

Observational prediction of gamma-ray emission from knee-energy cosmic rays accelerated by core-collapse supernovae

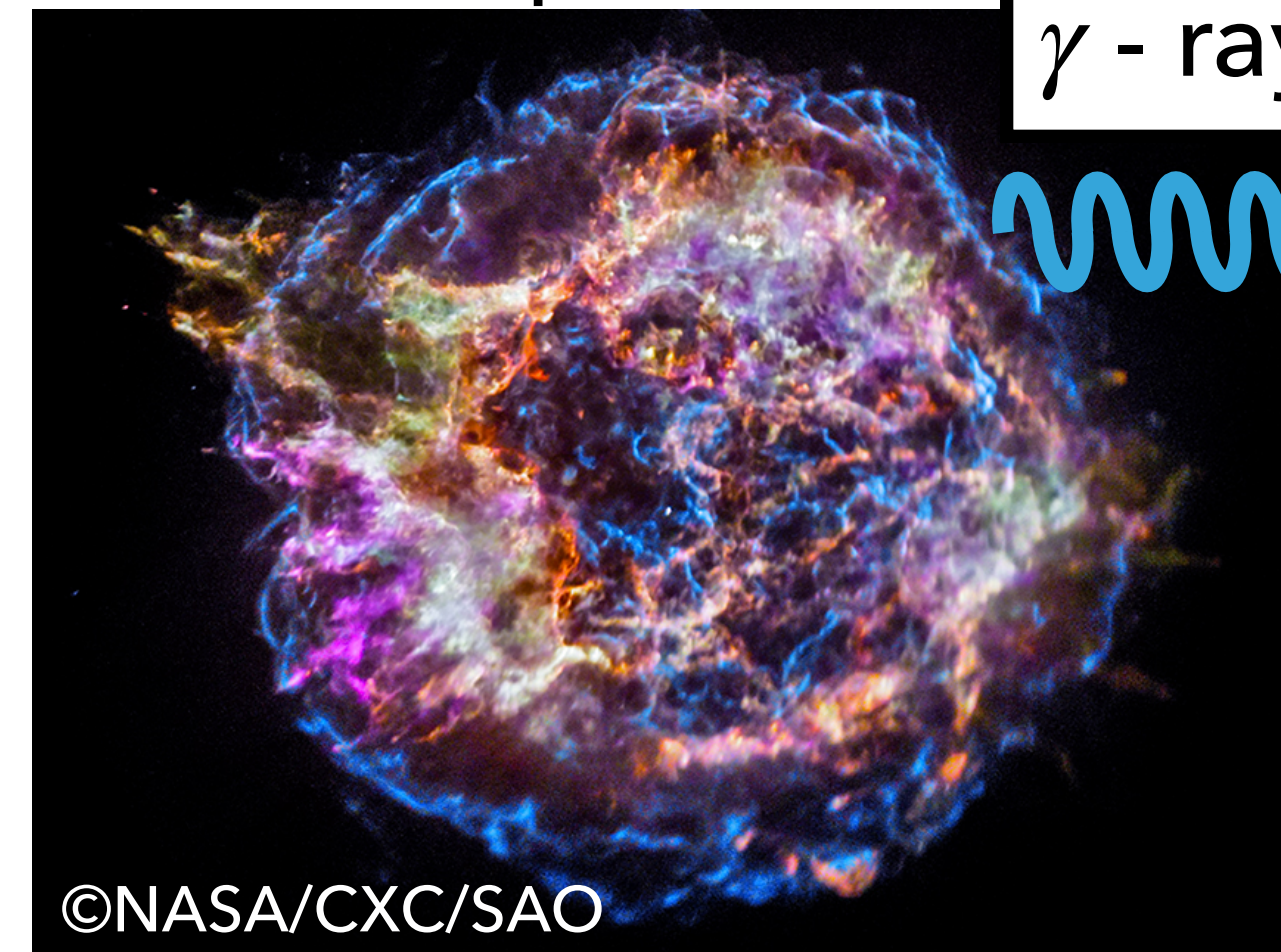
Nishikawa Tomotaka

(Nagoya Univ.)

Collaborator:

Tsuyoshi Inoue (Konan Univ.)

SNR Cassiopeia A



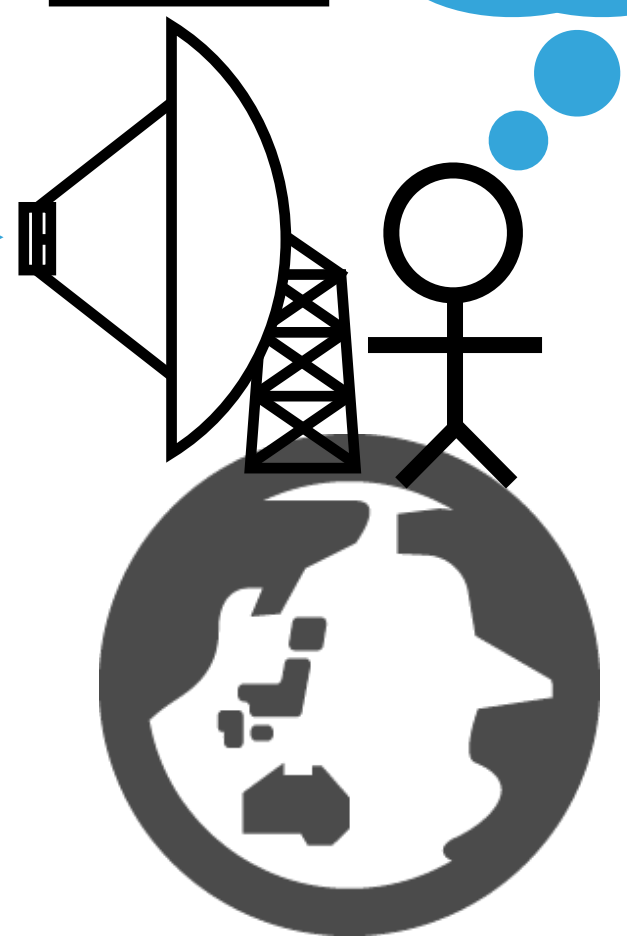
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Chandra X-ray Observatory

γ - ray

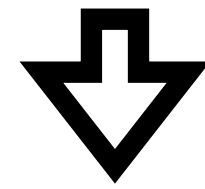


CTA

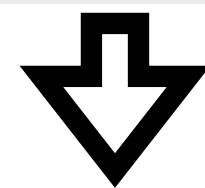


Simulation of the CR acceleration with Non-resonant hybrid instability

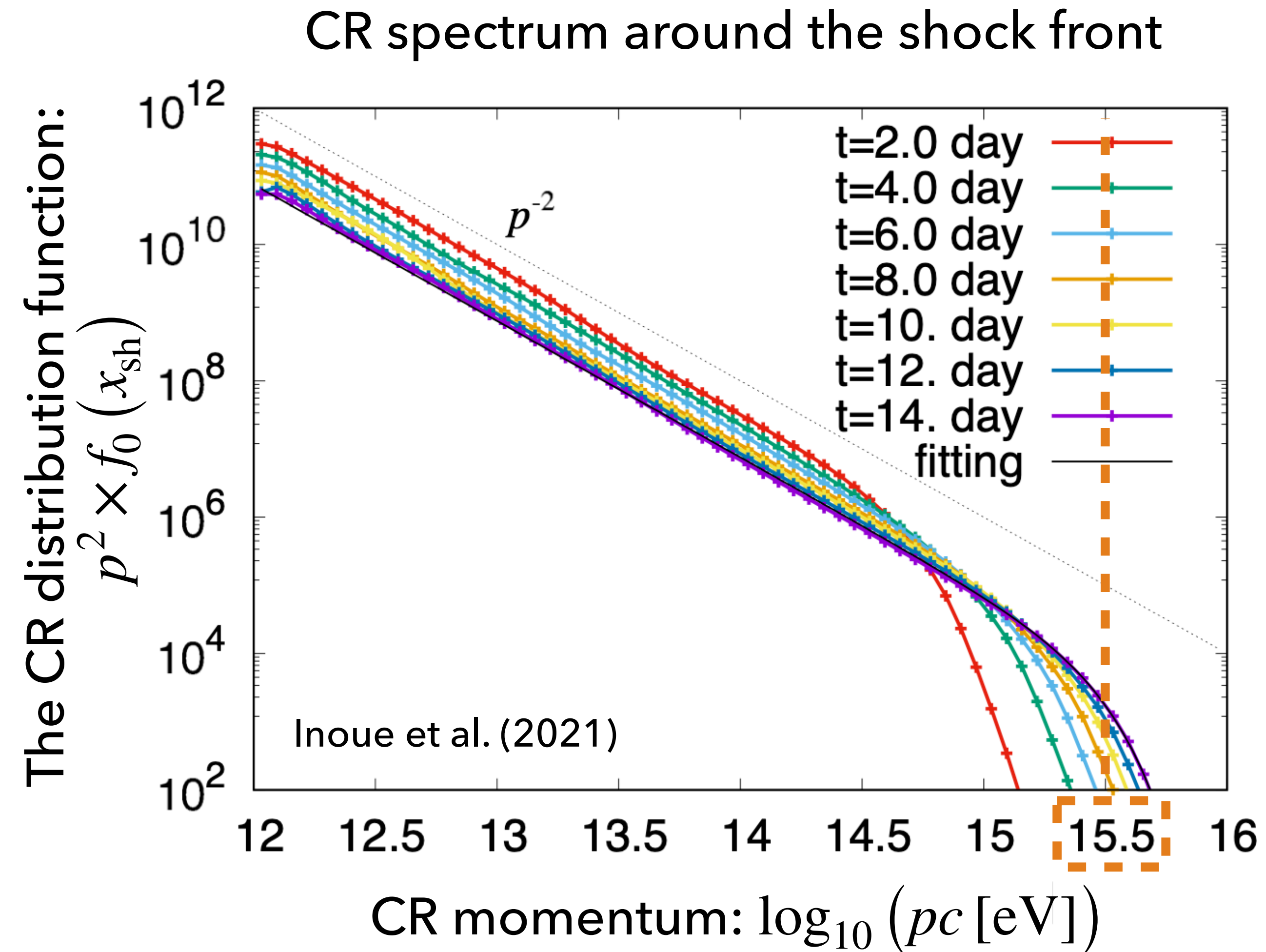
Cosmic rays (CRs) up to $10^{15.5}$ eV are believed to be accelerated by **shock wave in Supernova remnants (SNRs)**.



Previous study (Inoue et al. 2021; Marcowith et al. 2018)
The simulation of CR acceleration incorporating **Non-resonant hybrid instability (NRHI or Bell instability)** suggests that CR protons can be accelerated to $10^{15.5}$ eV during the **very early phase** of a supernova expansion in a **dense circumstellar medium**.

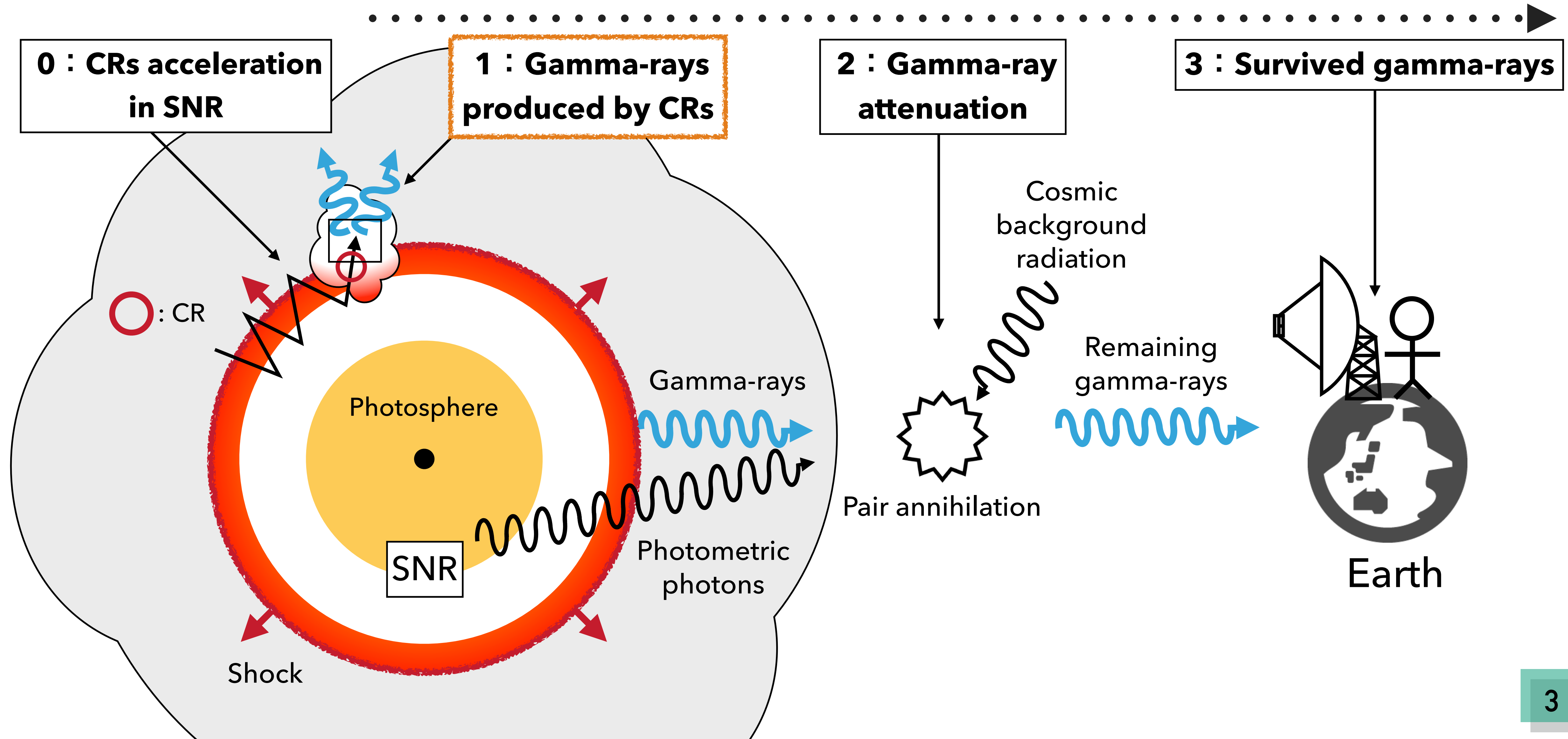


Purpose of this research
Theoretically study whether observational verification of such an acceleration is possible through gamma-ray observations by Cerenkov Telescope Array (CTA).



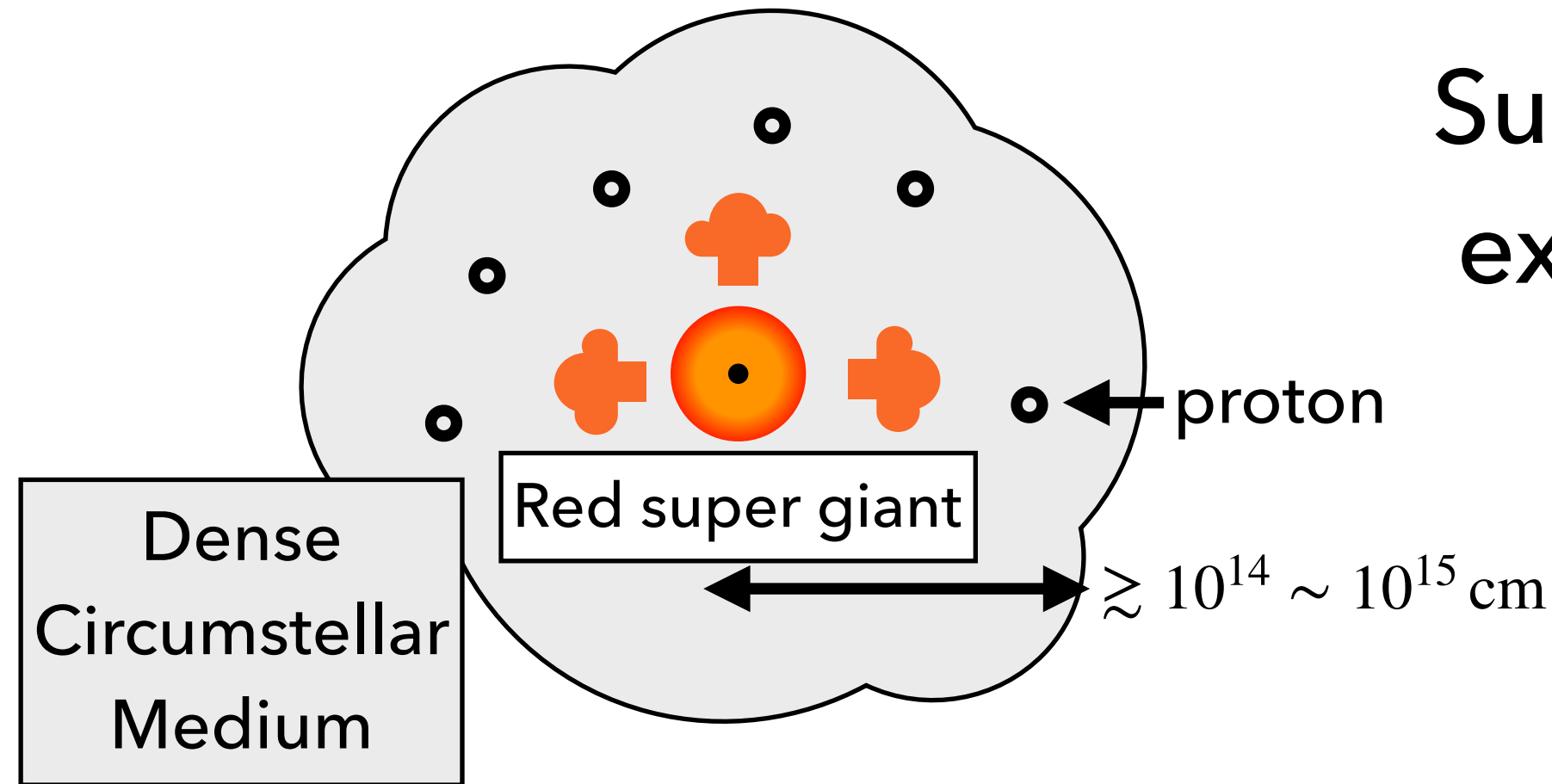
Overview: Observational prediction of gamma-rays emitted from SNR

From gamma-ray generation to their observation (This research)



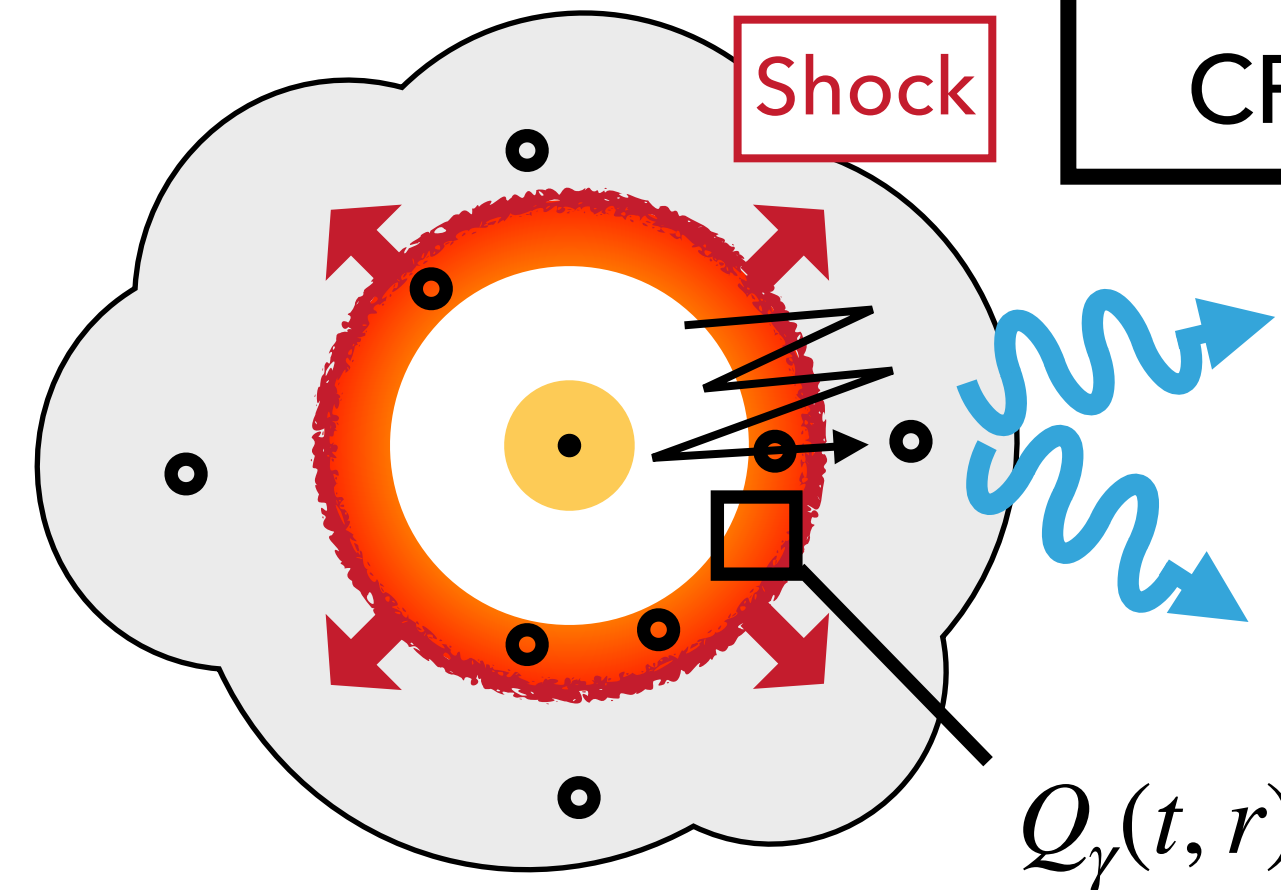
Gamma-rays produced by CRs

- Before SN explosion



Supernova explosion

- After SN explosion



- CR collision
 $p(\text{CR}) + p(\text{CSM}) \rightarrow p + p + \pi^0$
- Decay of π^0
 $\pi^0 \rightarrow 2\gamma$

100 TeV gamma-ray

- Intrinsic gamma-ray flux

$$F_{\gamma, \text{intr}}(t, r) = \frac{\int_{\text{shell}} Q_\gamma(t, r) d^3r}{4\pi D^2}$$

$$Q_\gamma(t, r) = q_\gamma n(t, r) E_{\text{CR}}(t, r) [\text{cm}^{-3} \text{s}^{-1}]$$

Q_γ : Emissivity of gamma-ray radiation from shocked CSM

t : Time after core collapse

D : Distance to the SNR

• $q_\gamma(E_\gamma) [\text{s}^{-1} \text{erg}^{-1} \text{cm}^3]$: γ -ray emissivity normalized to the CR energy density (cf. Drury + 94)

$E_\gamma [\text{eV}]$: γ -ray energy (where $E_\gamma \geq 100 \text{ TeV}$)

• $n(r) [\text{cm}^{-3}]$: Number density of CSM

Inoue et al. (2021)

• $E_{\text{CR}}(r) [\text{erg cm}^{-3}]$: CR energy density

$$E_{\text{CR}}(r) = \int 4\pi p^2 f_0(r, p) pc dp$$

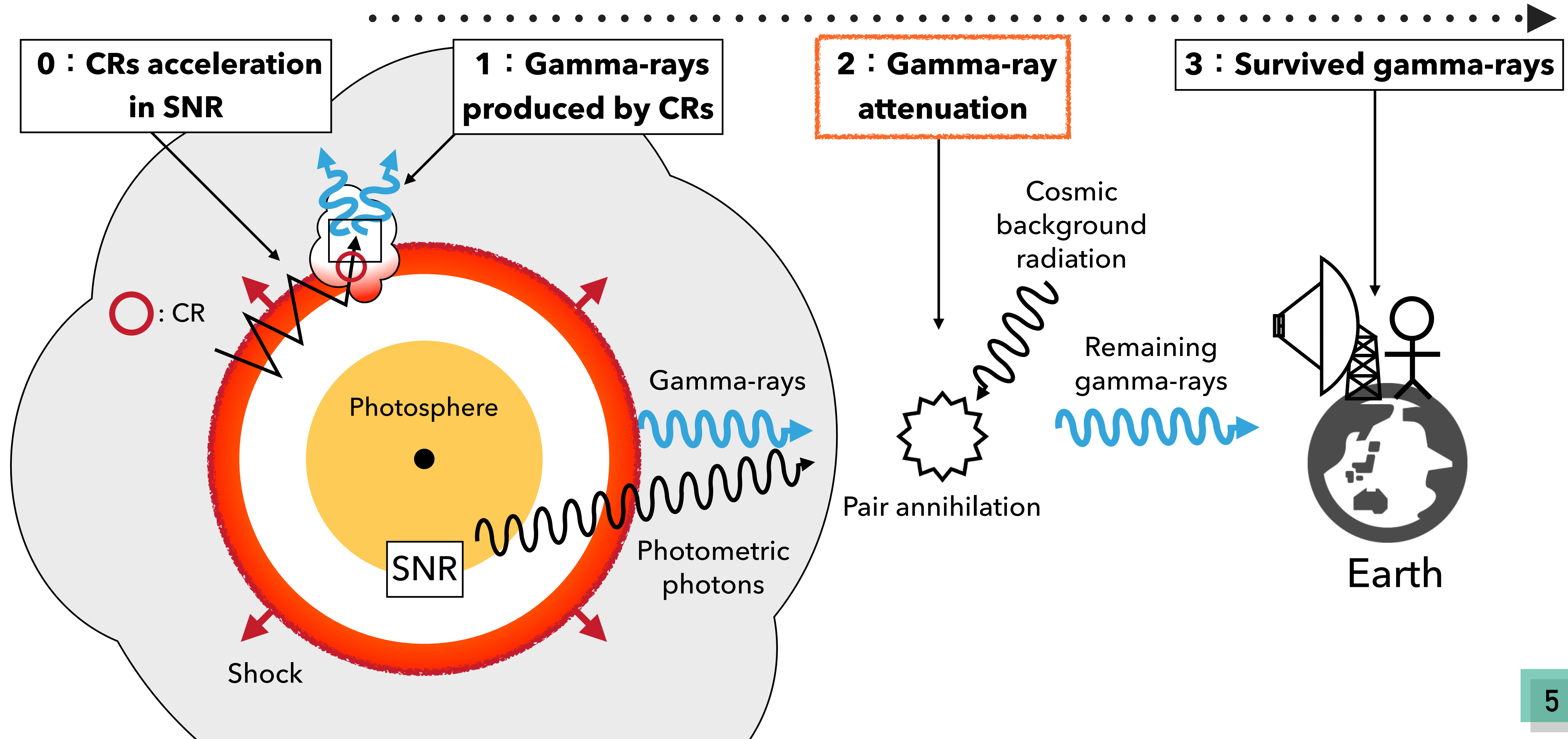
$f_0(r, p) [\text{cm}^{-6} \text{g}^{-3} \text{s}^3]$: CR distribution function

Inoue et al. (2021)

Gamma-ray fluxes emitted from CRs can be calculated.

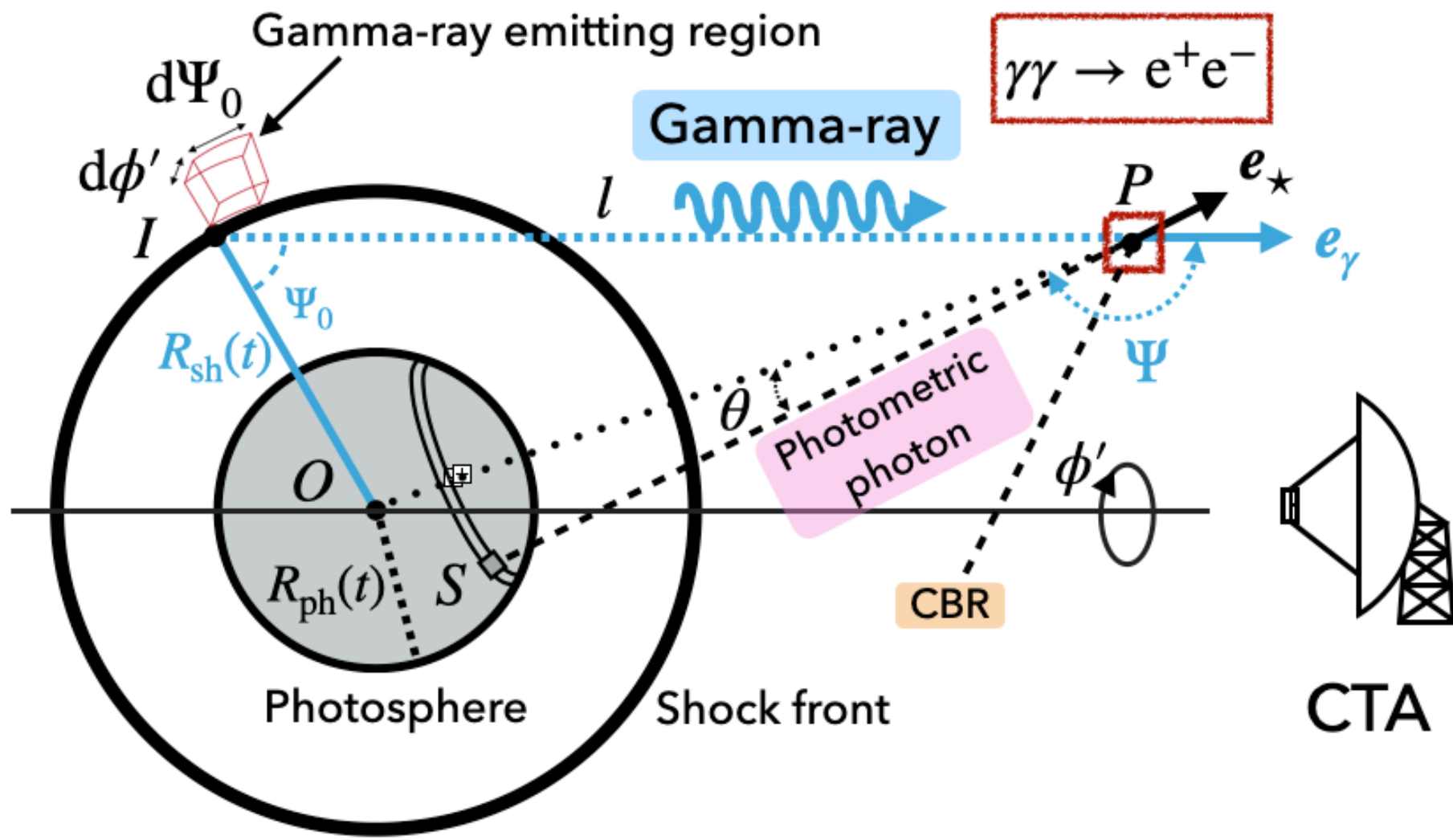
Overview: Observational prediction of gamma-rays emitted from SNR

From gamma-ray generation to their observation (This research)



Gamma-rays attenuation

- Model of supernova remnants (SNRs)



SNR model: Cristofari et al. 2020 improvement

- Target:

Core-collapse Supernova (type II-P SN)

- Gamma-ray:

Energy: $E = 100 \text{ TeV}$

Emitting region: shocked CSM

- Detector:

Cherenkov Telescope Array

- Observable gamma-ray fluxes : $F_{\gamma,\text{abs}} \left[\text{cm}^{-2}\text{s}^{-1} \right]$

$$F_{\gamma,\text{abs}}(\geq 100 \text{ TeV}) = \frac{1}{4\pi D^2} \int_0^{2\pi} d\phi' \int_{\Psi_{0,\text{min}}}^{\pi} d\Psi_0 \int dr$$

$$\times q_{\gamma}(\geq 100 \text{ TeV}) n(r) E_{\text{CR}}(r) \exp\left(-\tau_{\text{ph}} - \tau_{\text{CBR}}\right)$$

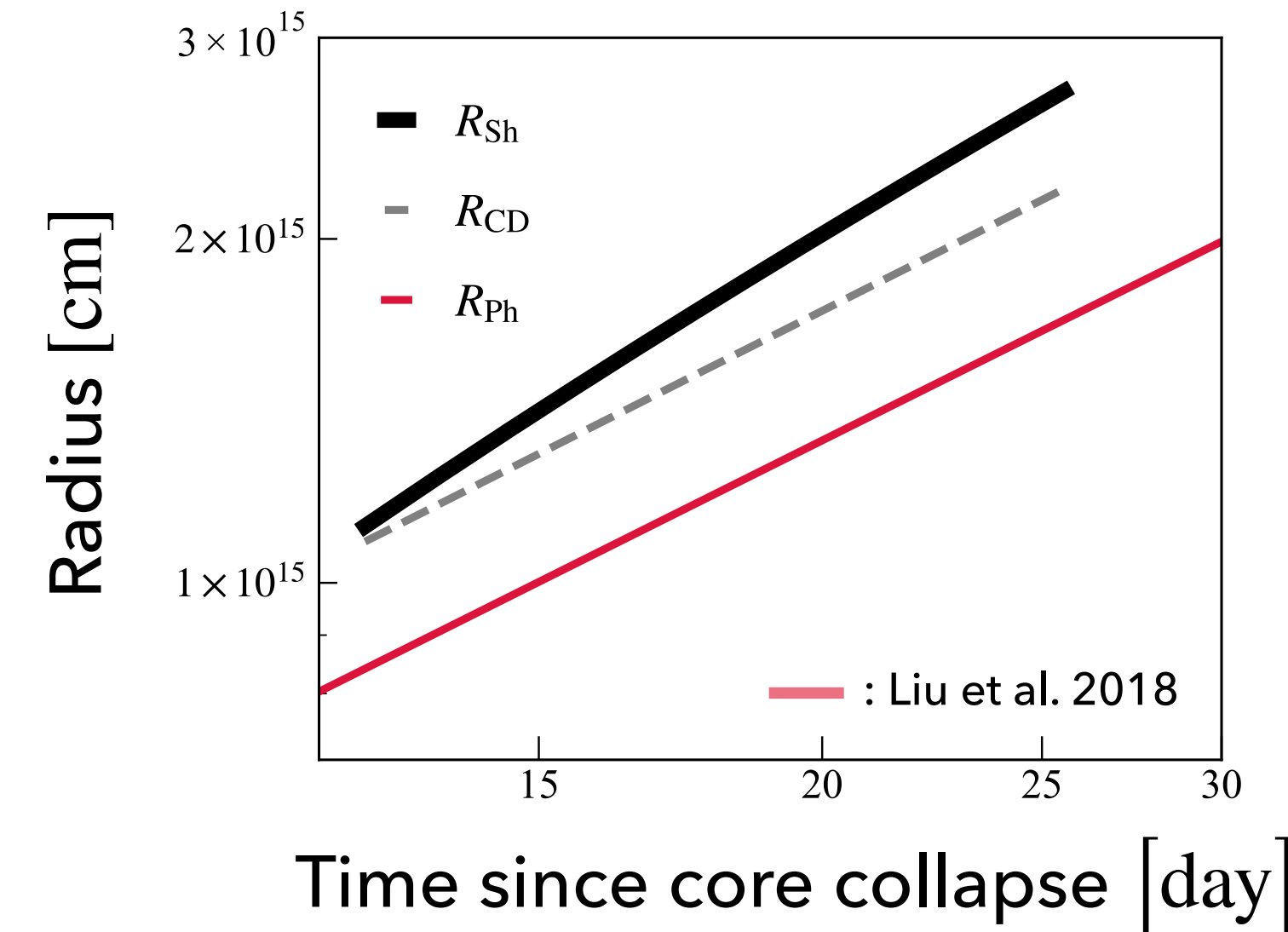
Attenuation by Photosphere

Attenuation by Cosmic background radiation

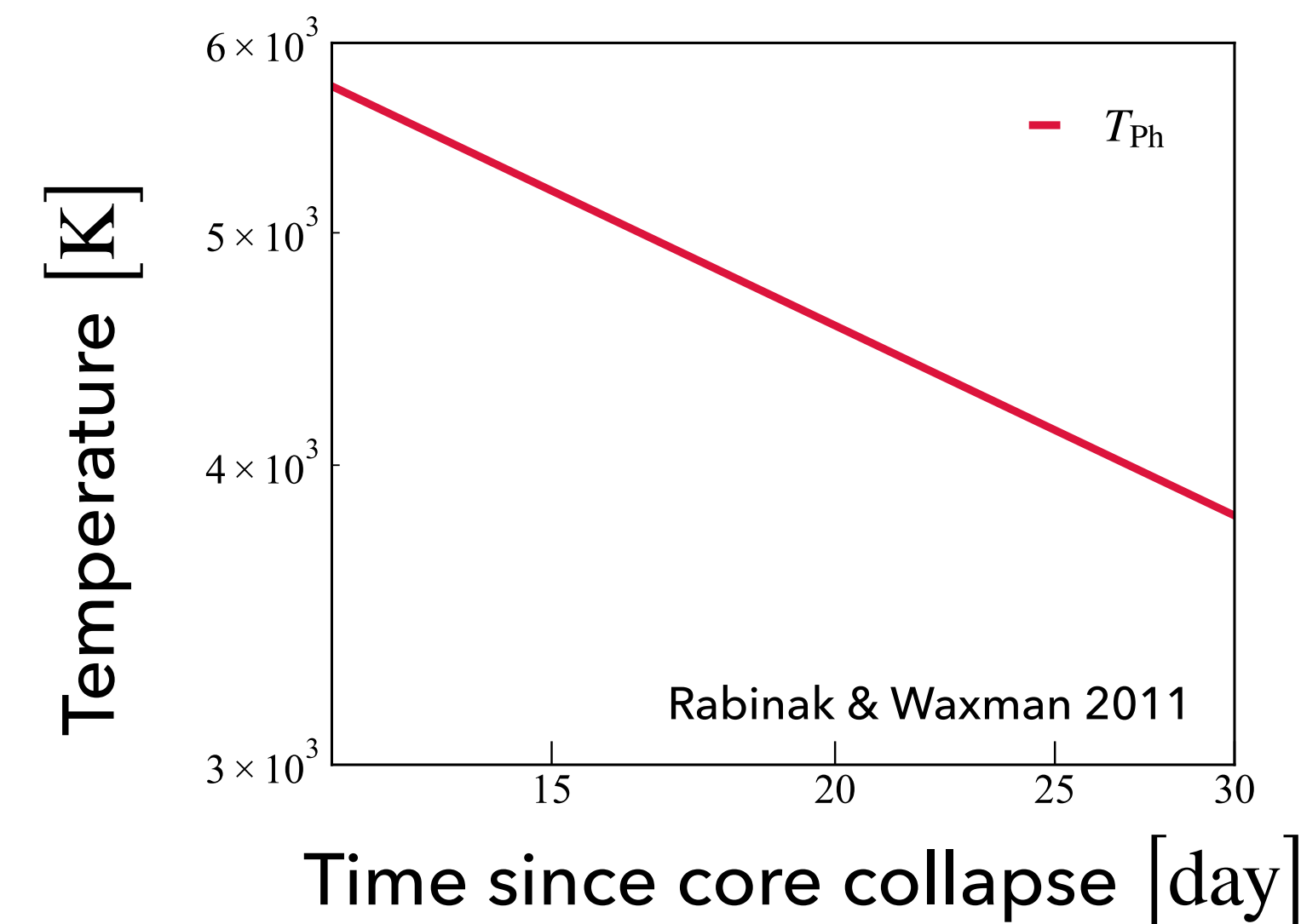
- Numerical integration method: Gaussian quadrature

Protheroe et al. 2000

Evolution of photosphere and shock radius



Evolution of photometric temperature



• **Attenuation by Photosphere**

t : Time since SN explosion E : γ -ray energy ϵ : soft photon energy

$$\tau_{\gamma\gamma}(t, \Psi_0, E) = \int_0^{+\infty} dl \int_{c_{\min}}^1 d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon \overset{\textcircled{1}}{n_\epsilon} \overset{\textcircled{2}}{\sigma_{\gamma\gamma}} \overset{\textcircled{3}}{\left(1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star\right)}$$

- ① Number density of soft photons emitted on the photosphere surface
- ② Cross section of electron-positron pair production ($\gamma\gamma \rightarrow e^+e^-$)
- ③ Angular dependence of a gamma-ray direction ($\mathbf{e}_\gamma$) and a photometric photon ($\mathbf{e}_\star$)

Integral section:

$\epsilon_{\min}$: **Photon energy threshold** of soft photon

$c_{\min}$: Gamma-ray **shading by the photosphere**

Time lag:

The emission time difference between gamma-ray and soft photons.

$$F_{\gamma,\text{abs}}(\geq 100 \text{ TeV}) = \frac{1}{4\pi D^2} \int_0^{2\pi} d\phi \int_{\Psi_{0,\min}}^{\Psi_0} d\Psi \int_{\epsilon_{\min}}^{+\infty} d\epsilon \times q_\gamma(\geq 100 \text{ TeV}) n(r) E_{\text{CR}}(r) \exp\left(-\tau_{\text{ph}} - \tau_{\text{CBR}}\right)$$

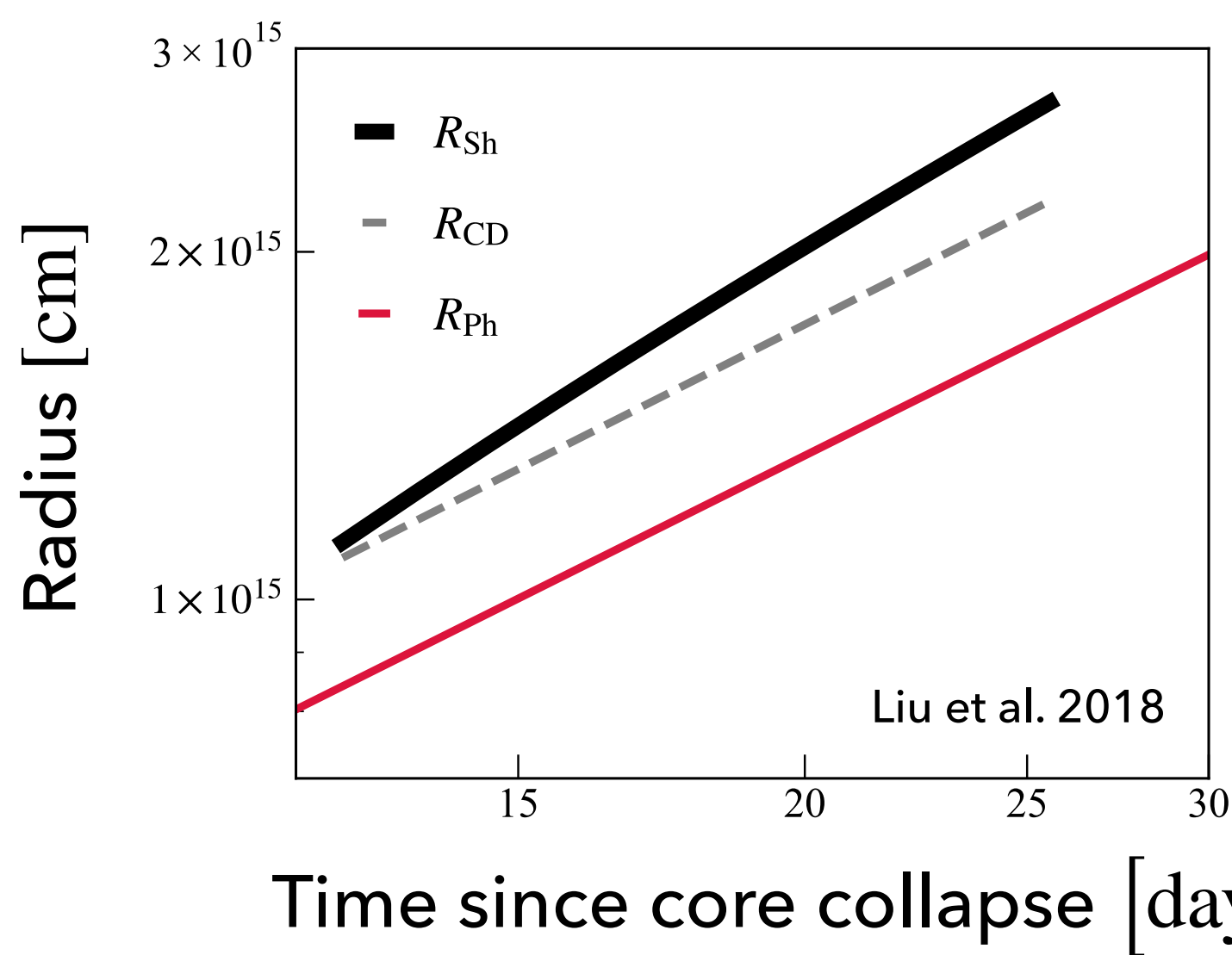
Attenuation by
Photosphere

Attenuation by
Cosmic background radiation

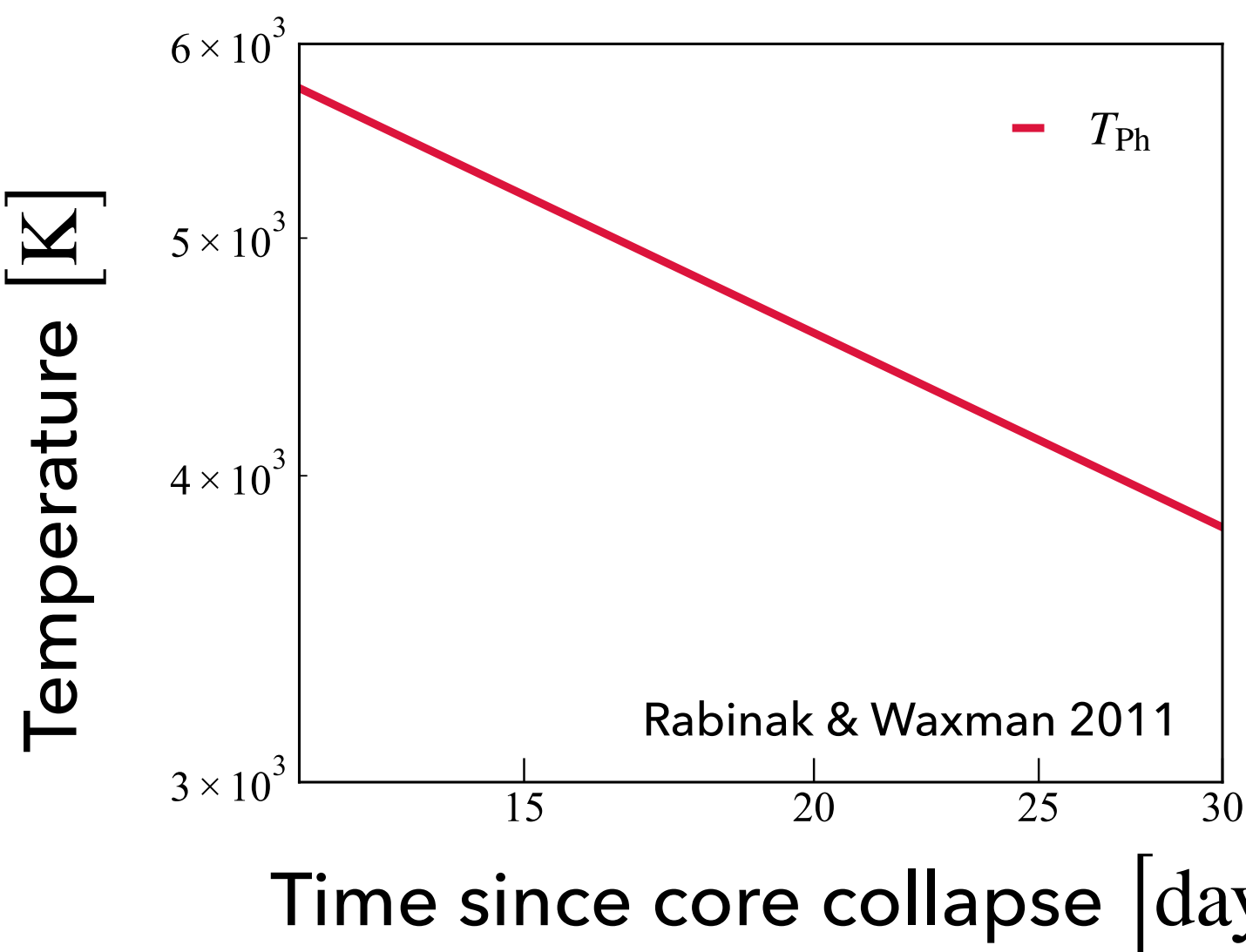
• Numerical integration method: Gaussian quadrature

Protheroe et al. 2000

Evolution of photosphere and shock radius



Evolution of photometric temperature



• **Attenuation by or CBR**

t : Time since SN explosion E : γ -ray energy ϵ : soft photon energy

$$\tau_{\text{CBR}}(t, \Psi_0, E) = \int_0^{+\infty} dl \int_{-1}^1 d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon \underbrace{n_\epsilon}_{\textcircled{1}} \underbrace{\sigma_{\gamma\gamma}}_{\textcircled{2}} \underbrace{\left(1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star\right)}_{\textcircled{3}}$$

- ① Number density of CBR
- ② Cross section of electron-positron pair production ($\gamma\gamma \rightarrow e^+e^-$)
- ③ Angular dependence of a gamma-ray direction ($\mathbf{e}_\gamma$) and CBR photon ($\mathbf{e}_\star$)

Integral section

$\epsilon_{\min}$: **Photon energy threshold** at which gamma-ray annihilation occurs

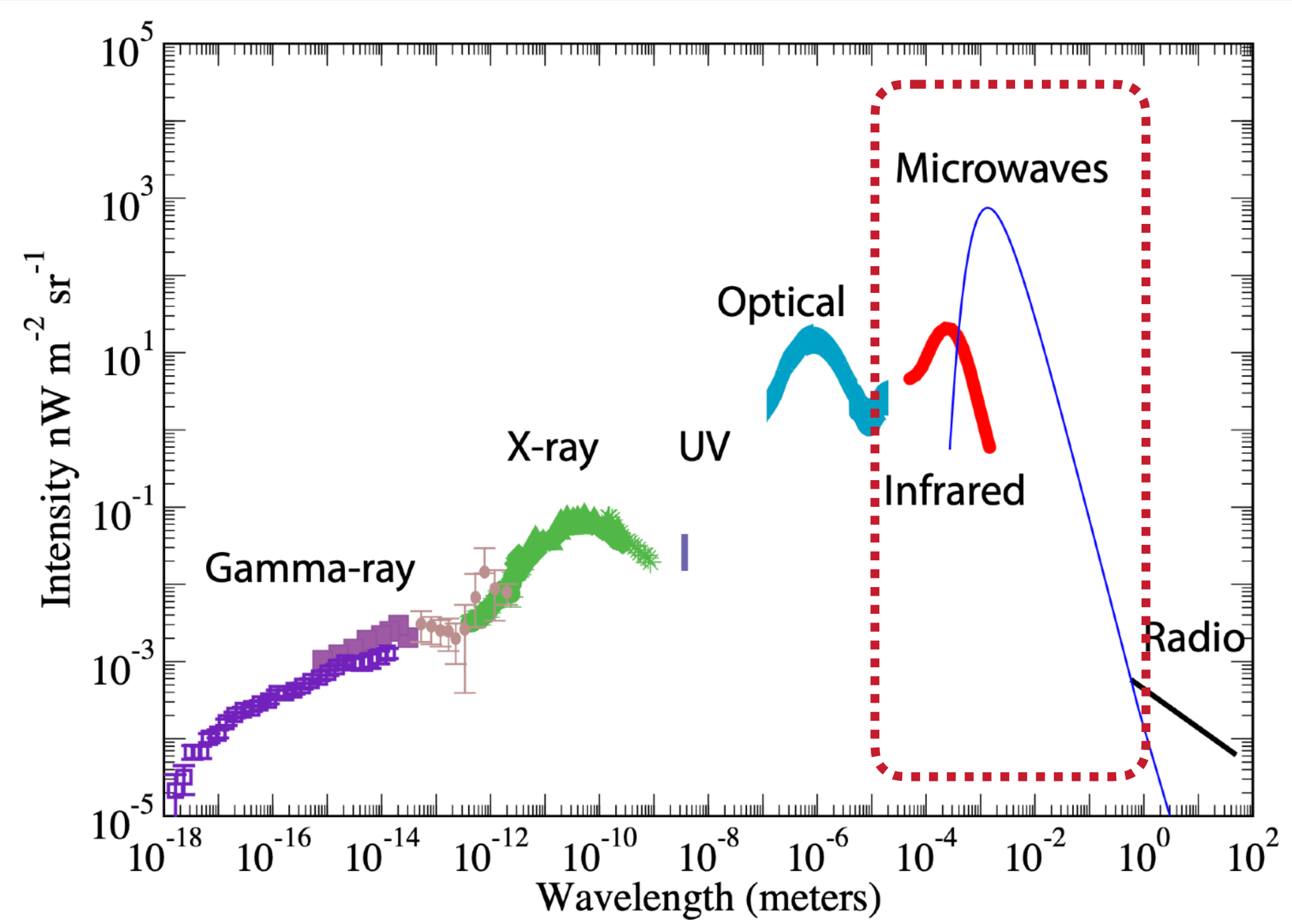
$$F_{\gamma,\text{abs}}(\geq 100 \text{ TeV}) = \frac{1}{4\pi D^2} \int_0^{2\pi} d\phi' \int_{\Psi_{0,\min}}^{\pi} d\Psi_0 \int dr \times q_\gamma(\geq 100 \text{ TeV}) n(r) E_{\text{CR}}(r) \exp\left(-\tau_{\text{ph}} - \tau_{\text{CBR}}\right)$$

Attenuation by
Photosphere

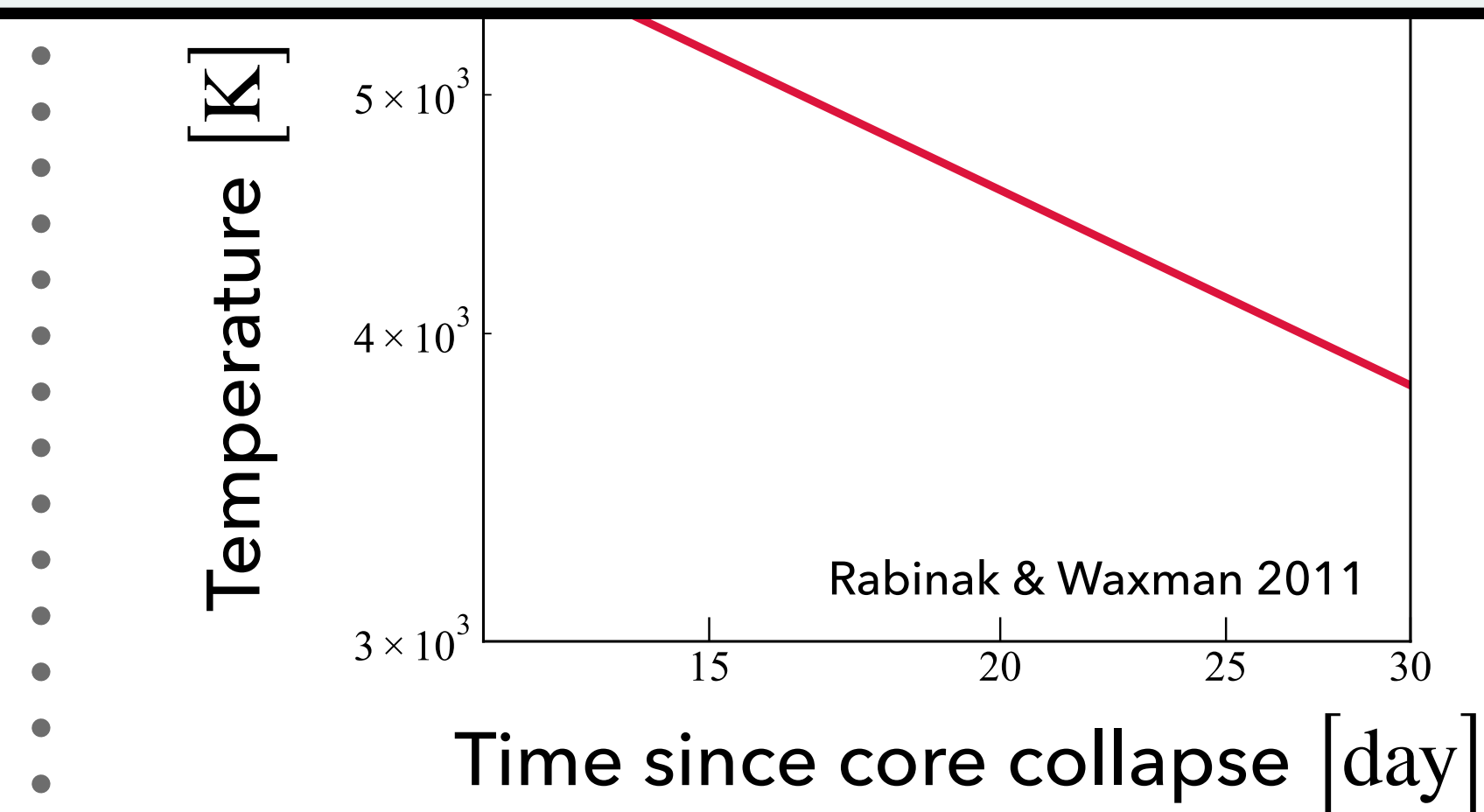
Attenuation by
Cosmic background radiation

• Numerical integration method: Gaussian quadrature Protheroe et al. 2000

Intensity of cosmic background radiation



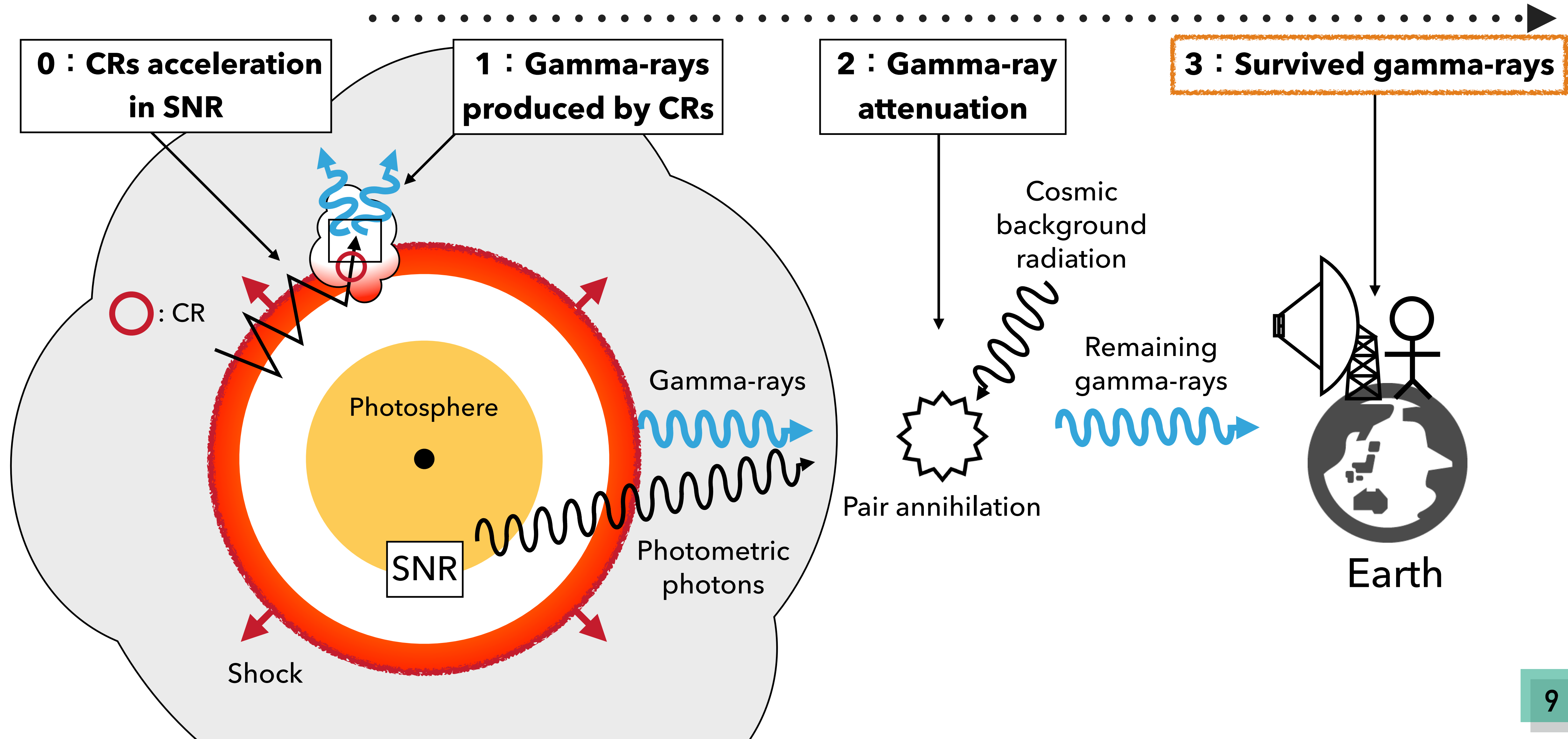
A.Cooray 2016



Rabinak & Waxman 2011

Overview: Observational prediction of gamma-rays emitted from SNR

From gamma-ray generation to their observation (This research)



Time evolution of gamma-ray flux above 100 TeV

~ Calculation Setup ~

Distance to the target object: $D = 1$ Mpc

CR injection rate: $\eta_{\text{inj}}^{\text{p}} = 6 \times 10^{-4}$

Mass loss rate of RSG: $\dot{M}_{\text{RSG}}$

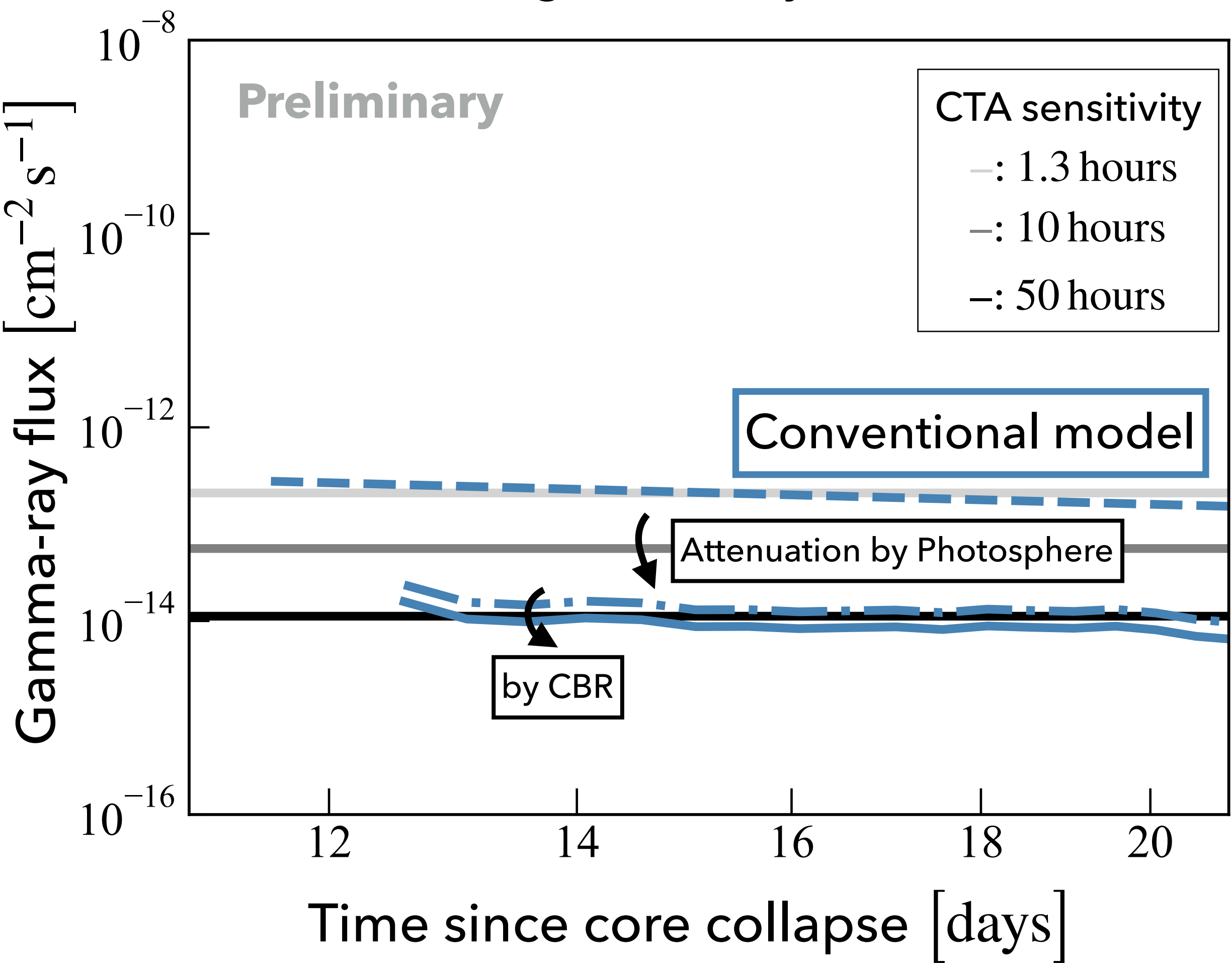
Conventional model (Cristofari et al. 2020)

$$\dot{M}_{\text{RSG}} = 10^{-5} M_{\odot} \text{ yr}^{-1}$$

Conventional mass loss rate values created by the stellar winds of red supergiants.

	Photometric photon	CBR
---	OFF	OFF
-. .	ON	OFF
---	ON	ON

Time evolution of gamma-ray flux above 100 TeV



The gamma-ray flux is attenuated to $\sim 1/10$ or less by **photosphere** 14 days after the core collapse.
It is further attenuated to $\sim 2/3$ by **cosmic background radiation**.

Time evolution of gamma-ray flux above 100 TeV

~ Calculation Setup ~

Distance to the target object: $D = 1 \text{ Mpc}$

CR injection rate: $\eta_{\text{inj}}^{\text{p}} = 6 \times 10^{-4}$

Mass loss rate of RSG: $\dot{M}_{\text{RSG}}$

Conventional model
 $\dot{M}_{\text{RSG}} = 10^{-5} \text{ M}_{\odot} \text{ yr}^{-1}$

Modern model
 $\dot{M}_{\text{RSG}} = 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1}$

$\dot{M}_{\text{RSG}}$ of most RSG winds are enhanced by **two orders** of magnitude in a few years before explosion

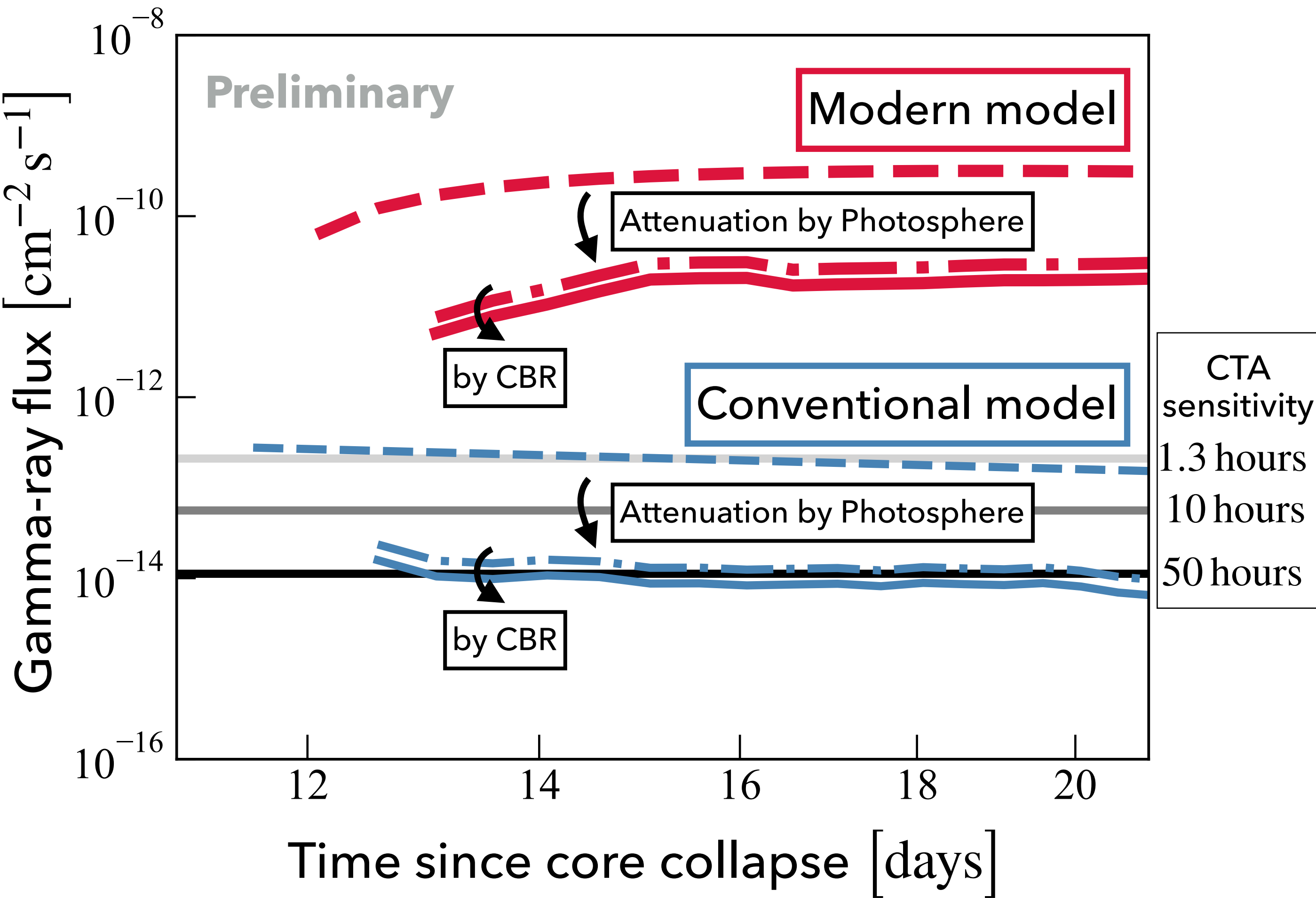
Förster et al. (2018)

Taking into account magnetic field amplification (NRHI) in the very early stage of supernova remnants.

Inoue et al. (2021)

	Photometric photon	CBR
--	OFF	OFF
-.	ON	OFF
—	ON	ON

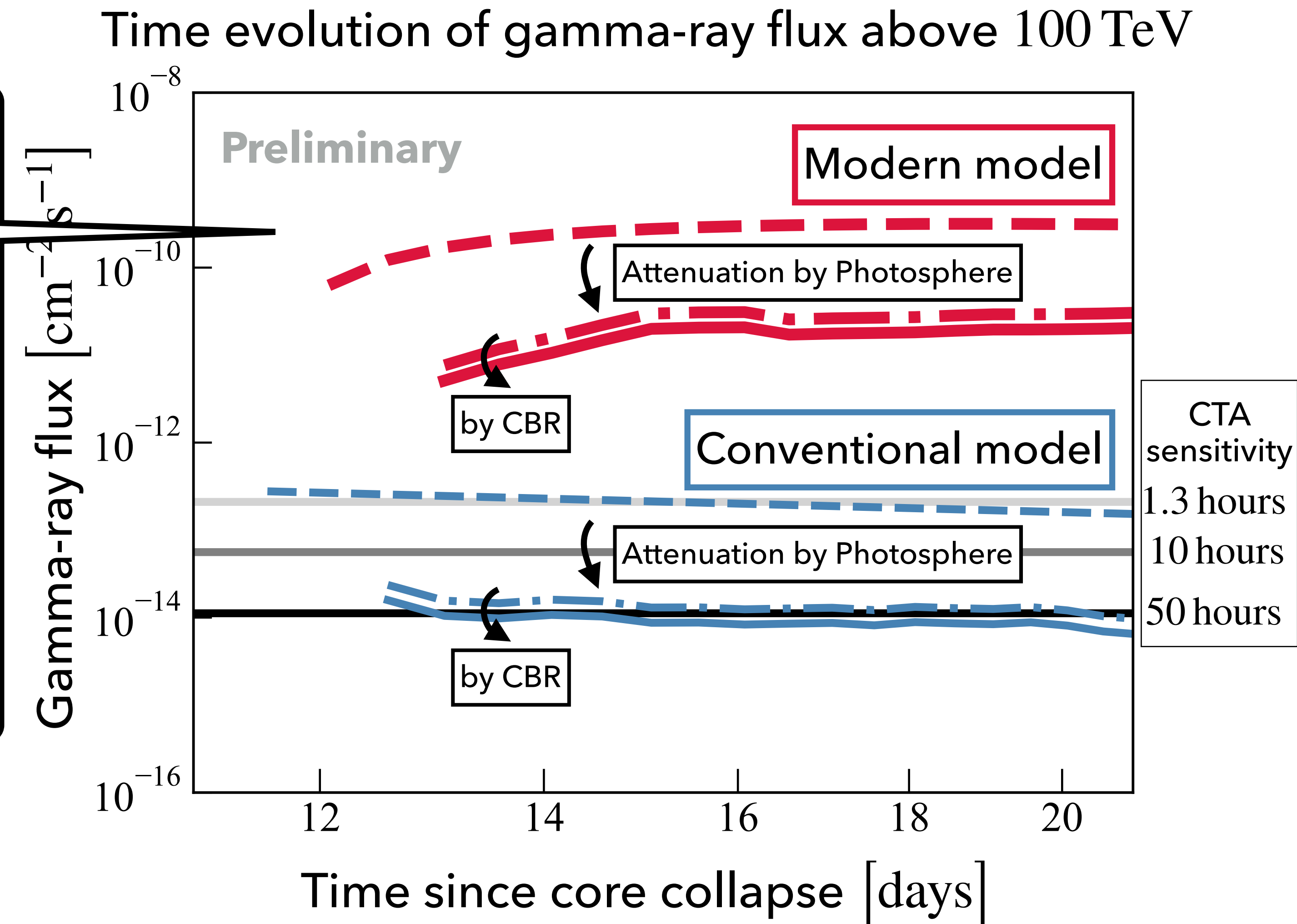
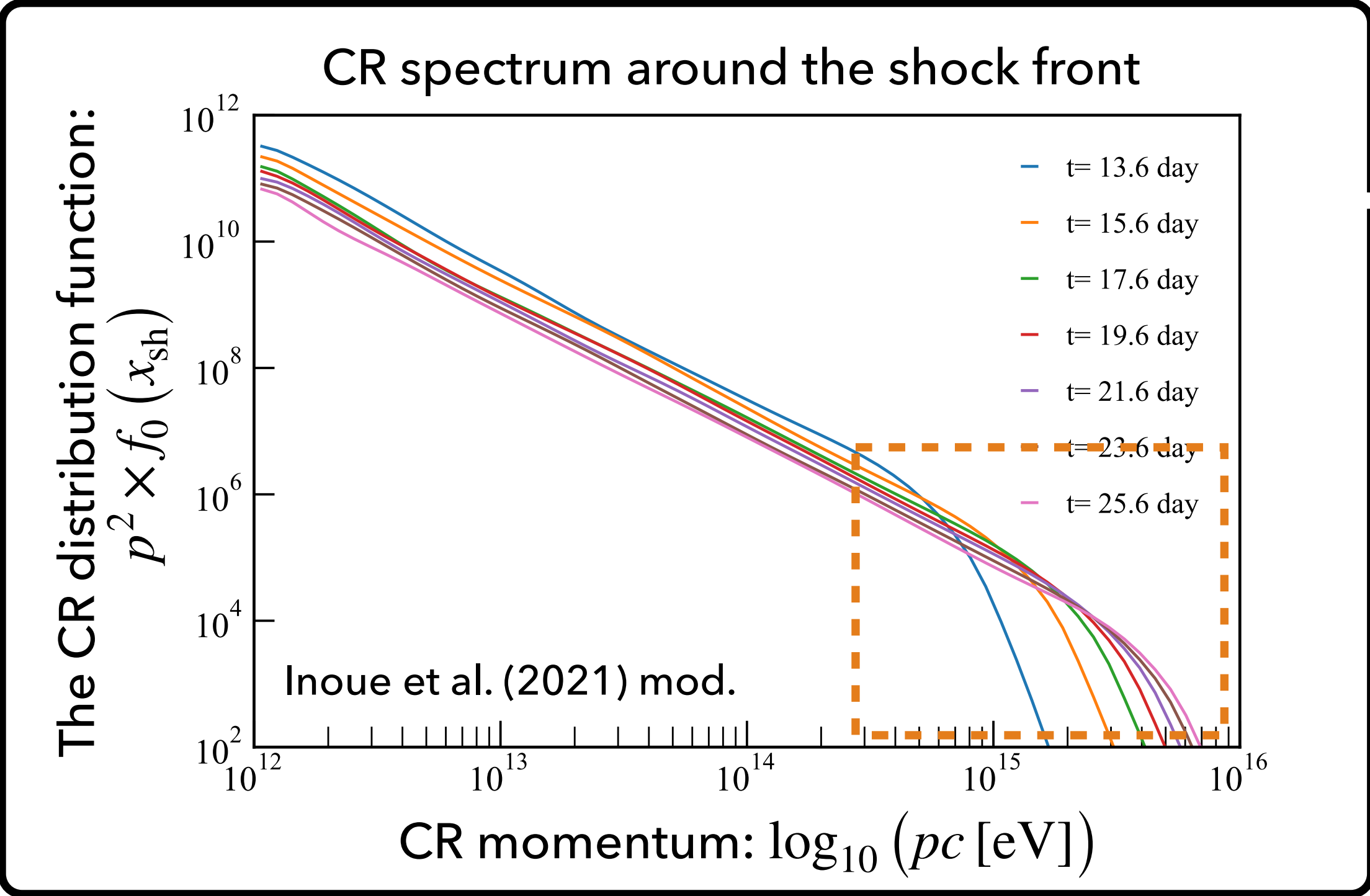
Time evolution of gamma-ray flux above 100 TeV



Modern CSM model with high mass-loss-rate enhances gamma-ray flux to 4 orders of magnitude that is possible to detect!

Time evolution of gamma-ray flux above 100 TeV

~ Calculation Setup ~



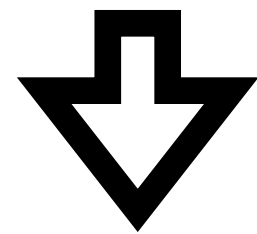
	Photometric photon	CBR
--	OFF	OFF
- .	ON	OFF
—	ON	ON

Modern CSM model with high mass-loss-rate enhances gamma-ray flux to 4 orders of magnitude that is possible to detect!

Probability of detection by CTA

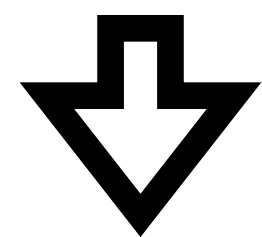
Condition

- Gamma-ray detector:
Cherenkov Telescope Array (Northern Array)
- Observation time: 1.3 hours



Observable up to the distance of **7.17 Mpc**

Star formation rate of galaxies within D_{lim}

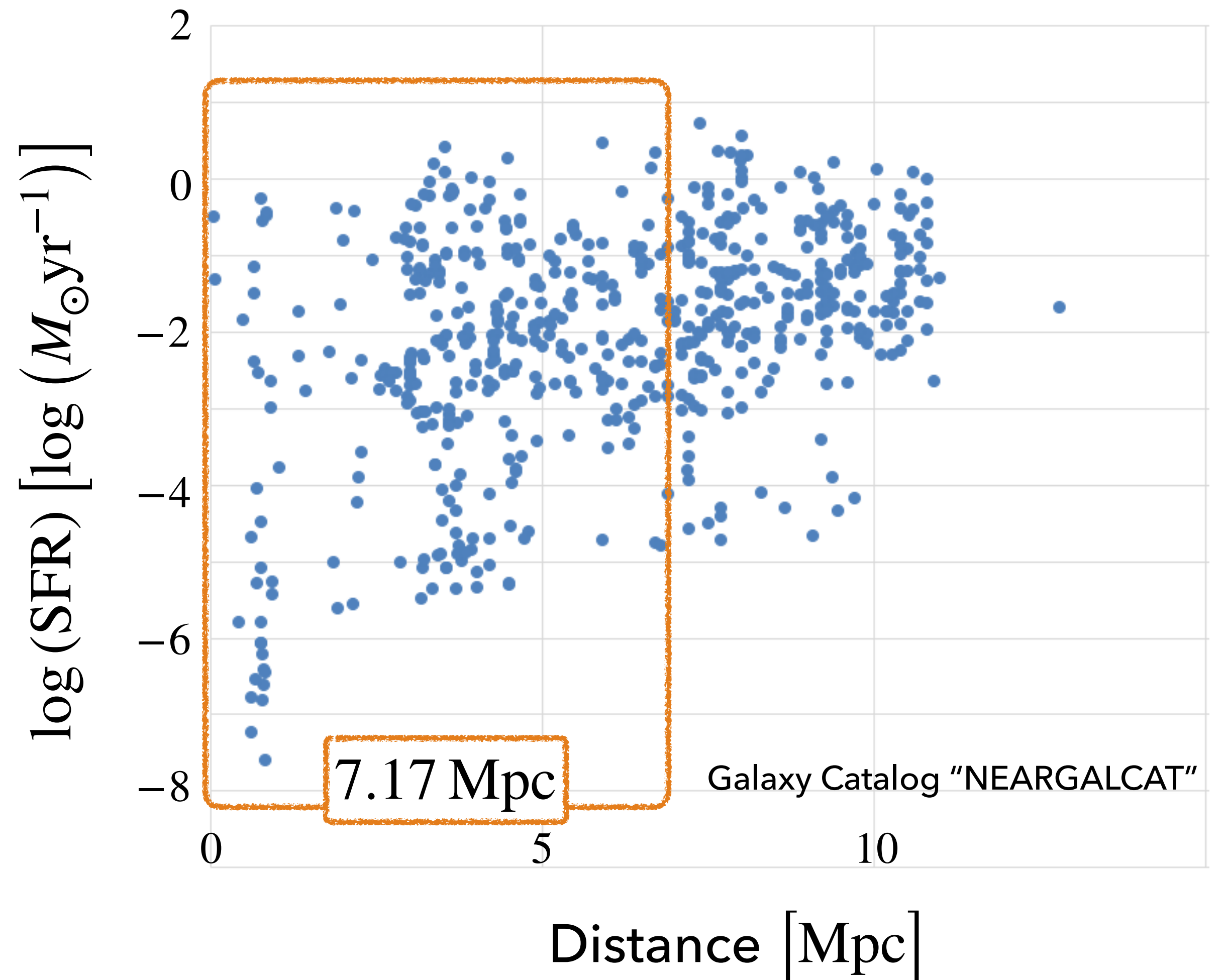


Assume that stars with $M > 8 M_{\odot}$ become core collapse SNe.

Detection frequency by CTA becomes 0.250 yr^{-1}

Once every 4 year!!

Distance to galaxy and star formation rate

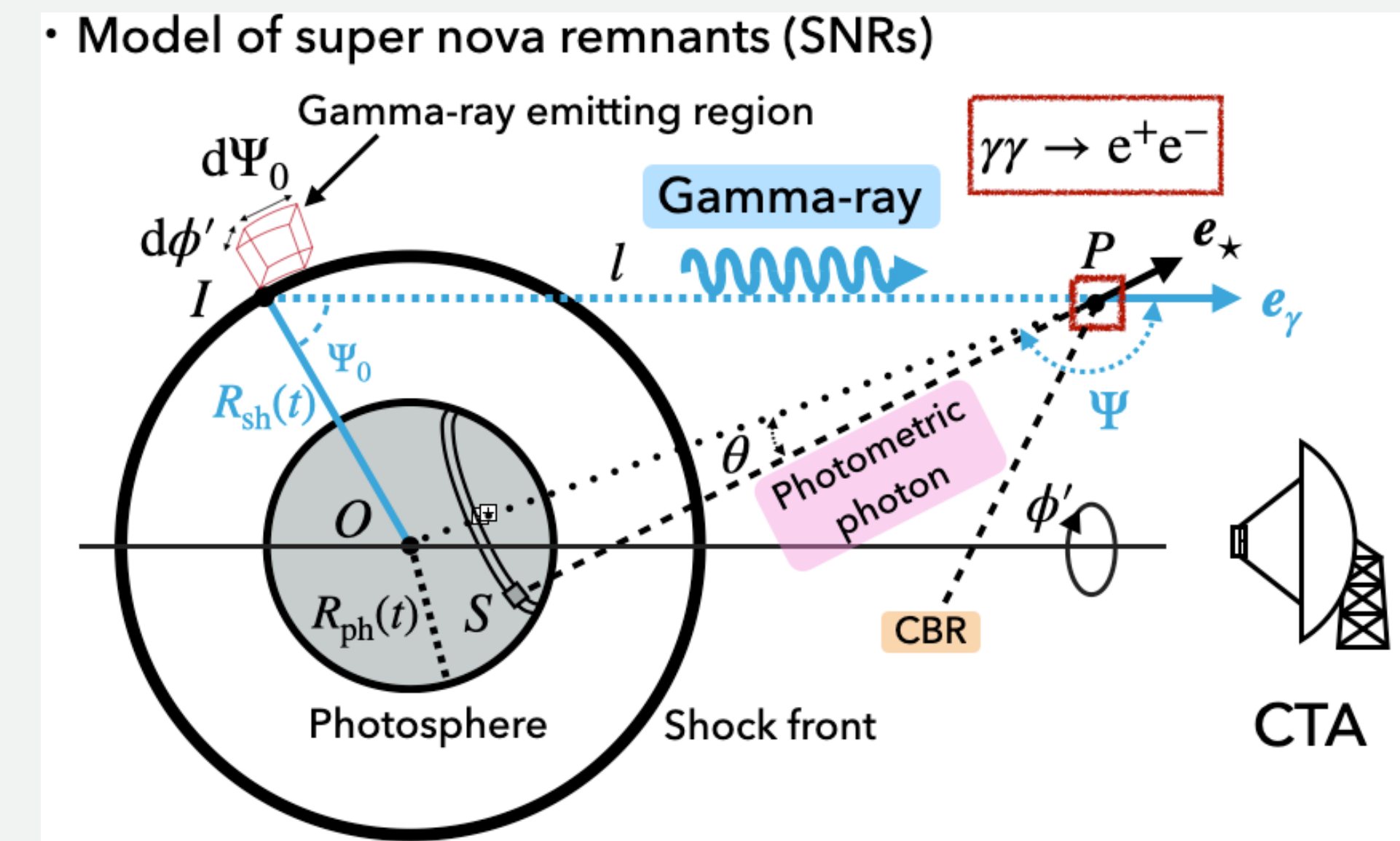


Summary

- ① We calculated the flux of 100TeV gamma-rays from the very early phase of a supernova remnant, taking into account magnetic field amplification by **non-resonant hybrid instability (or Bell instability)** and attenuation by **photosphere** and **cosmic background radiation**.

The gamma-ray flux is attenuated to $\sim 1/10$ by photosphere 14 days after the explosion.

It is further attenuated to $\sim 2/3$ by cosmic background radiation.



- ② Taking into account the the enhanced mass loss rate of the RSG immediately before the explosion, the flux increases by **4 orders** of magnitude compared to the estimation by the previous study (Christofari et al.2020).

mass loss rate of RSG	detection
Conventional model: $10^{-5} M_{\odot} \text{ yr}^{-1}$	×
Modern model: $10^{-3} M_{\odot} \text{ yr}^{-1}$	⊙

- ③ CTA can detect 100 TeV gamma-rays from very young supernova remnants **once per 4 years**.



Back-up

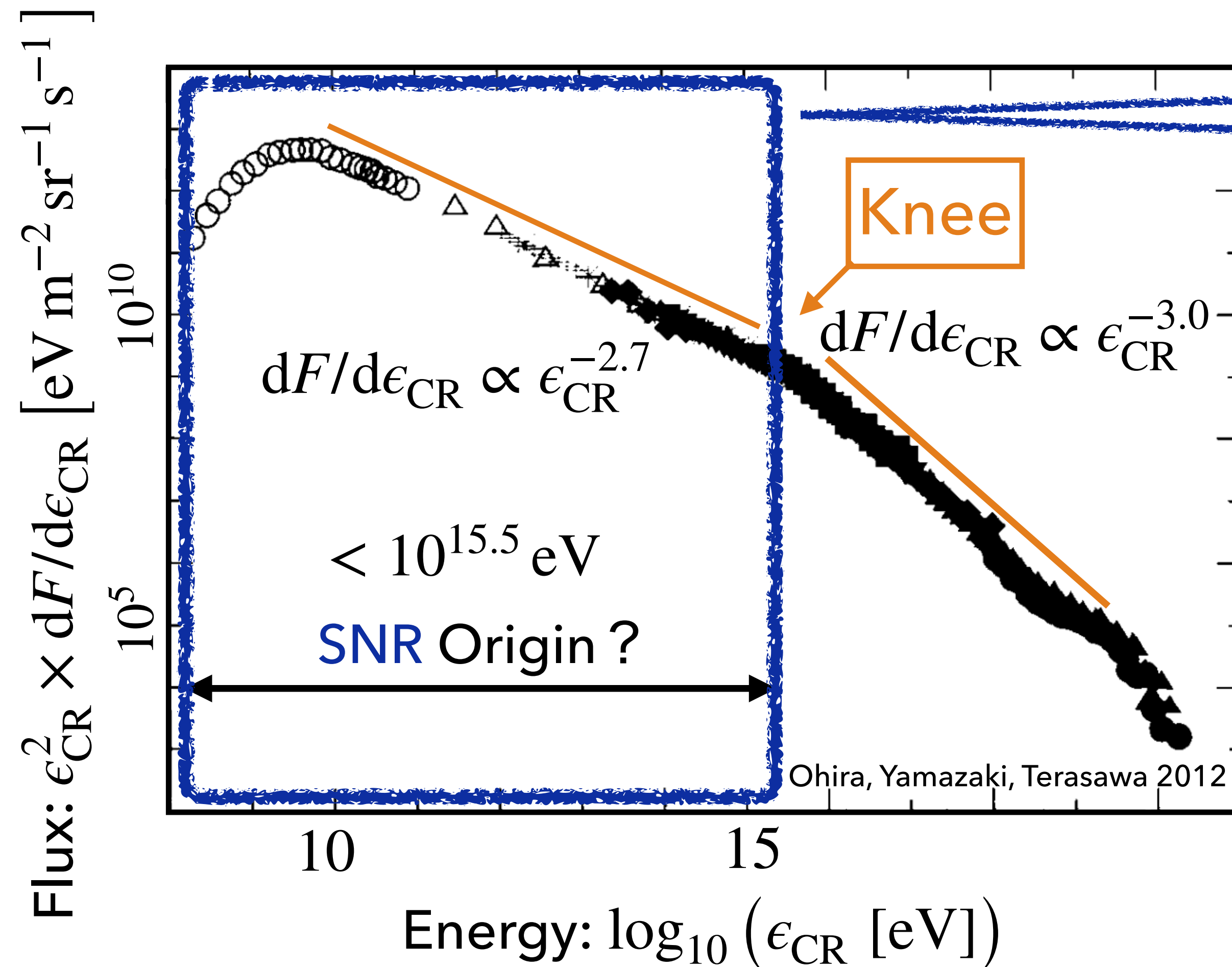


INTRODUCTION

Cosmic Rays

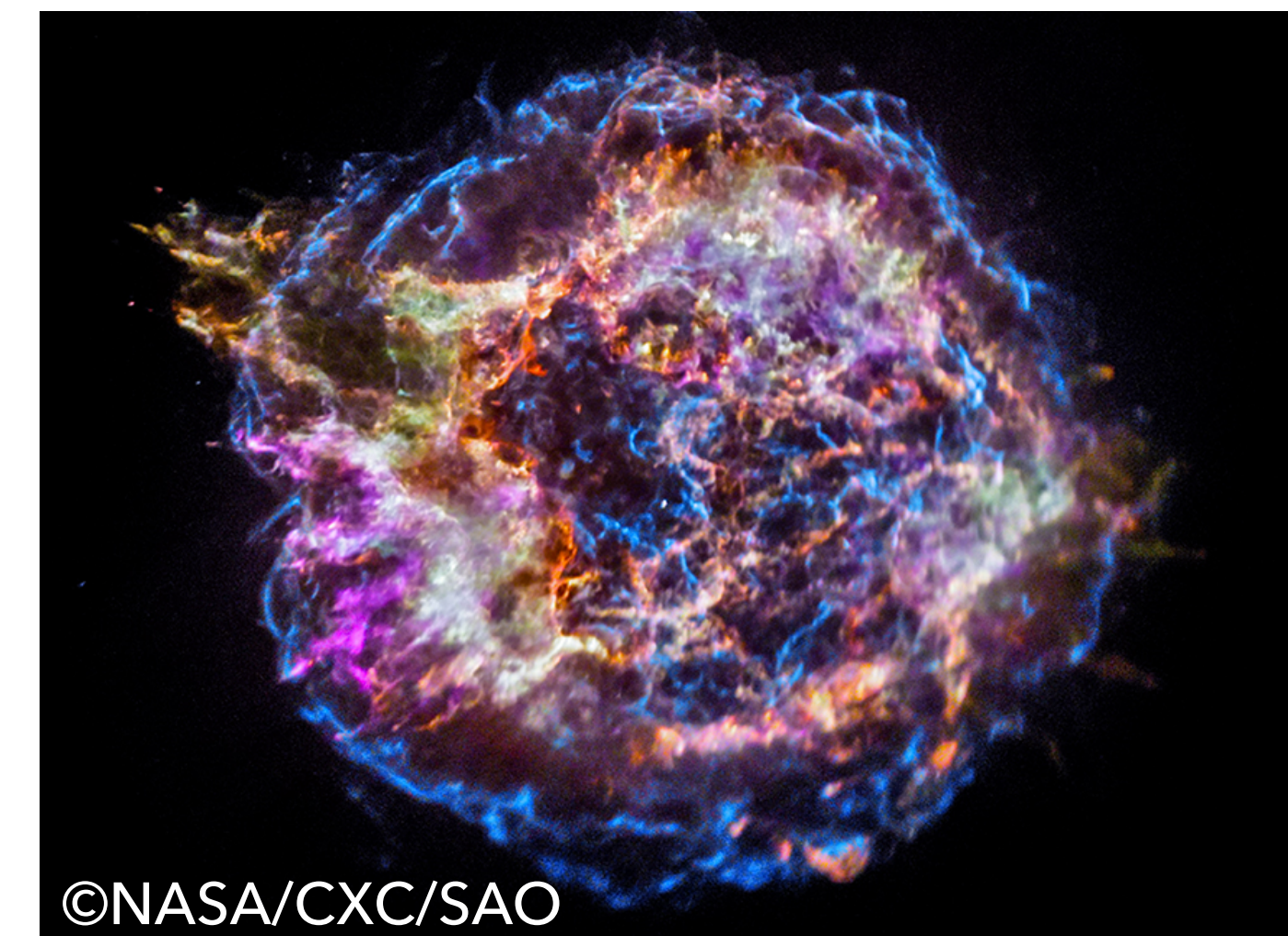
High energy particle that move through space

Energy spectrum of cosmic rays



- Power-law spectrum in energy
- The power exponent varies at $10^{15.5} \text{ eV}$; **Knee energy**.
- **Supernova remnants (SNRs)** are believed to be accelerators of CRs up to Knee energy.

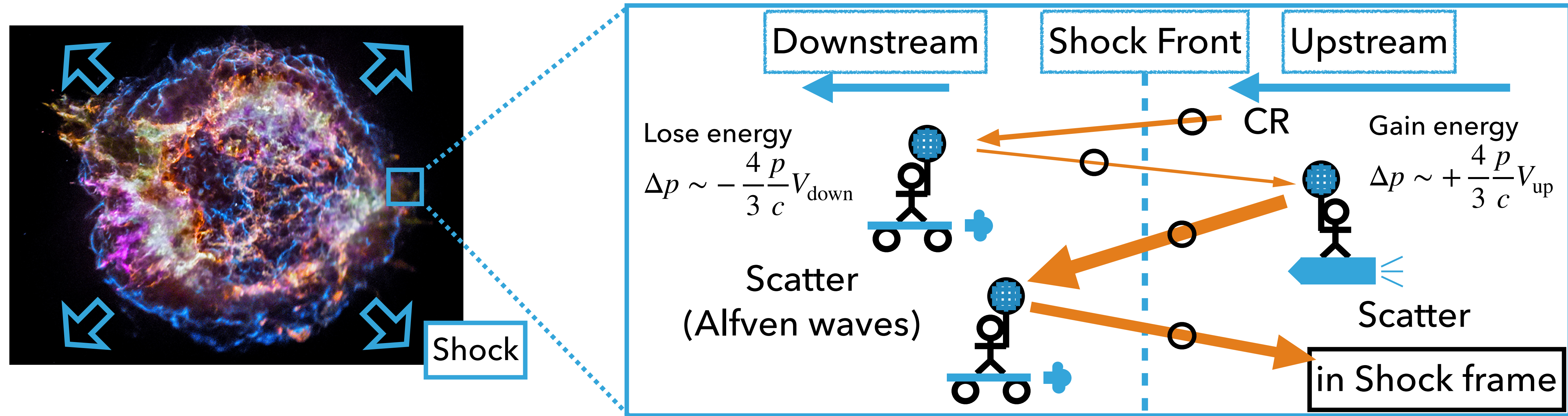
SNR Cassiopeia A



Chandra X-ray Observatory

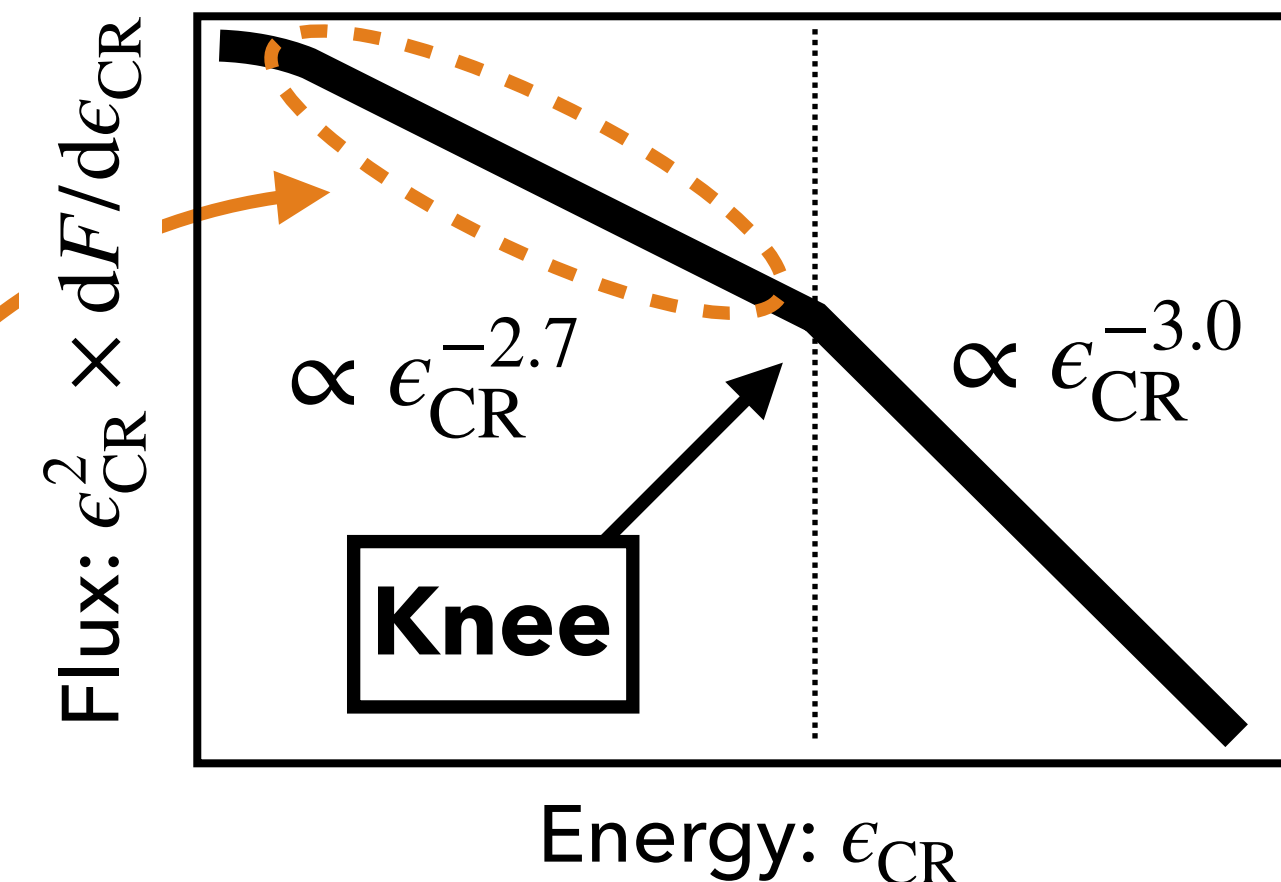
Fermi Acceleration

- SNR : Objects left after a supernova explosion



- ① CRs can be accelerated during "round-trip".
- ② Fermi Acceleration is a good theory to explain the origin of the "Power-law spectrum" and "Its exponent"

Energy spectrum of cosmic rays



Maximum Energy by Fermi Acceleration

- CRs' Maximum energy accelerated by Fermi Acceleration

$$E_{\max} \approx 3 \times 10^{13} \text{ eV} \left(\frac{V_{\text{sh}}}{10^4 \text{ km s}^{-1}} \right)^2 \left(\frac{B_{\text{ISM}}}{3 \mu \text{ G}} \right) \left(\frac{t_{\text{age}}}{200 \text{ yr}} \right)$$

$< 10^{15.5} \text{ eV}$ (knee energy)

V_{sh} : Shock speed

B_{ISM} : ISM magnetic field

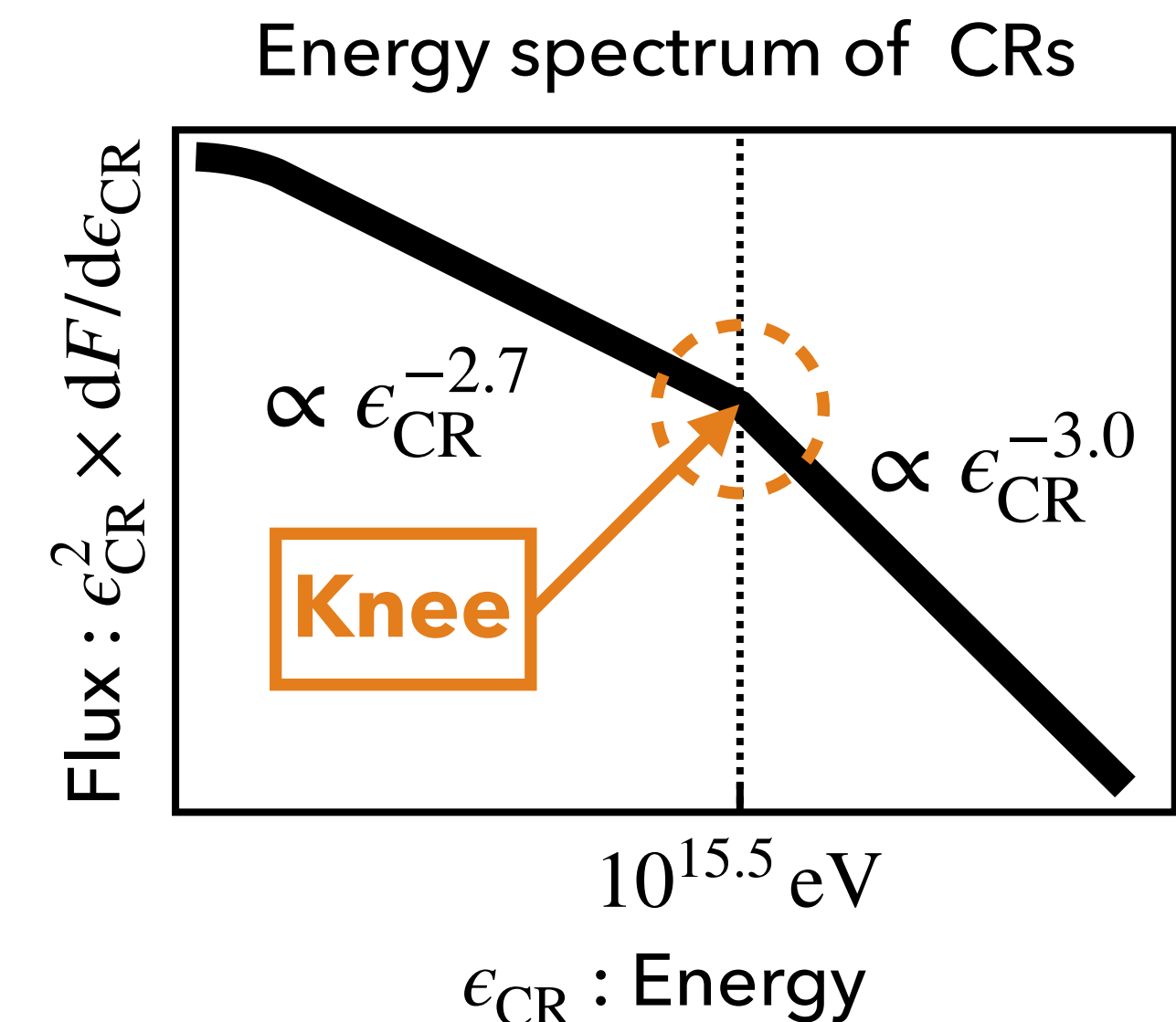
t_{age} : Age of SNR

CRs cannot reach the knee energy in typical magnetic field.

Magnetic field amplification is necessary.

Non-Resonant Hybrid (NRH) instability
(or Bell instability) was proposed.

Bell (2004)

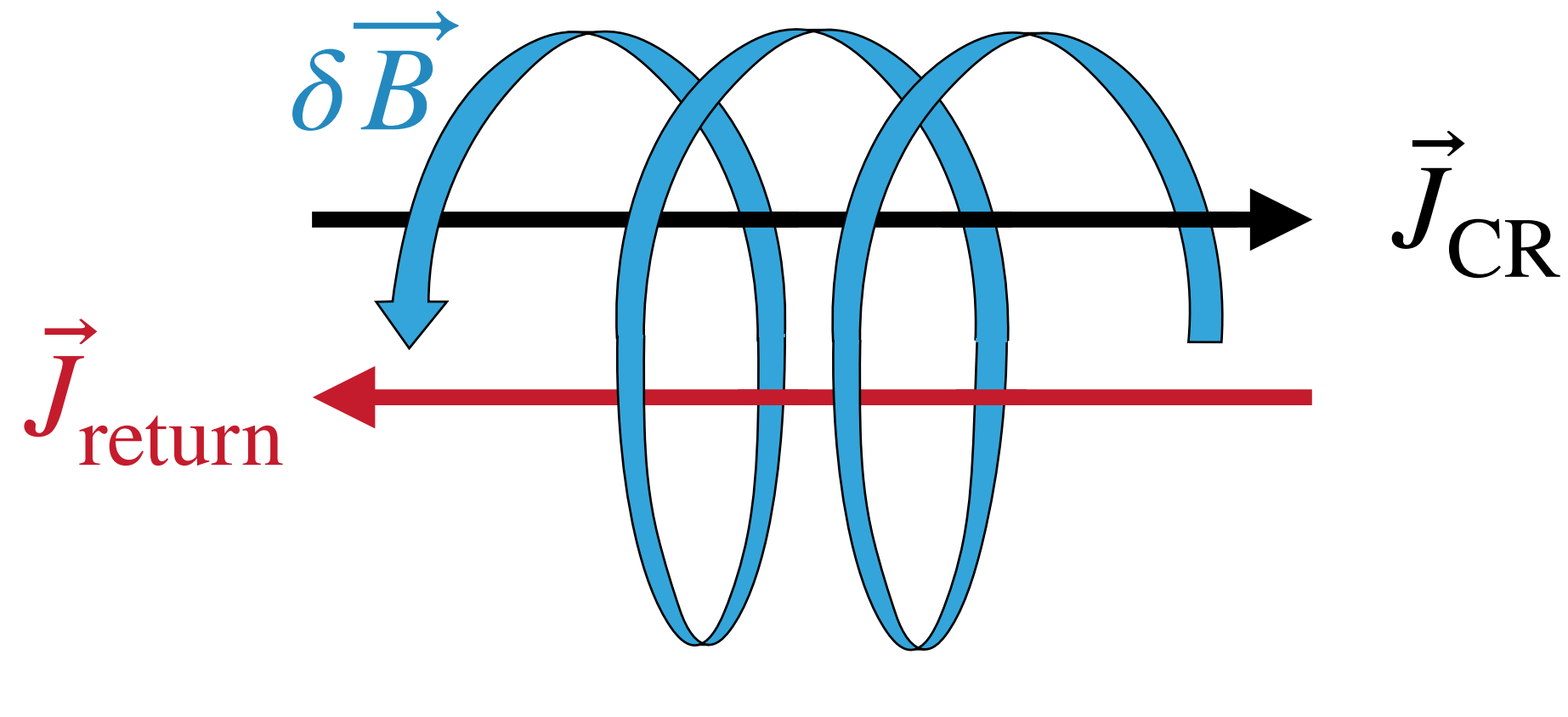


Non Resonant Hybrid (NRH) instability

STEP 1

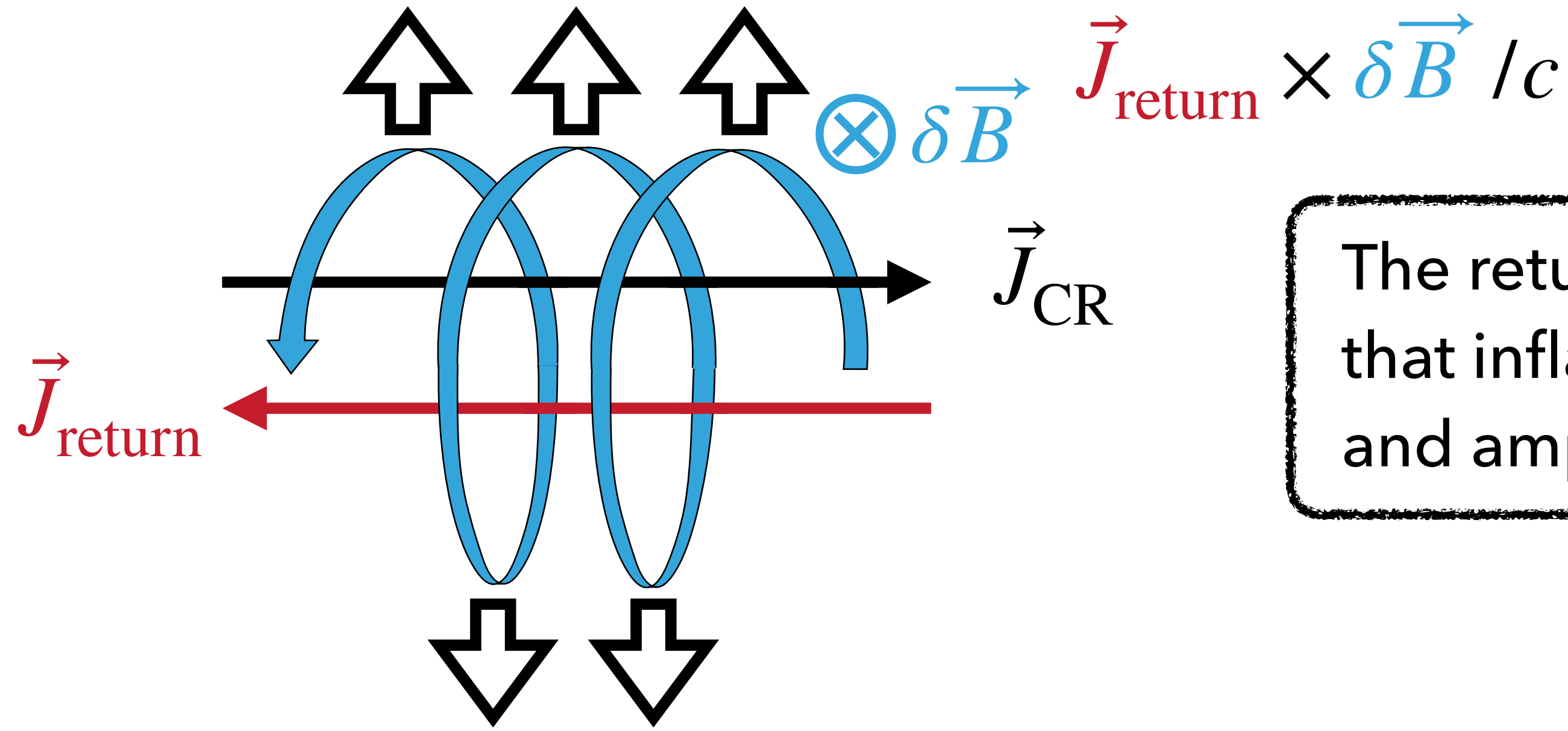
Shock Front

Upstream



When the motion of cosmic rays (protons) generates an electric current $\vec{J}_{CR}$, a return current (return current) $\vec{J}_{return}$ is generated to maintain electrical neutrality.

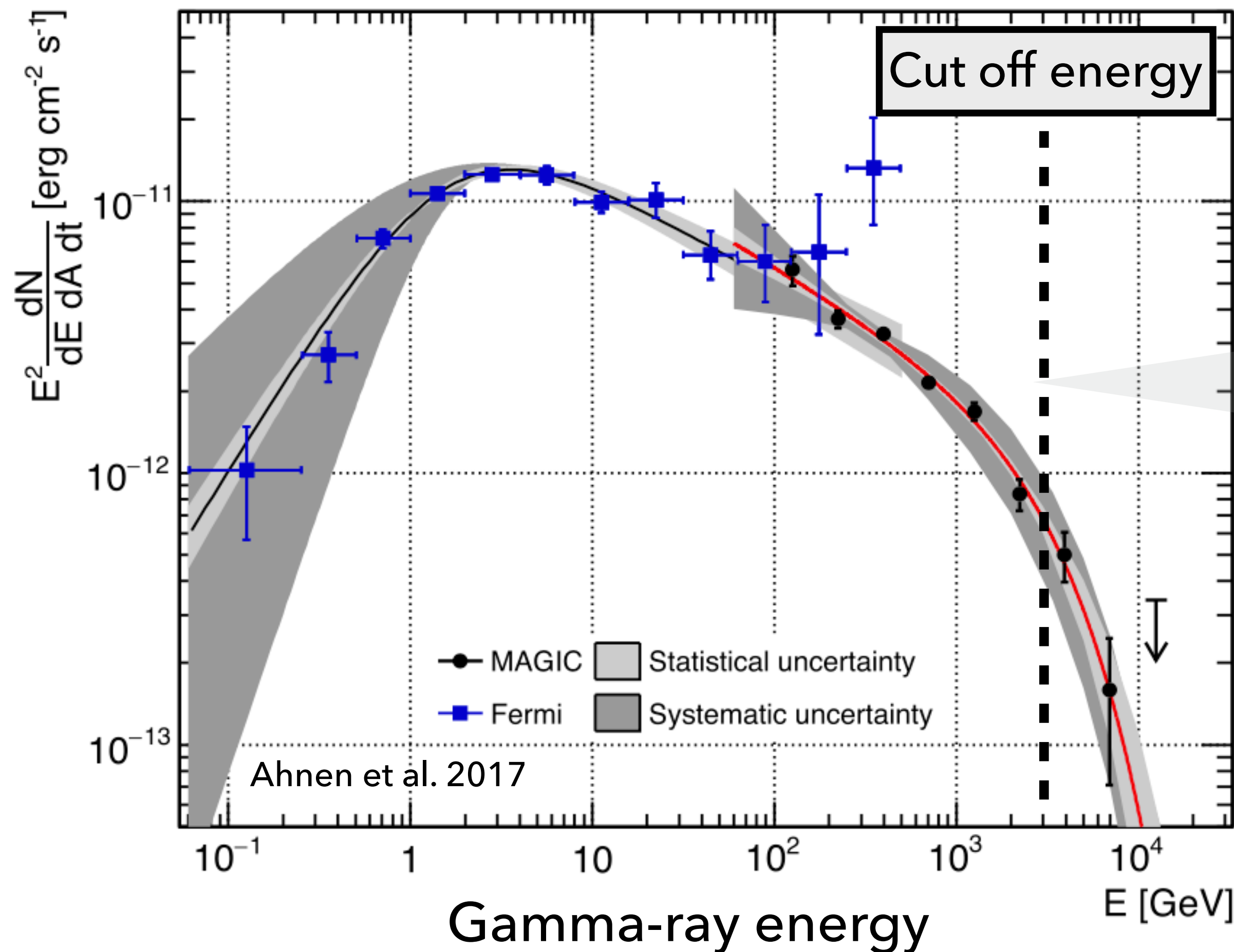
STEP 2



The return current induces Lorentz force that inflates magnetized fluid and amplifies the magnetic field.

Gamma-ray observations of SNRs

Gamma-ray energy spectrum of Cassiopeia A



- SNR Cas A

Detector: MAGIC & *Fermi*

Age: ~ 300 yr :
late free-expansion phase or early Sedov-phase

Cut off: 3.5 TeV
< 100 TeV (Derived from Knee energy CR)

~ Other gamma-ray observations ~

- SNR Tycho

Age: ~ 440 yr
Cut-off: 6 – 7 TeV

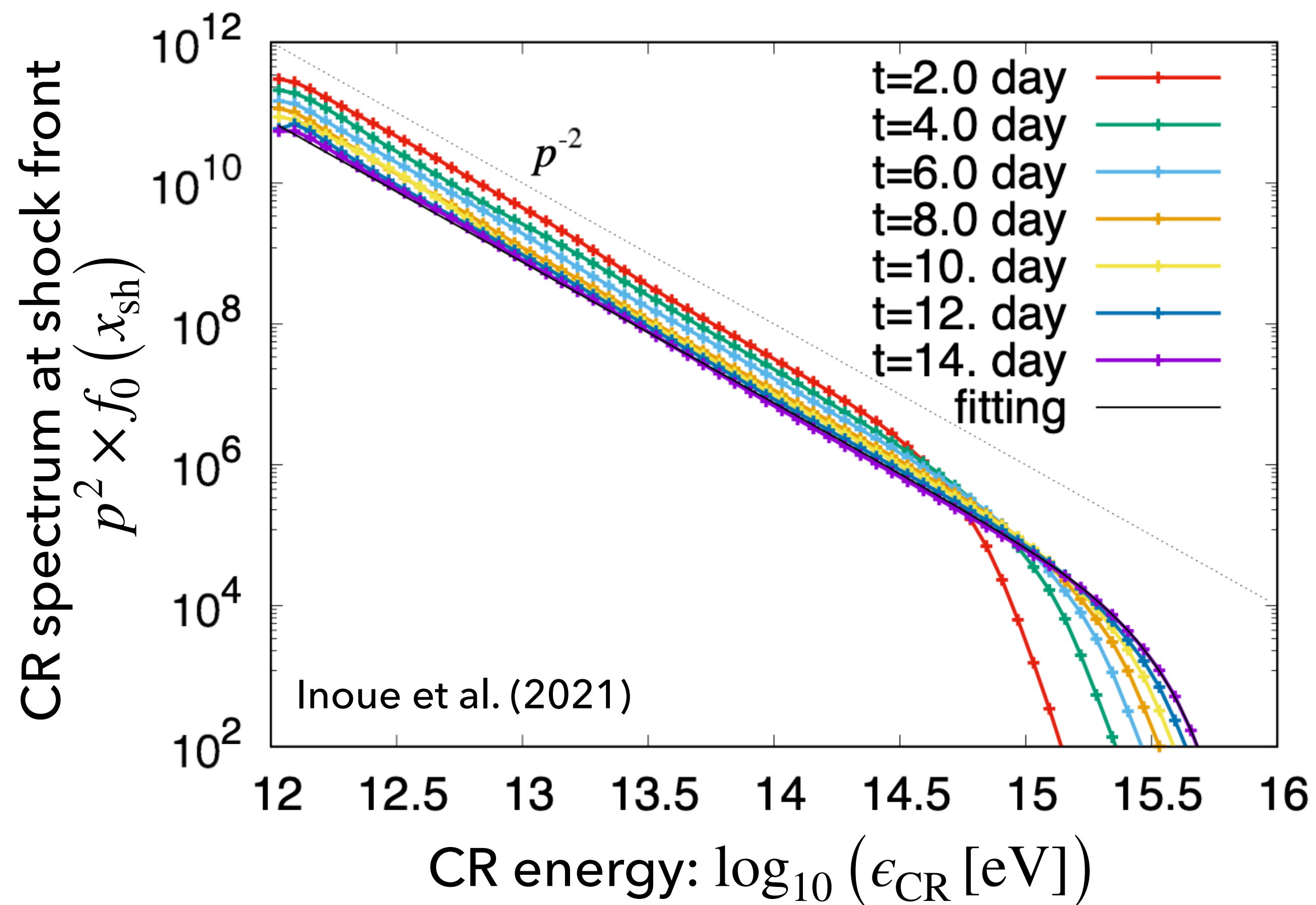
- SNR W49B

Age: $\sim 1000 - 4000$ yr
Cut-off: $8.4 \text{ GeV} \pm 2.2 \text{ GeV}$

Observations suggest that young SNRs ($t_{\text{age}} \sim 10^2 - 10^3$ yr) are not PeVatron.

Simulation of the Fermi Acceleration with NRH instability

Energy spectrum of protons accelerated at shock front generated by the simulation



Inoue et al. (2021) performed direct numerical simulations of the Fermi acceleration with magnetic field amplification by the **Non-Resonant Hybrid (NRH) instability** (or **Bell instability**).

~ Result ~

- Age of SNR:

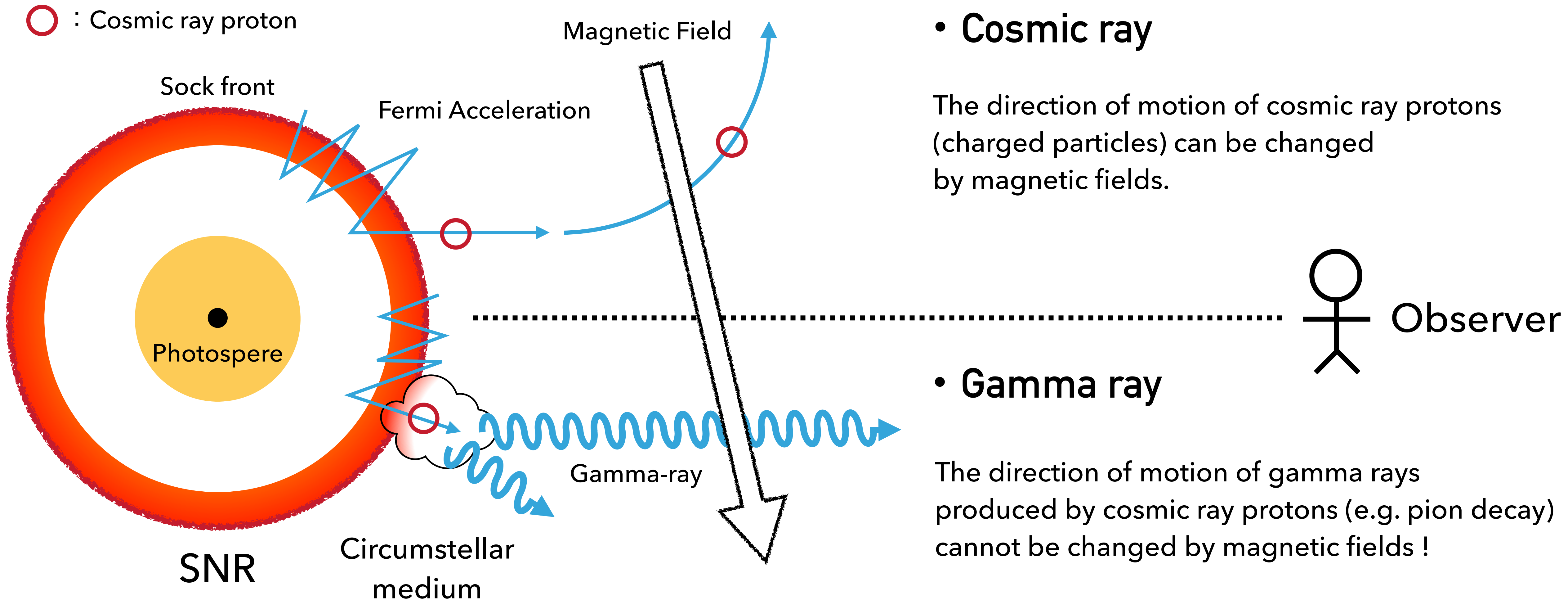
Early phase of supernova expansion (~ 14 days)

- Circumstellar medium:

Dense gas created by red supergiant (progenitors of type-II SN) wind ($\sim 10^{-3} M_{\odot}$)

They showed that CRs can be accelerated up to knee energy $10^{15.5}$ eV in very young SNRs.

The usefulness of focusing on gamma rays

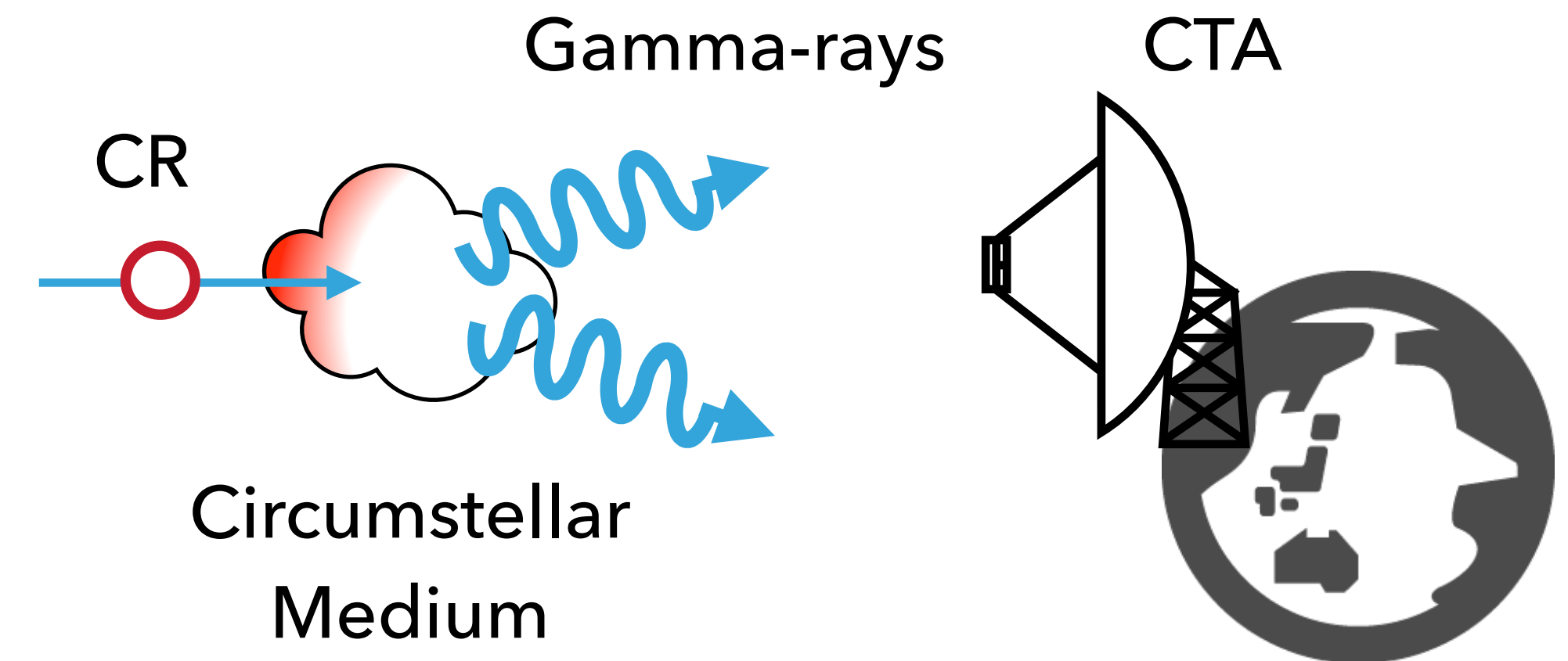


The direction of gamma rays provides information on the direction of the source of CR protons.

Purpose of this research

**Validate the numerical simulation results
of CR acceleration performed in Inoue+21**

- ① We focus on **gamma-rays** produced by collisions between CR and circumstellar medium.
- ② We calculate the evolution of the gamma-ray flux based on the **time evolution of the CR distribution performed in Inoue+21**.
- ③ We verify the **possibility of observing gamma rays** generated in the SNR immediately after the explosion with "**C**herenkov **T**elescope **A**rray".

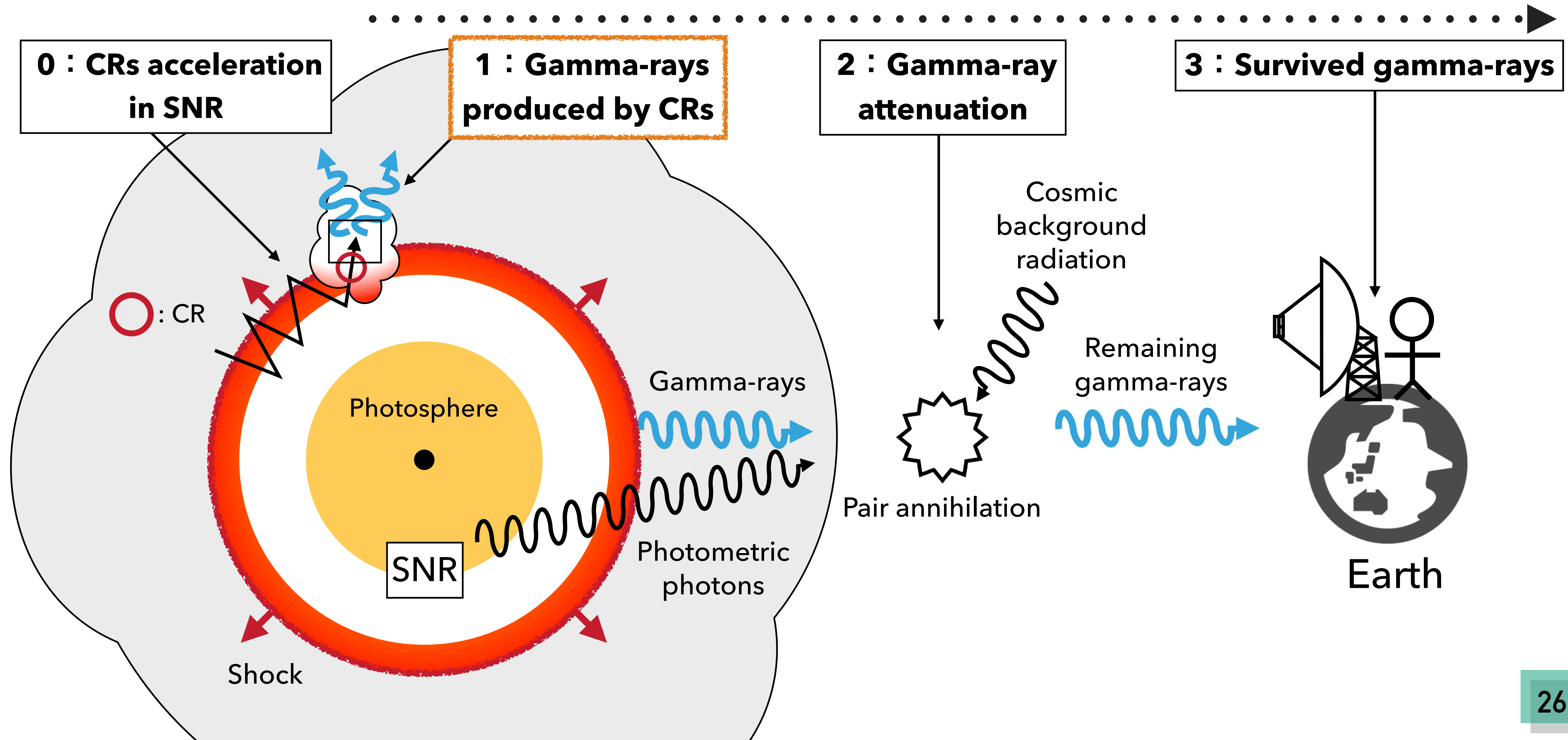




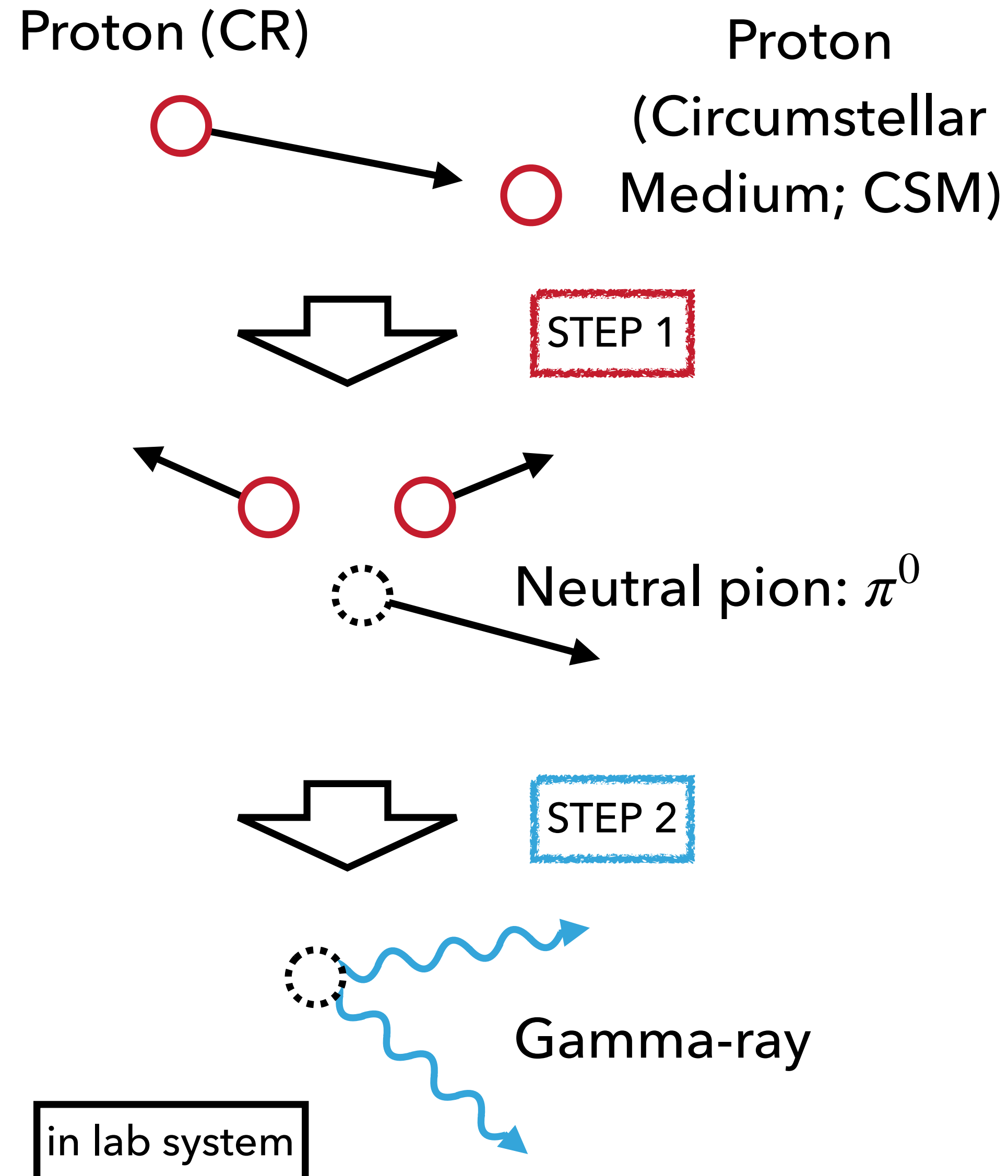
METHOD

Overview: Observational prediction of gamma-rays emitted from SNR

From gamma-ray generation to their observation (This research)



Gamma-rays produced by CRs



STEP 1 : Generation of neutral pion: π^0



Threshold: (Kinetic energy of CR proton) $\gtrsim 1.2 \text{ GeV}$

in lab system ($p(\text{CSM})$ static system)

STEP 2 : Decay of neutral pion

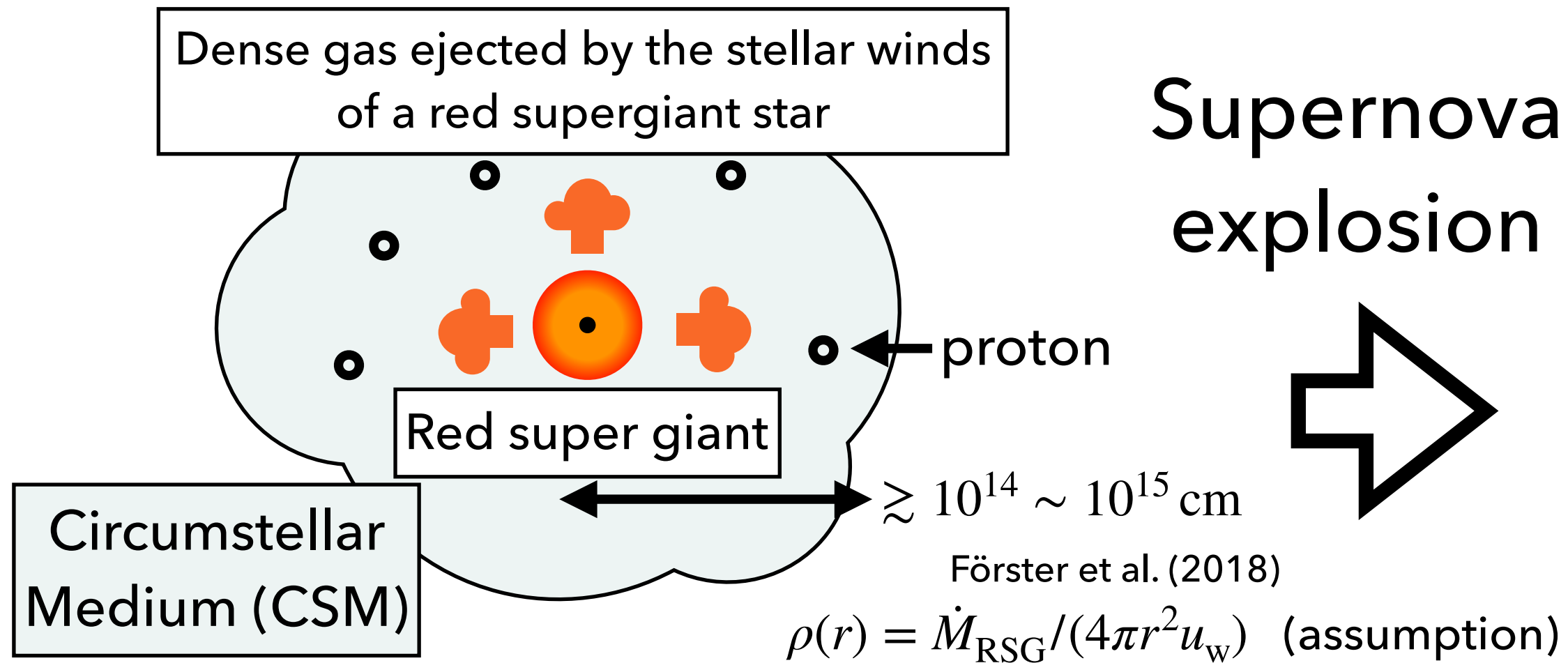
$$\pi^0 \rightarrow 2\gamma$$

Gamma-rays with energy above $\frac{1}{2}m_{\pi^0}c^2 \approx 67.5 \text{ MeV}$ are emitted.

in π^0 static system

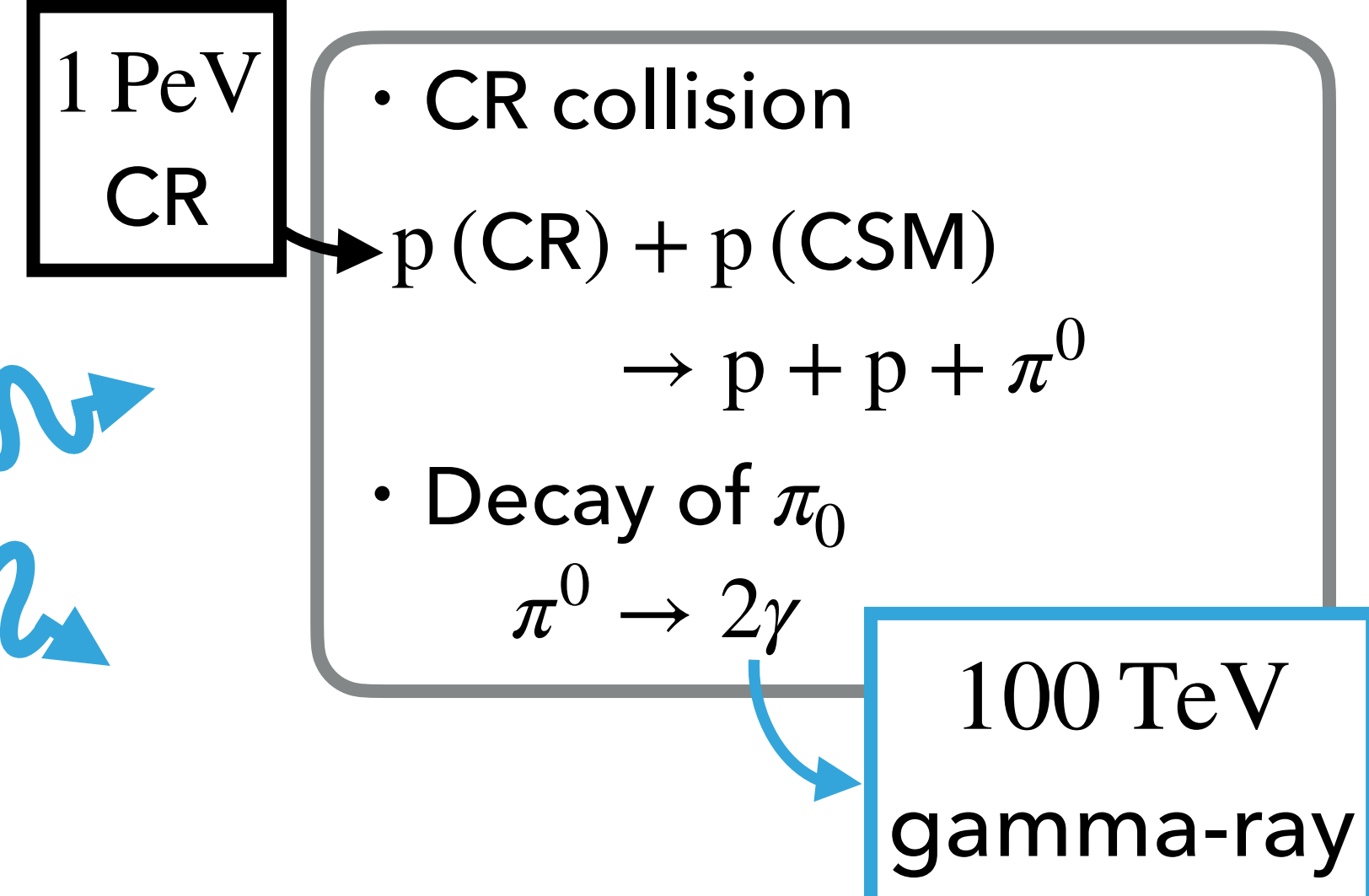
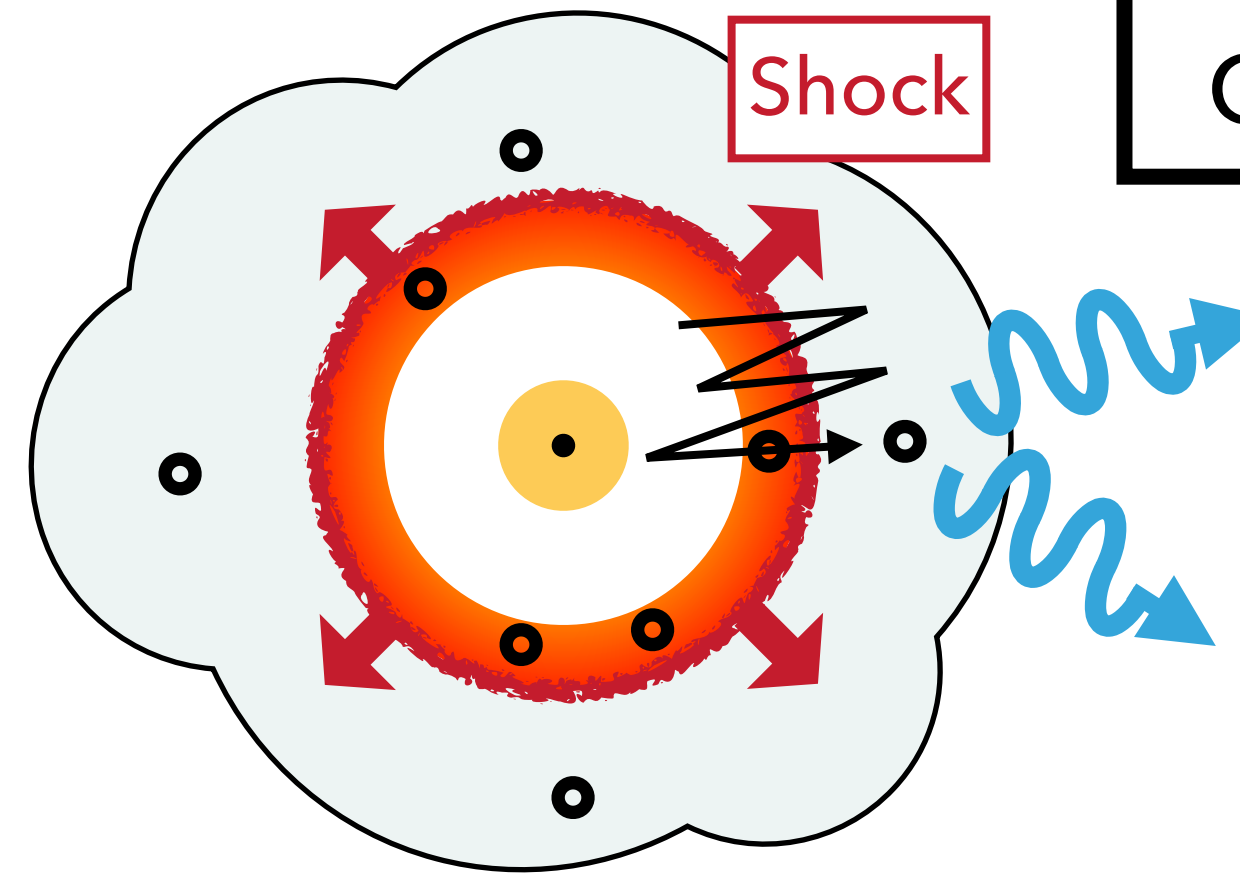
Gamma-rays produced by CRs

• Before SN explosion



• After SN explosion

Supernova explosion



• Unabsorbed gamma-ray flux

$\propto$ (Number of cosmic rays accelerated) $\propto$ (Number of protons collided)

$$F_{\gamma, \text{unabs}}(> 100 \text{ TeV}) \approx 2 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \left(\frac{\eta_{\text{inj}}^p}{10^{-4}} \right) \left(\frac{\dot{M}_{\text{RSG}}}{10^{-3} M_{\odot} / \text{yr}} \right) \left(\frac{u_w}{10 \text{ km/s}} \right)^{-1} \left(\frac{\dot{M}_{\text{RSG}}}{10^{-3} M_{\odot} / \text{yr}} \right) \left(\frac{u_w}{10 \text{ km/s}} \right)^{-1} \\ \times \left(\frac{D}{1 \text{ Mpc}} \right)^{-2} \left(\frac{t}{\text{days}} \right)^{-1} \quad (\text{Tatischeff 2009})$$

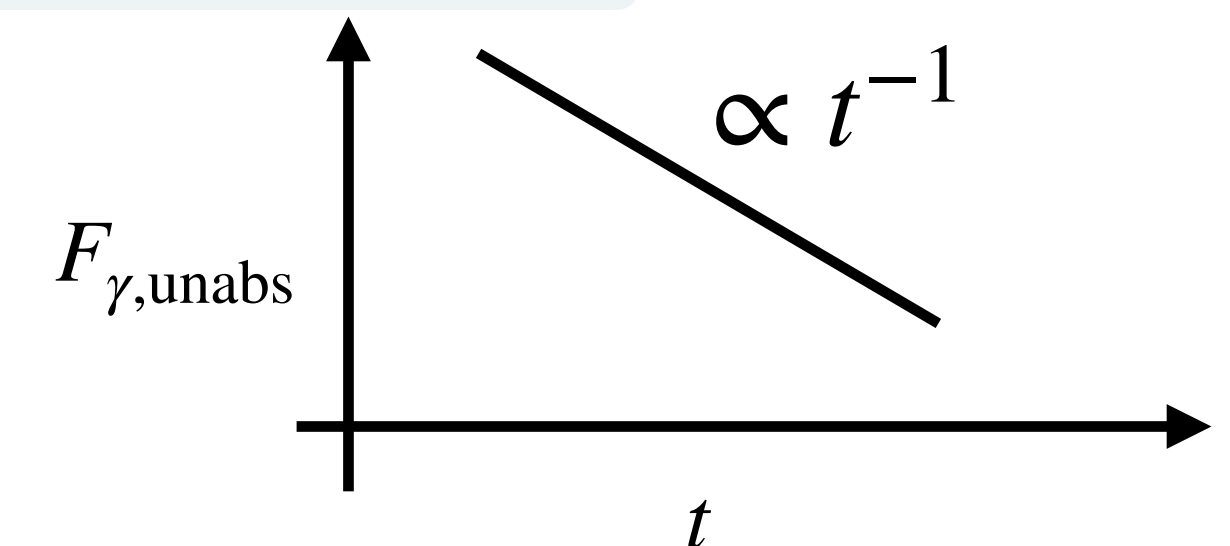
η_{inj}^p : CR injection rate

$\dot{M}_{\text{RSG}}$: Mass loss rate of RSG

D : Distance to the target object

u_w : Stellar wind velocity of RSG

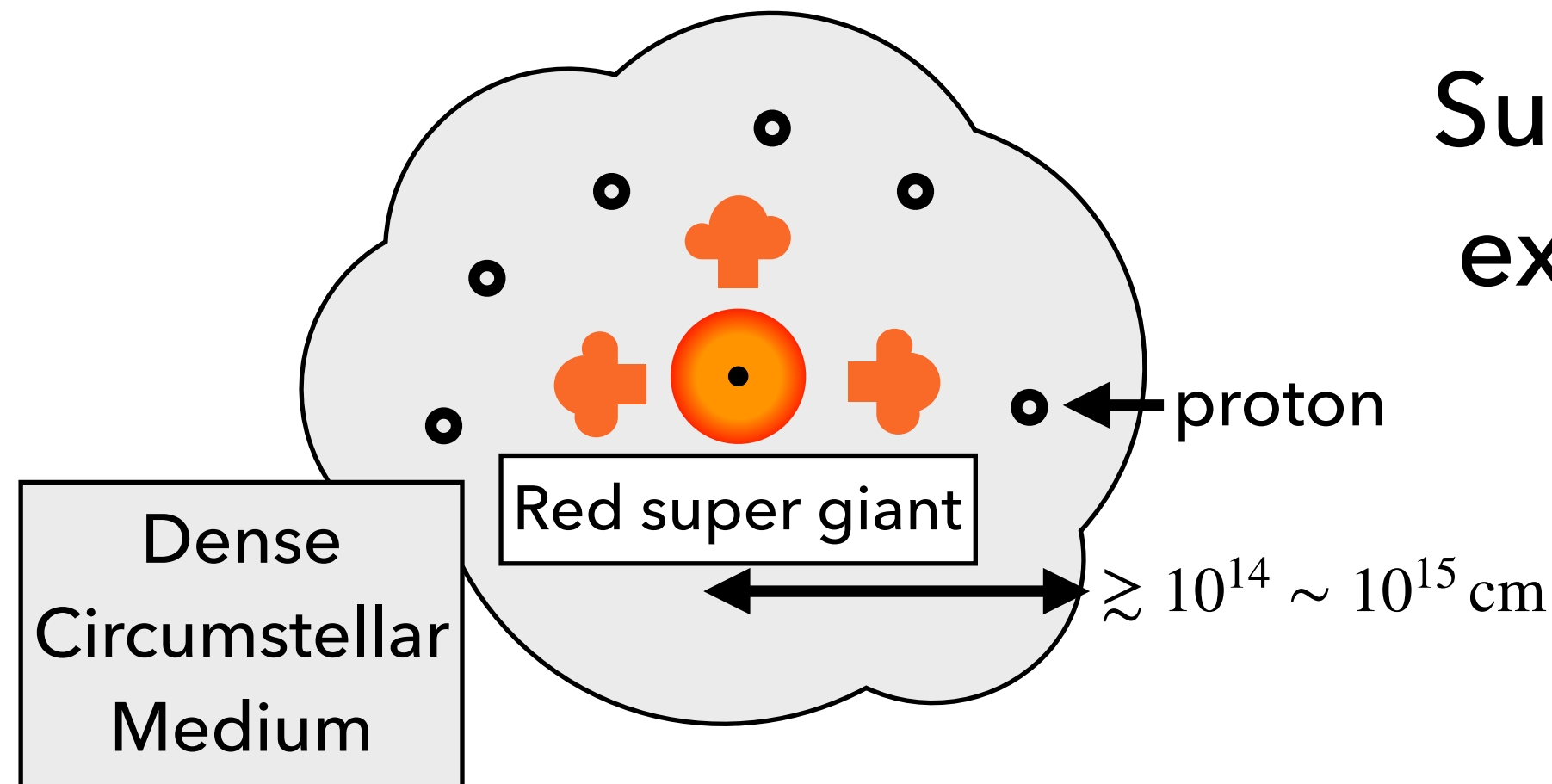
t : Time after SN explosion



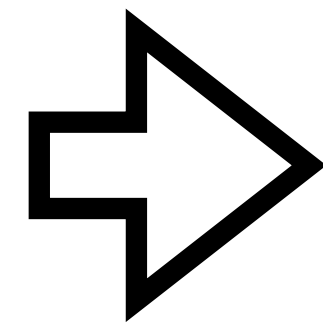
Gamma-ray fluxes emitted from CRs can be calculated.

Gamma-rays produced by CRs

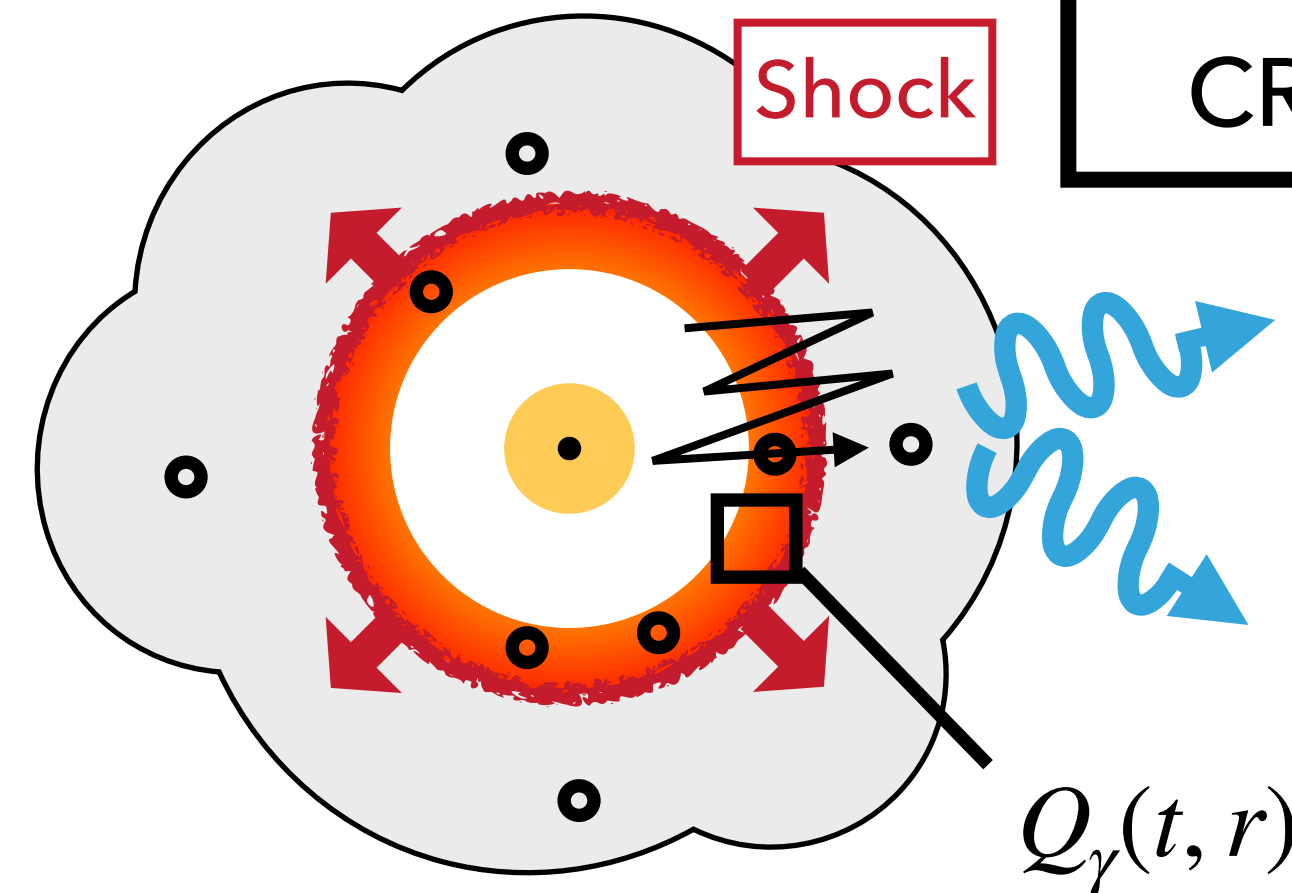
- Before SN explosion



Supernova explosion



- After SN explosion



- CR collision
 $p(\text{CR}) + p(\text{CSM}) \rightarrow p + p + \pi^0$
- Decay of π^0
 $\pi^0 \rightarrow 2\gamma$

100 TeV gamma-ray

- Intrinsic gamma-ray flux

$$F_{\gamma, \text{intr}}(t, r) = \frac{\int_{\text{shell}} Q_\gamma(t, r) d^3r}{4\pi D^2}$$

$$Q_\gamma(t, r) = q_\gamma n(t, r) E_{\text{CR}}(t, r) [\text{cm}^{-3} \text{s}^{-1}]$$

Q_γ : Emissivity of gamma-ray radiation from shocked CSM

t : Time after core collapse

D : Distance to the target object

- $q_\gamma(E_\gamma) [\text{s}^{-1} \text{erg}^{-1} \text{cm}^3]$: γ -ray emissivity normalized to the CR energy density (cf. Drury + 94)

$E_\gamma [\text{eV}]$: γ -ray energy (where $E_\gamma \geq 100 \text{ TeV}$)

- $n(r) [\text{cm}^{-3}]$: Number density of CSM

Inoue et al. (2021)

- $E_{\text{CR}}(r) [\text{erg cm}^{-3}]$: CR energy density

$$E_{\text{CR}}(r) = \int 4\pi p^2 f_0(r, p) pc dp$$

$f_0(r, p) [\text{cm}^{-6} \text{g}^{-3} \text{s}^3]$: CR distribution function

Inoue et al. (2021)

Gamma-ray fluxes emitted from CRs can be calculated.

未吸収のガンマ線 $F_{\gamma, \text{unabs}}$ ①

- ・ 未吸収のガンマ線フラックス

$$F_{\gamma, \text{unabs}}(> 1 \text{ TeV}) \approx 2 \times 10^{-12} \left(\frac{\eta_{\text{inj}}^p}{10^{-4}} \right) \left(\frac{D}{3.63 \text{ Mpc}} \right)^{-2} \left(\frac{\dot{M}_{\text{RSG}}}{3.8 \times 10^{-5} M_{\odot}/\text{yr}} \right)^2 \left(\frac{u_w}{10 \text{ km/s}} \right)^{-2} \left(\frac{t}{\text{days}} \right)^{-1} \text{ cm}^{-2} \text{ s}^{-1} \quad (\text{Tatischeff 2009})$$

η_{inj}^p : 宇宙線陽子の注入率 D : 超新星残骸と地球までの距離 u_w : 赤色超巨星の星風の速さ

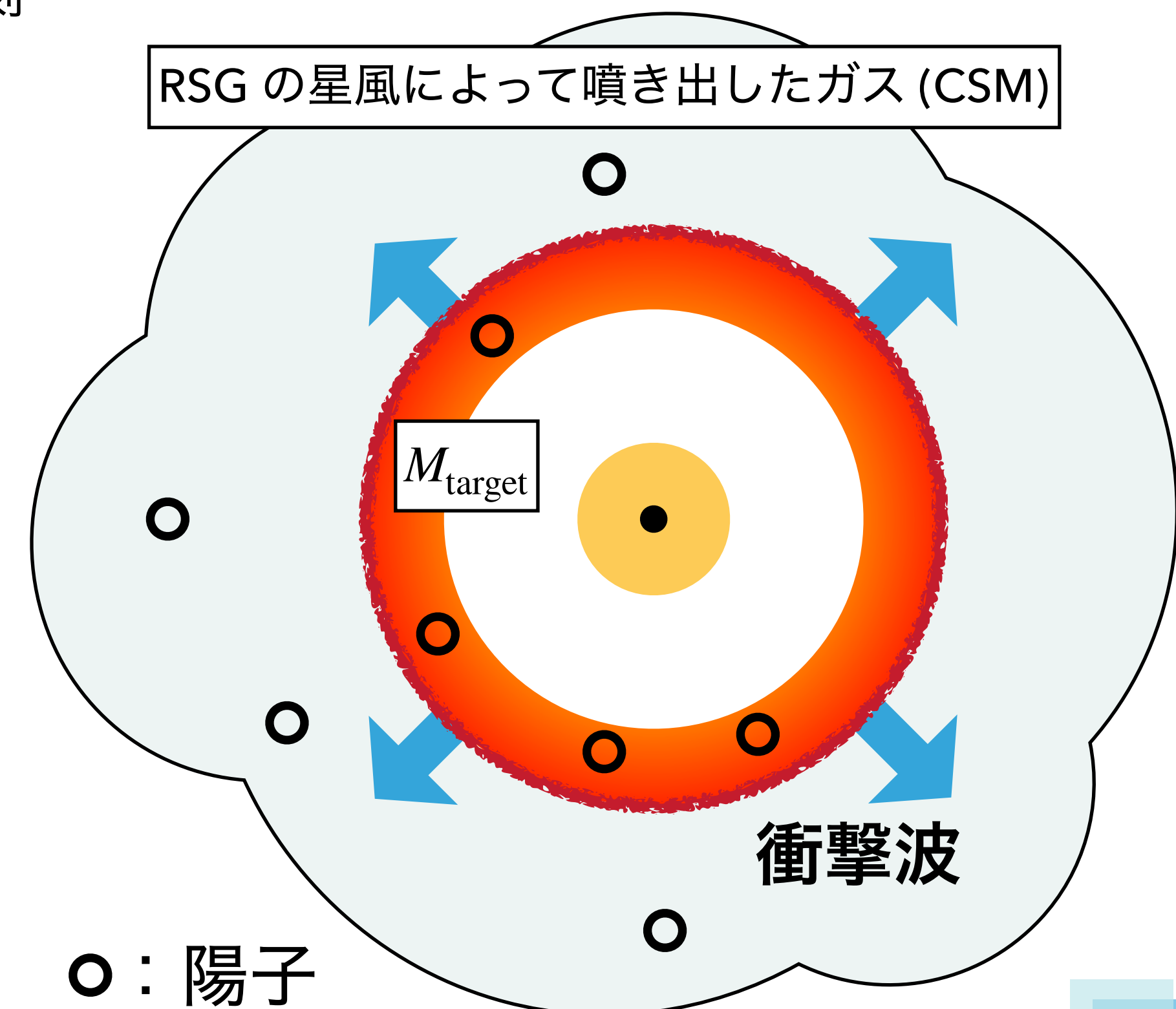
$\dot{M}_{\text{RSG}}$: 赤色超巨星の質量損失率 t : SN 爆発後からの経過時刻

$$F(> 1 \text{ TeV}) = \frac{q_{\gamma}(> 1 \text{ TeV}) E_{\text{CR}} M_{\text{target}} / \mu}{4\pi D^2}$$

$q_{\gamma}(> 1 \text{ TeV}) = 10^{-17} \text{ photon s}^{-1} \text{ erg}^{-1} \text{ cm}^3$: ガンマ線の放射効率 (実験値) (Drury et al. 1994)

$E_{\text{CR}} \left[\frac{\text{erg}}{\text{cm}^3} \right]$: 衝撃波下流での宇宙線陽子のエネルギー密度

$M_{\text{target}} [\text{g}]$: 衝撃波を受けた陽子の質量 $\mu [\text{g}]$: 平均分子質量



未吸収のガンマ線 $F_{\gamma, \text{unabs}}$ ②

- 未吸収のガンマ線フラックス

$$F_{\gamma, \text{unabs}}(> 1 \text{ TeV}) \approx 2 \times 10^{-12} \left(\frac{\eta_{\text{inj}}^{\text{p}}}{10^{-4}} \right) \left(\frac{D}{3.63 \text{ Mpc}} \right)^{-2} \left(\frac{\dot{M}_{\text{RSG}}}{3.8 \times 10^{-5} M_{\odot}/\text{yr}} \right)^2 \left(\frac{u_{\text{w}}}{10 \text{ km/s}} \right)^{-2} \left(\frac{t}{\text{days}} \right)^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

$$F(> 1 \text{ TeV}) = \frac{q_{\gamma}(> 1 \text{ TeV}) E_{\text{CR}} M_{\text{target}} / \mu}{4\pi D^2}$$

- ガンマ線の放射効率 (ガンマ線のエネルギーに依存) (実験値)

$$q_{\gamma}(> 1 \text{ TeV}) = 10^{-17} \text{ photon s}^{-1} \text{ erg}^{-1} \text{ cm}^3$$

$$\rho(r) = \dot{M}_{\text{RSG}} / (4\pi r^2 u_{\text{w}}) \quad (\text{仮定})$$

- 衝撃波を受けた陽子の質量 (CR が衝突する対象)

$$M_{\text{target}}(t) = \int_0^t dt' 4\pi R_{\text{sh}}^2(t') \rho(R_{\text{sh}}(t')) V_{\text{sh}}(t')$$

- 平均分子質量

$$\mu [g]$$

- 衝撃波下流での宇宙線陽子のエネルギー密度

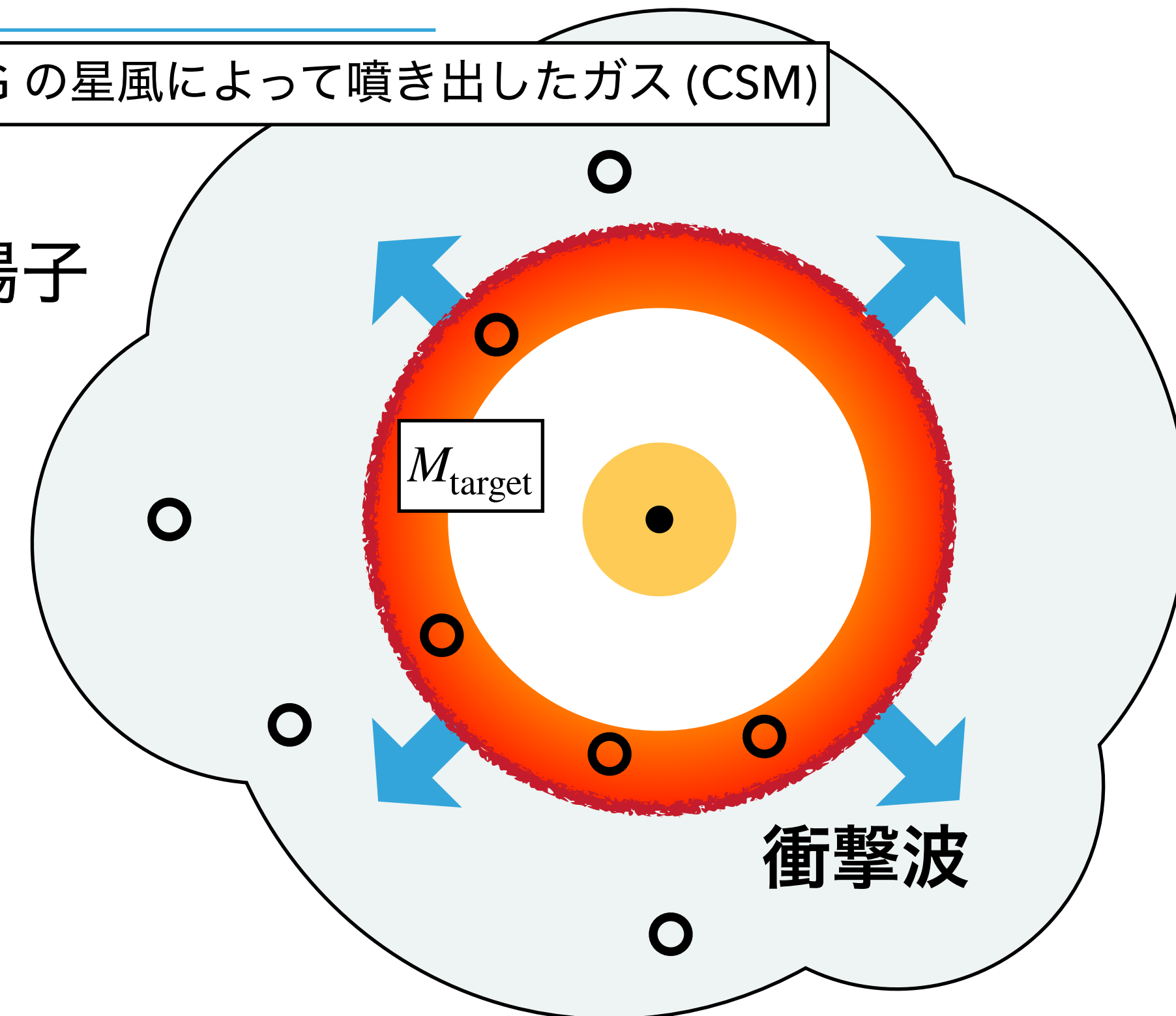
$$E_{\text{CR}} = \frac{\phi}{V(t)} \int_0^t dt' 4\pi R_{\text{sh}}^2(t') \frac{1}{2} \rho(R_{\text{sh}}(t')) V_{\text{sh}}^3(t')$$

- 下流での宇宙線陽子の占める体積

$$V(t) = f \frac{4\pi}{3} R_{\text{sh}}^3, \quad f: \text{filling factor}$$

RSG の星風によって噴き出したガス (CSM)

○ : 陽子



- エネルギー効率

ϕ : 運動エネルギーの内, CR へ与えられる割合

未吸収のガンマ線 $F_{\gamma, \text{unabs}} \propto t^{-1}$

$$F(> 1 \text{ TeV}) = \frac{q_{\gamma}(> 1 \text{ TeV}) E_{\text{CR}} M_{\text{target}} / \mu}{4\pi D^2}$$

- ・ 衝撃波を受けた陽子の質量 (CR が衝突する対象)

$$\begin{aligned} M_{\text{target}}(t) &= \int_0^t dt' 4\pi R_{\text{sh}}(t')^2 \rho(R_{\text{sh}}(t')) V_{\text{sh}}(t') \\ &= \int_0^t dt' 4\pi V_{\text{sh}}^2 t'^2 \times \frac{\dot{M}_{\text{RSG}}}{4\pi V_{\text{sh}}^2 t'^2 u_w} \times V_{\text{sh}} \end{aligned}$$

) t について陽に表す

$$\propto t$$

- ・ 衝撃波下流での宇宙線陽子のエネルギー密度

$$\begin{aligned} E_{\text{CR}} &= \frac{\phi}{V(t)} \int_0^t dt' 4\pi R_{\text{sh}}^2(t') \frac{1}{2} \rho(R_{\text{sh}}(t')) V_{\text{sh}}^3(t') \\ &= \frac{\phi}{f \frac{4\pi}{3} V_{\text{sh}}^3 t^3} \int_0^t dt' 4\pi V_{\text{sh}}^2 t'^2 \times \frac{1}{2} \frac{\dot{M}_{\text{RSG}}}{4\pi V_{\text{sh}}^2 t'^2 u_w} \times V_{\text{sh}}^3 \end{aligned}$$

) t について陽に表す

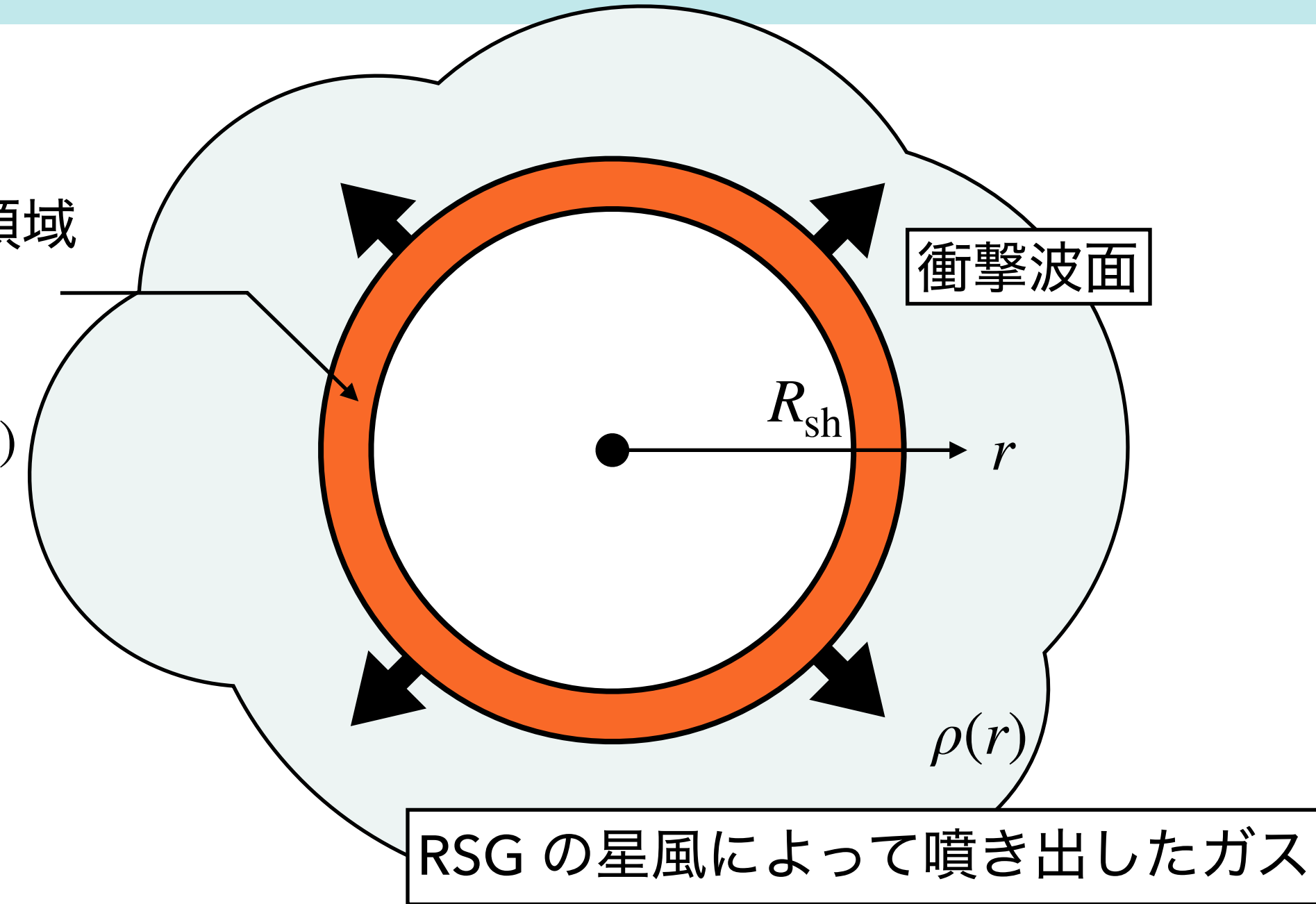
$$\propto t^{-2}$$

$$\therefore F(> 1 \text{ TeV}) \propto E_{\text{CR}} M_{\text{target}} \propto t^{-1}$$

微小時間 dt に
衝撃波が通過する領域

- ・ 体積

$$\int_0^t dt' 4\pi R_{\text{sh}}(t')^2 V_{\text{sh}}(t')$$



～ 仮定 ～

- ・ 星周ガス密度

$$\rho(r) = \dot{M}_{\text{RSG}} / (4\pi r^2 u_w)$$

- ・ 衝撃波半径

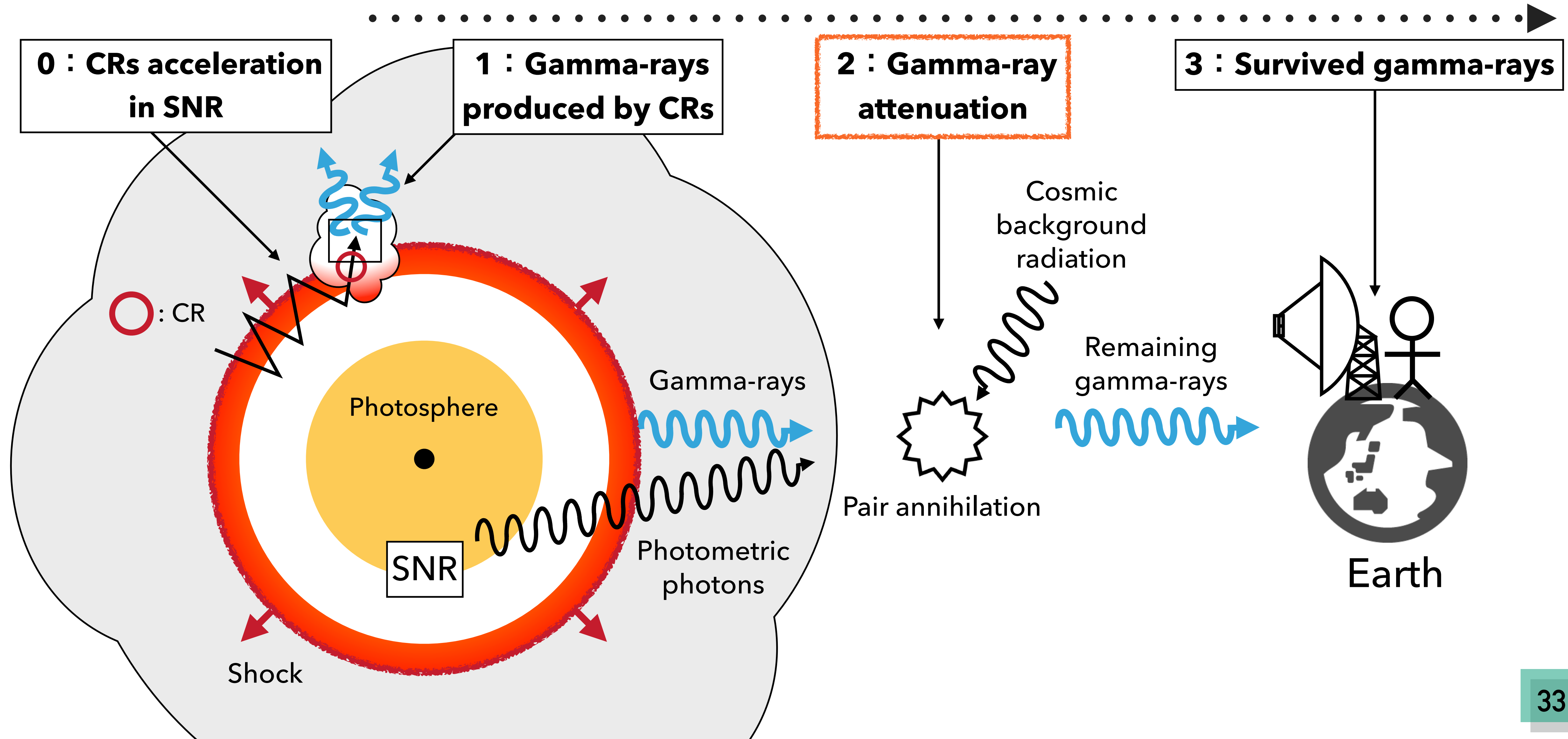
$$R_{\text{sh}}(t) = V_{\text{sh}} t$$

- ・ 下流での宇宙線陽子の占める体積

$$\begin{aligned} V(t) &= f \frac{4\pi}{3} R_{\text{sh}}^3, \quad f: \text{filling factor} \\ &= f \frac{4\pi}{3} V_{\text{sh}}^3 t^3 \end{aligned}$$

Overview: Observational prediction of gamma-rays emitted from SNR

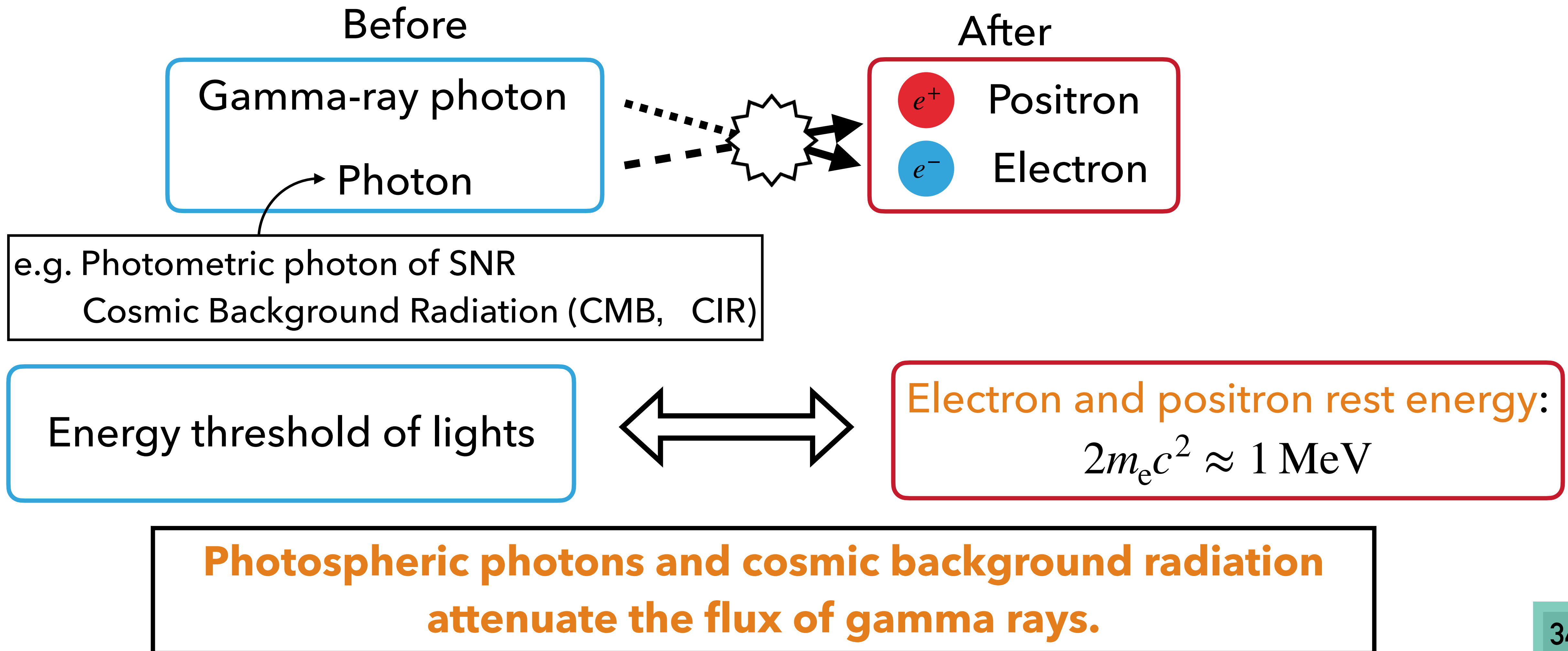
From gamma-ray generation to their observation (This research)



Gamma-rays attenuation

Photon pair annihilation:

Process by which an electron-positron pair is produced from two photons.



対消滅の閾値 $\epsilon_{\min}$ の意味

$$\tau_{\gamma\gamma}(E, \Psi) = \int_0^{+\infty} dl \int_{c_{\min}}^1 d \cos \theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon \left(1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star\right) n_\epsilon \sigma_{\gamma\gamma}$$

$$\underline{\underline{\epsilon_{\min}}} = \frac{2m_e^2 c^4}{E} \frac{1}{(1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star)}$$

- $\mathbf{e}_\gamma$ と $\mathbf{e}_\star$ が **並走**

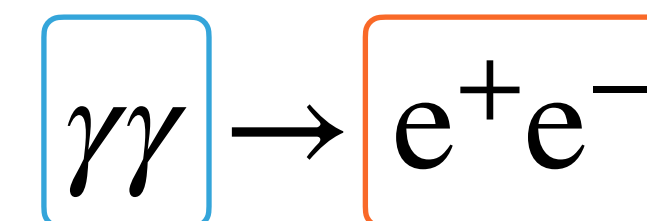
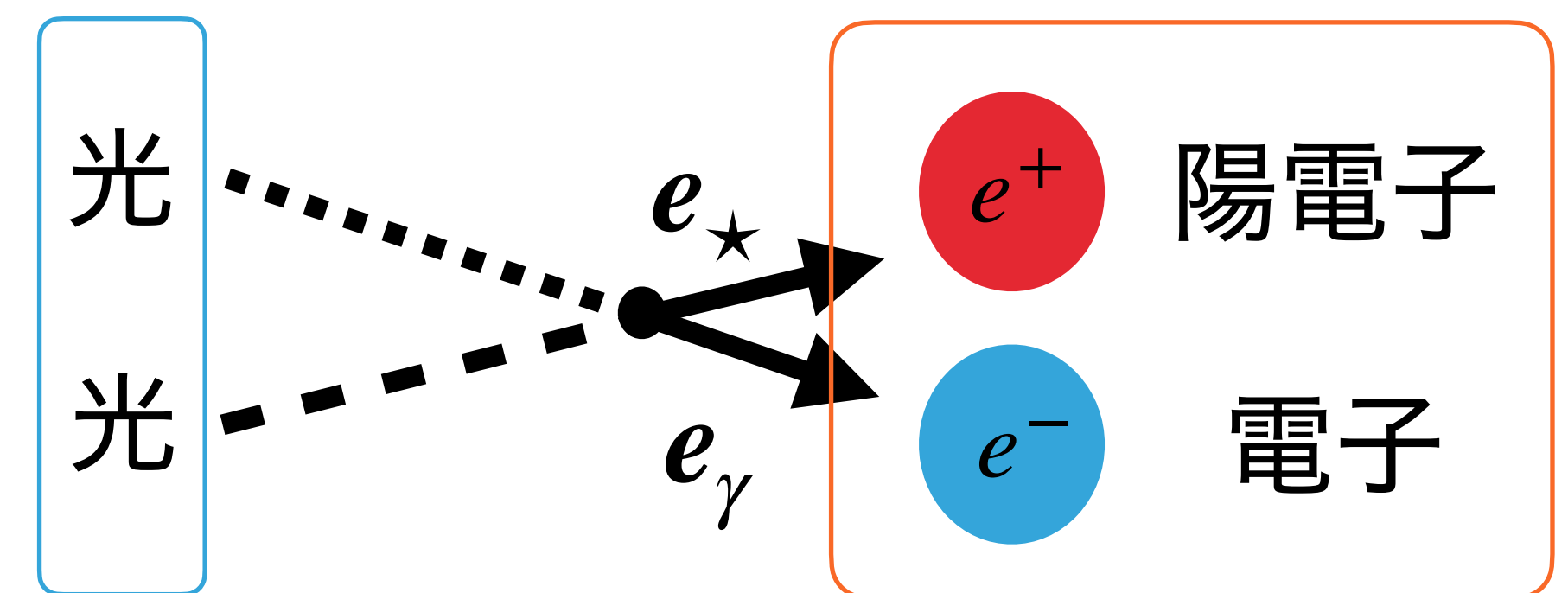
$\mathbf{e}_\gamma \cdot \mathbf{e}_\star = 1$ となり $\epsilon_{\min}$ が発散
→ 対消滅は起こらない

- $\mathbf{e}_\gamma$ と $\mathbf{e}_\star$ が **正面衝突**

$\mathbf{e}_\gamma \cdot \mathbf{e}_\star = -1$ となり $\epsilon_{\min}$ が最小値 $m_e^2 c^4 / E$
→ 小さいエネルギーで対消滅が起こる

反応前

反応後



③対消滅の閾値 $\epsilon_{\min}$ の導出

- ◆ 電子・陽電子対を作るための, 入射する光子の最低のエネルギーは,
CMS でていく電子・陽電子対ペアの 静止質量エネルギー ($E^* = 2m_e c^2$) を生成するための閾値と等価

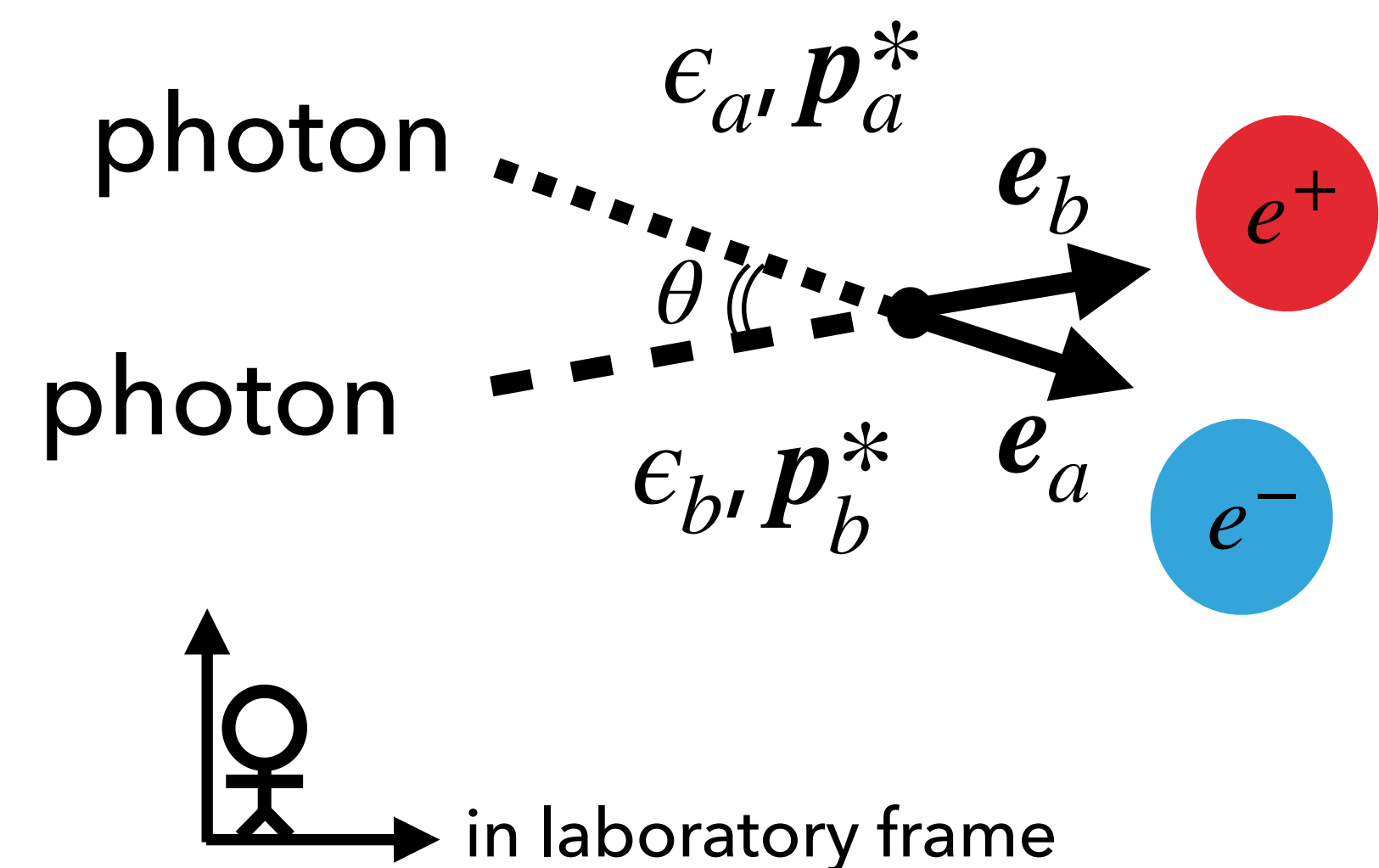
- ◆ CMS (center-of-momentum system): 運動量ベクトルの和が 0 となる系

$$\mathbf{p}_a^* + \mathbf{p}_b^* = 0 \quad \mathbf{p} : \text{three-momentum} \quad \begin{array}{l} \text{添字なし : 実験室系での物理量} \\ * : \text{CMS での物理量} \end{array}$$

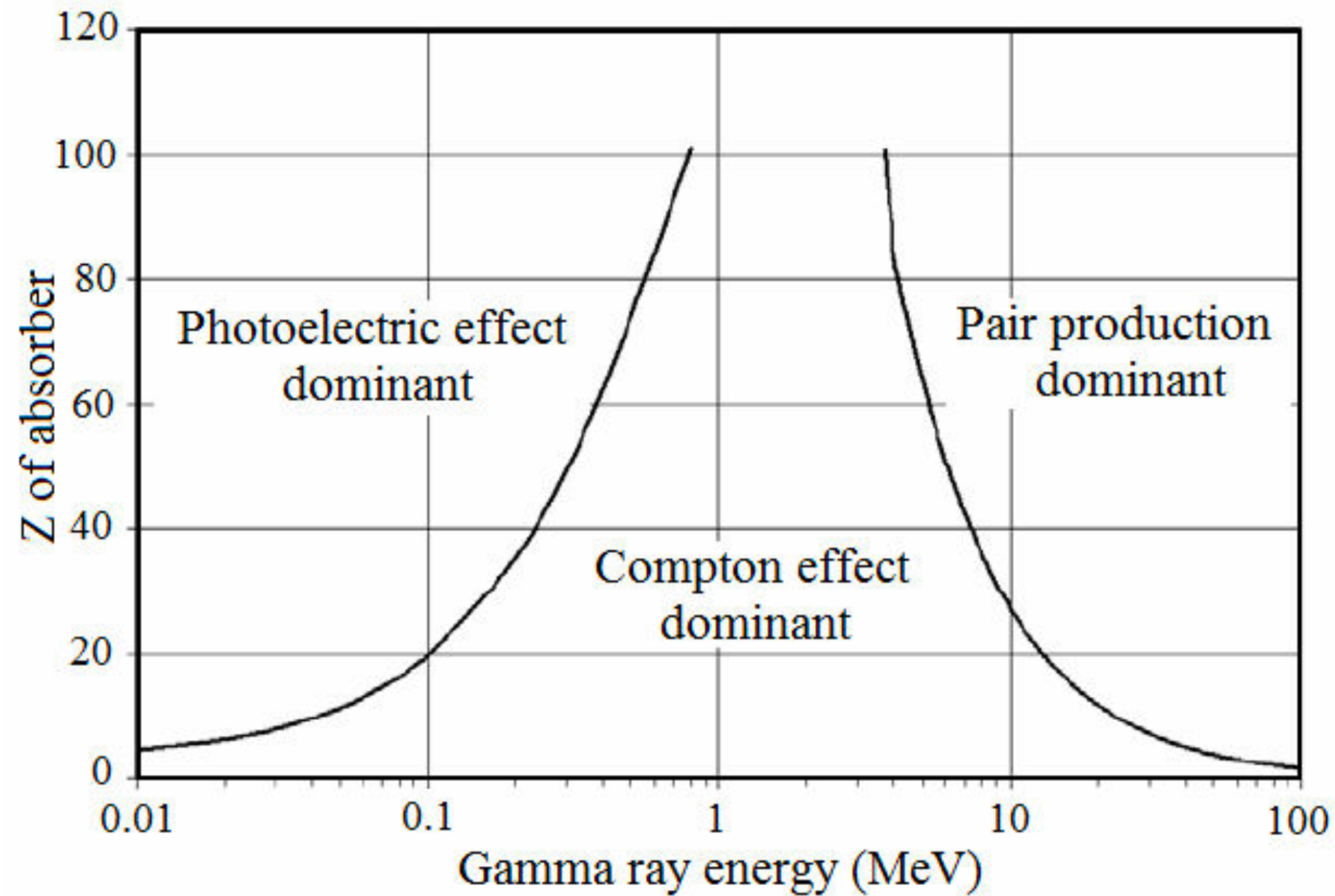
- ◆ 四元運動量の Lorentz 変換を考えると,

$$\begin{aligned} \frac{1}{c^2} (E^*)^2 &= \frac{1}{c^2} (\epsilon_a^* + \epsilon_b^*)^2 \\ &= \frac{1}{c^2} (\epsilon_a + \epsilon_b)^2 - (\mathbf{p}_a + \mathbf{p}_b)^2 && \because \text{Lorentz invariant of four-momentum (CMS} \rightarrow \text{lab.frame)} \\ &= \frac{2}{c^2} \epsilon_a \epsilon_b - 2\mathbf{p}_a \cdot \mathbf{p}_b && \because \epsilon = pc \text{ for photons} \\ \epsilon_a \epsilon_b &= \frac{2(m_e c^2)^2}{(1 - \mathbf{e}_a \cdot \mathbf{e}_b)} \end{aligned}$$

cf. Fulvio Melia, HIGH-ENERGY ASTROPHYSICS, 11.2.2 Gamma-ray Burst Theory, p.248 -249



主要なガンマ線と物質の相互作用過程



G.F. Knoll, Radiation Detection and Measurement,
2nd Edn, New York: John Wiley & Sons Inc, 1989, pp. 54.

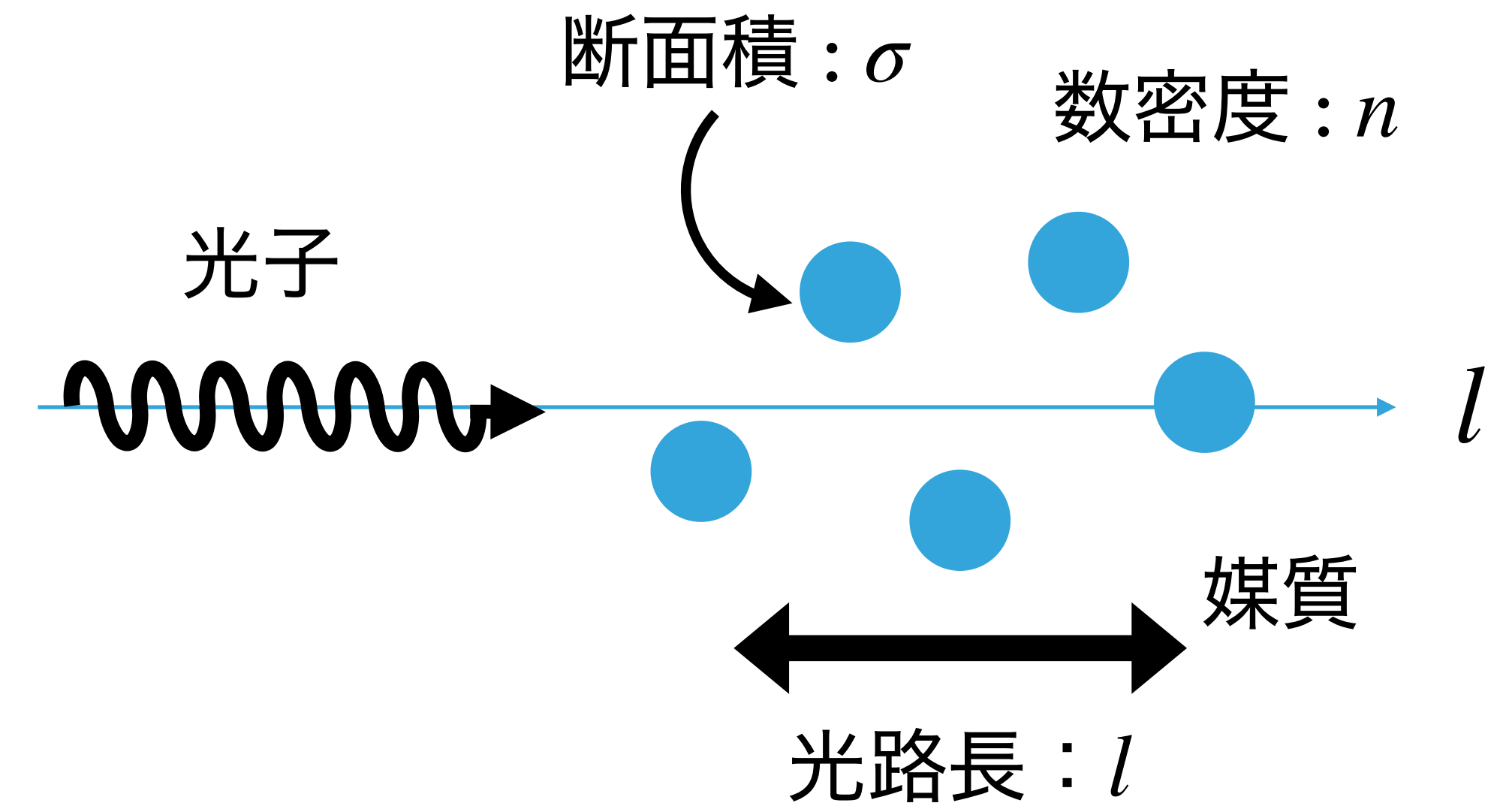
不透明度 τ について for B4

- l 軸方向に媒質中を伝播していく光子を考える

不透明度： τ [－]

$$\tau = \int \alpha dl \quad \text{光路長：} l [\text{cm}] \quad \text{吸収係数：} \alpha [\text{cm}^{-1}]$$

$$\frac{d\tau}{dl} = \alpha = (\text{平均自由行程})^{-1} = n\sigma$$

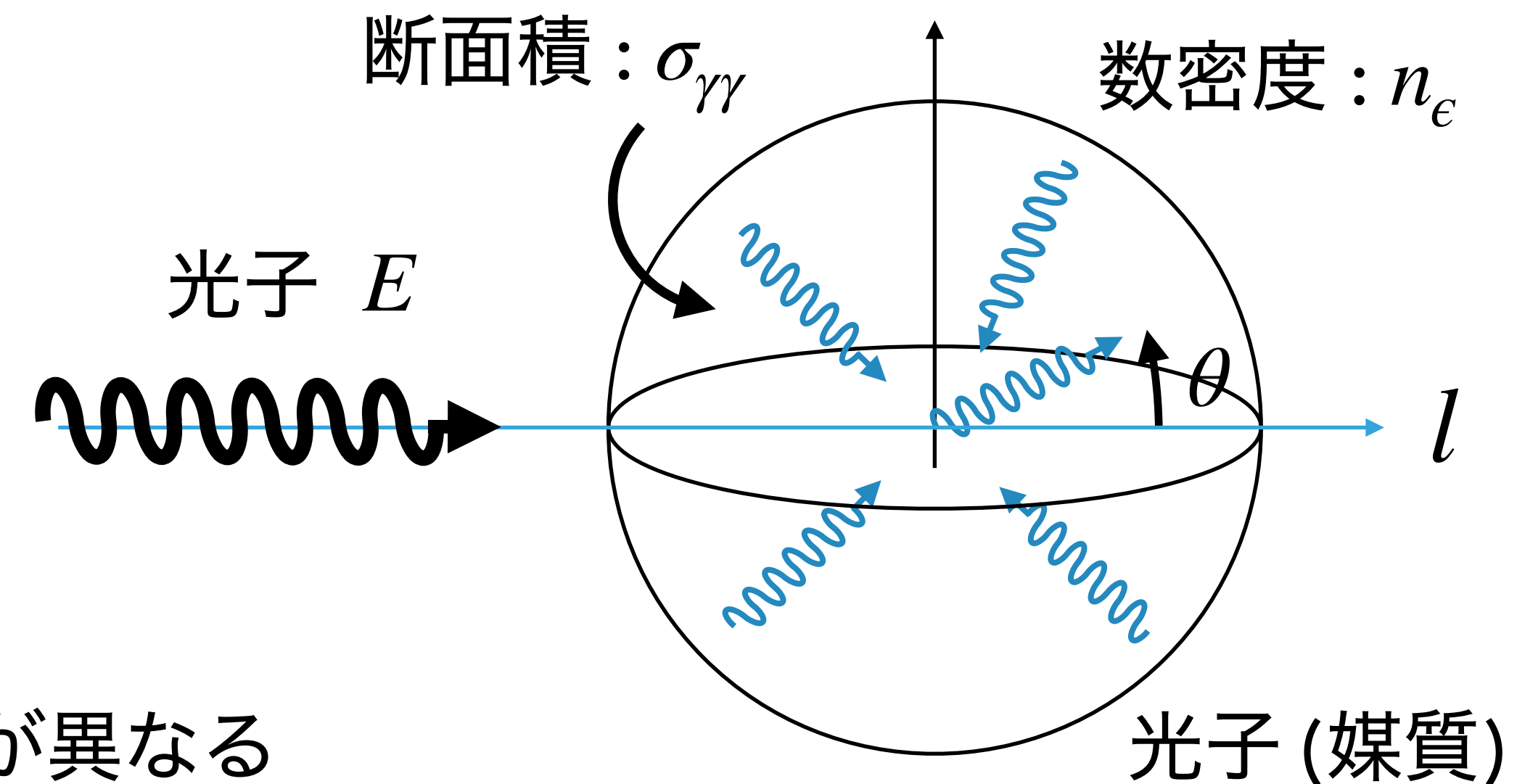


- 媒質が光子であるとき

θ ：入射光子と光子 (媒質) との進行方向のなす角

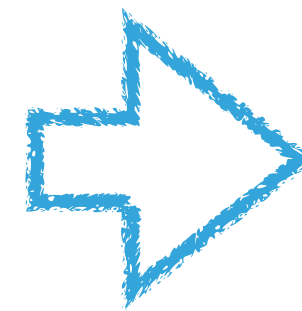
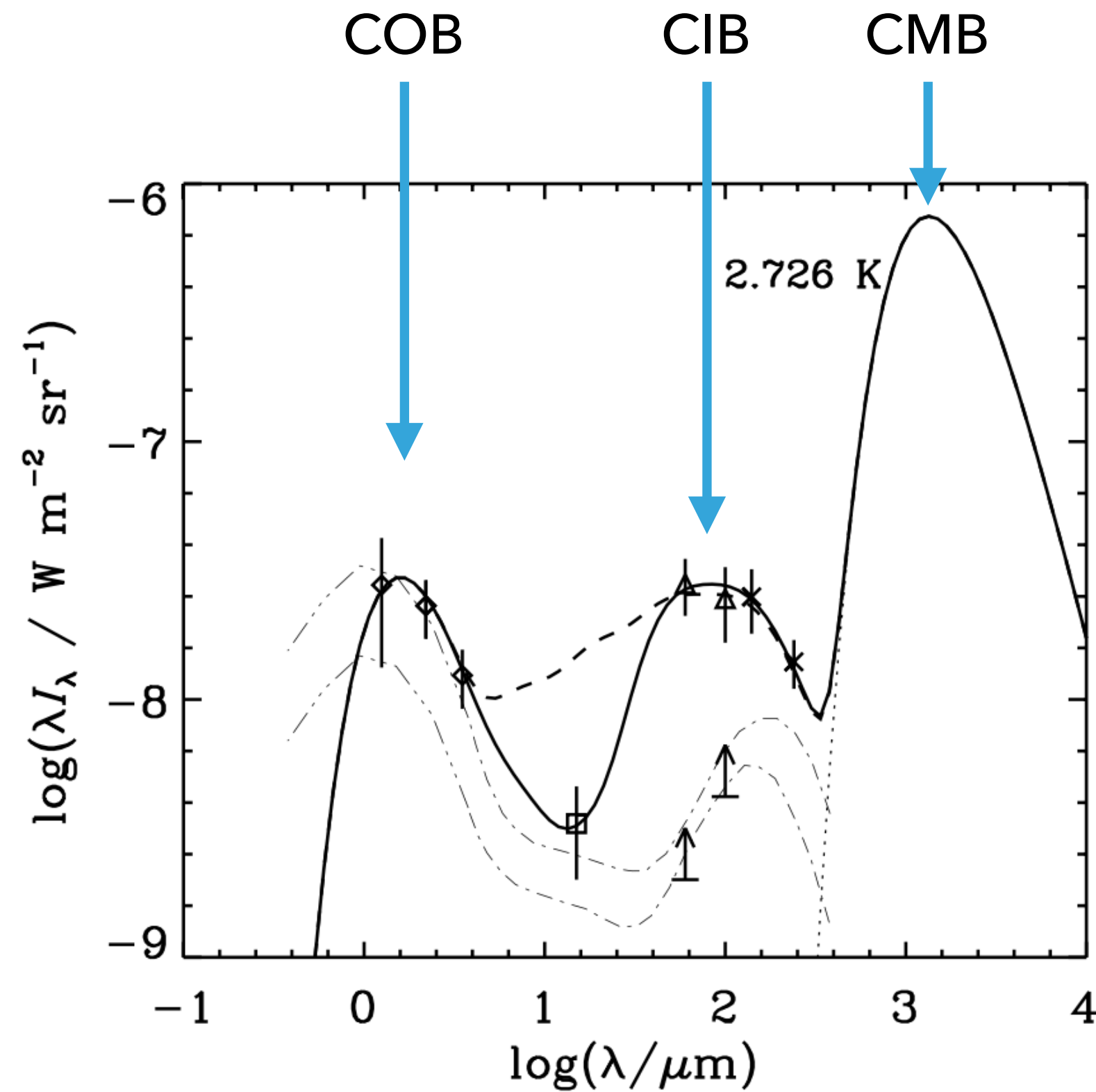
$$\frac{d\tau(E)}{dl} = (1 - \cos \theta) n_{\epsilon} \sigma_{\gamma\gamma}(E)$$

↑
散乱体 (光子) の進行方向によって, 相互作用する割合が異なる



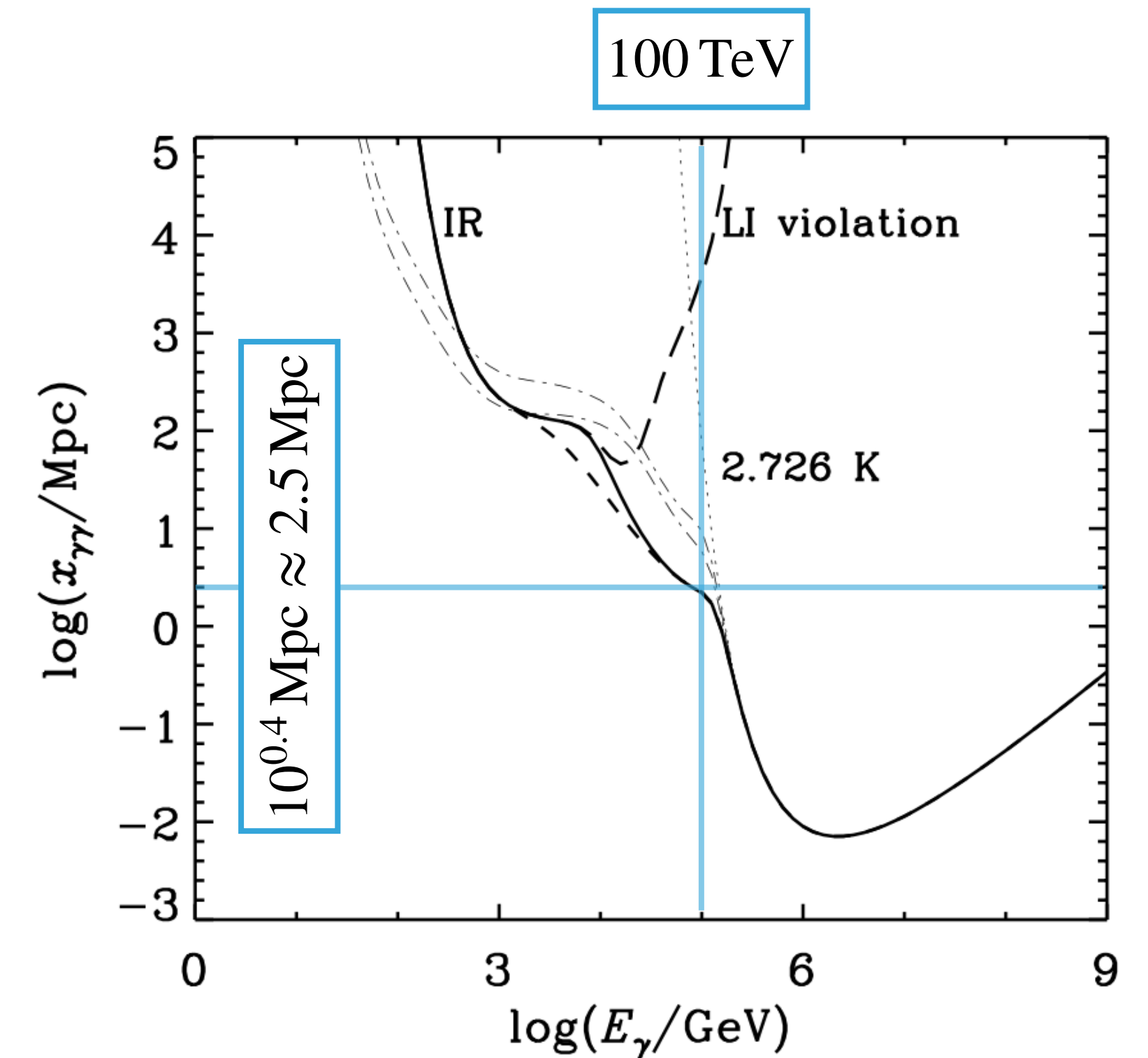
宇宙背景放射によるガンマ線の減衰 ②

宇宙背景放射の波長 - Intensity



背景放射の Intensity から
ガンマ線の平均自由行程を計算

ガンマ線のエネルギー - 平均自由行程



R. J. Protheroe et al. 2000

宇宙背景放射によるガンマ線減衰

- 100 TeV ガンマ線の宇宙背景放射に対する平均自由行程

$$\frac{d\tau}{dl} = x_{\gamma\gamma}^{-1}(E_\gamma) = 10^{0.4} \text{ Mpc} \approx 2.5 \text{ Mpc}$$

$$\begin{aligned}\tau &= x_{\gamma\gamma}^{-1}(E_\gamma) \int_0^L dl \\ &= x_{\gamma\gamma}^{-1}(E_\gamma) L \quad L = 3.6 \text{ Mpc} : \text{SN1993J までの距離 とする}\end{aligned}$$

$$= \frac{3.6 \text{ Mpc}}{2.5 \text{ Mpc}} \approx 1.44$$

$$\begin{aligned}I_{\text{obs}} &= I_{\text{emi}} \times e^{-\tau} \\ &= I_{\text{emi}} \times e^{-1.44} \approx 0.237 I_{\text{emi}}\end{aligned}$$

->宇宙背景放射を考慮すると,
100 TeV ガンマ線の Intensity は, 3.6 Mpc の経路の間に,
約 **1/4** に減衰される

ここで, ガンマ線の Intensity は等方的であることを仮定しているため,
Flux も同様に, 約 **1/4** に減衰される.

Cosmic ray injection rate: η_{inj}^p

・宇宙線注入率 η_{inj}^p

：衝撃波を受け加熱された粒子 (陽子) の内,
再び衝撃波上流へと戻る粒子の割合

・無衝突衝撃の場合

下流のプラズマが加熱され,

分布関数が Maxwell 型になるとは限らない。

しかし, 簡単のためここでは Maxwell 型を仮定する

$$\eta_{\text{inj}}^p = \frac{\int_{p_{\text{inj}}}^{\infty} \exp\left(-\frac{p^2}{p_{\text{th}}^2}\right) p^2 dp}{\int_0^{\infty} \exp\left(-\frac{p^2}{p_{\text{th}}^2}\right) p^2 dp}$$

η_{inj}^p の推定

(Blasi et al. 2005)

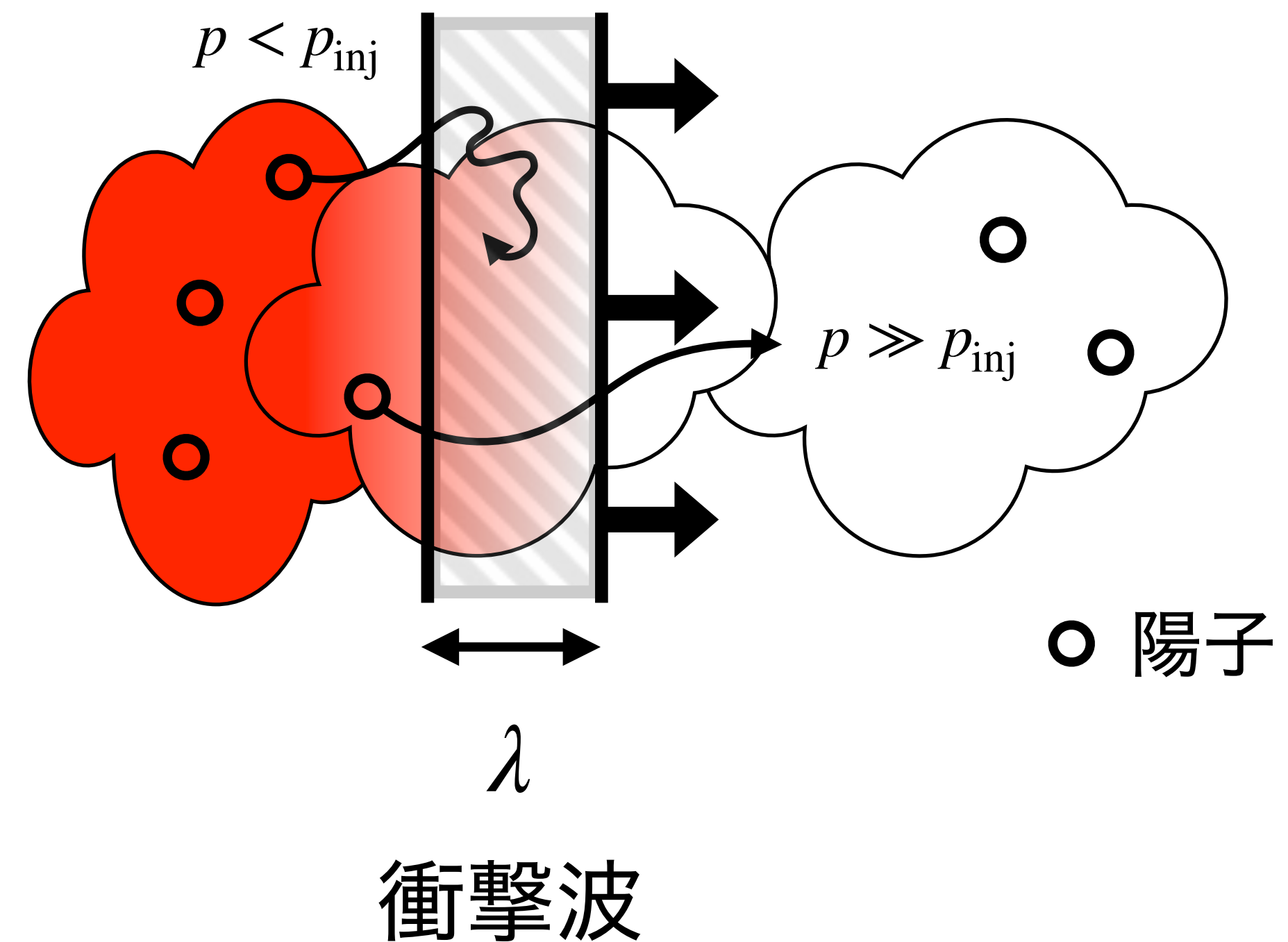
下流 (星中心側)

上流 (星中外側)

無衝突系のプラズマ

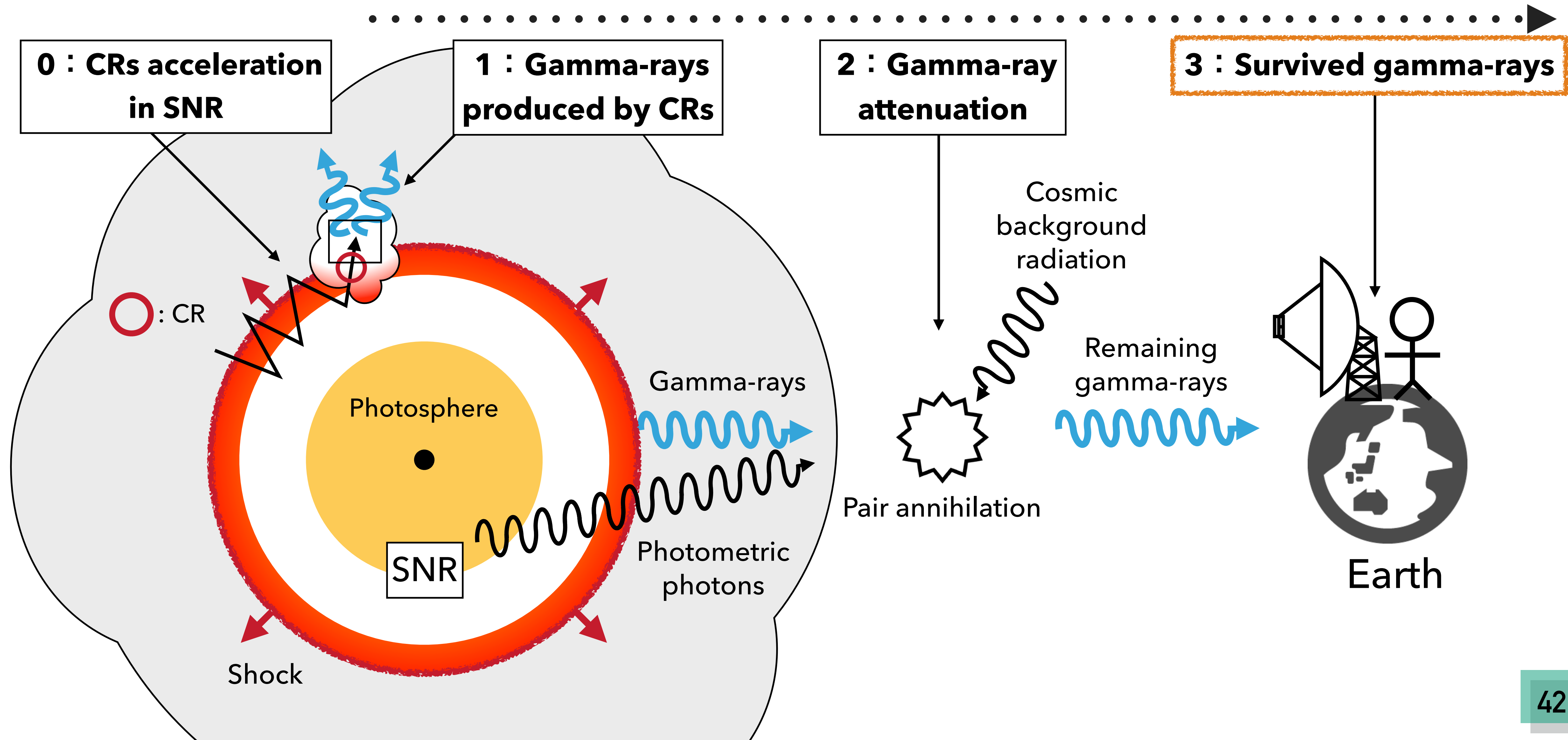
✕ 熱分布 (Maxwell 分布)

▲ 熱分布 + 幂分布 (近似) →



Overview: Observational prediction of gamma-rays emitted from SNR

From gamma-ray generation to their observation (This research)





RESULT

Time evolution of gamma-ray flux above 100 TeV

~ Calculation Setup ~

Distance to the target object: $D = 1$ Mpc

CR injection rate: $\eta_{\text{inj}}^{\text{p}} = 6 \times 10^{-4}$

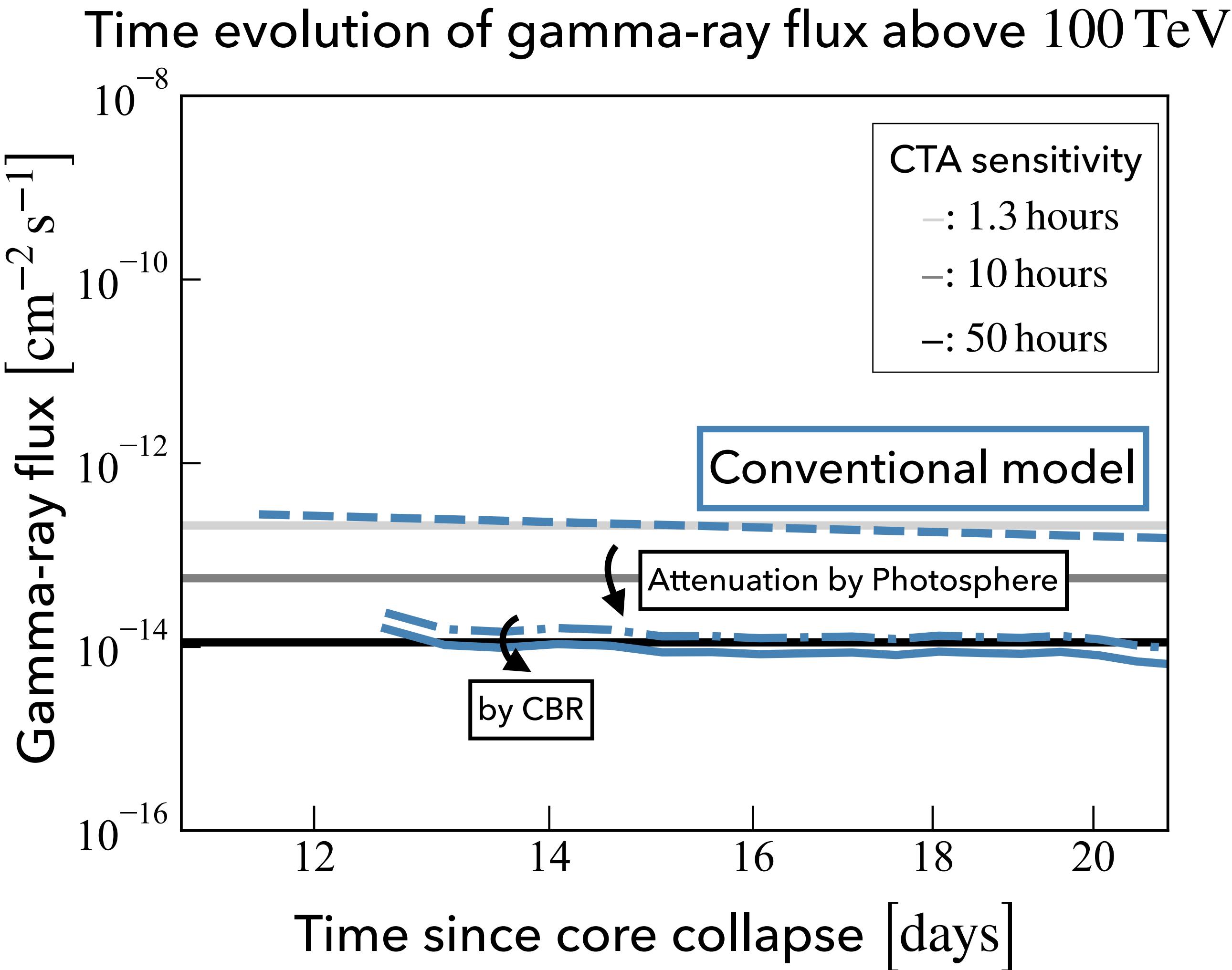
Mass loss rate of RSG: $\dot{M}_{\text{RSG}}$

Conventional model (Cristofari et al. 2020)

$$\dot{M}_{\text{RSG}} = 10^{-5} M_{\odot} \text{ yr}^{-1}$$

Conventional mass loss rate values created by the stellar winds of red supergiants.

	Photometric photon	CBR
— —	OFF	OFF
— .	ON	OFF
— —	ON	ON



The gamma-ray flux is attenuated to ~ **1/10** or less by **photosphere** 14 days after the core collapse.
 It is further attenuated to ~ **2/3** by **cosmic background radiation**.

Time evolution of gamma-ray flux using different mass loss rates of RSG

~ Calculation Setup ~

Distance to the target object: $D = 1 \text{ Mpc}$

CR injection rate: $\eta_{\text{inj}}^{\text{p}} = 10^{-4}$

Mass loss rate of RSG: $\dot{M}_{\text{RSG}}$

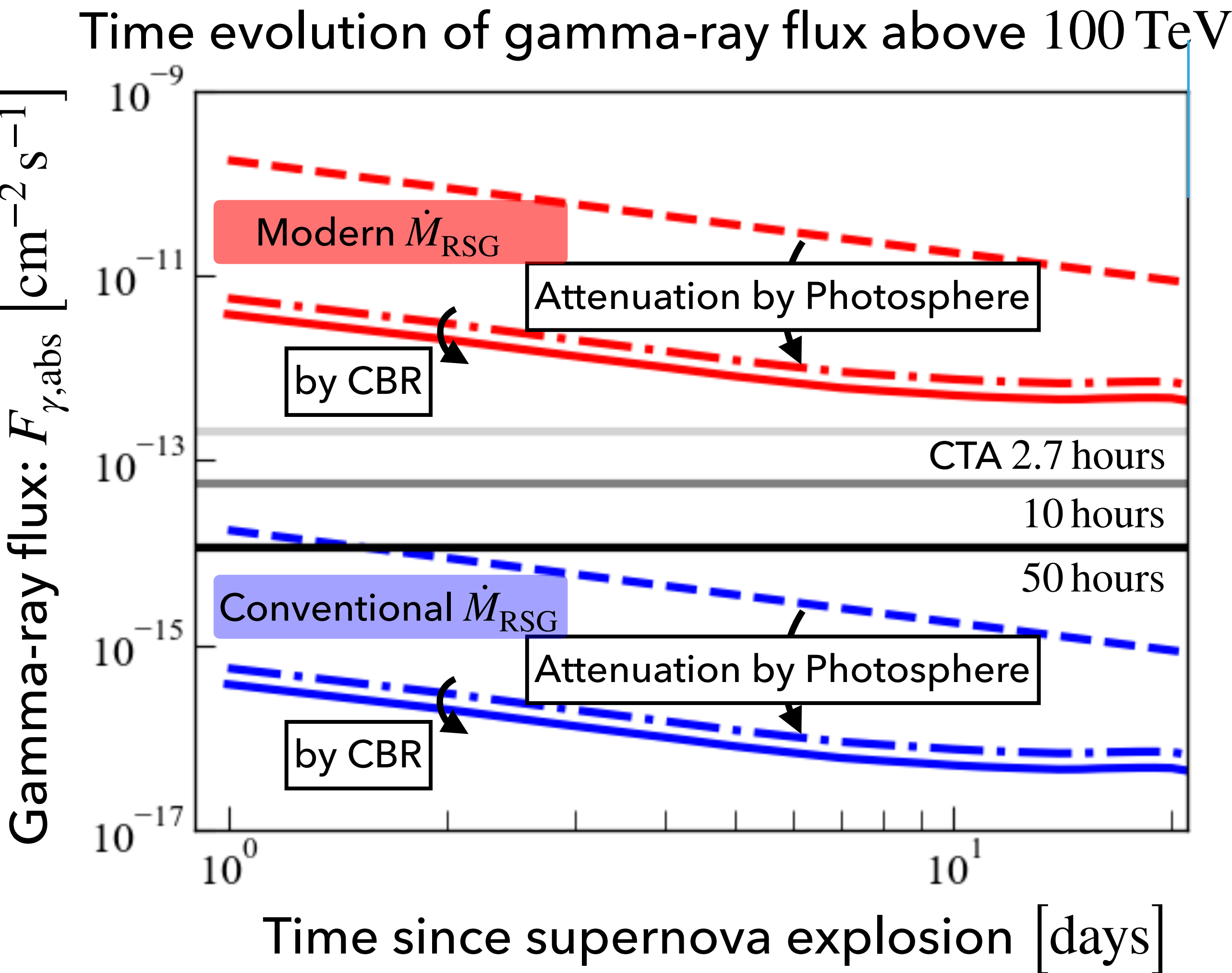
Conventional $\dot{M}_{\text{RSG}} = 10^{-5} M_{\odot} \text{ yr}^{-1}$

Modern $\dot{M}_{\text{RSG}} = 10^{-3} M_{\odot} \text{ yr}^{-1}$

$\dot{M}_{\text{RSG}}$ of most RSG winds are enhanced by two orders of magnitude a few years

Förster et al. (2018)

	Photometric photon	CMB, CIB
--	OFF	OFF
-.	ON	OFF
-	ON	ON



The **increase in the mass loss rate** the gamma-ray flux of **4 orders of magnitude**.

Time evolution of gamma-ray flux using different cosmic ray injection rates

~ Calculation Setup ~

Distance to the target object: $D = 1 \text{ Mpc}$

CR injection rate: $\eta_{\text{inj}}^{\text{p}} = 10^{-4} \sim 10^{-3}$

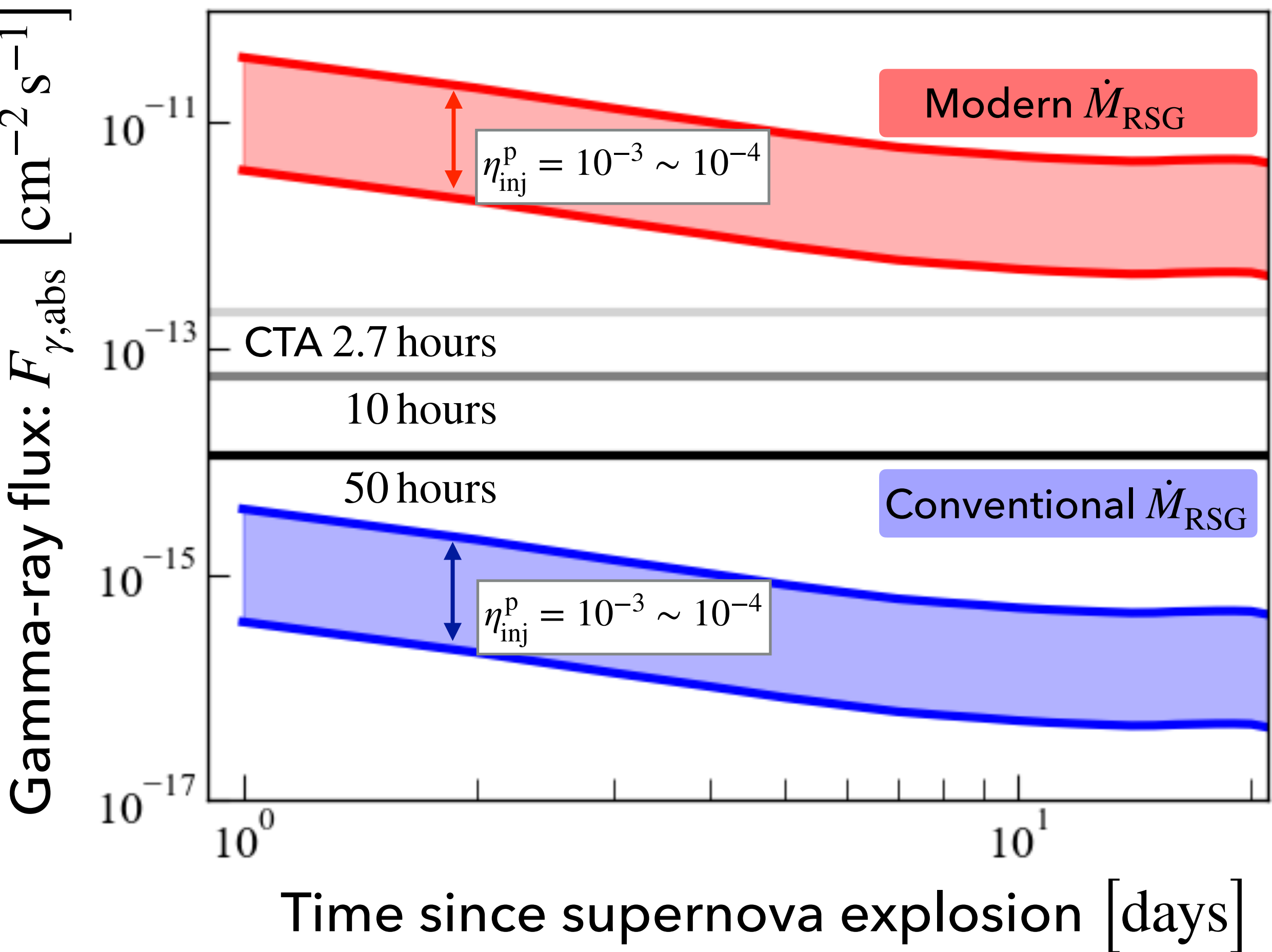
Mass loss rate of RSG: $\dot{M}_{\text{RSG}}$

Conventional $\dot{M}_{\text{RSG}} = 10^{-5} M_{\odot} \text{ yr}^{-1}$

Modern $\dot{M}_{\text{RSG}} = 10^{-3} M_{\odot} \text{ yr}^{-1}$

	Photometric photon	CMB, CIB
—	ON	ON

Time evolution of gamma-ray flux above 100 TeV



The flux increases by **another 1 order** of magnitude when accounting for **the uncertainty in η_{inj}** .

C.C.SNe number rate

- C.C.SN (core collapse supernova) の前駆体の星質量下限 $\approx 8 M_{\odot}$ とすると,

誕生した星の内, C.C.SNe の前駆体の星となる割合 : $f_N = 0.205 \%$

銀河のカタログ

- 銀河までの距離
- 銀河での星形成率

∴

- べき乗の IMF (initial mass function) $\frac{dN}{dM} \propto M^B$ を用いる

- 星の数

$$N = A \int M^B dM = \frac{A}{B+1} M^{B+1} \text{ (if } B \neq -1 \text{)}$$

- SN number rate = ($M \geq 8 M_{\odot}$ の星の数)/(全ての星の数)

$$\begin{aligned} f_N &= \frac{\text{number of SNe}}{\text{number of stars}} = \frac{\int_{8 M_{\odot}}^{20 M_{\odot}} M^B dM}{\int_{0.1 M_{\odot}}^{20 M_{\odot}} M^B dM} \\ &= \frac{\left. \frac{A}{B+1} M^{B+1} \right|_8^{20}}{\left. \frac{A}{B+1} M^{B+1} \right|_{0.1}^{20}} = \frac{\left. M^{-4/3} \right|_8^{20}}{\left. M^{-4/3} \right|_{0.1}^{20}} \approx \frac{0.018 - 0.063}{0.018 - 21.544} \approx 0.00205 = 0.205 \% \end{aligned}$$

C.C.SNe の質量の占める割合

全ての星質量の内, C.C.SNe の前駆体の質量となる割合 :

$$f_M = 7.3768 \%$$

∴ ・ べき乗の IMF (initial mass function) $\frac{dN}{dM} \propto M^B$ を用いる $B = -7/3$ を仮定

$$(\text{星の数} : N = A \int M^B dM = \frac{A}{B+1} M^{B+1} \text{ (if } B \neq -1))$$

$$f_M = \frac{\int_{8 M_\odot}^{20 M_\odot} M \times M^{-7/3} dM}{\int_{0.1 M_\odot}^{20 M_\odot} M \times M^{-7/3} dM} = \frac{M^{-1/3} \Big|_8^{20}}{M^{-1/3} \Big|_{0.1}^{20}}$$

$$\approx 0.07368 = 7.3768 \%$$

参考

<http://star-www.st-and.ac.uk/~kdh1/ce/ce09.pdf>

iPad にメモ入り

典型的な SN の質量

- ・ 質量の中央値

$$\frac{1}{2} = \frac{\int_{8 M_{\odot}}^{\bar{M}_{\text{SN}}} M \times M^{-7/3} dM}{\int_{8 M_{\odot}}^{20 M_{\odot}} M \times M^{-7/3} dM} = \frac{\bar{M}_{\text{SN}}^{-1/3} - 0.500 M_{\odot}^{-1/3}}{(-0.368 - 0.500) M_{\odot}^{-1/3}}$$

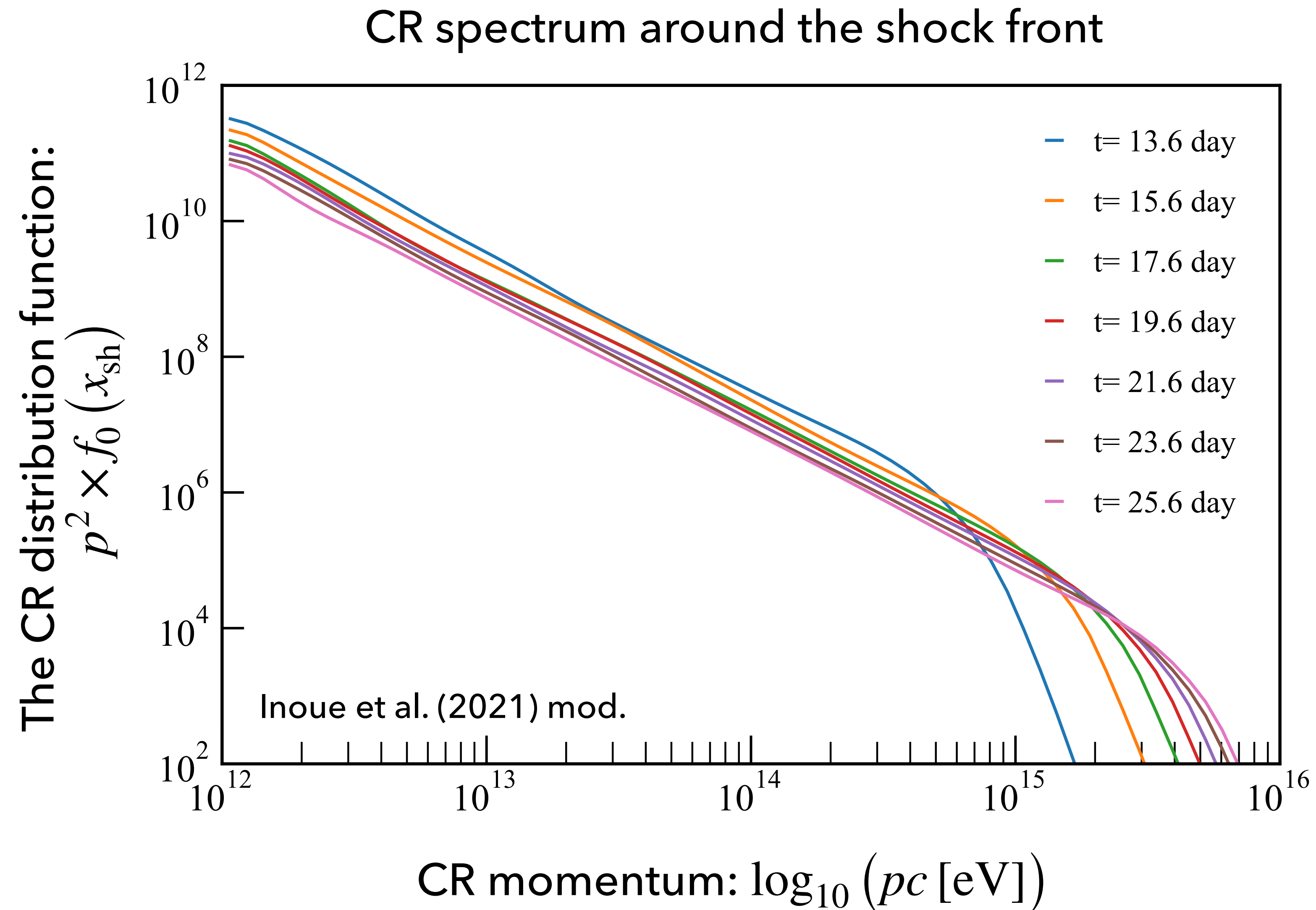
$$\bar{M}_{\text{SN}} = 12.216 M_{\odot}$$

- ・ 質量の平均値

$$\langle M \rangle = \frac{\int_{8 M_{\odot}}^{20 M_{\odot}} M \times M^{-7/3} dM}{\int_{8 M_{\odot}}^{20 M_{\odot}} M^{-7/3} dM} = \frac{\frac{1}{-1/3} M^{-1/3} \Big|_8^{20}}{\frac{1}{-4/3} M^{-4/3} \Big|_8^{20}}$$

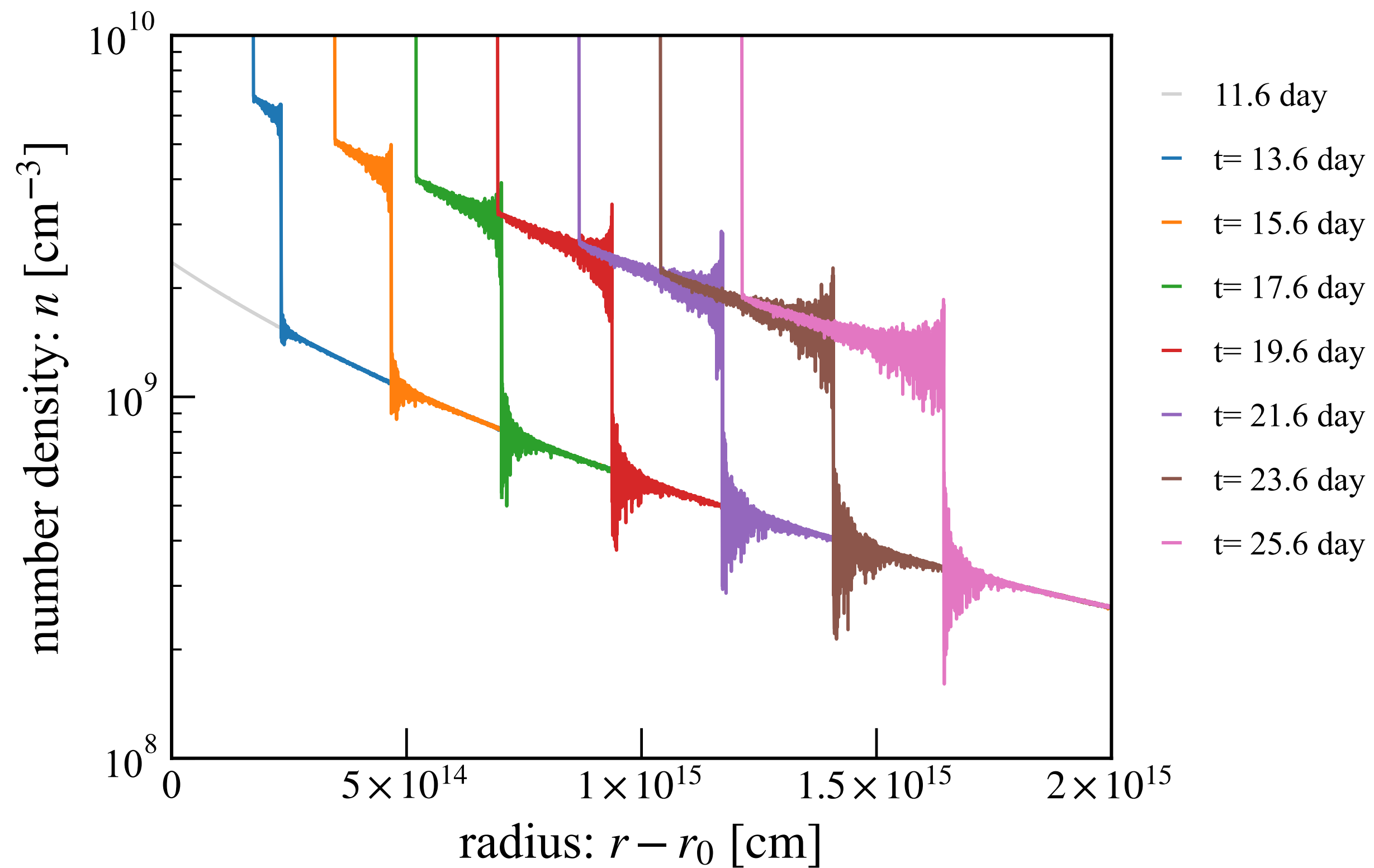
$$\langle M \rangle = 11.9417 M_{\odot}$$

Evolution of CR spectrum

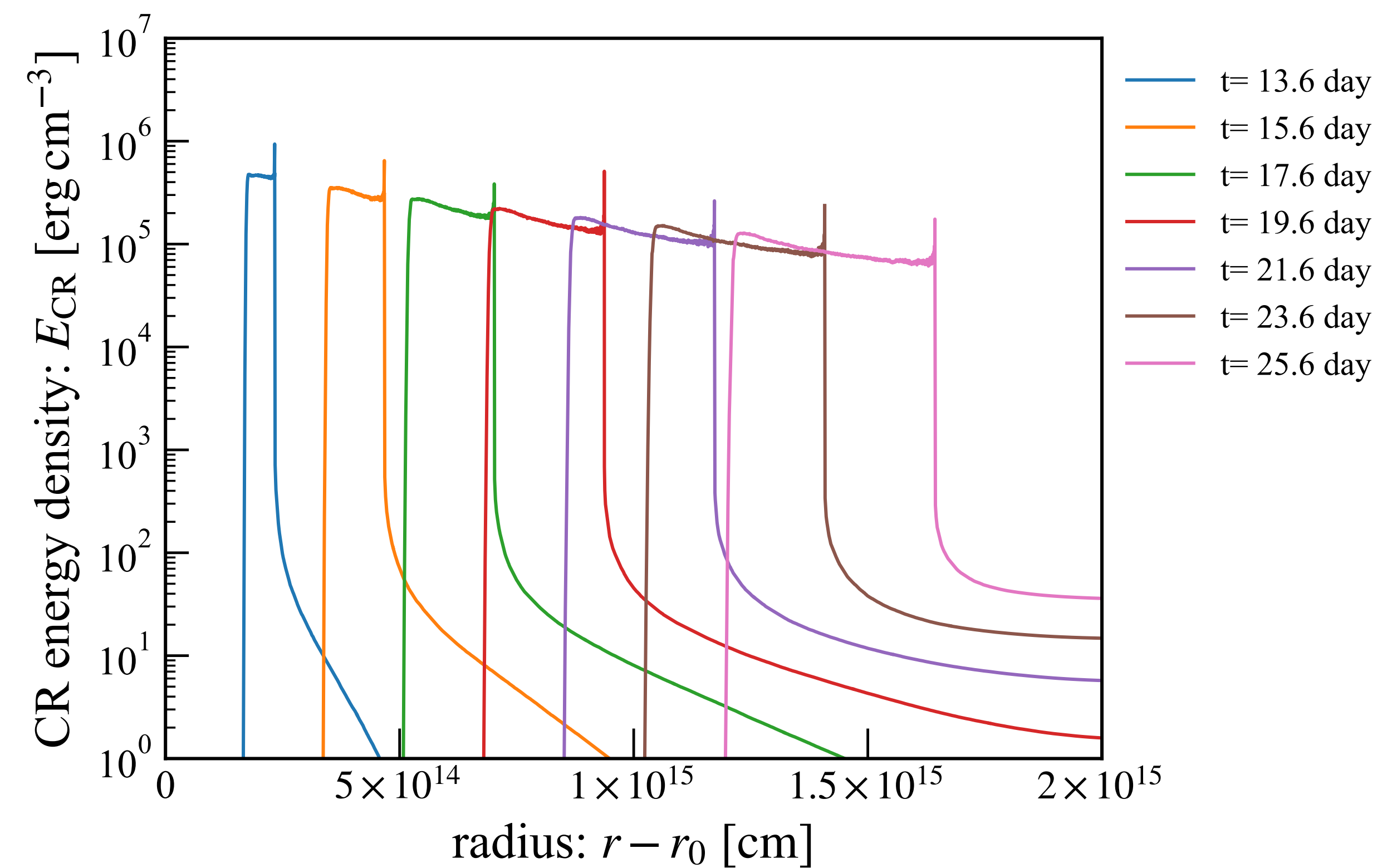


Evolution of number density and CR energy density

Evolution of number density

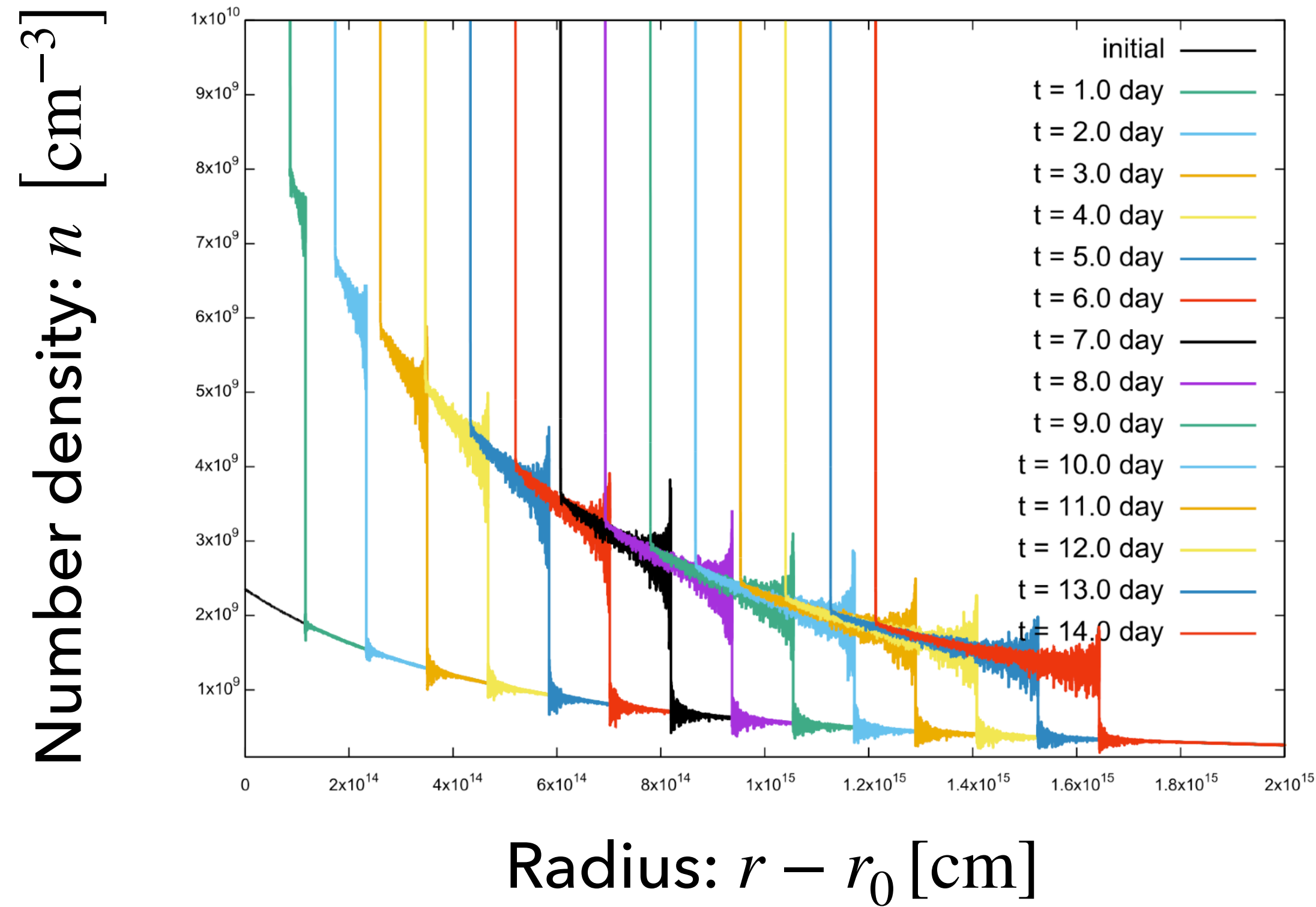


Evolution of CR energy density



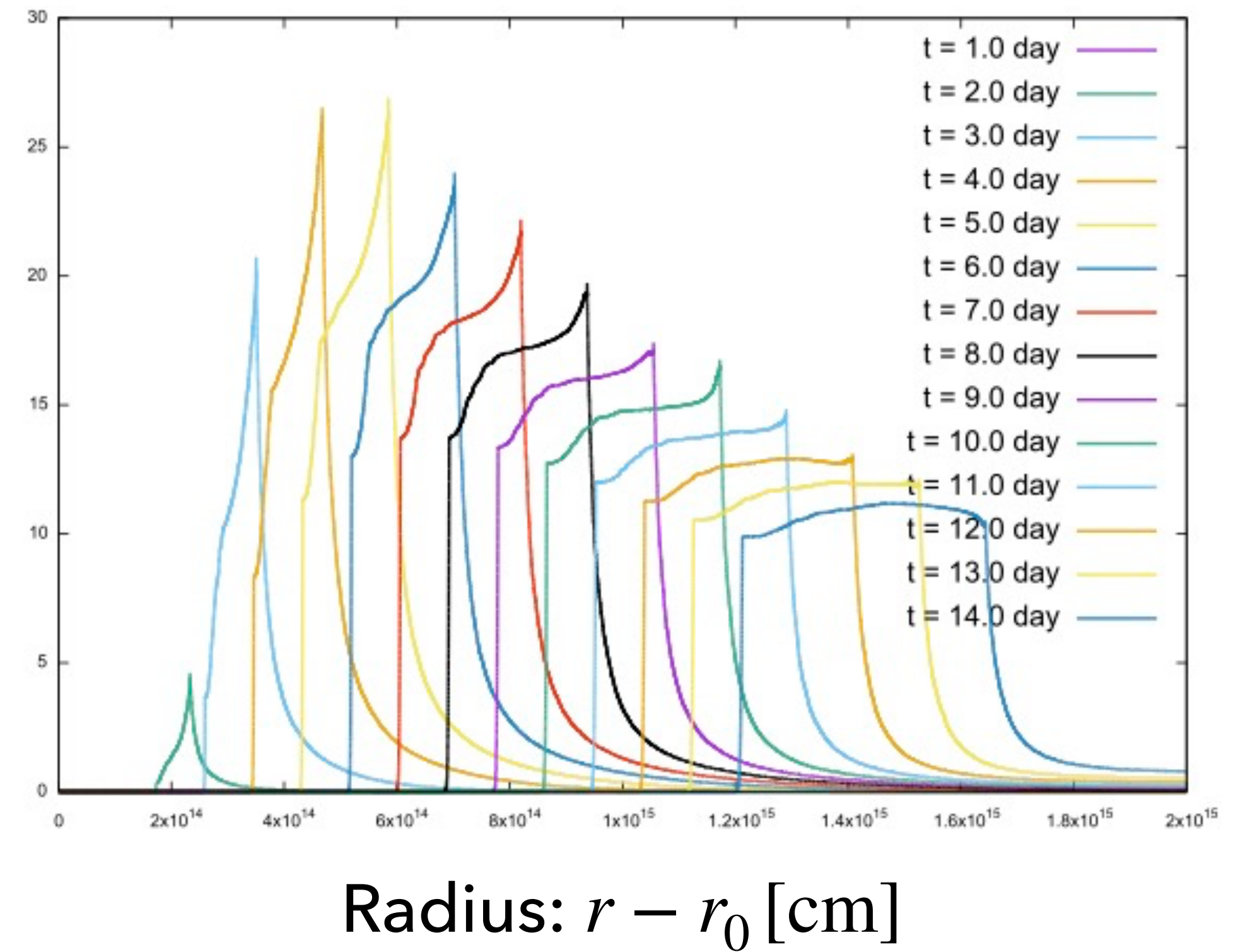
CSM number density & CR energy density

Number density of CSM



Energy density of CR ($E_{\text{kin}} = 1 \text{ PeV}$)

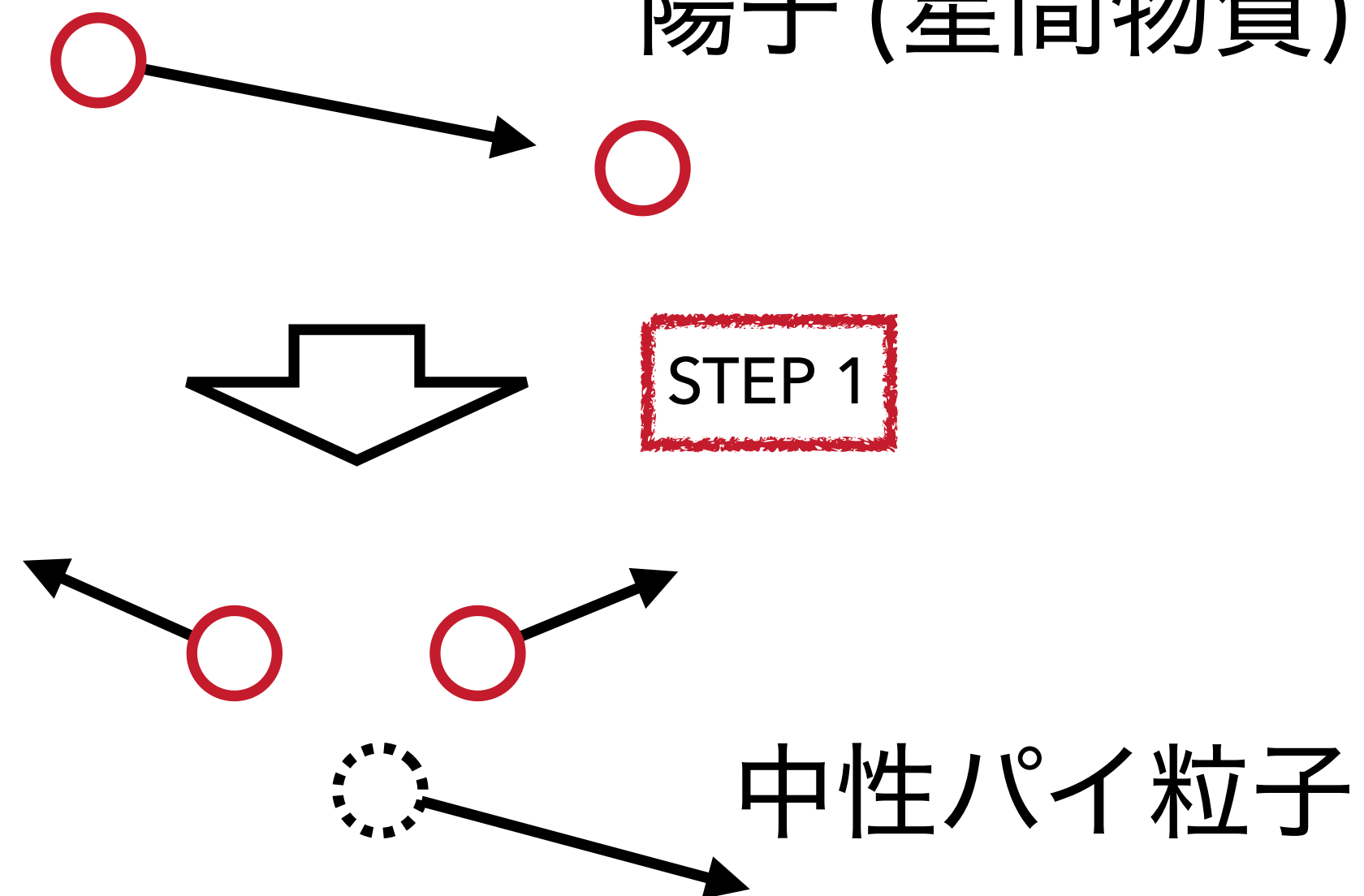
CR energy density:
 E_{CR} [erg cm^{-3}]



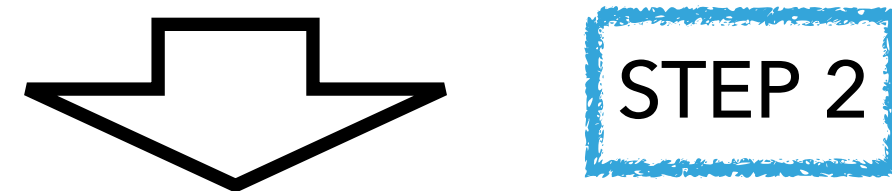
1. ガンマ線発生機構

陽子 (宇宙線)

陽子 (星間物質)



中性パイ粒子



ガンマ線

in 実験室系

STEP 1 : 中性パイ粒子の生成

$$p (\text{宇宙線}) + p (\text{星間物質}) \rightarrow p + p + \pi^0$$

(宇宙線陽子のエネルギー) $\gtrsim 1.2 \text{ GeV}$ で起こり得る

in 実験室系 (p (星間物質) 静止系)

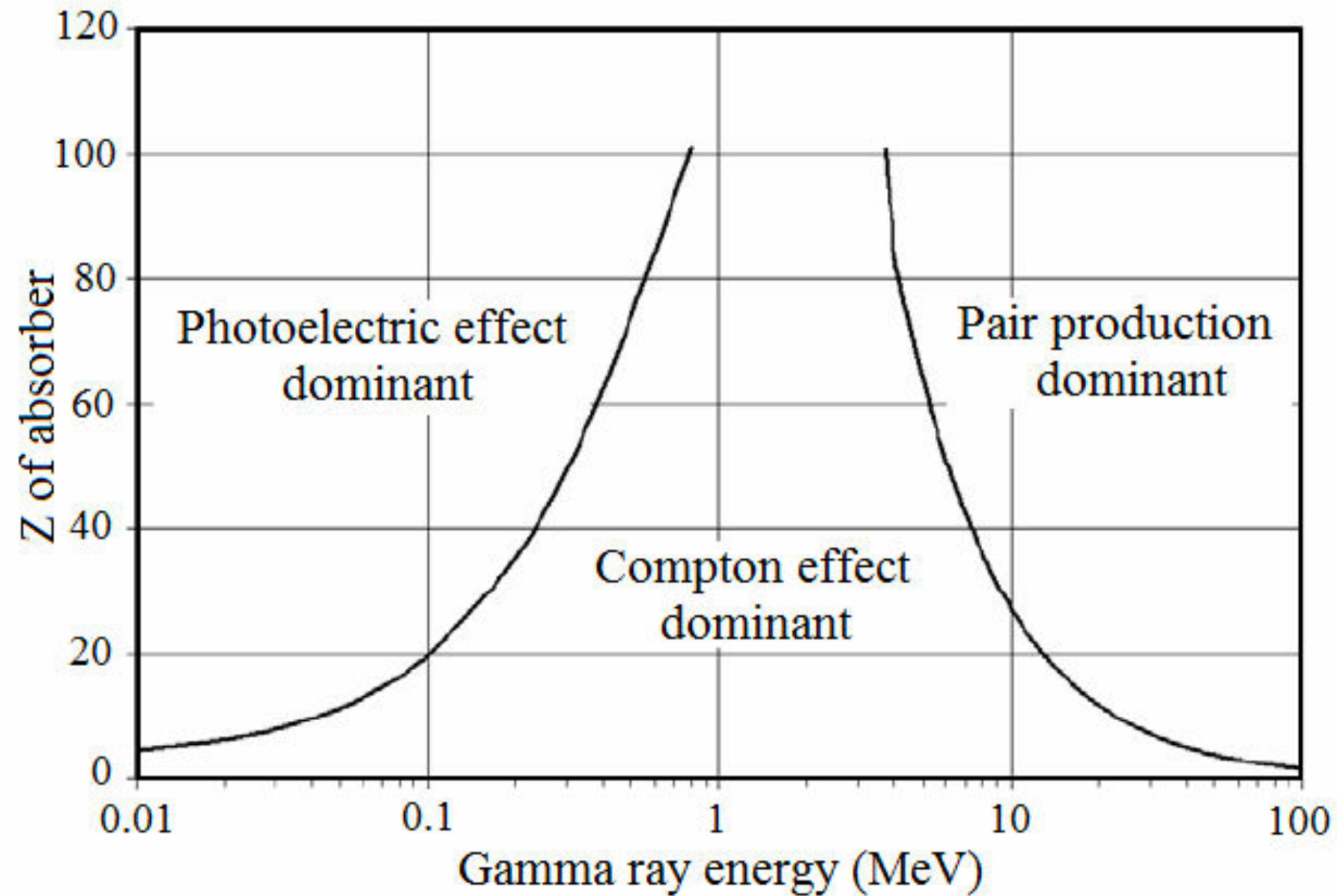
STEP 2 : 中性パイ粒子の崩壊

$$\pi^0 \rightarrow 2\gamma$$

$$\frac{1}{2}m_{\pi^0}c^2 \approx 67.5 \text{ MeV} \text{ のガンマ線が放出される}$$

in 中性パイ粒子 π^0 静止系

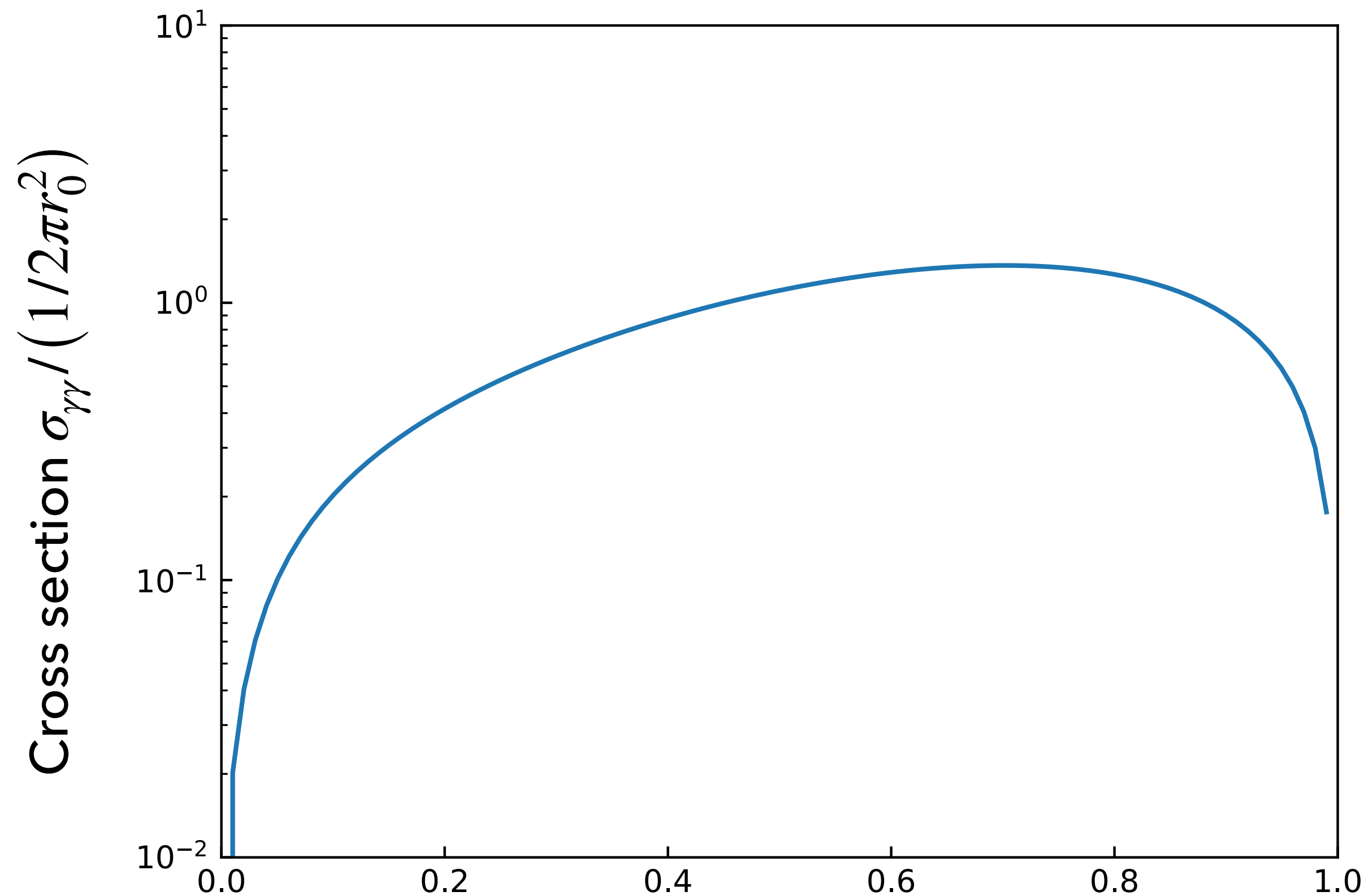
Gamma-ray interaction process



G.F. Knoll, Radiation Detection and Measurement,
2nd Edn, New York: John Wiley & Sons Inc, 1989, pp. 54.

Cross section: $\gamma\gamma \rightarrow e^+ + e^-$

$$\sigma_{\gamma\gamma} = \frac{1}{2}\pi r_0^2 (1 - \beta^2) \left[(3 - \beta^4) \ln \frac{1 + \beta}{1 - \beta} - 2\beta (2 - \beta^2) \right]$$



$$\beta = \sqrt{1 - \frac{(m_e c^2)^2}{E_\gamma \epsilon}}$$

E_γ, ϵ : Gamma-ray, soft photon energy

r_0 : classical electron radius

- maximum of σ

When $\beta = 0.8$, $E_\gamma \epsilon / (m_e c^2)^2 \sim 2.78$

$\epsilon \sim (500 \text{ GeV} / E_\gamma) \text{ eV}$

- When $E_\gamma = 1 \text{ TeV}$,

$\epsilon = 0.5 \text{ eV}$

: Infrared region

- When $E_\gamma = 100 \text{ TeV}$,

$\epsilon = 0.005 \text{ eV}$

: Microwave region

Scattered most efficiently in this region

ガンマ線の消滅モデルと基礎方程式 (詳細) GC ver.

- ◆ 時刻 t に生じたエネルギー E を持つ γ -ray の不透明度

$$\tau_{\gamma\gamma}(t, \Psi_0, E) = \int_0^{+\infty} dl \int_{c_{\min}}^1 d \cos \theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon \quad \textcircled{1} \quad \textcircled{2} \quad \textcircled{3} \quad \left(1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star\right)$$

t : SN 後の経過時間 E : γ -ray energy ϵ : soft photon energy

- ① 光球表面から生じた軟光子の相互作用点での数密度 (黒体輻射を仮定)

$$n_\epsilon = \frac{2\epsilon^2}{h^3 c^3} \frac{1}{\exp(\epsilon/k_B T(t)) - 1} \left[\text{cm}^{-3} \text{erg}^{-1} \text{sr}^{-1} \right]$$

- ② 電子陽電子対の散乱断面積

$$\sigma_{\gamma\gamma} = \frac{1}{2} \pi r_0^2 (1 - \beta^2) \left[(3 - \beta^4) \ln \frac{1 + \beta}{1 - \beta} - 2\beta (2 - \beta^2) \right]$$

$$\beta = \left(1 - \frac{1}{s} \right)^{1/2} \quad s = \frac{\epsilon E}{2m_e^2 c^4} (1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star)$$

cf. Gould & Schröder (1967)

- ③ 内積項

$$1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star = 1 + \cos \Psi \cos \theta + \sin \Psi \cos \phi \sin \theta$$

- ◆ 積分区間

$$\epsilon_{\min} = \frac{2m_e^2 c^4}{E (1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star)} \quad \text{対生成の閾値}$$

$$c_{\min} = \sqrt{1 - \left(\frac{R_{\text{ph}}(t)}{d} \right)^2} \quad \text{軟光子の発生領域の下限}$$

$$d = \sqrt{R_{\text{sh}}^2(t) + l^2 - 2R_{\text{sh}}(t)l \cos \Psi_0}$$

$$\Psi_{0,\min} = \arcsin \left(\frac{R_{\text{ph}}(t)}{R_{\text{sh}}(t)} \right) \quad \gamma\text{-ray の発生領域の下限}$$

- ◆ 衝撃波半径

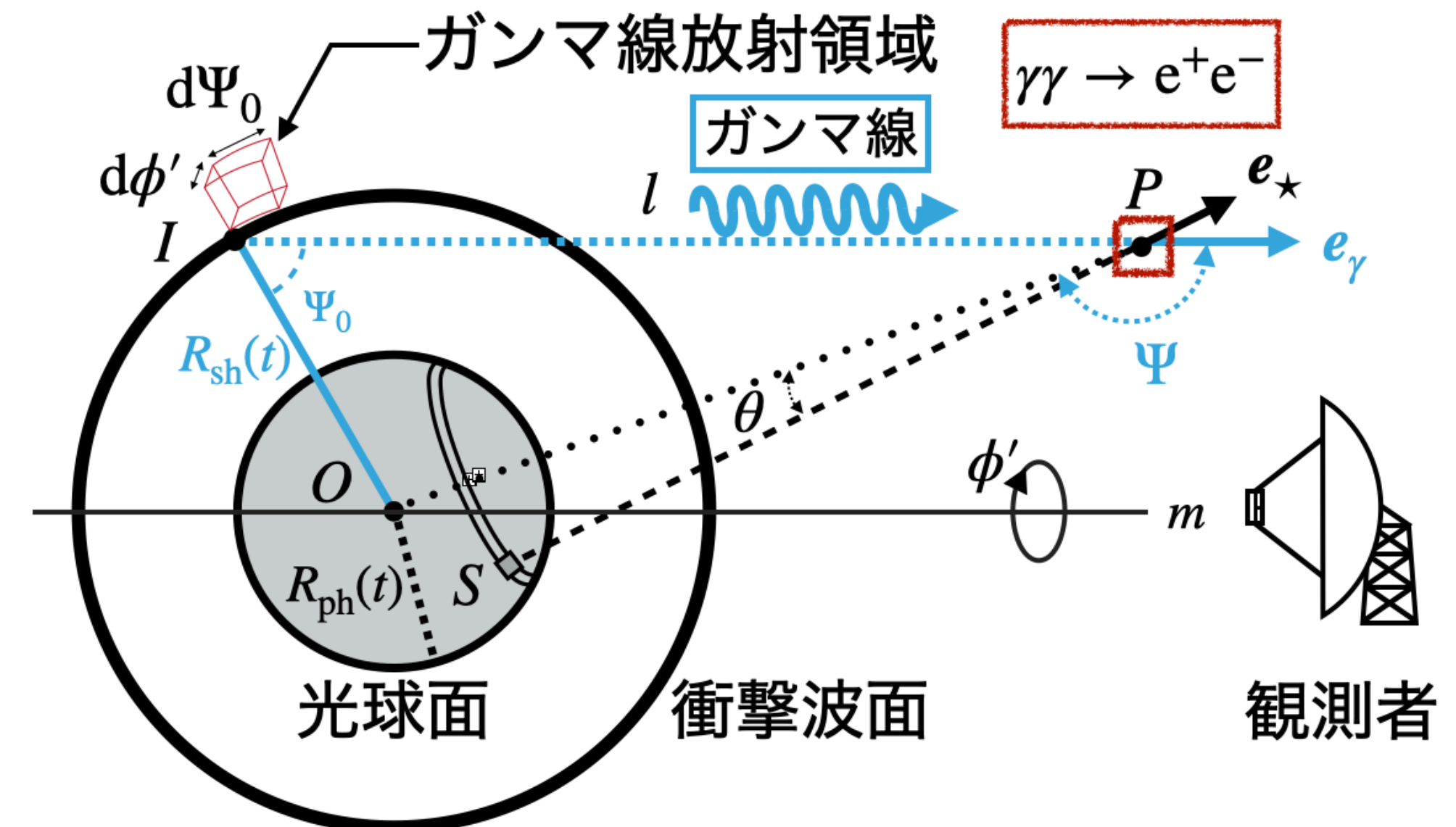
$$R_{\text{sh}}(t) = R_0 \times \left(\frac{t}{t_0} \right)^m$$

- ◆ 光球半径

$$R_{\text{ph}}(t) : \text{観測値}$$

- ◆ 光球表面温度

$$T_{\text{ph}}(t) : \text{観測値}$$



被積分関数の時間依存 GC ver.

- 時刻 t に点 I で放射されたガンマ線について

$$\tau_{\gamma\gamma}(t, E, \Psi_0) = \int_0^{+\infty} dl \int_{c_{\min}}^1 d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon \frac{d\tau_{\gamma\gamma}}{d\epsilon d\Omega dl}$$

$$d\tau_{\gamma\gamma} = \underbrace{(1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star)}_{\text{①}} \underbrace{n_\epsilon}_{\text{②}} \underbrace{\sigma_{\gamma\gamma}}_{\text{③}} d\epsilon d\Omega dl$$

- ② 点 P での軟光子数密度: n_ϵ

$$n(\epsilon, t) = \frac{2\epsilon^2}{h^3 c^3} \frac{1}{\exp(\epsilon/k_B T(t)) - 1} [\text{cm}^{-3} \text{erg}^{-1} \text{sr}^{-1}]$$

- 光球表面温度: $T(t)$

- ① 内積項: $1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star$

$$1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star = 1 + \cos\Psi \cos\theta + \sin\Psi \cos\phi \sin\theta$$

$$\Psi = \tan^{-1} \left(\frac{R_{\text{sh}}(t) \sin\Psi_0}{R_{\text{sh}}(t) \cos\Psi_0 - l} \right) \quad \text{for } l < d_0 \cos\Psi_0$$

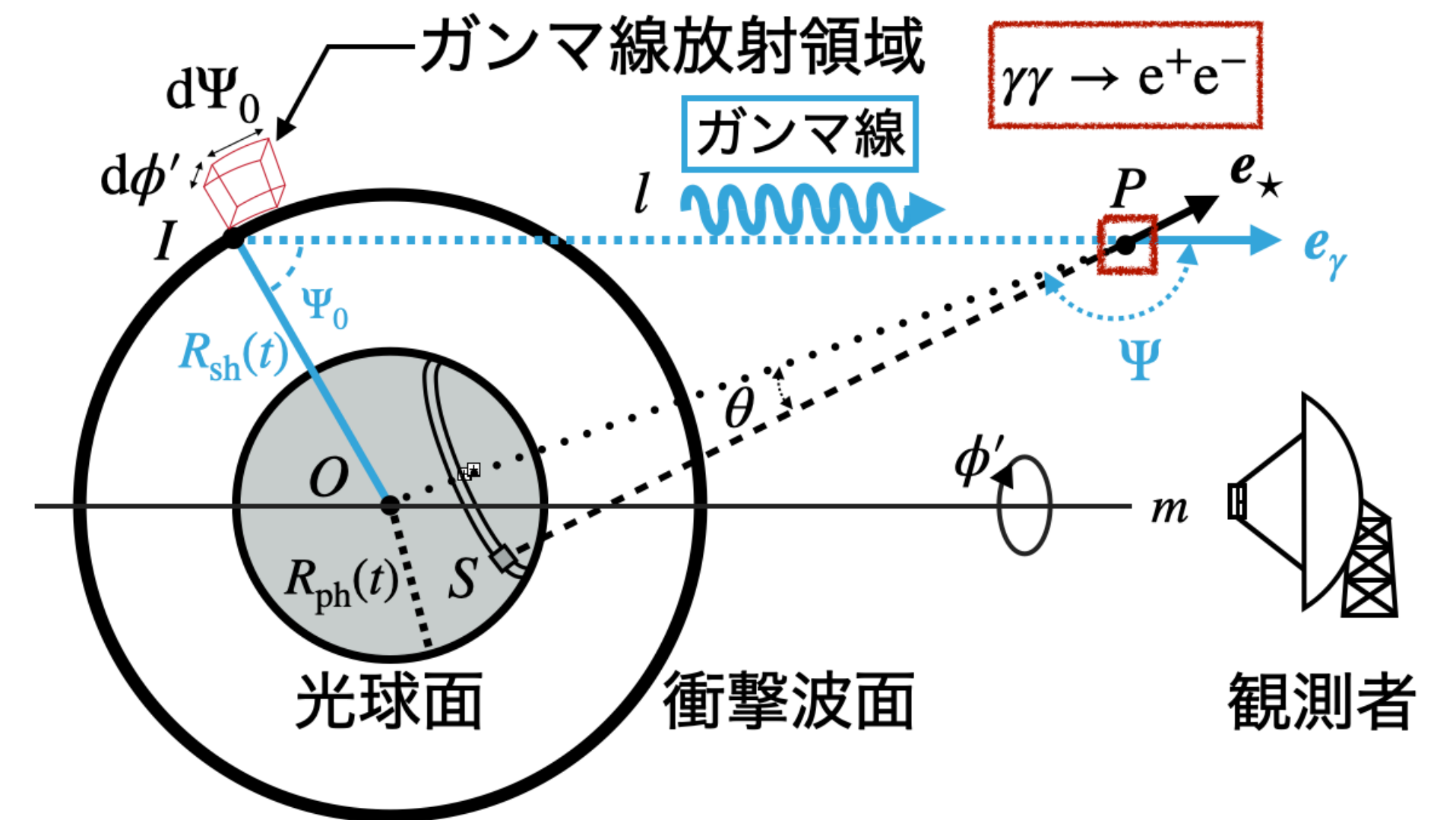
$$\Psi = \pi + \tan^{-1} \left(\frac{R_{\text{sh}}(t) \sin\Psi_0}{R_{\text{sh}}(t) \cos\Psi_0 - l} \right) \quad \text{for } l > d_0 \cos\Psi_0$$

- ③ 散乱断面積: $\sigma_{\gamma\gamma}$

$$\sigma_{\gamma\gamma} = \frac{1}{2} \pi r_0^2 (1 - \beta^2) \left[(3 - \beta^4) \ln \frac{1 + \beta}{1 - \beta} - 2\beta (2 - \beta^2) \right]$$

$$\beta = \left(1 - \frac{1}{s} \right)^{1/2} \quad s = \frac{\epsilon E}{2m_e^2 c^4} (1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star)$$

$1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star$ 時間依存あり



対消滅の閾値 $\epsilon_{\min}$ の意味

$$\tau_{\gamma\gamma}(E, \Psi) = \int_0^{+\infty} dl \int_{c_{\min}}^1 d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon n_{\epsilon} \sigma_{\gamma\gamma} (1 - \mathbf{e}_{\gamma} \cdot \mathbf{e}_{\star})$$

$$\underline{\underline{\epsilon_{\min}}} = \frac{2m_e^2 c^4}{E} \frac{1}{(1 - \mathbf{e}_{\gamma} \cdot \mathbf{e}_{\star})}$$

- $\mathbf{e}_{\gamma}$ と $\mathbf{e}_{\star}$ が **Parallel**

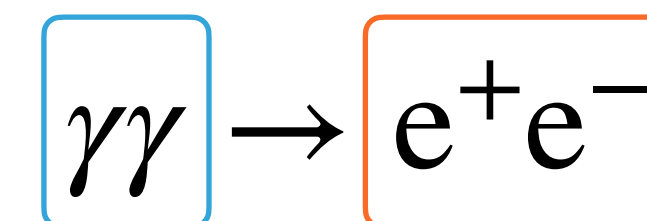
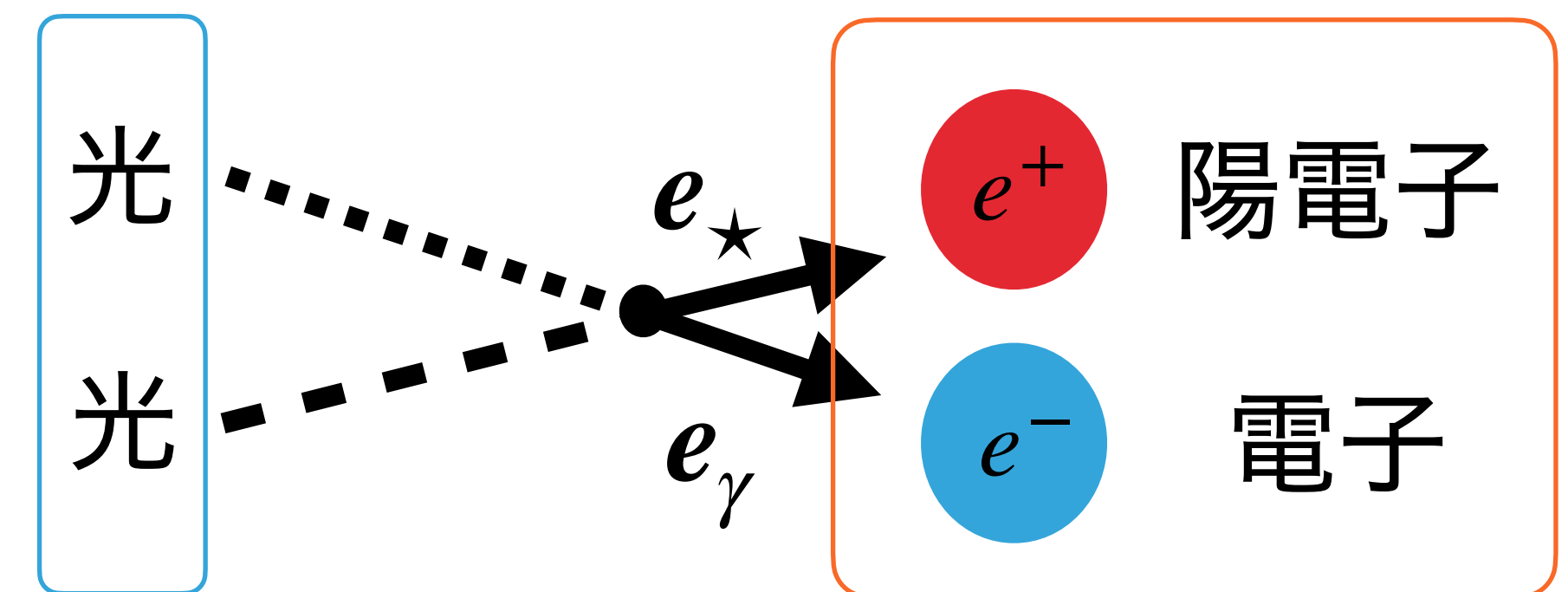
$\mathbf{e}_{\gamma} \cdot \mathbf{e}_{\star} = 1$ となり $\epsilon_{\min}$ が発散
→ 対消滅は起こらない

- $\mathbf{e}_{\gamma}$ と $\mathbf{e}_{\star}$ が **Head-on**

$\mathbf{e}_{\gamma} \cdot \mathbf{e}_{\star} = -1$ となり $\epsilon_{\min}$ が最小値 $m_e^2 c^4 / E$
→ 小さいエネルギーで対消滅が起こる

反応前

反応後



積分区間 $c_{\min}$

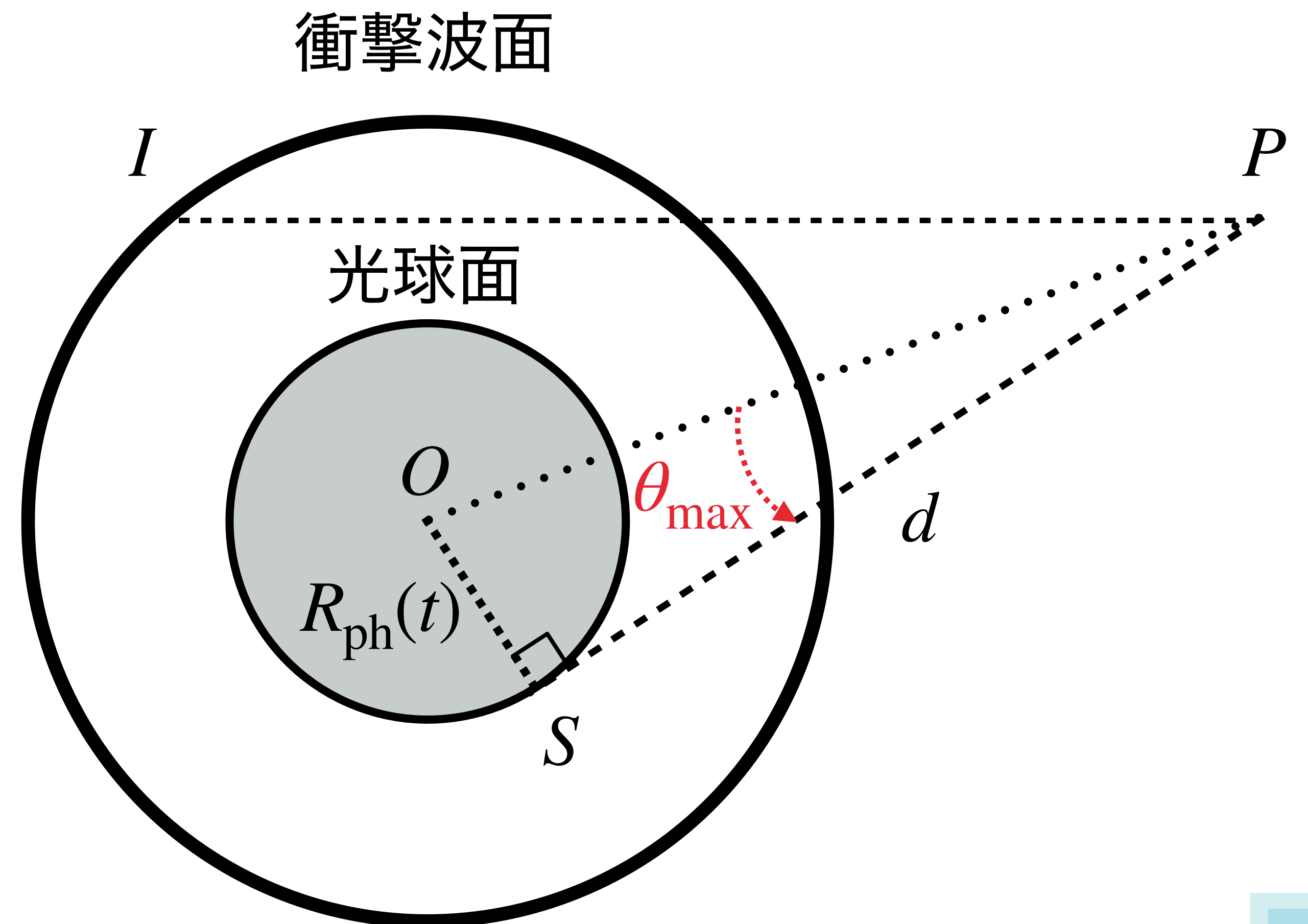
$$\tau_{\gamma\gamma}(E, \Psi) = \int_0^{+\infty} dl \int_{\underline{c_{\min}}}^1 d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon \left(1 - \mathbf{e}_\gamma \cdot \mathbf{e}_\star\right) n_\epsilon \sigma_{\gamma\gamma}$$

$\theta_{\max}$:
軟光子が相互作用点 P へ

到達する θ の最大値

$c_{\min}$ = $\cos(\theta_{\max})$: $\cos\theta$ の最小値

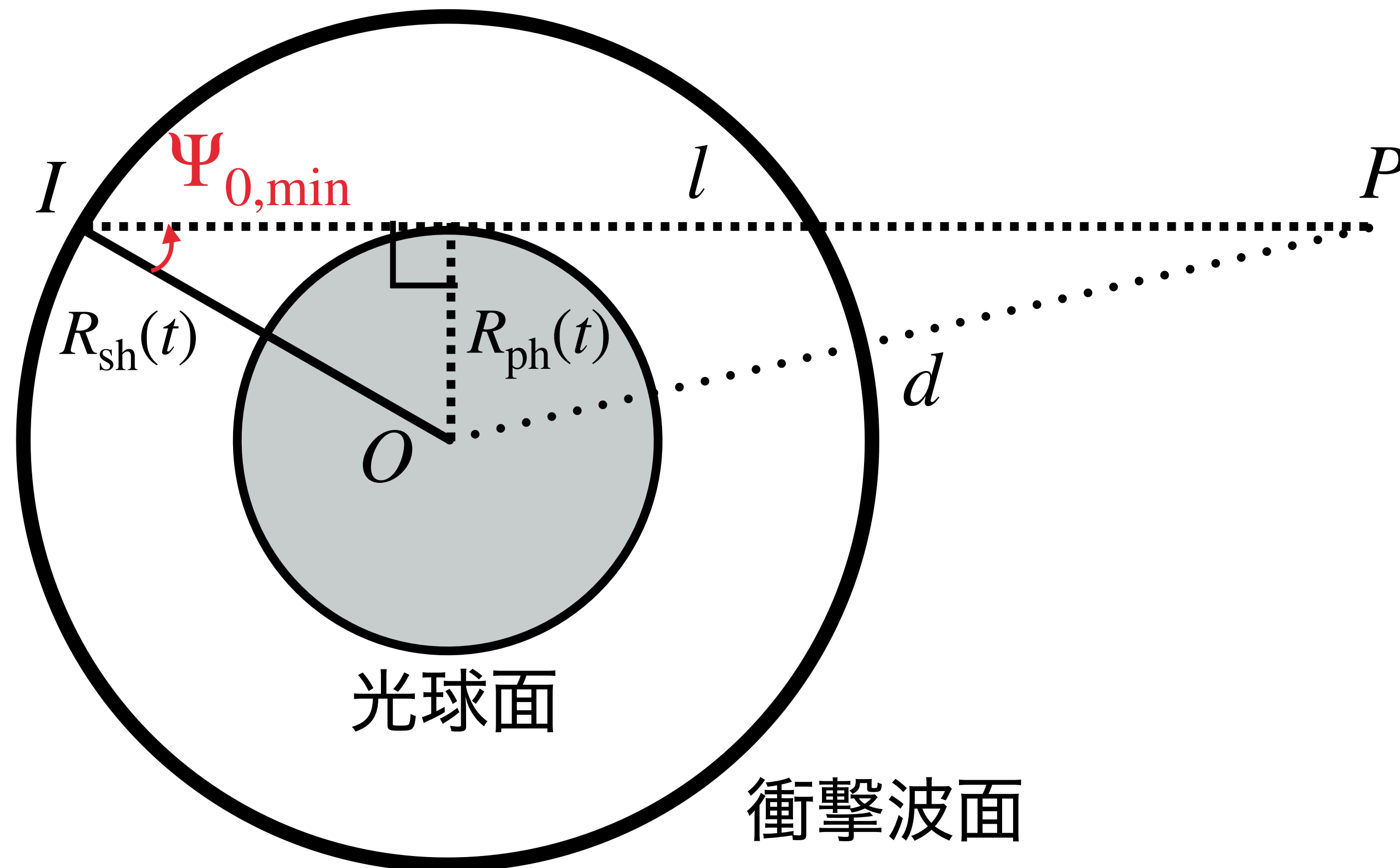
$$c_{\min} = \sqrt{1 - \left(\frac{R_{\text{ph}}(t)}{d}\right)^2}$$



積分区間 $\Psi_{0,\min}$

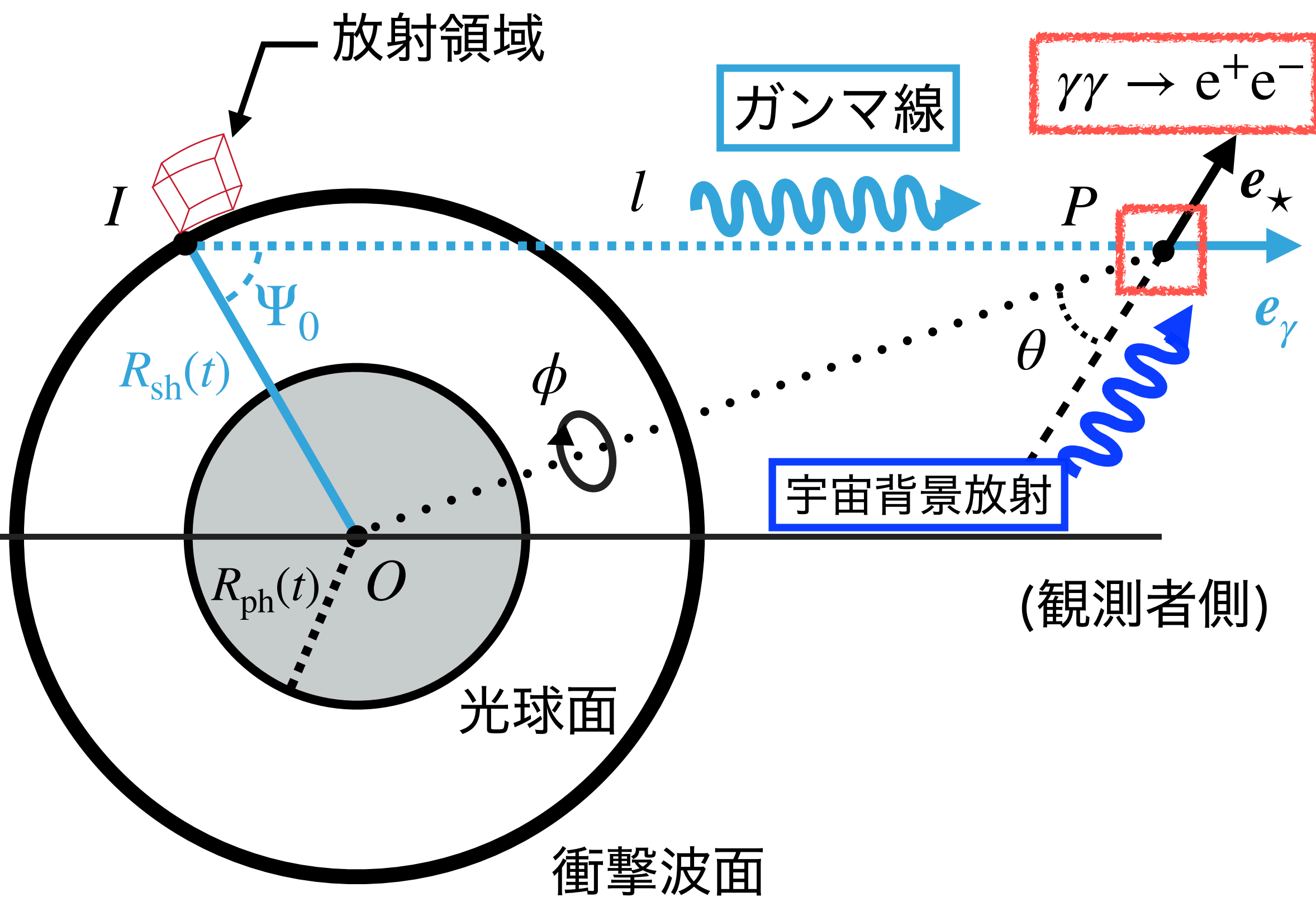
$\Psi_{0,\min}$: ガンマ線が光球に衝突せず, 点 P に到達できる Ψ_0 の最小値

$$R_{\text{sh}}(t) \sin(\Psi_{0,\min}) = R_{\text{ph}}(t)$$



$$\Psi_{0,\min} = \arcsin \left(\frac{\max(R_{\text{ph}}(t))}{R_{\text{sh}}(t)} \right)$$

ガンマ線の消滅モデル (by 宇宙背景放射)



・ $\tau_{\gamma\gamma}$ 光球光子の不透明度との相違点

- ① 宇宙背景放射はあらゆる方向から飛来する
- ② 宇宙背景放射の数密度のエネルギー分布が異なる

◆ 光球光子による, ガンマ線の不透明度

$$\tau_{\gamma\gamma}(t, \Psi_0, E) = \int_0^{+\infty} dl \int_{c_{\min}}^1 d \cos \theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon n_{\epsilon} \sigma_{\gamma\gamma} (1 - \mathbf{e}_{\gamma} \cdot \mathbf{e}_{\star})$$

①

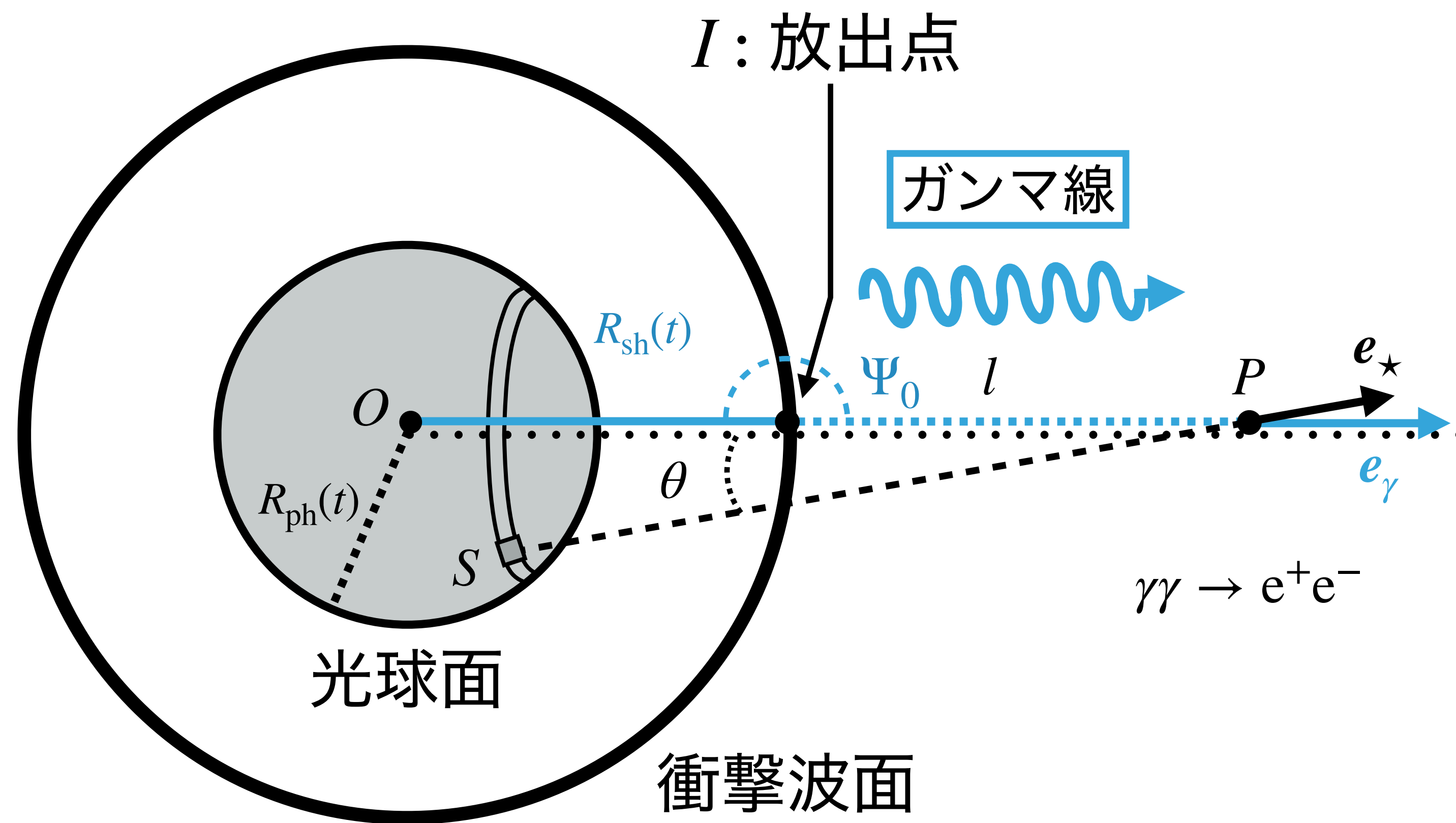
②

◆ 宇宙背景放射 (CBR) による, ガンマ線の不透明度

$$\tau_{\text{CBR}}(t, \Psi_0, E) = \int_0^{+\infty} dl \int_{-1}^1 d \cos \theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon n_{\epsilon} \sigma_{\gamma\gamma} (1 - \mathbf{e}_{\gamma} \cdot \mathbf{e}_{\star})$$

ガンマ線フラックスの減衰モデル (テスト計算)

$$\tau_{\gamma\gamma}(E, \Psi_0) = \int_0^{+\infty} dl \int_{c_{\min}}^1 d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^{+\infty} d\epsilon n_{\epsilon} \sigma_{\gamma\gamma} (1 - \mathbf{e}_{\gamma} \cdot \mathbf{e}_{\star})$$



・ 計算法 : 台形則

・ 計算条件

$$\Psi_0 = \pi$$

$E = 1 \text{ TeV}$: ガンマ線のエネルギー

$R_{ph} = 10 R_{\odot}$: 光球半径

$T_{ph} = 4 \times 10^4 \text{ K}$: 光球の表面温度

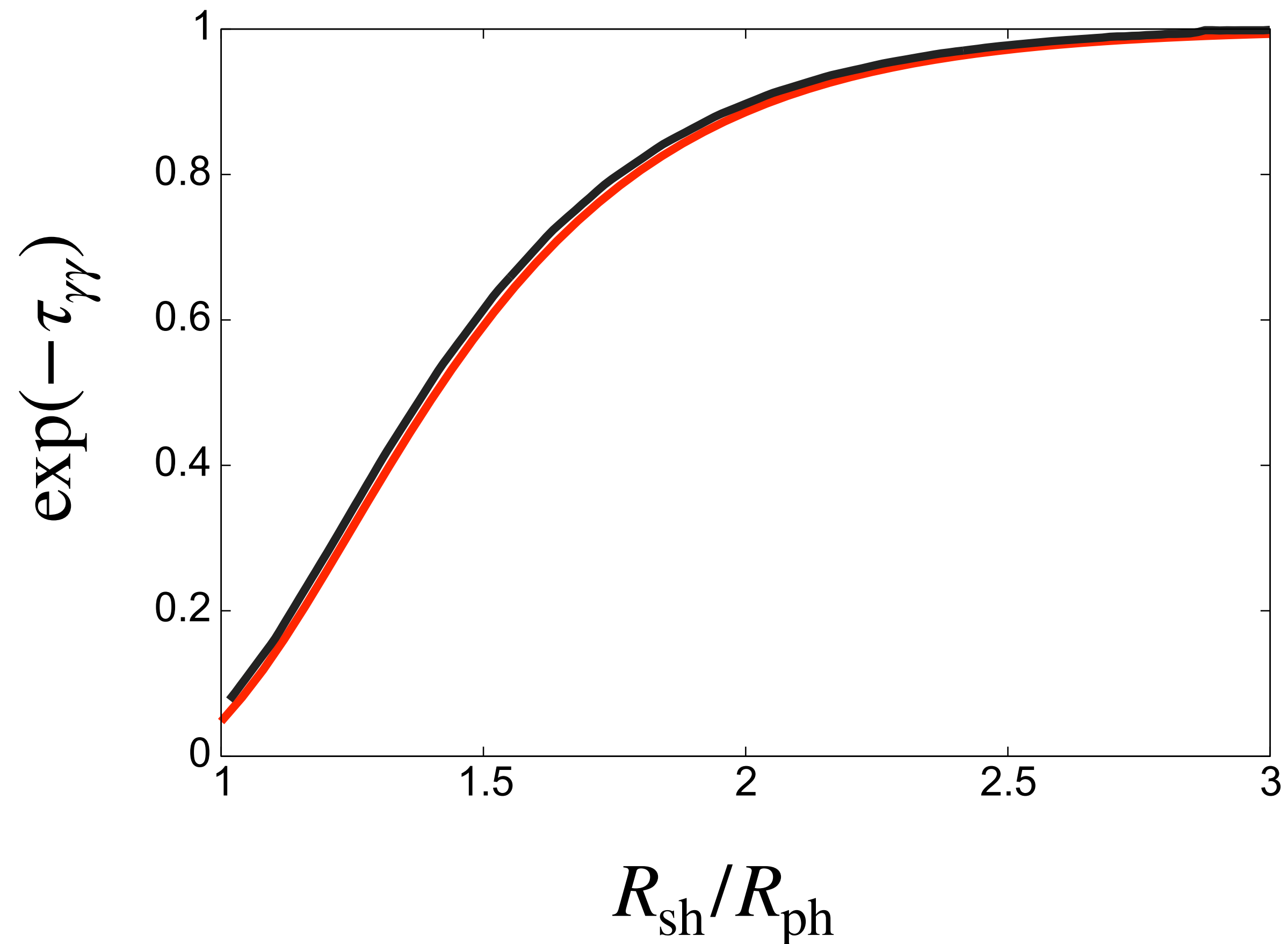
固定

(先行研究 : G. Dubus 2006)

衝撃波半径の広がりに対する不透明度
を求める

不透明度テスト計算結果

ある衝撃波半径 R_{sh} で放射されたガンマ線の不透明度 $\tau_{\gamma\gamma}$



—：テスト計算結果

—：先行研究 (G. Dubus 2006)

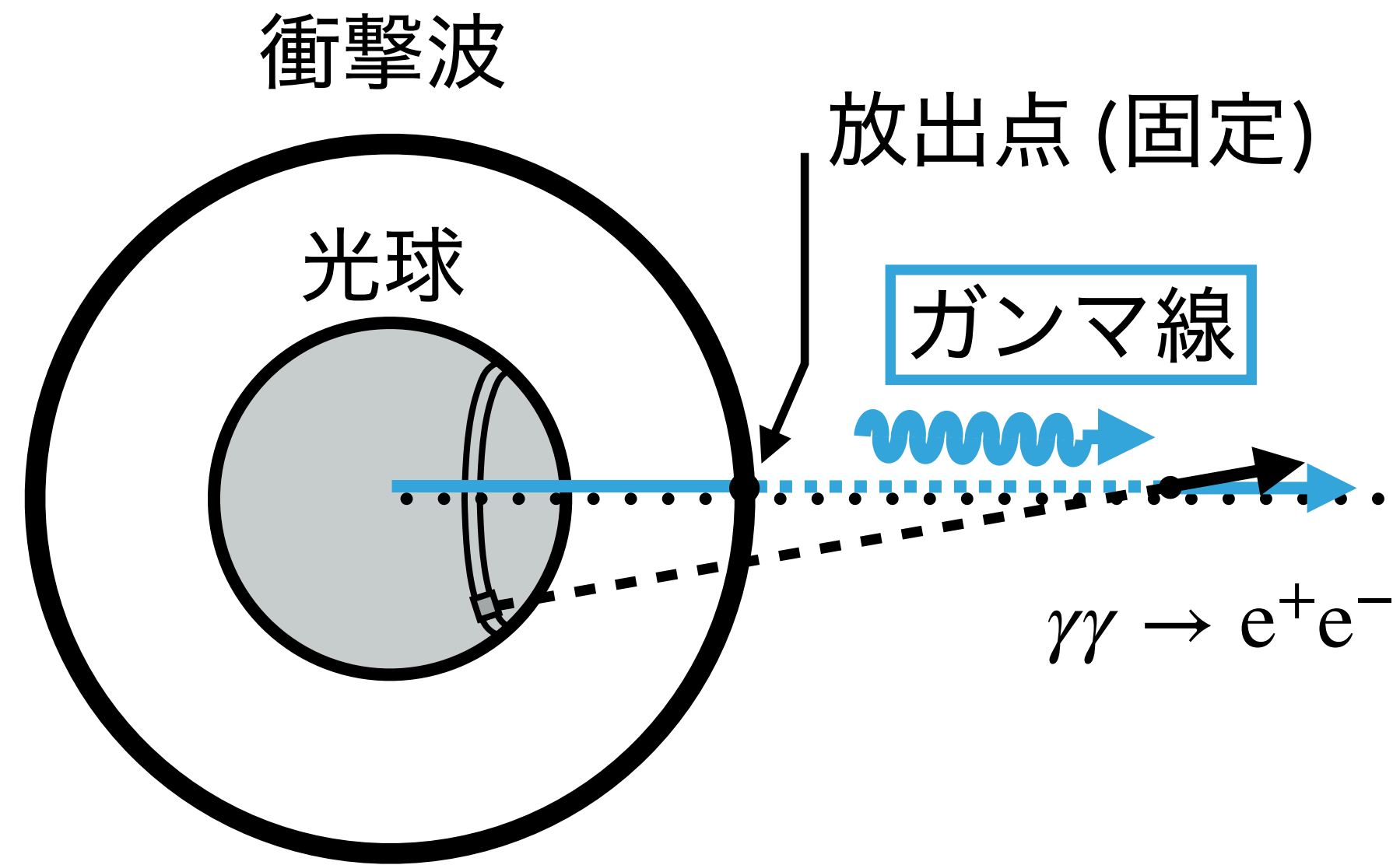
テスト計算結果は,

先行研究 (G. Dubus 2006) での計算結果と一致

星近傍において, 対消滅は高頻度で起こり,

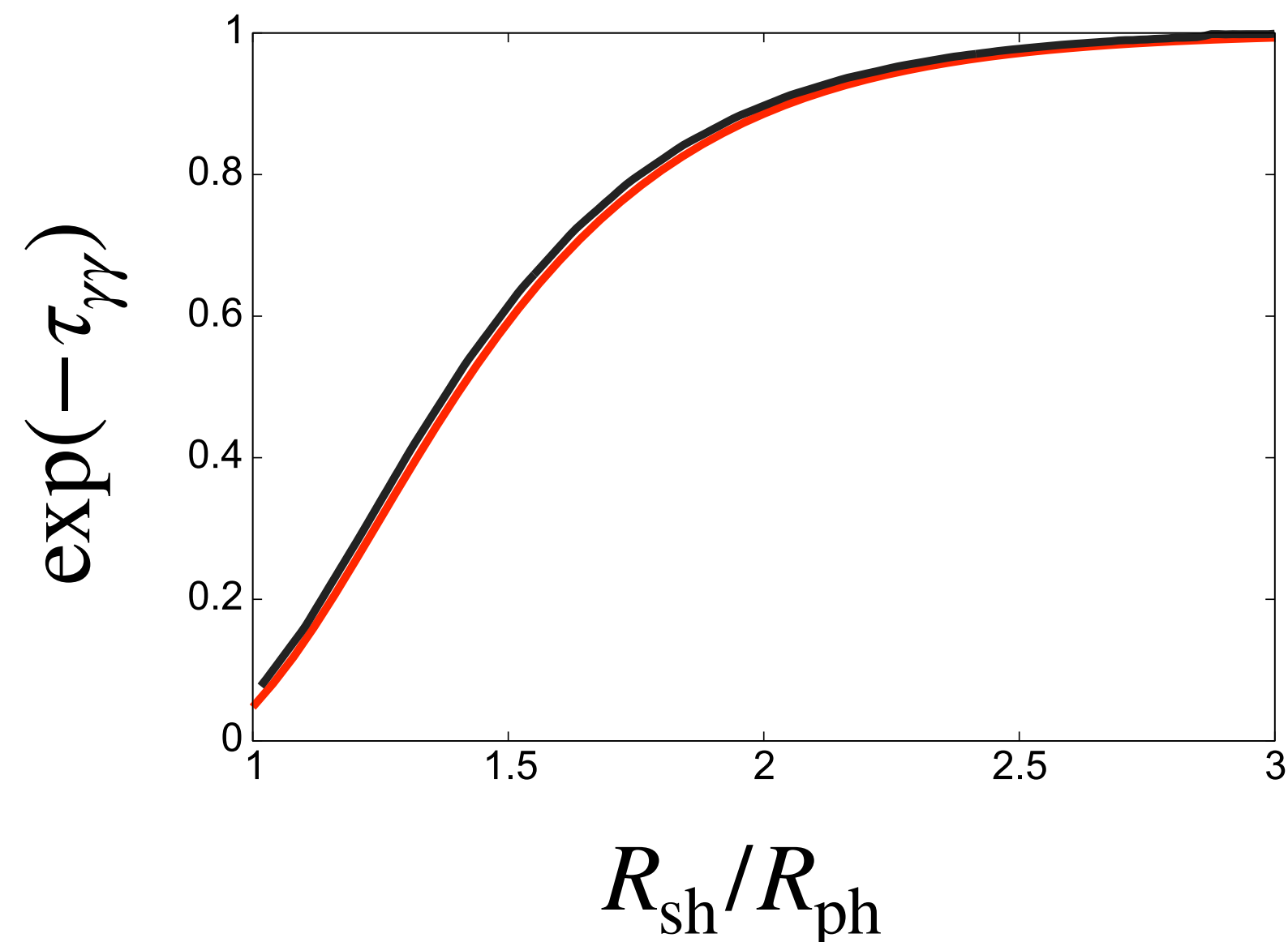
$R_{\text{sh}}/R_{\text{ph}} \geq 3$ 程度ではほとんど無視できる

不透明度テスト計算結果



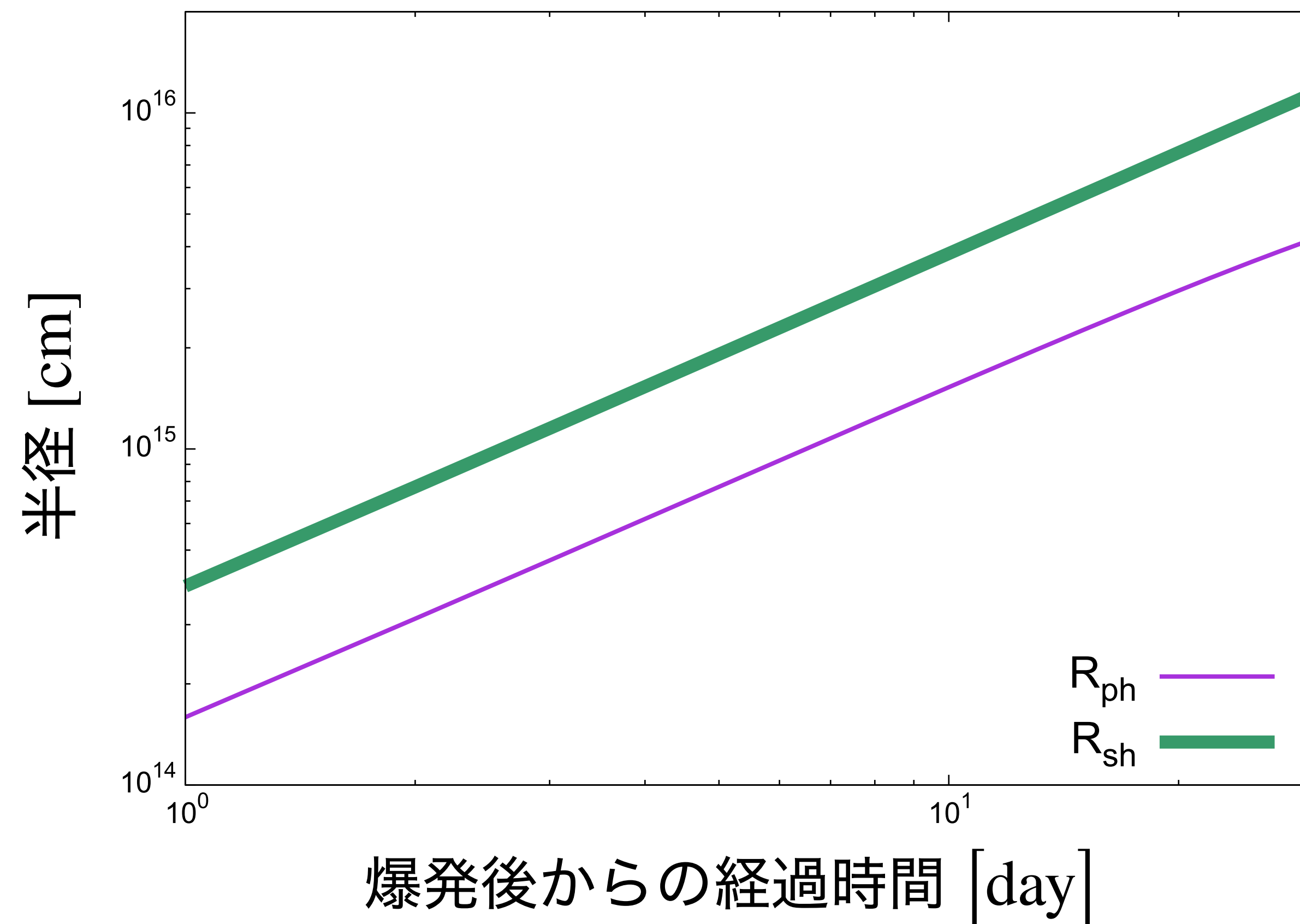
有限の大きさを持つ光球を考えると,
星中心から地球の直線上で放射されたガンマ線
($\Psi_0 = \pi$ or $\Psi = \pi$) でも対消滅が起こる
(光球が点源の場合は起こらない)

衝撃波半径 R_{sh} で放射されたガンマ線の不透明度 $\tau_{\gamma\gamma}$



星近傍において, 対消滅は高頻度で起こり,
 $R_{sh}/R_{ph} \geq 3$ 程度ではほとんど無視できる

光球 & 衝撃波モデル



- 衝撃波半径

$$R_{\text{sh}} = 3.8064 \times 10^{14} \times \left(\frac{t}{1 \text{ day}} \right) + R_0 \text{ cm}$$

$$V_{\text{sh}} = 4.40 \times 10^4 \text{ km s}^{-1}$$

$$R_0 = 1 \times 10^{13} \text{ cm (cf. } R_0 \text{ in Liu et al. 2018)}$$

- 光球半径

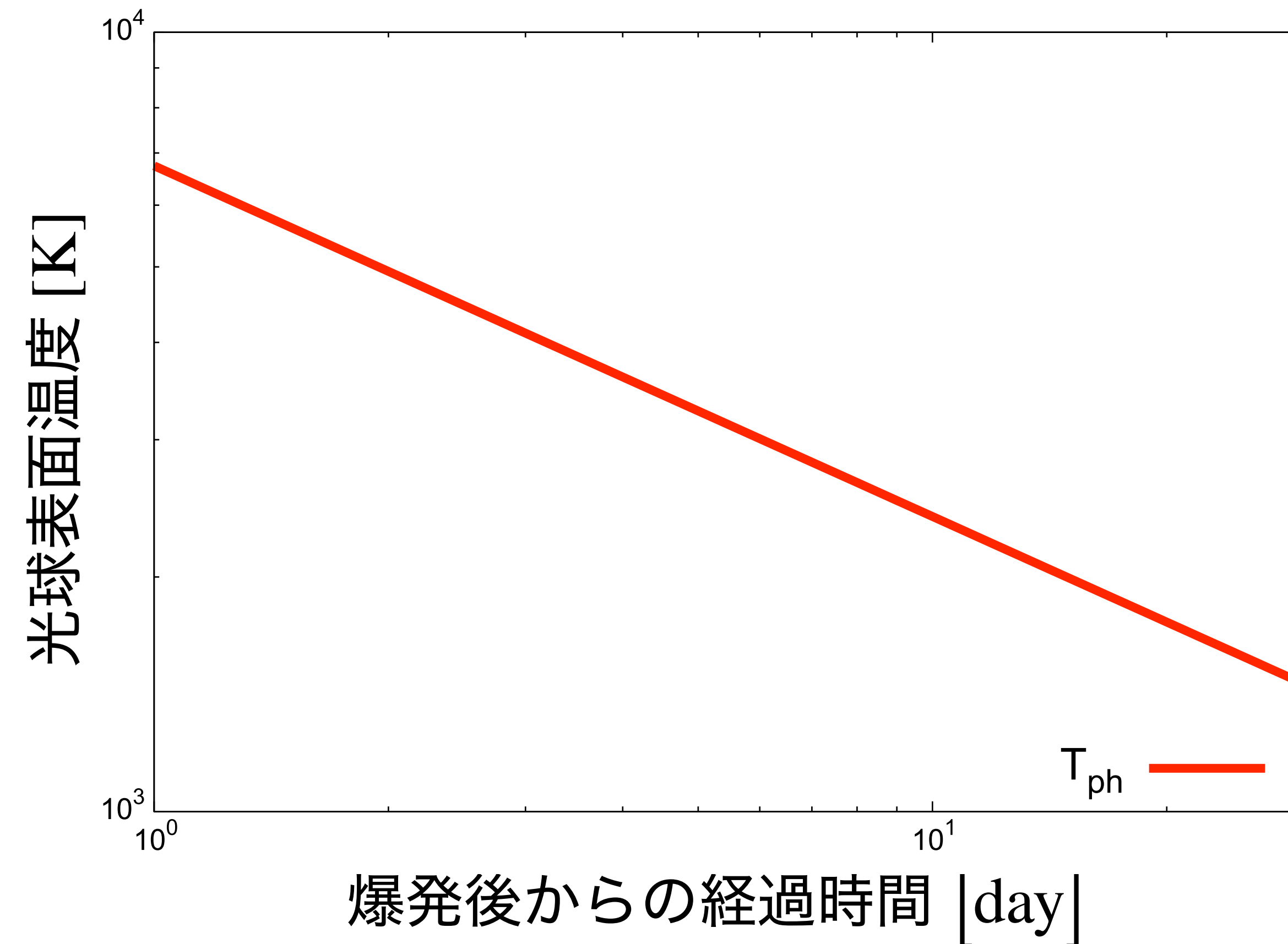
$$x_{\text{ph}} = x_0 \left[1 - \frac{2/3 - \tau_{\text{tot,out}}(t)}{\tau_{\text{tot,in}}(t)} \right] \text{ eq.(37)}$$

$$R_{\text{ph}}(t) = [R(t) - R_{\text{min}}(t)] x_{\text{ph}} + R_{\text{min}}(t) \text{ eq.(19)}$$

Liu et al. 2018

sample72.c
-> N_typical_72.dat (N_typical_71.dat でも可)
sample71_R.plt

光球表面温度モデル



- 光球表面温度

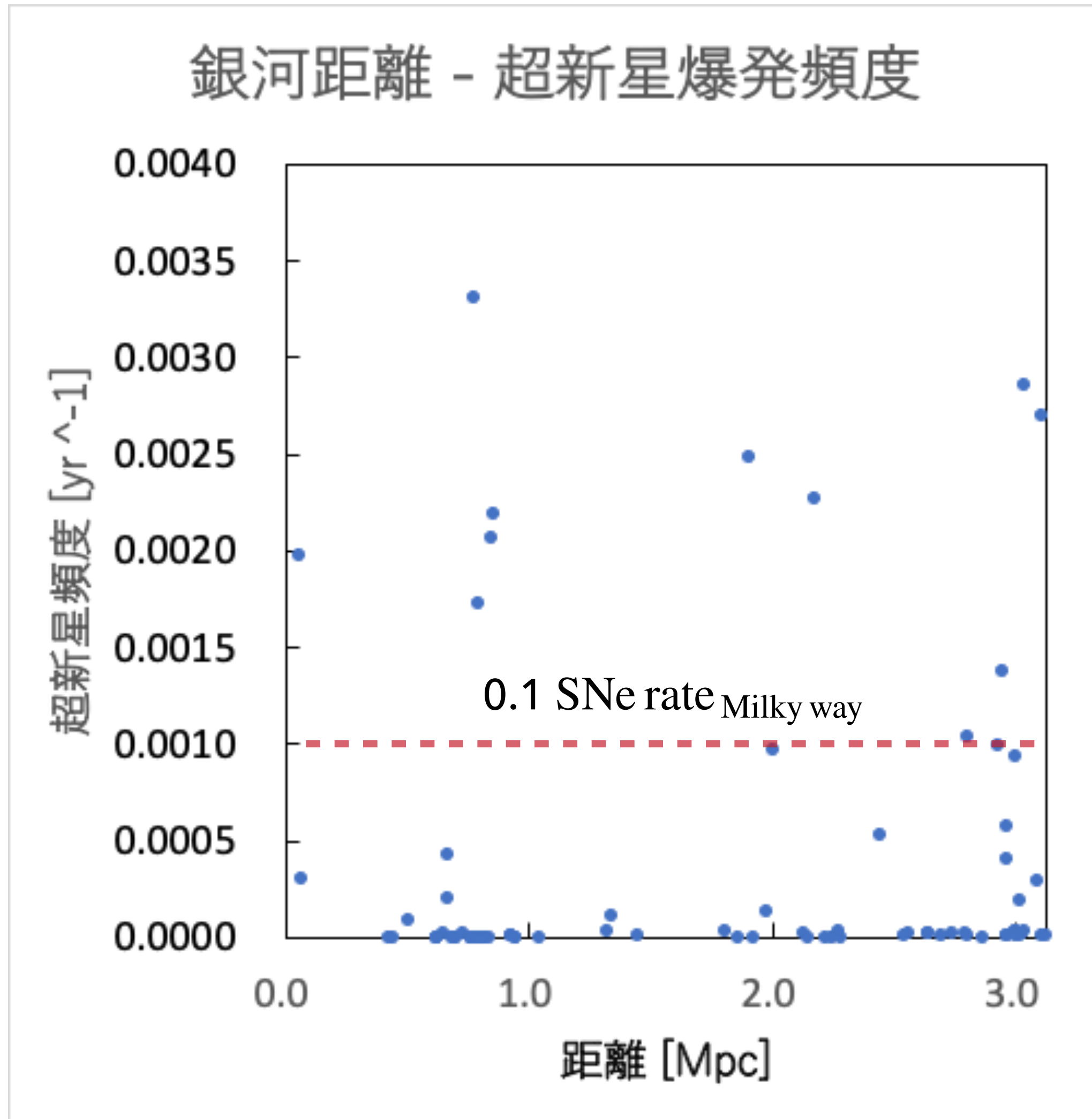
$$T_{\text{ph}} = 1.7 \left(\frac{f_{\rho}}{0.1} \right)^{-0.037} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{0.027} \left(\frac{R_*}{10^{13} \text{ cm}} \right)^{1/4} \left(\frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.28} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{-0.054} \left(\frac{t}{10^5 \text{ s}} \right)^{-0.45} \text{ eV}$$

$$1.7 \text{ eV} \approx 1.9 \times 10^4 \text{ K}$$

Rabinak I., Waxman E., 2011

sample69.c
-> N_typical_69.dat
sample69_T_ph.plt

近傍銀河における超新星頻度



最大：約 0.0033 yr^{-1}

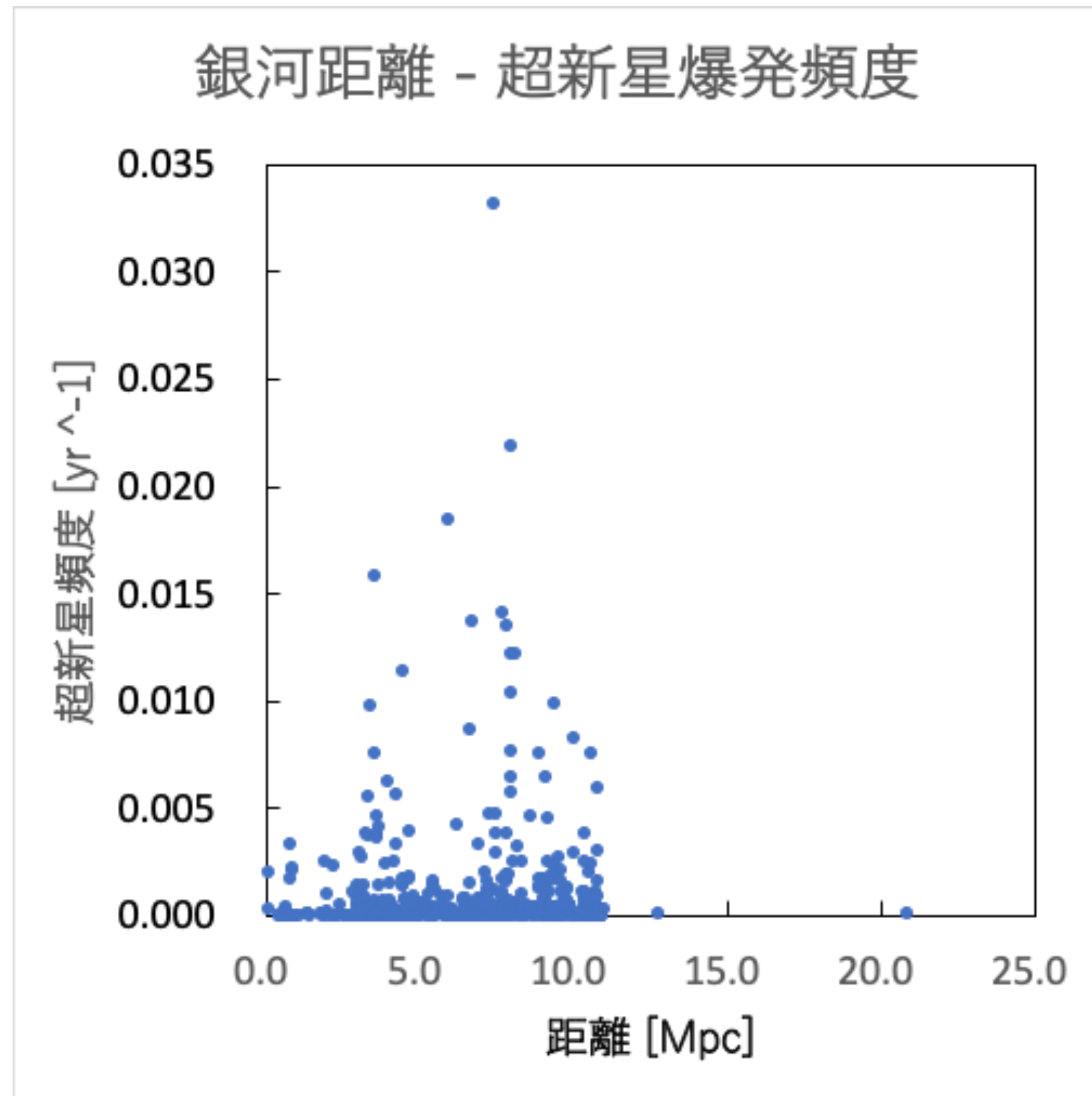
平均：約 0.00037 yr^{-1}

観測可能範囲（3.12 Mpc 以内）には、

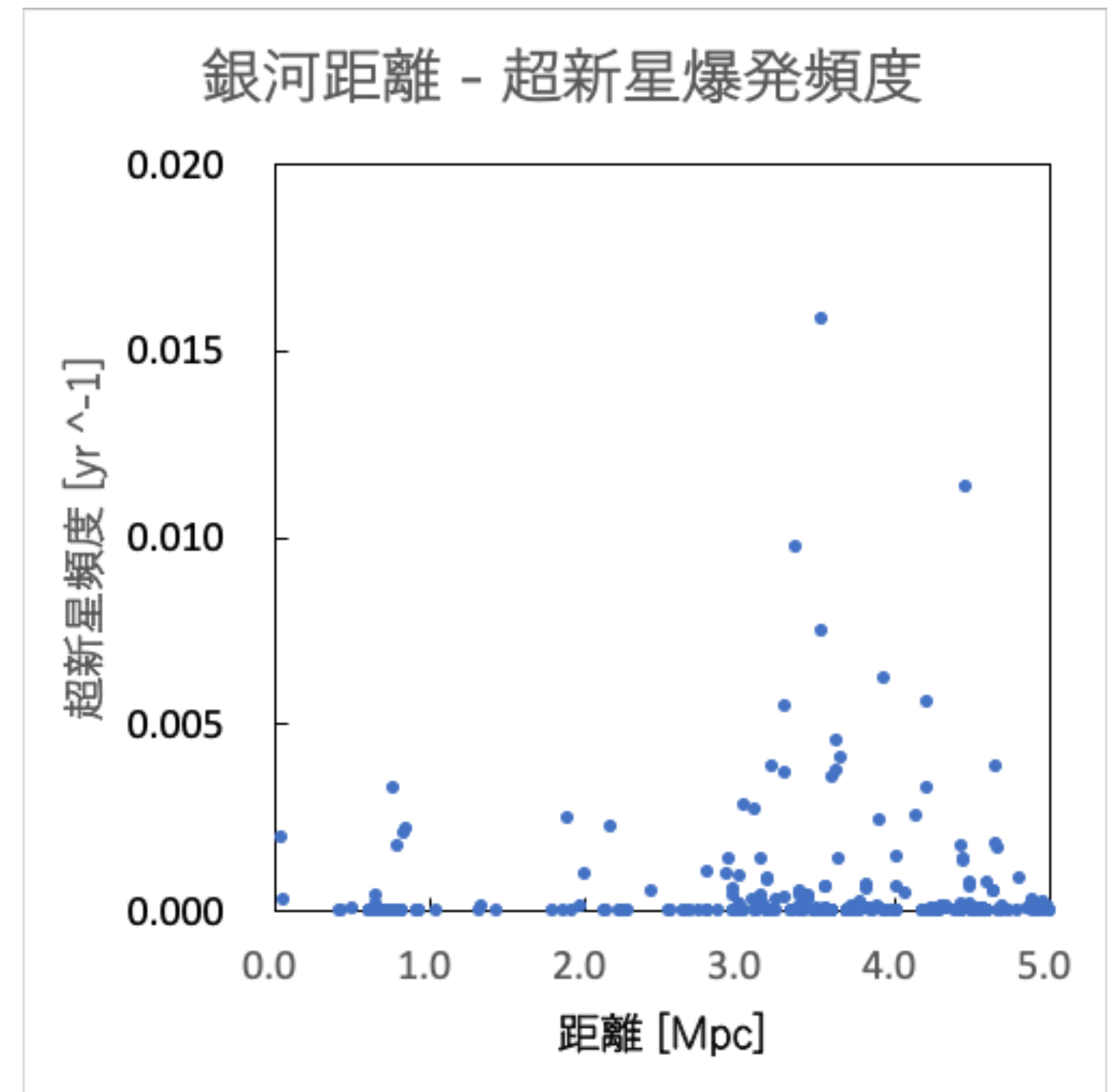
- ・ 天の川銀河の超新星頻度： $0.01 \sim 0.02 \text{ yr}^{-1}$
以上の超新星頻度を持つ銀河は存在しない
- ・ ほとんどが天の川銀河の超新星頻度の
1/10 を下回る

近傍銀河における超新星頻度 (メモ)

・全体データ



・5 Mpc 以内データ



宇宙線注入率 η_{inj}^p

・ 宇宙線注入率 η_{inj}^p

： 衝撃波を受け加熱された粒子 (陽子) の内,
再び衝撃波上流へと戻る粒子の割合

・ 無衝突衝撃の場合

下流のプラズマが加熱され,

分布関数が Maxwell 型になるとは限らない。

しかし, 簡単のためここでは Maxwell 型を仮定する

$$\eta_{\text{inj}}^p = \frac{\int_{p_{\text{inj}}}^{\infty} \exp\left(-\frac{p^2}{p_{\text{th}}^2}\right) p^2 dp}{\int_0^{\infty} \exp\left(-\frac{p^2}{p_{\text{th}}^2}\right) p^2 dp}$$

η_{inj}^p の推定

(Blasi et al. 2005)

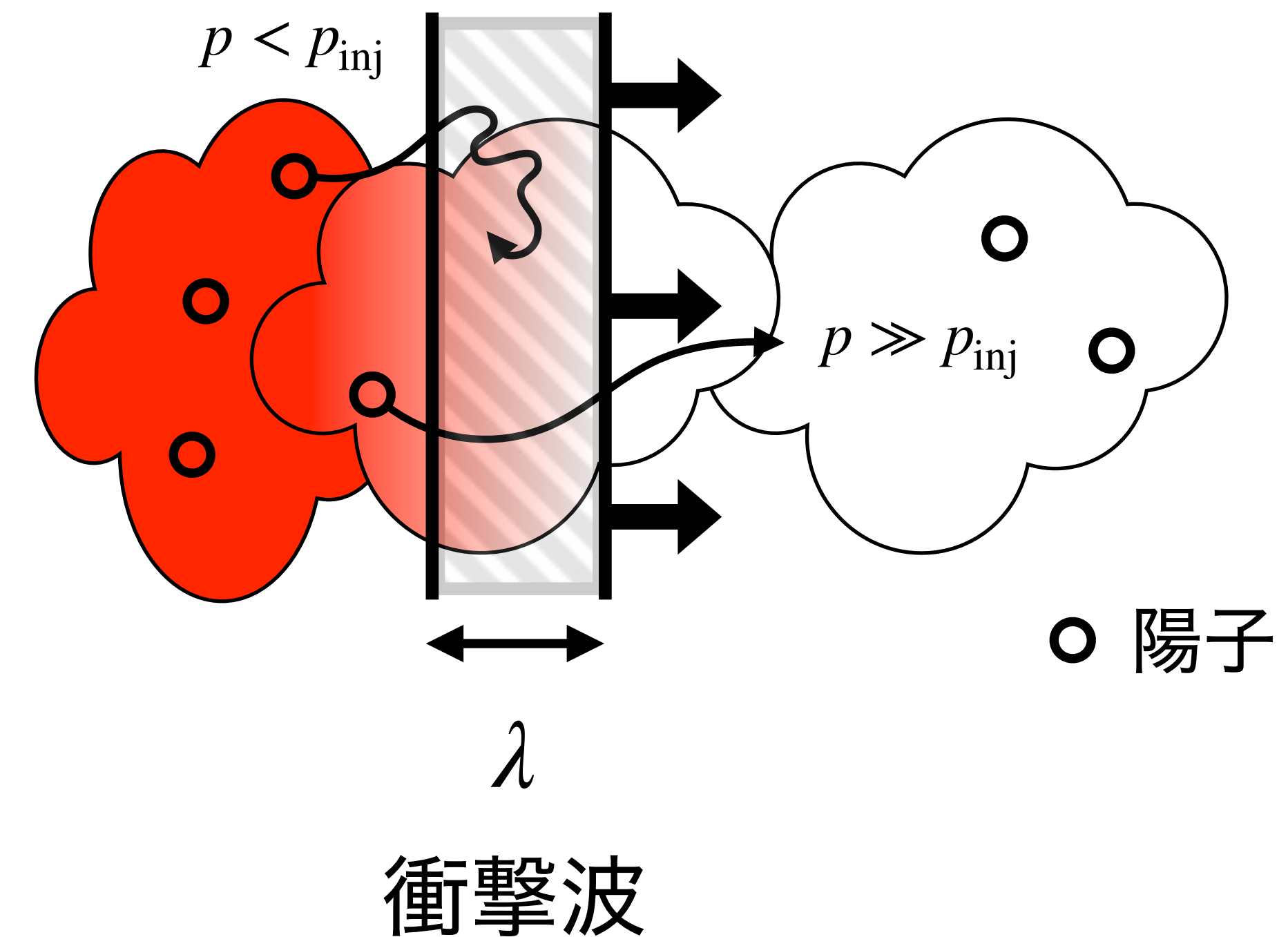
下流 (星中心側)

上流 (星中外側)

無衝突系のプラズマ

✕ 熱分布 (Maxwell 分布)

▲ 熱分布 + 冪分布 (近似) →

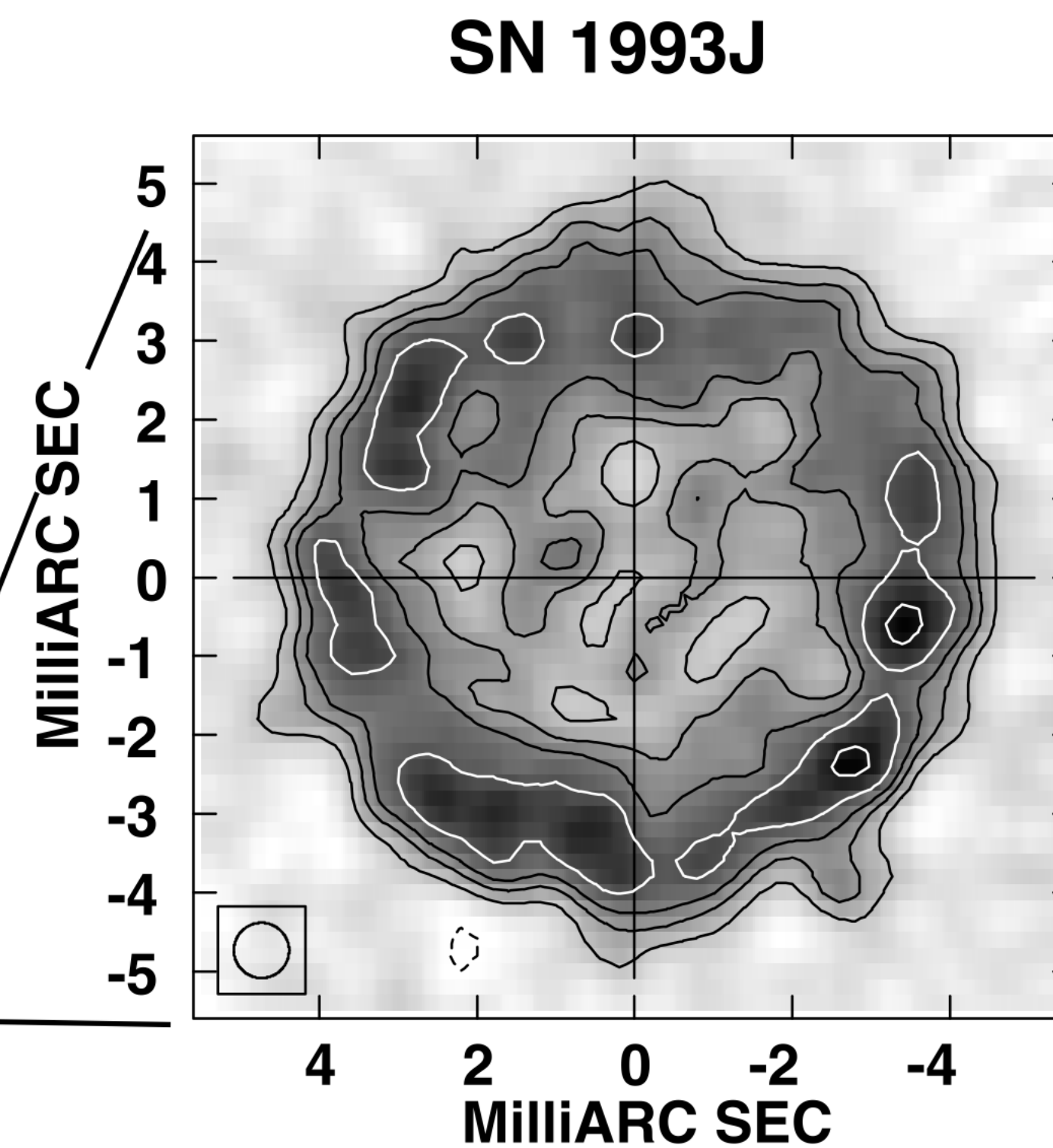
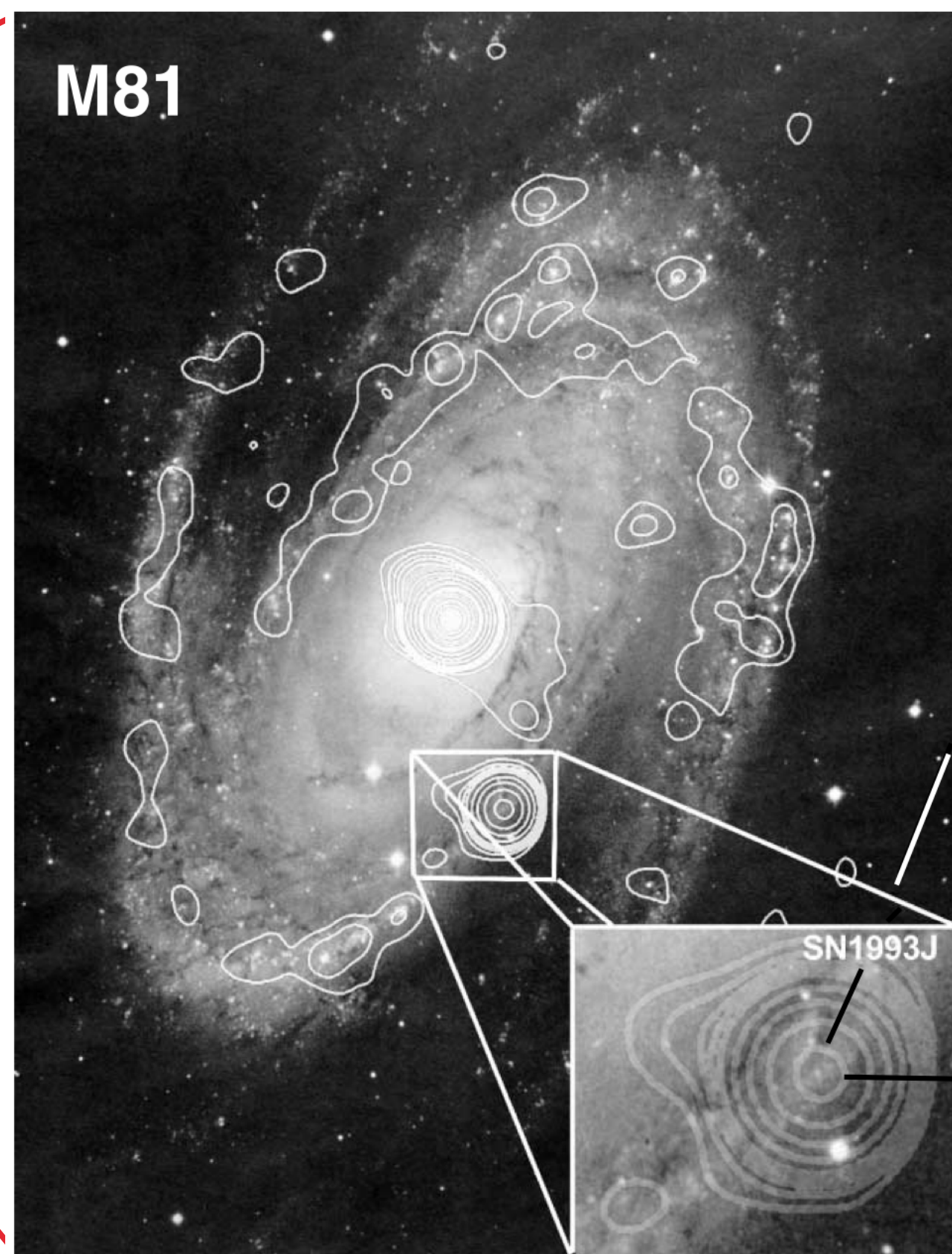
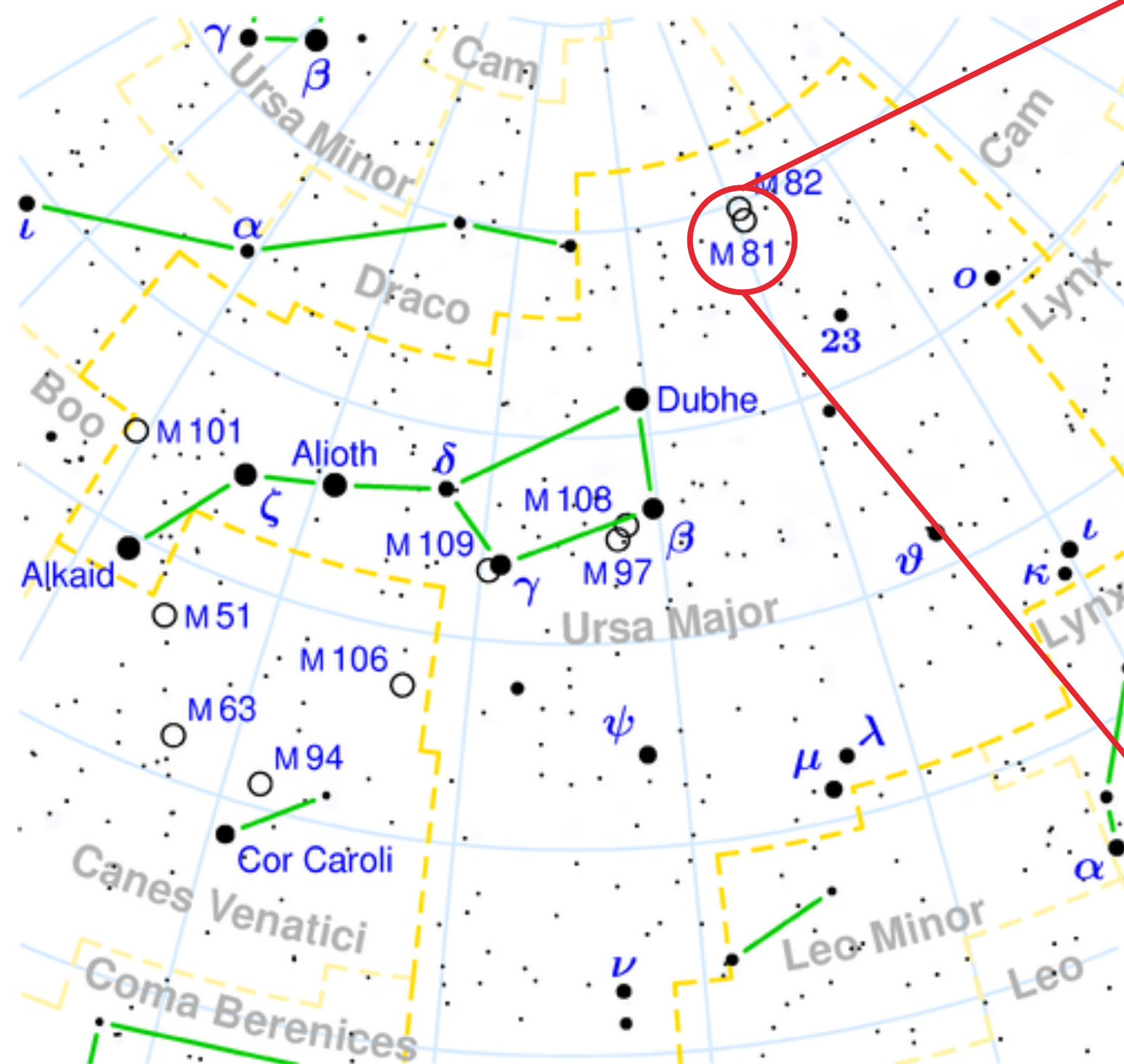


SN1993J

SN1993J in M81

・北天

Ursa Major : おおぐま座



光学画像に VLA (Very Large Array)

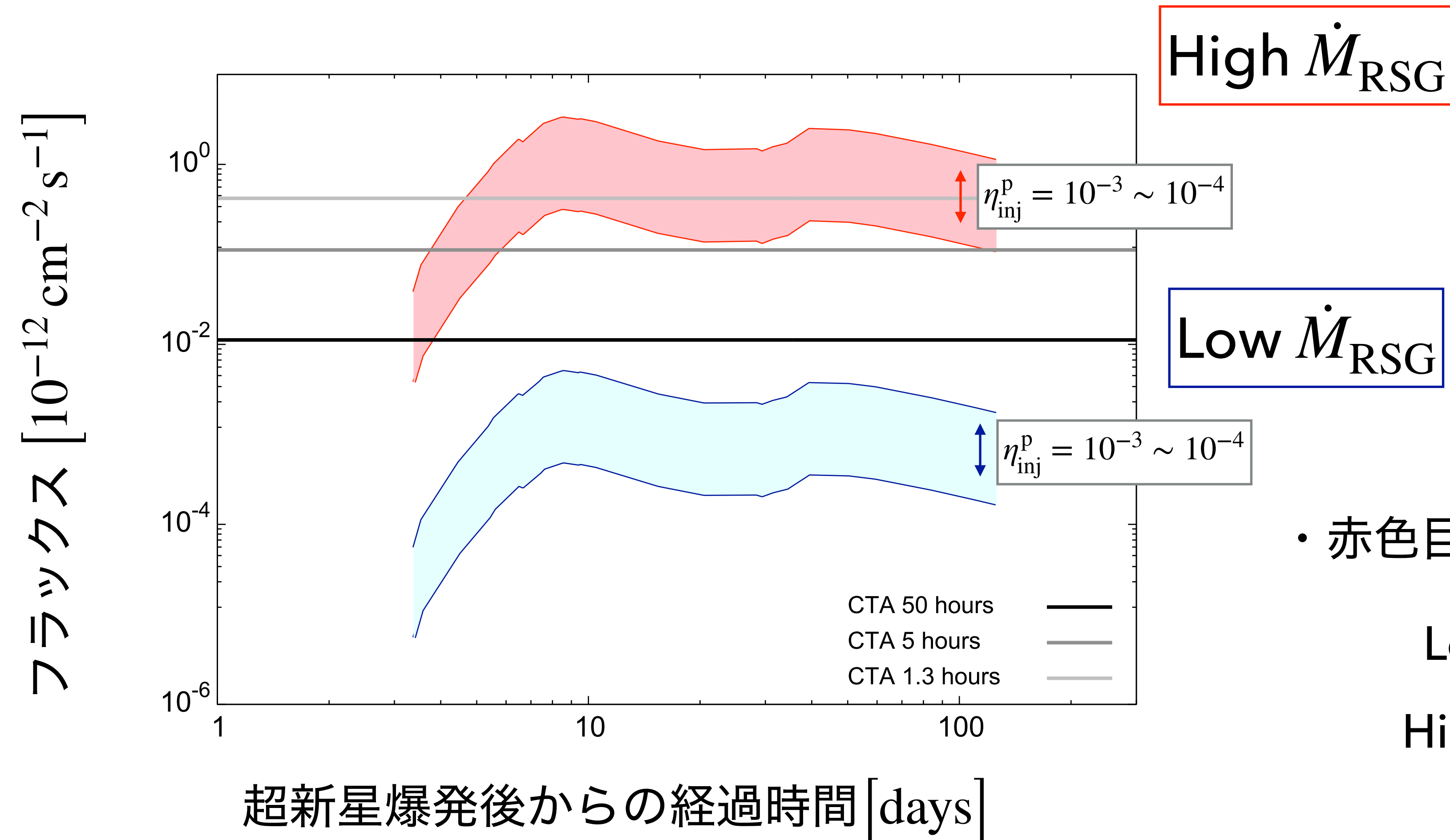
輝度の等高線を重ねた

N. Bartel et. al.

SN 1993J VLBI. IV. A GEOMETRIC DISTANCE TO M81 WITH THE EXPANDING SHOCK FRONT METHOD

SN1993Jのガンマ線フラックス時間発展

エネルギー $E = 100 \text{ TeV}$ のガンマ線について



$D = 3.63 \text{ Mpc}$

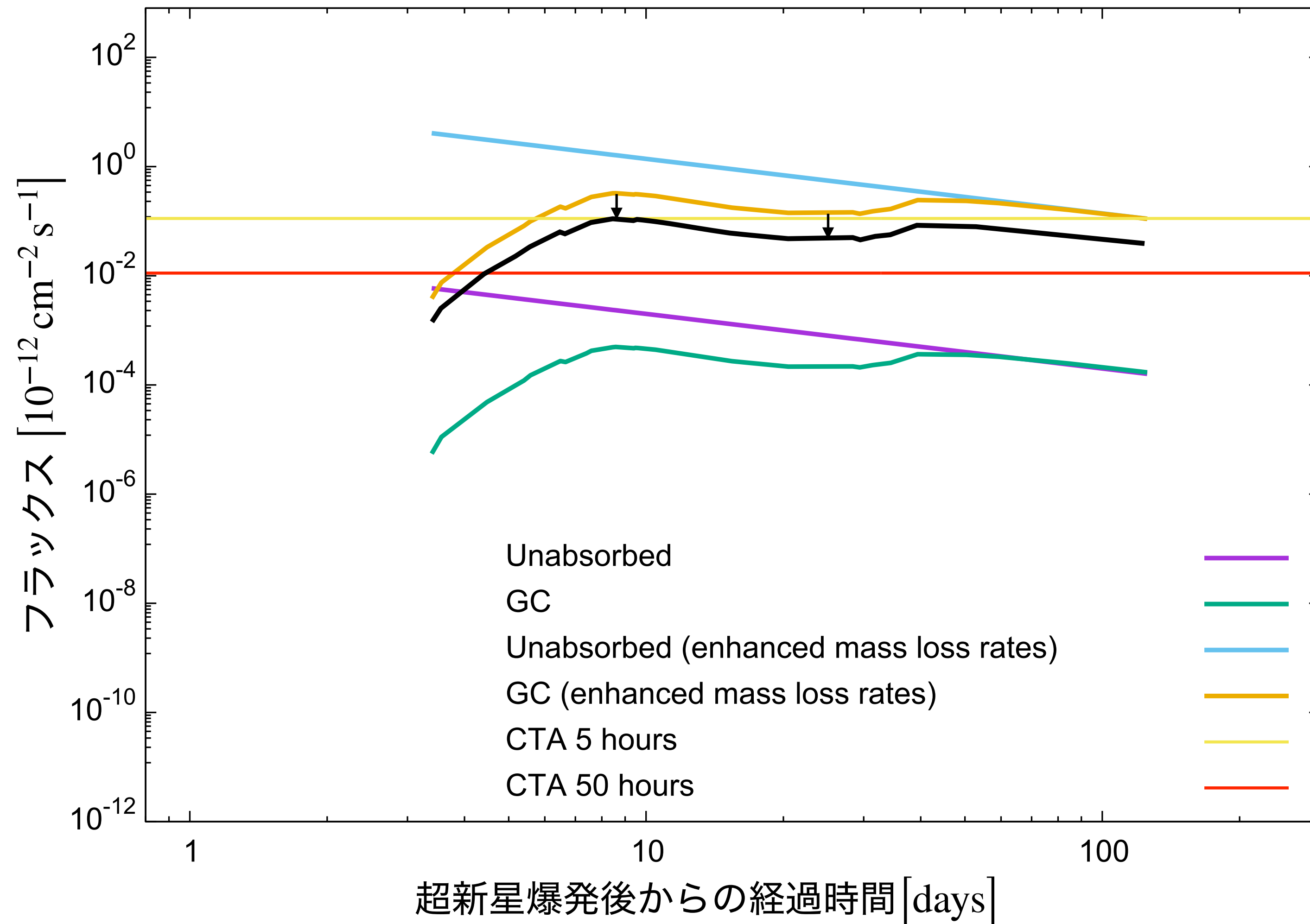
・ 赤色巨星からの質量欠損率 : $\dot{M}_{\text{RSG}}$

Low $\dot{M}_{\text{RSG}} : 3.8 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$

High $\dot{M}_{\text{RSG}} : 10^{-3} M_{\odot} \text{ yr}^{-1}$

t-tau_gg56_100TeV_2.plt

宇宙背景放射によるガンマ線減衰 ④



Unabsorbed : 吸収を考慮しない

GC : 吸収を考慮する

・ 計算条件 (SN1993J を想定)

$D = 3.63 \text{ Mpc}$

$\eta_{\text{inj}}^{\text{p}} = 10^{-4}$

no mark : $\dot{M}_{\text{RSG}} = 3.8 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$

enhanced mass loss rate $\dot{M}_{\text{RSG}} = 10^{-3} M_{\odot} \text{ yr}^{-1}$

— : 背景放射を考慮した Flux (概算)

Flux が約 1/4 となる

RSG の表面磁場

ベテルギウス (α ori)

B_l [Gauss] : 経線方向の磁場 (longitudinal magnetic field) ≈ 1 G

・ B_l の時間変化

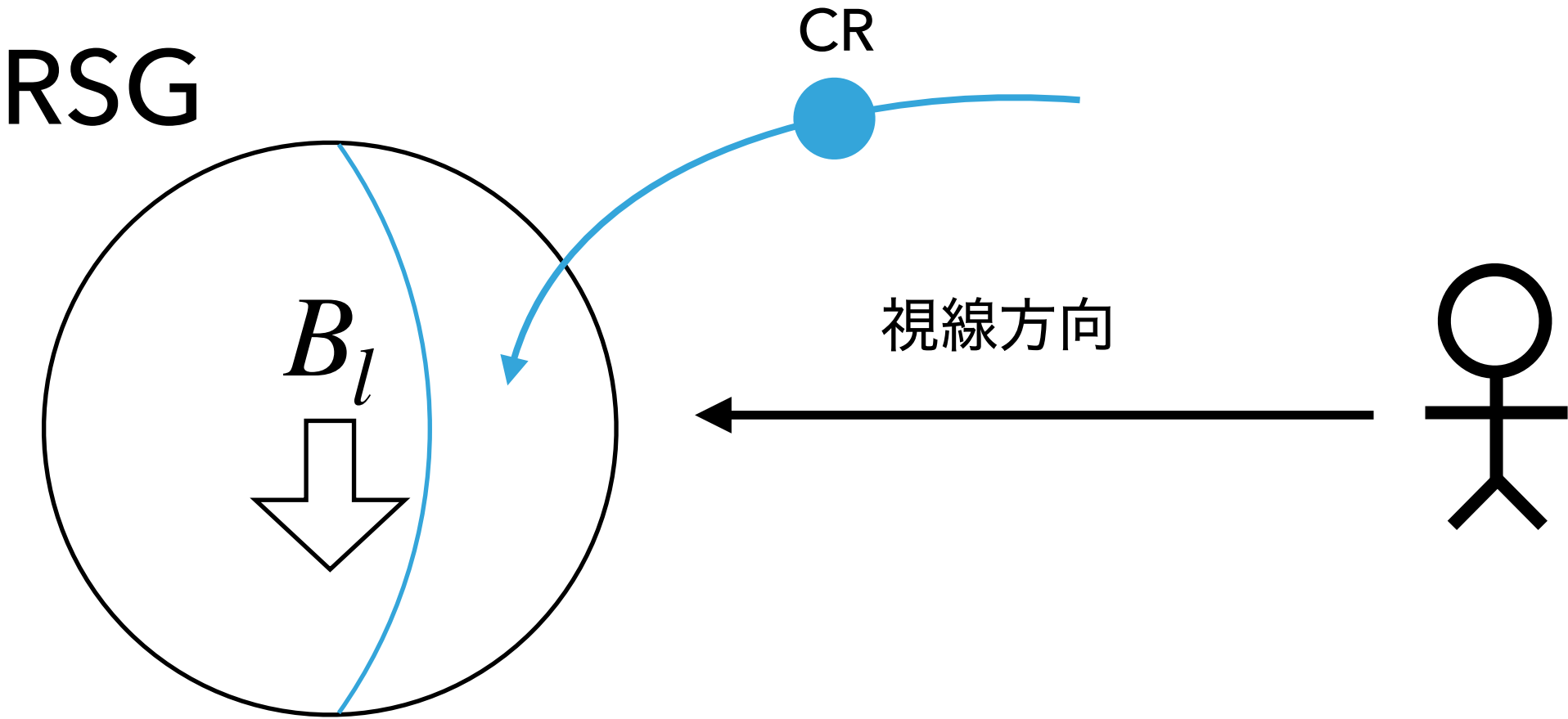
Table 1. Log of observations of Betelgeuse (for details, see Sect. 2).

Date	HJD (2 450 000+)	Tot exp. s	B_ℓ G	σ G
14 March 2010	5270.397	320	0.49	0.16
15 March 2010	5271.372	320	0.89	0.15
17 March 2010	5273.311	256	0.74	0.21
22 March 2010	5278.362	316	1.07	0.15
09 April 2010	5296.318	320	1.58	0.14
17 April 2010	5304.336	272	1.61	0.19

・ 観測方法

Télescope Bernard Lyot (@フランス) 搭載の NARVAL

Zeeman 効果による観測



星半径 : $764 R_\odot \approx 5.32 \times 10^{14}$ cm

ラーモア 半径

$$r_L = \frac{pc}{Ze B} \text{ [cm]}$$

pc [eV]

Ze [esu] : 電荷

B [Gauss] : 磁場の大きさ

$K = 10^{15}$ eV (CR 運動エネルギー)

$$pc = \sqrt{K^2 + 2m_p c^2}$$

$Ze = 1 e \text{ esu} = 4.80 \times 10^{-10} \text{ esu}$

$B = 1 \text{ Gauss}$

->

$$r_L \approx 3.34 \times 10^{12} \text{ cm}$$

・ 引用元

M. Aurière et al. 2010

<https://www.aanda.org/articles/aa/pdf/2010/08/aa14925-10.pdf>

※ 2017 年時点 : 表面磁場の直接検出が報告されている唯一の RSG (M型超巨星)

B. Tessore et al. 2017

<https://www.aanda.org/articles/aa/pdf/2017/07/aa30473-17.pdf>

CR の磁場中での m.f.p.

• λ : m.f.p.

$$\lambda = r_L \xi = r_L \left(\frac{B}{\delta B} \right)^2$$

$\xi = 1 \sim 10$?

• ボーム極限 : $\xi = 1$

• 太陽風中の Shock : $\xi = 10$

-> $\lambda = 1 \sim 10 r_L$ ($r_L \approx 3.34 \times 10^{12}$ cm)

• SNR の Shock : $\xi = 2$?

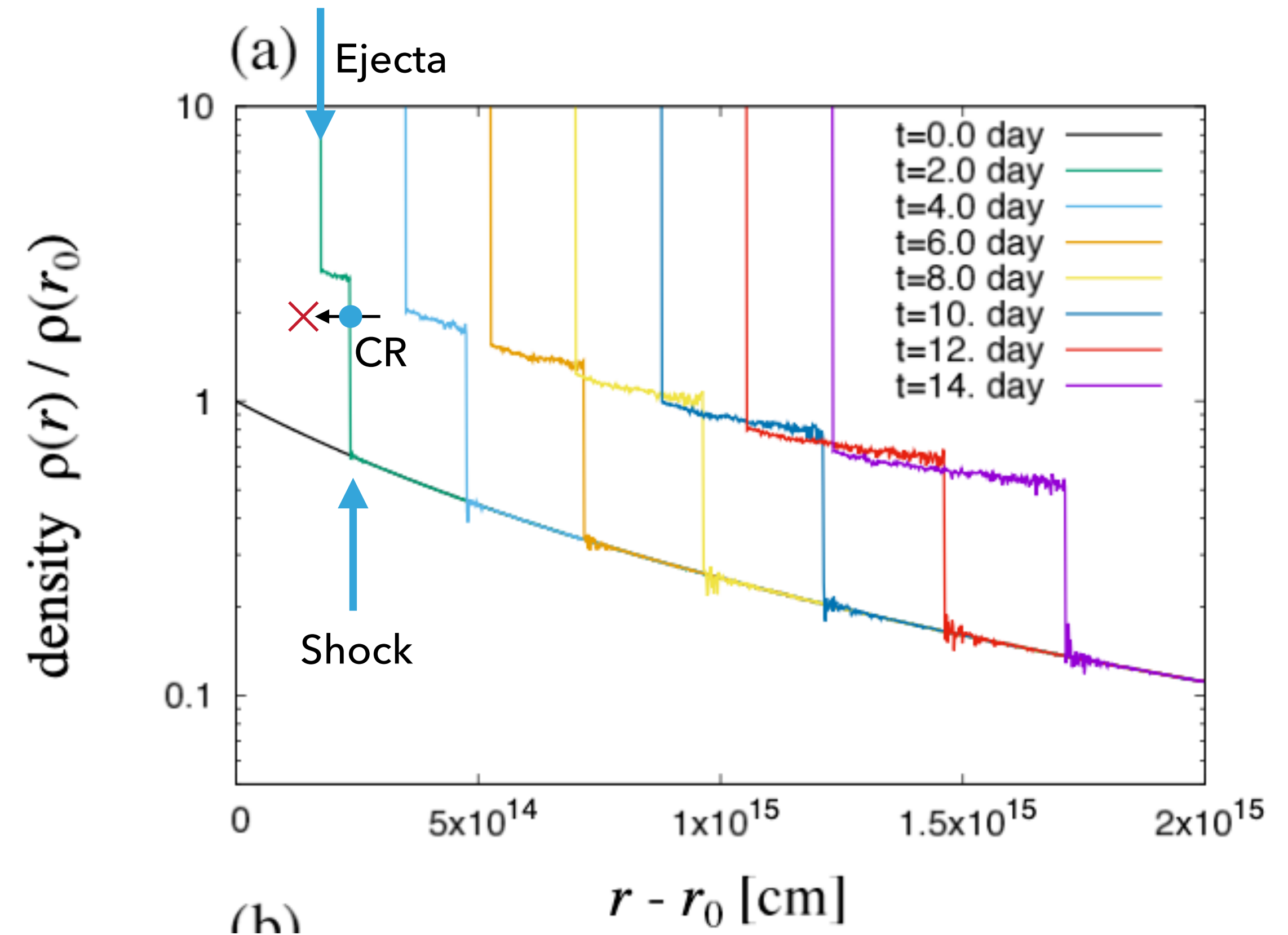
-> $\lambda \approx 6 \times 10^{12}$ cm

• $t = 2$ day

Shock 半径 : 2.5×10^{14} cm

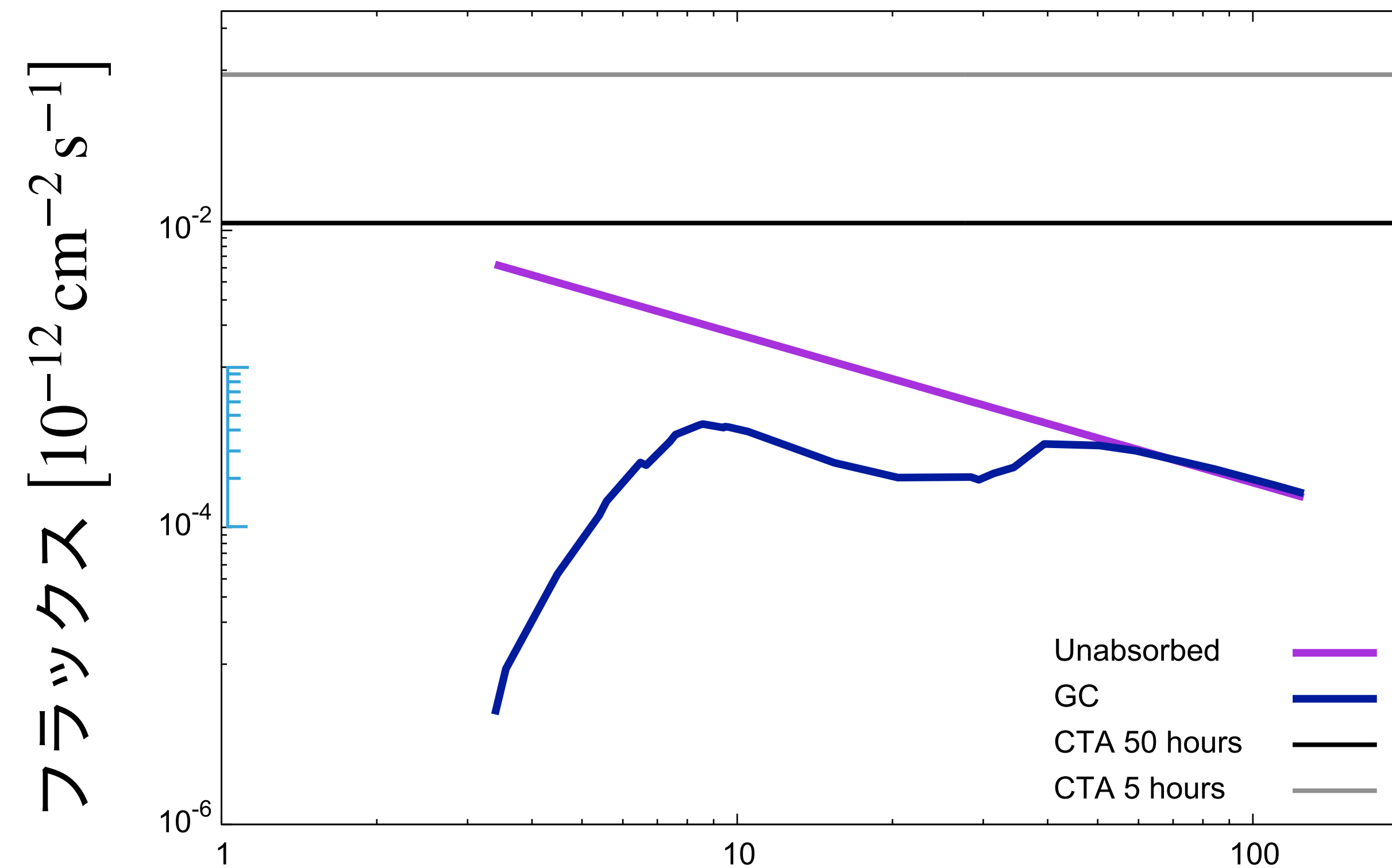
Ejecta 半径 : 2.0×10^{14} cm

-> Shock 近傍で生成された 1PeV の CR は, 磁場に曲げられ, Ejecta へは到達しない



SN1993Jのガンマ線フラックス時間発展

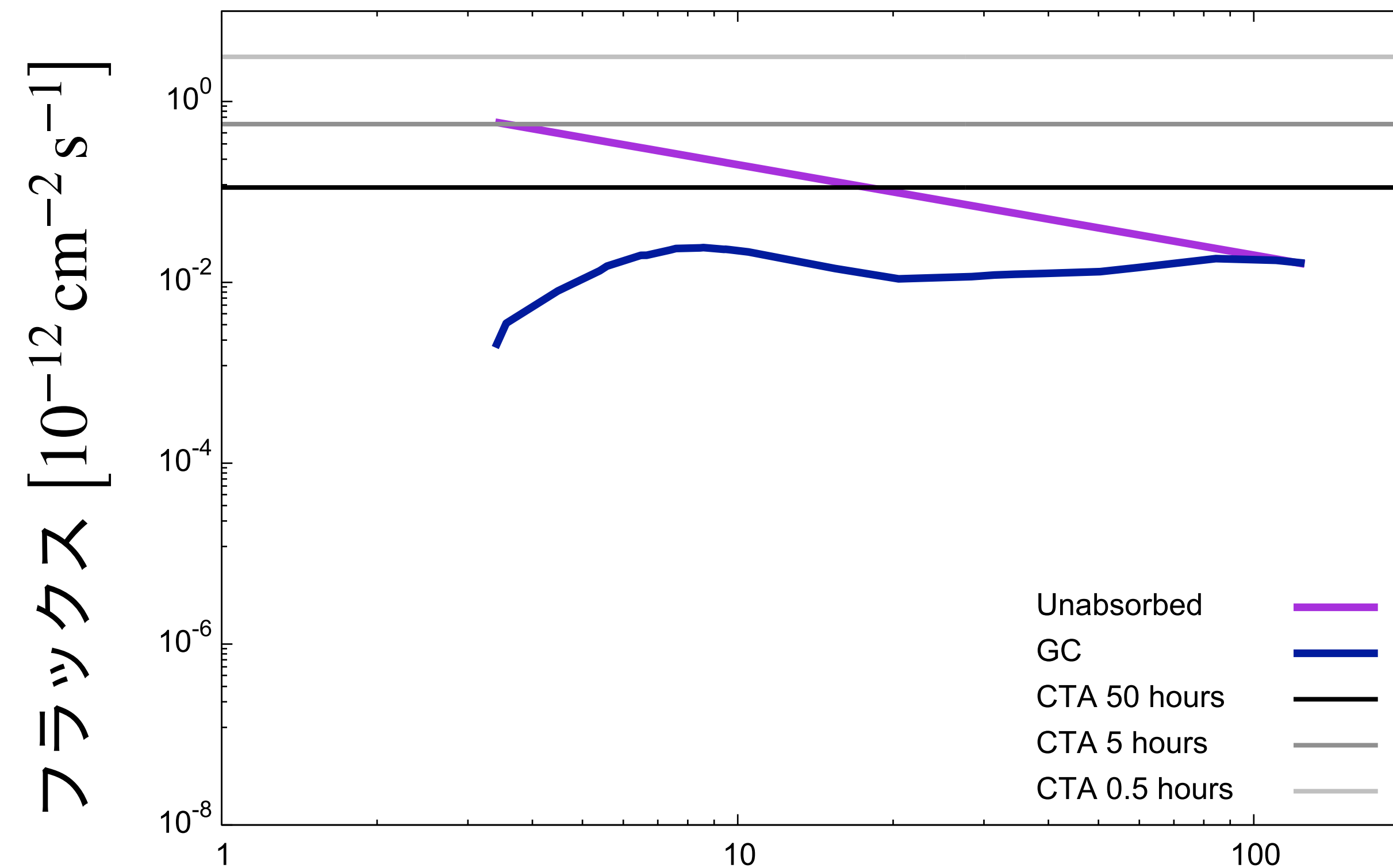
エネルギー $E = 100 \text{ TeV}$ (限定版) のガンマ線について



sample53.9.c ->
t-tau_gg53.9.dat ->
t-tau_gg53.9.plt &
t-tau_gg53.9_100TeV_2.plt

SN1993Jのガンマ線フラックス時間発展

エネルギー $E = 1 \text{ TeV}$ (比較用) のガンマ線について

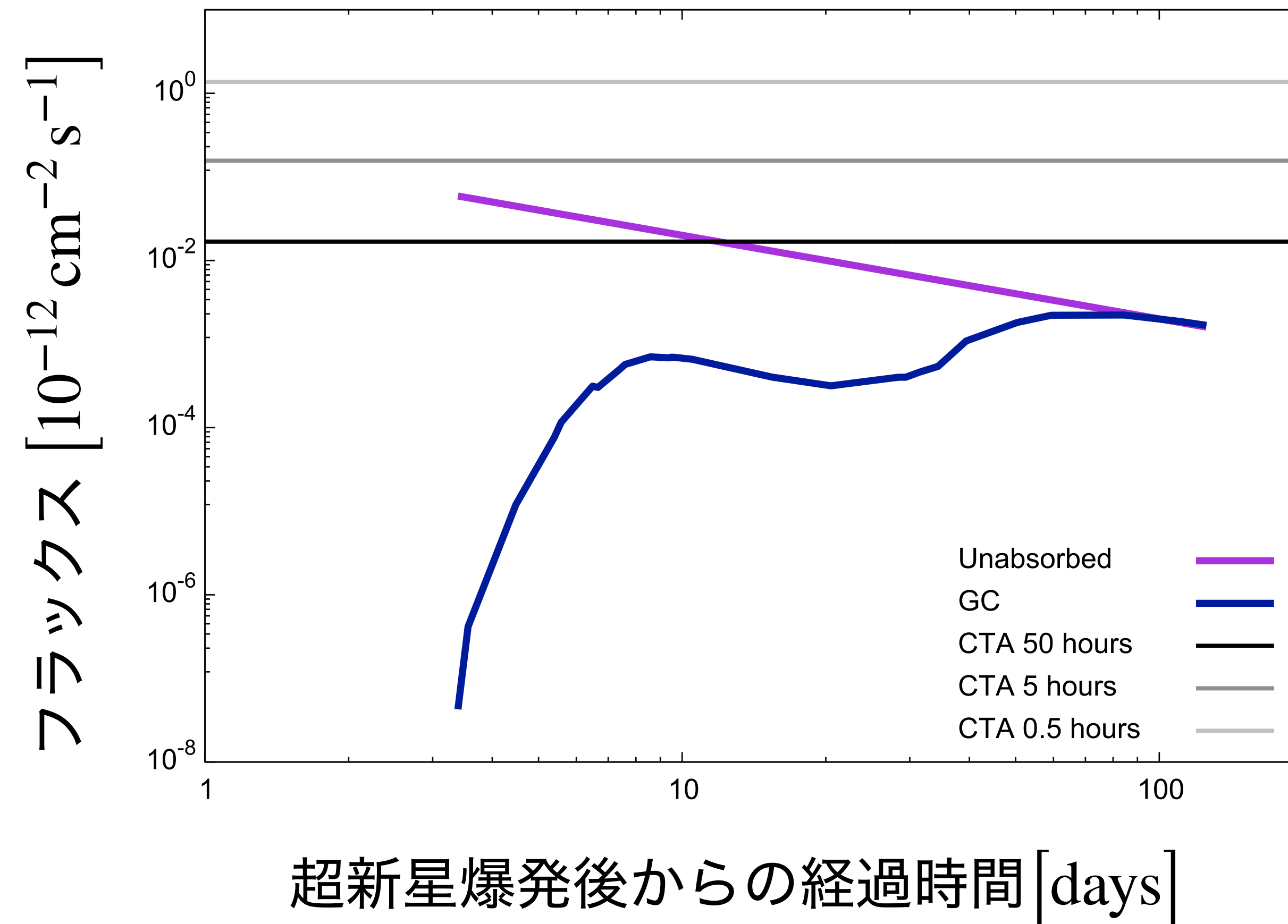


超新星爆発後からの経過時間[days]

sample53.4.c ->
t-tau_gg53.4.dat ->
t-tau_gg53.4.plt &
t-tau_gg53.4_1TeV.plt

SN1993Jのガンマ線フラックス時間発展

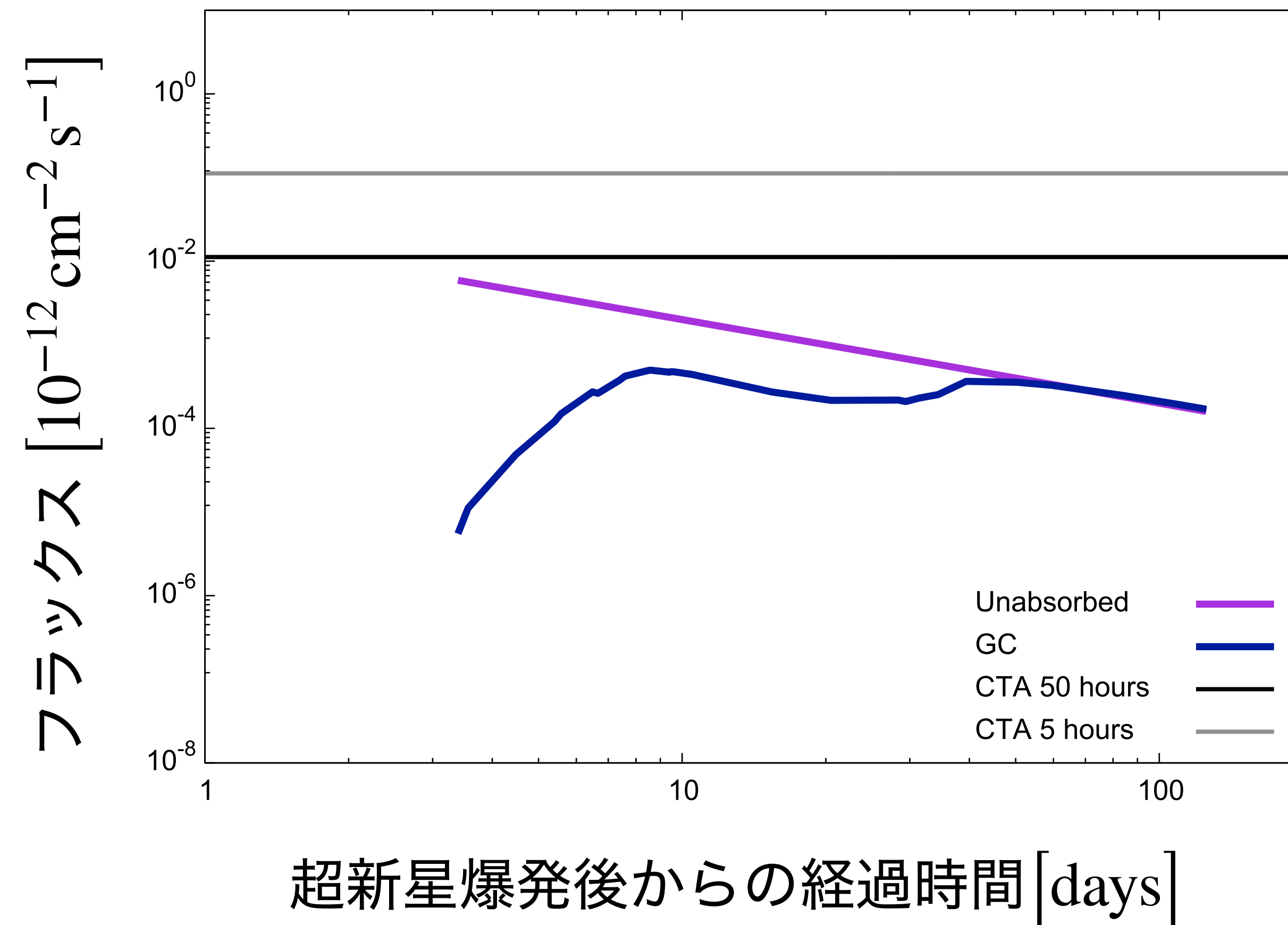
エネルギー $E = 10 \text{ TeV}$ (比較用) のガンマ線について



sample53.8.c ->
t-tau_gg53.8.dat ->
t-tau_gg53.8.plt &
t-tau_gg53.8_10TeV.plt

SN1993Jのガンマ線フラックス時間発展

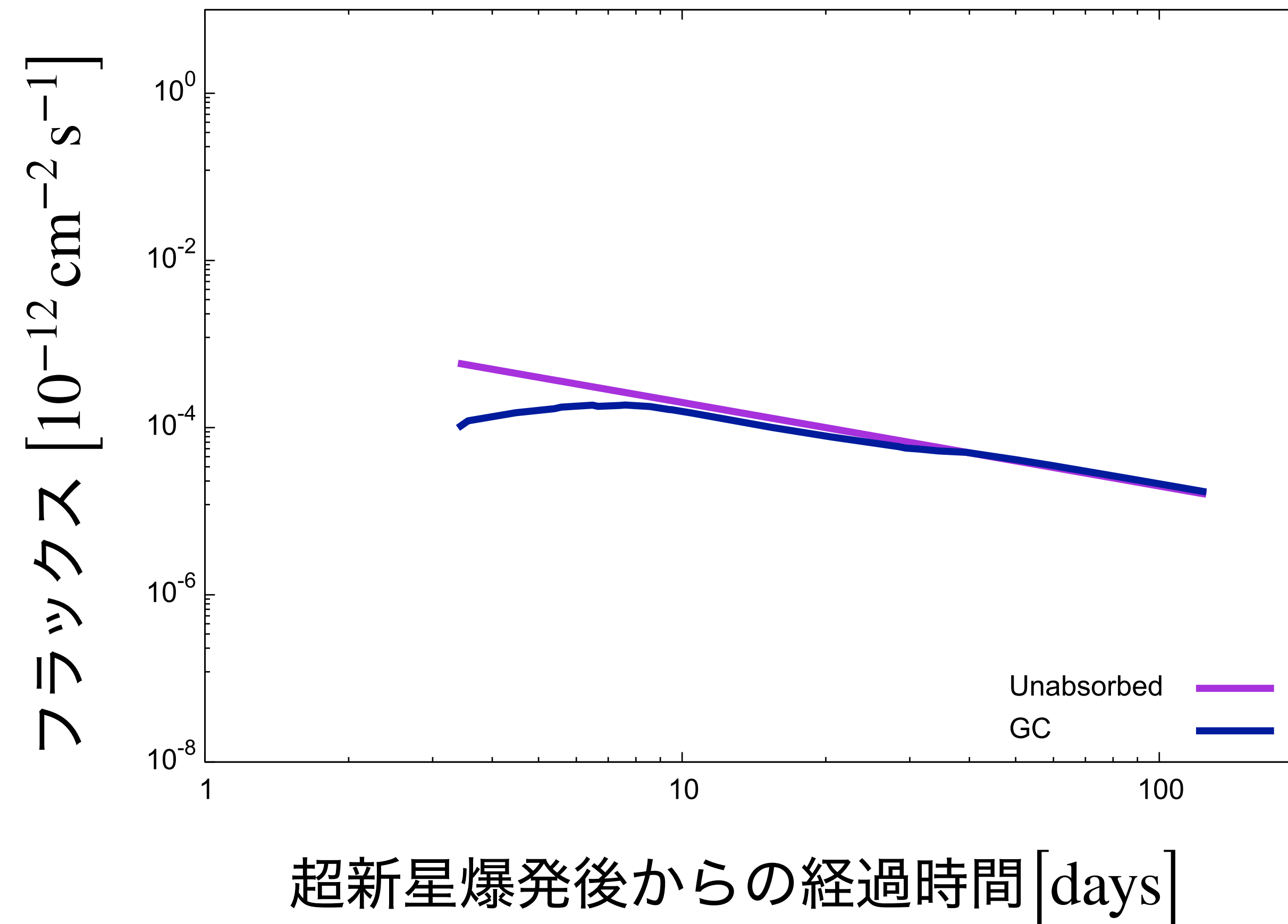
エネルギー $E = 100 \text{ TeV}$ (比較用) のガンマ線について



sample53.9.c ->
t-tau_gg53.9.dat ->
t-tau_gg53.9.plt &
t-tau_gg53.9_100TeV.plt

SN1993Jのガンマ線フラックス時間発展

エネルギー $E = 1 \text{ PeV}$ (比較用) のガンマ線について



```
sample53.7.c ->  
t-tau_gg53.7.dat ->  
t-tau_gg53.7.plt &  
t-tau_gg53.7_1PeV.plt
```

典型的な C.C.SN について

SN 1993J は典型的な重力崩壊型 (Type II) 超新星ではなく,
Type IIb であるため,
典型的な SN とは言い難い...

このため,
SN1993J の物理量の結果を用いたもので,
SN の発生頻度を計算したものは不自然!!
->
典型的な重力崩壊型の SN を考える

SN の分類 (メモ)

・特異な SN

・I Ib 型

爆発直後 : 水素の幅広い輝線が見られる

極大前後 : 水素輝線 弱まる

Ib 型に酷似したスペクトル (<- He 吸収線が見られる?)

e.g. SN1993J (in M81)

質量放出によって, 水素に富む外層が少量になった大質量星の爆発?

・特異 Ic 型

Ic 型

極大期 :

水素, ケイ素, ヘリウム吸収線が見られない

極大半年後 : 酸素とカルシウム (が主成分)

(星形成が活発な銀河でのみ出現)

の内, 線輪郭がごく広い(スペクトルの山が, などらか)

& 線の中心波長の青方偏移が大きい (膨張速度が特に大きい)

膨張速度 : 3×10^4 km/s (cf. 典型 Ic 型 : 数 10^3 km/s)

・線幅が極めて狭い SN

・I In 型 (n : narrow)

水素輝線が極めて狭い

<- 比較的濃い星周物質が,
超新星の光, 衝撃波を受けて光っている?

・I bn 型

水素輝線が見られない

ヘリウム輝線が極めて狭い

<- このうち,
超新星としてごく暗い or 増減光を繰り返す
青色超巨星の表面爆発によるものとして,
超新星としては扱われない

<- 極超新星爆発

膨張の運動エネルギーが

通常の SN の 10 倍程度 (10^{45} J)

SNの光度曲線

- ・光度曲線

：可視光領域での明るさの変化

- ・Ia 型

極大の絶対等級：-19 程度

爆発後

20 日：極大

30 日：3 等程減光

その後：100 日あたり 1.5 等の割合で減光

- ・Ib, Ic, II 型

極大の絶対等級：-17 程度 (特異 Ic 型：-21 も存在), ばらつき：大

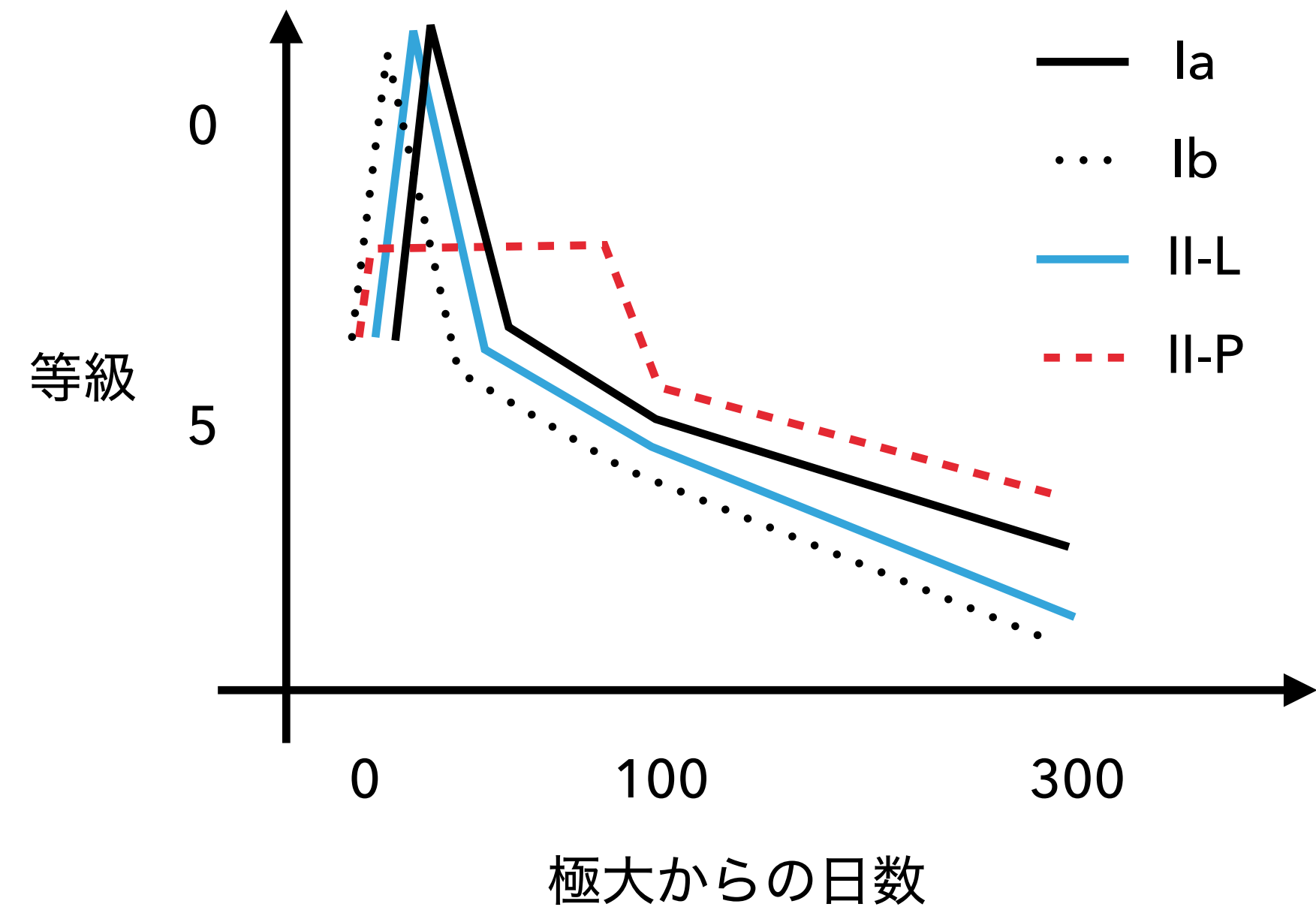
後期の減光：Ia 型と比べ, ややゆっくり

- ・II-P 型

極大後, 100 日程光度が一定の状態 (プラート; plateau) を保つ

- ・II-L 型

極大後, 日数に比例して光度が直線的 (リニア; linear) に減衰する



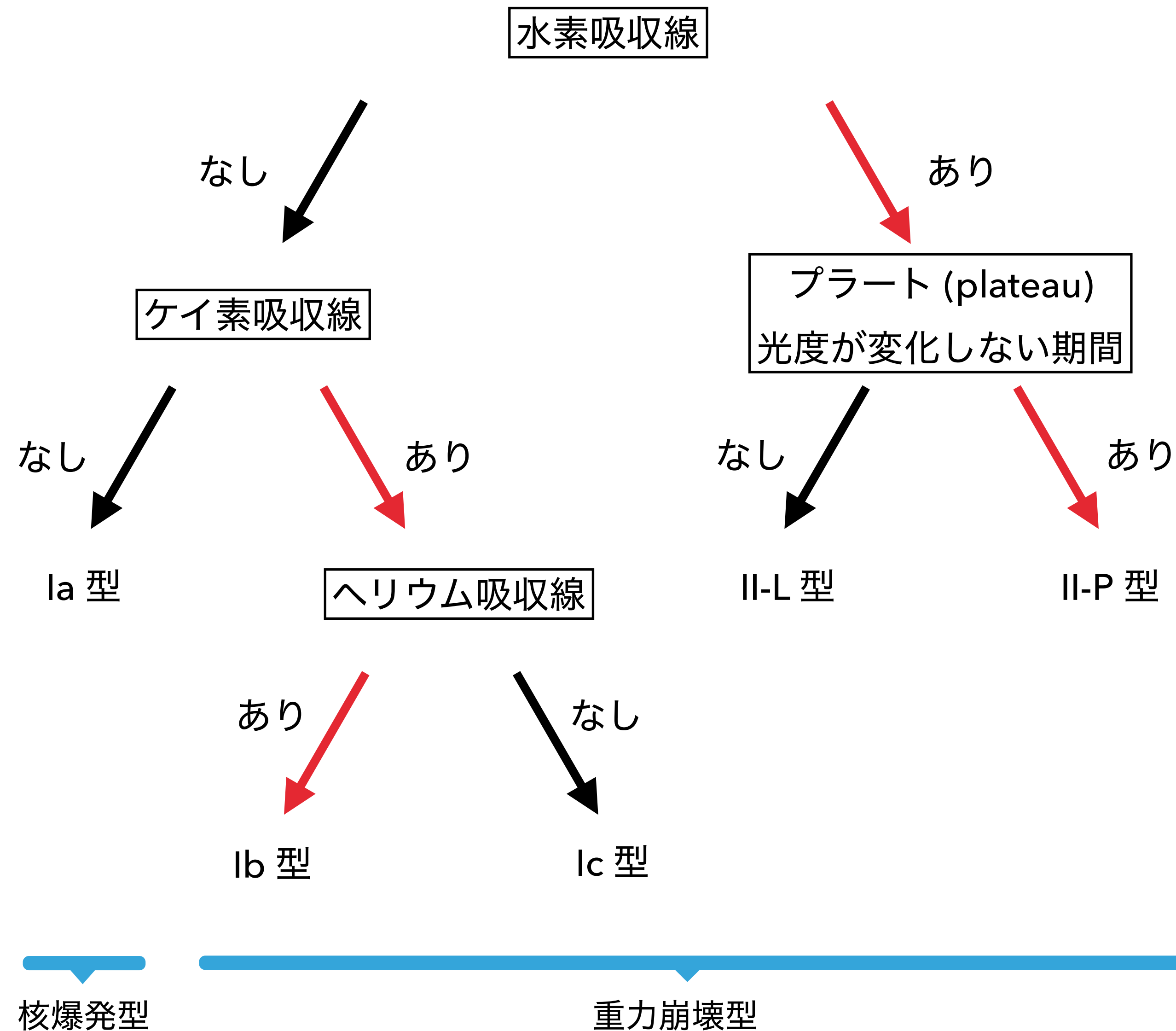
シリーズ現代の天文 7

恒星 p.288 Fig. 7.5

<- 水素に富む外層が多い

<- 水素に富む外層が少ない (Iib より多い)

SN 分類：吸収線



・ Ia 型
核爆発型超新星：近接連星系の白色矮星が爆発

・ Ib, Ic, II-P, II-L, IIb, IIc 型
重力崩壊型超新星：大質量星が爆発

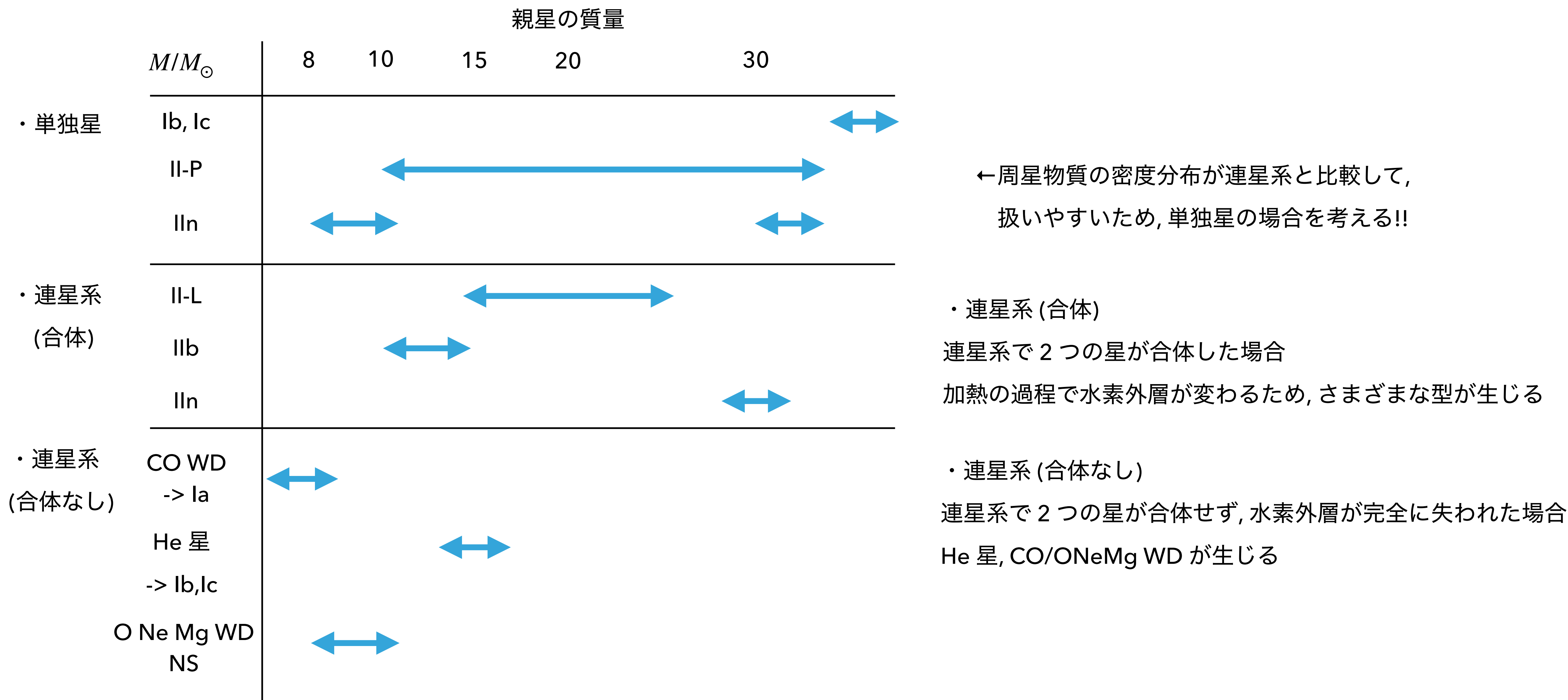
・ II-P 型
水素外層：大きいもの

・ II-L, IIb, IIc 型
水素外層：小さいもの

・ Ib, Ic 型
水素外層：とても小さいもの

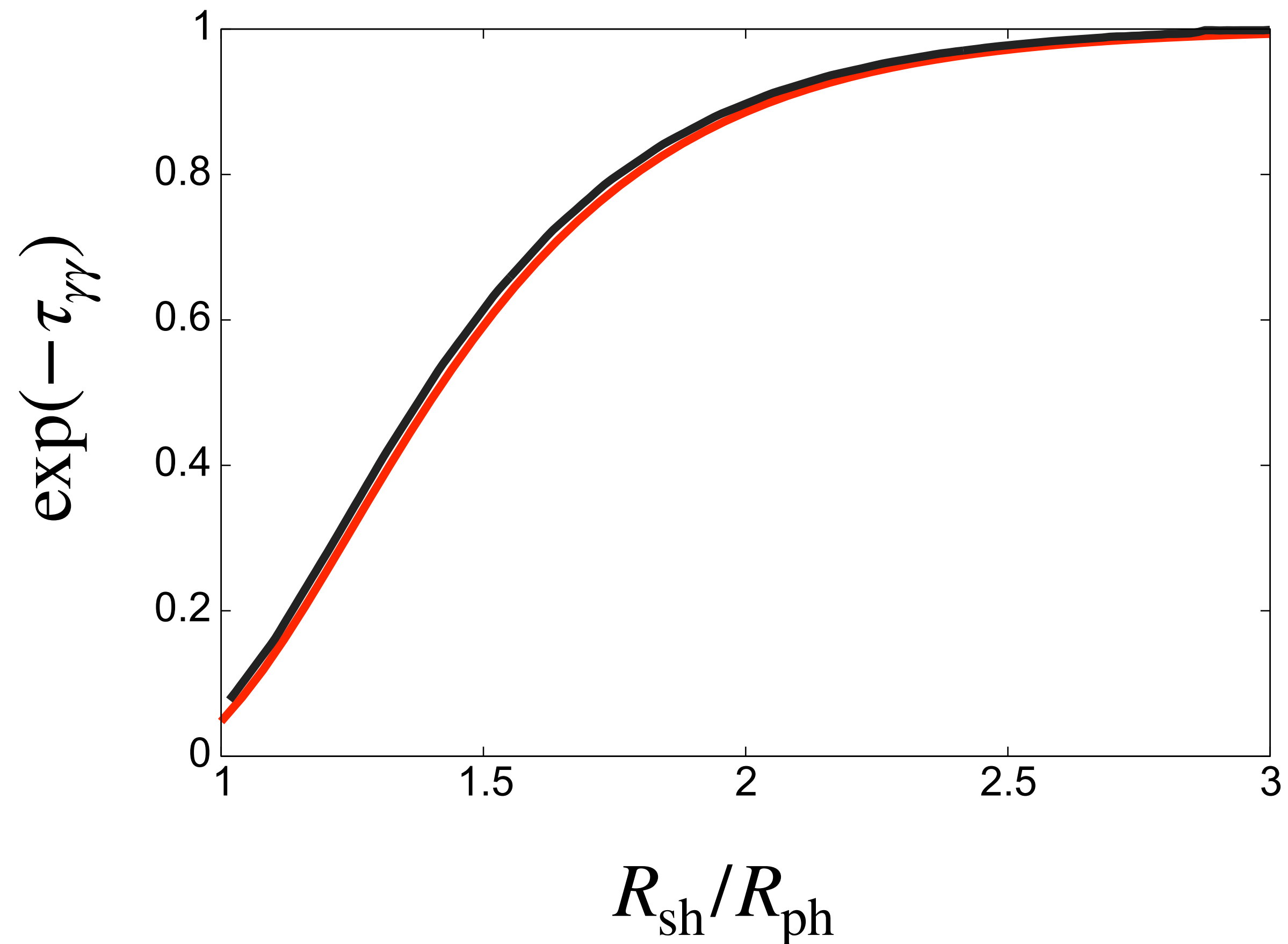
<- 星周ガスの密度：大

SN 分類：親星の質量



不透明度テスト計算結果

ある衝撃波半径 R_{sh} で放射されたガンマ線の不透明度 $\tau_{\gamma\gamma}$



—：テスト計算結果

—：先行研究 (G. Dubus 2006)

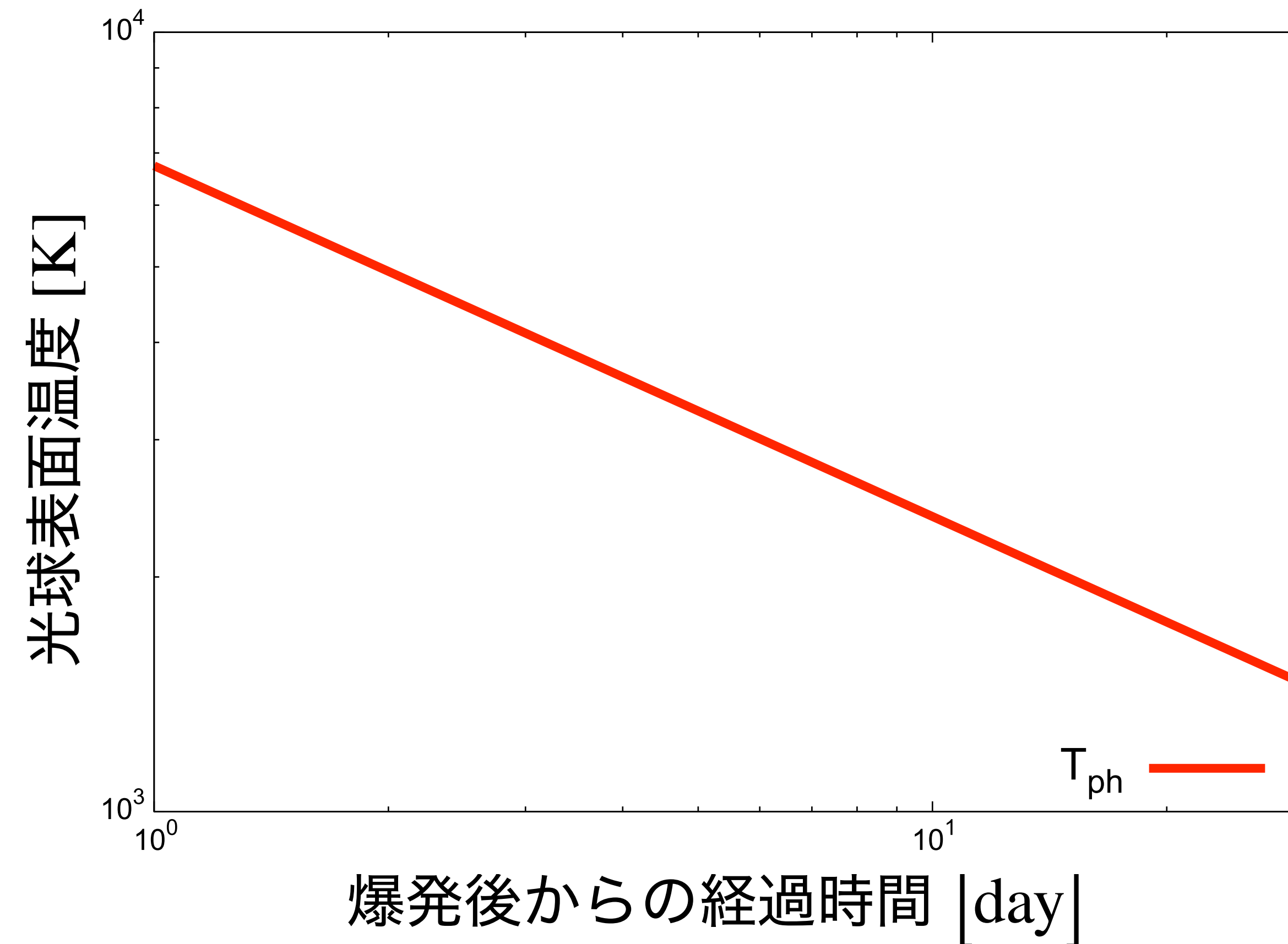
テスト計算結果は、

先行研究 (G. Dubus 2006) での計算結果と一致

星近傍において、対消滅は高頻度で起こり、

$R_{\text{sh}}/R_{\text{ph}} \geq 3$ 程度ではほとんど無視できる

光球表面温度モデル



• 光球表面温度

$$T_{\text{ph}} = 1.7 \left(\frac{f_{\rho}}{0.1} \right)^{-0.037} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{0.027} \left(\frac{R_*}{10^{13} \text{ cm}} \right)^{1/4} \left(\frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.28} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{-0.054} \left(\frac{t}{10^5 \text{ s}} \right)^{-0.45} \text{ eV}$$

$$1.7 \text{ eV} \approx 1.9 \times 10^4 \text{ K}$$

Rabinak I., Waxman E., 2011

sample69.c
-> N_typical_69.dat
sample69_T_ph.plt

Type IIの光球

Toshikazu Shigeyama and Ken'ichi Nomoto 1990

SN1987Aの光度曲線モデルの改良

光球の位置は、質量座標に対して内側に伝播していくが、
各層は膨張しているので、光球の位置 R はほとんど動かない

SN1987A

<- II-P 型光度曲線が大きく異なる!!

II-P 型の特徴である、プラトーが観測されず、
水素外層が少なく、緩やかなプラトーが観測された

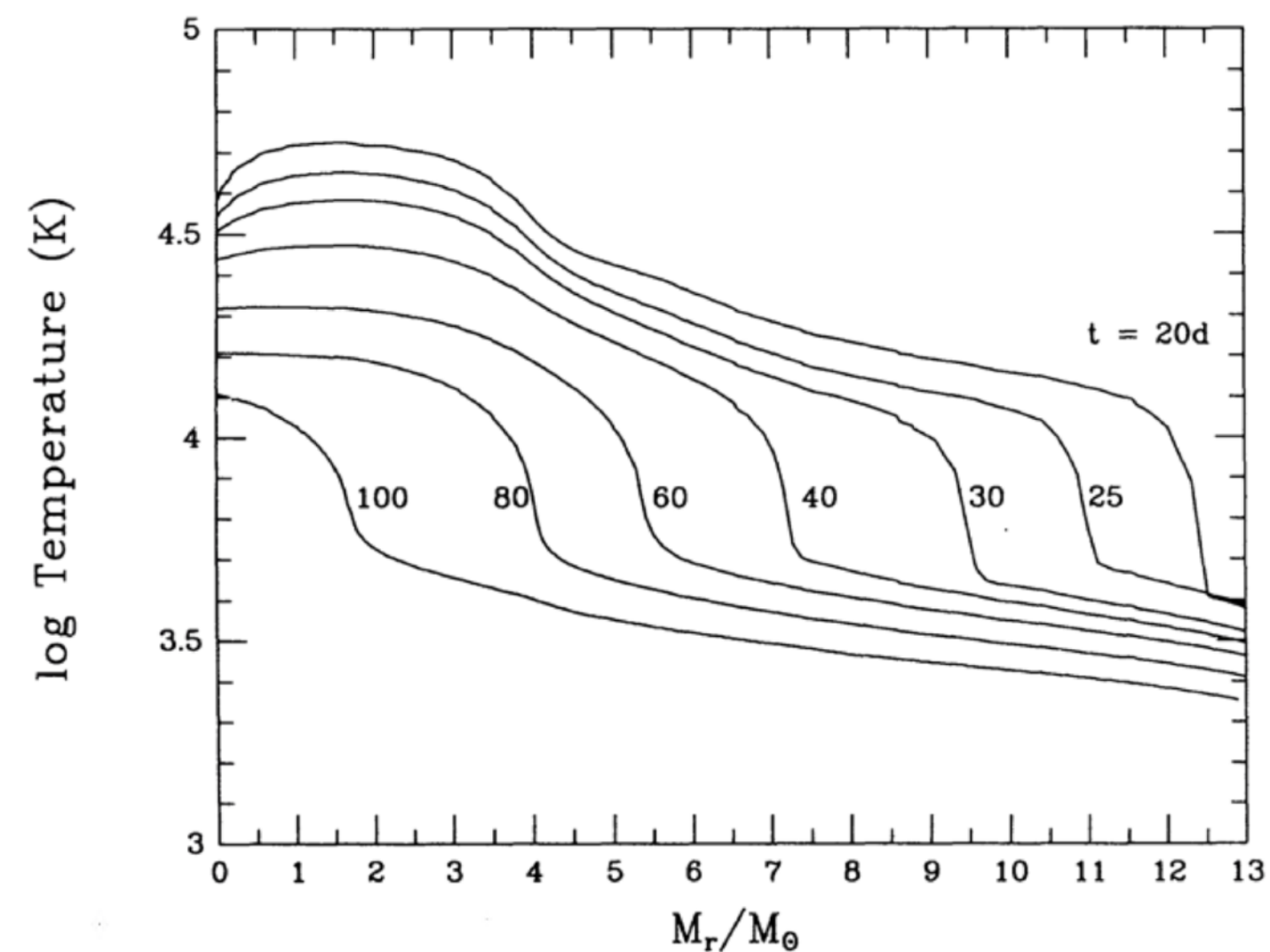


Fig.10

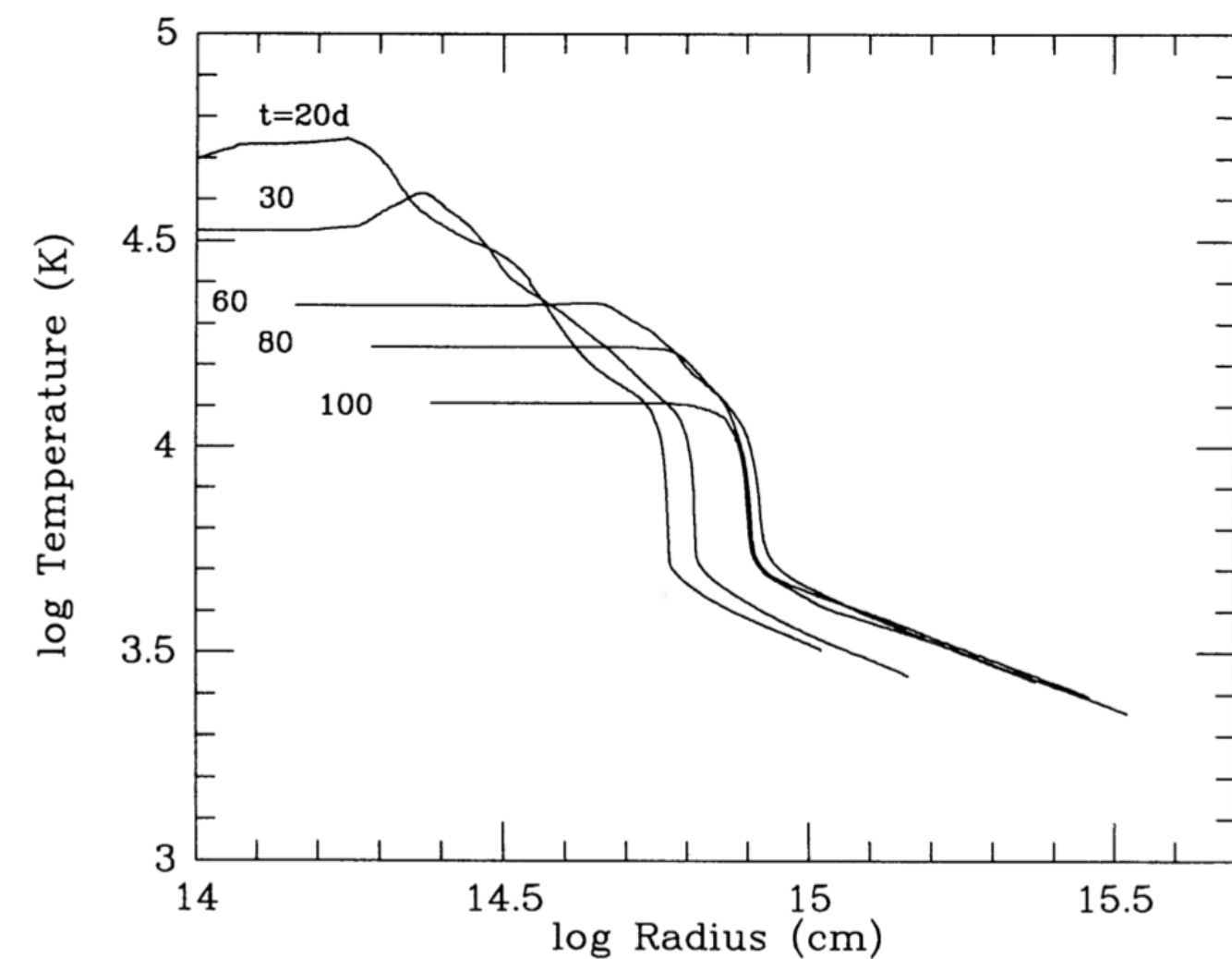
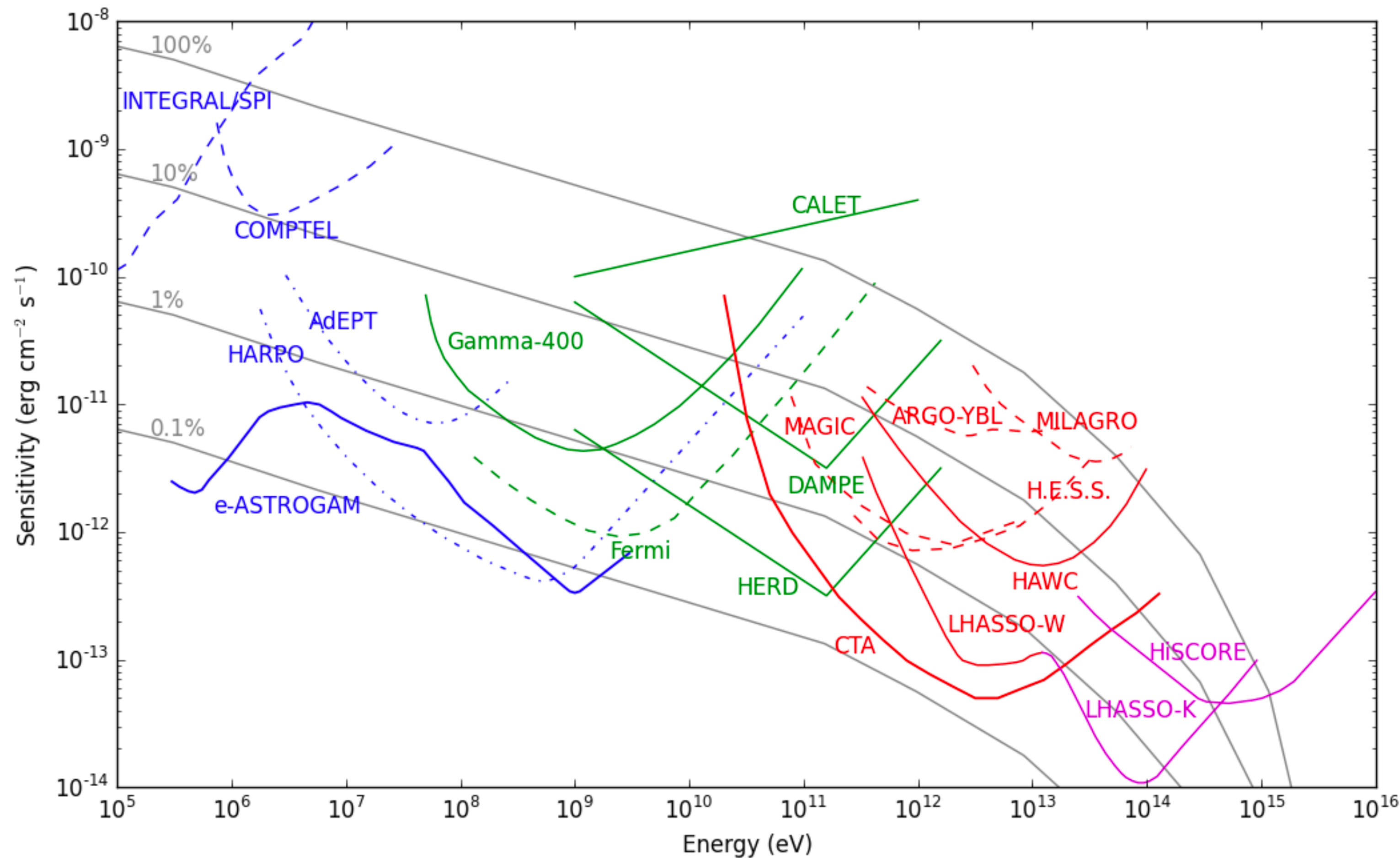


Fig.11

FIG. 11.—Change in the temperature profile against r for 14E1. The hydrogen recombination front is almost stationary during the plateau-like peak at $t = 60\text{--}100$ days.

СТА

望遠鏡感度一覧



- 観測装置

- : 将来の観測装置

- · : R&D work に基づく観測装置

- : 既存 & 過去の観測装置

(in 2016)

- 観測時間

- CTA : 50 hours

- LHASO : 1 year ≈ 9000 hours

- HiSCORE : 5 year ≈ 45000 hours

The future of gamma-ray astronomy, Jürgen Knödlseider 2016

CTA Sensitivity

