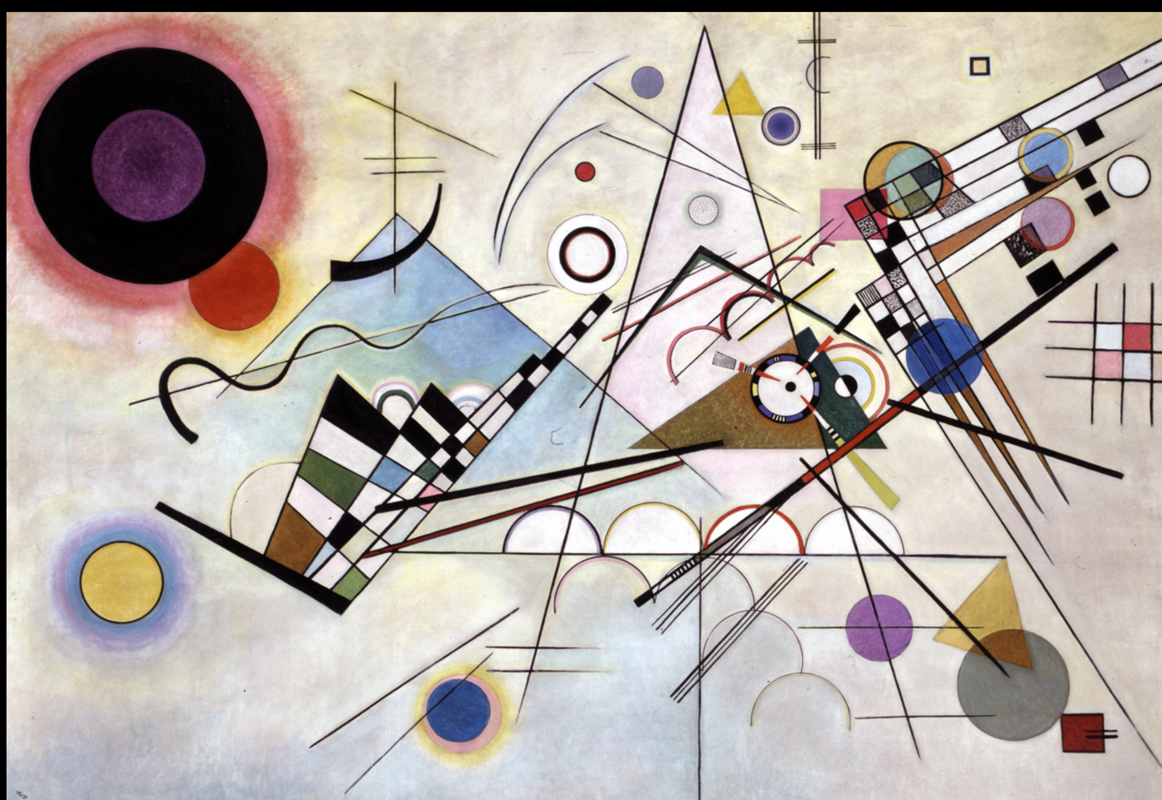
Physics & Astrophysics of Gamma-Ray Bursts

Frédéric Daigne (Institut d’Astrophysique de Paris - Sorbonne University)



Kandinksy – Composition 8- 1923

Kandinksy – Curves and sharp angles - 1923

Physics & Astrophysics of Gamma-Ray Bursts

Lecture #1

Introduction

- A brief history
- Observational Facts
- Basic Constraints on any GRB model: compact source + relativistic ejecta

Theory

- Progenitor - Central Engine - Relativistic Ejection
- Prompt Emission: internal dissipation in a relativistic ejecta
- Afterglow: interaction of a relativistic ejecta with its environment

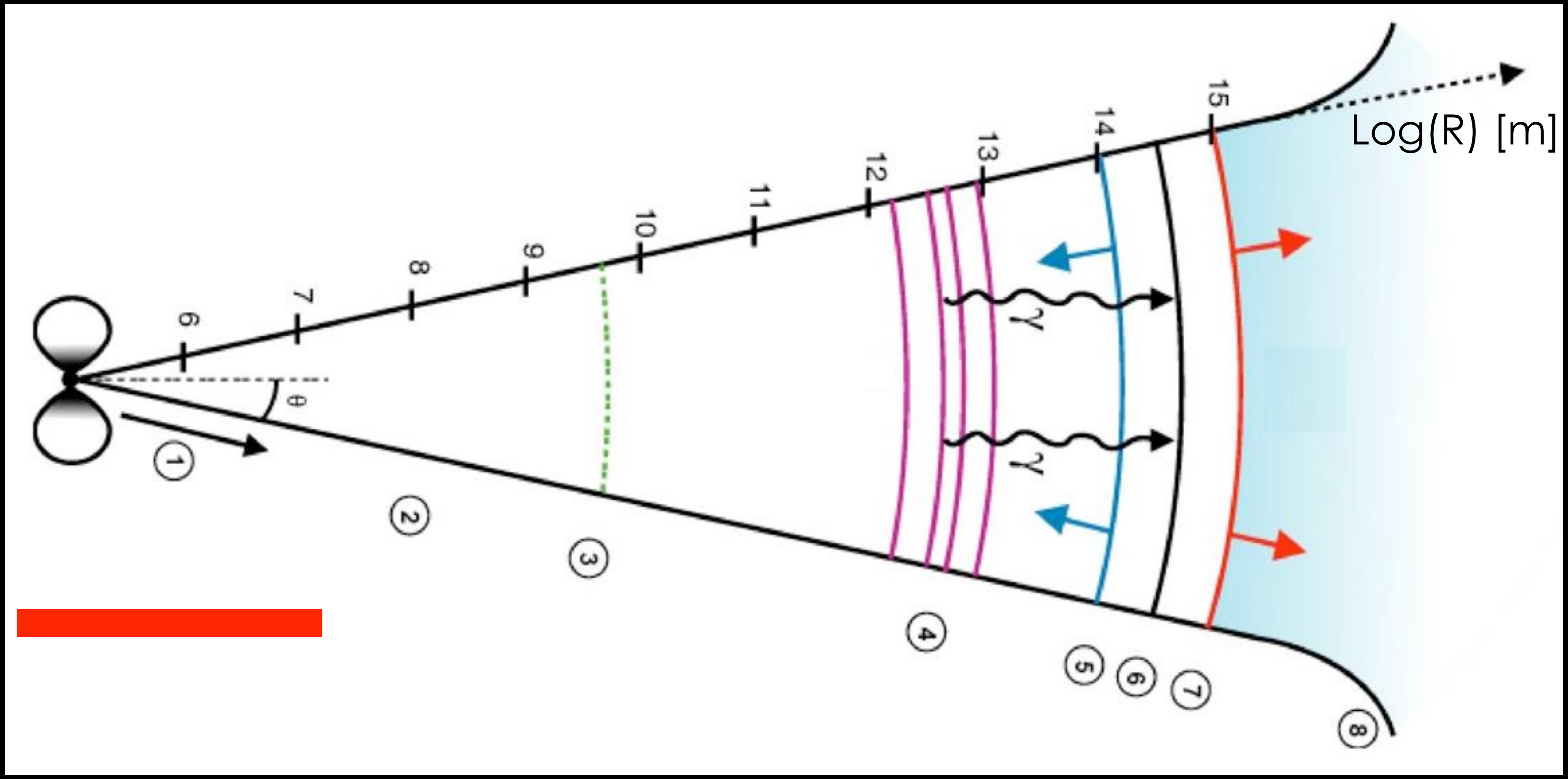
Focus on short GRBs: the binary neutron star merger connection - 170817

- Afterglow: Constraints on the geometry of the relativistic ejecta
- Origin of the prompt emission
- Prospects for future associations

GRB Physics: standard scenario & characteristic radii

GRB Physics: initial event & central engine

- Huge radiated energy ($E_{iso,\gamma}$~10^{50}-10^{55} erg) + short time scale variability (<100 ms): cataclysmic event leading to the formation of a stellar-mass compact object (accreting BH, magnetar)



GRB Physics: initial event & central engine

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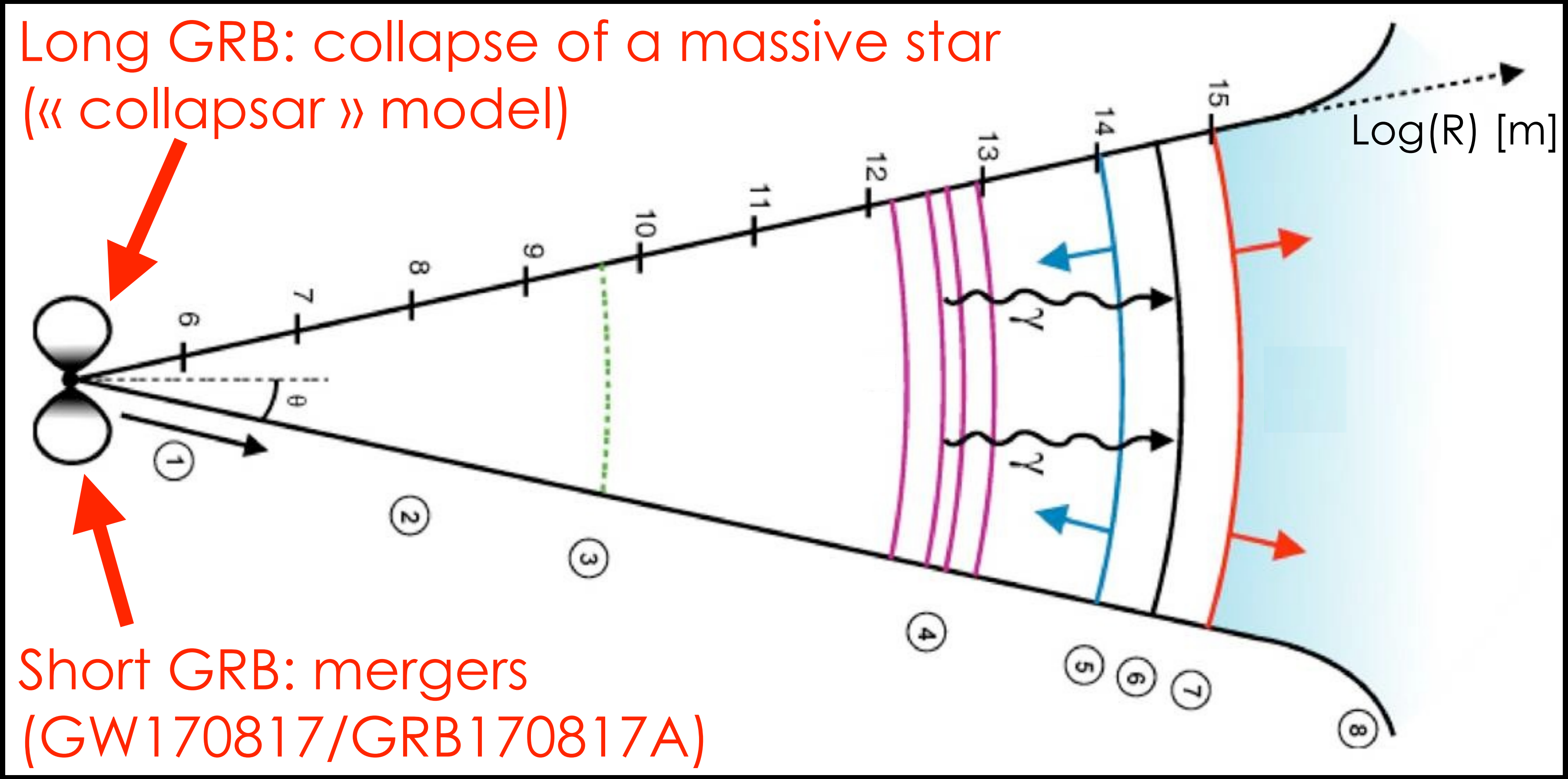


GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

- Non-thermal gamma-ray spectrum: relativistic ejection (prompt emission is produced at large distance from the source)

Pair production: $\gamma\gamma \rightarrow \mathrm{e}^+\mathrm{e}^-$

Threshold: $$\left(\frac{E_{\mathrm{LE}}}{m_{\mathrm{e}}c^2}\right)\left(\frac{E_{\mathrm{HE}}}{m_{\mathrm{e}}c^2}\right) \geq \frac{2}{1-\cos\theta}$$

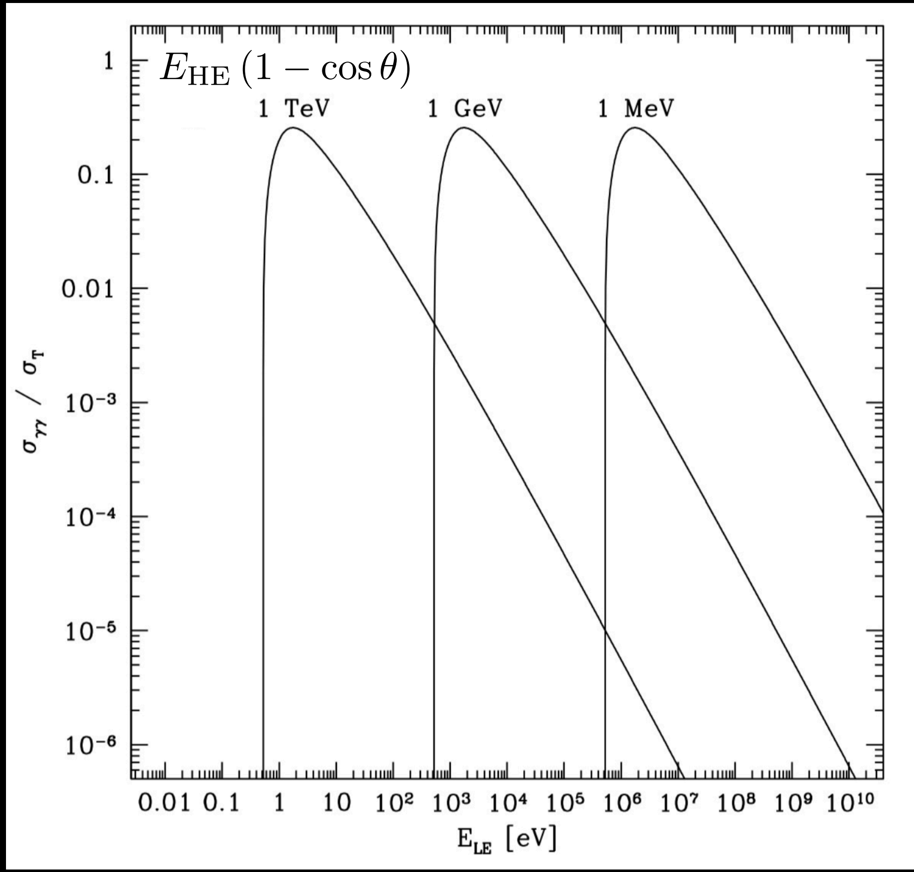
Cross section: $$\sigma_{\gamma\gamma}\left(E_{\mathrm{LE}}\,;E_{\mathrm{HE}},\theta\right) \simeq \sigma_{\mathrm{T}}\,\delta\left(1-\frac{E_{\mathrm{LE}}}{2E_{\mathrm{th}}(E_{\mathrm{HE}},\theta)}\right)$$

Observed soft-gamma ray spectrum (HE):

$$\frac{\mathrm{d}N}{\mathrm{d}E_{\mathrm{obs}}} \simeq (\beta-2)\,\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}}{E_{\mathrm{p,obs}}^2}\left(\frac{E_{\mathrm{obs}}}{E_{\mathrm{p,obs}}}\right)^{-\beta}$$

with $\beta \simeq 2.3$ $\quad E_{\mathrm{p,obs}} \simeq 150\,\mathrm{keV}$

$E_{\mathrm{max,obs}} \gtrsim 1\,\mathrm{MeV}$



$$\tau \sim \frac{\ell}{\bar{\ell}_{\gamma\gamma}} \qquad \text{escaping fraction} \sim e^{-\tau}$$

$$\tau_{\gamma\gamma}(E_{HE}) \simeq \int d\ell \int_{\theta=0}^{\pi} d\Omega \int_{E_{th}}^{\infty} dE_{LE} \underbrace{\frac{dn}{dE\, d\Omega}}_{ph/cm^3/keV/sr} (E_{LE})$$

$$\times \ \sigma_{\gamma\gamma}(E_{LE};\, E_{HE}, \theta) \times (1 - \cos\theta)$$

$$E_{th} = \frac{(m_e c^2)^2}{E_{HE}(1-\cos\theta)} \qquad \sigma_{\gamma\gamma} \simeq \sigma_T\, \delta\left(1 - \frac{E_{LE}}{2E_{th}}\right)$$

$$\tau_{\gamma\gamma} \simeq \ell \int_0^\pi 2\pi \sin\theta \, d\theta \; \frac{1}{4\pi} \frac{dn}{dE}(E_{th})(2E_{th})\, \sigma_T \,(1-\cos\theta)$$

$$\frac{dn}{dE} = \underbrace{\frac{dN}{dE_{obs}}}_{ph/s/keV} \times \underbrace{\frac{dE_{obs}}{dE}}_{\frac{E_{obs}}{E}} \times \frac{1}{V} = \frac{(\beta-2)}{V} \frac{\mathcal{E}_{\gamma,iso,HE}}{E_{p\,obs}\, E_p} \left(\frac{E}{E_p}\right)^{-\beta}$$

$$\simeq \ell \, \frac{2\pi}{4\pi} \, \frac{\beta-2}{V} \, \frac{\mathcal{E}_{\gamma\,iso\,HE}}{E_{p\,obs}} \sigma_T \left(\frac{4(\Gamma m_e c^2)^2}{E_{HE}\, E_p}\right)^{1-\beta} \underbrace{\int_0^\pi \sin\theta \, d\theta \,(1-\cos\theta)^{-(1-\beta)+1}}_{\text{a number}}$$

$$= \int_{-1}^{1} (1-x)^\beta \, dx = \frac{2^{\beta+1}}{\beta+1}$$

GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

- Non-thermal gamma-ray spectrum: relativistic ejection (prompt emission is produced at large distance from the source)

$$\tau_{\gamma\gamma}(E_{\mathrm{HE}}) \simeq 2^{2-\beta}\frac{\beta-2}{\beta+1}\left(\frac{\ell}{V}\right)\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}\sigma_{\mathrm{T}}}{E_{\mathrm{p,obs}}}\left(\frac{(m_{\mathrm{e}}c^2)^2}{E_{\mathrm{p}}E_{\mathrm{HE}}}\right)^{1-\beta}$$

Static case: $R \simeq ct_{\mathrm{var}}$ $\ell \simeq R$ $V \simeq \frac{4\pi}{3}R^3$ $E_{\mathrm{p}} = E_{\mathrm{p,obs}}$ $E_{\mathrm{HE}} = E_{\mathrm{max,obs}}$

$$\tau_{\gamma\gamma}(E_{\mathrm{HE}}) \simeq 6\,10^{15}\left(\frac{t_{\mathrm{var}}}{10\,\mathrm{ms}}\right)^{-2}\left(\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}}{10^{52}\,\mathrm{erg}}\right)\left(\frac{E_{\mathrm{p,obs}}}{150\,\mathrm{keV}}\right)^{0.3}\left(\frac{E_{\mathrm{max,obs}}}{1\,\mathrm{MeV}}\right)^{1.3}$$

gamma-ray photons cannot escape from the source!

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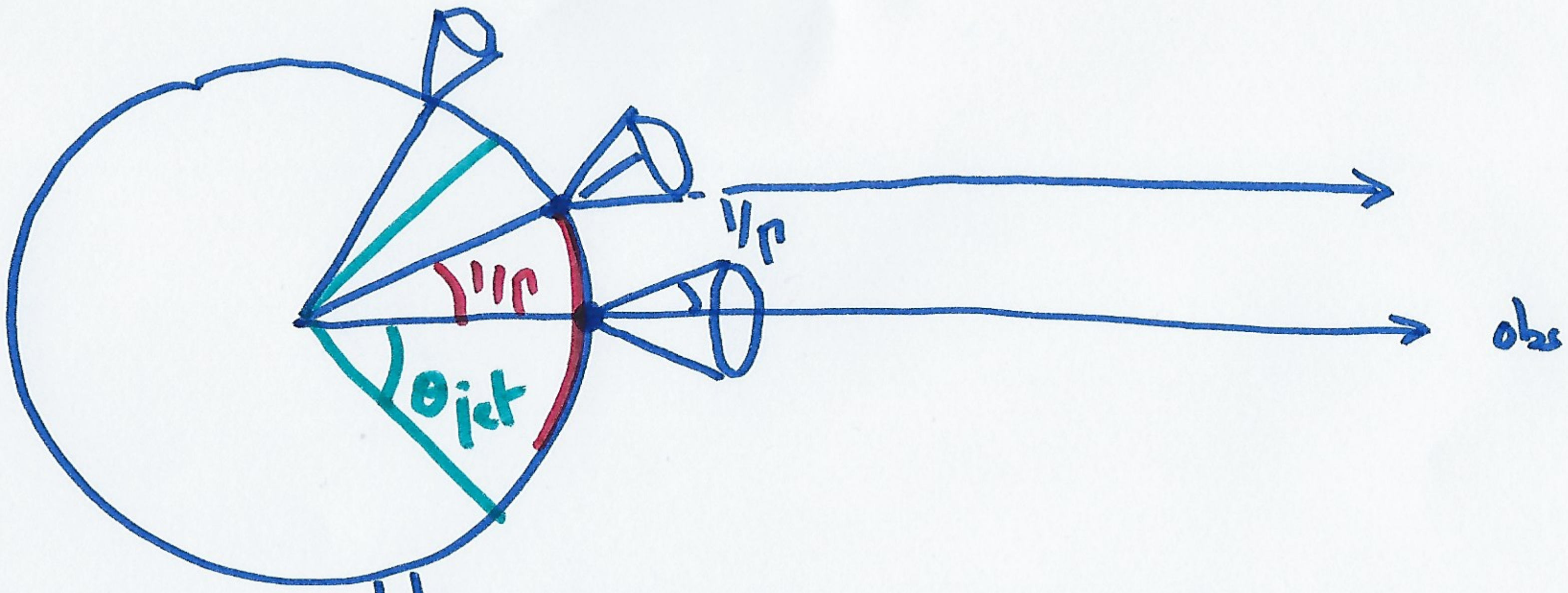
Relativistic case: comoving frame

$$R \simeq 2\Gamma^2 ct_{\mathrm{var}} \qquad \ell \simeq \frac{R}{\Gamma} \qquad V = 4\pi R^2\ell \qquad E_{\mathrm{p}} = \frac{E_{\mathrm{p,obs}}}{\Gamma} \quad E_{\mathrm{HE}} = \frac{E_{\mathrm{max,obs}}}{\Gamma}$$



$\Downarrow$ relativistic motion Γ

$$\Delta t_{obs} = \frac{R(1-\cos 1/\Gamma)}{c} \overset{\Gamma \gg 1}{=} \frac{R}{2\Gamma^2 c} \lesssim t_{var}$$

$$\boxed{R \lesssim 2\Gamma^2 c\, t_{var}}$$

GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

- Non-thermal gamma-ray spectrum: relativistic ejection
(prompt emission is produced at large distance from the source)

$$\tau_{\gamma\gamma}(E_{\mathrm{HE}}) \simeq 2^{2-\beta}\frac{\beta-2}{\beta+1}\left(\frac{\ell}{V}\right)\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}\sigma_{\mathrm{T}}}{E_{\mathrm{p,obs}}}\left(\frac{(m_{\mathrm{e}}c^2)^2}{E_{\mathrm{p}}E_{\mathrm{HE}}}\right)^{1-\beta}$$

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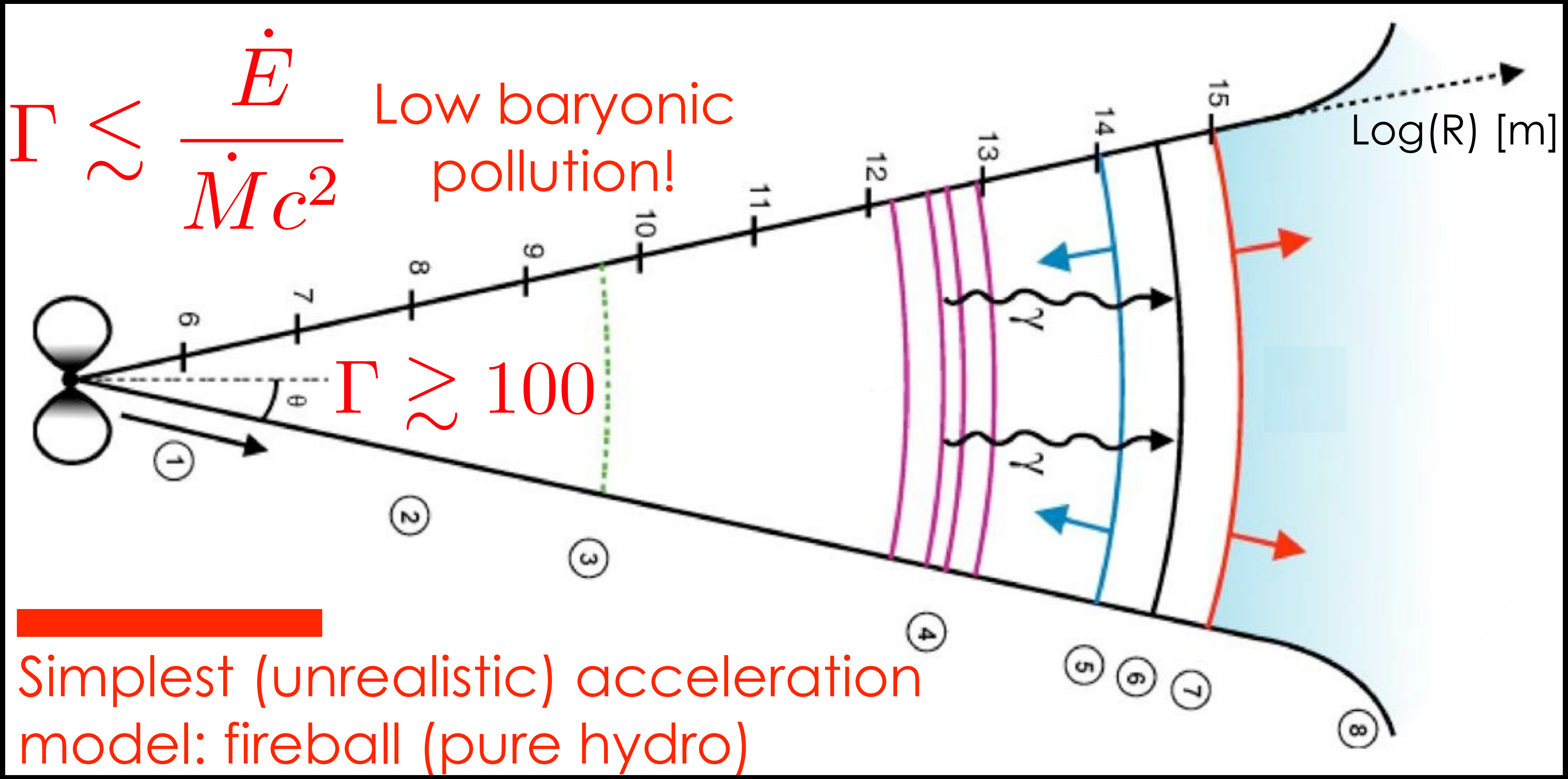
$$\tau_{\gamma\gamma}(E_{\mathrm{HE}}) \simeq 3\left(\frac{\Gamma}{100}\right)^{-6.6}\left(\frac{t_{\mathrm{var}}}{10\,\mathrm{ms}}\right)^{-2}\left(\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}}{10^{52}\,\mathrm{erg}}\right)\left(\frac{E_{\mathrm{p,obs}}}{150\,\mathrm{keV}}\right)^{0.3}\left(\frac{E_{\mathrm{max,obs}}}{1\,\mathrm{MeV}}\right)^{1.3}$$

gamma-ray photons can escape if they are produced at large distance in a relativistic ejecta

GRB Physics: relativistic ejection

- Non-thermal gamma-ray spectrum: the gamma-ray burst is emitted at large distance from the source by a relativistic outflow



UR

- $4\pi r^2 (\rho \Gamma)_c = \dot{M} = c^{st}$
- $4\pi r^2 (\rho\Gamma)_c \times (h\Gamma) = \dot{E} = c^{st}$

$$h = c^2 + \epsilon + \frac{P}{\rho}$$
$$= c^2 + \frac{\gamma}{\gamma-1}\frac{P}{\rho}$$

- $\frac{P^{1/\gamma}}{\rho} = c^{st}$ (adiabatic)

$$\rightarrow \quad h\Gamma = \frac{\dot{E}}{\dot{M}} = c^{st}$$

Phase 1: $\frac{P}{\rho} \gg c^2$

$\gamma = \frac{4}{3}$

$4\pi r^2 \rho \Gamma c = \dot{M} \rightarrow \rho \propto \frac{1}{r^2\Gamma}$

$\frac{\gamma}{\gamma-1}\frac{P}{\rho}\Gamma = \frac{\dot{E}}{\dot{M}} \rightarrow \Gamma \propto \frac{\rho}{P} \propto \frac{r^{8/3}\Gamma^{4/3}}{r^2\Gamma}$

$P^{1/\gamma} \propto \rho \rightarrow P \propto \frac{1}{r^{8/3}\Gamma^{4/3}}$

$\Gamma \propto r^{2/3}\Gamma^{1/3} \Rightarrow \Gamma \propto r$ acceleration.

Phase 2: $c^2 \gg P/\rho$

$$4\pi r^2 \rho \Gamma c = \dot{M}$$

$$c^2 \Gamma = \frac{\dot{E}}{\dot{M}}$$

$$\Rightarrow \Gamma = c^{st}$$

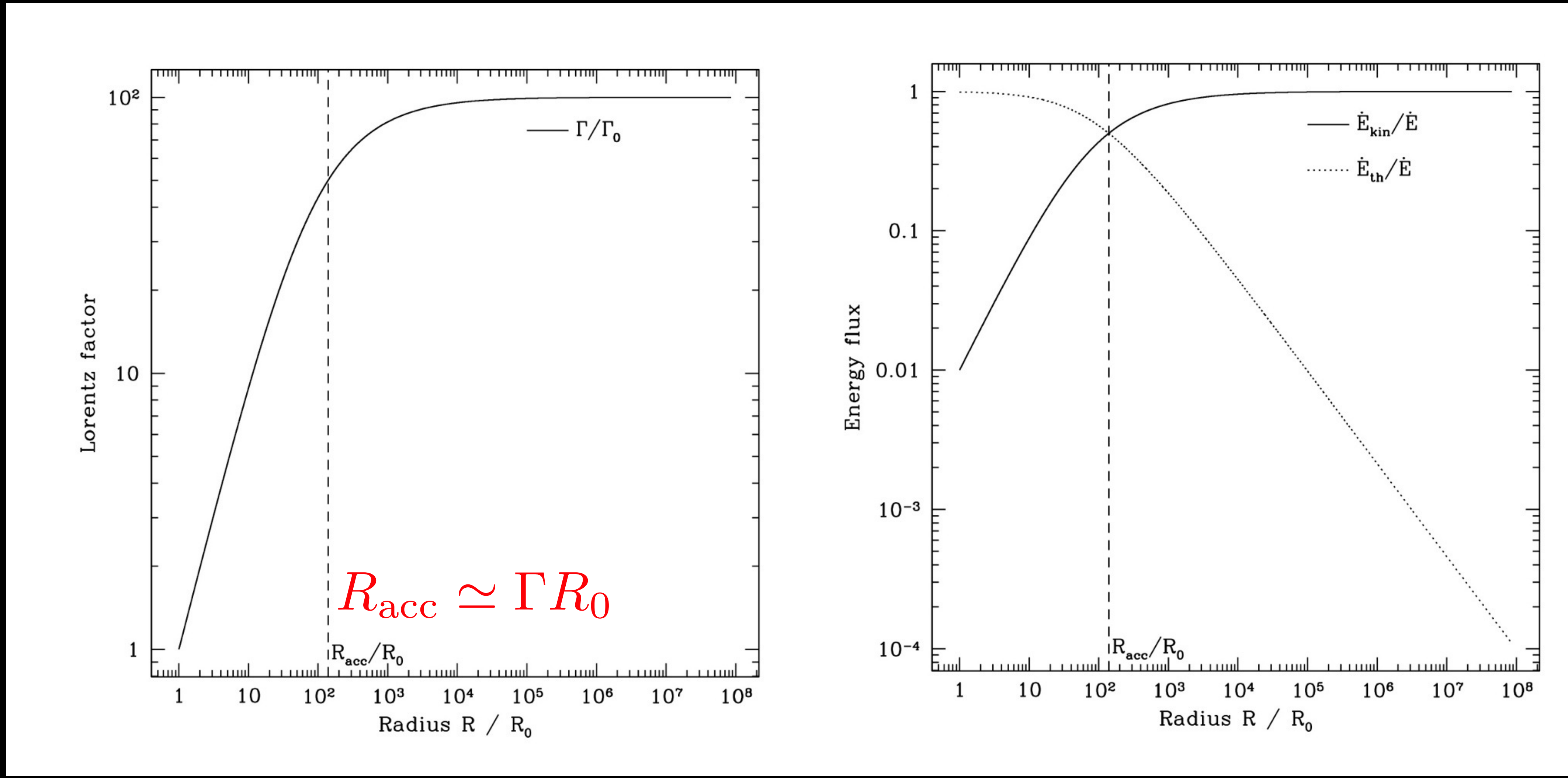
$$\Gamma_\infty = \frac{\dot{E}}{\dot{M} c^2} \rightarrow R_{acc} = R_0 \frac{\Gamma_\infty}{\Gamma_0} \leftarrow \approx 1$$

Approximation valid $\quad \underbrace{\Delta\beta}_{\frac{1}{2\Gamma_{min}^2}} c \frac{R}{c} \ll \Delta \Rightarrow R_{spread} \simeq 2\Gamma_{min}^2 \Delta$

$$\beta \sim 1 - \frac{1}{2\Gamma^2} \text{ (UR)}$$

Fireball

Internal → kinetic energy conversion



$$4\pi r^2 \rho \Gamma c \simeq \dot{M} = \mathrm{cst}$$

Fireball equations: $$4\pi r^2 \rho h \Gamma^2 c \simeq \dot{E} = \mathrm{cst}$$

$$\frac{P}{\rho^\gamma} = \mathrm{cst}$$

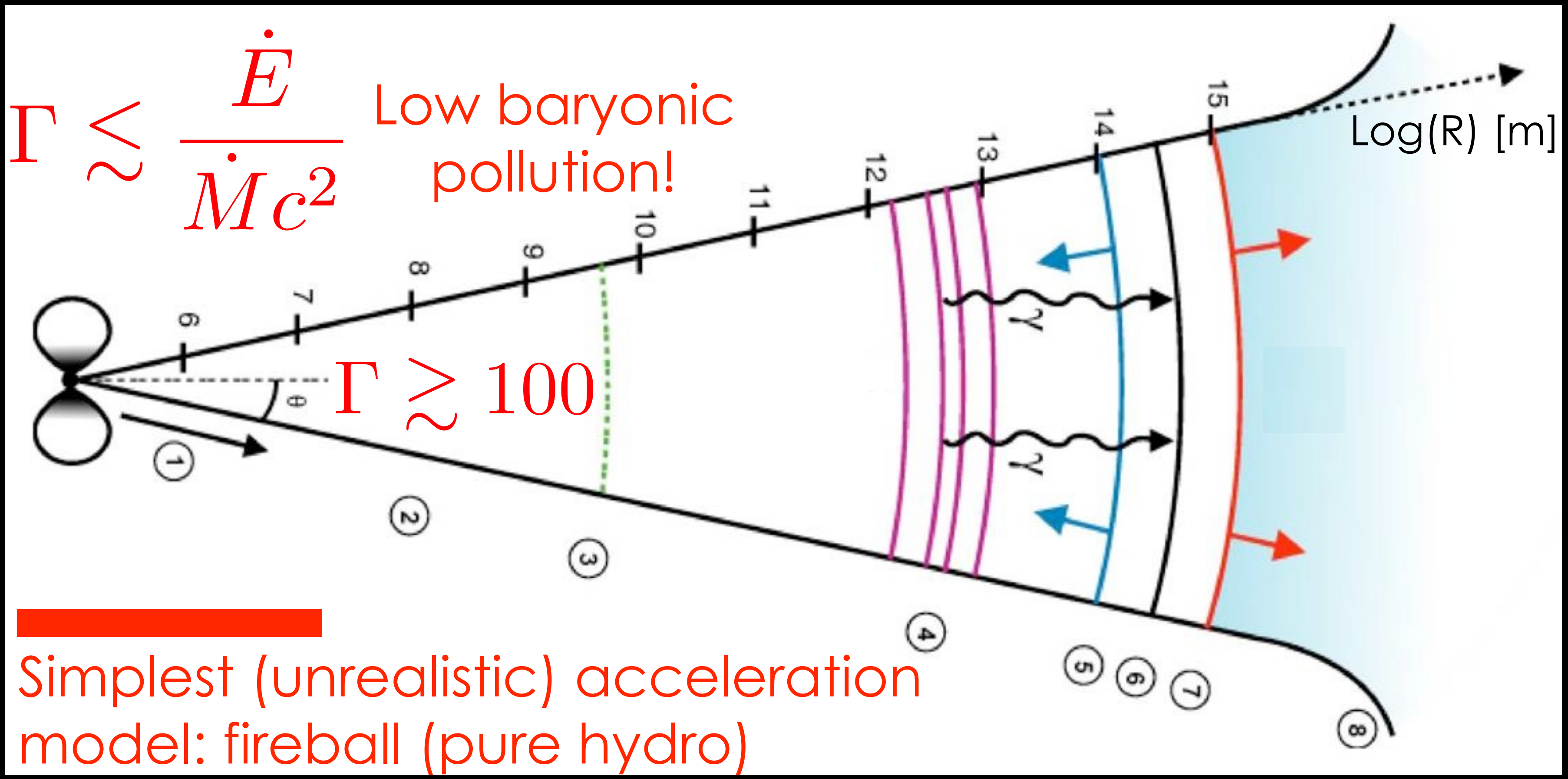
Valid as long as spreading is negligible

$$R \ll R_{\rm spread} \simeq \Gamma^2 \Delta$$

shell width ~ c . ejection duration

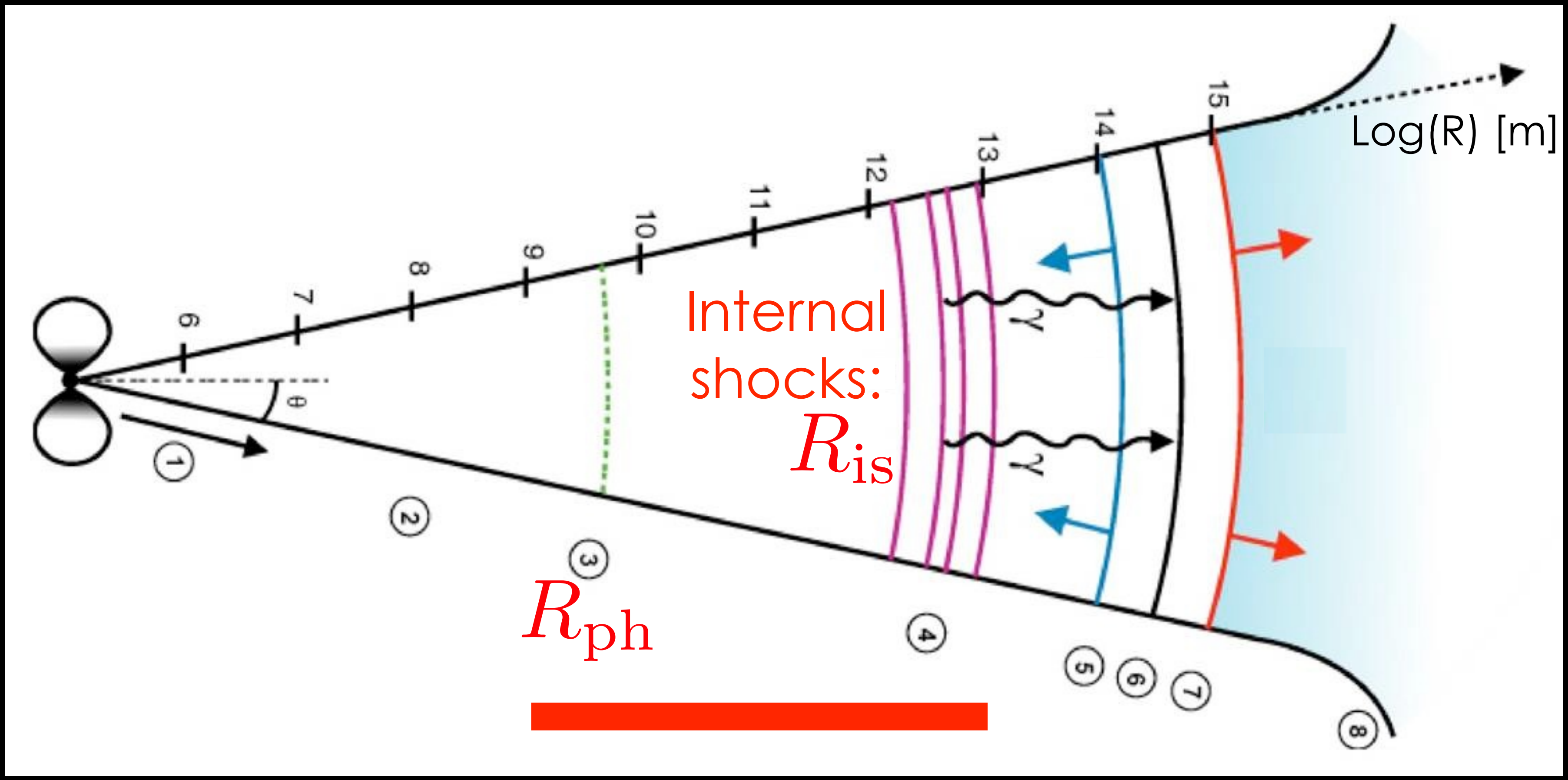
GRB Physics: relativistic ejection

- Non-thermal gamma-ray spectrum: the gamma-ray burst is emitted at large distance from the source by a relativistic outflow



GRB Physics: prompt emission

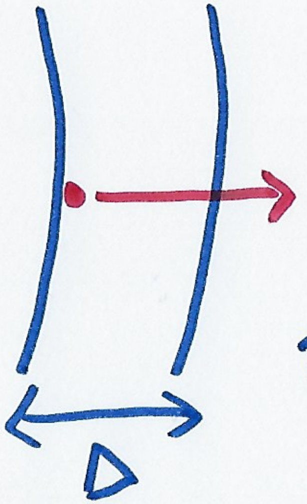
- Short time-scale non-evolving variability: the prompt emission has an internal origin



- Main possibilities of internal dissipation:
  (1) dissipative photosphere
  (2) optically-thin synchrotron emission from non-thermal elec. (shocks/reconnection)

$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,{\rm cm}\left(\frac{\dot{E}}{10^{52}\,{\rm erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

$$R_{\rm is} \simeq R_{\rm spread} \simeq 2\Gamma^2\Delta \simeq 6\,10^{14}\,{\rm cm}\left(\frac{\Gamma}{100}\right)^2\left(\frac{\Delta/c}{1\,{\rm s}}\right)$$



Lorentz factor Γ

D obs

$$\tau = \int_{R}^{R_{esc} = R + 2\Gamma^2 \Delta} dl' \, \rho' \kappa_T$$

$$dl' = \Gamma (dR - \beta c \, dt)$$

$$dR = c\, dt$$

$$= \Gamma (1-\beta)\, c\, dt = \frac{dR}{2\Gamma}$$

$$\rho' = \frac{M}{4\pi R^2 \Delta \Gamma}$$

$$\tau = \frac{M \kappa_T}{8\pi \Delta \Gamma^2} \int_{R}^{R_{esc}} \frac{dR}{R^2}$$

$$\frac{1}{R_{esc}} - \frac{1}{R} = \frac{2\Gamma^2 \Delta}{R(R+2\Gamma^2\Delta)} \sim \frac{1}{R}$$

$$R_{ph} = \frac{M \kappa_T}{8\pi \Delta \Gamma^2} = \frac{\dot{M} \kappa_T}{8\pi c \Gamma^2} = \frac{\dot{E} \kappa_T}{8\pi c^3 \Gamma^3}$$

GRB Physics: prompt emission

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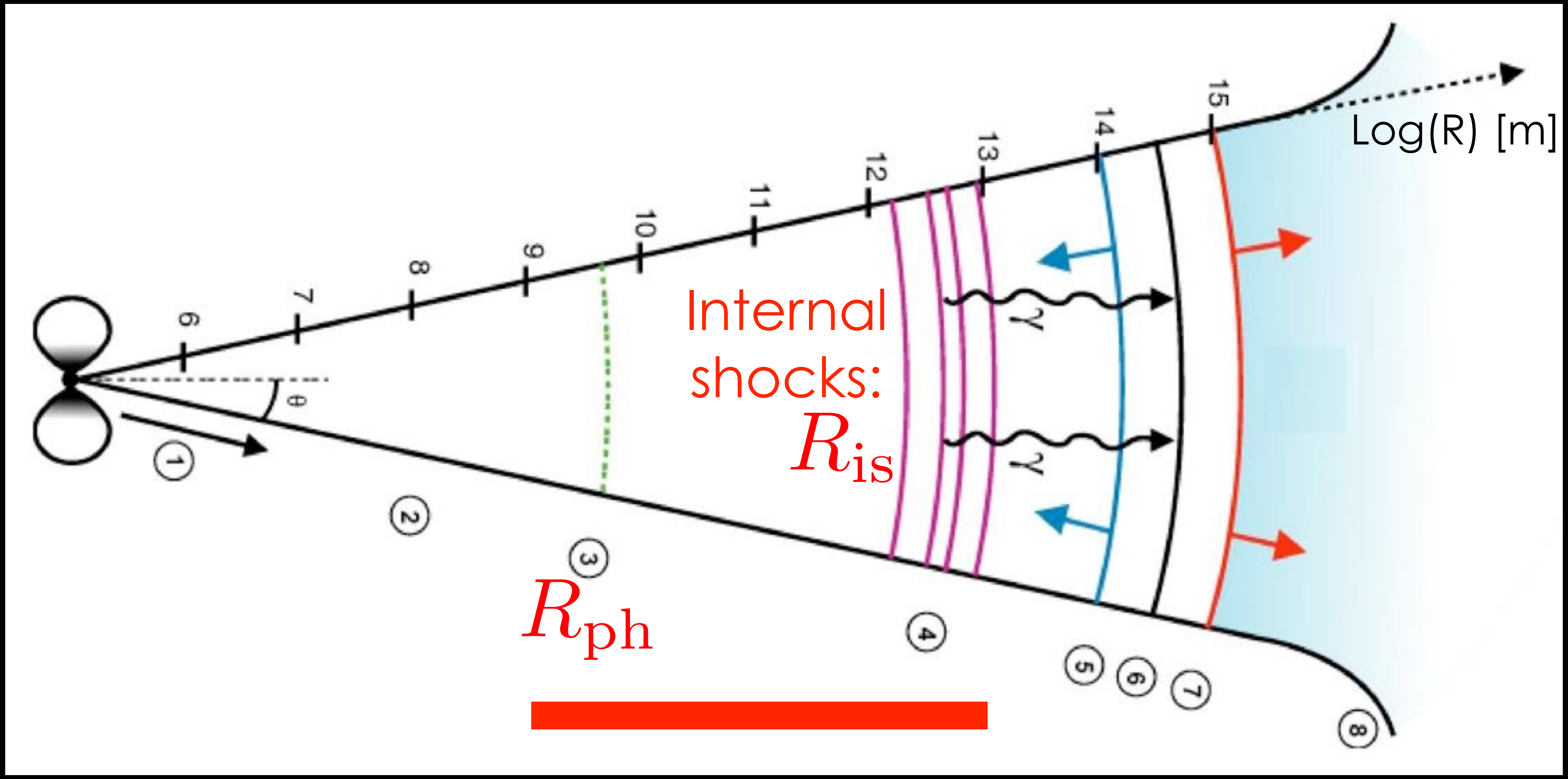

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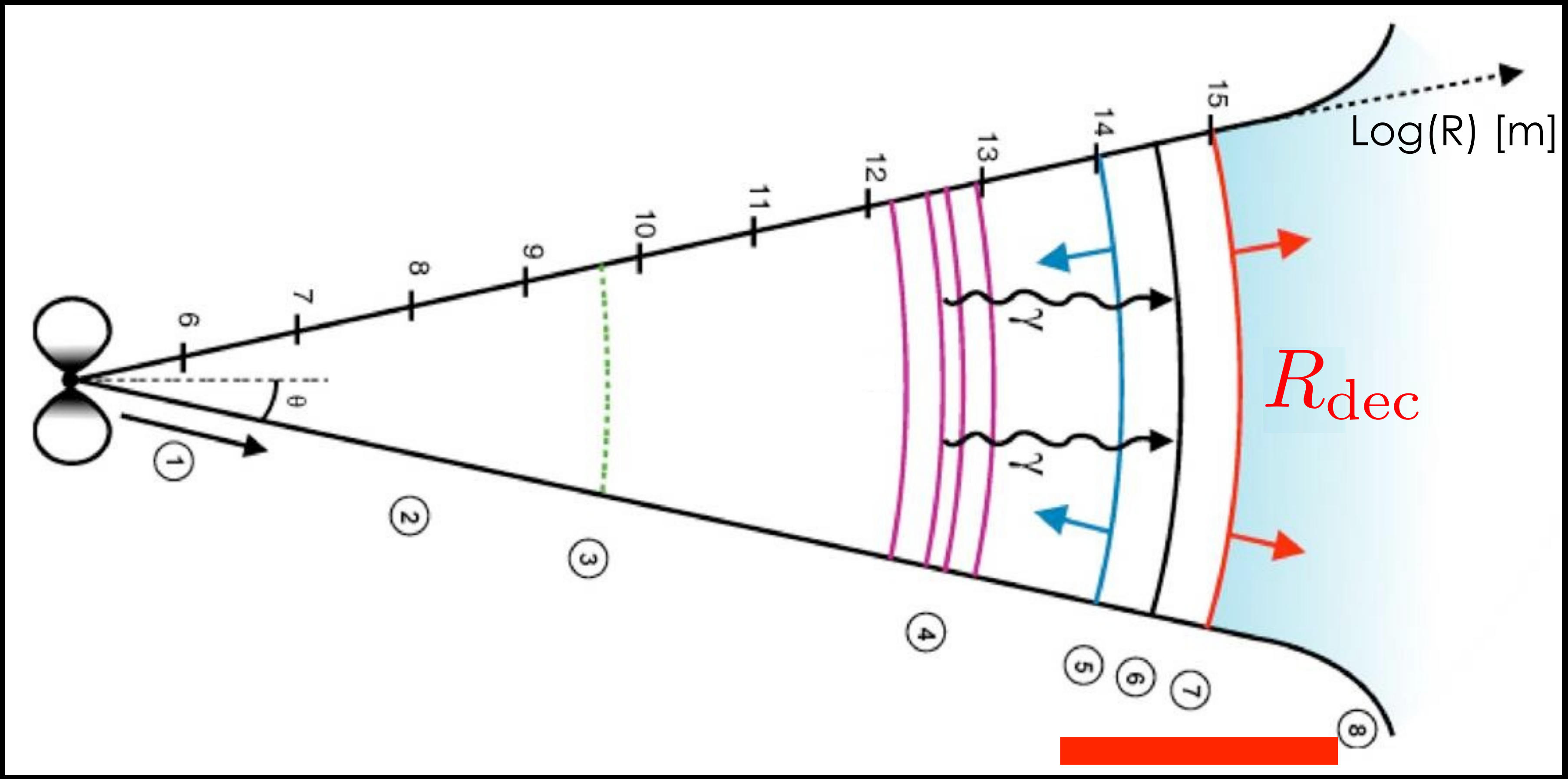
$$R_{\mathrm{is}} \simeq R_{\mathrm{spread}} \simeq 2\Gamma^2\Delta \simeq 6\,10^{14}\,\mathrm{cm}\left(\frac{\Gamma}{100}\right)^{2}\left(\frac{\Delta/c}{1\,\mathrm{s}}\right)$$

GRB Physics: afterglow

- Long timescales (hours/days/weeks/years): the afterglow has an <u>external</u> origin
- Interaction of the relativistic ejecta with the circus-burst medium: deceleration
- Forward shock: strong ultra-relativistic shock in the external medium = afterglow



- Reverse shock (if the ejecta has a low magnetization): additional contribution?

$$R_{\rm dec} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{\Gamma_0^2 n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 1.5\,10^{17}\,{\rm cm}\left(\frac{\Gamma_0}{100}\right)^{-2/3}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

$$R_{\rm Newton} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 3.2\,10^{18}\,{\rm cm}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

$$\Gamma_0 M_0 c^2 + M_{ext} c^2 = \Gamma M_0 c^2 + \Gamma^2 M_{ext} c^2$$

phase 1: $\Gamma_0 M_0 c^2 \gg M_{ext} c^2$; $\Gamma^2 M_{ext} c^2 \ll \Gamma M_0 c^2$

$$\Rightarrow \Gamma = \Gamma_0$$

phase 2: " ; $\Gamma^2 M_{ext} c^2 \gg \Gamma M_0 c^2$

$$\Gamma_0 M_0 c^2 \simeq \Gamma^2 M_{ext} c^2 \Rightarrow \Gamma \propto M_{ext}^{-1/2}$$

uniform medium $\Gamma \propto R^{-3/2}$

stellar wind $\Gamma \propto R^{-1/2}$

Transition 1 → 2:

$$M_{ext} = \frac{M_0}{\Gamma_0} \longleftrightarrow R_{dec}$$

phase 3: $M_{ext} c^2 \gg \Gamma_0 M_0 c^2 \Rightarrow M_{ext} c^2 \simeq \Gamma^2 M_{ext} c^2$

$\Rightarrow \Gamma = 1$ Newtonian regime

Sedov

Deceleration

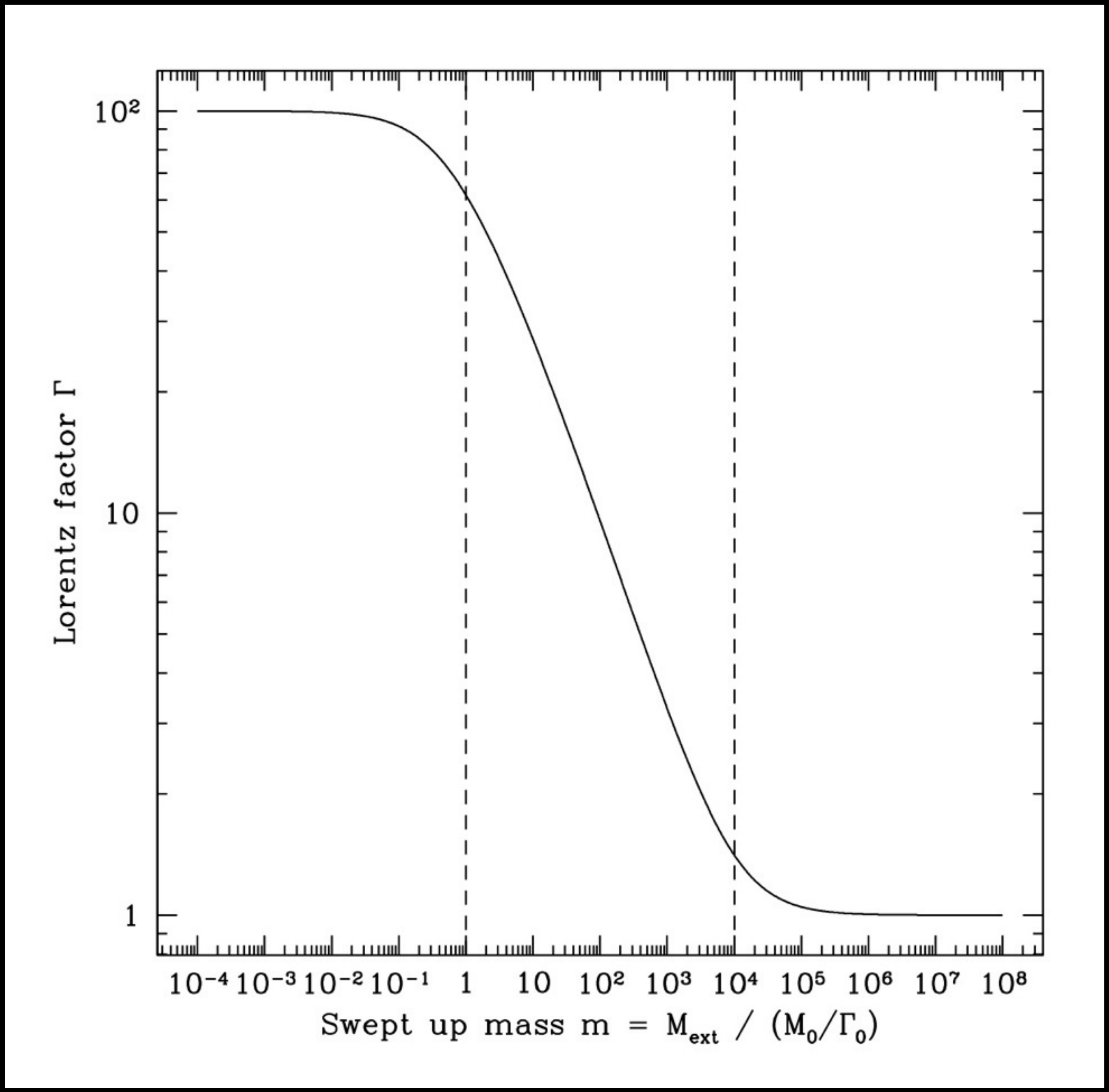
Ejecta is decelerated
by the external medium

$$R_{\rm dec} \longleftrightarrow M_{\rm ext} \simeq \frac{M_0}{\Gamma_0}$$

$$\Gamma \simeq \Gamma_0 \quad \text{if} \quad R \ll R_{\rm dec}$$

$$\Gamma \simeq \Gamma_0 \left(\frac{R}{R_{\rm dec}}\right)^{-3/2} \quad \text{if} \quad R_{\rm dec} \ll R \ll R_{\rm Newton}$$

$$\Gamma \simeq 1 \quad \text{if} \quad R \gg R_{\rm Newton}$$ (Sedov: $\beta \propto R^{-3/2}$)



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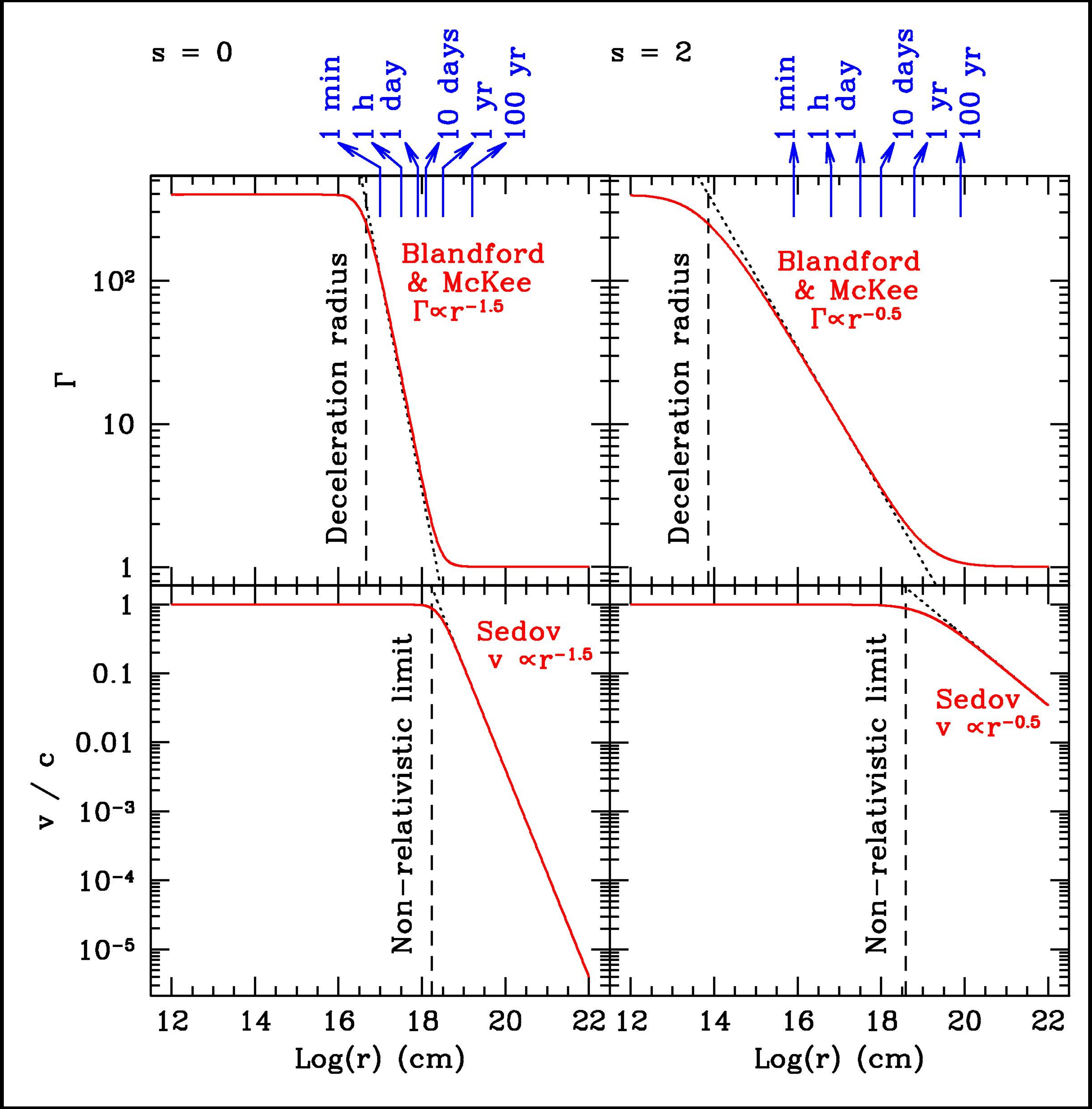
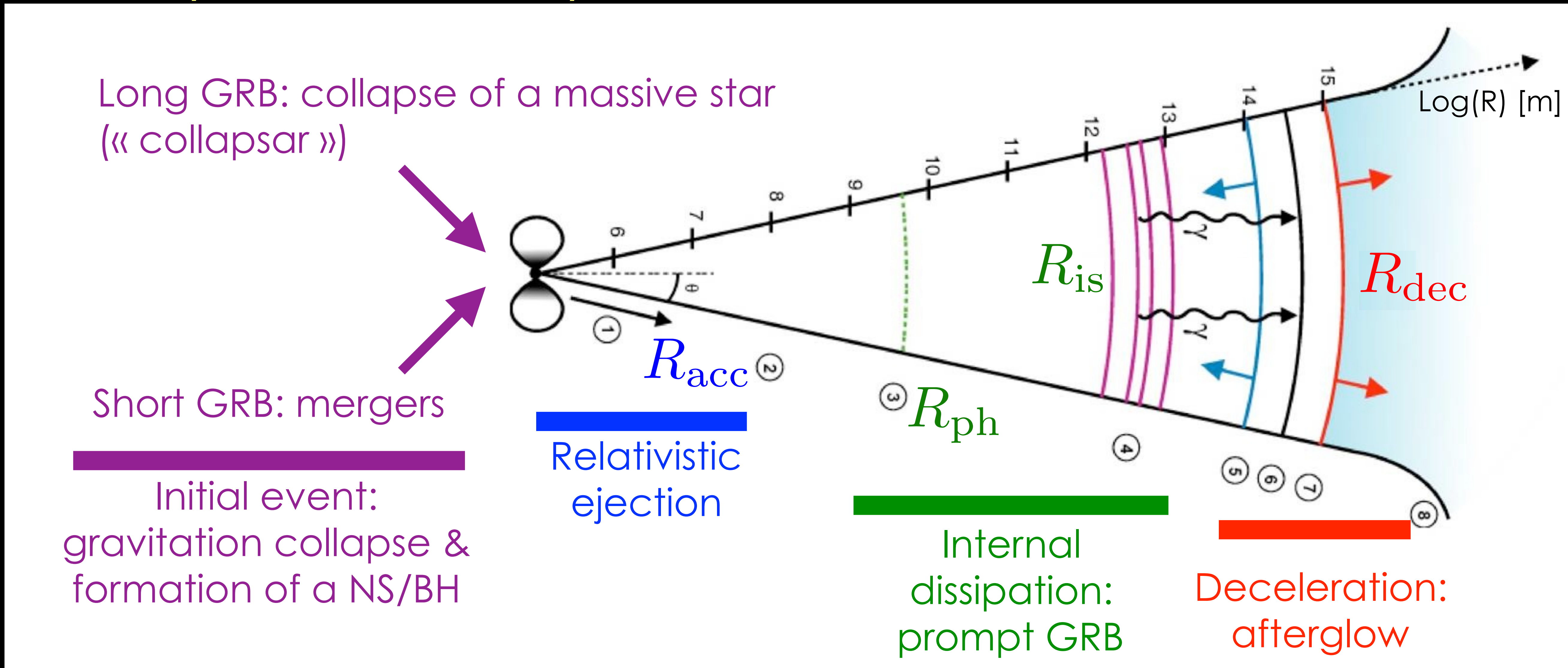
Deceleration

Ejecta is decelerated by the external medium



$$t_{\mathrm{obs}} = \left(\frac{D}{c}\right) + \int_0^R \frac{\mathrm{d}R}{2\Gamma^2 c}$$

GRB Physics: summary



Acceleration

$$R_{\rm acc} \simeq \Gamma R_0 \simeq 10^9\,{\rm cm}\left(\frac{\Gamma}{100}\right)\left(\frac{R_0}{100\,{\rm km}}\right)$$

Internal dissipation

$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,{\rm cm}\left(\frac{\dot{E}}{10^{52}\,{\rm erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

$$R_{\rm is} \simeq 2\Gamma^2\Delta \simeq 6\,10^{14}\,{\rm cm}\left(\frac{\Gamma}{100}\right)^2\left(\frac{\Delta/c}{1\,{\rm s}}\right)$$

Internal dissipation

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