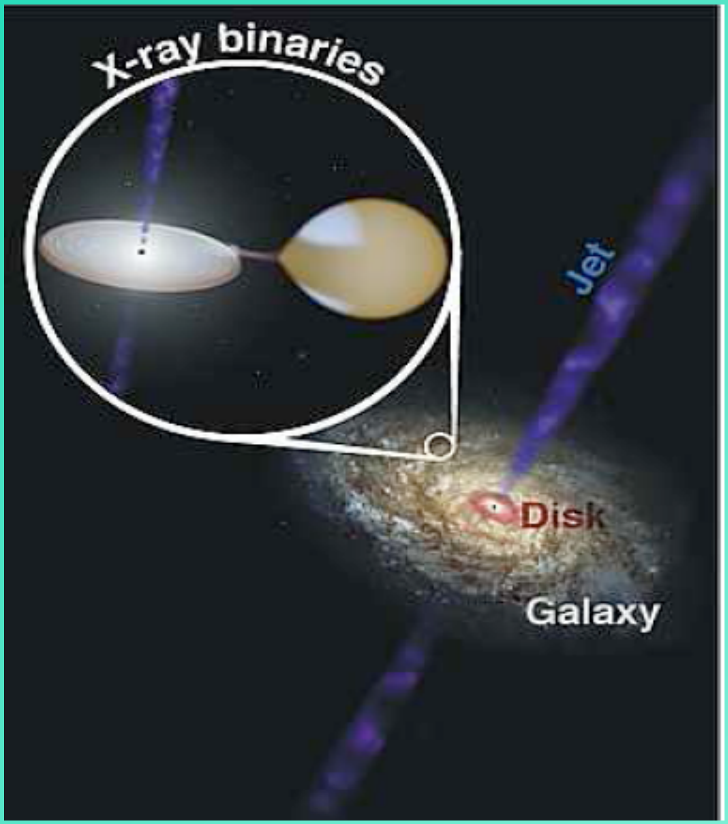
Effect of plasma composition on solutions of transonic accretion flows onto black holes



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Content of Presentation

- On BH Accretion
- A short note on relativistic fluid and its EoS (equation of state)
- Radial/Rotating multi-species fluid, onto a BH

  Sonic point properties and solution topologies
- Conclusion

Introduction: Basics of Black Hole (BH) accretion

What we already know

(i)Matter crosses the horizon at the speed of light (c), the maximum possible sound speed (a) i.e., $a^2_{max}=c^2/3$ => supersonic

(ii)At large distances away, from the BH matter has very low inward velocity => subsonic.

Which implies matter accreting onto BHs are transonic

(iii) Existence marginally stable orbit r_{ms} means matter falling BH has to be **sub-Keplerian** .

(iv)Properties (i) & (ii) also says, matter close to the BH horizon is relativistic and at the larger distance it is non-relativistic i.e., **trans-relativistic**.

- A fluid is relativistic, on account of its (a) bulk speed ($v \sim c$), and/or (b) its temperature T (thermal energy ≥ rest energy)

- A fluid is thermally relativistic is $p/\rho c^2 = kT/mc^2 >/\sim 1$, i.e, $\Gamma \rightarrow 4/3$, and thermally non-relativistic if $kT/mc^2 << 1$, i.e., if $\Gamma = 5/3$!!

- So fixed Γ EoS are inadequate to describe thermally tran-relativistic fluid, such as accreting fluid onto BHs.

- A relativistic EoS was proposed by considering relativistic Maxwellian distribution of fluid partic

$$h = \frac{e+p}{\rho c^2} = \frac{K_3(\rho c^2/p)}{K_2(\rho c^2/p)}$$

RP)

(Chandrashekhar 1938, Synge 1957)

- RP is the ratio of modified Bessel's function, solns of rel. fluid, numerically and analytically becomesexpensive. (Falle & Kommissarov, MNRAS 1986)

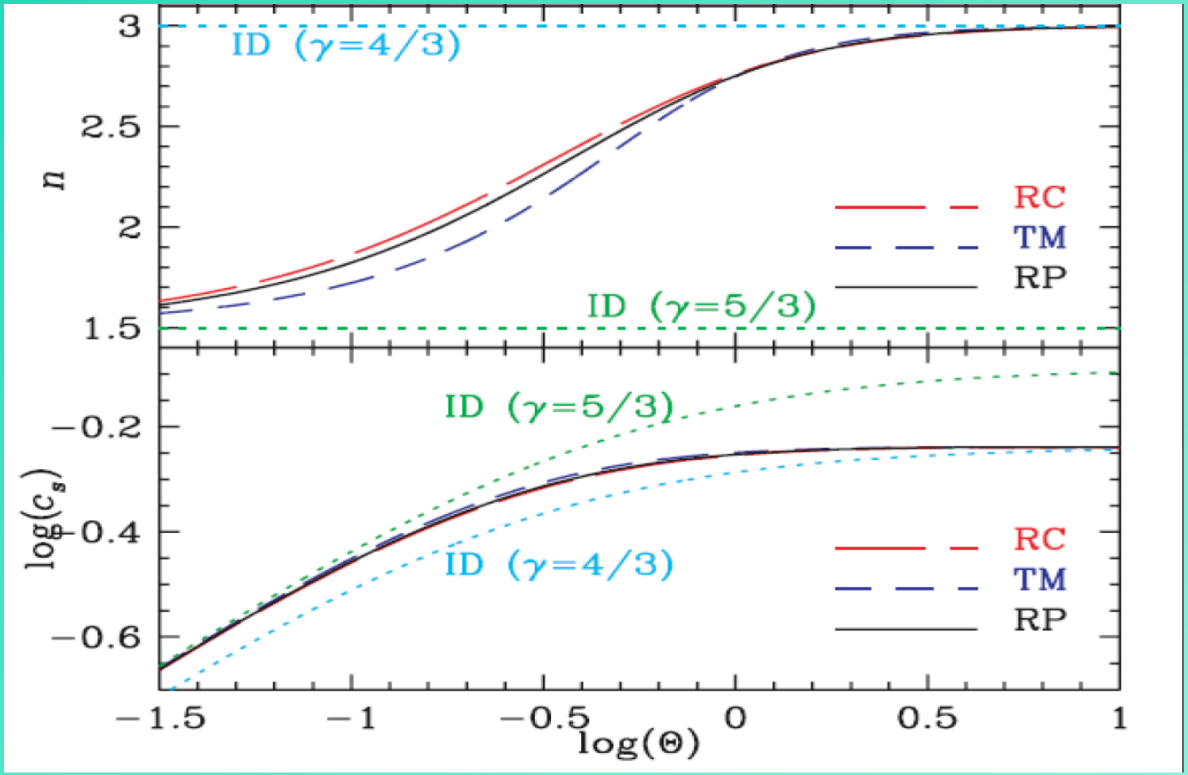
- Ryu etal, ApJS (2006) proposed a new E

$$e = \rho c^2 + p\left(\frac{9p + 3\rho c^2}{3p + 2\rho c^2}\right)$$

extremely good fit of RP and is given by,

- RC is extremely accurate,

$$\frac{|h_{\mathrm{RP}} - h_{\mathrm{RC}}|}{h_{\mathrm{RP}}} \lesssim 0.8\%$$



$\Theta = p/\rho c2$

$N = (1/k)df/dT$

$\Gamma = 1 + 1/N$,

$e = n\ f$

$c^2_s = \Gamma p/(e+p)$

(Ryu, Chattopadhyay, Choi, ApJS, 2006)

Multiple – species fluid?

- Now, $\Theta = p/\rho c^2 = kT/mc^2$!!, so the thermal state will as much depend on T as on m, (m=mass of fluid particles). This brings the issue of composition, or in other words the particles that constitutes the fluid.

- But would composition of fluid matter?

$$e = \rho c^2 + \frac{p}{\Gamma - 1}$$

$$(g_{i\nu} + u_i u_\nu) T^{\mu\nu}_{;\nu} = 0$$

$$(n u^\nu)_{;\nu} = 0$$

$$u_\mu T^{\mu\nu}_{;\nu} = j$$

For fixed Γ EoS i.e.,

if the cooling term is zero then the solutions are supposed to be independent of the composition of the fluid.

Following an idea floated by Blumenthal & Mathews (1976), we assume the fluid of electrons, protons and positrons. Let $\xi = n_+/n_e$. If n_+ positron number density

$$n = \Sigma n_i = n_e + n_+ + n_p,$$

$$n_e = n_+ + n_p,$$

$$\rho = \Sigma n_i m_i = n_e m_e \left\{2 - \xi \left(1 - \frac{1}{\eta}\right)\right\},$$

$$p = \Sigma p_i = 2 n_e kT.$$

The energy density of the fluid

$$e = \Sigma e_i = \Sigma \left[n_i m_i c^2 + p_i \left(\frac{9p_i + 3n_i m_i c^2}{3p_i + 2n_i m_i c^2}\right)\right]$$

Defining $\Theta = kT/m_e c2$, we can write,

$$e = n_e m_e c^2 f,$$

$$N = \frac{T}{p} \Sigma n_i \frac{d\Phi_i}{dT} = \frac{1}{2}\frac{df}{d\Theta},$$

The polytropic index

where Φ_i=

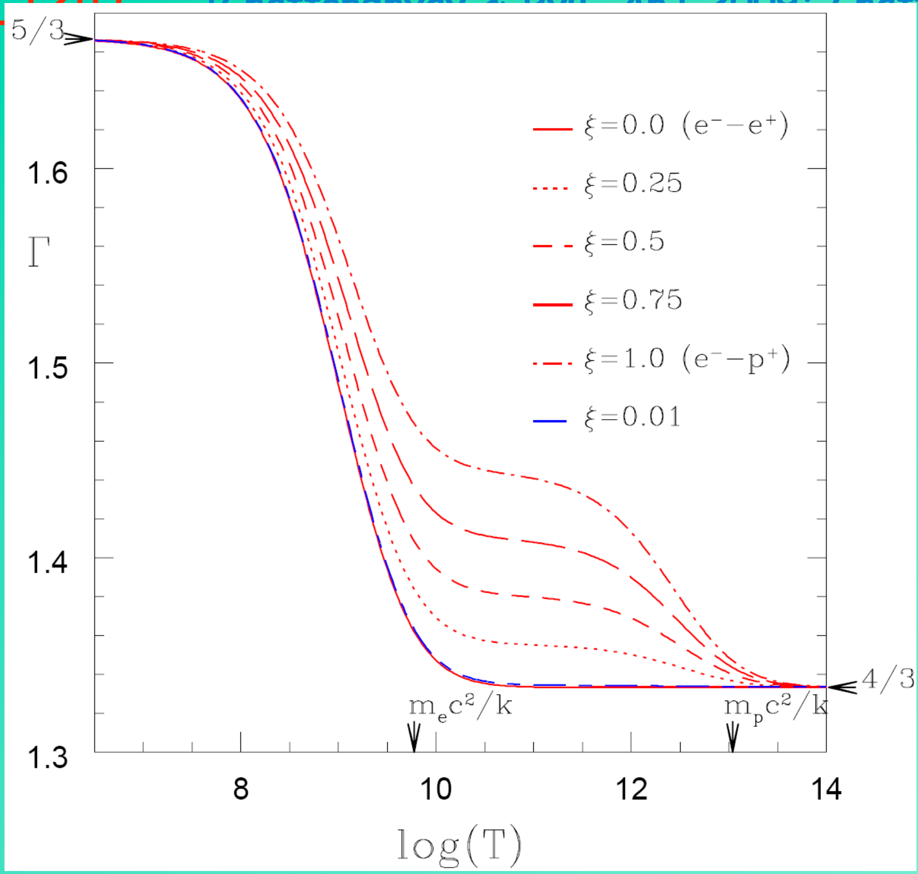
$$f = (2 - \xi)\left[1 + \Theta \left(\frac{9\Theta + 3}{3\Theta + 2}\right)\right] + \xi \left[\frac{1}{\eta} + \Theta \left(\frac{9\Theta + 3/\eta}{3\Theta + 2/\eta}\right)\right]$$

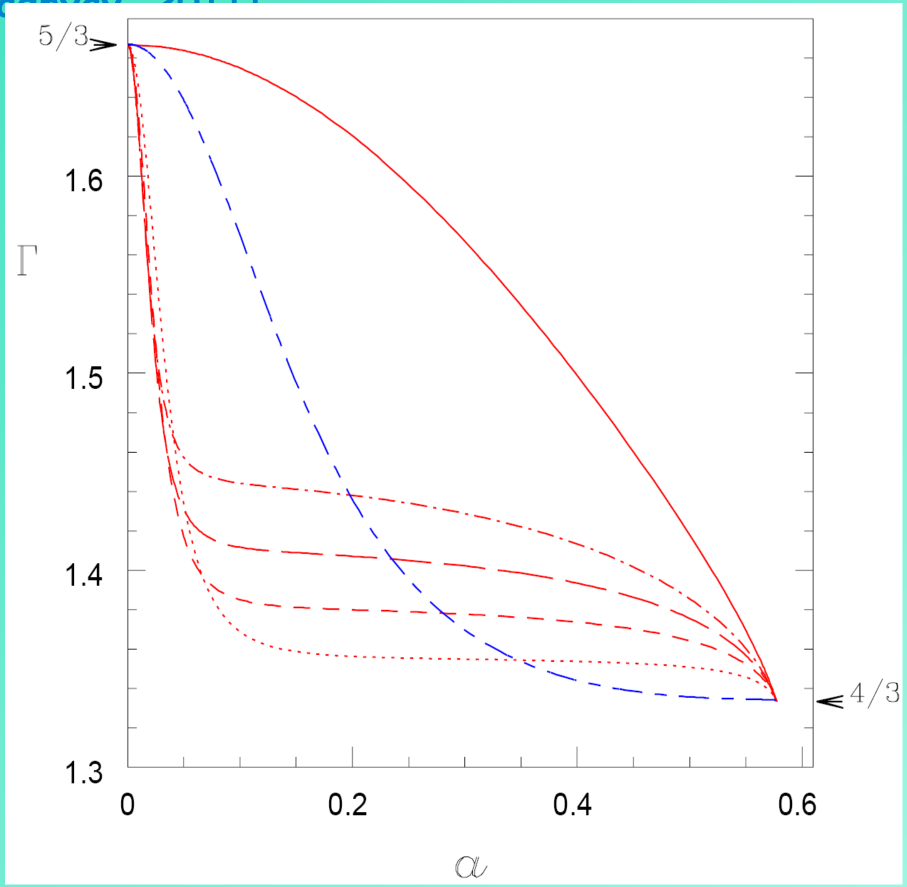
Chattopadhyay & Ryu ApJ, 2009

The sound speed is defined as,

$$\frac{a^2}{c^2} = \frac{\Gamma p}{e+p} = \frac{2\Gamma\Theta}{f+2\Theta}.$$

Γ as a function with T, a; dΓ/dT is slowly varying for $T<10^8$, $10^{10}<T<10^{12}$ & $T>10^{14}$ [Chattopadhyay & Ryu, ApJ 2009; Chattopadhyay, 2011]





Eqn of motion radial flow in strong gravity

- The eqns of motion presented earlier takes the form of relativistic Euler, entropy and number density conservation equations:

$$u^r \frac{du^r}{dr} + \frac{1}{r^2} = -\left(1 - \frac{2}{r} + u^r u^r\right) \frac{1}{e+p} \frac{dp}{dr},$$

$$\frac{de}{dr} - \frac{e+p}{n} \frac{dn}{dr} = 0,$$

$$\frac{1}{n} \frac{dn}{dr} = -\frac{2}{r} - \frac{1}{u^r} \frac{du^r}{dr}.$$

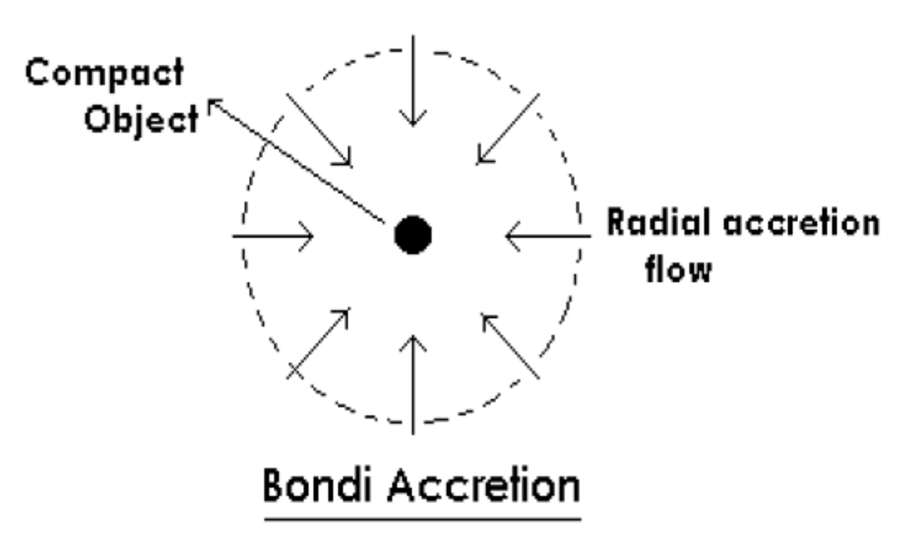
These equations take the following form

$$\frac{dv}{dr} = \frac{(1-v^2)[a^2(2r-3)-1]}{r(r-2)(v-a^2/v)},$$

$$\frac{d\Theta}{dr} = -\frac{\Theta}{N}\left[\frac{2r-3}{r(r-2)} + \frac{1}{v(1-v^2)} \frac{dv}{dr}\right]$$

Here, $v^2 = -u_r u^r/(u_t u^t)$, &

G=M=c=1, Schwarzschild



Integrating the conservation eqn, we get

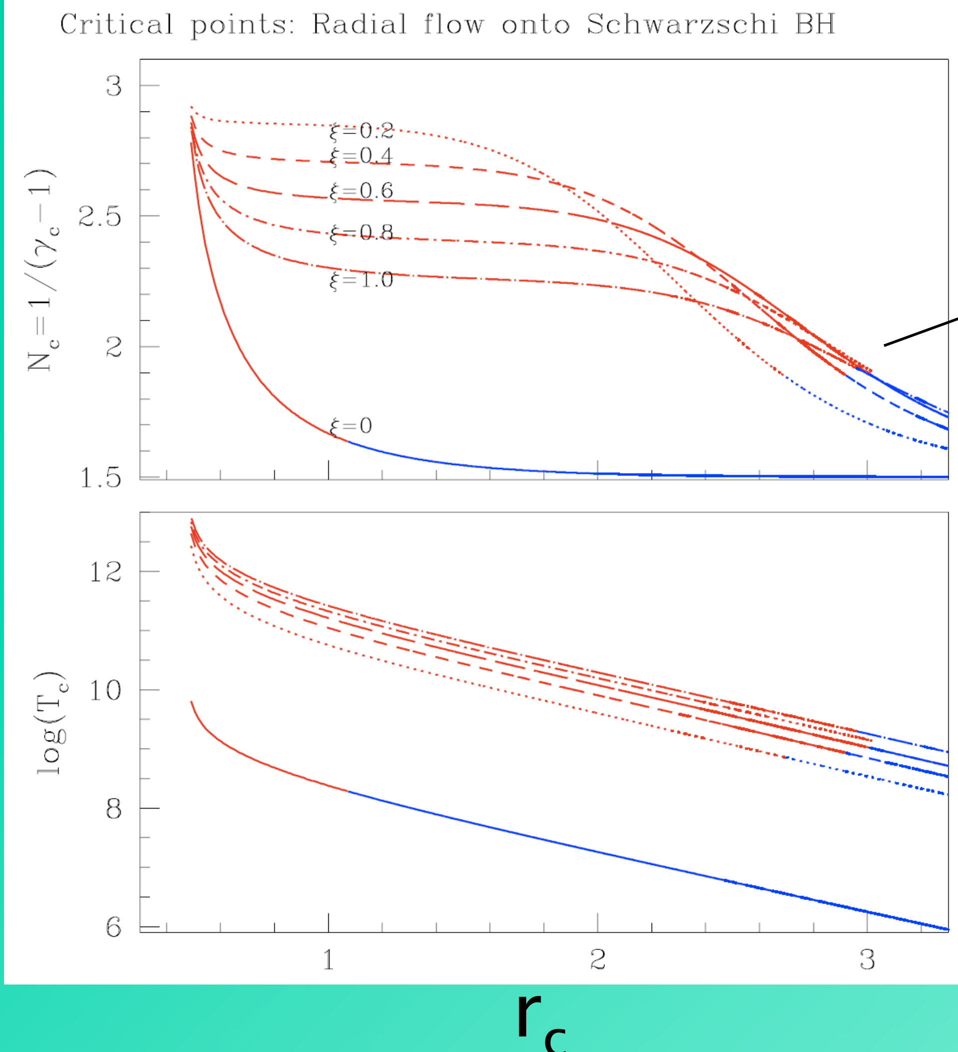
$$\mathcal{E} = \frac{(f + 2\Theta)u_t}{(2 - \xi + \xi/\eta)}$$

Sonic point properties of radial flow onto BHs

- At $r=r_c$, $dv/dr \Longrightarrow 0/0$, the sonic/critical point conditions (SPC/CPC), $a_c = v_c$ & $a_c^2 = \dfrac{1}{2r_c - 3}$
- $(dv/dr)_c$, is found by l'Hospitals rule & admits two solns
- When fluids are compared with same r_c, we are comparing fluids at the same a_c. $\mathcal{E}$ $\longrightarrow$
- When f As $r \rightarrow \infty$, $u_t \rightarrow 1$ $\mathcal{E} \rightarrow h_\infty \approx 1 + N_\infty a_\infty^2$ ge,

∞

Therefore, transonic flows are flows launched with similar

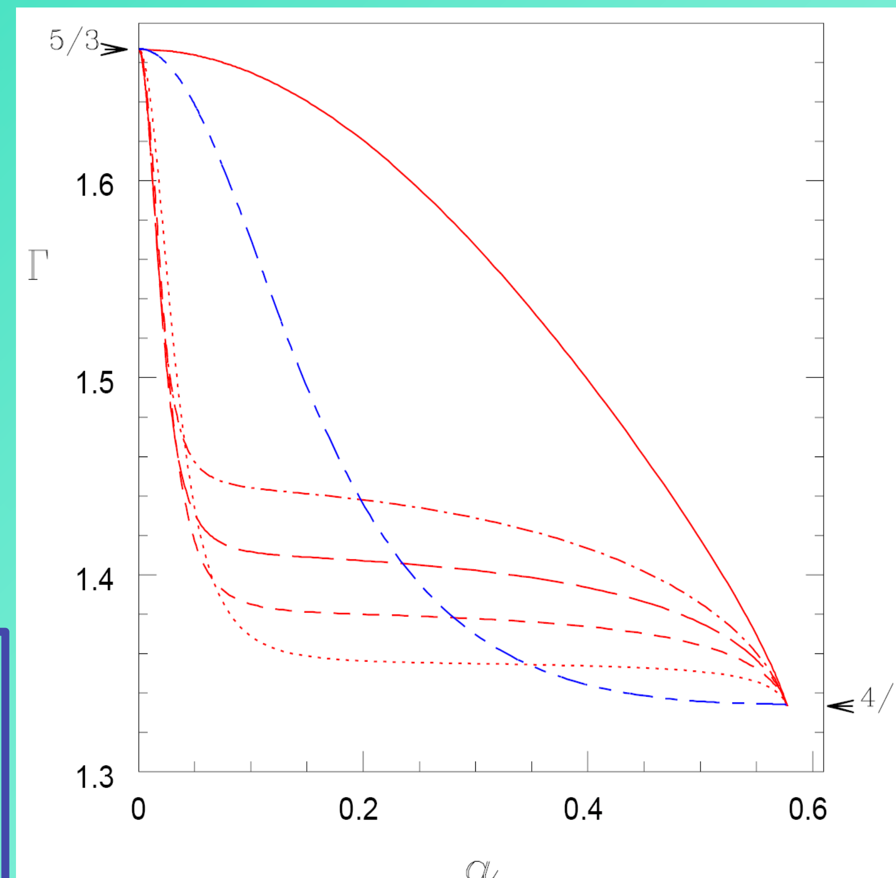


Chattopadhyay & Ryu, ApJ 2009

Γ=4/3, => N=3

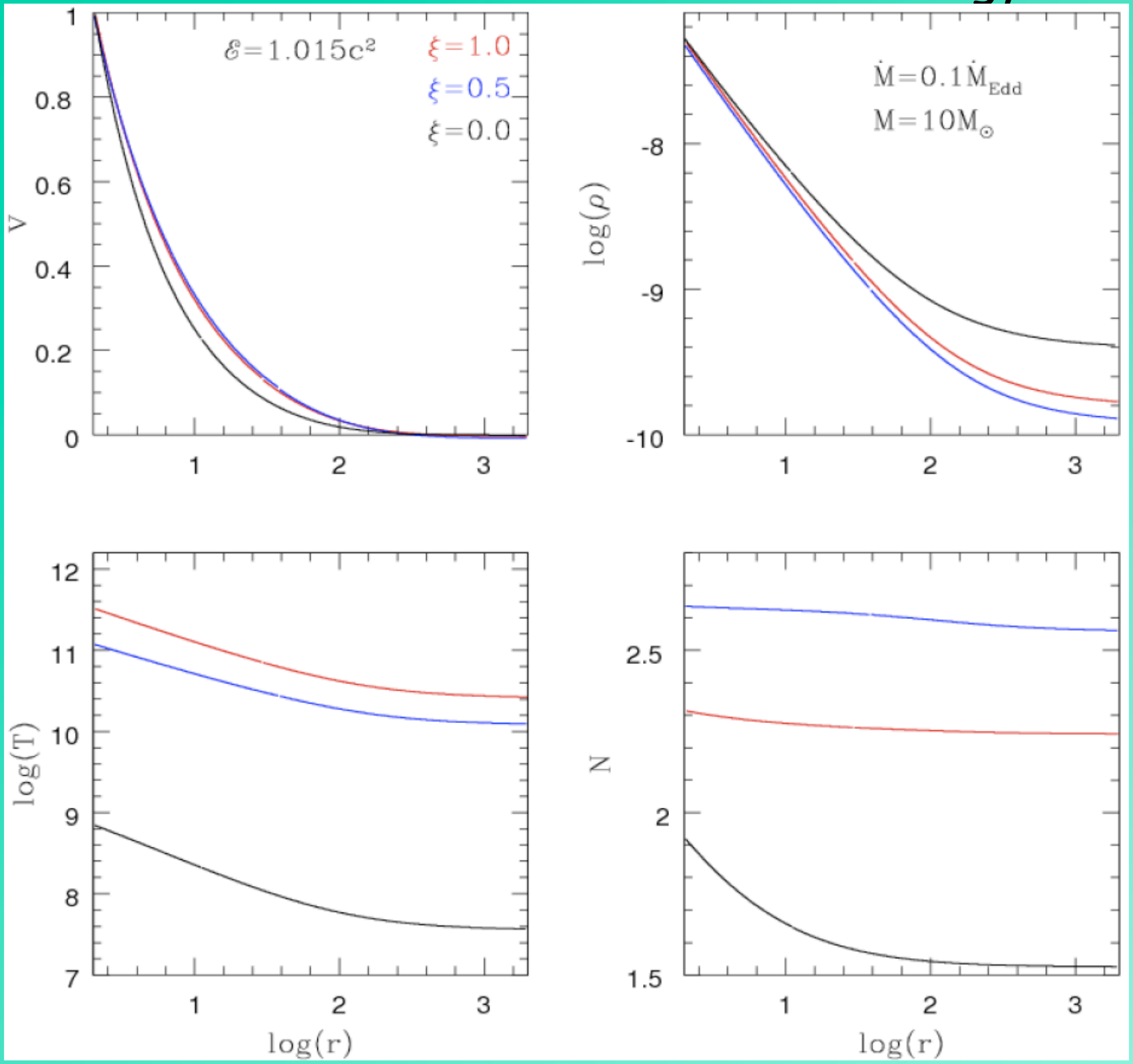
Γ=5/3 => N=3/2

Similar to Γ vs a plot.



- The polytropic index not only depends on T but also on ξ.
- Pair plasma ξ=0, has the coldest as well as the least relativistic sonic points.
- Red indicates $(dv/dr)_c$ to real and opposite sign (A), blue indicates real but of \`-'ve values (D).

Solutions of flow with same energy but different ξ



$$\mathcal{E} = \frac{(f + 2\Theta)u_t}{(2 - \xi + \xi/\eta)}$$

v, ρ, T, N all the variables depend on r as well as ξ.

N for ξ=0.5 and 1.0, are slowly varying function of r!

For rotating flow around Schwarzschild BH

The eqn of motion is:

$$u^r \frac{du^r}{dr} + \frac{1}{r^2} - (r-3)u^\phi u^\phi = \left(1 - \frac{2}{r} + u^r u^r\right) \frac{1}{e+p} \frac{dp}{dr},$$

$$\frac{de}{dr} - \frac{e+p}{n} \frac{dn}{dr} = 0,$$

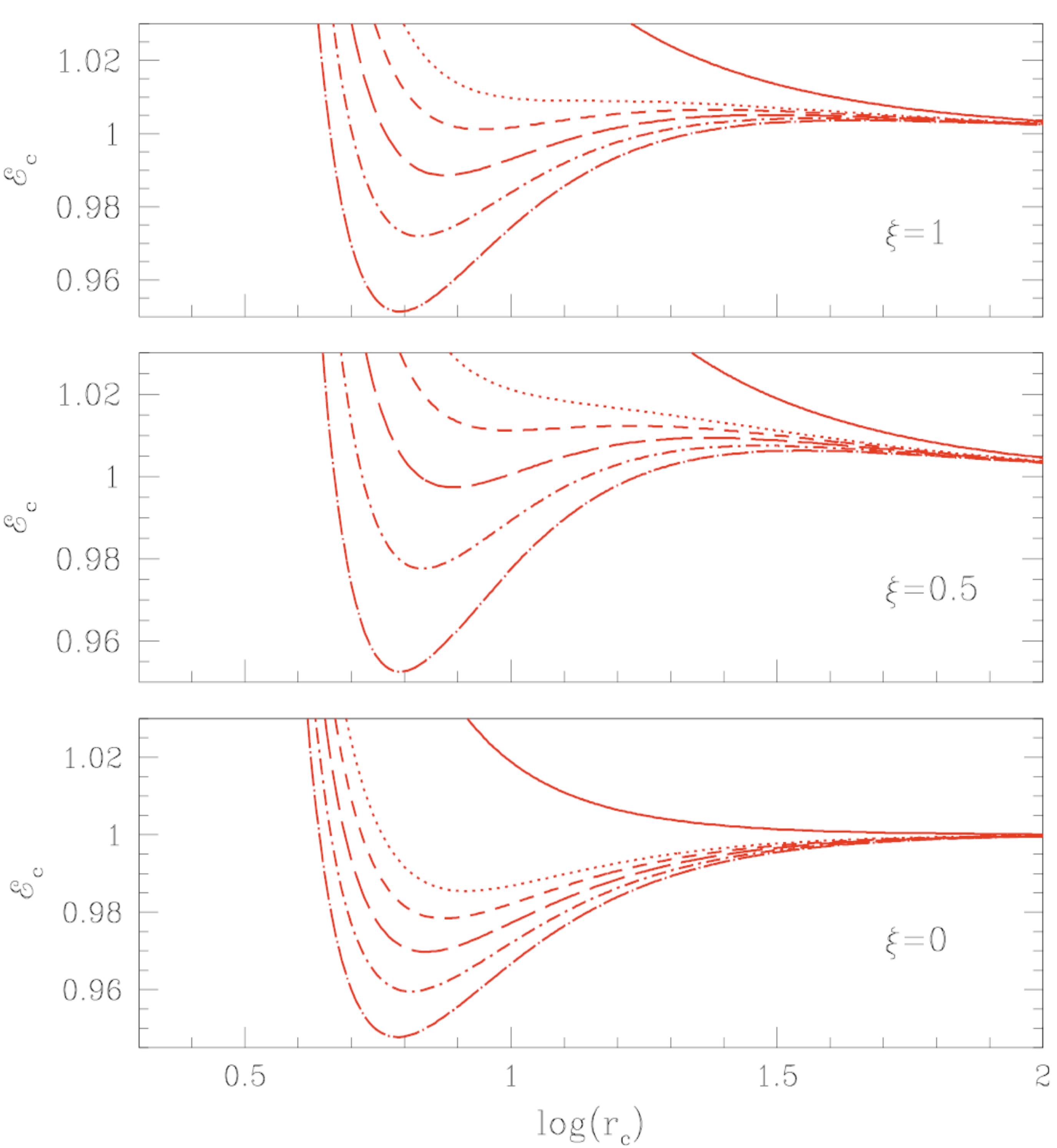
$$\dot{M} = 4\pi H(r) \rho(r) u^r,$$

where,

$$H \approx \sqrt{\frac{p}{\rho}[r^3 - \lambda^2(r-2)]},$$

(Das 2004, Lassota & Abramowicz 1997)

where sp. ang. mom $\lambda = -u_\varphi / u_t$.



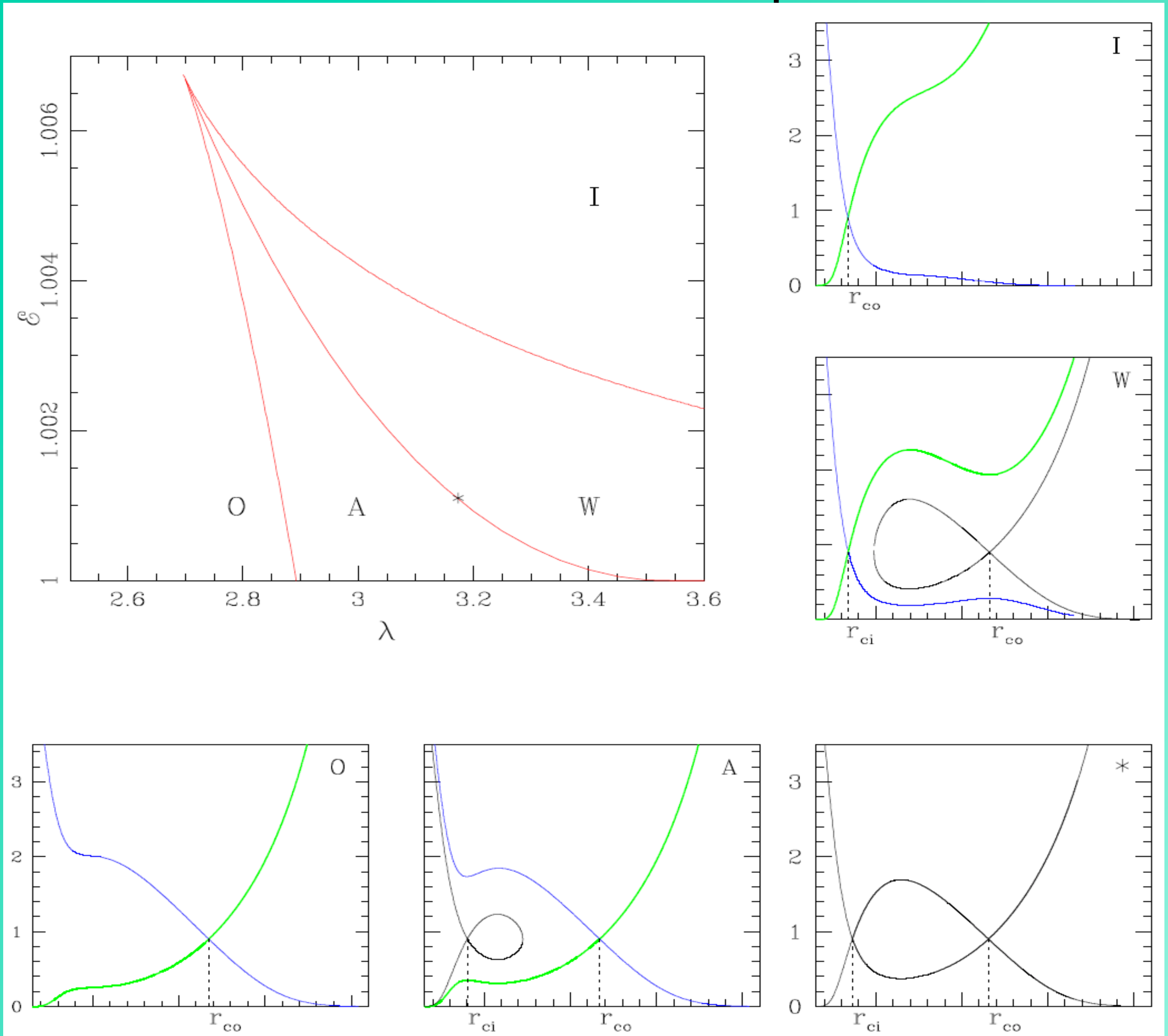
Existence of 3 sonic point for flows with significant proton proportion

λ=0 (solid), 2.8 (dot), 3.0 (dash), 3.2 (long-dash), 3.4 (dash-dot),3.6 (long-dash dot)

NO 3-sonic Point in pair-plasma

Chattopadhyay 2011

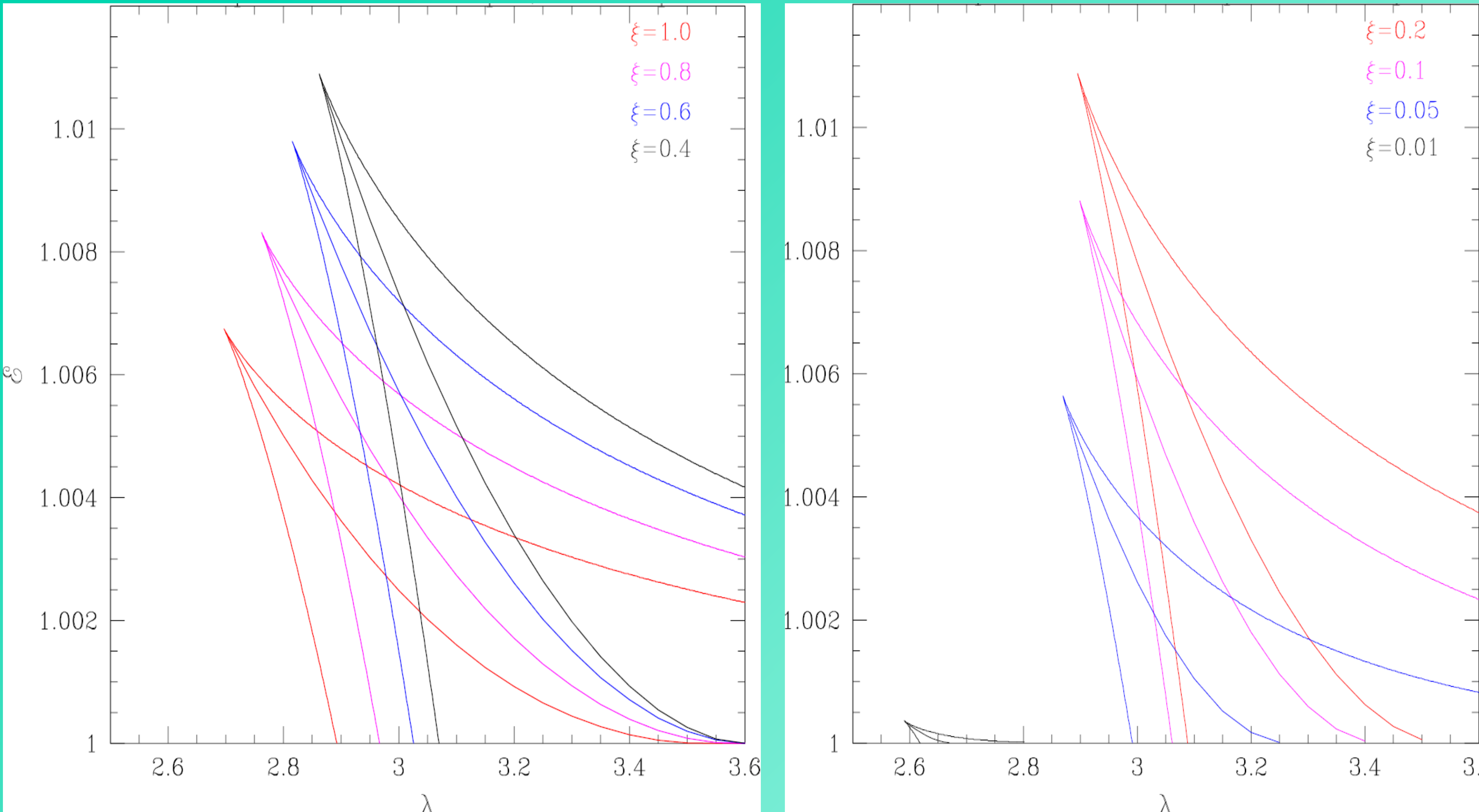
Expected solution topologies and its relation to the parameter space



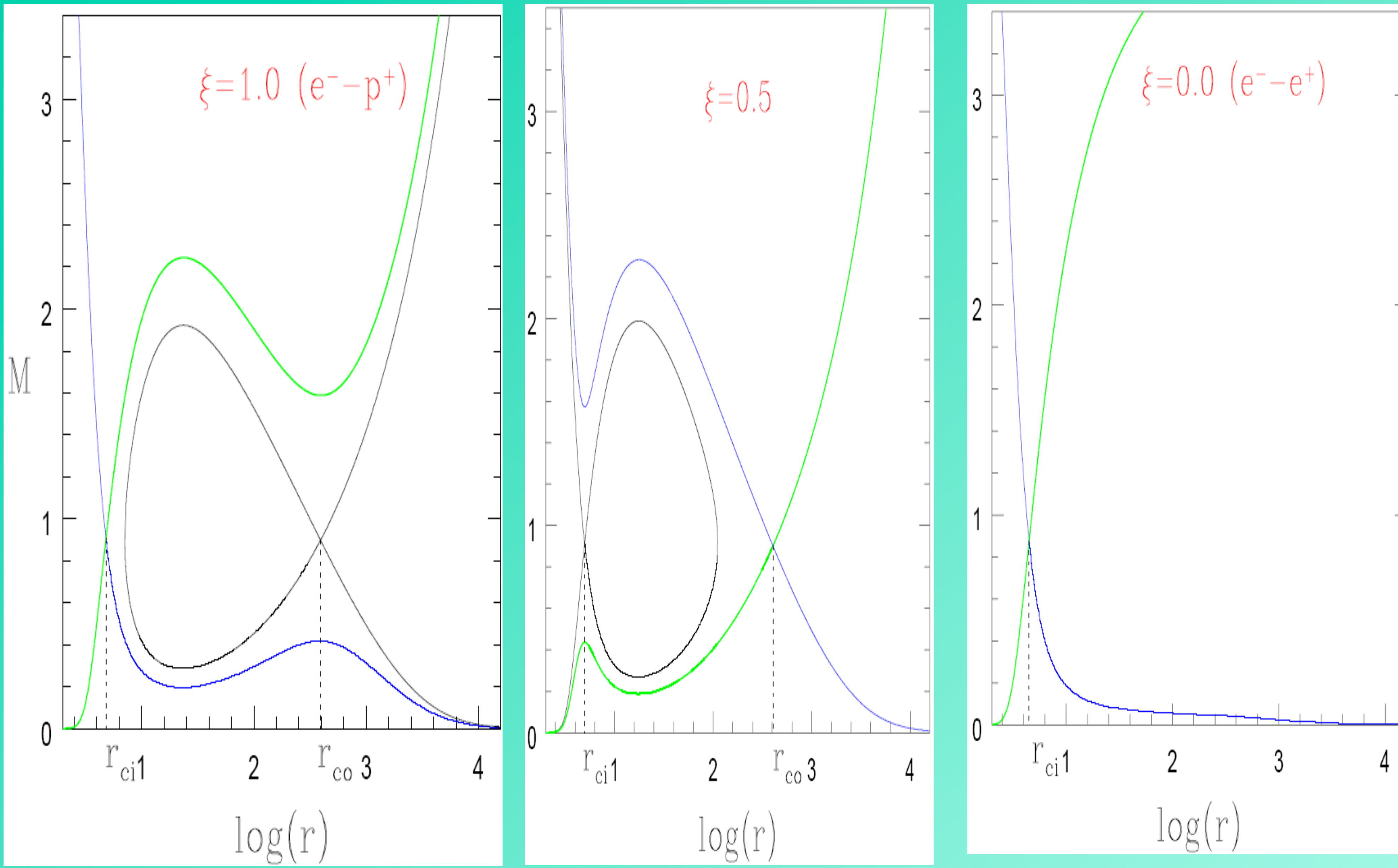
Parameter
Space
And typical
Topologies
For
ξ= 1.0 (electron-proton) fluid

Chattopadhyay (2011)

Parameter space for multi-sonic point (Chattopadhyay 2011)



Topologies at same energy and ang. mom.



$\mathcal{E} =$ 1.0004, λ=3.4; ***topologies can change drastically***

Chattopadhyay (2011)

Shock in Accretion

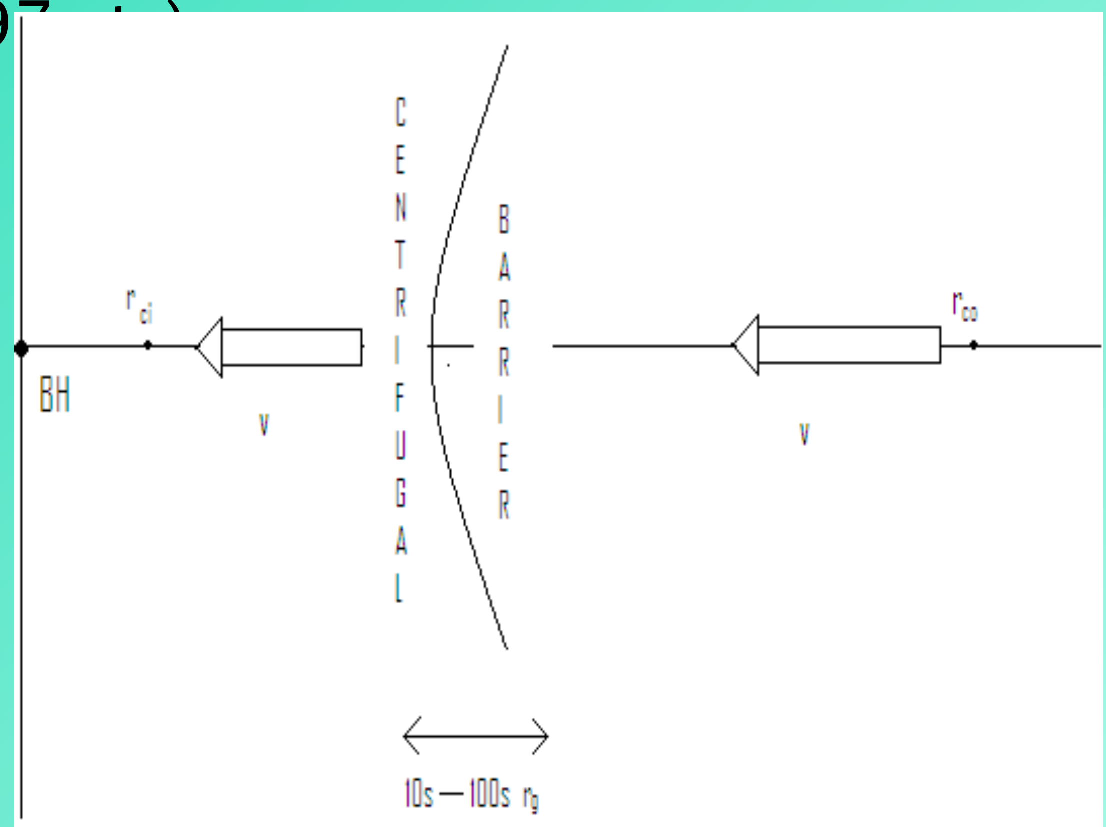
- In the supersonic region ~ few X10rg, the presence of centrifugal barrier (CB) may cause the fluid element in front to be slowed down, w.r.t the fluid that is following behind. If the CB is strong enough then this slowing down can cause internal shocks, generally called centrifugal +pressure mediated accretion shocks. (e.g. Fukue 87, Chakrabarti 89,96, Lu 9

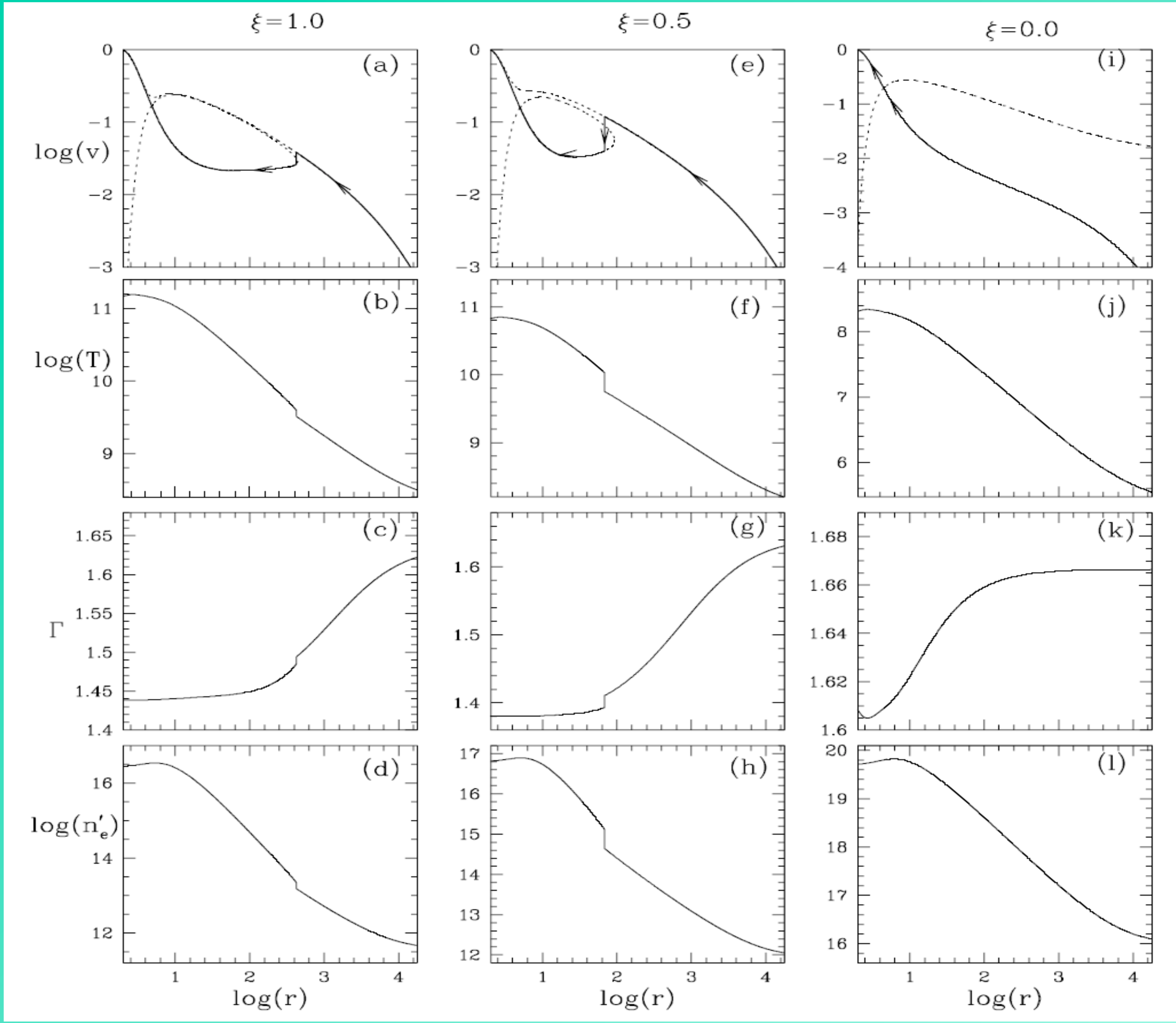
Rankine-Hugoniot Shock

$[nu]=0$

$[(e+p)u^2+p]=0$

$[(e+p)u_t u]=0$





E= 1.00009;λ=3.4; (Chattopadhyay 2011)

Shock location

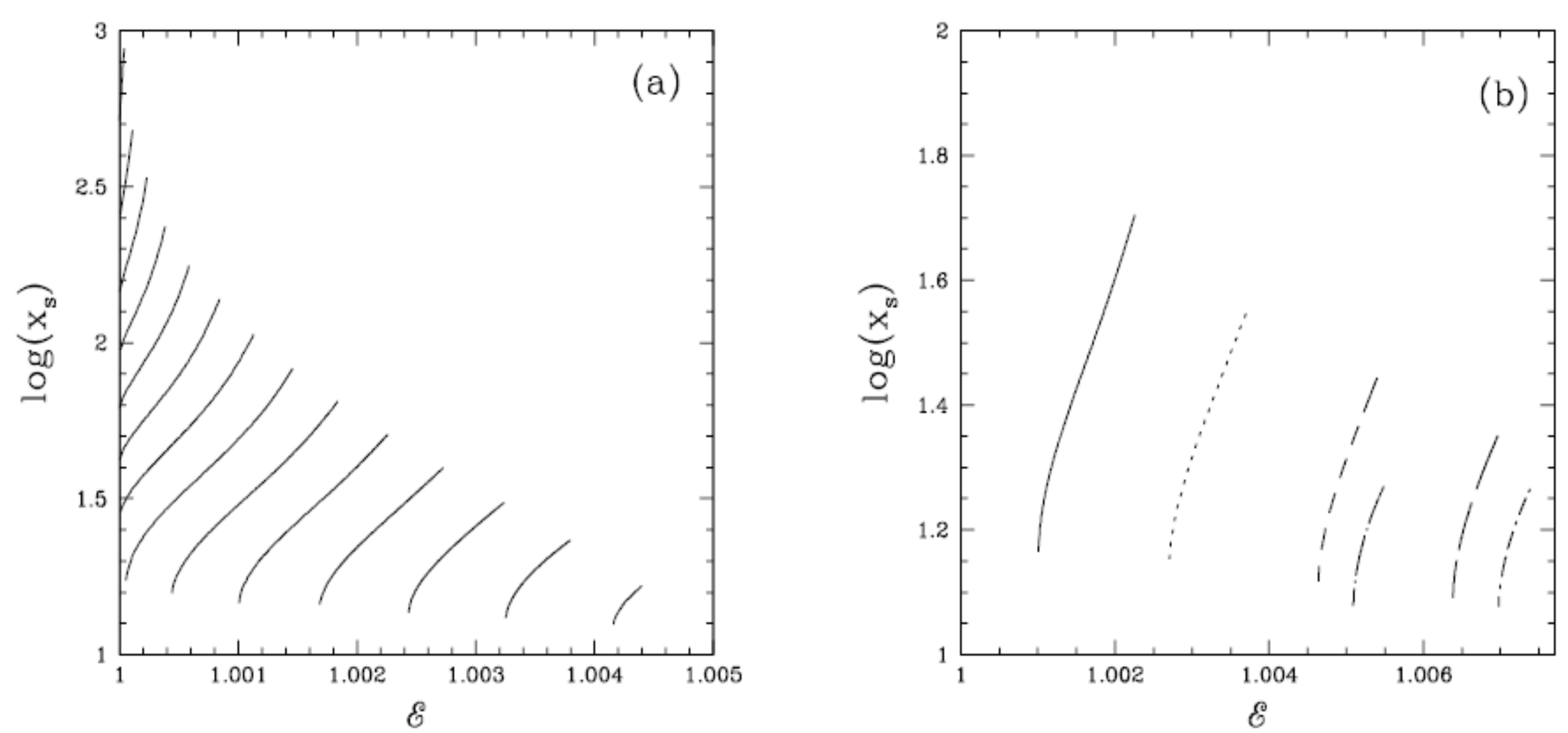
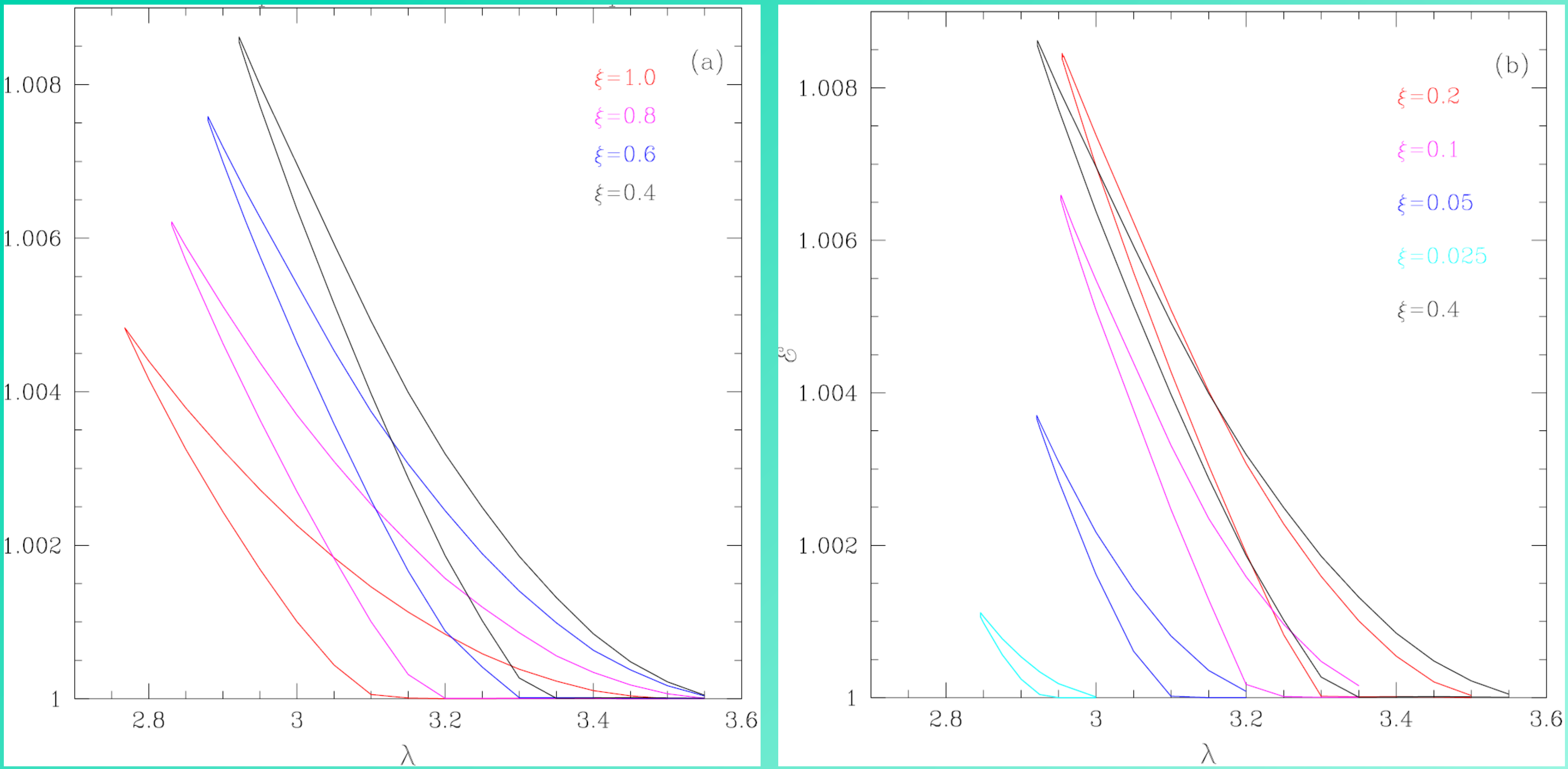


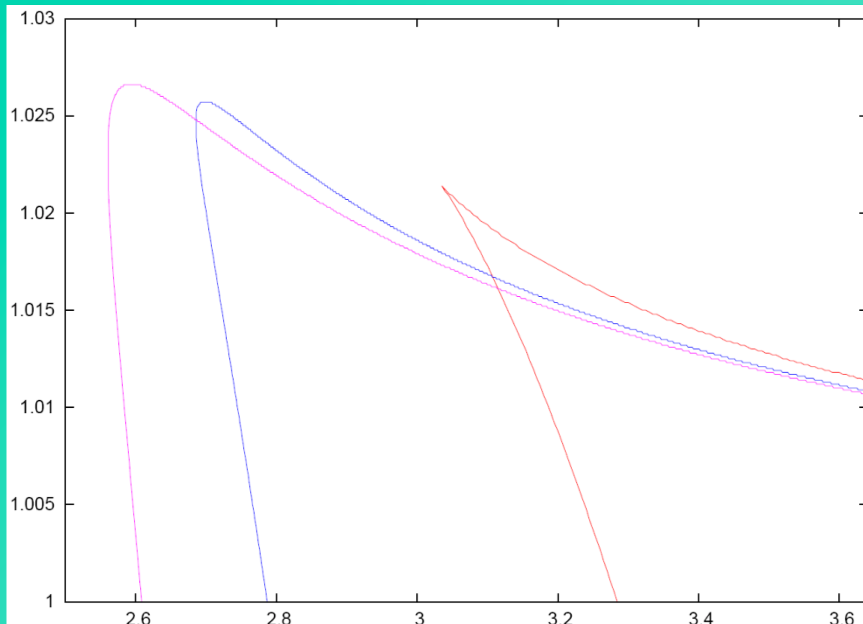
Fig. 9.— (a) Variation of $log(x_s)$ with $\mathcal{E}$ for $e^- - p^+$fluid. The leftmost curve is for $\lambda = 3.45$ and decreases by $d\lambda = 0.05$ for each curve towards right, up to $\lambda = 2.8$. (b) Variation of $log(x_s)$ with $\mathcal{E}$ for $\lambda = 3$, and each curve is for $\xi = 1.0$ (solid), 0.8 (dotted), 0.6 (dashed), 0.4 (long dashed), 0.2 (dashed), 0.1 (long dashed dotted).

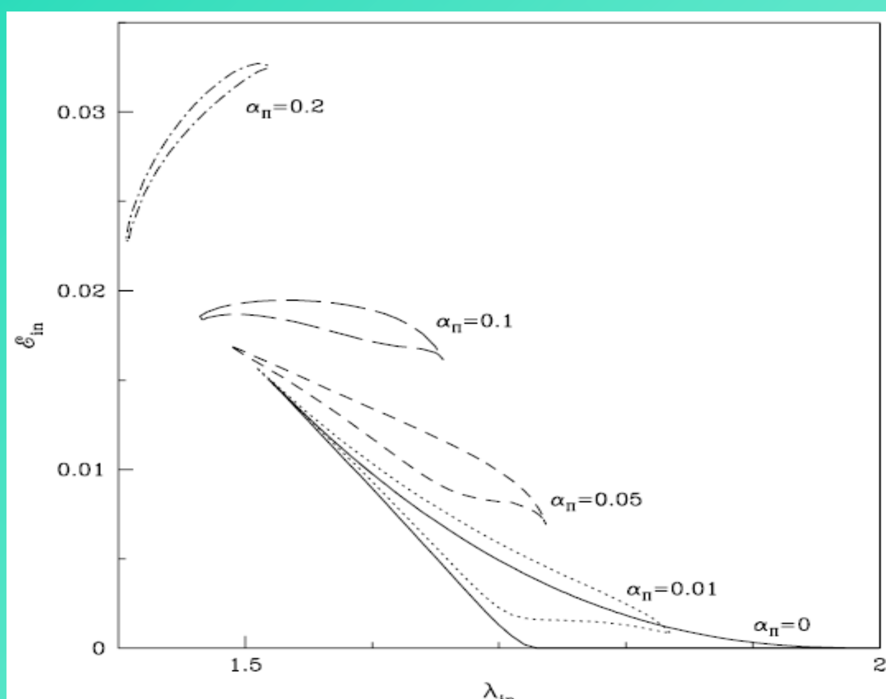
Parameter space for shocks



The variation with ξ is not monotonic

How other processes affects the solution





Red, a=0, Kerr parameter
Blue, a=0.4
Magenta, a=0.8

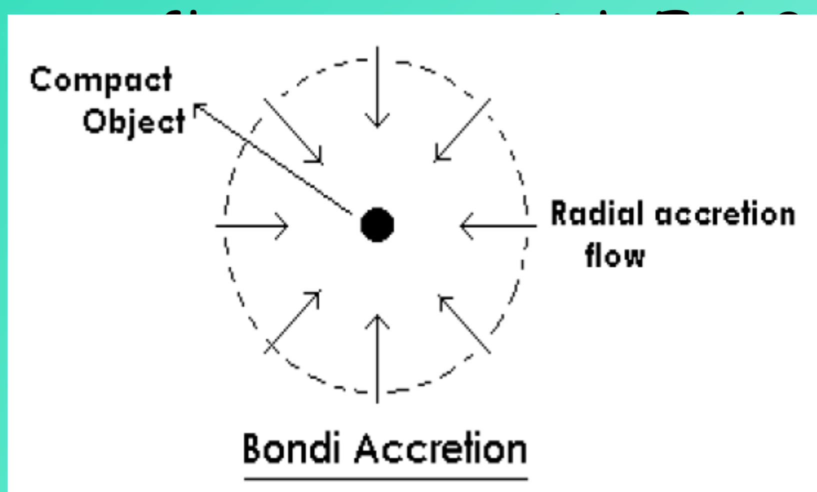
The E–λ parameter space for Multiple critical point. Shifts monotonically to the left with the increase of the Kerr parameter `a'.
(Chattopadhyay etal 2011, in preparation)

With the increase of viscosity parameter, the shock parameter space moves to the left. (Chakrabarti & Das, MNRAS 2004)

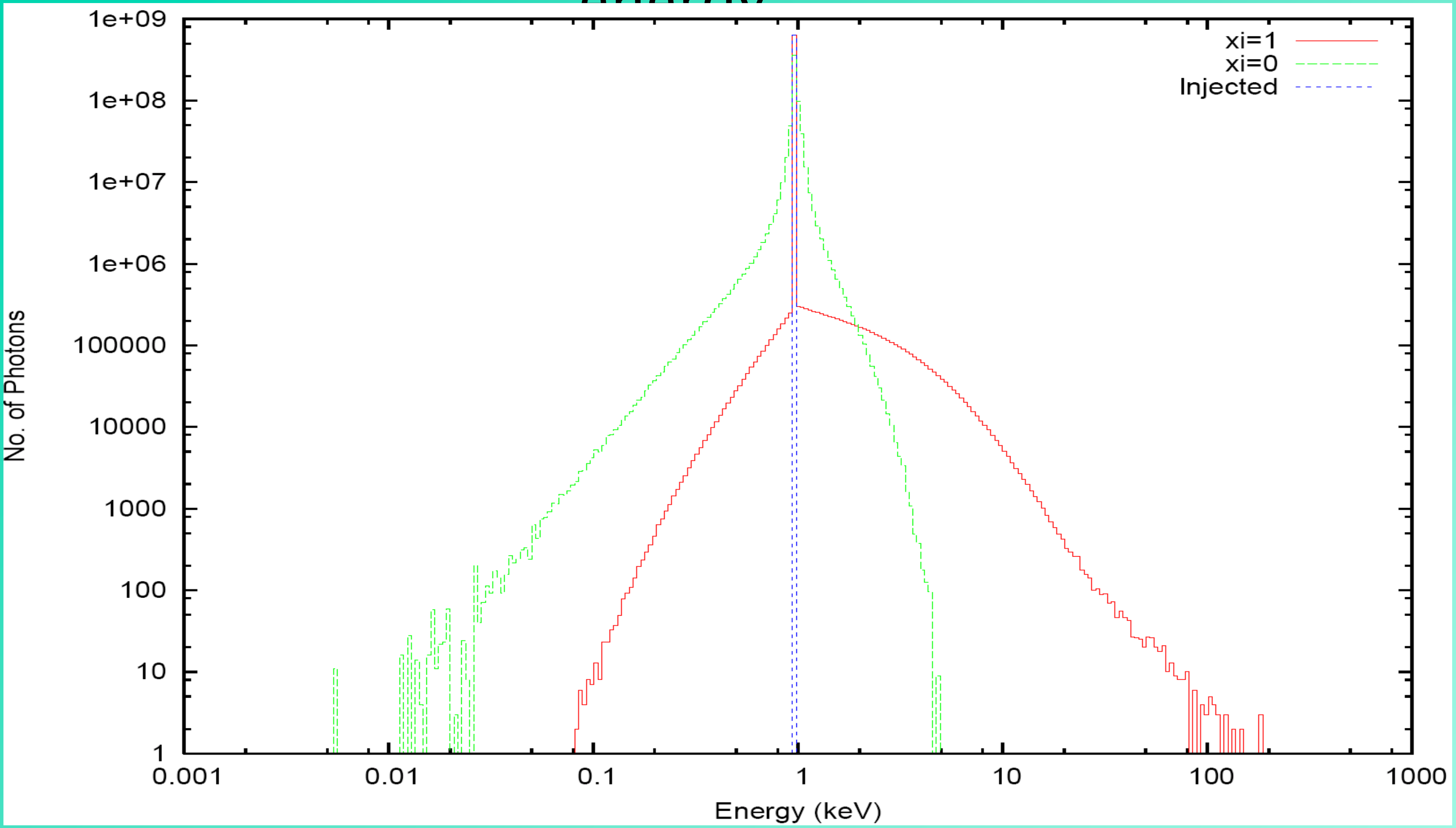
- However, with ξ the response of the parameter space is not monotonic. So in presence of dissipation the dependence of the solutions incorporating ξ will be important.

- Now, Why should anyone be concerned with these solutions in the first place? Will it have any observational significance?

Let us check with inverse-Compton spectra of radial accretion flow with external photons of 1KeV. The accretion [illegible] & fluids with ξ=0 & 1.



Inverse-Compton Spectrum of 1 KeV source photons for flow solutions starting with same sp. energy



The spectrum is completely different

(Chattopadhyay, Ghosh, Garain, Laurent 2011, in prep)

Conclusions

- Transonic pair plasma fluid is most non-relativistic fluid.
- It needs a certain proportion of baryons to make it relativistic.
- Pair plasma rotating fluid do not have 3-sonic points. And admits only I type solutions.
- Parameter space for multiple critical pt strongly depends on ξ.
- The shock parameters differs with ξ too.
- Finally, the spectra will be different in the high energy range.

Thank you