Hydrodynamics of internal shocks - a comprehensive study

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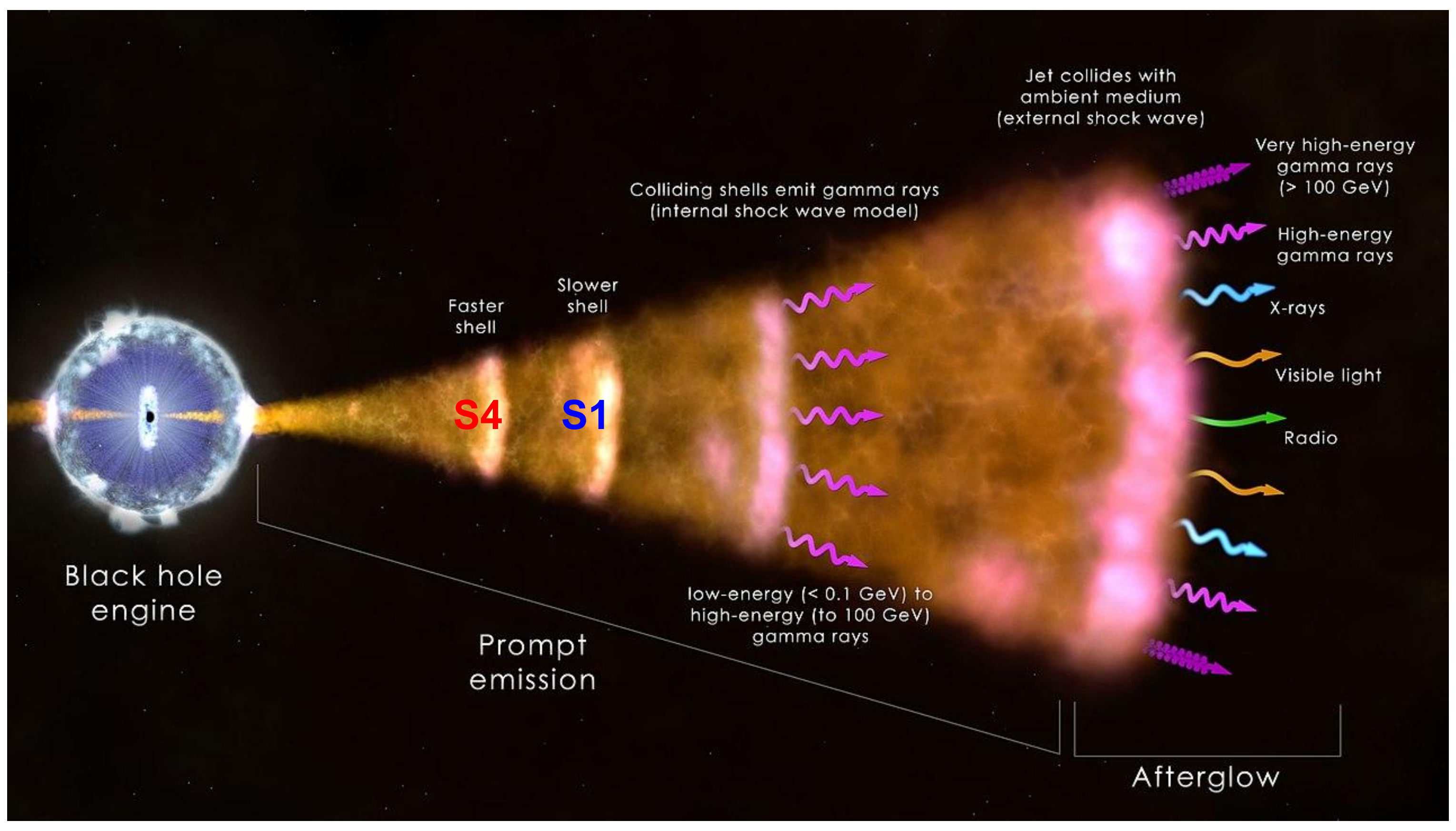

Fig 1: An illustration of the internal shocks model (Image credit: *NASA/Goddard Space Flight Center/ICRAR*). In the internal shocks model the central (black hole) engine ejects a slower shell S1 (in red) followed by a faster shell S4 (in blue) that catches up and collides with it, leading to energy dissipation that gives rise to gamma-ray emission.

1) Abstract:

Black holes are leading candidates for the central engines that power gamma-ray bursts (GRBs) and are known to power also blazars. Internal shocks are one of the prominent dissipation mechanisms for GRB prompt gamma-ray emission. As a useful approximation, we consider a toy model where the central engine ejects two cold shells that collide and produce a pair of shock fronts - a forward shock front (FS) and a reverse shock front (RS). The two shocked regions of the shells are separated by a contact discontinuity (CD). We aim to track the energy dissipation in both shocks and the physical conditions behind them.

2) Description of the shells before collision:

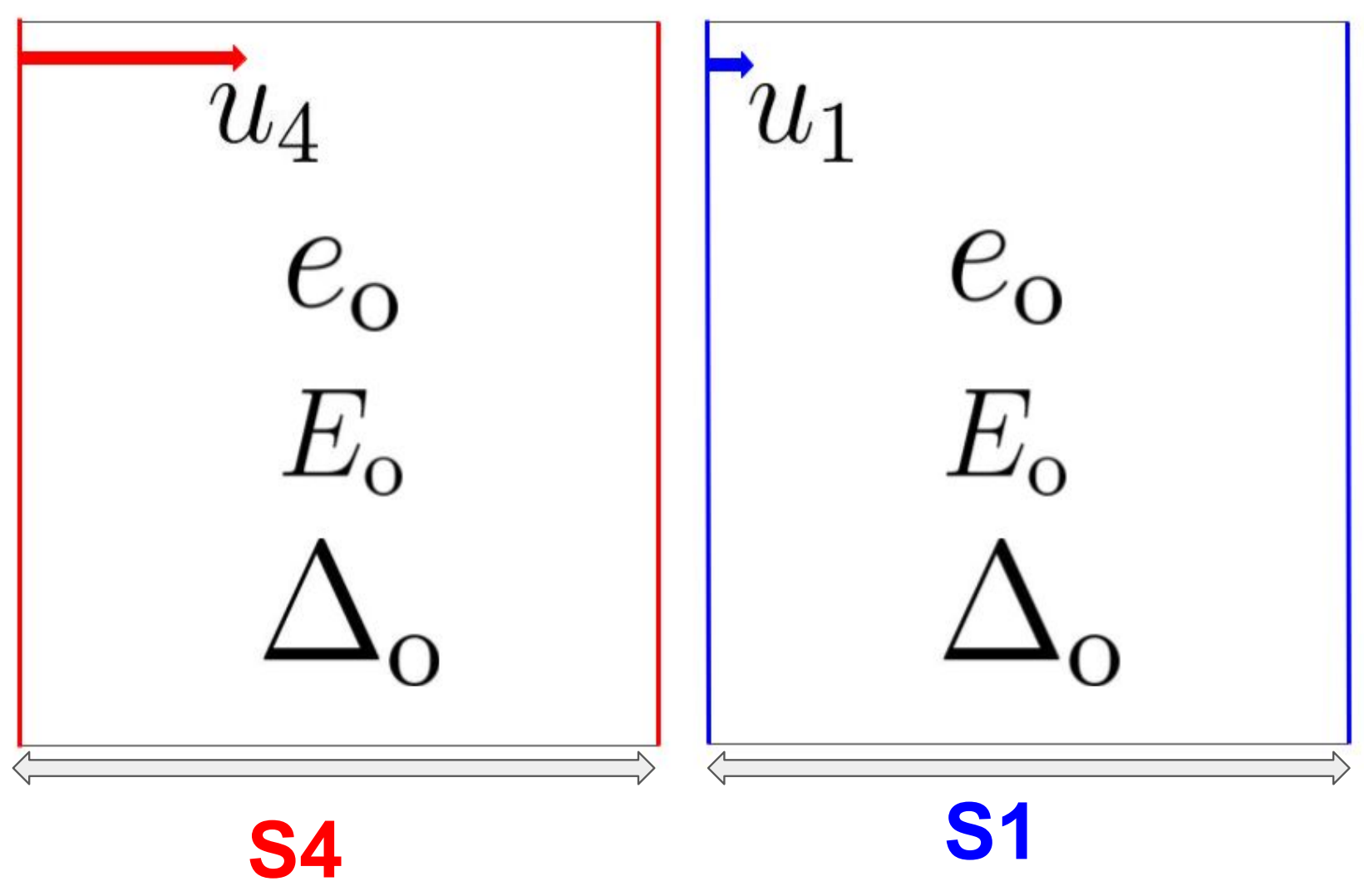

Fig 2: As a specific example we consider a central engine which ejects two successive cold shells (S1, S4) of equal energy density e_o , kinetic energy E_0 and radial width Δ_o. The illustrations assume a planar geometry and a proper velocity u = $\Gamma\beta$ of $u_1 = 100$, $u_4 = 500$. The initial internal energy of the shells before the collision is zero, and therefore their initial pressure is also zero. The shells collide at time t_o.

3) Description of the shells after collision:

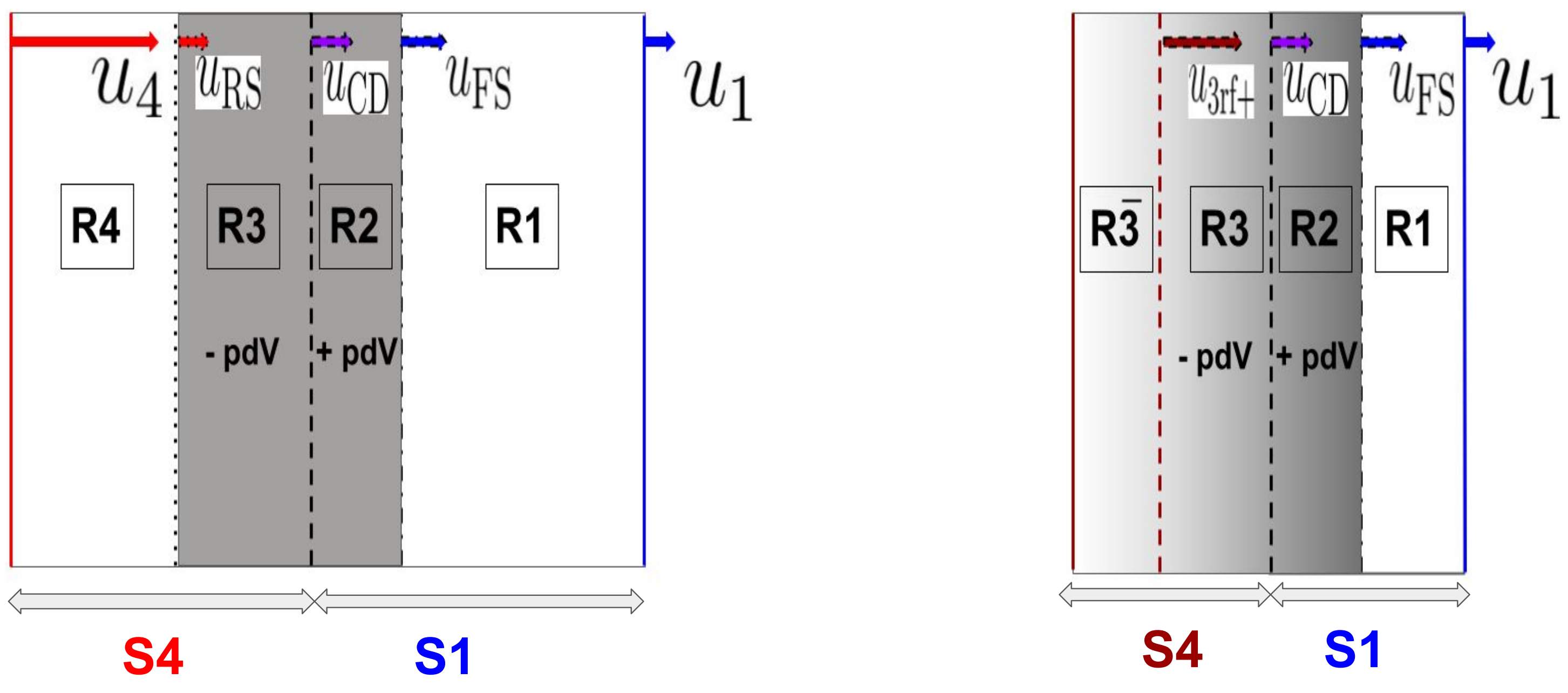

Fig 3:(***Left panel**:*) Post collision (at $t>t_o$), two new regions develop. Shell S1 contains regions (R1,R2) and shell S4 contains regions (R3,R4). Regions (R1,R4) represent unshocked portions of shells (S1,S4) while regions (R2,R3) (shown in shaded grey) are shocked by the (FS,RS) respectively. The arrows represent (in scale) the proper speeds of R4, RS, CD, FS and R1. The shock passage also leads to the reduction in the radial width (see also Fig. 4).
(***Right panel**:*) After the reverse shock finishes crossing region R4 (at $t>t_o+t_{RS}$), a rarefaction (rf) wave starts propagating towards the CD and a new region $R\bar{3}$ forms behind the rf wave. The drop in pressure in the region behind rf wave is shown by a gradient in grey.

__Applying the shock jump conditions:__
Post collision (for $t > t_o$), we employ the Blandford & McKee[1] (1976) solution for the shock jump conditions, assuming equal pressure and velocity across the CD. The shock fronts heat up the material in regions (R2,R3), where the increase in internal energy gives rise to pressure. As a result of the non-zero pressure, R3 can perform pdV work on R2 across the CD (see Fig. 5).
__Formation of a rarefaction wave:__
At $t = t_o + t_{RS}$ the RS reaches the back edge of S4, while the FS reaches the front edge of S1 at $t = t_o + t_{FS}$. For equal initial radial width, we have $t_{FS}= 1.54\, t_{RS}$. As a result, the RS finishes crossing R4 before the FS finishes crossing R1. At this stage ($t = t_o + t_{RS}$) R4 vanishes completely and only R3 remains (not shown). After this a decompression or rarefaction wave forms and propagates into R3, reducing its width and energy, and forming a new region $R\bar{3}$ in S4.

5) Breakdown of energy density & radial width at a given instant

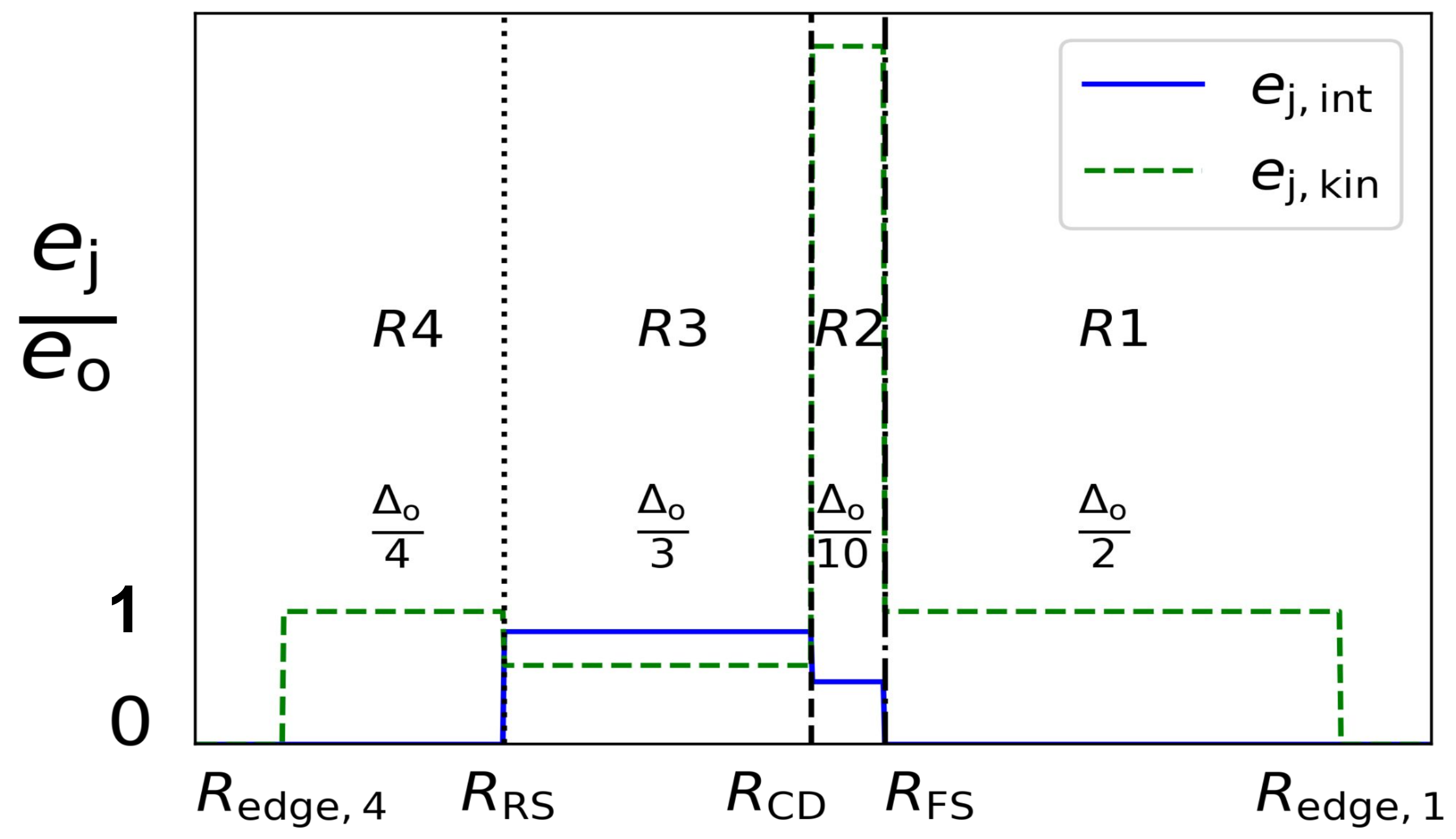

Fig 4: The energy density and radial width of regions (R1,R2,R3,R4) at $t = t_o + 0.75\, t_{RS}$. It can be seen that FS primarily increases the kinetic energy density of region R2 while the RS primarily increases the internal energy density of region R3. Note that the radial width of both shells decreases due to shock compression by both shocks, where the fractional change in width of each shell reflects its *lab frame* compression ratio.

6) The pdV transfer of energy from S4 to S1 for $t_o < t < t_0 + t_{FS}$

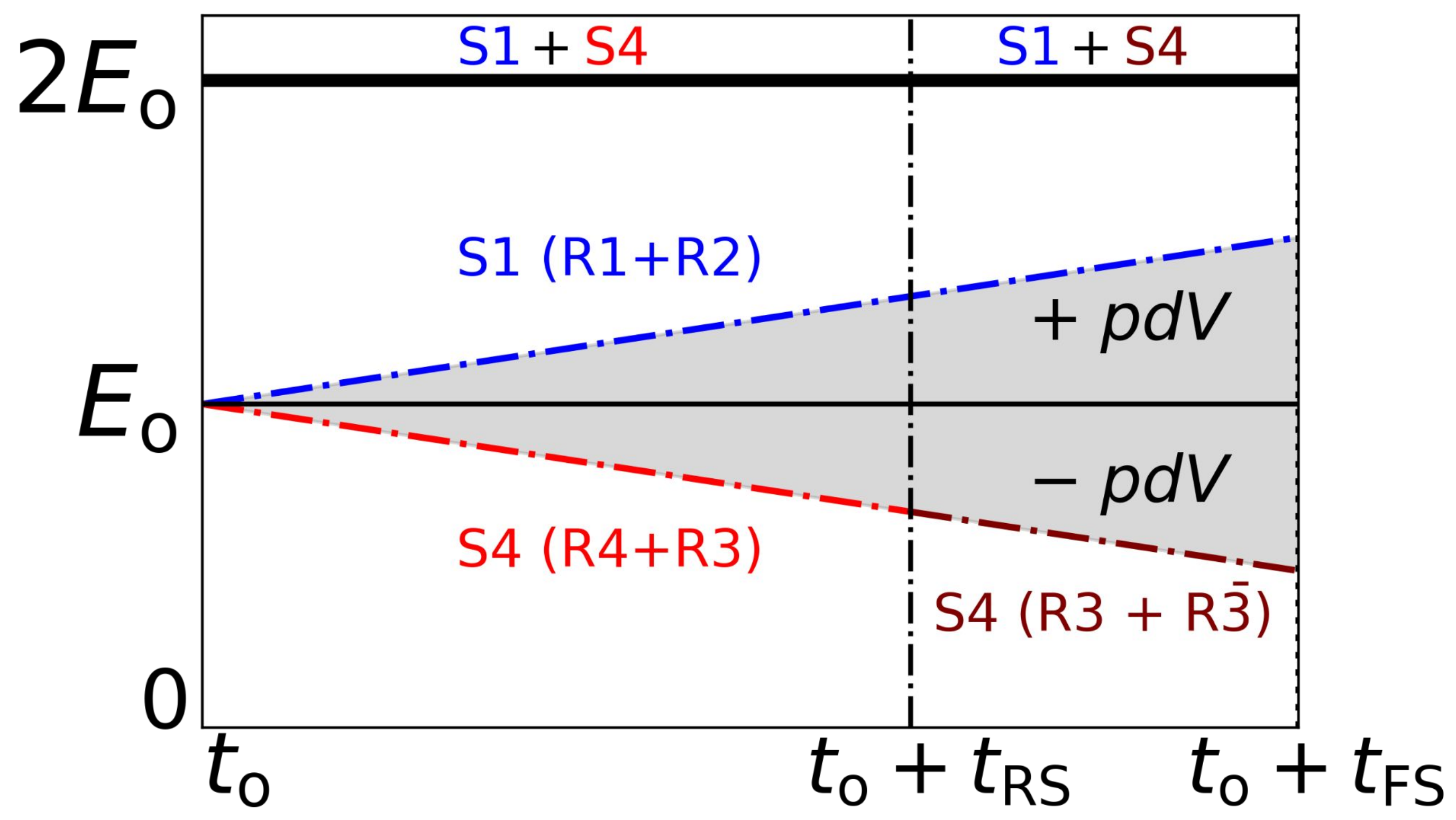

Fig 5: As alluded to in Fig. 3, region R2 performs negative pdV work on region R3, across the CD, while R3 performs an equal amount of positive pdV work on R2. As a result, the energy of S1 increases with time, while that of S4 decreases. However, the combined energy of both shells remains $2E_o$ at all times (assuming no radiative losses).

7) Breakdown of energy in all regions for $t_0 < t < t_0 + t_{FS}$

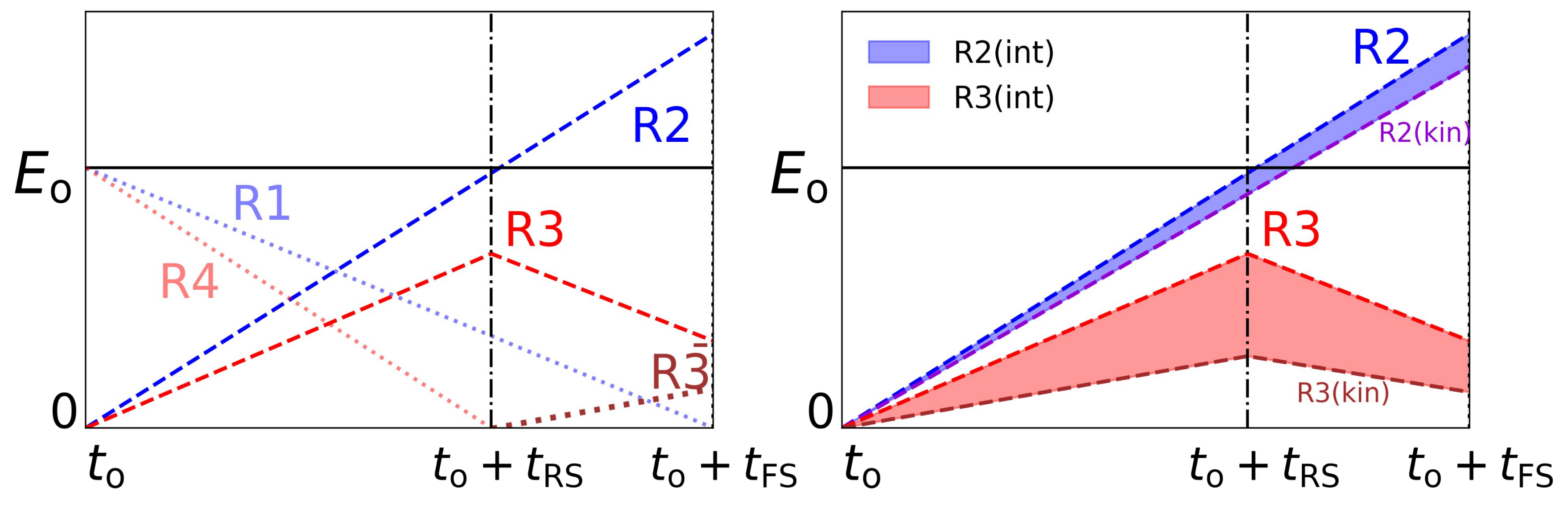

Fig 6: (***Left panel:***) the energy in region R2 increases steadily in time from t_o to $t_0 + t_{FS}$, while the energy in region R3 reaches maximum at t_o+t_{RS} and then starts decreasing due to the launch of a rf wave that forms a new region $R\bar{3}$ (see Fig 3). (***Right panel:***) It can be seen that in the time interval $t_0 < t < t_0 + t_{FS}$ the internal energy in R3 (shown in shaded red) remains larger than the internal energy in R2 (shown in shaded blue).

9) Conclusions:

Internal shocks models are prime candidates for the prompt GRB dissipation mechanism, and are also invoked in blazars, fast radio bursts and supernovae. The objective of this work is to explore the hydrodynamics of the collision between two cold shells. Upon adding an emission mechanism may help explain different electromagnetic features. We tracked the dissipative efficiency, and find that despite the transfer of energy from S4 to S1 by pdV work across the CD, the internal energy in the reverse shocked region R3 still remains higher than the forward shocked region R2. This is due to the reverse shock strength being higher than that of the forward shock strength. The FS primarily accelerates and increases the kinetic energy of S1. While we have presented the results for specific values of shell proper speeds ($u_1 = 100$, $u_4 = 500$) it is generally true that for a collision of two cold shells of equal kinetic energy and radial width:
i) The RS dissipates internal energy more efficiently than the FS,
ii) The RS finishes crossing S4 before FS finishes crossing S1,
Because of the different physical conditions in the forward and reverse shocked regions we expect different spatial and temporal emission signatures from these two regions. We propose the stronger and more relativistic reverse shock as a good candidate for the dominant prompt gamma-ray emission region. For more details please refer to our work[2].

References: [1]Blandford, R. D. & McKee, C.F. 1976, Physics of Fluids, 19, 1130.
[2] *"Characterizing internal shocks' hydrodynamics for two cold shell collision "*
Rahaman, Granot, Beniamini (in prep.)