相対論的輻射媒介衝撃波の第一原理計算

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Ref)
HI, Levinson, Stern, Nagataki, 2018 (*MNRAS, 474, 2828)*
HI, Levinson, Nagataki 2020 (*MNRAS, 492, 2902)*
HI, Levinson, Nakar 2020 (*MNRAS, 499, 469*)
HI, Levinson, Nakar *in prep*.

see also review by
Levinson & Nakar *2019 arXiv190910288L*

@高エネルギー宇宙物理学研究会2020 (Online)　*2020/12/17*

Plan of this talk

- Introduction
  - Brief overview of Radiation Mediated Shocks (RMS)
  - Photon rich and Photon starved regime
  - Non-relativistic, Relativistic RMS (RRMS)
- First principle calculation
  - Calculation method
  - Steady state solution of RRMS in photon starved regime
  - Application and Implication to shock breakout phenomena
- Summary

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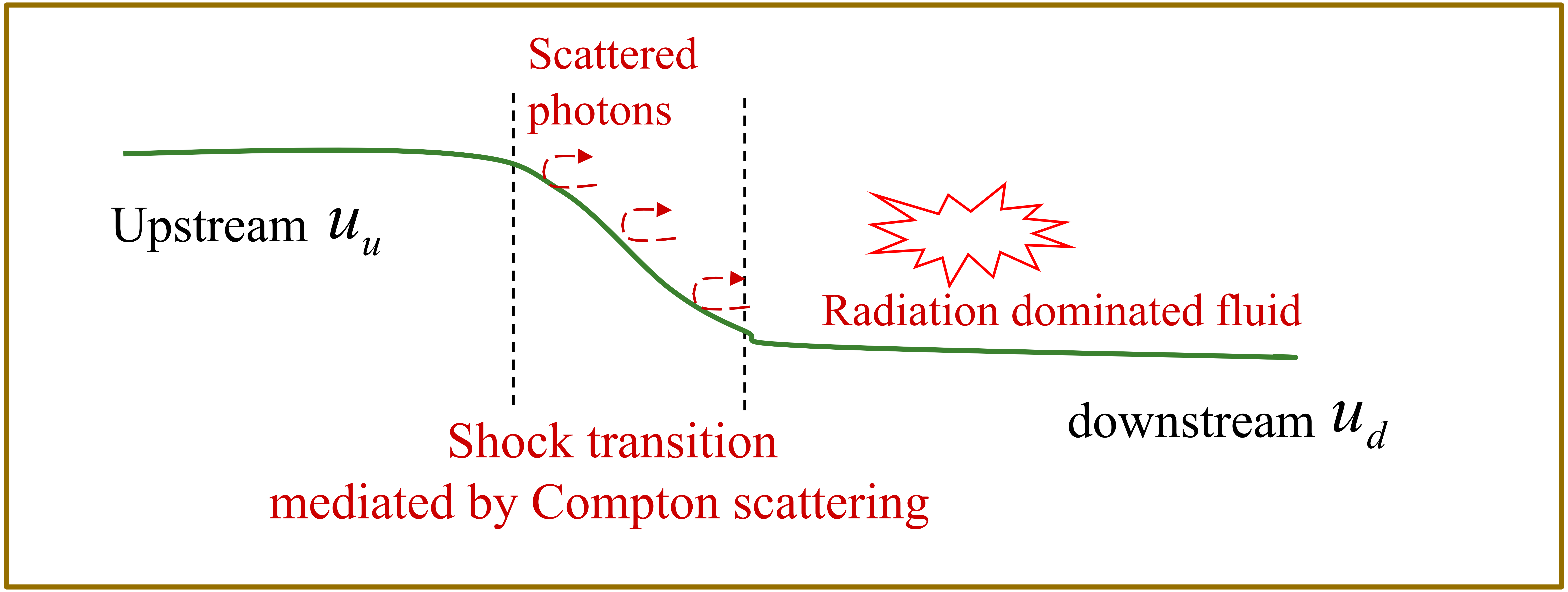
Radiation Mediated Shocks (RMS)



- downstream energy dominated by radiation
- upstream plasma approaching the shock is decelerated by scattering of counter streaming photons

Under which conditions a RMS forms ?

- Radiation dominance downstream: $aT_d^4 > n_d k T_d$
- Jump conditions: $n_u m_p c^2 \beta_u^2 \approx aT_d^4/3$

$$\Rightarrow \; \beta_u > 10^{-4}\left(\frac{n_u}{10^{15}\ \mathrm{cm}^{-3}}\right)^{1/6}$$

$$t_{diff} = \tau L/c$$

$$t_{cross} = L/v$$

But requires photon trapping:

$$t_{diff} > t_{cross} \Rightarrow \tau > 1/\beta_u$$

shock width: $\Delta\tau \sim 1/\beta_u$ (may altered by pair production and Klein-Nishina effect for relativistic shocks)

Why is it interesting ?

- The conditions required to form RMS are always satisfied below the photosphere of fast flows

Examples: shock breakout in SNe, LLGRB, etc
sub-photospheric shocks in GRBs
NS-NS mergers
accretion flows

Shock breakout

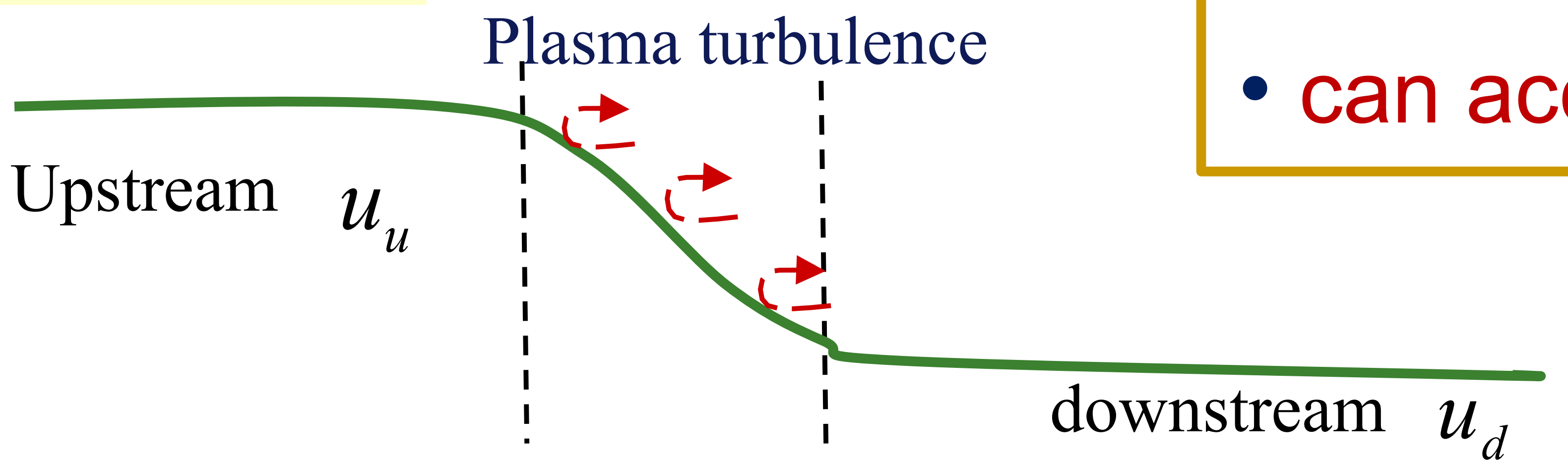
- Transition from RMS to collisionless shock
- Breakout signal depends on structure of RMS

Breakout when $\tau \sim 1/\beta_u$ (may altered by pair production and Klein-Nishina effect for relativistic shocks)

- From edge of stellar envelop (SNe)
- From a stellar wind (SNe, LLGRB)
- From a moving ejecta (NS mergers)
- From a jet (GRB)

Collisionless shocks .vs. RMS

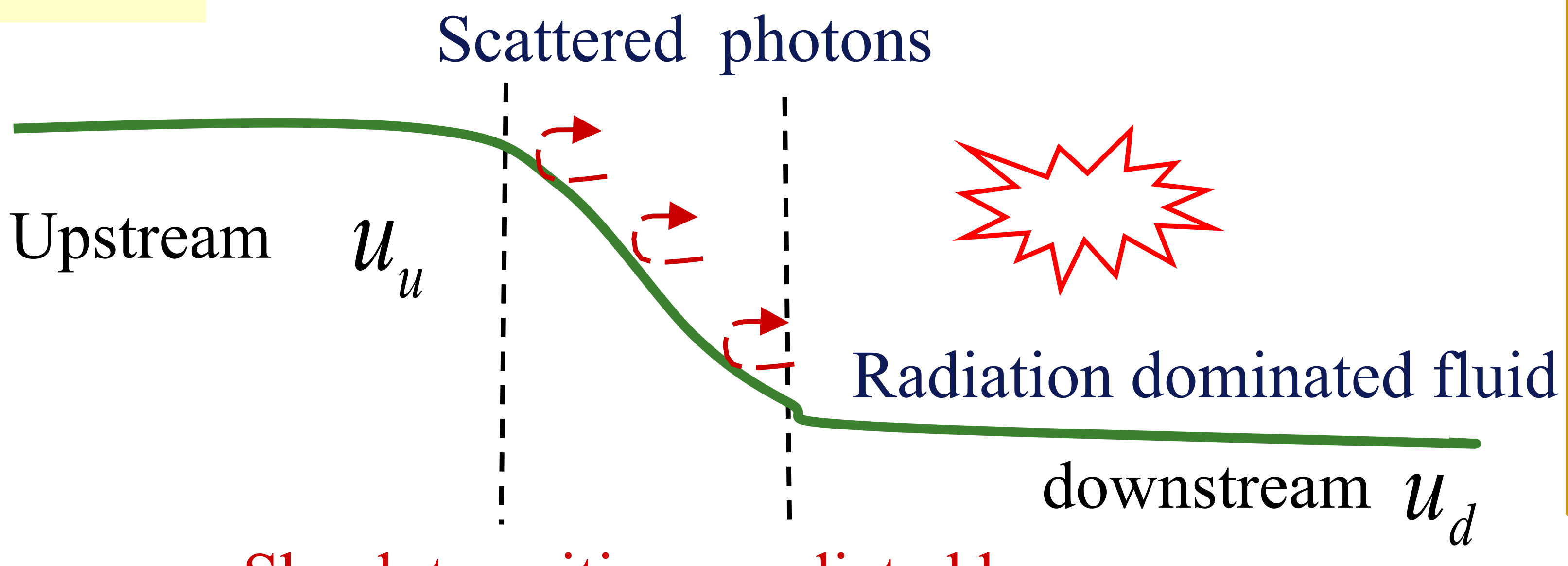
collisionless



Shock transition mediated by collective plasma processes

- Scale: $c/\omega_p \sim 1(n_{15})^{-1/2}$ cm , $c/\omega_B \sim 3\varepsilon(B_6)^{-1}$ cm
- can accelerate particles to non-thermal energies.

RMS



Shock transition mediated by Compton scattering

- scale: $(\sigma_T n \beta_s)^{-1} \sim 10^9 n_{15}^{-1}$ cm
- microphysics is fully understood
- cannot accelerate particles

(important implications for HE neutrino production)

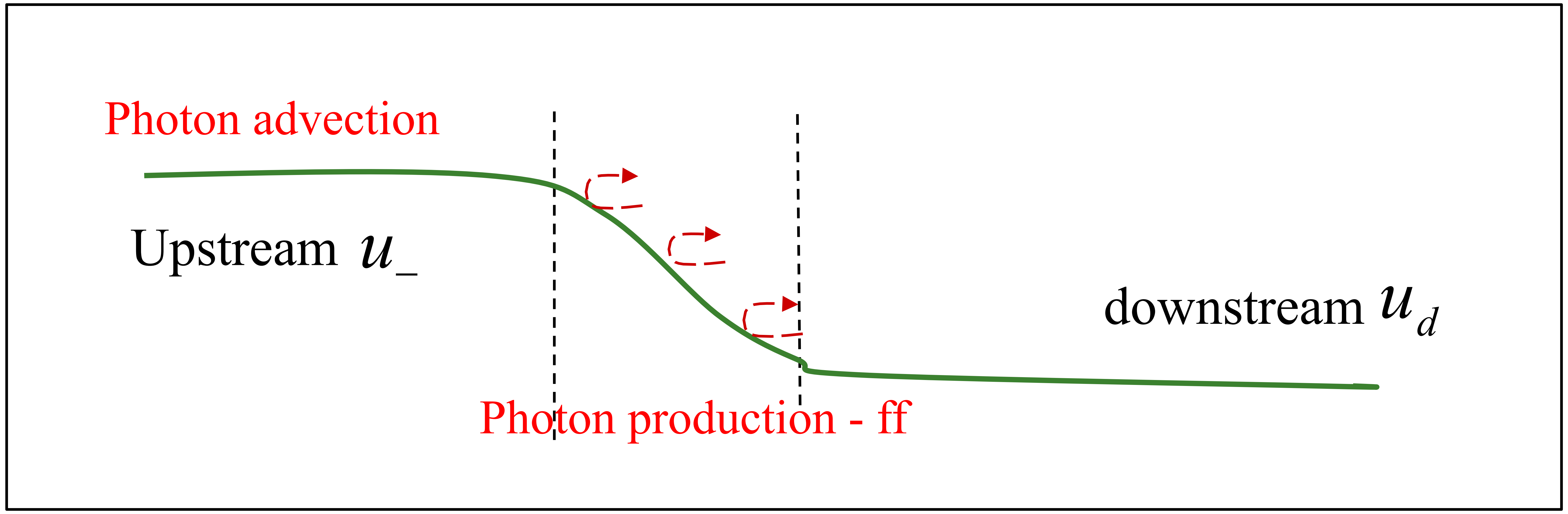
Photon source: two regimes

- **Photon starved shocks:**

  Photon production inside the shock (SNe, LLGRB, BNS merger)

- **Photon rich shocks:**

  Photon advection from upstream (sub-photospheric shock in GRB, BNS merger ?)



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Today's talk

- **Photon rich shocks:**
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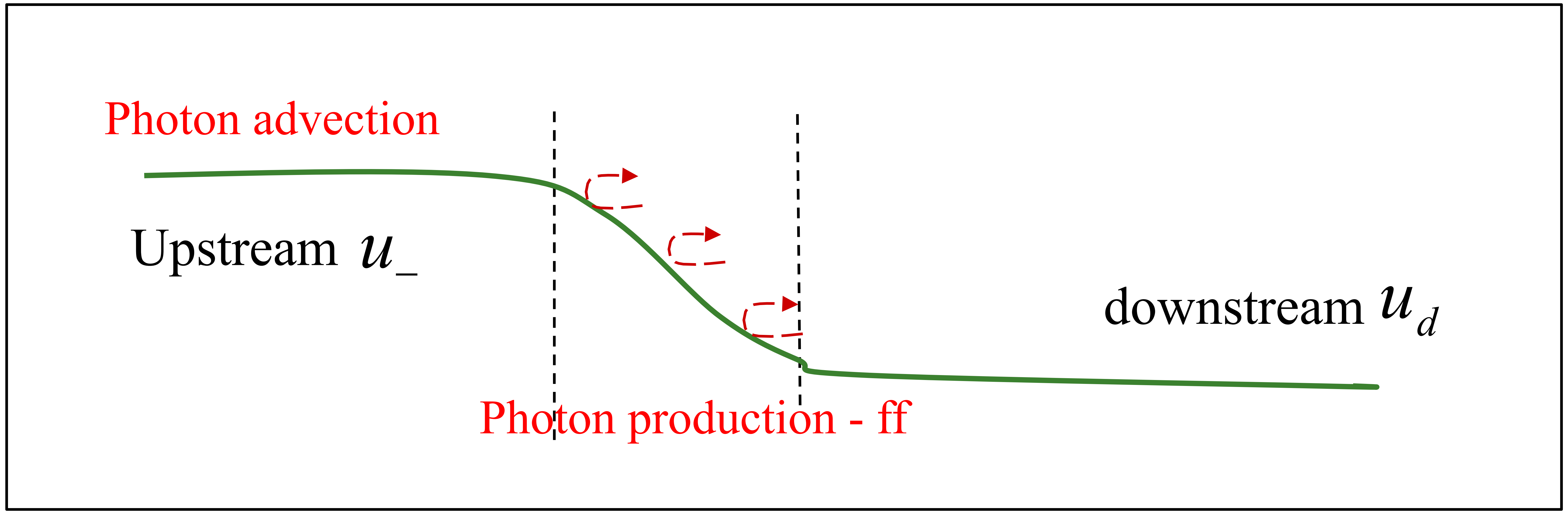
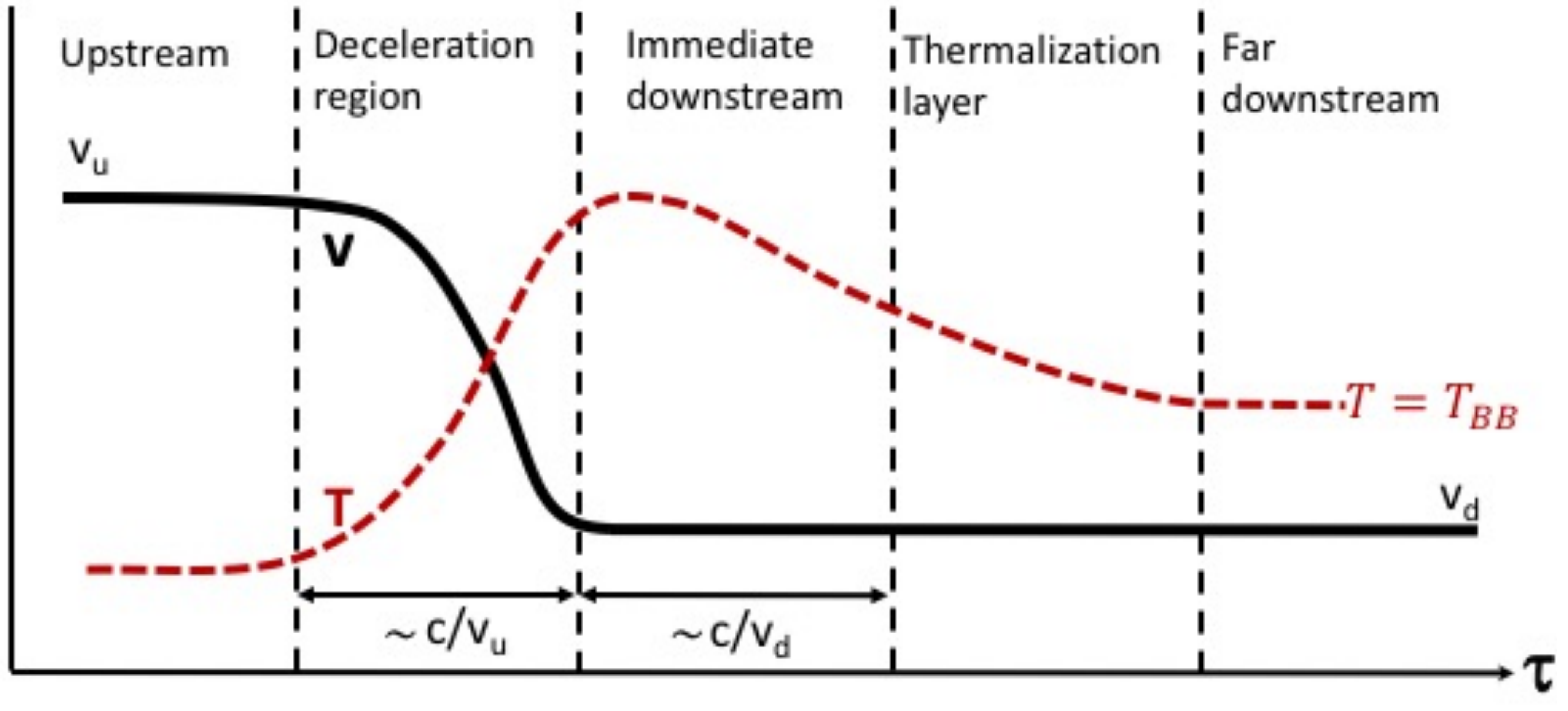


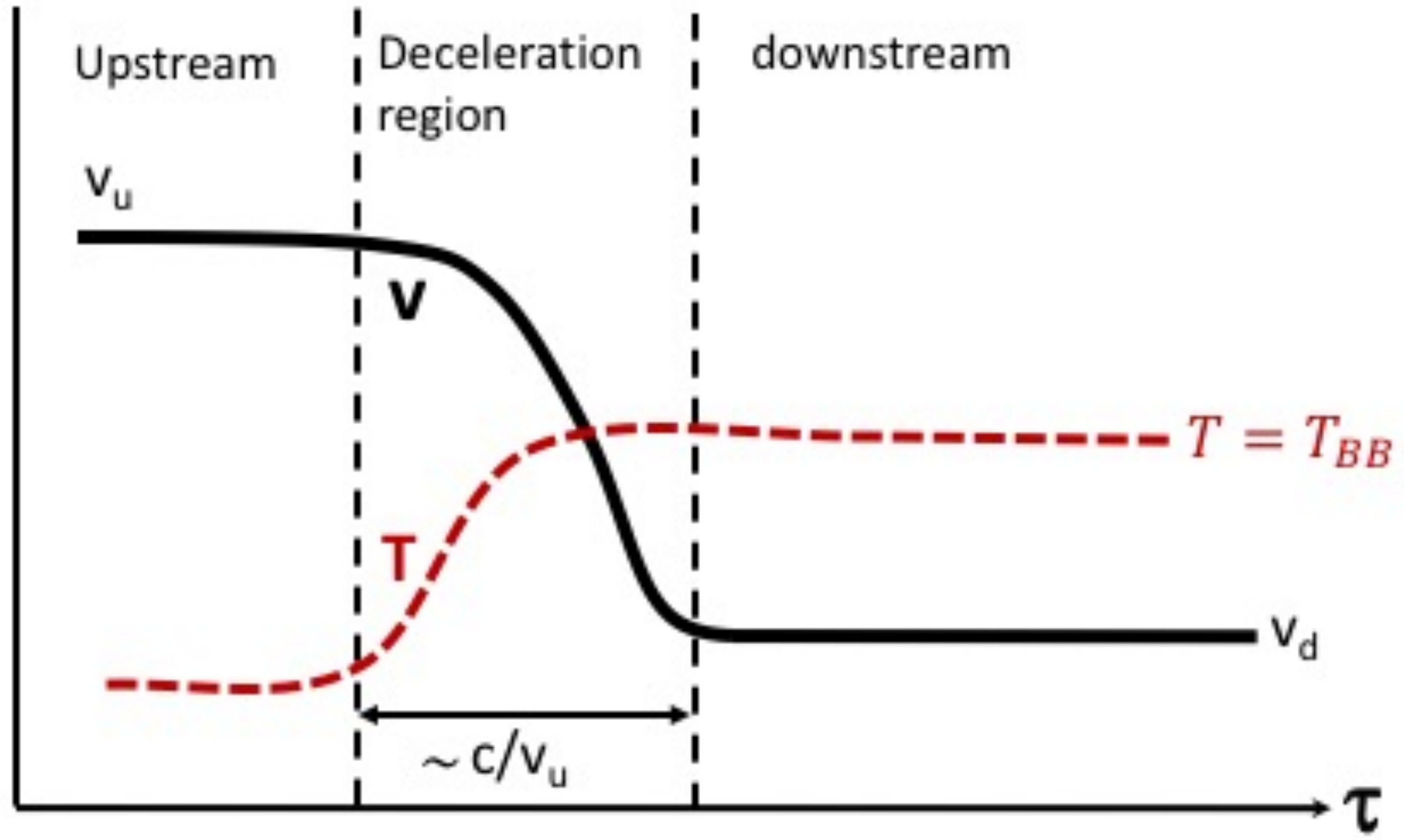
Shock velocity: three regimes

(2) **Fast Newtonian shocks** $0.5 > \beta_u >\sim 0.05$



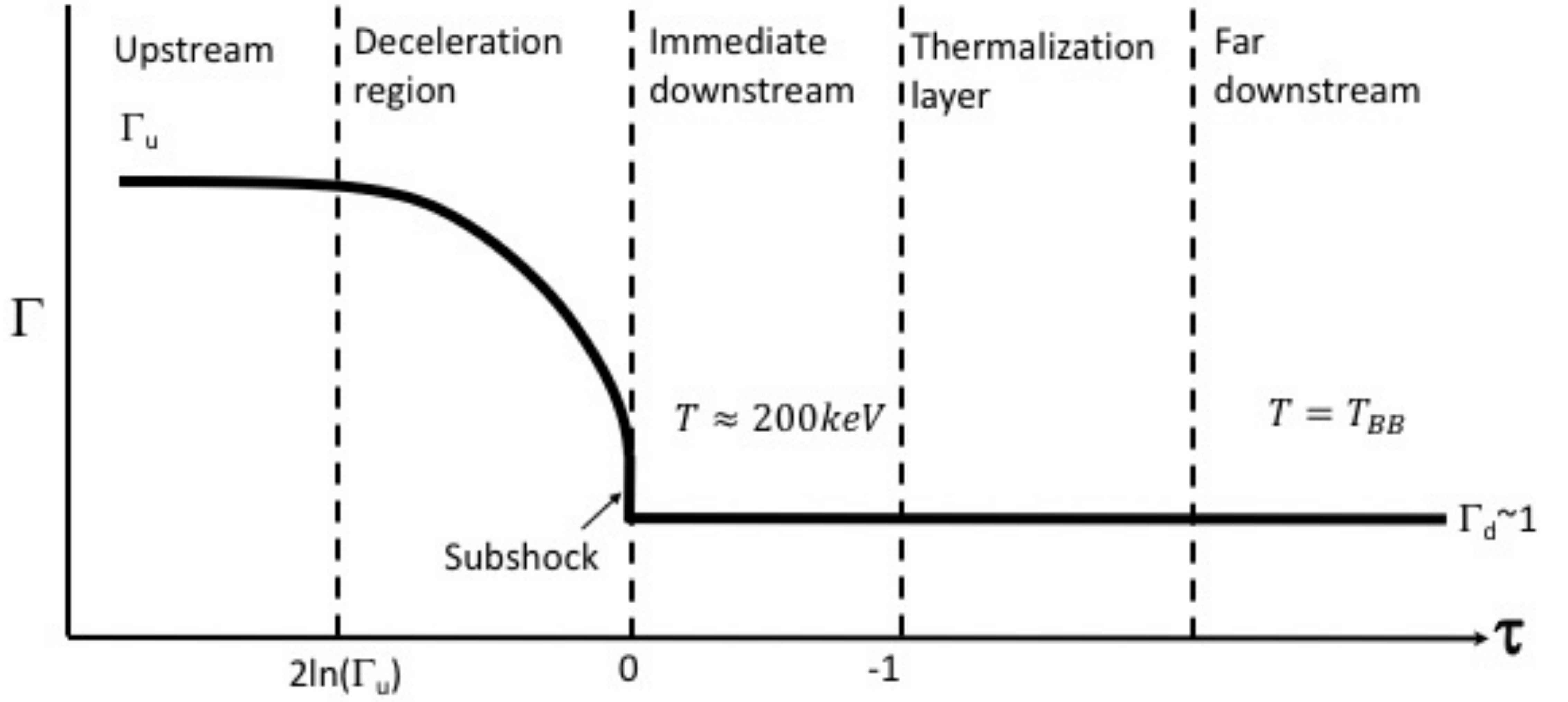
(1) **Slow shocks**

$\beta_u <\sim 0.05$ $t_{cr} > t_{th}$



$t_{cr} < t_{th}$

(3) **Relativistic shocks** $\beta_u > 0.5$



t_{cr} :shock crossing time

t_{th} :thermalization time

for review see
Levinson & Nakar *2019 arXiv190910288L*

Shock velocity: three regimes

Today's talk

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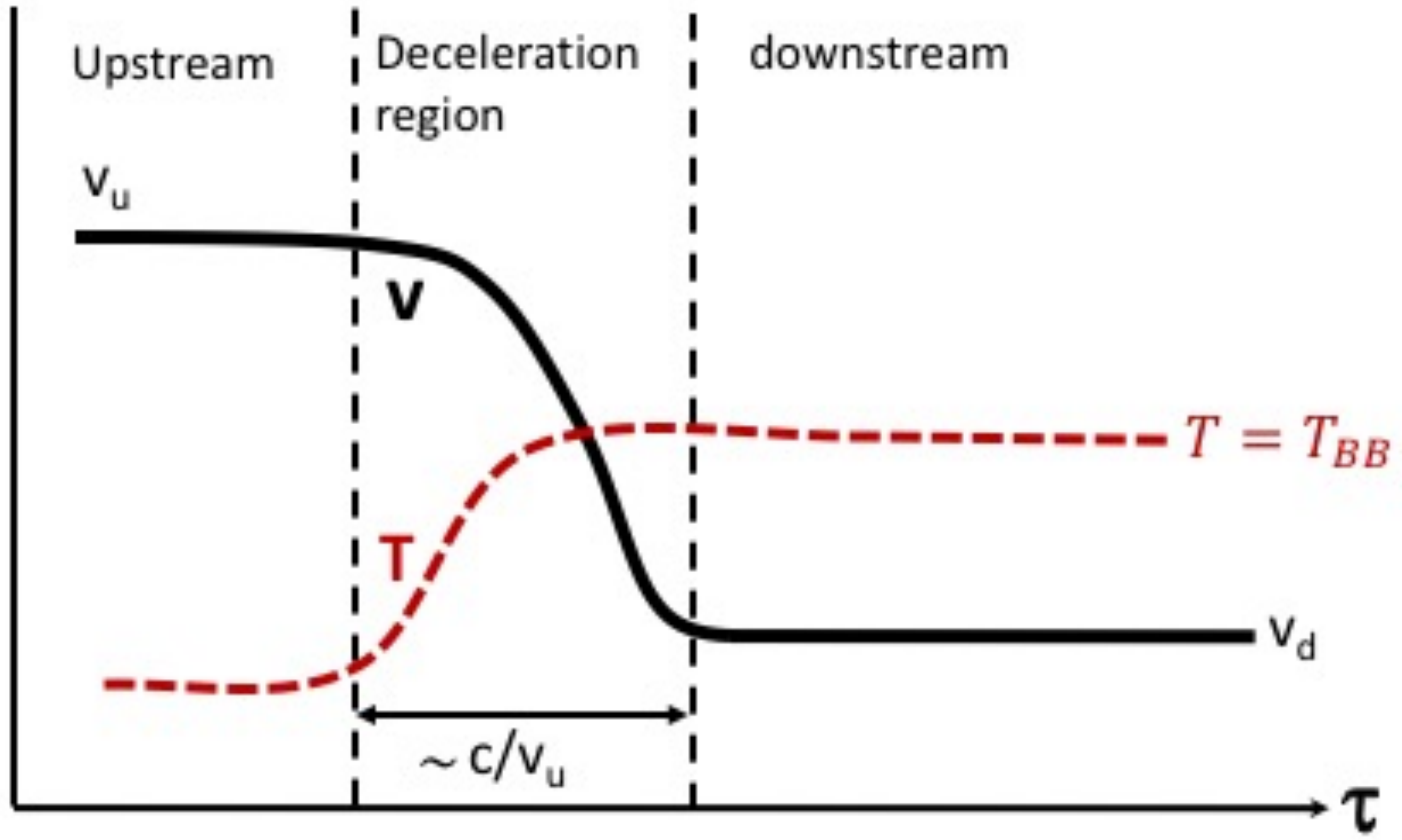
β_u <~0.05 $t_{cr} > t_{th}$



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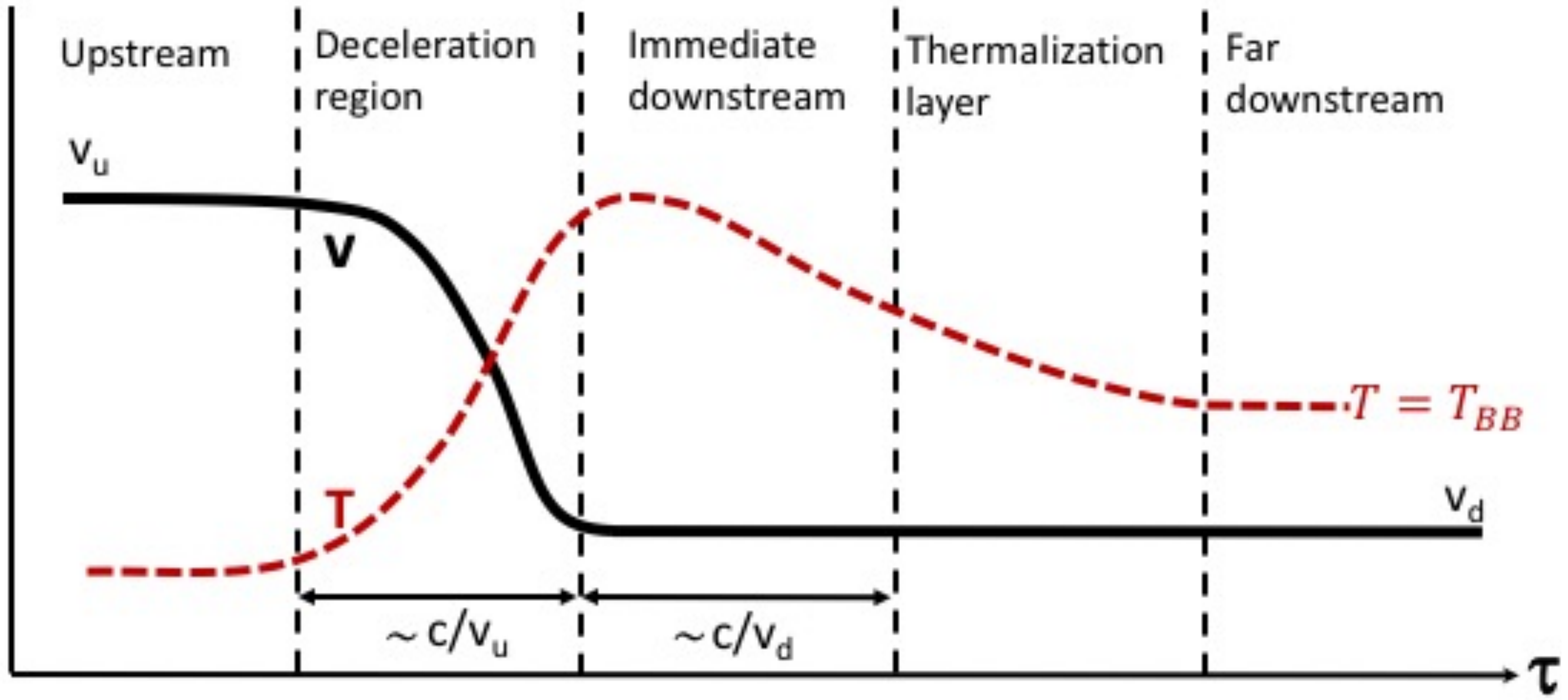

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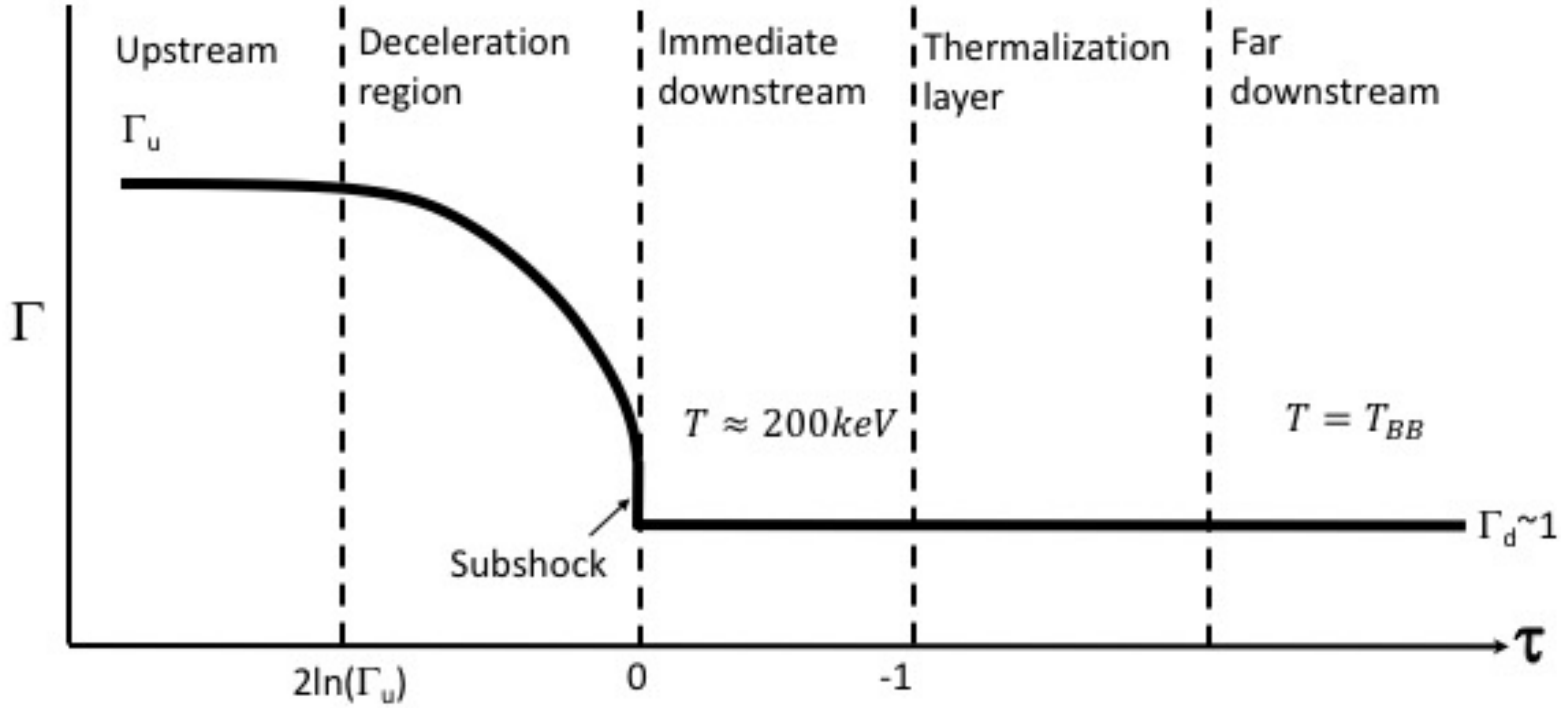

Non-relativistic .vs. Relativistic

Non-relativistic RMS

- small energy gain: $\Delta\varepsilon/\varepsilon \ll 1$
- **diffusion approximation holds**.

Zeldovich & Raiser 1967; Weaver 1976; Blandford & Payne 1981;

Relativistic RMS (RRMS)

- **photon distribution is anisotropic**
- energy gain large: $\Delta\varepsilon/\varepsilon > 1$

  optical depth depends on angle: $\tau \propto (1-\beta \cos\theta)$
- copious pair production

Levinson & Bromberg 08; Katz et al. 10; Budnik et al. 10; Beloborodov 2017

Self-consistent calculation which incorporates radiation transfer

Photon Rich regime

Levinson & Bromberg (2008)

Energy integrated intensity, Klein-Nishina effect, pair production neglected

Beloborodov (2017)

Full radiation transfer, effects of magnetic field, dynamical simulation   pair production neglected

Lundman, Beloborodov, & Vurm (2018)

Full radiation transfer, pair production effect, dynamical simulation   some approximation in temperature calculation ?

HI, Levinson, Stern & Nagataki (2018)

Full radiation transfer with pair production, no optimistic approximation   steady state

Lundman & Beloborodov (2020)

Dynamical simulation of shock breakout in photon rich merger ejecta   no pair production (found to be negligible)

Photon Starved regime

Budnik, Katz, Sagiv, & Waxman (2010)

Full radiation transfer with pair production and bremsstrahlung emission/absorption
steady state, some optimistic approximation on cross sections, limited to relativistic limit $6 < \Gamma < 30$

HI, Levinson & Nagataki (2020)

Full radiation transfer with pair production and bremsstrahlung emission/absorption, broad range in velocity **$0.1 < \Gamma\beta < 20$**
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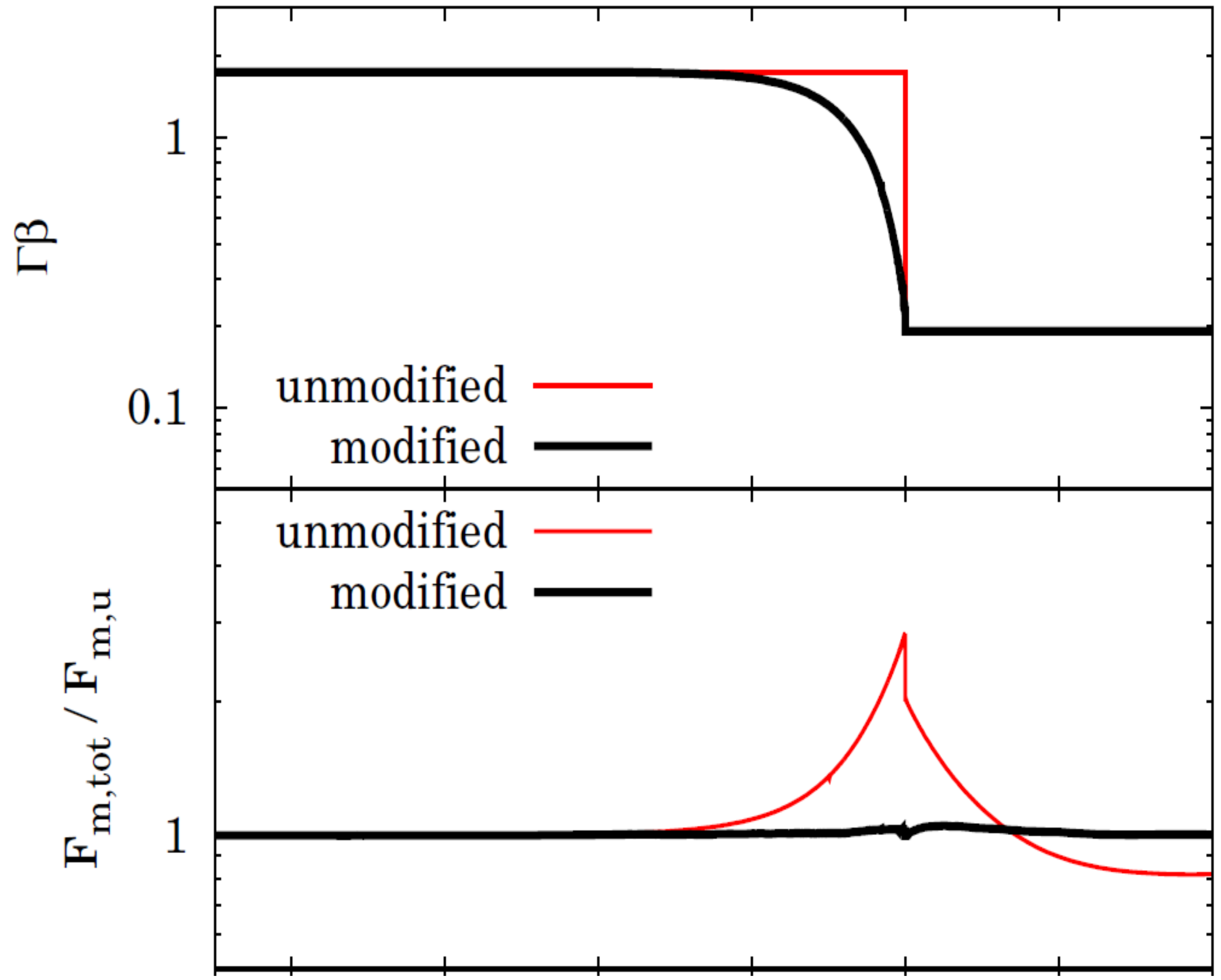
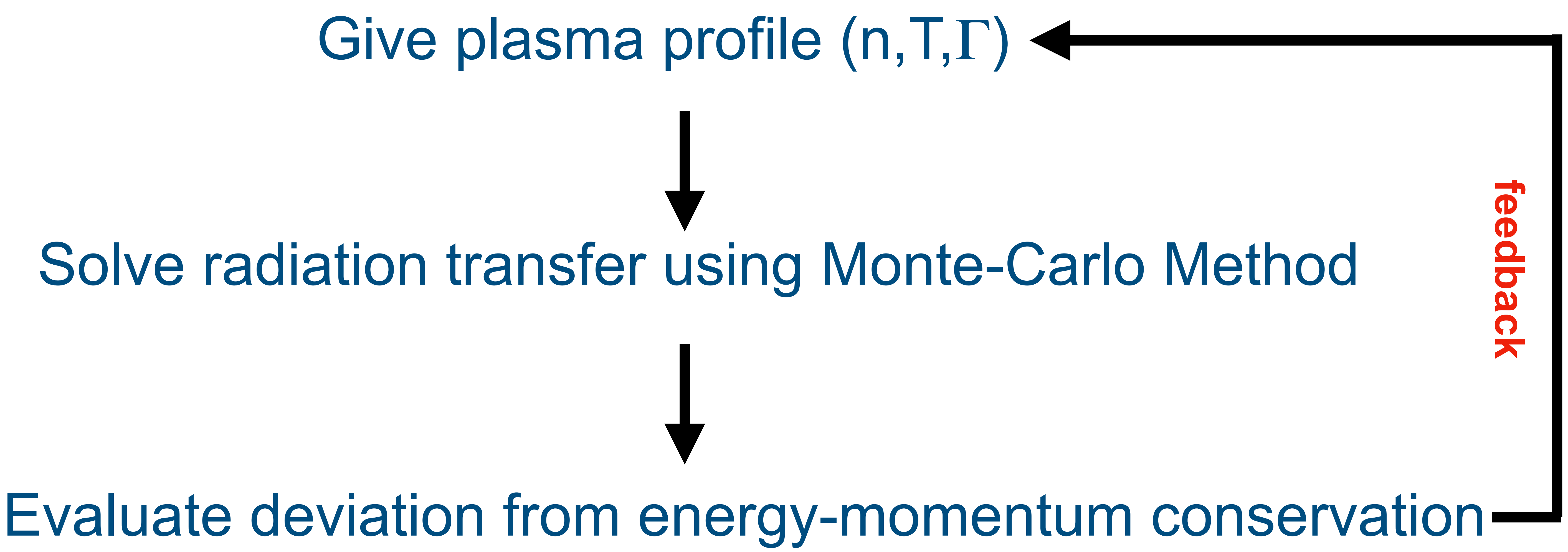
Numerical Method





Iterate until convergence is achieved

Microphysics

- Compton scattering with full Klein-Nishina cross section
- free-free emission & absorption
- pair production & absorption

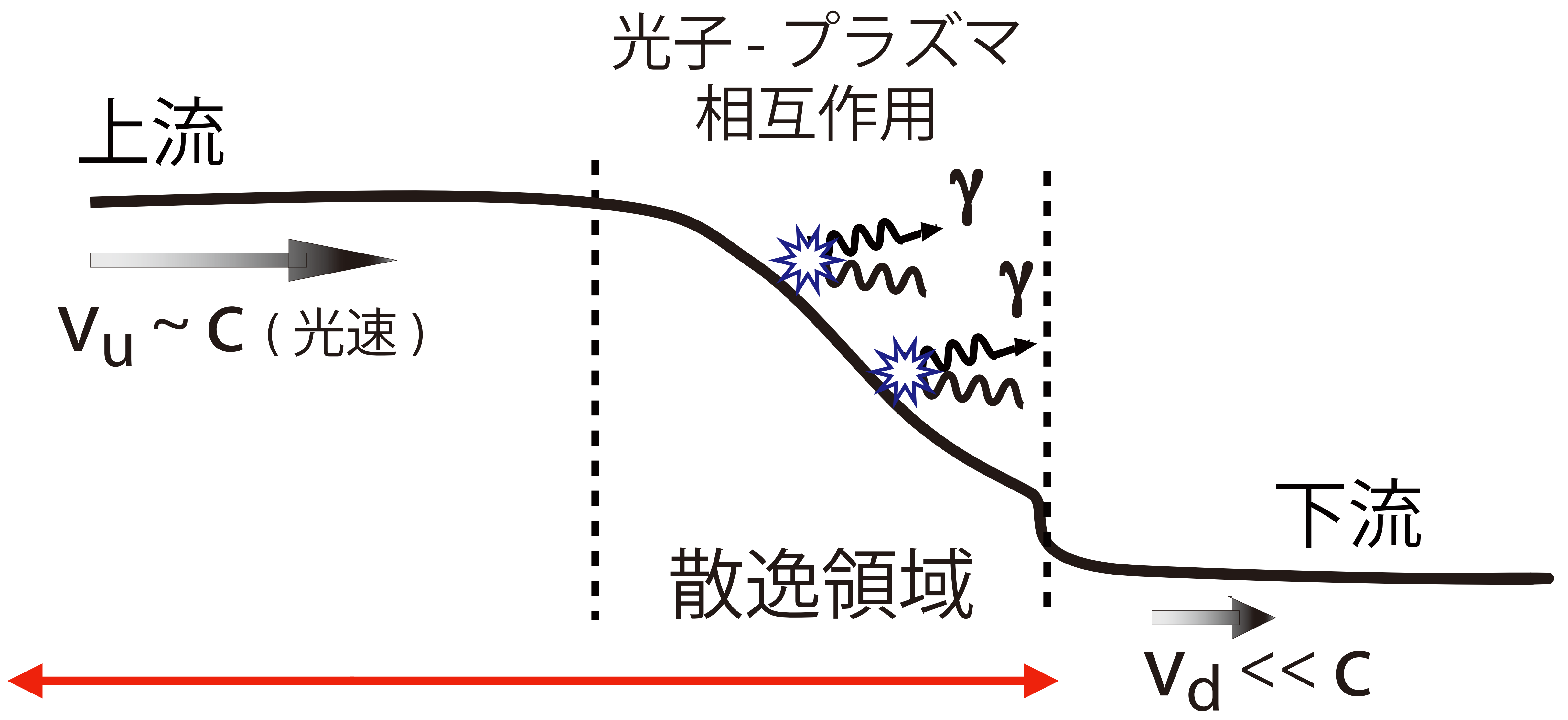
Assumptions

- electrons/positron and proton are single fluid with same temperature
- electron/positrons have Maxwell distribution

May breakdown near the subshock and when numerous pairs are present (Levinson 2020)

infinite RRMS

(photons are completely trapped)



$\tau_u >> 1$

(no photon escape from US boundary)

HI, Levinson, Nagataki 2020 (*MNRAS, 492, 2902)*

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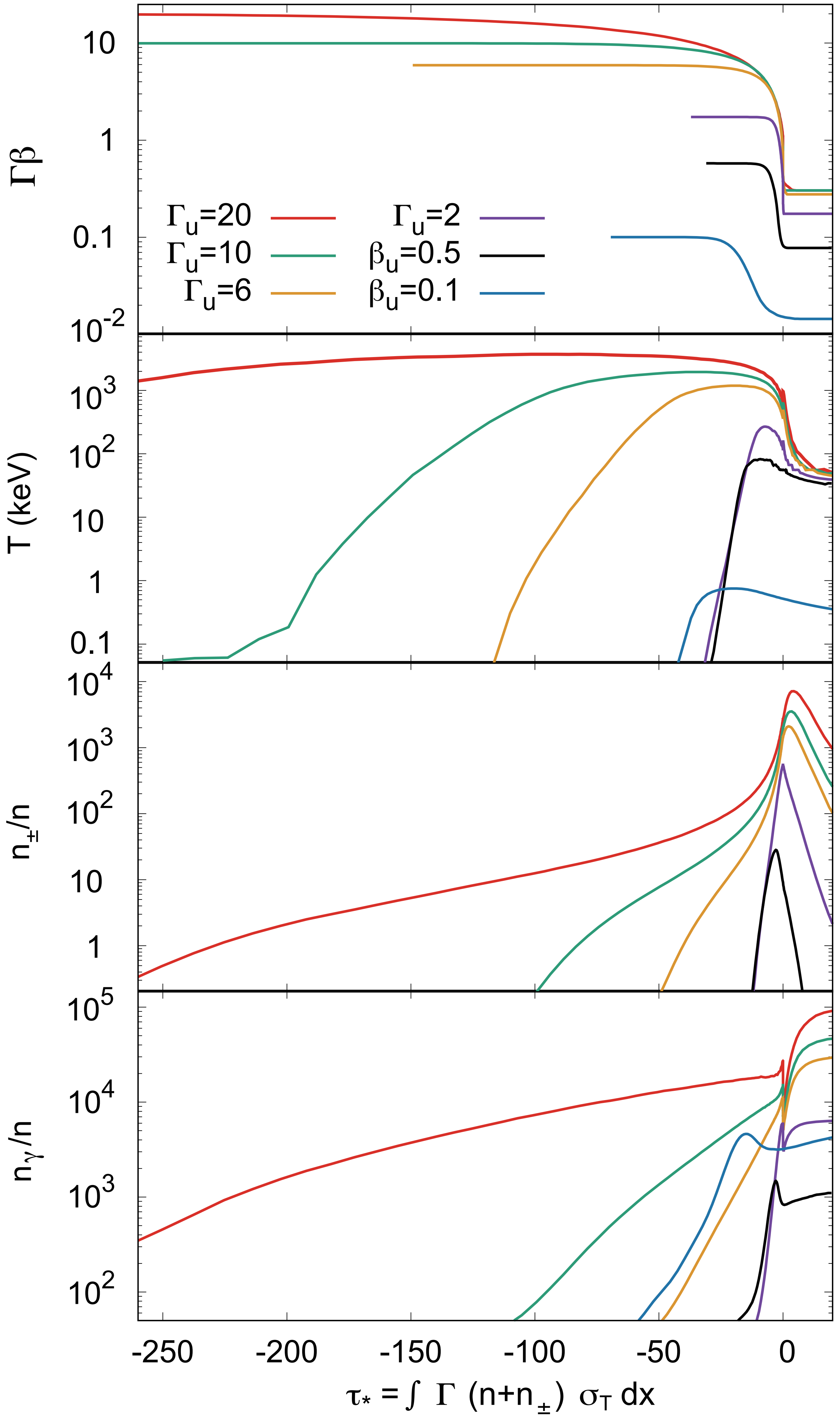
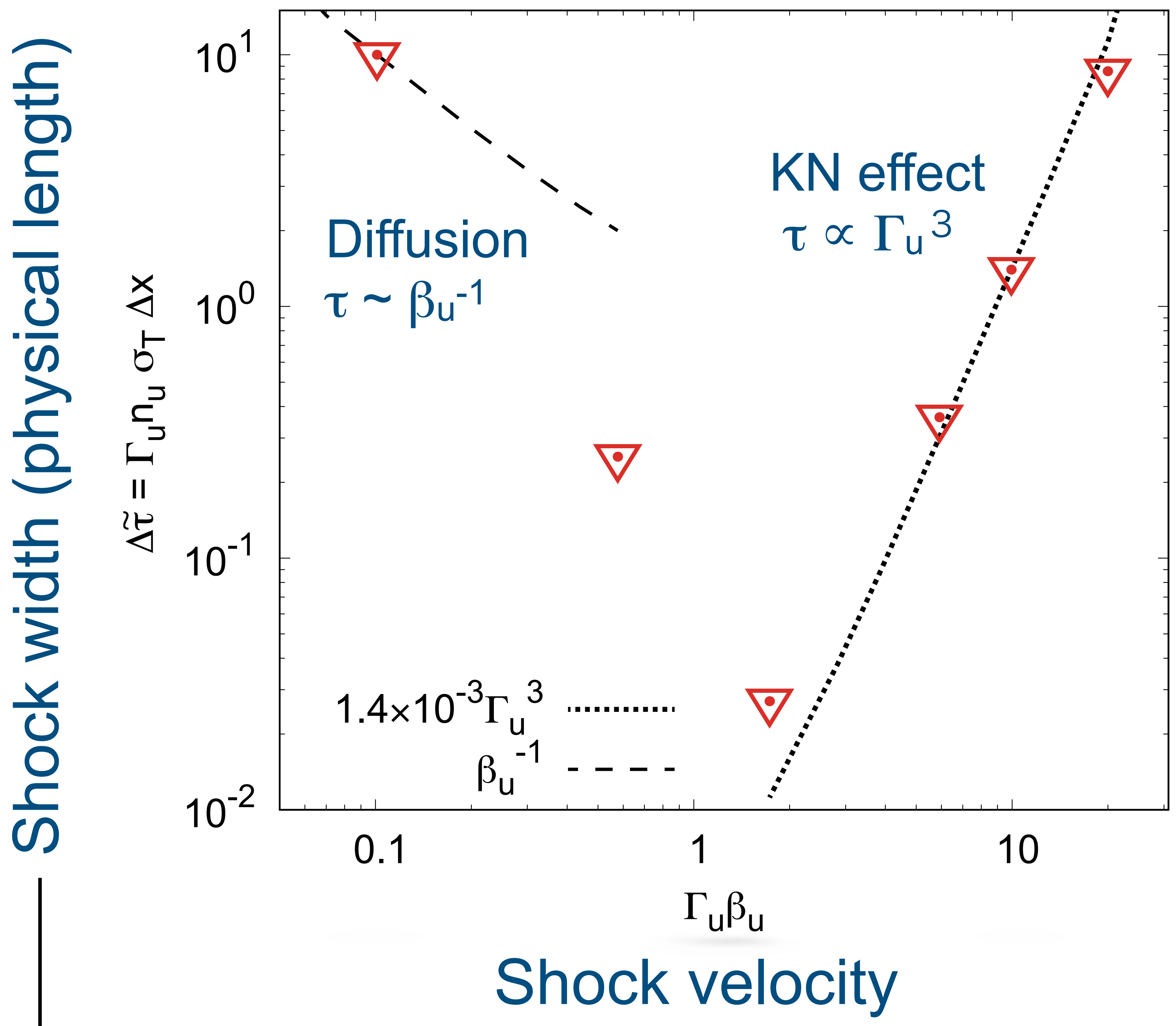
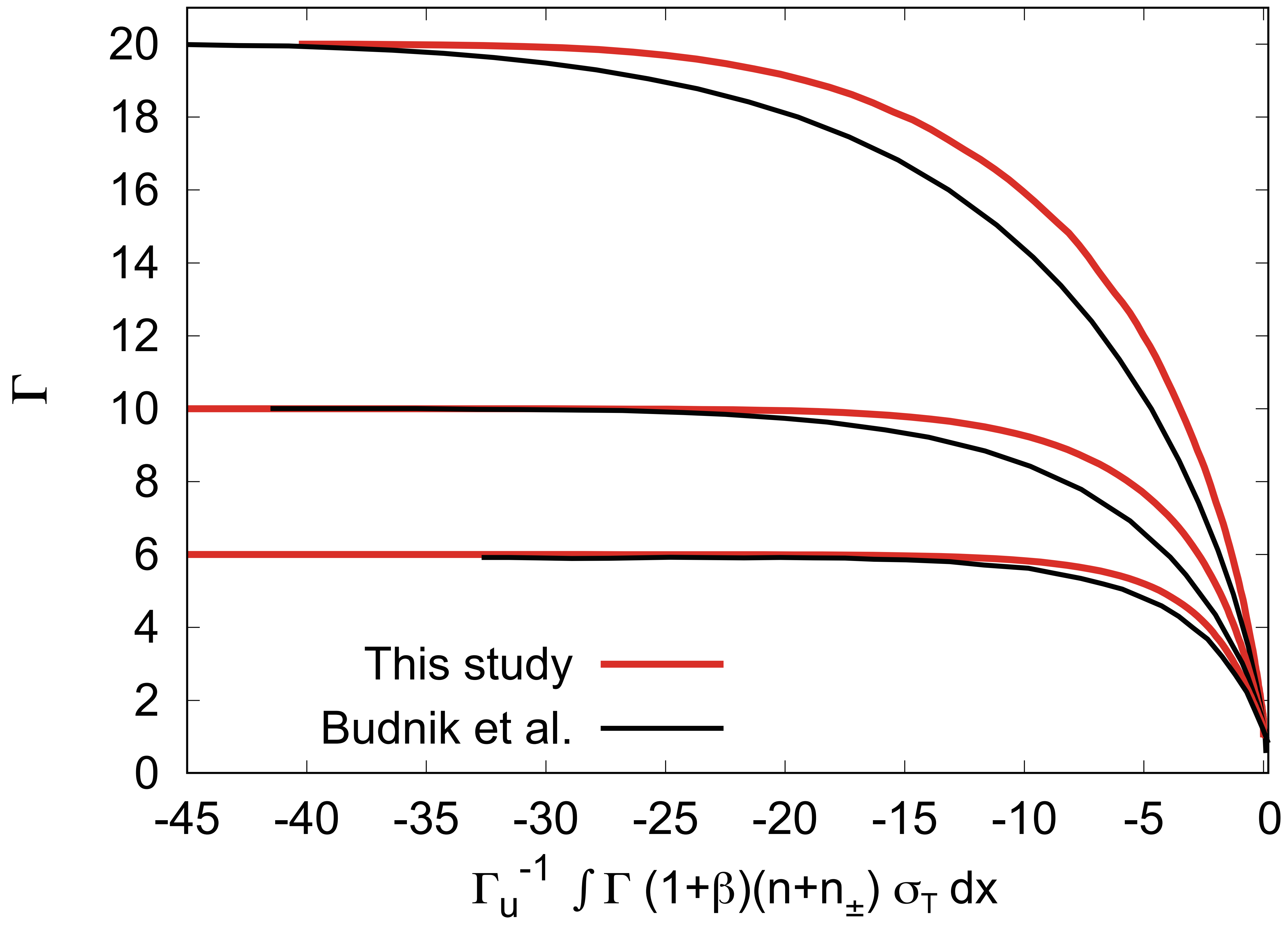
(photons are completely trapped)





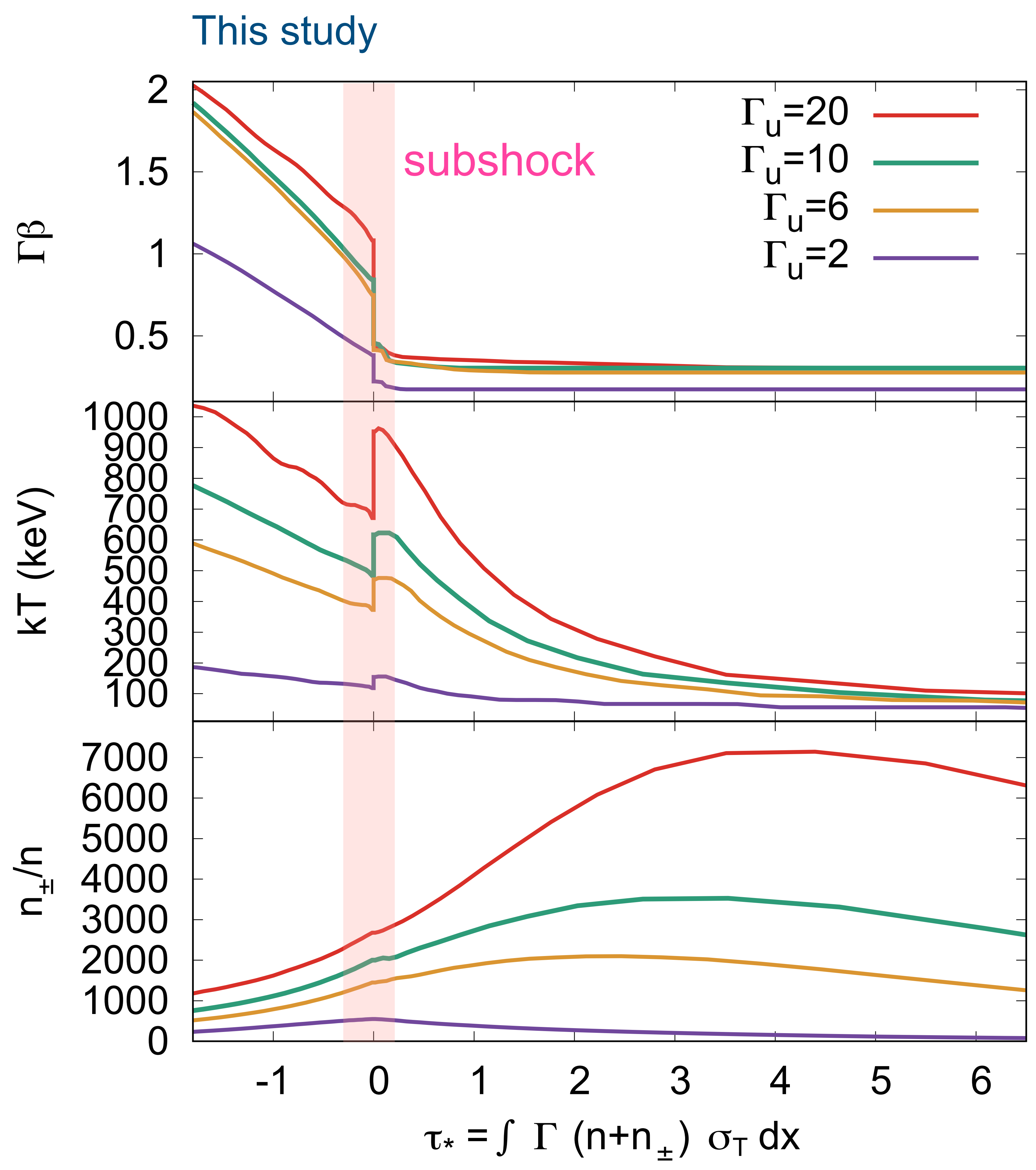
pair unloaded optical depth of shock upstream at which shock breakout commences
measured in upstream rest frame

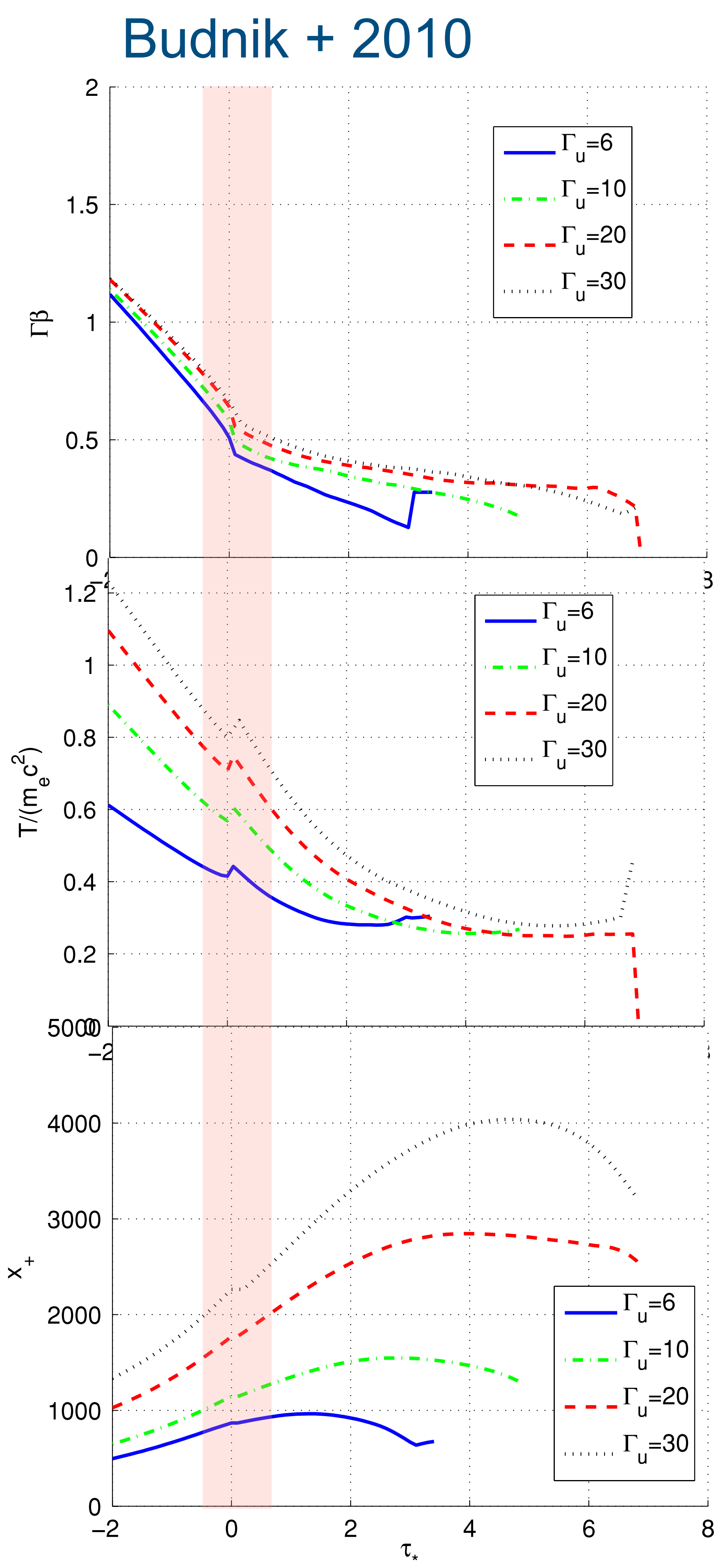
Comparison with Budnik et al. 2020



Broad agreement is obtained with the previous simulation

Comparison with Budnik et al. 2020 *@ immediate downstream (DS)*

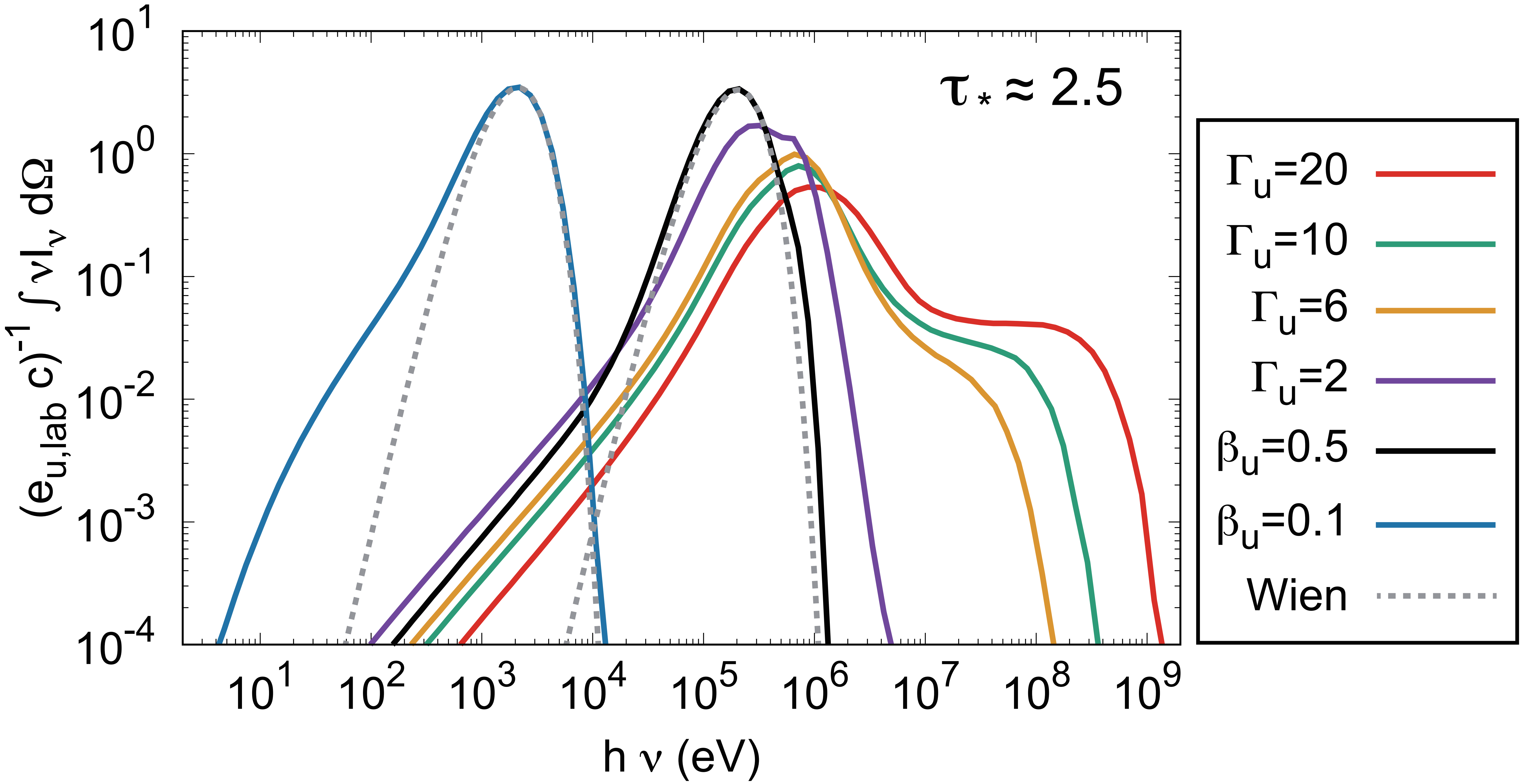




- T_d is regulated to ~ 200 keV due to vigorous pair production
- Weak subshock appears for Γ_u >~ 2

  Our simulations find stronger subshock (~few % of shock energy is dissipated) compared to Budnik + 2010

Spectrum at immediate DS



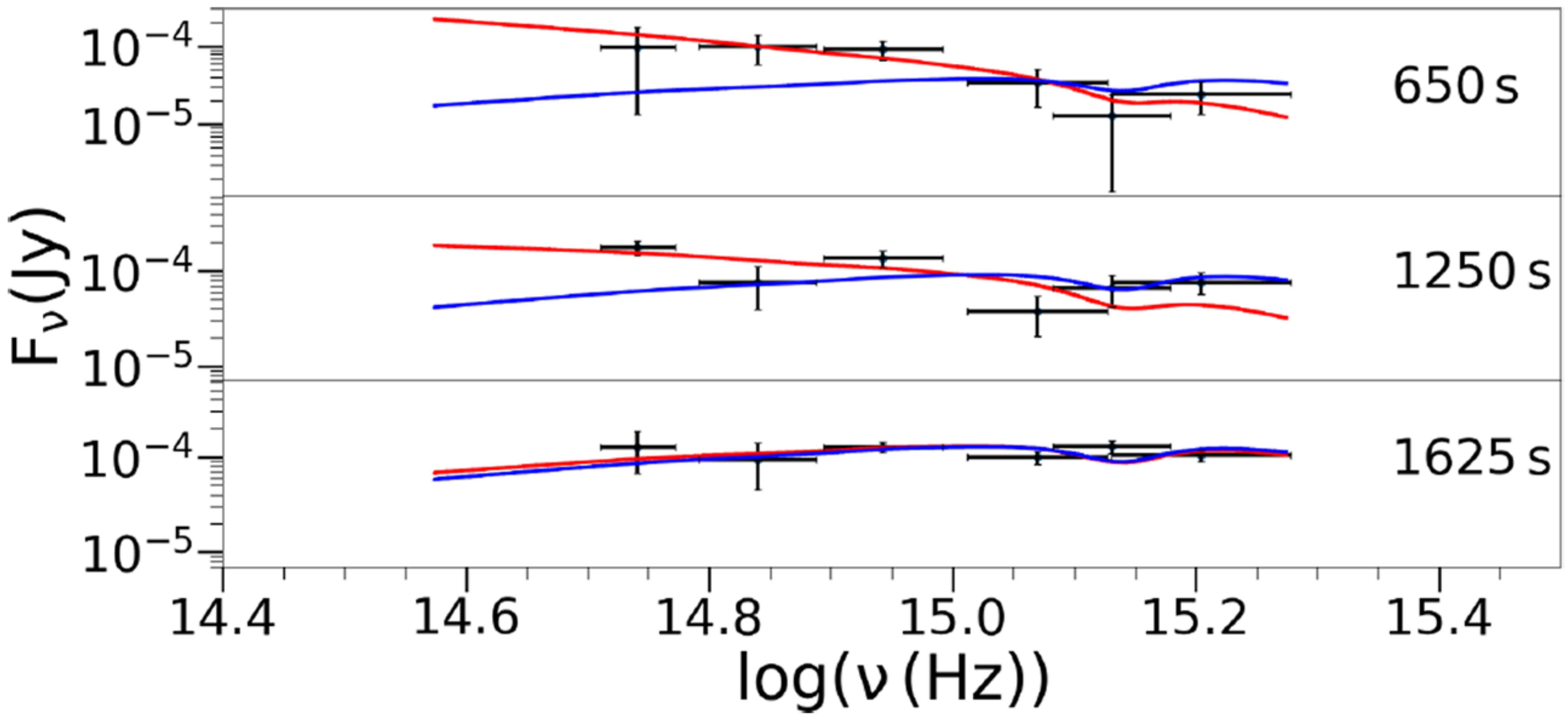
- Peak energy is regulated at ~$3kT_d$ ~ 600 keV for $\Gamma_u >> 1$
- Prominent non-thermal tail due to bulk Comptonization for $\Gamma_u >> 1$
- Substantially softer than Wien or Blackbody below the peak $f_\nu \propto\sim \nu^0$

quasi-saturated Compton

Implication to low-luminosity GRB 060218

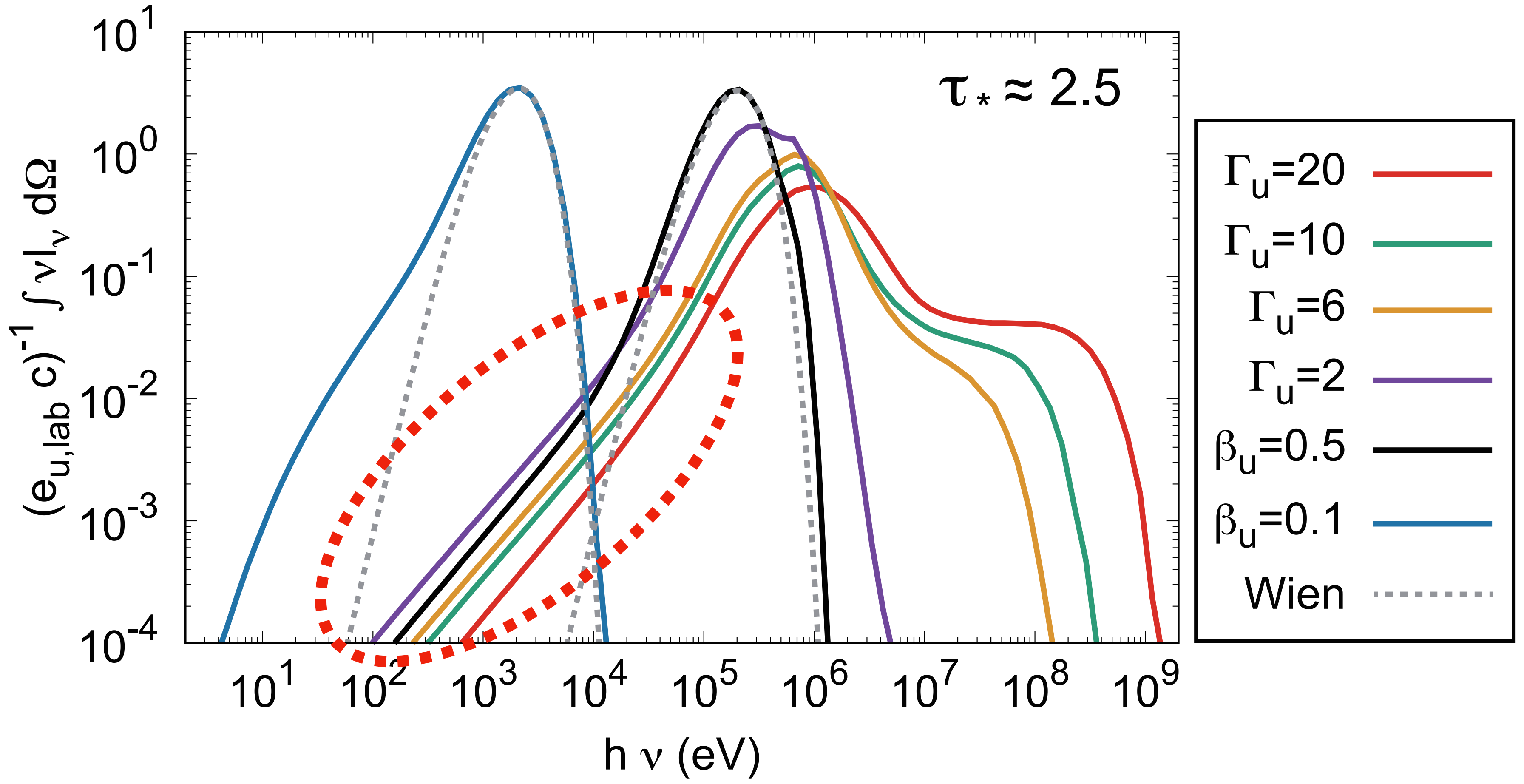
Possible origin: Shock breakout from an extended envelope driven by choked jet

Kulkarni et al. 1998, Campana et al. 2006; Waxman, Mesz ´ aros & Campana ´ 2007; Li 2007; Nakar 2015



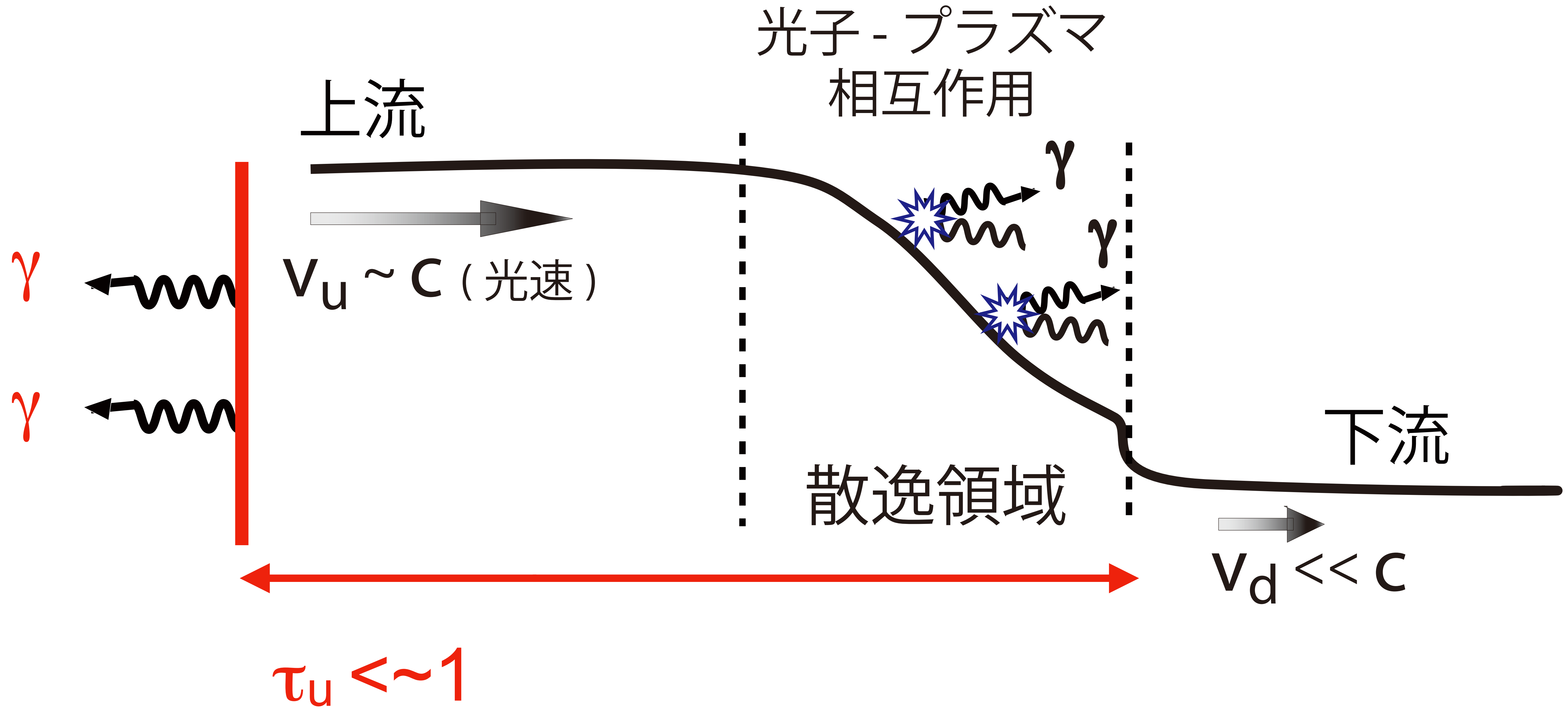
Emery et al. 2019 argues shock breakout model is challenged by the soft spectral shape in UV/Optical

However, the it is consistent with our simulation



finite RRMS

(photons escapes from the US boundary)

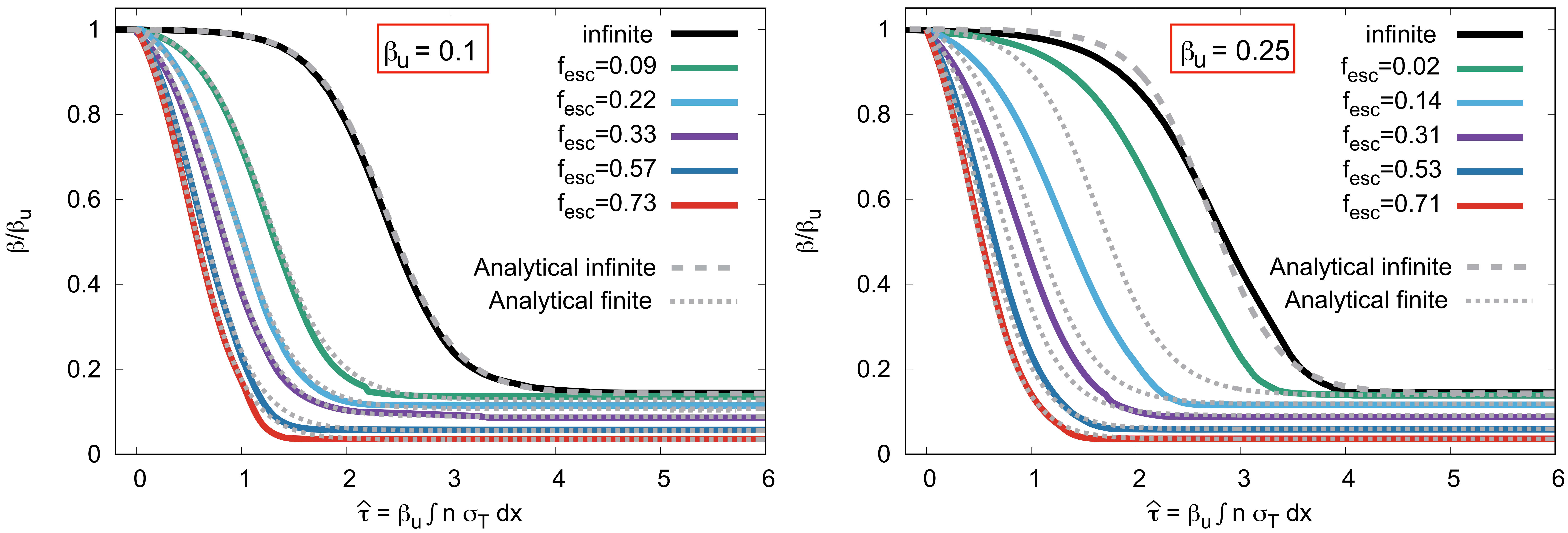


Steady state approximation is applicable for breakouts from an envelope with shallowly decaying density profile

HI, Levinson, Nakar 2020 (*MNRAS, 499,469*)

finite RMS

in fast Newtonian regime (0.1 < βu < 0.5)

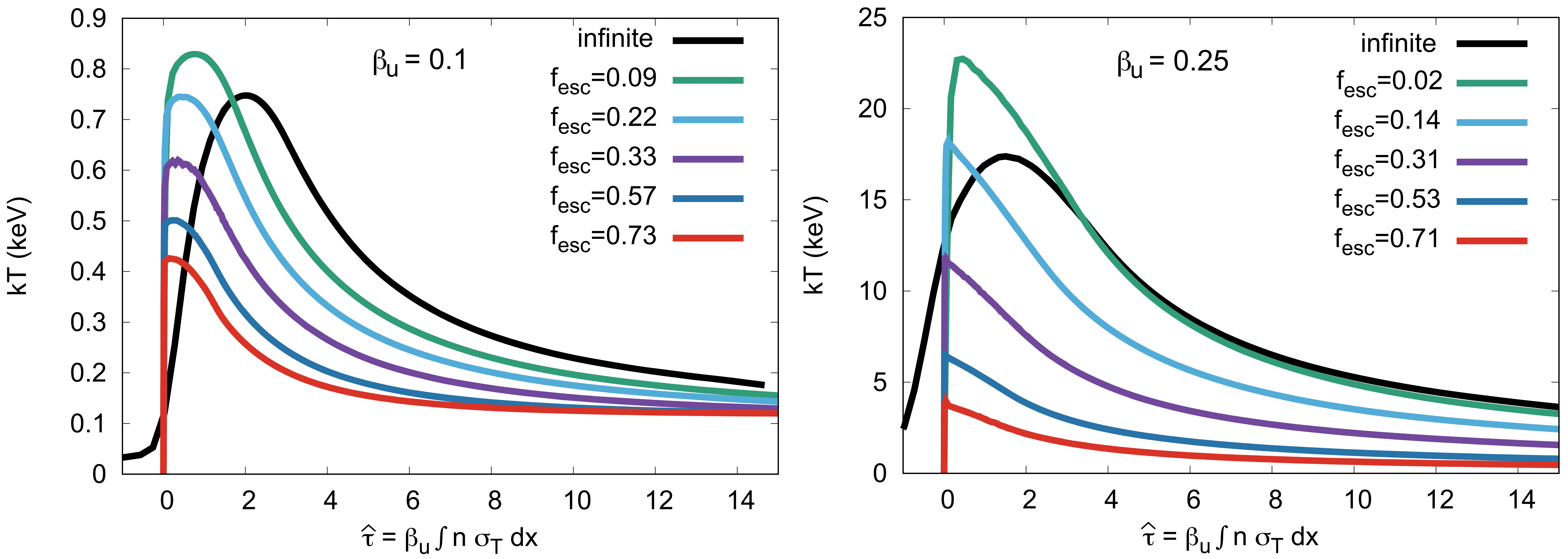


Good agreement with analytical solution based on diffusion approximation (Ioka, Levinson & Nakar 2019)

$\alpha = \dfrac{f_{\rm esc}}{2p_{\rm esc}}$: free parameter in the analytical solution

finite RMS

in fast Newtonian regime (0.1 < βu < 0.5)

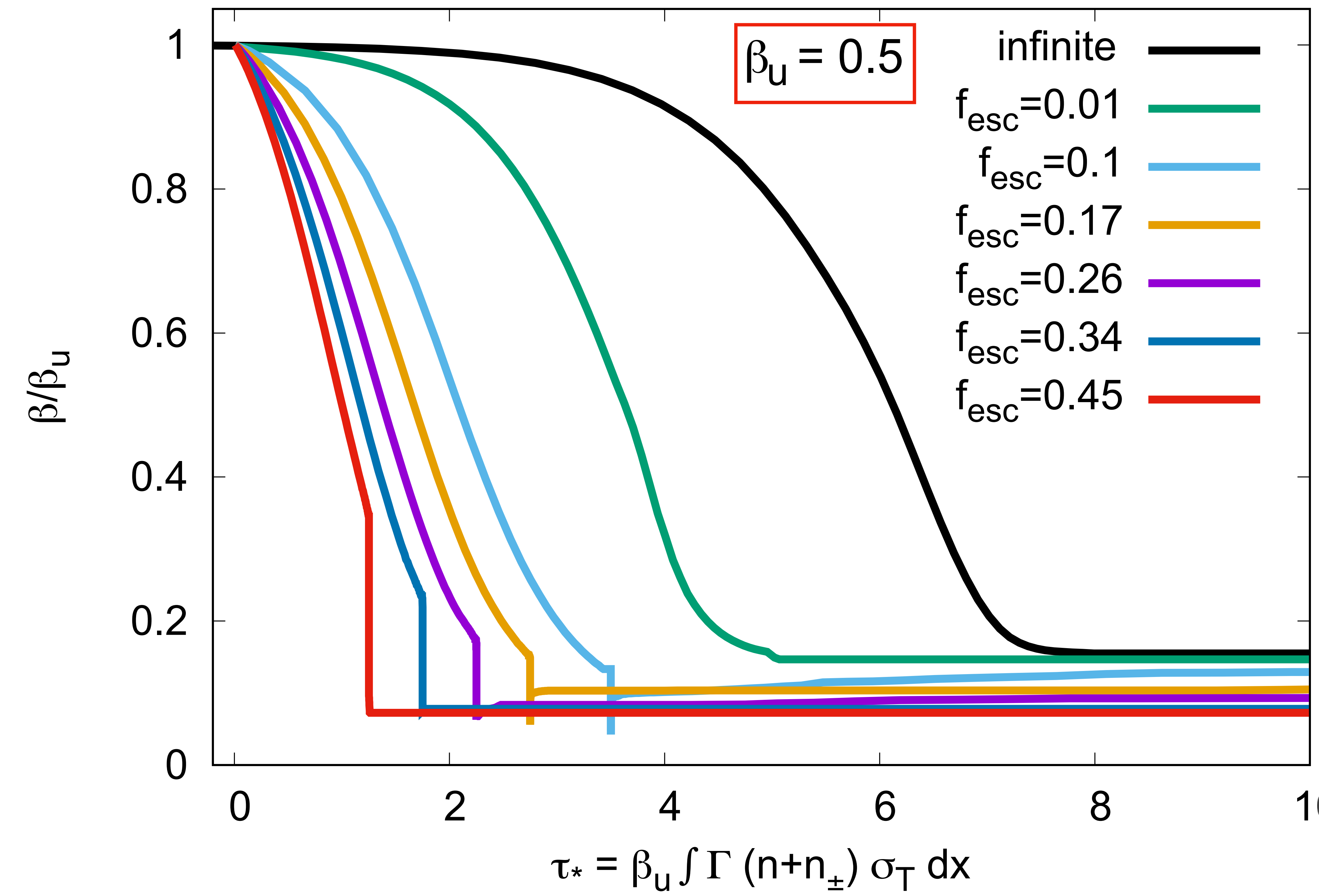


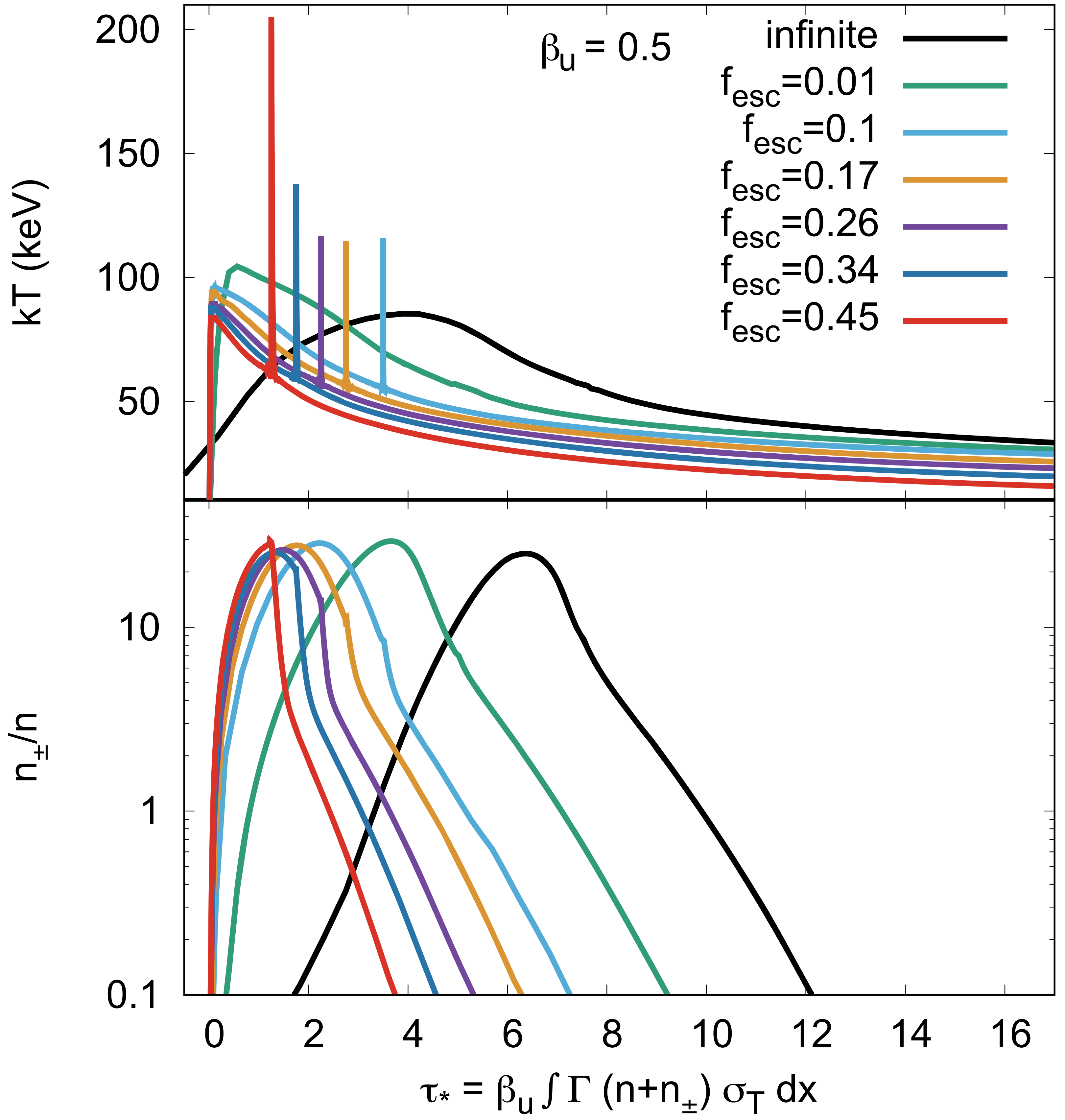
Good agreement with analytical solution based on diffusion approximation (Ioka, Levinson & Nakar 2019)

Temperature decreases as escape energy increases due to the increase in the photons produced within diffusion length

finite RMS

in fast Newtonian regime ($0.1 < \beta u < 0.5$)

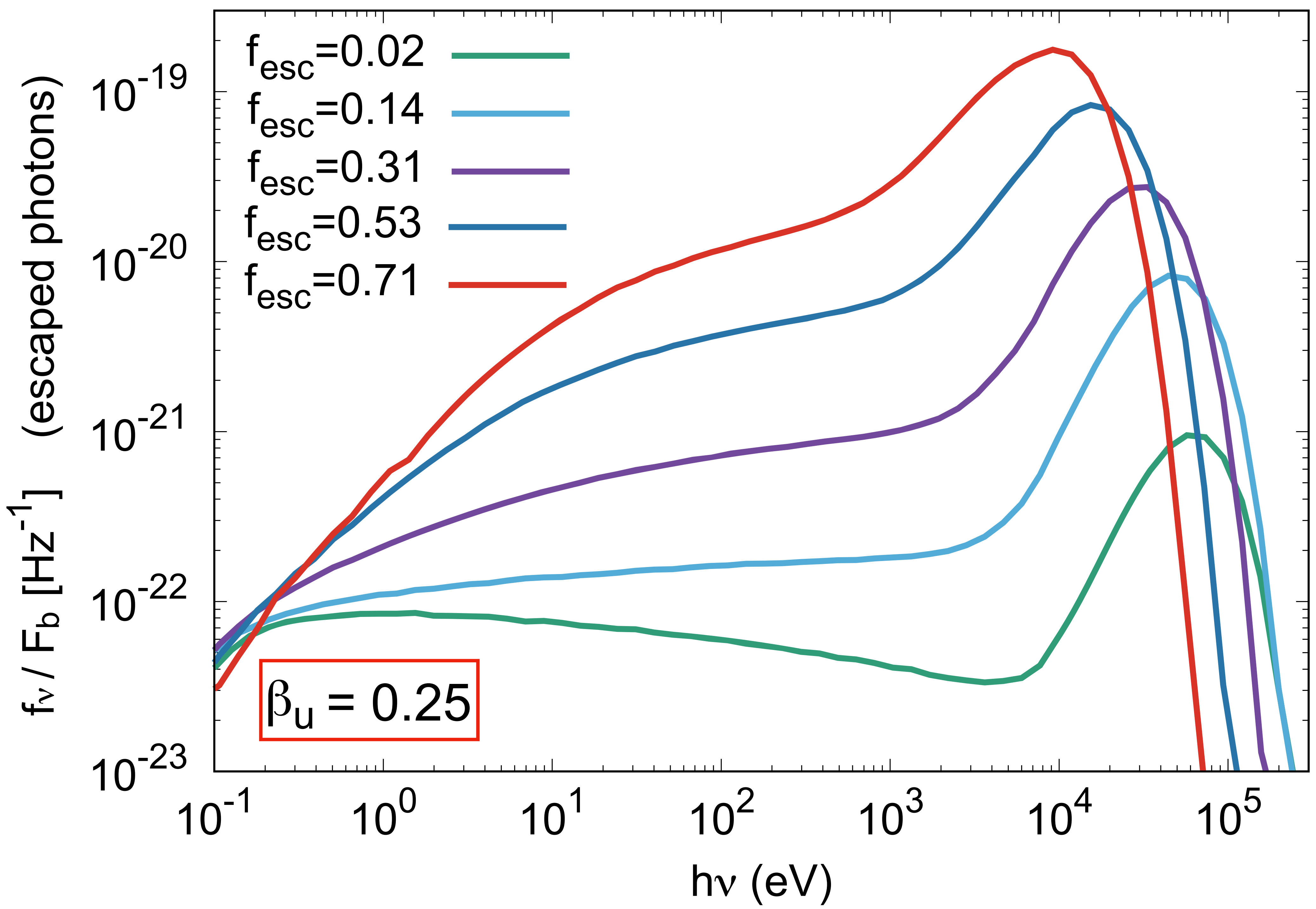


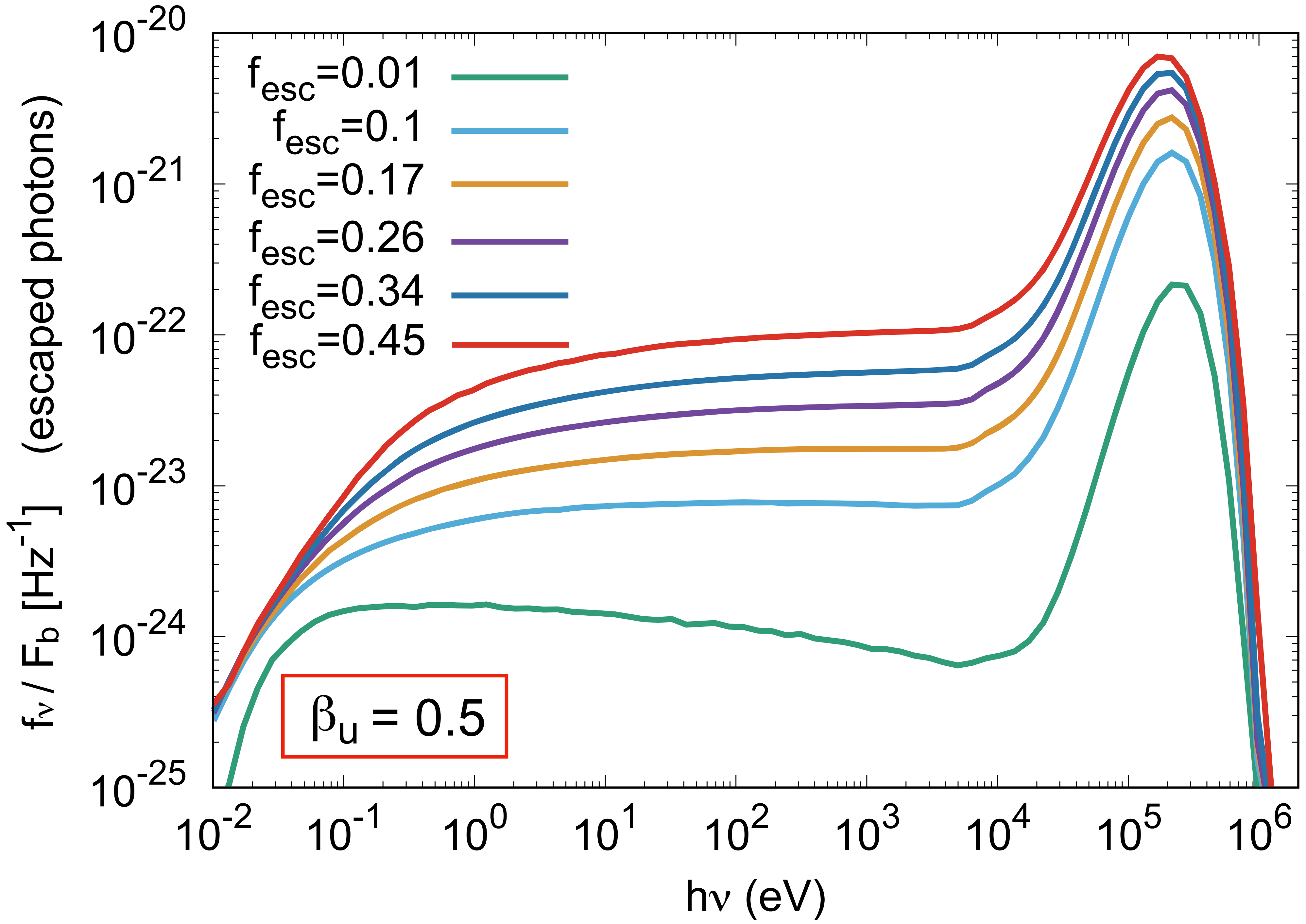


Strong subshock forms for large escape

Temperature is insensitive to the escape due to pair production

Spectra of escaped photons





- E_p decreases during the breakout due to the increase in the photon number for β_u <~0.2

  Possible origin for the non-thermal spectrum of XRT080109 (Ioka et al. 2019), bulk Compton origin is unlikely

- E_p is stable for β_u ~0.5, due to regulation by pairs
- Substantially softer than Wien or Blackbody below the peak $f_\nu \propto\sim \nu^0$

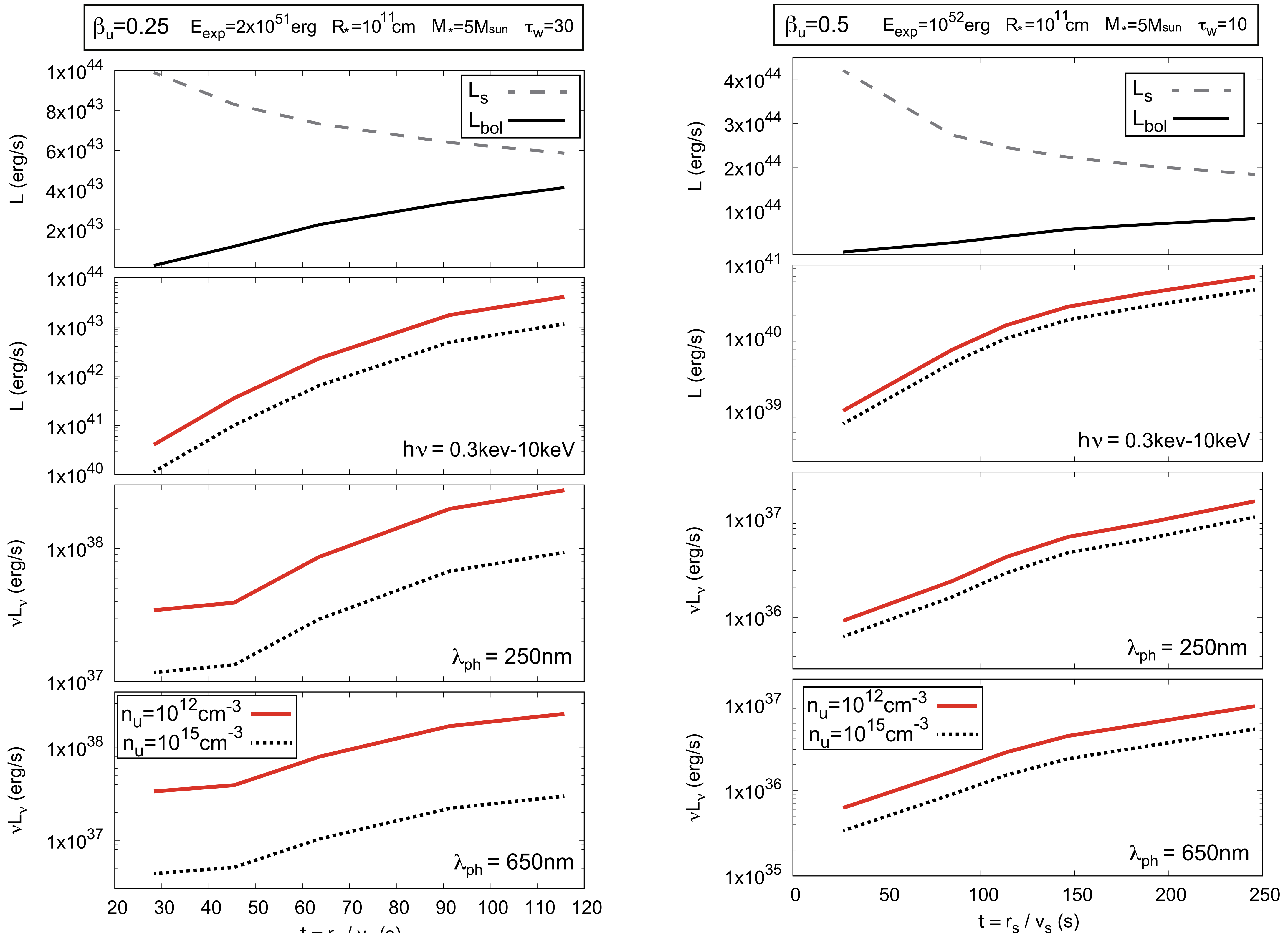
Application to shock breakout in wind ($\rho \propto r^{-2}$)

Initial rising phase of the breakout emission is modeled based on analytical model of shock propagation

$$E(v) = E_0(v/v_0)^{-\lambda} = \frac{4\pi c v_0}{\kappa} R_*^2 (v/v_0)^{\lambda},$$

$$E_s \approx 1.7 \times 10^{45}\,\mathrm{erg} \left(\frac{E_{\rm exp}}{10^{51}\,\mathrm{erg}}\right) \left(\frac{M_*}{5\,\mathrm{M}_\odot}\right)^{-0.72} \left(\frac{R_*}{10^{11}\,\mathrm{cm}}\right)^{1.4} \times \left(\frac{\tau_w}{30}\right)^{1.4} \left(\frac{\tau_s}{10}\right)^{-0.72},$$

$$v_s \approx 0.18c \left(\frac{E_{\rm exp}}{10^{51}\,\mathrm{erg}}\right)^{0.5} \left(\frac{M_*}{5\,\mathrm{M}_\odot}\right)^{-0.36} \left(\frac{R_*}{10^{11}\,\mathrm{cm}}\right)^{-0.29} \times \left(\frac{\tau_w}{30}\right)^{-0.29} \left(\frac{\tau_s}{10}\right)^{0.14}.$$



- βu ~ 0.2 predicts luminosity range and spectral evolution compatible with XRT080109

  Ep ~ 5keV around the peak is predicted, implying rising phase is harder than the decay (Svirski & Nakar 2014), Compatible with analysis of Soderberg 2008 which finds significant spectral softening

- βu ~ 0.1 - 0.35 (Ep ~0.3 - 10 keV) shock breakout is detectable by eRosita ~ 1/yr

  Assumption: thick wind breakout is common for type Ib/c SNe ~ 2.5 x 10^4 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

- Substantially brighter emission than the naive estimation (Wien) is found in UV/Optical, but still too faint to be detectable (M_{AB} ~ -9)

Summary

first principle simulations of RMS in photon starved regime is performed

- Detail shock structure in fast Newtonian and relativistic shock is computed
- Anisotropy develops near the shock and give rise to highly non-thermal spectrum and copious pair production for $\beta_u > \sim 0.5$
- Emergence of subshock at relativistic shocks
  it's strength increases as energy escape fraction increases
- Spectrum is far from thermal (Wien or Blackbody) even for fast Newtonian shock $\beta_u > \sim 0.1$
  Substantially softer than Wien or Blackbody below the peak $f_\nu \propto\sim \nu^0$
- Fast Newtonian shock breakout may be detectable by eRosita ~ 1 per yr