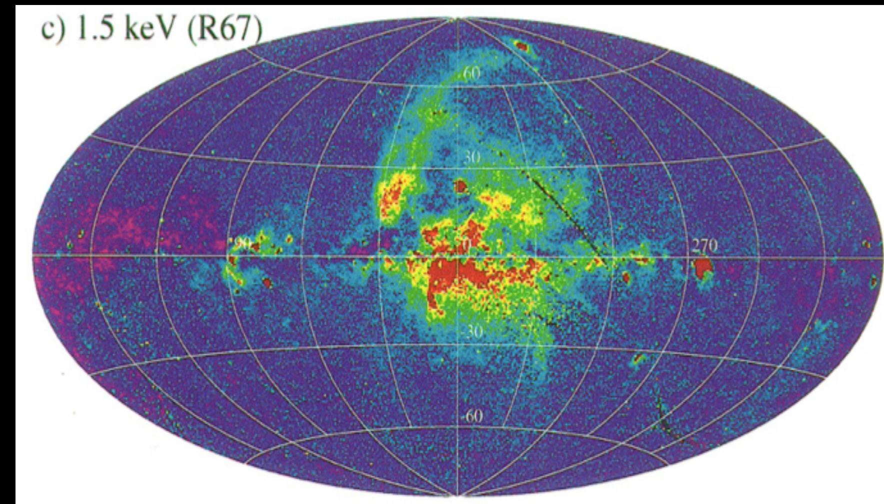
(Finkbeiner 2004, Dobler 2008; Planck Collaboration 2012)



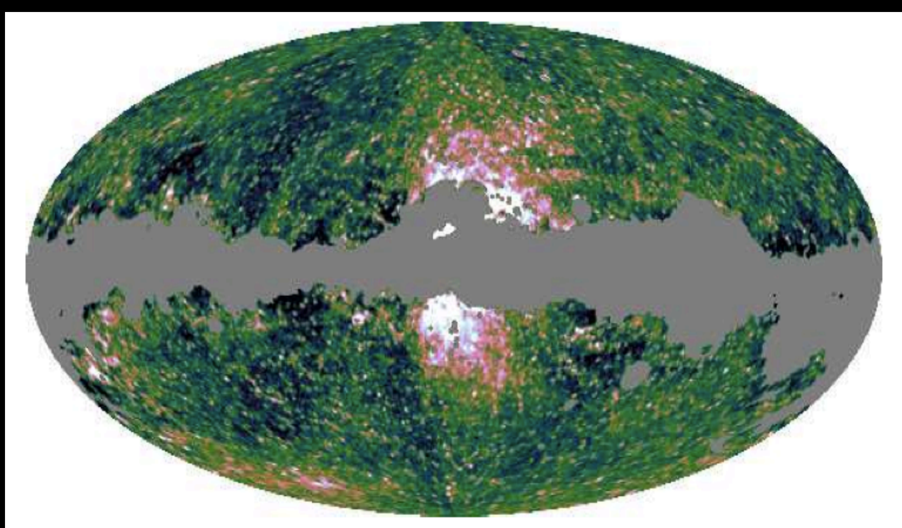
Fermi (Gamma-ray)



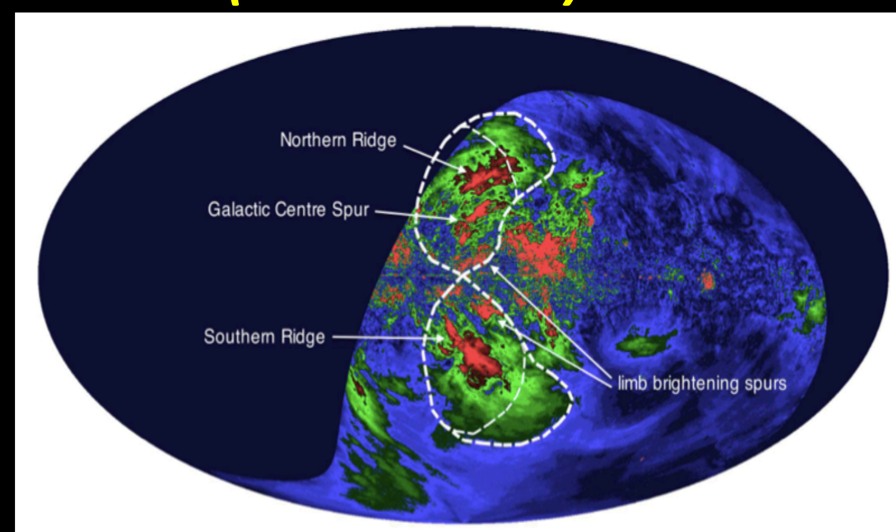
ROSAT (X-ray)



WMAP & Planck (Microwave)

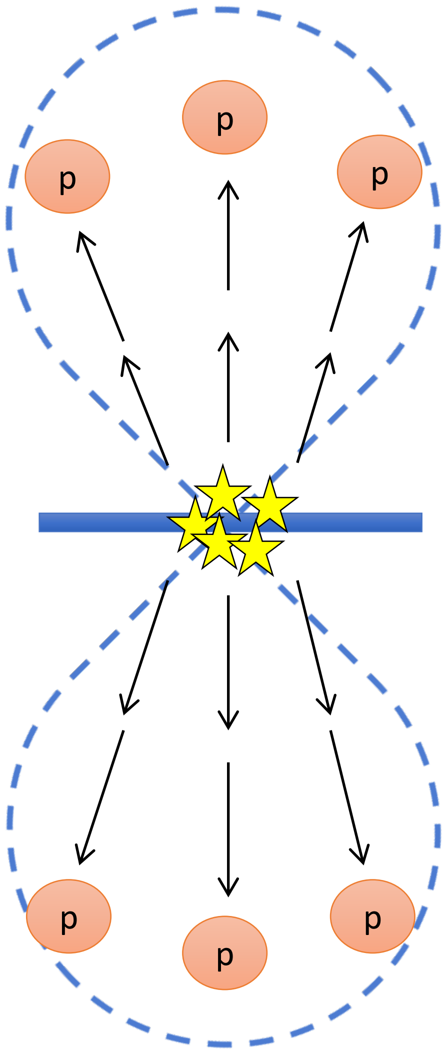


S-PASS (Polarization)



Theoretical Models Proposed

I. Hadronic winds



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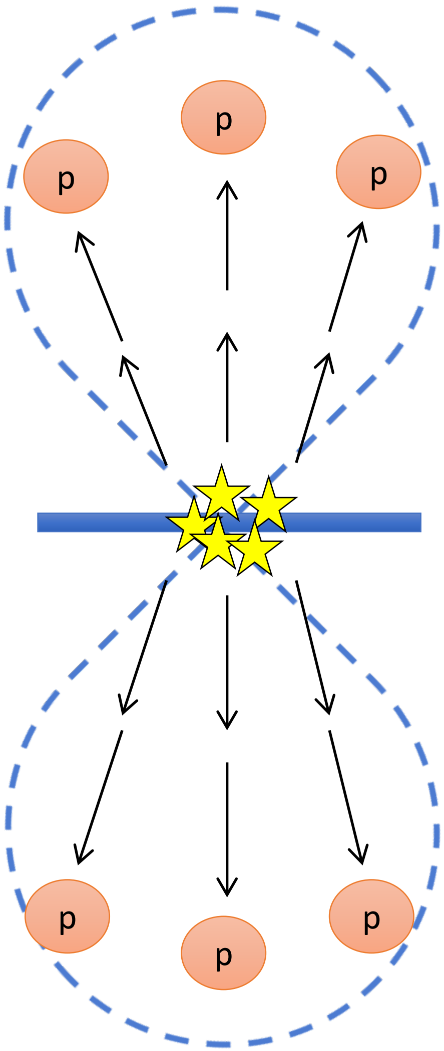
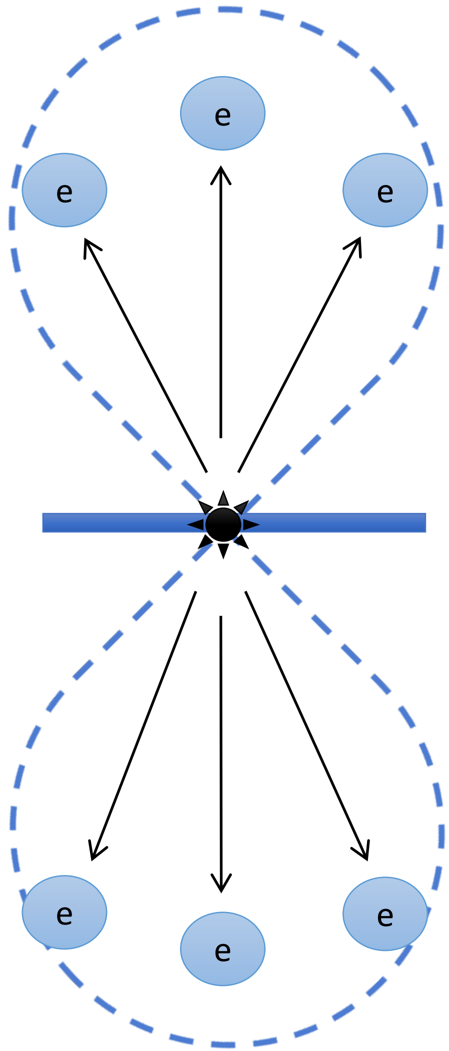


II. Leptonic jets



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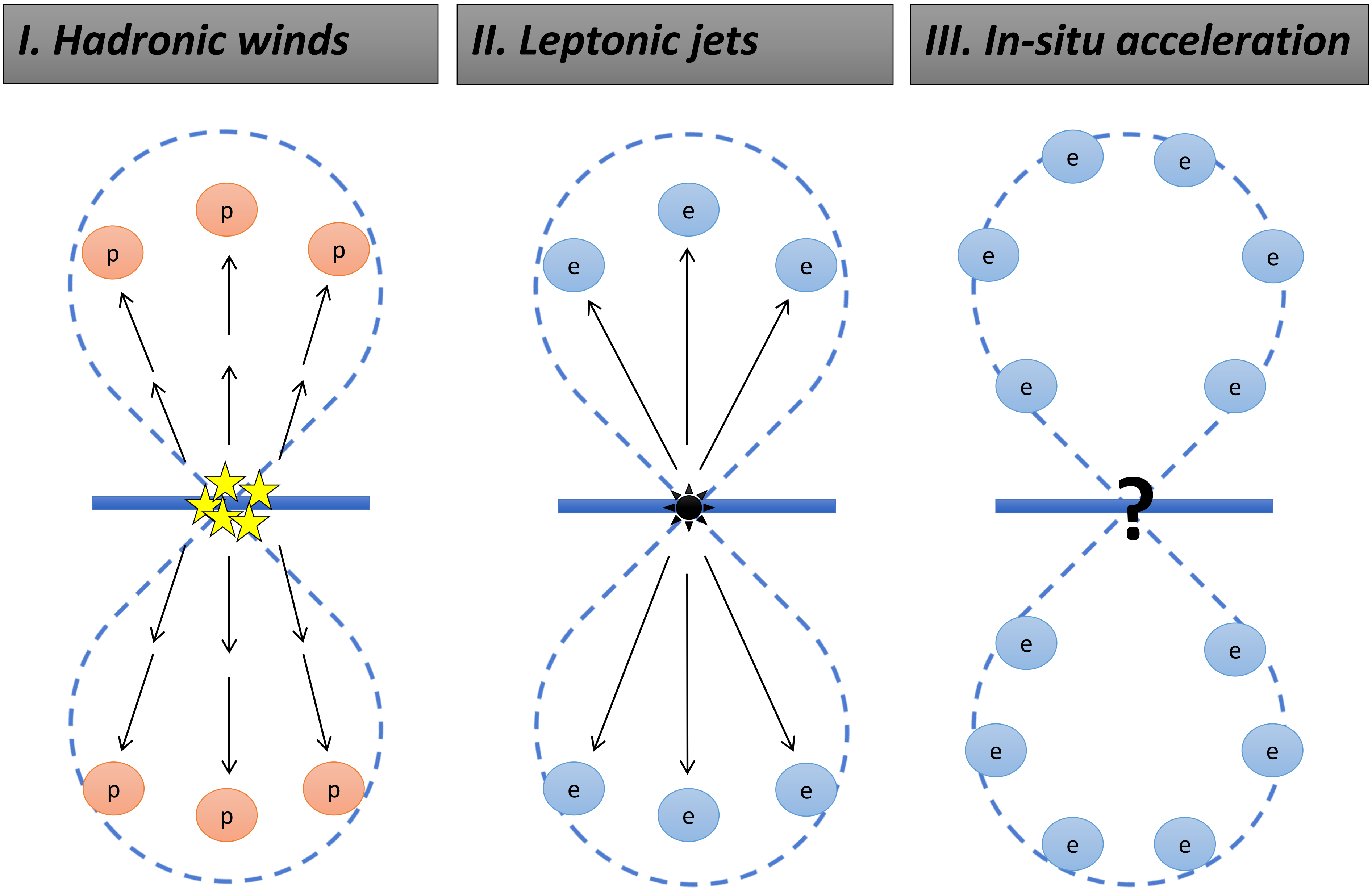
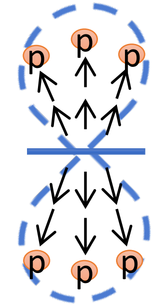


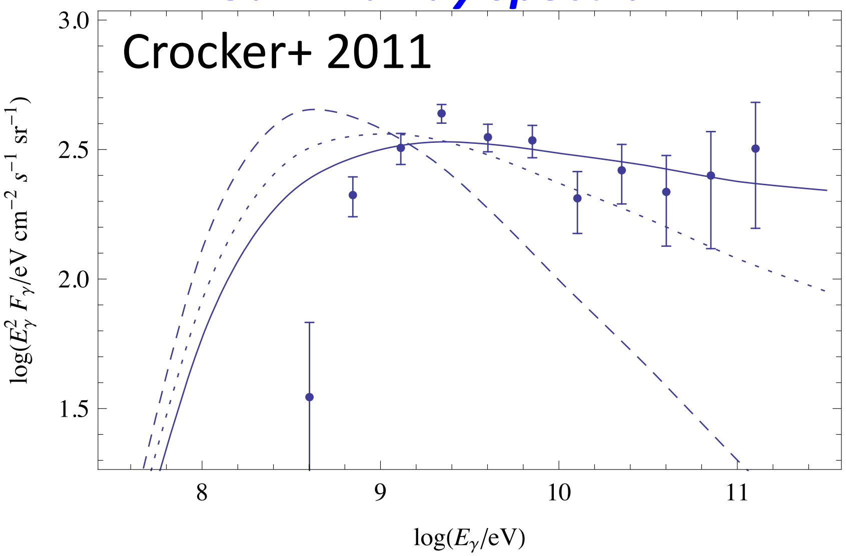
I. Hadronic wind models

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

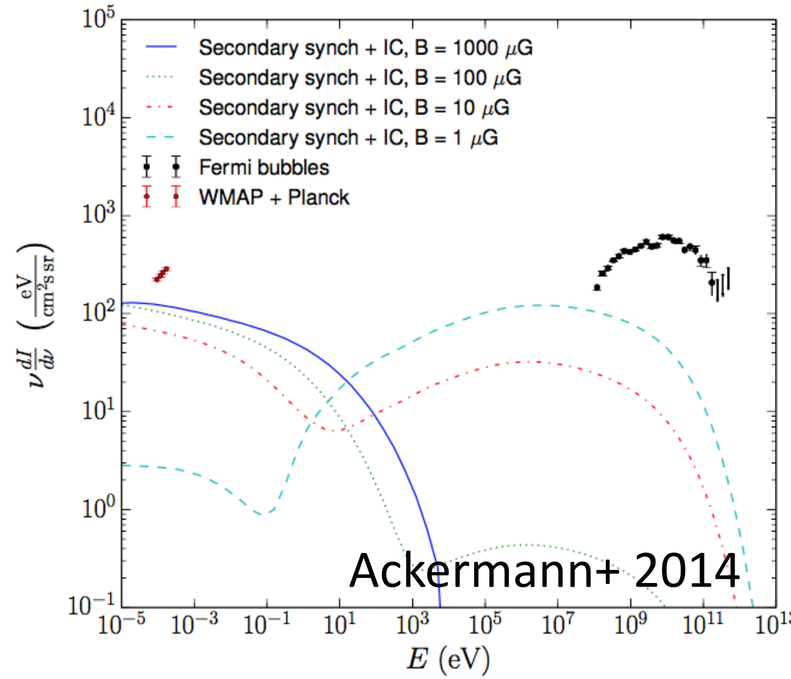


Pro: Hard spectrum naturally preserved

Gamma-ray spectrum



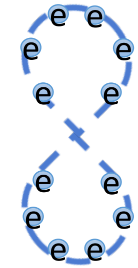
Gamma-ray and microwave spectrum



Con: Secondary leptons fail to reproduce microwave haze

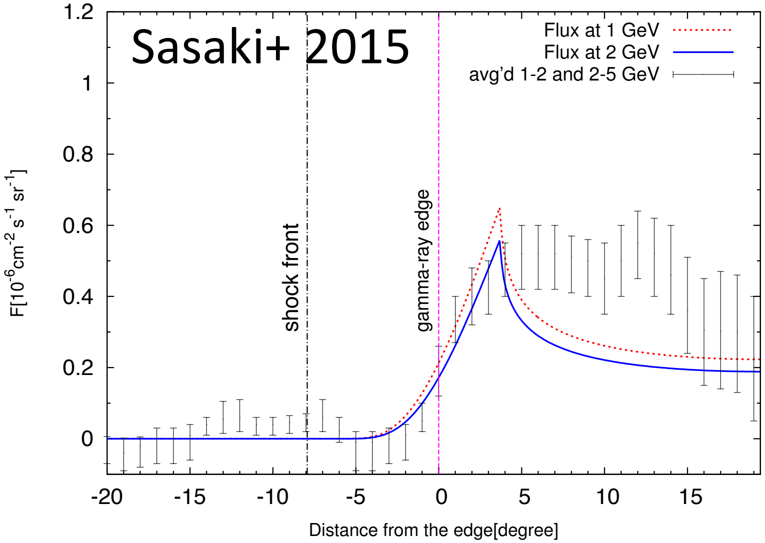
III. In-situ acceleration models

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

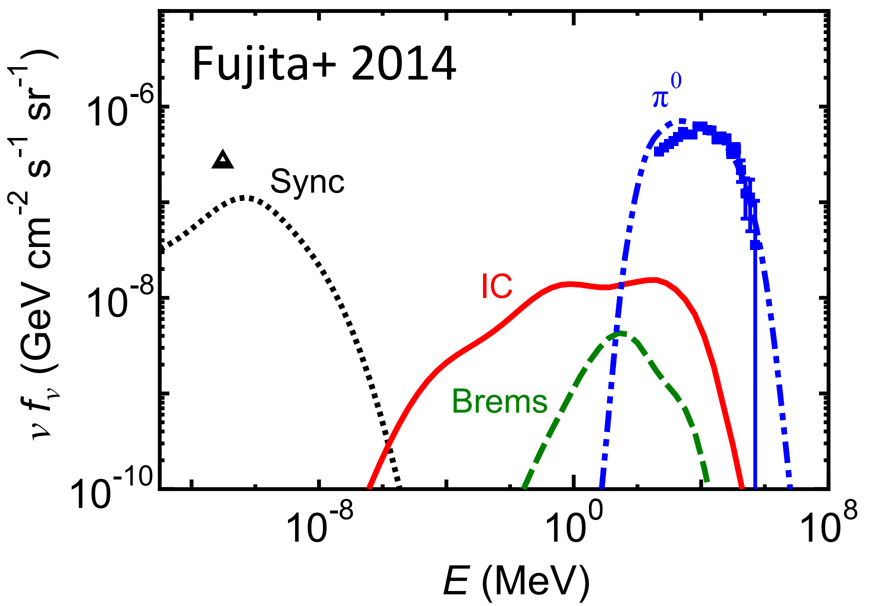


Pros: Free from age constraints, sharp edges

Leptonic gamma intensity



Gamma-ray and microwave spectrum (with CRp)



Cons: hard to produce flat intensity and microwave haze

Theoretical Models Proposed

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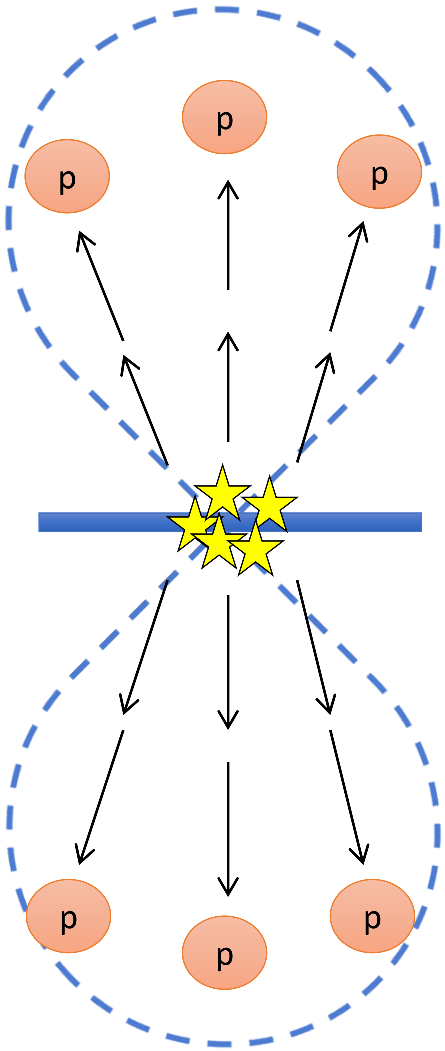

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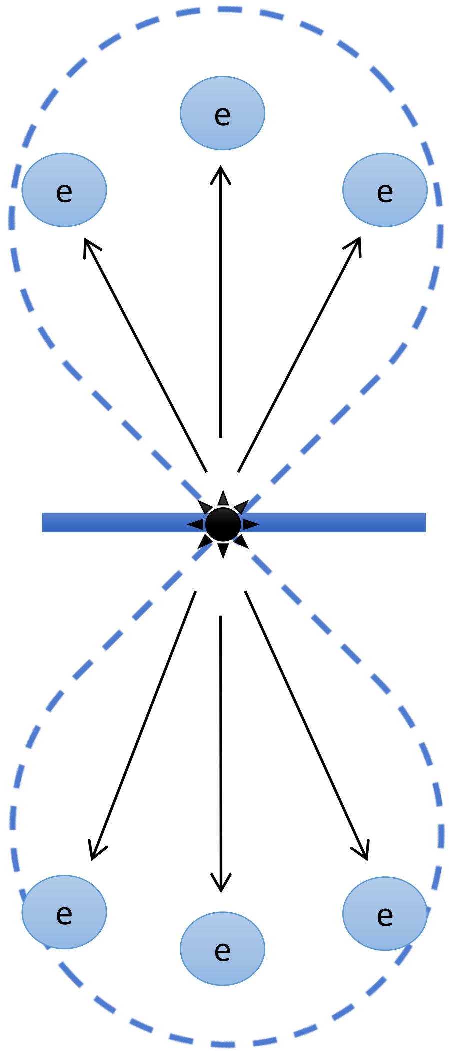

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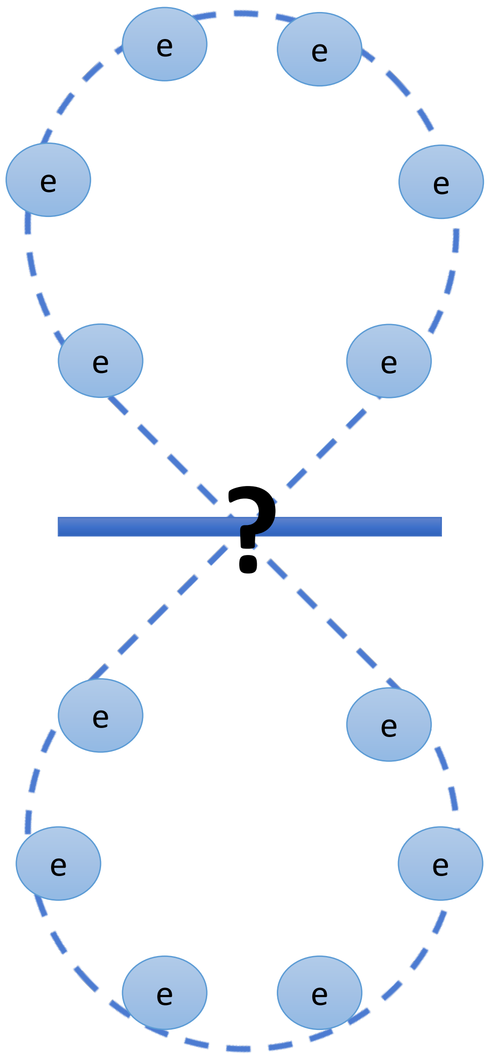
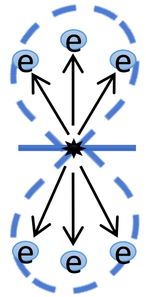
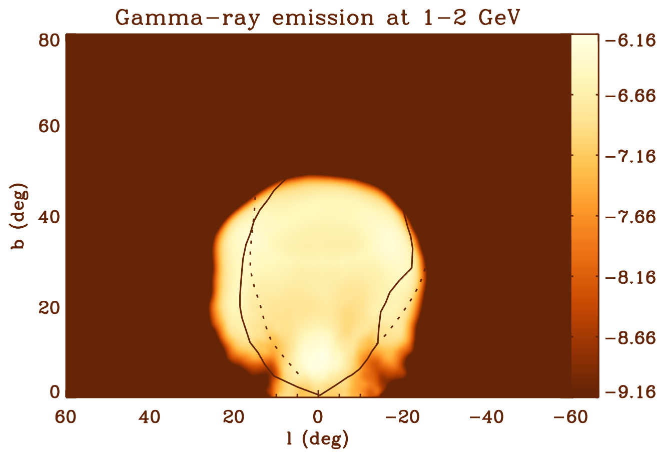


II. Leptonic AGN jet models

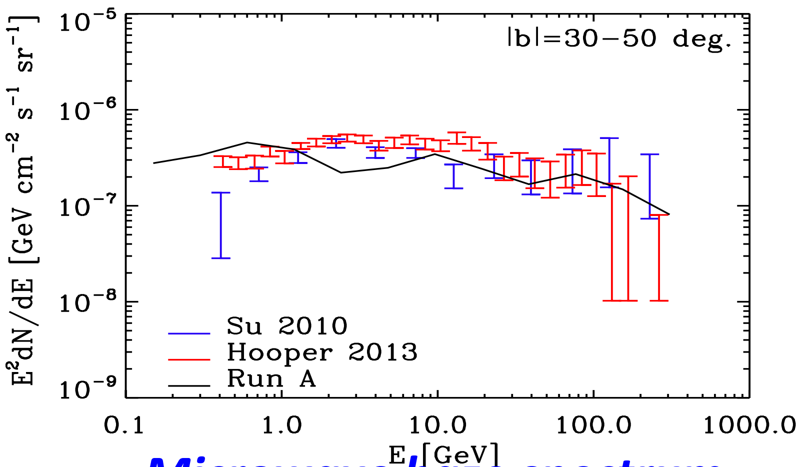
(Yang+ 2012, 2013, see also Guo+2011, 2012, Barkov+ 2013)



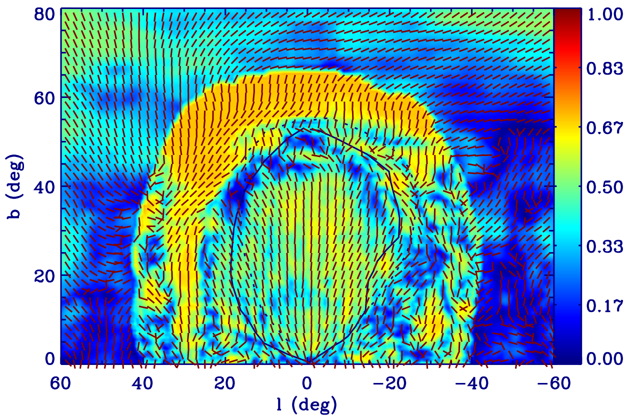
Pros: consistent with gamma-ray, microwave, and polarization signatures



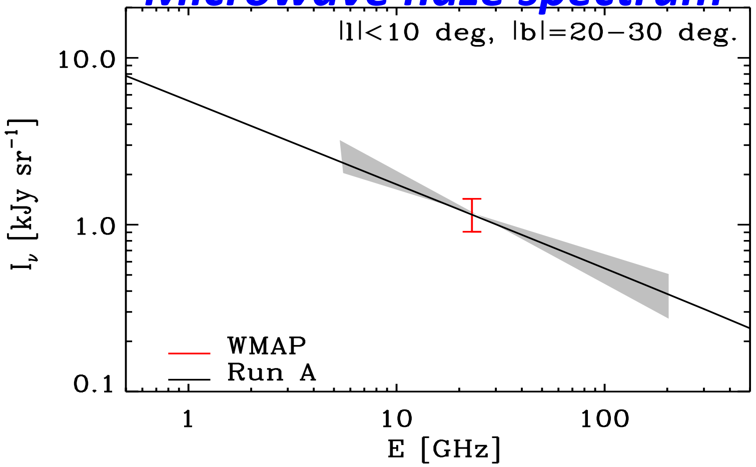
Gamma-ray bubble spectrum



Simulated polarization fraction



Microwave haze spectrum



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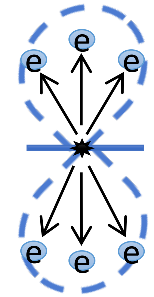

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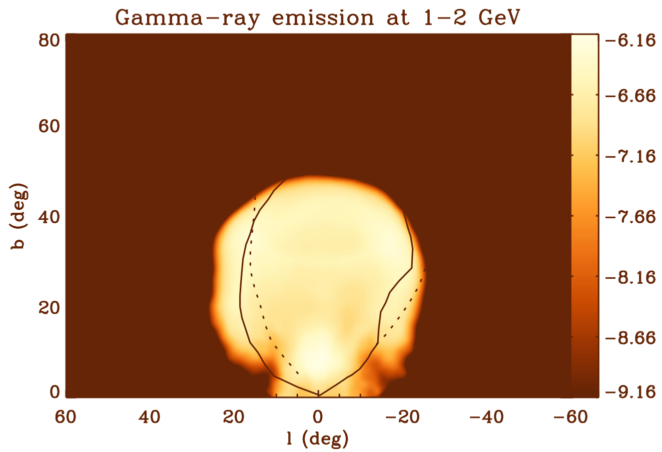
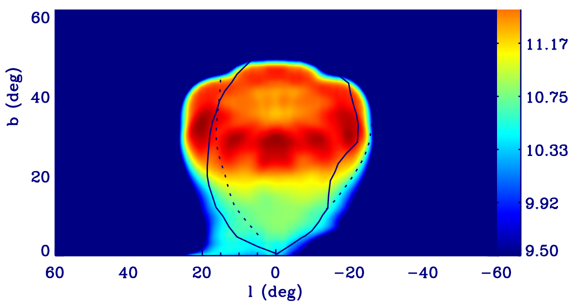
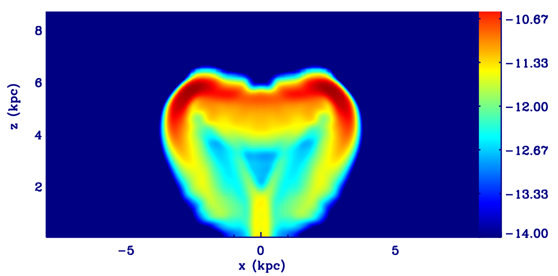


❖ Flat intensity requires correct 3D spatial distribution of CRs

Projected CR energy density

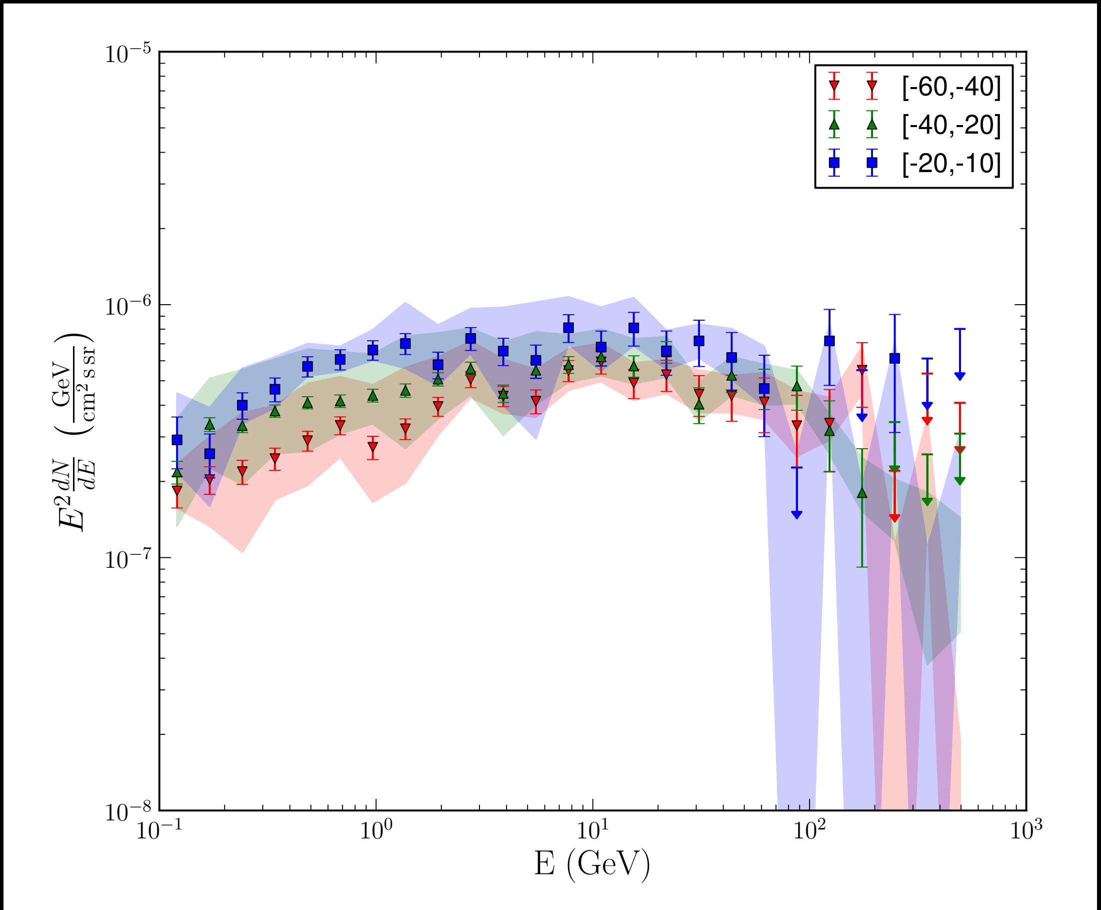


Slice of CR energy density



The spatially uniform high-E cutoff?

Gamma-ray spectrum of the south bubble



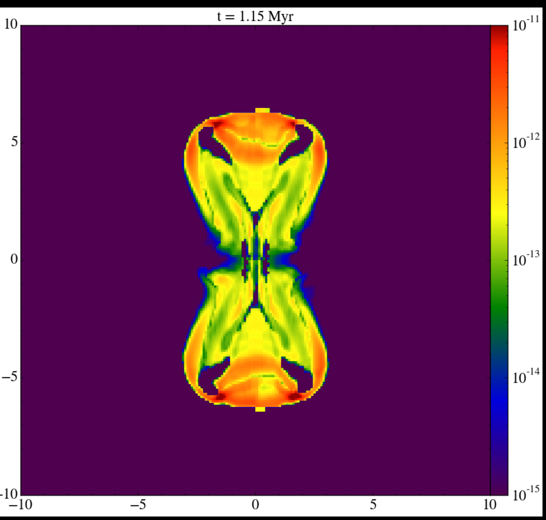
Ackermann et al. (2014)

- Spectrum well fit by a power-law + exp. cutoff
- Spectral index = 1.9
  Cutoff energy = 110 +- 50 GeV
- Latitude independent

Simulating the *Fermi* bubble spectrum
(Yang & Ruszkowski 2017)

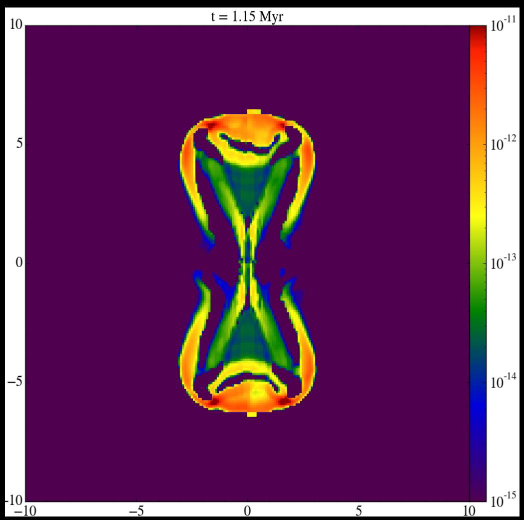
- Implemented *CRSPEC* module in FLASH **NEW!!**
- Injection spectrum: 10 GeV ~ 10 TeV, spectral index=2.1
- IC & syn. cooling (GALPROP's ISRF & B field)

Total CR energy density



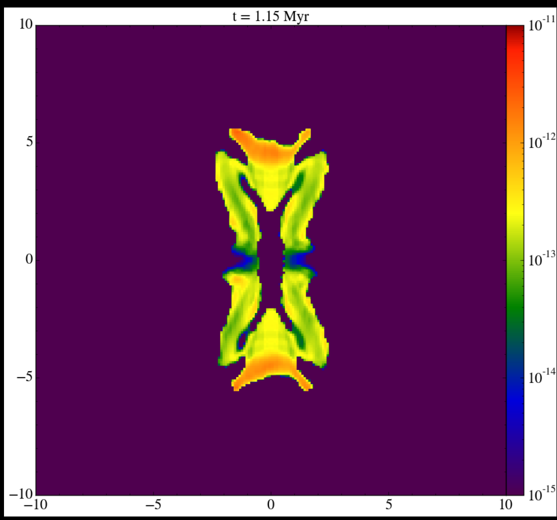
=

CR energy density (>10 GeV)



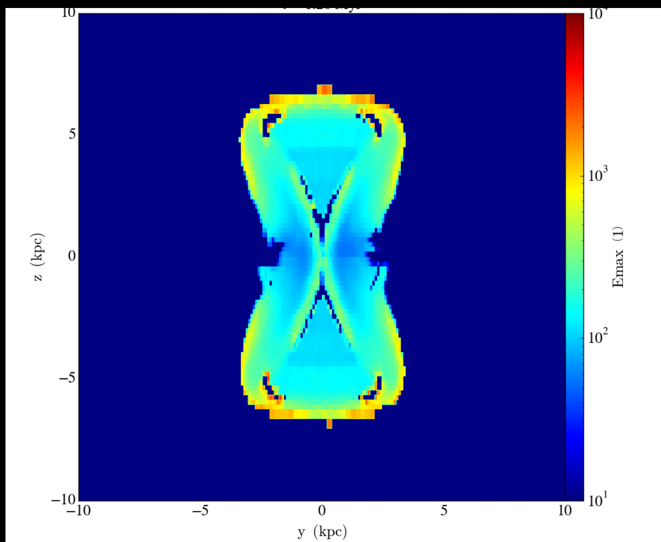
+

CR energy density (<10 GeV)



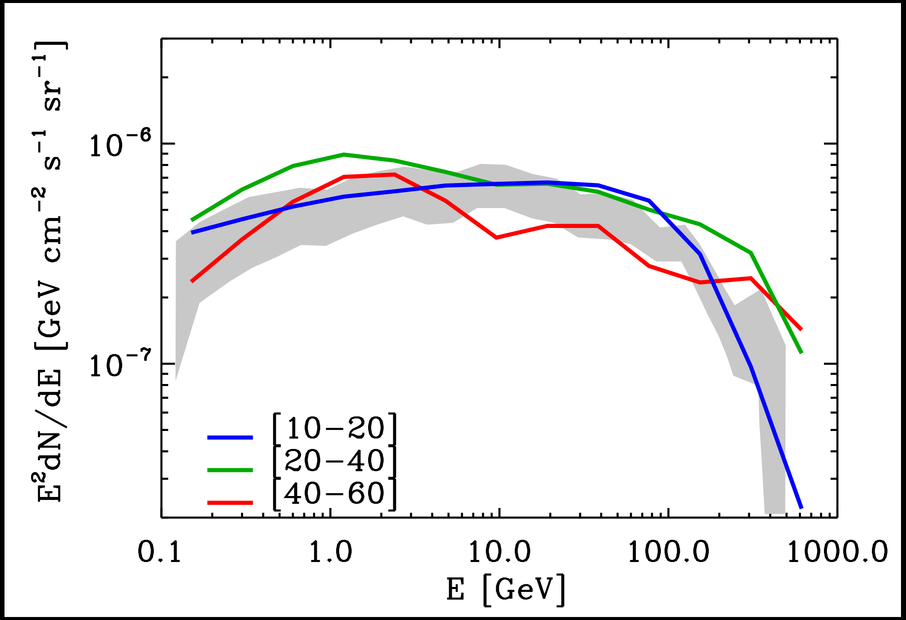
The spatially uniform high-E cutoff!!
(Yang & Ruszkowski 2017)

Maximum energy of the CR spectrum



- Emax ~ 300 GeV
- No significant spatial variation

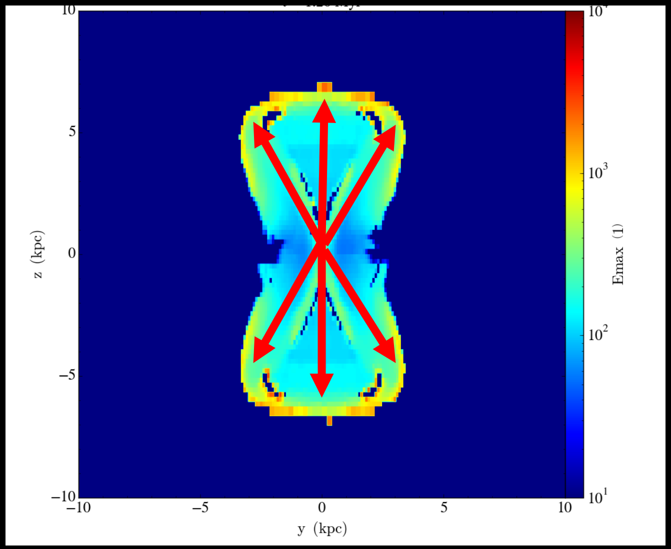
Simulated gamma-ray spectra



- Ecut ~ 100 GeV
- Latitude independent

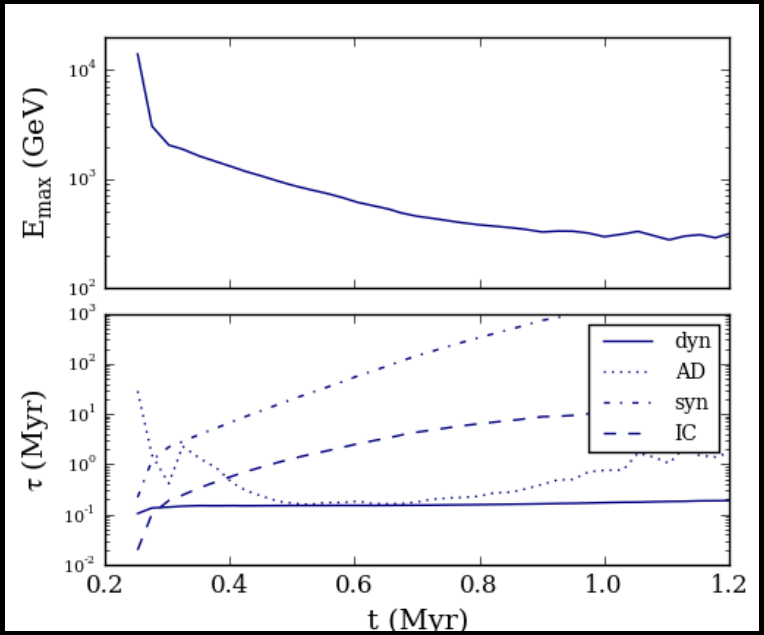
The spatially uniform high-E cutoff!!
(Yang & Ruszkowski 2017)

Maximum energy of the CR spectrum



- Emax ~ 300 GeV
- No significant spatial variation

Emax and timescales of a tracer particle



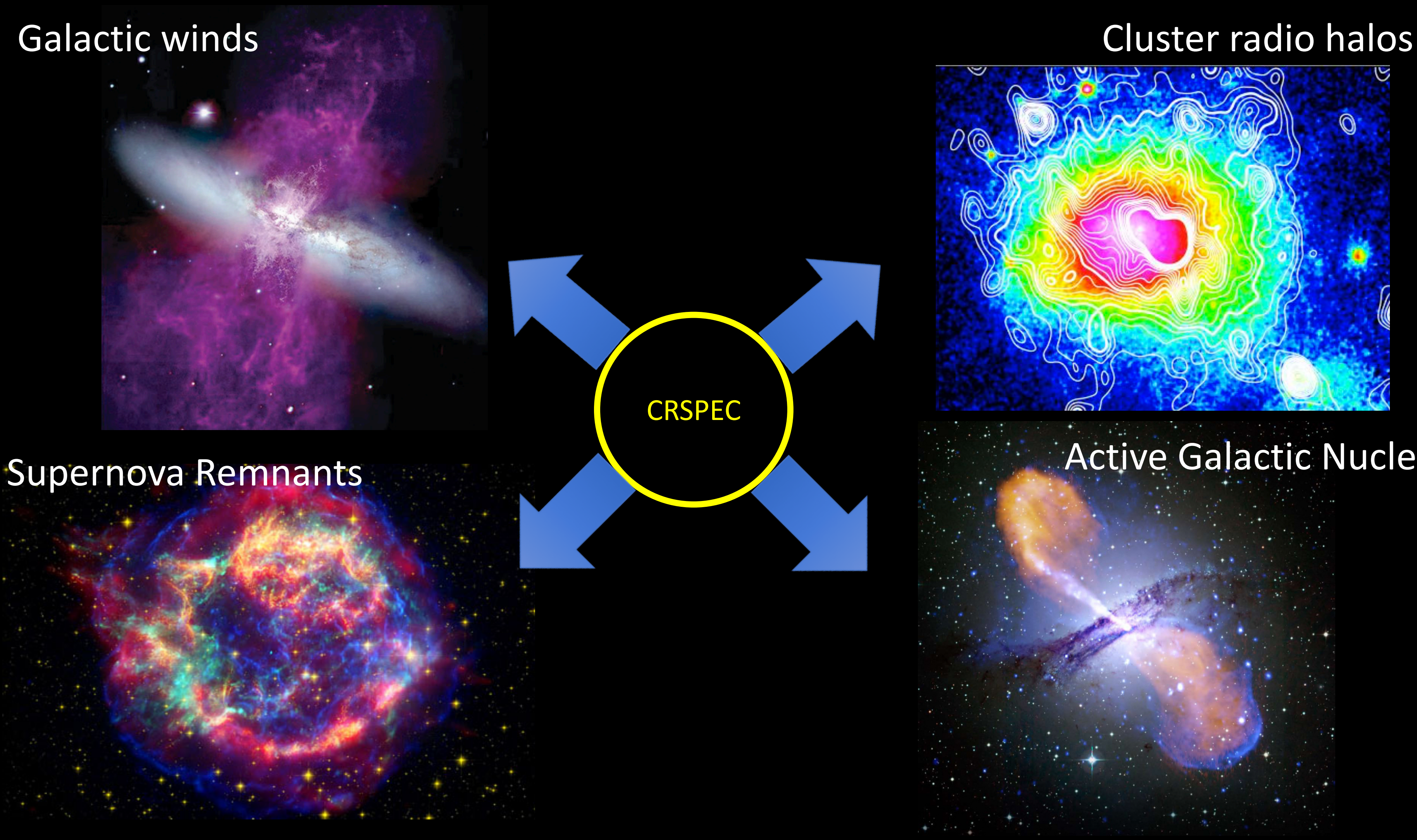
- Fast IC & syn. cooling near GC
- At later times, advection dominates w/ mild cooling due to ad. expansion

Summary

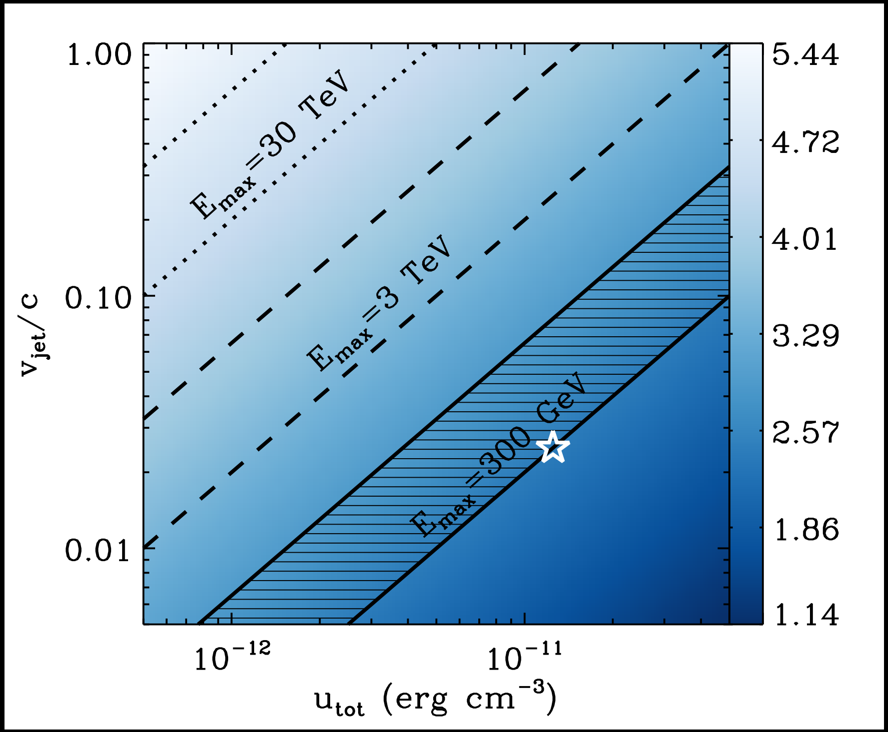
- The ***spatially uniform high-E spectral cutoff*** of the Fermi bubbles can be explained by ***leptonic AGN jets***
  -- ***fast cooling of CRe near the GC***
  -- ***fast advection by AGN jets*** afterwards

- The leptonic jet model predicts ***3D spatial and spectral*** CR distributions consistent with data

- The new ***CRSPEC*** module in FLASH could track CR spectral evolution on-the-fly, making it a powerful tool to study the non-thermal sky


Galactic winds
Cluster radio halos
CRSPEC
Supernova Remnants
Active Galactic Nuclei

Constraints on the initial conditions from Ecut



Requirements for successful models:

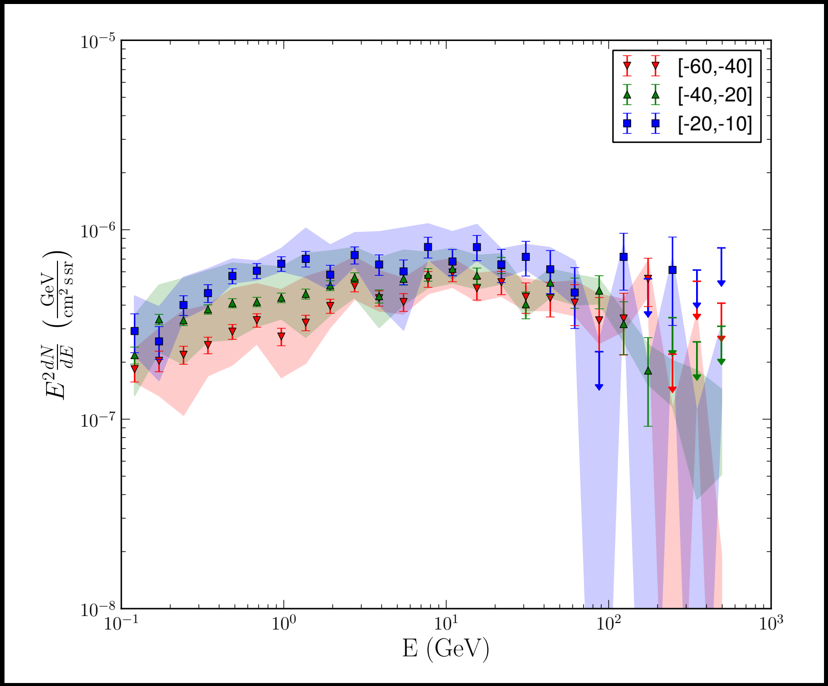
(1) $t_{cool} < t_{dyn}$ near the GC

(2) $E_{max} > E_{max,obs}$ today

- If B were larger, need faster jets
- For typical B, v_{jet} > 3000 km/s
- If future E_{cut} is larger, it requires smaller B or faster v_{jet}

The spatially uniform spectrum?

Gamma-ray spectrum of the south bubble



Ackermann et al. (2014)

- ❖Overall shape is uniform?

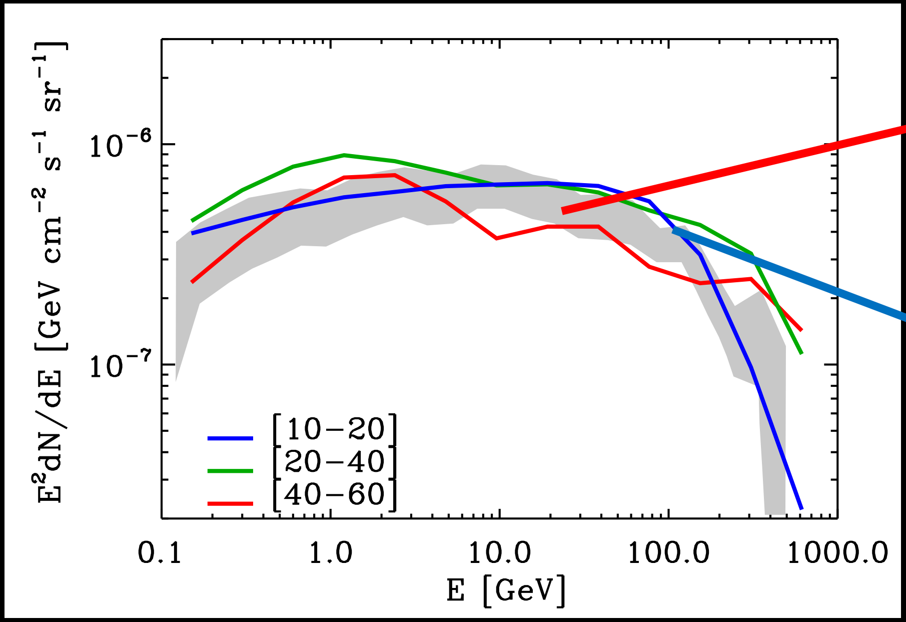
$$\langle E_\gamma \rangle = (4/3)\gamma^2 \langle E_{\mathrm{ph}} \rangle.$$

- ❖High energy cutoff ~ 110 GeV is latitude independent?

The spatially uniform spectrum – *overall shape*!!

(Yang & Ruszkowski 2017)

Simulated gamma-ray spectra

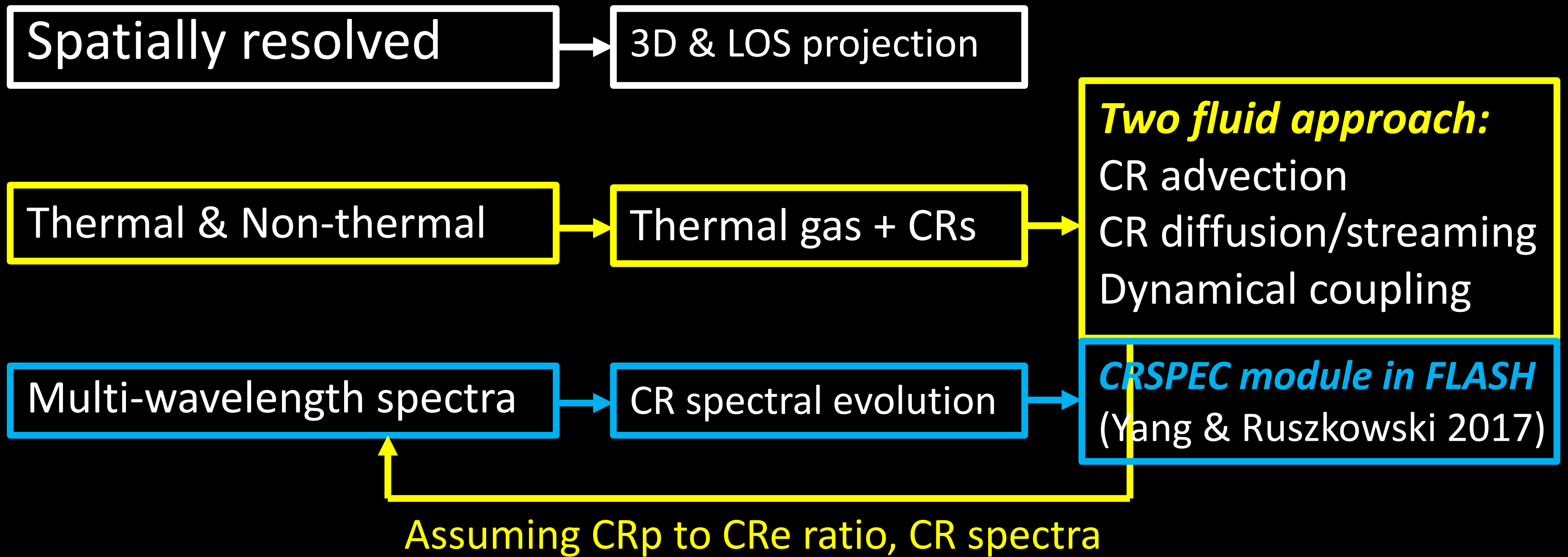


Higher-E CRs & CMB photons

lower-E CRs & optical photons

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

Modeling the *Fermi* bubbles



The *CRSPEC* module in FLASH

(Yang & Ruszkowski 2017, see also Miniati 2001)

NEW!!

- CRs are divided into N log-spaced momentum bins
- Assume f(p) is a piecewise power law => $(f_i, q_i) \leftrightarrow (n_i, e_i)$
- Update (n_i, e_i) using fluxes due to CR heating or cooling