Resolving Doppler factor crisis in AGNs: non-steady magnetized outflows

Maxim Lyutikov, Matthew Lister (Purdue)

Radio-gamma correlation & TeV-GeV relation

- Radio-gamma correlation is well established
  - Details not clear:
    1. radio or gamma leads, if any; (gamma leads-Pushkarev)
    2. OR radio starts before, but peaks after gamma
    3. is gamma generated within the radio-mm optically thick region or outside?
- TeV-GeV
  - TeV and GeV AGNs are (half) different: TeVs are mostly HBLs, half of GeVs are FSRQs
  - GeV variable on ~ hour, probably cannot do shorter due to low counts (TeV ~ minutes).

Doppler factor crisis in AGNs

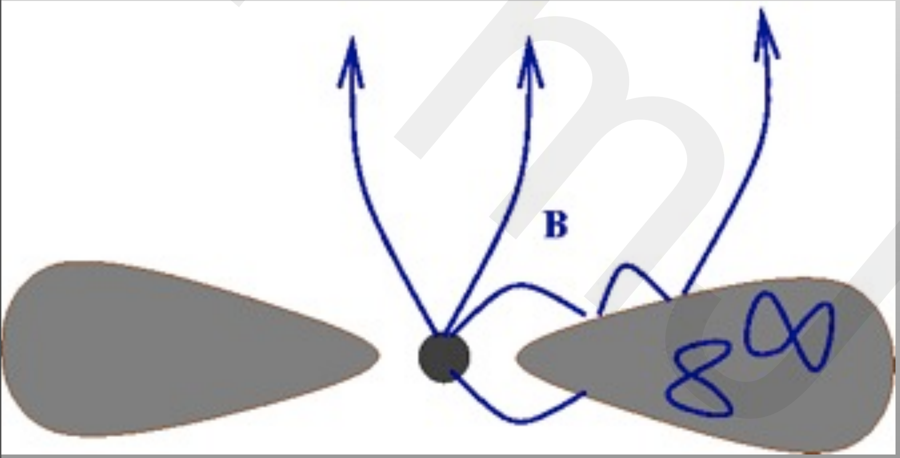
Henri & Sauge 2006

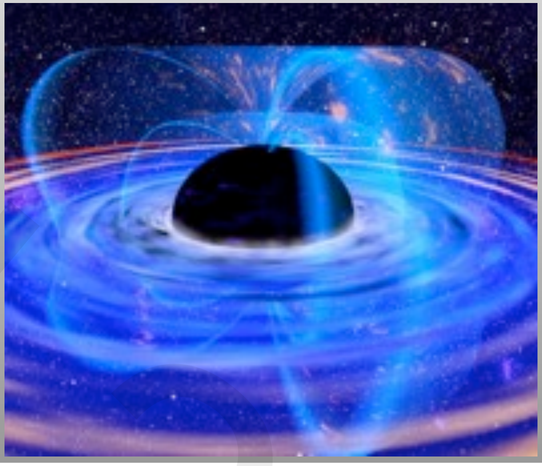
- Radiative modeling of TeV flares requires $\delta_{\rm TeV} \geq 100$
  - Fast variability $\Delta t \rightarrow \Delta t'/\Gamma^2$
  - Compactness parameter $\tau \rightarrow \tau'/\Gamma^6$
  - (I will mix up a bit TeV-GeV data. At least both IC.)
- Direct observations of superluminal radio knots imply $\delta_{\rm knot} \leq 10$
  - MOJAVE: blobs motion reflects underlying flow (bidirectional motions, no inward moving features, multiple blobs in the same jet with the same speed, correlations of jet speeds with other properties)
- Somewhat similarly (?) GeV photons in GRB 080916C -> Gamma ~2000.

Natural resolution: separate radio and GeV-TeV sites:

- in space (fast spine, slow sheath)
- time/space (decelerating jets, Georganopoulos & Kazanaz 2003)
- space: this work: **accelerating jets**

AGN launching: large-scale B-fields





- AGN (and GRB) jets are magnetically accelerated and collimated (Blandford&Znajek, Blandford&Payne).
- $c_s \sim c$, crossing time of SMBH ~ minutes-hours.
- Relax to **steady state**

Observations indicate non-stationarity, blob ejection etc.

Probably related to instabilities of the inner disk

- Clear disk-jet connection in galactic BHs
- Some indication in AGNs (3C 120)

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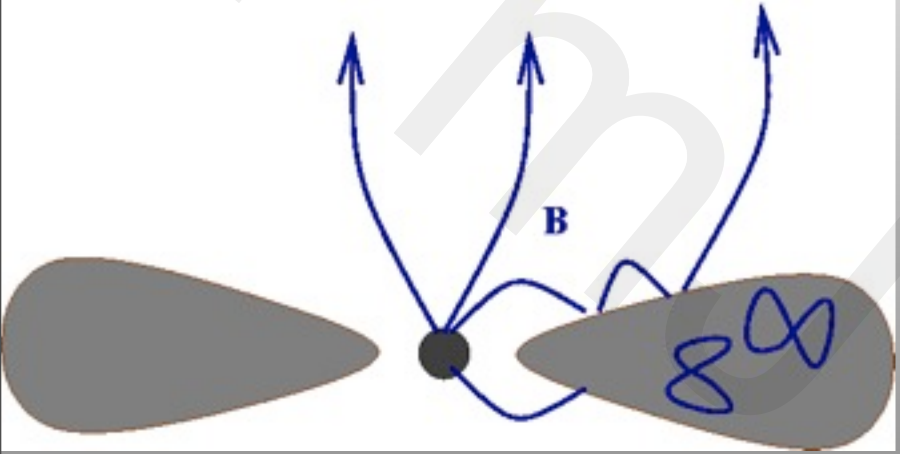

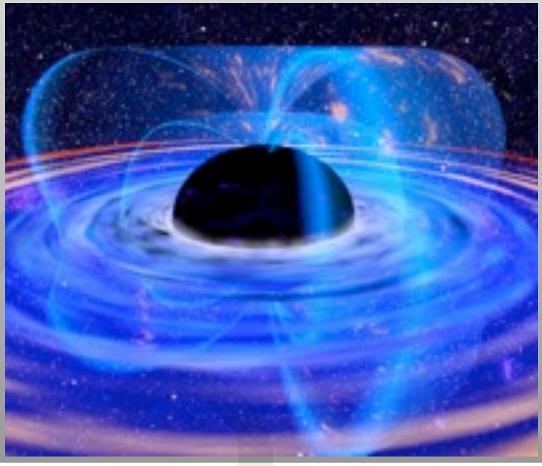

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What are the consequences of non-stationary jet injection?

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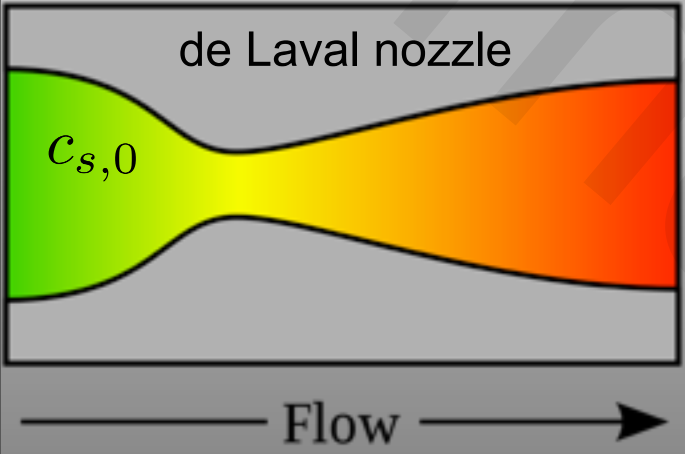
Acceleration: pressure- & magnetic-driven, Newtonian, Relativistic.



Fluid, non-relativistic:

Stationary:

$$v_{max,statioanry} = \sqrt{\frac{2}{\gamma_{ad}-1}} c_{s,0} \sim c_{s,0}$$

Non-stationary

$$v_{max,non-stationary} = \frac{2}{\gamma_{ad}-1} c_{s,0} > v_{max,stationary}$$

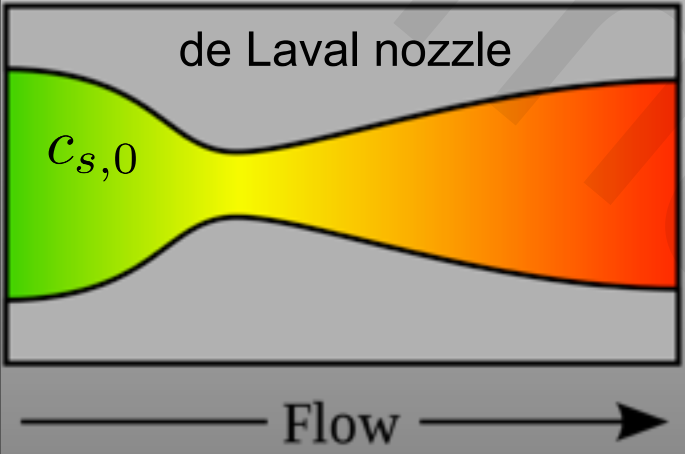
MHD, relativistic: $\sigma = \frac{B^2}{4\pi\rho c^2}, \Gamma_A = \sqrt{1+\sigma}$

There is enough energy to have $\Gamma \sim \sigma$

Yet in a stationary regime $\Gamma_{\text{inf}} \sim \sigma_0^{1/3}$

Acceleration: pressure- & magnetic-driven, Newtonian, Relativistic.

Most internal energy is converted into bulk



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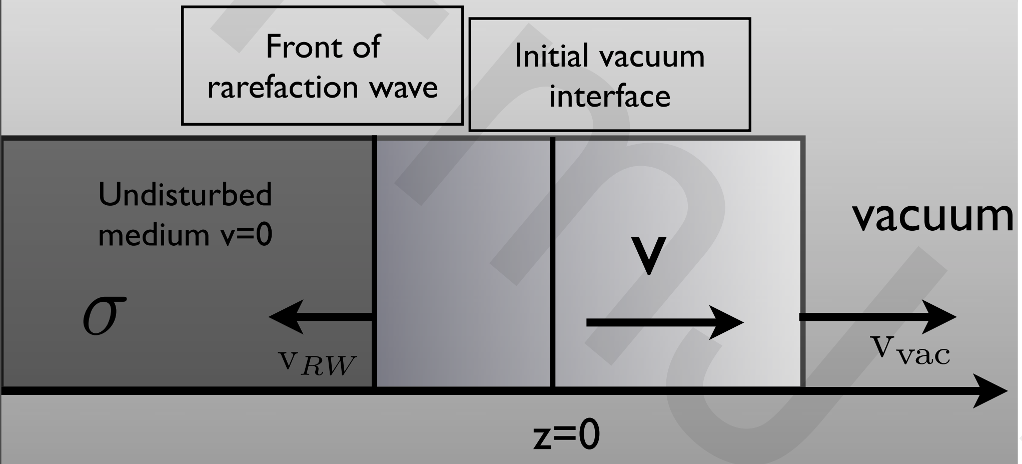
In non-stationary magnetically-driven expansion $\Gamma_{max} = 1 + 2\sigma$

Leading edges of non-stationary outflows can accelerate to much higher Lorentz factors and may dominate highly boosted high energy emission.

Steady state: $\Gamma \sim \sigma^{1/3}$

Relativistic Riemann problem



$$(\partial_t + \beta\partial_z)\,\beta = -\frac{(\beta\partial_t + \partial_z)\,P}{(\mathcal{E} + \rho + P)\gamma^2}$$

$$(\partial_t + \beta\partial_z)\,P = -(\mathcal{E} + \rho + P)\gamma^2\,(\beta\partial_t + \partial_z)\,\beta$$

Exact, fully non-linear solution for Riemann problem (Riemann invariants and characteristics)

$$\boxed{\begin{aligned}\delta_\beta &= \delta_\eta^{2/3}\delta_{A,0}^{2/3}\\ \delta_A &= \frac{\delta_{A,0}^{2/3}}{\delta_\eta^{1/3}}\end{aligned}}$$

$$\eta = z/t$$

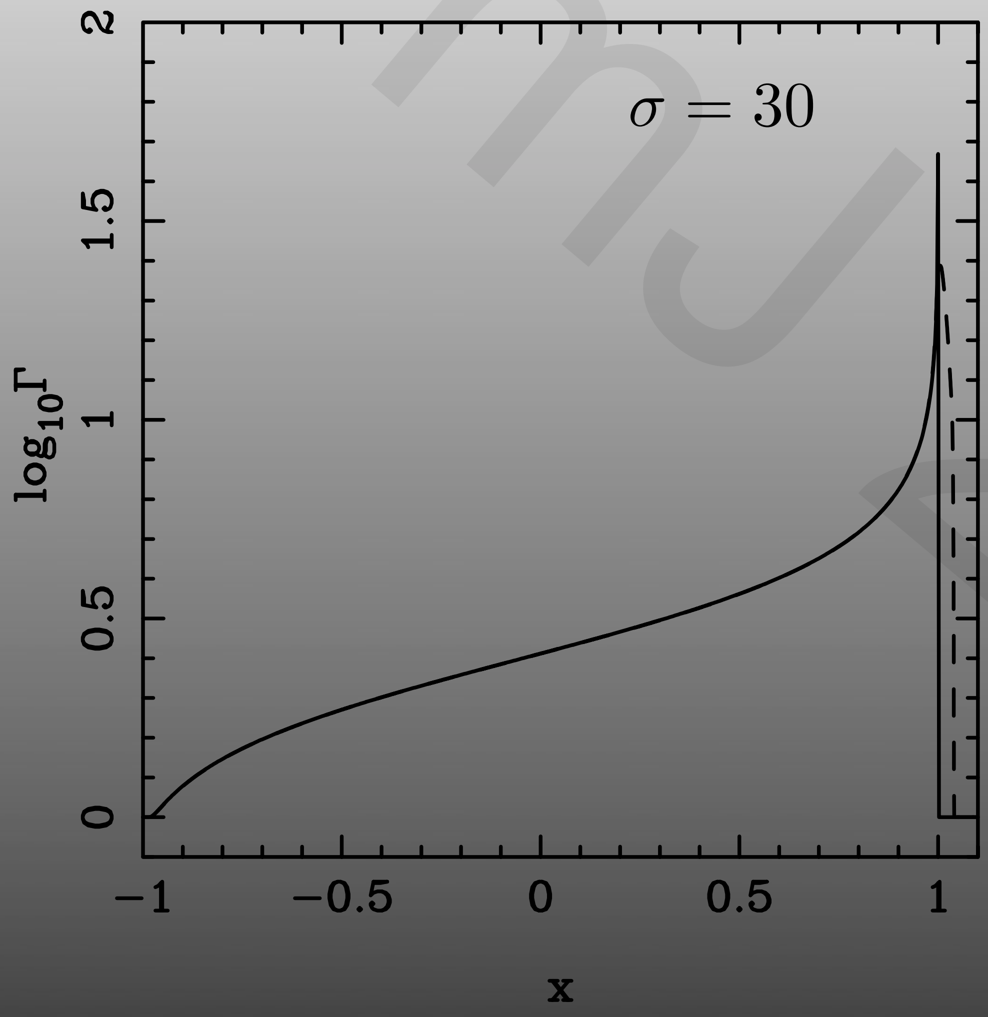
$$\delta = \sqrt{\frac{1+\beta}{1-\beta}}$$

Modern shock-capturing numerical schemes (Godunov) are based on Riemann invariants. Exact non-linear solutions are rare, needed for code testing.

Marti&Muller (1996) found $J_\pm$

we found shape of characteristics

Testing theory and codes



Two (!) curves for density: analytical (Lyutikov) and simulations (Komissarov).

Codes can deal with high magnetization, high Lorentz factors, large density contrast.

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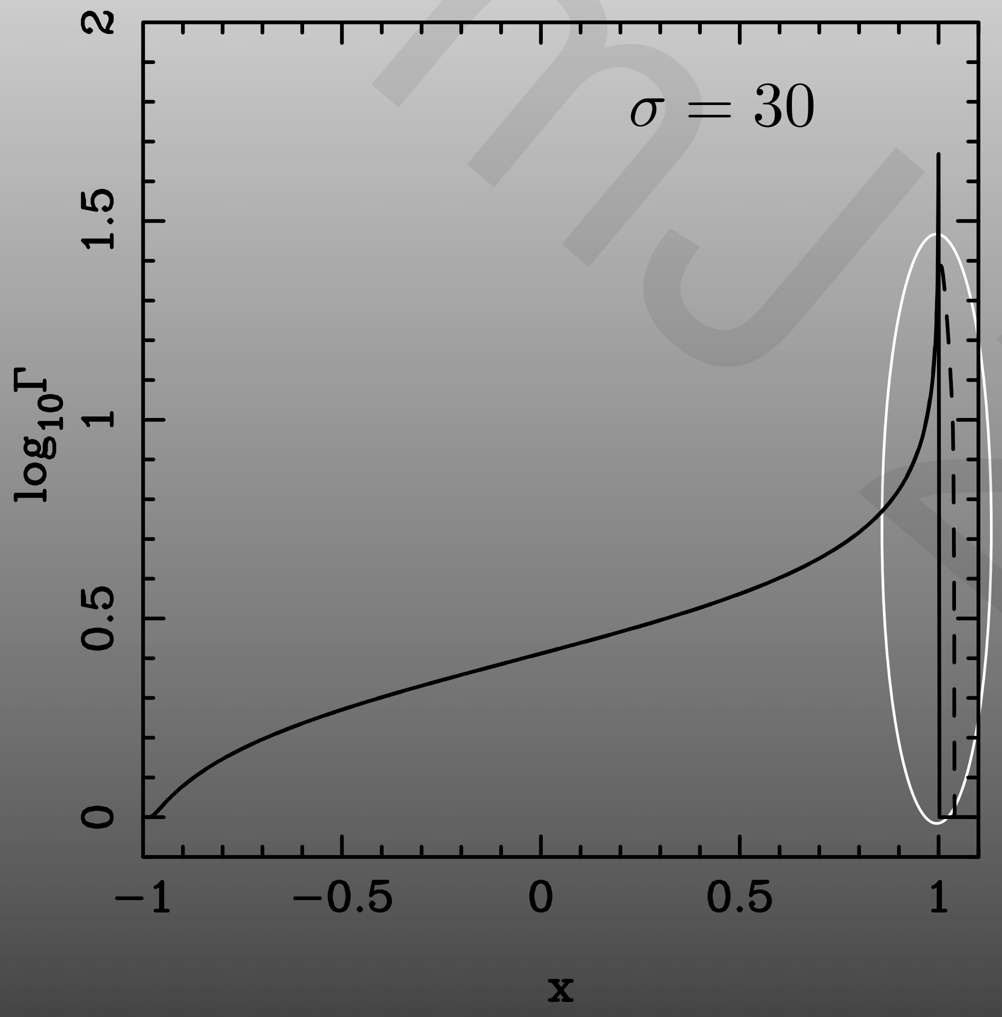

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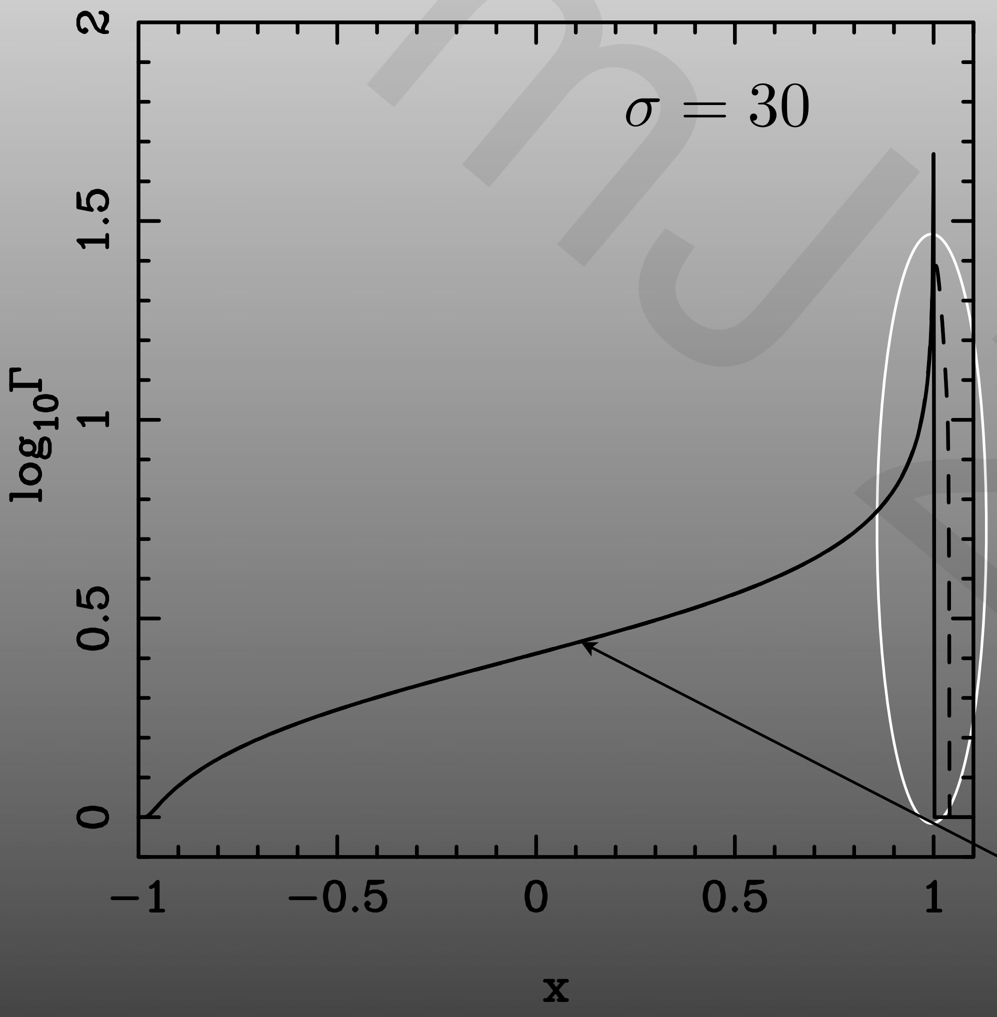

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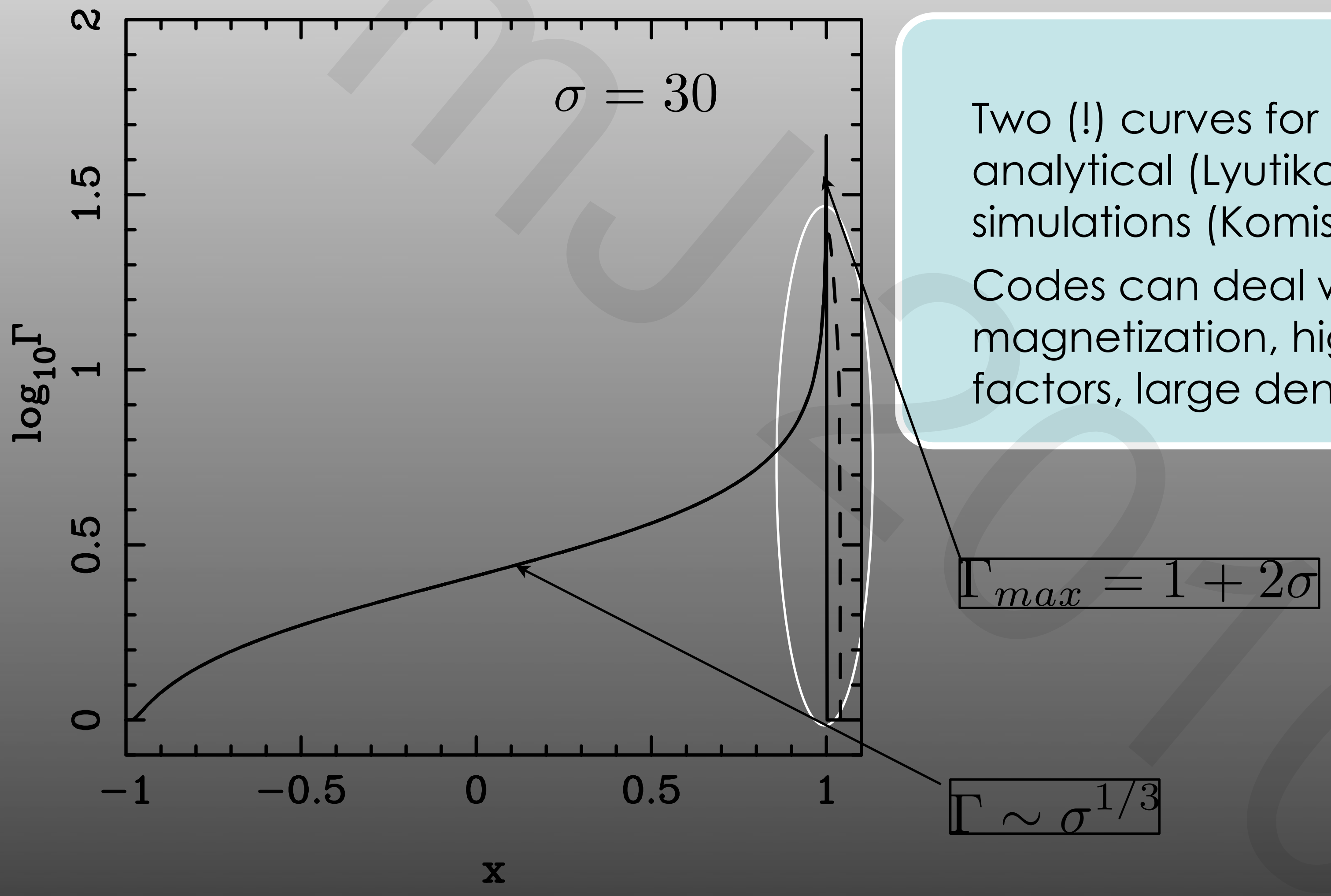

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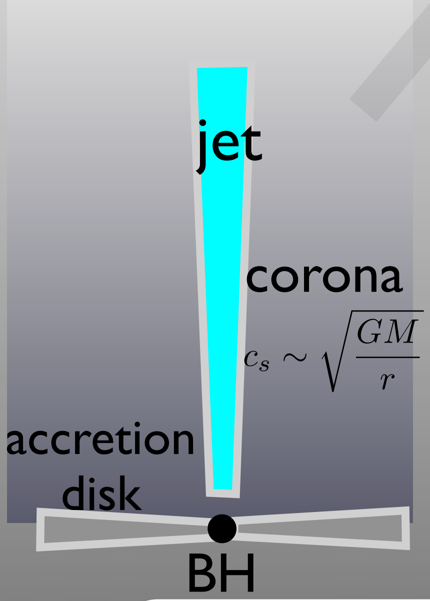
Non-stationary jet injection in static corona



Dynamic time across the jet

$$t_{dyn} \sim r\Theta_j / c_s$$

Variations in disk/ launching

$$t_j \sim \xi\, r_{BH}/c$$

At sufficiently large radii,

$$r_{\text{breakout}} \geq \left(\frac{\xi}{\theta_j}\right)^{2/3} r_{BH} = 2\times10^{16}\,\text{cm} M_{\odot,9}\xi_2^{2/3}\theta_{j,-1}^{-2/3}$$

variations of launching proceed on time scales shorter than the dynamical time scale across the jet,

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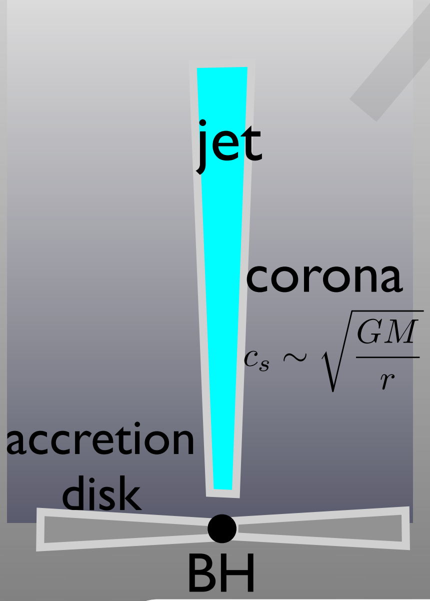

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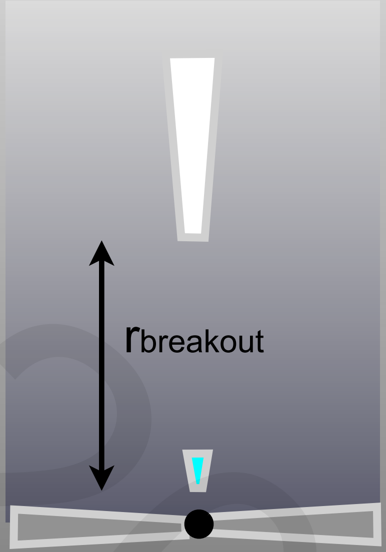

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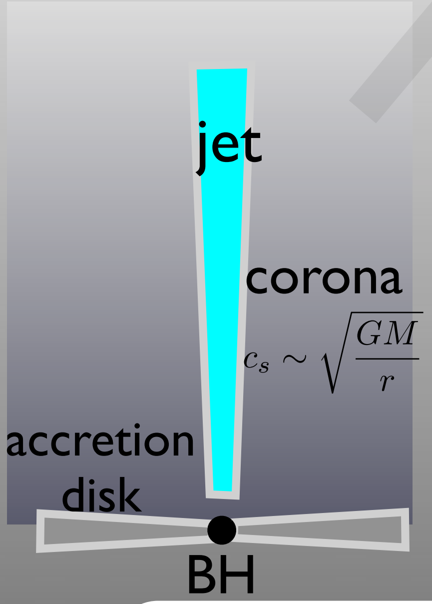

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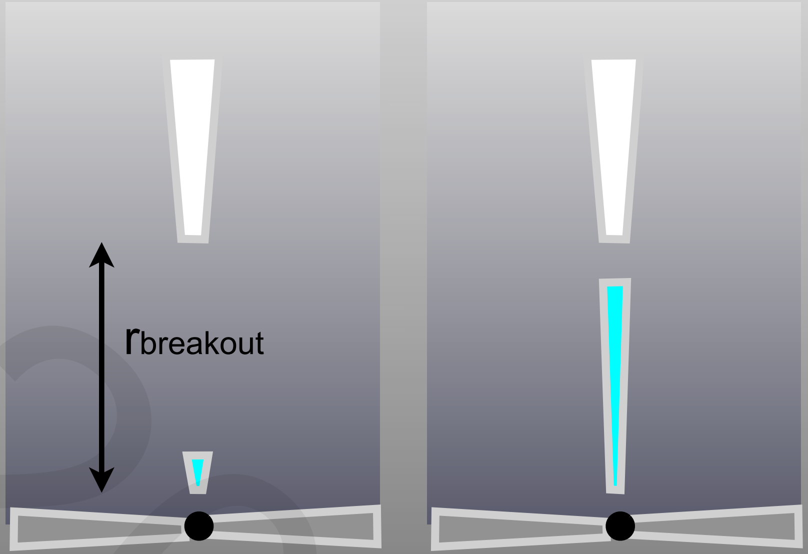

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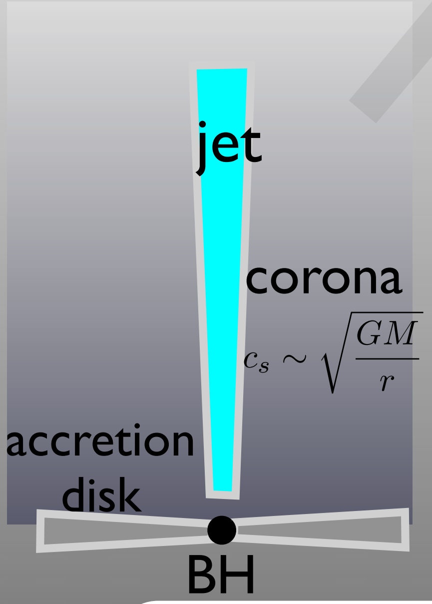

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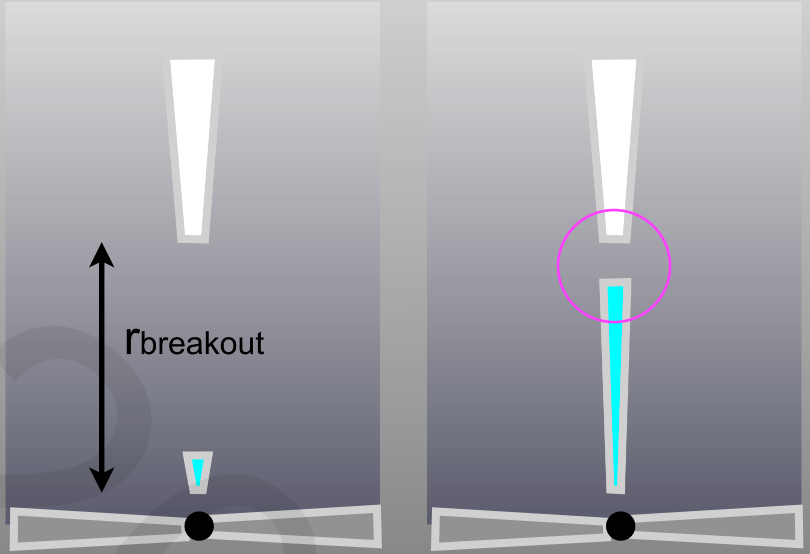

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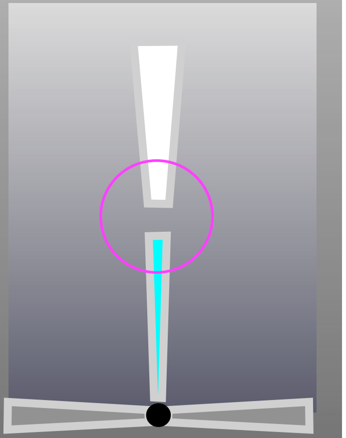
TeV/GeV flares and radio blobs

TeV and GeV emission in blazars is produced in the leading expansion edge moving with Gamma ~100, while the observed velocities of the radio blobs correspond to the bulk motion with Gamma ~10



Before breakout

$$\gamma_w = \left(\frac{L}{\rho_{\rm ex} c^3}\right)^{1/4} r^{-1/2} \sim 10$$

After breakout:

leading edge $\gamma \sim 4\gamma_w \sigma \sim 100$

bulk: $\gamma \sim 2\gamma_w \sigma^{1/3} \sim 10$

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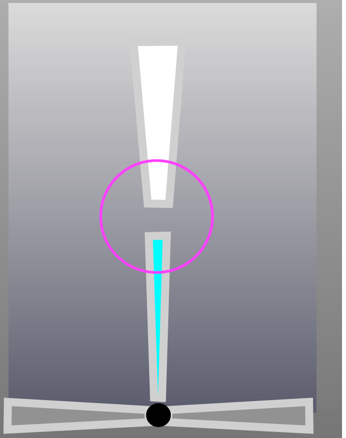

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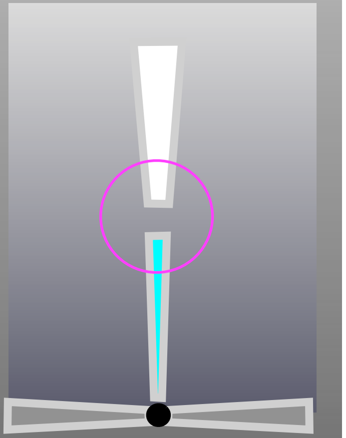

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Radio blobs

Predicted correlations

- Cores are optically thick at $r_{\rm gamma}$, typically $r_c > r_{\rm breakout}$:

$$r_{\rm core} \approx 1.4{\rm pc}\,\zeta_R^{2/3} L_{46}^{2/3} \gamma_{w,1}^{-1/3} \nu_9^{-1}$$

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- Jet breakout will occur while the jet is still optically thick in radio.

$$\Delta t_{\gamma-R} \sim \frac{r_{\rm core}/c}{2\gamma_w^2} \sim {\rm weeks} - {\rm months}$$

$$\gamma_{\rm Gev} \sim 4\gamma_w \sigma \sim 100$$

$$\gamma_{\rm R} \sim 2\gamma_w \sigma^{1/3} \sim 10$$

- **Gamma-rays correlate with radio leading by ~ weeks**
- Better correlated (shorter delay) at higher radio frequencies
- Acceleration at large r: avoid Compton drag near BH.

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Kinematically related

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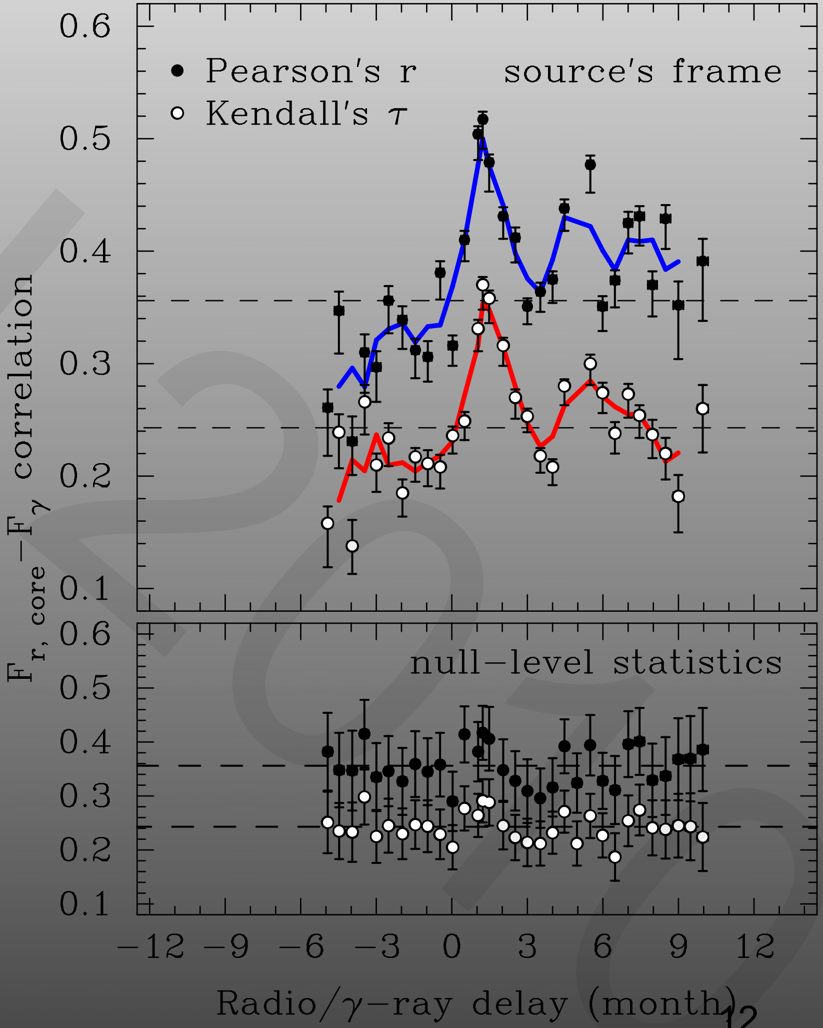
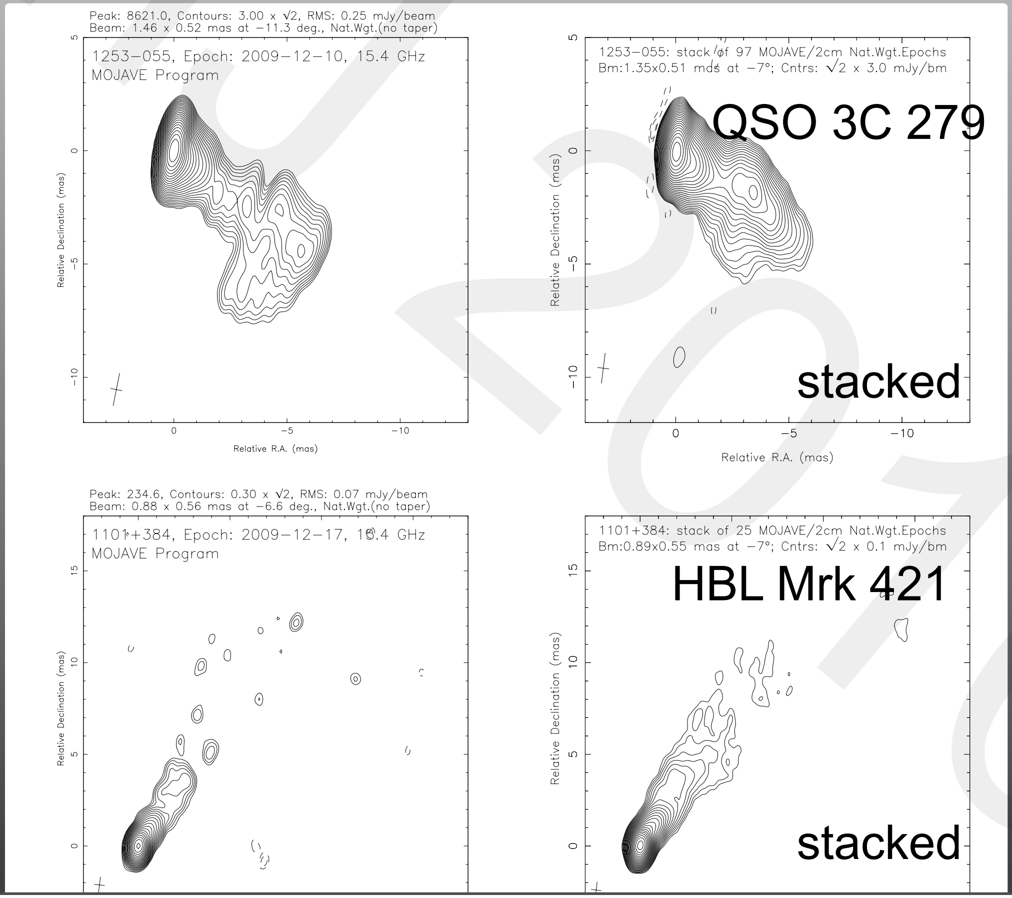
Radio-gamma correlation

Gamma-rays-radio correlation with ~ months delay (Pushkarev et al 2010), radio 15 GHz trailing.



Morphologies

- Jet morphology: higher gamma blobs merge later (e.g. variable jets in FSRQ); low gamma: smooth jets in LBLs).

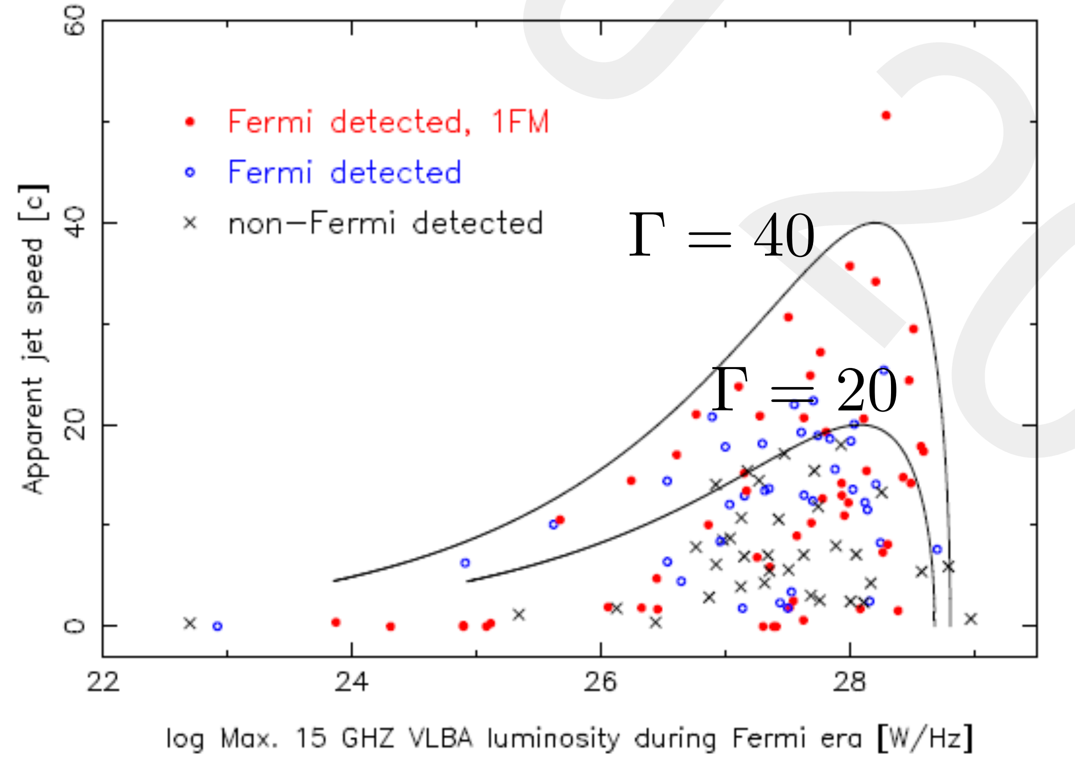


High Gamma,
late merging,
knotty jet

Low Gamma,
early merging,
smooth jets

Predicted correlations

- Fermi-detected have higher Gamma
- jets of gamma-ray-selected AGNs are more aligned than those in radio-selected (but: mini-jets?)
- Gamma-ray emission is more boosted than radio, shorter variability times



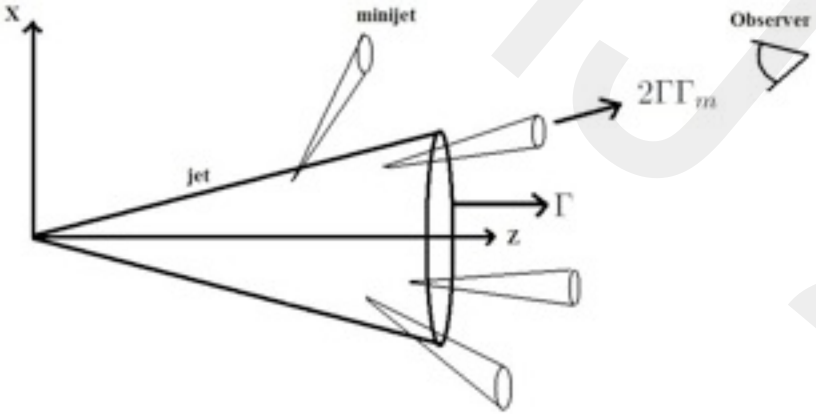
Acceleration on 1-10 pc - observed? (Lobanov)

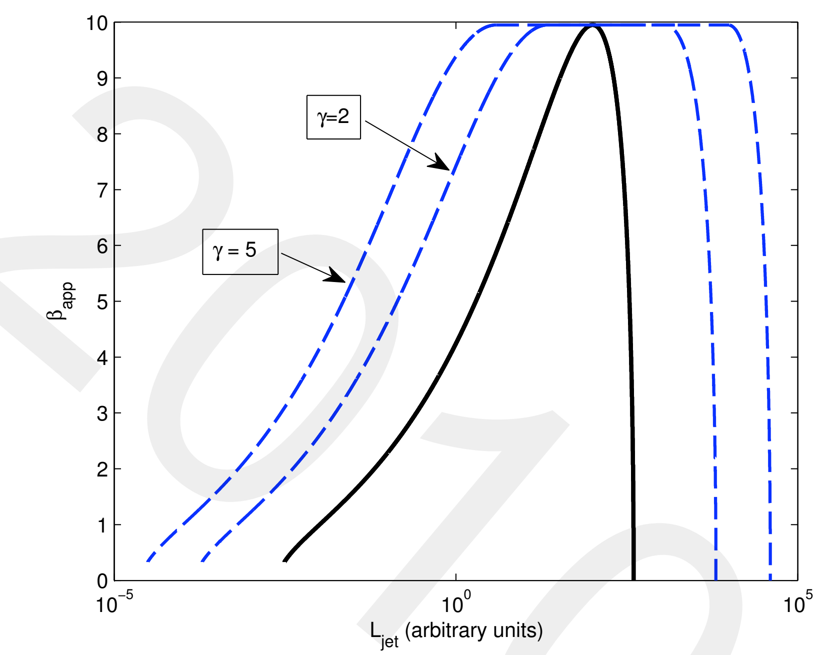
Conclusion

- Non-stationary outflows can accelerate much more efficiently than stationary ones.
- Beaming in GeV-TeV is different from beaming in radio (prediction)
- gamma rays generated ~ 0.1 - 1 pc from BH, at blob leading edge, mostly inside optically thick region
- The model is able to accommodate both the requirement of small optical depth for gamma-ray photons, short time-scale variability and slow speeds in radio
- Key prediction: radio-gamma delay, confirmed by Fermi (?)
- We do not specify how emission is generated; Blandford: it does not matter, Doppler beaming dominates
- Exact non-linear solutions to the Riemann problem can be used for code testing (and are cute)

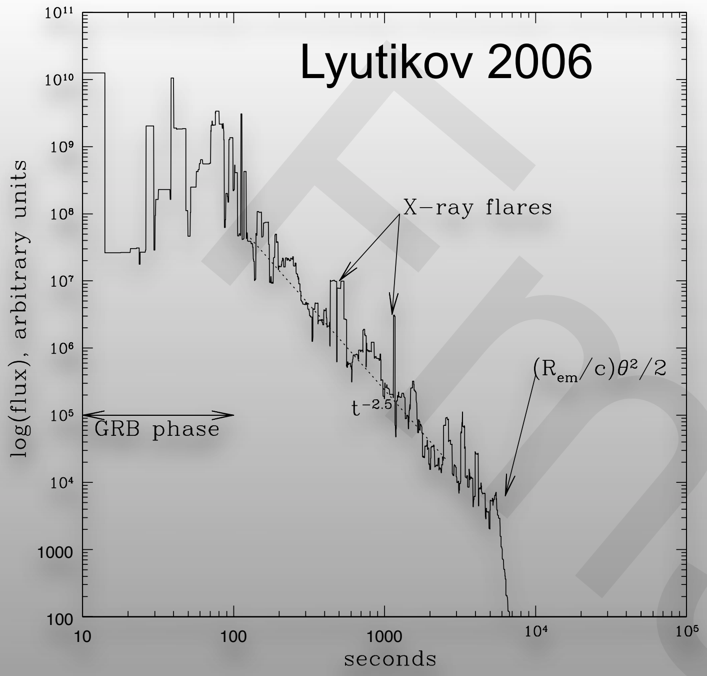
Mini-jets

- Emission beamed in jet frame (Blandford & Lyutikov 2003, Lyutikov 2006, Ghisellini et al. 2008, Lazar et al. 2009, Giannios et al. 2009, Narayan & Kumar 2009)

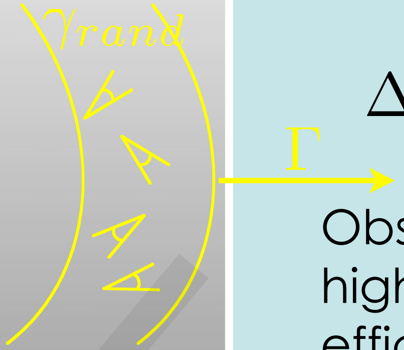




- HST1 in M87: high r, short variability
- Pic A: knots (~kpc) vary on 1yr


Lyutikov 2006

Also: Ghisellini et al. 2008, Lazar et al. 2009, Giannios et al. 2009, Narayan & Kumar 2009



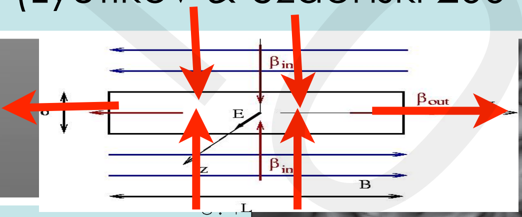
$$\Gamma_{eff} = 2\Gamma\gamma_{rand}$$

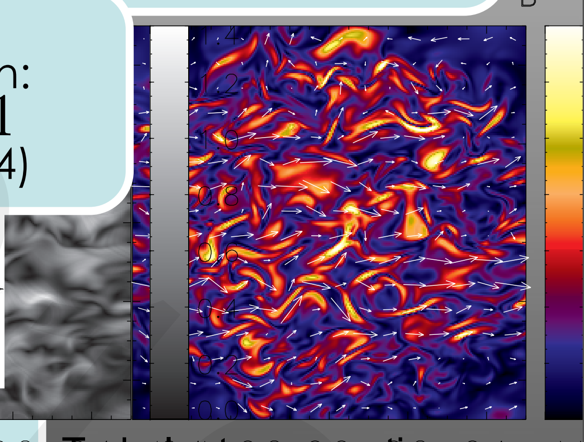
$$\Delta t \sim \frac{c}{R}\frac{1}{8\Gamma^2\gamma_{rand}^2}$$

Observed emission can be highly variable and with high efficiency (tapping into most of the proper volume)

- Not fluid "turbulence", $\gamma_{\rm rand} \sim \sqrt{9/8} = 1.06$
- RM & RT instabilities will produce vT<< c turbulence

- Relativistic reconnection: jets with $\gamma_{out} \sim \sigma \gg 1$ (Lyutikov & Uzdenski 2004)





Turbulent reconnetion (Lazarian & Vishniac)

- Spectrum is harder during flare (Burrows et al 2005)
- Are flares becoming longer and softer as function of flare time?
- Can some Shorts be "one spike Long"? (failed SN-type)
- Can explain optical -gamma correlations in 080319B? E.g. emitting "blobs" expand, killing both