Stochastic Acceleration by Turbulence in the Fermi Bubbles

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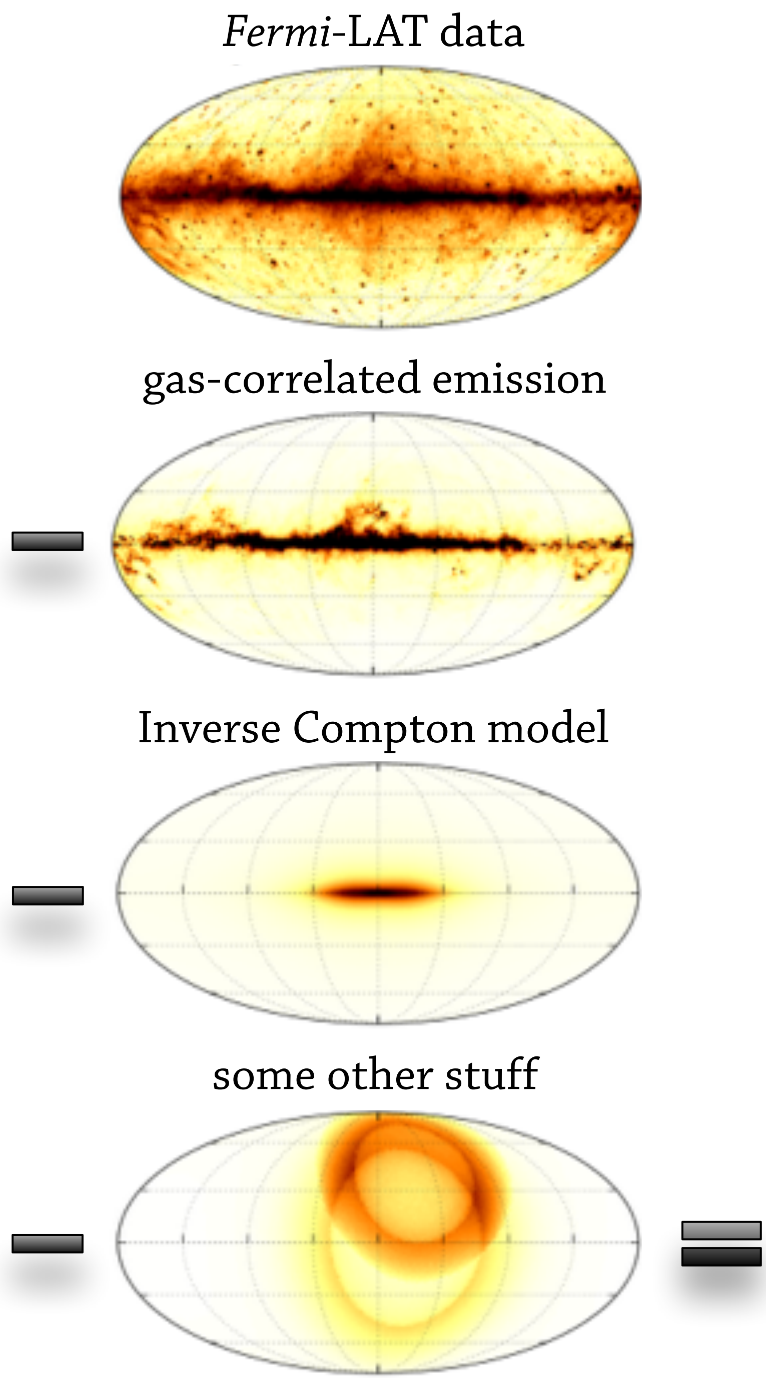
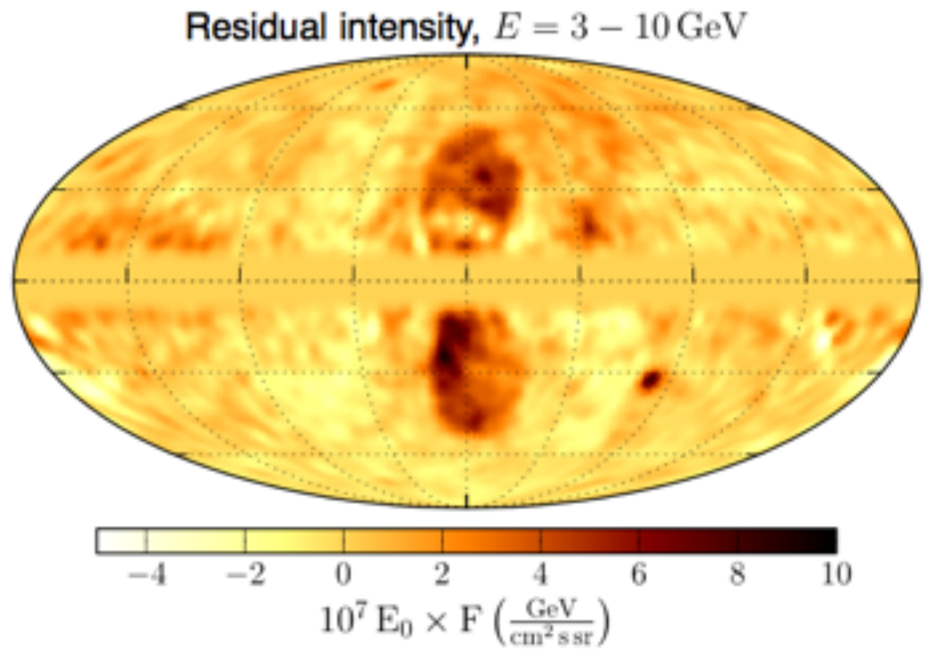
The Niels Bohr International Academy

UNIVERSITY OF COPENHAGEN
FACULTY OF SCIENCE

Fermi bubbles



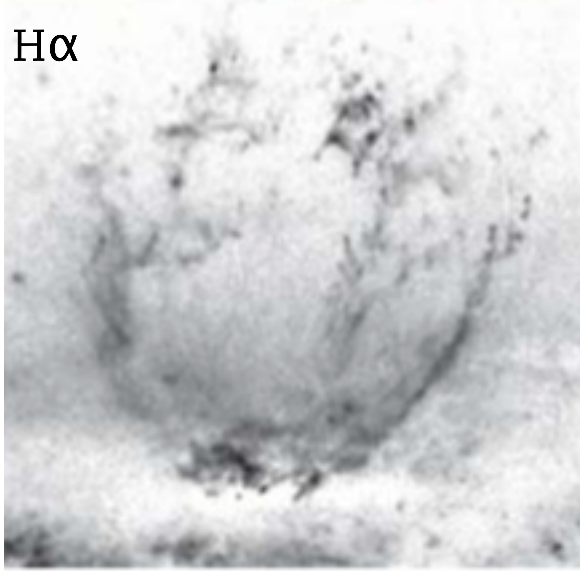


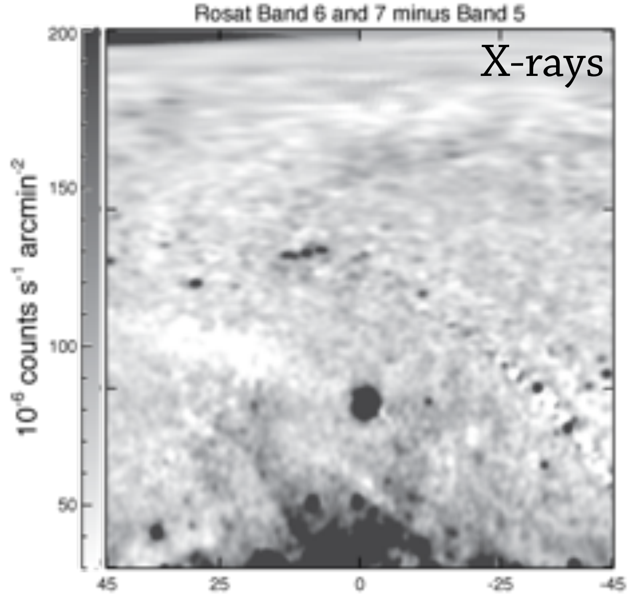
- hard spectrum
- sharp edges
- no spectral variation

Ackermann *et al.* (2014); also Su et al. ApJ 724 (2010) 1044

Hints

NGC 3079, Veilleux *et al.*, Ann. Rev. Astron. Astrophys. **43** (2005) 769

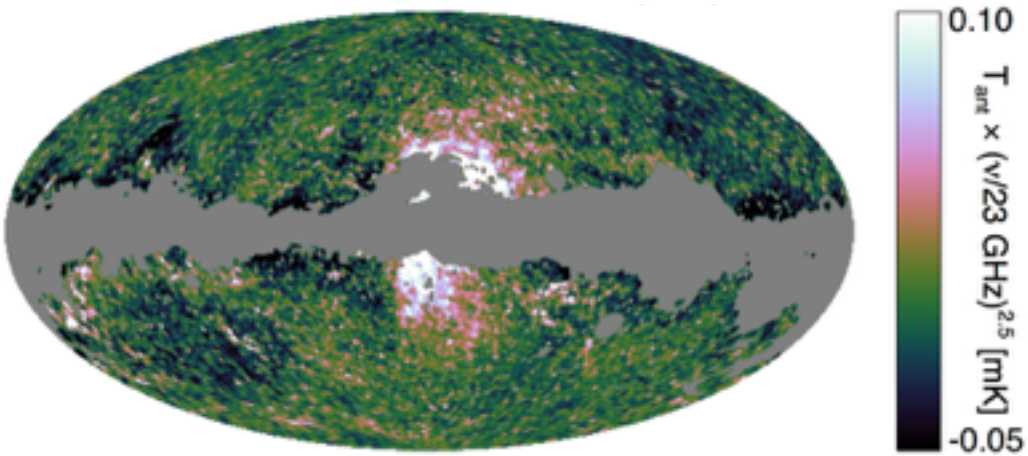




Su *et al.* ApJ **724** (2010) 1044

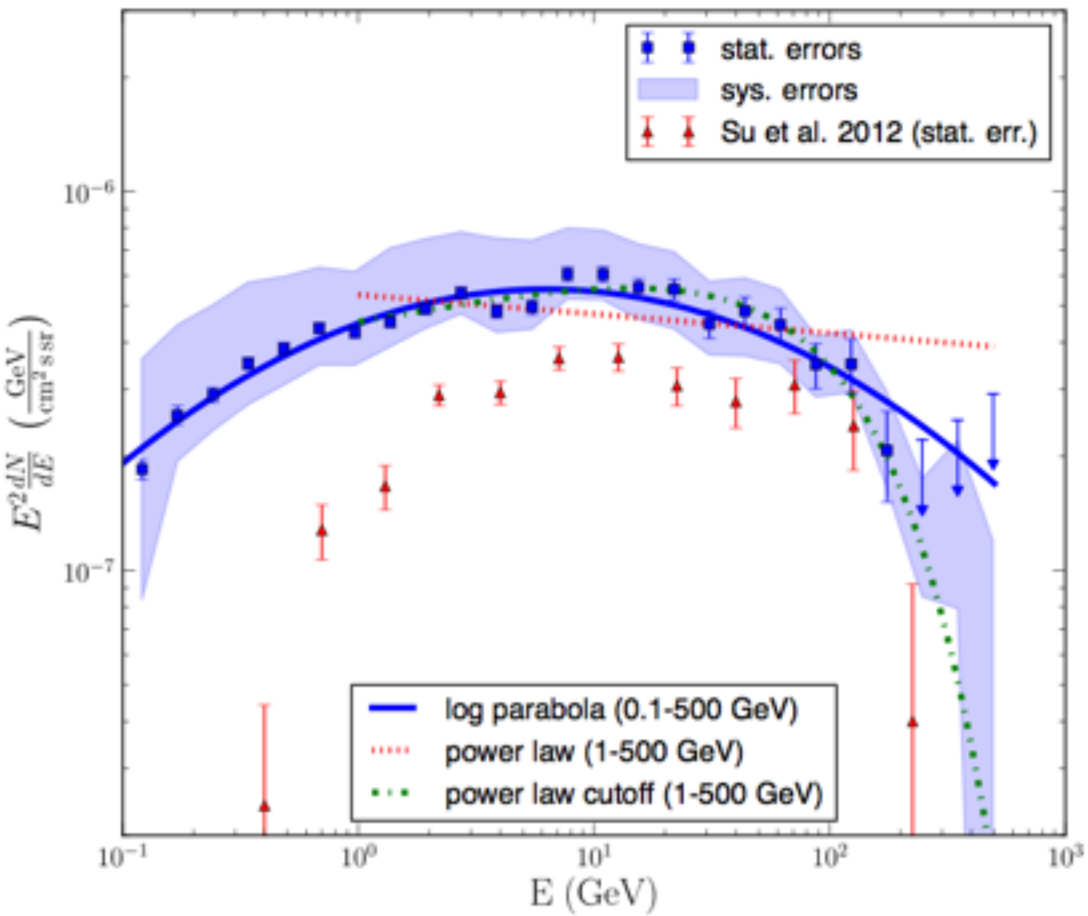
microwaves

Ade *et al.*, A&A **554** (2013) A139



Hard spectrum

Ackermann *et al.*, ApJ **793** (2014) 64



hadronic model

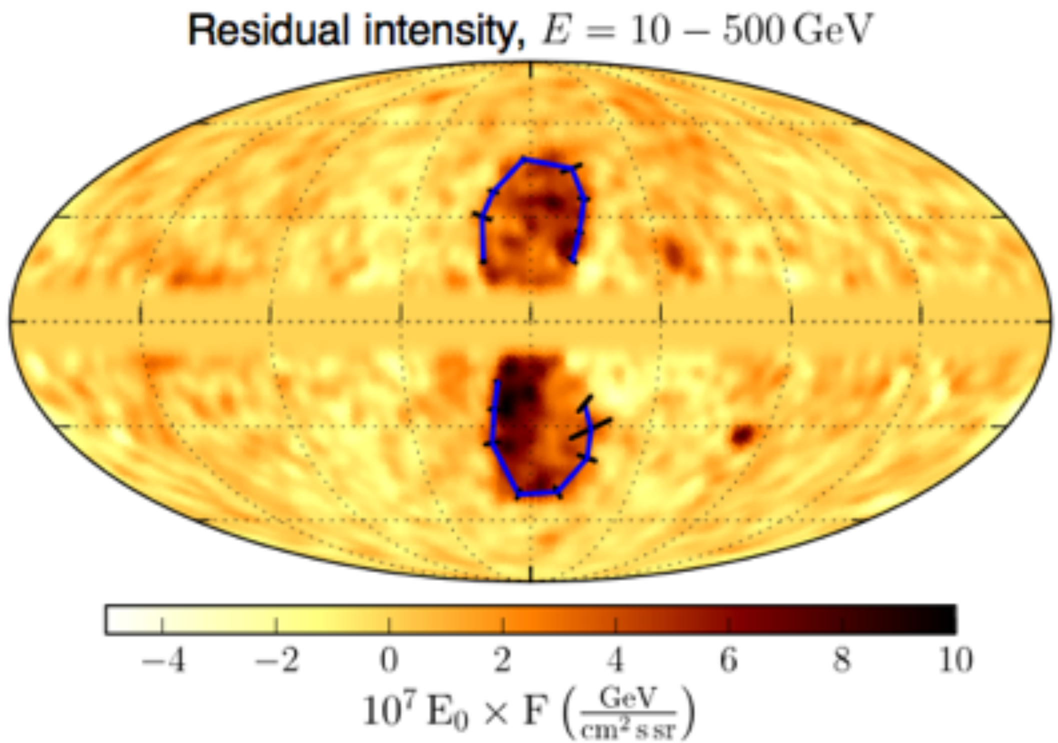
- ☺ low energy hardening
- ☹ cutoff around few hundred GeV

leptonic model

- ☺ cutoff due to energy losses
- ☺ can also get hardening at low energies
- ☹ how to maintain TeV energies over Myrs?

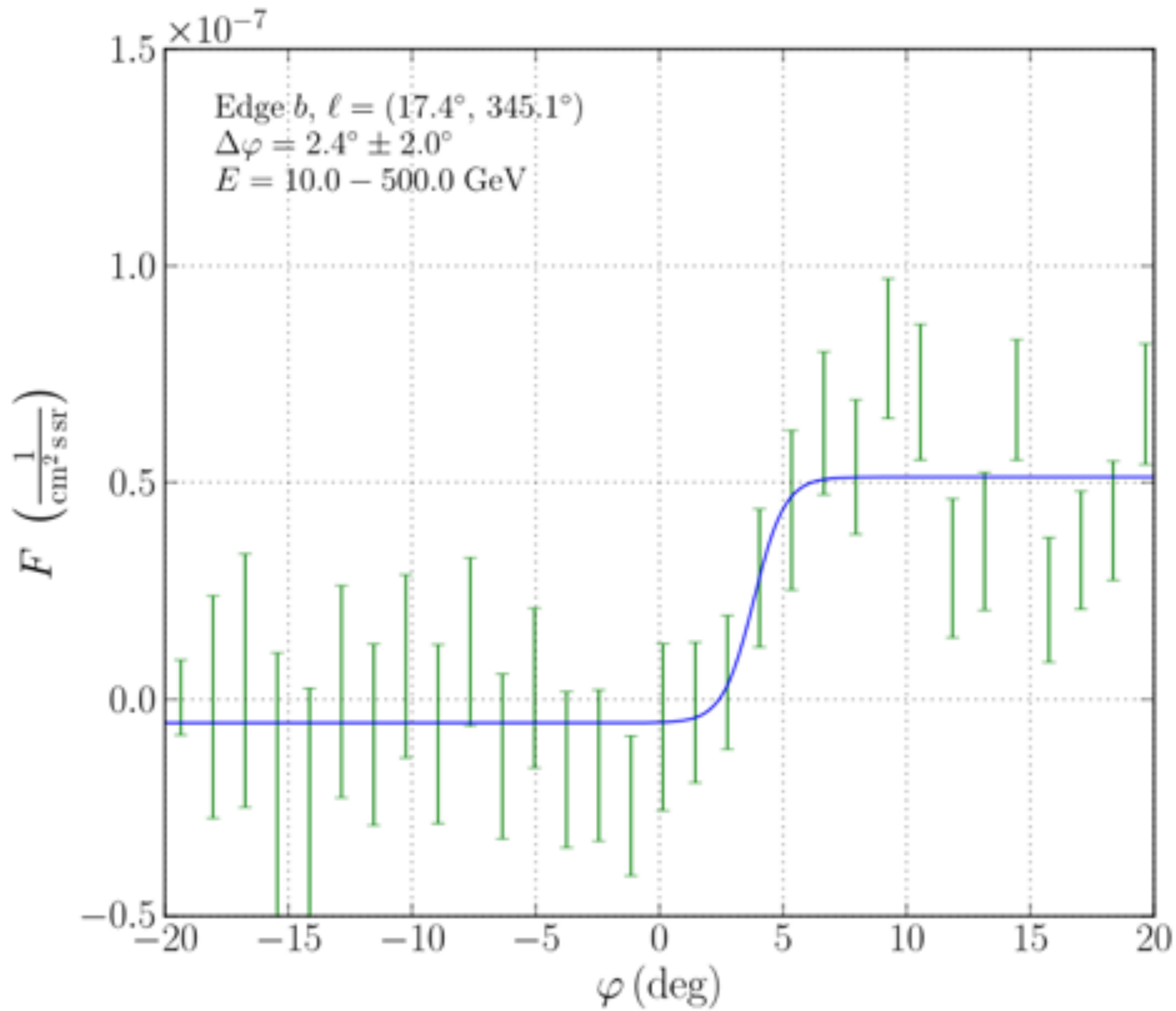
→ *in-situ* acceleration

Sharp edges



Ackermann *et al.*, ApJ **793** (2014) 64

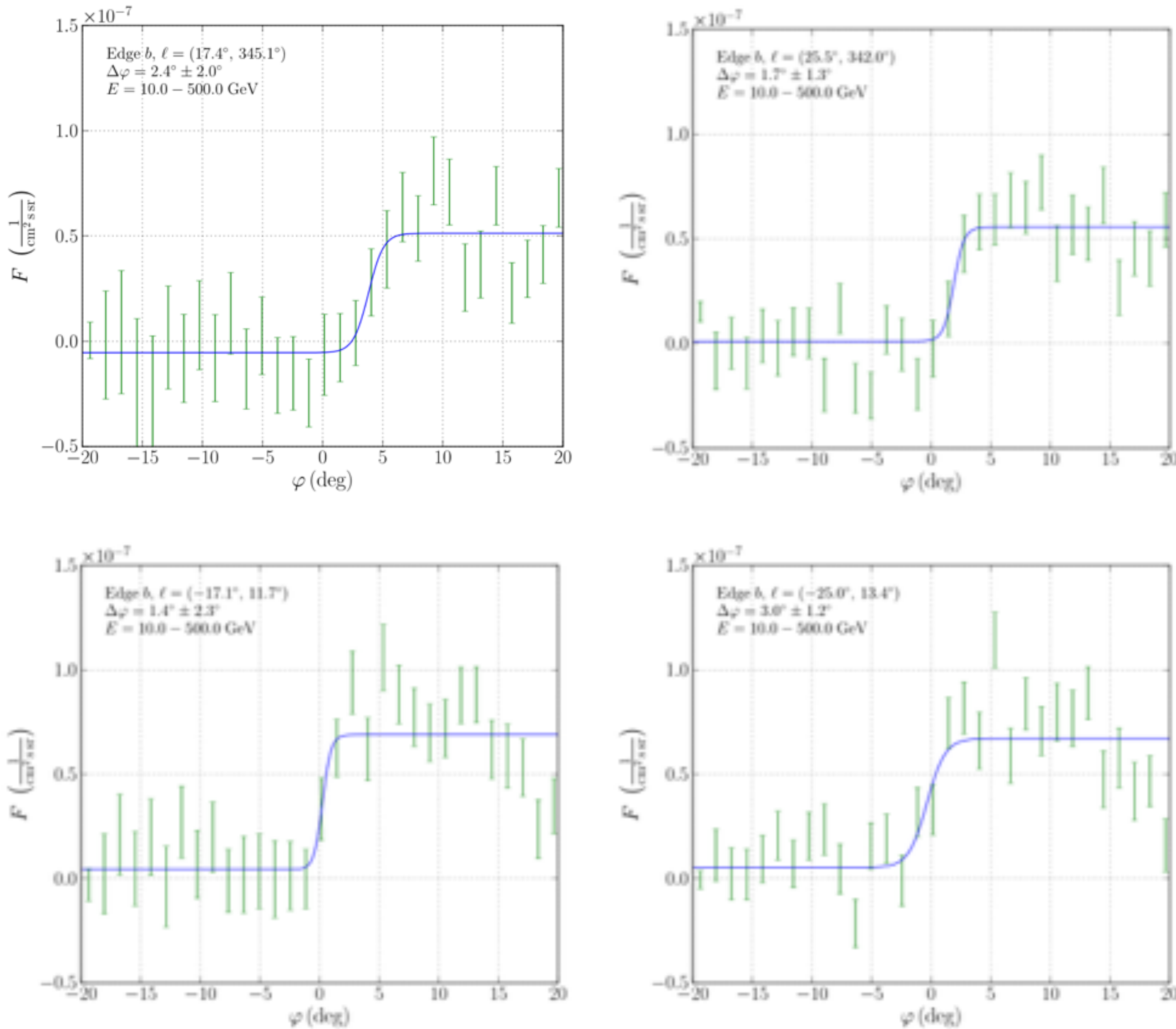
Sharp edges



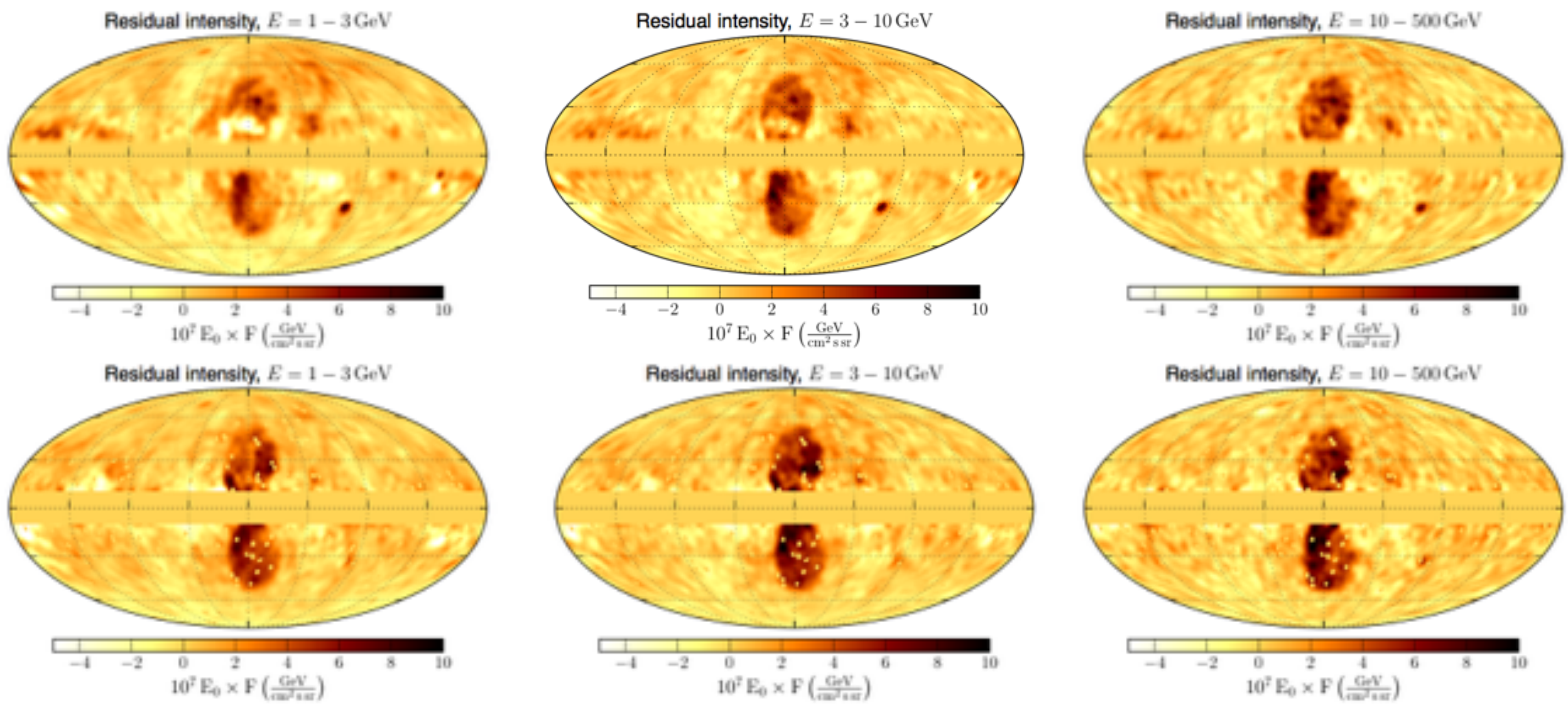
Ackermann *et al.*, ApJ **793** (2014) 64

Sharp edges

Ackermann *et al.*, ApJ **793** (2014) 64



No spectral variation



Ackermann *et al.*, ApJ **793** (2014) 64

No spectral variation

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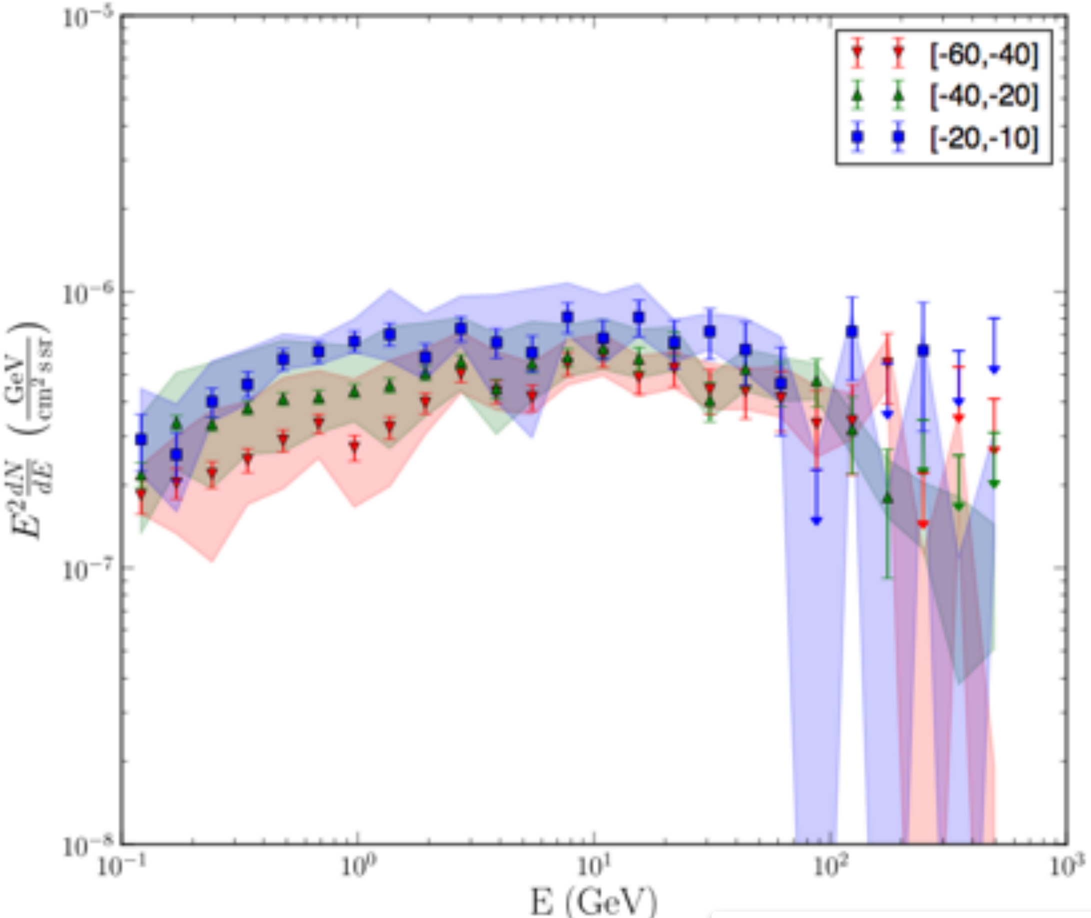


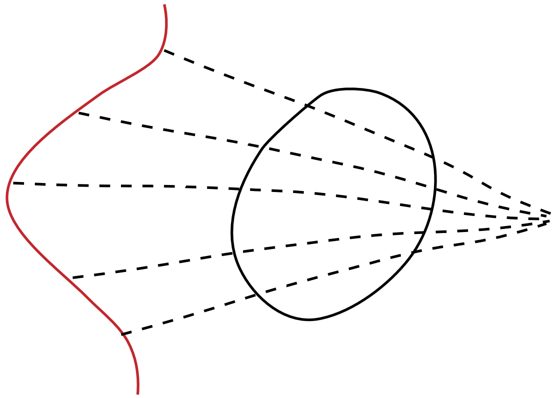
see also: Su *et al.* ApJ **724** (2010) 1044;
Hooper & Slatyer, Phys. Dark Univ. **2** (2013) 118;
Narayanan & Slatyer, arXiv:1603.006582

Would naively expect variation

Models

Crocker & Aharonian, PRL **106** (2011) 101102;	starbust acitivity; hadronic, 10 Gyr
Guo & Mathews, ApJ 756 (2012) 181; Guo *et al.*, ApJ **756** (2012) 182	jet; viscosity
Cheng *et al.*, ApJL **731** (2011) 17; ApJ **746** (2012) 116	tidal disruption of stars by SMBH
Zubovas *et al.*, MNRAS **415** (2012) L21; MNRAS **424** (2012) 666	accretion, possibly with jet
Mertsch & Sarkar, PRL **107** (2011) 091101	stochastic acceleration of e^-; morphology
Yang *et al.*, **761** (2012) 185 and MNRAS **436**, 2734 (2013)	jet; B-fields
Fujita *et al.*, ApJL **775** (2013)	scaled up supernova remnant
Crocker *et al.*, ApJL **791** (2014) 20; ApJ **808** (2015) 107	outflow; reverse shock, contact discontinuity
Lacki, MNRAS **444** (2014) L39	starbust activity
Muo *et al.*, ApJ **790** (2014) 109; ApJ **811** (2015) 37	accretion wind
Sarkar *et al.*, MNRAS **453** (2015) 3827	starbust activity
Sasaki *et al.*, ApJ **814** (2015) 94	time-dependent stochastic acceleration
Taylor & Giacinti, arXiv:1607.08862	outflow

Morphology and spectrum



Homogeneous volume emissivity gives bump-like profile

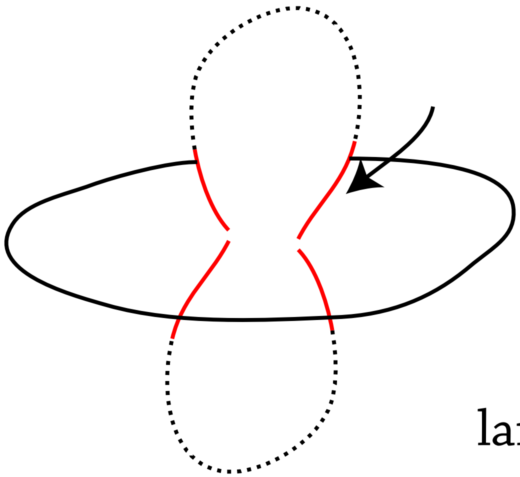
thermal bubbles:

- What is the source of energy?
- (M)HD simulations
- Age, size & shape

non-thermal bubbles:

- What is accelerating CRs?
- Kinetic simulations
  = solve transport equation
- Morphology and spectrum
  in gamma-rays

Shock(s) and morphology



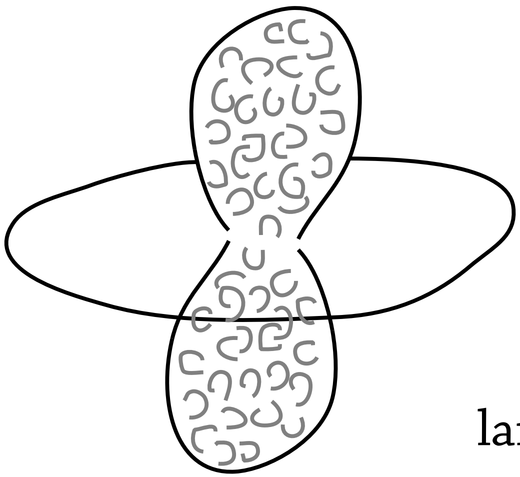
evidence for shock at bubble edges
(from ROSAT)

turbulence produced at shock
and convected downstream

2nd order Fermi acceleration by
large-scale, fast-mode turbulence

Mertsch & Sarkar, PRL 107 (2011) 091101

Shock(s) and morphology



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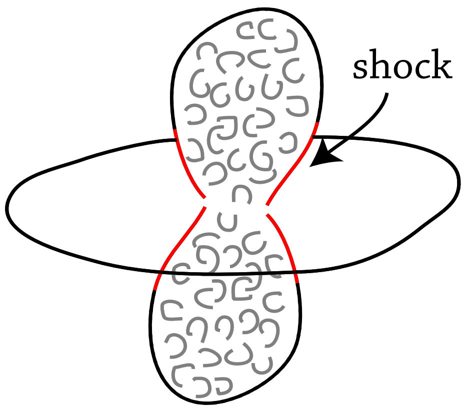
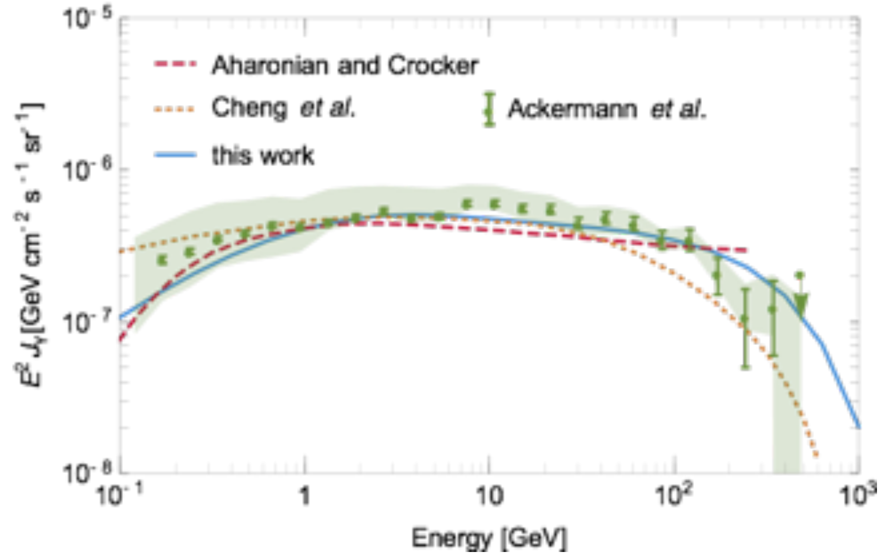
A first model

Mertsch & Sarkar, PRL 107 (2011) 091101

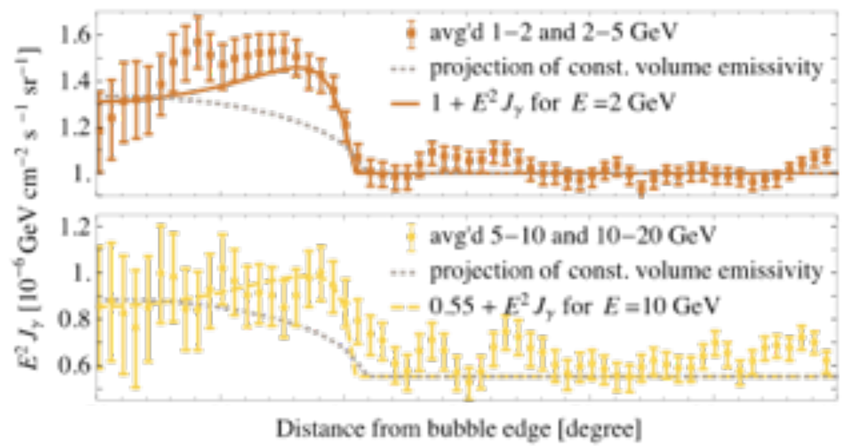




- Bubbles filled with turbulence
- Acceleration by large-scale fast modes
- Inverse Compton scattering:

  $e^- + \gamma_{soft} \rightarrow \gamma + e^-$
- Can use steady-state or time-dependent solutions

  Stawarz & Petrosian (2008);
  Mertsch, JCAP **12** (2011) 10



Open questions

- Steady-state
- Spatial transport
- Inhomogeneous radiation fields

Spatial transport

simplified transport equation:

$$\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial p}\left(-\dot{p}\,\psi + p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right) - \frac{\psi}{\tau}$$

full Fokker-Planck equation:

$$\frac{\partial \psi}{\partial t} = \nabla \cdot \left(K \cdot \nabla\psi - \vec{V}\psi\right) + \frac{\partial}{\partial p}\left(\frac{p}{3}\left(\nabla \cdot \vec{V}\right)\psi\right) + \frac{\partial}{\partial p}\left(-\dot{p}\,\psi + p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right) - \frac{\psi}{\tau} + Q$$

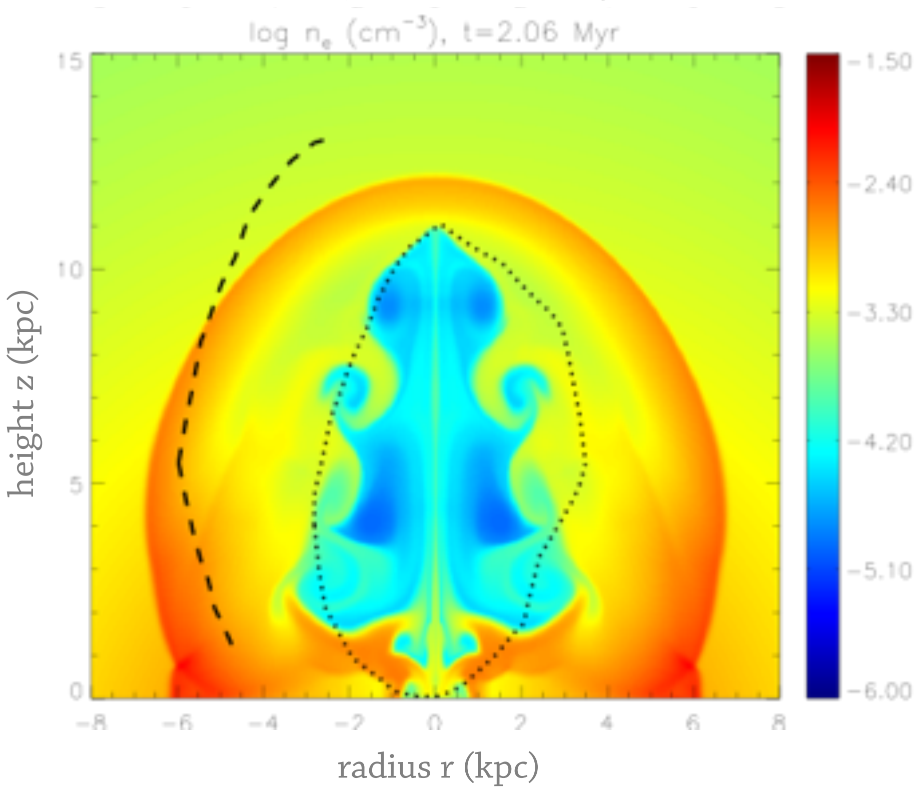
diffusion & advection

discontinuous velocity
→ shock acceleration

Shock geometry

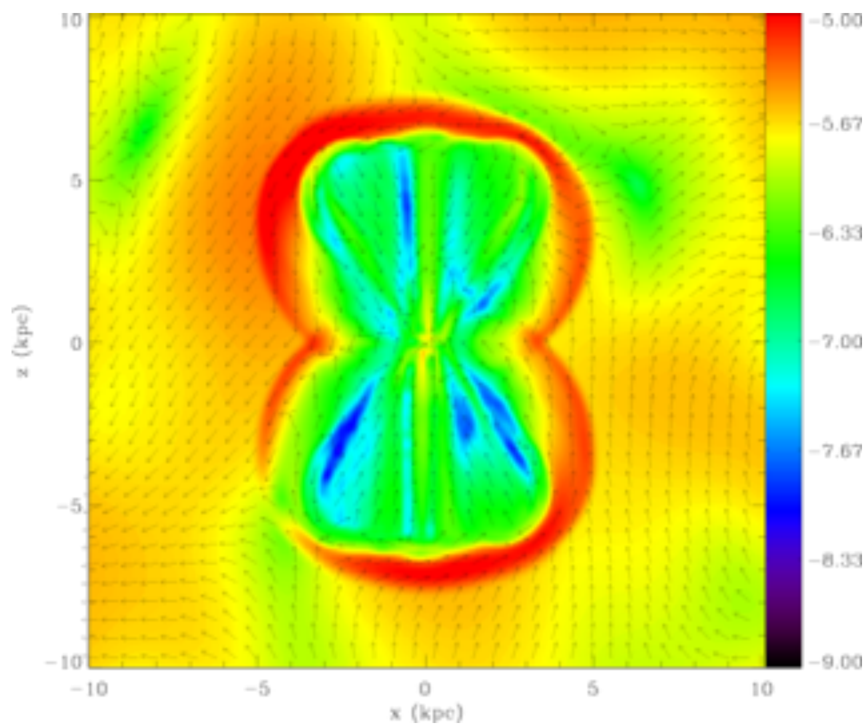
examples from (M)HD simulations of jets:

density of thermal gas



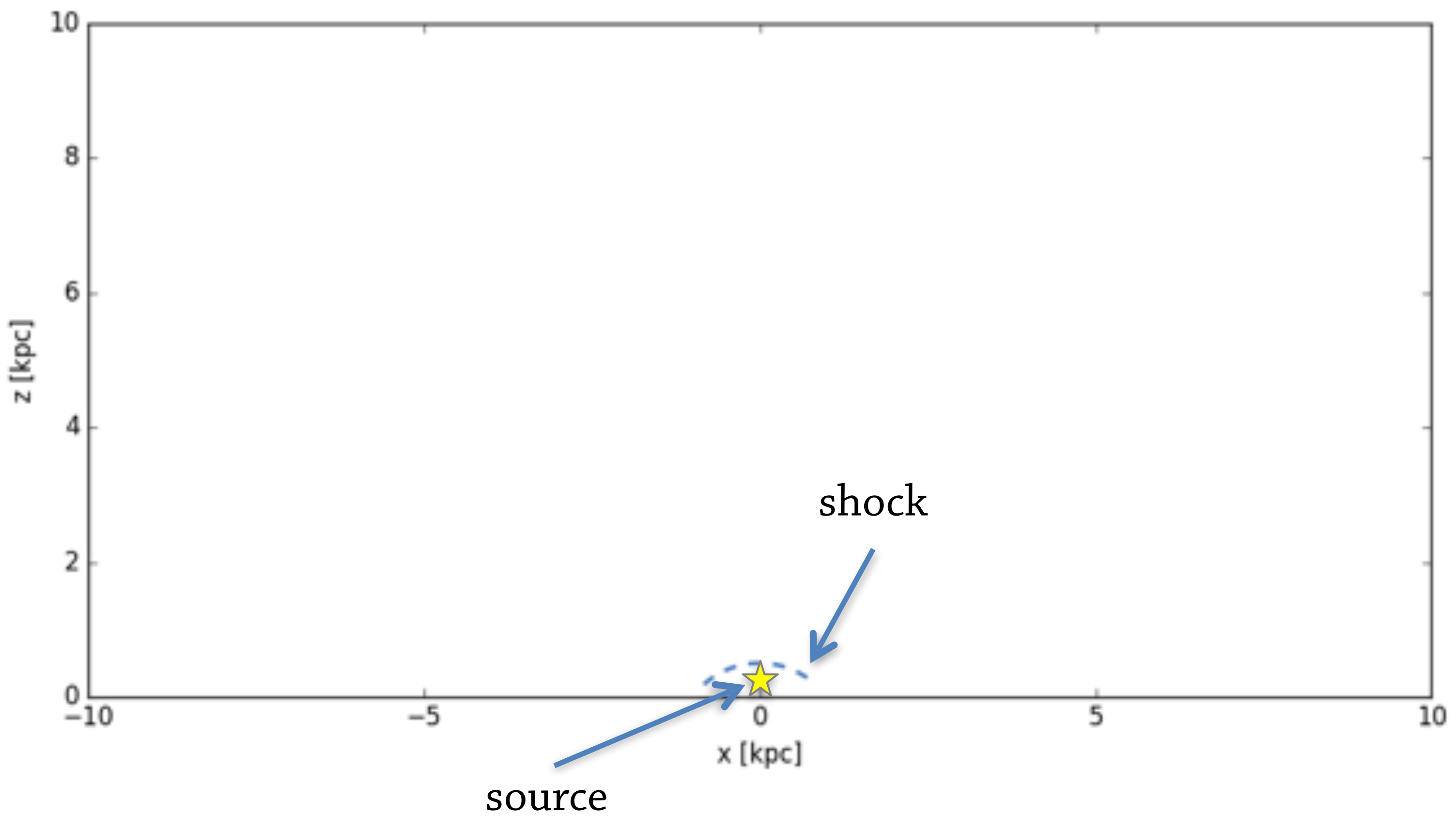
Guo & Mathews, ApJ 756 (2012) 181

magnetic field



Yang et al., ApJ 761 (2012) 185

Coordinates



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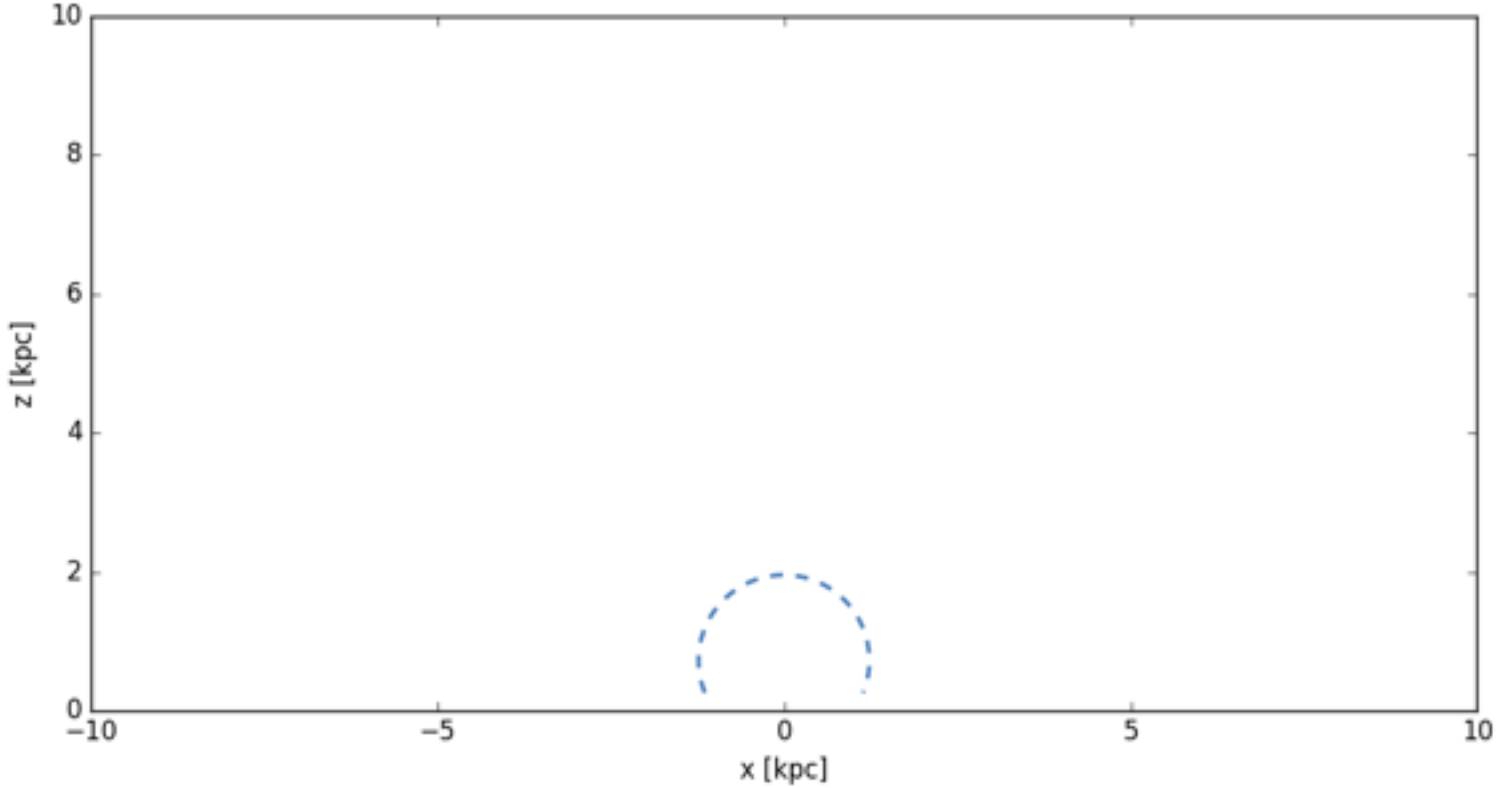
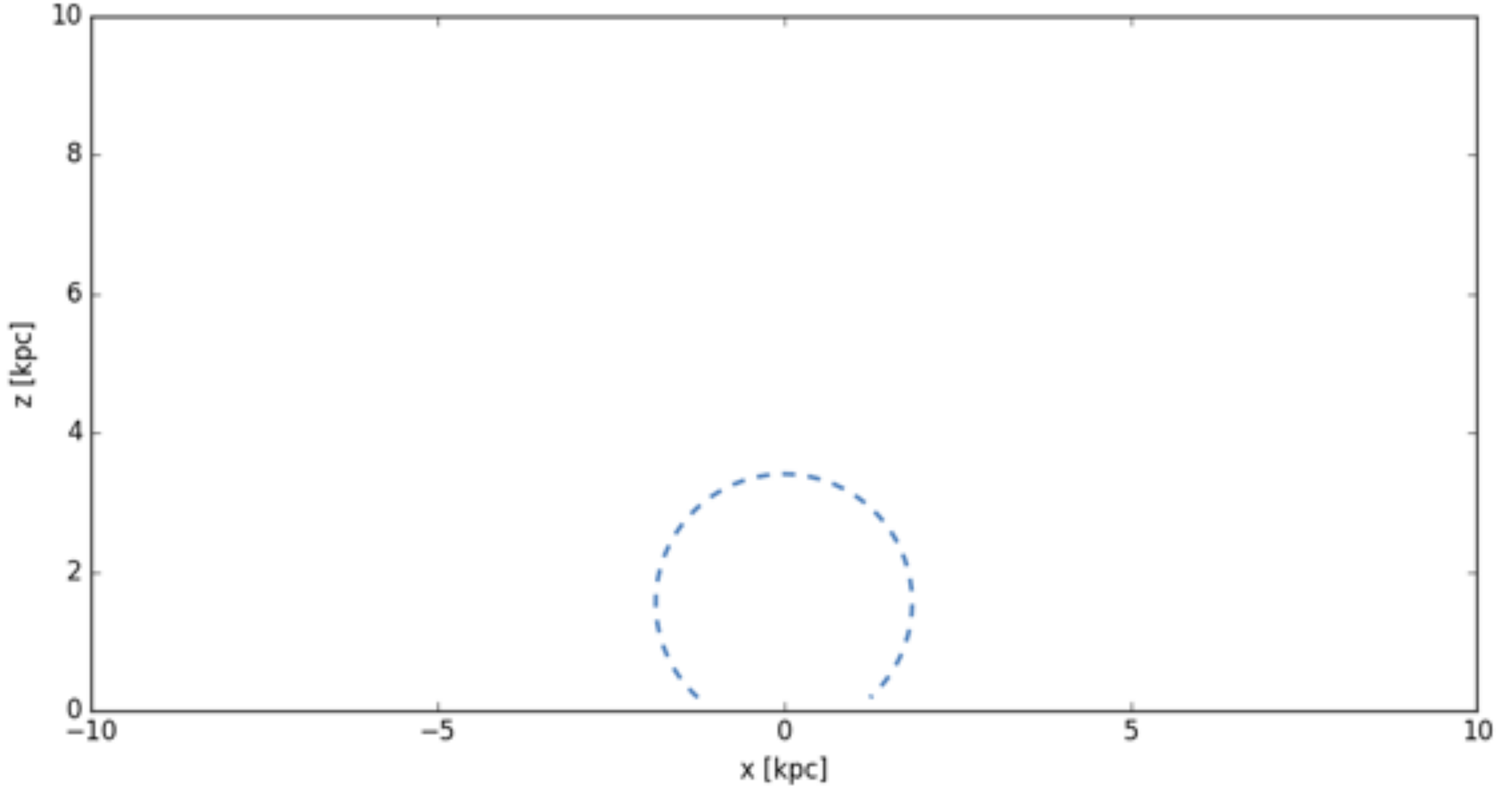


Coordinates



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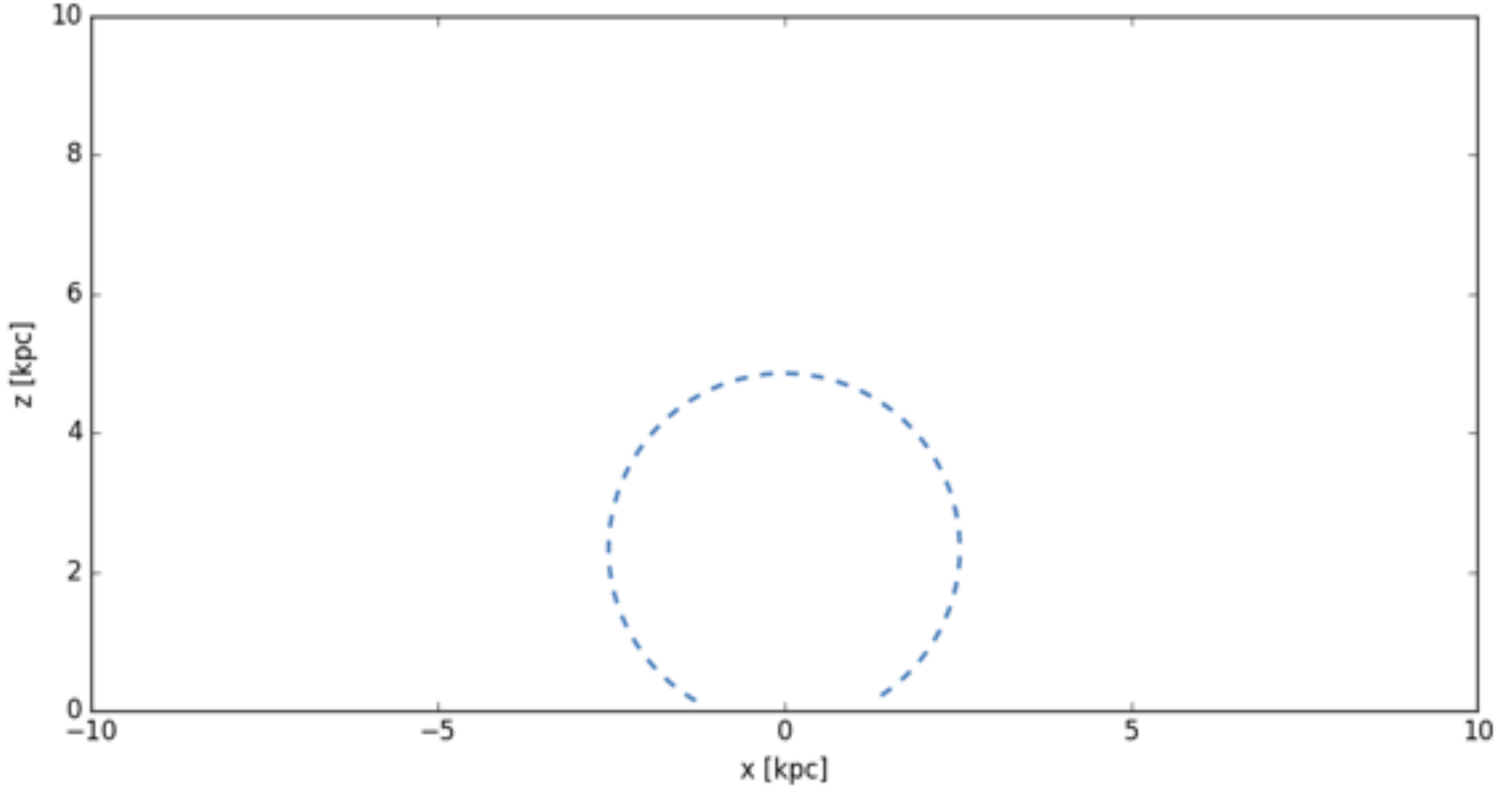

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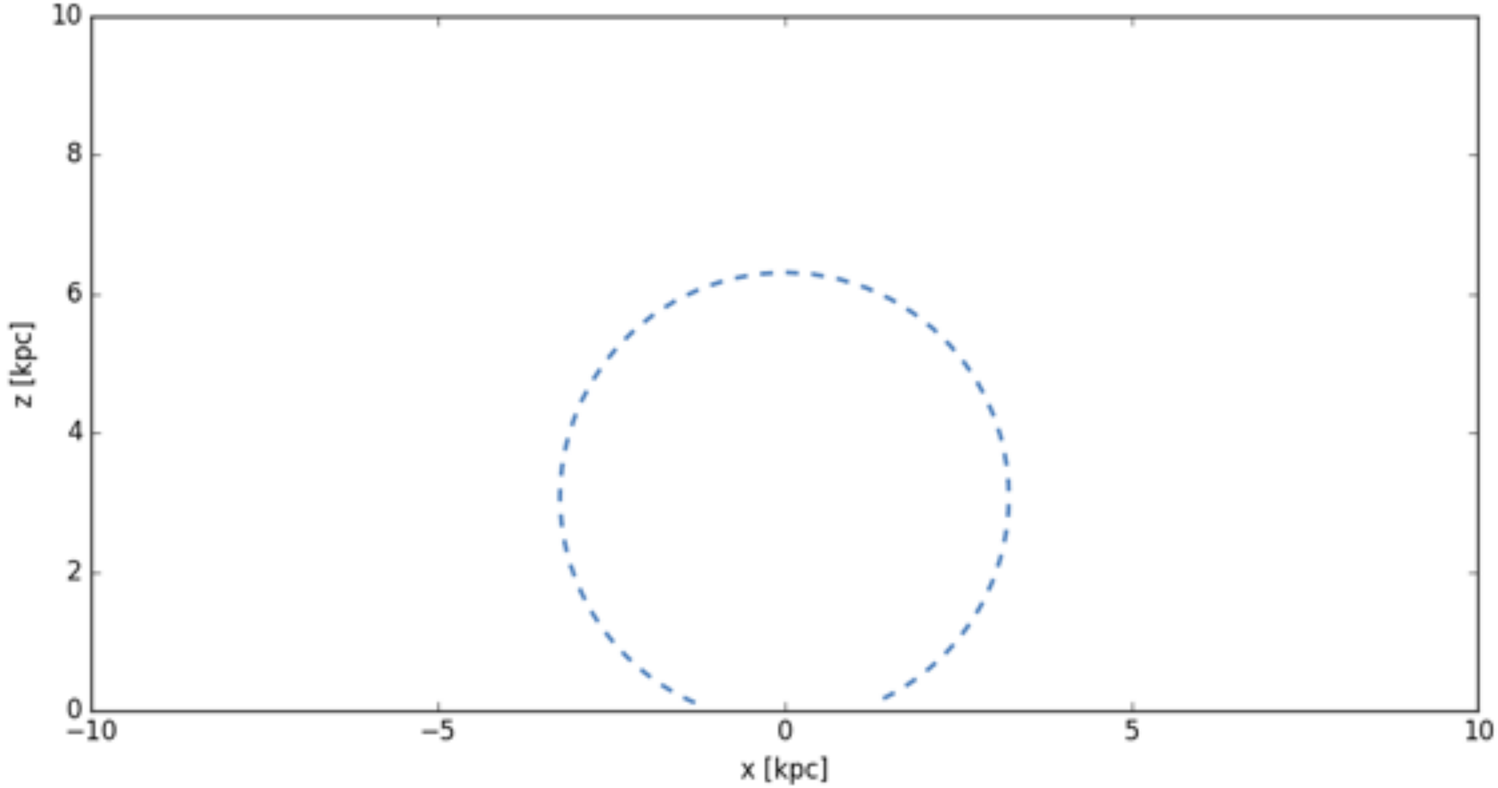

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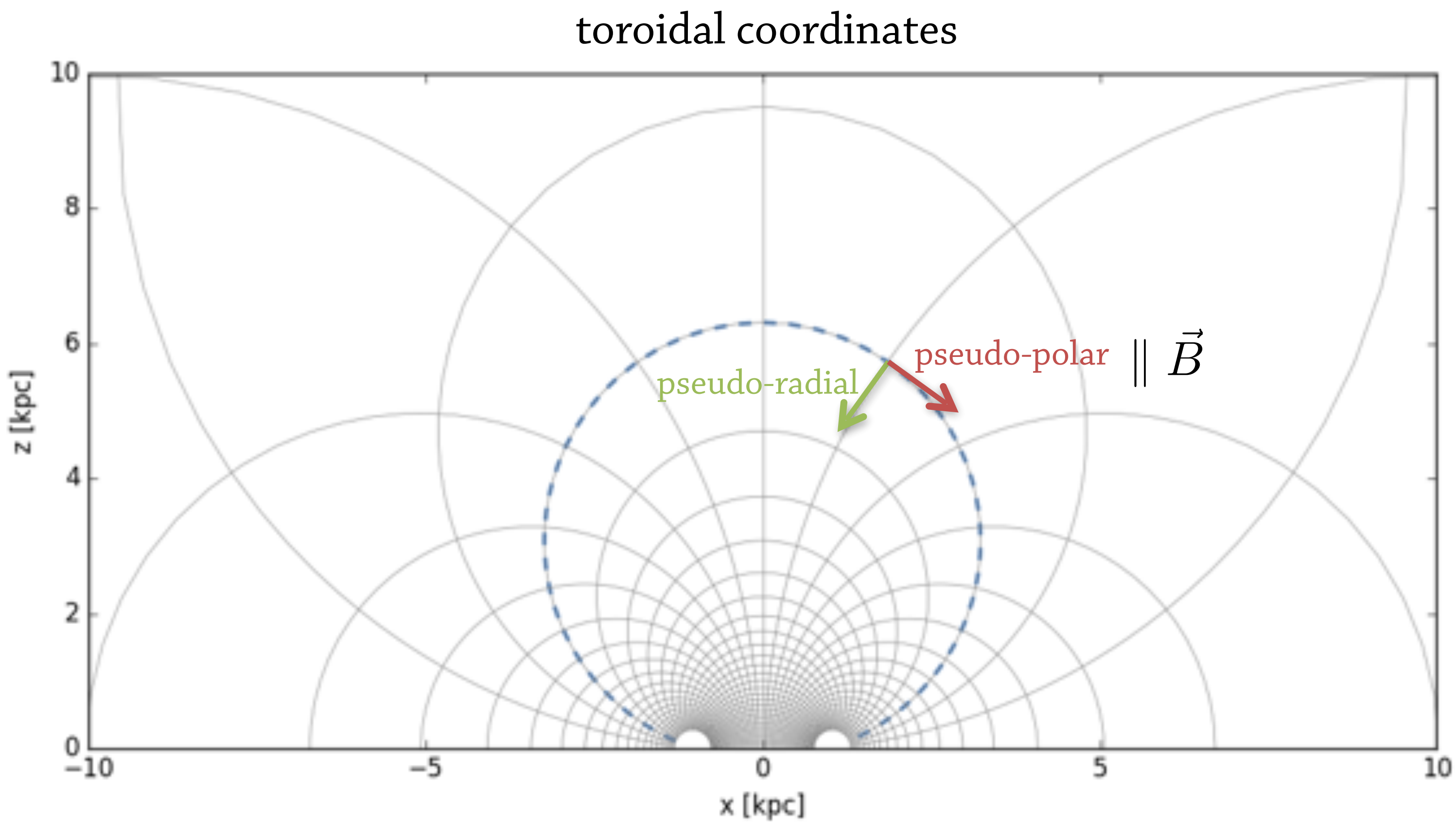


Score card

finite difference code:

- semi-implicit Crank-Nicolson scheme
- 3D: 1 momentum & 2 spatial variables
- cartesian, spherical or toroidal coordinates
- shock in (pseudo-)radial direction

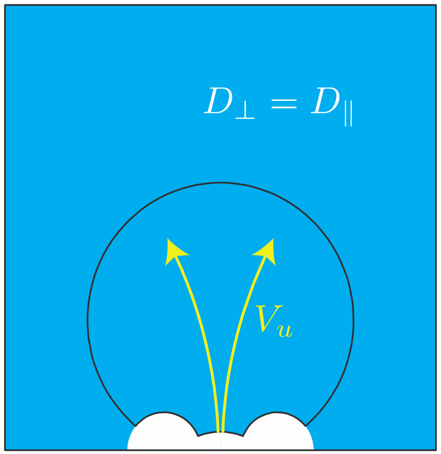
radiation module:

- energy losses: ionisation, Coulomb, Bremsstrahlung, inverse Compton, synchrotron
- inverse Compton on CMB, IR & UV/opt.
  Porter & Strong, ICRC 2005
- synchrotron emission on B-field

other possible applications:

- solar flares/coronal mass ejection
- solar modulation of Galactic cosmic rays
- supernova remnants
- Galactic propagation of cosmic rays

Setups



advection:
- pseudo-radial

diffusion:
- isotropic everywhere

stochastic acceleration:
- homogeneous

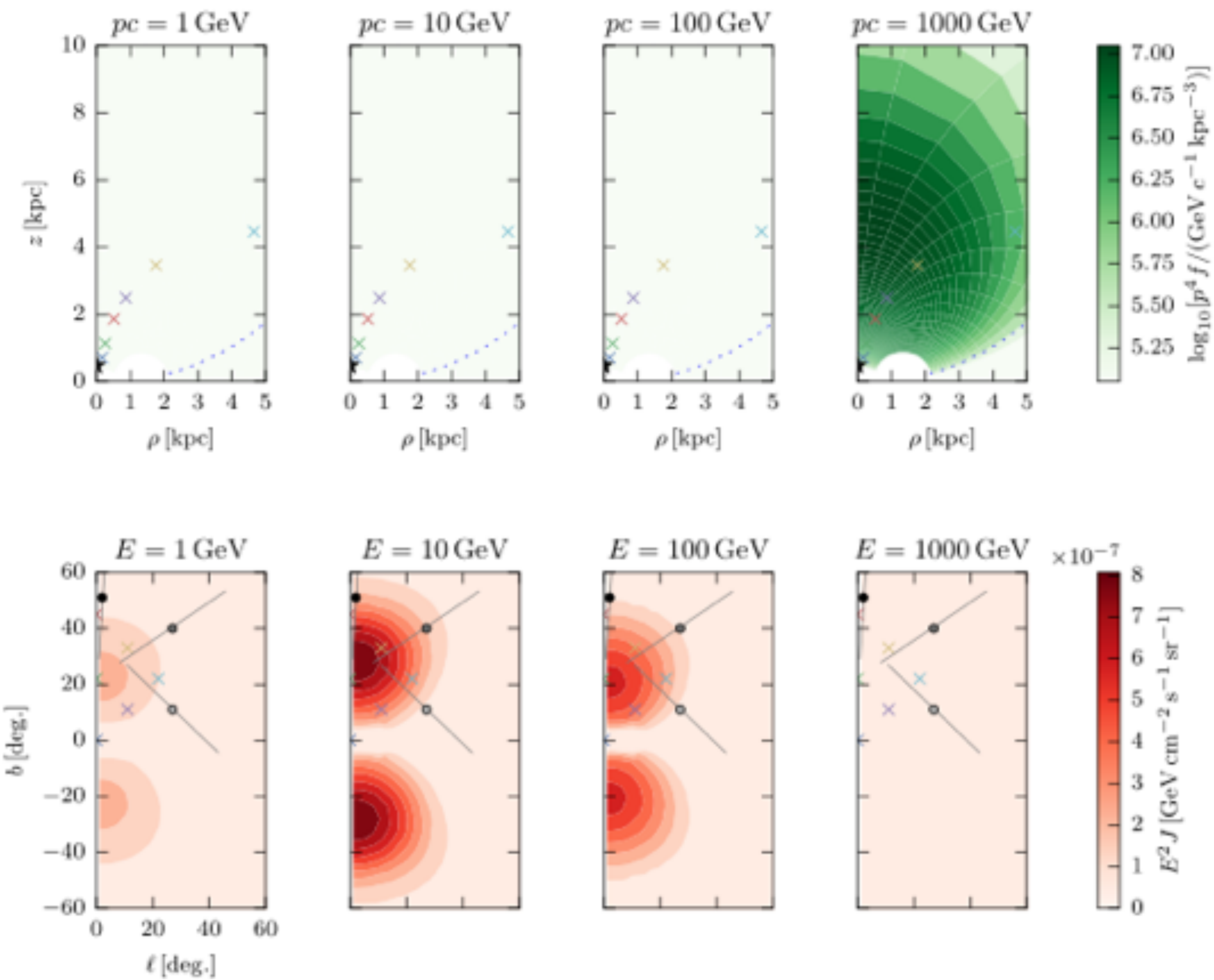
- pseudo-radial
- *an*isotropic everywhere
- homogeneous

- pseudo-radial
- isotropic in shell
- *an*isotropic in halo and bubble
- enhanced in shell

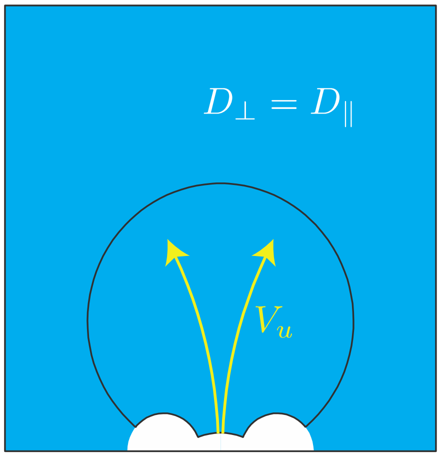
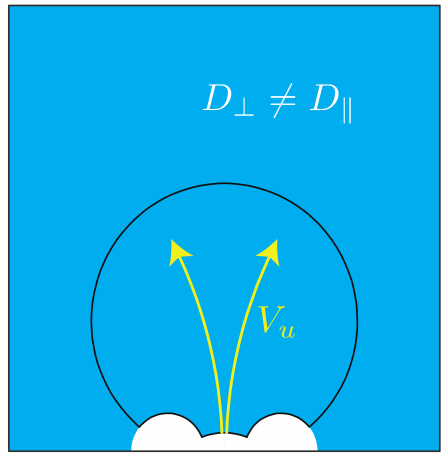
Setup 1: isotropic diffusion

electrons

gamma-rays



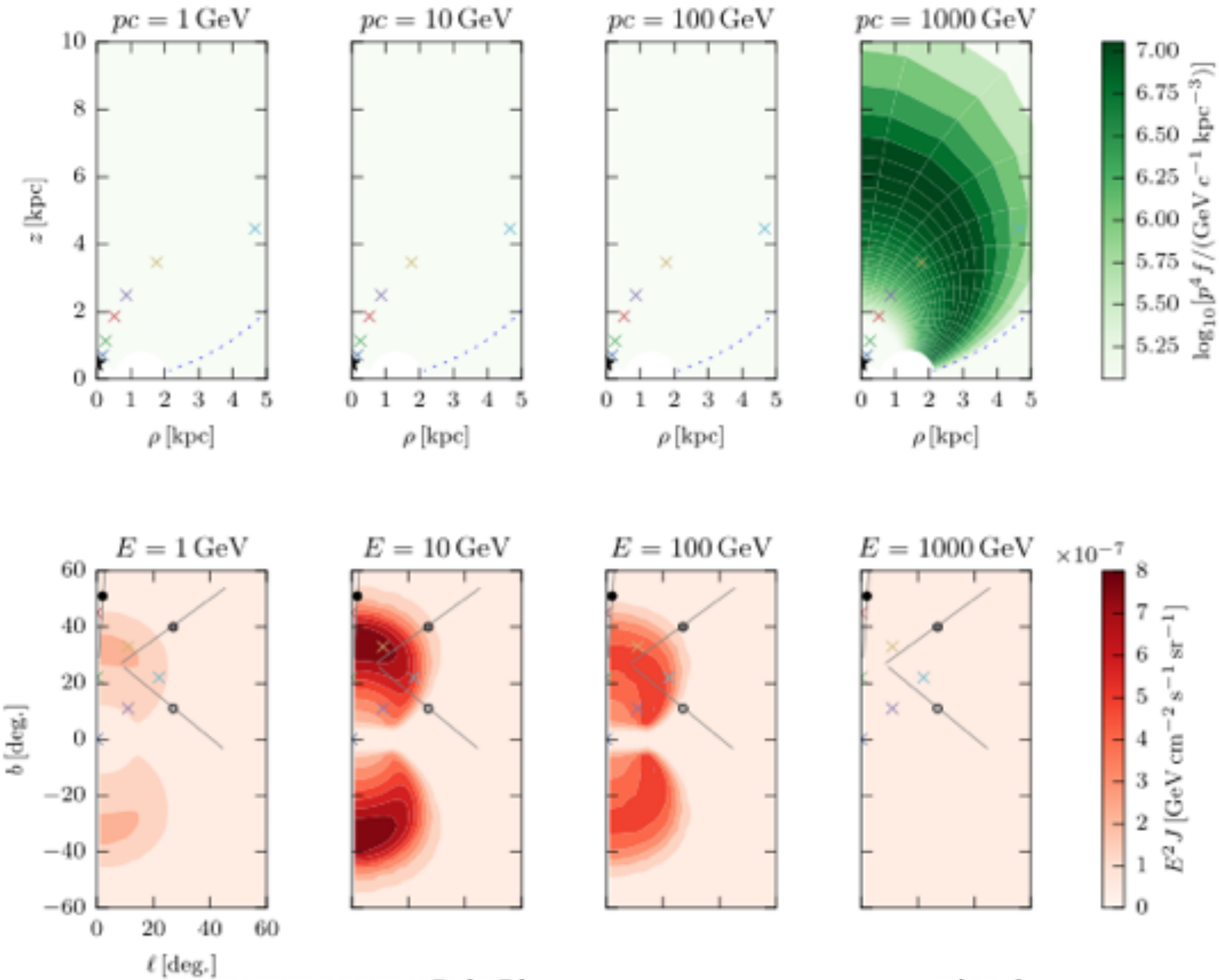
Setups

		
<u>advection:</u>		
• pseudo-radial	• pseudo-radial	• pseudo-radial
<u>diffusion:</u>		
• isotropic everywhere	• *an*isotropic everywhere	• isotropic in shell • *an*isotropic in halo and bubble
<u>stochastic acceleration:</u>		
• homogeneous	• homogeneous	• enhanced in shell

Setup 2: *an*isotropic diffusion

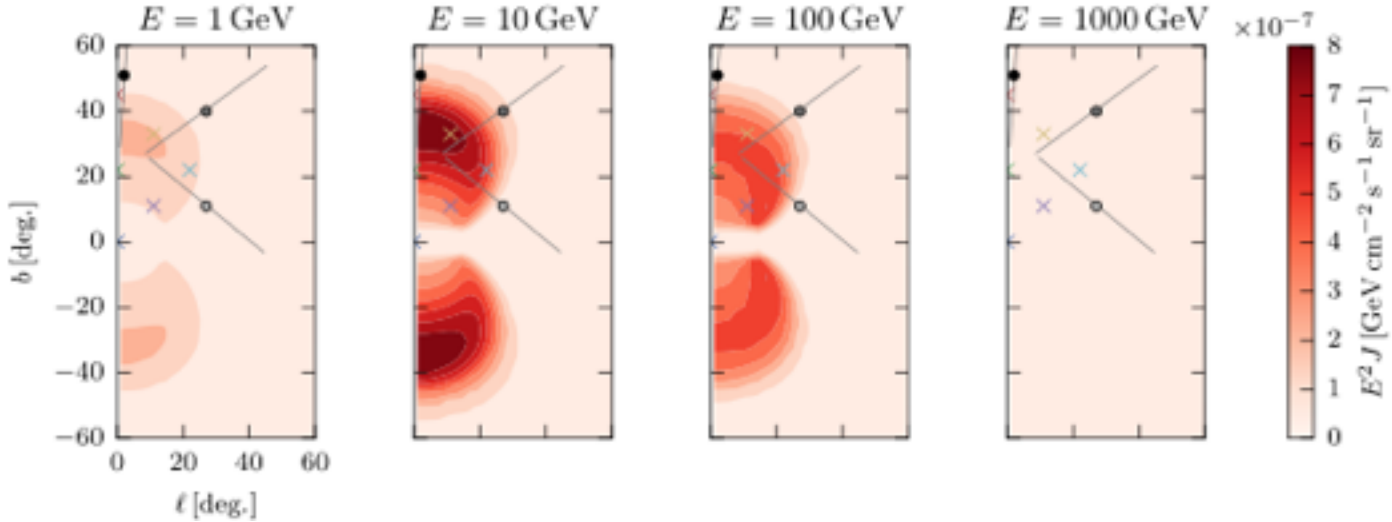
electrons

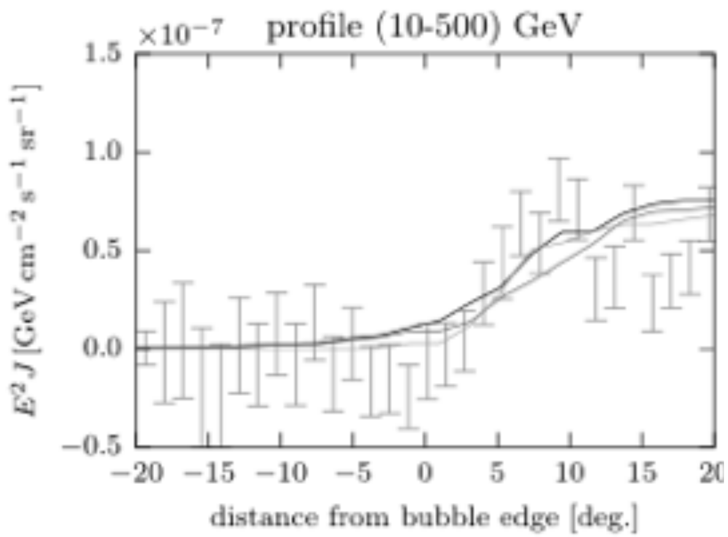
gamma-rays

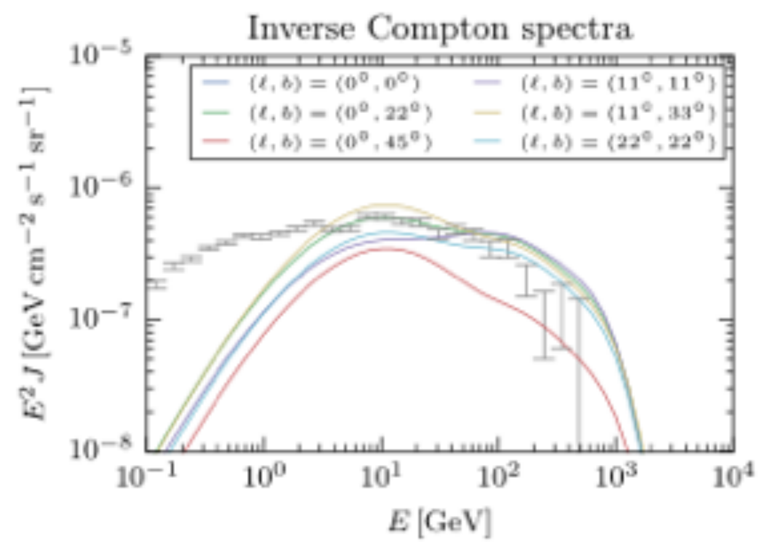


Setup 2: *an*isotropic diffusion

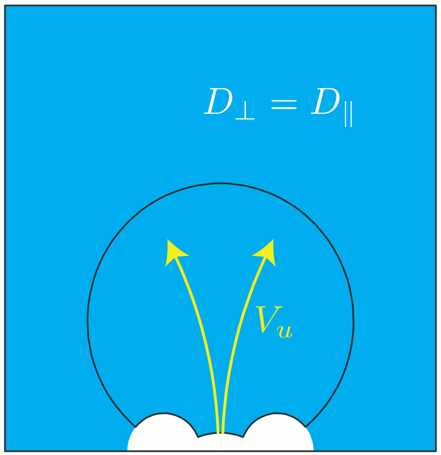
gamma-rays

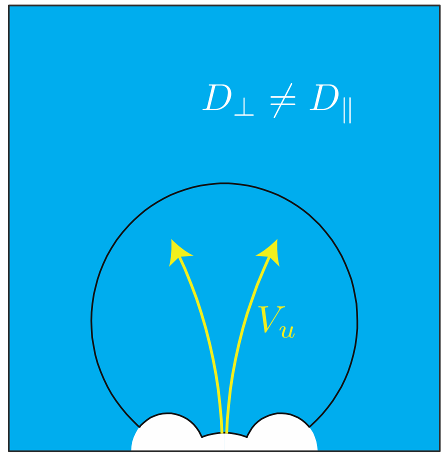


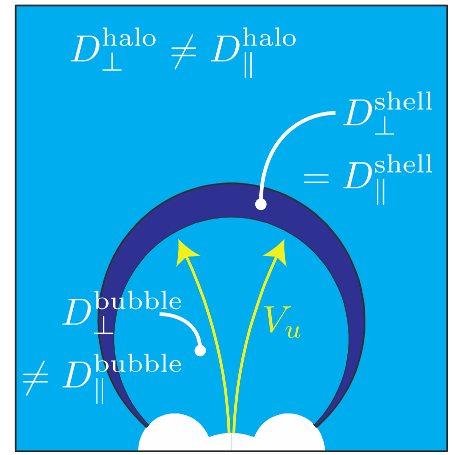




Setups



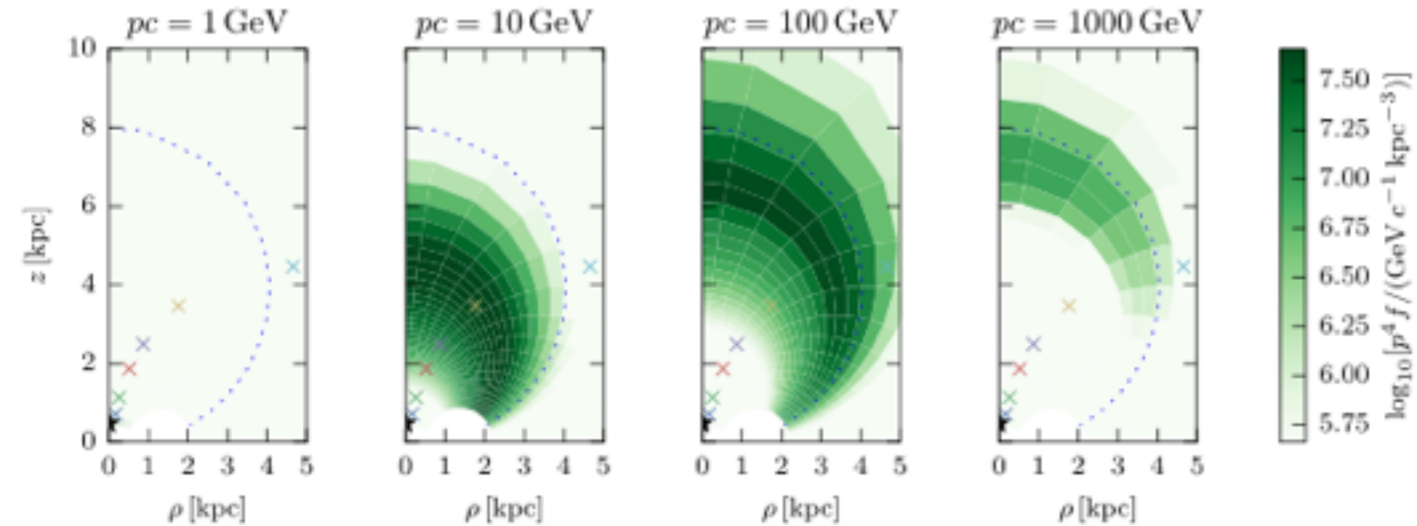




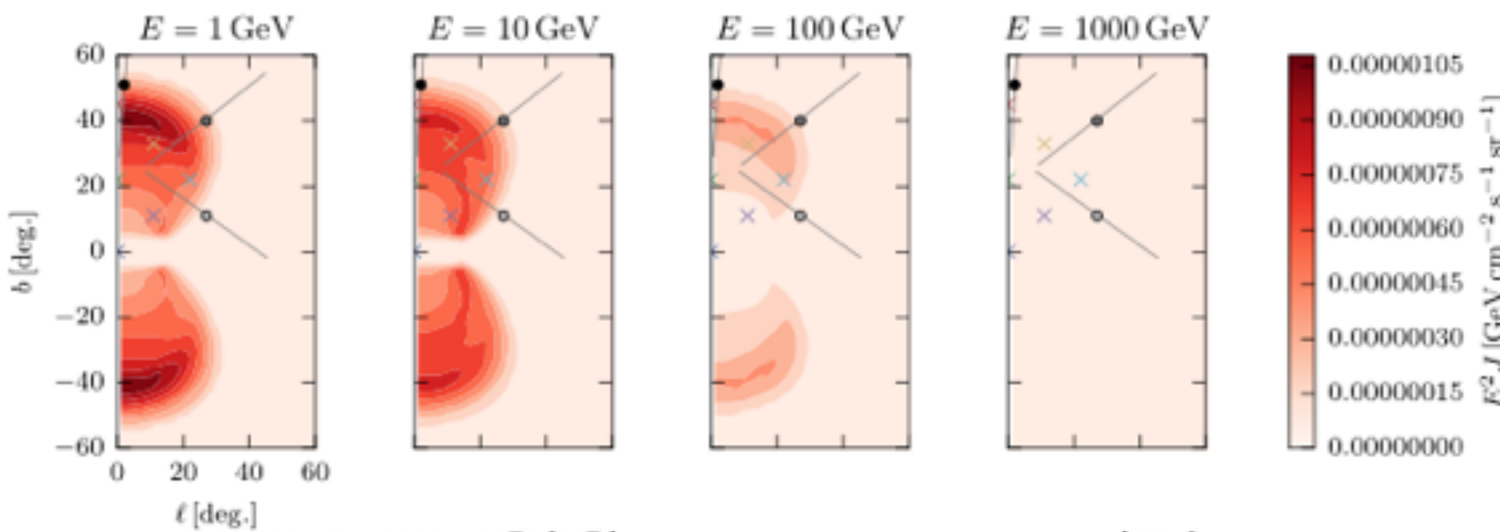
<u>advection:</u>		
• pseudo-radial	• pseudo-radial	• pseudo-radial
<u>diffusion:</u>		
• isotropic everywhere	• *an*isotropic everywhere	• isotropic in shell • *an*isotropic in halo and bubble
<u>stochastic acceleration:</u>		
• homogeneous	• homogeneous	• enhanced in shell

Setup 3: turbulent shell

electrons

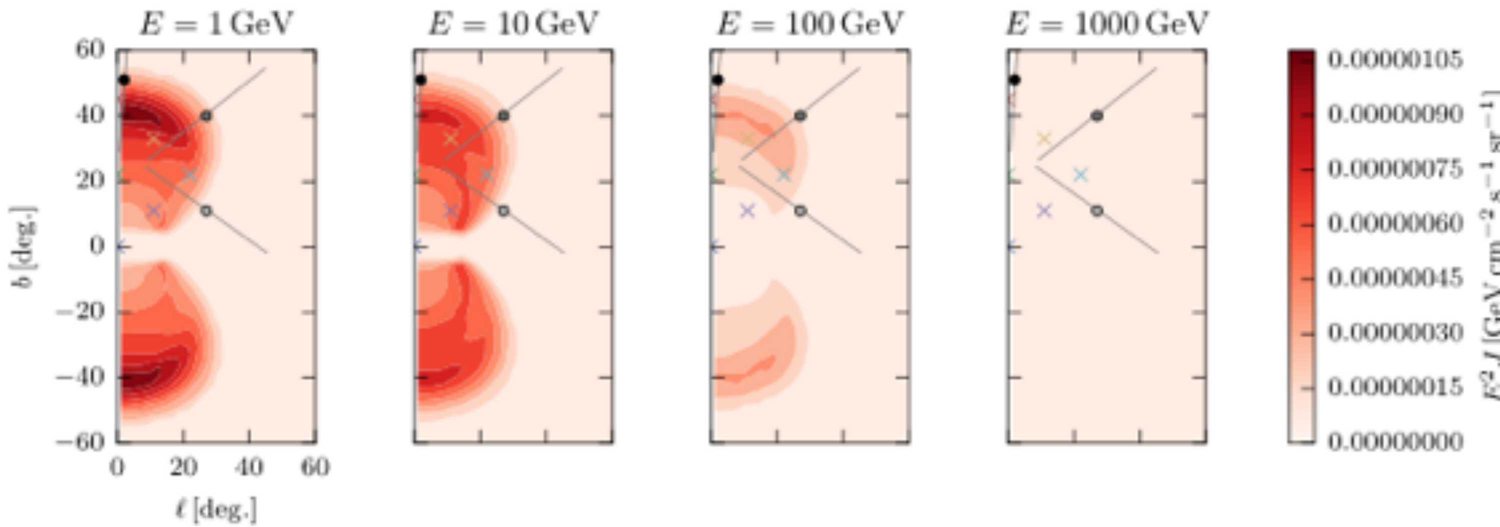


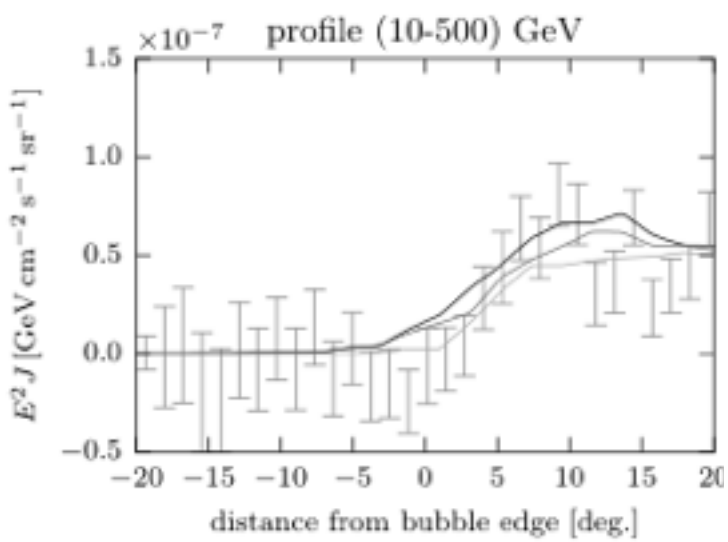
gamma-rays

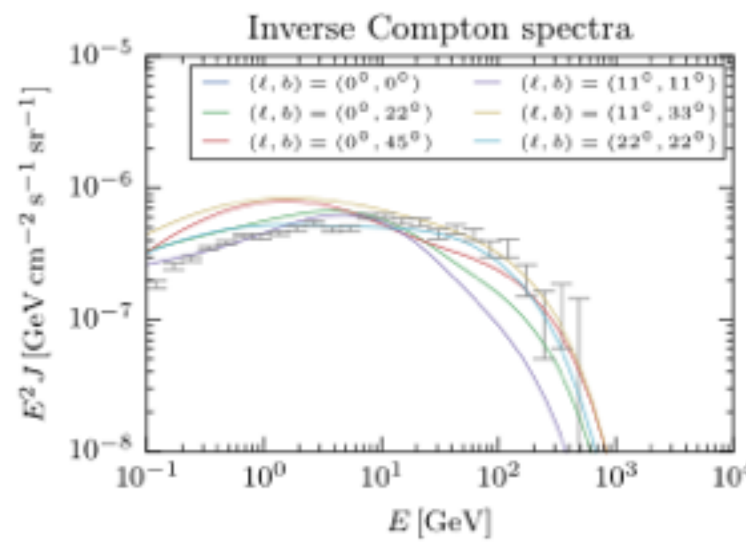


Setup 3: turbulent shell

gamma-rays

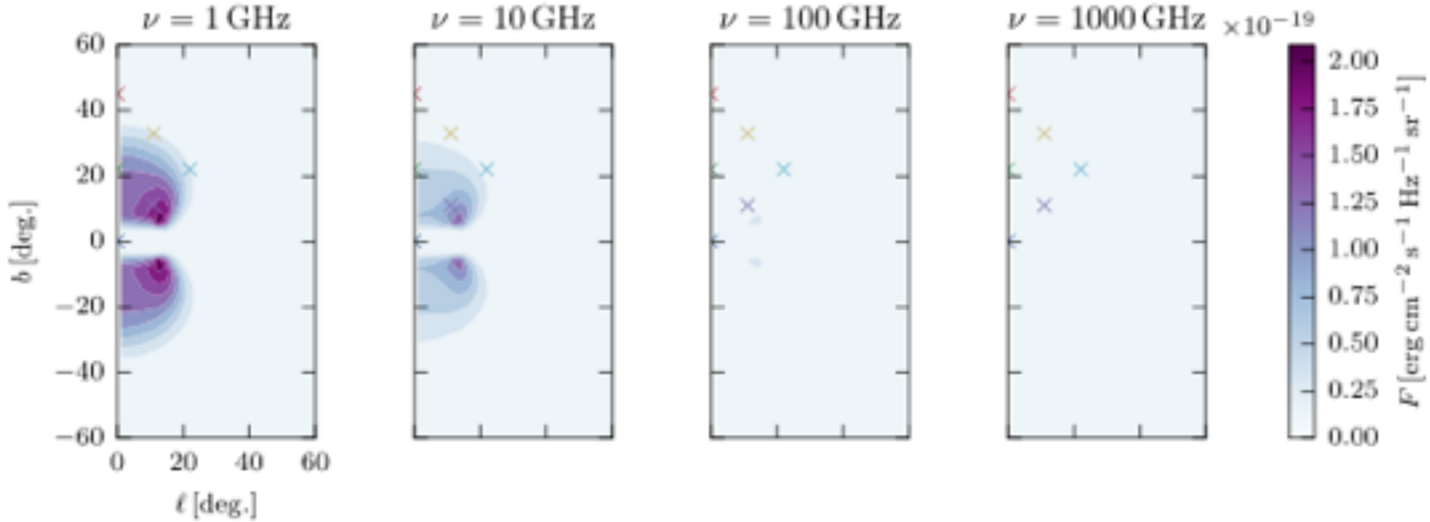


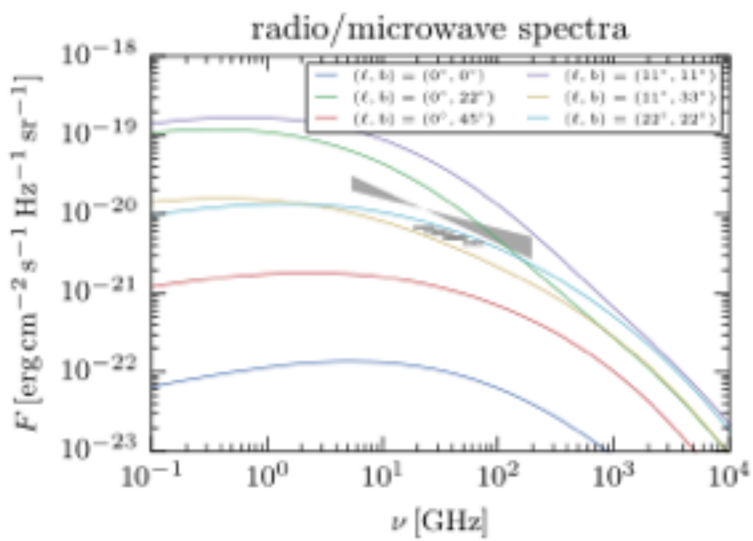




Setup 3: turbulent shell

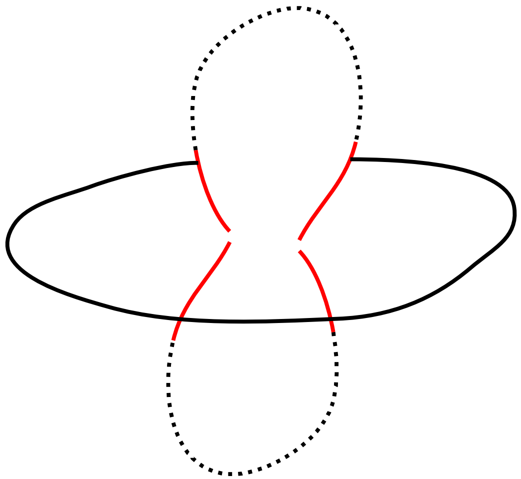
microwaves



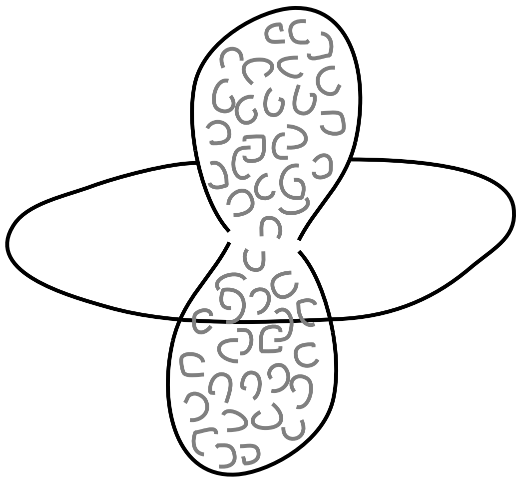


Summary

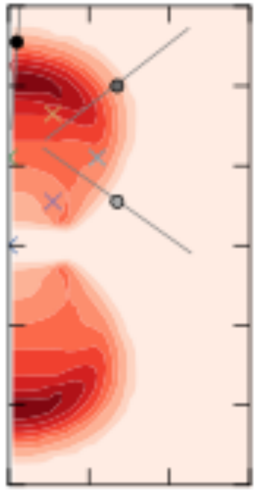
Mertsch & Sarkar, PRL 107 (2011) 091101



shock at bubble edge, e.g. from jets



large-scale, fast mode or small-scale Alfvénic turbulence



energy-dependent distribution such that profile is flat