Particle Acceleration in Active Galactic Nuclei on different scales

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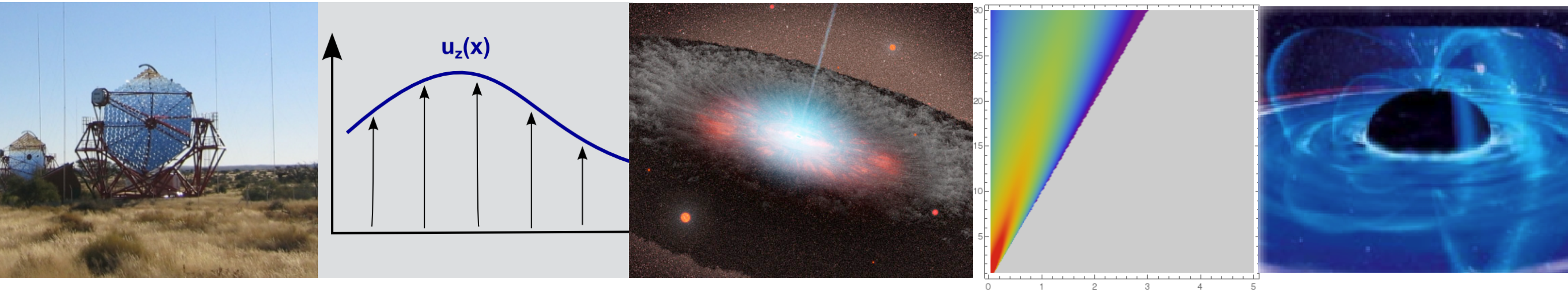

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Outline

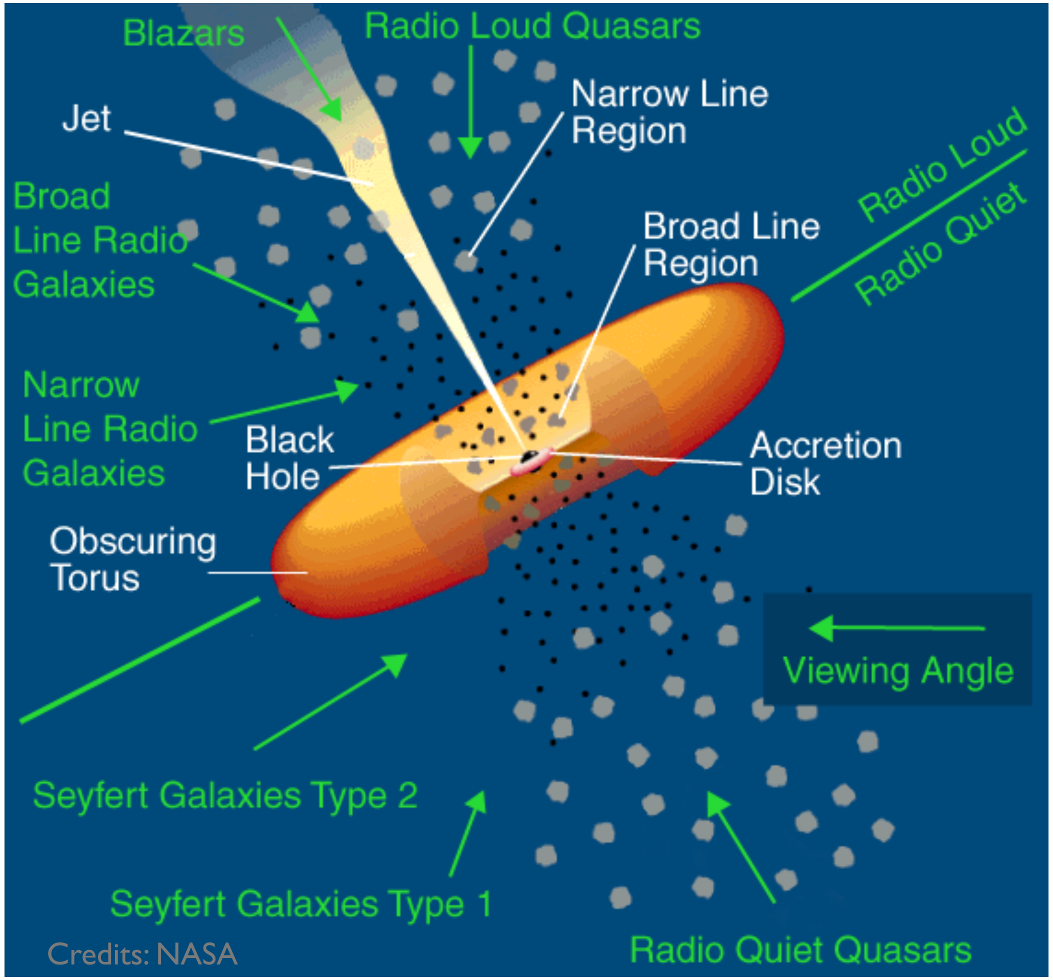
- Acceleration sites & processes in AGN
- Focus
  - Gap-type particle acceleration in BH magnetosphere
  - 2nd stage shear acceleration in complex jet flows
- Conclusions

Context of Sources

Radio-bright Active Galaxies with central engine *(AGN)* consisting of **supermassive BH** surrounded by **accretion disk** and ejecting a **relativistic jet**

Radio Galaxy **Centaurus A** (Cen A), core region, nearest *Active Galaxy* (d ~ 4 Mpc)

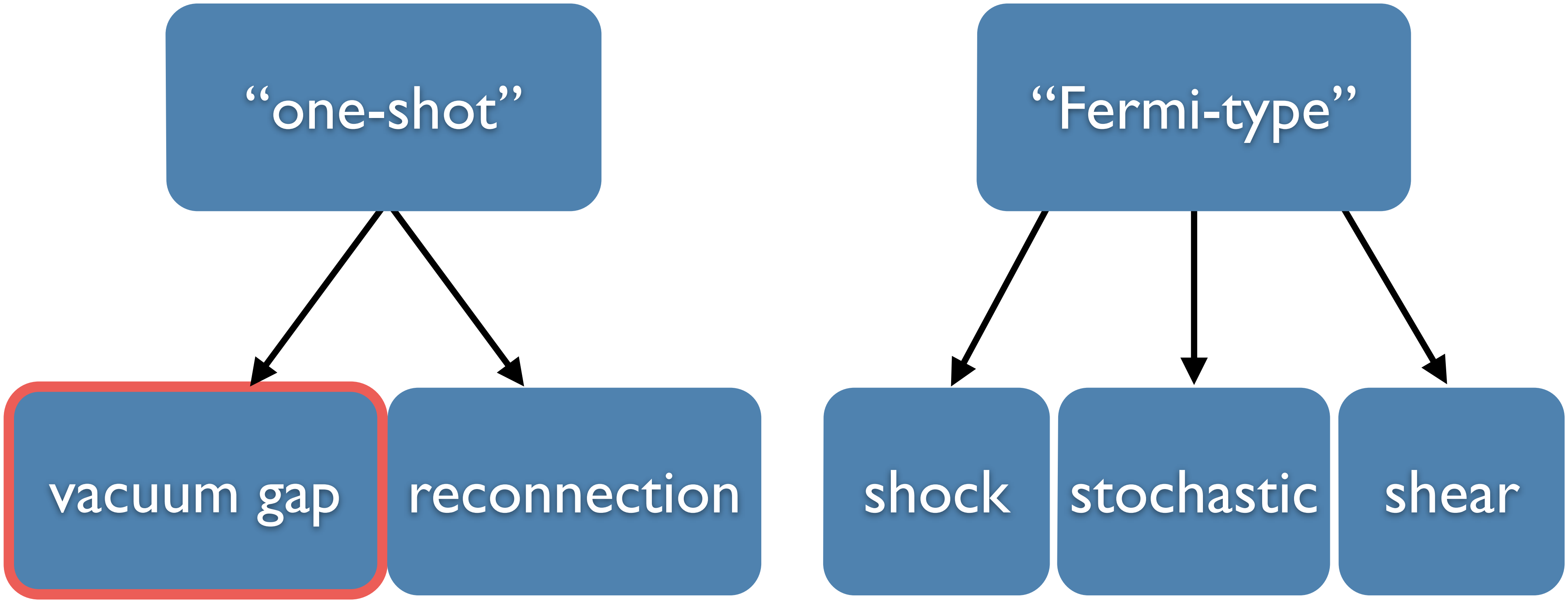
X-rays (Chandra/blue), radio (orange) & optical



Credits: NASA

Central engine in AGN & unification

Acceleration processes & sites (*not exhaustive*)



“one-shot”

“Fermi-type”

vacuum gap	reconnection	shock	stochastic	shear
BH magnetosphere	*inner jet*	*jet, hot spots*	*jet, lobes*	*jet*
charge density? topology? transparency?	limited in size? efficiency? spectral shape?	efficiency (Γ_s, σ)? localized?	efficiency? spectral shape?	efficiency? energetic seeds?

A gap-type, magnetospheric origin of VHE emission ?

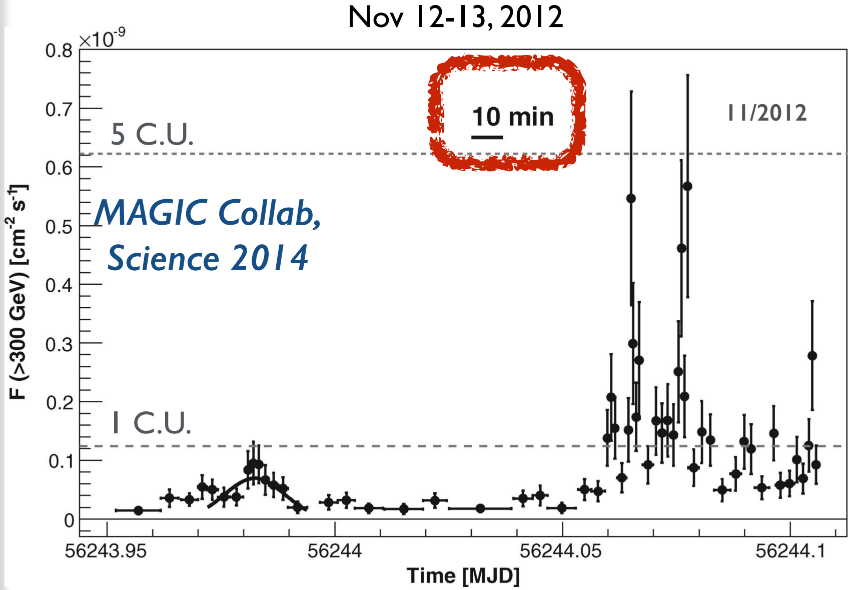
IC310: VHE flare in 2012 (MAGIC):

- very hard VHE spectrum up to ~10 TeV
  - $\Gamma < 2$ (EBL-corrected),
  - no evidence for break
- extreme short-term VHE variability,
  - doubling time ~ 5 min
  - BH timescale $r_g(3x10^8 M_\odot)/c = 25$ min
  - ***sub-horizon "gap-type" particle acceleration (?)***
    - gap height $h \sim 0.2\, r_g$
- ***possible probe of near-BH environment***

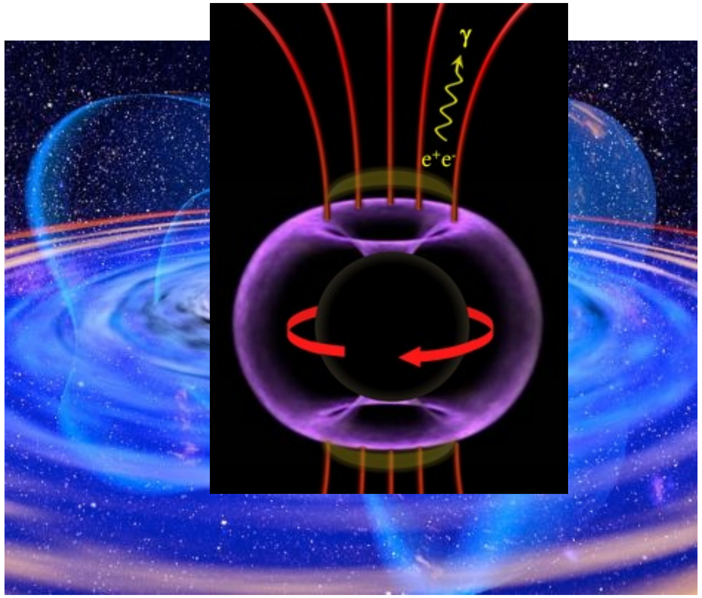
Possible Caveats:

- too luminous for gap ($L_{VHE} \sim 10^{44}$ erg/s ~ L_{jet}) ?
- hard spectrum without evidence for any absorption ($\gamma + \gamma \rightarrow e^- + e^+$)
- BL Lac core ?

IC 310 (d~80 Mpc, Perseus)

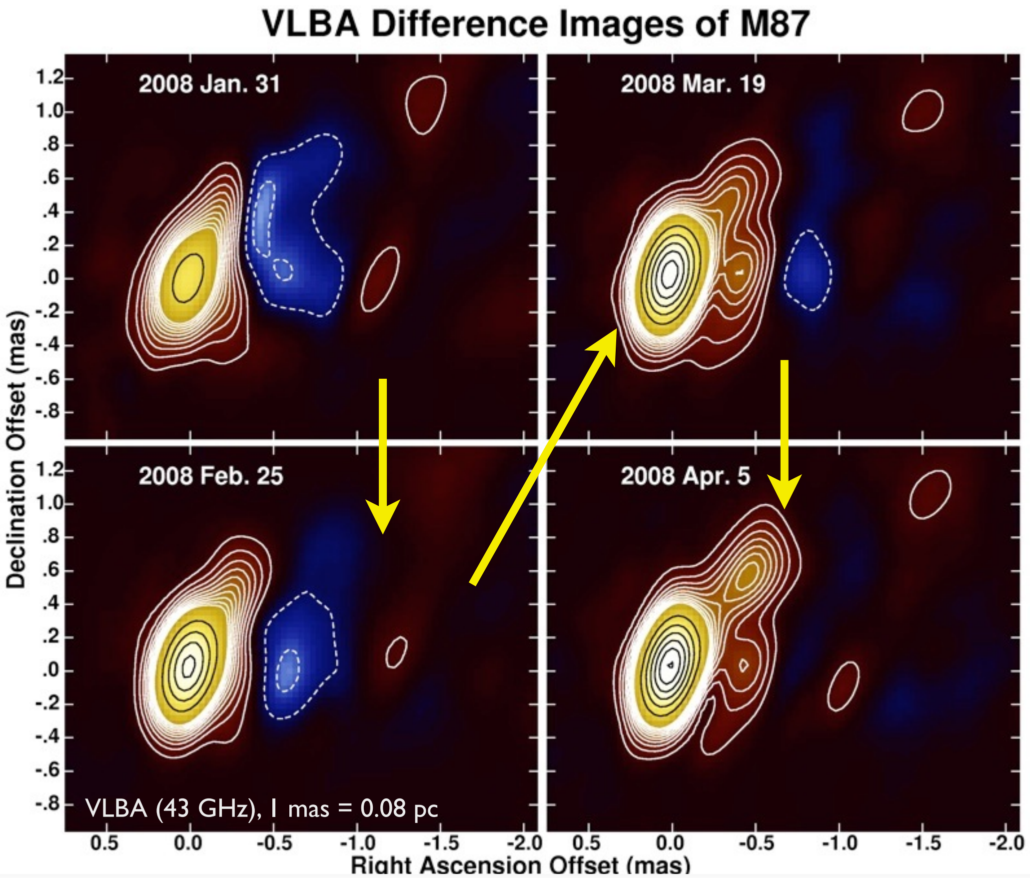


MAGIC Collab, Science 2014

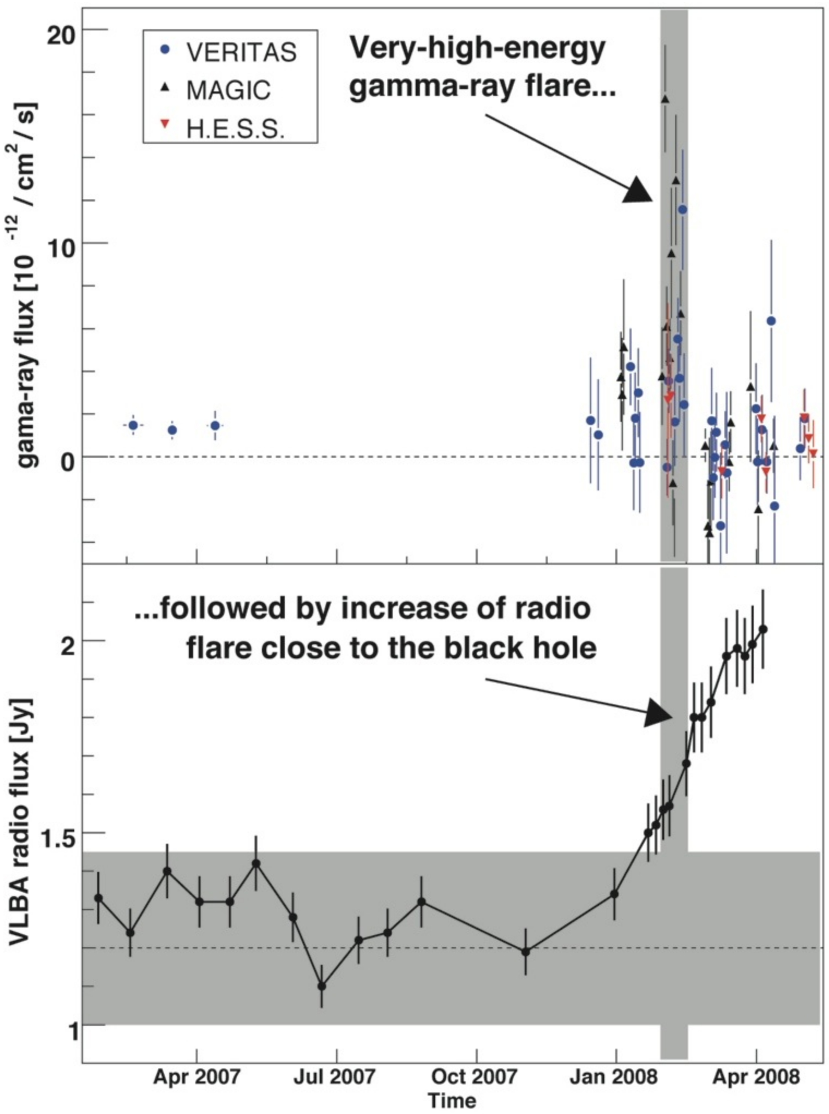


(Levinson & FR 2011; Hirotani & Pu 2016)

Magnetospheric VHE in **M87** ? - Zooming-in with radio VLBA



VLBA Difference Images of M87



Very-high-energy gamma-ray flare...

...followed by increase of radio flare close to the black hole

Acciari+ 2009, Science, 325

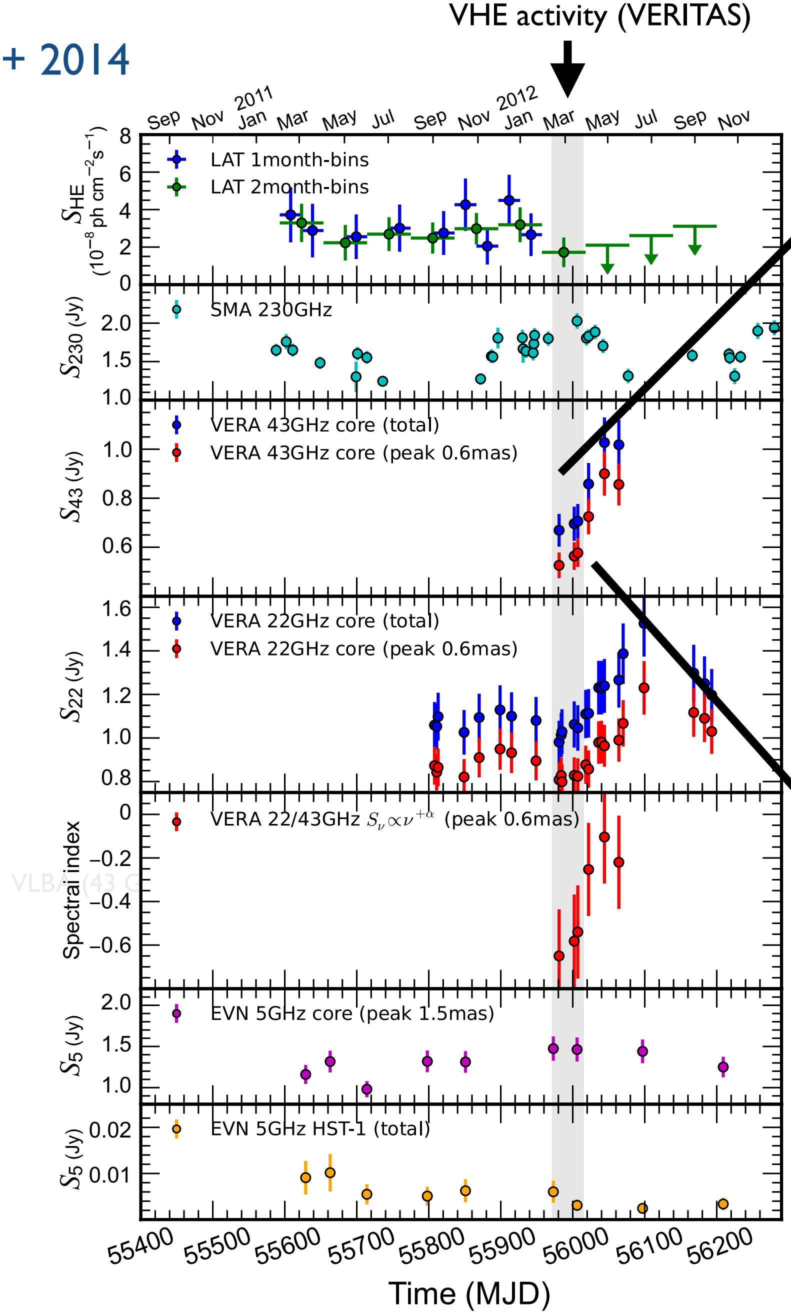
Feb. 2008 VHE flare:

- VHE day-scale variability implies size ~ a few r_s
- mas radio nucleus progressively brightened,
- energetic particle injection close to BH ($<10^2$ r_s)

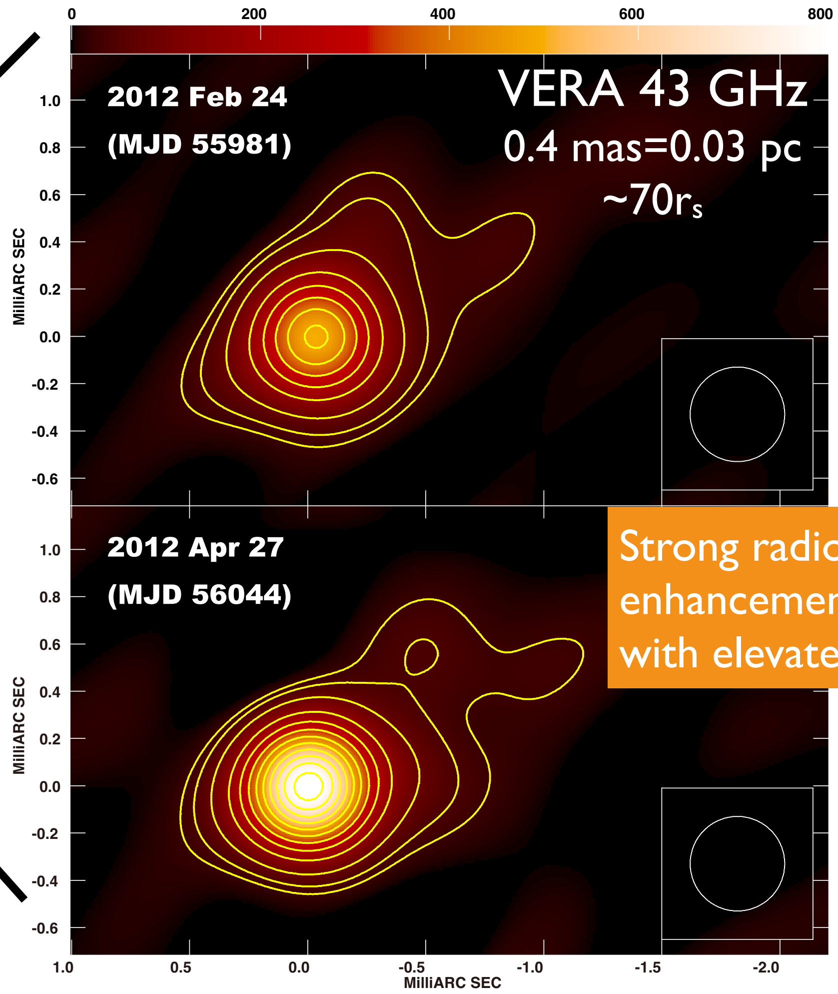
IACT resolution ~0.1° =30 kpc

M87: Combining VHE with high radio resolution - 2012

Hada+ 2014



VHE-radio link (*increase*):
+2008, ±2010,+2012



Strong radio core flux enhancement coinciding with elevated VHE state

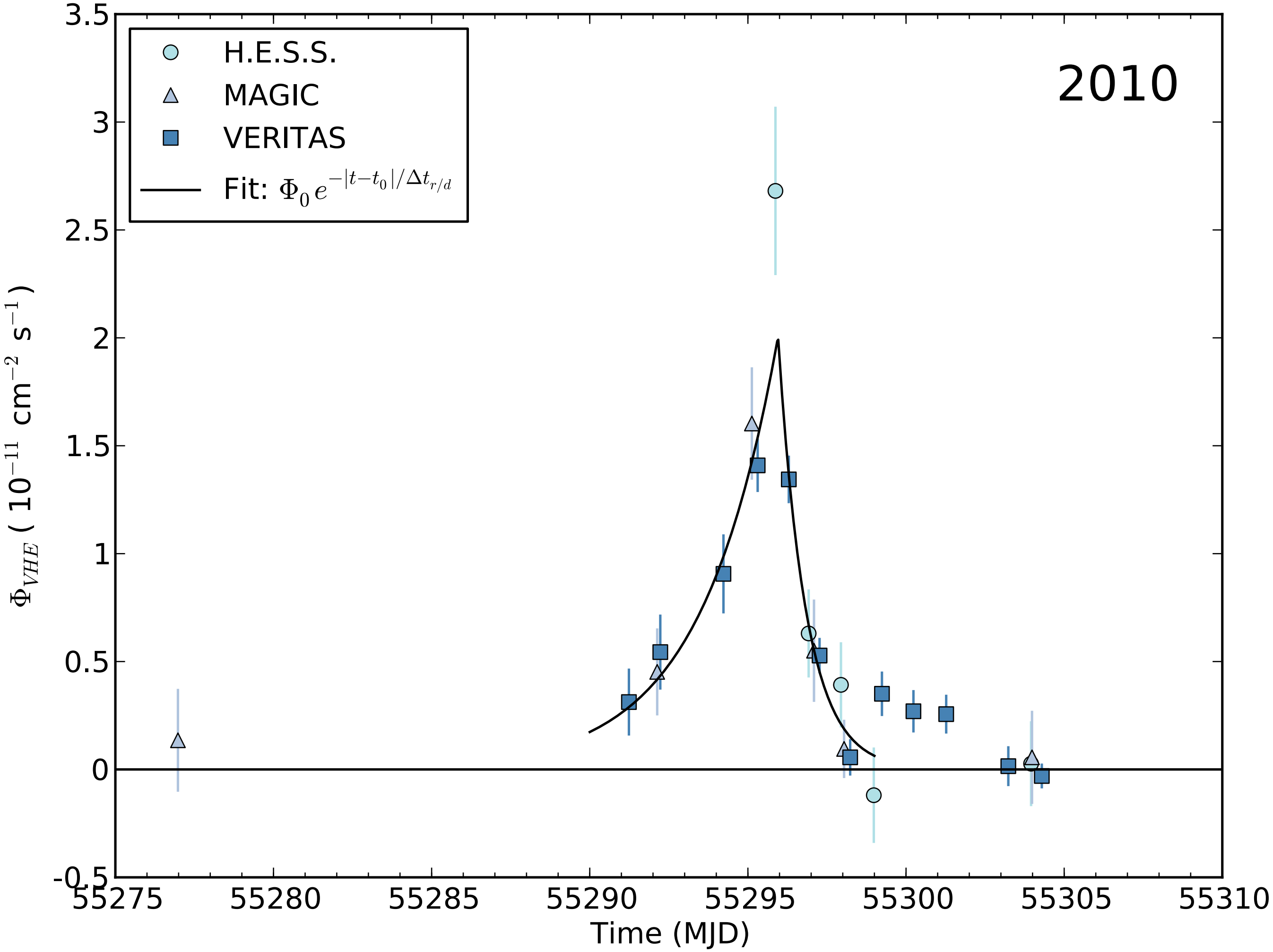
elevated VHE state in **Feb./March 2012:**

- 2-3 times higher than average, weekly variability

Beilicke+ (VERITAS) ‘2012

M87 seen at VHE gamma-rays (continued)

M87 during VHE flare in **April 2010**: best-defined rise and decline



Abramowski+ 2012

Fastest variability ever seen at any wavelength!

Possible scenarios for (variable) VHE in M87

HST-1		EC starlight photons	⟺ *(too) high VHE power ?*
inner jet (sub-parsec)	leptonic	decelerating flow (e.g. Georganopoulos+05)	⟺ *(flow gradient) timescale ?*
		spine-shear (e.g. Tavecchio+08)	⟺ *internal absorption ?*
		mini/multi-blobs (e.g. Lenain+08)	⟺ *(strongly) out of equipartition ?*
		reconnection (e.g. Giannios+10)	⟺ *guide field ?*
	hadronic	proton synchrotron & p-γ (e.g. Reimer+04)	⟺ *max. energy constraints ?*
		jet-star interactions / pp (e.g. Barkov+12)	⟺ *(too) high jet power ?*
		combined lepto-hadronic (e.g. Reynoso+11)	⟺ *jet power constraints ?*
Magneto-sphere		rotational acceleration & IC (e.g. FR & Aharonian 08)	⟺ *external absorption ?*
		gap-type particle acceleration & IC (e.g. Levinson & FR 11)	⟺ *external absorption ?*

for discussion see, e.g. R & Aharonian' 2012

Magnetospheric origin of VHE emission in **M87**?

Gamma-rays from close to black hole (< few r_g)

- ✔ Naturally satisfies variability $t_{var} \sim$ few $(r_g/c) > 0.2$ d (M87)
- ✔ accounts for VHE-radio link

But requires:

(I) VHE electrons ($\gamma_e > 10^7$) for Compton up-scattering

electron energy transferred to photon $h\nu \sim \gamma_e m_e c^2$

(II) Gap-type magnetospheric particle acceleration

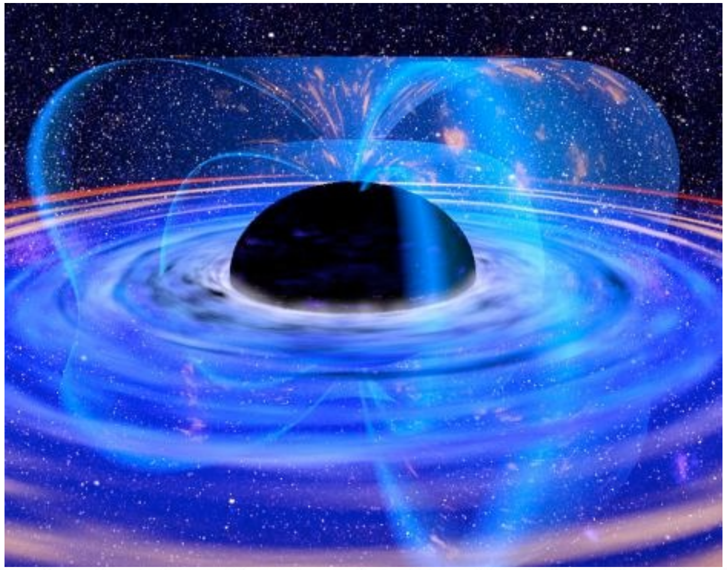
unscreened *E*-fields vs plasma-rich AGN environment

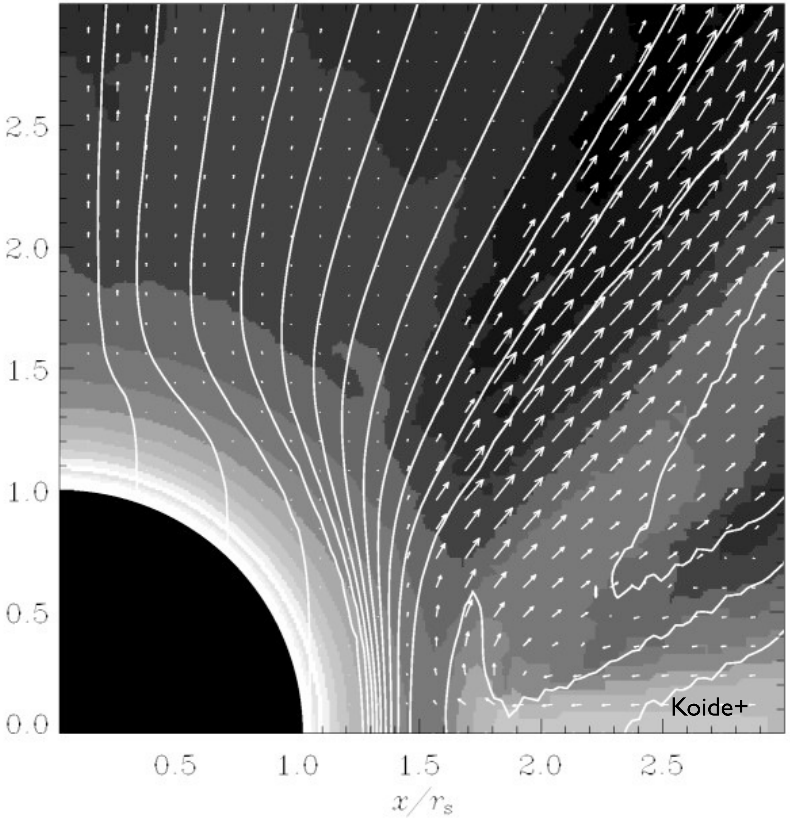
pair production in hot ADAF: $n_e/n_{GJ} = 10^{13}$ (accretion rate)$^{3.5}$

(III) Little $\gamma\gamma$-absorption below 10 TeV

want VHE gamma-rays to escape $\gamma\gamma \rightarrow e+e-$

(e.g., Levinson 2000; Beskin 2009; Levinson & FR 2011; FR & Aharonian 2008;. Neronov & Aharonian 2007; Broderick & Tchekhovskoy 2015; Ptitsyna & Neronov 2015; Hirotani & Pu 2016)



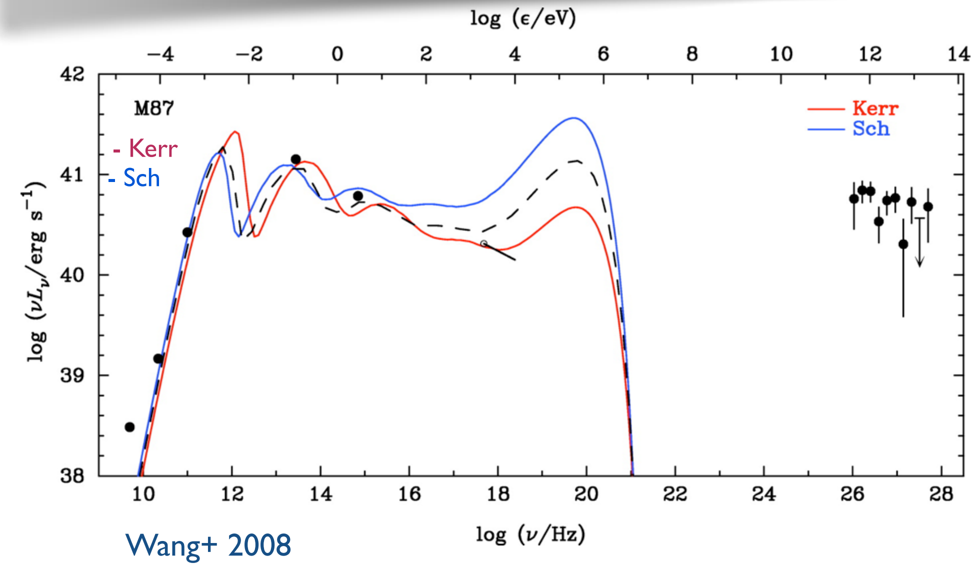


How it could possibly work in the case of **M87**…

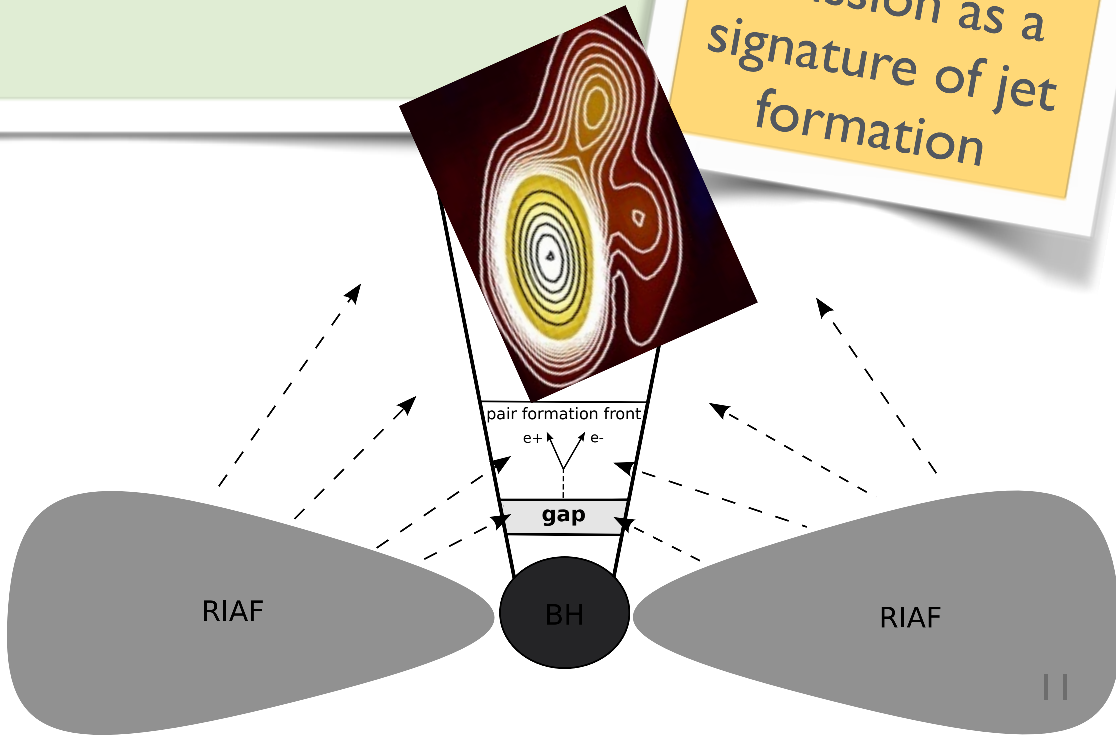
Variable VHE emission and the onset of jet formation: (e.g., Levinson & FR. 2011)

1. Rotating BH surrounded by hot accretion flow (ADAF: $kT \sim m_e c^2$)
2. Injection of primary electrons via pair-production ($\gamma_{\mathrm{MeV}}\gamma_{\mathrm{MeV}} \rightarrow e^+e^-$) in hot RIAF/ADAF
3. Gap-type particle acceleration of these electrons up to $\gamma_e \sim 10^{9\text{-}10}$
4. Direct IC (KN regime ~ 10^{15} eV) contribution (attenuated above 10 TeV, $\gamma_{\mathrm{VHE}}\gamma_{\mathrm{rad}} \rightarrow e^+e^-$); direct curvature contribution below 1 TeV
5. Electromagnetic cascade (initiated by absorption in ADAF field)
6. Pair creation: High enough multiplicity to ensure force-free outflow
7. ….

Variable VHE emission as a signature of jet formation



Wang+ 2008



Magnetospheric Potential & Jet Power - *Differences*

Levinson & FR. 2011

- Gap potential:
  - $\phi \sim a\ r_g\ B\ (\mathbf{h/r_g})^2$
- Constraining losses:
  - inverse Compton
- Jet power:
  - $L_{VHE} \sim L_{BZ}\ (\mathbf{h/r_g})^2$ …

Hirotani & Pu 2016

- Gap potential:*
  - $\phi \sim a\ r_g\ B\ (\mathbf{h/r_g})^3$
- Constraining losses:
  - curvature
- Jet power:
  - $L_{VHE} \sim L_{BZ}\ (\mathbf{h/r_g})^4$ …

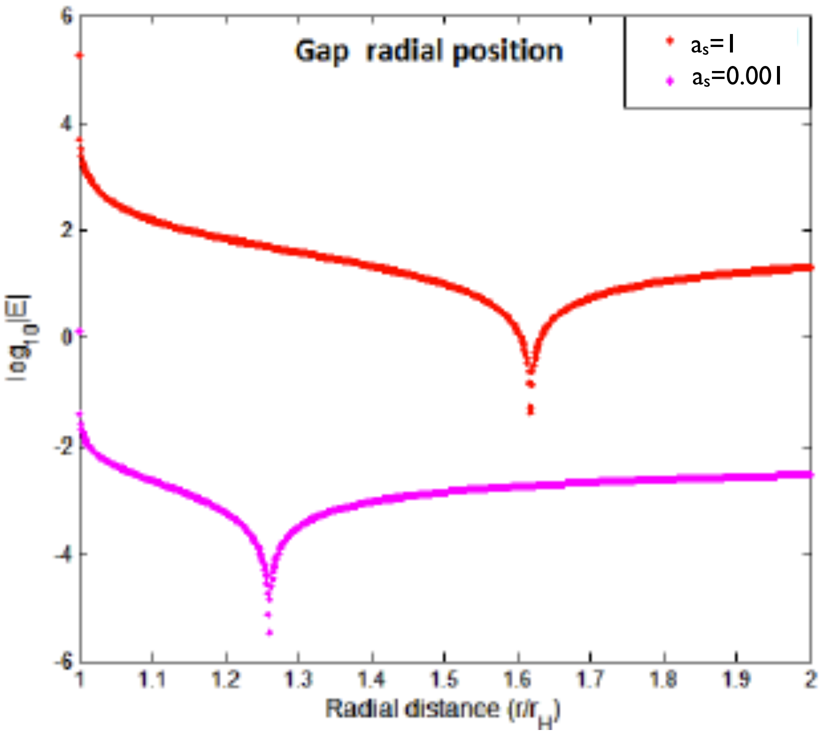
*cf. boundary condition for $E_{\parallel}(h)$ in pulsar case with $dE_{\parallel}/d$

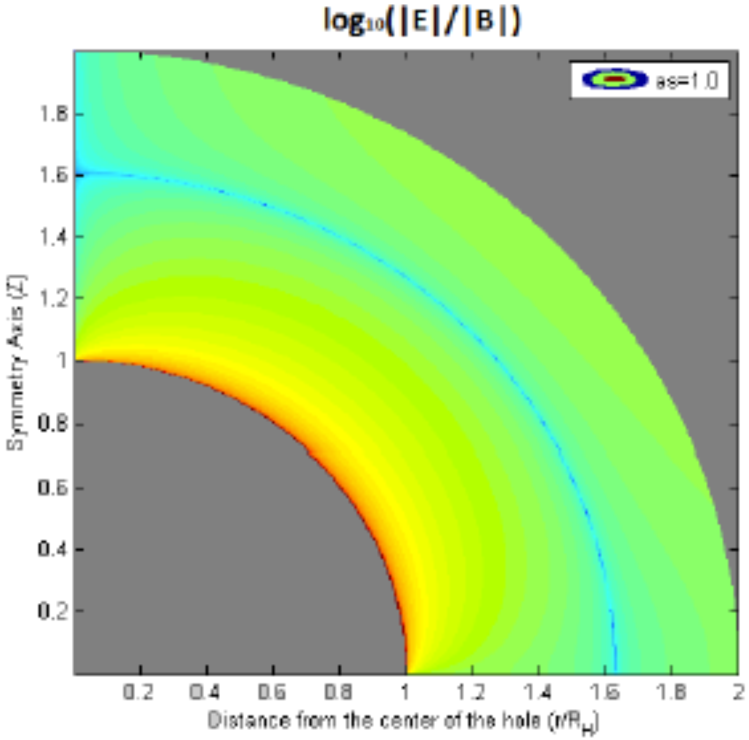
"*non-free escape*" (*Ruderman*) $E_{\parallel}(h=0)\neq 0,\ \rho_e << \rho_{GJ}$ $\Rightarrow E_{\parallel}$

"*free escape*" (*Mestel*) $E_{\parallel}(h=0)=0,\ \rho_e \sim \rho_{GJ}$ $\Rightarrow E_{\parallel} \propto h^2$

Jet power constraints will be important

Gap Location (Null-surface)….





BH environment: **E** = $E_{||}$ +E_{FF} (in non-force-free regions: **E** = $E_{||}$)

GR-Effect: radius r_i , at which $\Omega_F = \omega$ and theref $E_{FF} = 0$ (Beskin 1992)

force-free case: $\mathbf{E}^P = -(\Omega_F - \omega)/(2\pi c \alpha_L)\, \nabla \Psi_B$

with $\omega = 2\, a\, M\, r / \Sigma^2$ (Lense-Thirring),

flux function: $\Psi^{FF}_B = \pi B_o r^2 \sin \theta^2$,

field line rotation: $\Omega^F = \Omega_H/2$

horizon radius: r

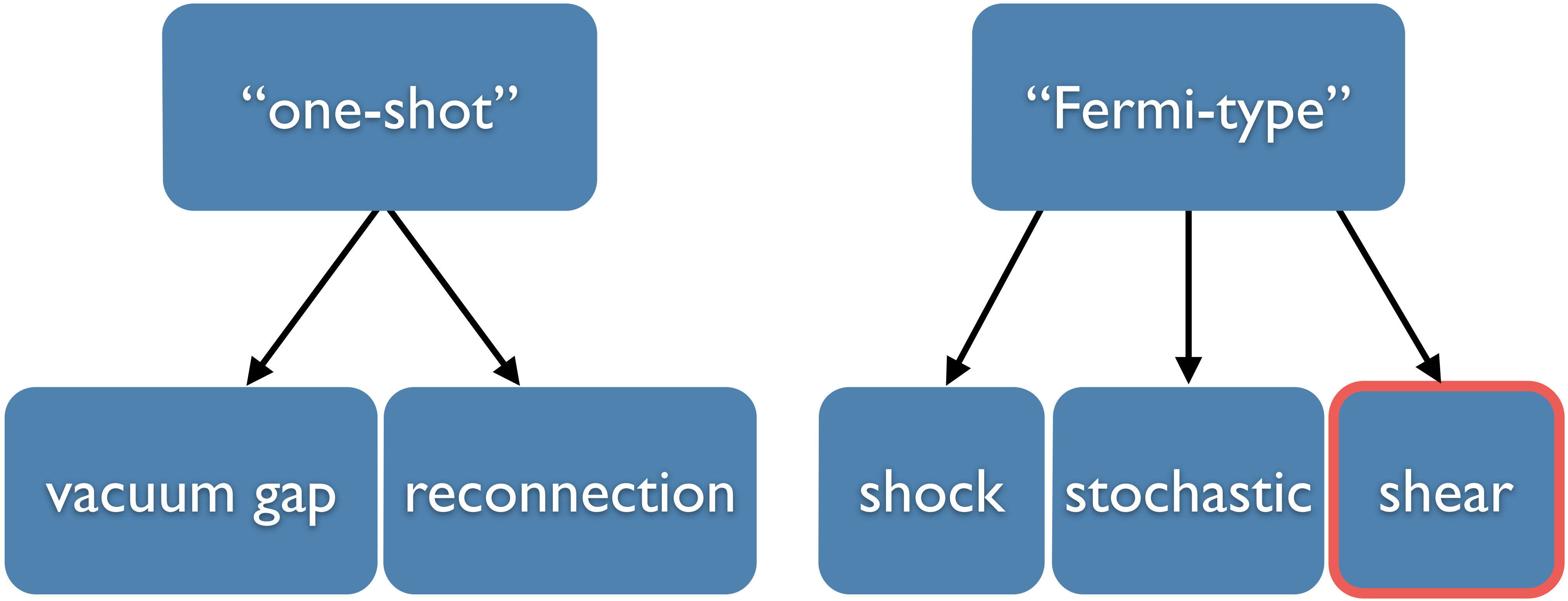
Gap location might be close enough to accommodate variability

Conclusion I

Fast VHE variability in under-luminous AGN (Radio Galaxies)

- putative probe of near BH environment & jet formation
- link to accretion state (transparency, injection…)
- relevance of radio observations…
- less promising as UHECR accelerators…
- challenges: gap-formation non-steady, emission processes…

Acceleration processes & sites (*not exhaustive*)



“one-shot”

- vacuum gap
- reconnection

“Fermi-type”

- shock
- stochastic
- shear

vacuum gap	reconnection	shock	stochastic	shear
BH magnetosphere	*inner jet*	*jet, hot spots*	*jet, lobes*	*jet*
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:

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

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

- **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 energisation 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….*

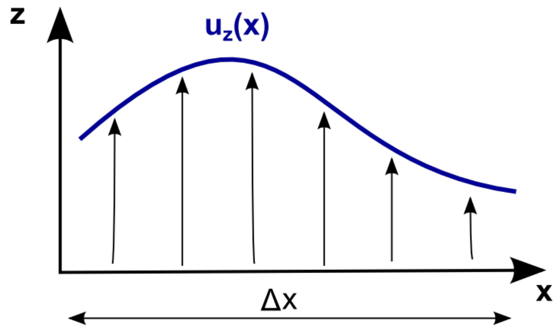
Shear acceleration (gradual - characteristics)

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

non-relativistic

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

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



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

using *characteristic effective velocity:*

$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda$$

, where λ = *particle mean free path*

- So:

$$\boxed{t_{acc} = \frac{\epsilon}{(d\epsilon/dt)} \sim \frac{\epsilon}{<\Delta\epsilon>} \times \frac{\lambda}{c} \propto \frac{1}{\lambda}}$$

  - needs seed from acceleration @ shock or stochastic….
  - easier for protons….

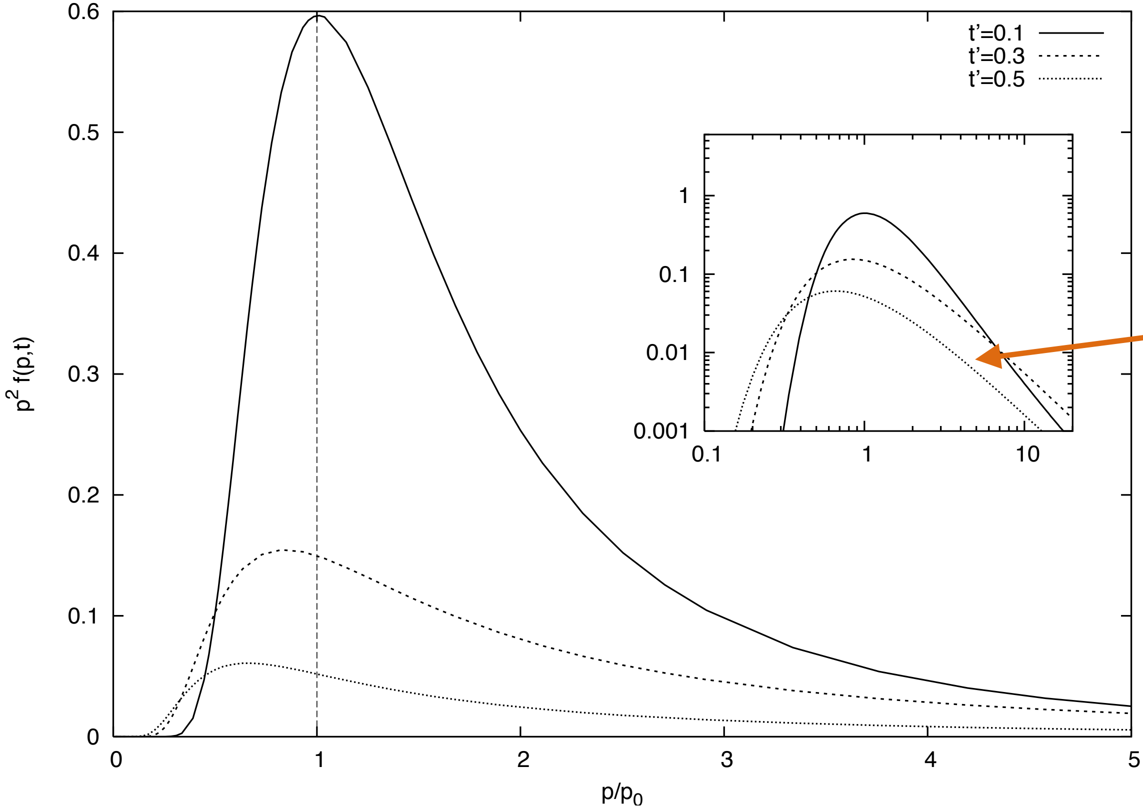
e.g., Jokipii & Morfill 1990; FR. & Duffy 2004, 2006…

Shear acceleration (gradual - characteristics)

In absence of losses, local *power law formation with index depending on mean free path scaling:*

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

- 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 with no escape using impulsive injection at p_0 at t_0 =0 for α =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* $\kappa \sim \lambda c$

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

_2nd order Fermi (stochastic):

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

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

_Shear - **gradual** (non-relativistic):

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

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

talk by Ruoyu

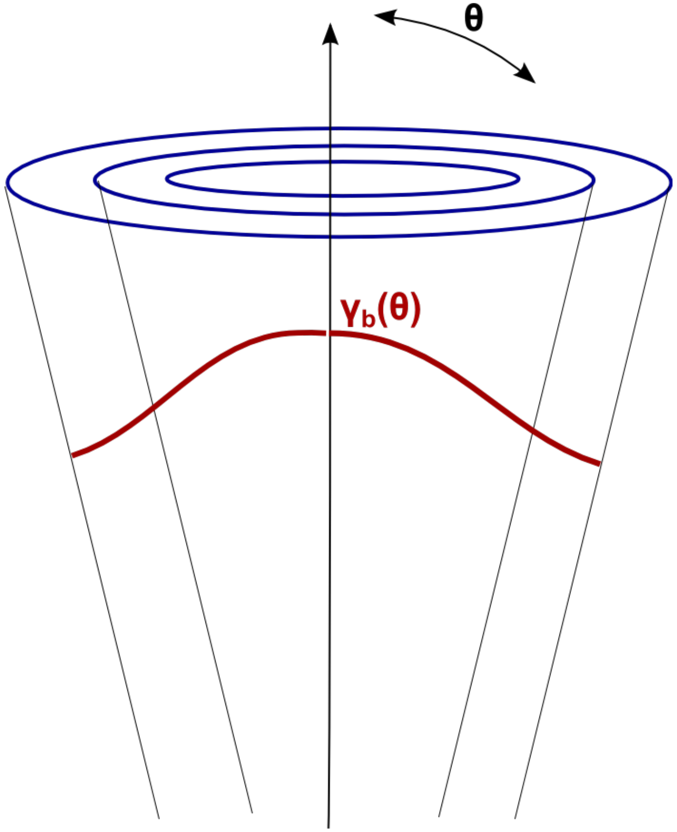
- **UHECR acceleration** in AGN jets
  - could push up cosmic rays to UHE energies when shock speed is too slow (*Cen A*)
  - change in spectrum & composition possible
- **GRB jets**
  - might be faster than (internal) shock acceleration
  - delayed and extended electron acceleration possible
- **Multi-stage 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….

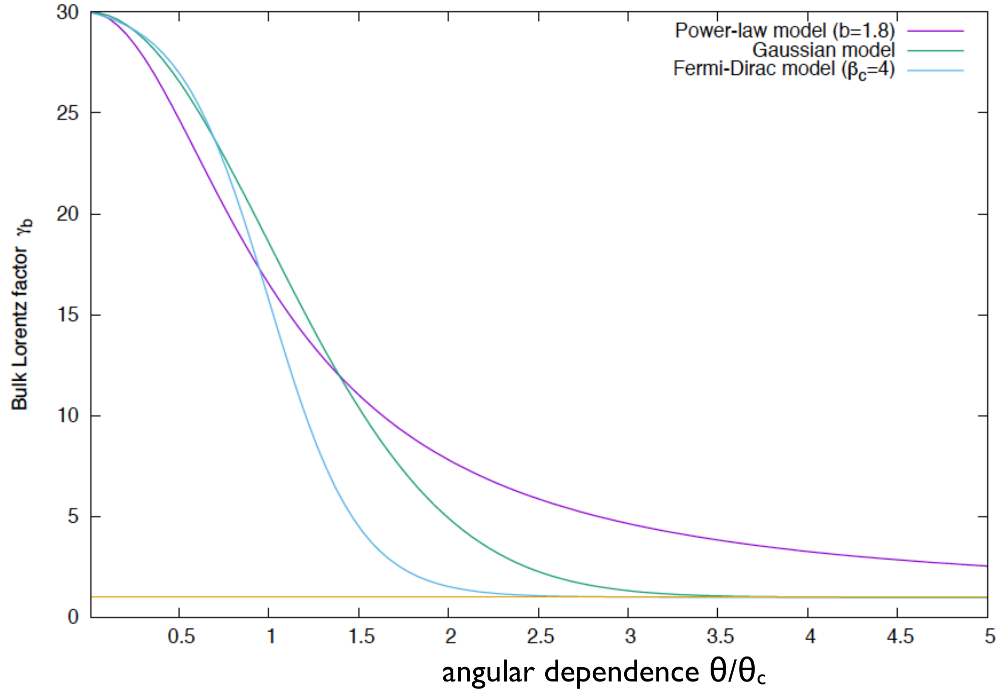
Example

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.

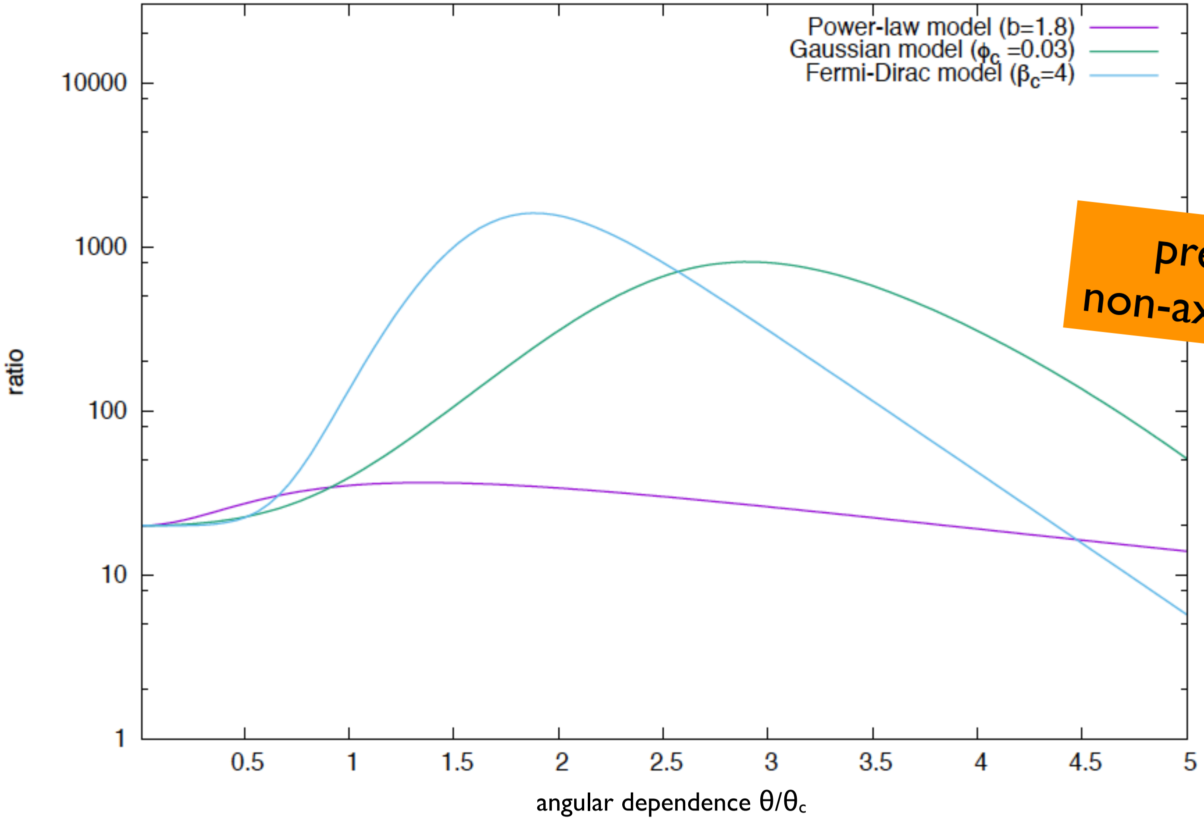
Example (continued)

- 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 ($\lambda/r > 10^{-3}$)

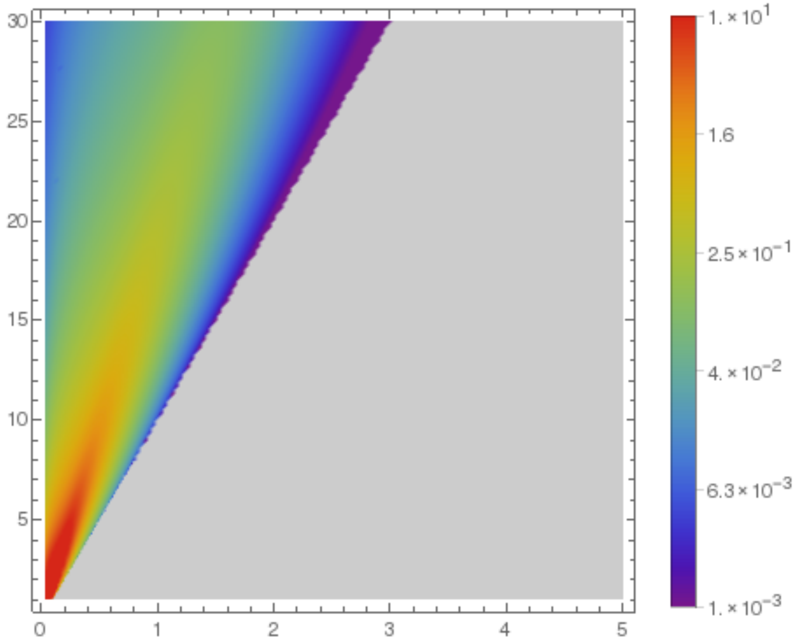
Ratio of viscous shear gain versus adiabatic losses times (λ/r), illustrated for $\theta_c = 0.03$ rad and $\gamma_0 = 30$.



preference for non-axis acceleration

Example (continued)

- continued acceleration possible
- energetic seeds required ("easier" 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



Conclusion II

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!