Non-thermal particle acceleration in astrophysical shear flows

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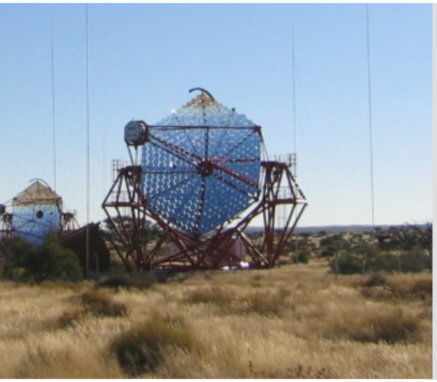

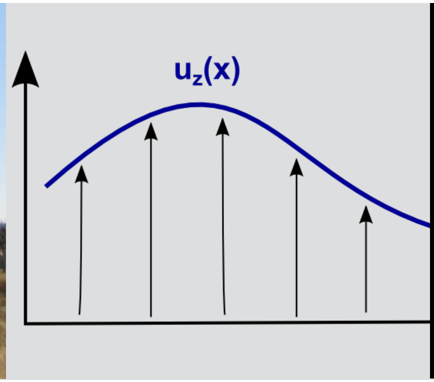

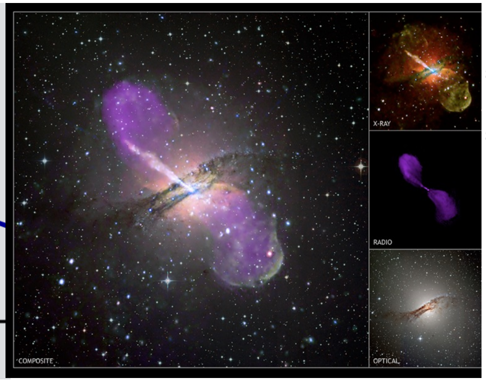

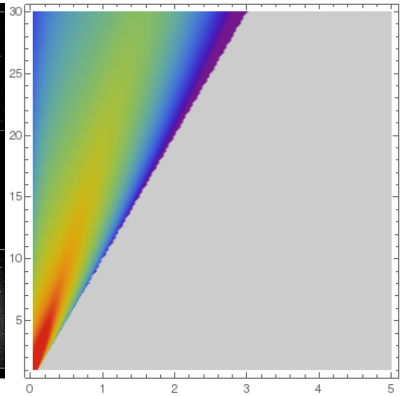

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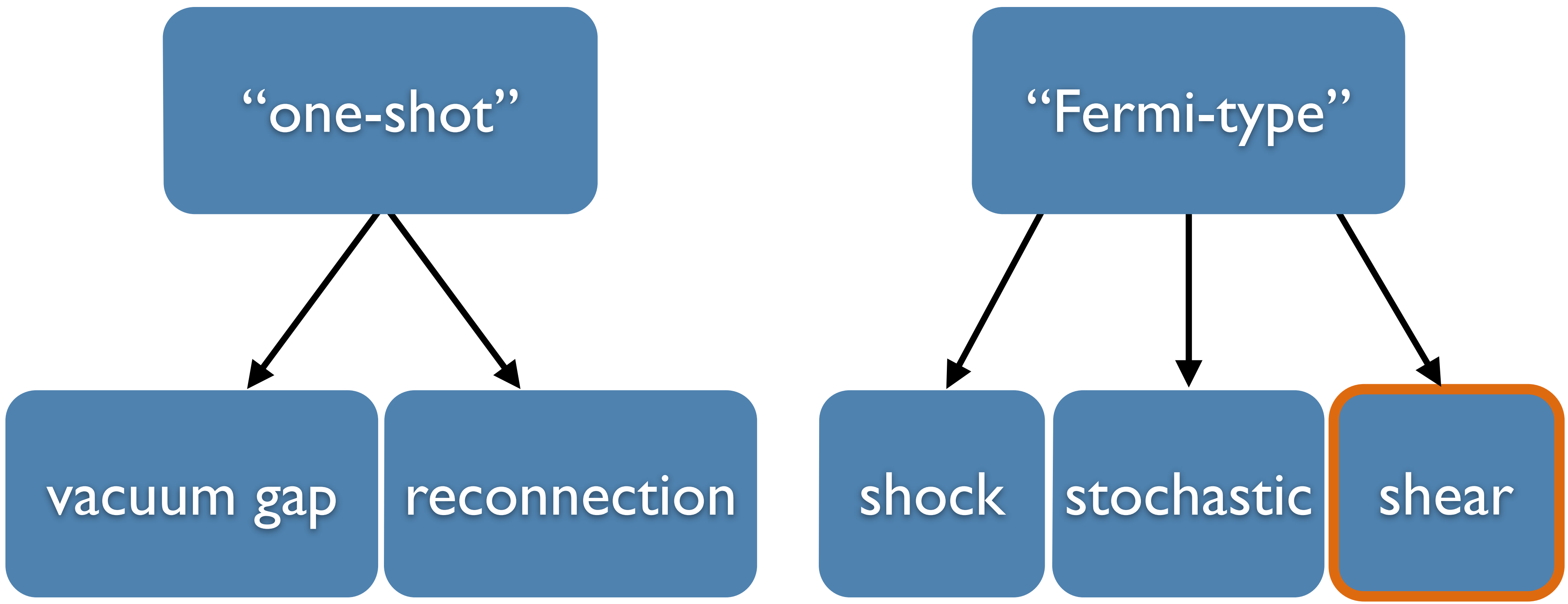
Outline

_Non-thermal particle acceleration in astrophysical outflows

("We see radiation from energetic particles and we want to understand their origin")

- Particle acceleration mechanisms
- The ubiquity of shear flows
- Shear particle acceleration (characteristics)
- Example: expanding flows

Particle acceleration mechanisms (*not exhaustive*)



charge density? topology? transparency?	limited in size? luminosity output? spectral shape?	efficiency (Γ_s, σ)? localized?	efficiency? spectral shape?	efficiency? energetic seeds?

Fermi-type particle acceleration

Kinematic effect resulting from *scattering off magnetic inhomogeneities*

Fermi, Phys. Rev. 75, 578 [1949]

_Ingredients: in frame of scattering centre

- momentum magnitude conserved
- particle direction randomised

_Characteristic energy change per scattering:

$$\Delta\epsilon = \epsilon_2 - \epsilon_2 = 2\,\gamma_u^2\,(\epsilon_1\,u^2/c^2 - \vec{p}_1 \cdot \vec{u})$$

➡ *energy gain for head-on ($\mathbf{p}\ \mathbf{u} < 0$), loss for following collision ($\mathbf{p}\ \mathbf{u} > 0$)*

- **stochastic**: average energy gain 2nd order: $\langle\Delta\varepsilon\rangle \sim (u/c)^2\ \varepsilon$
- **shock:** spatial diffusion, head-on collisions, gain 1st order: $\langle\Delta\varepsilon\rangle \sim (u_s/c)\ \varepsilon$

The ubiquity of shear (out)flows

Particle energization by drawing on velocity difference between scattering events

Expect internal velocity stratification = shear due to e.g.

- BH-driven jet encompassed by disk wind (generic)…
- velocity stratification in jet simulations (interaction)…
- angular momentum transport (disk-jet connection)…
- phenomenological evidence:
    - different m.f. structure across jet (polarization)
    - higher energy emission laterally confined
    - …..

⇒ new emergence of multi-zone emission/shear layer/acceleration models:

e.g., *Aloy & Mimica 2008; Sahayanathan 2009; Liang+ 2013; Grismayer+2013; Ohira 2013; Laing & Bridle 2013; Tavecchio & Ghisellini 2015….*

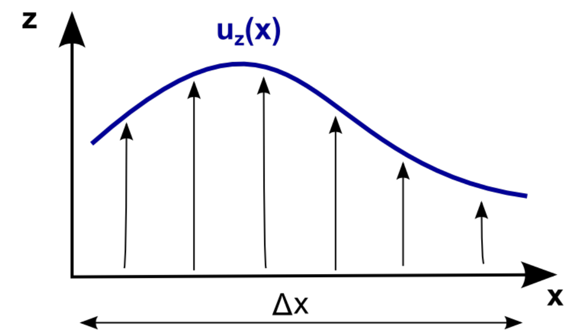
Shear acceleration (gradual - characteristics)

non-relativistic

$$\vec{u} = u_z(x)\ \vec{e}_z$$

- *Gradual* shear flow with frozen-in scattering centres:

- like 2nd Fermi, stochastic process with average gain:



$$\frac{<\Delta\epsilon>}{\epsilon_1} \propto \left(\frac{u}{c}\right)^2 = \left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2$$

using *characteristic effective velocity:*

$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda$$, where λ = *particle mean free path*

- So: $$t_{acc} = \frac{\epsilon}{(d\epsilon/dt)} \sim \frac{\epsilon}{<\Delta\epsilon>} \times \frac{\lambda}{c} \propto \frac{1}{\lambda}$$
  - seed from acceleration @ shock or stochastic….
  - easier for protons….

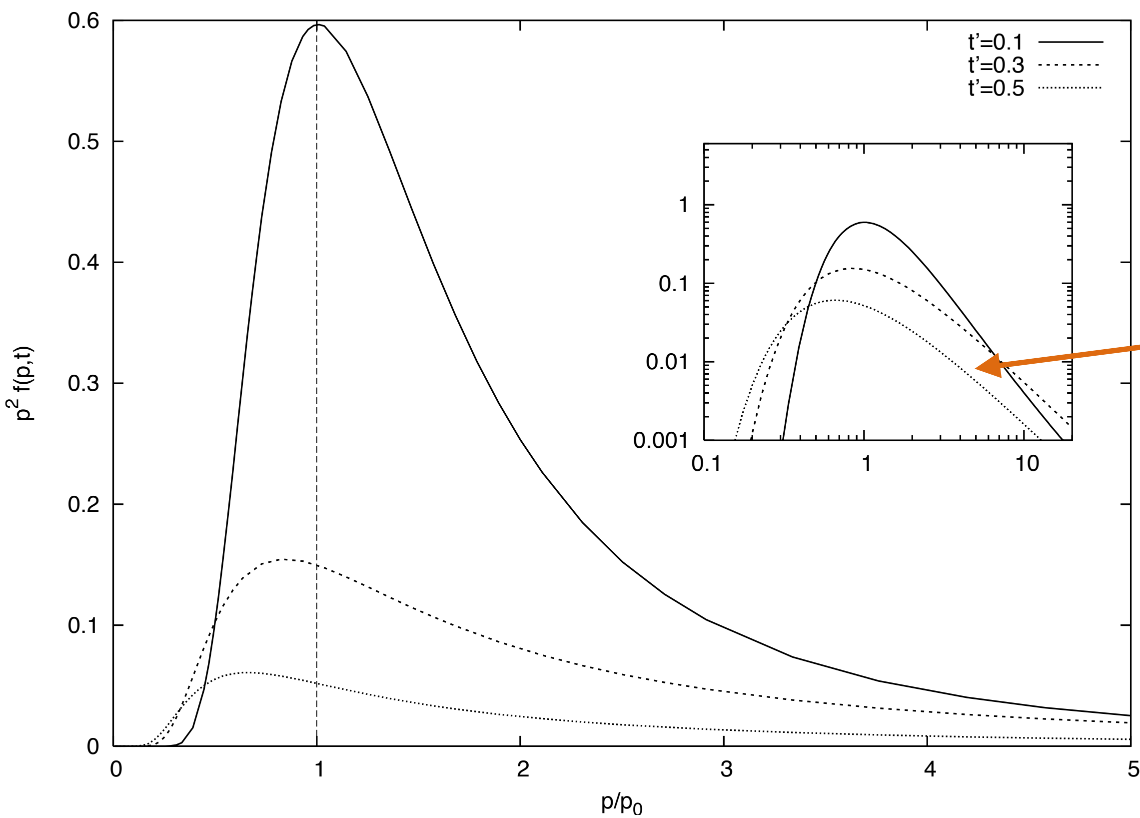
e.g., Jokipii & Morfill 1990; FR. & Duffy 2004, 2006…

Shear acceleration (gradual - characteristics)

Local power law formation with index depending on scaling of particle mean free path:

$$n(\gamma) \propto \gamma^{-(1+\alpha)}$$

- for $\lambda \propto p^{\alpha}$
- e.g. $\alpha=1$ for $\lambda \sim r_g$ (Bohm)
- change of slope possible



Time-dependent solution of Fokker-Planck equation for non-relativistic shear using impulsive injection with p_0 at $t_0=0$ for $\alpha=1$

power law formation

Fermi Acceleration Timescales

(e.g., Drury 1983; Kirk 1994; Duffy & Blundell 2005; FR.+ 2007)

_1st order Fermi - standard shock (non-relativistic):

with shock crossing time $t_c \sim \kappa/(u_s c)$*, where* $\kappa \sim \lambda c$

$$\mathrm{t_{acc}} = \frac{\epsilon}{d\epsilon/dt} \simeq \frac{\epsilon}{\Delta\epsilon}\, t_c \sim \frac{\kappa}{u_s^2} \propto \frac{\lambda}{u_s^2}$$

_2nd order Fermi (stochastic):

with scattering time $\tau \sim \lambda/c$

$$\mathrm{t_{acc}} = \frac{\epsilon}{d\epsilon/dt} \simeq \frac{\epsilon}{\Delta\epsilon}\, \tau \sim \left(\frac{c}{v_A}\right)^2 \left(\frac{\lambda}{c}\right) \propto \frac{\lambda}{v_A^2}$$

_Shear - gradual (non-relativistic):

$$\mathrm{t_{acc}} = \frac{\epsilon}{d\epsilon/dt} \simeq \frac{\epsilon}{\Delta\epsilon}\, \tau \sim \left(\frac{c}{\frac{\partial u_z}{\partial x}\lambda}\right)^2 \left(\frac{\lambda}{c}\right) \propto \frac{1}{\lambda}$$

Significance - (i) scales with synchrotron losses...
- (ii) requires energetic seed particles

Potential & possible relevance of shear acceleration

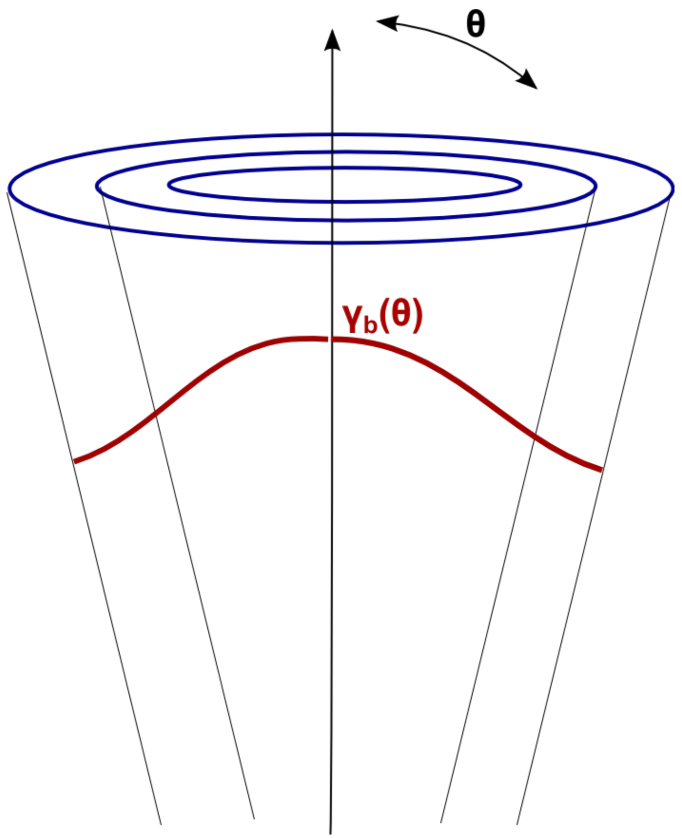
- Extended emission (optical, X-rays) in large-scale jets of AGN
- UHECR acceleration in AGN jets
  - can push up cosmic rays to UHE energies when shock speed is too slow (*Cen A*)
  - change in spectrum & composition possible
- GRB jets
  - can be faster than (internal) shock acceleration
  - delayed and extended electron acceleration possible
- Multi-stage acceleration in AGN jets
  - multi-component particle distribution…

e.g., Ostrowski 2000; FR & Mannheim 2002; Stawarz & Ostrowski 2002; FR & Duffy 2004ff; FR+ 2007; FR & Aharonian 2009….

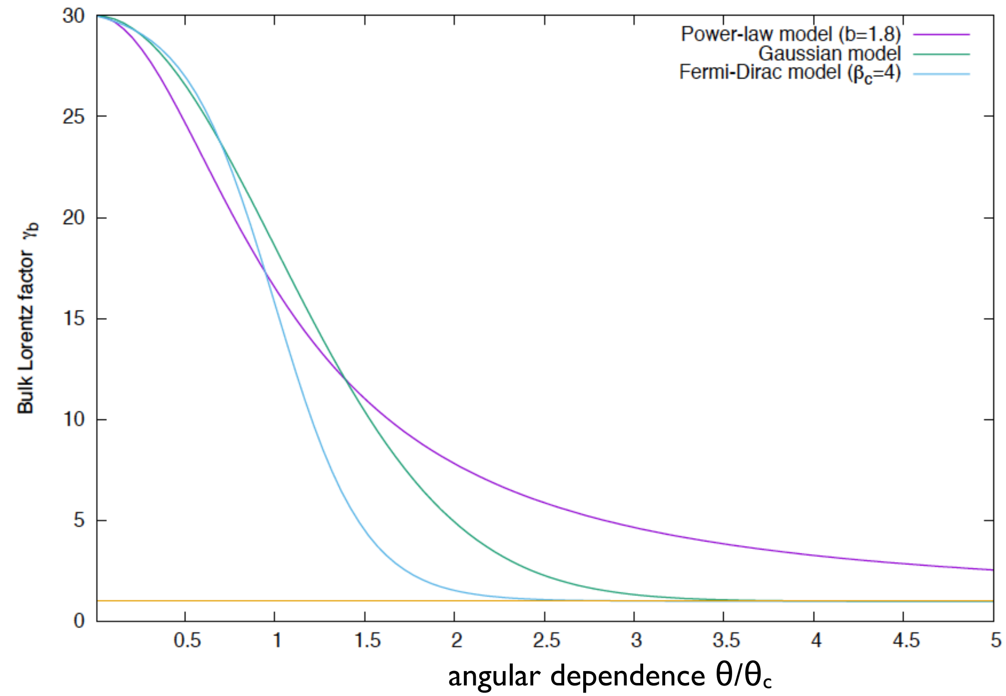
Example

Application: Shear acceleration in expanding *relativistic* outflows

- Flow profile: $u^\alpha = \gamma_b(\theta)\ (1,\ v_r(\theta)/c\ ,\ 0,\ 0)$ θ = polar angle
- power-law, Gaussian and Fermi-Dirac profile for γ_b :



Example: $\gamma_0 = 30$



FR. & Duffy 2016, ApJ, tbs…

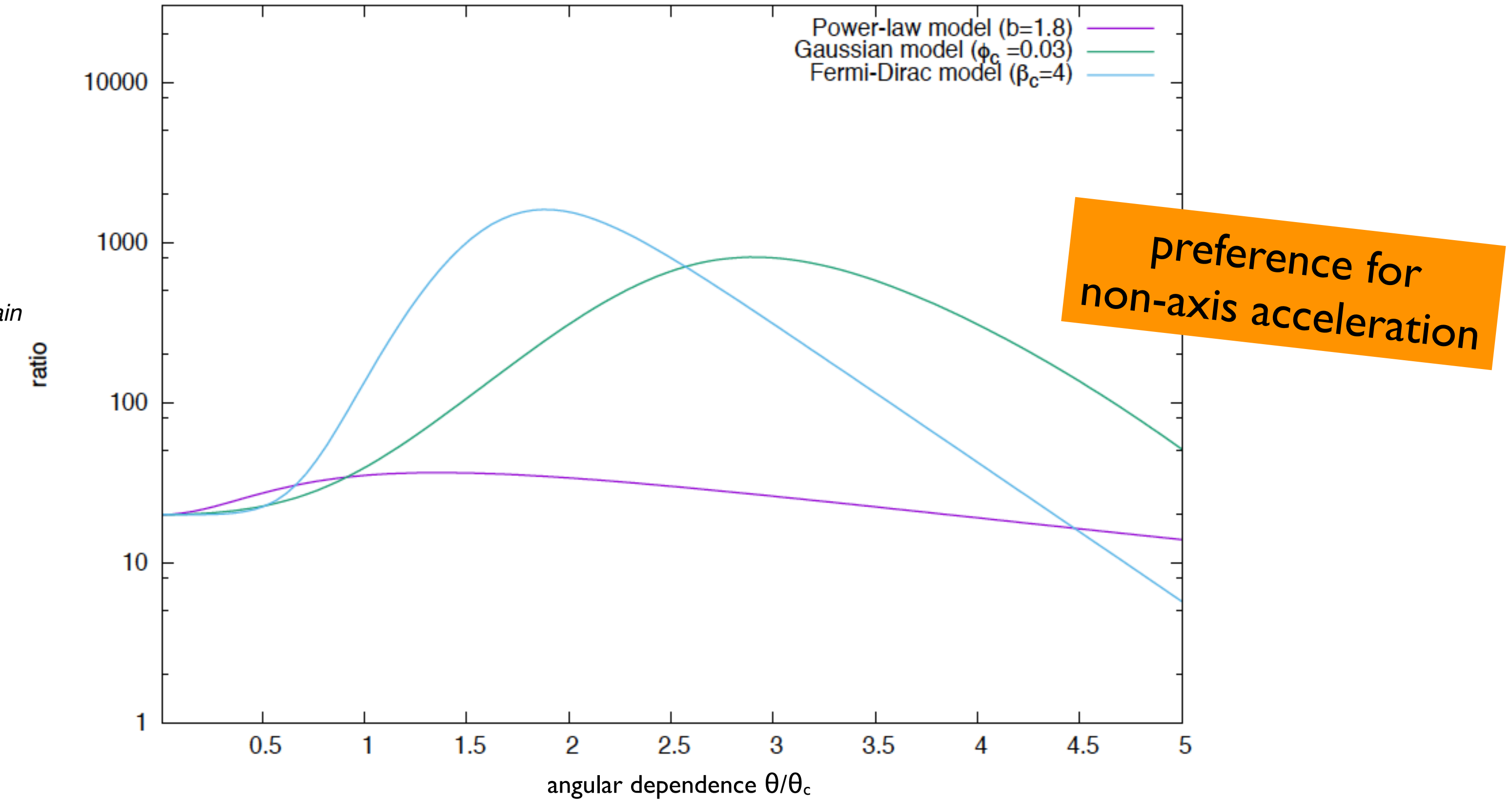
Example (continued)

- Characteristic acceleration time scale:

$$t_{acc}(r,\theta)' \sim r^2 / [\gamma_b^2 \lambda] \times 1/[v_r^2 + 0.75\, \gamma_b^2 (\partial v_r/\partial\theta)^2]$$

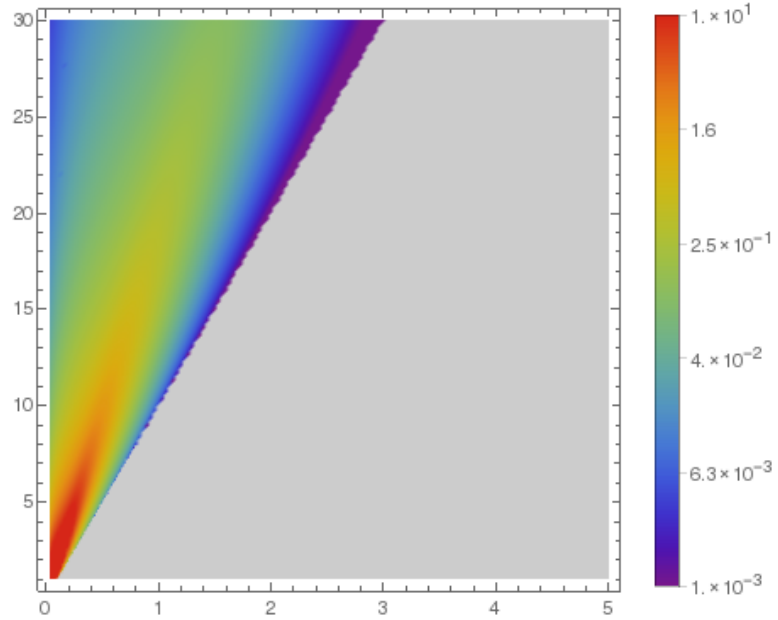
- acceleration versus adiabatic losses ($t' \sim r/c\, \gamma_b$)
- need sufficient energetic particles ($\lambda/r > 10^{-3}$)

Ratio of viscous shear gain versus adiabatic losses times (λ/r), illustrated for θ_c =0.03 rad and γ_0=30.



Example (continued)

- continued acceleration possible
- energetic seeds required (“easy” for protons/hadrons)
- multi-stage for electrons needed
  - requires weak magnetic fields (synchrotron losses)
  - delayed onset (B ~ $1/r^{\alpha}$) expected
  - prominent off-axis emission (ridge line….) possible



To conclude

Non-thermal particle acceleration in (gradual) shear outflows

- possibility for continued acceleration (as long as shear continues)
- needs energetic seed particle
  - "easy" for e.g., protons => UHECR ?
  - electrons more difficult (weak magnetic fields)
  - seeds via e.g. shock or stochastic processes
- multi-stage acceleration => multi-component particle distribution
- acceleration in Bohm limit can overcome synchrotron
- sensitive to turbulence characteristics
- complex jet morphology and multi-zone emission scenarios

THANK YOU!