The Spectrum of a Fast Shock Breakout from a Stellar Wind

Kunihito IOKA

(Center for Gravitational Physics, YITP, Kyoto U.)

KI, Levinson & Nakar 18

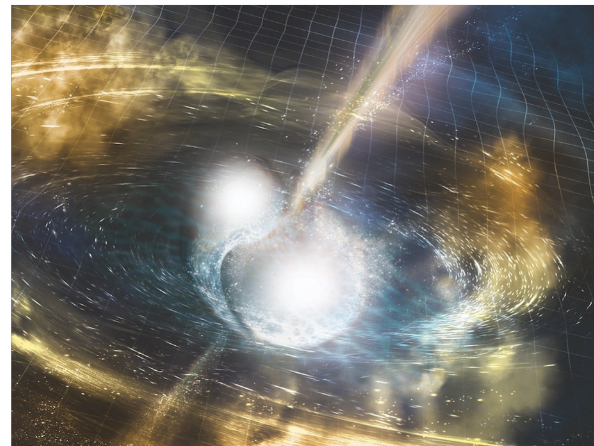
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

CGP
Center for Gravitational Physics
Yukawa Institute for Theoretical Physics

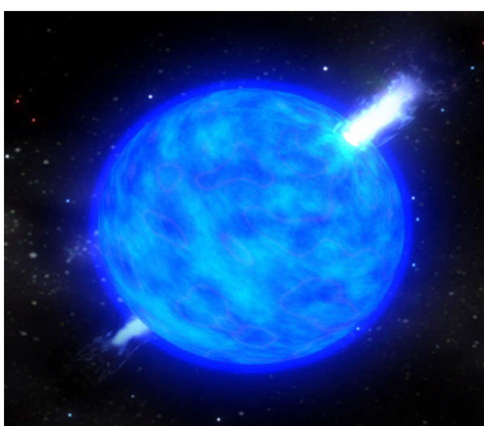
Shock Breakout

Supernova

Neutron star merger



Gamma-ray burst

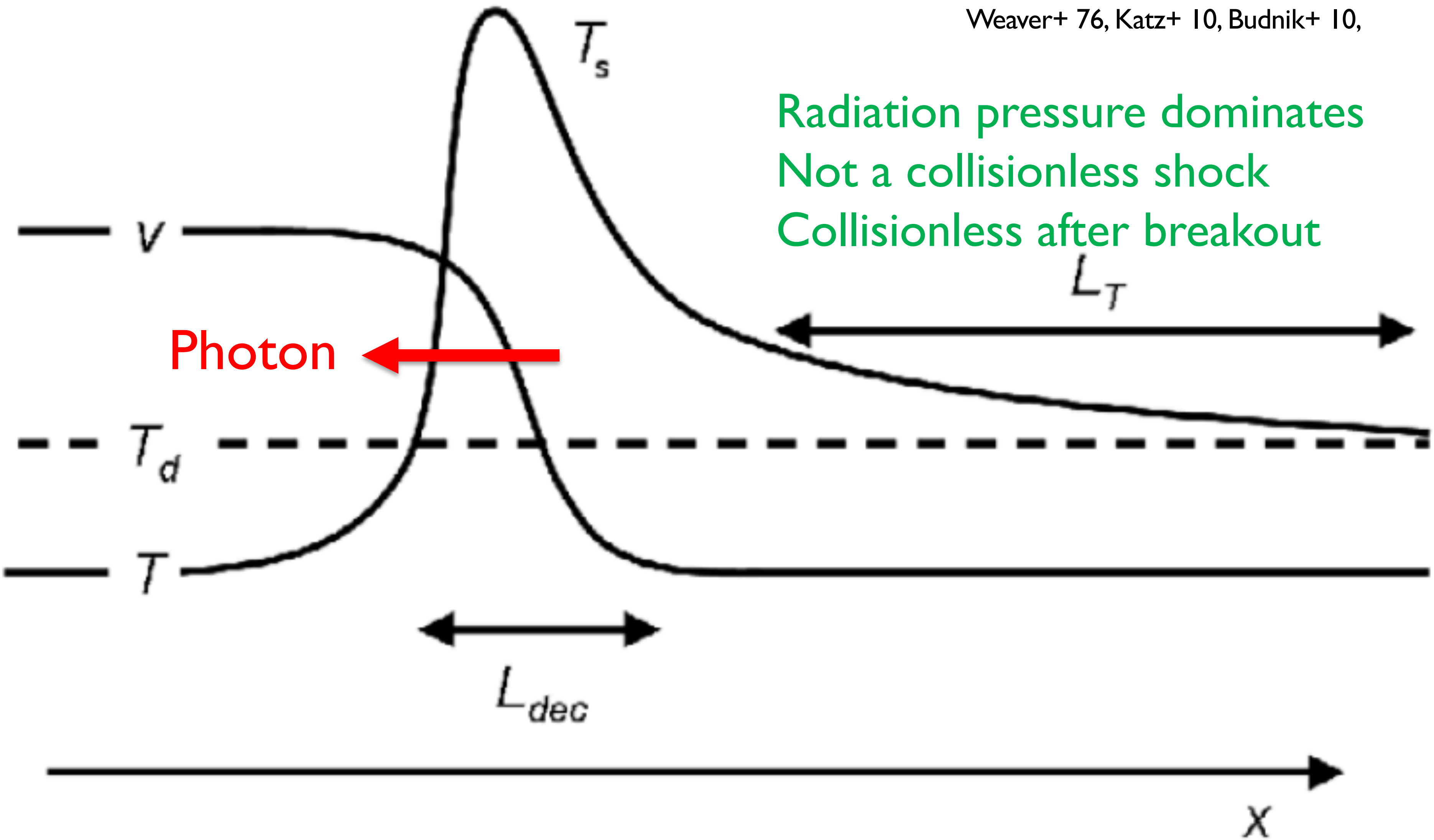


Tidal disruption event

Radiation-Mediated Shock

Weaver+ 76, Katz+ 10, Budnik+ 10,

Radiation pressure dominates
Not a collisionless shock
Collisionless after breakout

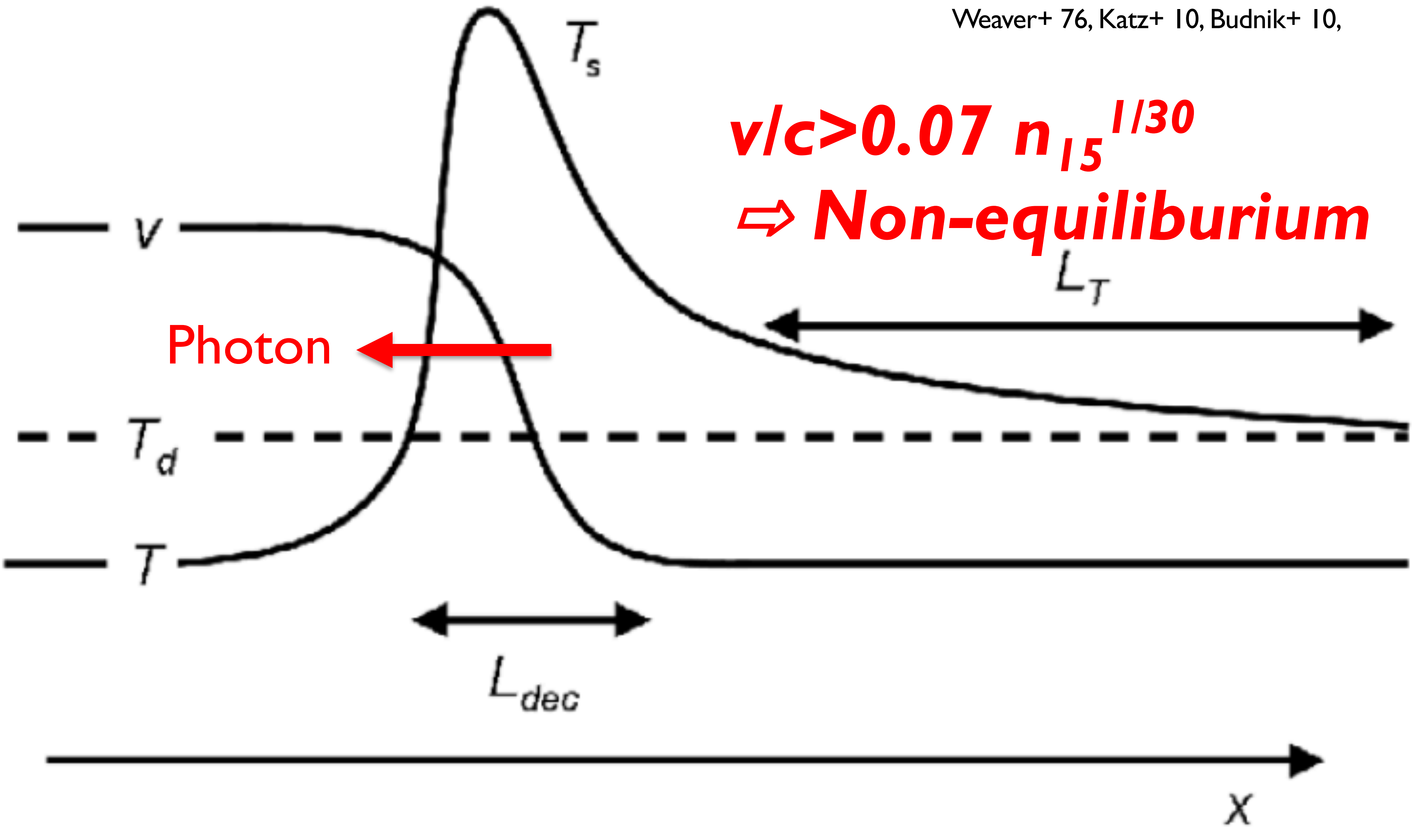


Fast Shock Breakout

Weaver+ 76, Katz+ 10, Budnik+ 10,

$v/c > 0.07\, n_{15}^{1/30}$

⇨ Non-equilibrium

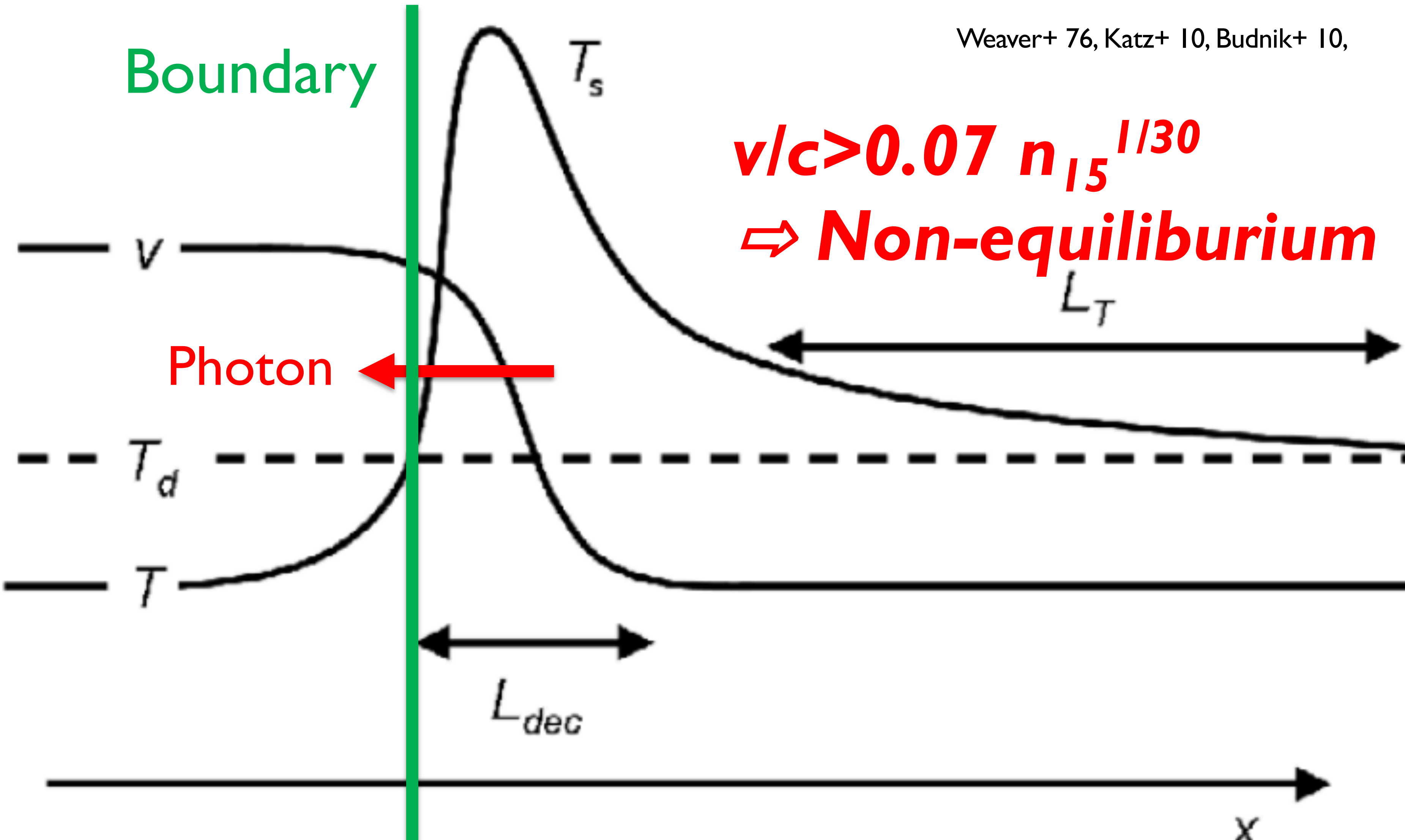


Photon Escape

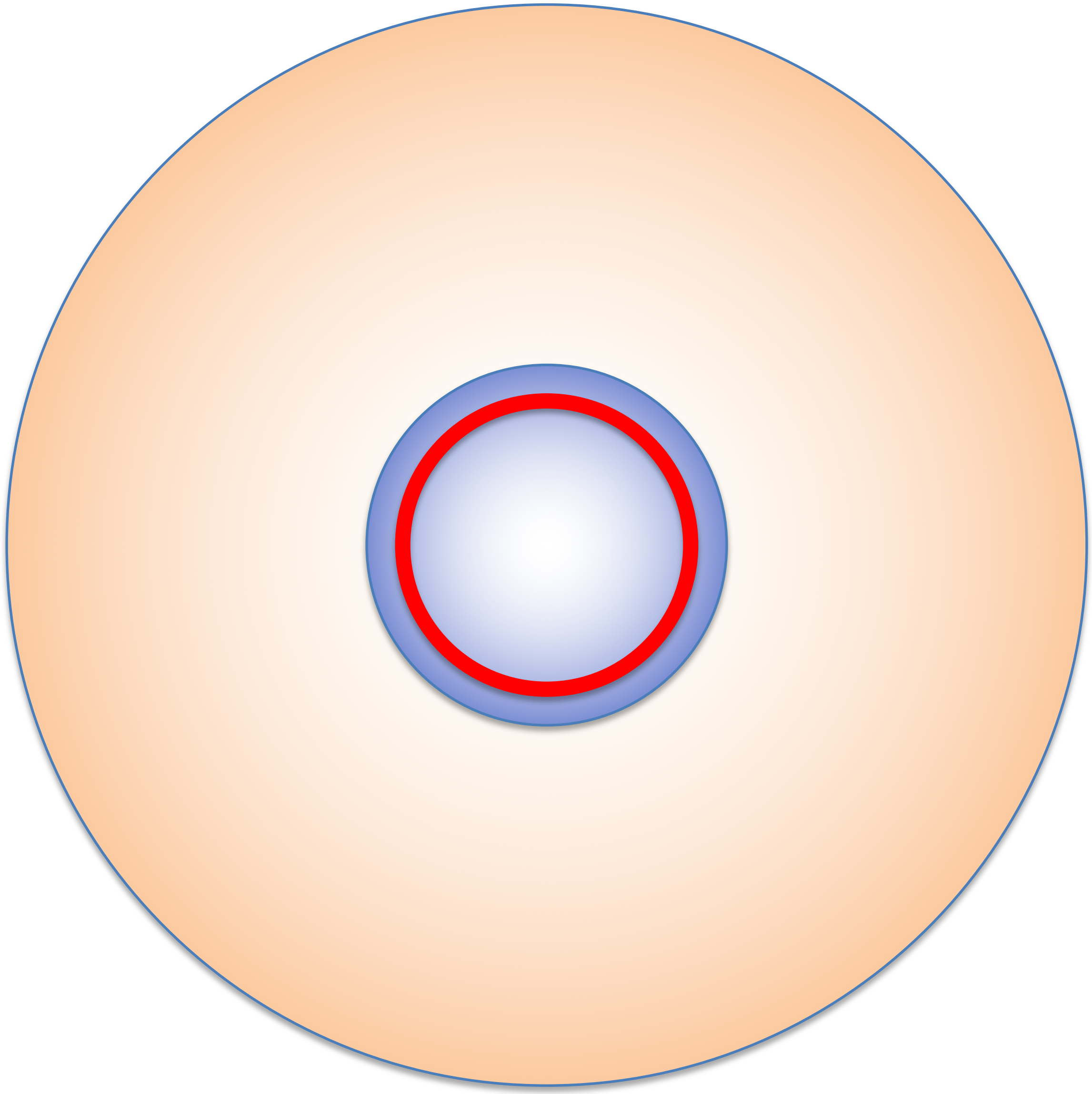
Weaver+ 76, Katz+ 10, Budnik+ 10,

$v/c > 0.07\ n_{15}^{1/30}$

⇨ Non-equiliburium

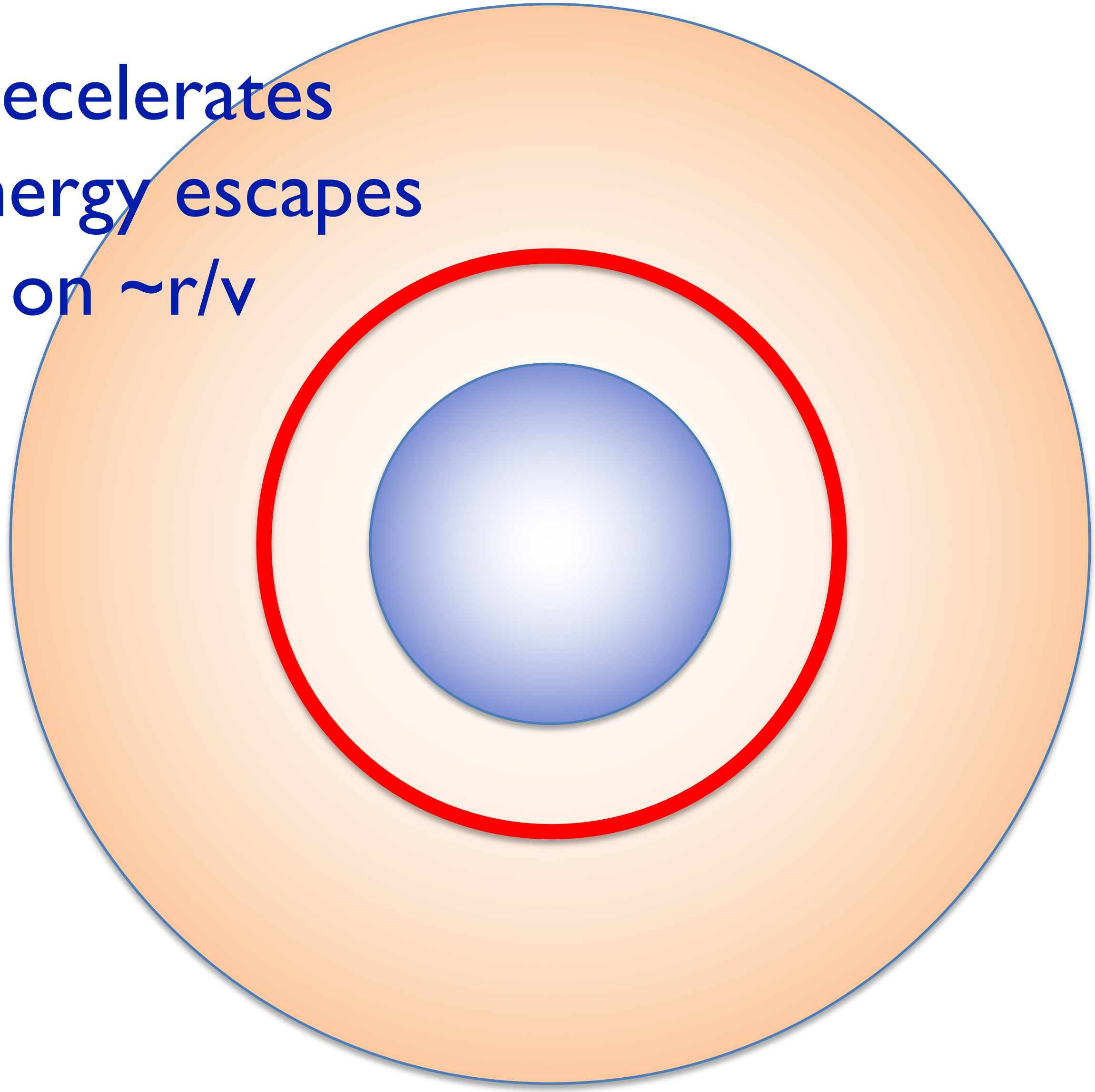


Breakout from a Wind



Breakout from a Wind

1. Shock decelerates
2. Most energy escapes
3. v varies on ~r/v



Relativistic Breakout

- Ultra-relativistic case

  Granot+ 18

  - High temperature
  - electron positron creation
  - Only require $\tau \sim (m_e/m_p)\Gamma_{sh}$
  - Breakout is delayed

- How about a sub-relativistic case?
  - Photon escape, $\#_{photon}$ decreases, T rises?, $e^{\pm}$?

Basic Equations

Sub-rela radiation-mediated shock
Stationary
Pressure is dominated by radiation
Diffusion approximation
No pairs
x=0: escape boundary

Radiation energy flux

$$f_\gamma = 4p_\gamma v - \frac{c}{n\sigma_T}\frac{dp_\gamma}{dx},$$

$$m_p n v = m_p n_u v_u \equiv J,$$

$$\frac{d}{dx}(Jv + p_\gamma) = 0,$$

$$\frac{d}{dx}\left(Jv^2/2 + f_\gamma\right) = 0.$$

Analytic Solutions

$\tilde{p}_\gamma = p_\gamma / J v_u, \tilde{v} = v/v_u,$ $d\tau^\star = (v_u/c) n_e \sigma_T dx$

$$\tilde{v} + \tilde{p}_\gamma = 1 + \tilde{p}_{\gamma u},$$
$$\frac{d\tilde{p}_\gamma}{d\tau^\star} = -\frac{1}{2} + \frac{1}{2}\tilde{v}^2 + 4\tilde{p}_\gamma \tilde{v} - \frac{1}{2}\tilde{f}_{\gamma u},$$

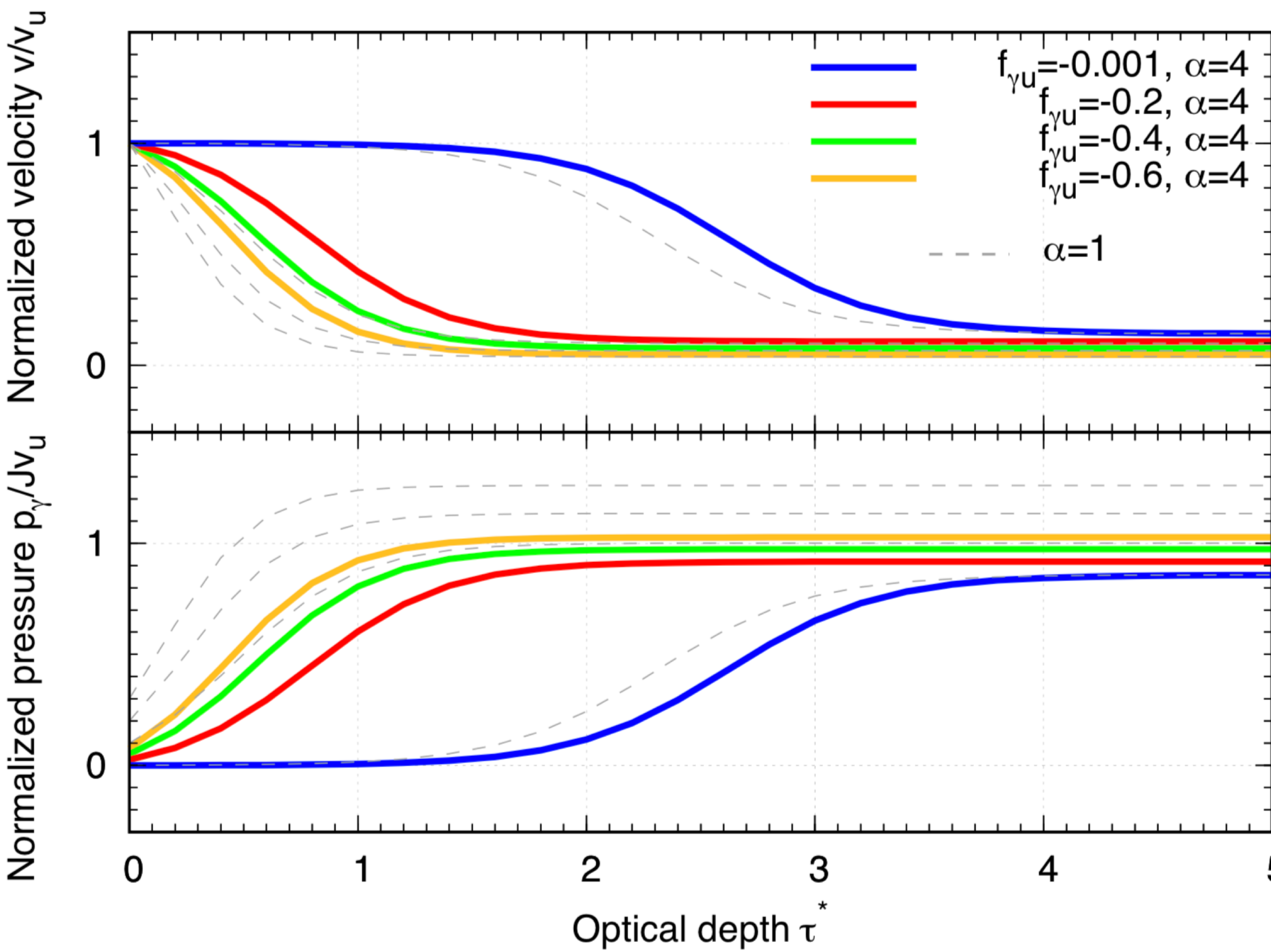
$$\tilde{f}_{\gamma u} = \frac{2 f_{\gamma u}}{J v_u^2}$$

$$\tilde{v} = \frac{4}{7}(1 + \tilde{p}_{\gamma u}) + \frac{\eta}{7} \tanh\left[\frac{\eta}{2}(\tau_0 - \tau^\star)\right]$$

$$\eta = \sqrt{(3 - 4\tilde{p}_{\gamma u})^2 + 56\tilde{p}_{\gamma u} - 7\tilde{f}_{\gamma u}}$$

$$\tau_0 = \frac{2}{\eta} \operatorname{arctanh}\left[\frac{3 - 4\tilde{p}_{\gamma u}}{\eta}\right] = \frac{1}{\eta} \ln \frac{\eta + 3 - 4\tilde{p}_{\gamma u}}{\eta - 3 + 4\tilde{p}_{\gamma u}},$$

Shock Structure



$$\tilde{f}_{\gamma u} = -2\alpha \tilde{p}_{\gamma u},$$

$\alpha = c/v_u$: complete beaming

$\alpha = 3$: isotropic

Shock width is ~c/v even if photons escape

Photon Temperature

$$kT(x) = \frac{p_\gamma(x)}{n_\gamma(x)},$$

$$\frac{dj_\gamma}{dx} = \dot{n}_\gamma,$$

$$j_\gamma = vn_\gamma - \frac{c}{3n\sigma_T}\frac{dn_\gamma}{dx},$$

$$\dot{n}_\gamma = Q_{ff} f_{ab}.$$

Bremsstrahlung

$$Q_{ff} = \frac{1}{2}\alpha_e n_p n_e \sigma_T c \Theta^{-1/2} \Lambda_{eff},$$

$$\Theta = kT/m_e c^2$$

$$f_{ab} = 1 - \frac{n_\gamma}{n_{BB}} = 1 - 2.4 \times 10^{-31} \Theta^{-3} n_\gamma,$$

Boundary Condition

$$j_{\gamma u} = \frac{f_{\gamma u}}{3kT_u}$$

Green's function method

$$\tilde{n}_\gamma(\tilde{x}) = \frac{\tilde{j}_{\gamma u}}{\tilde{v}_{\rm eff}(\tilde{x})} + \int_0^\infty G(\tilde{x},\tilde{y})\tilde{Q}_\gamma(\tilde{y})d\tilde{y},$$

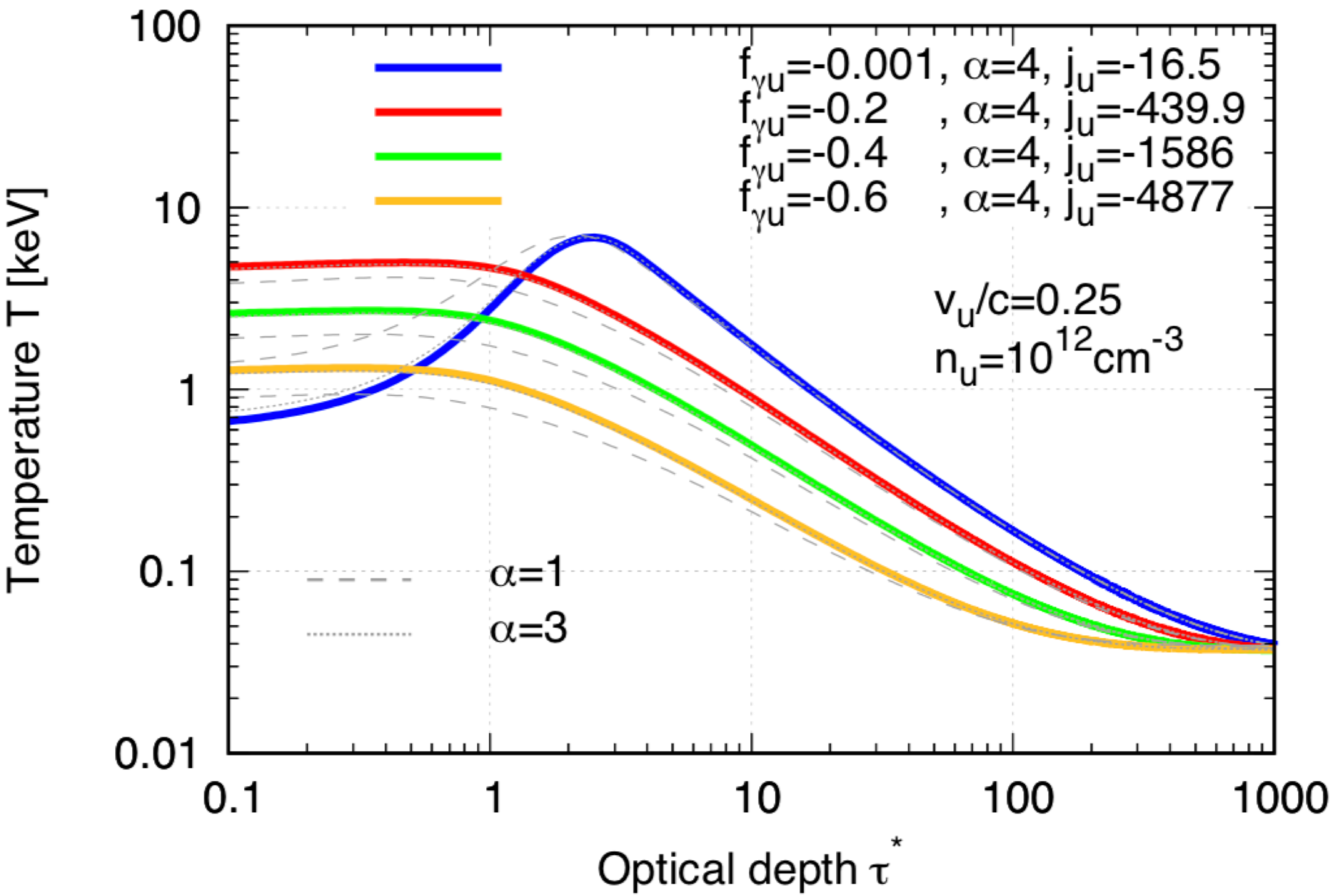
$$d\tilde{x} = 3(v_u/c)n_u\sigma_T dx = 3\tilde{v}d\tau^\star,$$

$$G(\tilde{x},\tilde{y}) = \begin{cases} \dfrac{e^{\tilde{x}-\tilde{y}}}{\tilde{v}_{\rm eff}(\tilde{y})}, & (\tilde{x} \le \tilde{y}) \\ \dfrac{1}{\tilde{v}_{\rm eff}(\tilde{x})}, & (\tilde{x} > \tilde{y}) \end{cases}$$

$$\frac{1}{\tilde{v}_{\rm eff}(\tilde{x})} = \int_{\tilde{x}}^\infty \frac{e^{-(\tilde{x}'-\tilde{x})}}{\tilde{v}(\tilde{x}')}d\tilde{x}'.$$

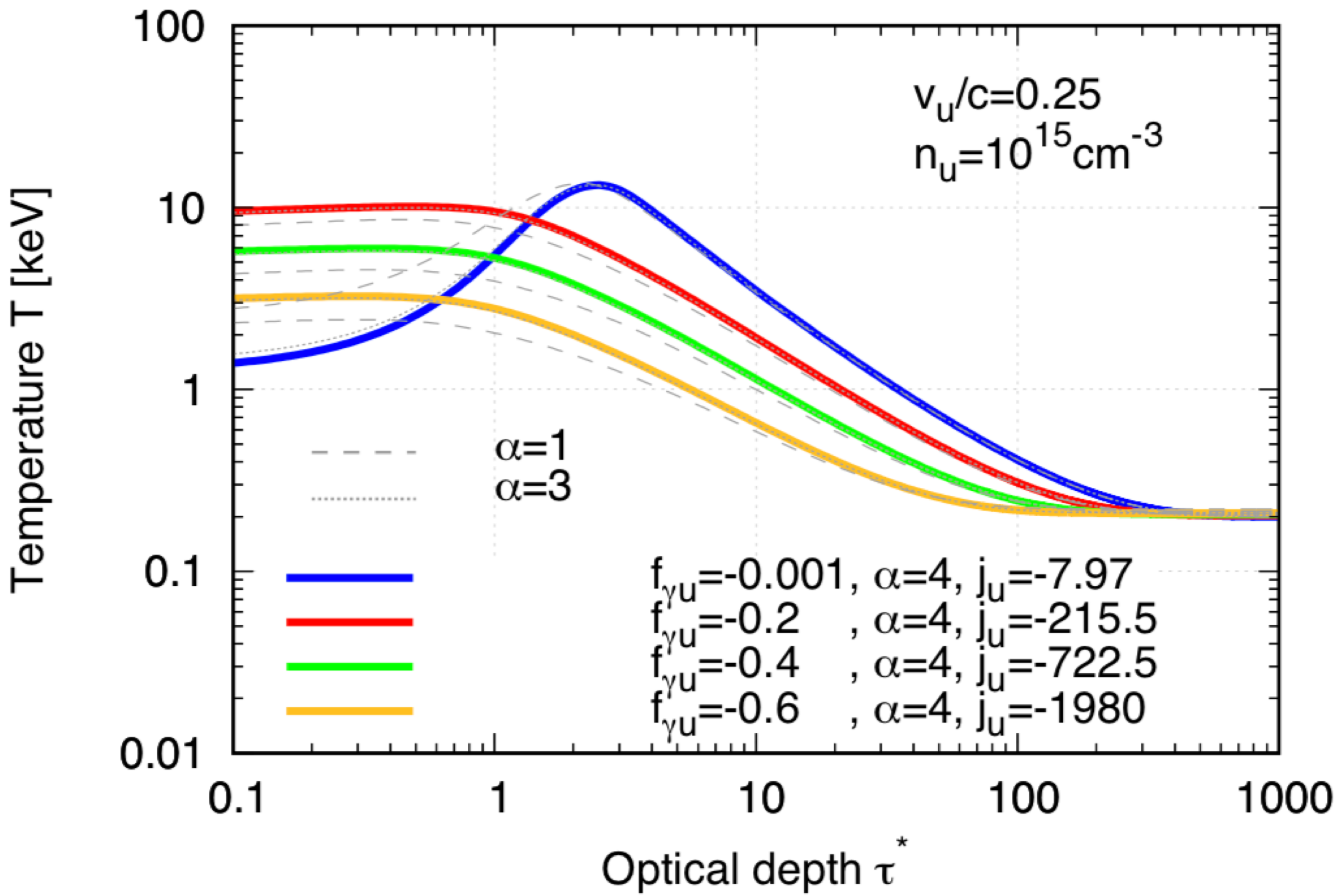
Numerical iterations

Solutions



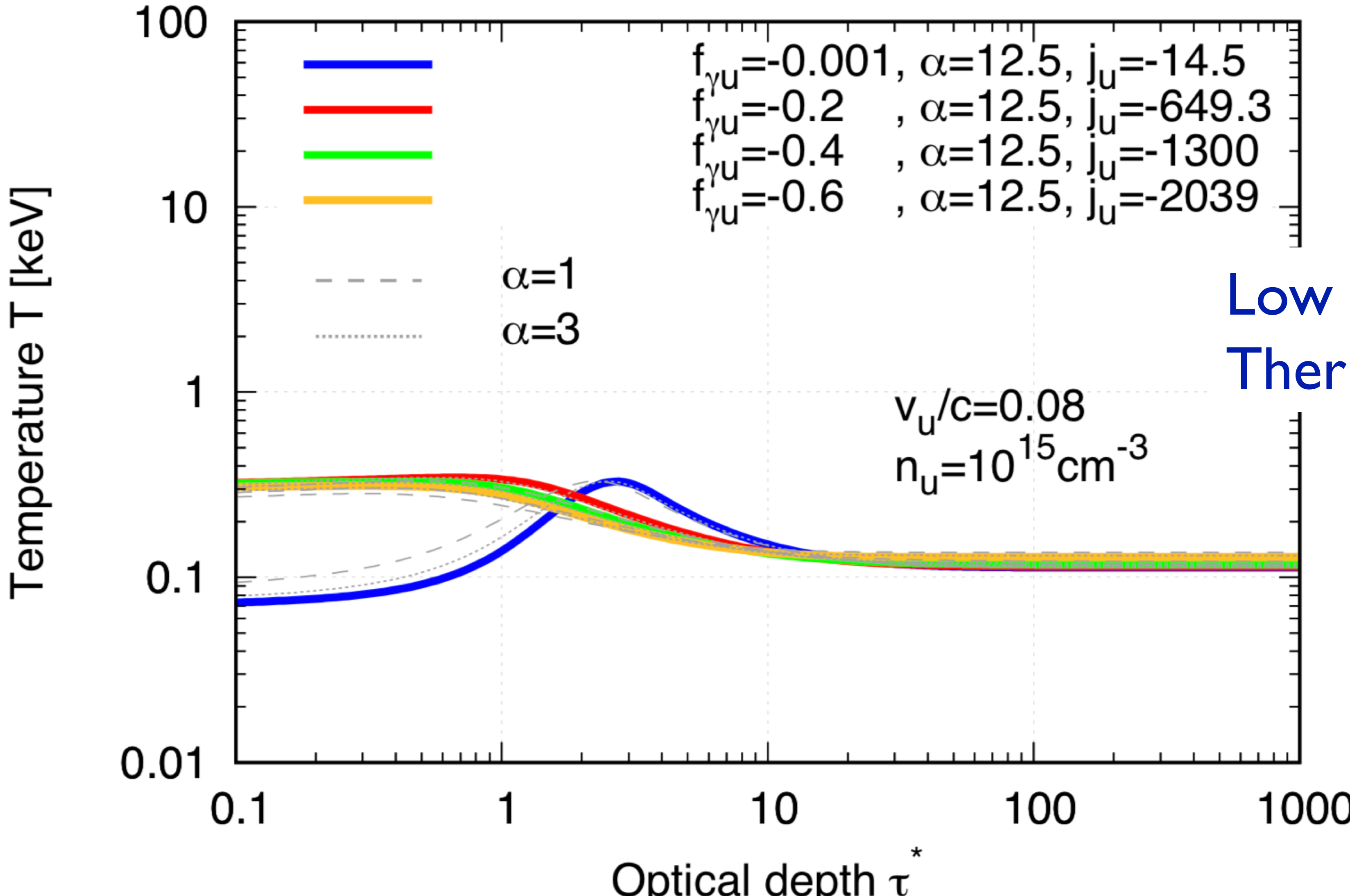
100
10
1
0.1
0.01
0.1
1
10
100
1000
Temperature T [keV]
Optical depth τ*
fγu=-0.001, α=4, ju=-16.5
fγu=-0.2 , α=4, ju=-439.9
fγu=-0.4 , α=4, ju=-1586
fγu=-0.6 , α=4, ju=-4877
vu/c=0.25
nu=10^12 cm^-3
α=1
α=3

Solutions



Temperature T [keV]
100
10
1
0.1
0.01
0.1
1
10
100
1000
Optical depth τ*
vu/c=0.25
nu=10^15 cm^-3
α=1
α=3
fγu=-0.001, α=4, ju=-7.97
fγu=-0.2 , α=4, ju=-215.5
fγu=-0.4 , α=4, ju=-722.5
fγu=-0.6 , α=4, ju=-1980

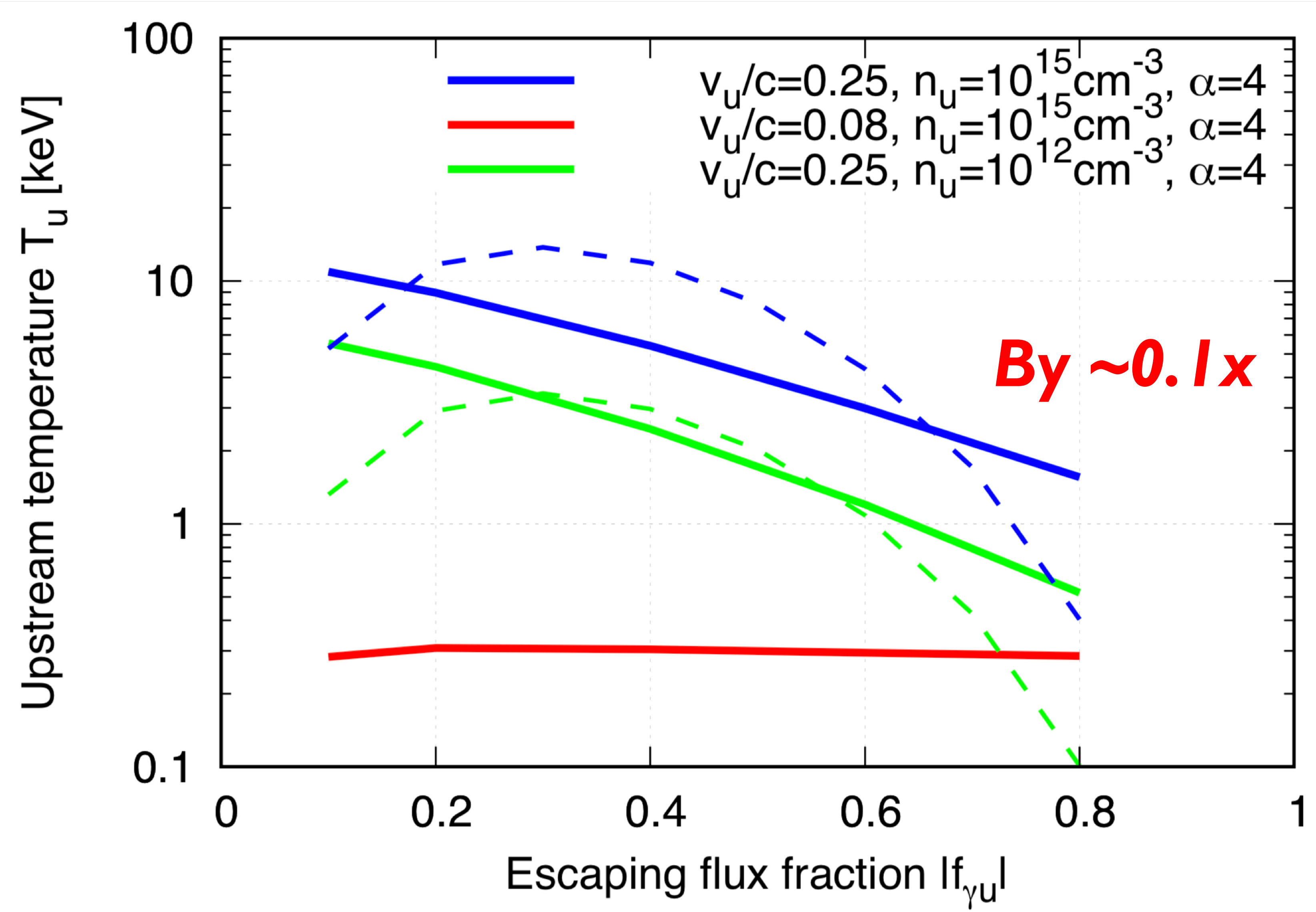
Solutions



Low v

Thermalized

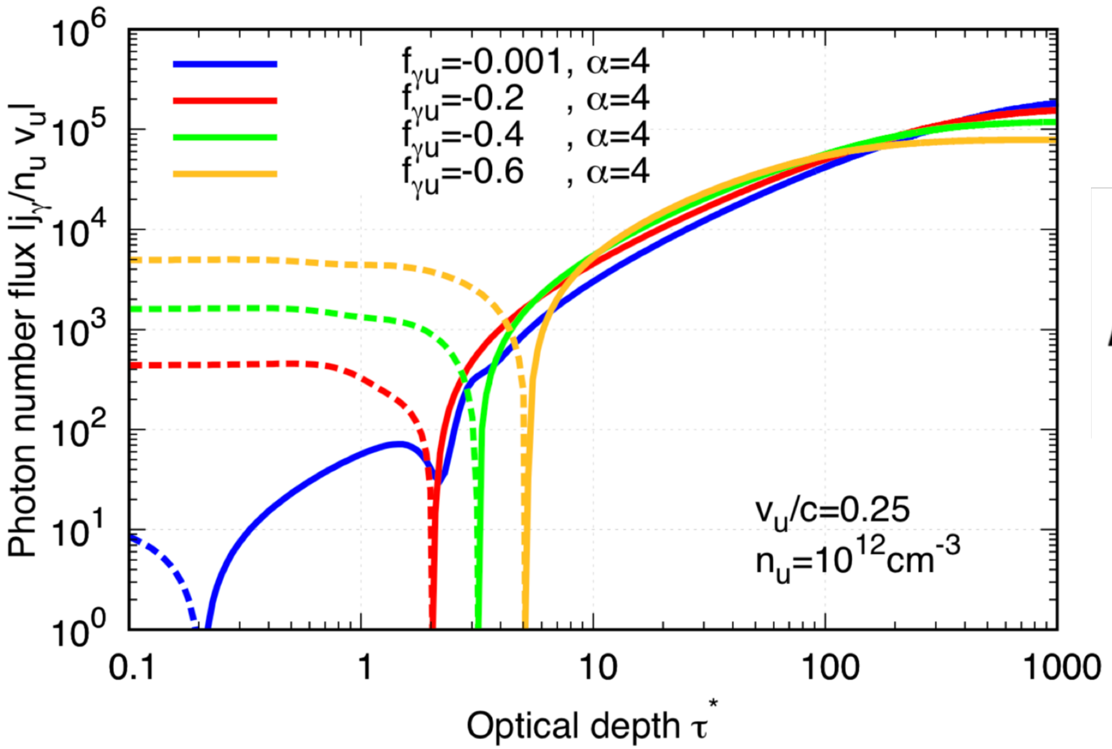
Temperature Evolution



Analytic Approximation

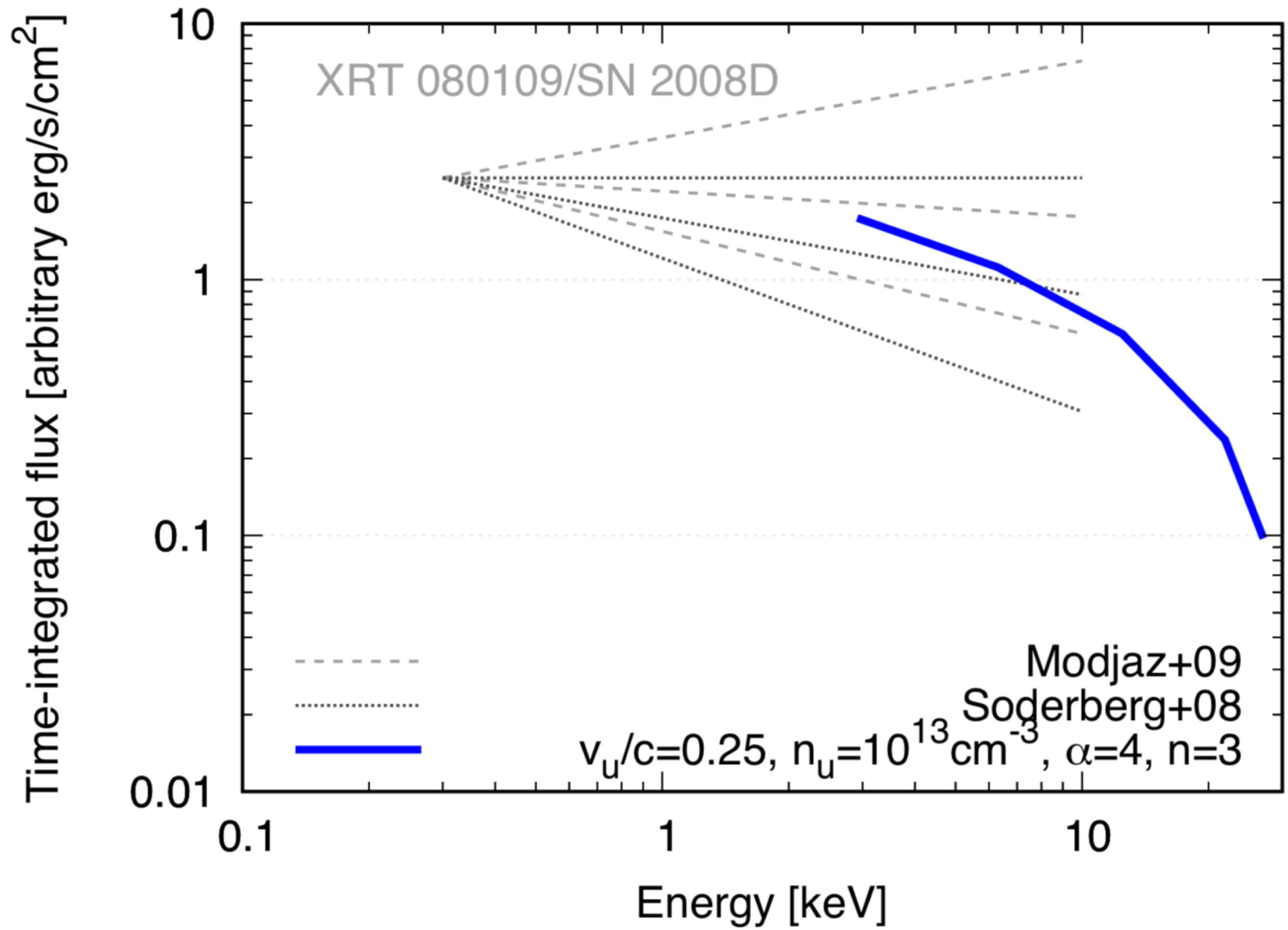
$$j_\gamma \sim Q_{ff} f_{ab} \Delta x/4 \sim \alpha_e n c^2 \Theta^{-1/2} \Lambda_{eff}/8\nu,$$

approximating $j_\gamma \sim |j_{\gamma u}|$ and $T \sim T_u$, $\quad v \sim v_d$



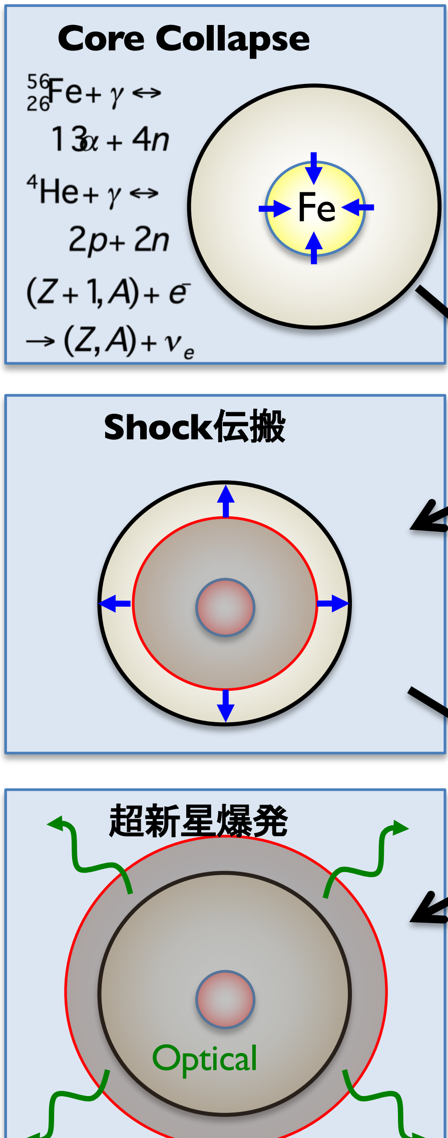
$$kT_u \sim \frac{1}{m_e c^2}\left(\frac{4 m_p v_u^2 v_d^2 \tilde{f}_{\gamma u}}{3\alpha_e c^2 \Lambda_{eff}}\right)^2$$

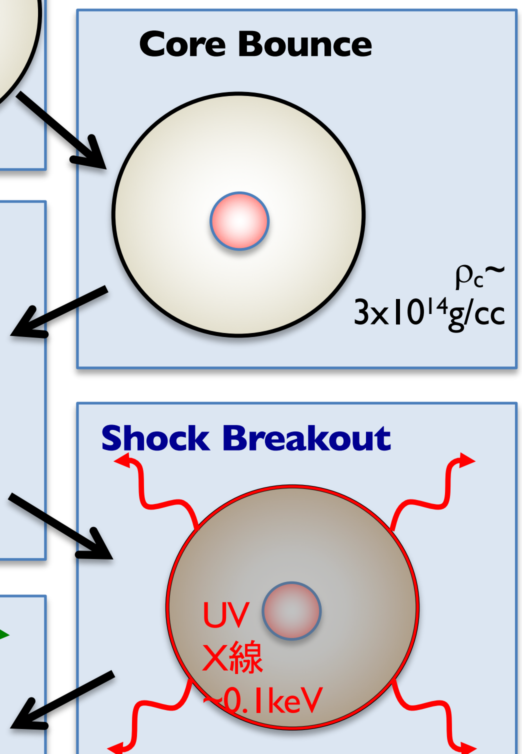
Time-Integrated Spectrum



超新星 Shock Breakout

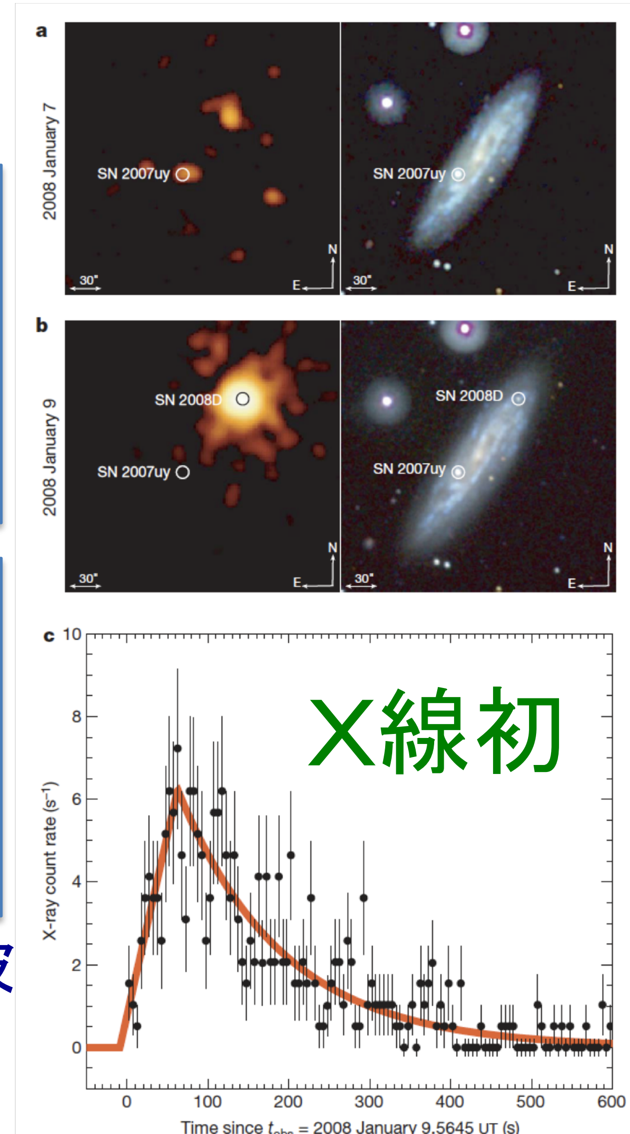
M>~8-10M$_\odot$





輻射媒介衝撃波

(Klein & Chevalier 78, Weaver 76, Colgate 74)



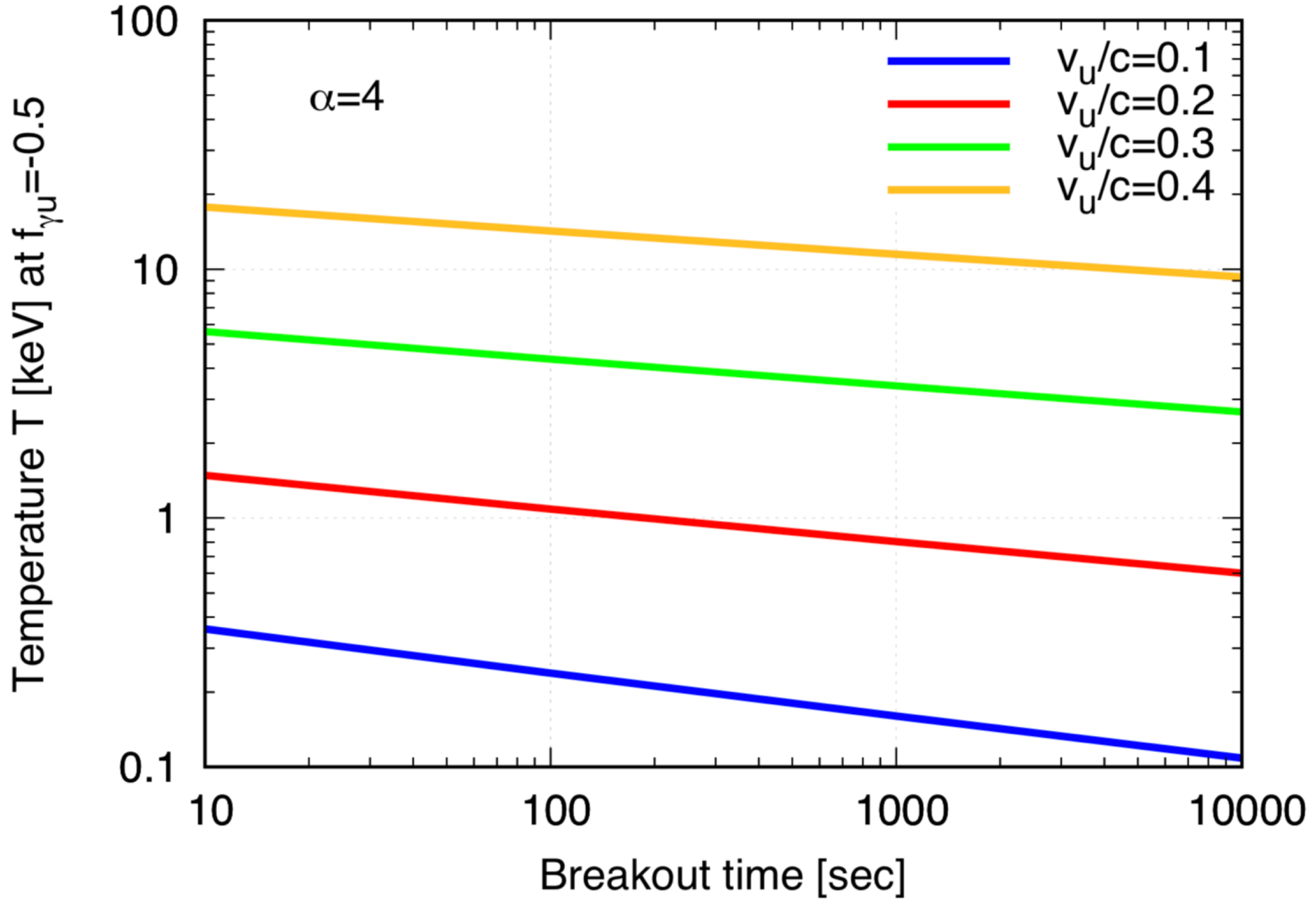
XRF080109/
SN2008D
(Ib/c)
@27Mpc

Single PL
or PL+BB
Γ~-2.3
T~0.1keV

非熱的成分

Soderberg+ 08

Closure Relation



$$t_{bo} \approx \frac{R_{bo}}{v_{bo}},$$

$$L_{bo} \approx 1.5 \times 10^{42} t_{bo,2} v_{bo,-1}^{3} \ \mathrm{erg/s}.$$

Summary

- Sub-relativistic breakout + Photon escape
- Softening during breakout for v>0.1c
- Shock compression → Bremss enhanced
- Time-integrated spectrum is non-thermal
- Consistent with XRT 080109/SN 2008D
- A closure relation btw t_{bo}, L_{bo} & T_{bo}

Thank You

Shock Width