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Relativistic Thermodynamics in CFD codes

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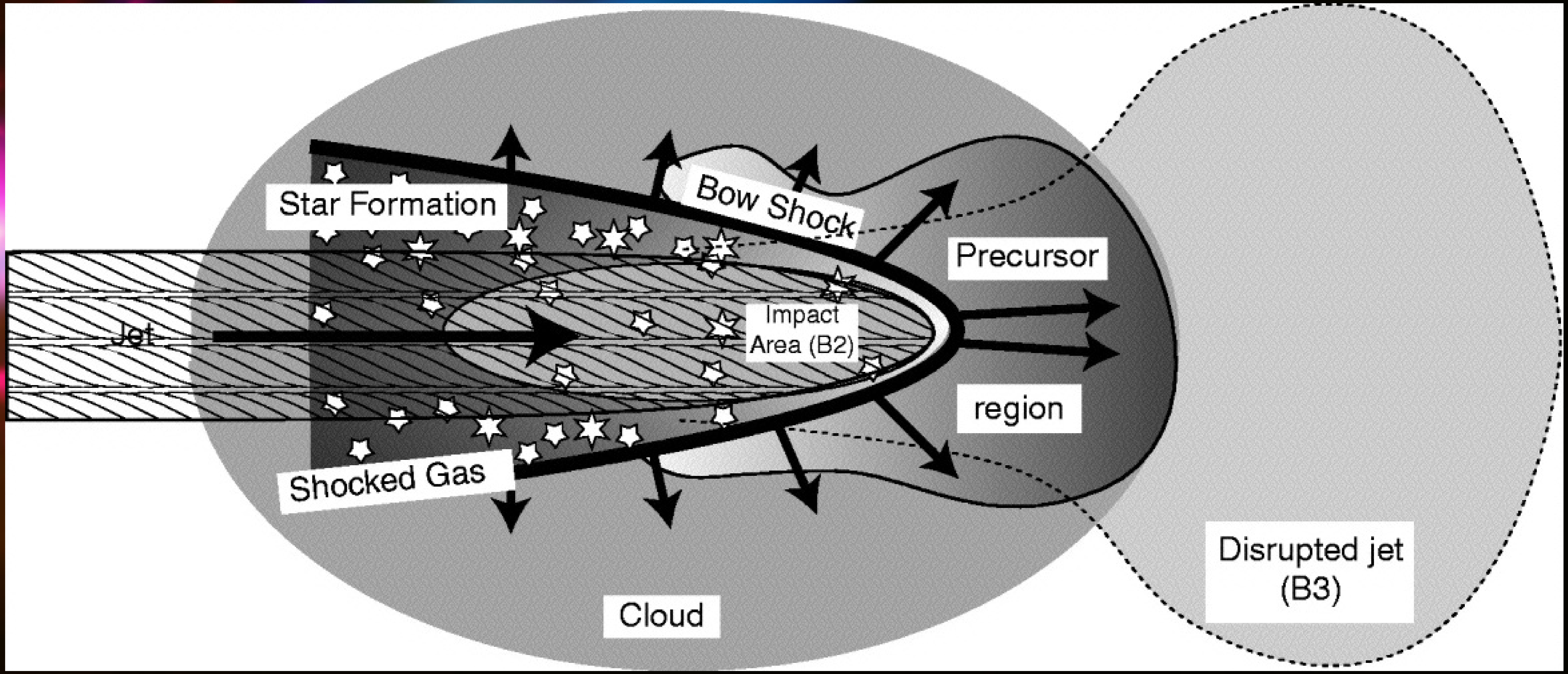
AGN *"mechanical"* feedback is modelled by the interaction of relativistic jets with ISM cold clouds.

$p_{j,kin} \approx \rho_j c^2 \beta_j^2 \sim n_c k_B T_c$

Jet ram pressure comparable to ISM cold clouds internal energy →

The thermodynamics of jet-ISM interaction is as relevant as the purely mechanical feedback.



Relativistic Thermodynamics (RT) is not based on firm grounds.

How does *Temperature* transforms between relatively moving reference frames?

- $T' = \gamma^{-1} T_0$ (Einstein 1907, Planck 1908)? $T' = \gamma T_0$ (Einstein, 1952; Ott, 1963)? $T' = T_0$ (Landsberg et al., 2004)

Consider a jet's fluid parcel, speed β_j. Its *hydrostatic pressure* $p_j = n_j k_B T_j$ is **Lorentz invariant** (Pathria, 1965), and: $n_j = \gamma n_{j0} \rightarrow \boldsymbol{T_j = \gamma^{-1} T_{j\,0}}$ (i.e. Einstein-Planck).

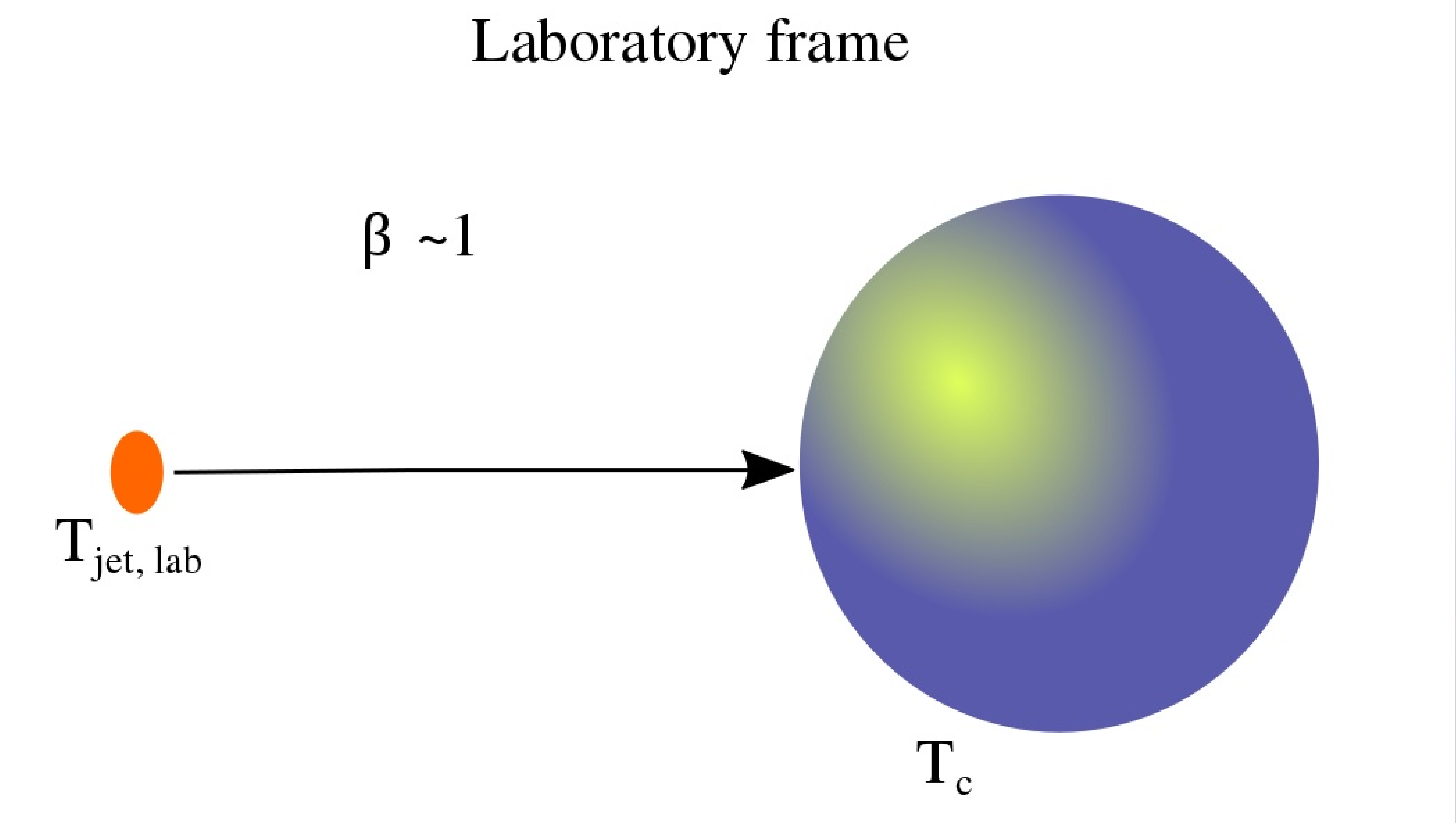
<u>However</u>, the *internal energy* of the parcel is: $U_j = (3/2) n_m R T_j$, n_m = # of moles (Lorentz **invariant**), and $U_j = \gamma U_{j0} \rightarrow \boldsymbol{T_j = \gamma T_{j\,0}}$.

BOTH choices are physically consistent: which one should we adopt in numerical experiments?

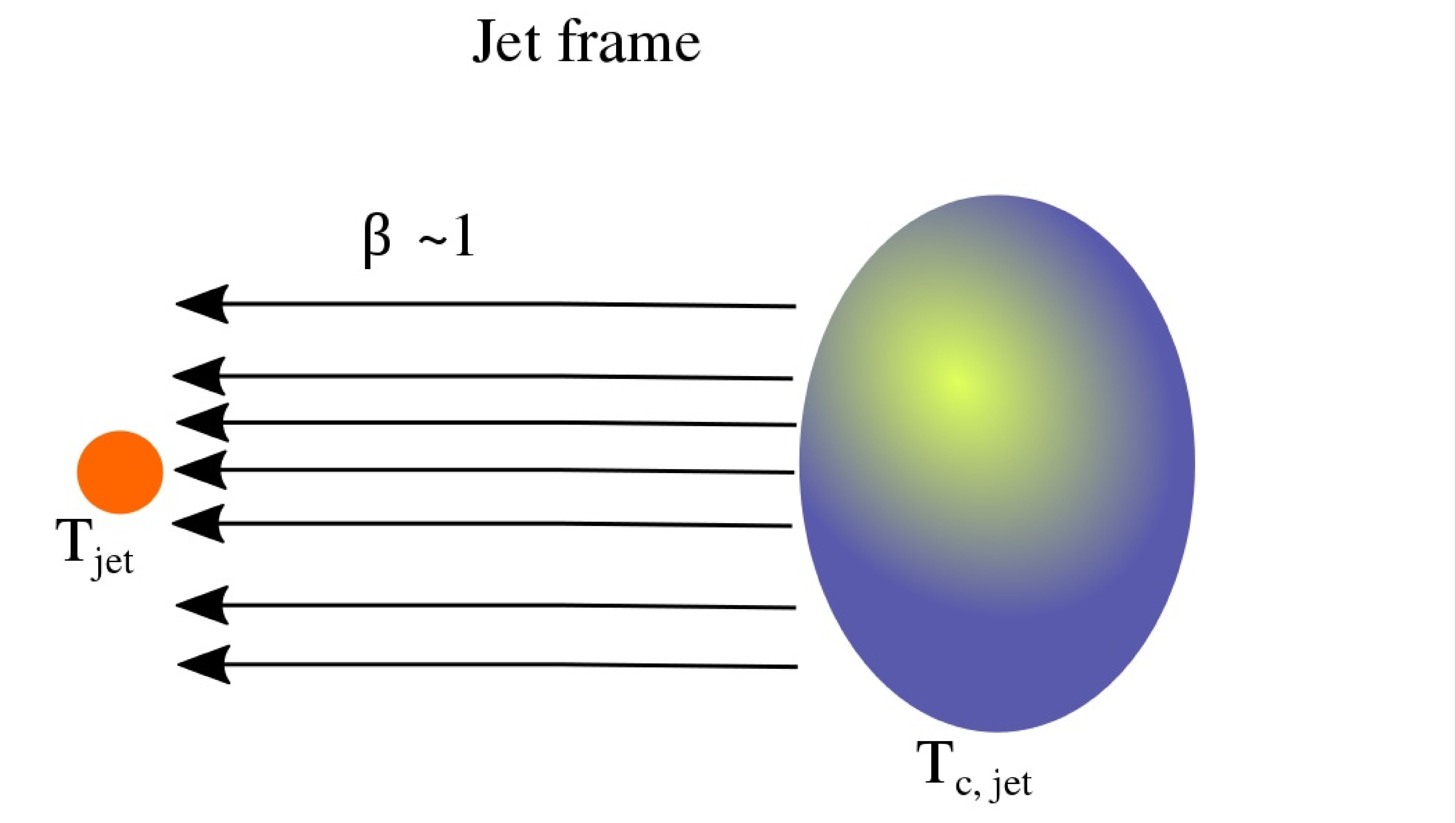
Classical Thermodynamics only holds for Galileian transformations (Landsberg, 2003).

RT is relevant to AGNs' feedback

When a jet fluid parcel hits a cloud t exchanges *internal energy* even within an *ideal Relativistic Hydrodynamic* context.



Laboratory frame: $T_{jet,lab} = f(\gamma) T_{jet}$



Jet frame: $T_{c,jet} = f(\gamma) T_c$

Iff $f(\gamma)=1$ (Landsberg) one can apply standard thermal conduction theory.

Actual value of T_c determines the *excitation temperature* of observed fluorescence lines.

Embedding RT in AMR codes: Module RTHD in Flash 4.7

Main target: Allow different *f(γ)* and predict continuum emission (*agnpy*) and line shapes.

In *ideal RHD* temperature is derived from pressure, assuming $p = \Gamma n k_B T$.

Current module RH solves the conserved equations:

$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ m \\ E \end{pmatrix} + \nabla \cdot \begin{pmatrix} Dv \\ mv + pI \\ m \end{pmatrix} = 0$$

Problem: Derive *primitive* variables from conserved ones:

$$\rho = \frac{D}{\gamma}, \quad v = \frac{m}{E+p}, \quad p = Dh\gamma - E\,.$$

Combining these one obtains:

$$p = Dh\big(p, \tau(p)\big)\gamma(p) - E\,.$$

whwre the relativistic enthalpy is:

$$h = 1 + \frac{\Gamma}{\Gamma - 1}\frac{p}{\rho}$$

Temperature in the lab. frame is obtained by combining with the model for *f(γ)*.