Neutrino-driven electron-positron plasma near an accreting black hole

Ray Sawyer

UCSB

Making $e^+ e^-$ plasma from $\nu, \bar{\nu}$ beams.

Applications :

Last few seconds of an accretion torus around a black hole—short gamma ray bursts

Supernova????

Mechanisms:

a. Direct ---

$\bar{\nu}$

ϕ $\quad e^+ + e^-$

ν

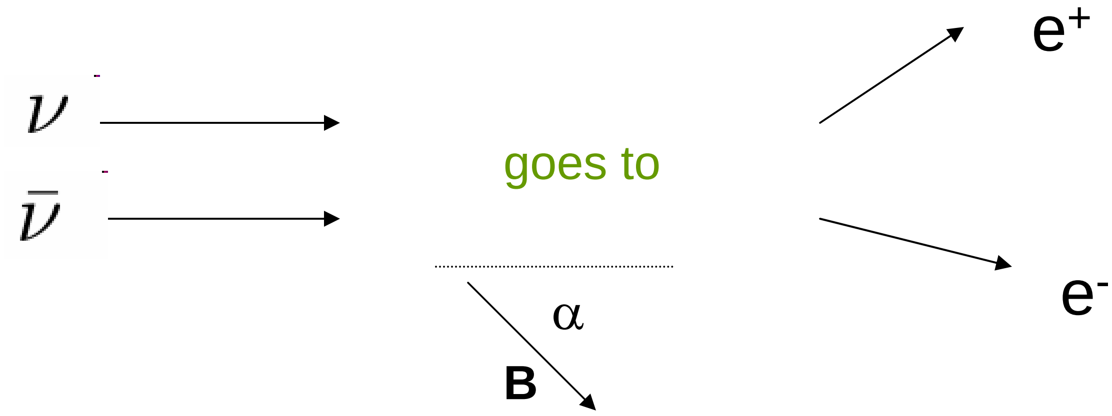
$(1- \cos \phi)$ dependence makes this inefficient for collimated beams

b. Heating pre-existing $e^+ e^-$ plasma through ν– e^{+-} scattering.

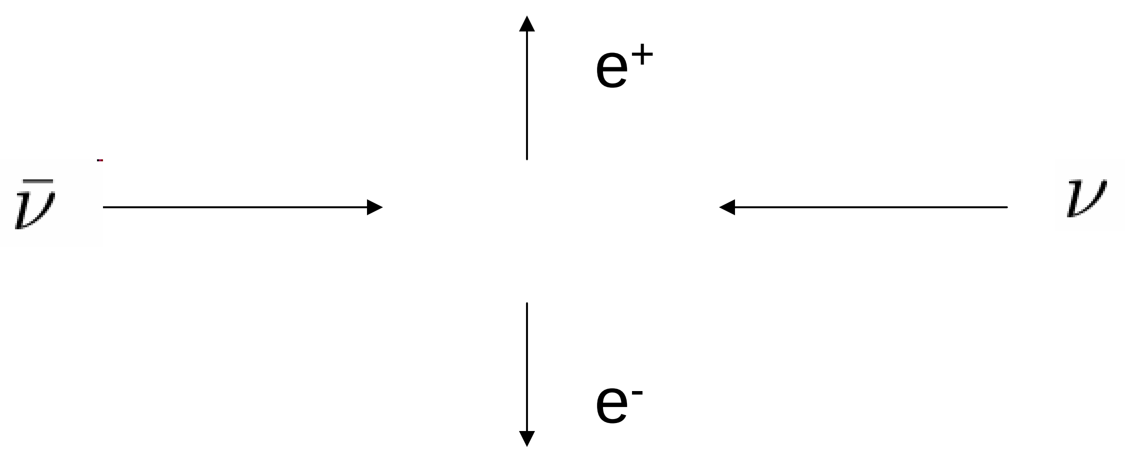
c. Same as (a), but in magnetic field. Or through,

$$\nu \to e^+ + e^- + \nu$$

Co-linear ν's to e^+ e^- in magnetic field



Compare to head-on, B=0 case



Compare rates of $e^+ e^-$ production in two cases:

a. All ν and anti-ν co-moving at an angle α to B

b. Two clouds ; head-on;

total # density of ν's the same as in (a);

B=0

Ground and first excited Landau levels only

$$\frac{\Gamma_{\text{parallel}}}{\Gamma_{\text{head-on; B=0}}} = 3\sin^2\alpha\ e^{-2\omega^2 \sin^2\alpha/B}\ \theta[2\omega^2 \sin^2\alpha - B]$$

$\omega = \nu$ energy

Schwinger's Greens function for const. EM field $F_{\mu\nu}$

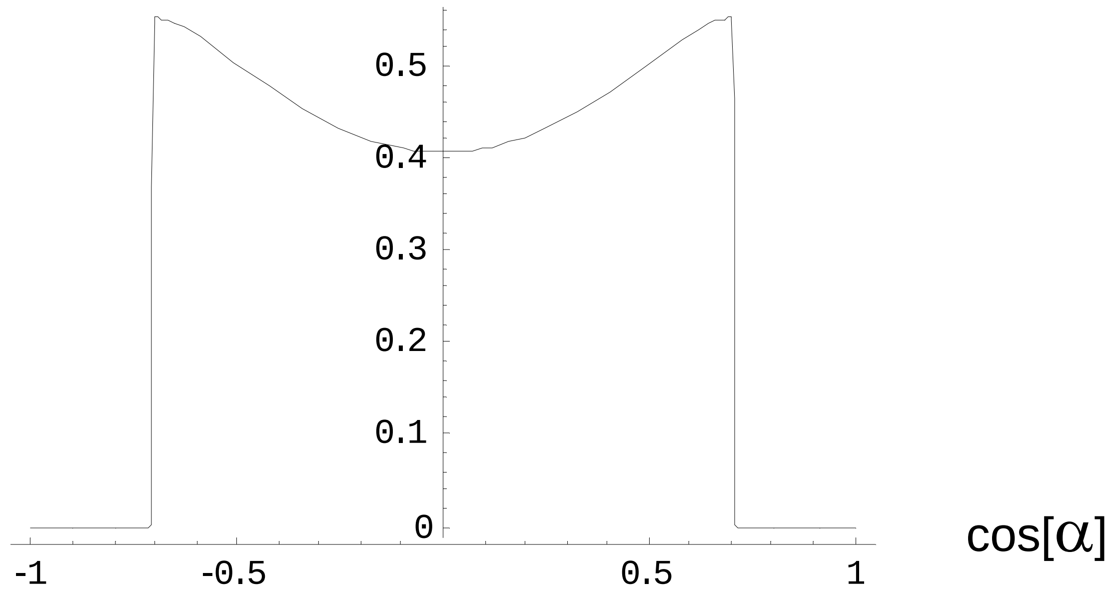
$$S(x,x') = -i[i\partial\!\!\!/ - e\,A\!\!\!/(x) + m]\int_{-\infty}^{0} ds\, U(x,x',s)$$

$$U(x',x'',s) = \frac{-i}{(4\pi)^2 s^2}\exp\Big\{ -ie\int_{x''}^{x'} dx^\mu A_\mu(x) - \frac{1}{2}\mathrm{tr}\ln[(eFs)^{-1}\sinh(eFs)]$$
$$+\frac{i}{4}(x'-x'')eF\coth(eFs)(x'-x'') + \frac{i}{2}\sigma_{\mu\nu}F^{\mu\nu}s + i(m^2 - i\epsilon)s\Big\}$$

Rate calculated from,

$$\Gamma = \frac{G_F^2 n}{4\omega_1\omega_2}\mathrm{Im}\Big\{Tr[\gamma^\mu(1-g_A\gamma_5)p\!\!\!/_1\gamma^\nu(1-g_A\gamma_5)p\!\!\!/_2]$$
$$\int d^4(x'-x'')Tr[\gamma_\mu(1-g_A\gamma_5)S(x'-x'')\,\gamma_\nu(1-g_A\gamma_5)S(x''-x')]\Big\}$$

Ratio [parallel with field B / head-on B=0]　　　for $\omega^2 = B$



α = angle between p and B

B=4 X10[15] G　;　$\omega^2 = B$　$\longrightarrow$　$\omega = 5$ MeV

A standard scenario for the final moments NS-BH mergers

1, Process:

$$\nu_e + \bar{\nu}_e \rightarrow e^+ + e^-$$

populates the region very near the black hole with plasma.

2. The plasma is accelerated upwards, converting internal energy into kinetic energy—

eventually achieving a high value of Γ.

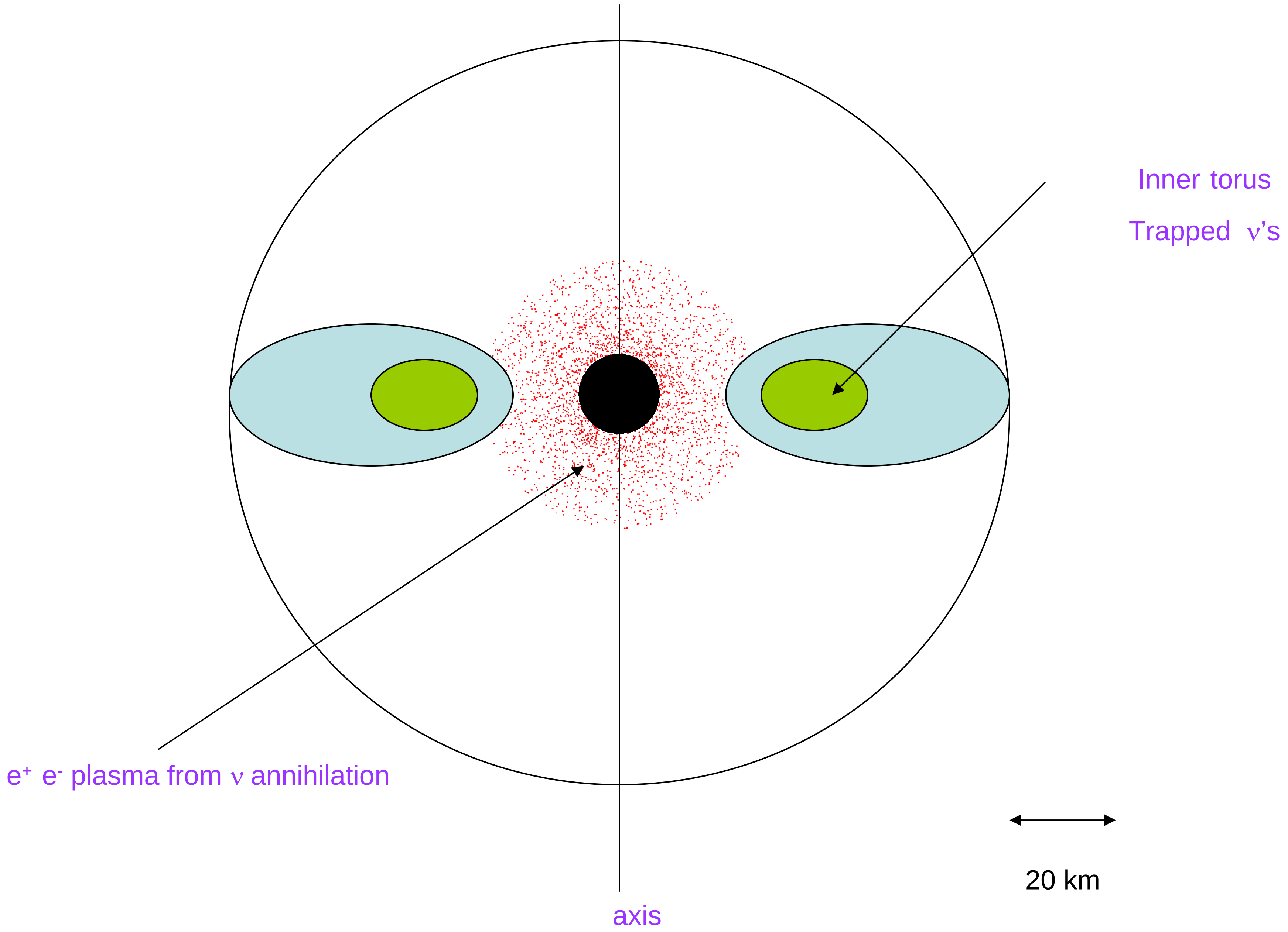
(**Of course, the plasma quickly cools below T=.5 MeV as it is accelerated—thereafter dominated by photons**.)

3. At some distance from the hole, a jet forms, influenced by the pressure of the surrounding gas.

(However, in these models, the transition from subsonic to supersonic presumably occurs <u>below</u> the region of jet formation.)

We suggest some substantial changes.

Cross-section of black hole plus accretion torus



Time dependent radial flow with a source.

$$\frac{\partial P}{\partial x^\nu} g^{\mu\nu} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x_\nu} [\sqrt{g}(P+\rho)U^\mu U^\nu] + \Gamma^\mu_{\nu,\lambda} U^\nu U^\lambda (P+\rho) = h^\mu$$

For the sources we take,

$$h^0 = \frac{\dot{s}}{-g_{00}} = \frac{\dot{s}}{1 - r_s/r}$$

$$h^r = 0$$

where, e.g., following Aloy et al*,

$$\dot{s} = \text{const.}\ r^{-5}$$

* Astron-Astrophys 436, 273 (2005)

For spherically symmetrical case

and completely relativistic plasma

$P = \rho/3$:

Steady flow

$$\frac{\partial}{\partial r}(v y^2 r^2 \rho) = \frac{-3 g_{00}}{4} r^2 h^0$$

$$\frac{\partial}{\partial r}\log[\rho y^4] = \frac{3(h^r + v\, g_{00} h^0)}{(1 - v^2)\rho y^2}$$

where

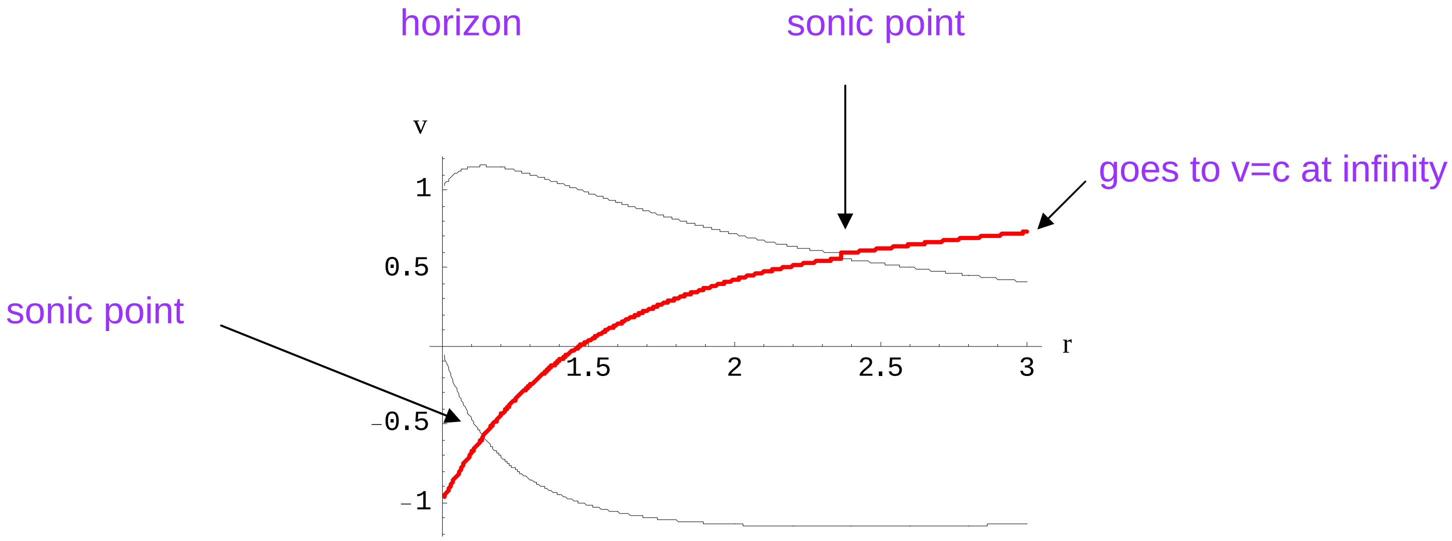
$$\rho = \text{energy density}$$

$$g_{00} = 1 - \frac{r_s}{r} \qquad , \qquad y = \left[\frac{-g_{00}}{(1 - v^2)}\right]^{1/2}$$

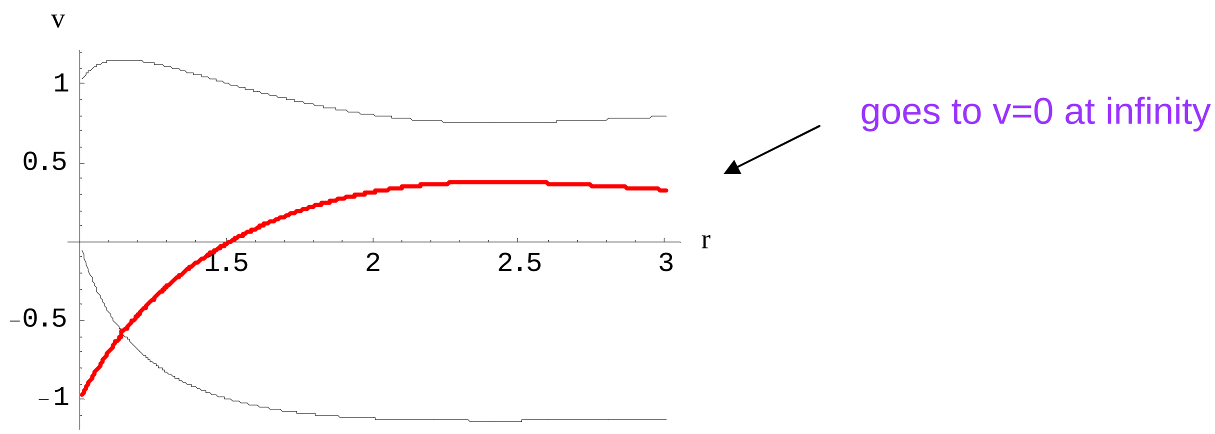
Solve for v(r) , all $r > r_s$,.

Boundary condition: $v(r_s) = -1$ (c)

Radial velocity/c vs. distance/r_s



or

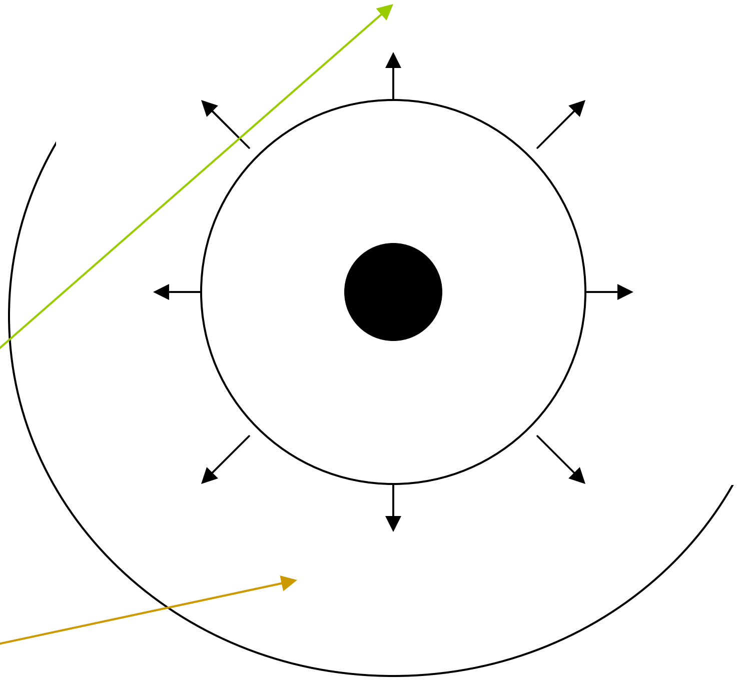


for identical sources $h^0 = -r^{-5}/g_{00}$, $h^r = 0$

Flows above an injection surface that is outside of the source region:

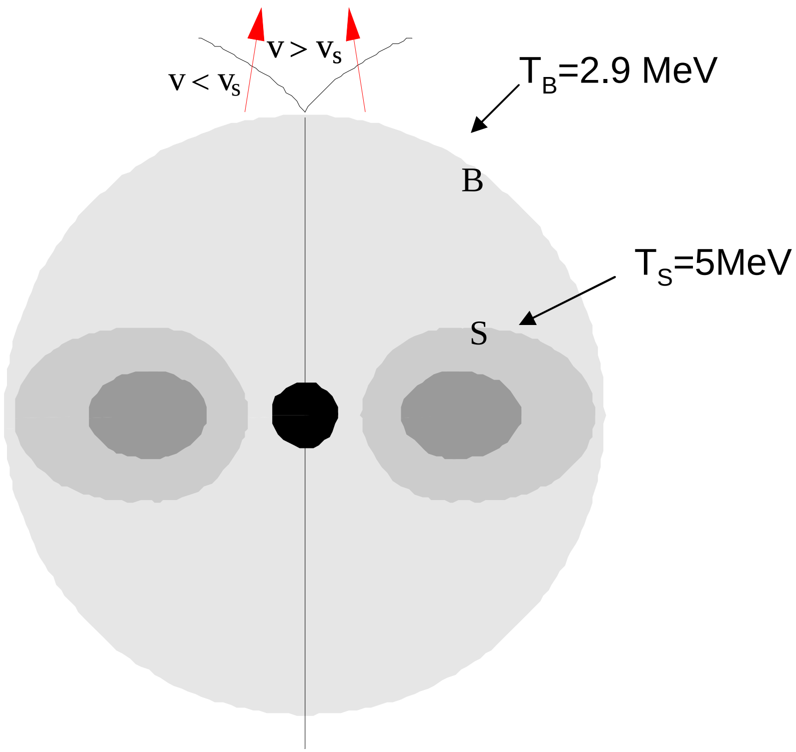
1. Supersonic injection--accelerates above injection surface.

2. Subsonic injection—decelerates above injection surface



For subsonic injection - these regions would fill with a lot of e^+e^- plasma drifting up from below.

This plasma also gets heated through ν,e collisions.



B=point on “injection surface”

S=point on ν – surface

Determination of temperature T_B :

Balance cooling from $e^+ + e^- \to \nu + \bar{\nu}$

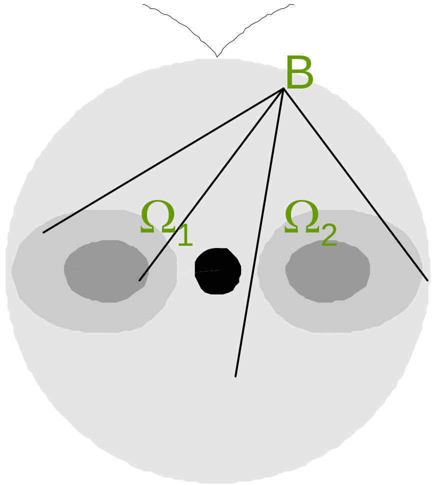
with net heating from $\nu + e^{\pm} \to \nu + e^{\pm}$, $\bar{\nu} + e^{\pm} \to \bar{\nu} + e^{\pm}$

Cooling

$$\dot{q}_{\rm cool} = .35 G_F^2 T_B^9 \approx 3.8 \times 10^{33} T_{11}^9 \,{\rm ergs}\,({\rm c})^{-3}\,{\rm s}^{-1}$$

Heating

$$\dot{q}_{\rm heat} = \lambda(2\pi)^{-6} \int d^3p\, d^3q f(E_p, T_B) f(E_q, T_S) \times (E_p - E_q)\sigma_T$$



$\lambda = (\Omega_1 + \Omega_2)/4\,\pi$

solid angle subtended at B
by the ν surface

$$\sigma_T = \sum_{i=e,\nu,\tau} (\sigma_{\nu_i,e^-} + \sigma_{\bar{\nu}_i,e^-} + \sigma_{\nu_i,e^+} + \sigma_{\bar{\nu}_i,e^+}) = \frac{14 G_F^2}{3\pi} p_\mu q^\mu$$

Cooling

$$\dot{q}_{\rm cool} = .35 G_F^2 T_B^9 \approx 3.8 \times 10^{33} T_{11}^9 \,{\rm ergs}\,({\rm c})^{-3}\,{\rm s}^{-1}$$

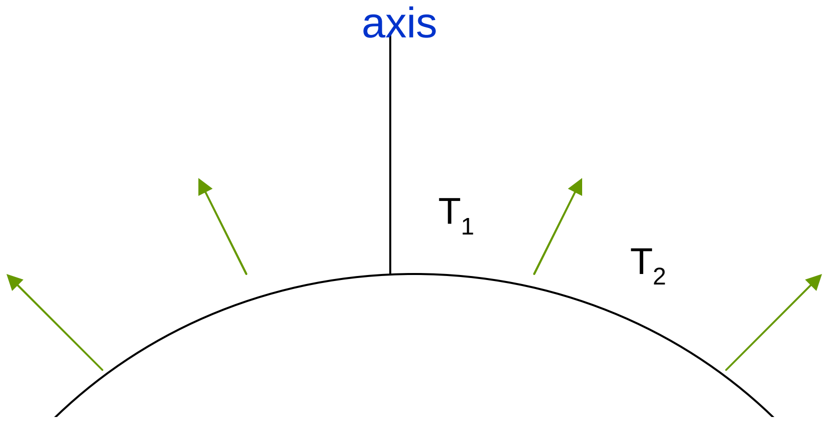
Heating

$$\dot{q}_{\rm heat} = \lambda (2\pi)^{-6} \int d^3p\, d^3q\, f(E_p, T_B) f(E_q, T_S) \times (E_p - E_q) \sigma_T(p,q)$$

$\lambda = (\Omega_1 + \Omega_2)/4\pi$ =(approx) .1

$$\textbf{Choosing } \mathbf{T_B = (2.9/5) T_S} \quad \textbf{gives} \quad \dot{\mathbf{q}}_{\rm \mathbf{heat}} \approx \dot{\mathbf{q}}_{\rm \mathbf{cool}}$$

So we shift to considering the problem of subsonic plasma injected through the larger surface S.



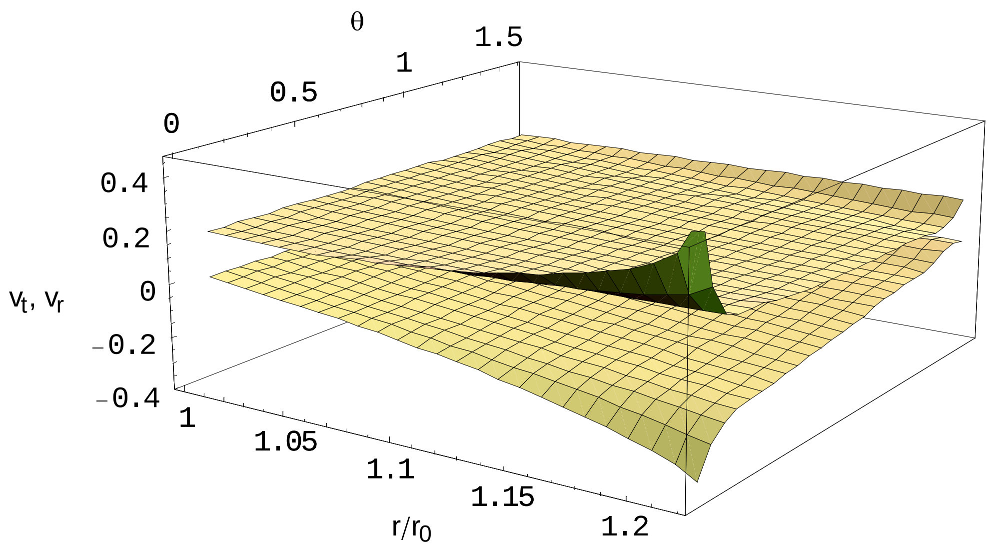
In the calculation of T shown earlier the temperature is somewhat higher at higher angles on the injection surface, due to greater proximity to the ν–surface.

$T_2 > T_1$

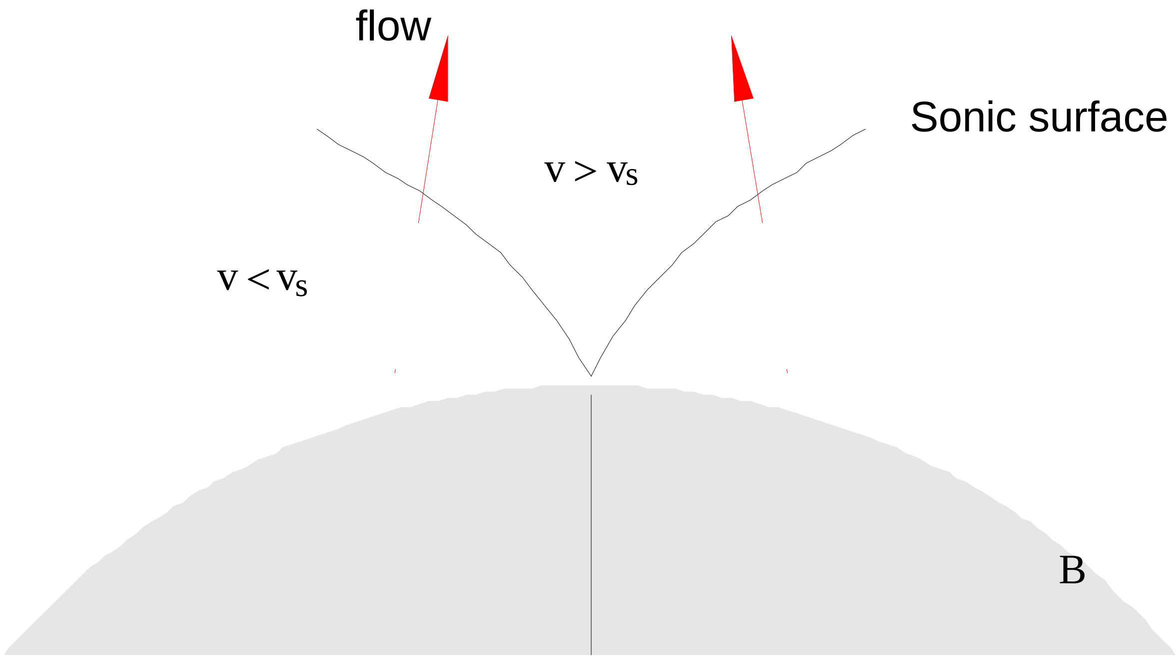
Spherically symmetrical subsonic injection gives decelerating flow above the injection surface. However…….

Solving for the motion with the calculated polar angle dependence of the injection temp. (or ρ) , gives a sonic surface.

We plot radial and tangential velocities in a rectangular region of r,θ in which one corner is very near the sonic surface.



Repeating this for a carefully chosen set of rectangles allows us to plot out the sonic surface .



Of course, once the plasma enters the supersonic region, where it accelerates rapidly, it soon cools to below the $e^+ e^-$ region, and becomes completely photon dominated. The density of ordinary matter in the region then enters in a more important way.

From then on, usual jet theory, with lateral plasma pressure balanced by gas pressure on the sides, probably applies.

Conclusions for this B=0 model

1. The plasma from ν annihilation very near the hole drifts upward with decreasing speed and little change in energy density.

2. More than 50% of energy deposited near the hole by annihilation goes down into the hole.

3. The escaping plasma can serve as a seed for a more robust plasma in a bigger region (10’s of kms.), sustained by neutrino scattering on the e^+ e^- in the plasma.

4. A sonic surface develops due to the anisotropy in this process.

5. Above this point, business as usual.

If the inner accretion torus is cooler (3 MeV ?) this mechanism cannot make the requisite (self sustaining) large sphere full of plasma.

Instead –production of large amounts of plasma from ν collisions in a magnetic field as discussed earlier.?????

Or perhaps, even better, through the reaction,

$$\nu \to \nu + e^+ + e^-$$

in the big magnetic field.

Conclusions for large B case???

None, of course, since our fluid mechanical equations no longer apply.

However, at a hand-waving level,

1. Big fields can be made through magneto-rotational instability.

2. If you fill the inner region with enough e+ e- plasma, a lot of it will find its way out.