Relativistic Radiation Mediated Shocks

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Collaborators

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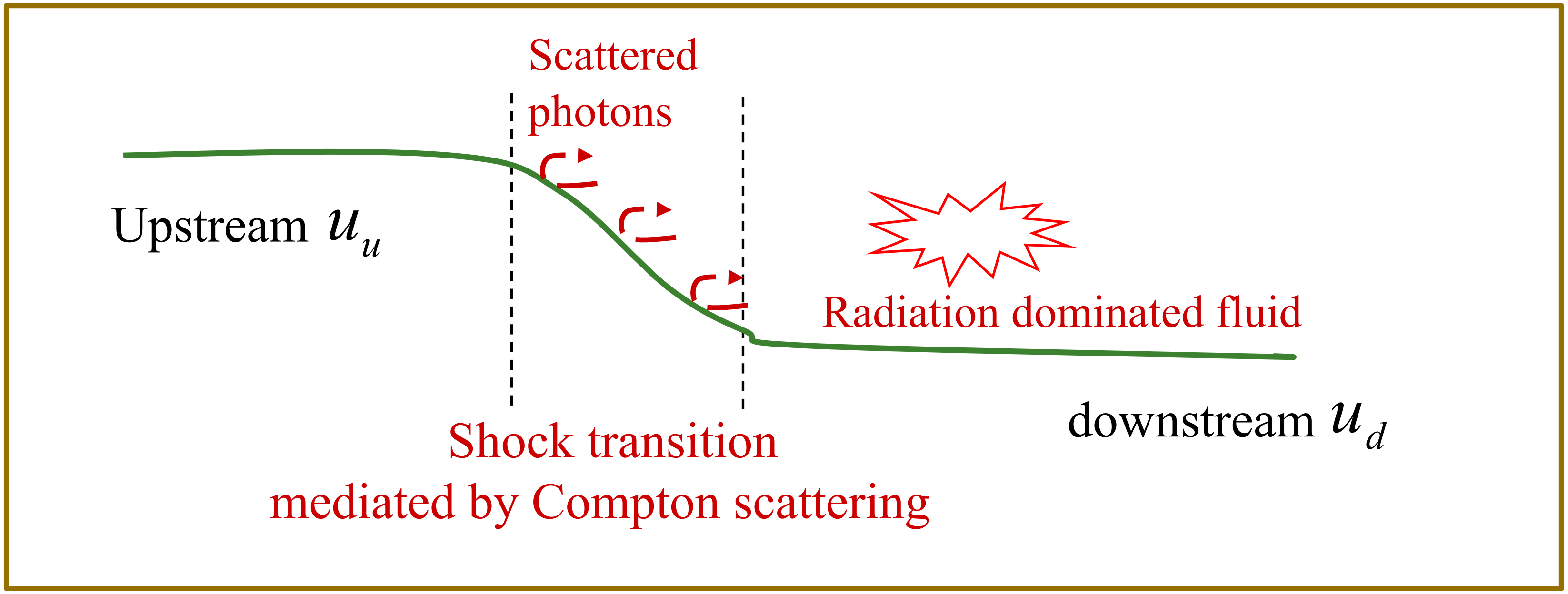
Plan of this talk

- Introduction
  - Brief overview of Radiation Mediated Shocks (RMS)
  - Photon rich and photon starved regime
  - Non-relativistic and Relativistic RMS (RRMS)
  - Motivation
- Self-consistent calculation of RRMS
  - Method for deriving steady solution for RRMS
  - Photon rich regime
  - Photon starved regime
- Summary

Radiation Mediated Shocks (RMS)



Scattered photons

Upstream u_u

Radiation dominated fluid

downstream u_d

Shock transition mediated by Compton scattering

- 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 be altered by PP and KN)

Why is it interesting?

- The conditions required to form RMS are always satisfied below the photosphere of fast flows
- properties of RMS are vastly different than those of collisionless shocks

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

Shock breakout

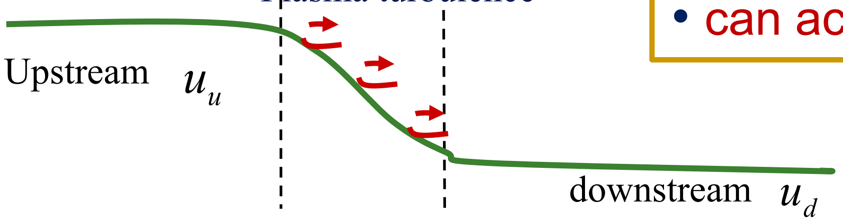
- Transition from RMS to collisionless shock..
- Breakout signal depends on structure of RMS

Breakout when $\tau \sim 1/\beta_u$

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

Collisionless shocks .vs. RMS

collisionless



Plasma turbulence

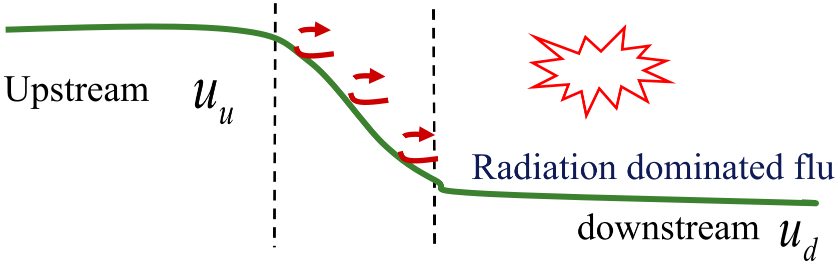
Upstream u_u

downstream u_d

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



Scattered photons

Upstream u_u

Radiation dominated fluid

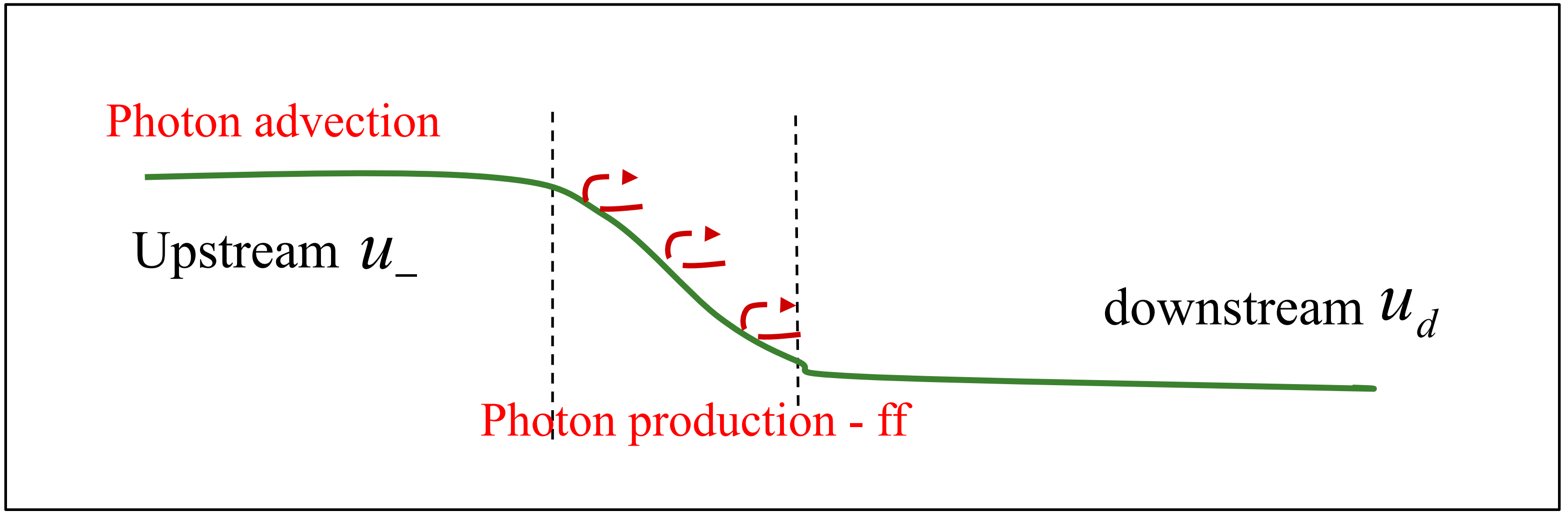
downstream u_d

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, NS merger)
- Photon rich shocks: photon advection by upstream fluid (GRBs)



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 numerical calculation of RRMS

Photon Rich regime : photons advected from the upstream is dominant

Levinson & Bromberg (2008)

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

Beloborodov (2017)

Full radiation transfer, effects of magnetic field considered,
pair production neglected

Lundman et al. (2018)

Full radiation transfer, pair production effect included,
some approximation is given on the temperature calculation

Ito et al. (2018)

Full radiation transfer with pair production, no optimistic approximation
wide range of upstream condition is covered

Photon Starved regime : photons produced in the downstream is dominant

Budnik et al. (2010)

Full radiation transfer with pair production and bremsstrahlung emission
some assumption on cross sections. $6 < \Gamma < 30$

All studies consider Infinite shocks:
Shock Breakout simulation has not been performed

Self-consistent numerical calculation of RRMS

Photon Rich regime : photons advected from the upstream is dominant

Ito et al. (2018) Infinite shock

Full radiation transfer with pair production, no optimistic approximation

wide range of upstream condition is covered

$2 < \Gamma_u < 10$, $0.01 < \xi_u < 10$, $10^3 < n < 10^5$

Ito et al. in prep I ., finite shock (shock breakout)

Simulation with photon escape (shock breakout)

structure, spectra, application to GRBs

Photon Starved regime : photons produced in the downstream is dominant

Ito et al. in prep II ., Infinite shock

Full radiation transfer with pair production,
free-free emission + *absorption,* no optimistic approximation

Self-consistent numerical calculation of RRMS

Photon Rich regime : photons advected from the upstream is dominant

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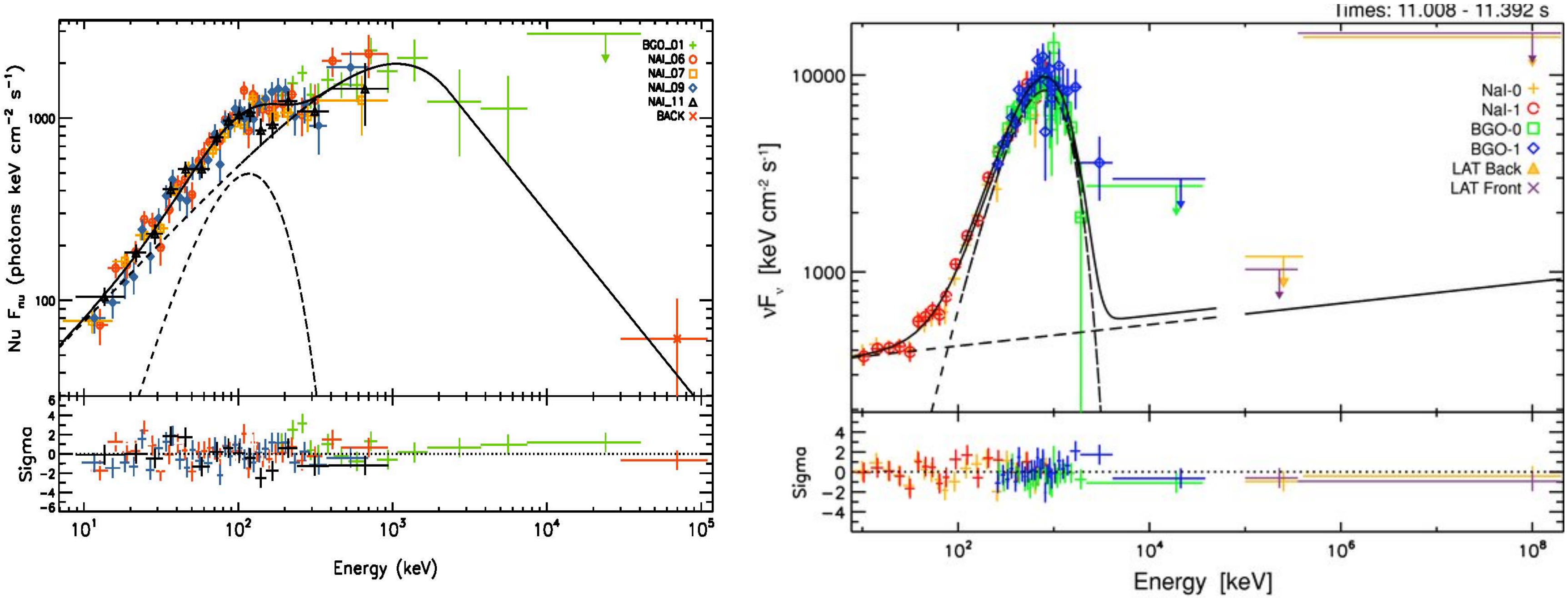
GRBs: sub-photospheric shocks

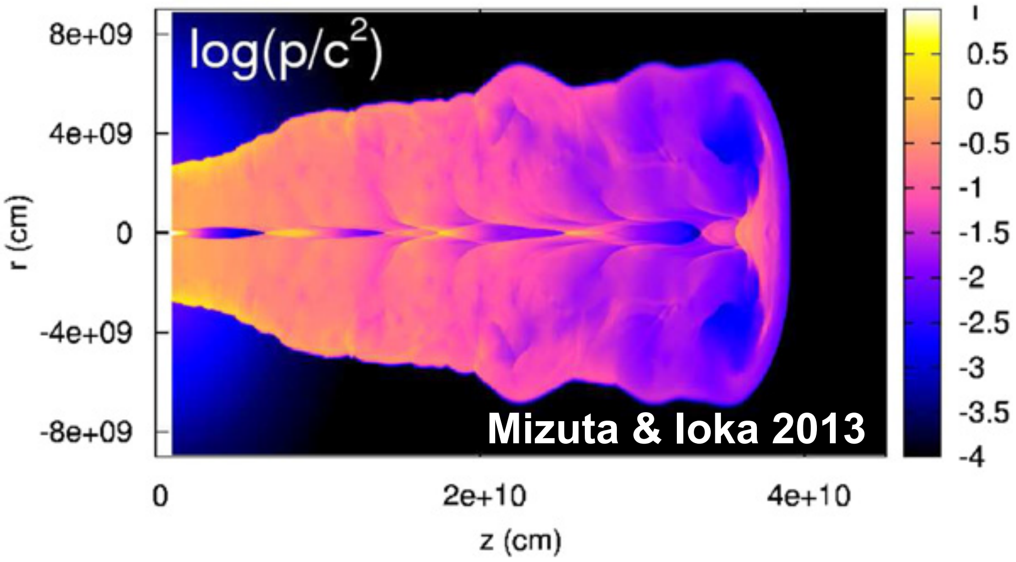
Levinson 12, Levinson & Keren 14, Beloborodov 17, HI+18

Evidence for photospheric emission ? (Peer+Ryde)

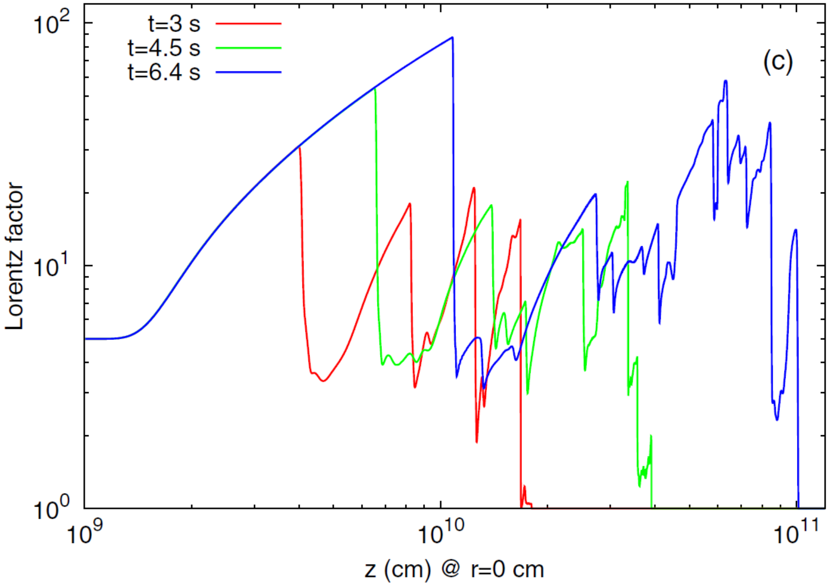


Band spectrum from photospheric emission? (Beloborodov 13, Vurm+ 13, Keren+AL 14, HI + 15, Lazzati 16, Parsotan+18)

Application to GRBs



Mizuta & Ioka 2013



RRMS naturally develops within jet

Condition for RMS to form

Weaver 1976

- Optically thick（τ>>1）
- propagation velocity

$$\beta_s \gg 4 \times 10^{-5} n_{15}^{1/6}$$

$$n = 10^{15} n_{15} \ \mathrm{cm}^{-3}$$

always satisfied for GRB fireball at subphotospheric region

(e.g., Bromberg + 2011)

RRMS in GRB fireball

Hot upstream ($n_\gamma / n_p \sim 10^4 - 10^6 \gg 1$)

Thermalization depth

$$L_T \sim \beta c \frac{n_{\gamma,\mathrm{eq}}}{Q_{\gamma,\mathrm{eff}}}$$

Photon generation: Bremst. + double Compton

Free-free: $\tau'_{\mathrm{ff}} = 10^5 \Lambda_{\mathrm{ff}}^{-1} (n_{u15})^{-1/8} \gamma_u^{3/4}$

Double Compton: $\tau'_{\mathrm{DC}} = 10^6 \Lambda_{\mathrm{DC}}^{-1} (n_{u15})^{-1/2} \gamma_u^{-1}$

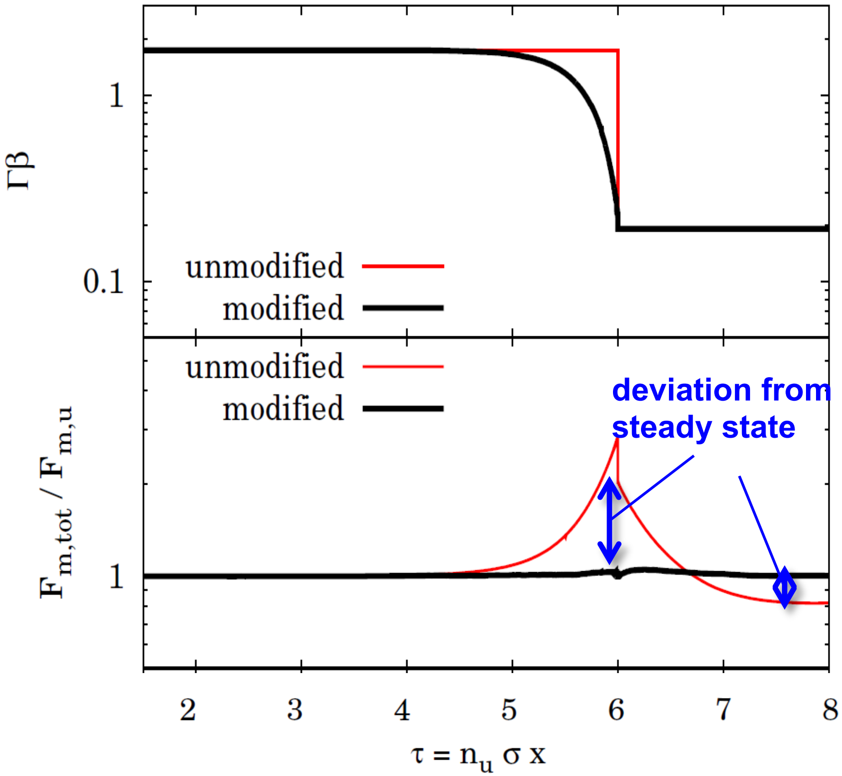
Thermalization length >> shock width ($\tau \sim$ few)

→ Photon advection dominant (Photon Rich)

(Photon generation and absorption can be neglected)

Levinson 2012

Method・Model



deviation from steady state

Give plasma profile (n,T,Γ)

↓

Solve radiation transfer using Monte-Carlo Method

↓

Evaluate the deviation from steady profile

feedback

Iterate until convergence

Assumption

- advection dominated
  (emission、absorption neglected、only scattering)
- large photon to proton ratio
  ($n_{ph} / n_p = 10^3 - 10^5$)

- pair production/annihilation included
- thermal distribution at far up stream
- electron has Maxwellian distribution

$\Gamma_u = 2 - 10$

Parameters

Γ_u : Lorentz factor of shock

$\tilde{n} = n_{ph} / n_p$: photon to baryon number ratio

$\xi_u = 3 n_{ph} k_B T_u / n_p m_p c^2$: photon to baryon inertia ratio

@ far upstream region

Dependences on :

(I) ξ_u

(II) $\tilde{n}$

(III) Γ_u

Parameters

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@ far upstream region

Dependences on :

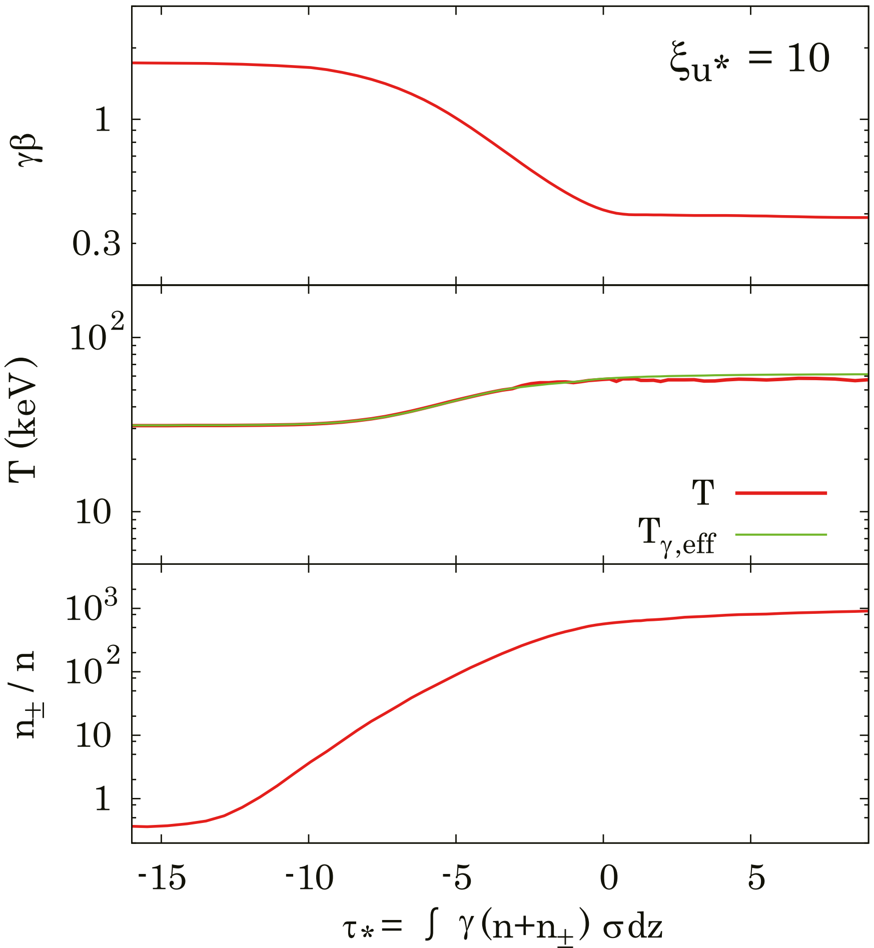
(I) ξ_u

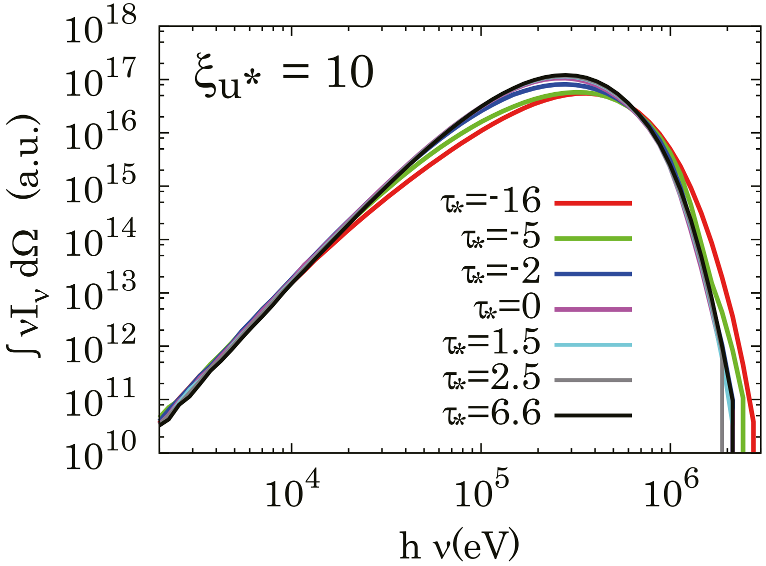
$\tilde{n} = 10^5 \quad \Gamma_u = 2$

(II) $\tilde{n}$

(III) Γ_u

$\xi_u = 3n_{ph} k_B T_u / n_p m_p c^2 = 10$ $\Gamma_u = 2$ $\tilde{n} = 10^5$





Radiation dominant US

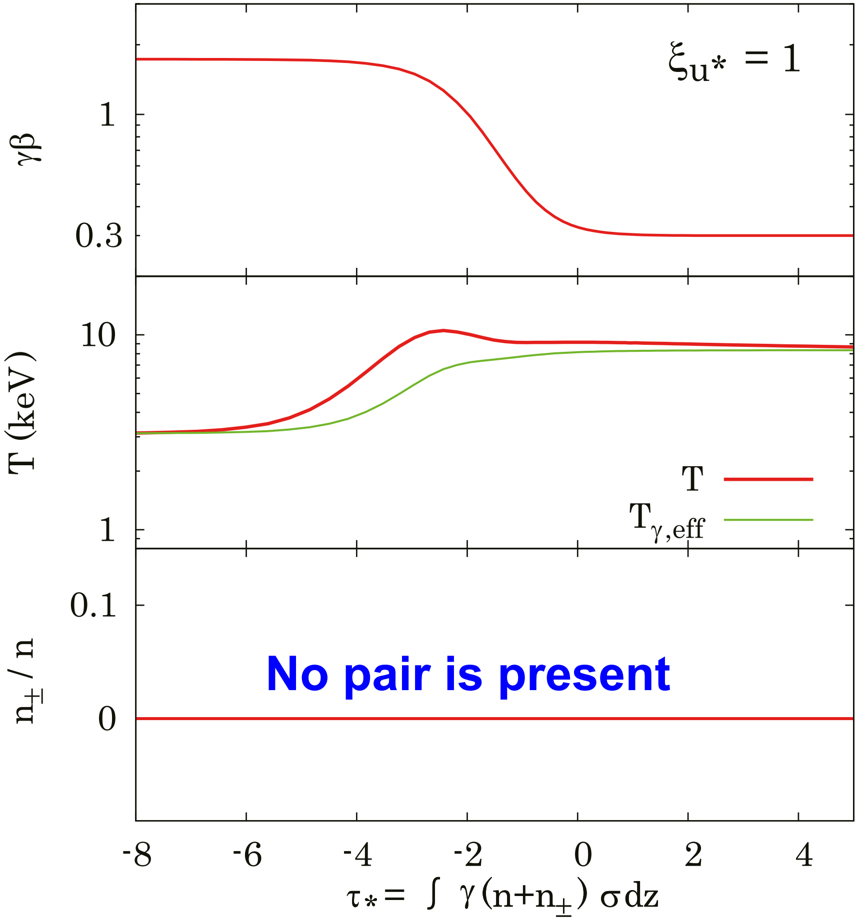
”force-free“ flow profile

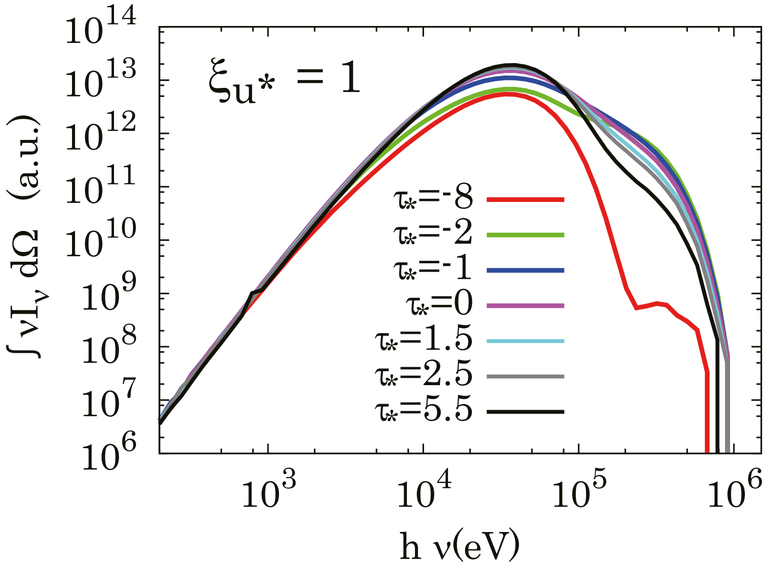
no strong anisotropy appears

Beloborodov 2017

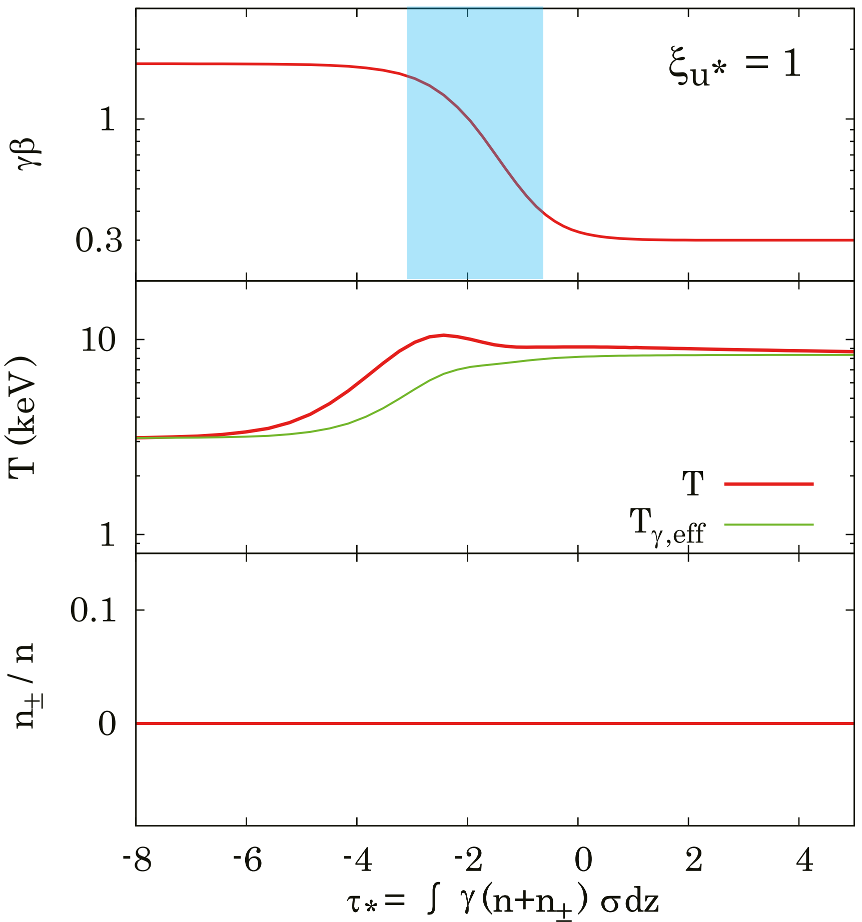
Spectra is mostly thermal

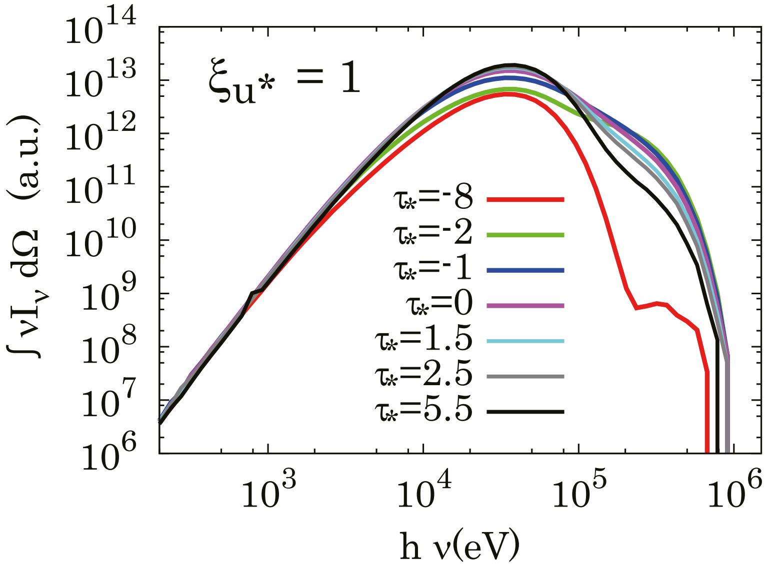
$\xi_u = 3n_{ph}\, k_B\, T_u / n_p m_p c^2 = 1$ $\Gamma_u = 2$ $\tilde{n} = 10^5$





$\xi_u = 3n_{ph} k_B T_u / n_p m_p c^2 = 1$ $\Gamma_u = 2$ $\tilde{n} = 10^5$

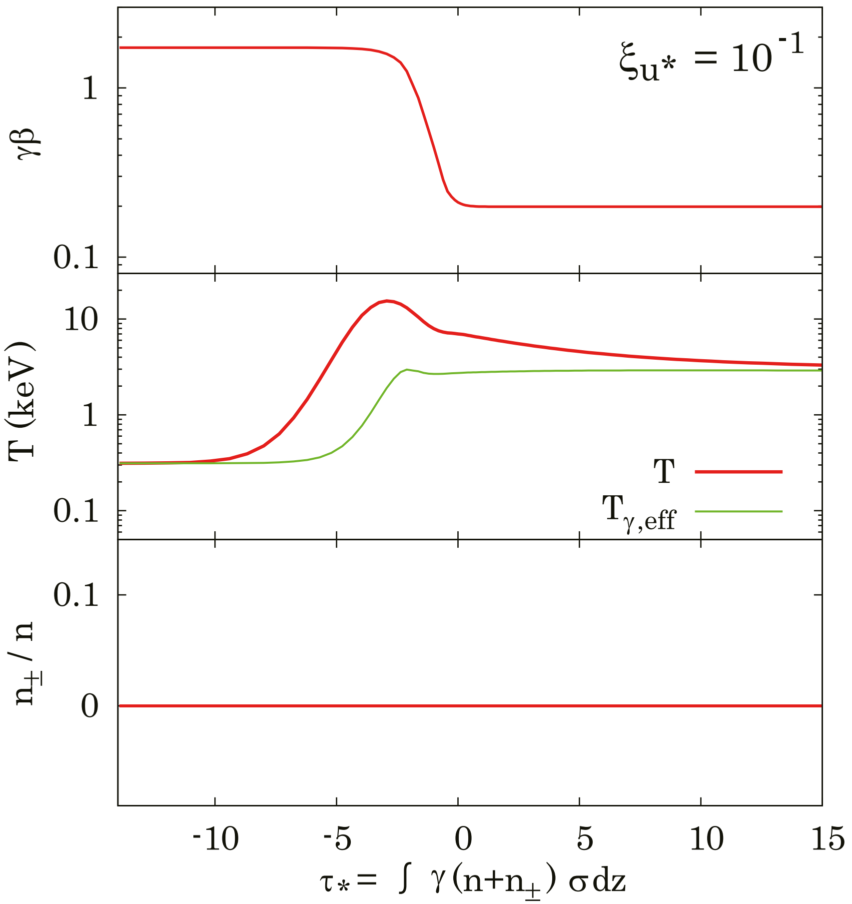


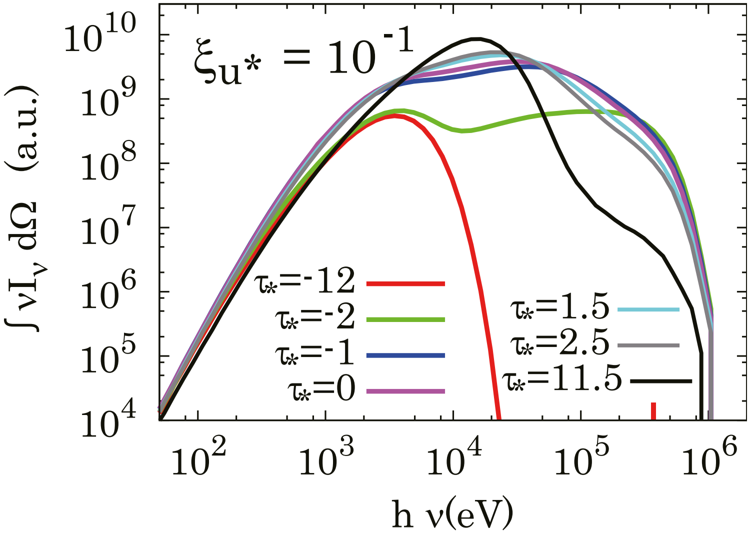


Deceleration in Δτ ~ 1

Anistropy and
Non-thermal spectra appears

$\xi_u = 3 n_{ph} k_B T_u / n_p m_p c^2 = 0.1$ $\Gamma_u = 2$ $\tilde{n} = 10^5$

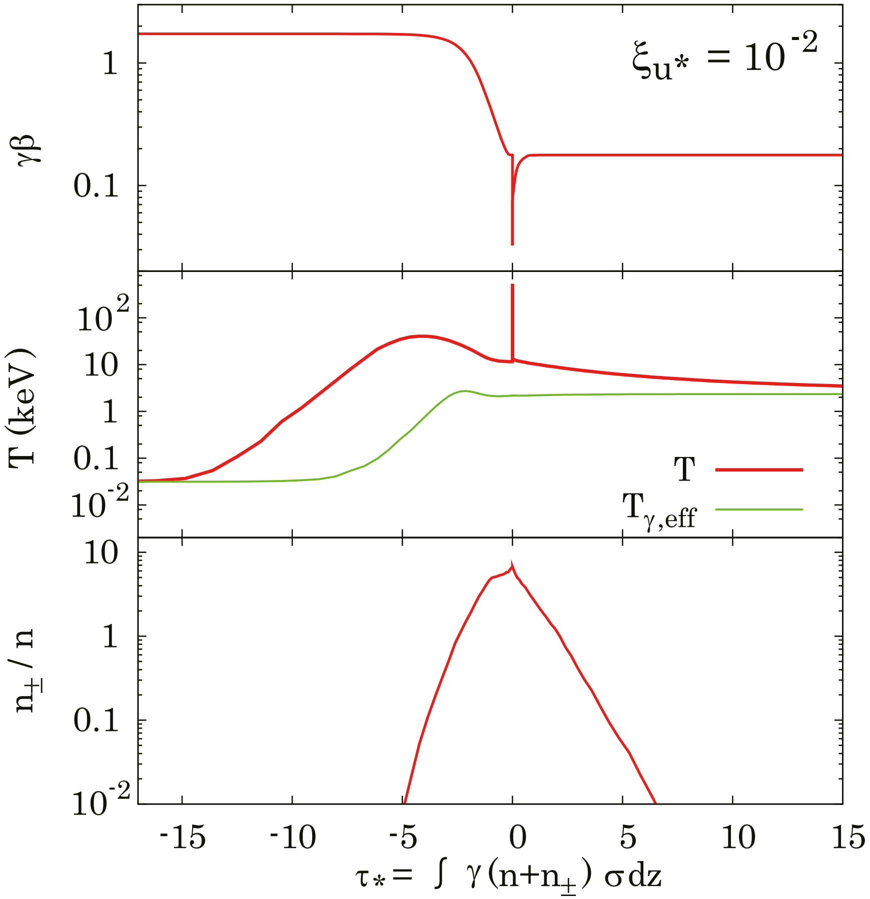


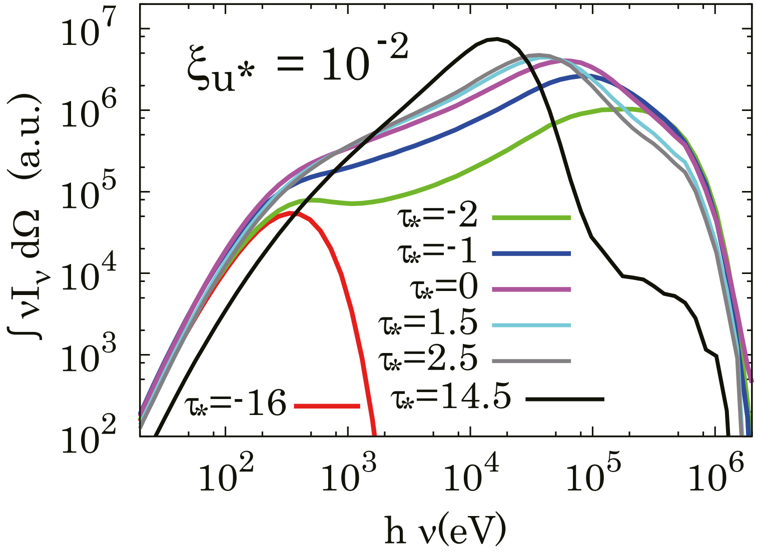


Deceleration in $\Delta\tau \sim 1$

Anistropy and
Non-thermal spectra appears

$\xi_u = 3 n_{ph} k_B T_u / n_p m_p c^2 = 0.01$ $\Gamma_u = 2$ $\tilde{n} = 10^5$





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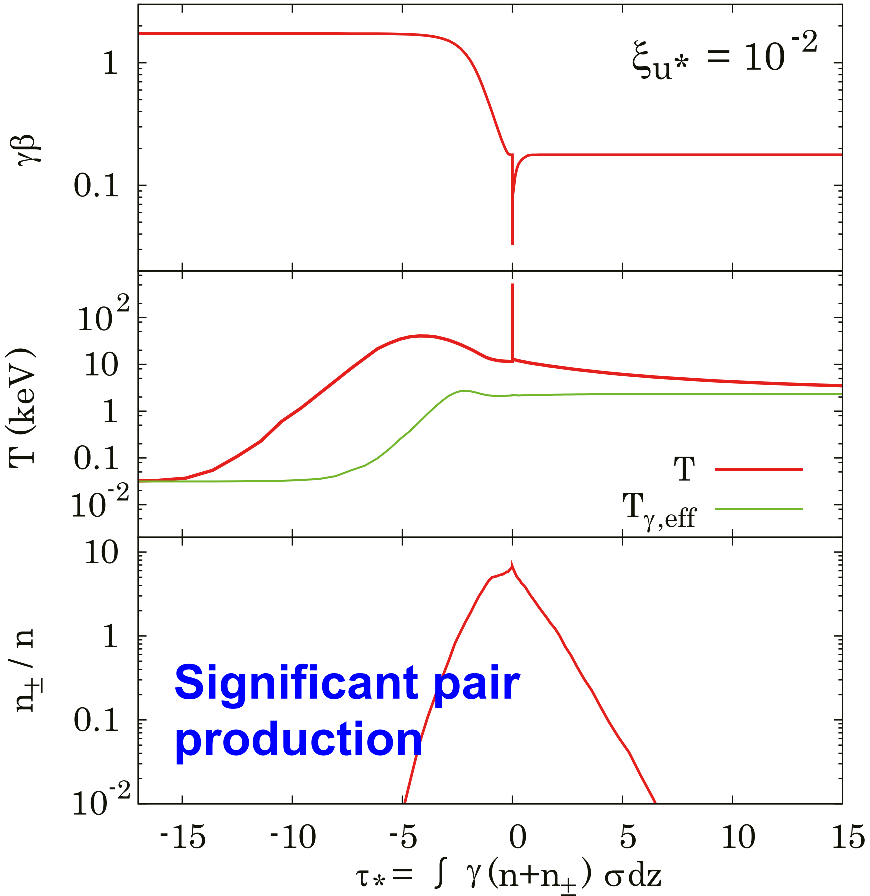
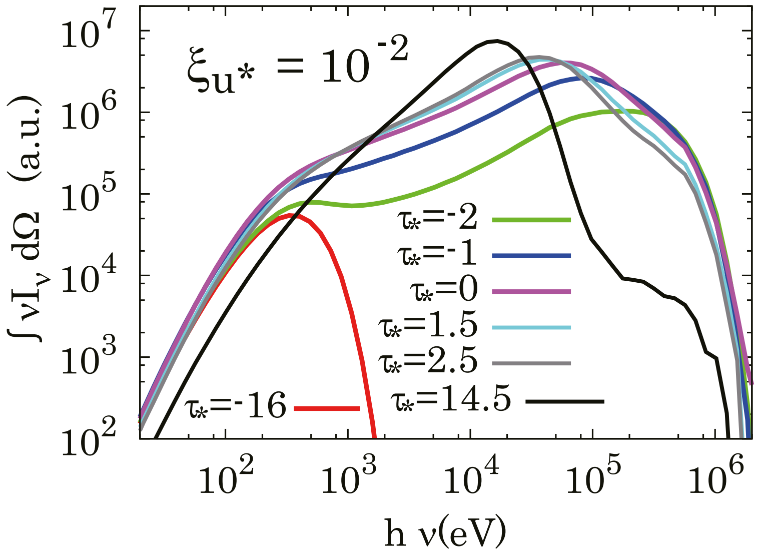


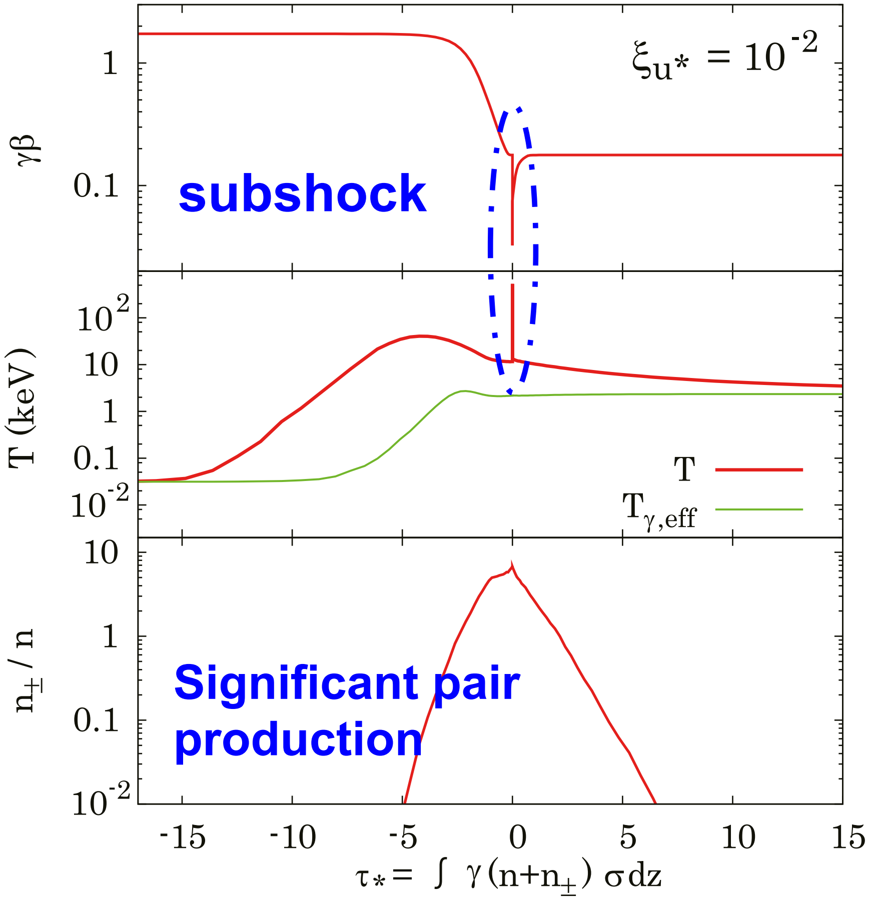
Significant pair production



Deceleration in $\Delta\tau \sim 1$

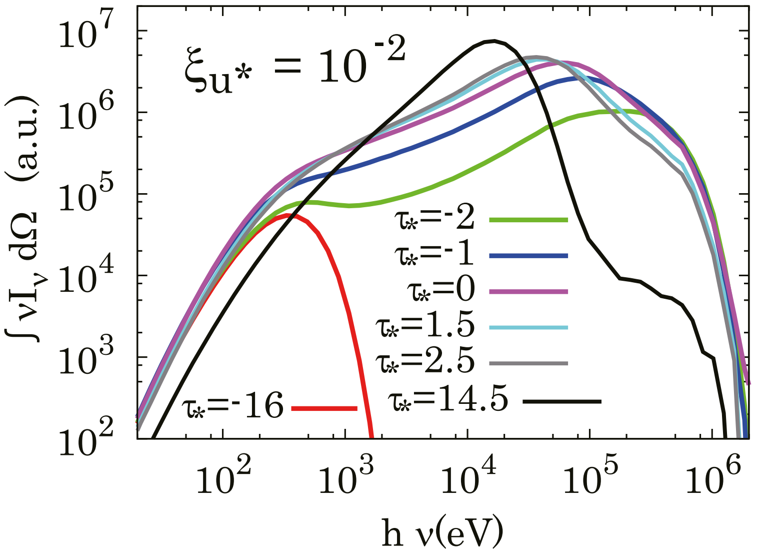
Anistropy and Non-thermal spectra appears

$\xi_u = 3 n_{ph} k_B T_u / n_p m_p c^2 = 0.01 \quad \Gamma_u = 2 \quad \tilde{n} = 10^5$



subshock

Significant pair production



Deceleration in $\Delta\tau \sim 1$

Anistropy and
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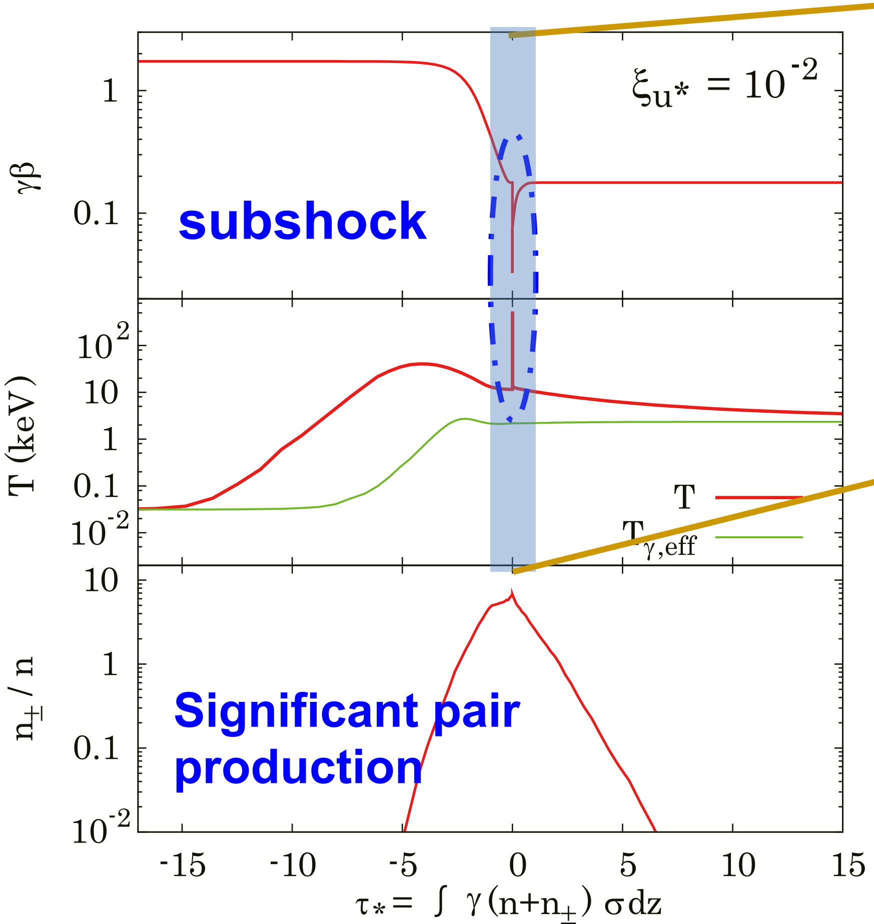
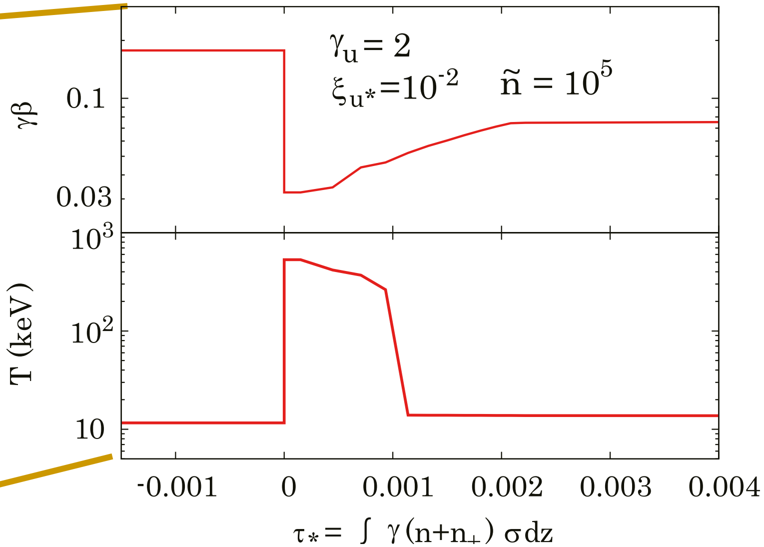


subshock

Significant pair production

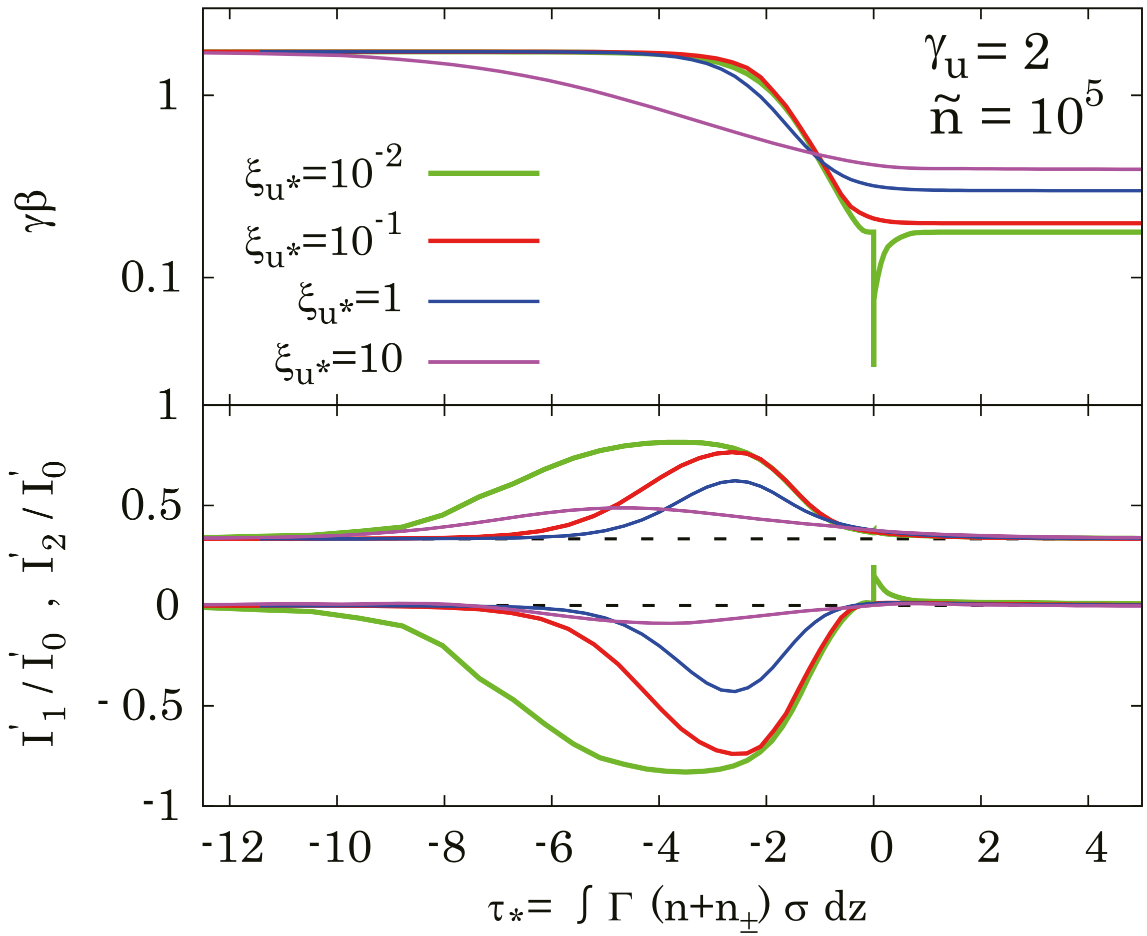


Post subshock plasma is rapidly cooled and accelerated by the radiation

$$
\begin{aligned}
d\tau_{*,\rm cool} &\sim \beta_{\rm d,sub}\, c(n+n_\pm)\sigma_{\rm T} t_{\rm cool} \\
&\sim 1.5\times 10^{-3} \left(\frac{kT_{\gamma,\rm eff}}{2\ \rm keV}\right)^{-1} \left(\frac{\tilde{n}}{10^5}\right)^{-1} \left(\frac{\frac{n+n_\pm}{n}}{10}\right) \\
&\quad \times \left(\frac{\frac{\beta_{\rm u,sub}}{\beta_{\rm d,sub}}}{8}\right) \left(\frac{\beta_{\rm d,sub}}{0.03}\right).
\end{aligned}
$$

** negligible fraction of energy is dissipated in the weak subshock*

Dependence on ξ_u



Parameters

Γ_u : Lorentz factor of shock

$\tilde{n} = n_{ph} / n_p$: photon to baryon number ratio

$\xi_u = 3 n_{ph} k_B T_u / n_p m_p c^2$: photon to baryon inertia ratio

@ far upstream region

Dependences on :

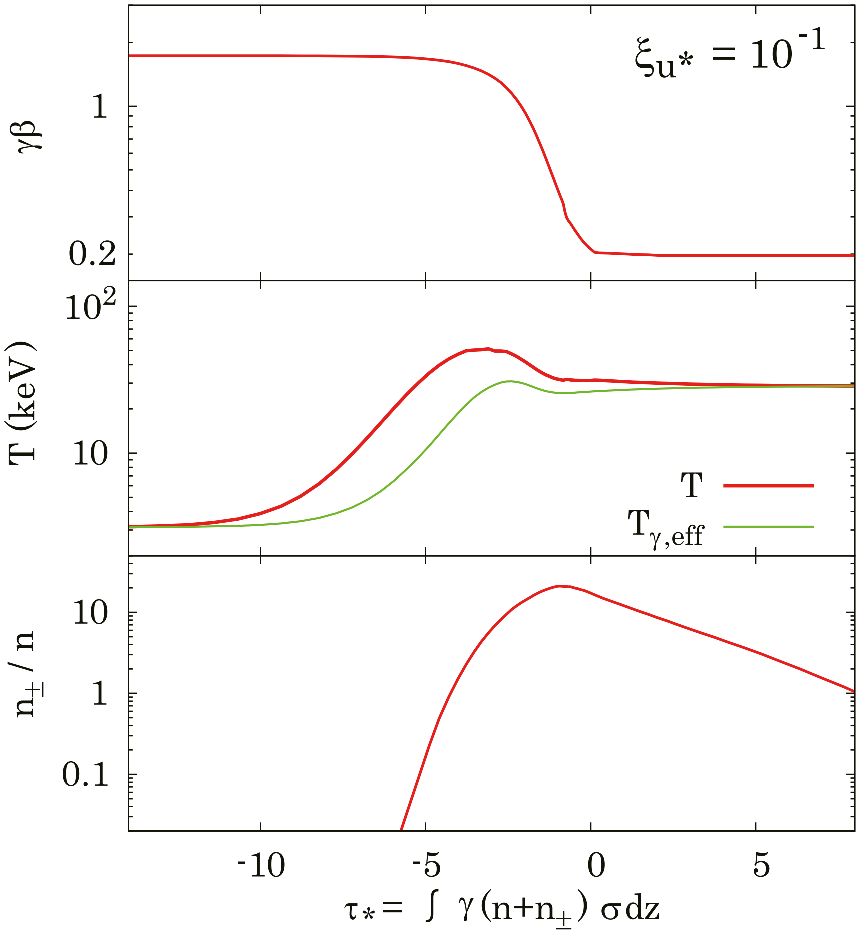
(I) ξ_u

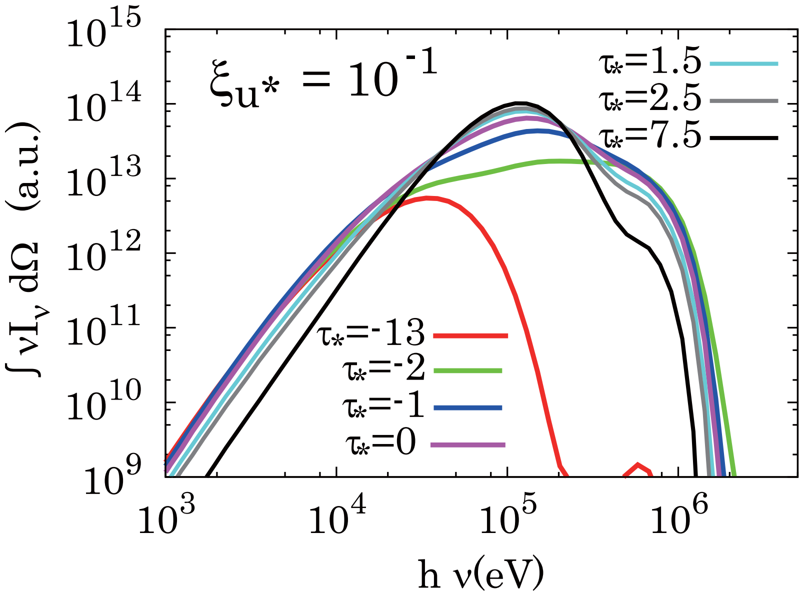
(II) $\tilde{n}$

$\xi_u = 0.1$ $\Gamma_u = 2$

(III) Γ_u

$\tilde{n} = n_{ph} / n_p = 10^4$ $\xi_u = 0.1$ $\Gamma_u = 2$

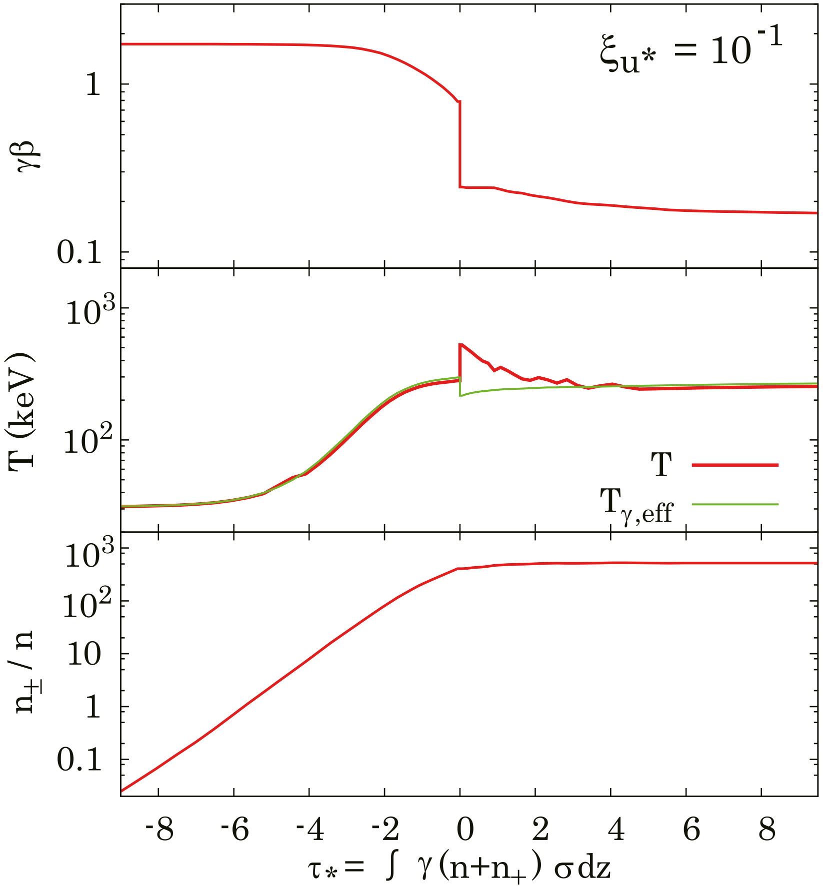


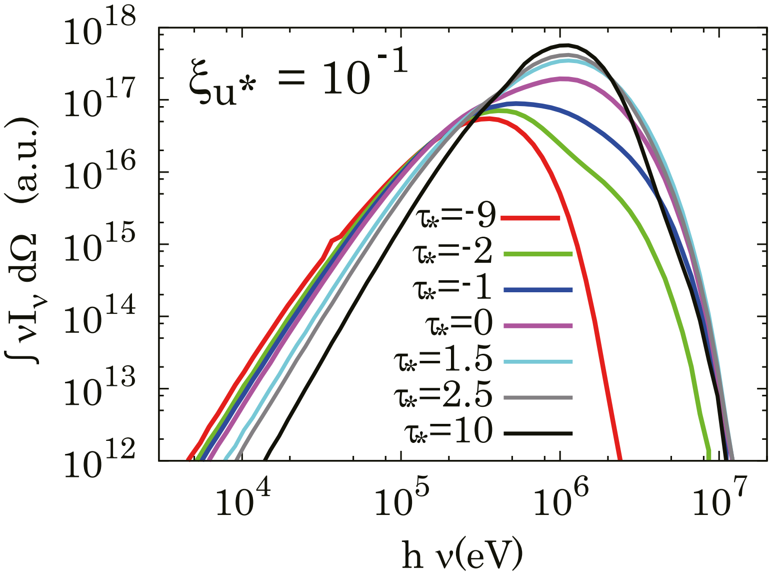


$T_d \sim 30\,(\Gamma_u / 2)\,(\tilde{n} / 10^4)^{-1}$ keV

Pair enrichment is enhanced due to high temperature

$\tilde{n} = n_{ph} / n_p = 10^3$ $\xi_u = 0.1$ $\Gamma_u = 2$





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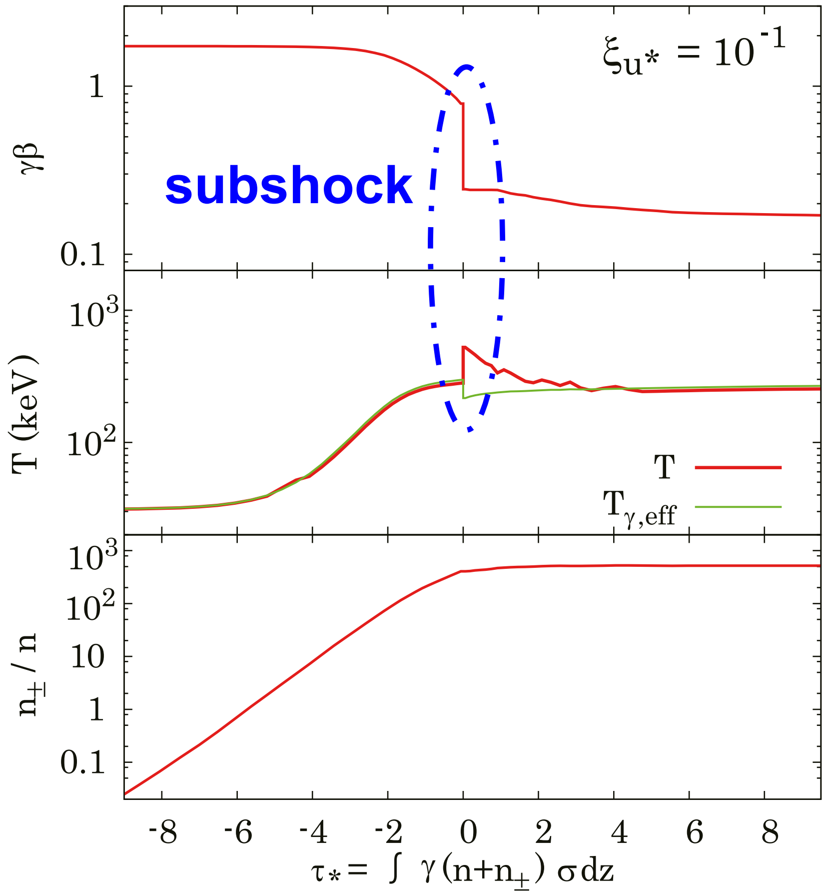
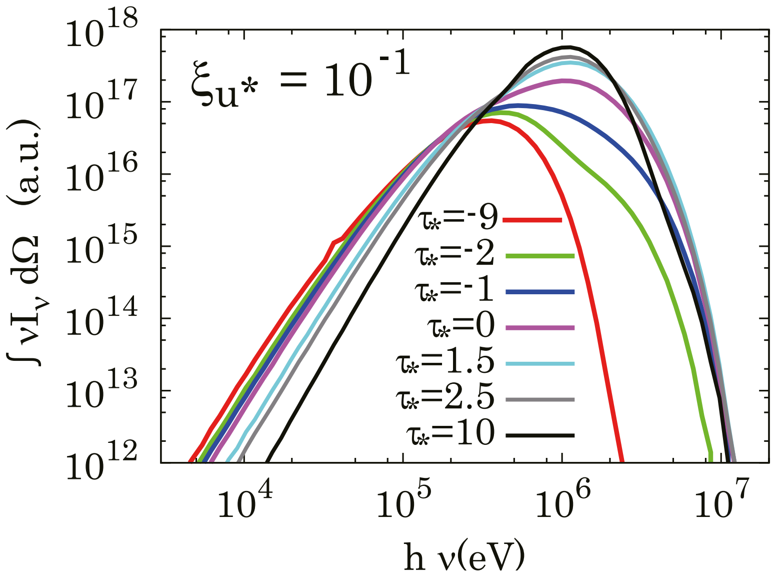




Strong subshock plasma is appears for $n_{ph} / n_p < m_p / m_e$

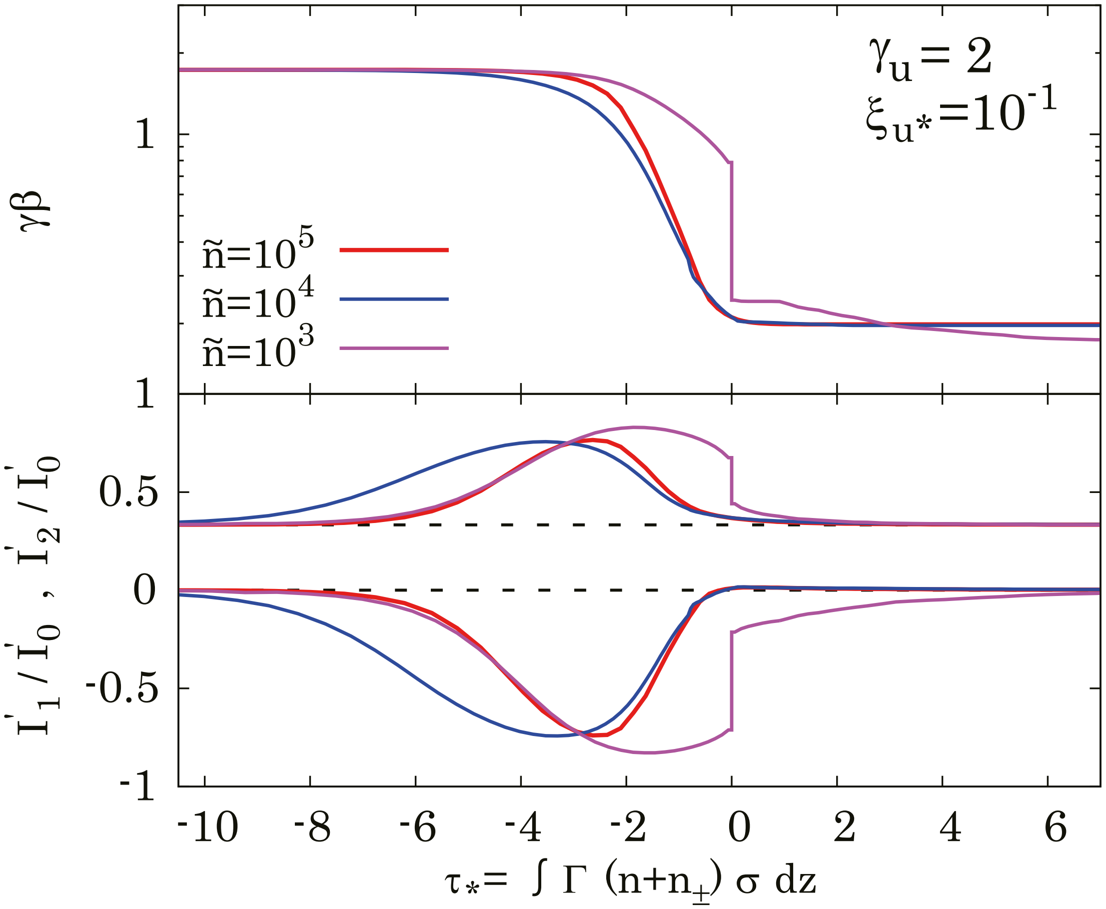
$E_{ph,max} = \Gamma_u m_e c^2$

➡ **Necessary condition for conversion from kinetic energy to radiation**

$\Gamma_u n_p m_p c^2 < n_{ph} \Gamma_u m_e c^2$

* Reasonable range of parameter, photon generation cannot be neglected
=> subshock may disappear or be significantly weaker

Dependence on $\tilde{n}$



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@ far upstream region

Dependences on :

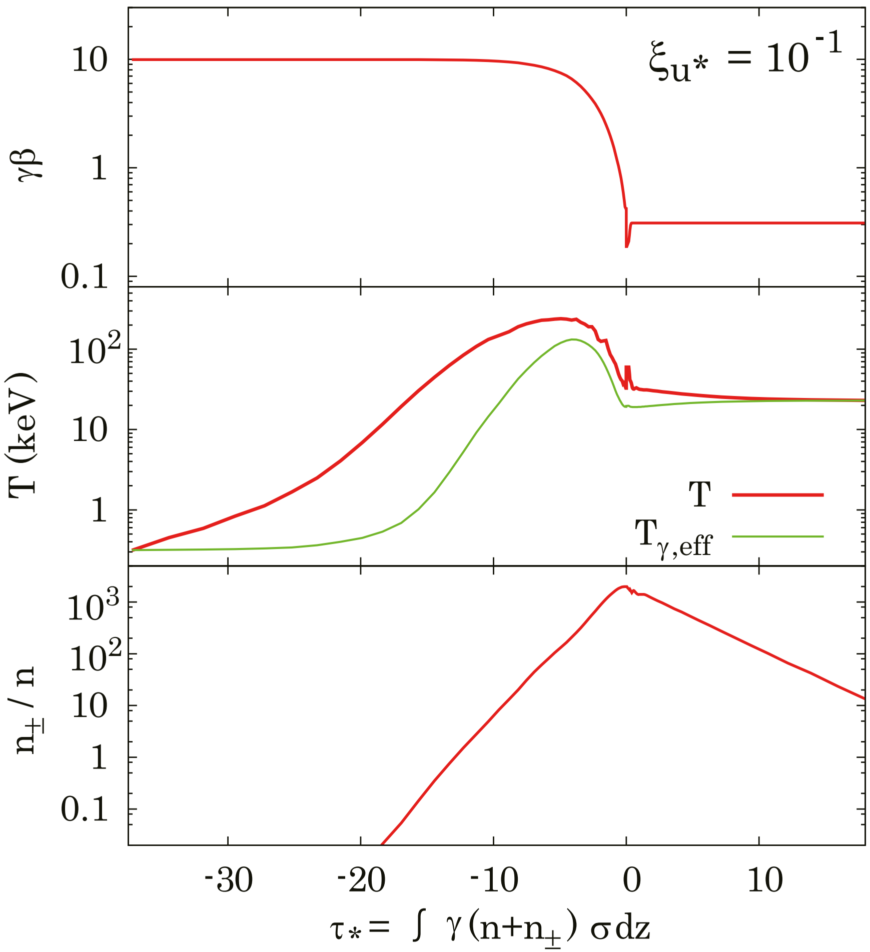
(I) ξ_u

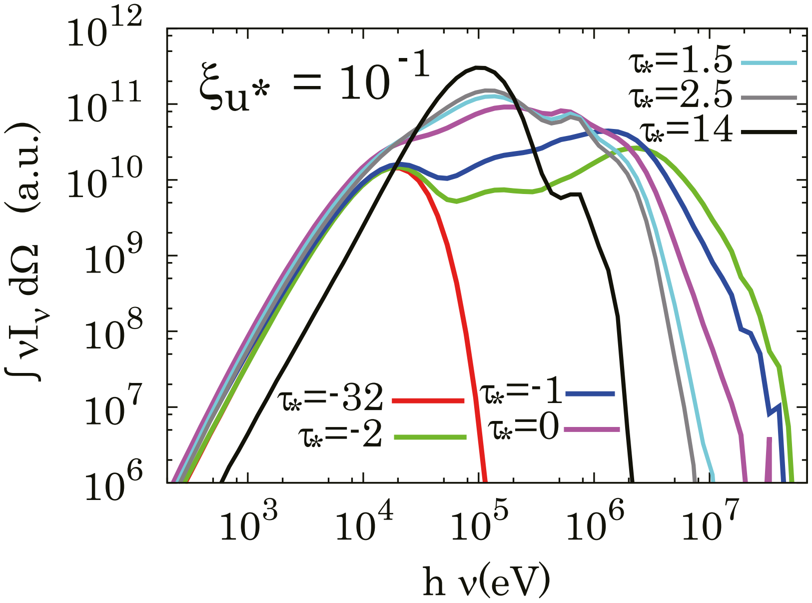
(II) $\tilde{n}$

(III) Γ_u

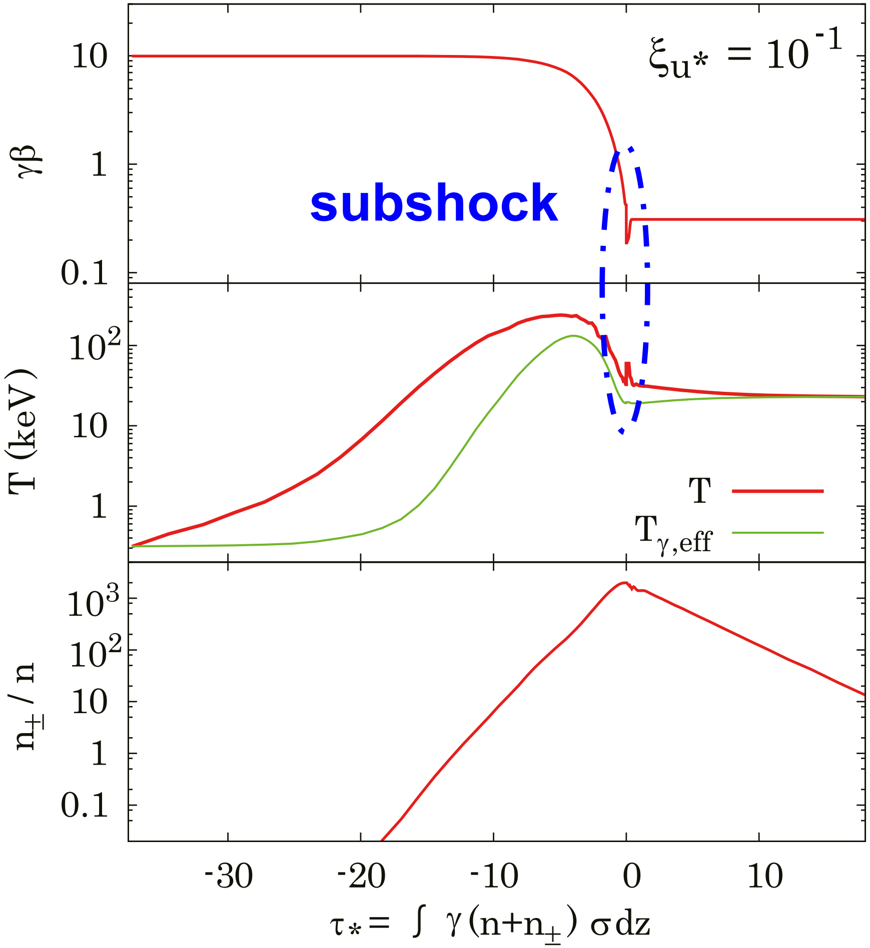
$\xi_u = 0.1$ $\tilde{n} = 10^5$

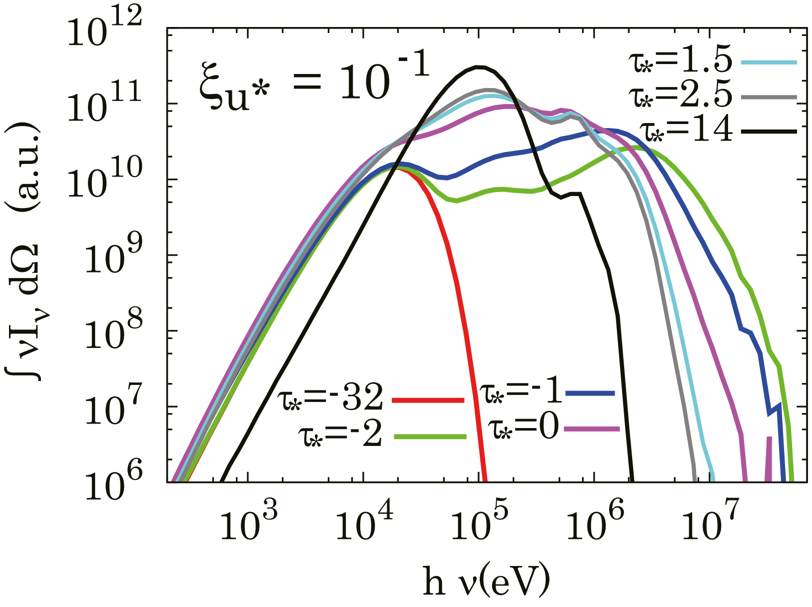
$\Gamma_u = 10$ $\xi_u = 0.1$ $n = 10^5$





$\Gamma_u = 10$ $\xi_u = 0.1$ $n = 10^5$





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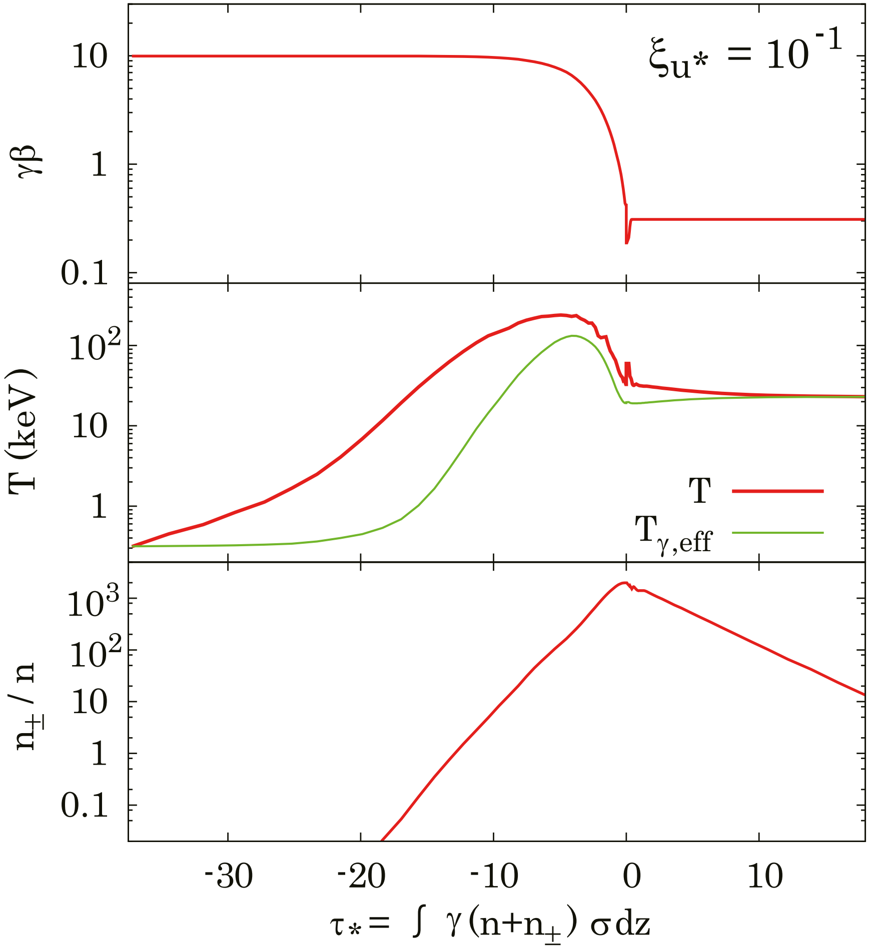
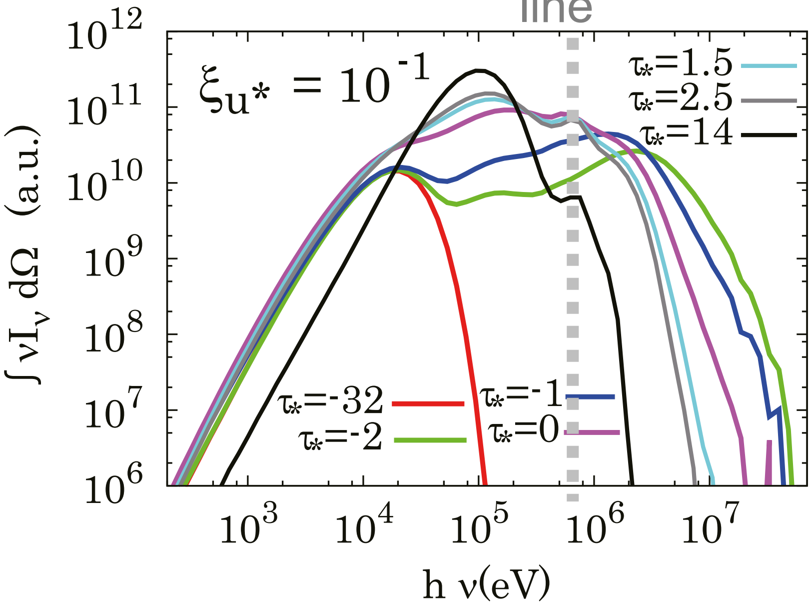
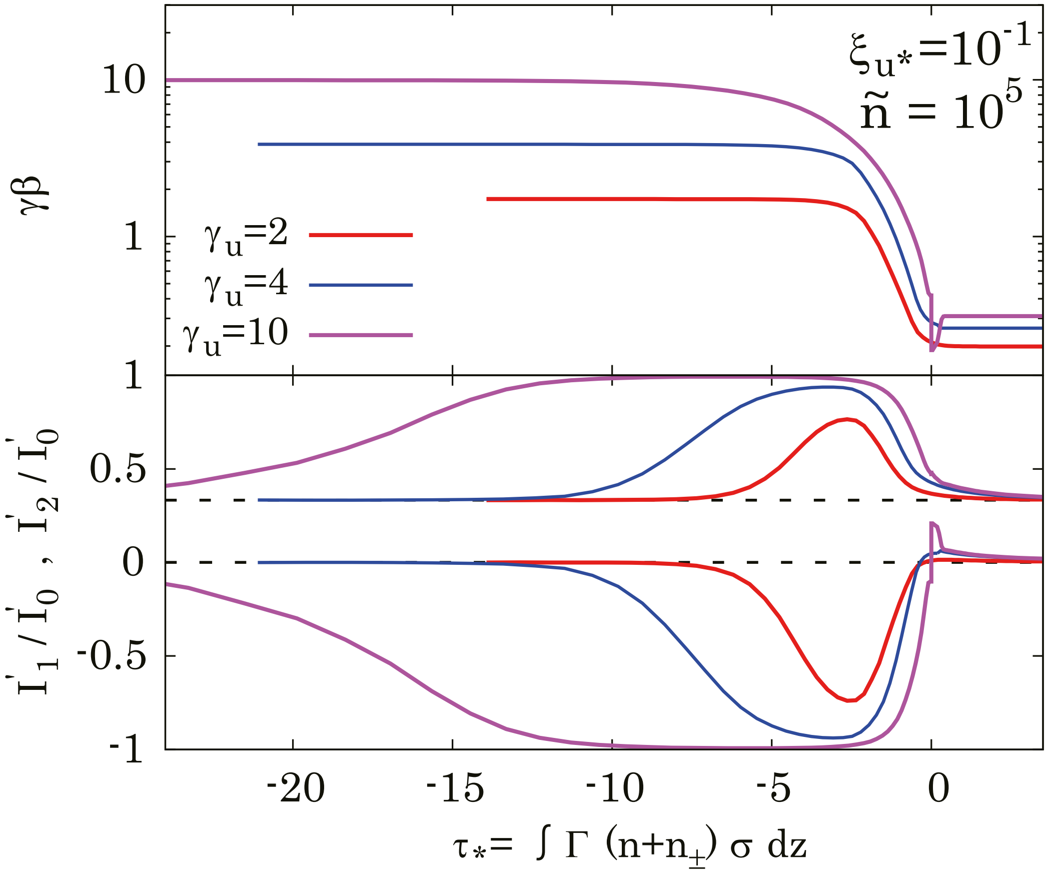


511 keV line

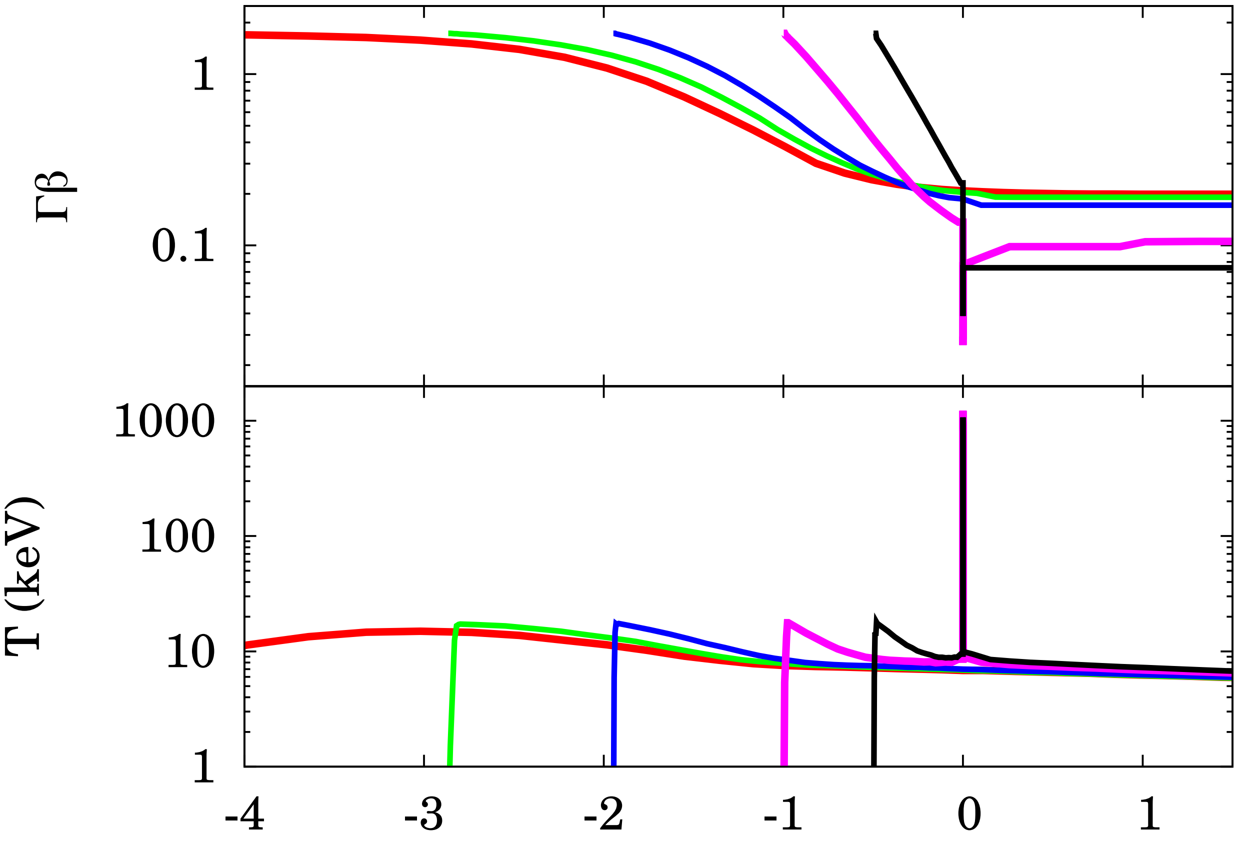


Pair enrichment is enhanced due to strong bulk Comptonization

Dependence on Γ_u



Simulation with escape



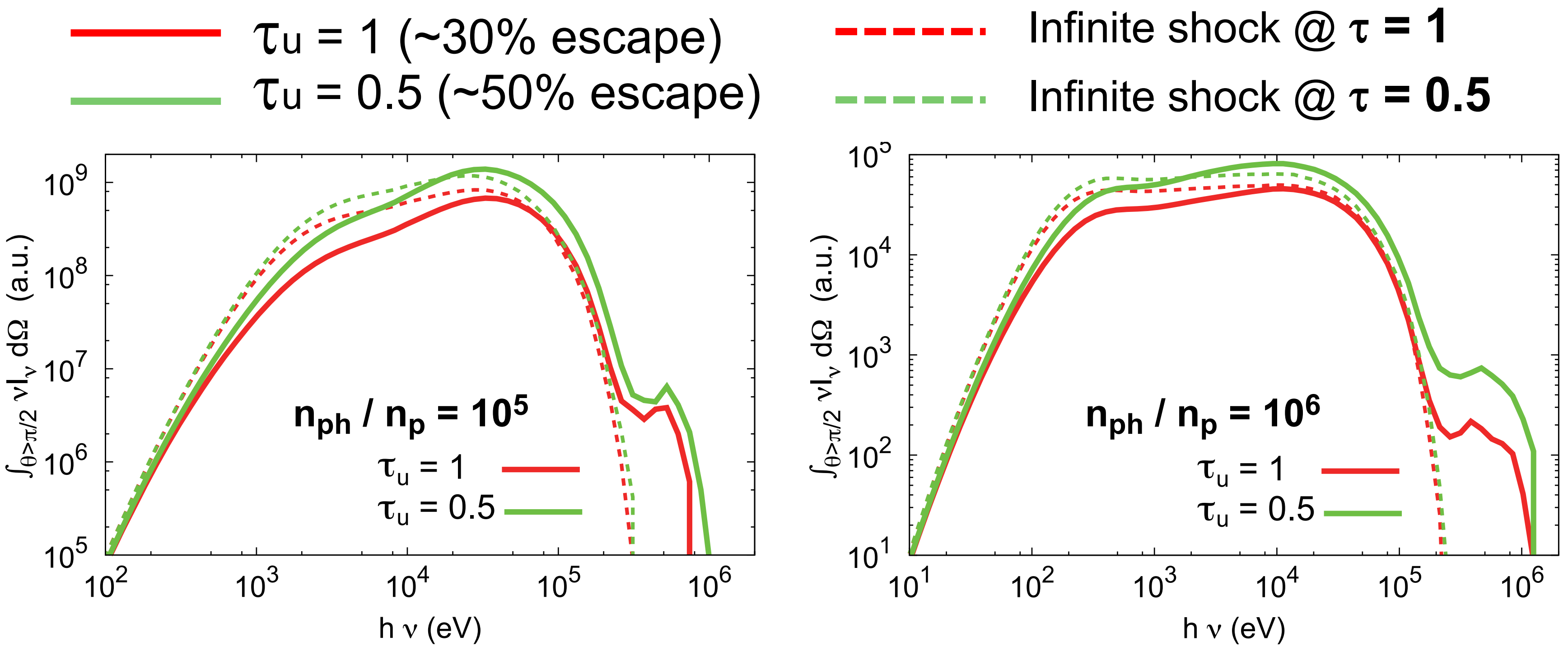
As Escape fraction increases

Compression ratio increases

Subshock appears

HI + in prep,

Escaped Spectrum



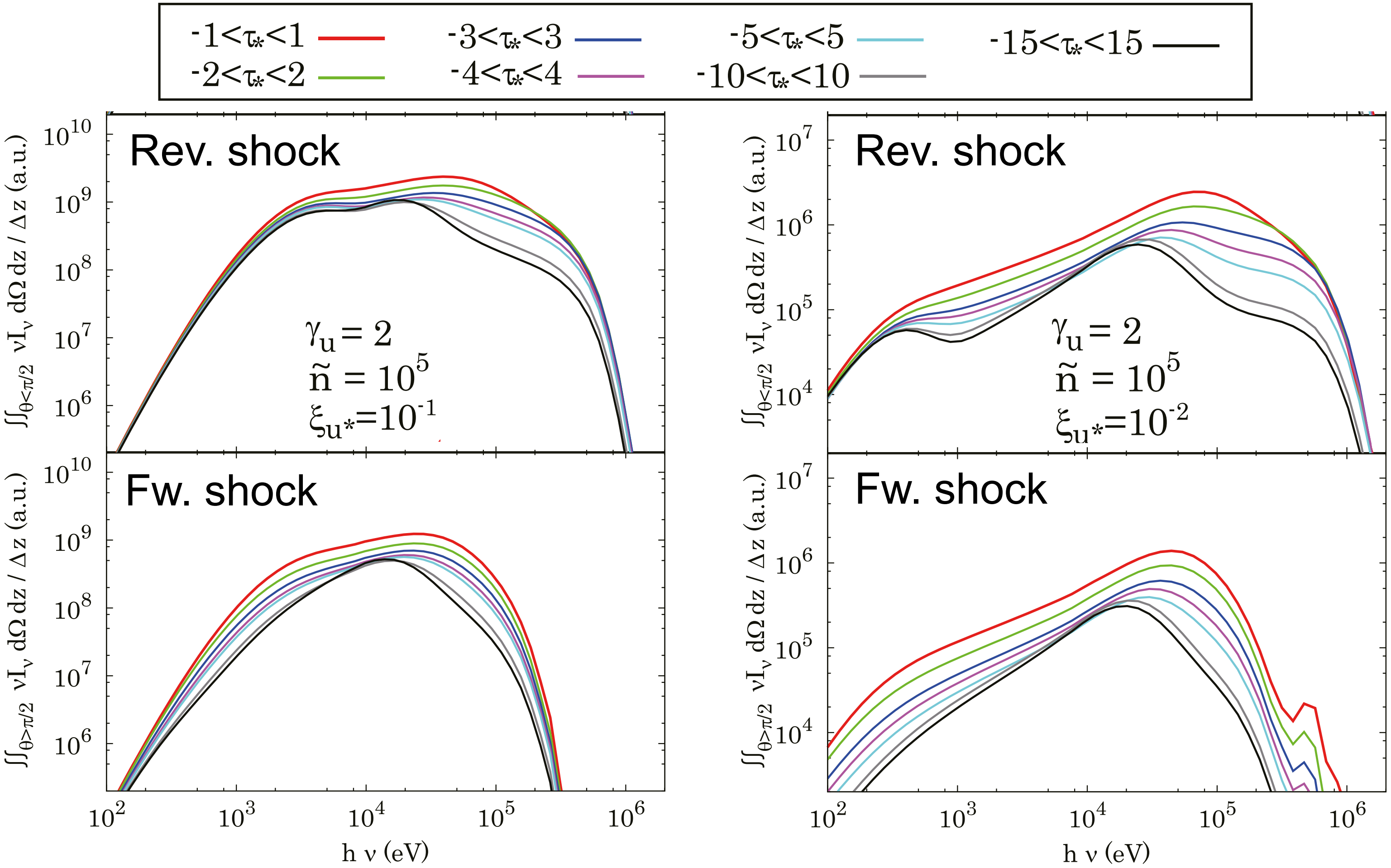
Broad non-thermal spectrum appears

Small difference from the infinite shock at same position

➡ Infinite shock is a good approximation for the breakout emission

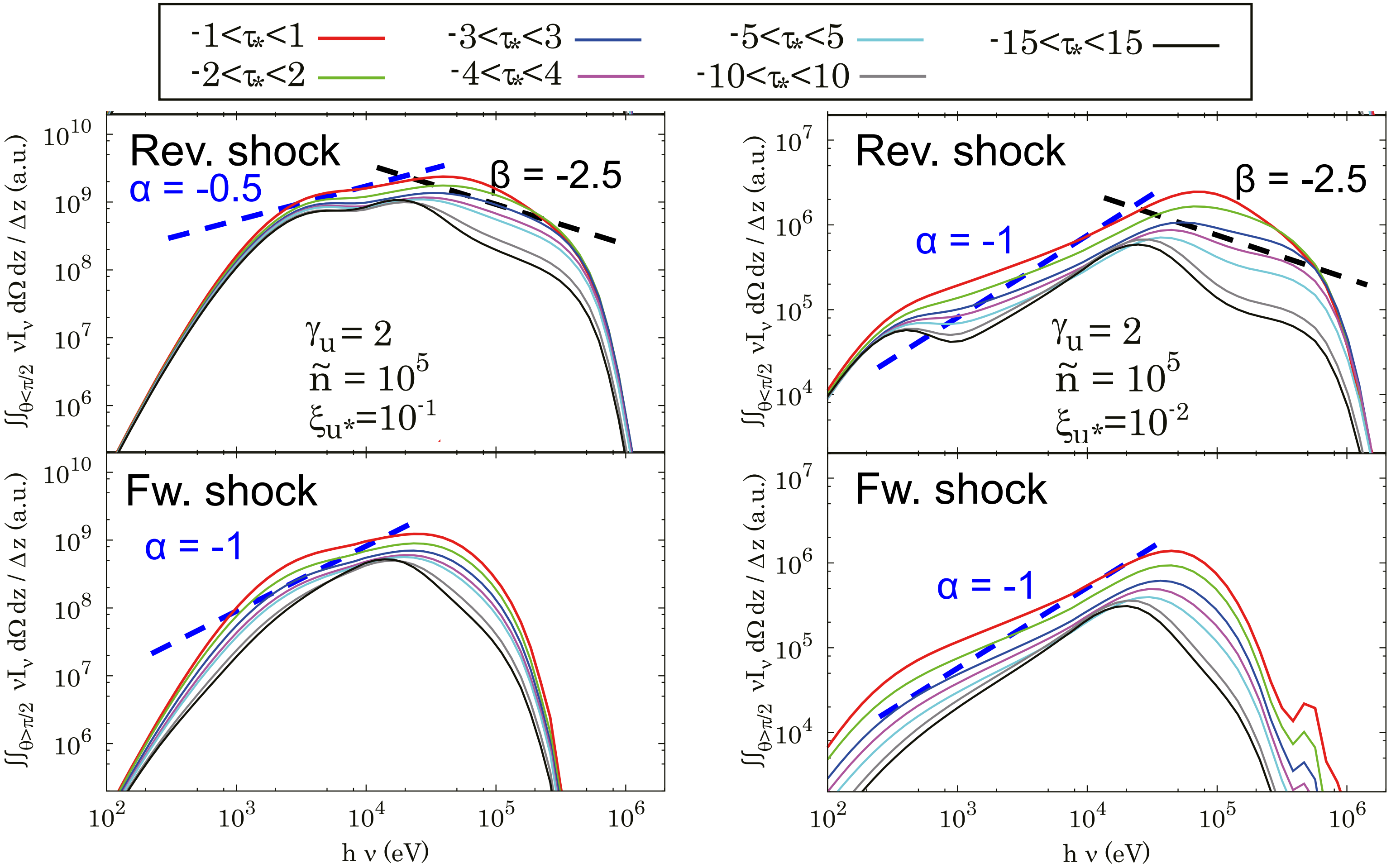
HI + in prep,

Spacially averaged spectra



Highly non-thermal spectra appears near the shock

Spacially averaged spectra

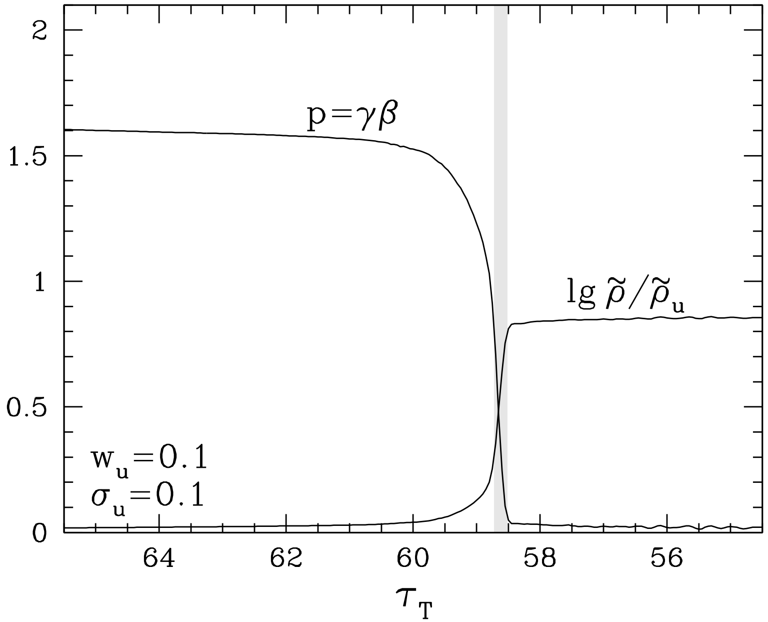


Highly non-thermal spectra appears near the shock

Possible origin of Band spectrum

Effects of magnetic field

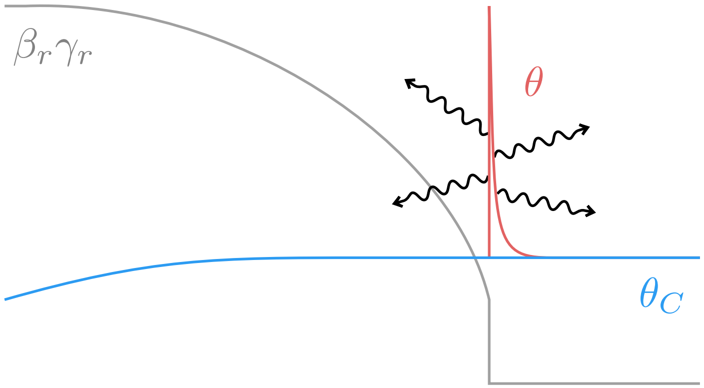
Beloborodov 2017



Certain fraction of DS energy is contained in compressed B-field

➡ Subshock is formed

Lundman et al. 2018



Synchrotron emission at subshock can be an important source of photons

Self-consistent numerical calculation of RRMS

Photon Rich regime : photons advected from the upstream is dominant

Ito et al. (2018) Infinite shock

Full radiation transfer with pair production, no optimistic approximation
wide range of upstream condition is covered

$2 < \Gamma_u < 10, \quad 0.01 < \xi_u < 10, \quad 10^3 < n < 10^5$

Ito et al. in prep I ., finite shock (shock breakout)

Simulation with photon escape (shock breakout)

structure, spectra, application to GRBs

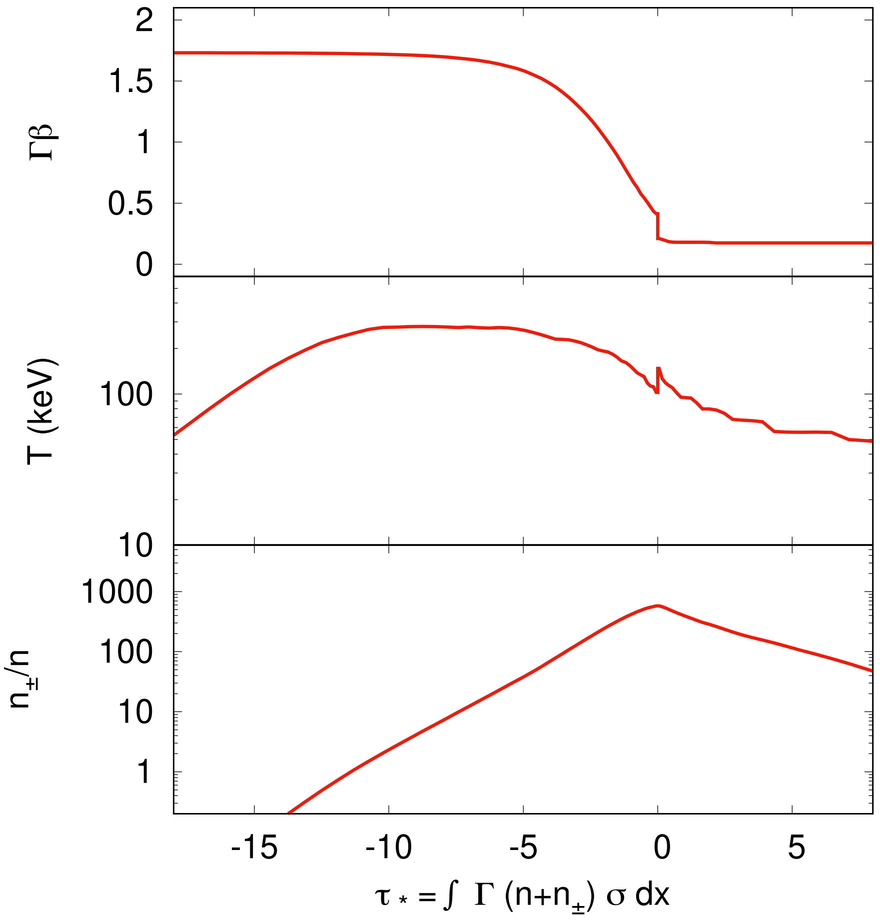
Photon Starved regime : photons produced in the downstream is dominant

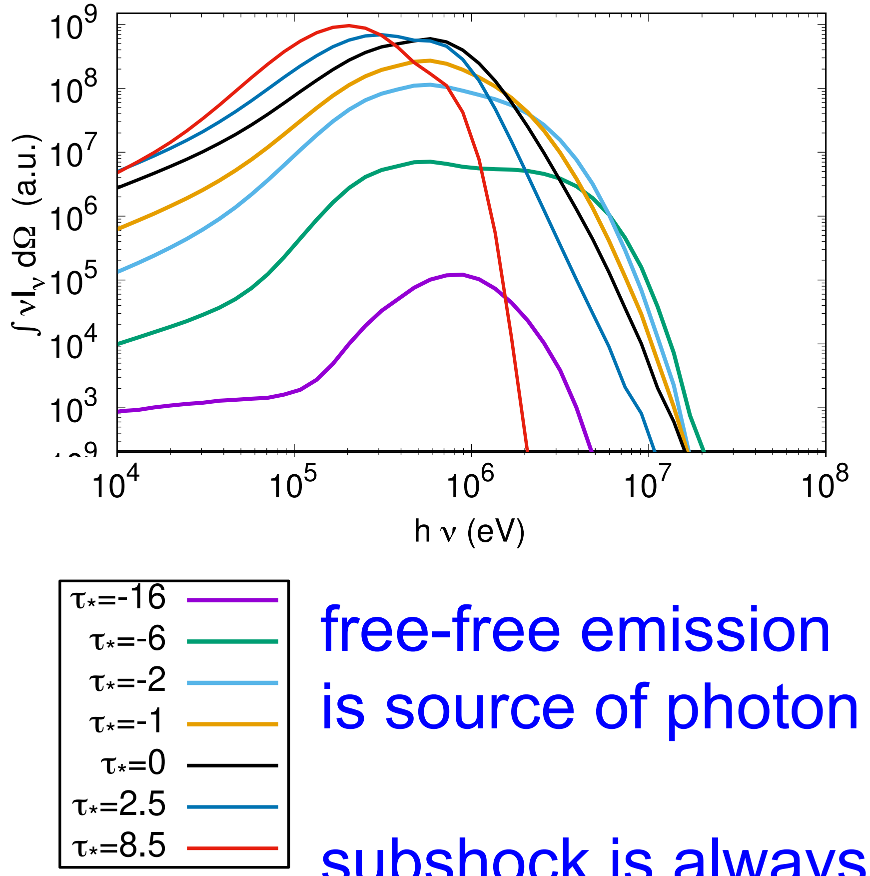
Ito et al. in prep II ., Infinite shock

Full radiation transfer with pair production,
free-free emission + *absorption,* no optimistic approximation

Photon Starved regime

$\Gamma_u = 2$ $n_u = 10^{15}$ cm^{-3} $\tilde{n} = 10$



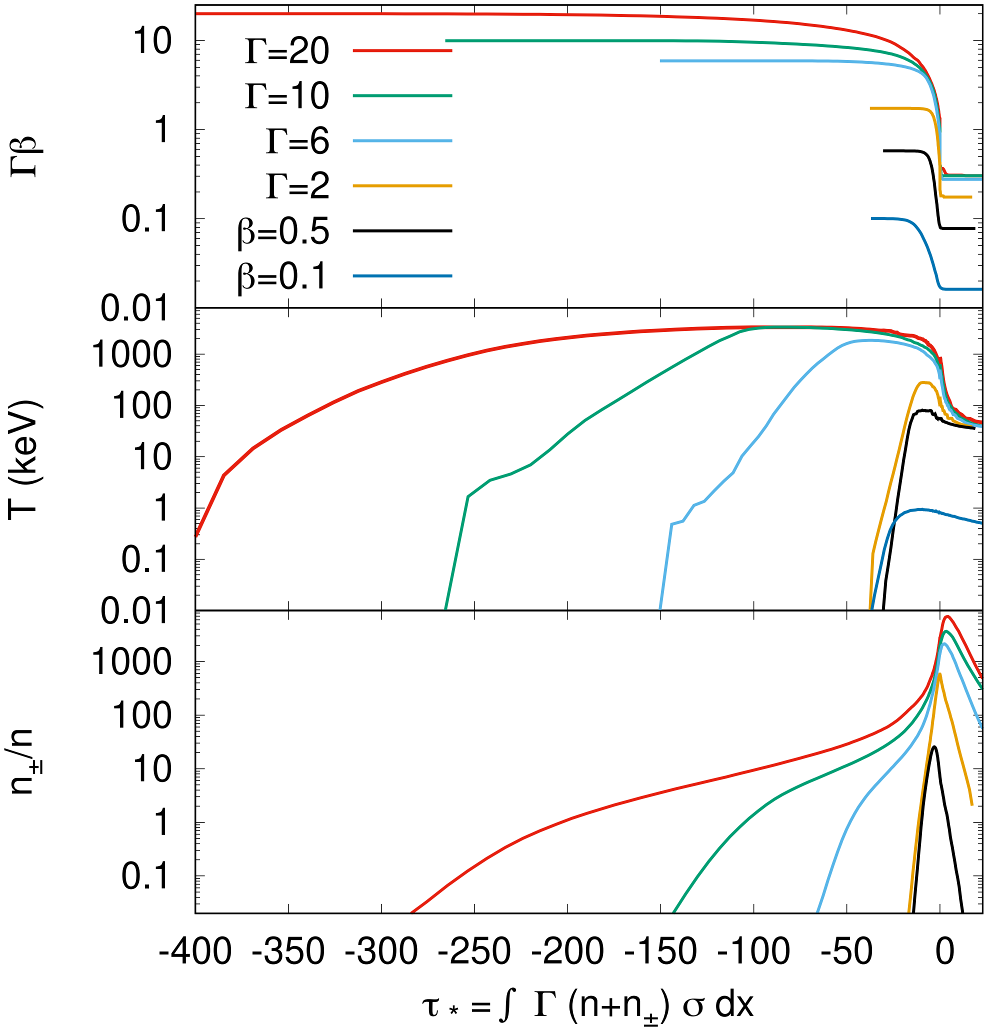


free-free emission is source of photon

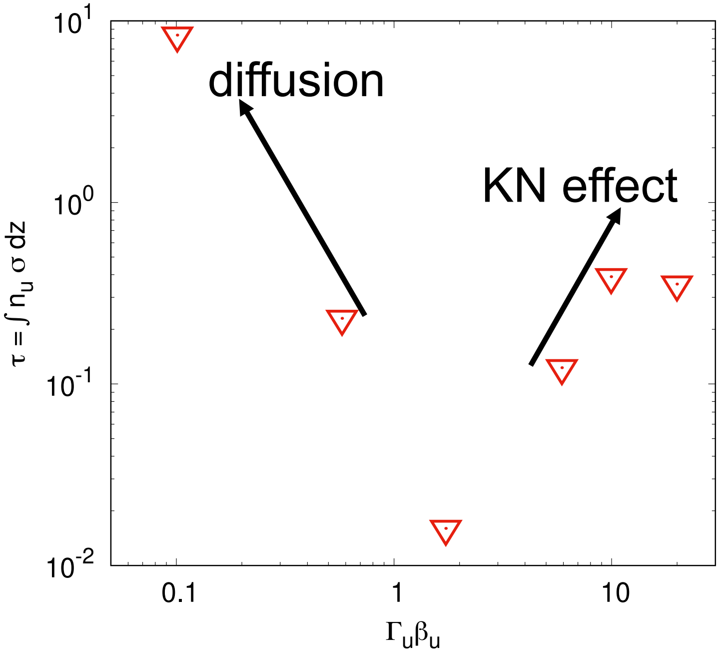
subshock is always present for Γ_u >~ 2

HI + in prep,

Photon Starved regime



Shock width (physical length)



Shock velocity

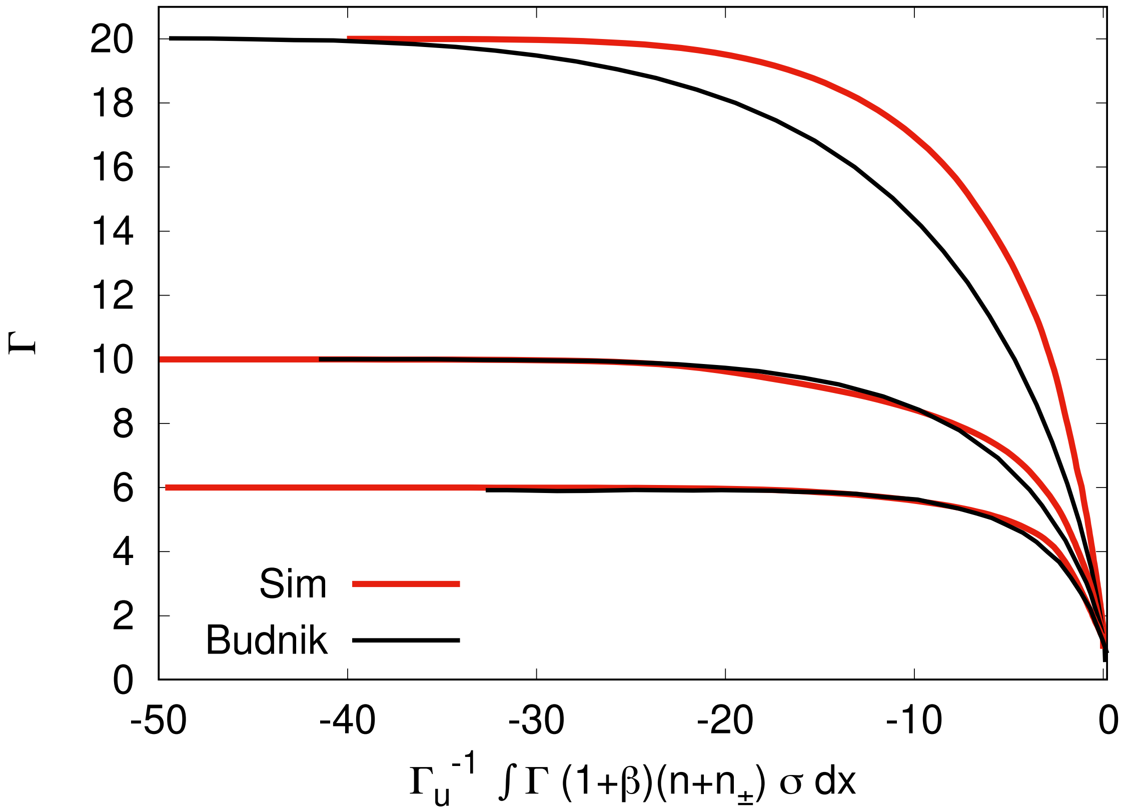
Optical depth of shock upstream at which break out starts

HI + in prep,

Photon Starved regime

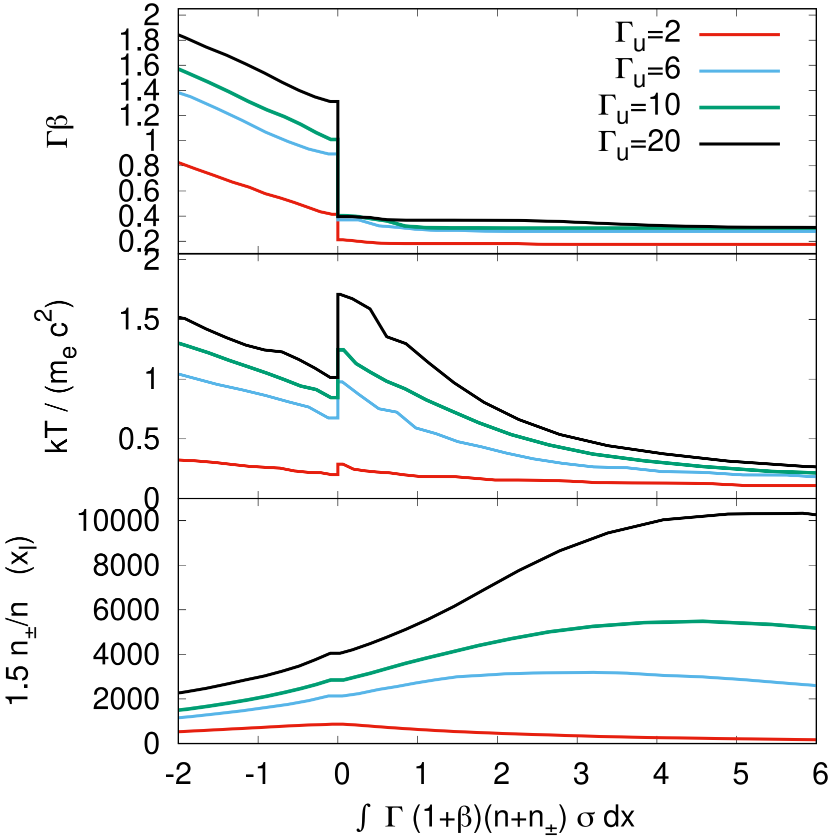
Comparison with Budnik + 2010

US region

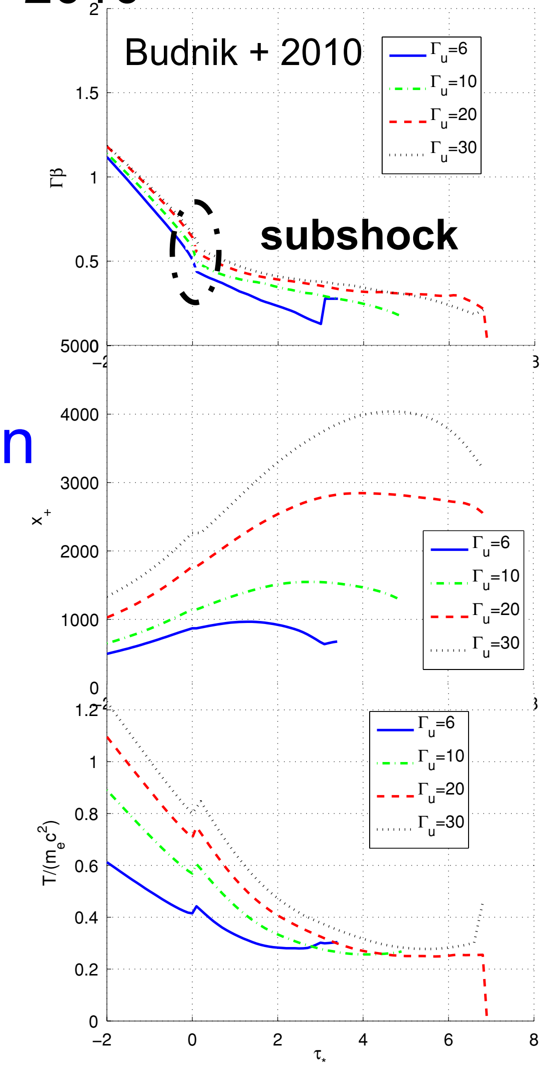


Photon Starved regime

Comparison with Budnik + 2010



DS region



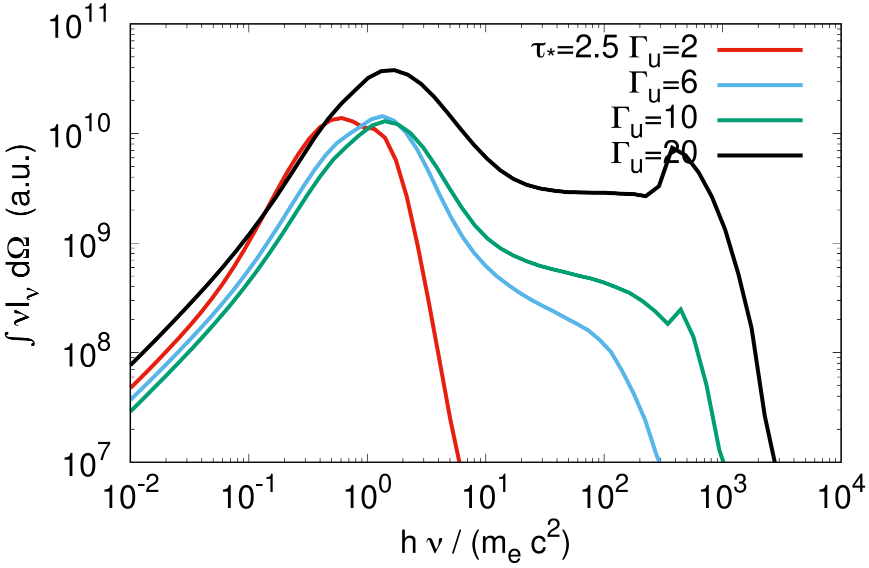
DS temperature is regulated to ~ 200 keV for Γ_u >> 1 due to vigorous pair production

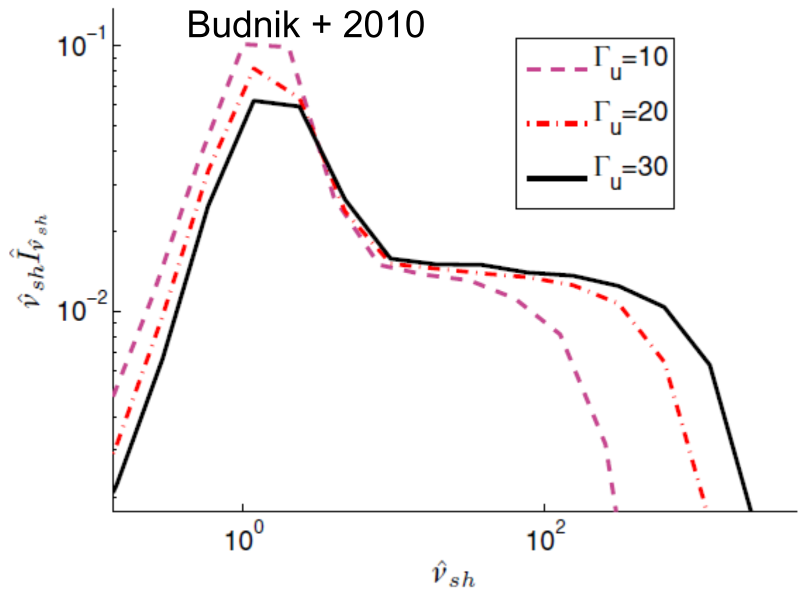
Subshock is stronger

Photon Starved regime

Comparison with Budnik + 2010

Spectrum inside the shock



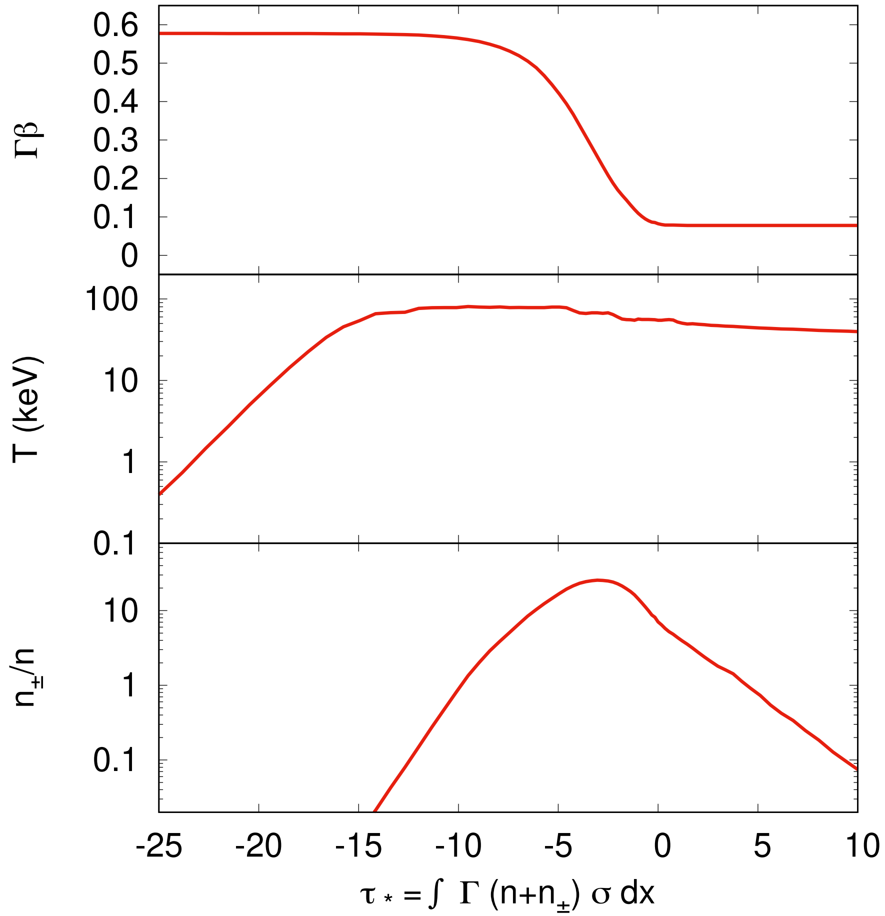


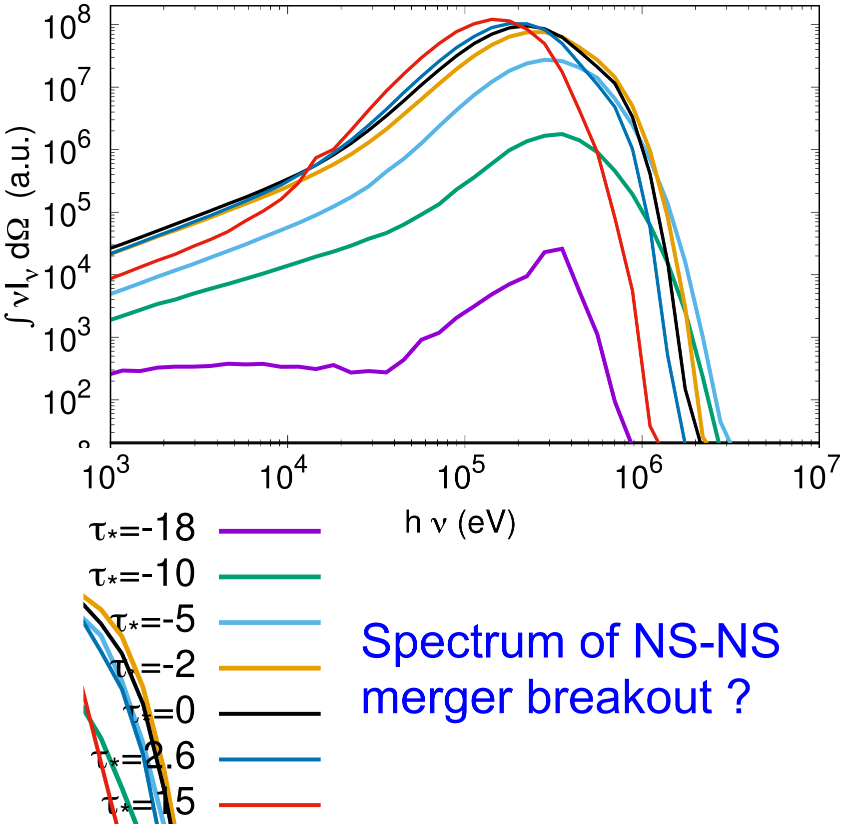
Peak position is fixed at ~ 3 kT_d ~ 600 keV for $\Gamma_u >> 1$

Notable difference in the high energy spectrum

Photon Starved regime

$\beta_u = 0.5$ $n_u = 10^{15}\ \mathrm{cm}^{-3}$ $\tilde{n} = 10$





Spectrum of NS-NS merger breakout ?

Summary

Self consistent simulation of RRMS is performed

- As in the previous studies we find the deceleration length to be $\Delta\tau \sim 1$
- Strong anisotropy develops near the shock and give rise to highly non-thermal spectrum and copious pair production
- Necessity of subshock at certain regime
- Possible origin of Band spectrum
- Broad agreement with Budnik + 2010 is obtained for photon starved regime, but there is also notable difference

Future work

- photon escape calculation at photon starved regime
- Implementation of magnetic fields