Plasma injection and outflow formation in BH magnetosphere

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Purpose of this talk

To elucidate the role of plasma injection in the magnetosphere:

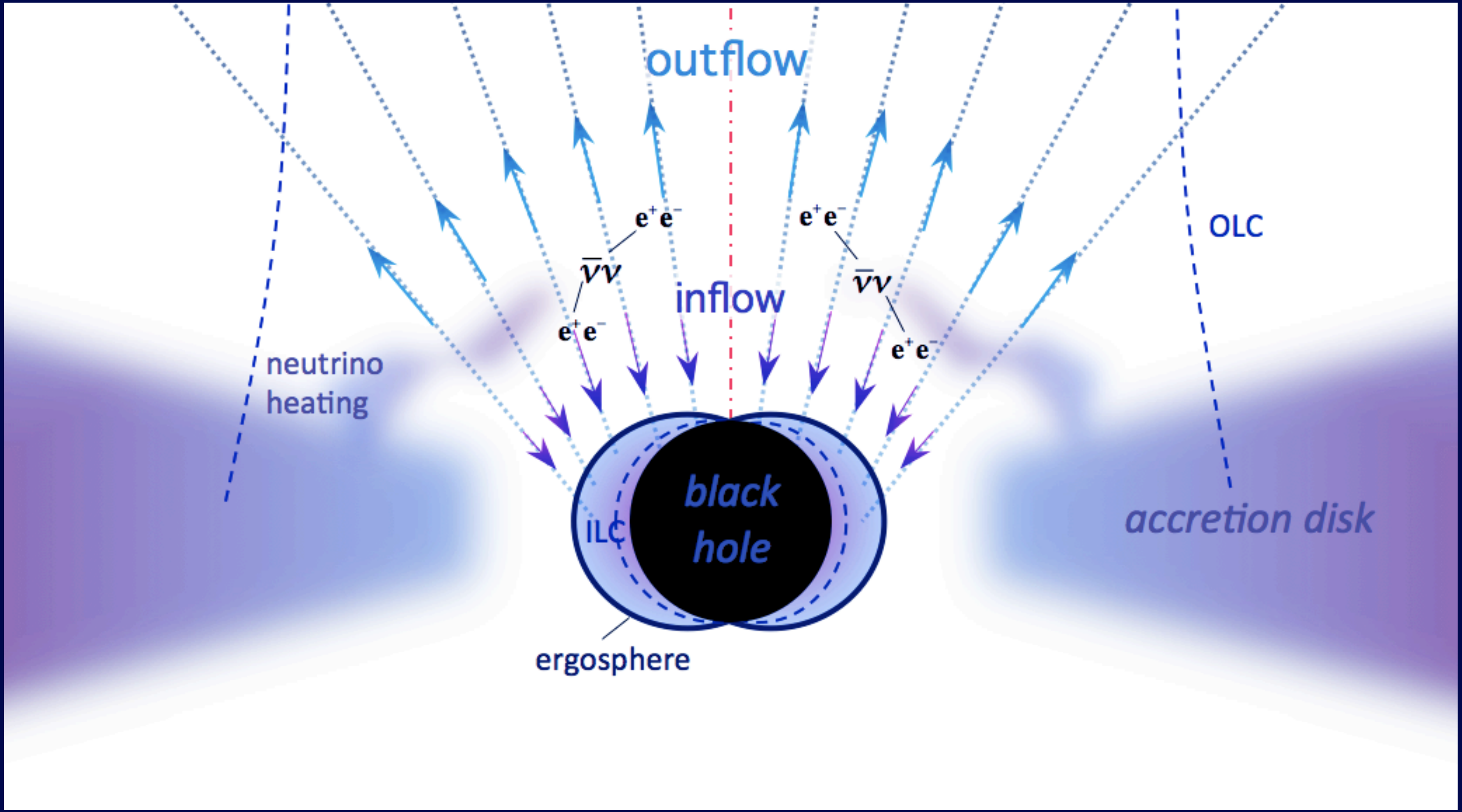
- ➢ formation of a force-free structure requires sufficient charges, $n_e > n_{GJ} = \Omega B/(2\pi ec)$
  - In faint sources (e.g., M87, SgrA*) a gap may form, leading to HE magnetospheric emission .

    Levinson 00,06; Neronov & Aharonian 07,08; Rieger 10; Levinson & Rieger 11

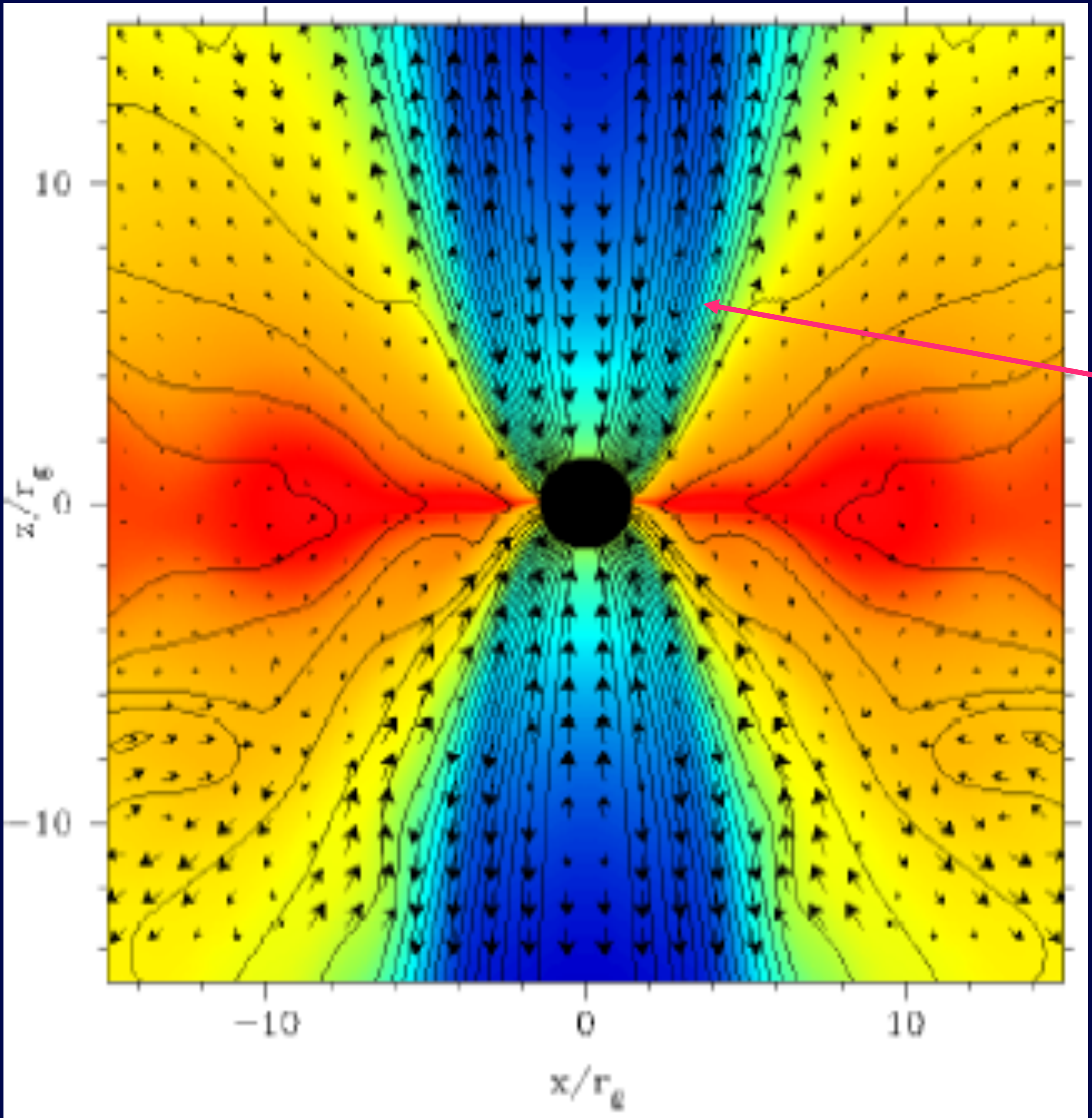
- ➢ Extraction of spin down energy requires sufficiently low inertia. Properties of outflow depends on injection rate:
  - below critical load, BZ process activated
  - above it, outflow is powered by external energy source

Plasma injection in the magnetosphere

- $\gamma\gamma \rightarrow e^{\pm}$ in AGNs
- $\nu\nu \rightarrow e^{\pm}$ in GRBs
- mass loading

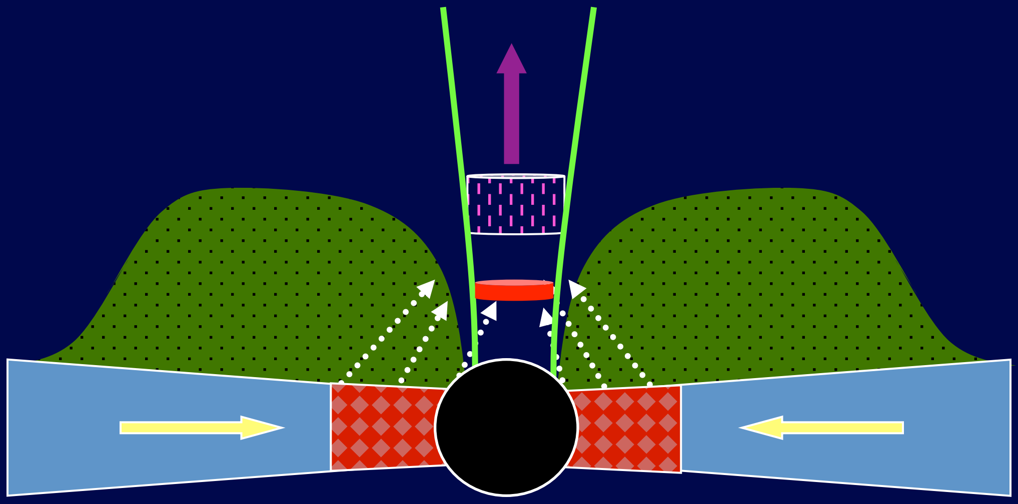


Simulations by Barkov + Komissarov '08



stagnation zone

Charge injection in AGNs



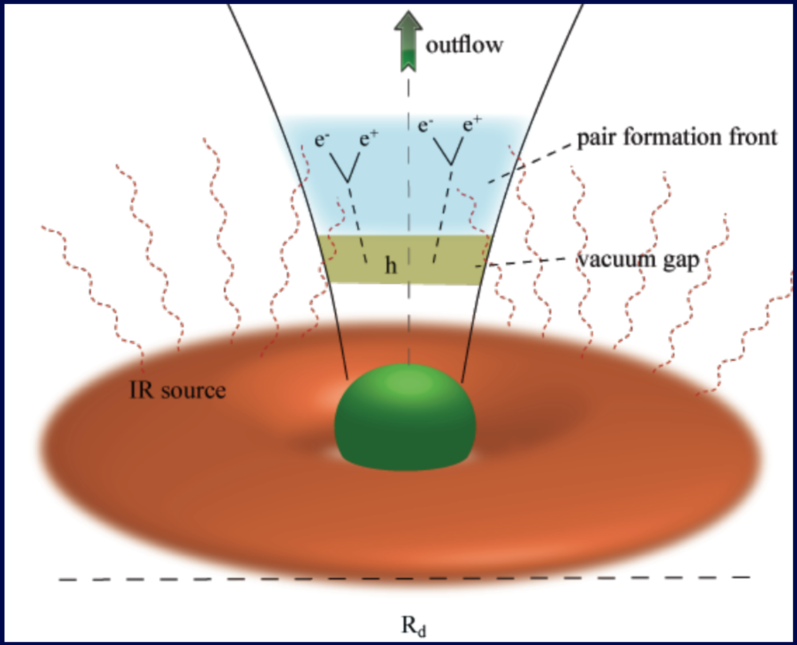
- Protons from A.F ?
- Protons from n decay ?
- $e^{\pm}$ from $\gamma\gamma$ annihilation ?
- Other source ?

➢ Protons have to cross magnetic field lines. Diffusion length over accretion time is extremely small.

➢ Neutrons, if produced at sufficient quantities, decay over a distance 0.05 r_s – unlikely to account for charge injection.

Charge injection by γγ annihilation

- Requires sufficiently hot accretion flow that emit gamma rays
- RIAF in low luminosity sources (e.g., M87) may be hot enough
- AD in powerful blazars too cold.



Charge injection in LLAGN is a sensitive function of acretion rate

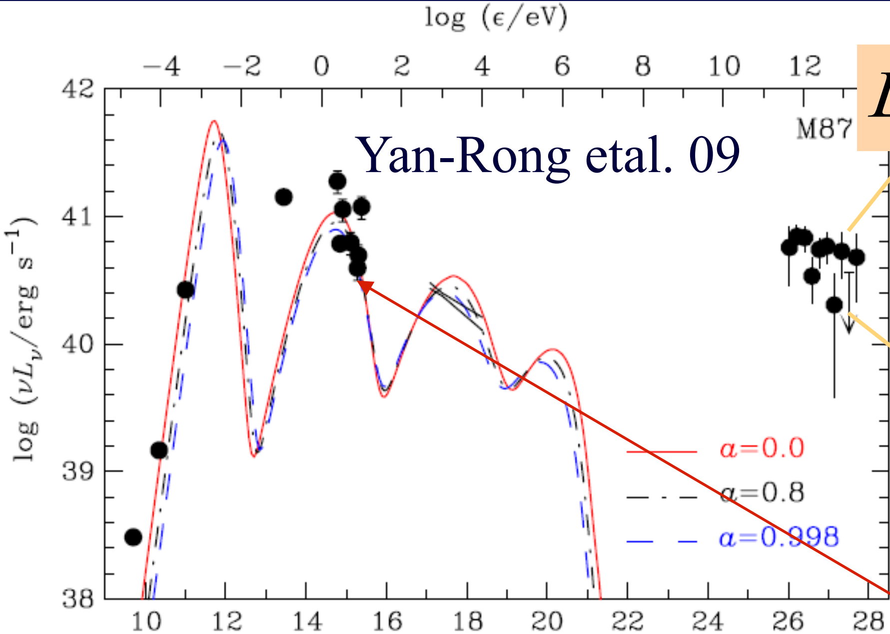
(AL+ Rieger ‘11, Moscibrodzka + ’11)

A gap must form between inner and outer LC.

May be a source of HE gamma rays

Variable TeV in M87 - gap emission?

M87 – a dark outflow



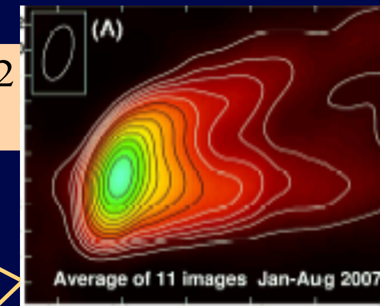
Yan-Rong etal. 09

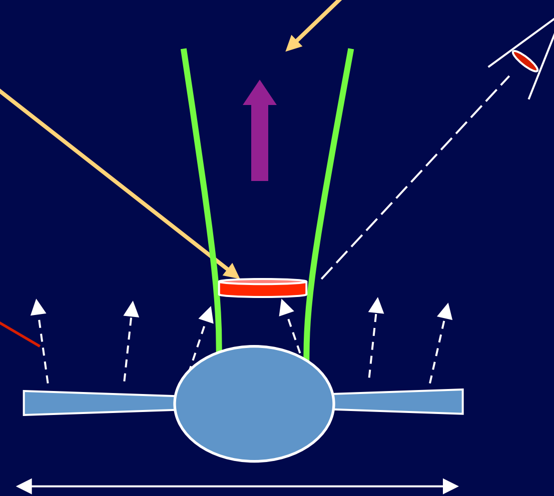
Table 3

Jet Power from the Published Literature

L_j/erg s^{-1}	Ref.
$\sim 10^{44}$	Bicknell & Begelman (1996)
2×10^{43}	Reynolds et al. (1996)
$\sim 10^{44}$	Owen et al. (2000)
3×10^{42}	Young et al. (2002)
$\sim 10^{44}$	Stawarz et al. (2006)
5×10^{43}	Bromberg & Levinson (2008)

$$L_\gamma \approx L_{BZ}(h/r_s)^2$$





AL+ Rieger '11

AL '00, Neronov + Aharonian '07,

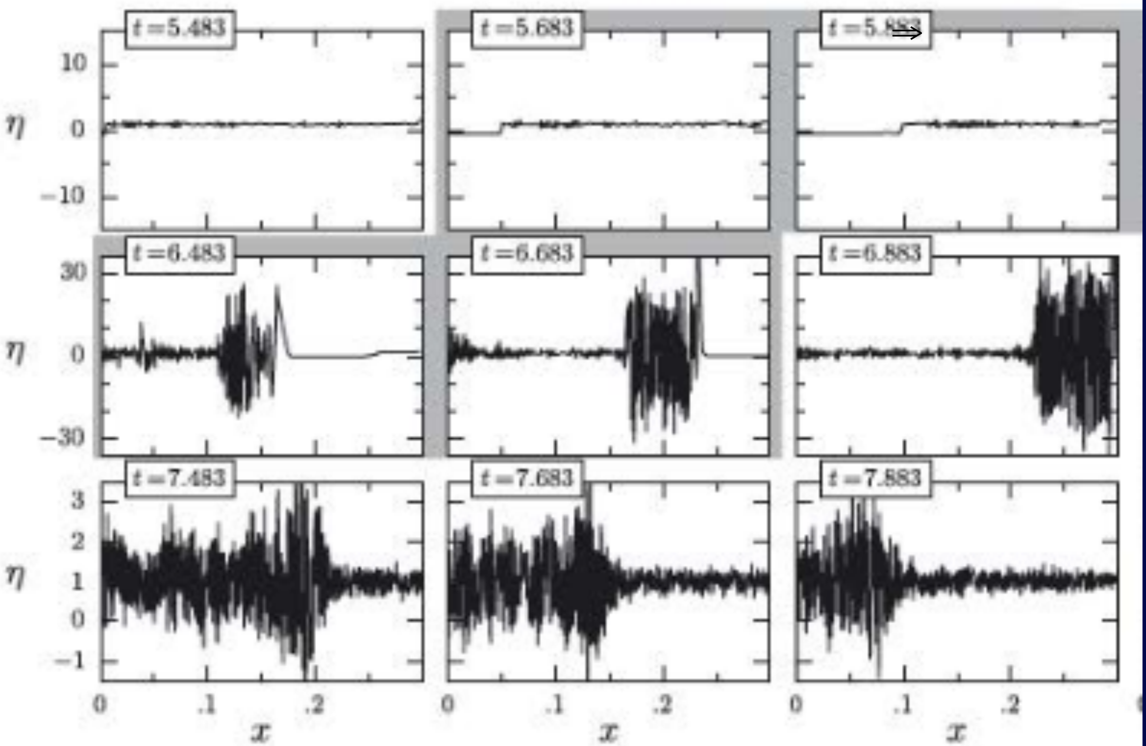
Powerful blazars – cyclic pp?

- No direct charge injection
- Large opacity near BH. ➘

Self-sustained cascade ?

Intermittent GeV-to-TeV emission?

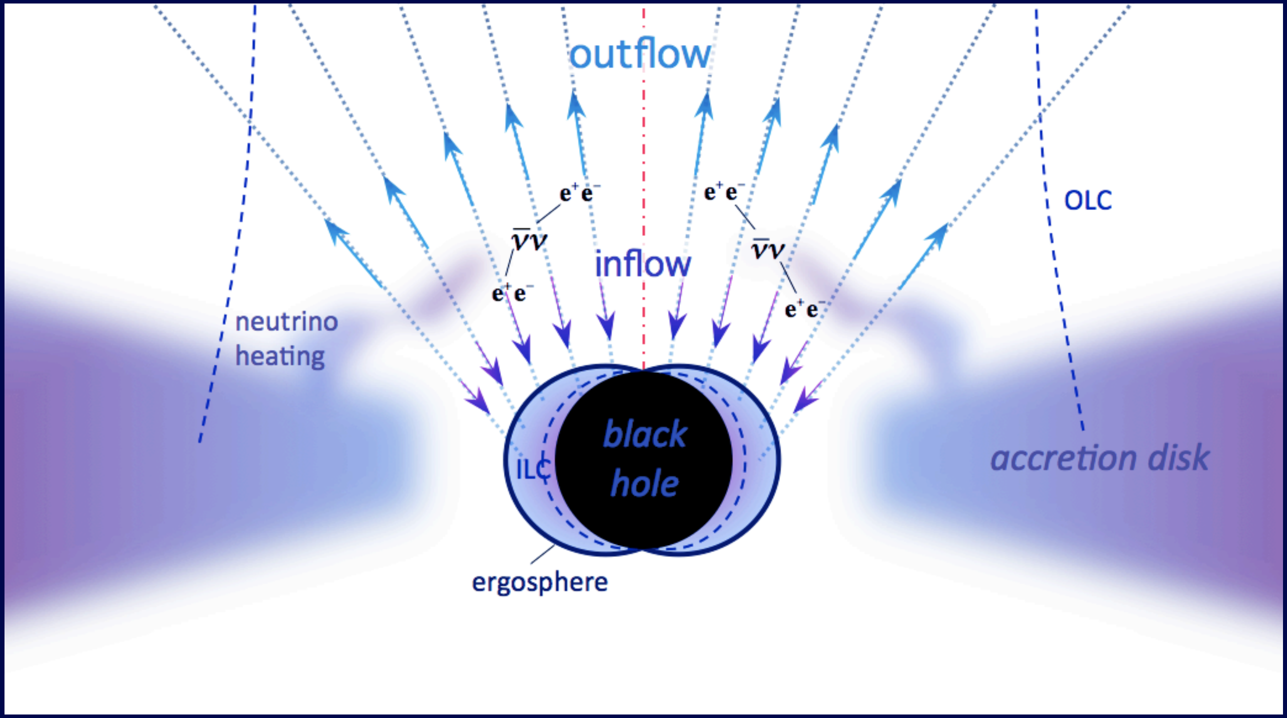
Pair cascades in NS – Timokhin 2012



Loaded flows in GRBs

- $\nu\nu \rightarrow e^{\pm}$
- mass loading by neutron leakage?

Injected density >> GJ density



A model for a double transonic flow with injection

Globus + Levinson '13, '14

- stationary + axi-symmetric GRMHD
- mass and energy injection included
  source terms: particle q_n; energy-momentum q^α
- split-monopole geometry invoked

- stream function (magnetic flux) : $\Psi(r,\theta)$ (assumed)
- angular velocity: Ω (a free parameter)
- particle flux per unit B flux: η
- specific energy (per baryon): ε
- specific angular momentum : L
- specific entropy : s

basic equations

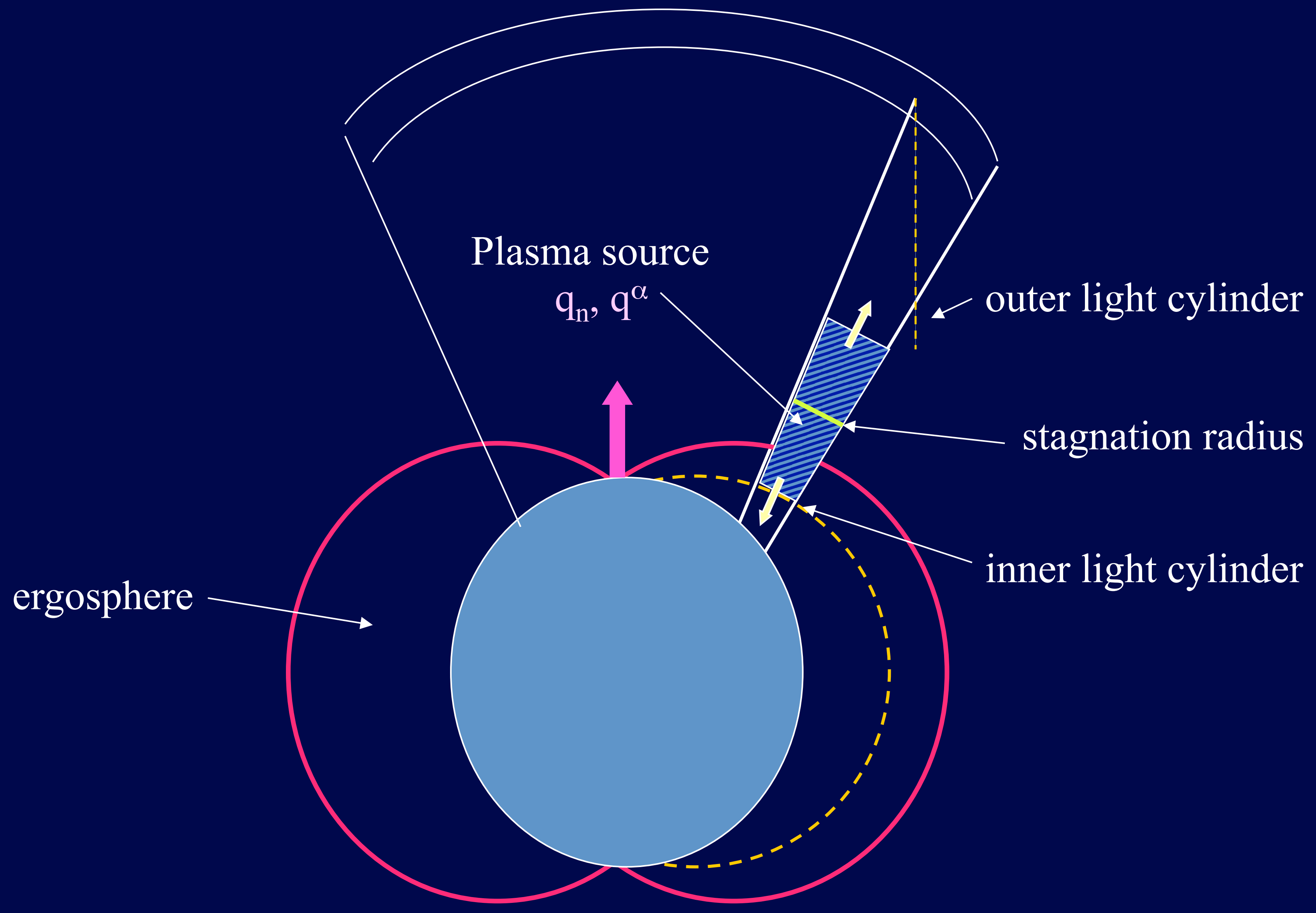
$$\partial_r\left(\sqrt{-g}\,\rho\,u^r\right)=\sqrt{-g}\,q_n;$$ mass injection

$$\partial_r\left(\sqrt{-g}\,\rho u^r \varepsilon\right)=-\sqrt{-g}\,q_t;$$ energy injection

$$\partial_r\left(\sqrt{-g}\,\rho u^r L\right)=\sqrt{-g}\,q_\varphi;$$ L injection

$$\partial_r\left(\sqrt{-g}\,\rho u^r s\right)=-\sqrt{-g}\,(q_\alpha u^\alpha);$$ entropy generation

$$\partial_r \ln u_p = \frac{N(M,\Omega,\varepsilon,L,s)}{(u_p^2-u_A^2)(u_p^2-u_{SM}^2)(u_p^2-u_{FM}^2)};$$ equation of motion



inflow/outflow must pass through inner/outer slow and fast points

conditions on H

particle flux — net energy per particle

energy flux: $\varepsilon^r = \rho u^r \varepsilon$

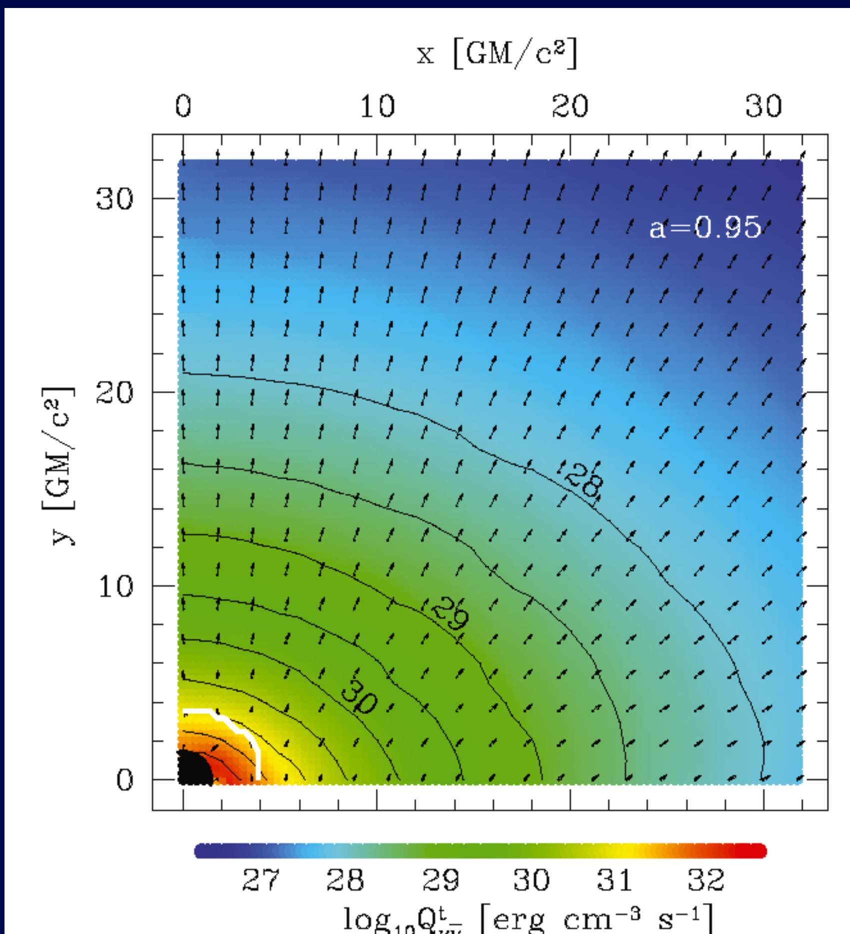
on the horizon: $u^r < 0$

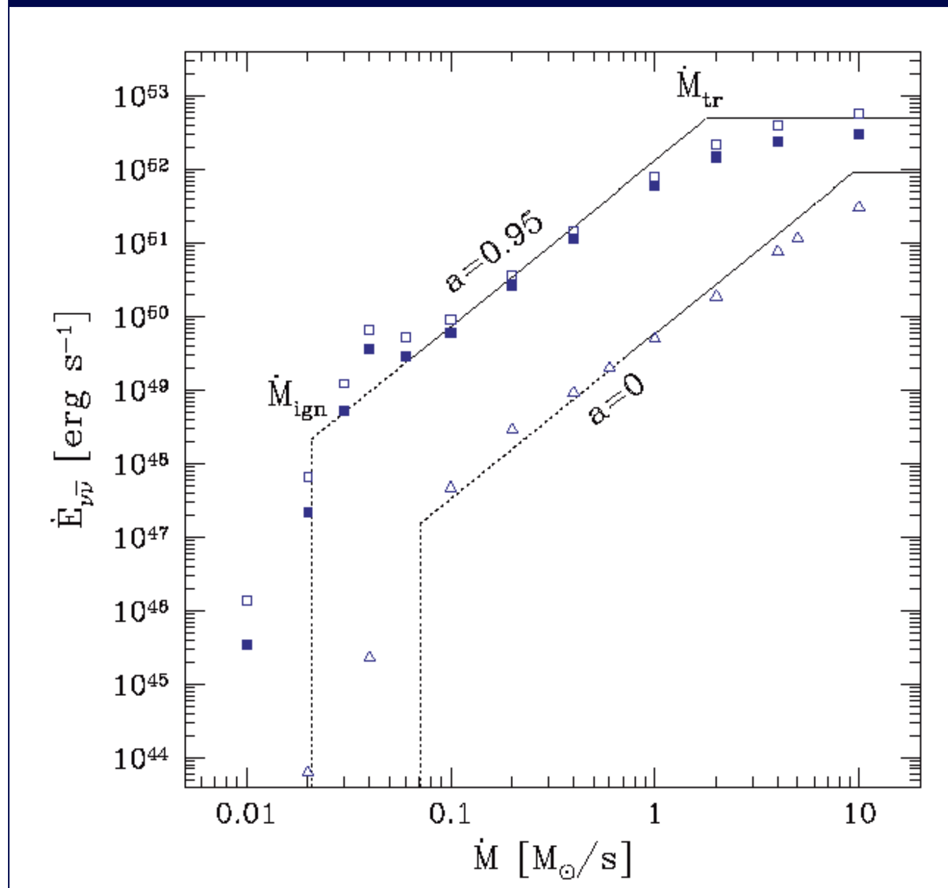
so: $\varepsilon_H < 0 \Rightarrow \varepsilon^r > 0$ (extraction)

$\varepsilon_H > 0 \Rightarrow \varepsilon^r < 0$ (feeding)

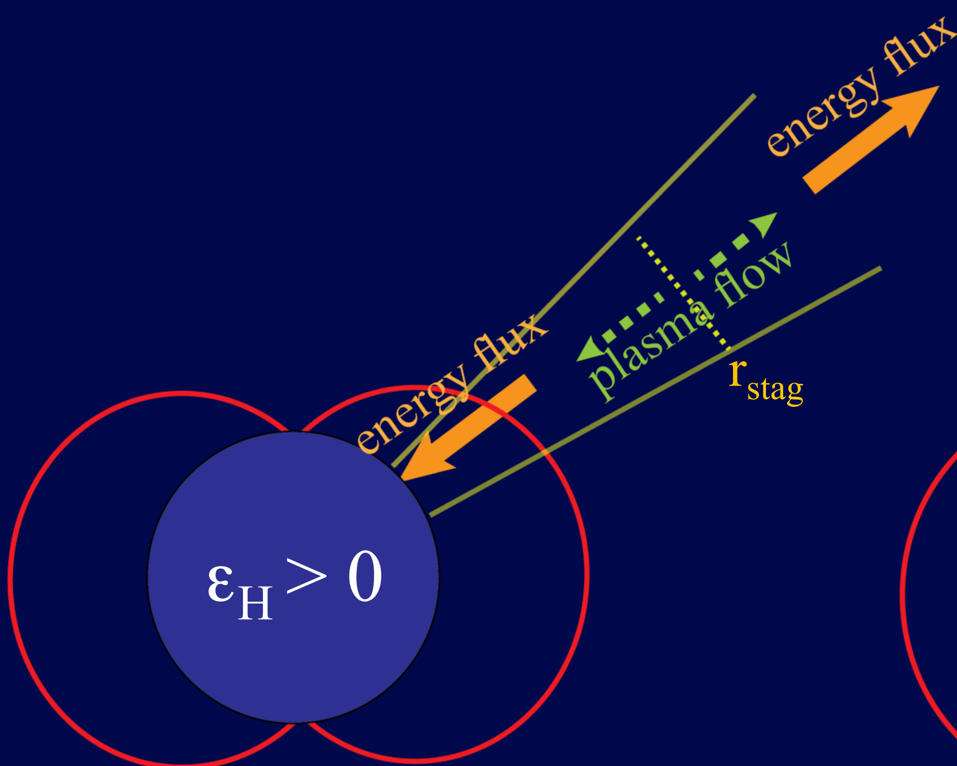
GRBs: energy deposition by $\nu\nu \rightarrow e^-e^+$

From Zalamea & Beloborodov 2011

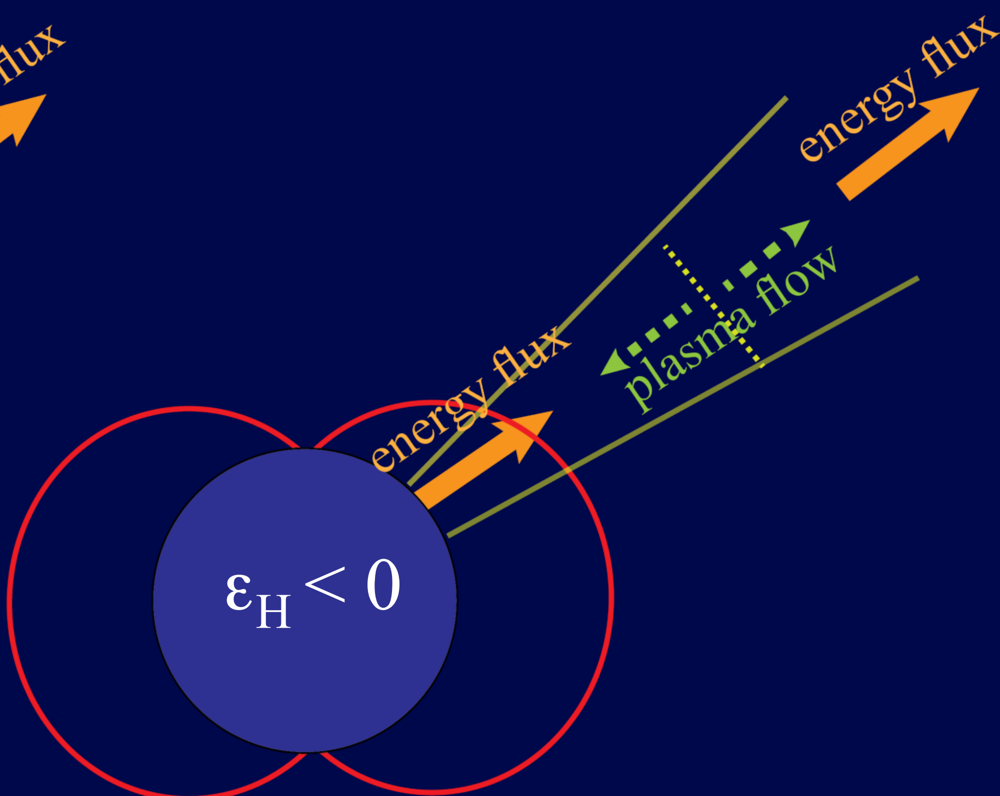




under-loaded vs. over-loaded flows



above critical load
powered by external source

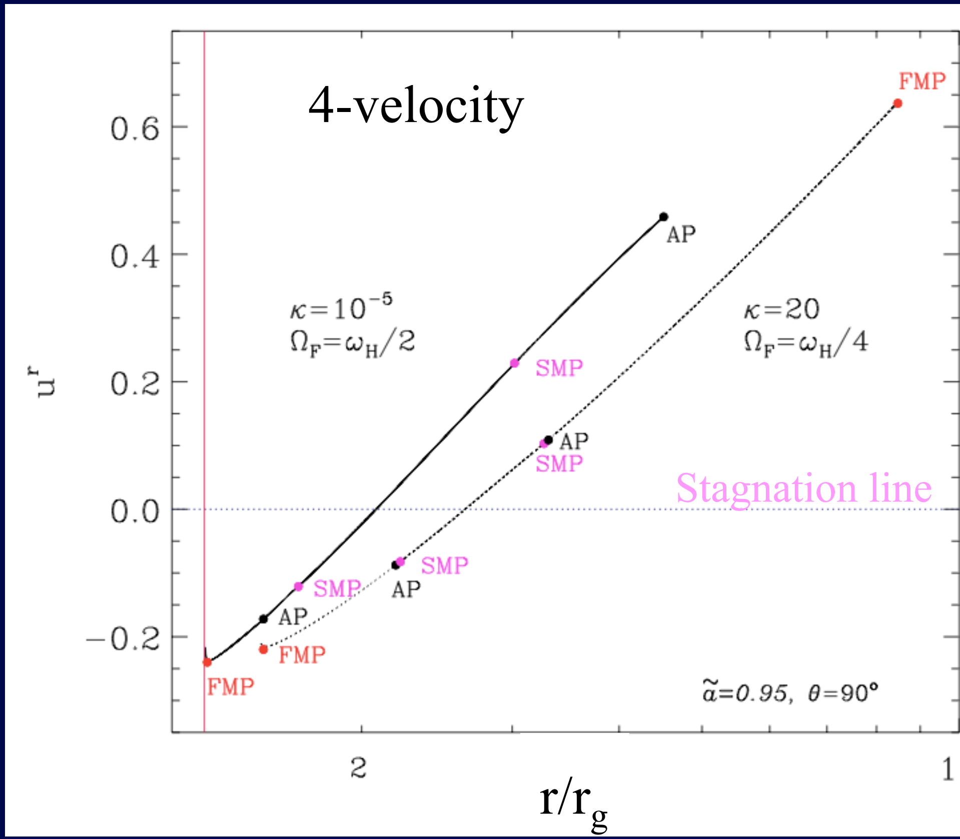


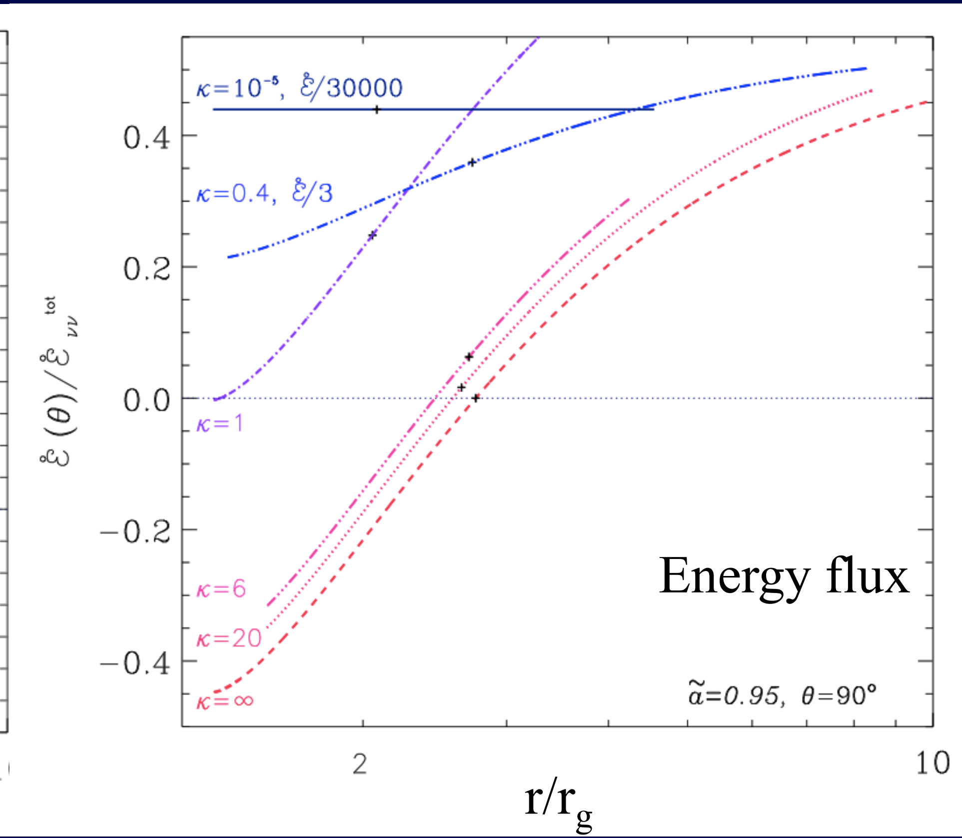
below critical load
powered by BH

Double flow structure (GL '14)

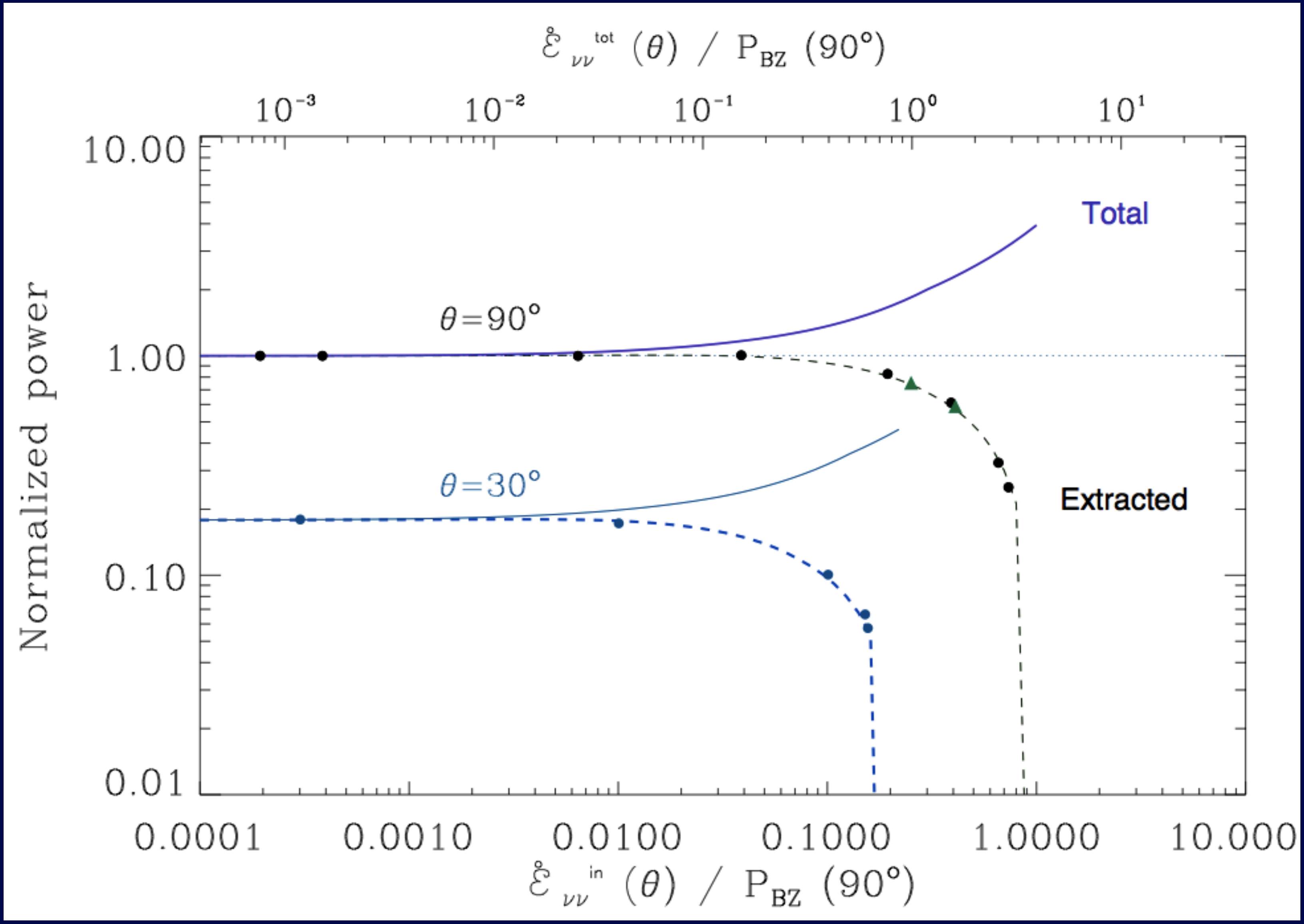
Load parameter: $\kappa = \dfrac{\text{injected power}}{\text{BZ power}}$

($\kappa = 0$: force-free, $\kappa = \infty$: HD)

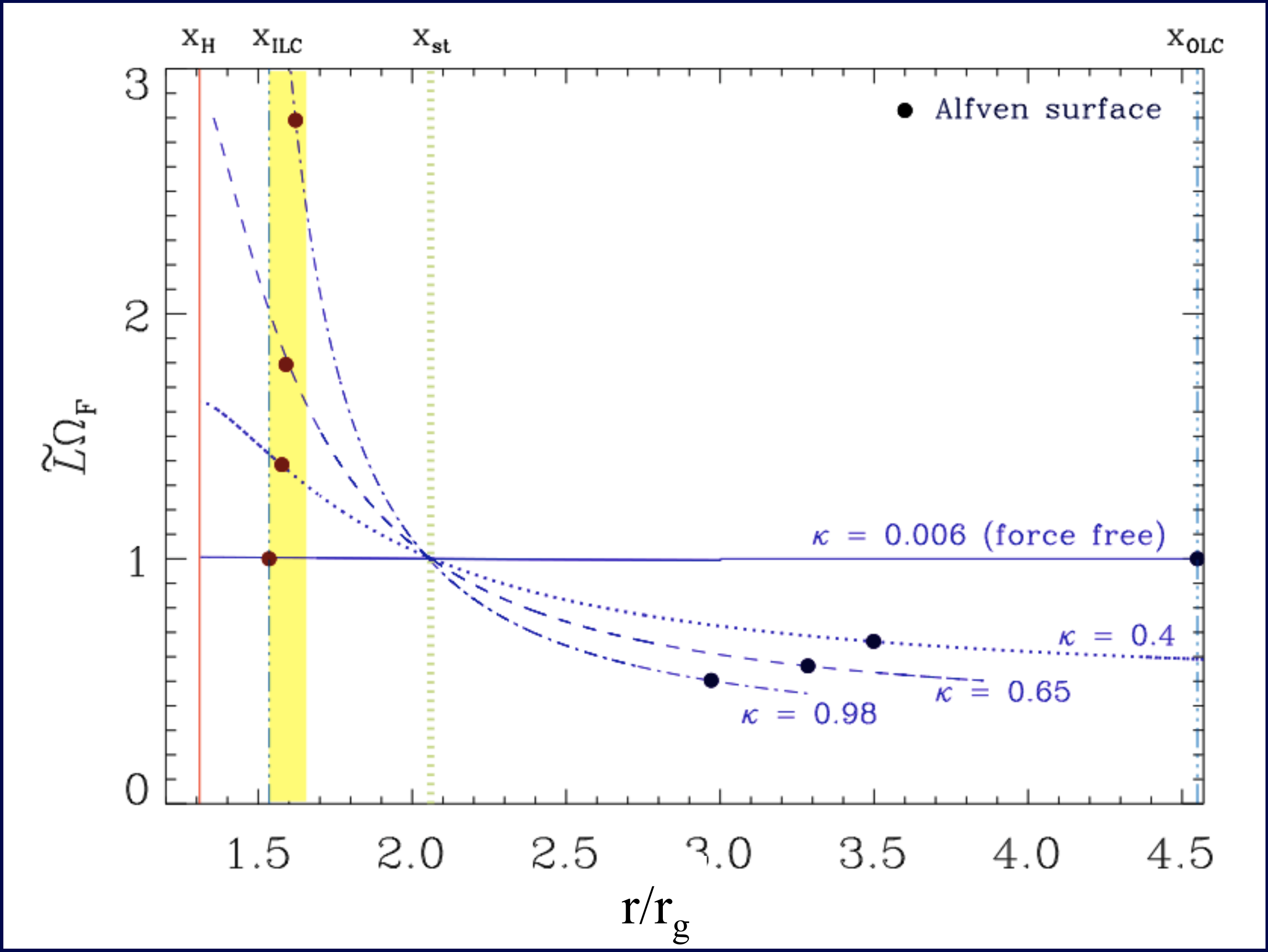




Regime of energy extraction



Inner Alfven point



BZ versus neutrino driven outflow

Outflow is powered by BH if

$$\dot{E}_{\nu\nu} < P_{BZ}$$

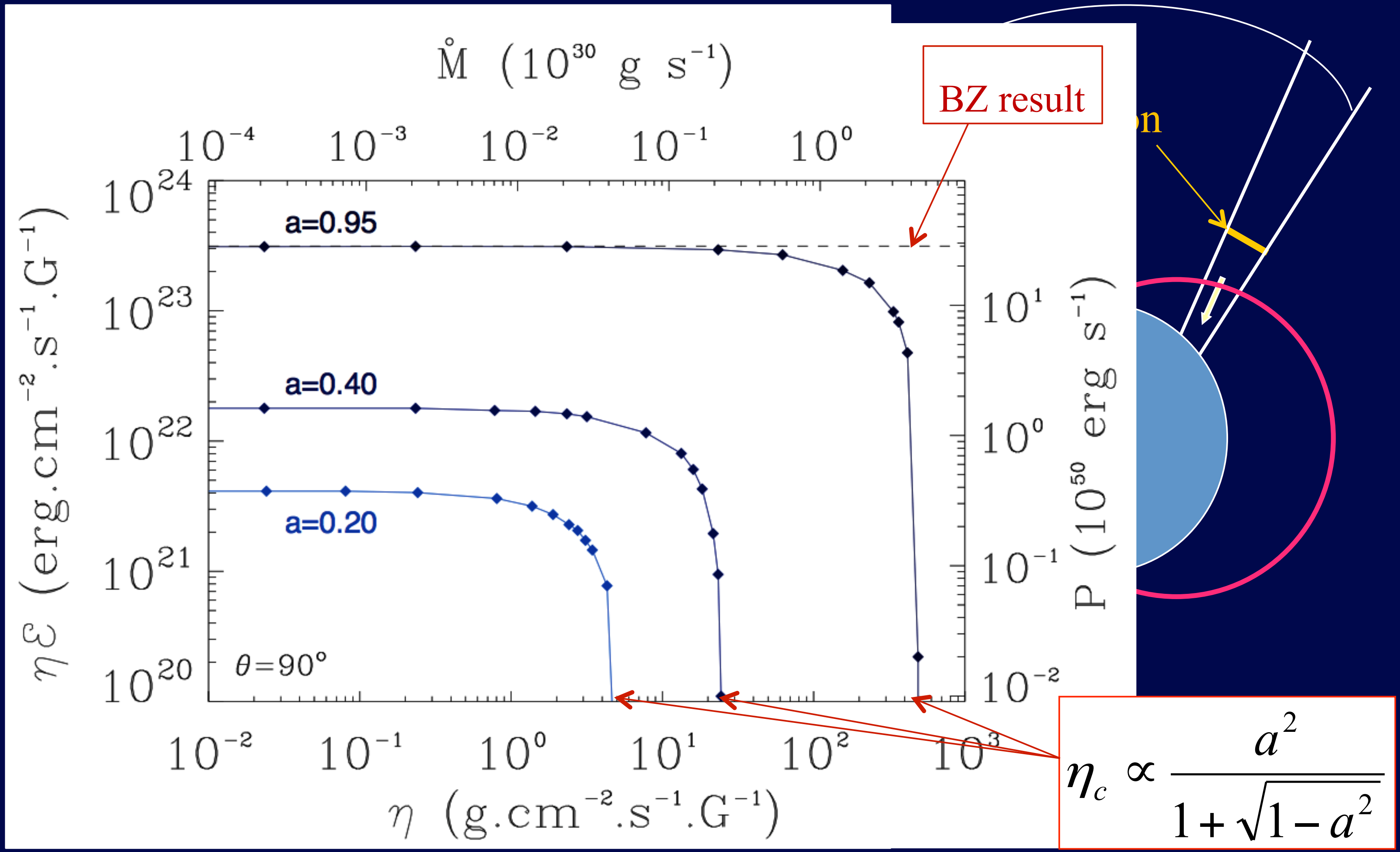
$$\Rightarrow \quad \dot{m}_{acc} < \dot{m}_c = 0.1 \left(\frac{M_H}{3M_\otimes}\right)^{-2/9} \left(\frac{\Psi_B}{10^{27}\ G\ cm^2}\right)^{8/9} f(\mathrm{a})$$

Otherwise it's driven by neutrino annihilation

- From the disk model of Chen+Beloborodov '07 we estimate $\dot{m}_c \sim 0.1$ for $B^2/(8\pi\, p)=0.1$

Cold flow (mass injection)

Plasma inflow on equatorial plan, θ=π/2



$$\eta_c \propto \frac{a^2}{1+\sqrt{1-a^2}}$$

Conclusions

- In faint sources a gap may form, giving rise to magnetospheric VHE emission (e.g., Tev emission from M87).
- At high injection rates two regimes are expected: below a critical load BZ process activated. Above it, flow is driven by external source.
- In GRBs a BZ jet can form if the magnetic flux is high enough. Otherwise, the flow is driven by neutrino annihilation.
- In AGNs, mass loading of field lines with high inclination angles may result in a nontrivial dependence of jet power on BH spin