2026.8.31 TeV Particle Astrophysics 2026 @Takinoyu Hotel, Yamagata

Time evolution of particle acceleration at supernova remnants and gamma-ray emission from clumps in the vicinity

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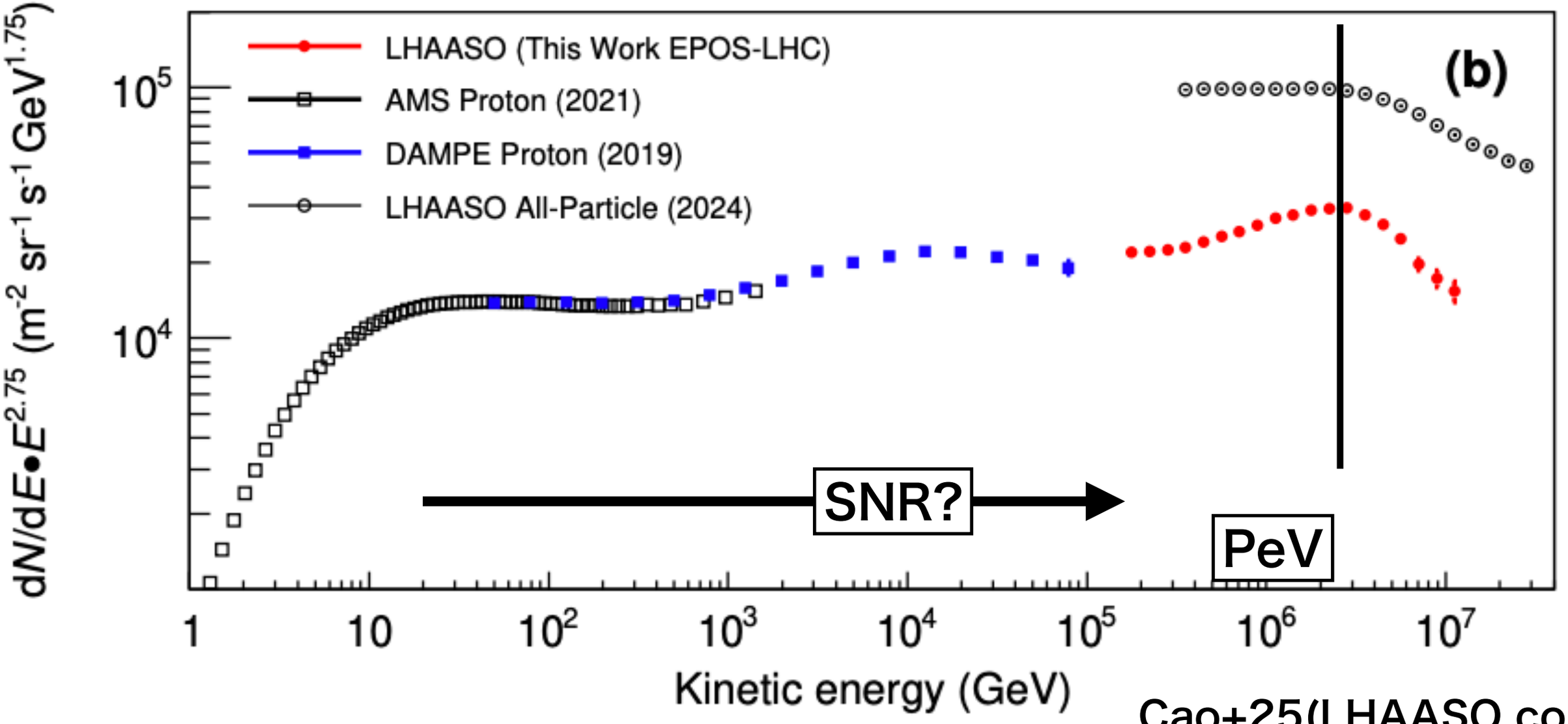
SNRs as Galactic CR Origin

Supernova remnants (SNRs):

- Enough Energetics: 10^51erg/SN
- Shock Acceleration?→Diffusive Shock Acceleration
- Bulk origin of GCR@GeV? **How high $p_{\max}$? How much?**

CR flux

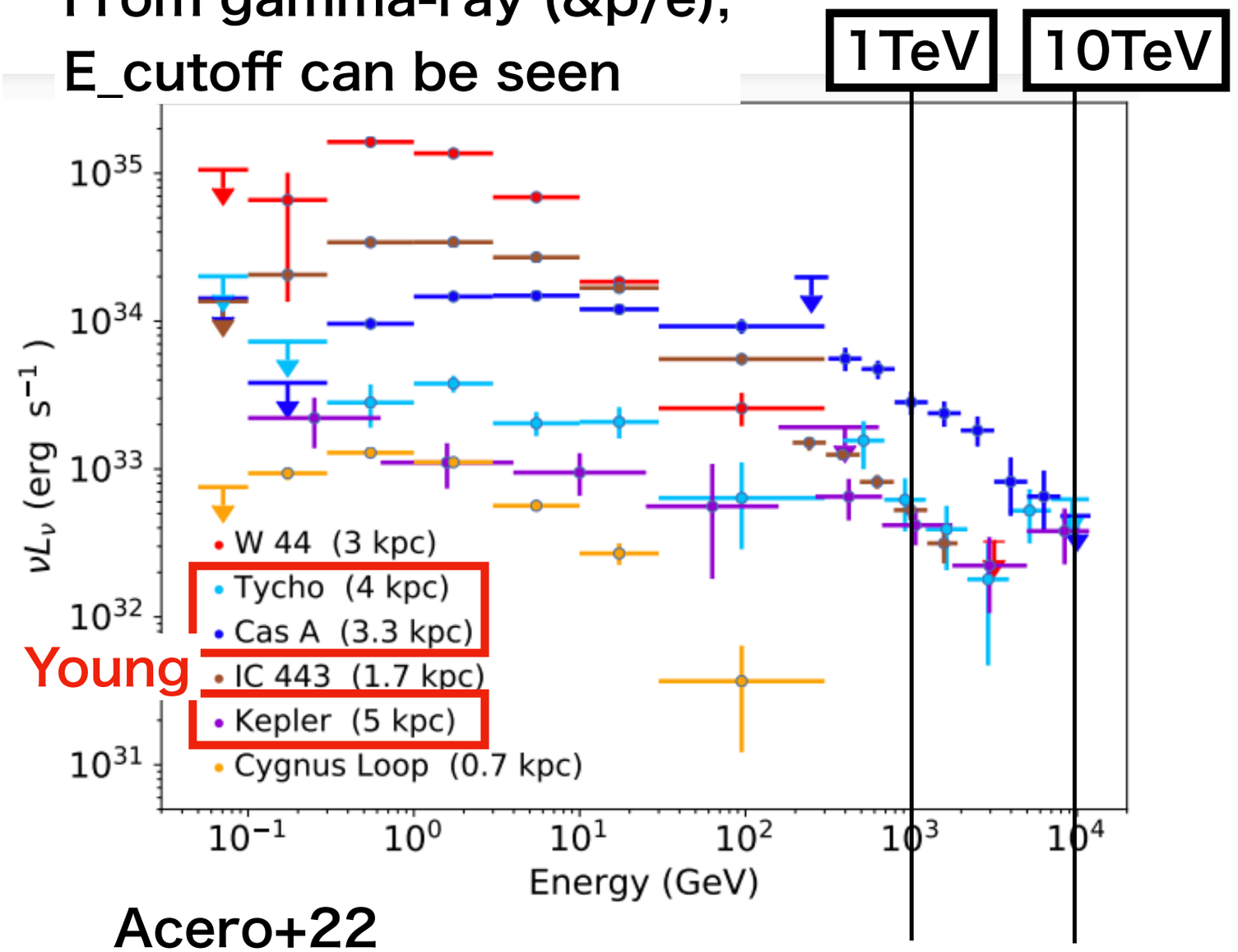


Cao+25(LHAASO col)

SNR cannot accelerate up to PeV?

- Gamma-ray is a good probe to know CR energy
- For many young (~a few 100 yr; have strong shock) SNR, E_{max,p}～10-100TeV, and for old, begin to escape and not reached to PeV　: Consistent with theory (normal B)

From gamma-ray (&p/e),
E_cutoff can be seen



Acero+22

PeVatron candidates associating SNRs

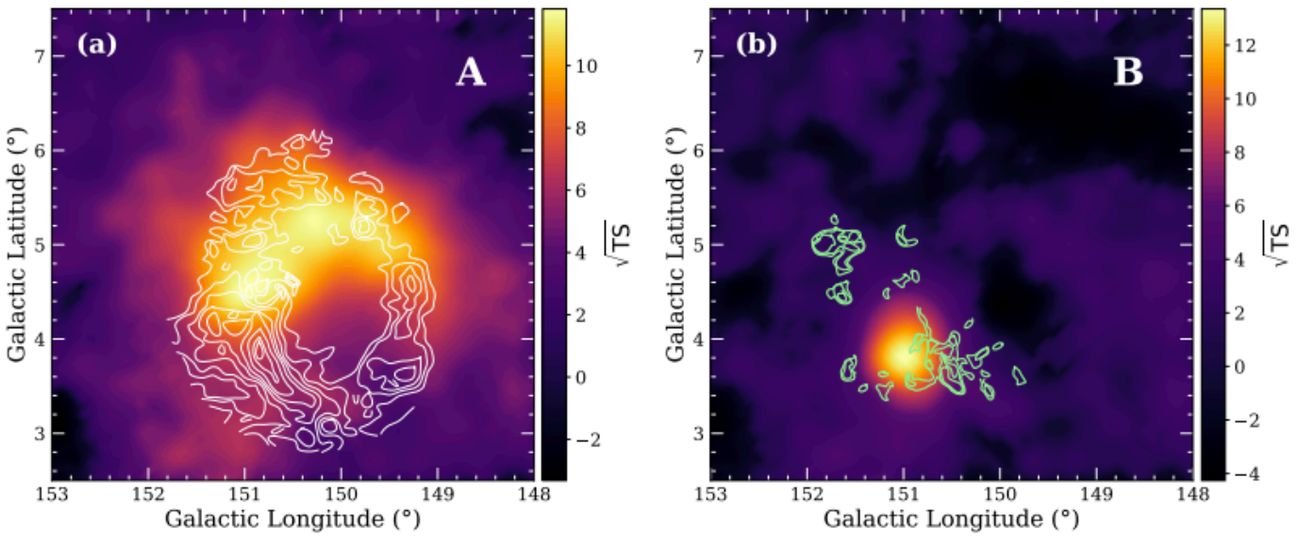
- So far E_max from SNRs ~100 TeV.

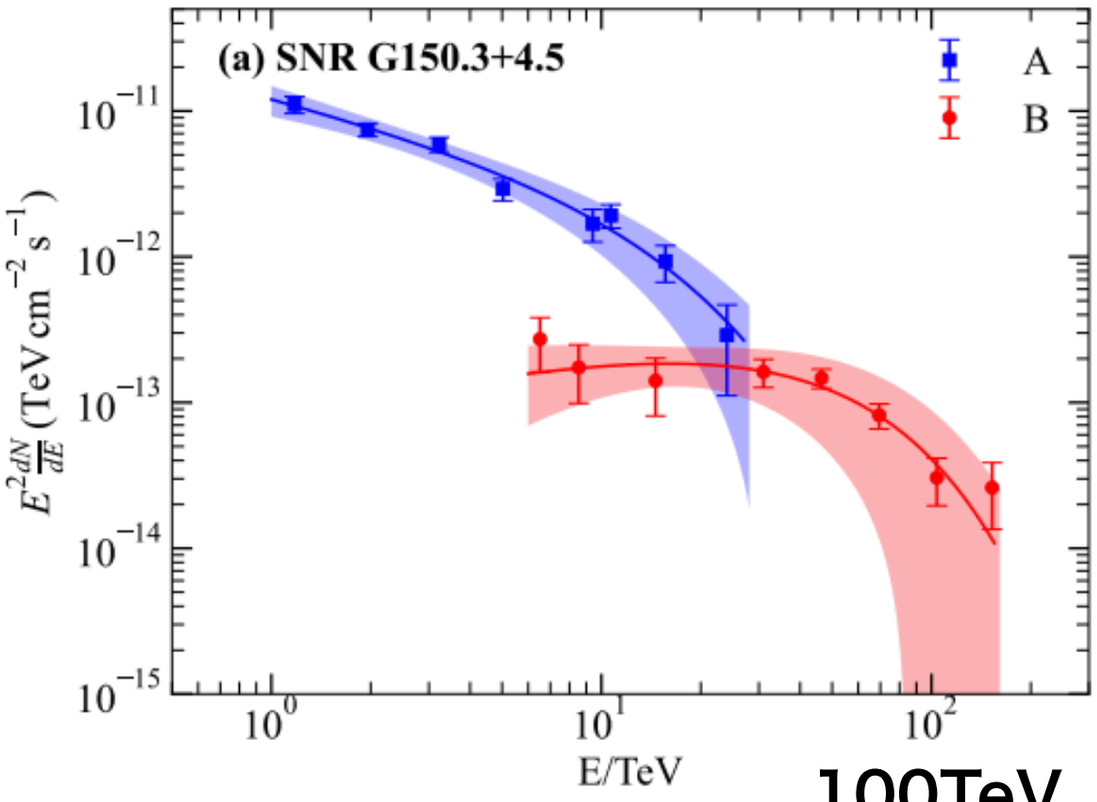
- G150.3+4.5(old SNR~10-180kyr?) a candidate of PeVatron

  Absence of PWN

  Compact(HE source), Extended(LE source)

  →**Collision of CR hadron with MCs?**





100TeV

PeVatron candidates associating SNRs

- So far E_max from SNRs ~100 TeV.

- G150.3+4.5(old SNR~10-180kyr?) a candidate of PeVatron

A
C
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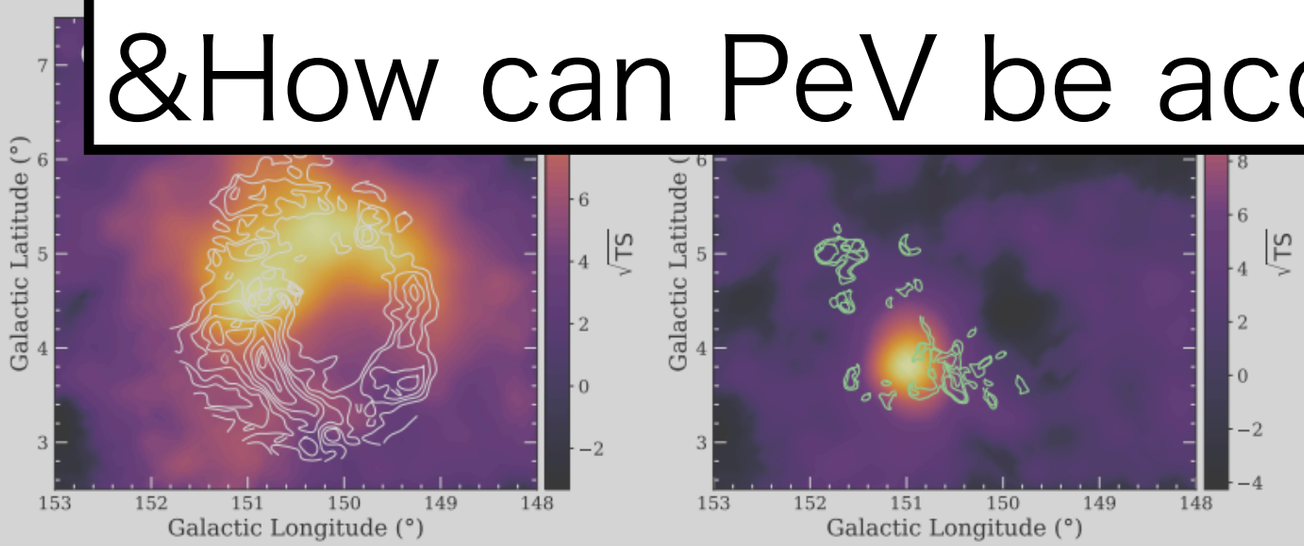
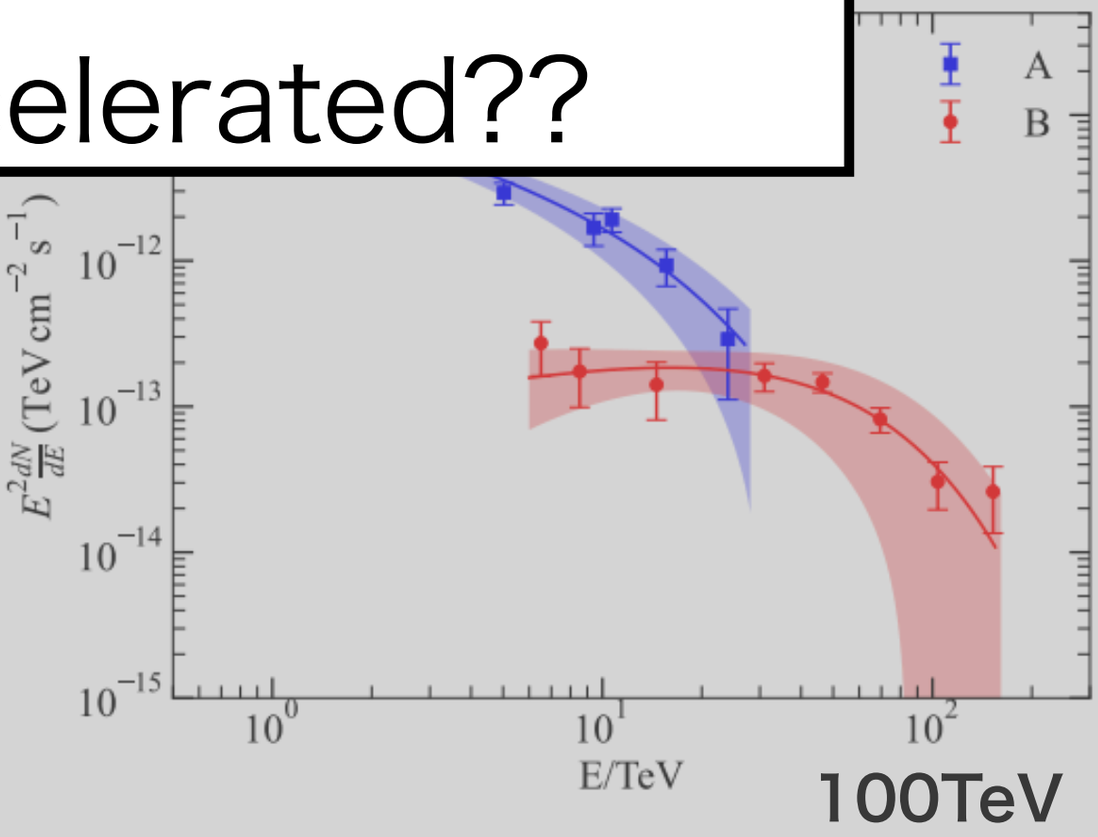
HE emission around SNRs
→Extended emission from Old-ages
: Escape and illuminate at ups?
&How can PeV be accelerated??



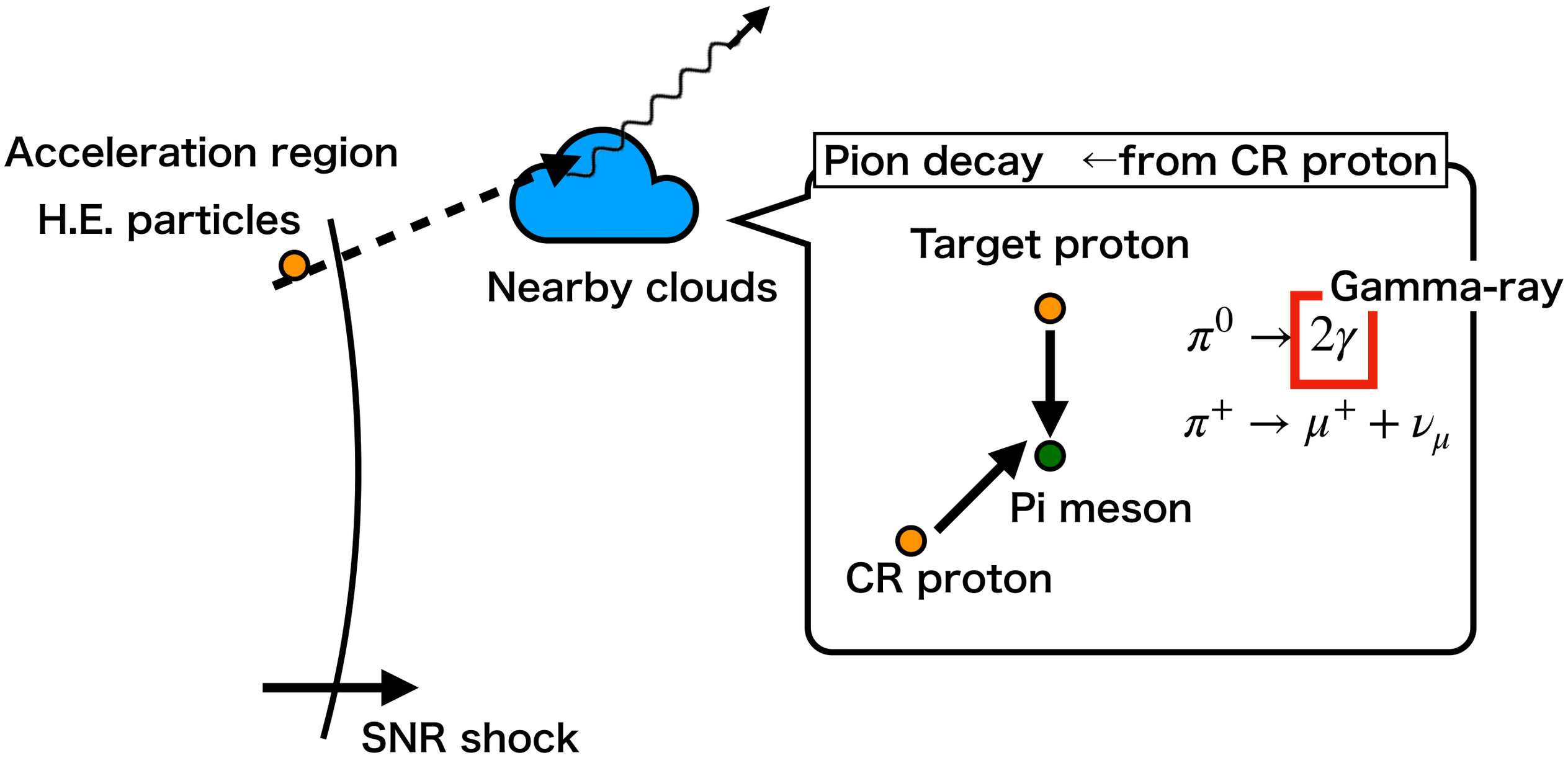


100TeV

Need to include CR escape

- **Consider CR escape and emit outside of a SNR**

  — **Interstellar gas associated with SNR** can play an important role in understanding gamma-ray and CRs

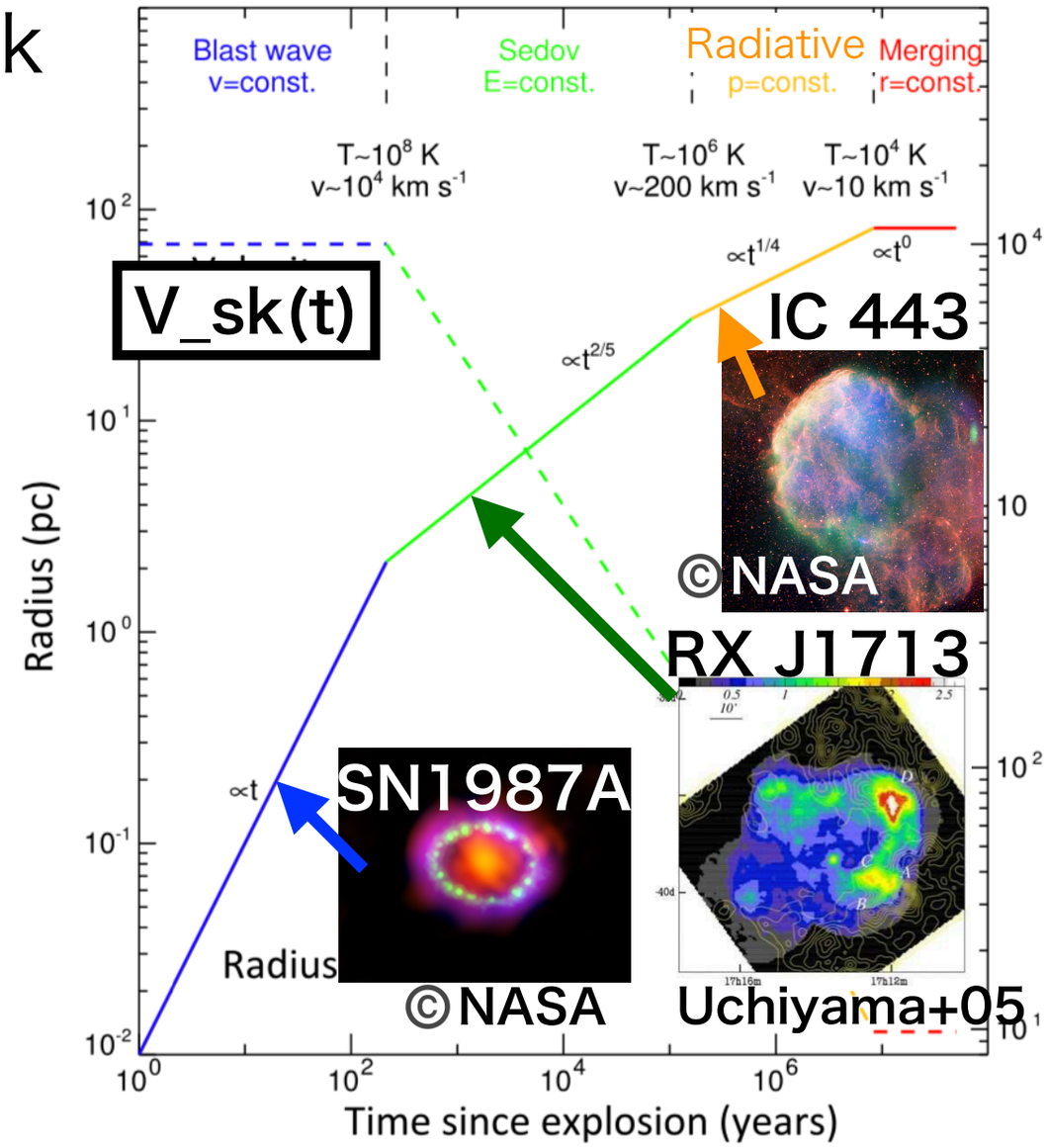


Motivation: Multi-zone acceleration at evolving shock

- To investigate **the particle acceleration with solving the spatial diffusion** by evolving shock and **resulting gamma-ray emission →→CTA, LHAASO etc**

— **Solve** Acceleration and diffusion **spatially (cf Kang&Jones91)** and use analytical model for hydrodynamics

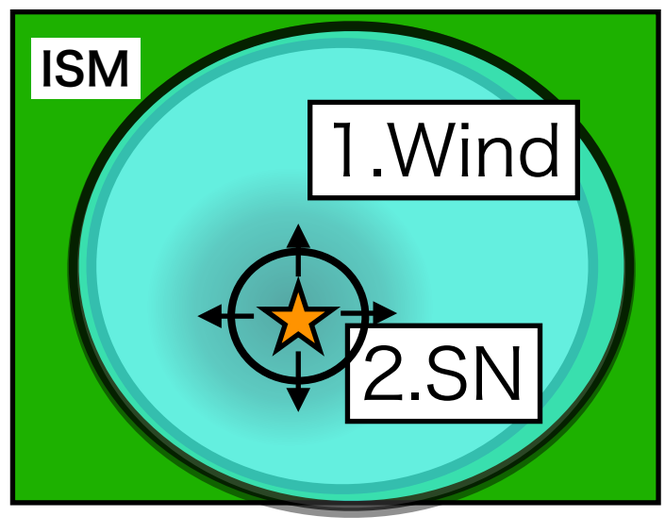
Shock velocity evolution (dashed)

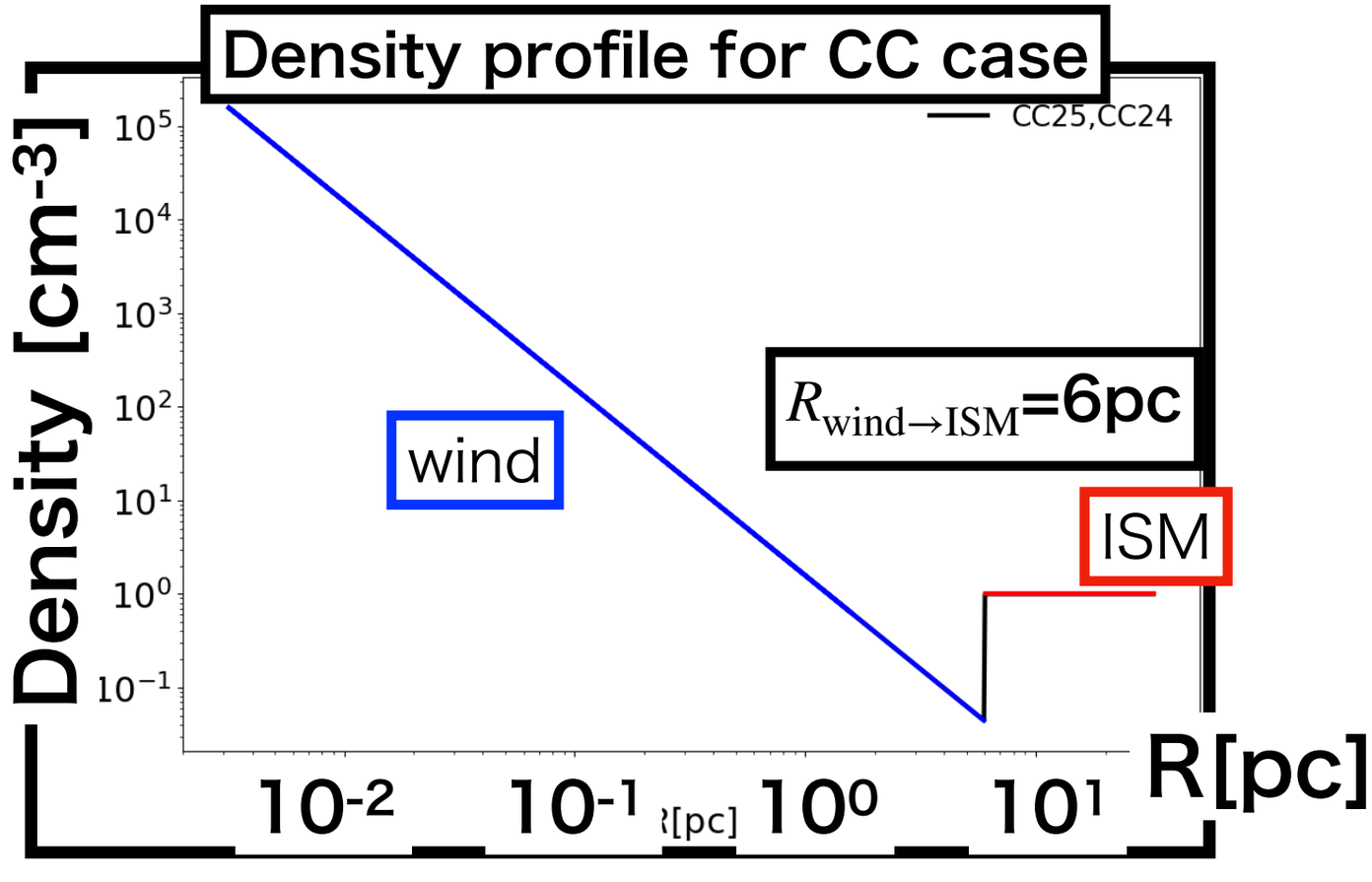


Micelotta+ 18

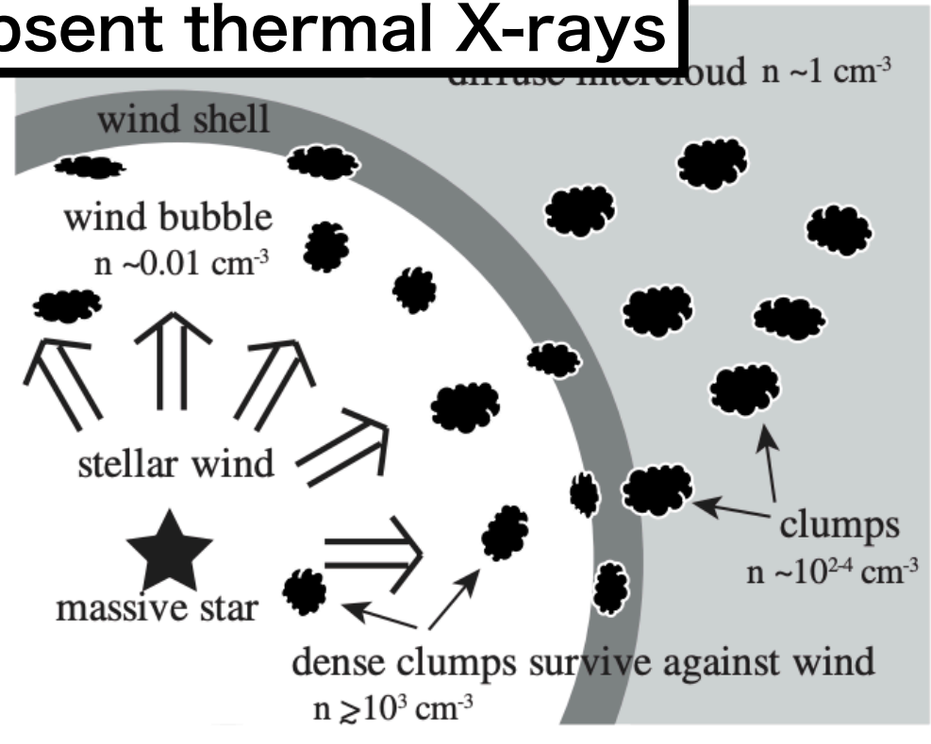
Environments -Setup

- Environment surrounding SNRs have been less understood
- But some hints for environments :
  - — Uniform ISM (Ia from low-mass star)
  - — Wind+(clumpy)ISM for CC(massive star)
    - eg) RXJ1713:wind cavity + (clumpy) ISM





Wind +ISM model Requirement from absent thermal X-rays



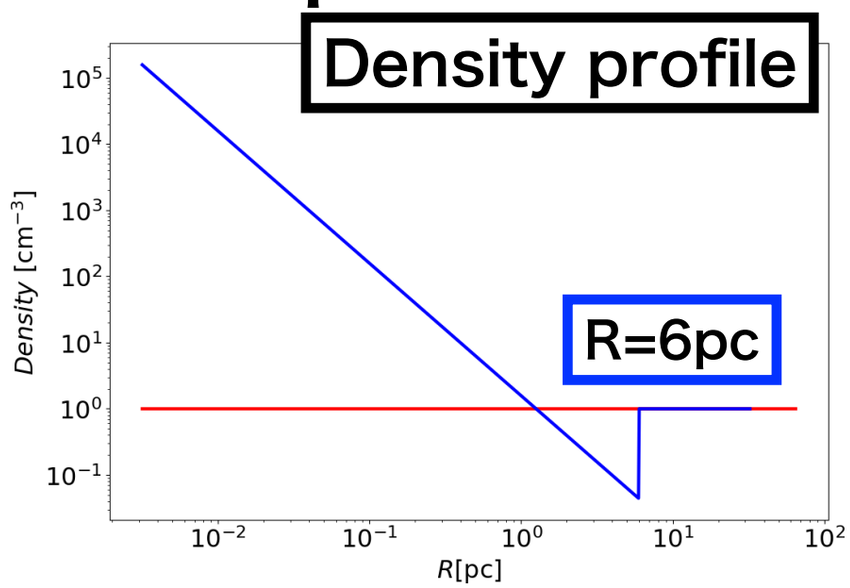
Inoue+12

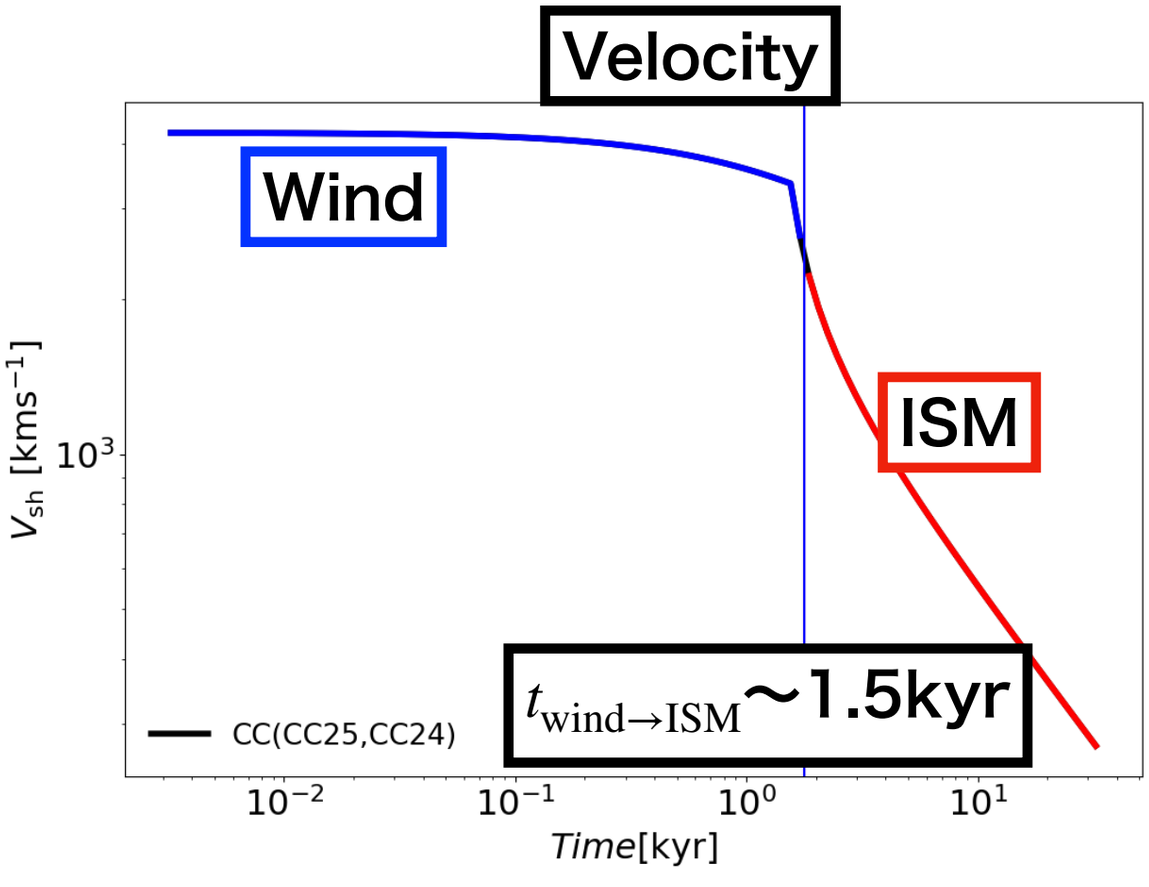
Shock evolution-Setup

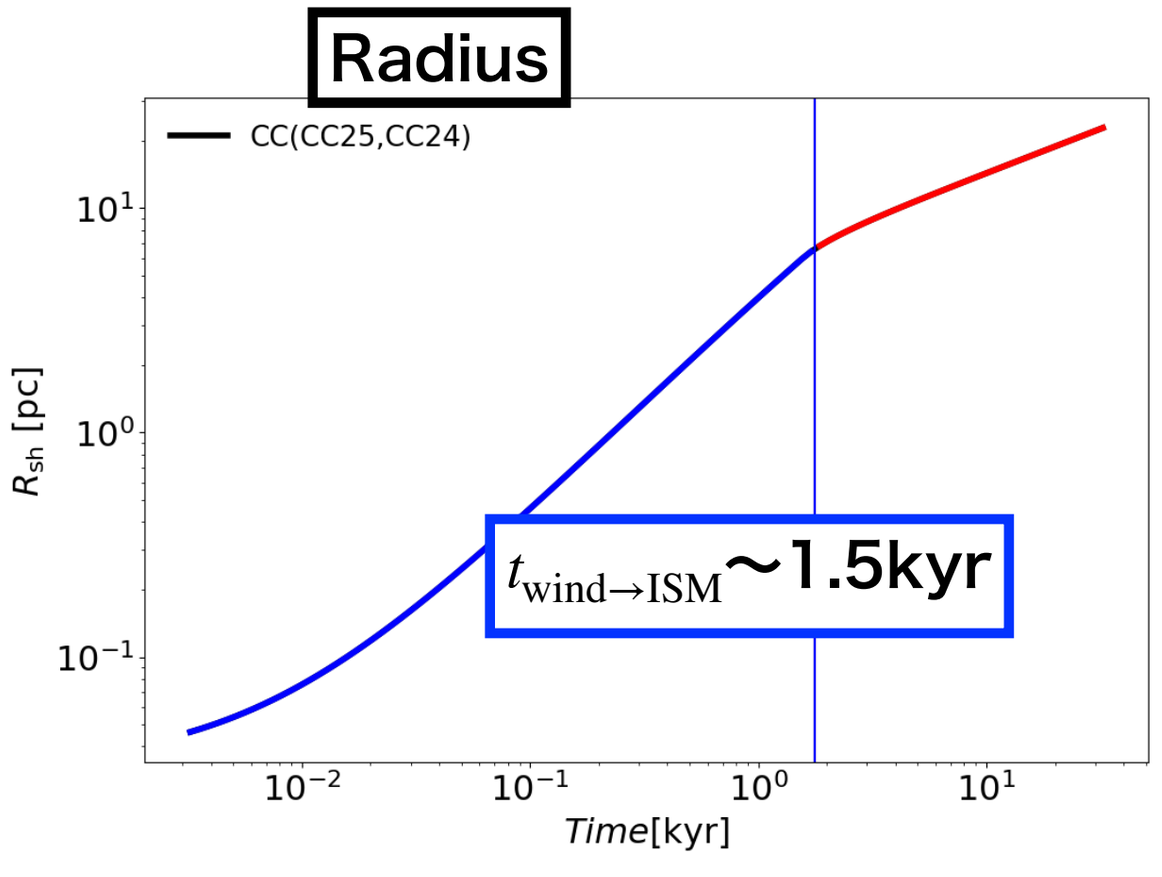
- Does not consider the ejecta, but only **shock speed** analytically

$$V_{\rm sk}(t) = V_{\rm sk,0}\sqrt{M_{\rm ej}/(M_{\rm ej}+2M_{\rm sw})}$$

- Shock evolution for CC in Wind+ISM(1/cc) **until 30kyr** (=radiative phase; reach to R∼30pc)







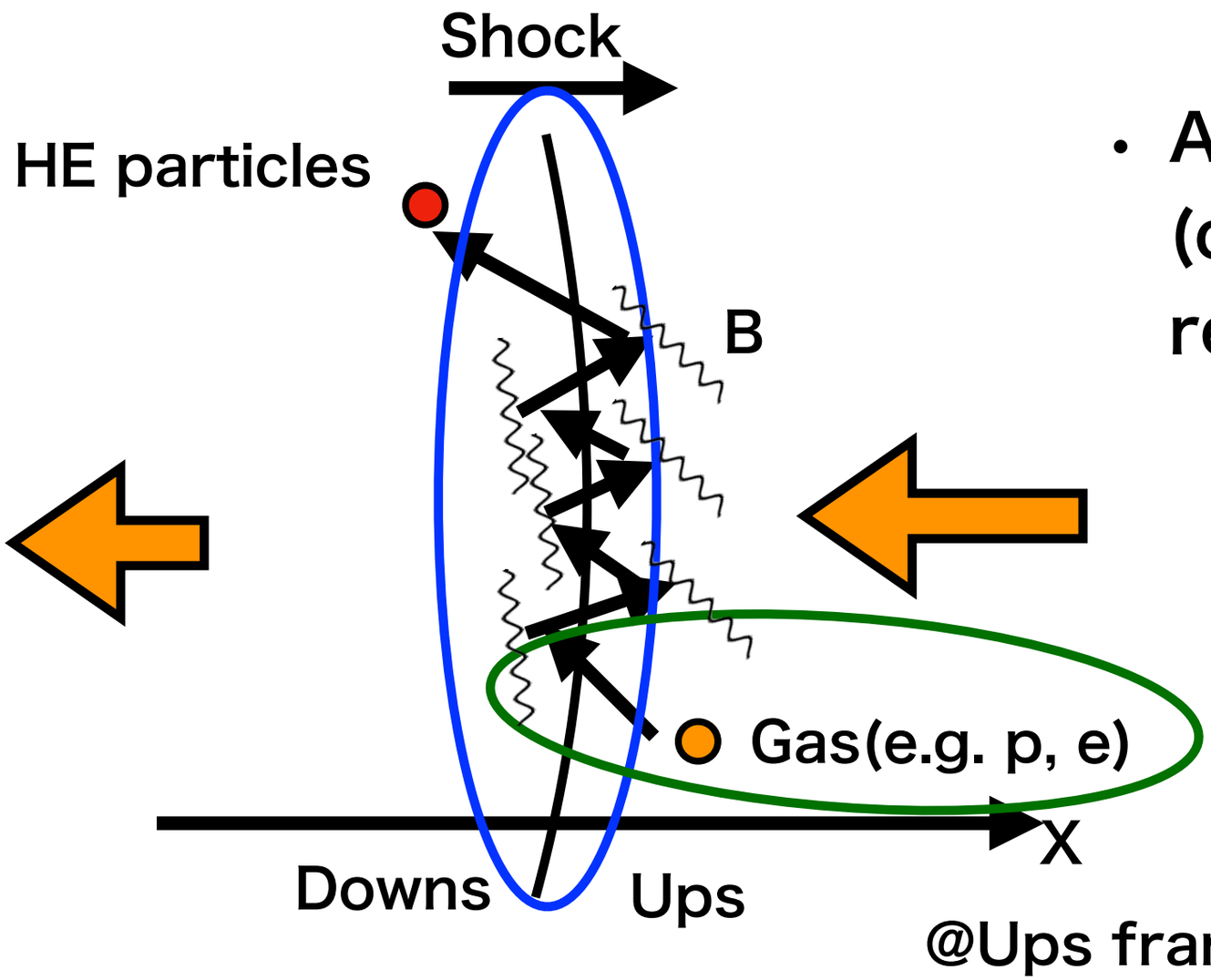
CR transport

- **Particle acceleration at astrophysical shock** $\phi = \phi(x,p) = \frac{dN}{dVdp}$

$$\frac{\partial \phi}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}[r^2(v\phi - D\frac{\partial \phi}{\partial r})] + \frac{\partial}{\partial p}\left(\frac{d(r^2 v)}{3r^2 dr}p\phi\right) + Q_{\mathrm{inj}}(r,p)$$

Adv. / Diffusion / Compression / Injection

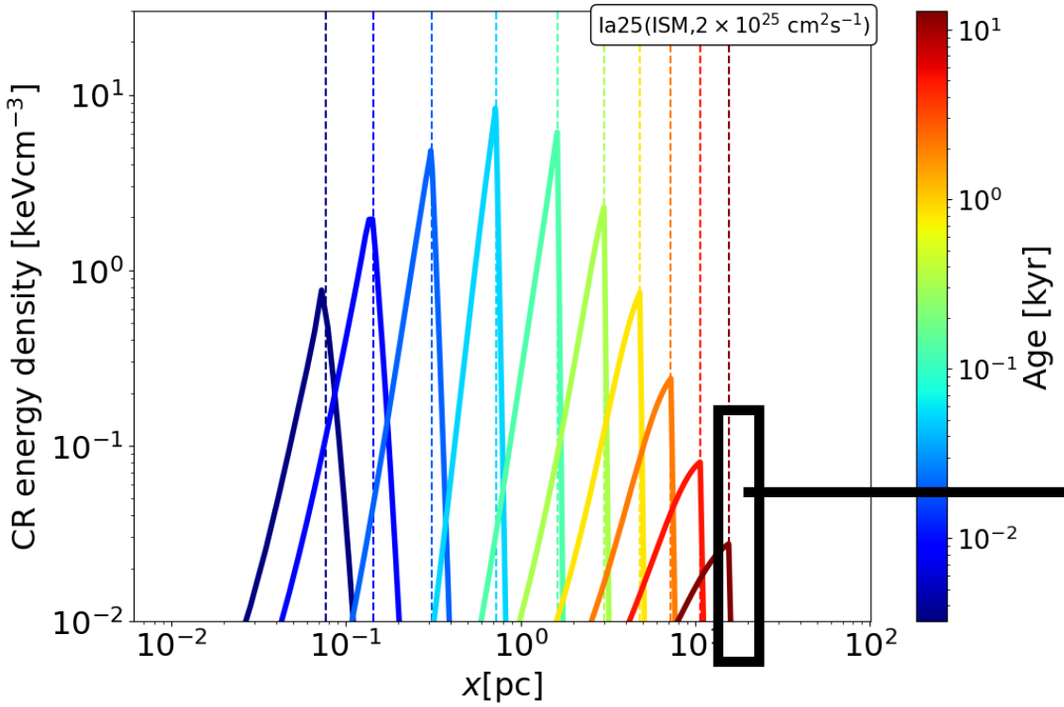
: 1-D Diffusion-Convection Eq.



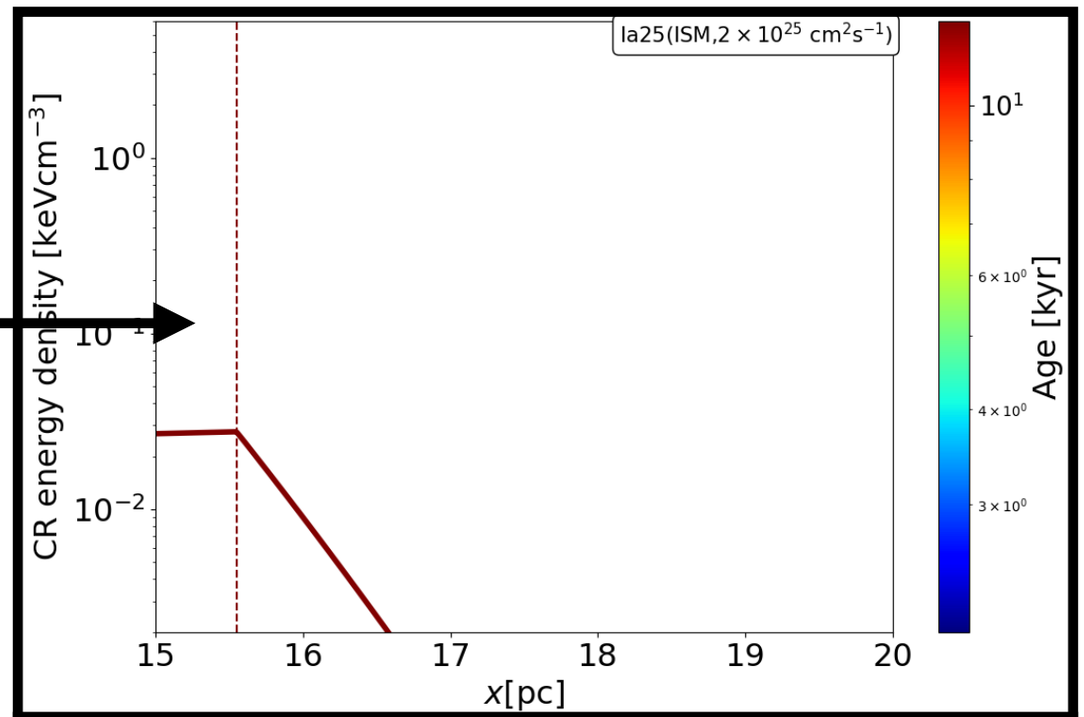
- Acceleration: DSA mechanism (crossing n-times by reflection at B turbulence)
- Propagation (up to 60pc):
  -Downs: Adv.&Diffusion
  -Ups: Diffusion

Results : Spatial profile

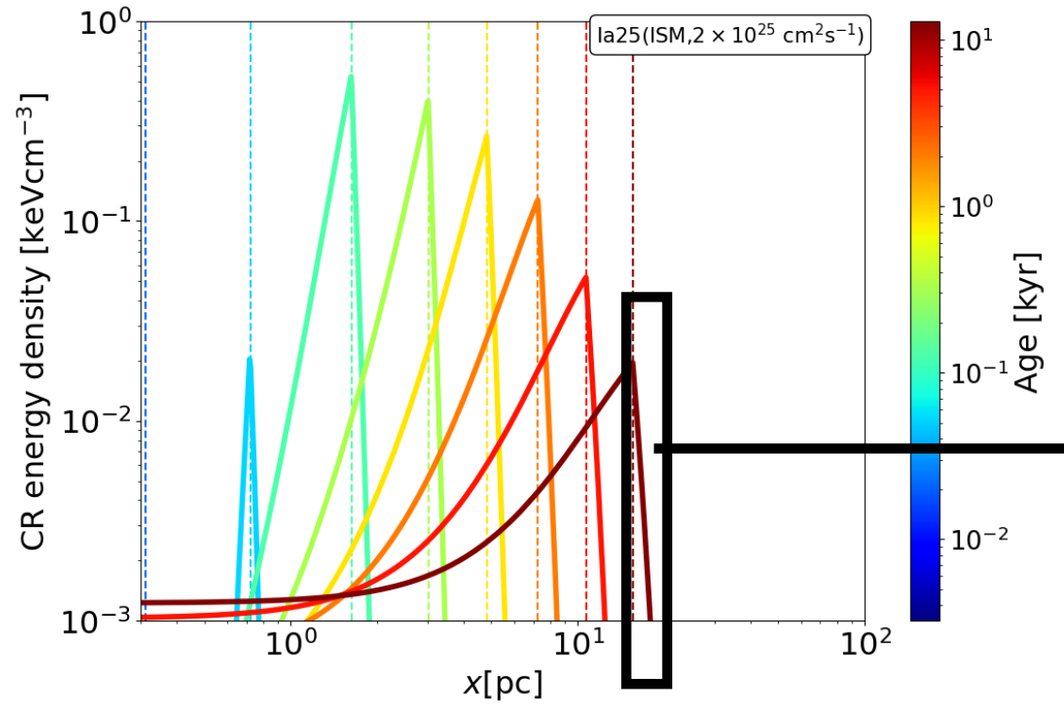
- Spatial Profile @26GeV/c
- 0.1- 30 [kyr] in colorbar

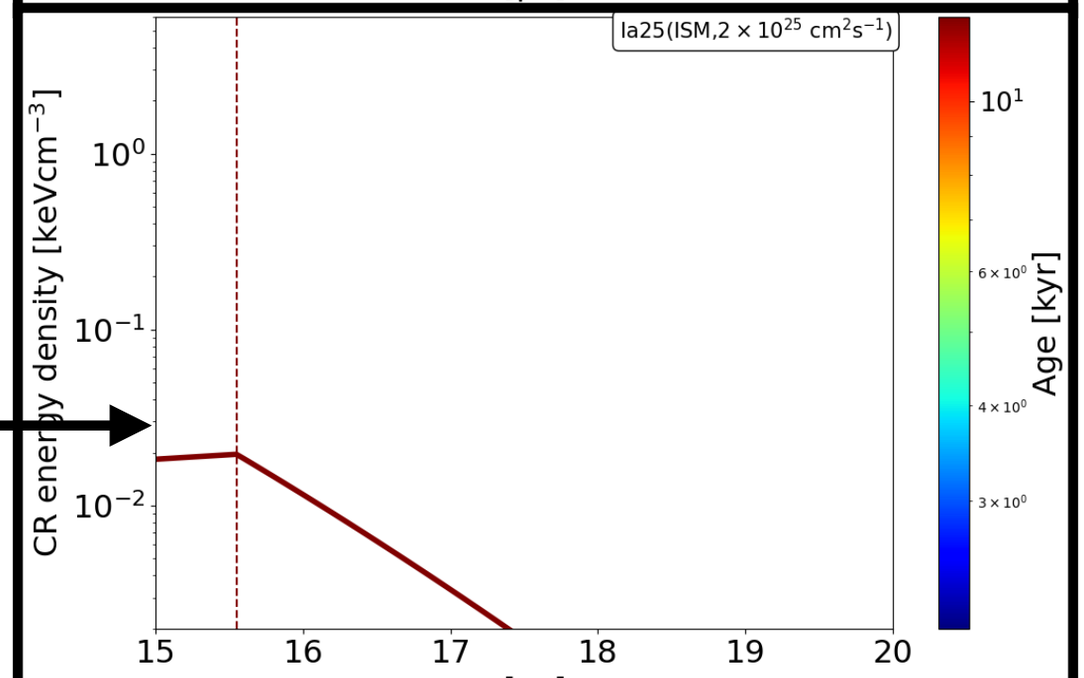


- **Larger Diffusion in higher energy**



- Spatial Profile @300GeV/c





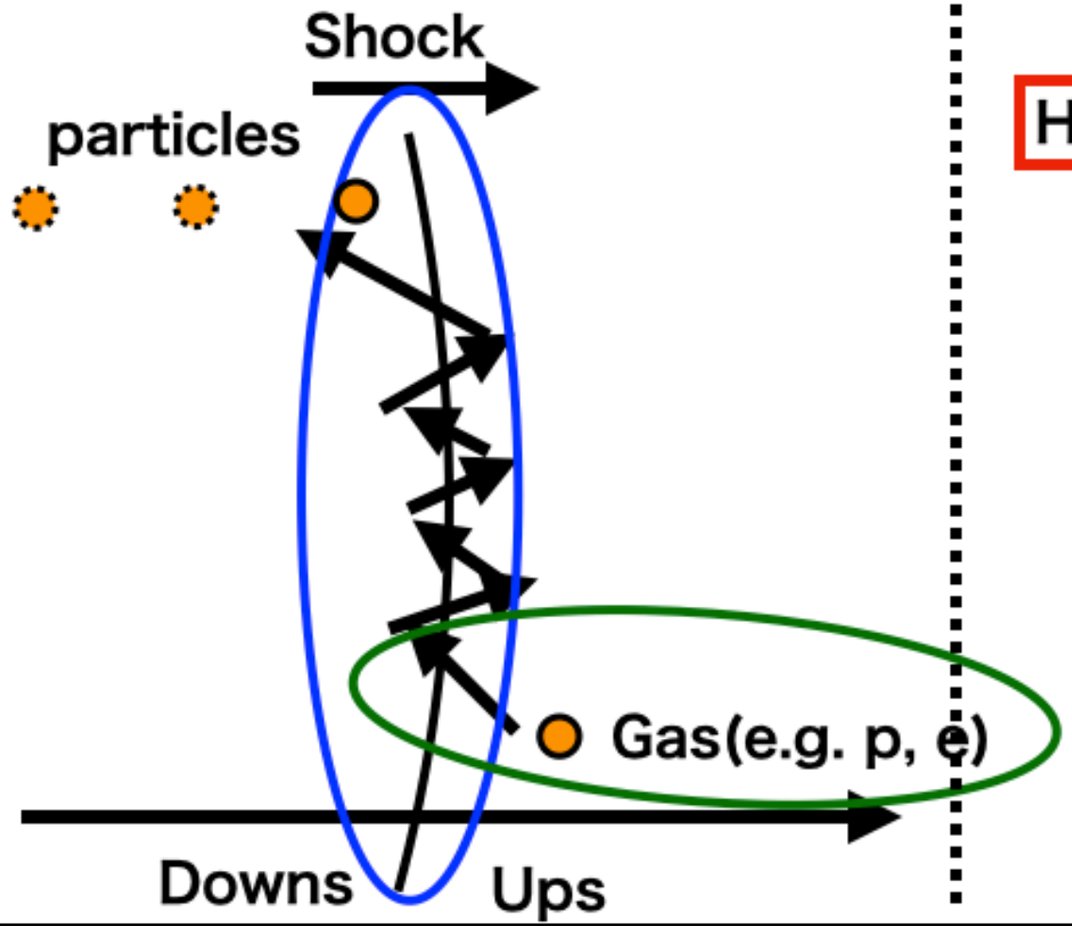
Results : Spatial profile

- Spatial Profile @26GeV/c
- 0.1- 30 [kyr] in colorbar

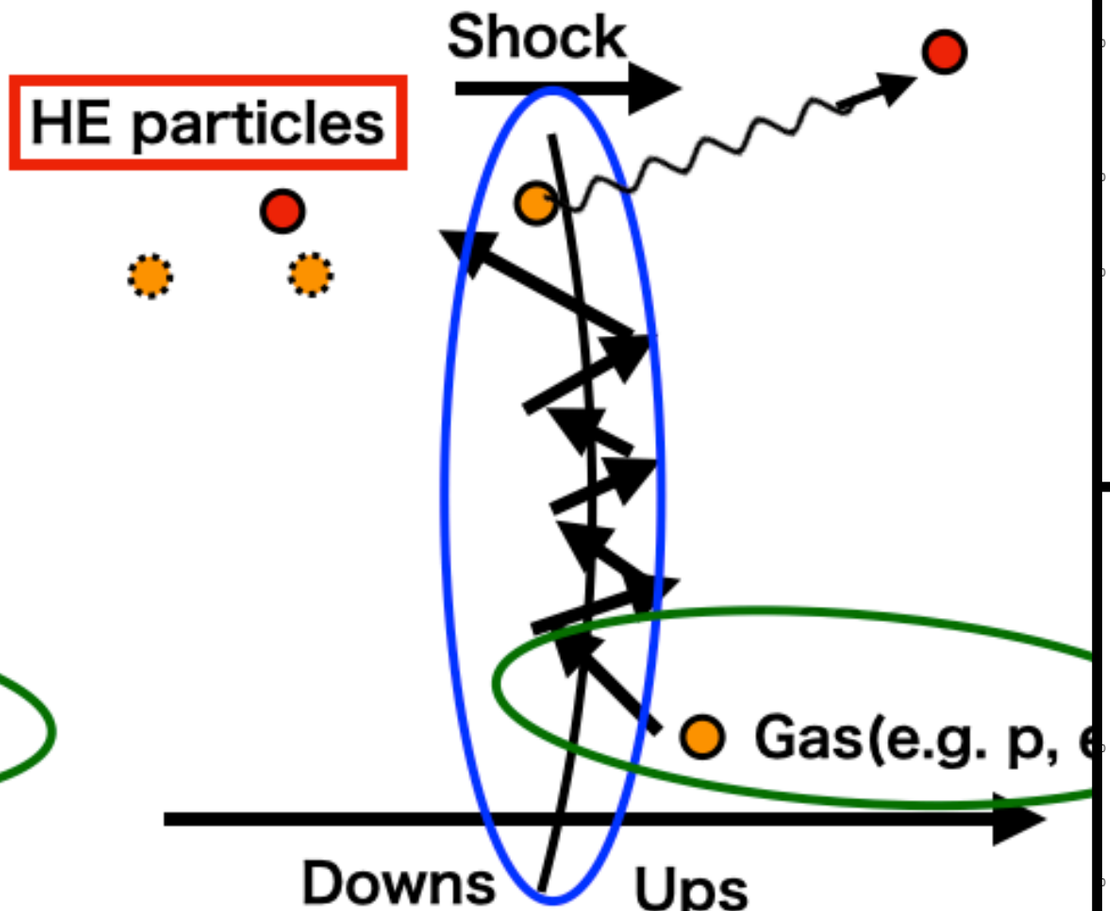
Reflecting that high-E particles escape further

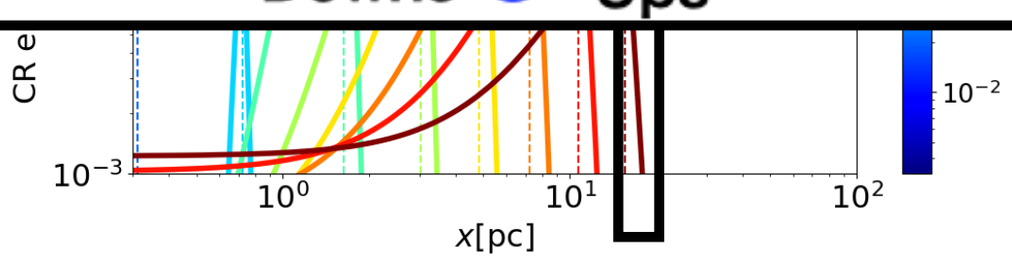
- Diffusion scale l_diff=D(p)/V→ **Large l_diff @High p**
  →Hard spectrum @ shock **upstream**

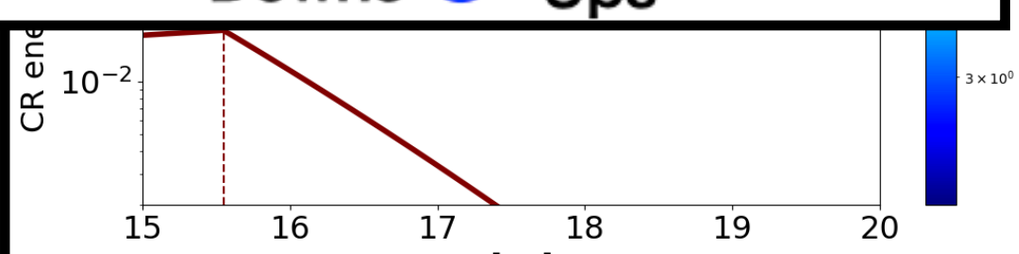
- Acc **Particle@ Low p**



- Acc **Particle@ High p**

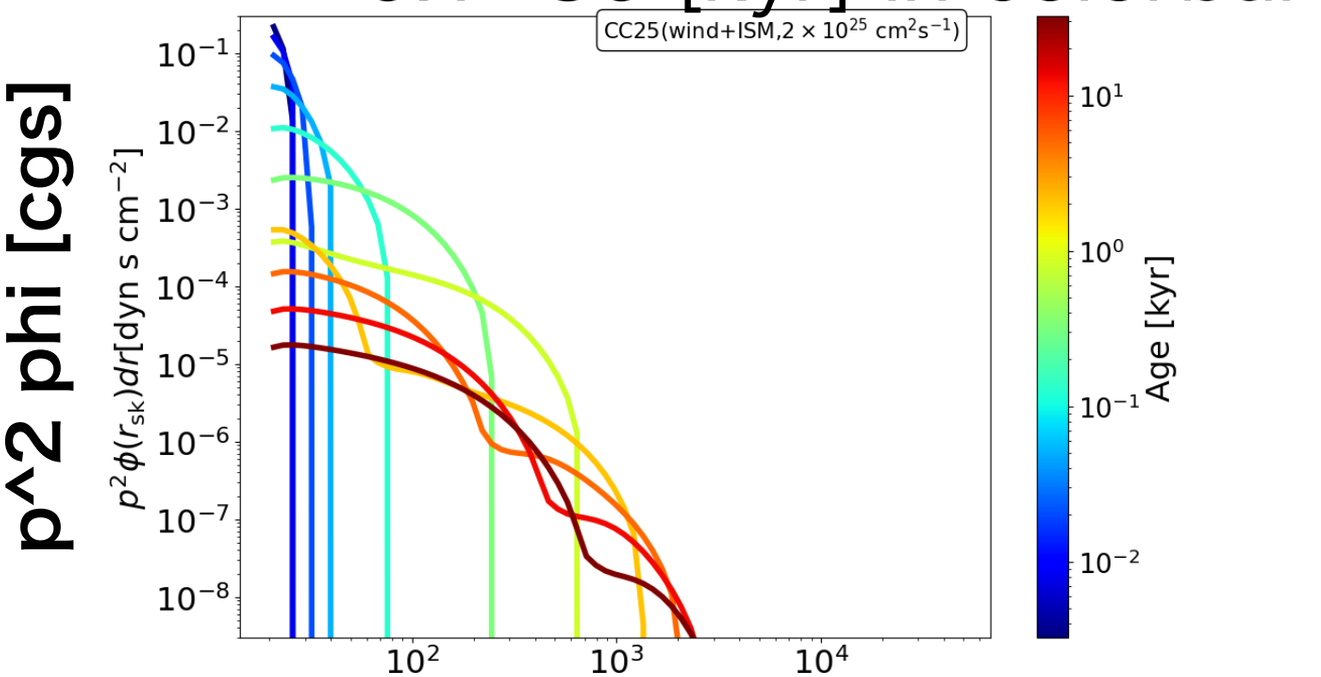




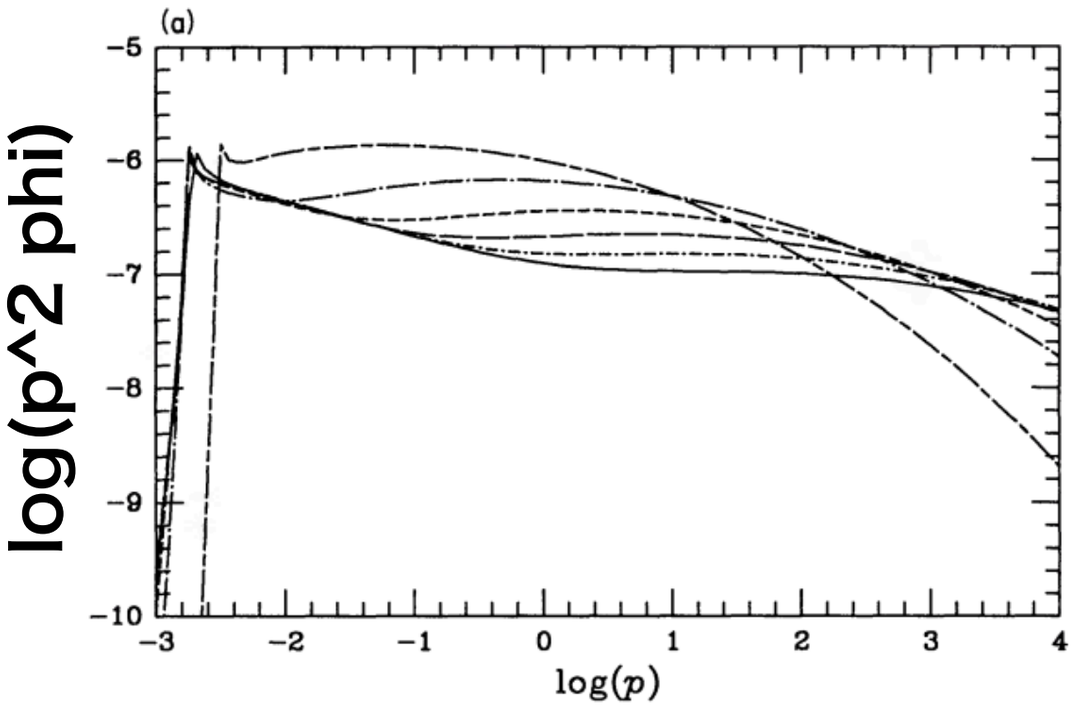


Results：Particle Spectrum (wind+ISM)

- Spectrum @R_sk bin
- **Hardening stops at Sedov time**
  - 0.1- 30 [kyr] in colorbar

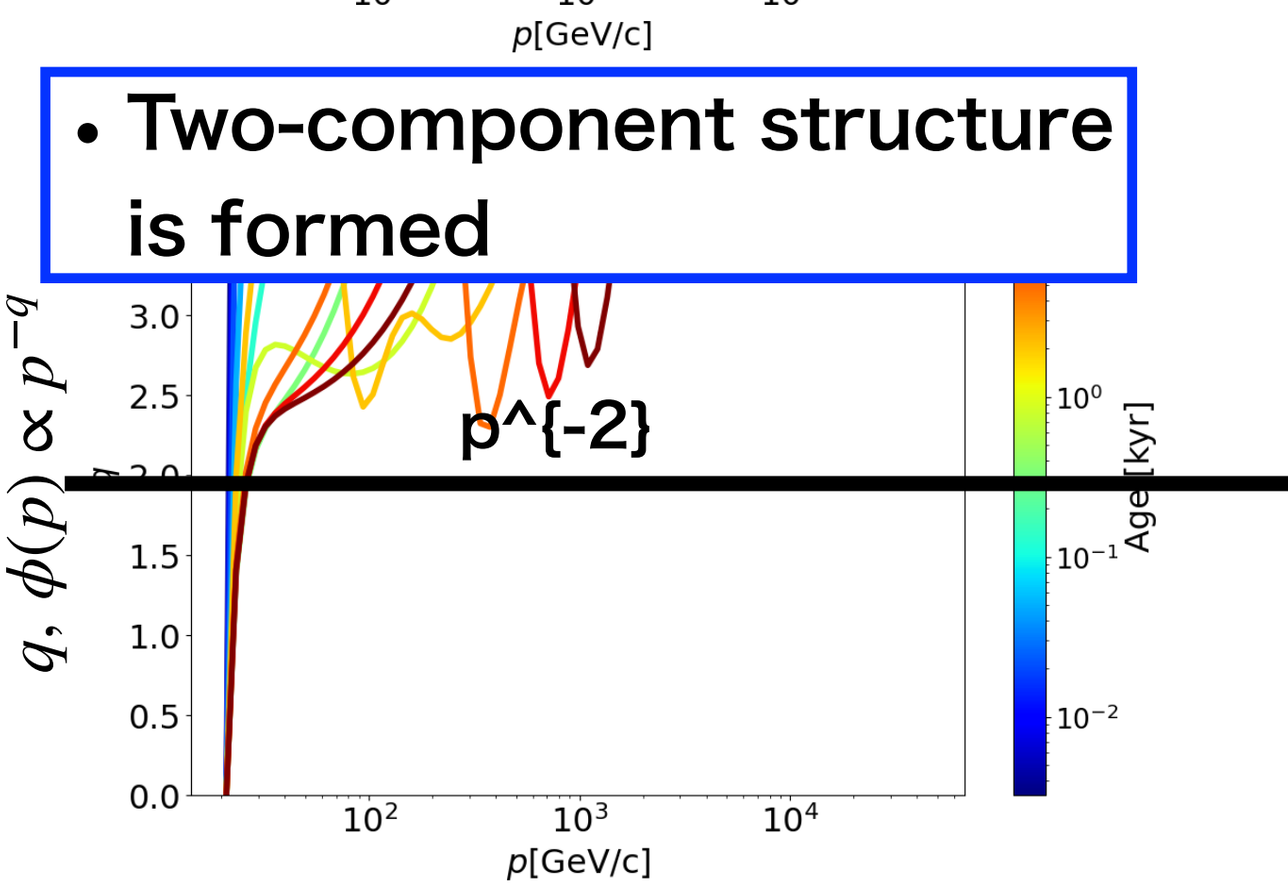


- Softer than plane shock



Kang&Jone91

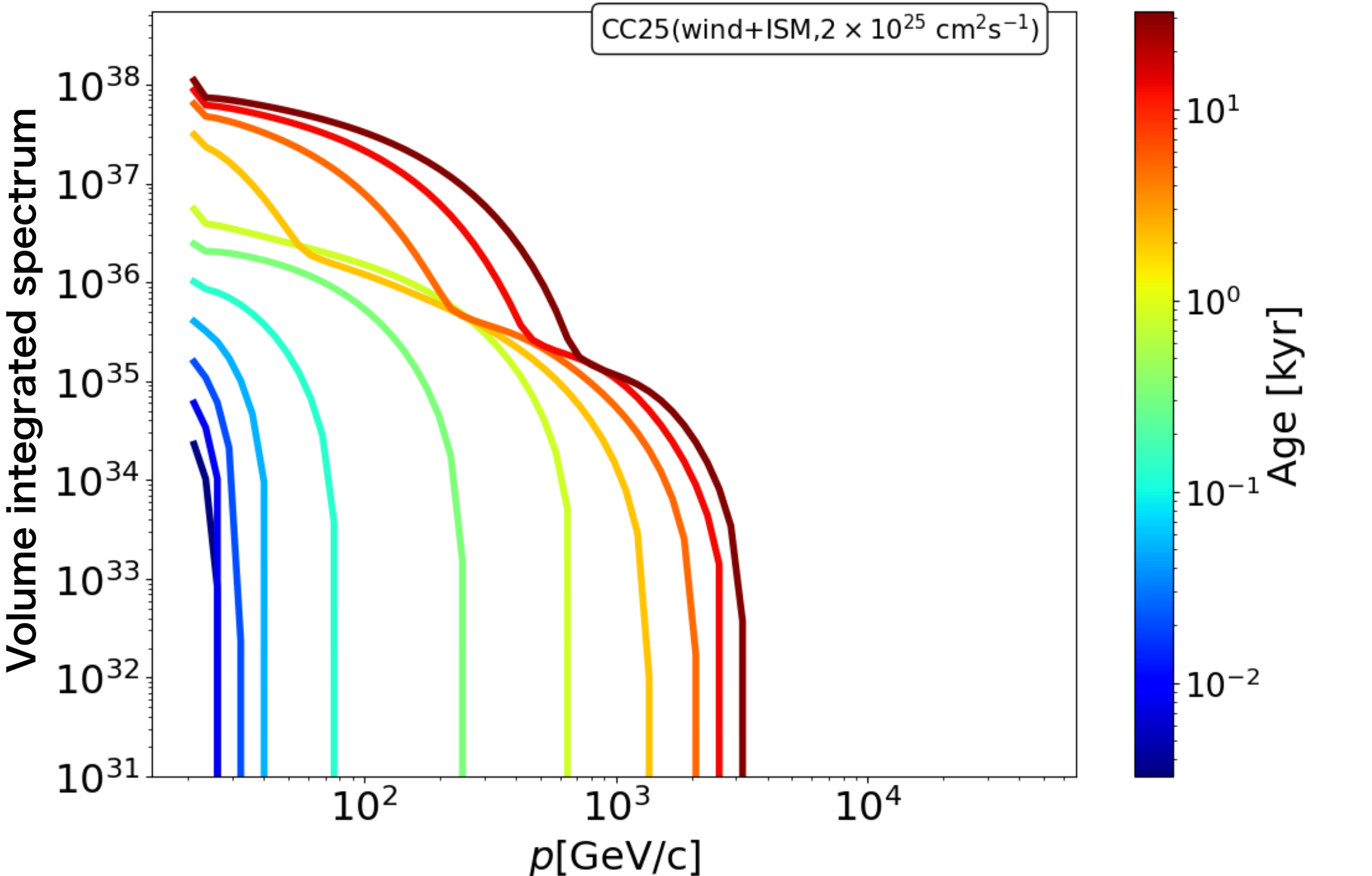
- **Two-component structure is formed**



Results：Volume-integrated Spectrum (wind+ISM)

- 0.02- 30 [kyr] in colorba

- Spectrum @Entire regions $t_{\rm tr} \sim 1.6\ {\rm kyr}$



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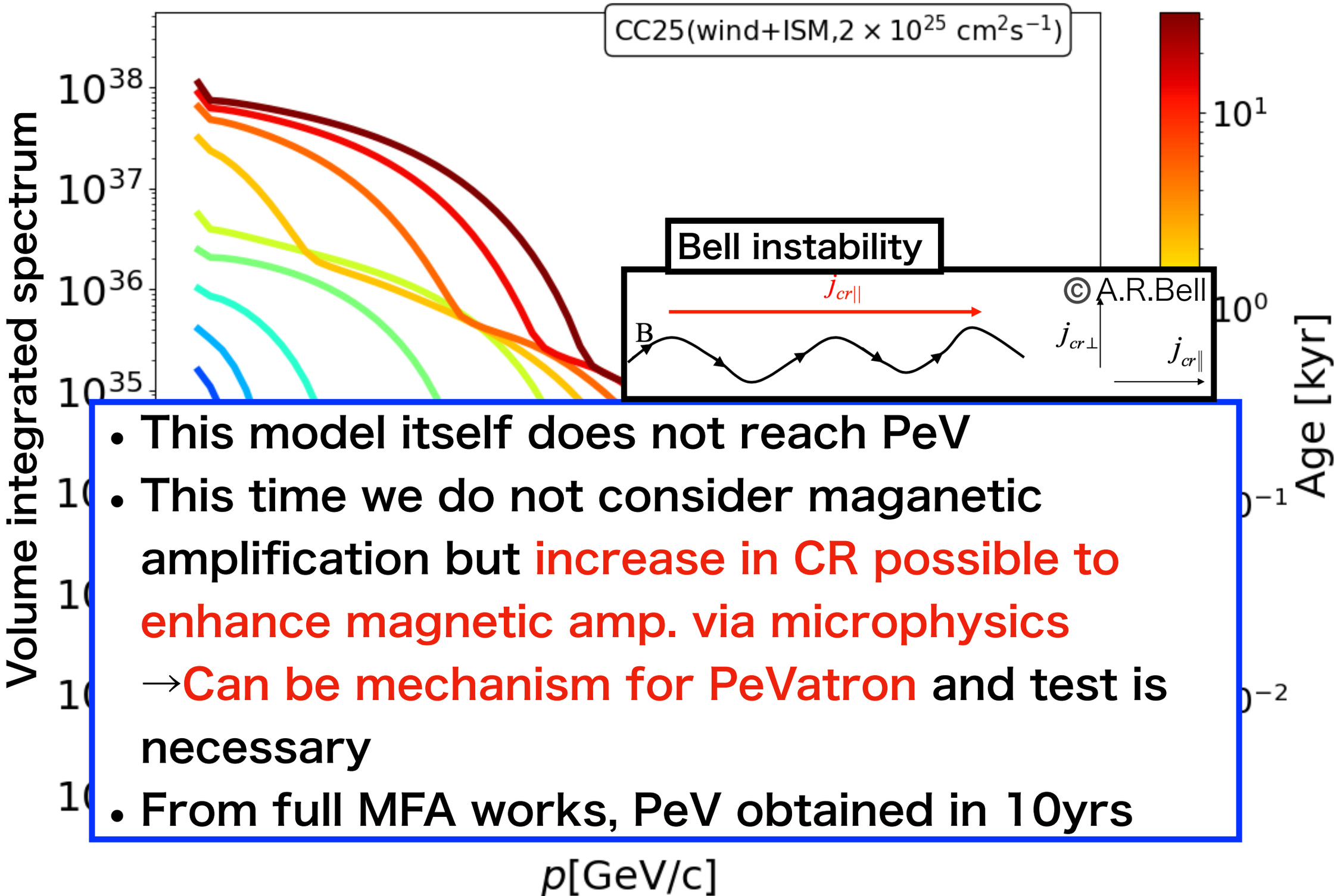
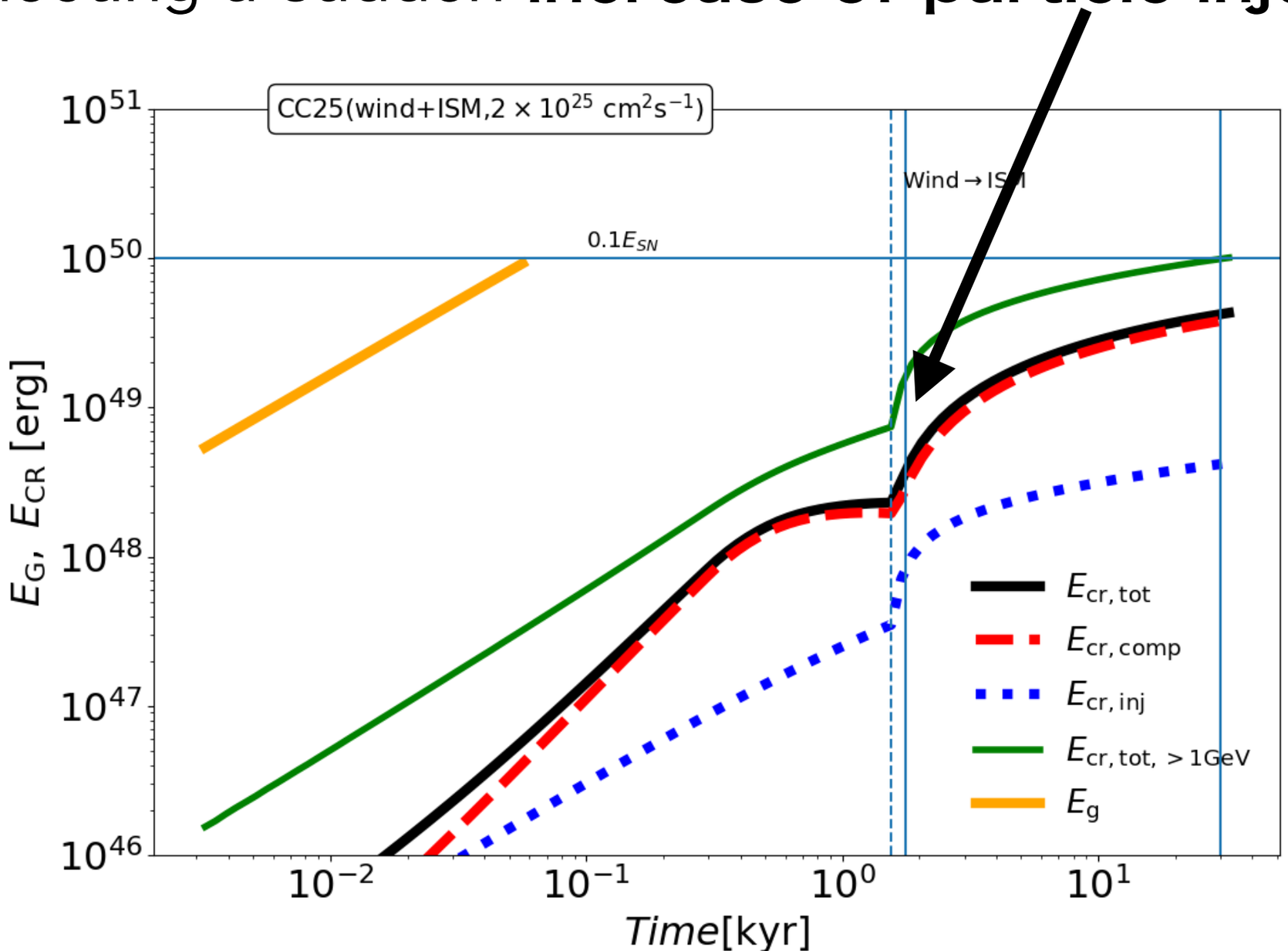
- Spectrum @Entire regions



- This model itself does not reach PeV
- This time we do not consider maganetic amplification but increase in CR possible to enhance magnetic amp. via microphysics
  →Can be mechanism for PeVatron and test is necessary
- From full MFA works, PeV obtained in 10yrs

Total gas energy evolution (wind+ISM case)

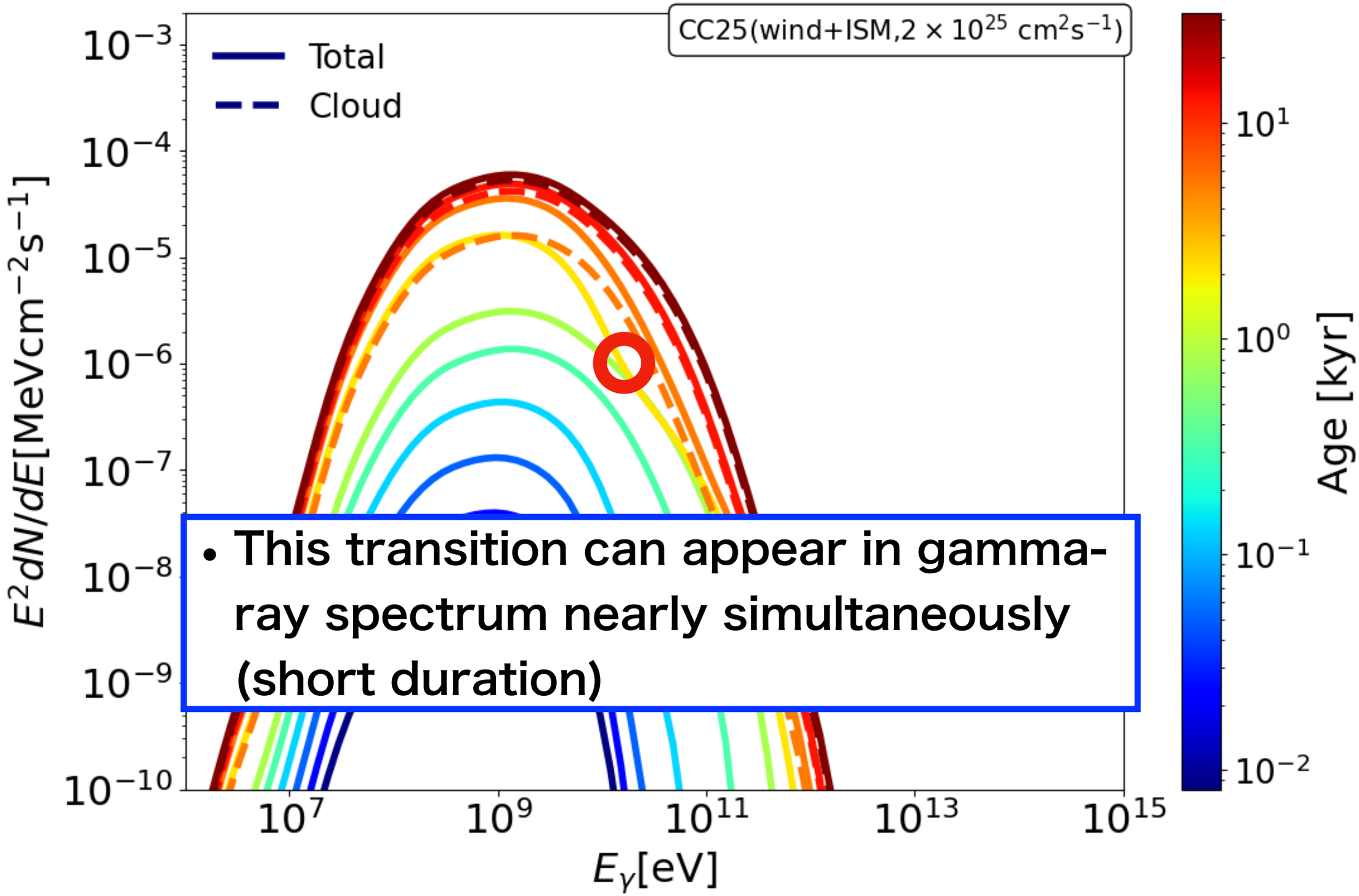
- Total component(—) is dominated by shock compression(—) after～10yr over injection energy increase(—)
- In this wind+ISM model, the increase at the transition can be seen reflecting a sudden **increase of particle injection**



Results：Pi0 emission Spectrum (wind+ISM)

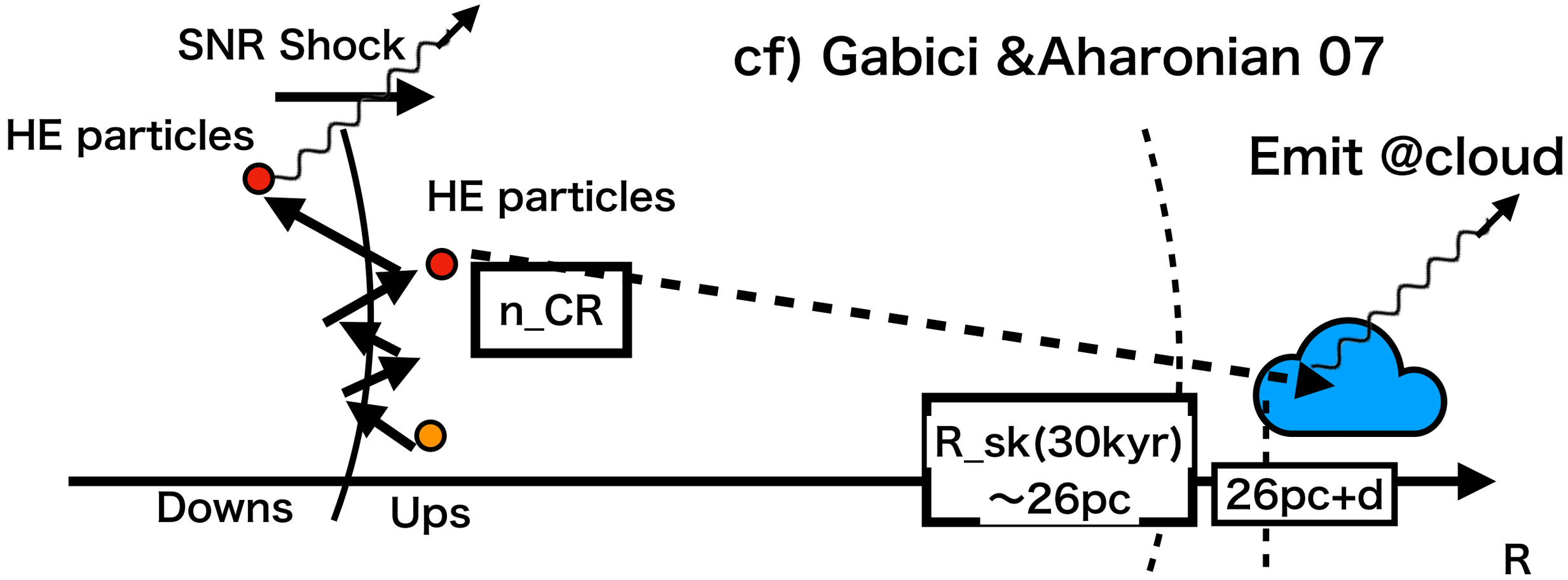
- 0.02- 30 [kyr] in colorba

- Photon Spectrum @Entire regions

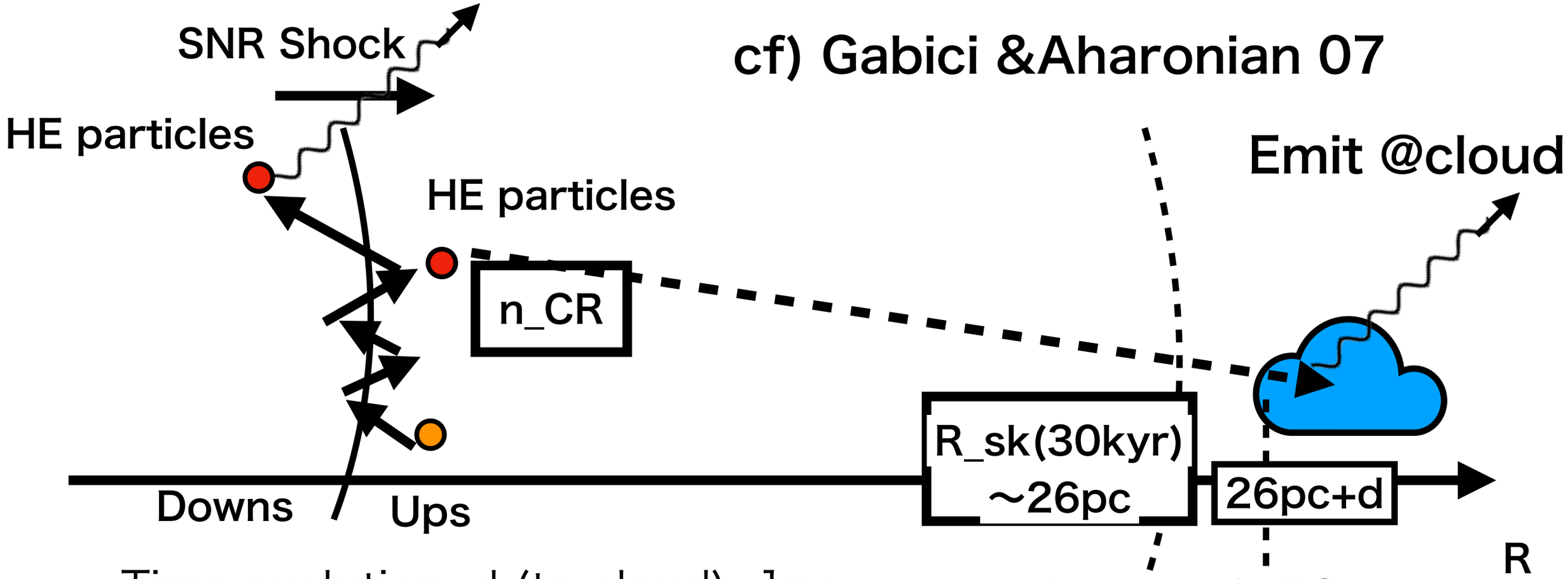


- This transition can appear in gamma-ray spectrum nearly simultaneously (short duration)

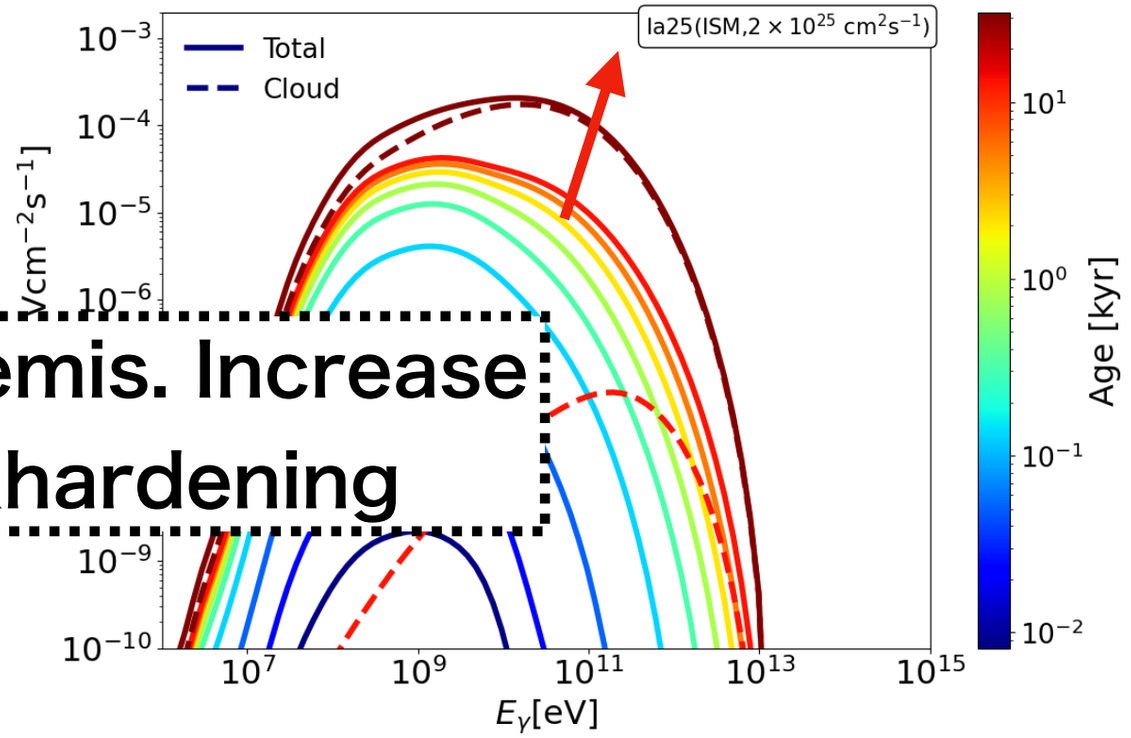
π0-Emission Setup: Cloud @near ups.



π0-Emission: Cloud @near ups.

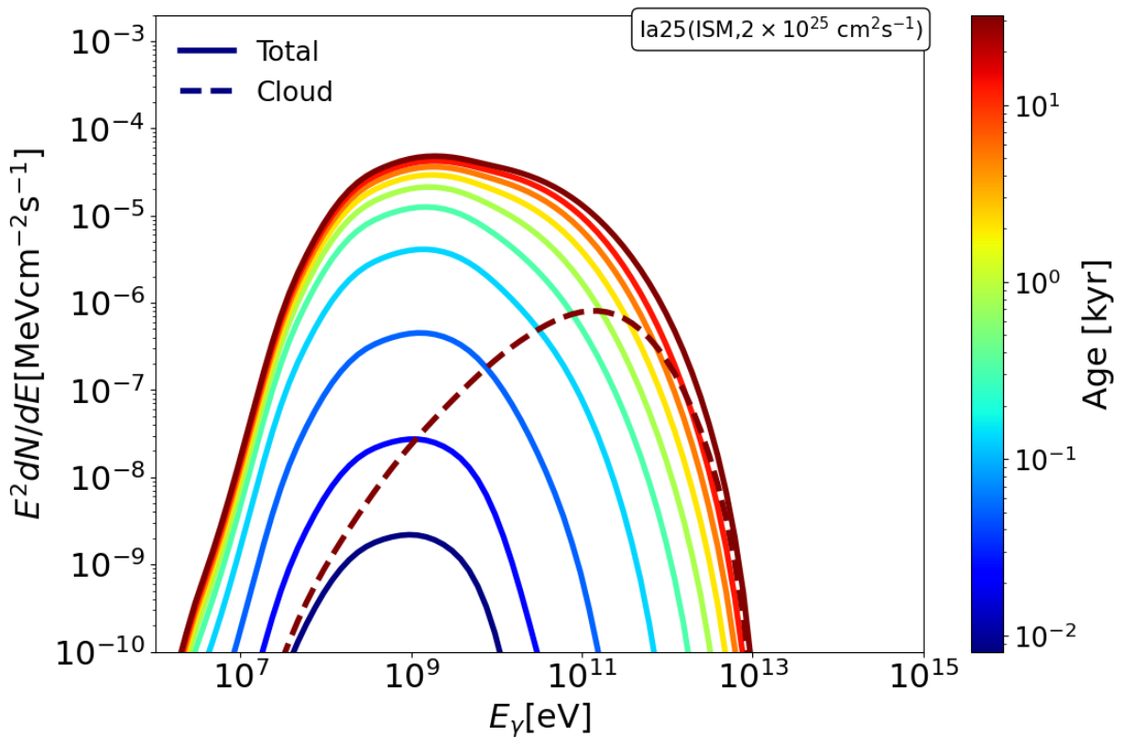


- Time evolution, d (to cloud)=1pc

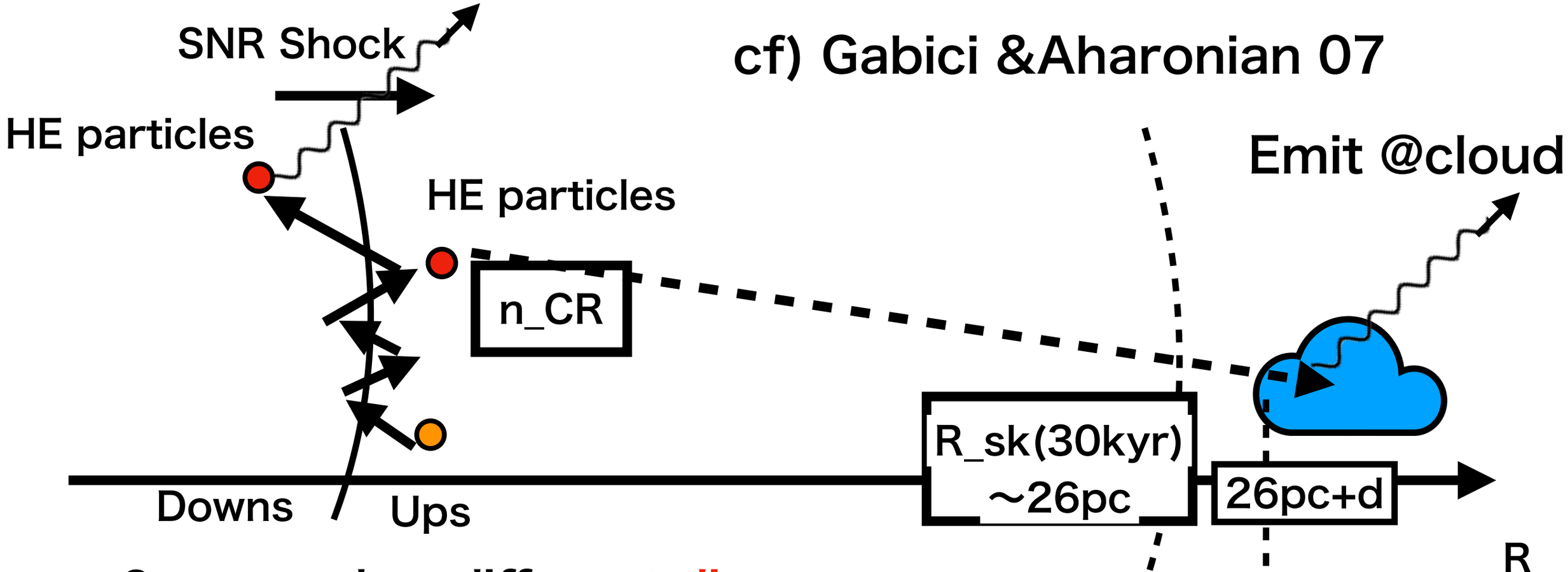


MC emis. Increase &hardening

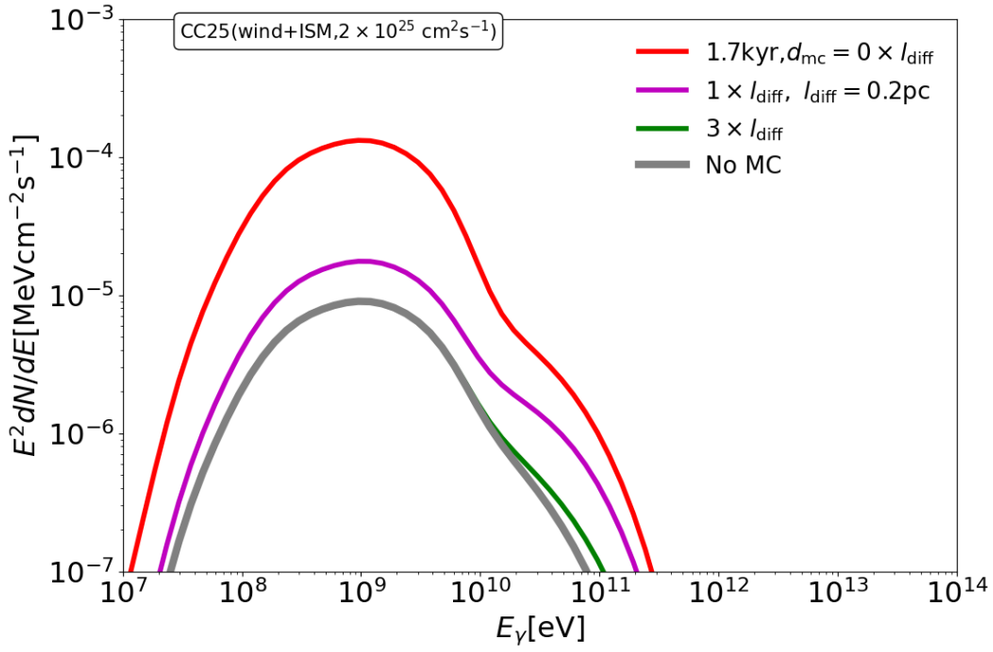
- d (to cloud)=10pc



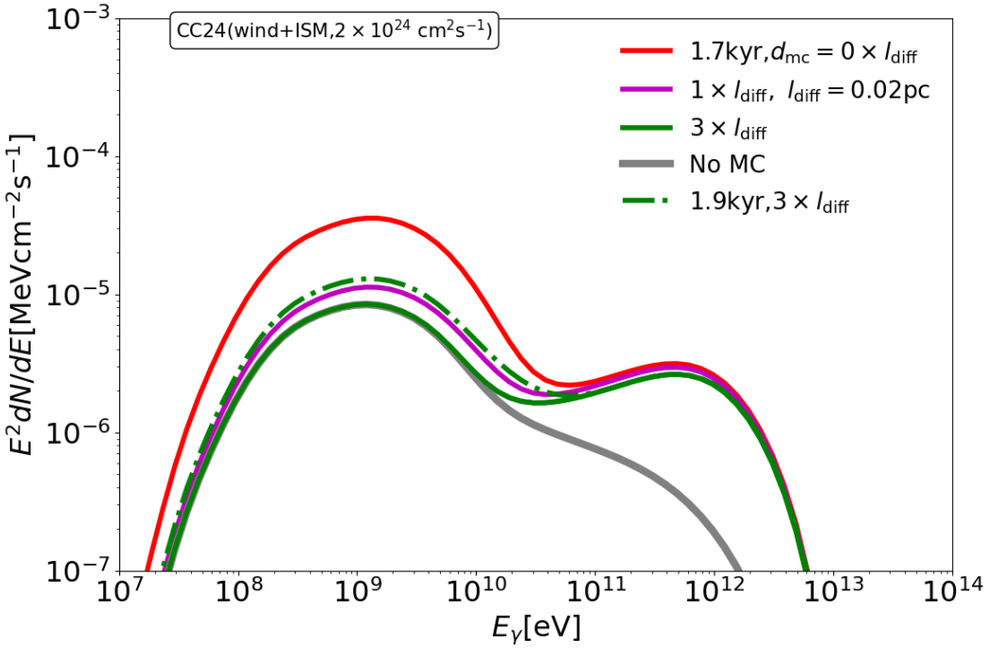
π0-Emission: Cloud @near ups.



- Same age **but different** distance
  - Fiducial diffusivity



  - Lower diffusivity

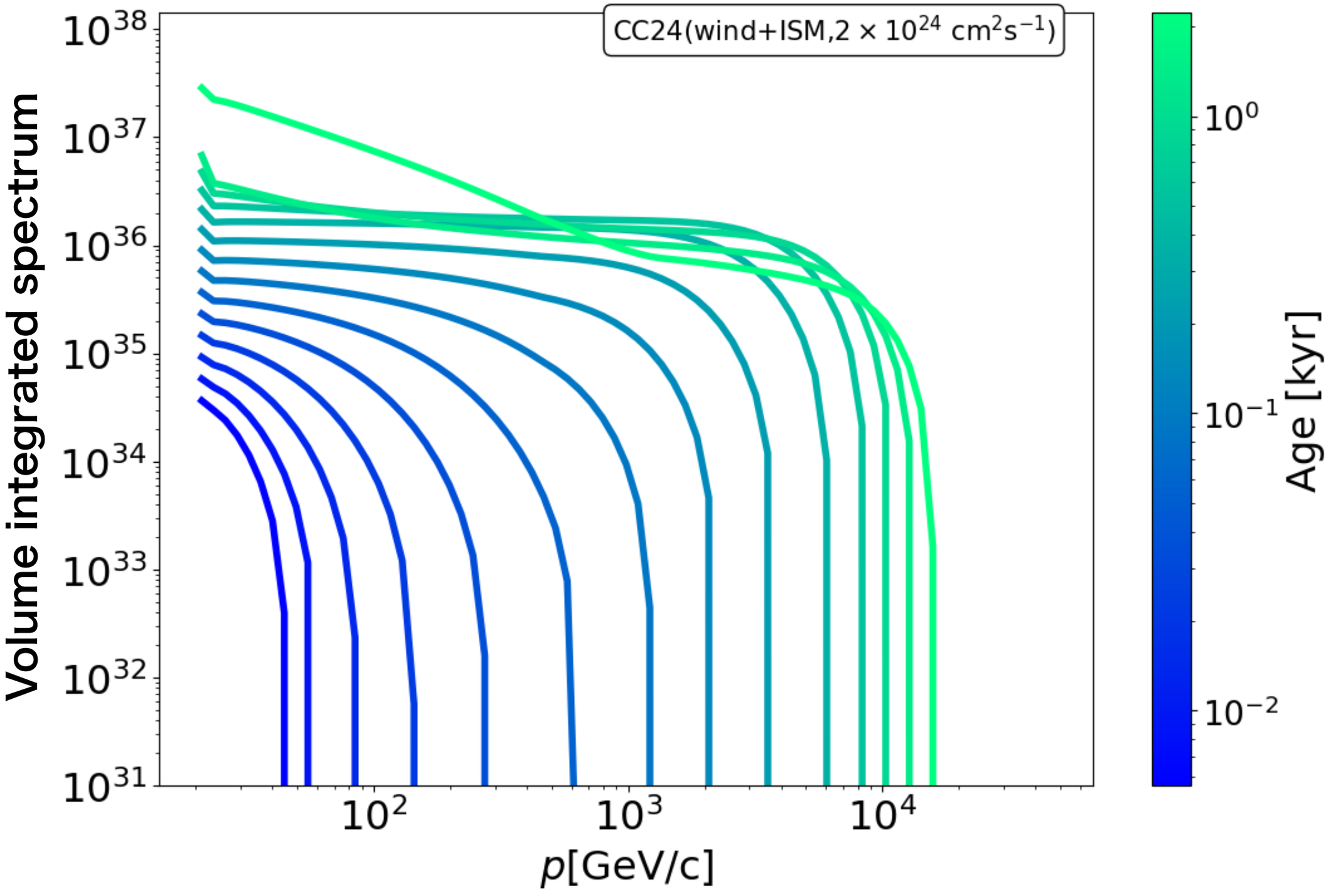


Summary

- SNRs as particle accelerator:
  For some SNRs, the gamma-rays from extended region has revealed the existence of high-energy CR
- We developed a tool to calculate the **spatial/momentum distribution of particles** accelerated at the shock and CR propagation
- Our wind+ISM model shows **the possibility of** efficient **acceleration at transition phase** (→PeVatron??)
- Pi0 Gamma-ray from upstream can largely **enhance when** clumps exists near shock
  (Also reproduces some young & old objects)

Results：Volume-integrated Spectrum (**Low diffusivity**)

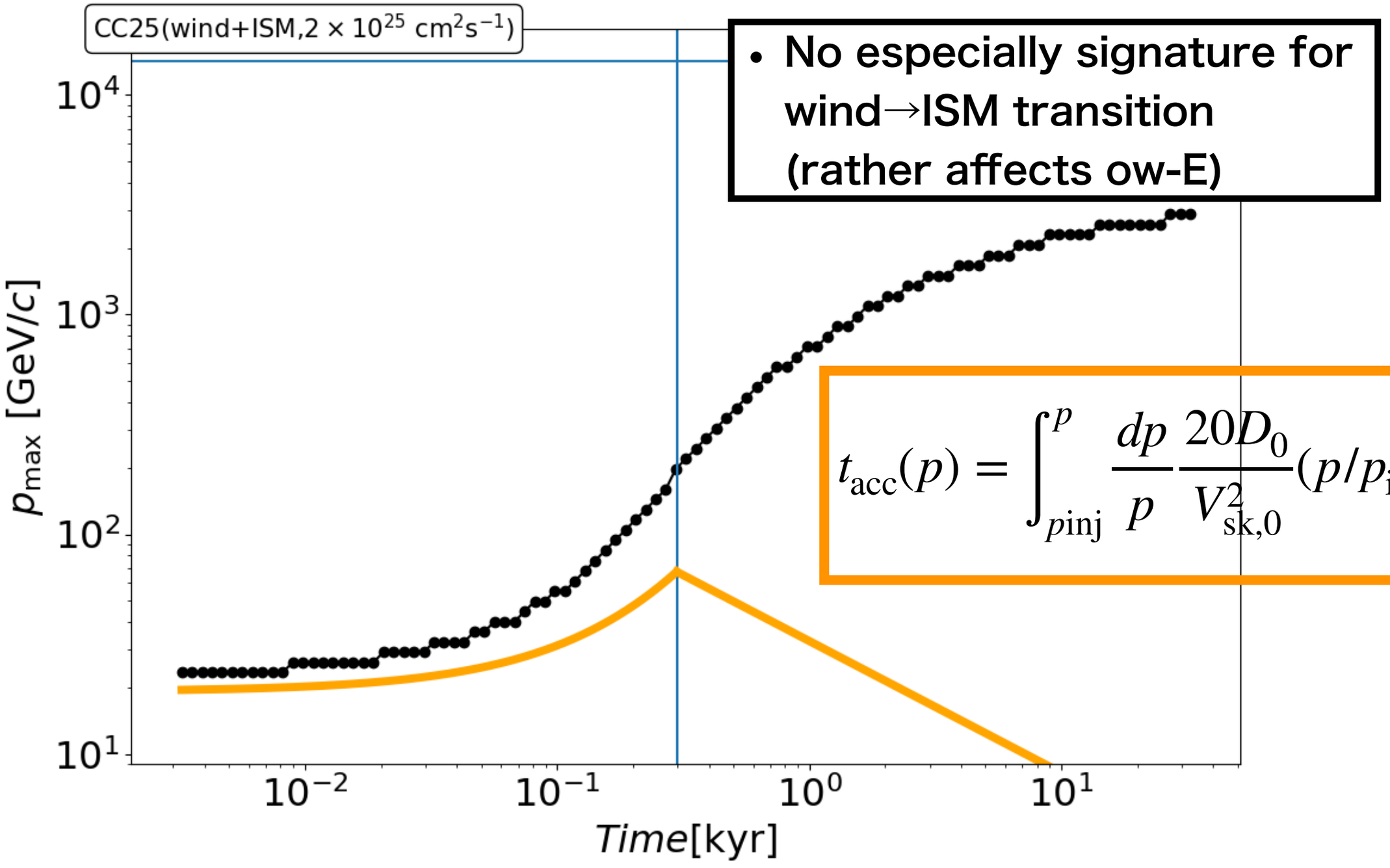
- 0.006- 2 [kyr] in colorba
- Spectrum @Entire regions $t_{\rm tr} \sim 1.6\ {\rm kyr}$



E_max(t)

- E_max(t)～1 TeV in our $D_0 \sim 10^{25}$

—$D(p) \propto p^{1/3}$ leads to lasting acceleration gradually after t_{Sedov}



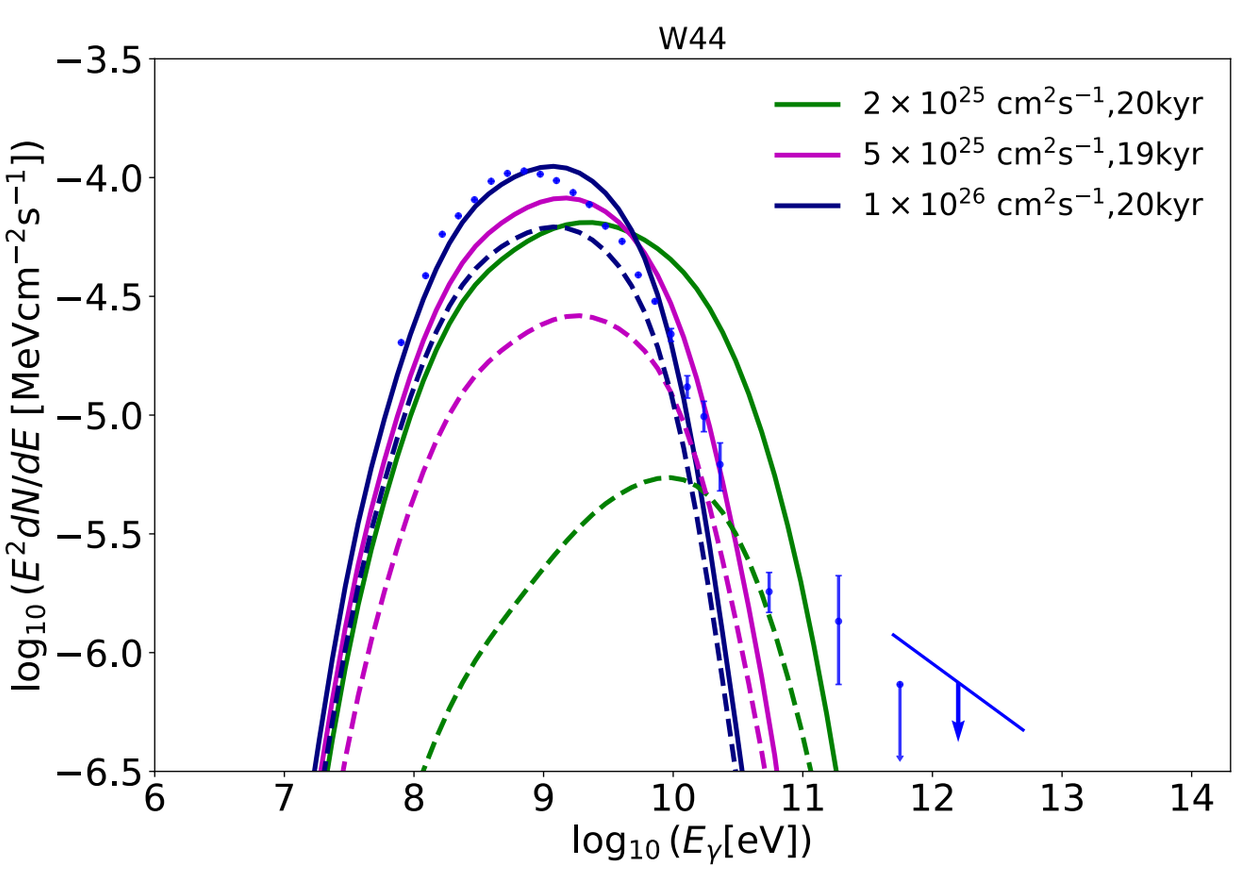
- **No especially signature for wind→ISM transition (rather affects ow-E)**

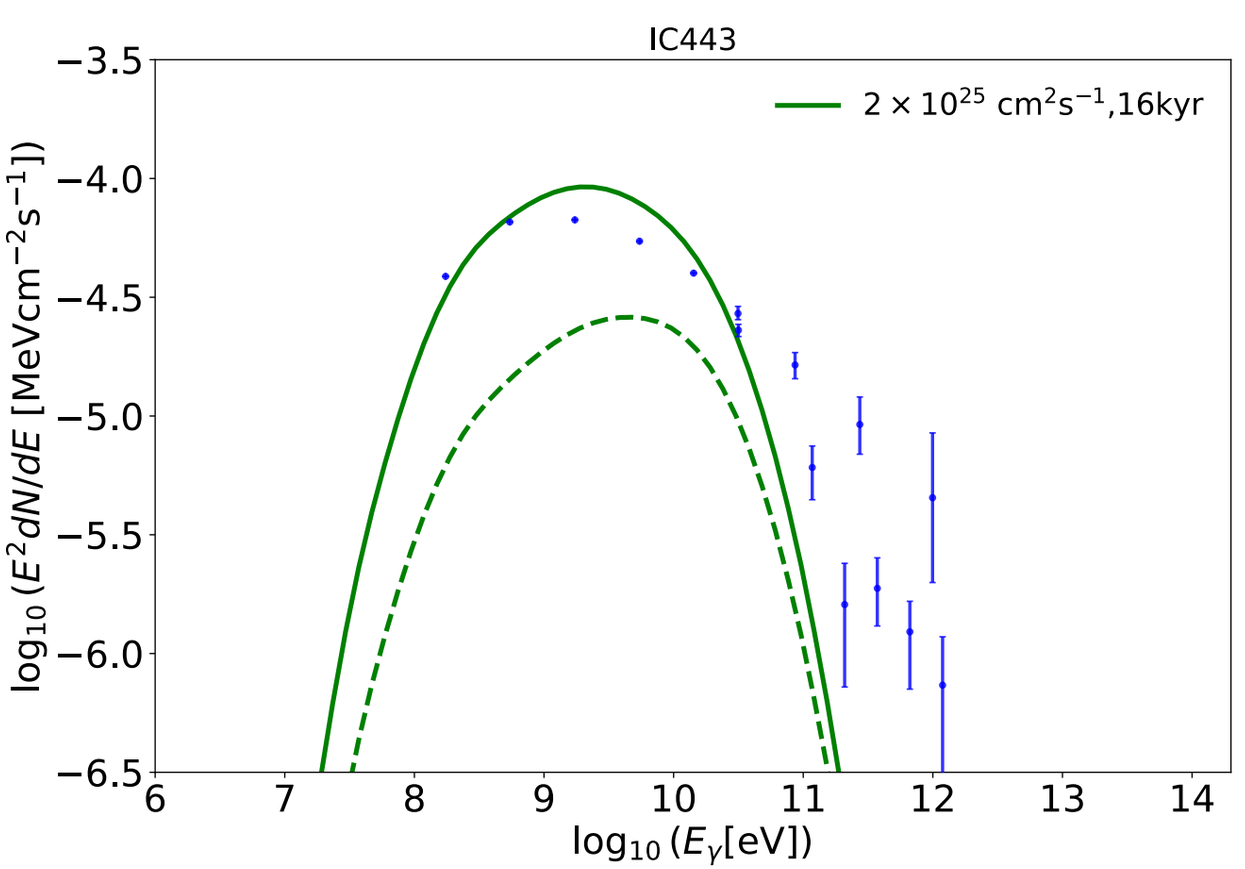
$$t_{\mathrm{acc}}(p) = \int_{p\mathrm{inj}}^{p} \frac{dp}{p} \frac{20 D_0}{V_{\mathrm{sk},0}^2} (p/p_{\mathrm{inj}})^{1/3}$$

Results : Pi0 emission against obs.

- Case: **Old CC : W44**(~20kyr)**, IC443**(~10-30kyr)
  — Fitting (cloud parameter) and Almost explain the data

Rcl - Rsk,model(30kyr)～0pc **n_cl=10^4/cc**	**Rcl - Rsk,model(30kyr)～0.5pc** **n_cl=5000/cc**





Results : Pi0 emission against obs.

- Case: **Young type Ia : Tycho**(454yr)**, Kepler**(422yr)
- Case: **Old CC : W44**(~2kyr)**, IC443**(~1-3kyr)

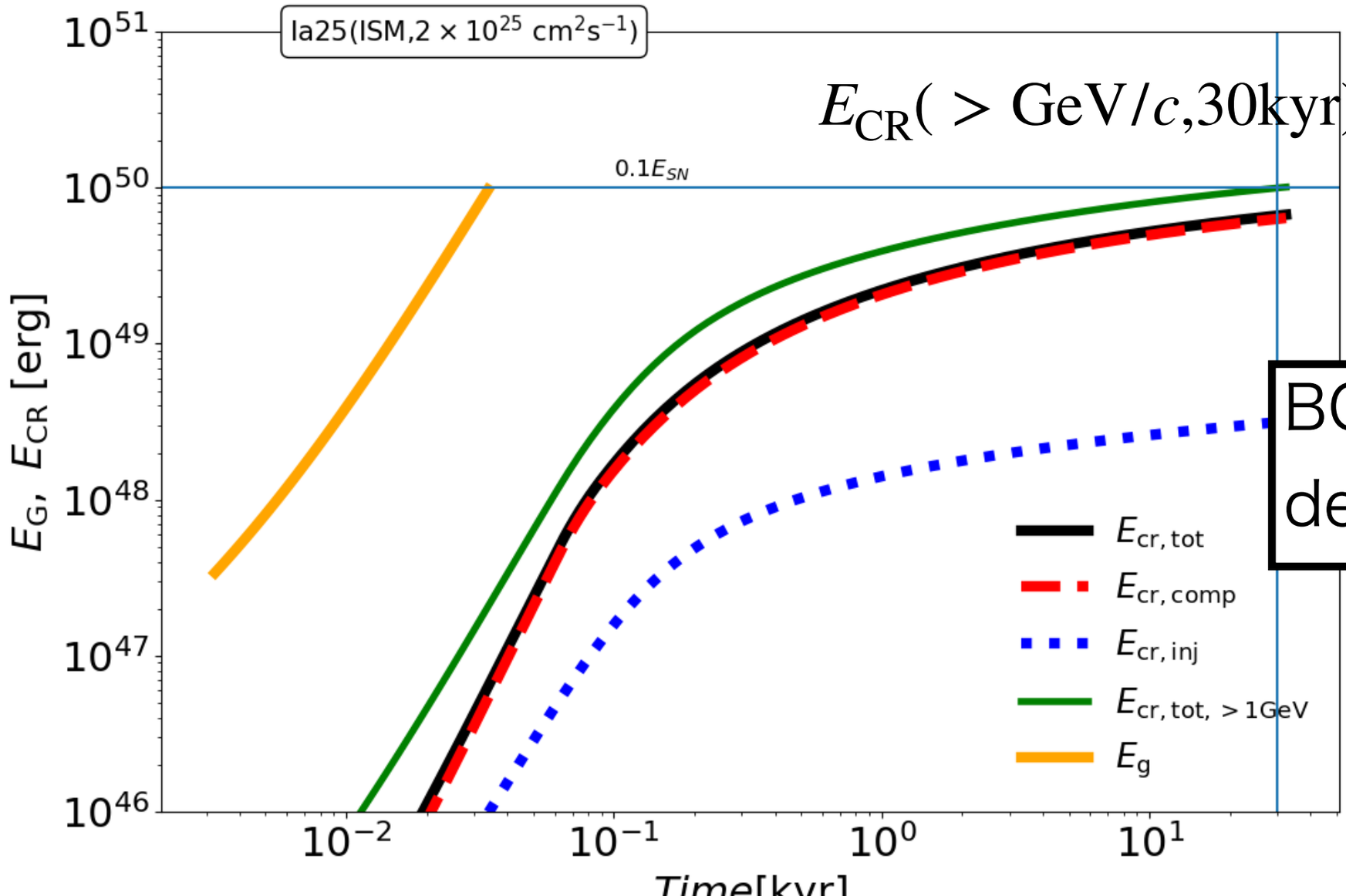
SNR	SN type	Age kyr	Distance kpc	MC or dense gas
Tycho	Ia	0.454	~3[Tycdis]	√[2]
Kepler	Ia	0.422	4.4 – 7.5[Kepdis]	×
W44	CC	~20	2.9±0.3[w44dis]	√[15]
IC443	CC	15±5	1.35±0.65	√[17]

Total gas energy evolution (ISM case)

- After 10yr, $E_{\rm cr}(t)$ is dominated by compression

$$E_{\rm G}(t) \propto \int dt R_{\rm sk}^2 V_{\rm sk}^3 \propto t^3 \ (V_{\rm sk} \propto t^0) \quad , \quad \propto \ln t \quad \textbf{@Sedov}$$

→ Assume injection(—) proportional to gas energy(—)



$E_{\rm CR}(>{\rm GeV}/c, 30{\rm kyr}) \sim 10\,\% E_{\rm SN}$

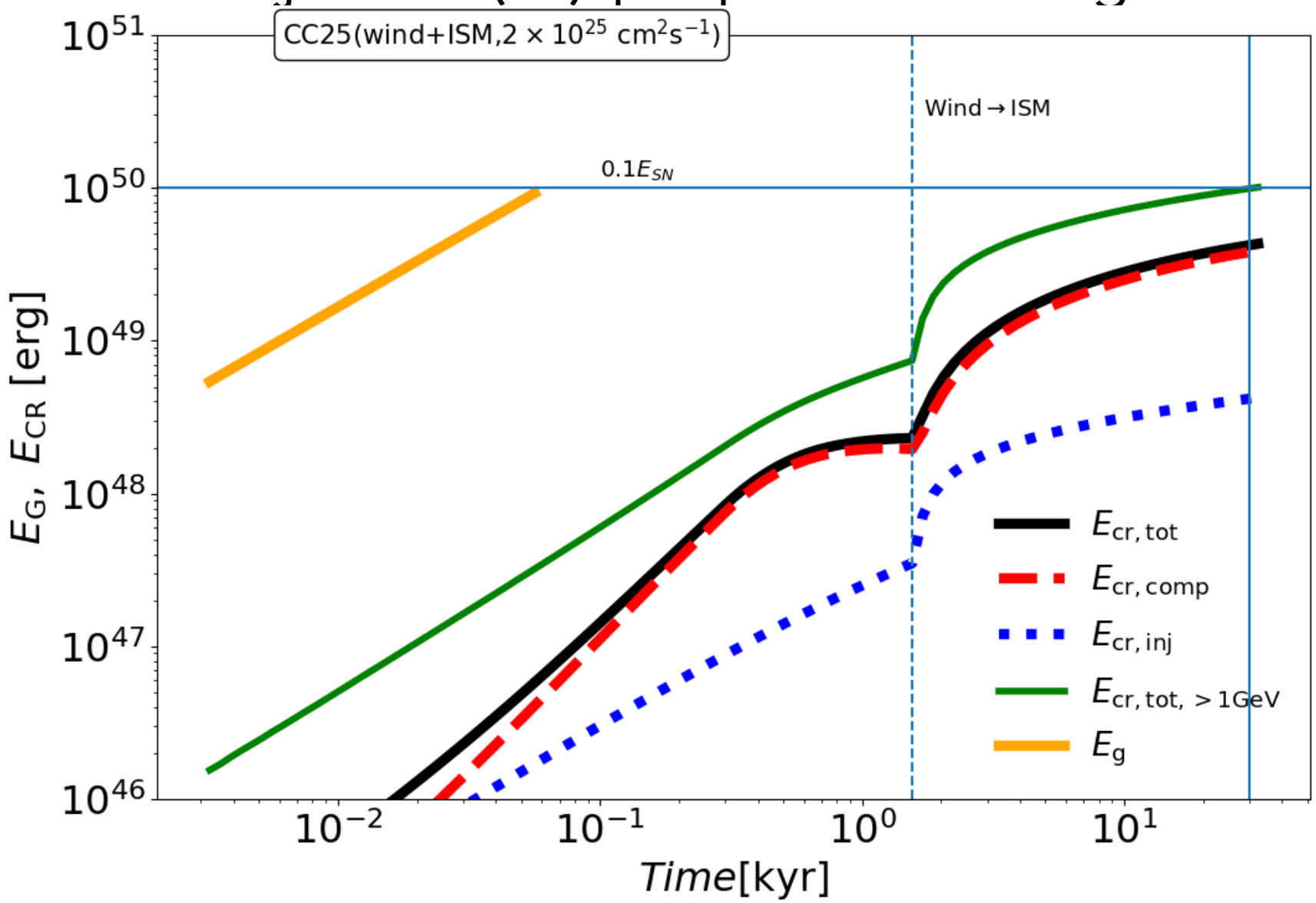
BC: we determine f

Total gas energy evolution (wind+ISM case)

- Sedov begin : $E_{\rm G} \sim E_{\rm SN}/2$ when t=t_Sed

$$E_{\rm G}(t) \propto \int dt R_{\rm sk}^2 V_{\rm sk}^3 \propto t^3 \ (V_{\rm sk} \propto t^0) \quad , \quad \propto \ln t \quad \textbf{@Sedov}$$

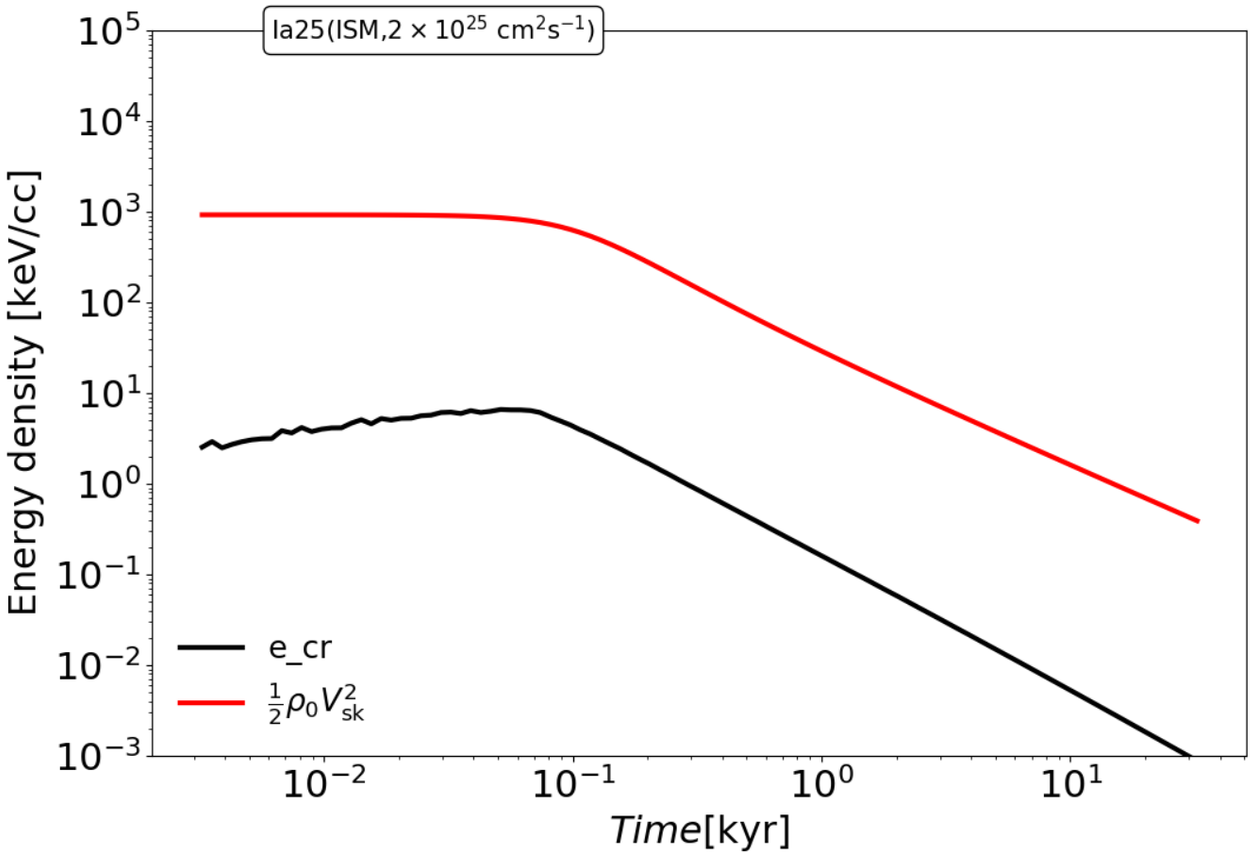
→ Assume injection(—) proportional to gas energy(—)



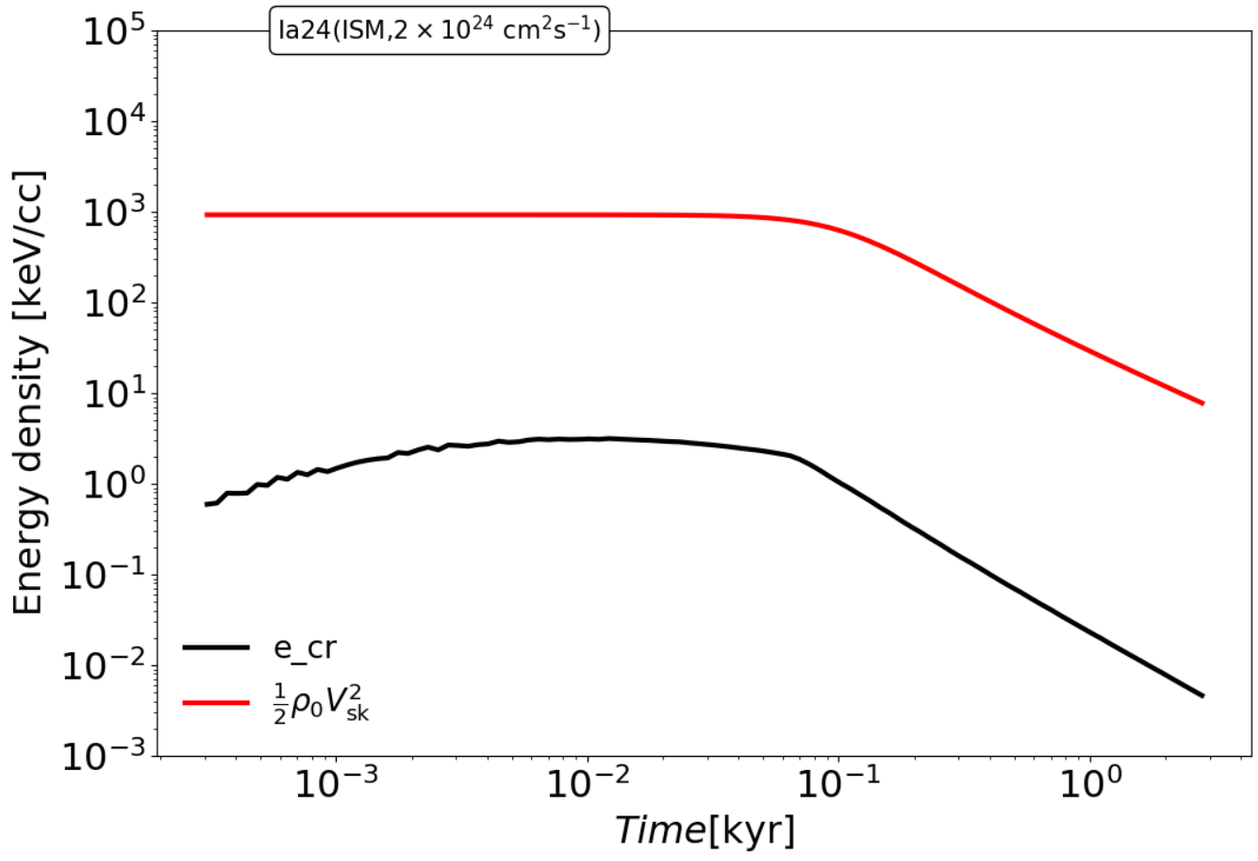
Results : Injection history

- e_cr$(R_{\rm sk}, t)$, $\frac{1}{2}\rho_0 V_{\rm sk}(t)^2$ The ratio will be the injection efficiency based on energy

$D_0 = 2\times10^{25}[\mathrm{cm^{-2}s^{-1}}]$

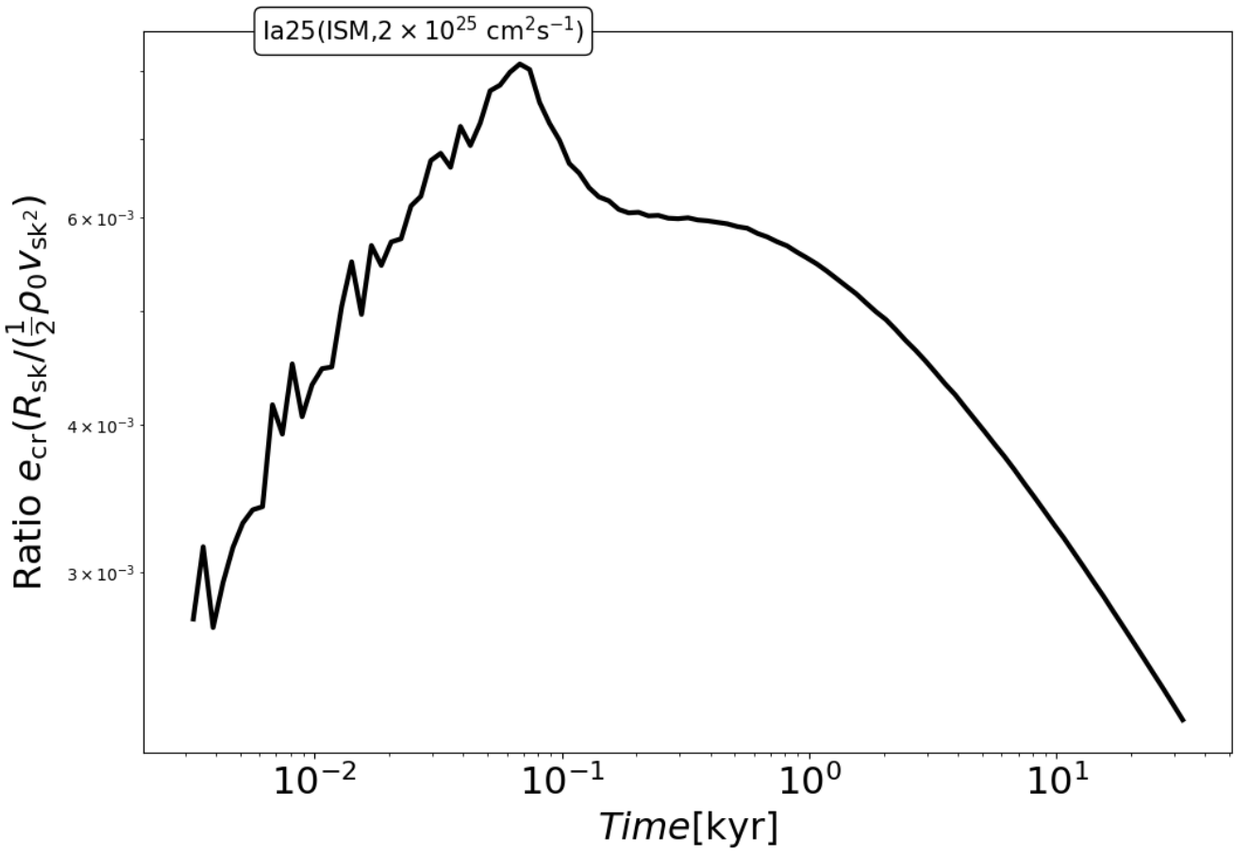


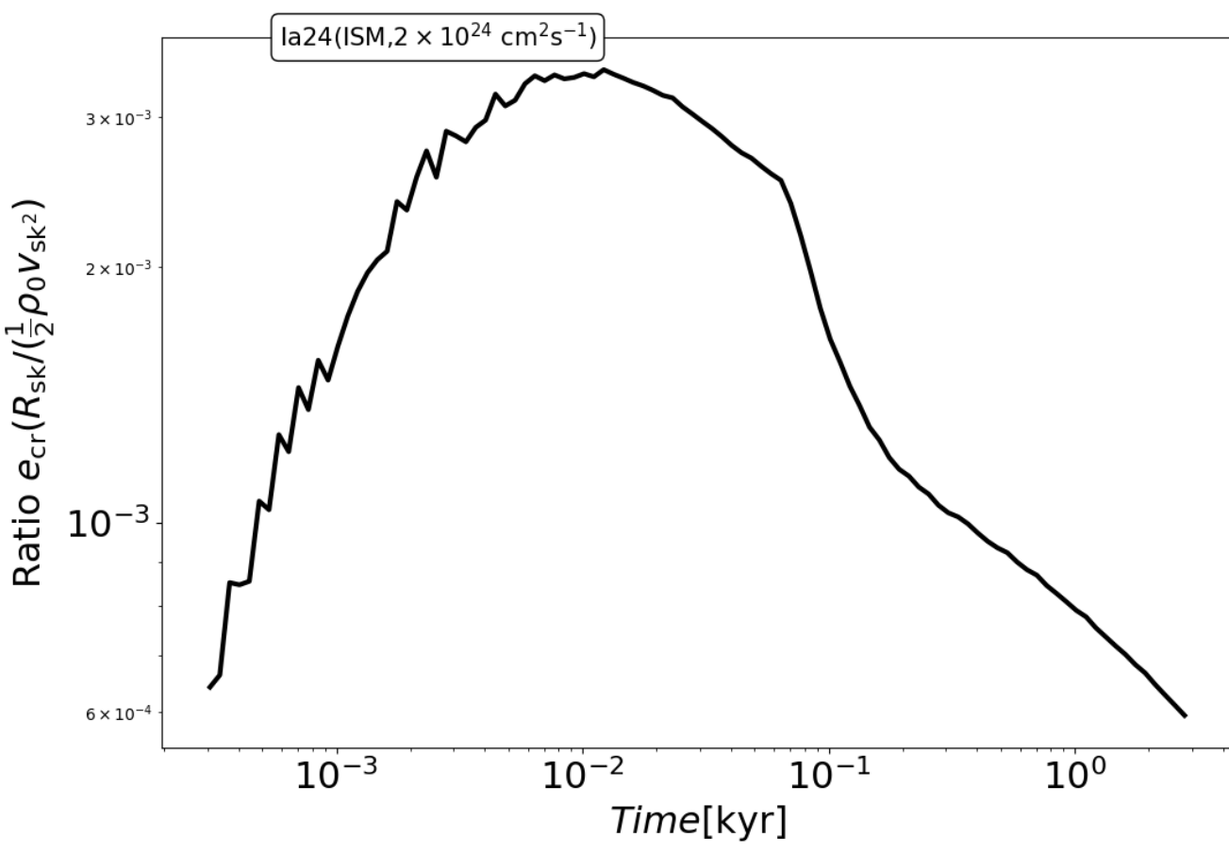
$D_0 = 2\times10^{24}[\mathrm{cm^{-2}s^{-1}}]$



Results：Injection history

- e_cr$(R_{\rm sk}, t)/(\frac{1}{2}\rho_0 V_{\rm sk}(t)^2)$ ～a few %

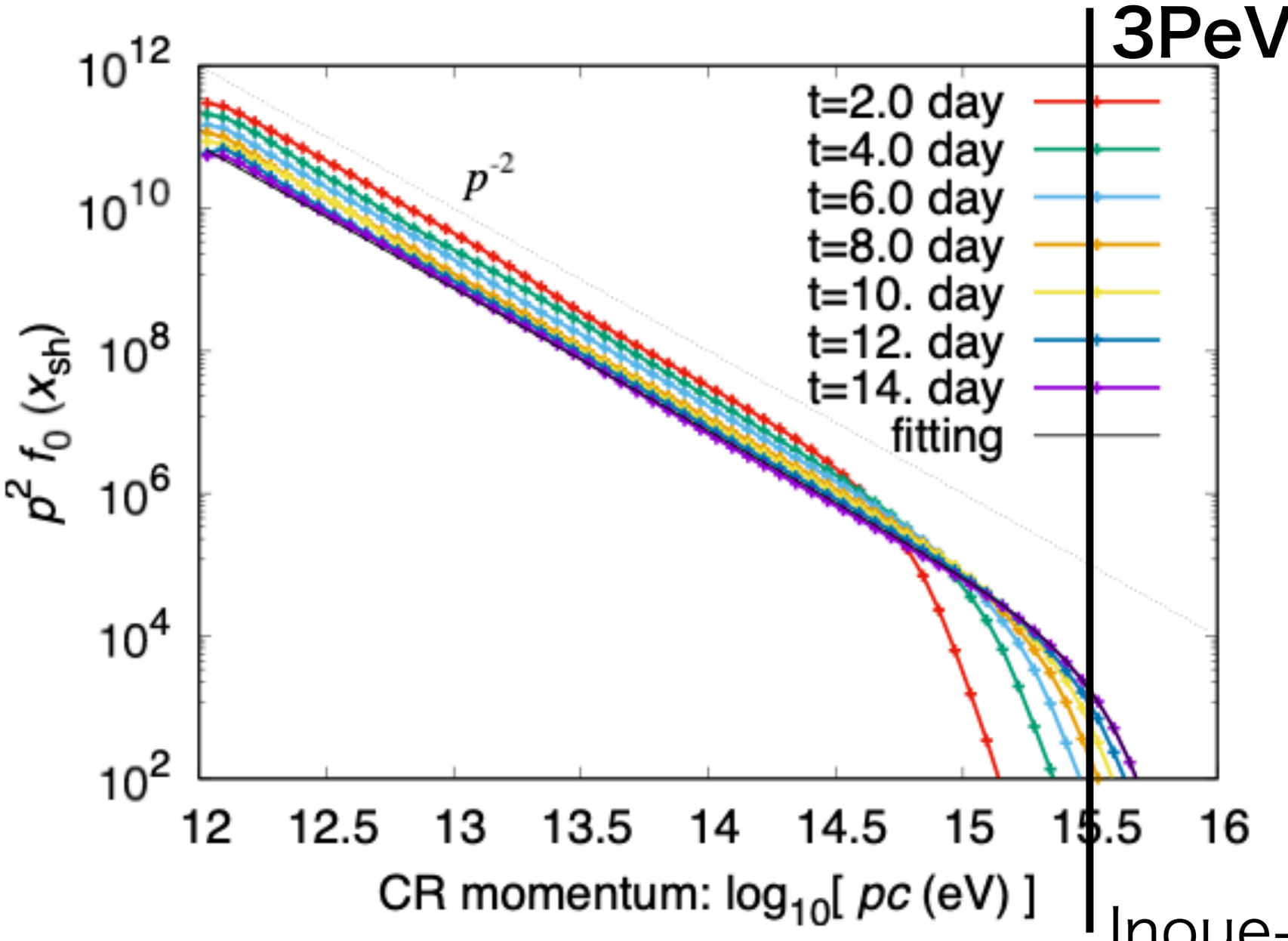




Theoretical work towards PeVatron

- CR acc by using simulation of Bell instability → ~PeV
  (e.g., Marcowith+2018, Inoue+2021; Diesing 2023)

- Proton energy can reach ≳ PeV lastsm but within ~10 days



Inoue+21

CTA sensitivity

- CTA sensitivity @CTA North