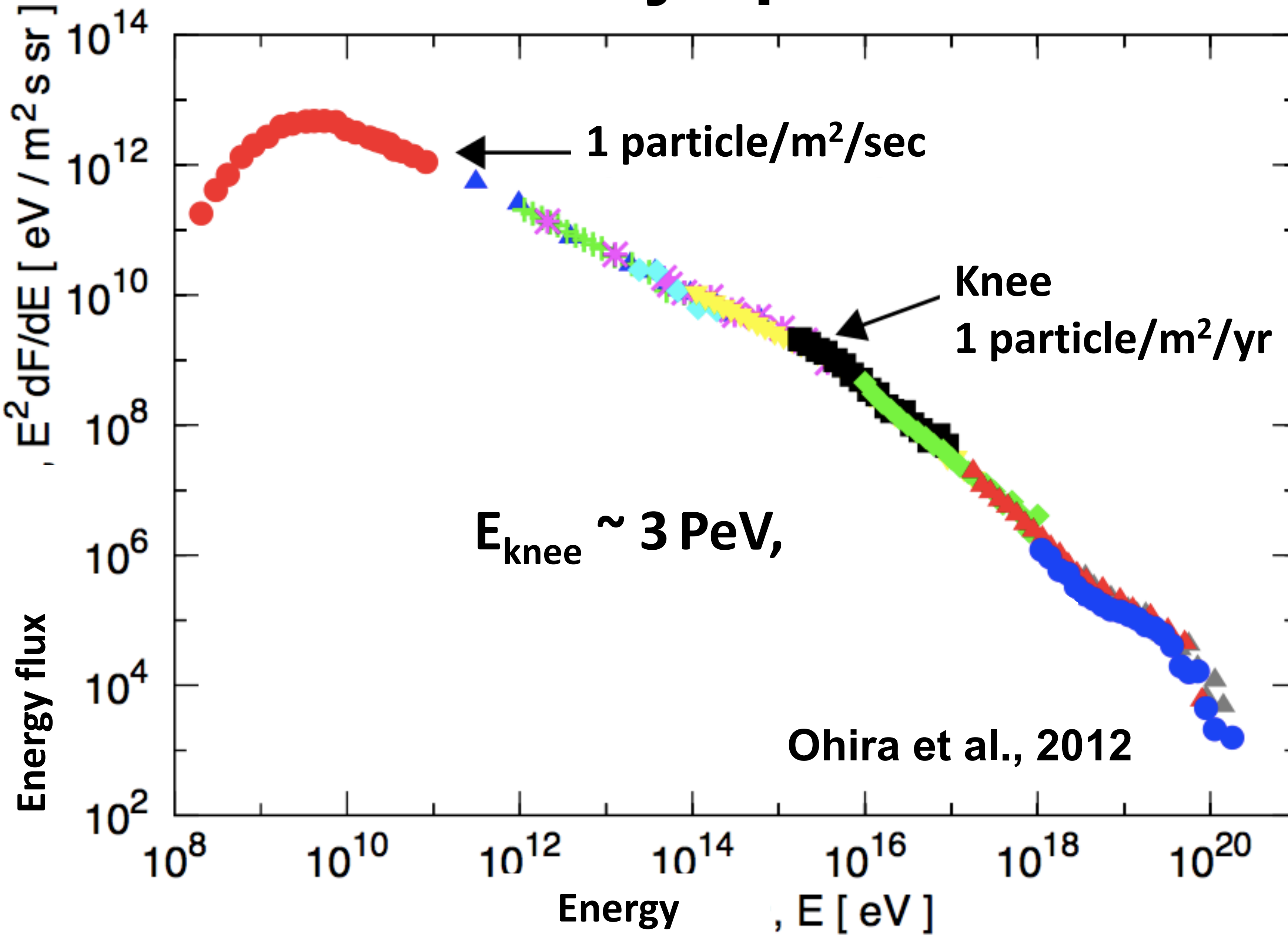
The origin of the cosmic-ray knee

Yutaka Ohira, Shota Kisaka, Ryo Yamazaki
(Aoyama Gakuin University)

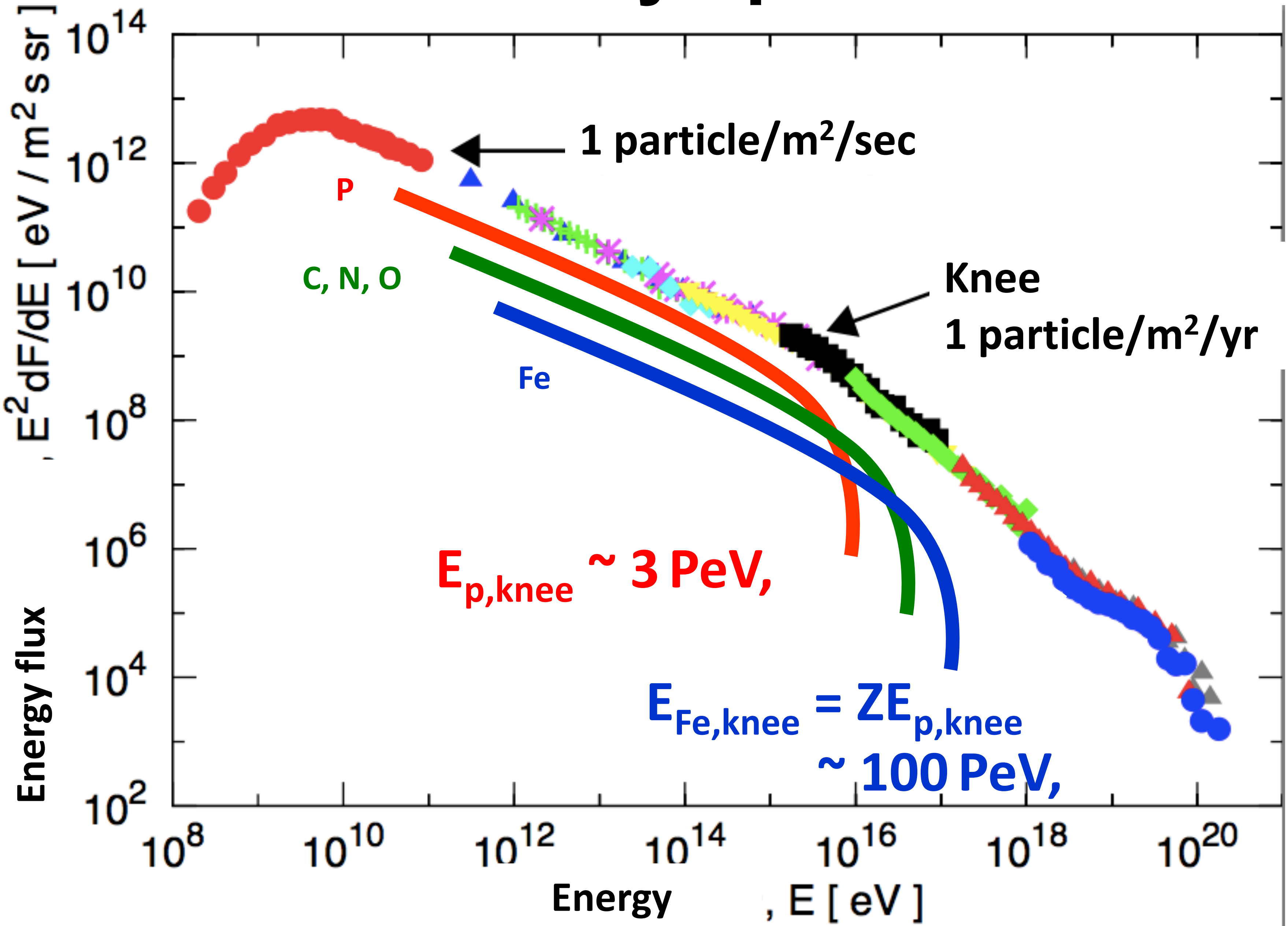
Outline

1) Problem for the cosmic-ray knee
2) Pulsar wind nebulae (PWNe) inside an SNR
3) Particle acceleration by the PWN-SNR system
4) Monte Carlo simulation
5) Summary

Cosmic-ray spectrum

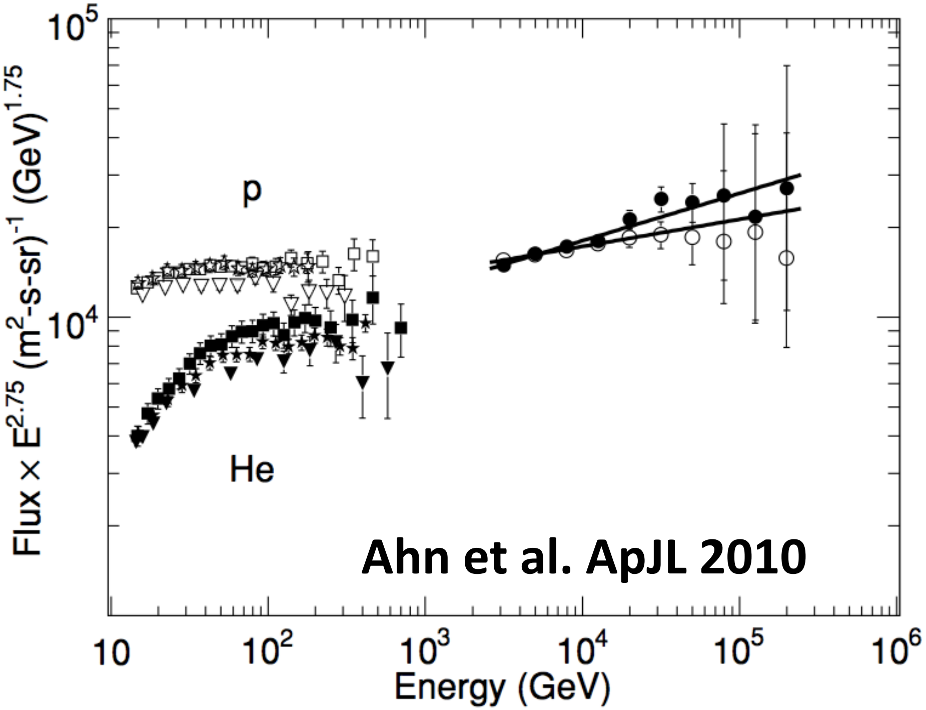


Cosmic-ray spectrum

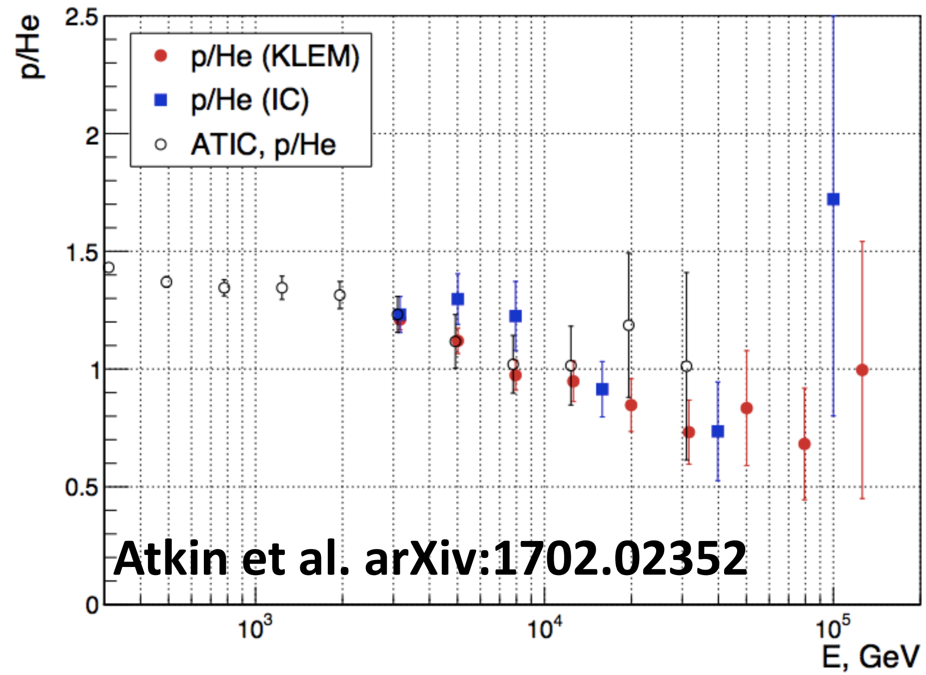


Proton and Helium spectra (E<0.2PeV)

CREAM



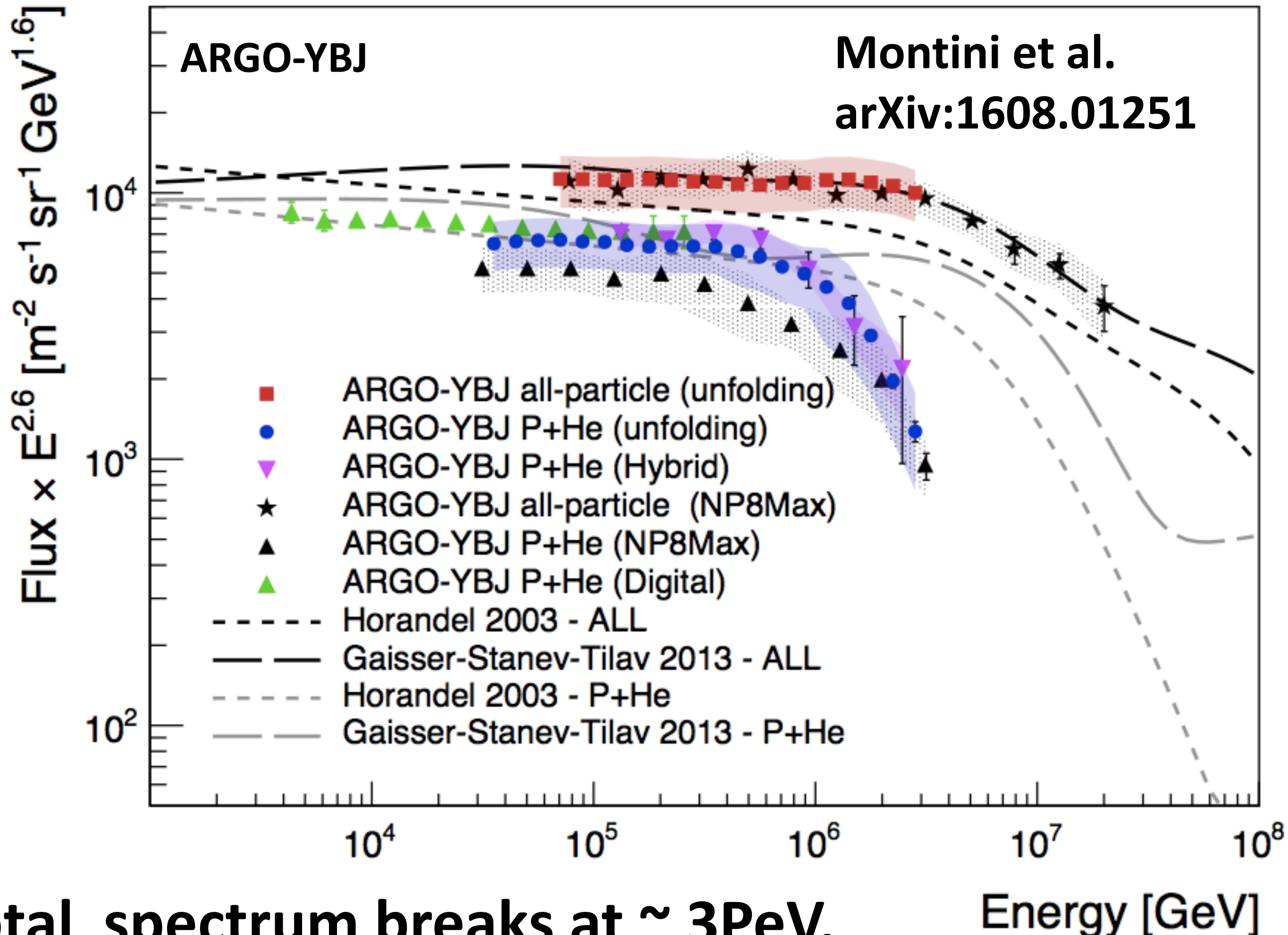
NUCLEON



The spectrum of CR He is harder than that of protons.

CR Helium dominates at ~ 0.1PeV !?

P+He spectrum (E~1PeV)



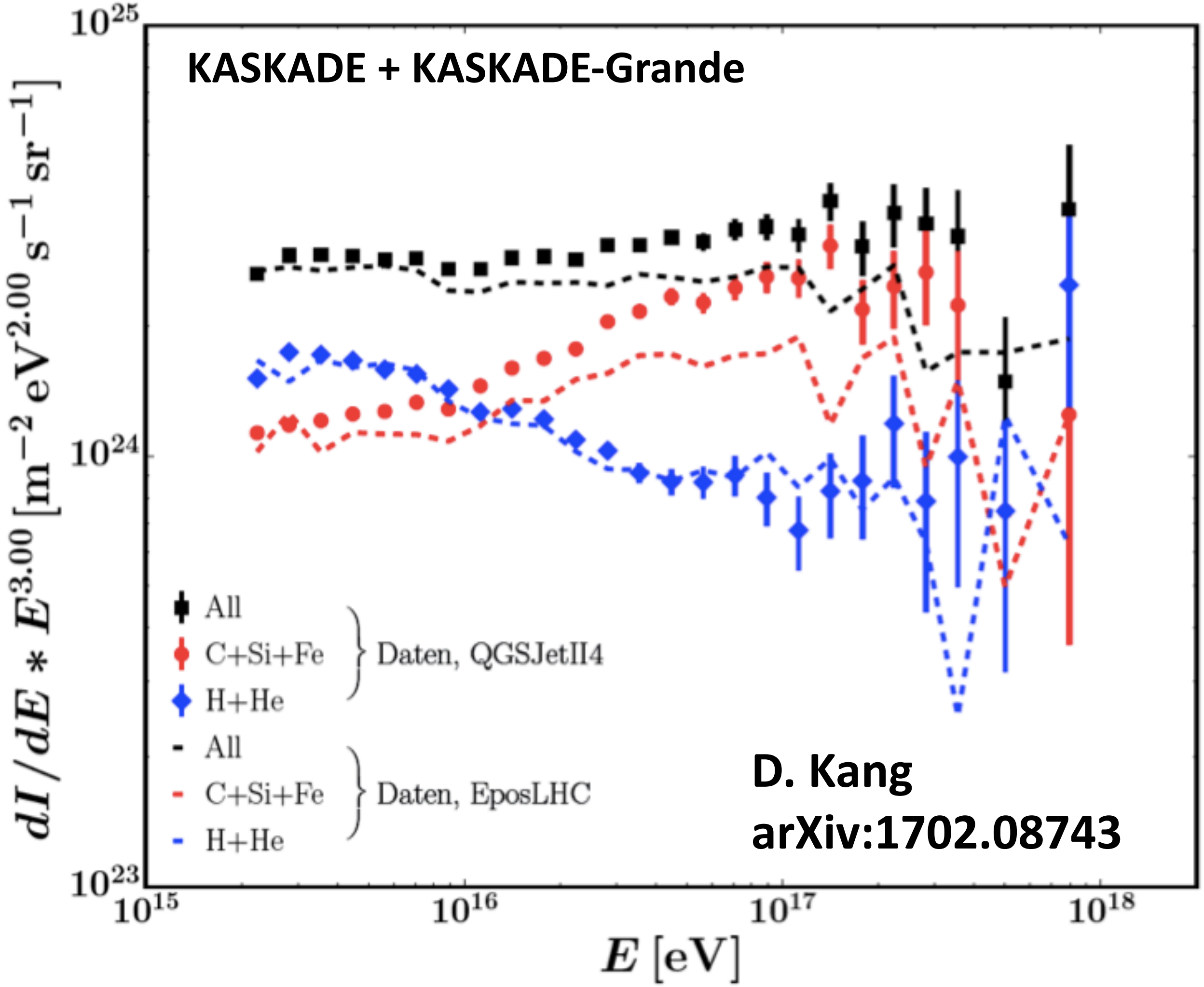
The total spectrum breaks at ~ 3PeV.

The p+He spectrum breaks at ~ 1PeV.

If CR He dominates over CR p at 1PeV,

the proton spectrum breaks at 0.5PeV (< 3PeV).

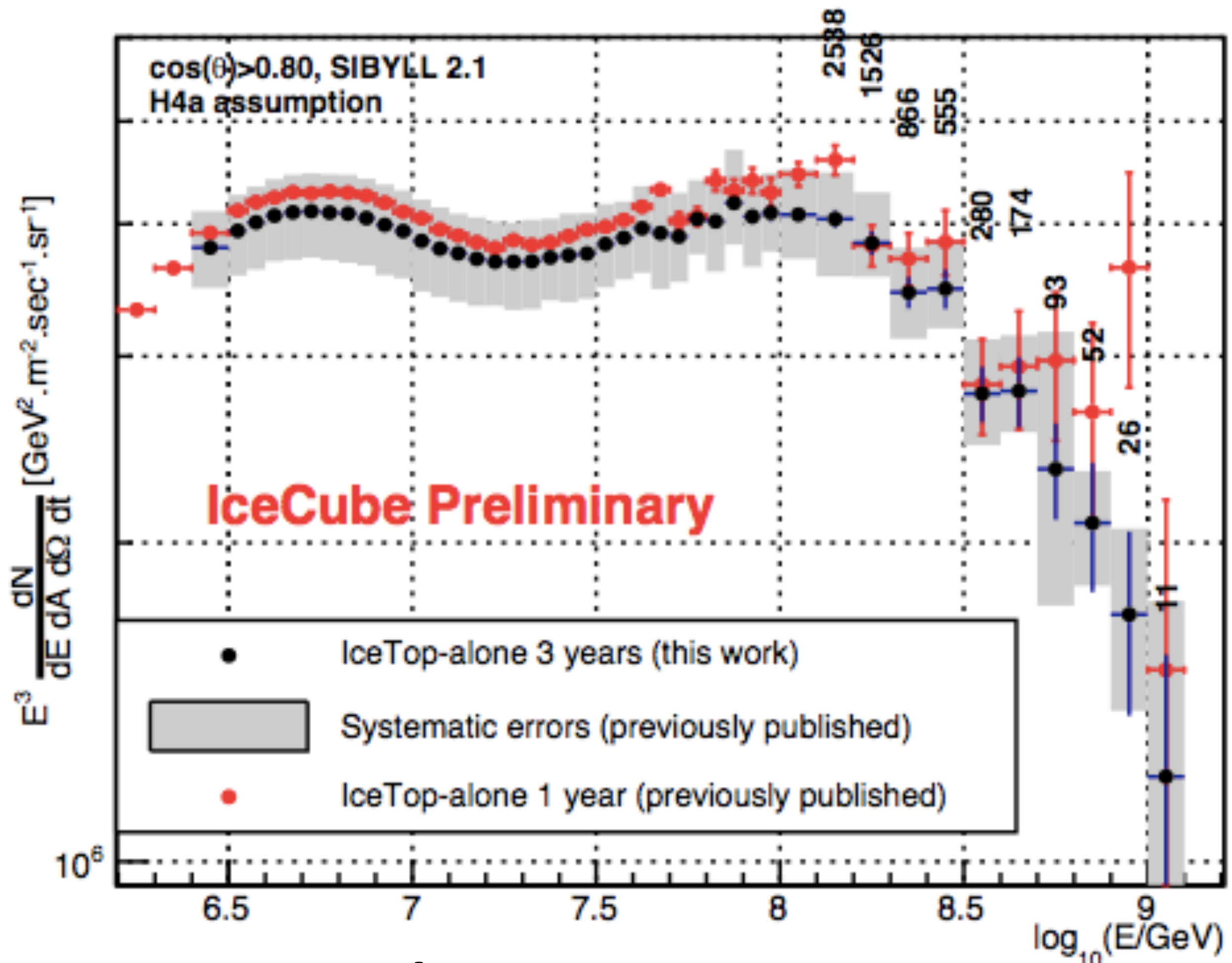
P+He spectrum (E>1PeV)



Heavy CRs dominate over the CR p+He above 10 PeV.

The P+He spectrum does not fall off exponentially.

Total CR spectrum (IceTop)

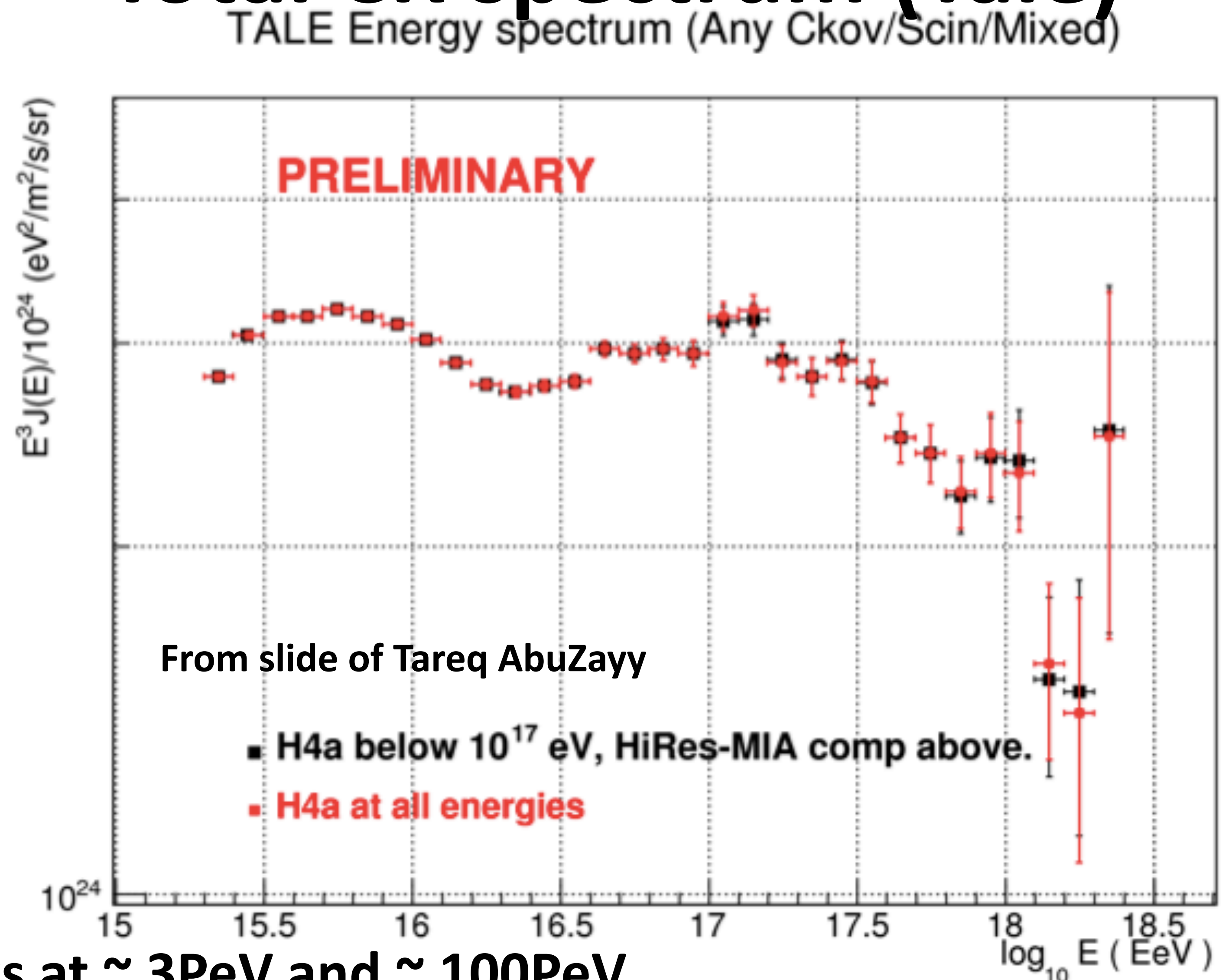


Breaks at ~ 3PeV and ~ 100PeV

Rawlins et al. 2016

Dip structure at 10PeV

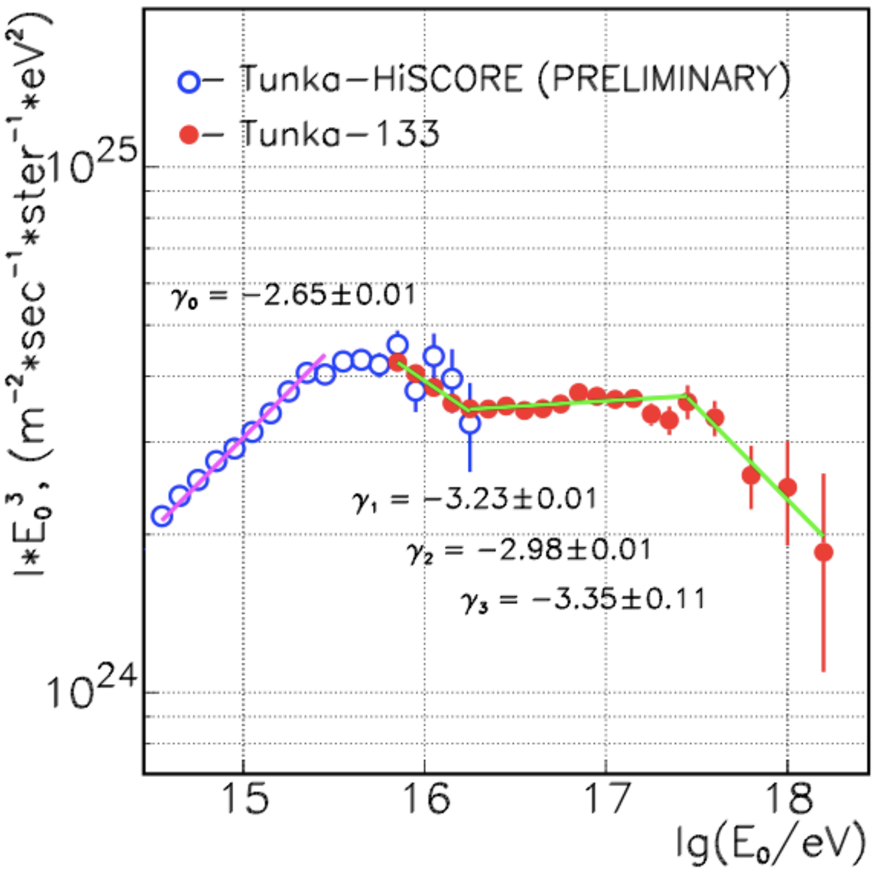
Total CR spectrum (Tale)

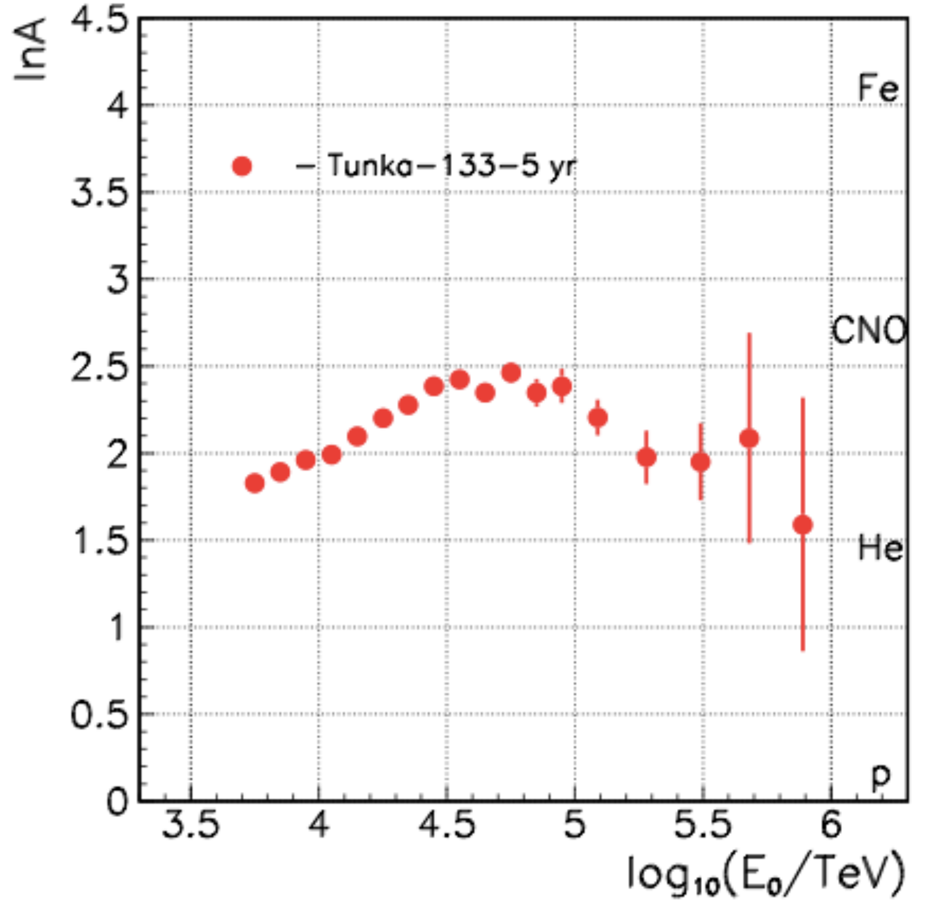


Breaks at ~ 3PeV and ~ 100PeV

Dip structure at 10PeV

Total CR spectrum (Tunka-HiSCORE, Tunka-133)





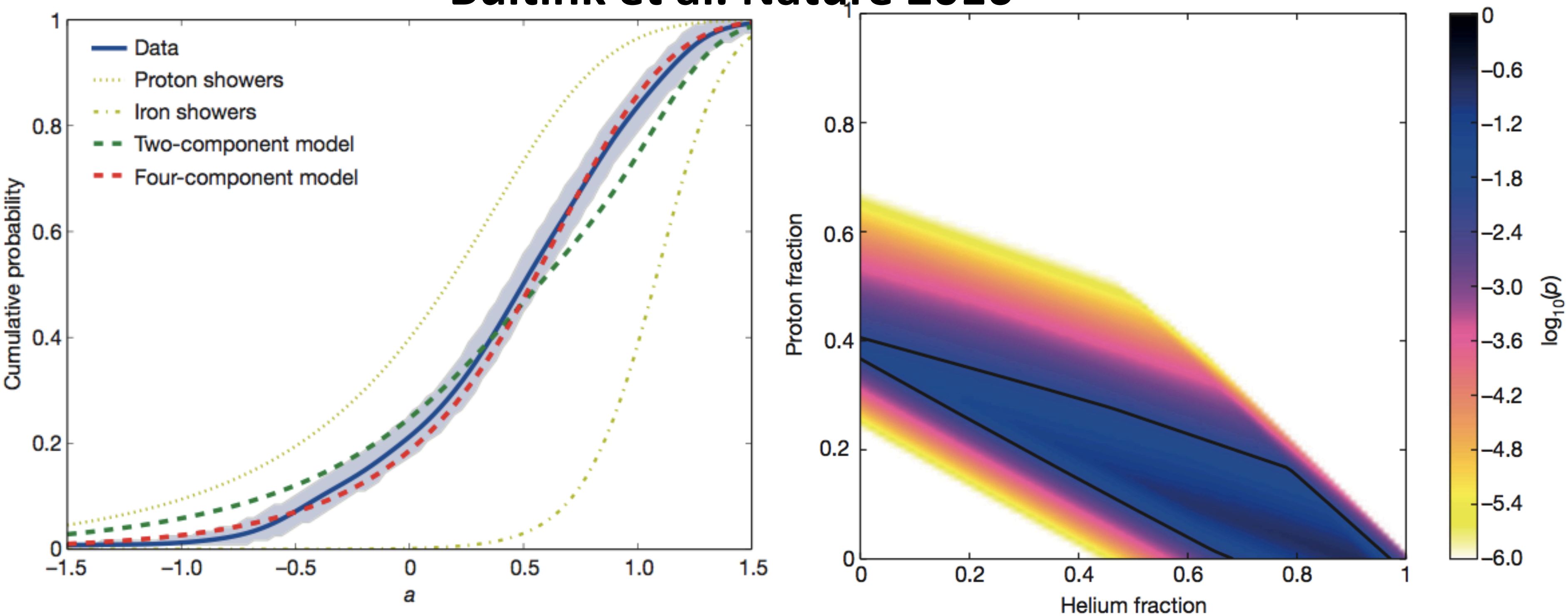
Breaks at ~ 3PeV and ~ 100PeV

Dip structure at 10PeV

Irons do not dominate at 100PeV.

LOFAR(E=100PeV-300PeV)

Buitink et al. Nature 2016



$a = (\langle X_{proton}\rangle - X_{max}) / (\langle X_{proton}\rangle - X_{iron})$

The cumulative X_{max} distribution shows that the total fraction of p+He at 100PeV is in the range [0.38,0.98] at a 99% confidence level, with a best-fit value of 0.8.

Irons do not dominate at 100PeV.

Summary of CR observations

There are some unexpected results and tensions.

CR He dominates at ~ 0.1PeV. (CREAM, NUCLEON)

The p+He spectrum breaks at ~ 1PeV < 3PeV. (ARGO-YBG)

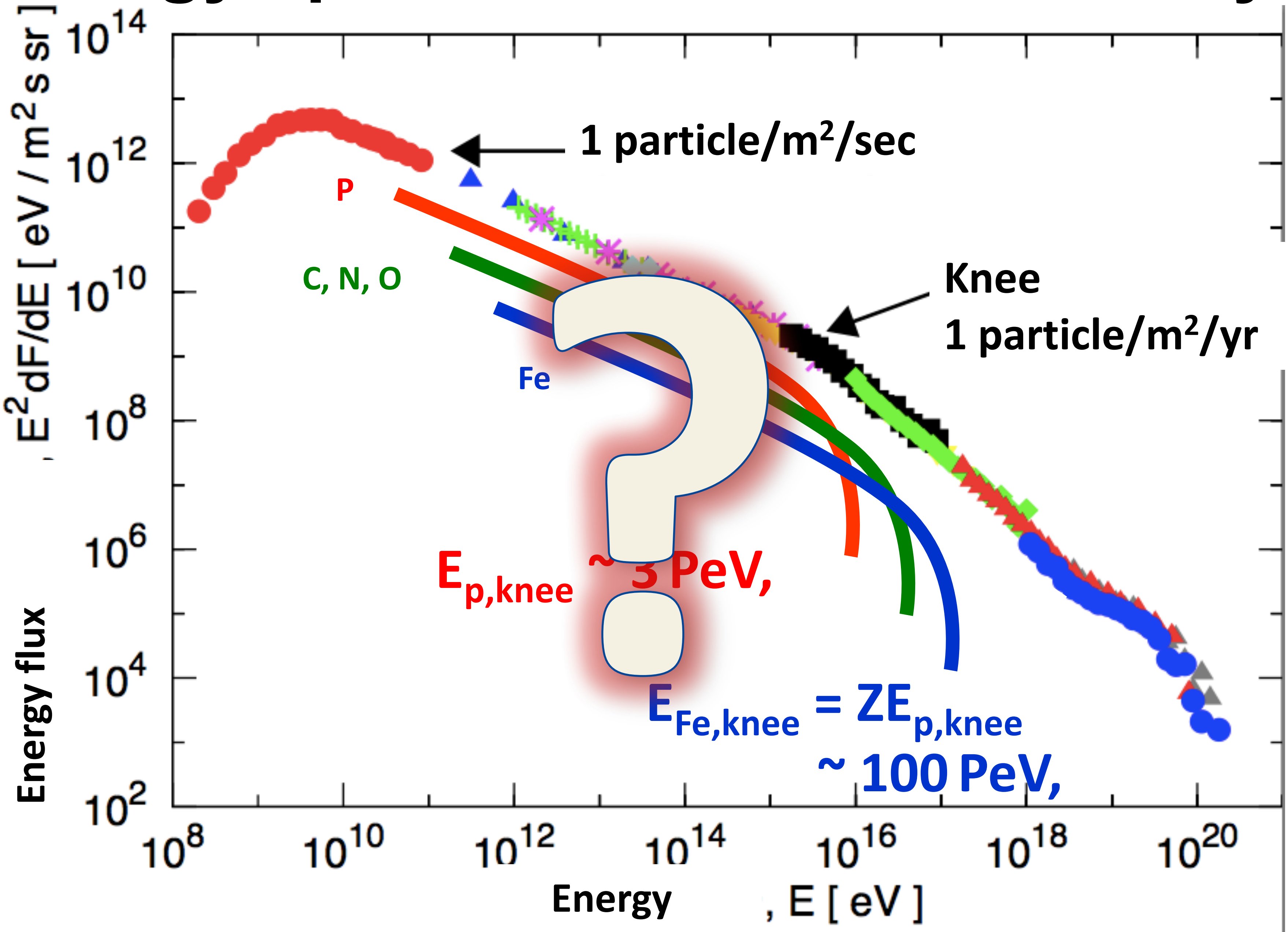
The p+He spectrum does not fall off exponentially above 3PeV.
(KASKADE+KASKADE-Grande)

Heavy CRs dominate over the CR p+He at ~ 100 PeV.
(KASKADE+KASKADE-Grande)

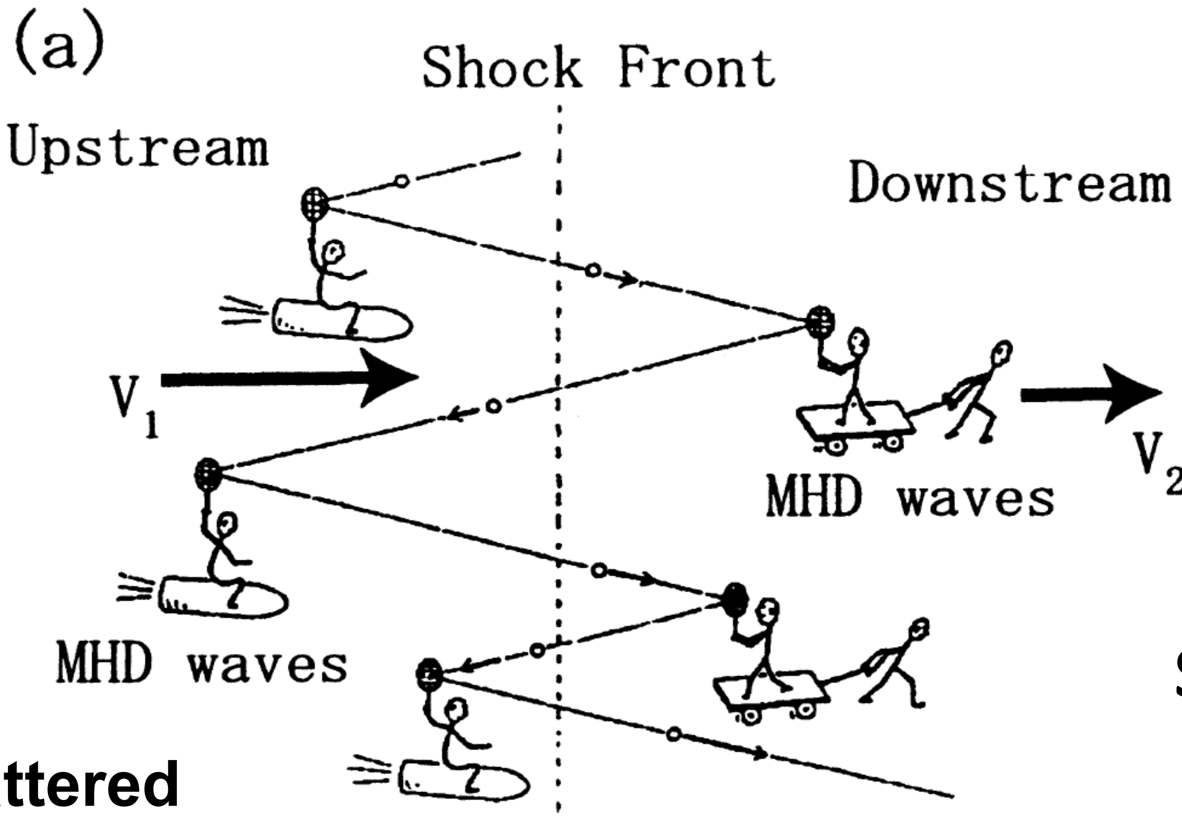
The total CR spectrum breaks at 3PeV and 100PeV, and dips at 10PeV.
(IceTop, TALE, Tunka-133)

CR p+He dominates over heavy CRs at ~ 100PeV. (LOFAR)

Energy spectrum of total cosmic rays



Diffusive Shock Acceleration(DSA)



Scholer

CRs are scattered by MHD waves.

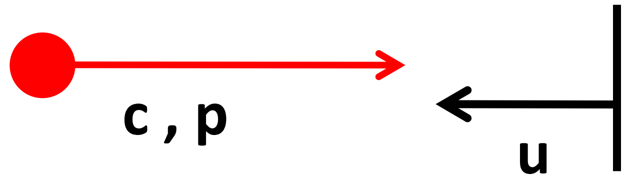
CRs excite the MHD waves.

$$dN/dE \propto E^{-s} \qquad s = \frac{u_1/u_2 + 2}{u_1/u_2 - 1} = 2$$

Axford 1977, Krymsky 1977, Blandford&Ostriker 1978, Bell 1978

E_{max} of DSA

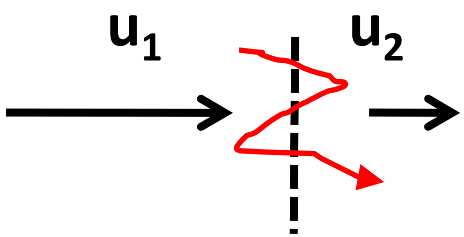
Momentum change by particle scattering, Δp



After scattering,

$$\Delta p = 2\frac{u}{c}p$$

For a shock,



Δp per one cycle is

$$\Delta p = \frac{4(u_1 - u_2)}{3c}p = \frac{u_1}{c}p$$

Time of one cycle, $\Delta t = (\lambda_{mfp,1}/u_1 + \lambda_{mfp,2}/u_2) \sim T_{gyro,1}(c/u_1) + T_{gyro,2}(c/u_2)$

$t_{acc} = p\,\Delta t/\Delta p \sim T_{gyro,1}(c/u_{sh})^2 + 4T_{gyro,2}(c/u_{sh})^2$ (Krymsky et al. 1979, Drury 1983)

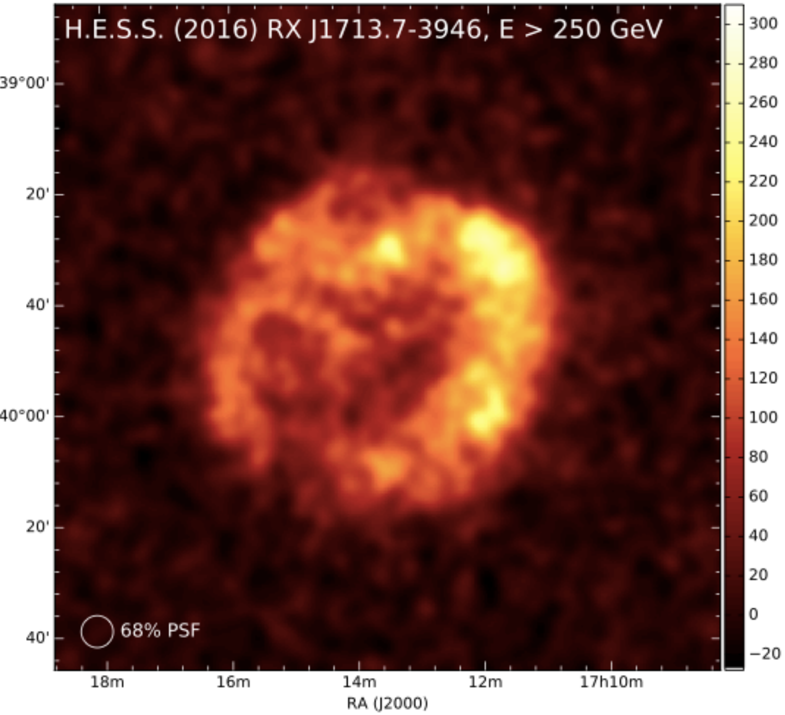
$t_{acc} = t_{Sedov} \sim 200\text{yr}$, and $T_{gyro,1} >> T_{gyro,2}$

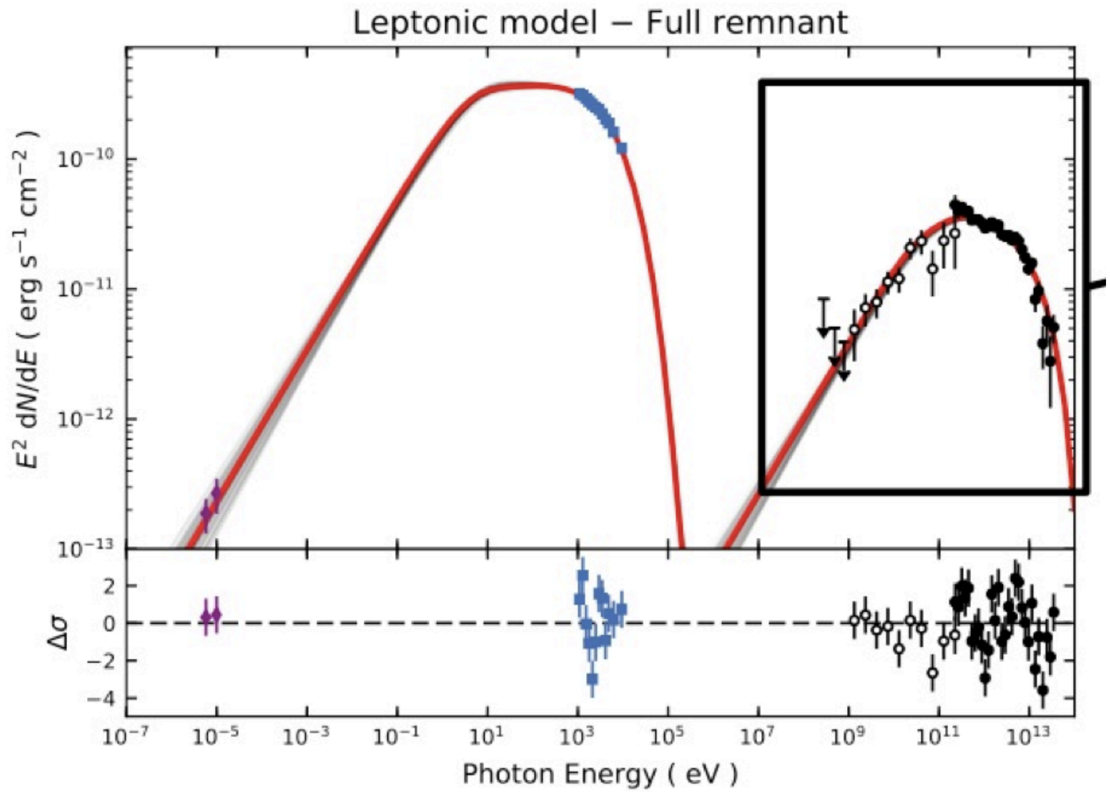
→ $E_{max} \sim$ **0.03PeV** $B_{up,1\mu G}(\lambda_{mfp}/r_g)(u_{sh}/3000\text{km/s})^2$

To accelerate CRs to 3PeV, B >~100μG in the upstream region, but no simulations demonstrate the sufficient magnetic field amplification.

RX J1713.7-3946

Abdalla+2017





If γ-rays are due to IC, we can measure B_{down}.

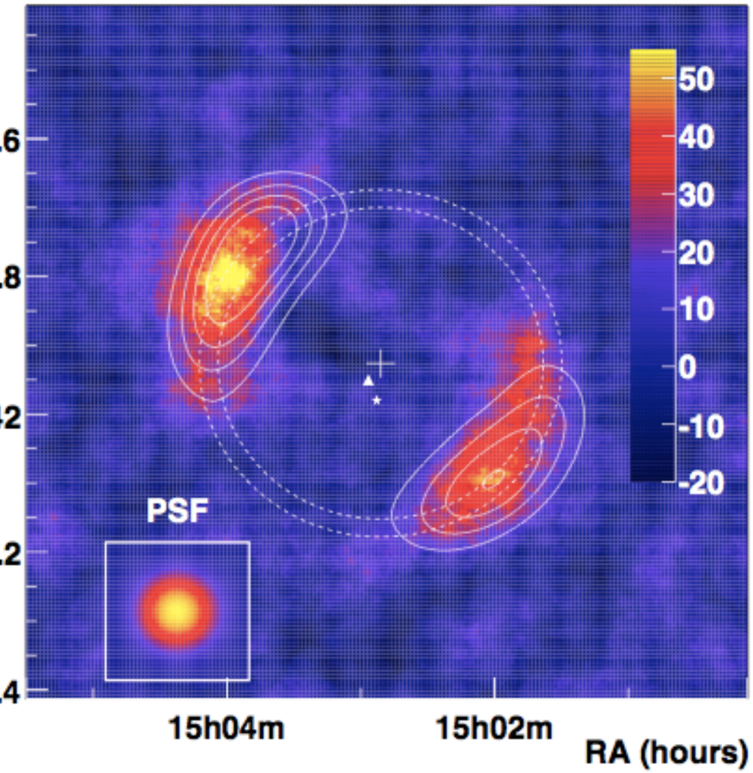
$\nu F\nu_{syn}/\nu F\nu_{IC}$ ~ 16 → B_{down} ~ 12 μG **Ohira&Yamazaki17**

If γ-rays are due to the pion decay, we can estimate $E_{p,max}$.

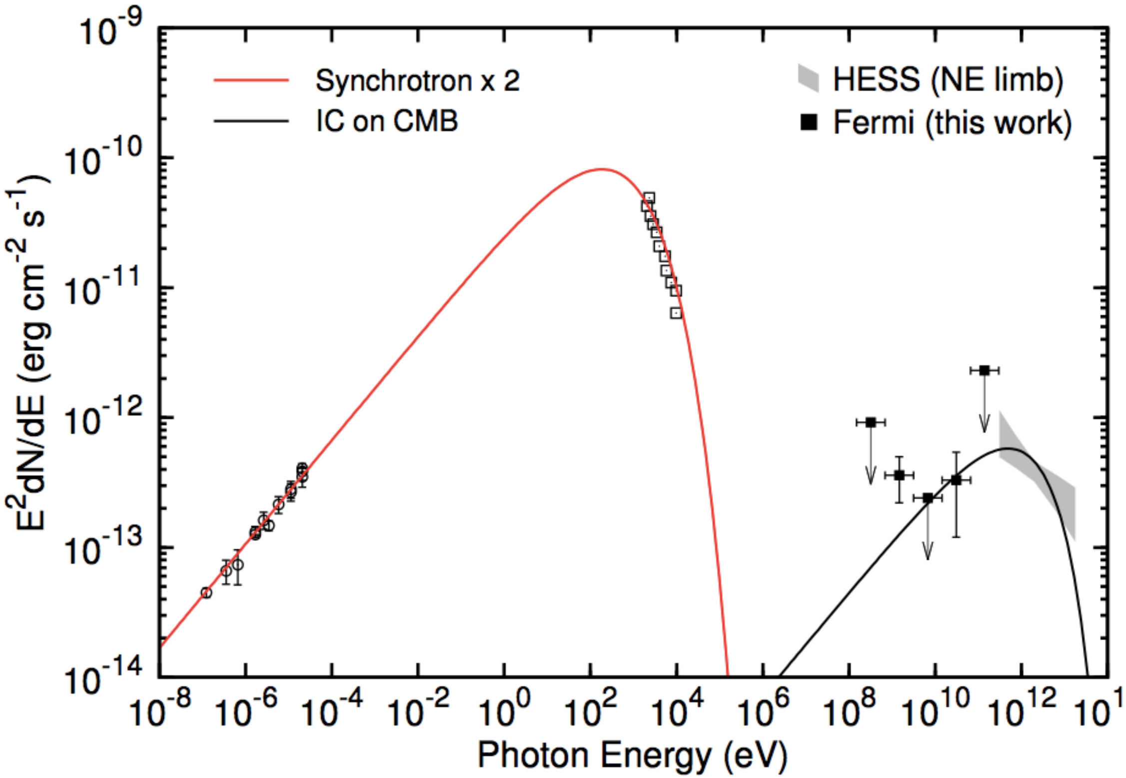
$E_{\gamma,max}$ ~ 0.01PeV → $E_{p,max}$ ~ 0.1 PeV

SN1006

Acero+2010



Xing+2016



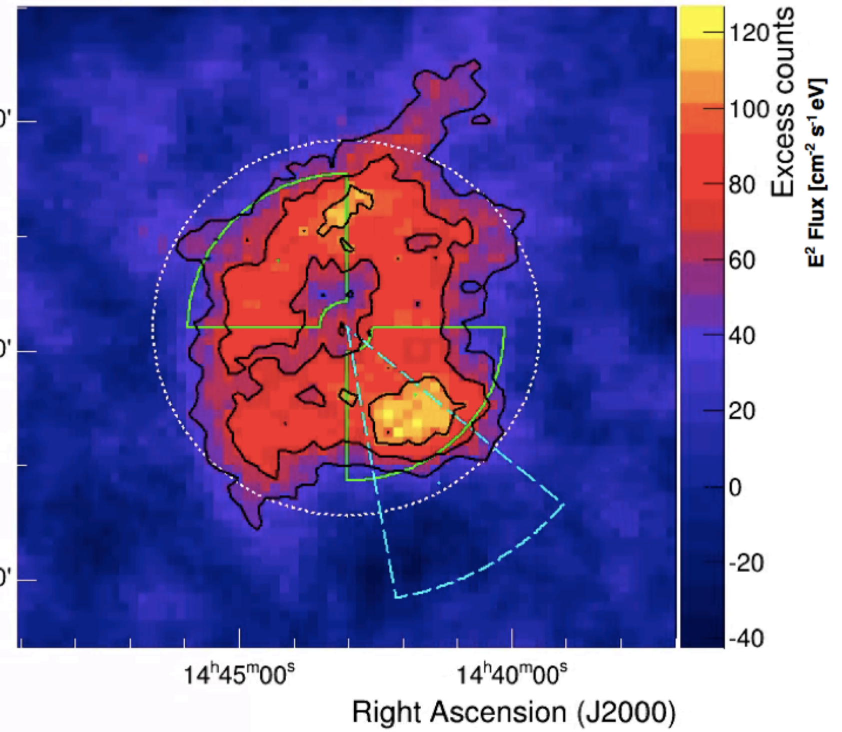
If γ-rays are due to IC, we can measure B_{down}.

$\nu F \nu_{syn} / \nu F \nu_{IC} \sim 100 \rightarrow B_{down} \sim 30\ \mu G$

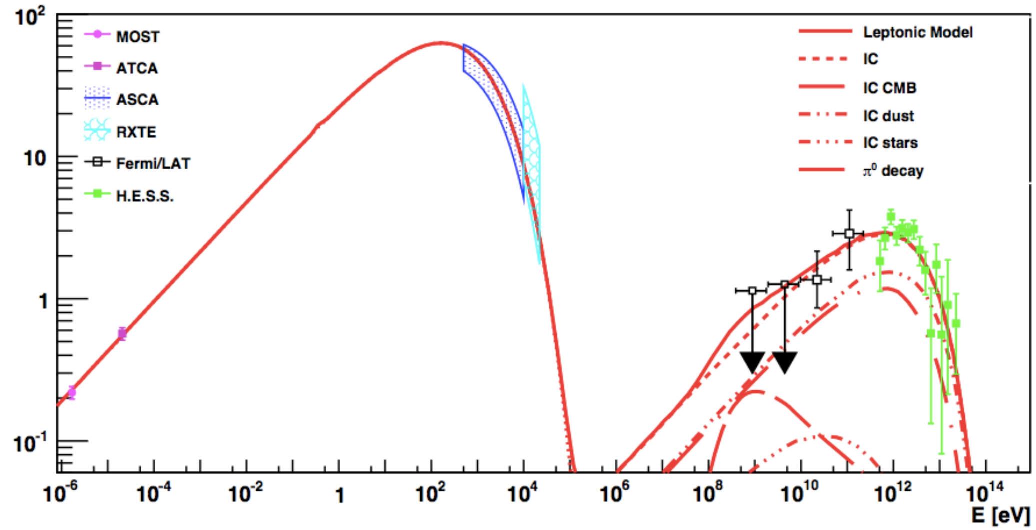
If γ-rays are due to the pion decay, we can estimate $E_{p,max}$.

$E_{\gamma,max} \sim 0.008 PeV \rightarrow E_{p,max} \sim 0.08\ PeV$

RCW86



Abramowski+2016



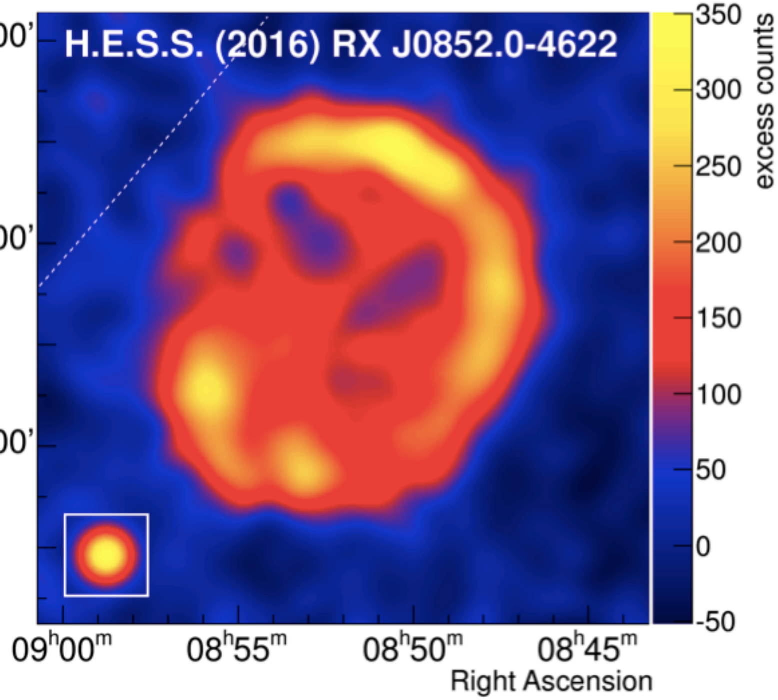
If γ-rays are due to IC, we can measure B_{down}.

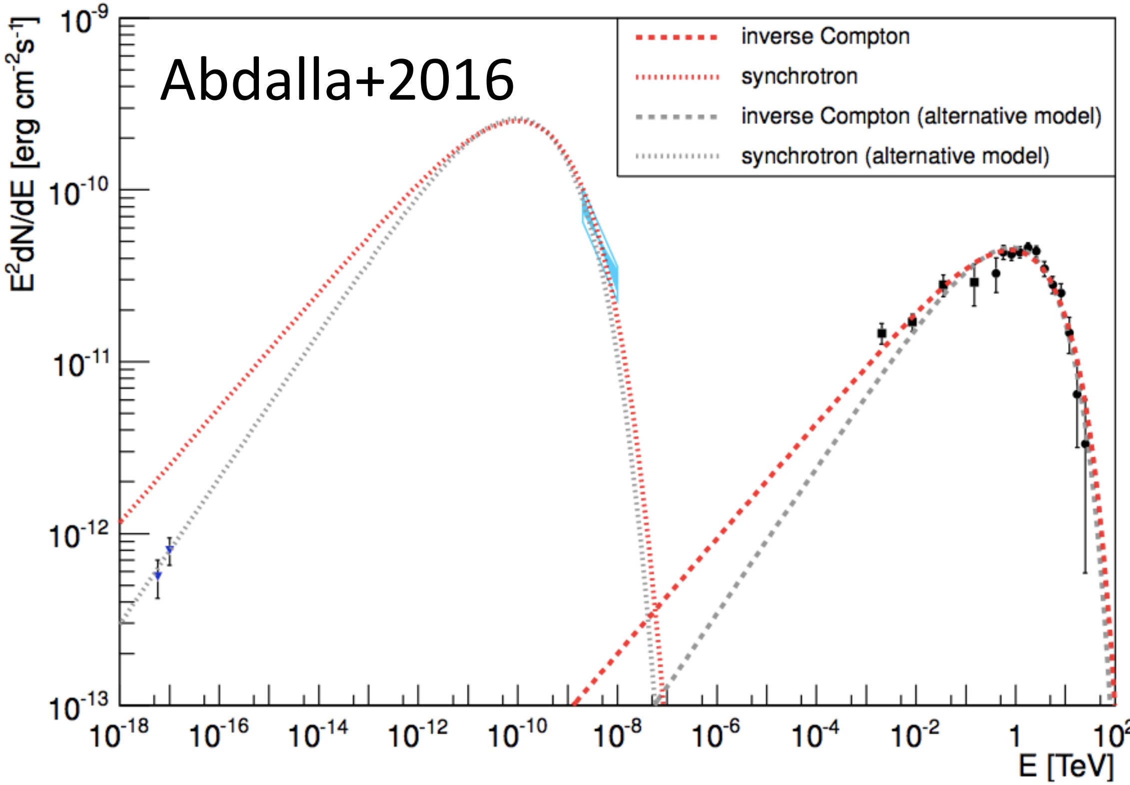
$\nu F\nu_{syn}/\nu F\nu_{IC}$ ~ 50 → B_{down} ~ 22 μG

If γ-rays are due to the pion decay, we can estimate $E_{p,max}$.

$E_{\gamma,max}$ ~ 0.0035PeV → $E_{p,max}$ ~ 0.035 PeV

RX J0852.0-4622(Vela Junior)





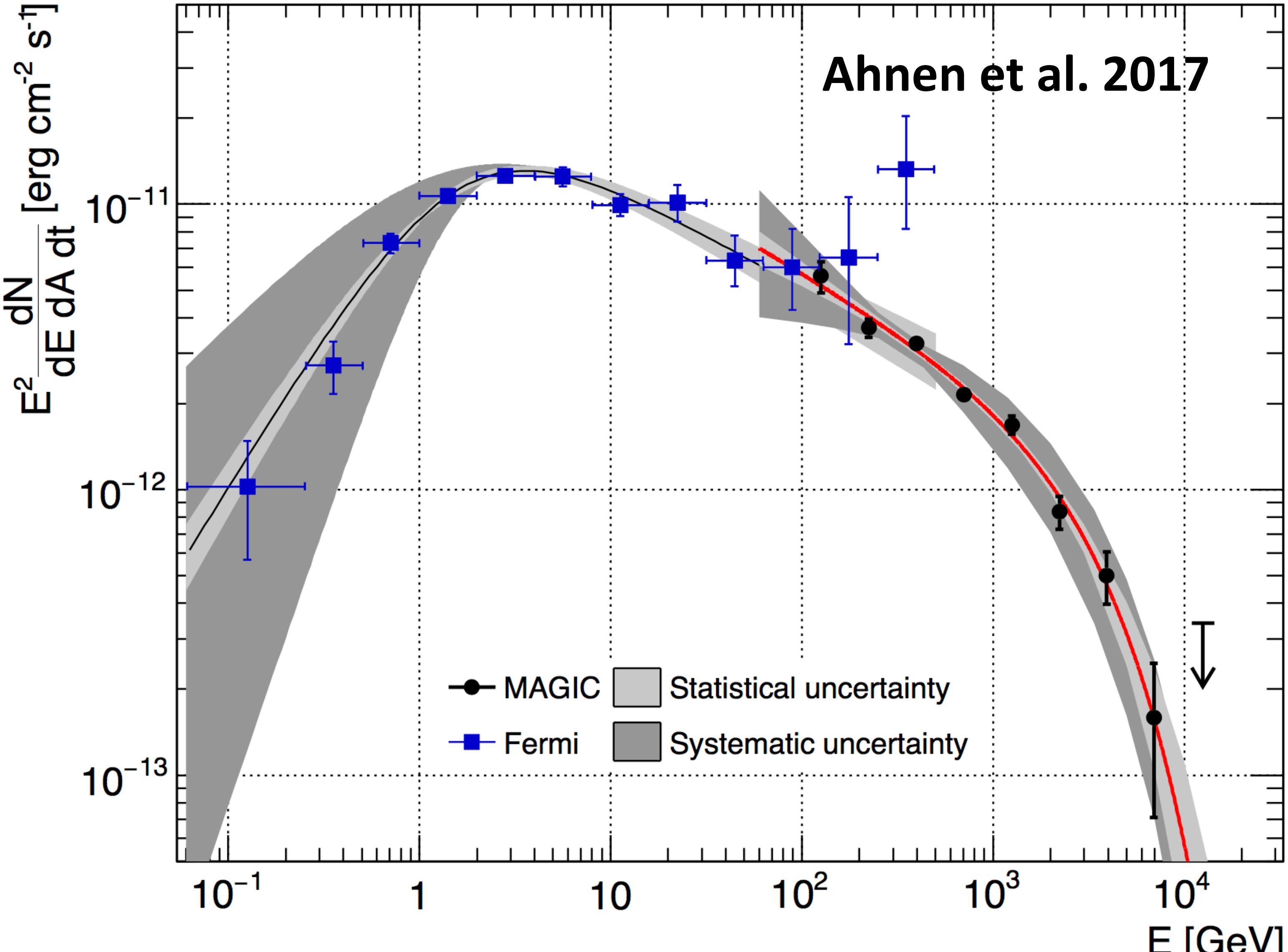
If γ-rays are due to IC, we can measure B_{down}.

$\nu F\nu_{syn}/\nu F\nu_{IC} \sim 4 \rightarrow B_{down} \sim 7\ \mu G$

If γ-rays are due to the pion decay, we can estimate $E_{p,max}$.

$E_{\gamma,max} \sim 0.0055PeV \rightarrow E_{p,max} \sim 0.055\ PeV$

Cas A



$E_{\gamma,c}$ = 3.5TeV

$E_{p,c}$ = 12TeV

$U_{CR} \sim 10^{50}$ erg

$dN/dE \propto E^{-2.4}$

Pulsar wind nebulae inside SNRs

Watters & Romani, ApJ, 2012

Fermi observed many gamma ray pulsars.

→ Pulsar birthrate ~ 1 per 59 yr, Initial spin period, P_0 ~ 50 ms

$B_0 = 10^{12.66}$ G, $L_{sd,0} \sim 10^{38}$ erg/s, $E_{rot,0} \sim 10^{49}$ erg, $T_{sd} \sim 3$ kyr

Most core-collapse SNRs have pulsar wind nebulae (PWNe).

The PWN region has strong magnetic fields, B >~ 100 μG

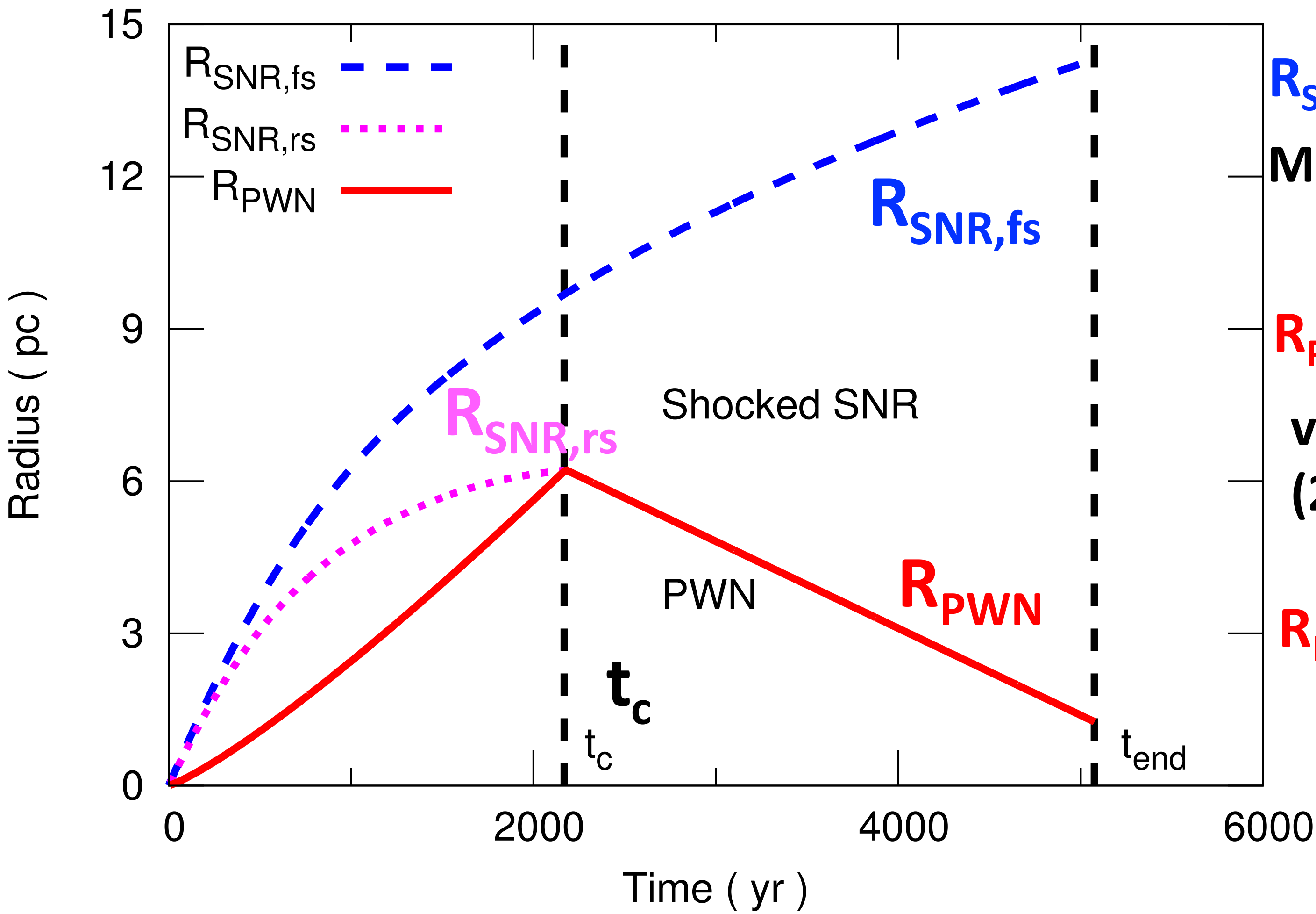
Shocked regions of SNRs are also expected to have strong magnetic field, B >~ 100μG

In this talk, we propose the following two things.

The shocked region of SNRs and PWN region reaccelerate CRs to the knee energy from 0.1 PeV.

The PWN-SNR system could be the origin of heavy CR nuclei.

Evolution of a PWN inside the SNR



$R_{SNR,fs}$ and $R_{SNR,rs}$

McKee&Trulove (1995)

R_{PWN} ($t < t_c$)

van der Swaluw et al. (2001)

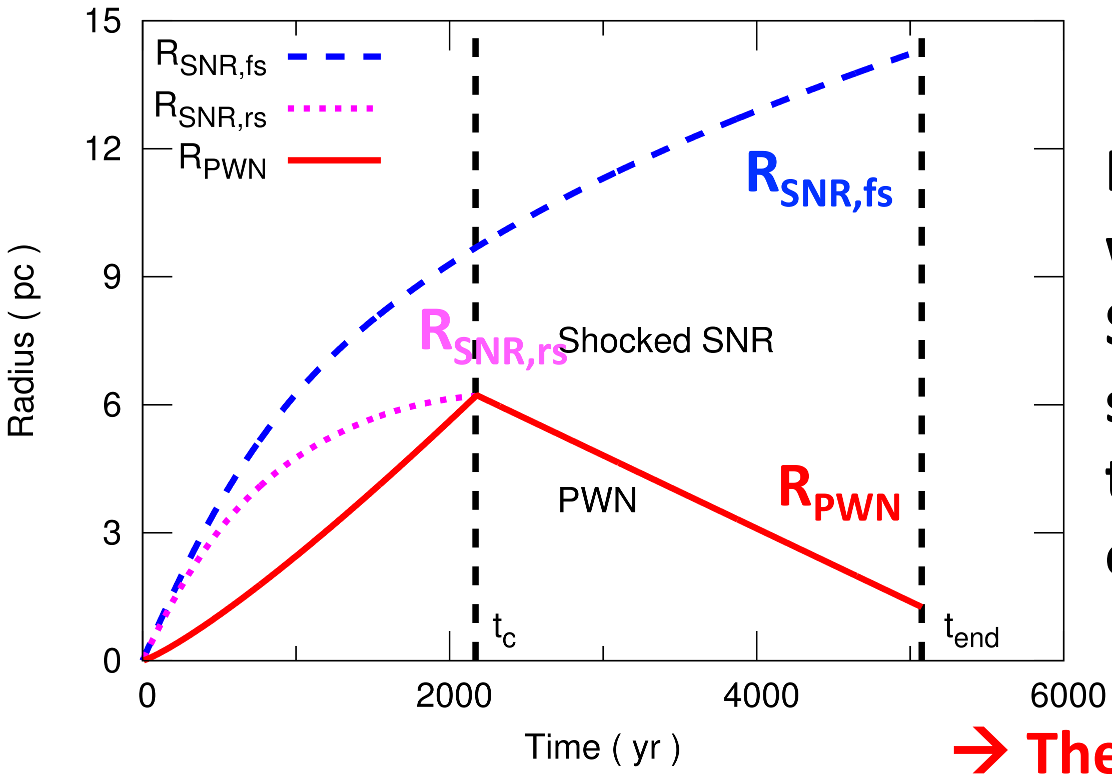
R_{PWN} ($t > t_c$)

$V_{PWN} = - V_{PWN}(t_c) / 2$

$M_{ej} = 3\ M_{\odot}$, $E_{SN} = 10^{51}$ erg , $n_{ISM} = 0.1\ cm^{-3}$, $L_{sd} = 3\times10^{38}$ erg/s

ρ_{ej} and ρ_{ISM} = uniform, and L_{sd} = constant.

Particle acceleration ($t < t_c$)



Before the PWN interacts with the reverse shock of the SNR ($t < t_c$), the PWN-SNR system can be interpreted as two walls approaching each other.

→ The two walls can accelerate CRs.

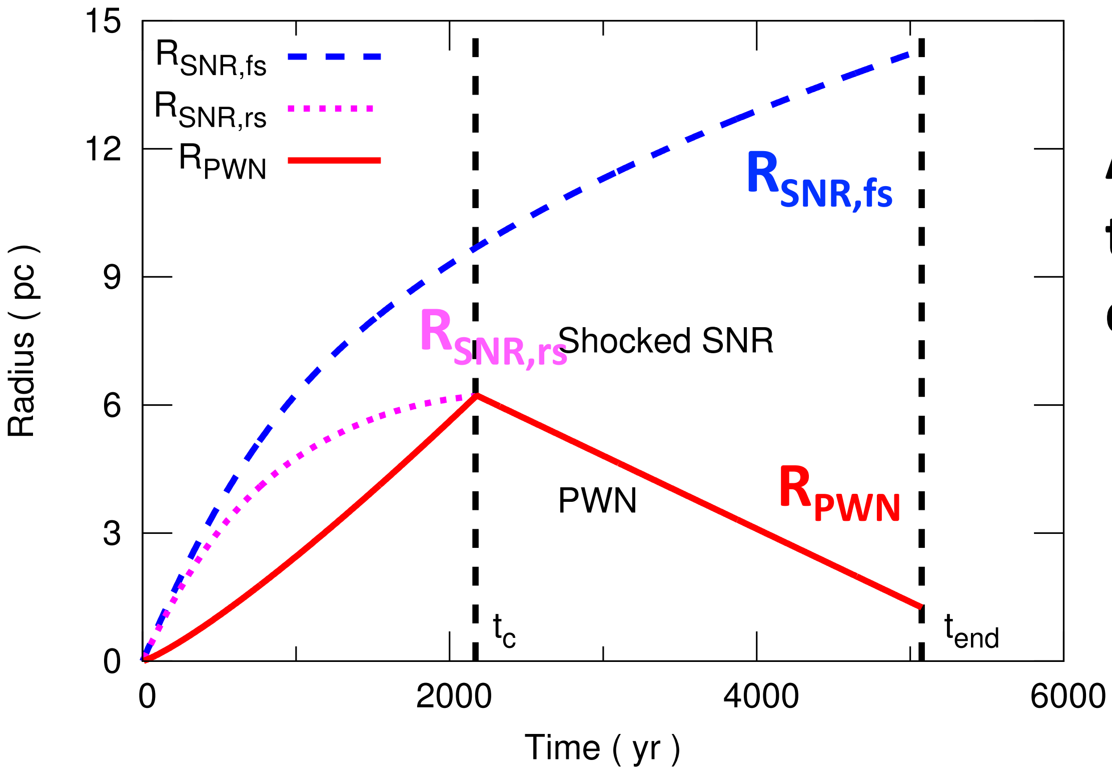
The energy gain in each cycle is $\Delta E/E \sim \Delta V/c \sim (V_{SNR,shocked} - V_{PWN}) / c$.

The time scale in each cycle is $\Delta t \sim \Delta R/c \sim (R_{SNR,rs} - R_{PWN}) / c$.

The acceleration time is $t_{acc} = \Delta t(E/\Delta E) \sim \Delta R/\Delta v \sim t_{cu}$.

→ $E \sim 2E_0$

Particle acceleration ($t > t_c$)



After the PWN interacts with the reverse shock, the PWN is compressed by the SNR.

→Particles inside the PWN are accelerated by the compression.

$$dE/dt = -(E/3)\mathrm{div}\, V_{PWN,in} = - (E / R_{PWN})(dR_{PWN} / dt)$$

$$\rightarrow E(t_{end}) / E(t_c) = R_{PWN}(t_c) / R_{PWN}(t_{end}) = 5$$

$$E_{max} \sim 1\ \mathrm{PeV} \left(\frac{E_{Inj}}{0.1\ \mathrm{PeV}} \right) \left(\frac{R_{PWN}(t_c) / R_{PWN}(t_{end})}{5} \right)$$

Size of PWNe after the compression

The size of PWNe is determined by the pressure balance.

$$p_{SNR} = p_{PWN} \rightarrow E_{SN}/R_{SNR,fs}^3 = \eta E_{rot}/R_{PWN}^3$$

Synchrotron cooling

$E_{SN} = 10^{51}$ erg, $E_{tot} = 10^{49}$ erg, $\eta = 0.1 \rightarrow R_{PWN}(t_{end}) = 0.1\ R_{SNR,fs}(t_{end})$

$R_{SNR,fs}(t_{end}) \sim 13$pc, $R_{PWN}(t_c) \sim 6$pc $\rightarrow R_{PWN}(t_c) / R_{PWN}(t_{end}) \sim 5$

Monte Carlo Simulation

Velocity fields

For $t < t_c$, the velocity field is assumed to be uniform.

$$V_{SNR,shocked} = (R_{SNR,rs}/t - V_{SNR,rs})/4 - V_{SNR,rs} \quad (R_{SNR,rs} < r < R_{SNR,fs})$$

$$V_{PWN} = dR_{PWN}/dt \quad (r < R_{PWN})$$

For $t > t_c$, the velocity field is assumed to be as follows.

$$V_{PWN,in}(r,t) = -(V_{PWN}(t_c) / 2) (r / R_{PWN}(t))$$

Particles

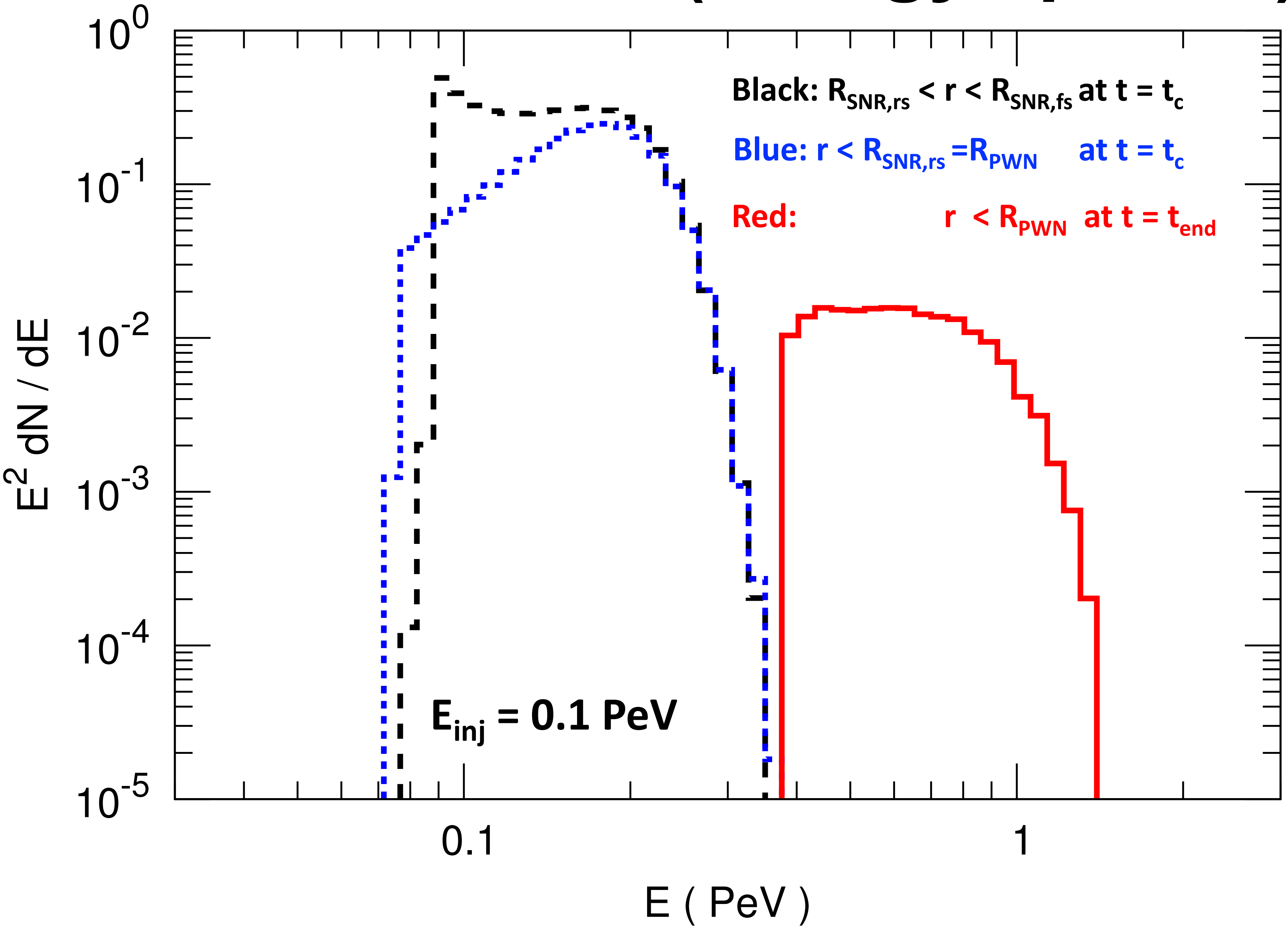
$E_0 = 0.1$ PeV, $\tau_{sc} = \Omega_c^{-1} \propto E / B$ (Bohm scattering),

B=0 in the freely expanding ejecta, B=300μG in other regions.

At $t_{inj} = 3$ kyr, simulation particles are isotropically injected on the reverse shock sphere, $r = R_{SNR,rs}$.

Simulation particles are isotropically and elastically scattered in the local fluid frame.

Simulation result (Energy spectra)



Summary

The observed CR spectrum breaks at about 1 PeV.

Since the upstream magnetic field amplification is not sufficient, a simple SNR system cannot accelerate protons to 1 PeV.

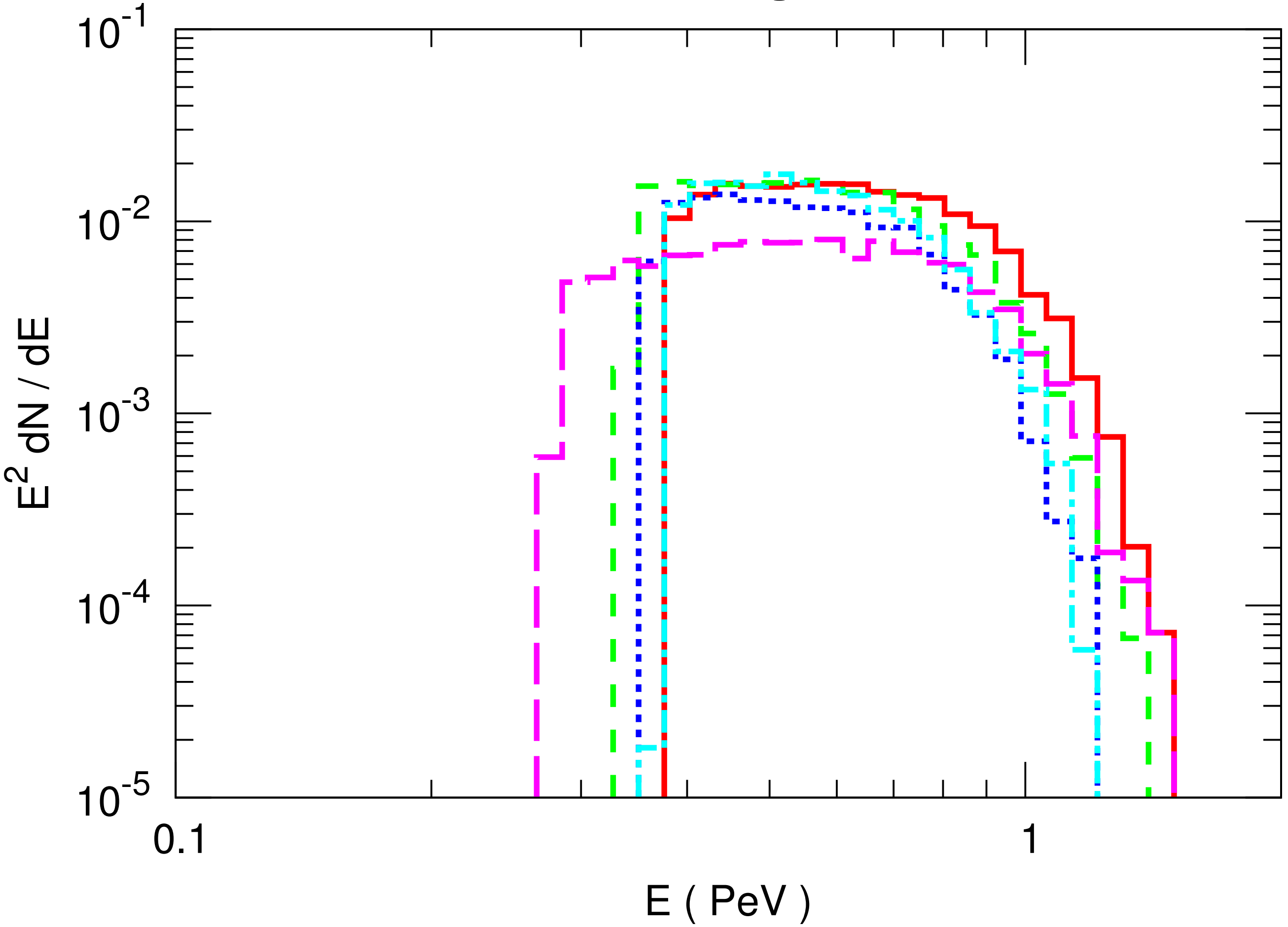
Reverse shocks of SNRs are expected to be the origin of heavy CR nuclei, but particles accelerated by the reverse shock lose their energy by adiabatic loss. → The maximum rigidity of heavy CR nuclei < 1PV?.

The recent observation of gamma-ray pulsars suggest that most core-collapse SNRs have pulsars with the spindown luminosity of 10^{38} erg/s.

The PWN-SNR system can reaccelerate 0.1PeV CRs to 1PeV.

The PWN-SNR system is PeVatrons and the source of heavy CR nuclei.

Parameter dependence



Model	M_{ej} $[M_\odot]$	n $[cm^{-3}]$	L_{sd} $[erg\ s^{-1}]$	t_{inj} [s]	B $[\mu G]$
A	3	0.1	3×10^{38}	5×10^{10}	300
B	10	0.1	3×10^{38}	1×10^{11}	300
C	3	1.0	3×10^{38}	2.5×10^{10}	300
D	3	0.1	3×10^{37}	5×10^{10}	300
E	3	0.1	3×10^{38}	5×10^{10}	150

Evolution of a PWN-SNR system

For ρ_{ej} and ρ_{ISM} = uniform,

$$R_{\rm SNR,fs} = R_{\rm S} \times \begin{cases} 1.37\frac{t}{t_{\rm S}}\left\{1+0.60\left(\frac{t}{t_{\rm S}}\right)^{3/2}\right\}^{-2/3} & (t < t_{\rm S}) \\ \left(1.56\frac{t}{t_{\rm S}} - 0.56\right)^{2/5} & (t \geq t_{\rm S}) \end{cases},$$

$$R_{\rm SNR,rs} = R_{\rm S} \times \begin{cases} 1.24\frac{t}{t_{\rm S}}\left\{1+1.13\left(\frac{t}{t_{\rm S}}\right)^{3/2}\right\}^{-2/3} & (t < t_{\rm S}) \\ \frac{t}{t_{\rm S}}\left\{0.78 - 0.03\frac{t}{t_{\rm S}} - 0.37\ln\left(\frac{t}{t_{\rm S}}\right)\right\} & (t \geq t_{\rm S}) \end{cases},$$

where $R_{\rm S}$ and $t_{\rm S}$ are given by

McKee & Truelove (1995)

$$R_{\rm S} \approx 8.73\ {\rm pc}\left(\frac{M_{\rm ej}}{6M_\odot}\right)^{1/3}\left(\frac{n}{0.1{\rm cm}^{-3}}\right)^{-1/3}$$

$$t_{\rm S} \approx 2\times10^3\ {\rm yr}\left(\frac{E_{\rm SN}}{10^{51}\ {\rm erg}}\right)^{-\frac{1}{2}}\left(\frac{M_{\rm ej}}{6\ {\rm M}_\odot}\right)^{\frac{5}{6}}\left(\frac{n}{0.1\ {\rm cm}^{-3}}\right)^{-\frac{1}{3}}.$$

For L_{sd} = constant,

van der Swaluw et al. (2001)

$$R_{\rm PWN} = 1.04\ R_{\rm S}\left(\frac{L_{\rm sd}t_{\rm S}}{E_{\rm SN}}\right)^{1/5}\left(\frac{t}{t_{\rm S}}\right)^{6/5} \qquad (t < t_c)$$

We assume $V_{PWN}(t,r) = -(V_{PWN}(t_c)/2)(r/R_{PWN}) \qquad (t > t_c)$