Physics of Relativistic Radiation Mediated Shocks

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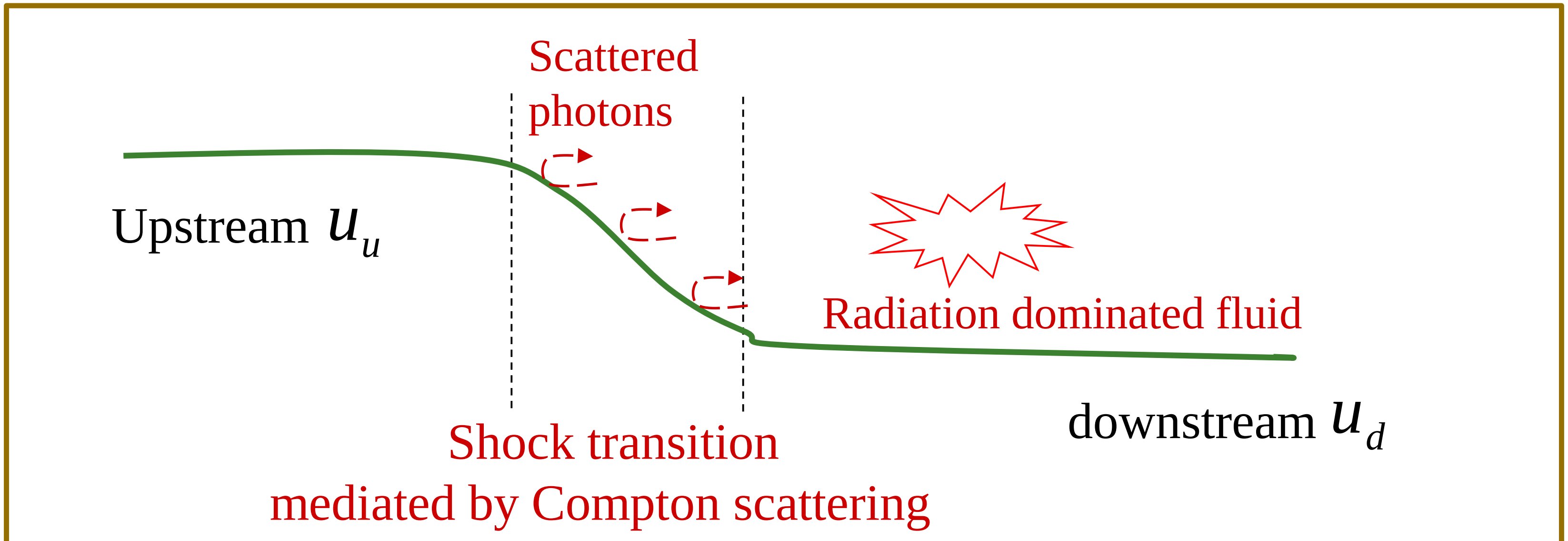
Plan of this talk

- Introduction
  - Brief overview of Radiation Mediated Shocks (RMS)
  - Non-relativistic and Relativistic RMS
- Application to GRBs
  - Motivation for the application
  - New method for RRMS using Monte-Carlo
  - Results and current status
- Summary

Radiation Mediated Shocks (RMS)



picture taken from Levinson @ Gamma-Ray Burst "NEW MISSIONS TO NEW SCIENCE"

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

Under which conditions a RMS forms ?

Weaver 1976

(I) Radiation dominance downstream: $aT_d^4 > n_d kT_d$

from jump conditions: $n_u m_p c^2 \beta_u^2 \approx aT_d^4$

$$\Rightarrow \boxed{\beta_u > 4 \times 10^{-5} (n_u / 10^{15}\ \mathrm{cm}^{-3})^{1/6}}$$

(II) Photon trapping at shock region

Diffusion time $t_D \approx$ shock crossing time t_{sh}

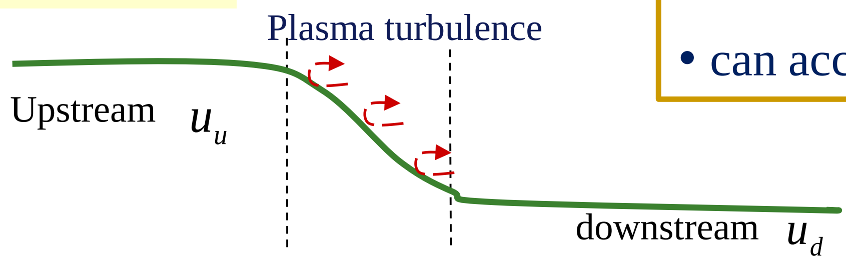
$$\Rightarrow \boxed{\tau >> \tau_{dec} \sim 1/\beta_u}$$

Relevant Astrophysical Phenomena

- Shock breakout from stellar surface (e.g, SN, HN)
- Shocks in Accretion flows (e.g., AGN, μQSO)
- Shocks in Jet (GRBs, AGNs)

Collisionless shocks versus RMS

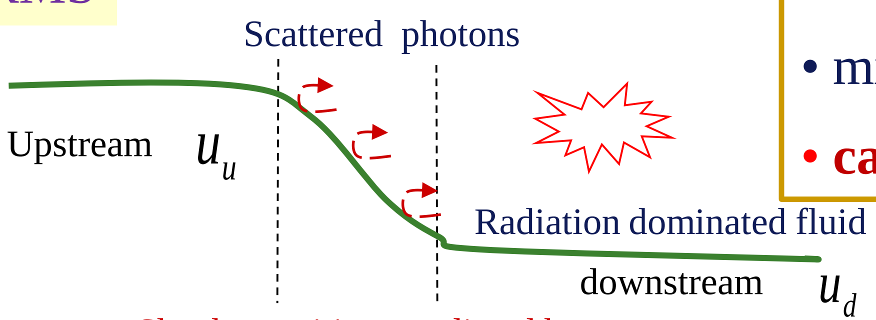
collisionless



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**

Non-relativistic .vs. Relativistic

Non-relativistic RMS

- small energy gain: $\Delta\varepsilon/\varepsilon \ll 1$
- **diffusion approximation holds**. Used in most early treatments

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

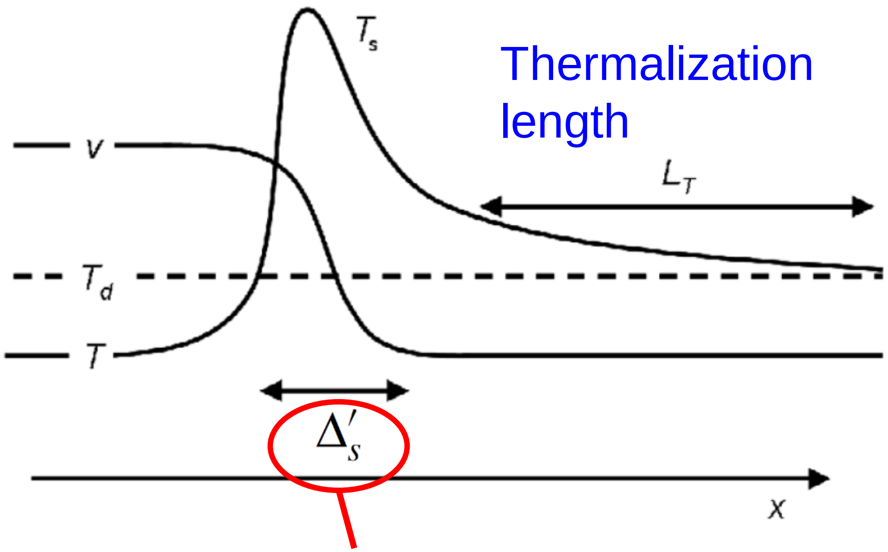
Relativistic RMS

- **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 2016

Non-relativistic RMS



Katz et al. 2010

Shock crossing time

$$t'_s = \Delta'_s/(c\beta_s)$$

diffusion time

$$t'_D \simeq n_e\sigma_T\Delta'^2_s/c$$

$$\Delta'_s \simeq (n\sigma_T\beta_s)^{-1}$$

Jump Condition in strong shock

$$n_u\beta_s = n_d\beta_d,$$
$$p_{\gamma,d} = n_u\beta_s(\beta_s - \beta_d)m_pc^2,$$
$$4p_{\gamma,d}\beta_d = n_u\beta_s(\beta_s^2 - \beta_d^2)m_pc^2/2$$

$$n_{\gamma,\mathrm{eq}} \approx p_{\gamma,d}/T_d$$

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

diffusion approximation significantly reduces the difficulty of problem

Assumption : strong shock ($p_u = 0$), Thomson limit (energy independent scattering)
radiation dominant pressure

Conservation

$$\begin{cases} n_p \beta = n_u \beta_s \\ p_\gamma = n_u \beta_s (\beta_s - \beta) m_p c^2 \\ (e_\gamma + p_\gamma)\beta c - \frac{c}{3 n_p \sigma_T} \frac{d e_\gamma}{dx} = n_u \beta_s m_p \frac{\beta_s^2 - \beta^2}{2} c^3 \end{cases}$$

diffusion

EOS

$$e_\gamma = 3 p_\gamma$$

$$\rightarrow \quad \frac{d\tilde{\beta}}{d\tilde{x}} = -\frac{(7\tilde{\beta} - 1)(1 - \tilde{\beta})}{6\tilde{\beta}}$$

$$\tilde{x} = 3\sigma_T n_u \beta_s x$$

$$\tilde{\beta} = \beta / \beta_s$$

analytic solution

$$\tilde{x} = \frac{1}{7} \ln \left[\frac{(1 - \tilde{\beta})^7}{(7\tilde{\beta} - 1)} \right]$$

Katz et al. 2010

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Assumption : strong shock ($p_u = 0$), Thomson limit (energy independent scattering)
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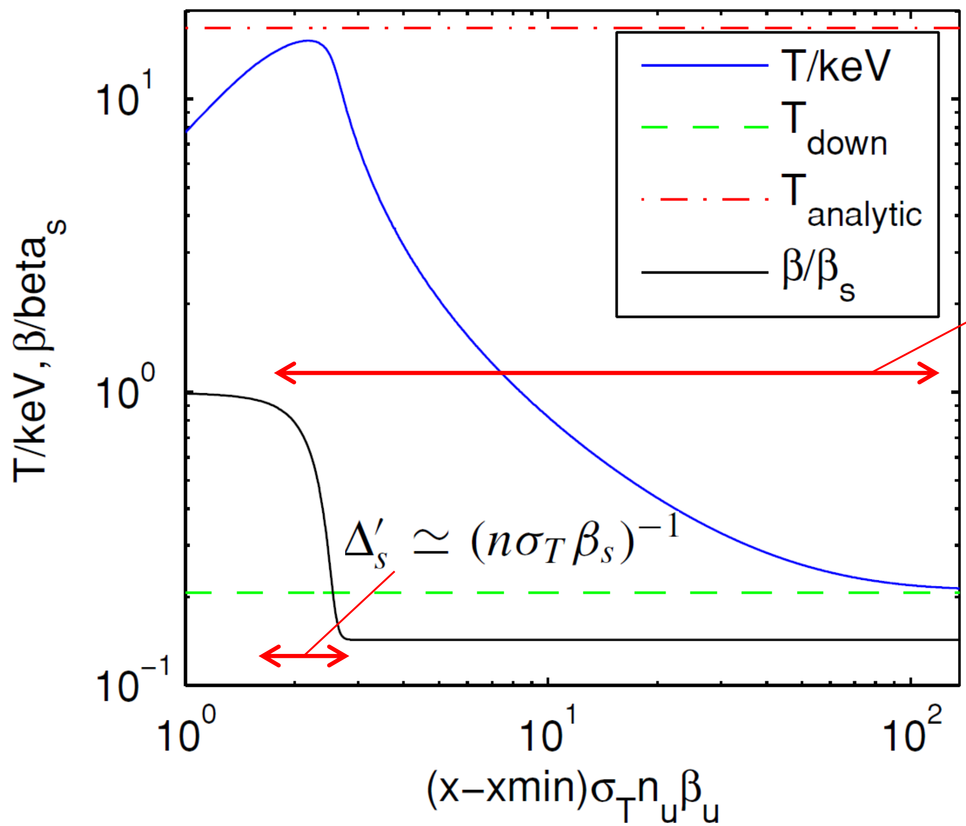


$$L_T \sim \beta c \frac{n_{\gamma,\mathrm{eq}}}{Q_{\gamma,\mathrm{eff}}}$$ ~100

analytic solution

$$\tilde{x} = \frac{1}{7} \ln \left[\frac{(1-\tilde{\beta})^7}{(7\tilde{\beta}-1)} \right]$$

Katz et al. 2010

Relativistic RMS

Radiation transfer and copious pair productions needs to be solved

Levinson & Bromberg (2008), Beloborodov (2016)

Hot up stream

photons advected from upstream mediate the shock

Up to Lorentz factor $\Gamma=2$

Pair creation is not included

Budik et al. (2010)

Cold up stream plasma (no photons)

Photons produced in the downstream mediates the shock

Up to Lorentz factor $\Gamma = 30$

Approximated cross sections for scattering and pair creation

Budnick (2010)

$$\frac{d}{dz_{\rm sh}} T^{0z}_{\rm sh} = 0,$$:energy

$$\frac{d}{dz_{\rm sh}} T^{zz}_{\rm sh} = 0,$$:momentum

$$n_p = n_{p,u} \frac{\Gamma_u \beta_u}{\Gamma \beta},$$:baryon number

$$\frac{d(\Gamma \beta n_+)}{dz_{\rm sh}} = \frac{Q_+}{c},$$:pair creation, annihilation

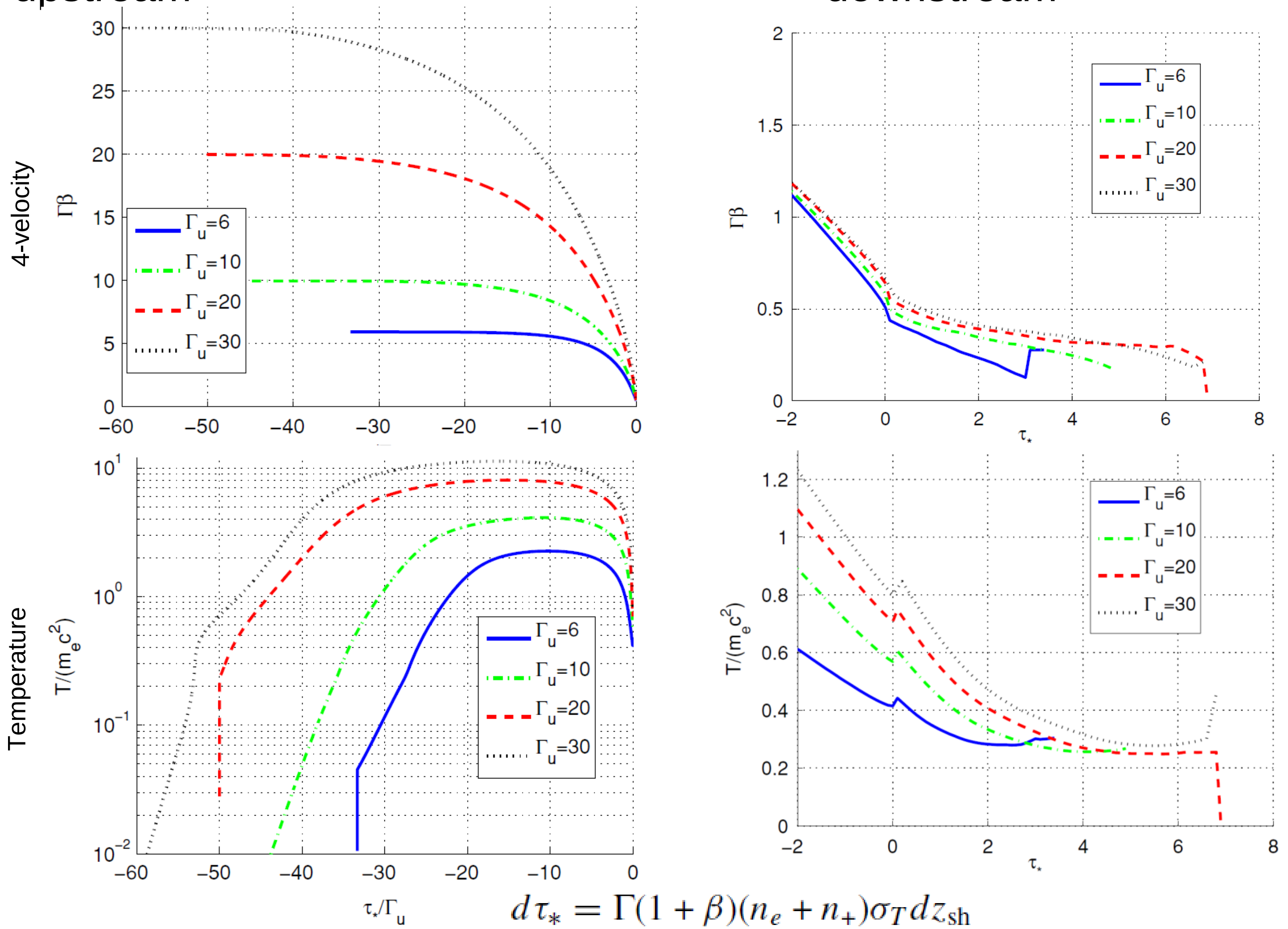
$$\mu_{\rm sh} \frac{dI_{\nu_{\rm sh}}(\mu_{\rm sh})}{dz_{\rm sh}} = \underbrace{\eta_{\rm sh}(\mu_{\rm sh}, \nu_{\rm sh})}_{\text{emission}} - \underbrace{I_{\nu_{\rm sh}}(\mu_{\rm sh}) \chi_{\rm sh}(\mu_{\rm sh}, \nu_{\rm sh})}_{\text{absorption}}$$:radiation transfer

emission absorption

[Budnick (2010)](#)

upstream

downstream

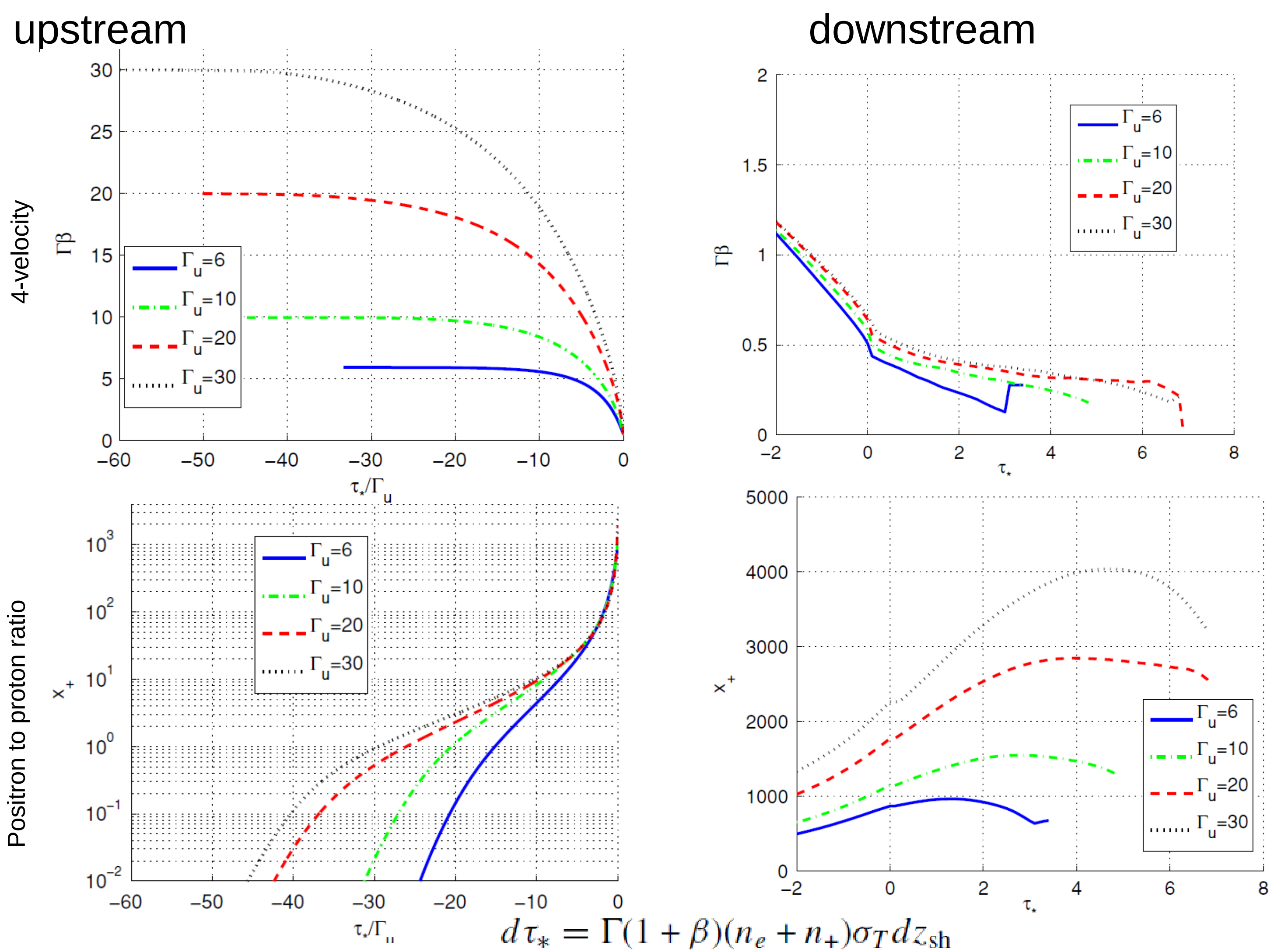


$$d\tau_* = \Gamma(1+\beta)(n_e + n_+)\sigma_T dz_{sh}$$

Shock width $\Delta_s = 0.01(\sigma_T n_u)^{-1}\gamma_u^2$

Optical depth inside shock is dominated by $e^{\pm}$

Budnick (2010)



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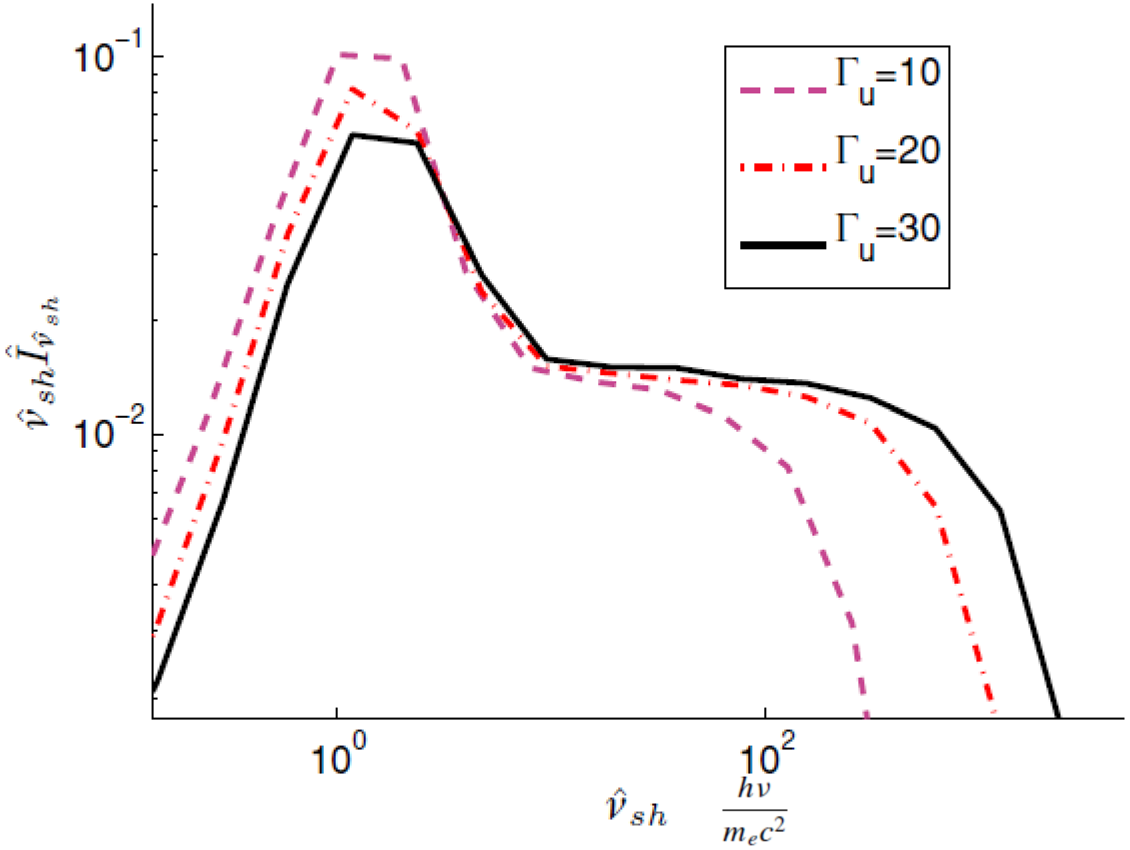
Spectrum inside the shock



Non-thermal spectrum appears due to bulk Comptonization

Previous studies of RRMS

Levinson & Bromberg (2008), Beloborodov (2016)

photons advected from the upstream is dominant

Up to Lorentz factor Γ=2

Pair creation is not included

Budik et al. (2010)

Photons produced in the downstream is dominant

Up to Lorentz factor Γ = 30

Approximated cross sections for scattering and pair creation

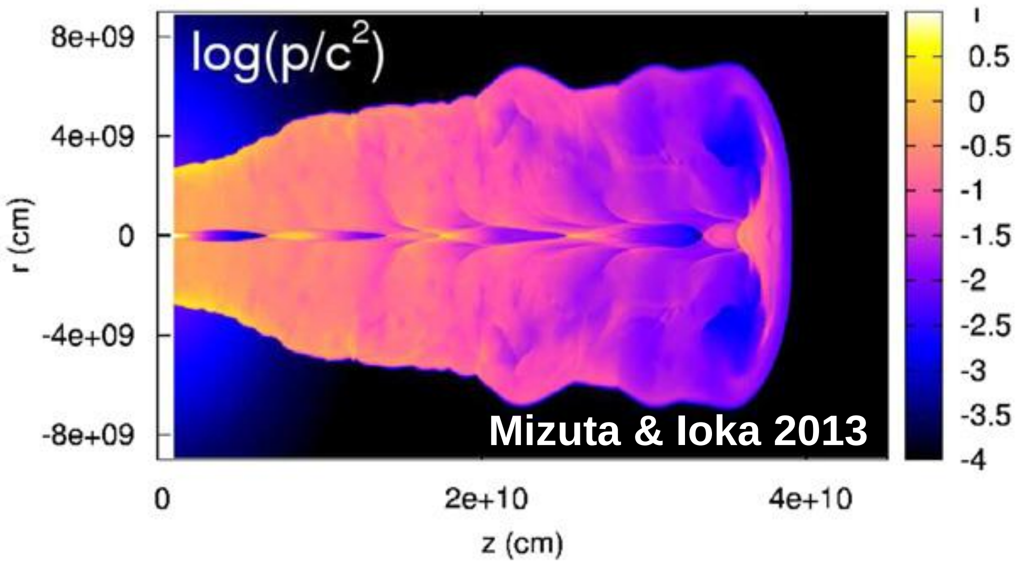
Limited range of parameters

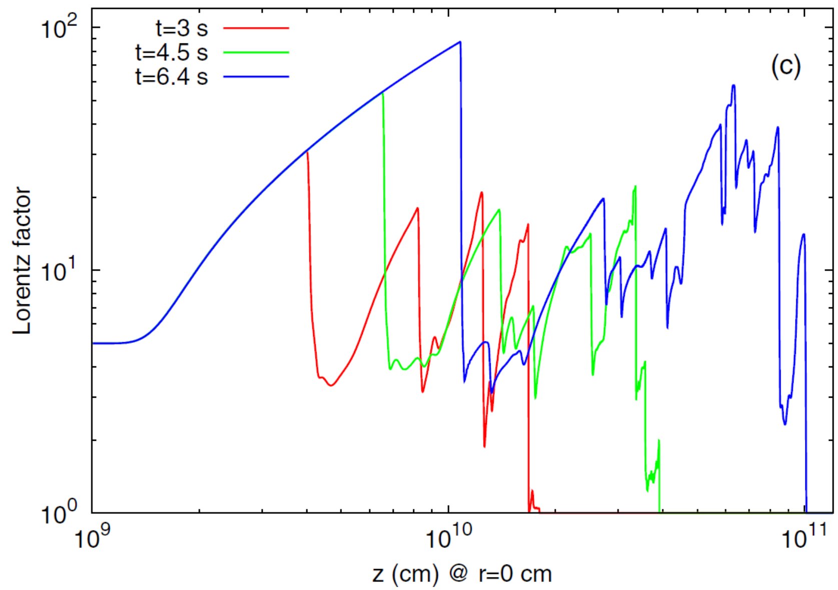
Aim of the present study

Construction a fully self-consistent steady solution of RRMS

application to GRBs, Shock breakout , etc..

Application to GRBs





Relativistic shocks naturally develops within jet

<u>Condition for RMS to form</u>

Weaver 1976

- Optically thick ($\tau \gg 1$)
- 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 will have significant impact on the emission

RRMS in GRB fireball

Photon rich in upstream ($n_\gamma / n_p \sim 10^4 - 10^5 >> 1$)

Thermalization depth

Photon generation: Bremst. + double Compton

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

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

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

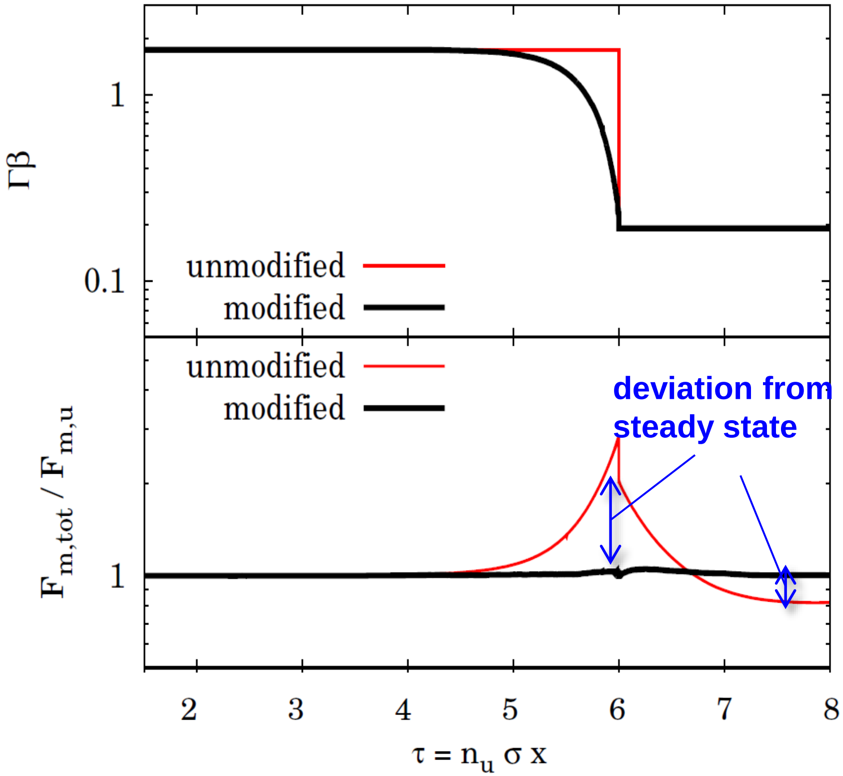
Thermalization length >> shock width ($\tau \sim$ few)

→ **Photon advection dominant**

(Photon generation and absorption can be neglected)

Levinson 2012

Method・Model



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）

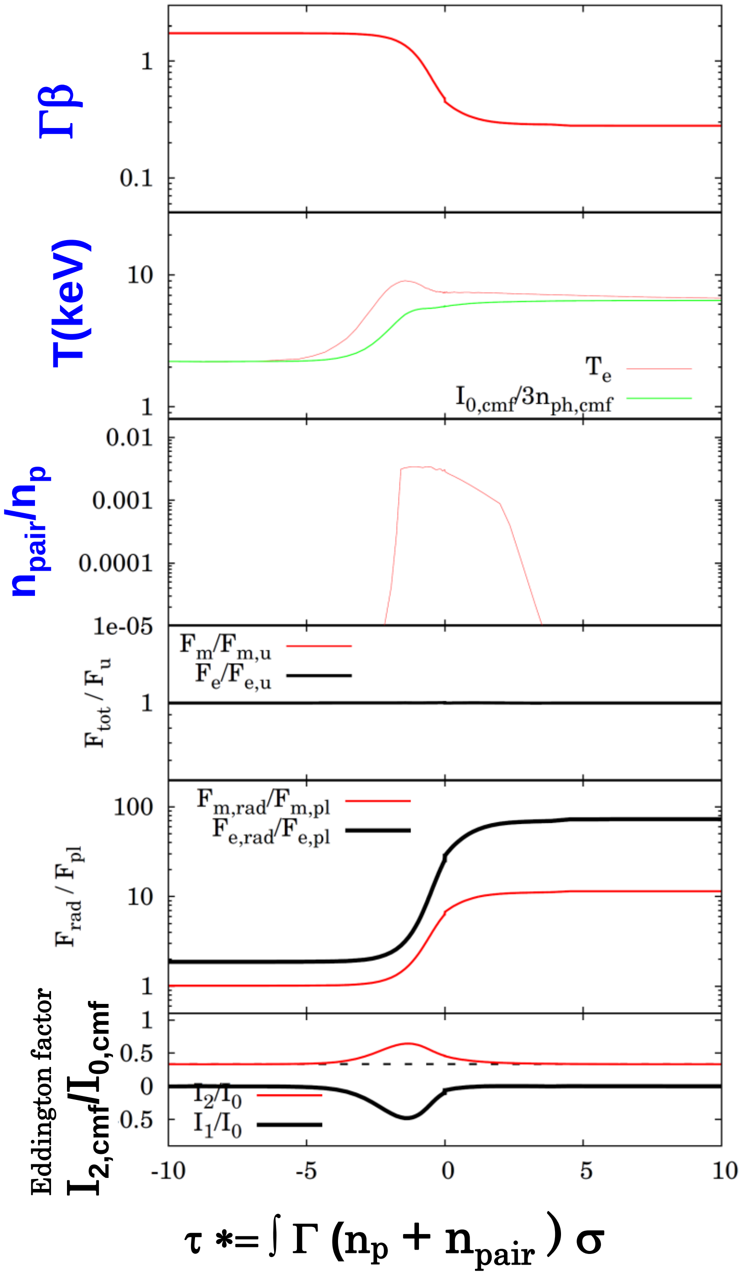
・large photon to proton ratio
(n_{ph} / n_p = 10^4 - 10^5)

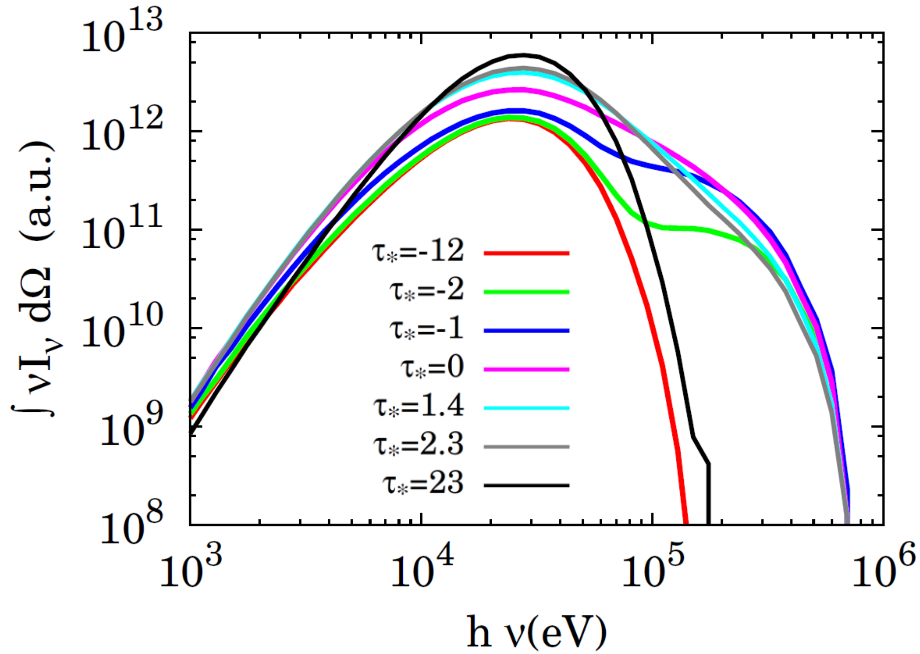
・thermal distribution at far up stream

・electron has Maxwellian distribution

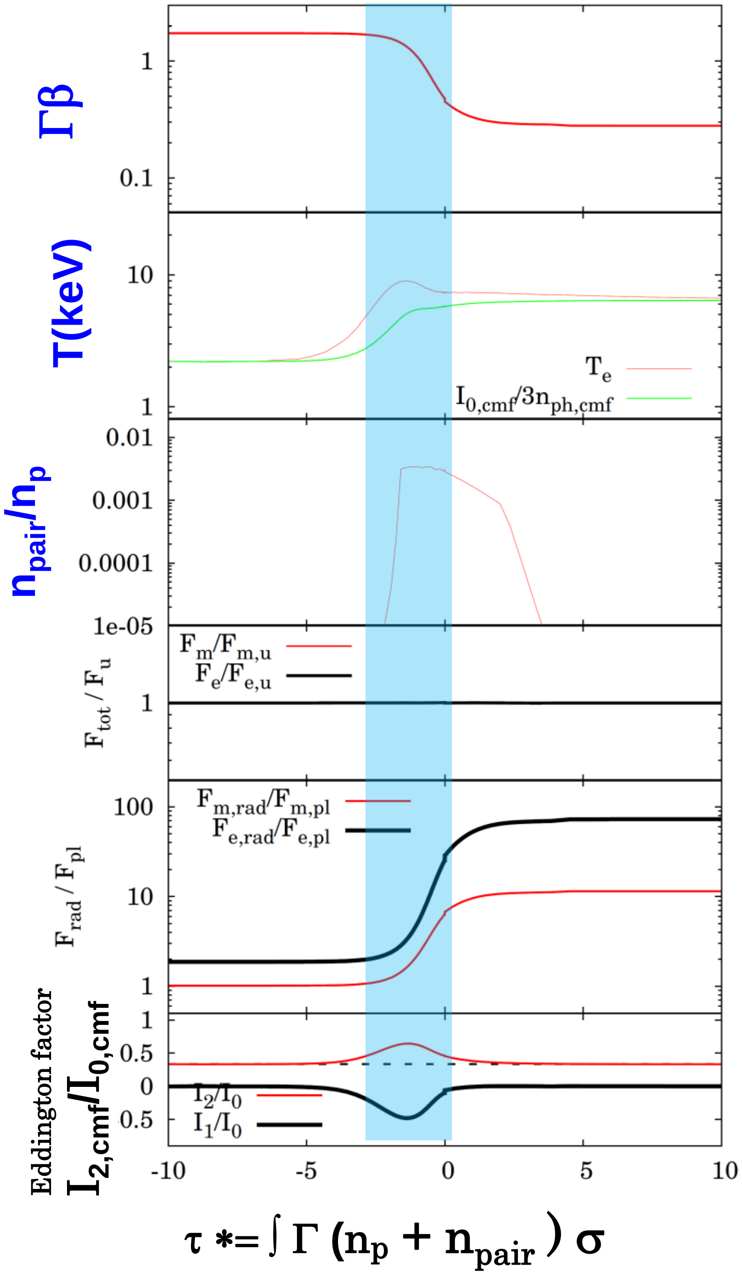
Γ_u = 2

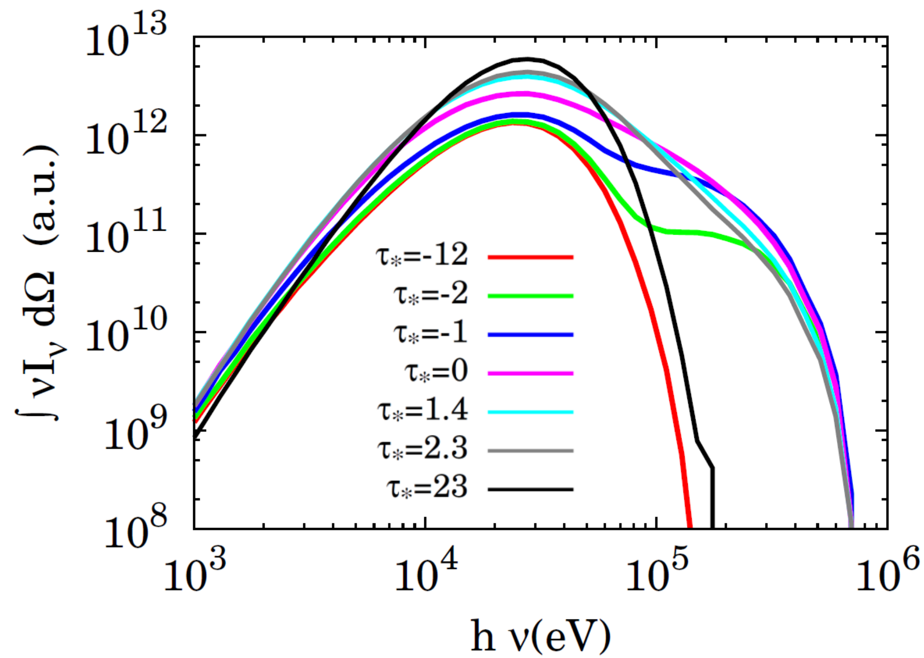
· $F_{m,rad}$ (radiation momentum flux) = 1 $F_{m,matt}$ (plasma mom flux) @ far upstream region





· $F_{m,rad}$ **(radiation momentum flux) = 1 $F_{m,matt}$ (plasma mom flux)** @ far upstream region

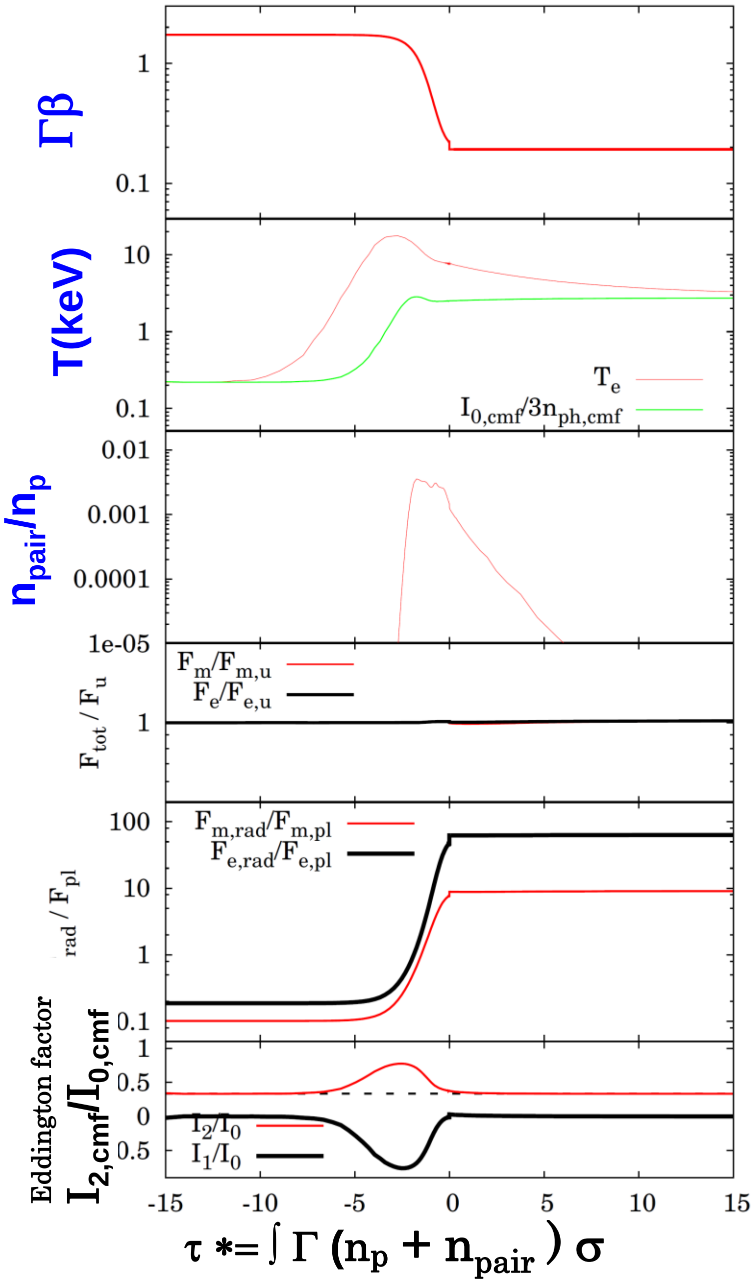


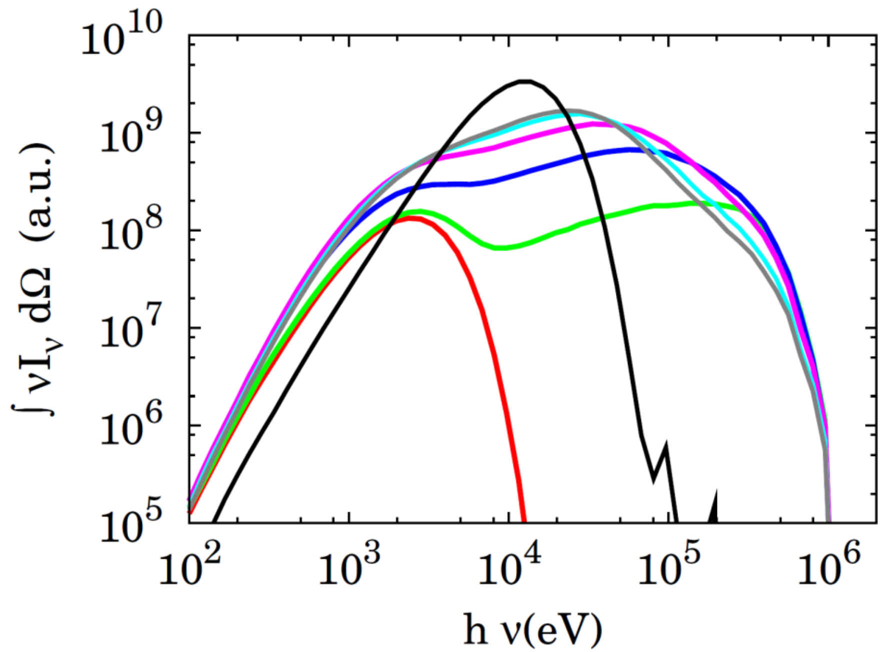


Deceleration in Δτ ~ 1

non-thermal spectrum

- $F_{m,rad}$ **(radiation momentum flux)** = **0.1 $F_{m,matt}$** (**plasma mom flux**) @ far upstream region

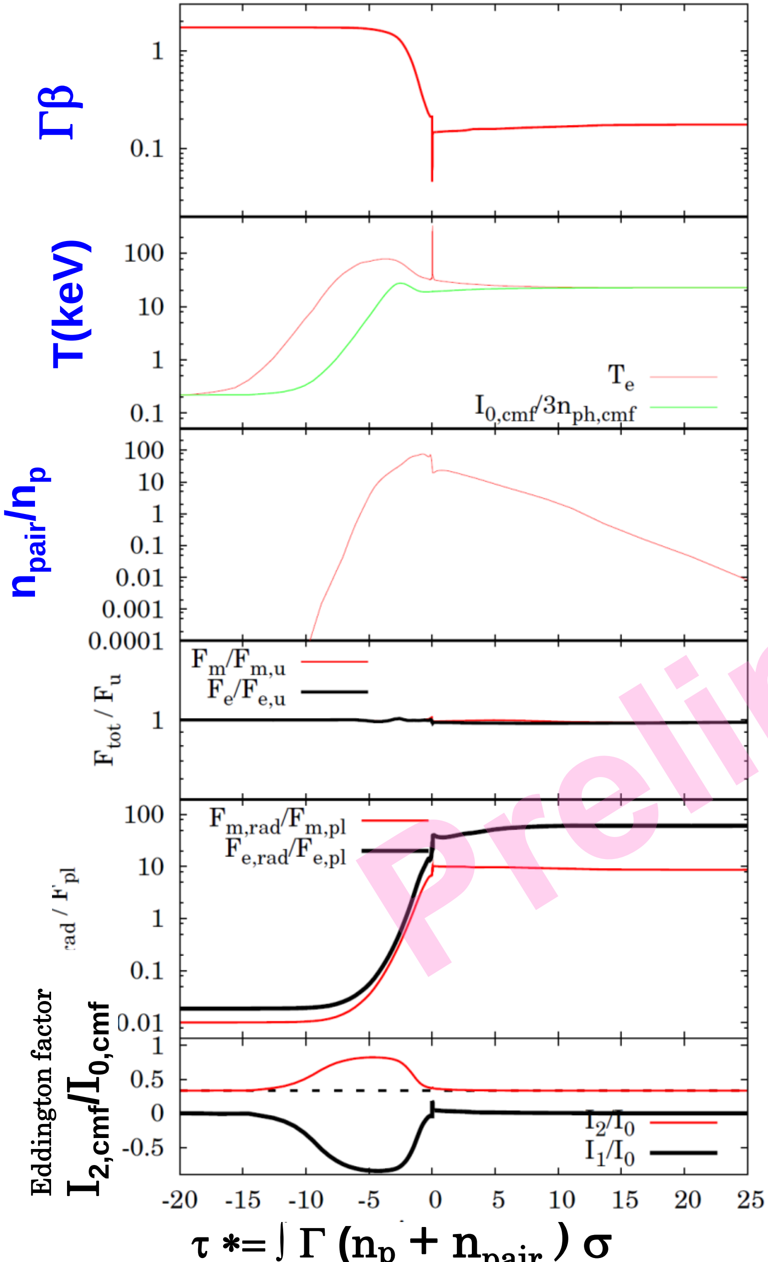


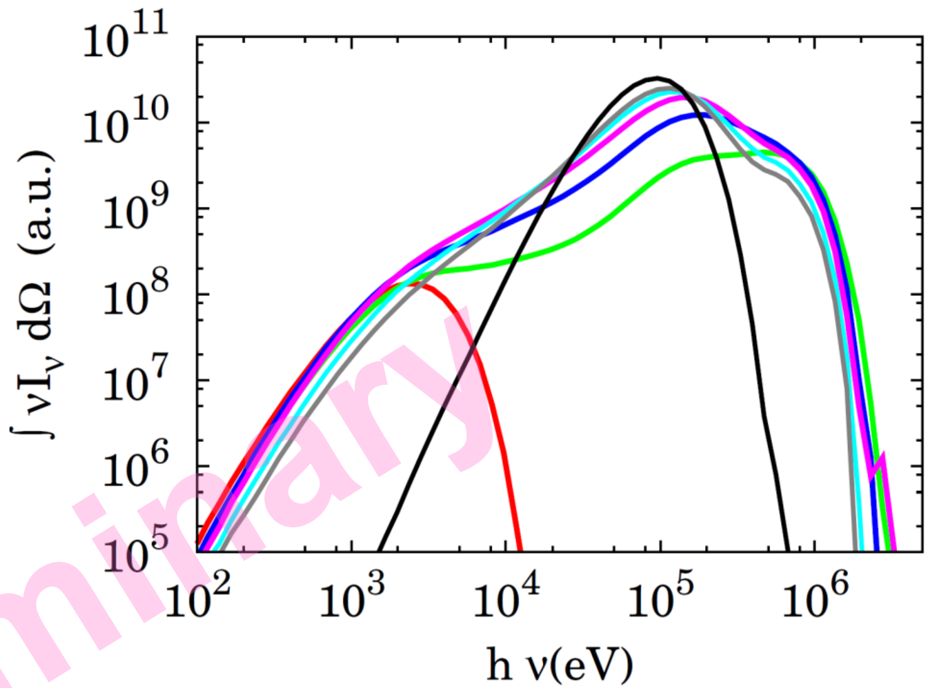


Deceleration in Δτ ~ 1

non-thermal spectrum

· $F_{m,rad}$ **(radiation momentum flux) = 0.01 $F_{m,matt}$ (plasma mom flux)** @ far upstream region





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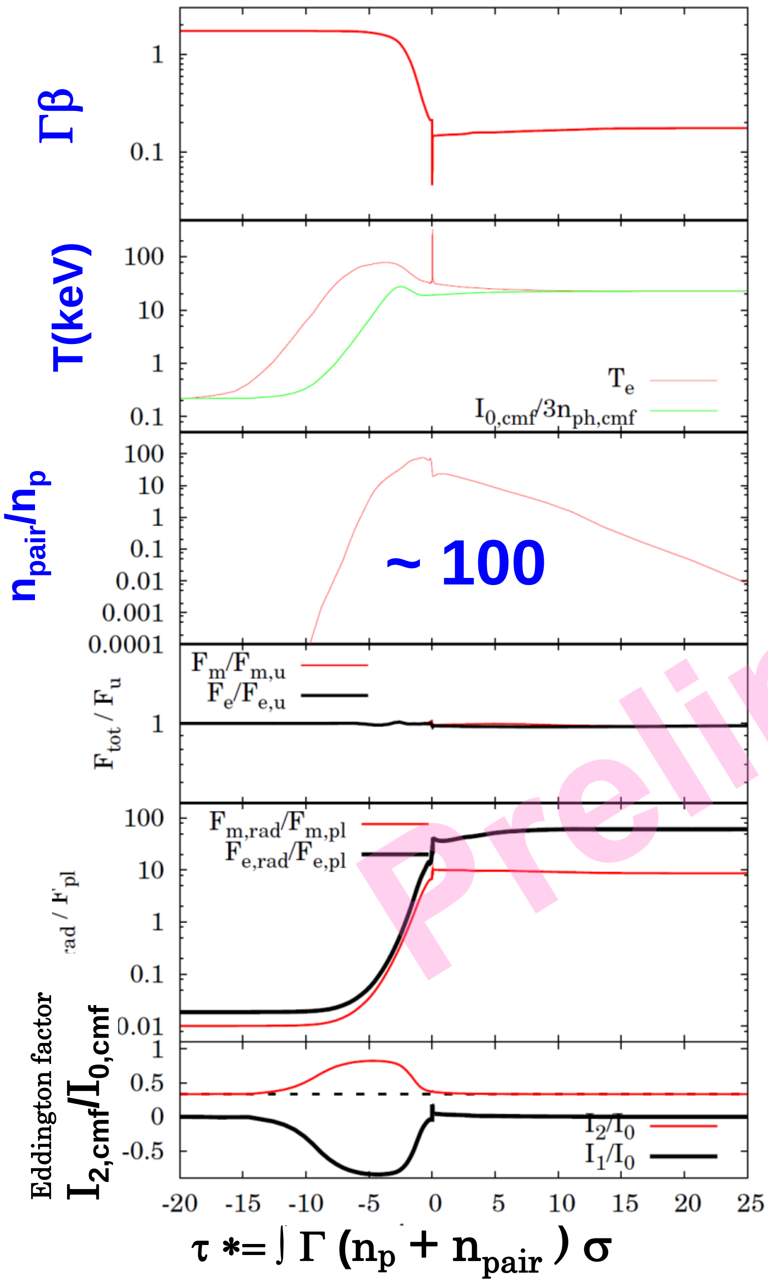
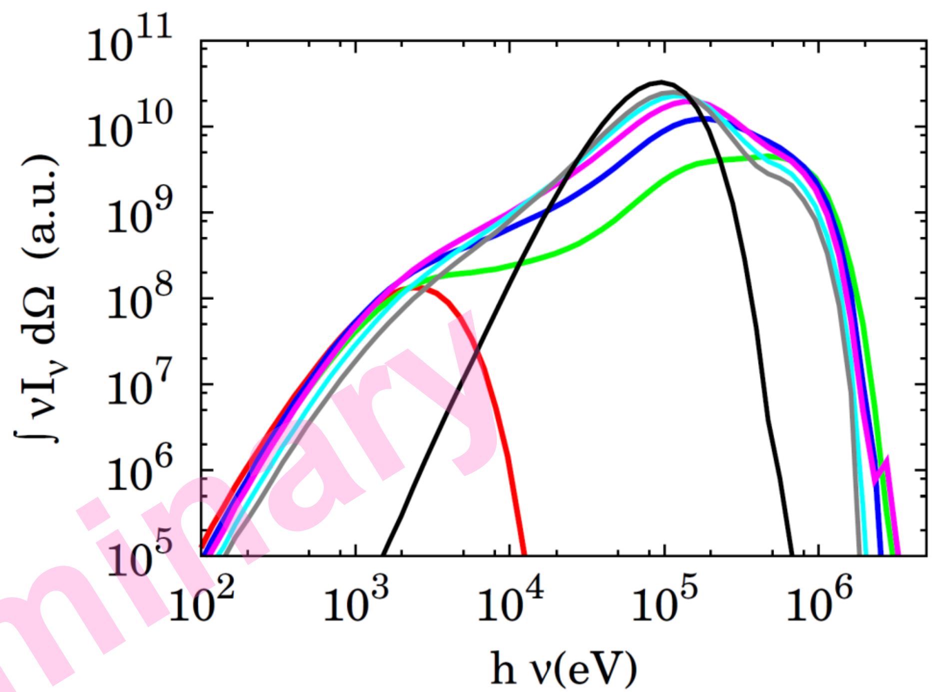
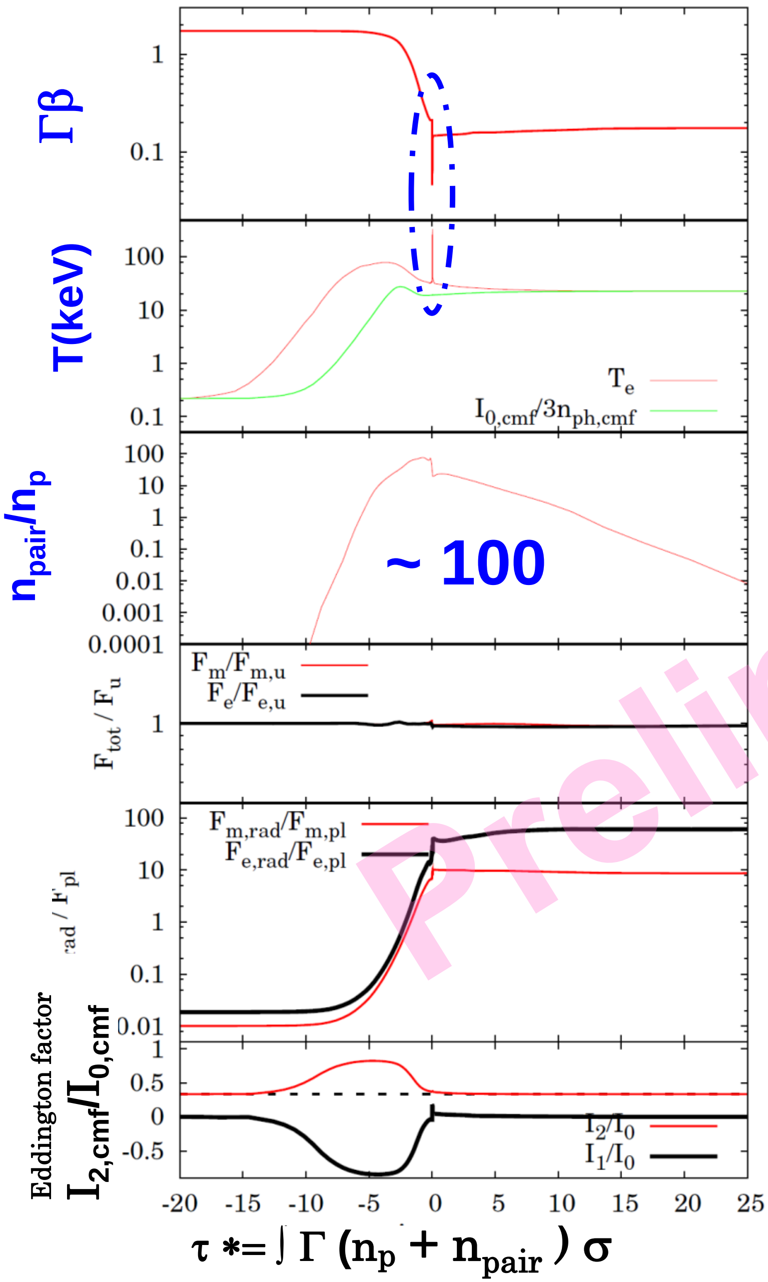
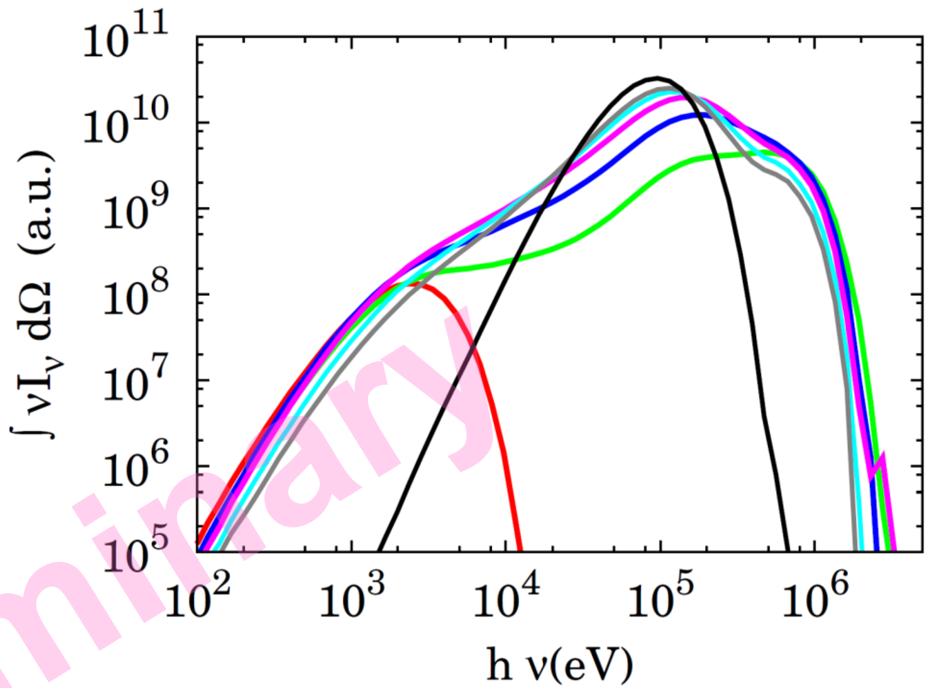




Pairs dominates the opacity near the shock

- $F_{m,rad}$ (**radiation momentum flux**) = **0.01 $F_{m,matt}$** (**plasma mom flux**) @ far upstream region

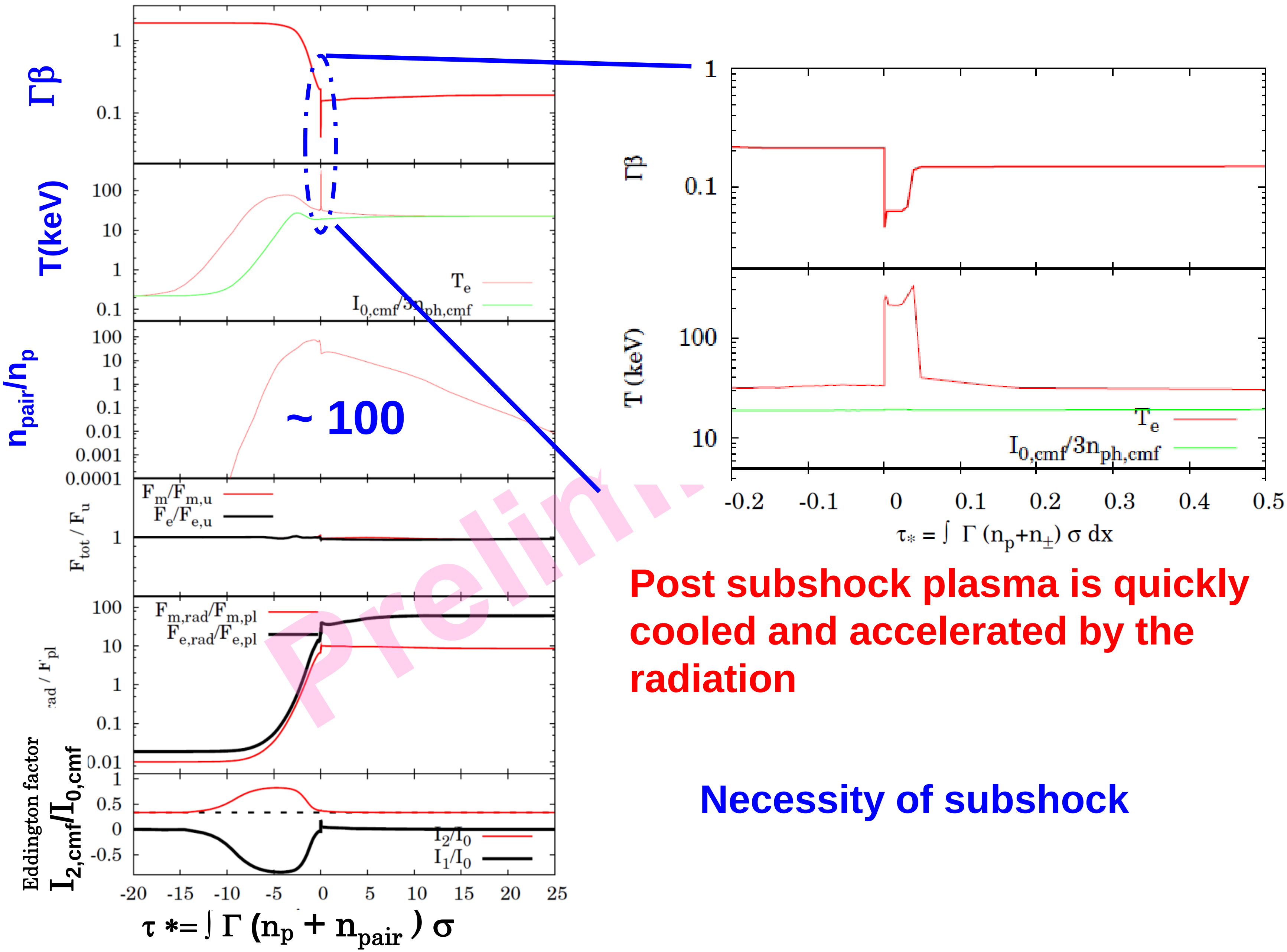




Pairs dominates the opacity near the shock

Necessity of subshock

- $F_{m,rad}$ (radiation momentum flux) = $0.01\ F_{m,matt}$ (plasma mom flux) @ far upstream region

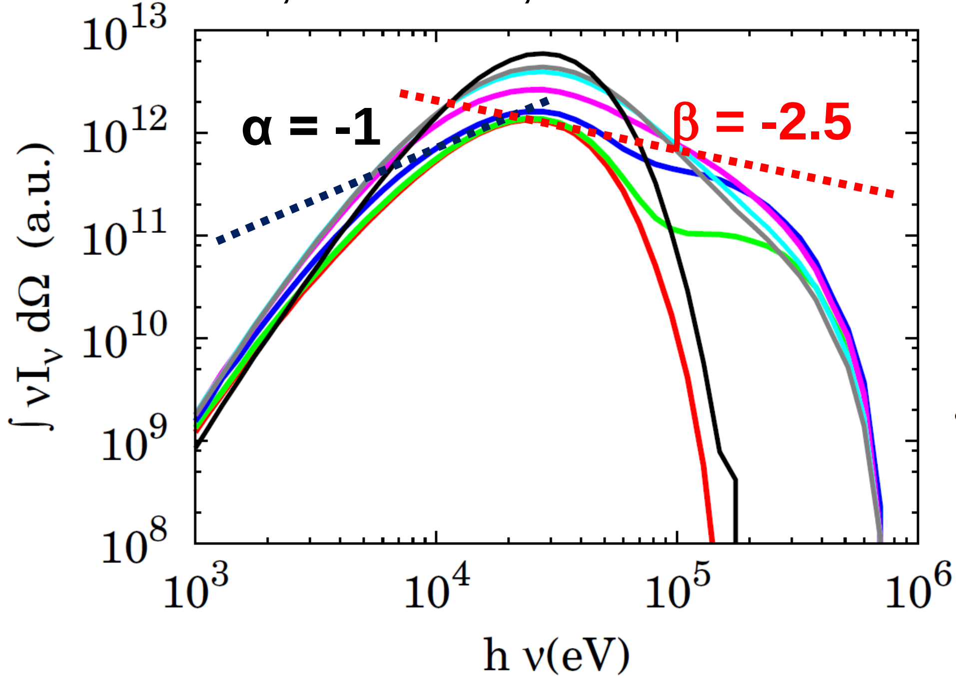


Post subshock plasma is quickly cooled and accelerated by the radiation

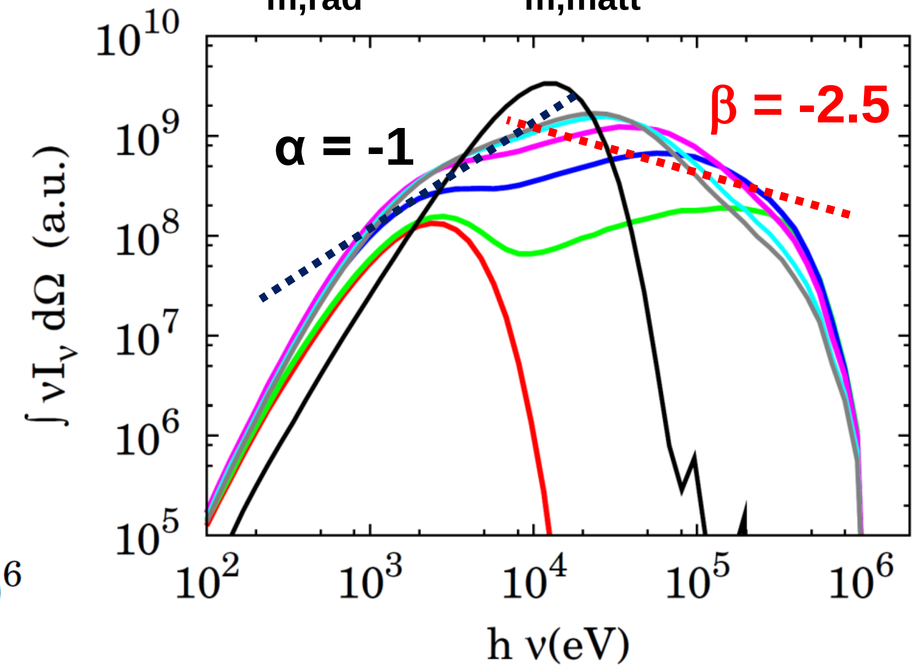
Necessity of subshock

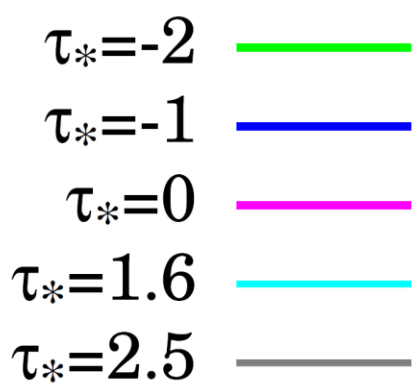
Comparison with Band spectra

$F_{m,rad} = 1\ F_{m,matt}$



$F_{m,rad} = 0.1\ F_{m,matt}$





Highly non-thermal spectra appears near the shock

Possible origin of Band spectrum

Summary

RRMS in photon advection dominated regime is computed

- 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
- Necessity of subshock for $\mathbf{F}_{\mathbf{m,rad}} >> \mathbf{F}_{\mathbf{m,matt}}$
- Possible origin of Band spectrum

Future work

- Parameter survey
- Implementation of photon production and absorption
- Implementation of magnetic fields