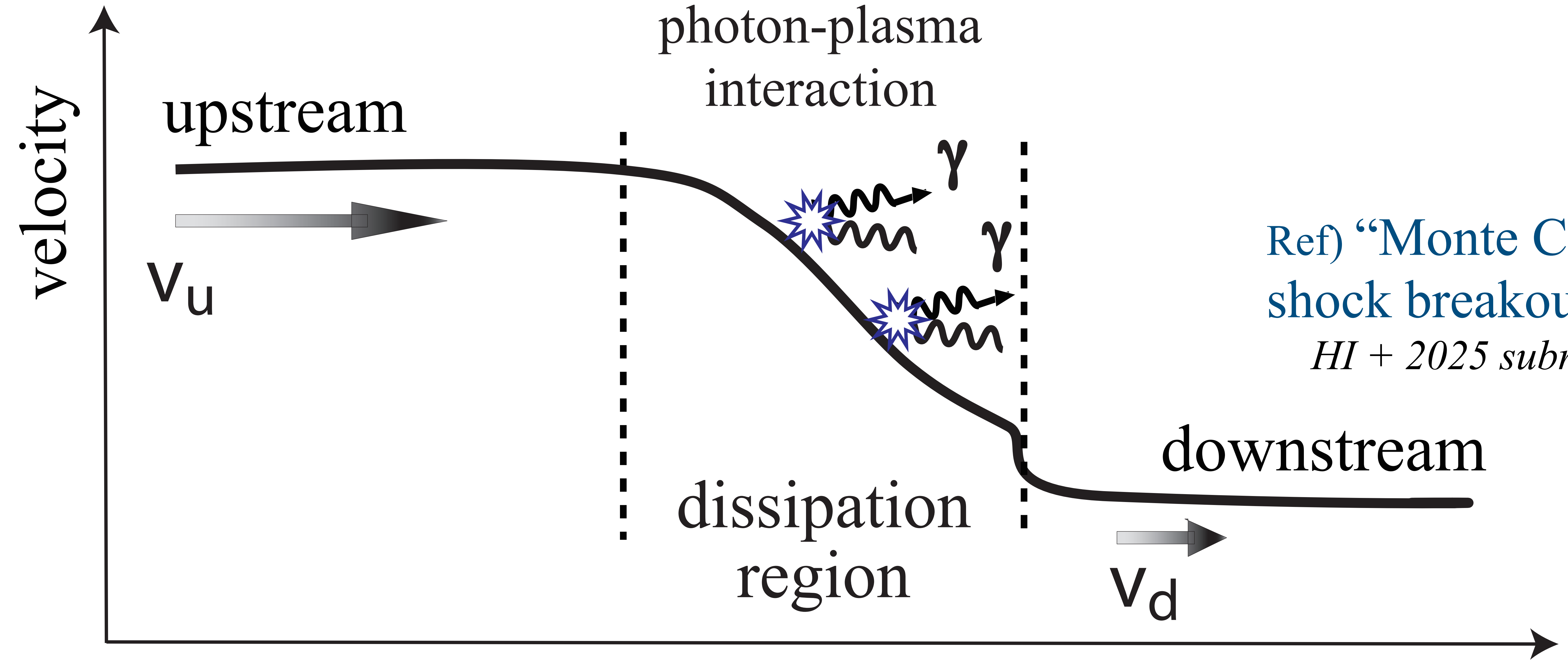
Monte Carlo Simulations of Radiation Mediated Shocks



Ref) "Monte Carlo simulations of relativistic shock breakout from a stellar wind"
HI + 2025 submitted to MNRAS, arXiv:2506.01398

Hirotaka Ito RIKEN

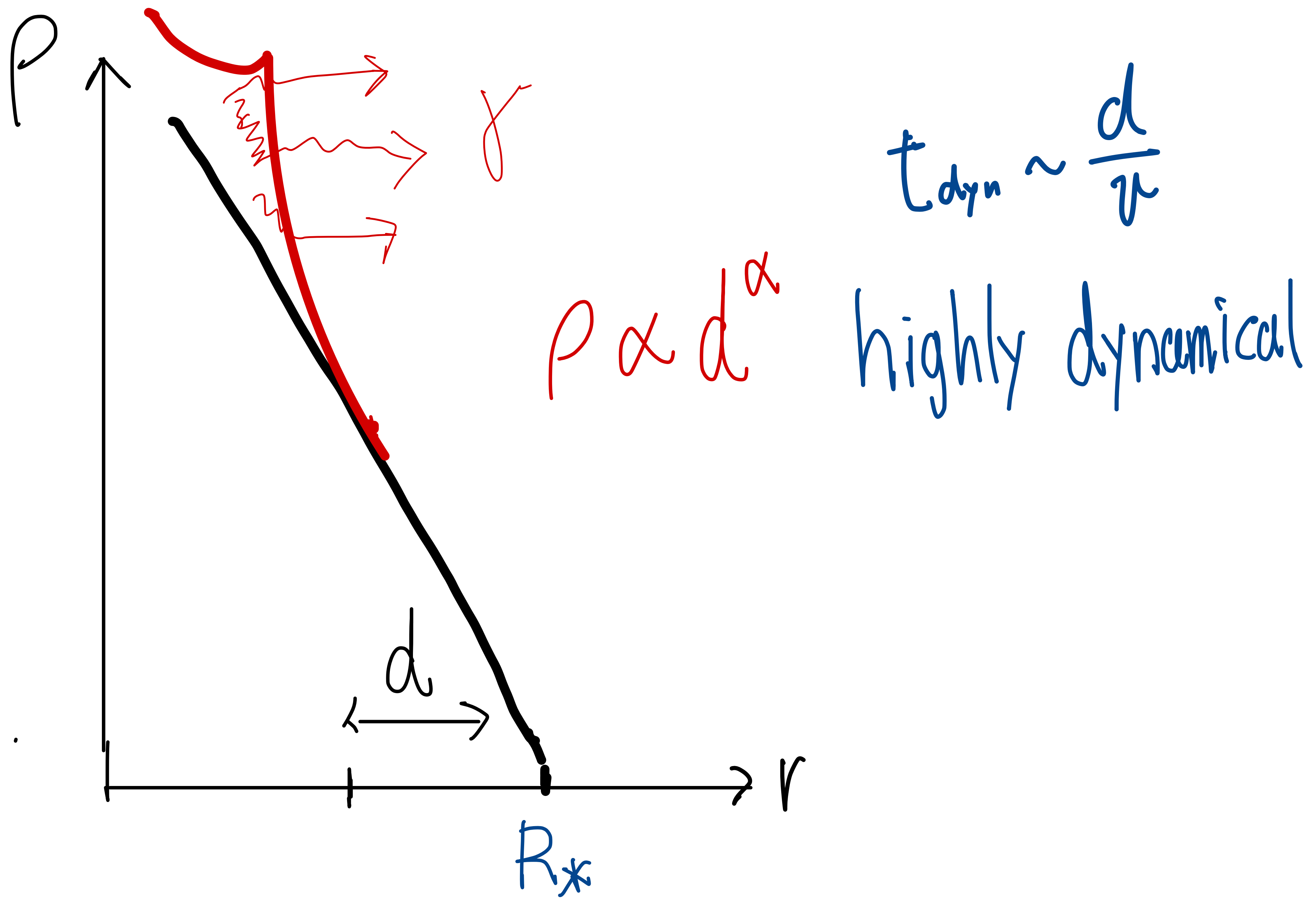
Collaborators : Amir Levinson (Tel Aviv Univ.), Ehud Nakar (Tel Aviv Univ.), Shigehiro Nagataki (RIKEN)

@学術変革(A)マルチメッセンジャー天文学:第3回領域研究会 *2025/11/19*

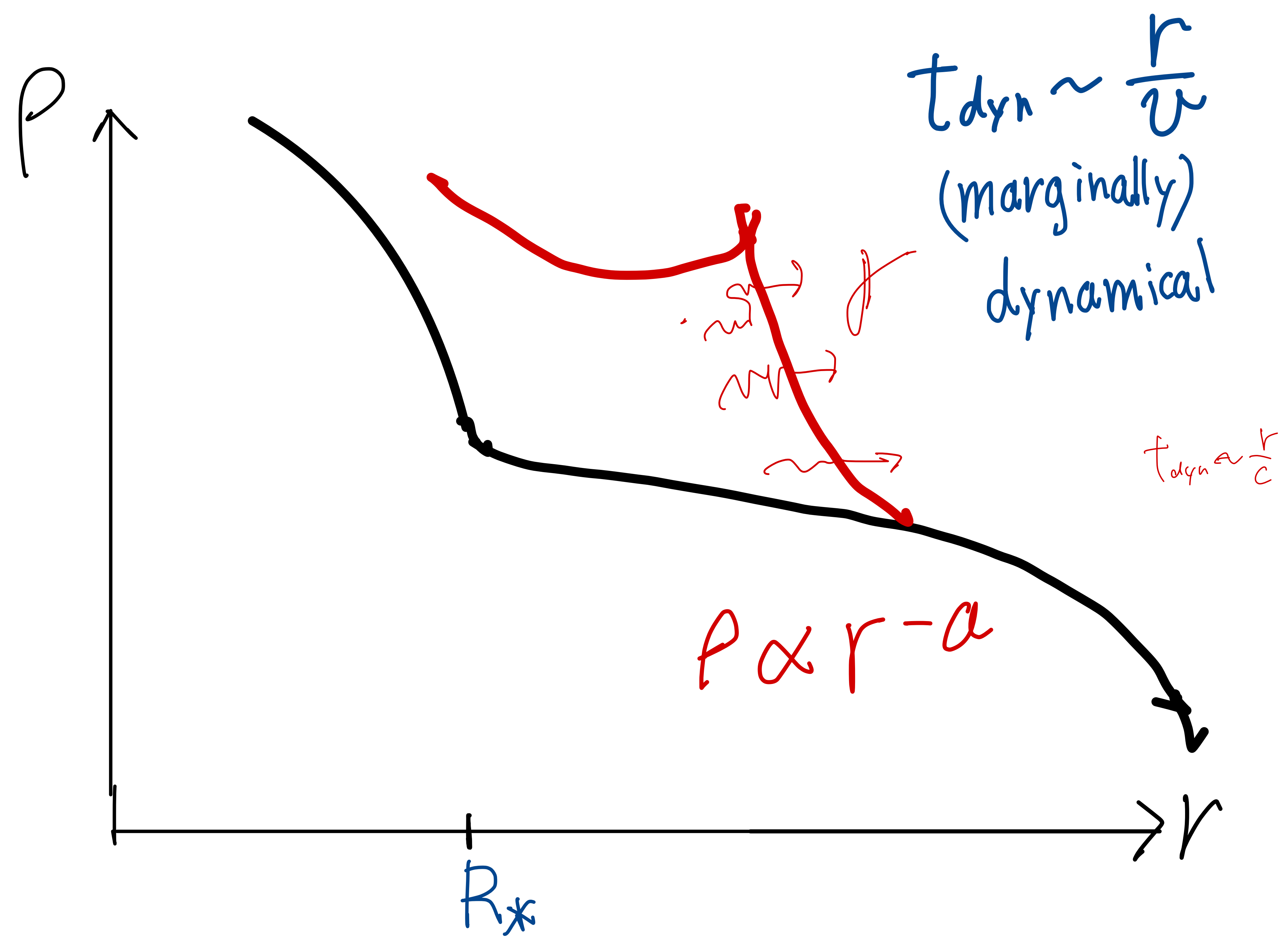
Shock Breakout

$t_{dyn} \approx t_{diff}$ ($\simeq t_{cross}$) の時発生 @ $\tau \sim \frac{c}{v}$ ※ $v \gtrsim 0.5c$ の時, pair の発生, Klein-Nishina の効果などで修正される

@ sharp edge
(stellar surface)

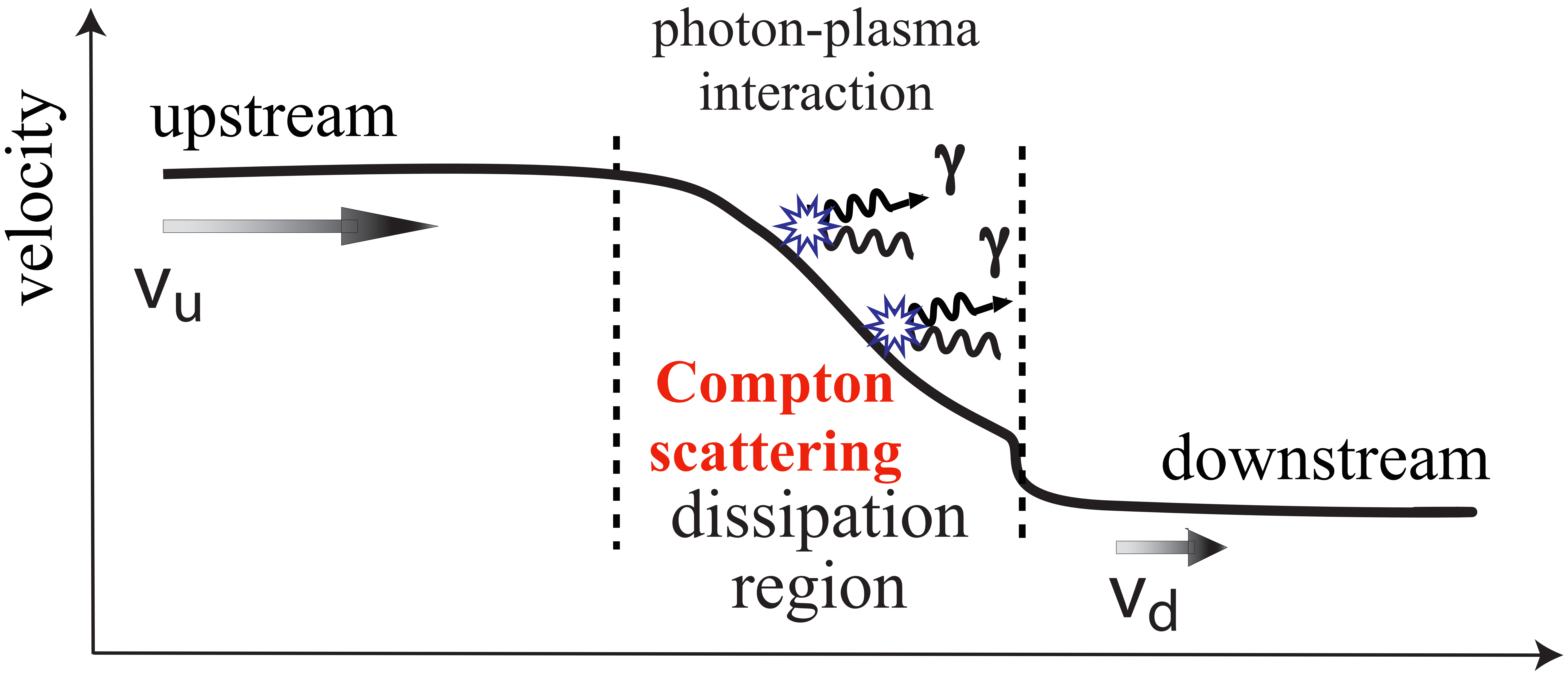


@ extended envelope, wind



”radiation mediated shock (RMS)”

Radiation Mediated Shocks (RMS)



(1) Radiation dominated downstream

$$aT_d^4 > n_d k T_d$$

jump condition yields

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

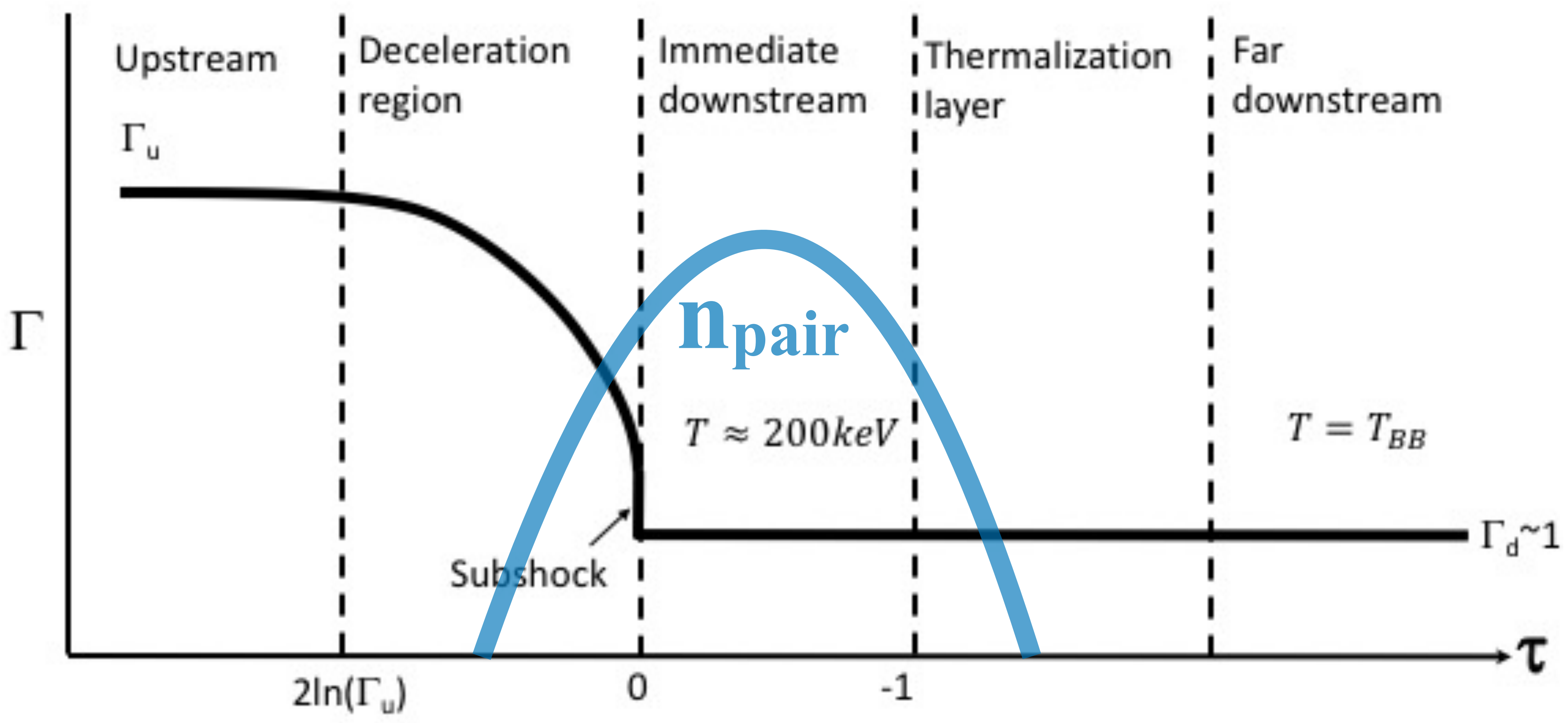
(2) photon trapping

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

upstream plasma approaching the shock is decelerated by scattering of counter streaming photons

Relativistic RMS (RRMS) ($v_u \sim c$)

- **full radiation transfer calculation is necessary**
- **Klein-Nishina effect & e^{+-} pair production/annihilation are important**



Pairs produced by γ-γ interaction dominates the opacity and the photon production

First principle calculations
for photon-starved (Cold US) RRMS

Budnik, Katz, Sagiv, & Waxman (2010)

HI, Levinson & Nagataki (2020)
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HI, Levinson & Nakar, Nagataki *submitted*

See also,

Levinson & Bromberg (2008)
Beloborodov (2017)
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HI, Levinson, Stern & Nagataki (2018)
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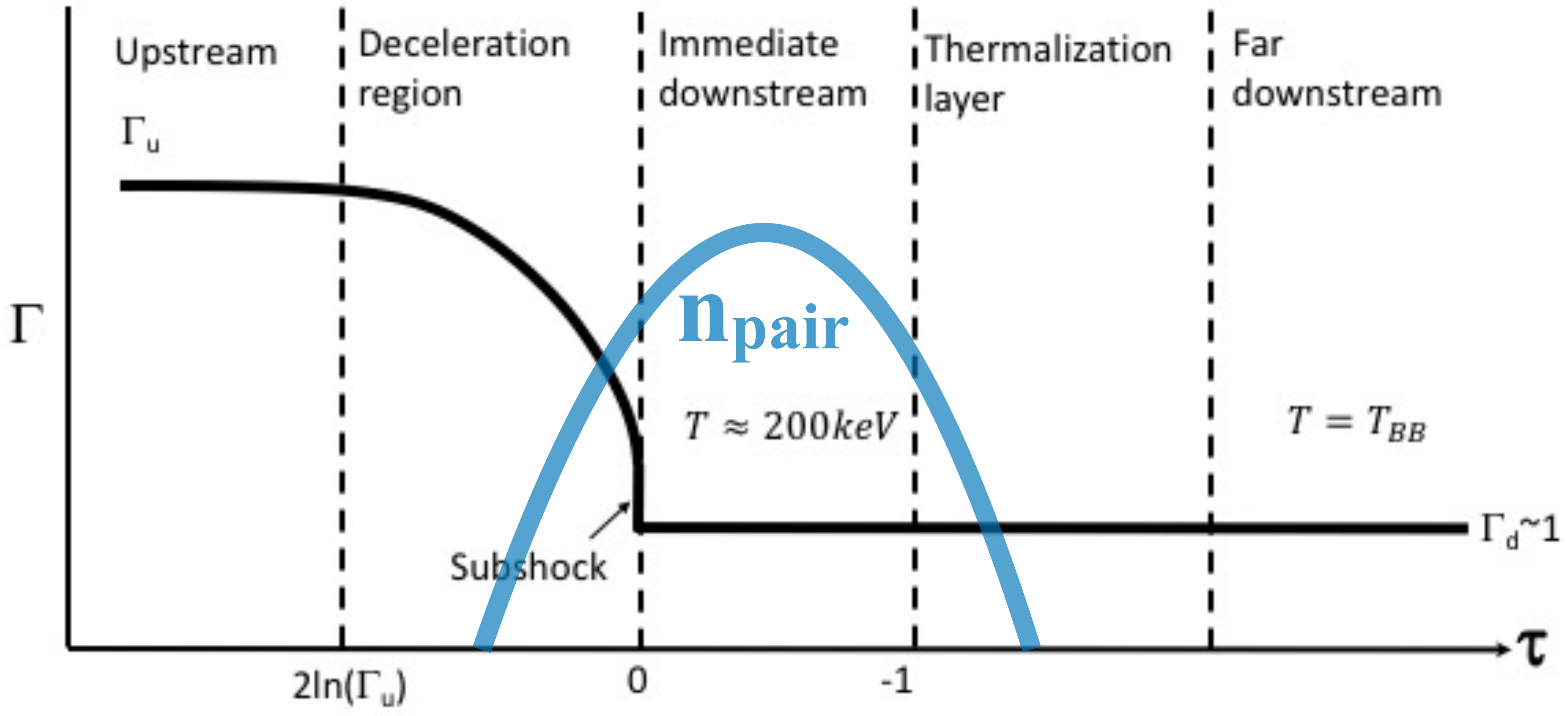

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Today's talk

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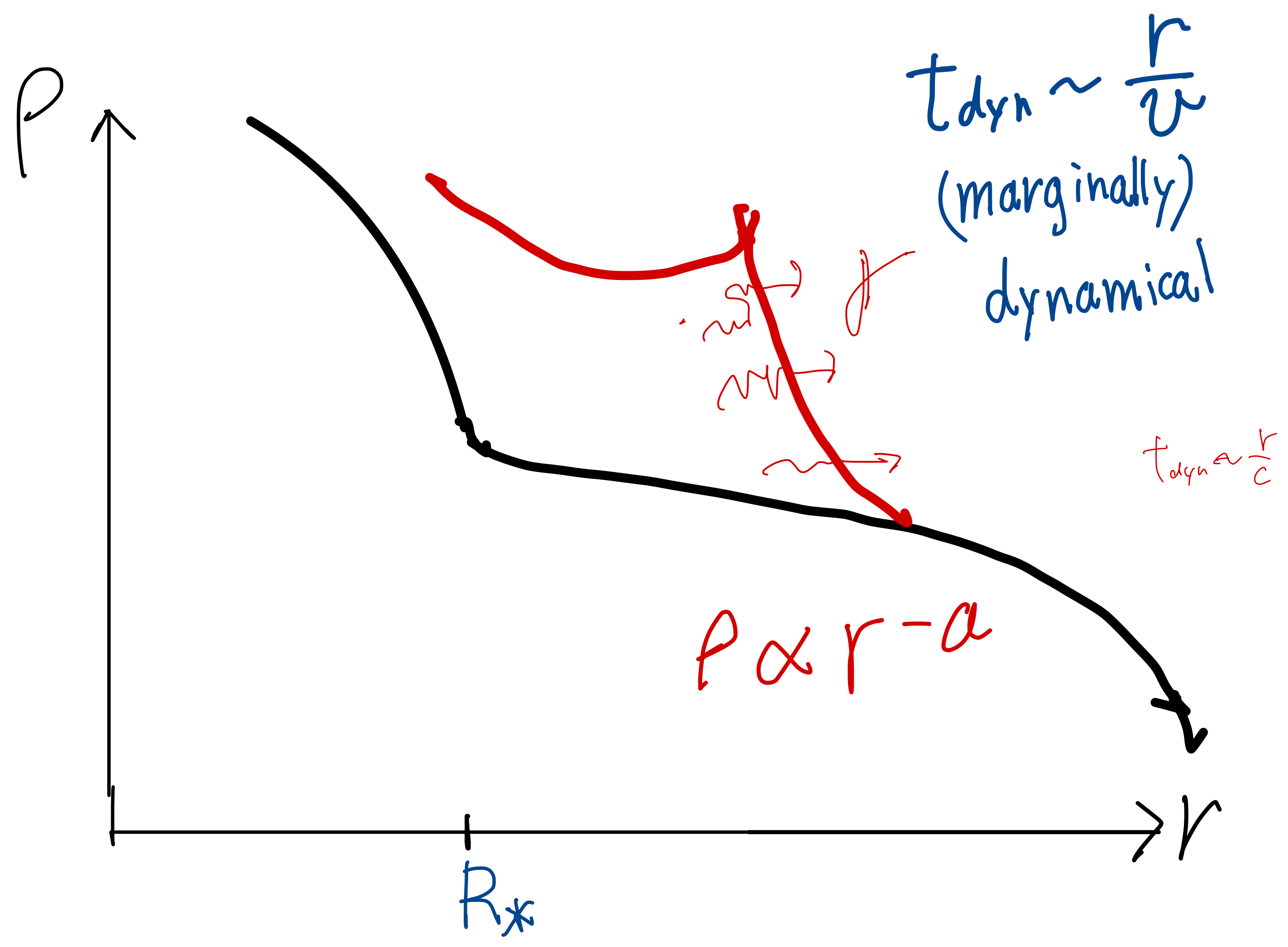
RRMS breakout from a wind

quasi-steady approximation is applicable for breakout

@ extended envelope, wind



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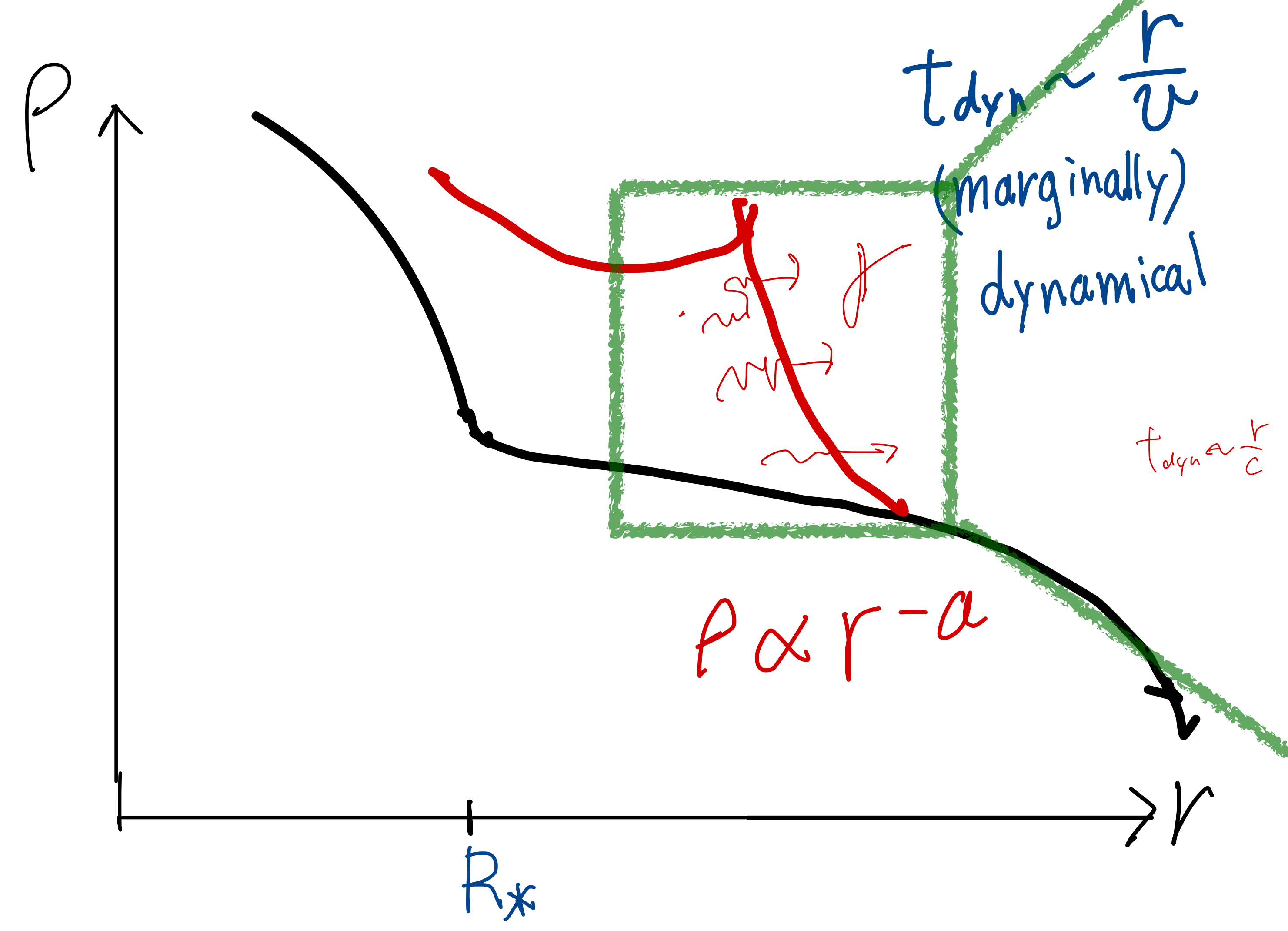

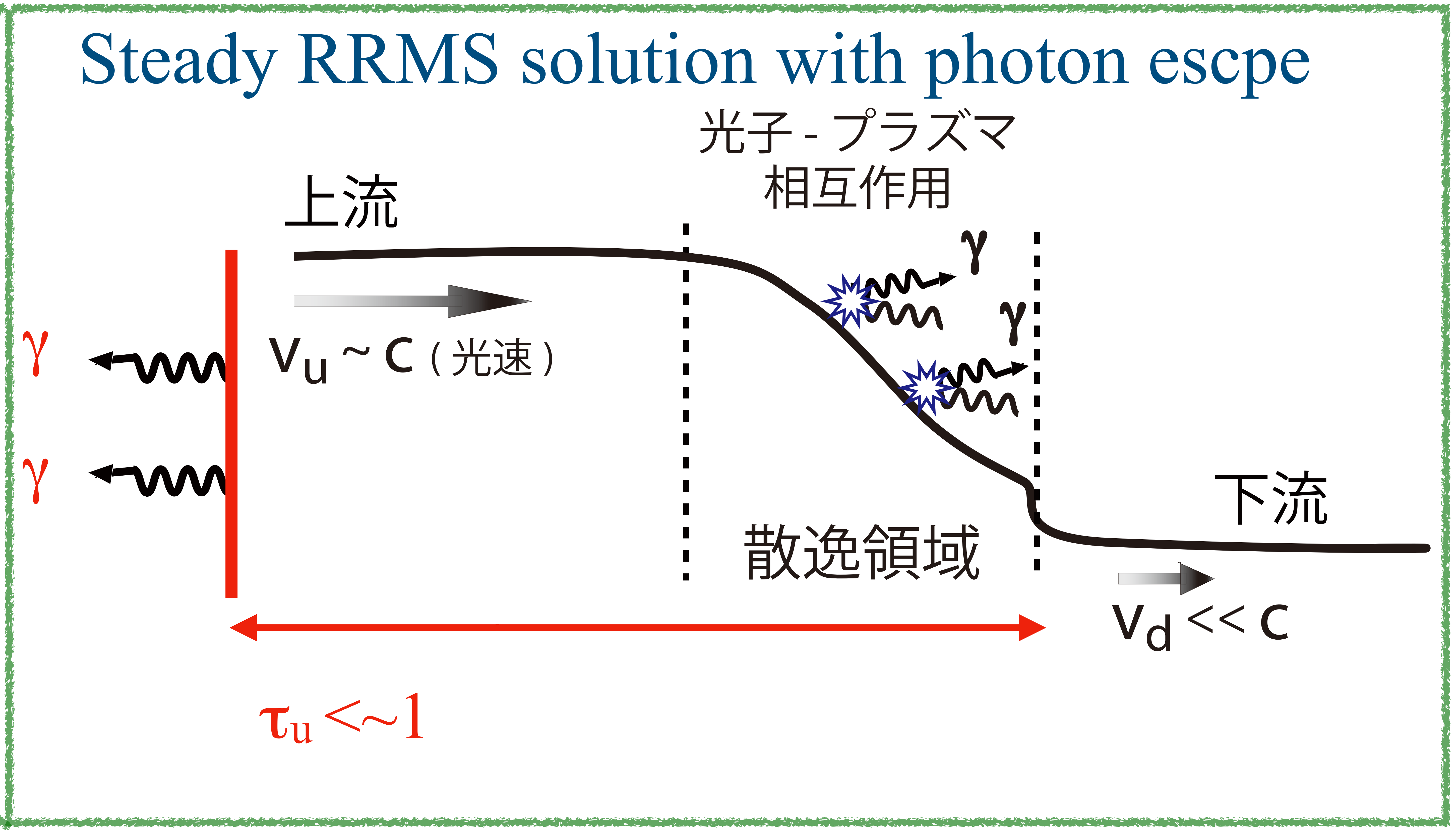

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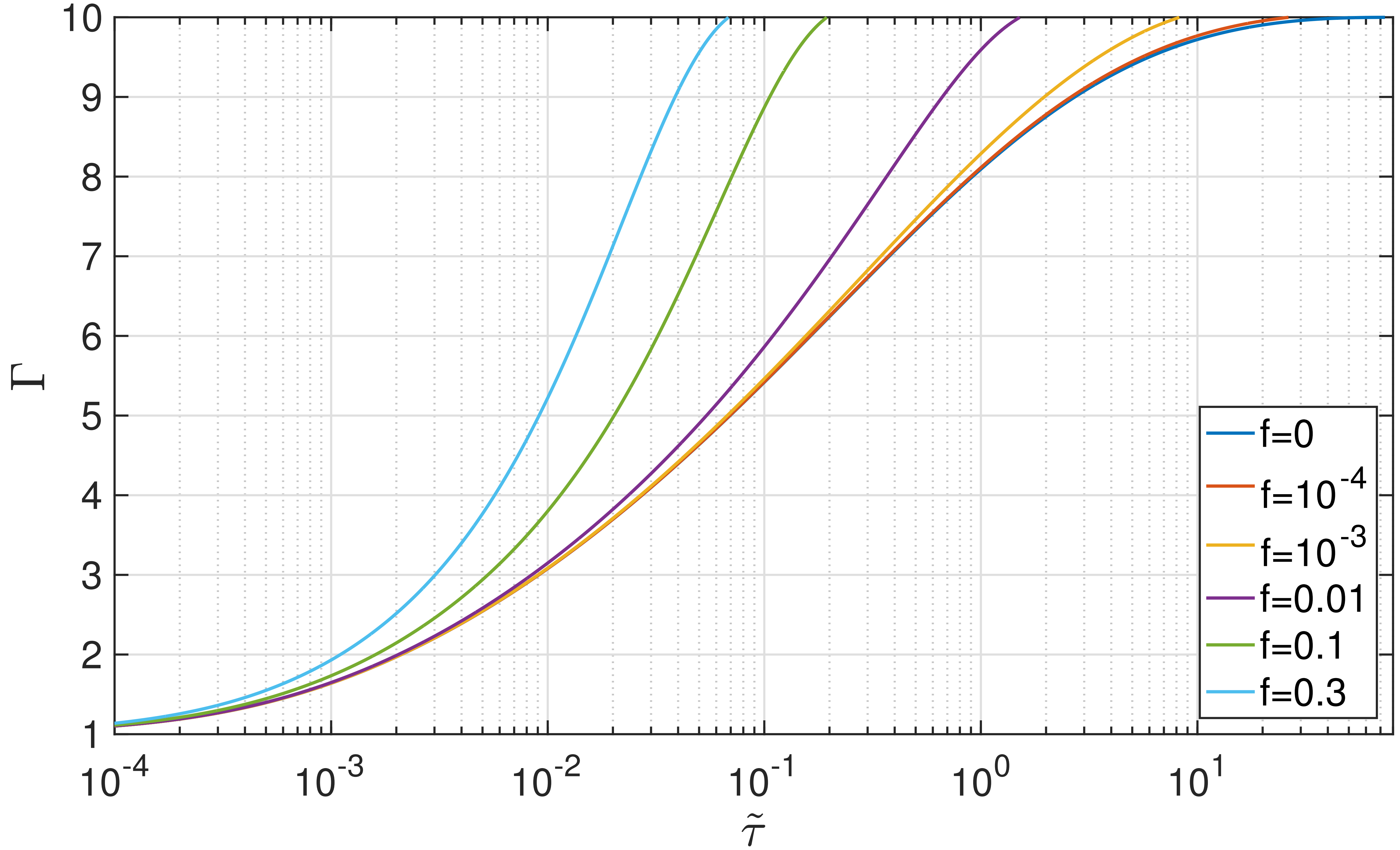
Analytical Model of Granot, Levinson, Nakar 2018 **(GLN18)**

Reproduces infinite shock solutions of Budnik+2010 and HI+2020



$$f \equiv \frac{x_{\rm esc}}{x_0}$$ Escape fraction of photons

$$\Delta\tilde{\tau} = \begin{cases} 10\eta\mu\Gamma_{\rm u}^3 & f \ll \frac{1}{\Gamma_{\rm u}^2} \\ \frac{\mu\Gamma_{\rm u}}{f} & f \gg \frac{1}{\Gamma_{\rm u}^2} \end{cases}$$

$\mu = \frac{m_{\rm e}}{m_{\rm p}}$

$$\Delta\tau \propto \Gamma_u f^{-1}$$

Breakout optical depth: $\tau_{bo} \sim (m_e / m_p)\,\Gamma_{bo}$

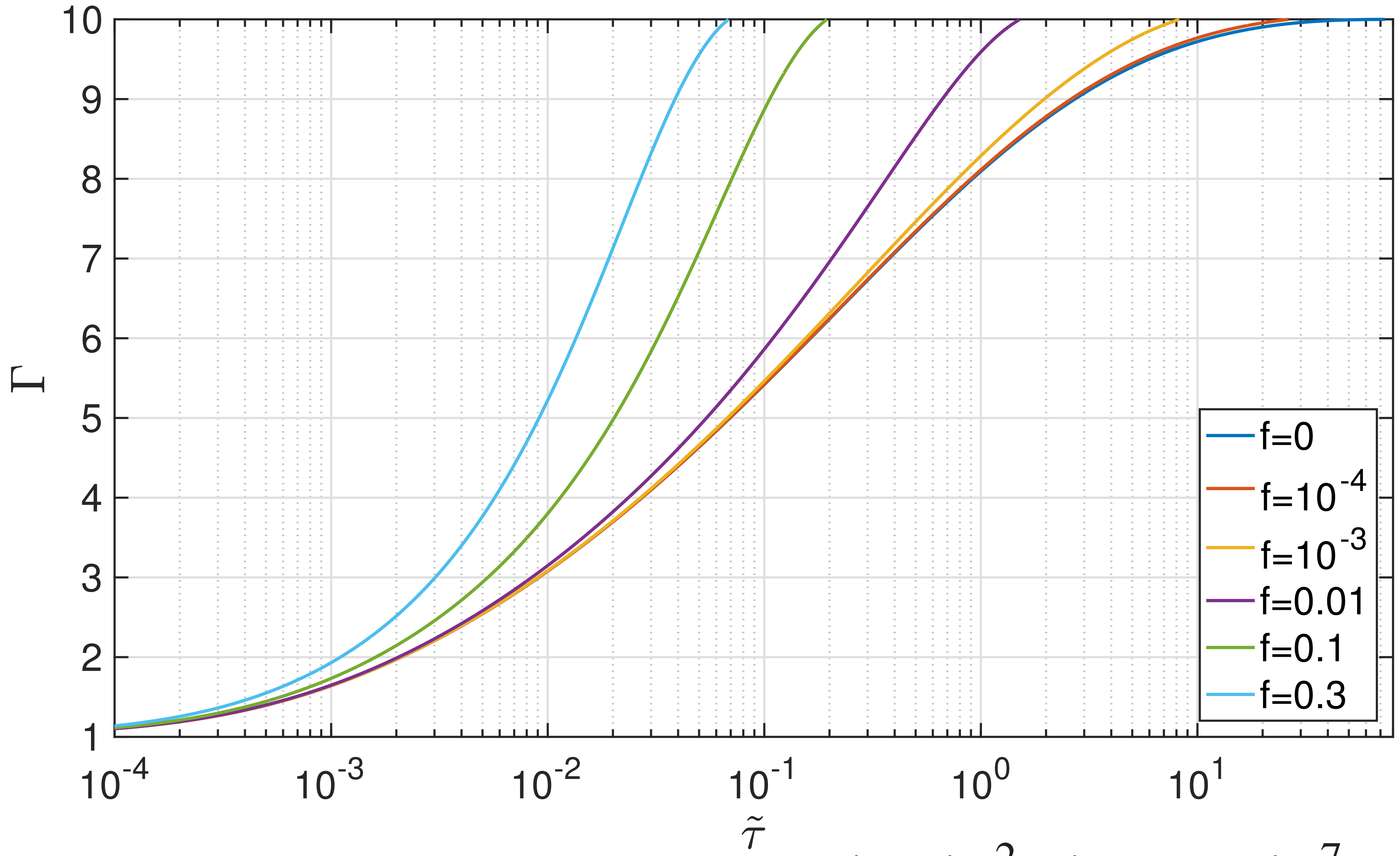
Assumption

- **Γ >> 1 , steady**
- Td ~ 100 - 200 keV => couterstreaming photon energy $\varepsilon_\gamma \sim m_e c^2$
- Scatterback or pair converted pairs deposite theramal energy $\sim \eta\,\Gamma m_e c^2$ $(\eta \sim 1)$

$$\frac{dx_l}{d\tau} = -(x_l + x_{\rm esc}) \qquad \Gamma(1 + (x_l + 1)\mu\hat{T}) = \Gamma_{\rm u}$$

Analytical Model of Granot, Levinson, Nakar 2018 **(GLN18)**

Reproduces infinite shock solutions of Budnik+2010 and HI+2020



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Breakout optical depth: $\tau_{bo} \sim (m_e / m_p)\,\Gamma_{bo}$

Closure relation: $$E_{bo} \approx 10^{48}\kappa_{0.2}^{-1}\left(\frac{t_{bo}}{1\,s}\right)^2\left(\frac{T_{obs,bo}}{2\,MeV}\right)^7\ erg$$

Application to Spherical relativistic explosion model $E(>\Gamma) \approx E_0(\Gamma/\Gamma_0)^{-1.1}$

Johnson & McKee 1971; Pan & Sari 2006

$$t_{bo} \approx 1.6\times10^3 E_{53}^{-5.1} M_{ej,5}^{3.6} R_{*,11}^{3.85}\tau_{w*}^{3.86}\ s$$

$$T_{obs,bo} \approx 250 E_{53}^{1.7} M_{ej,5}^{-1.2} R_{*,11}^{-0.95}\tau_{w,*}^{-0.95}\ keV(\Gamma_{bo} > 1)$$

$$E_{bo} = 10^{48} E_{53}^{1.7} M_{ej,5}^{-1.2} R_{*,11}^{1.05}\tau_{w,*}^{1.05}\kappa_{0.2}^{-1}\ erg(\Gamma_{bo} > 1)$$

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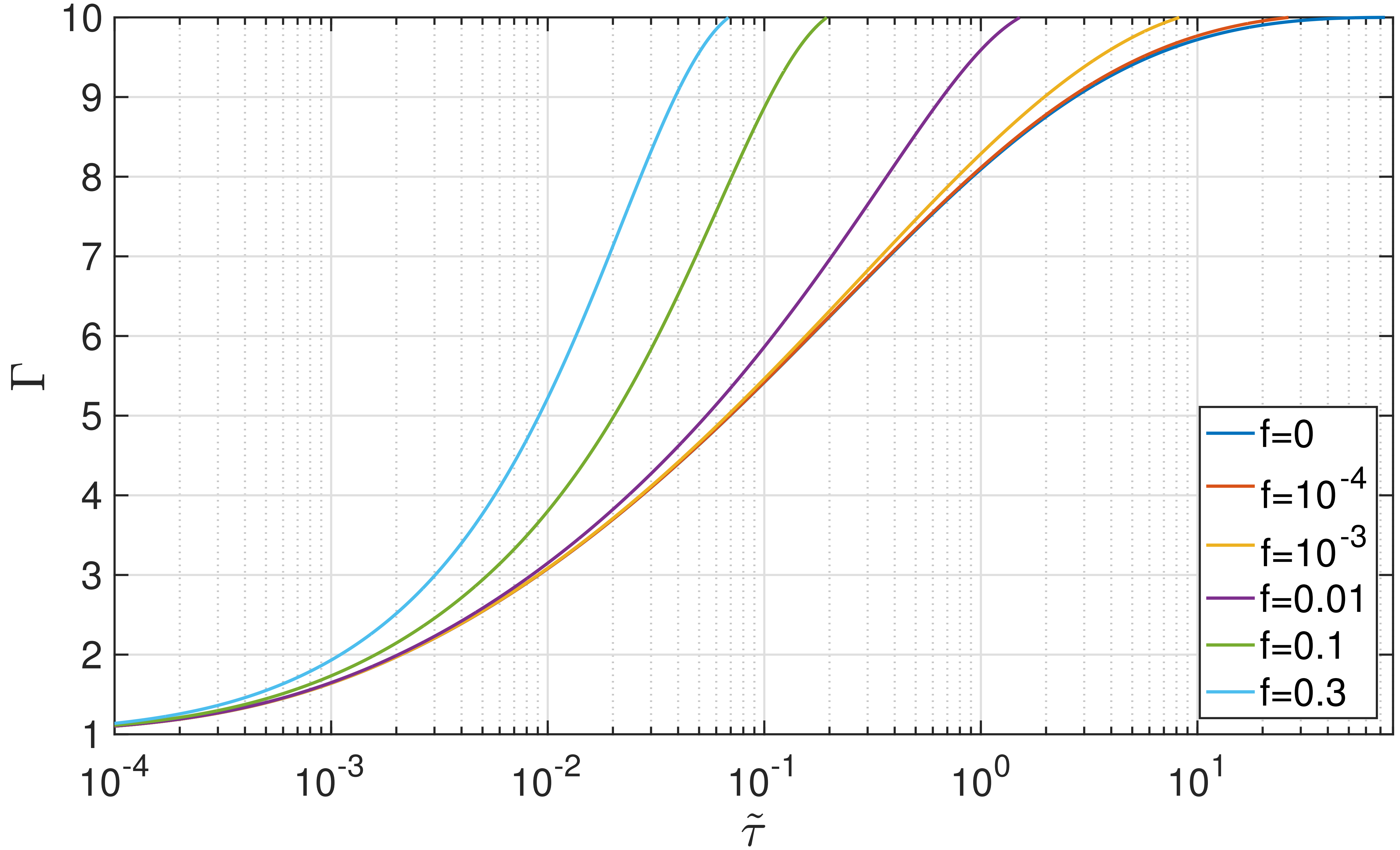

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$$\mu = \frac{m_{\rm e}}{m_{\rm p}}$$

$\Delta\tau \propto \Gamma_u f^{-1}$

Breakout optical depth: $\tau_{bo} \sim (m_e / m_p)\,\Gamma_{bo}$

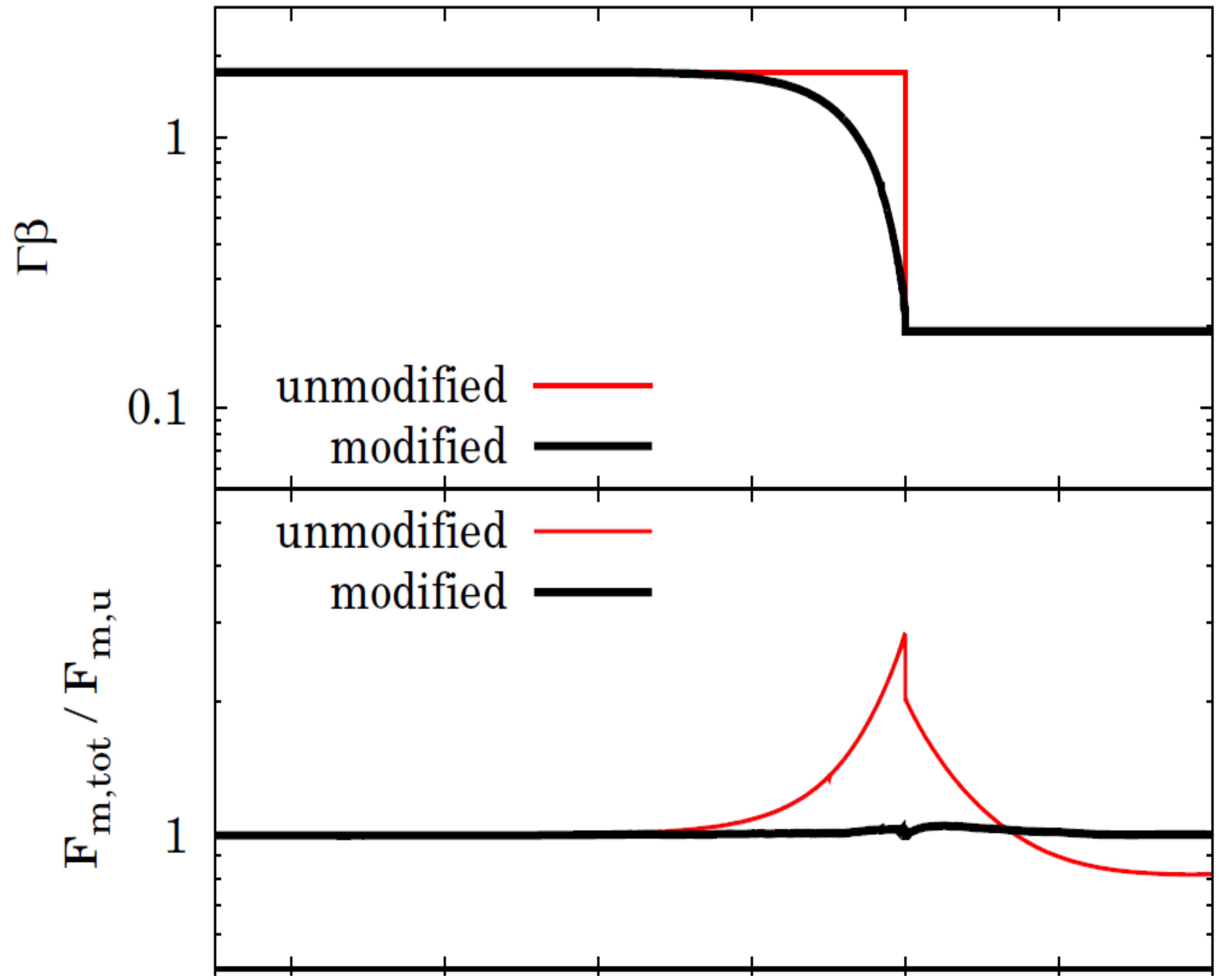
However

- Several crude approximations
- No numerical solution that can calibrate solutions fesc >0
- Spectra cannot be evaluated

This study

Monte Carlo simulations of RRMS for fesc > 0

Numerical method HI et al. 2018, 2020a,2020b



Give plasma profile (n,T,Γ)

↓

Solve radiation transfer using Monte-Carlo Method

↓

Evaluate deviation from energy-momentum conservation

feedback

Iterate until convergence is achieved

Microphysics

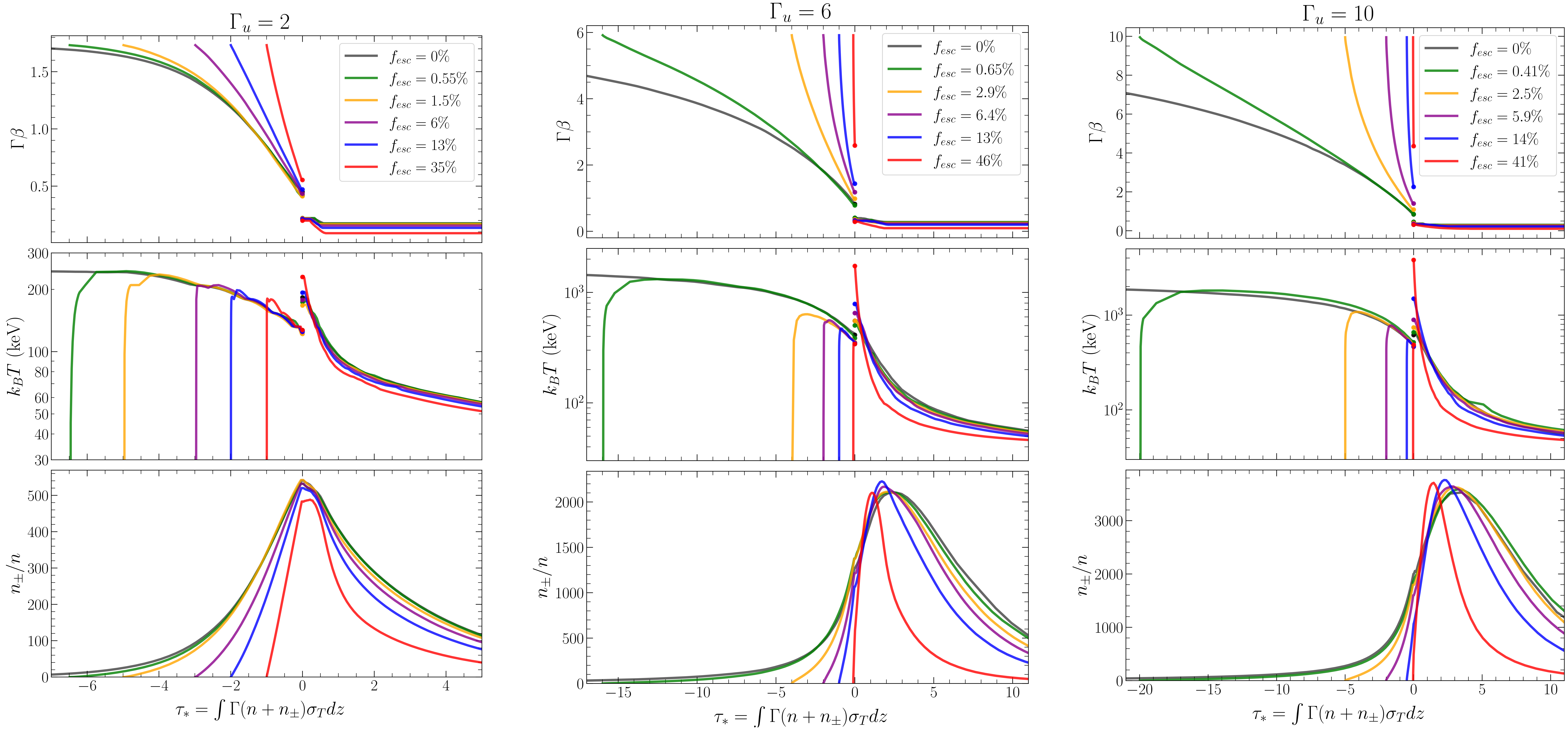
- Compton scattering with full Klein-Nishina cross section
- free-free emission & absorption
- **e^- - e^+** production & absorption

Assumptions

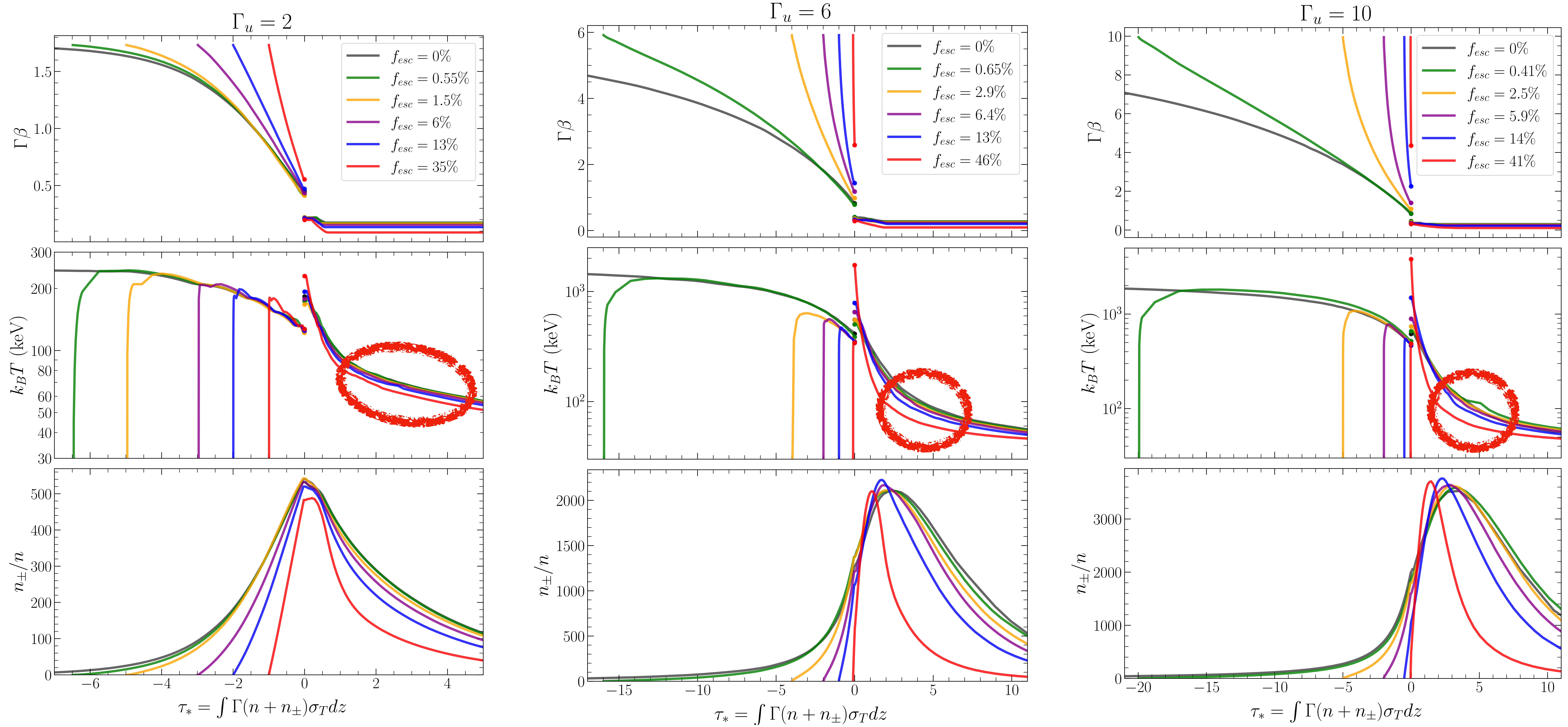
- pure **p-e** plasma upstream
- **p-e(-e^+)** are single fluid with same temperature
- **p-e -(e^+)** obey Maxwell distribution

Likely to breakdown near the subshock and when numerous pairs are present (Levinson + 2020)

RRMS with photon escape

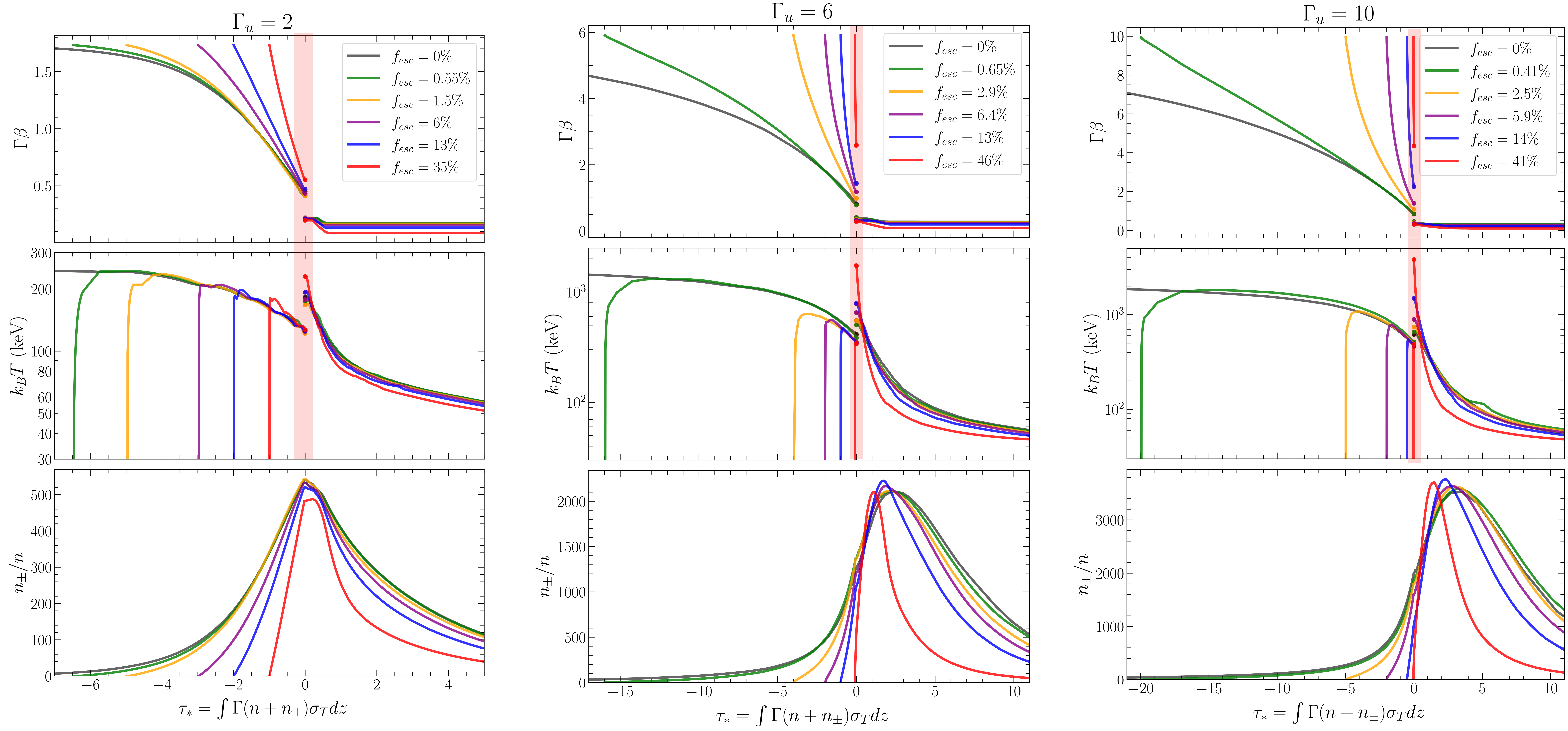


RRMS with photon escape



T_d ~100-200 keV , regardless of f_{esc}

RRMS with photon escape



Strength of subshock $[\Gamma\beta]_{sub}$ increases with f_{esc}

RRMS with photon escape

Spectra of escaped photons

- **E_p ~ $m_e c^2$** is stable for due to regulation by pairs

RRMS with photon escape

Spectra of escaped photons

- $E_p \sim m_e c^2$ is stable for due to regulation by pairs
- Substantially softer than Wien or Blackbody below the peak $f_\nu \propto \nu^0$

RRMS with photon escape

Spectra of escaped photons

- **$E_p \sim m_e c^2$** is stable for due to regulation by pairs
- Substantially softer than Wien or Blackbody below the peak $f_\nu \propto \nu^0$
- High energy extension at hv > E_p due to Comptonization at subshock

Comparison with GLN18

- Contrary to expectation, **gap between GLN18 and numerical solutions increases with Γ**
- gap increases with fesc

shock width Δτ beomes more than an order of magnitude smller than GLN18

Comparison with GLN18

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shock width Δτ beomes more than an order of magnitude smller than GLN18

<u>Reason：Change in the deceleration mechanism</u>

small **Γ, fesc** ： **collision between**

counterstreming photon ($\varepsilon \sim m_e c^2$) and advected plasma and photon

large **Γ, fesc**： **collision among** counterstreming photons

bulk of photons ($\varepsilon \sim m_e c^2$) and upscattered photons at subshock($\varepsilon > m_e c^2$)

Comparison with GLN18

GLN18

$$\Delta\tilde{\tau} \sim (m_e/m_p)\Gamma_u f_{esc}^{-1}$$

This study

$$\Delta\tilde{\tau} \approx 1.0\times 10^{-2}\Gamma_u^{-2} f_{esc}^{-1.6}, \quad (6 \lesssim \Gamma_u \lesssim 10)$$

Closure relation:

GLN18: $$E_{\rm bo} \approx 10^{48}\kappa_{0.2}^{-1}\left(\frac{t_{\rm bo}}{1\,{\rm s}}\right)^2\left(\frac{T_{\rm obs,bo}}{2\,{\rm MeV}}\right)^7 \ {\rm erg}$$

This study: $$E_{bo} \approx 5.7\times 10^{46}\kappa_{0.2}^{-1}\left(\frac{t_{bo}}{1.7\,{\rm s}}\right)^2\left(\frac{kT_{obs}}{1.7\,{\rm MeV}}\right)^4 \ {\rm erg}$$

Spherical relativistic explosion model：

GLN18:

$$t_{bo} \approx 1.6\times 10^3 E_{53}^{-5.1} M_{\rm ej,5}^{3.6} R_{*,11}^{3.85}\tau_{w*}^{3.86}\ {\rm s}$$

$$T_{\rm obs,bo} \approx 250 E_{53}^{1.7} M_{\rm ej,5}^{-1.2} R_{*,11}^{-0.95}\tau_{\rm w,*}^{-0.95}\ {\rm keV}$$

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This study:

$$t_{bo} \approx 1.7\times 10^2 R_{*,11}\tau_{w*} \quad {\rm s.}$$

$$kT_{obs} \approx 330 E_{53}^{0.7} M_{ej,5}^{-0.49} R_{*,11}^{-0.39}\tau_{w*}^{-0.39}\ {\rm keV}$$

$$E_{bo} \approx 8.1\times 10^{47}\kappa_{0.2}^{-1} E_{53}^{2.8} M_{\rm ej,5}^{-2} R_{*,11}^{0.44}\tau_{w*}^{0.43} \quad {\rm erg}$$

Comparison with GLN18

GLN18	This study
$\Delta\tilde{\tau} \sim (m_e/m_p)\Gamma_u f_{esc}^{-1}$	$\Delta\tilde{\tau} \approx 1.0 \times 10^{-2}\Gamma_u^{-2} f_{esc}^{-1.6}, \quad (6 \lesssim \Gamma_u \lesssim 10)$

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$E_{53} = 5$

$t_{bo} \approx 0.42{\rm s}$

$\Gamma_{bo} \approx 19\ (kT_{obs} \approx 3.3\,{\rm MeV})$

$t_{bo} \approx 170{\rm s}$

$\Gamma_{bo} \approx 6\ (kT_{obs} \approx 1\ {\rm MeV})$

$$T_{\rm obs,bo} \approx 250 E_{53}^{1.7} M_{\rm ej,5}^{-1.2} R_{*,11}^{-0.95} \tau_{\rm w,*}^{-0.95}\ {\rm keV}$$

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Summary

- Detail shock structure RRMS with photon escape in is computed

- Shock width shrinks as Γ, fesc increases

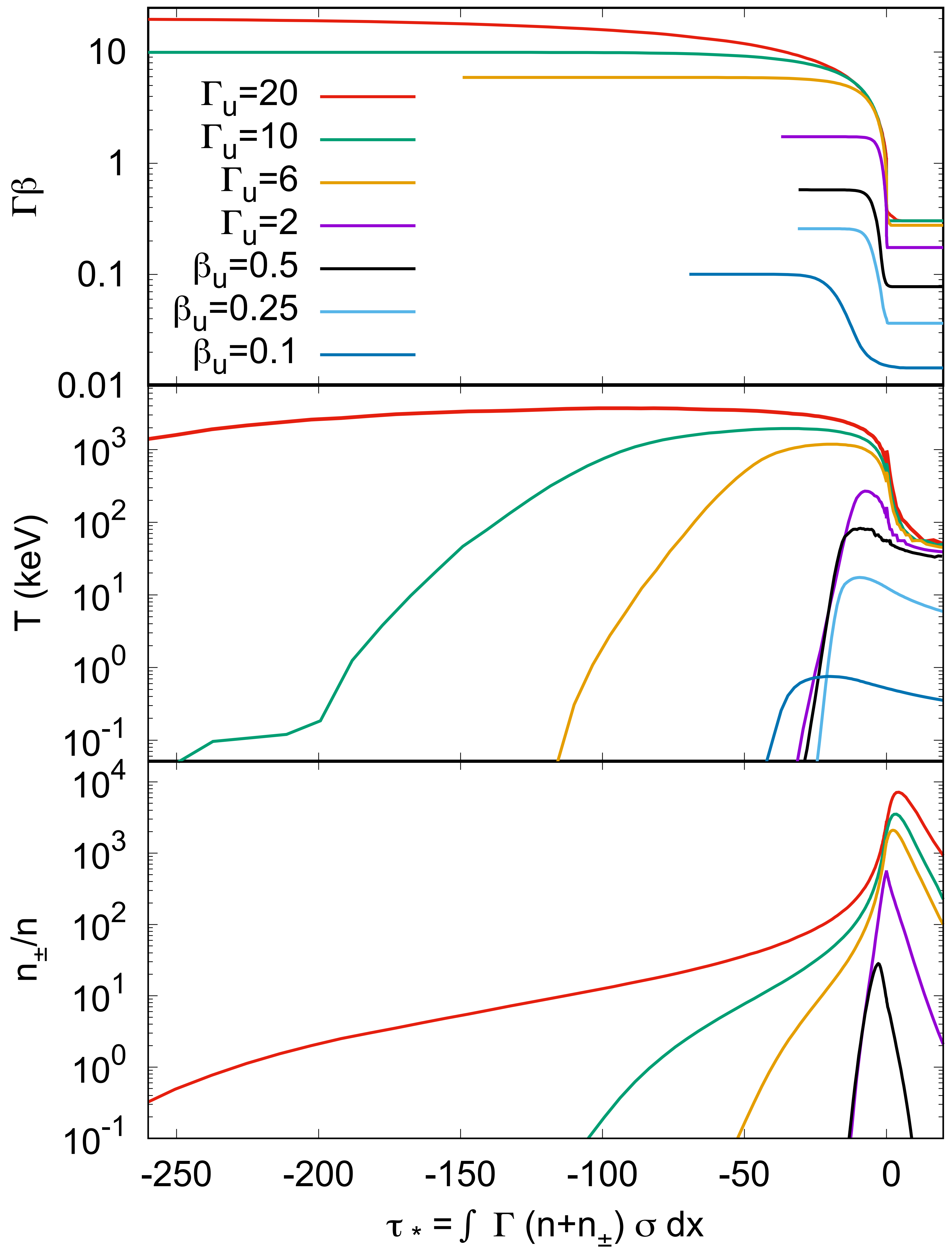
- Spectrum is far from thermal (Wien or Blackbody)

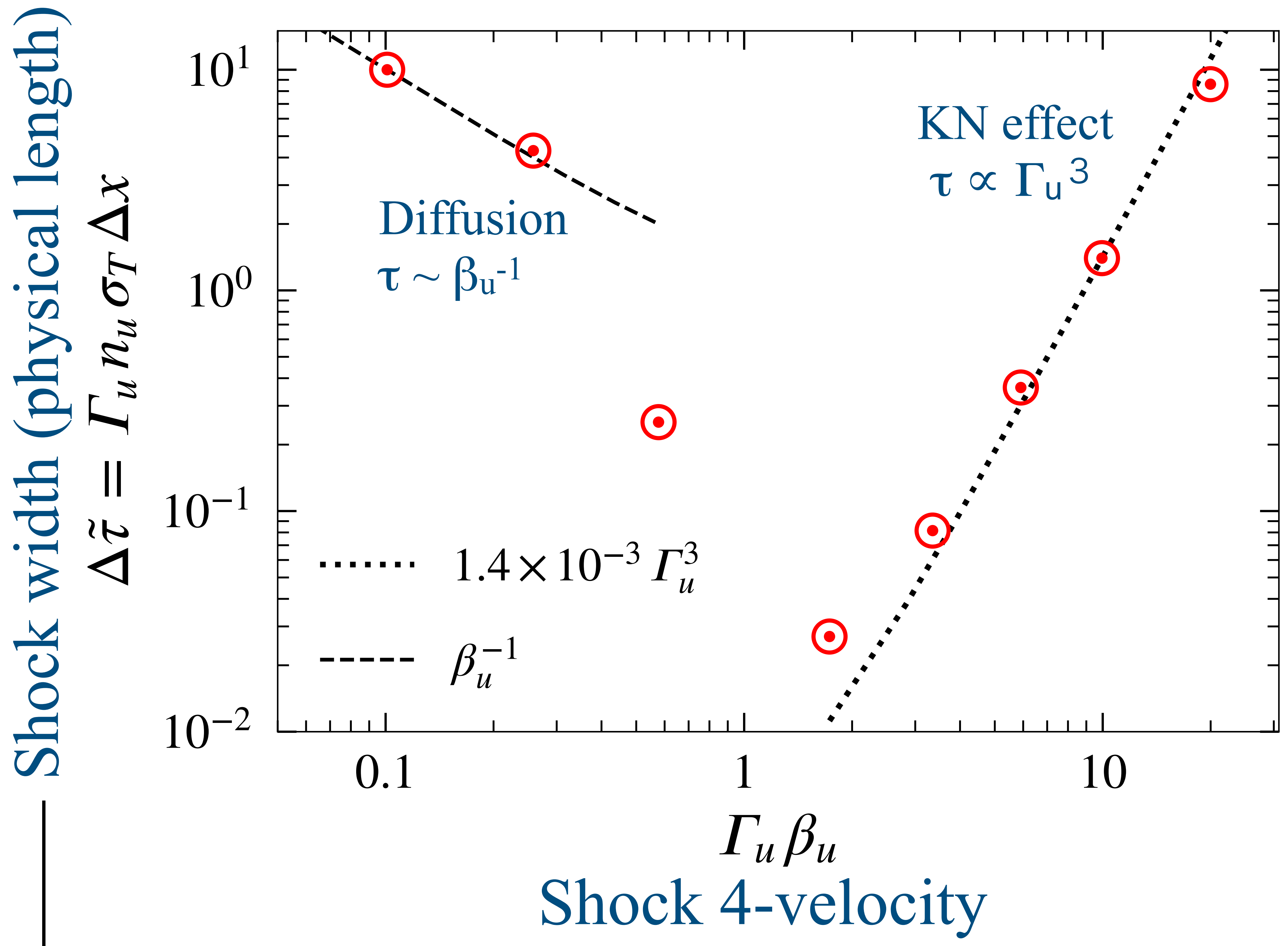
  Substantially softer than Wien or Blackbody below the peak $f_\nu \propto\sim \nu^0$
  High energy extension due to subshock

- Updates the previous predictions by GLN18

  ~ 200 s breakout duration, insensitive to the explosion energy
  Relativistic explosion within 100 Mpc, may be detectable by MeV detector
  e.g., Fermi, Amego-X, COSI, e-ASTROGAM

Structure of RRMS (no escape: $f_{esc} = 0$)





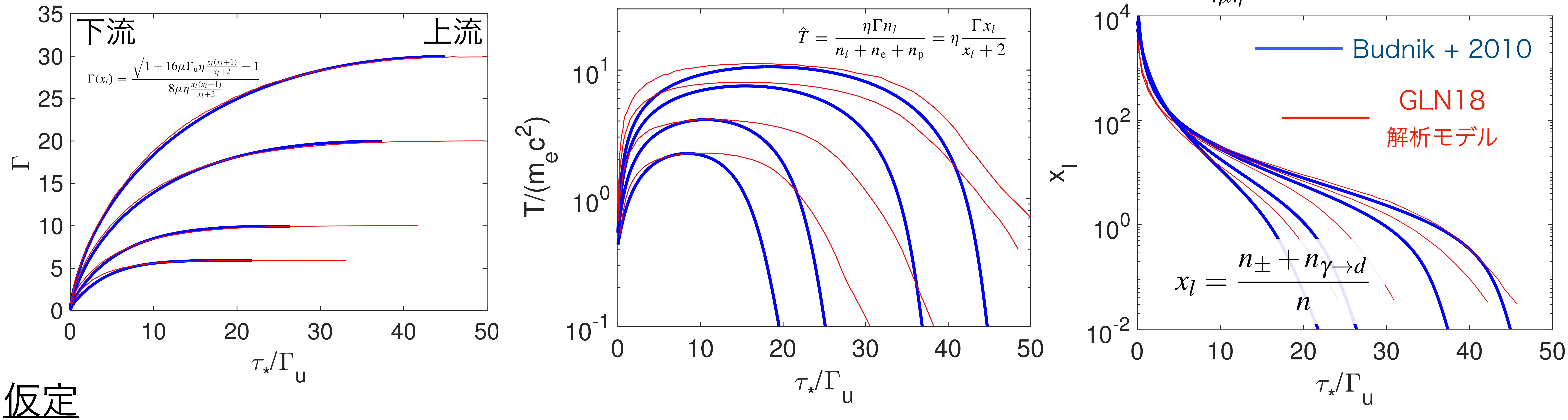
pair unloaded optical depth of shock upstream at which shock breakout commences

measured in upstream rest frame

Analytical Model of Granot, Levinson, Nakar 2018 (GLN18)

Budnik + 2010の計算を再現する解析モデル

$x_l = \frac{\Gamma_u}{4\mu\eta}e^{-\tau}$



仮定

- **Γ >> 1 , 定常**
- 下流の温度　Td ~ 100 - 200 keV => 　couterstreaming photon energy **$\varepsilon_\gamma \sim m_e c^2$**
- 上流に向かう光子は、scatterback もしくはpair productionを起こして、上流plasmaとともにadvectする
  pair と advected photonがそれぞれscattering opacity と pair production opacity となる
- Scatterback もしくはpair になった光子は、**$\sim \eta\,\Gamma m_e c^2$ の熱エネルギーを上流にdeposit**する　($\eta \sim 1$)

$$\frac{dx_l}{d\tau} = -(x_l + x_{esc})$$

$$\Gamma(1+(x_l+1)\mu\hat{T}) = \Gamma_u$$

$$\mu = \frac{m_e}{m_p}$$

Structure of RRMS (no escape: $f_{esc} = 0$)

Comparison with Analytical Model of Granot, Levinson, Nakar 2018

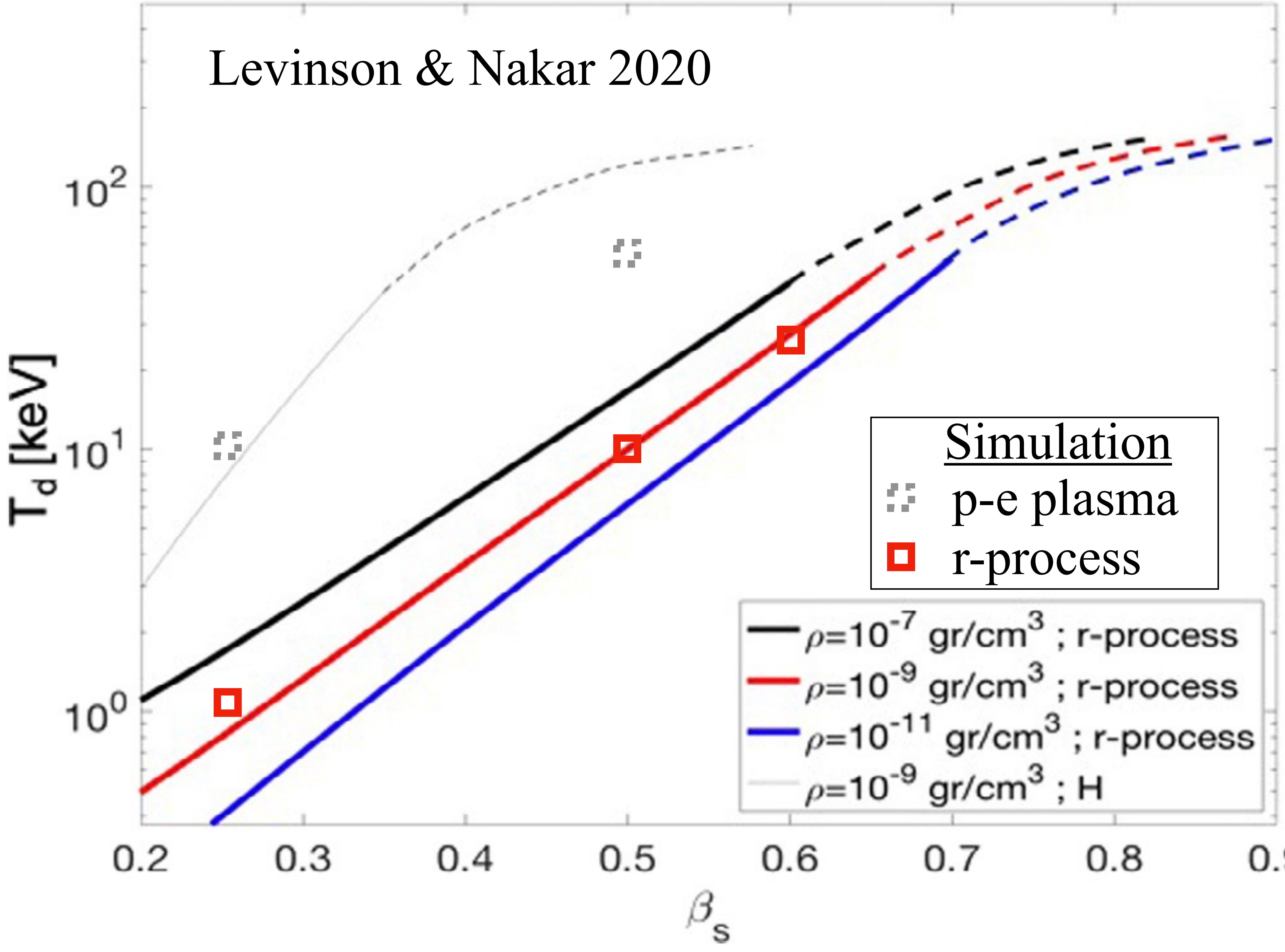
Effects of r-process elements

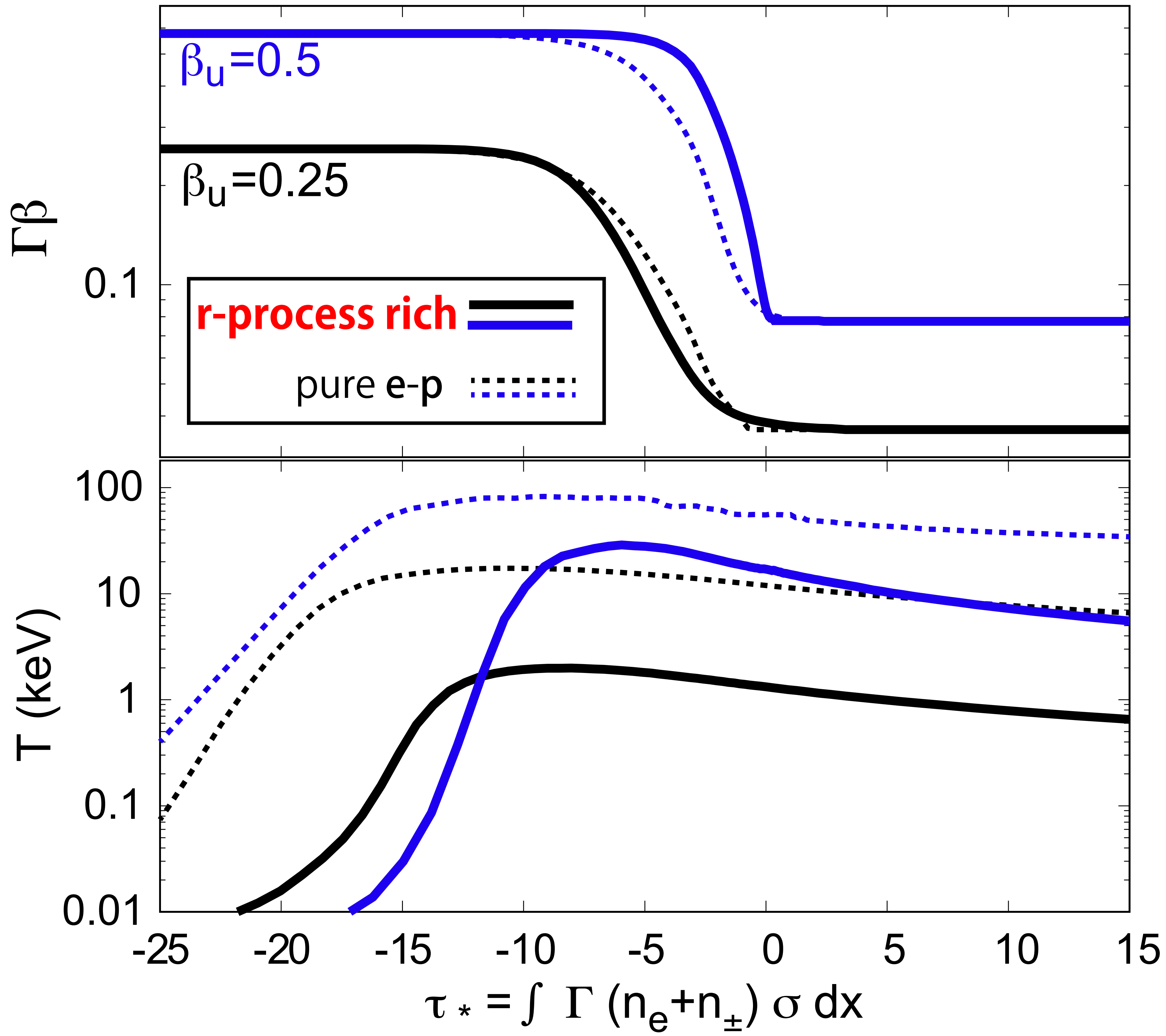
Bremsstrahlung photon production rate

$$\dot{n}_{ff} \approx 4 \times 10^{36}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-3} \frac{\langle z\rangle \langle z^2\rangle}{\langle A\rangle^2} \rho_d^2 T_d^{-1/2} \Lambda_{ff}$$

$\langle z\rangle \langle z^2\rangle / \langle A\rangle^2 \approx 10$ for r- process element

$\langle z\rangle \langle z^2\rangle / \langle A\rangle^2 = 1$ for e-p plasma

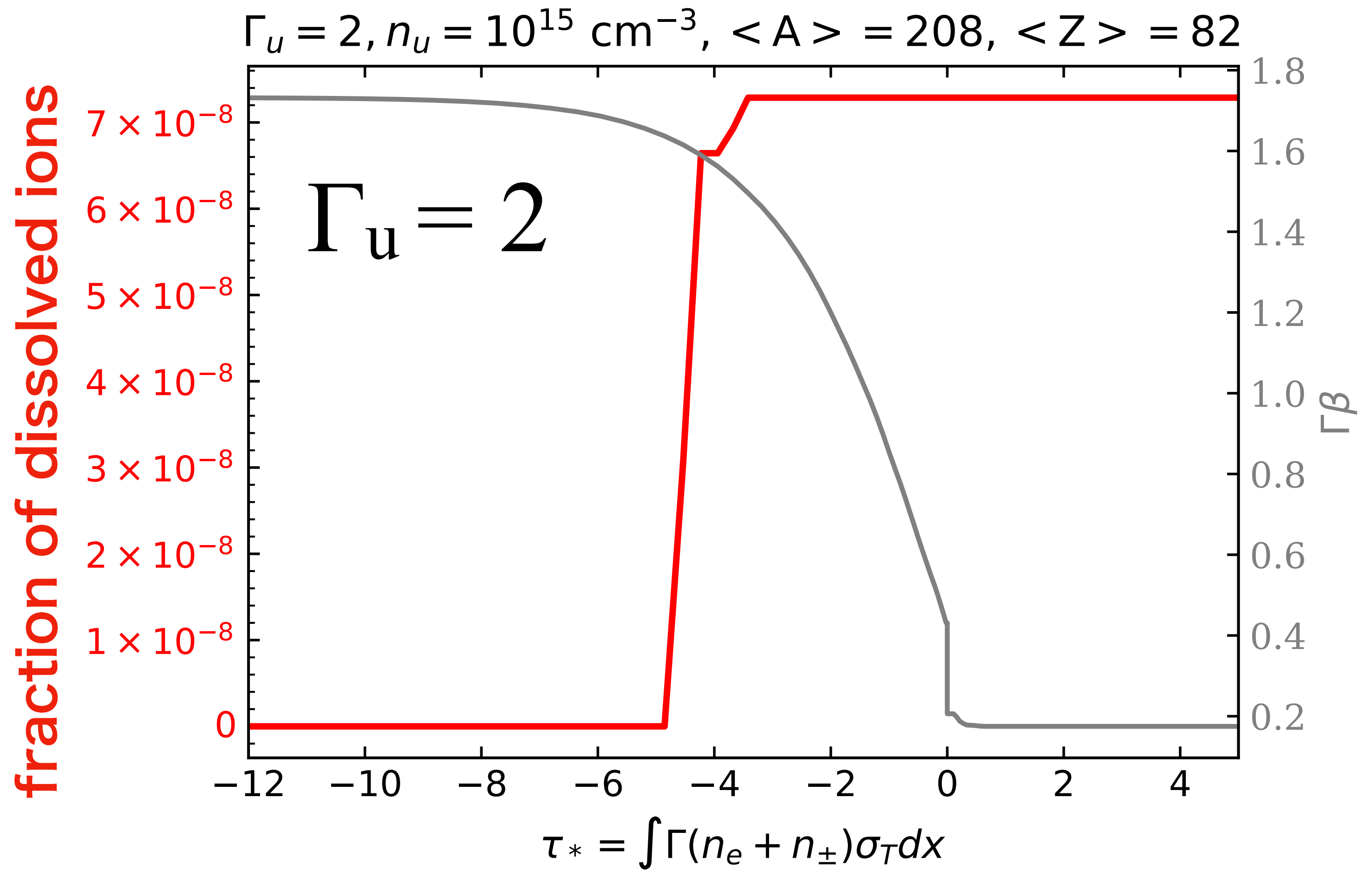


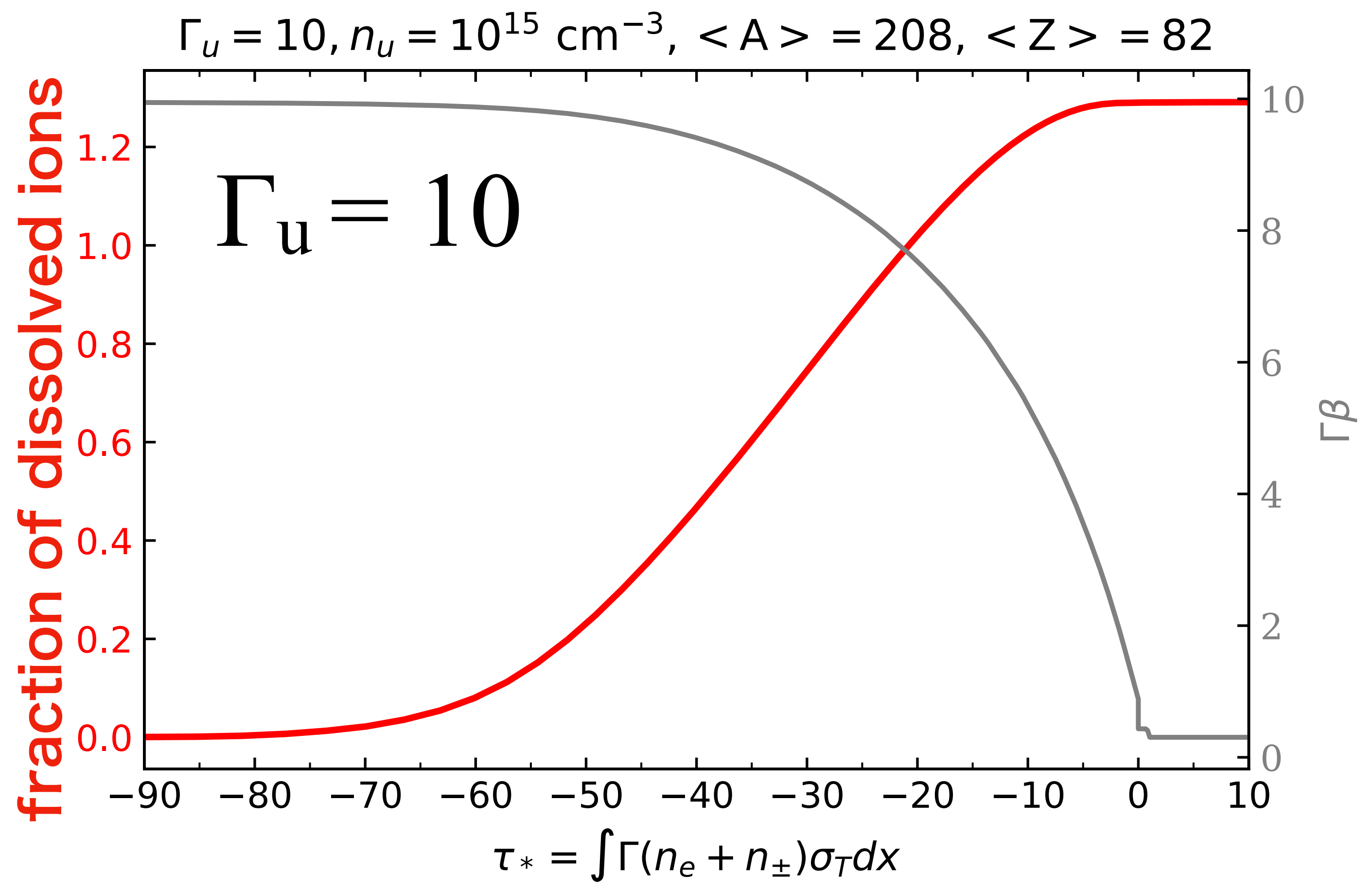


On the possibility of photo-disintegration

Departure from thermal spectrum may dissolve r-process elements

However, we find the effect is negligible for $\Gamma_u < 6$

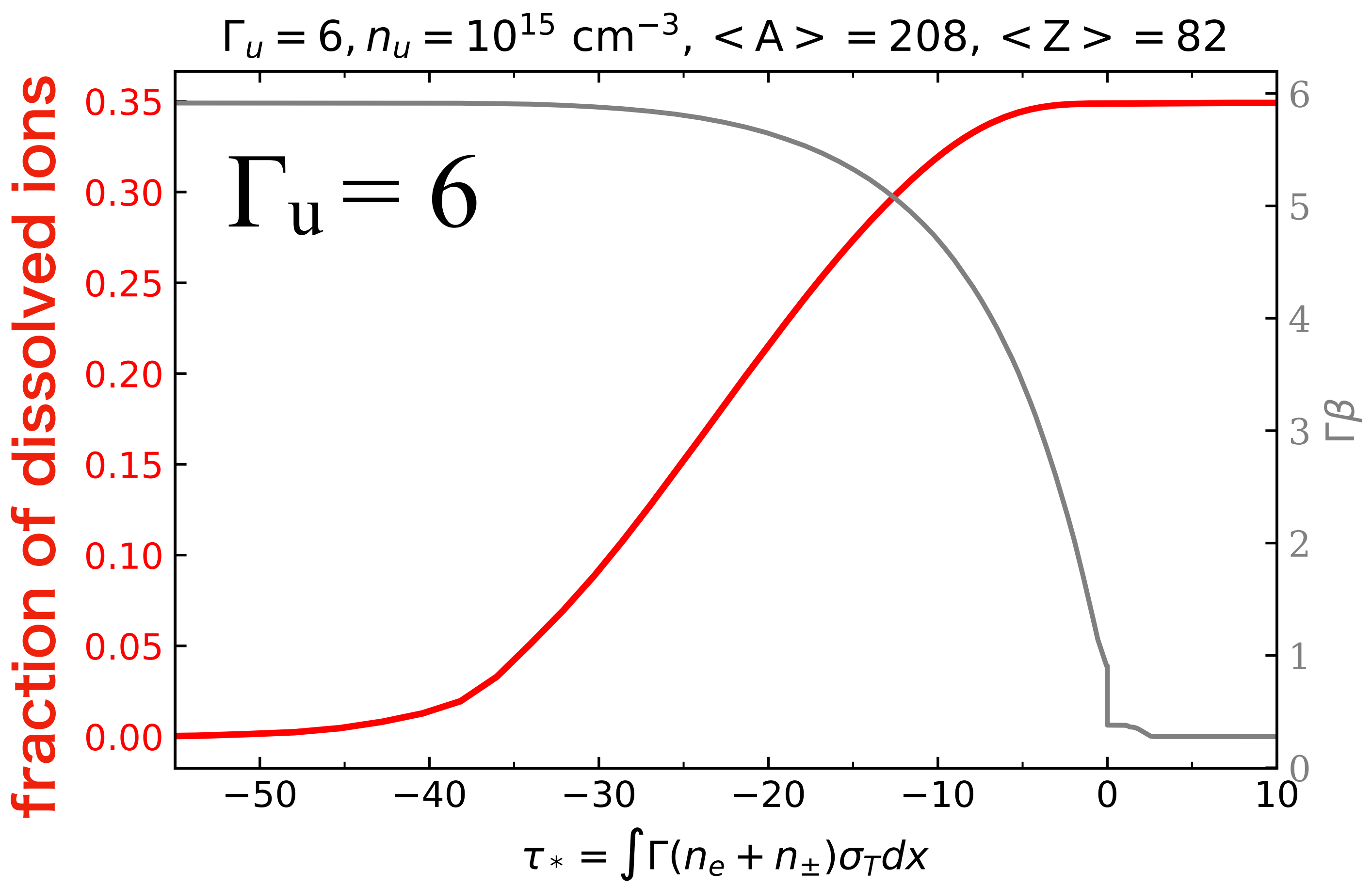


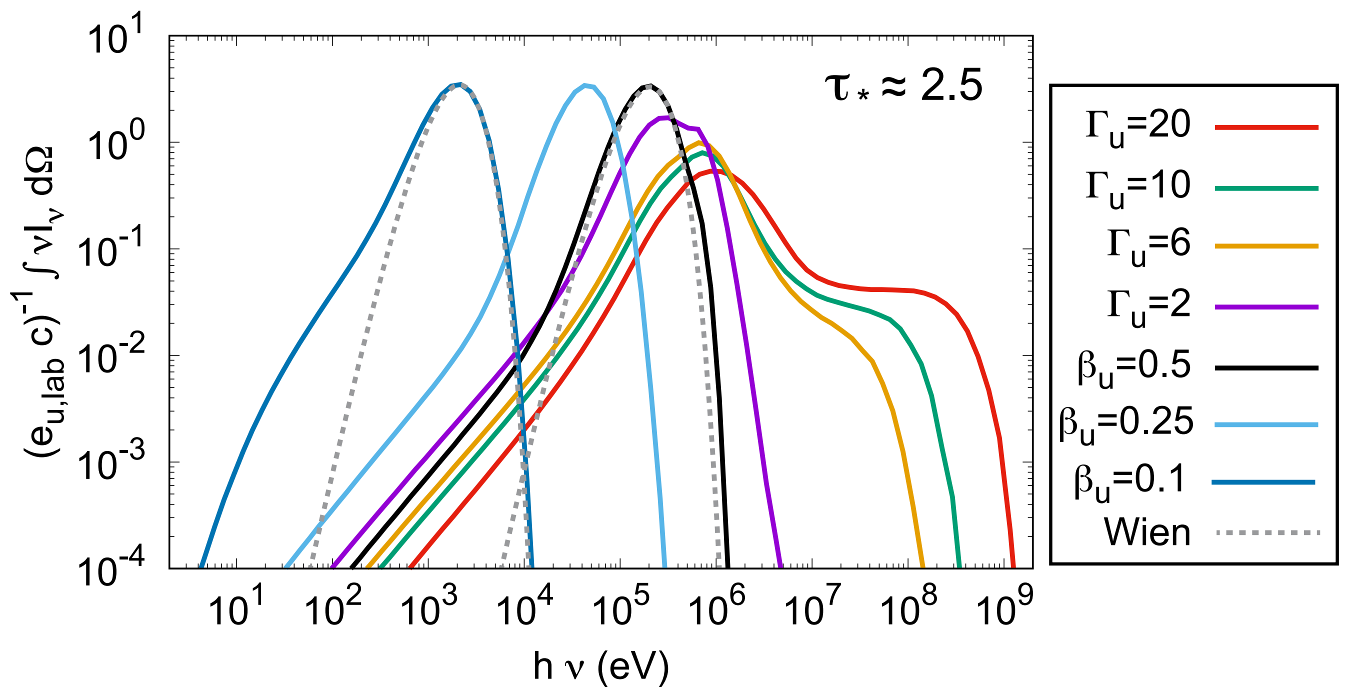


Assumption

Heaviside function for the cross section of photodisintegration

$$\sigma_{ph} = 15 \text{ mb for } h\nu > 8\text{MeV}$$



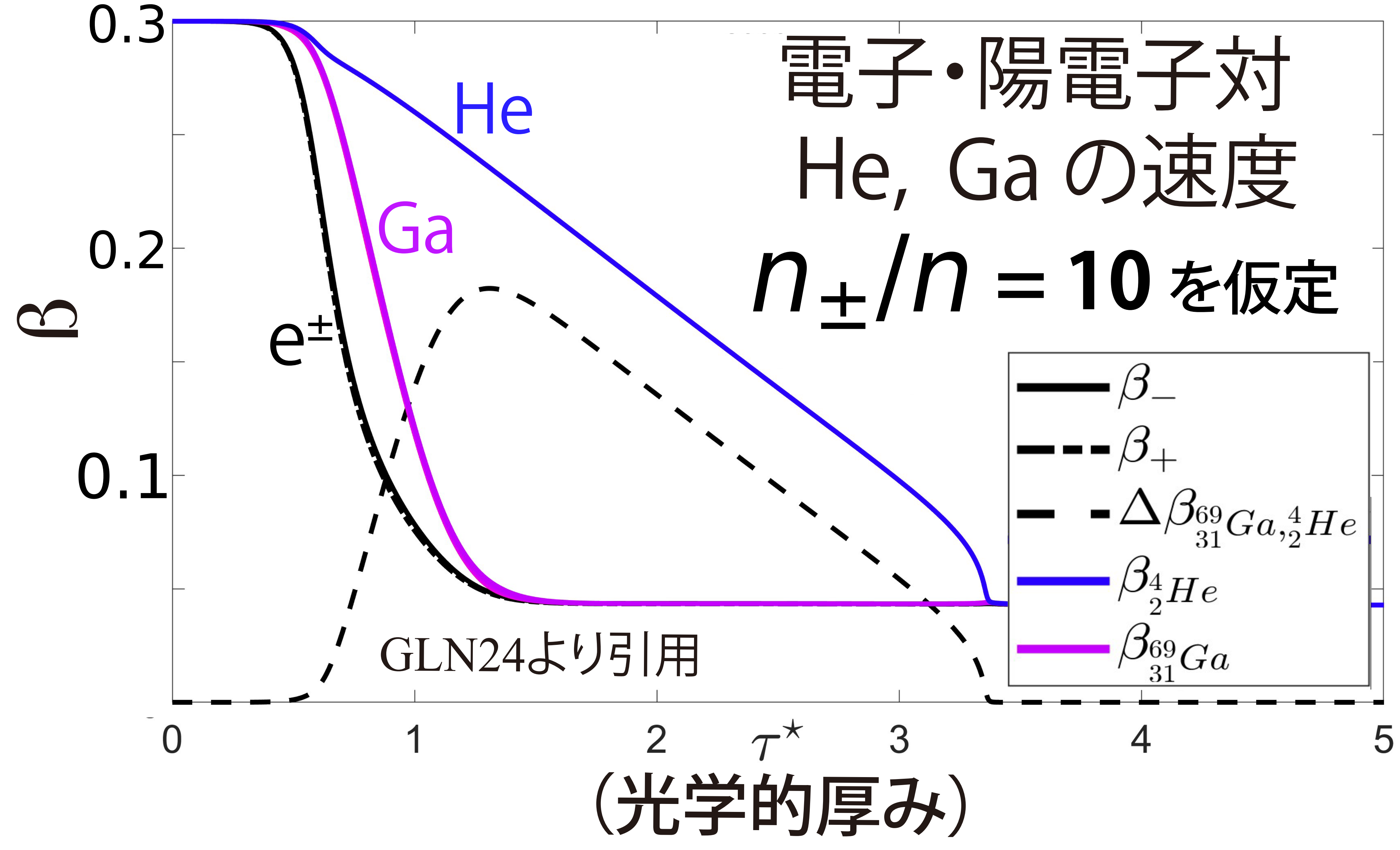


On the possibility of fission/fusion by ion-ion collision

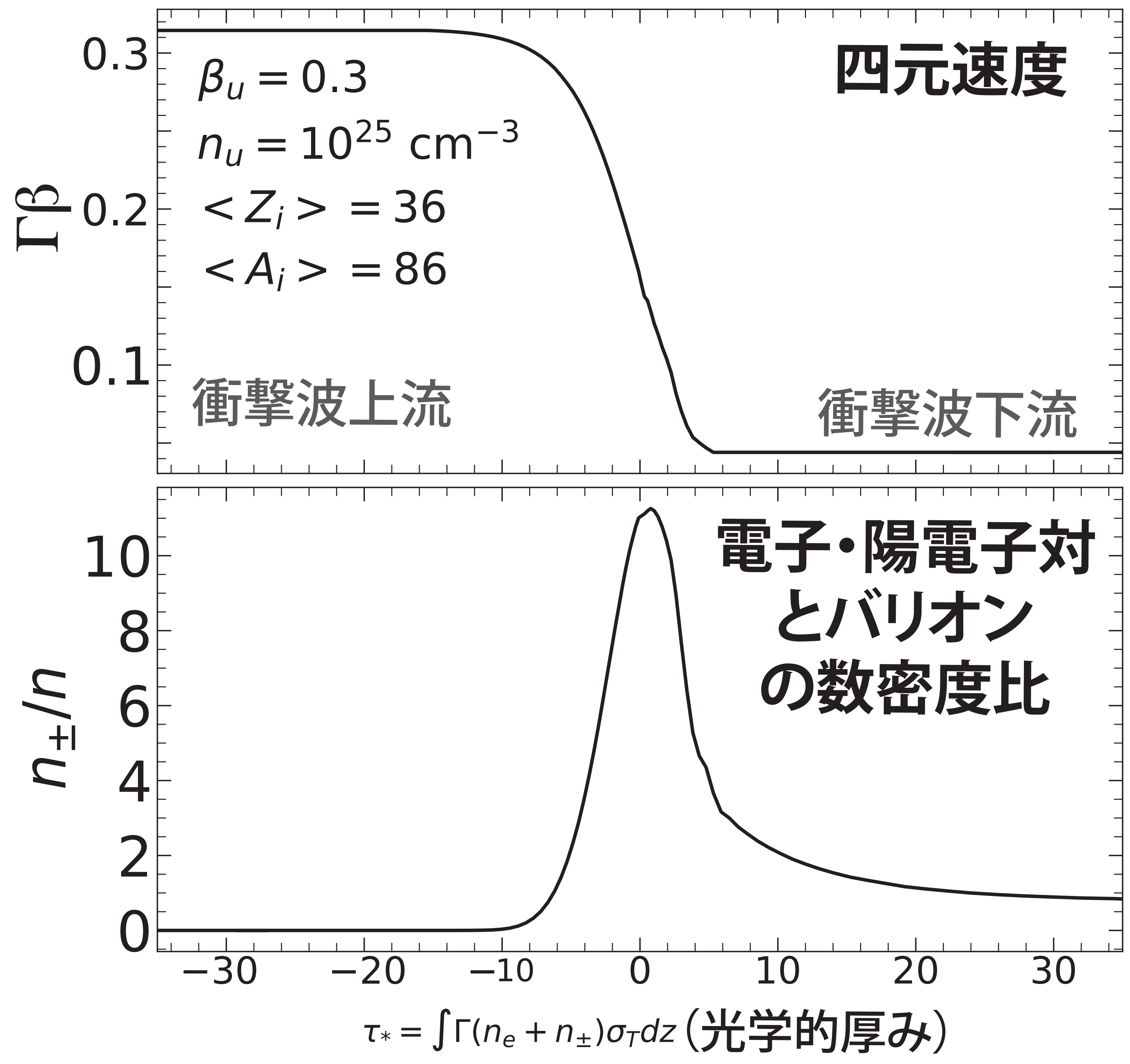
(Granot et al. 2024)

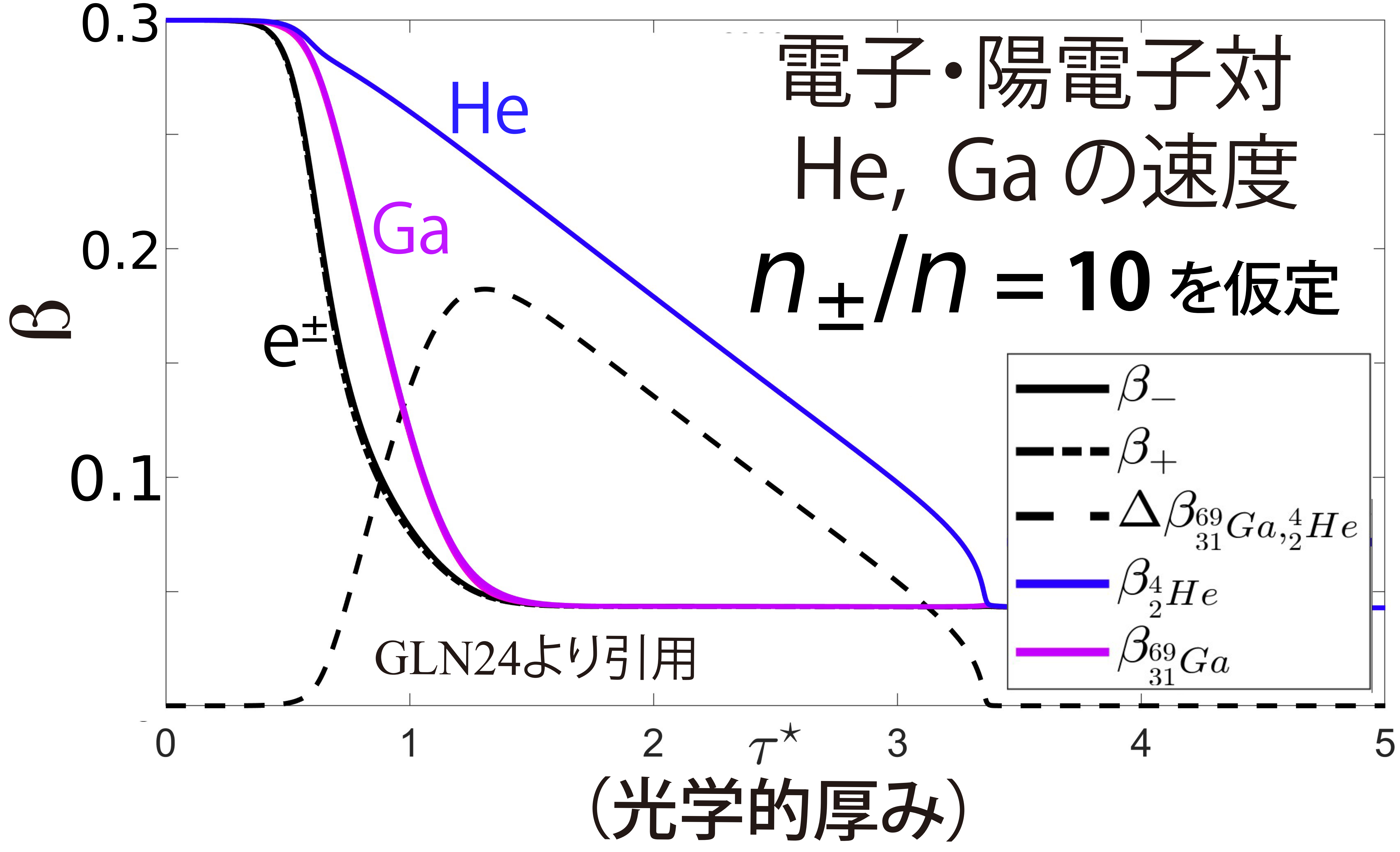
shock is fast enough, $\beta_u \gtrsim 0.2$, collisions between neutron rich isotopes just behind the shock can trigger fission and fusion, leading to

Granot et al. 2024 (Analytical Multi-fluid)

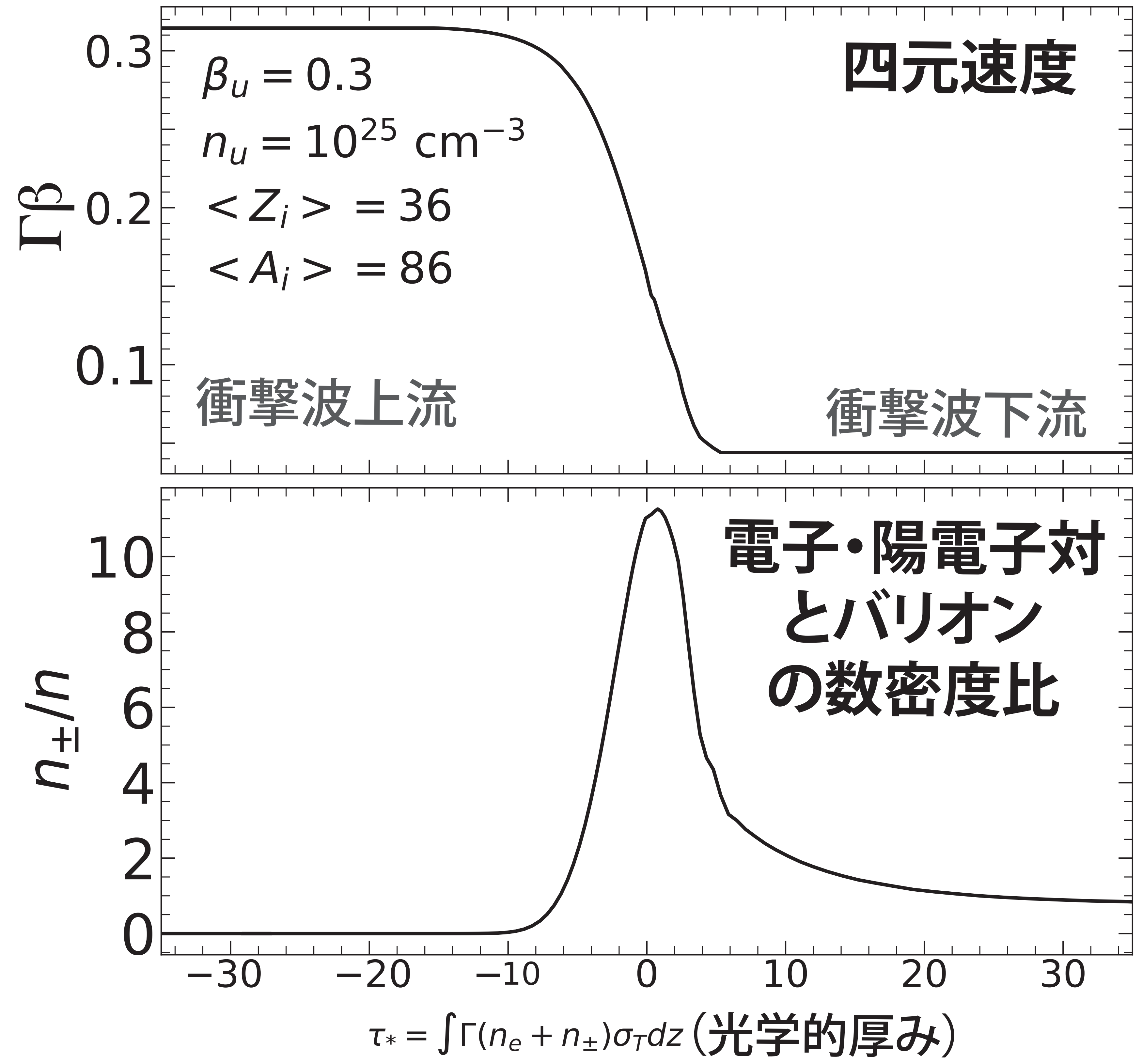


Simulation Single-fluid





電子・陽電子対
He, Ga の速度
$n_\pm/n = 10$ を仮定
He
Ga
$e^\pm$
GLN24より引用
β_-
β_+
$\Delta\beta_{^{69}_{31}Ga,^{4}_{2}He}$
$\beta_{^{4}_{2}He}$
$\beta_{^{69}_{31}Ga}$
β
0.3
0.2
0.1
0 1 2 3 4 5
$\tau^\star$
(光学的厚み)



四元速度
$\beta_u = 0.3$
$n_u = 10^{25}\ \mathrm{cm}^{-3}$
$< Z_i > = 36$
$< A_i > = 86$
衝撃波上流
衝撃波下流
Γβ
電子・陽電子対
とバリオン
の数密度比
$n_\pm/n$
$\tau_* = \int \Gamma(n_e + n_\pm)\sigma_T dz$ (光学的厚み)