中国科学技术大学
University of Science and Technology of China

DSEL DEEP SPACE EXPLORATION LAB
深空探测实验室

MeV de-excitation lines as a probe of low energy cosmic rays

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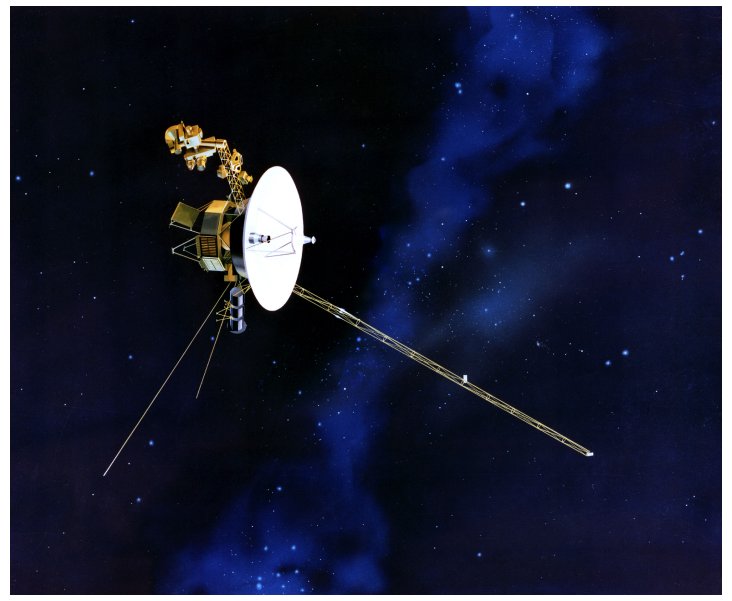
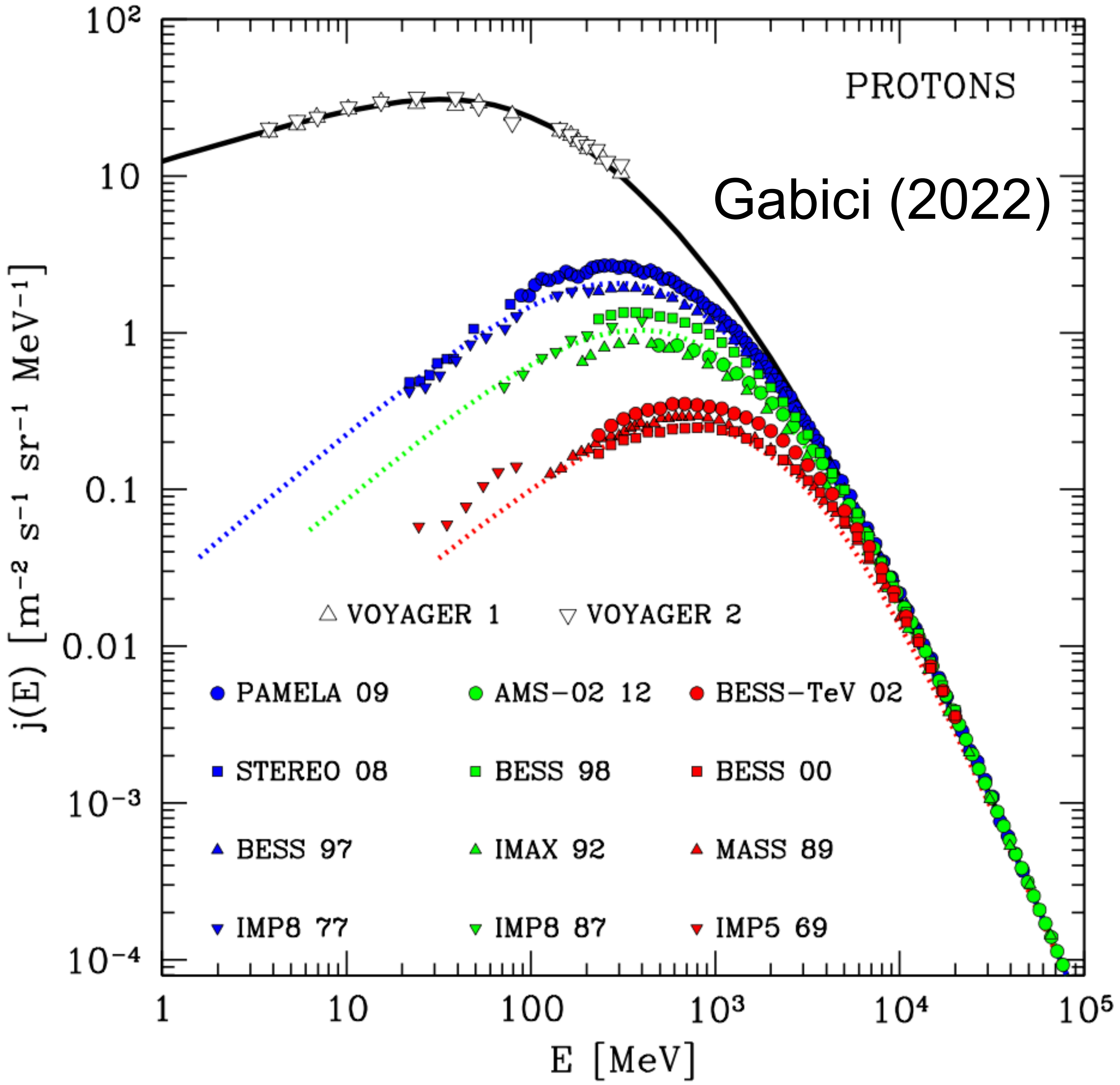
Low-energy Cosmic Rays

LECRs (E <1 GeV/nucleon)

Significantly contribute the ionization and heating of the gas and the energy balance of the ISM, play an important role on the star-forming process

- **Indirect study**:
  ionization rate, non-thermal X-ray emission (6.4 KeV Fe Kα line) …
- **Direct observations**:
  very difficult, solar modulation,
  Measurements of Voyager 1 and 2 cannot represent the property of LECRs in the Galaxy…



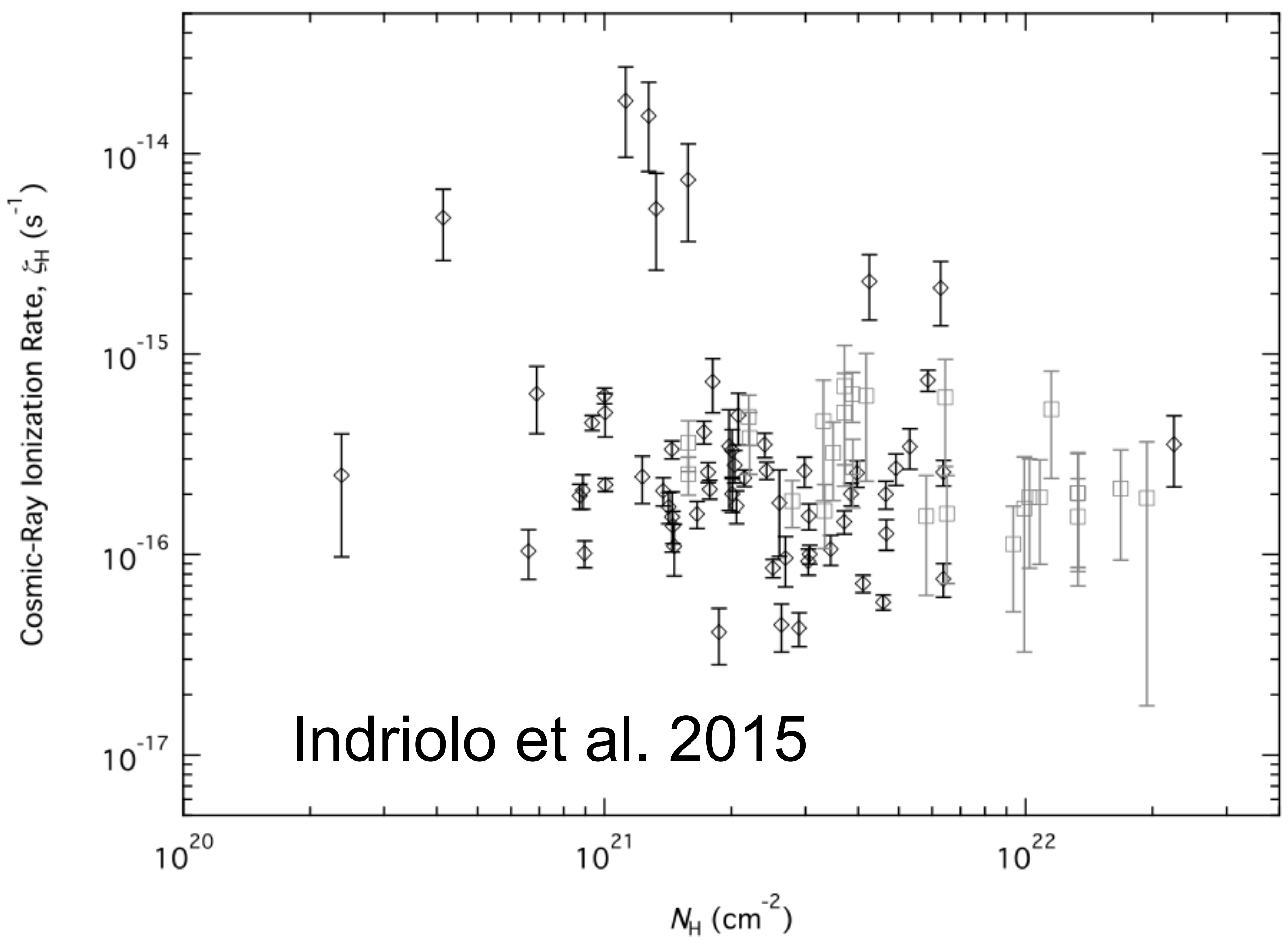


Due to slower diffusion and faster energy loss, the distribution of LECRs in our Galaxy should be more inhomogeneous than high-energy CRs.

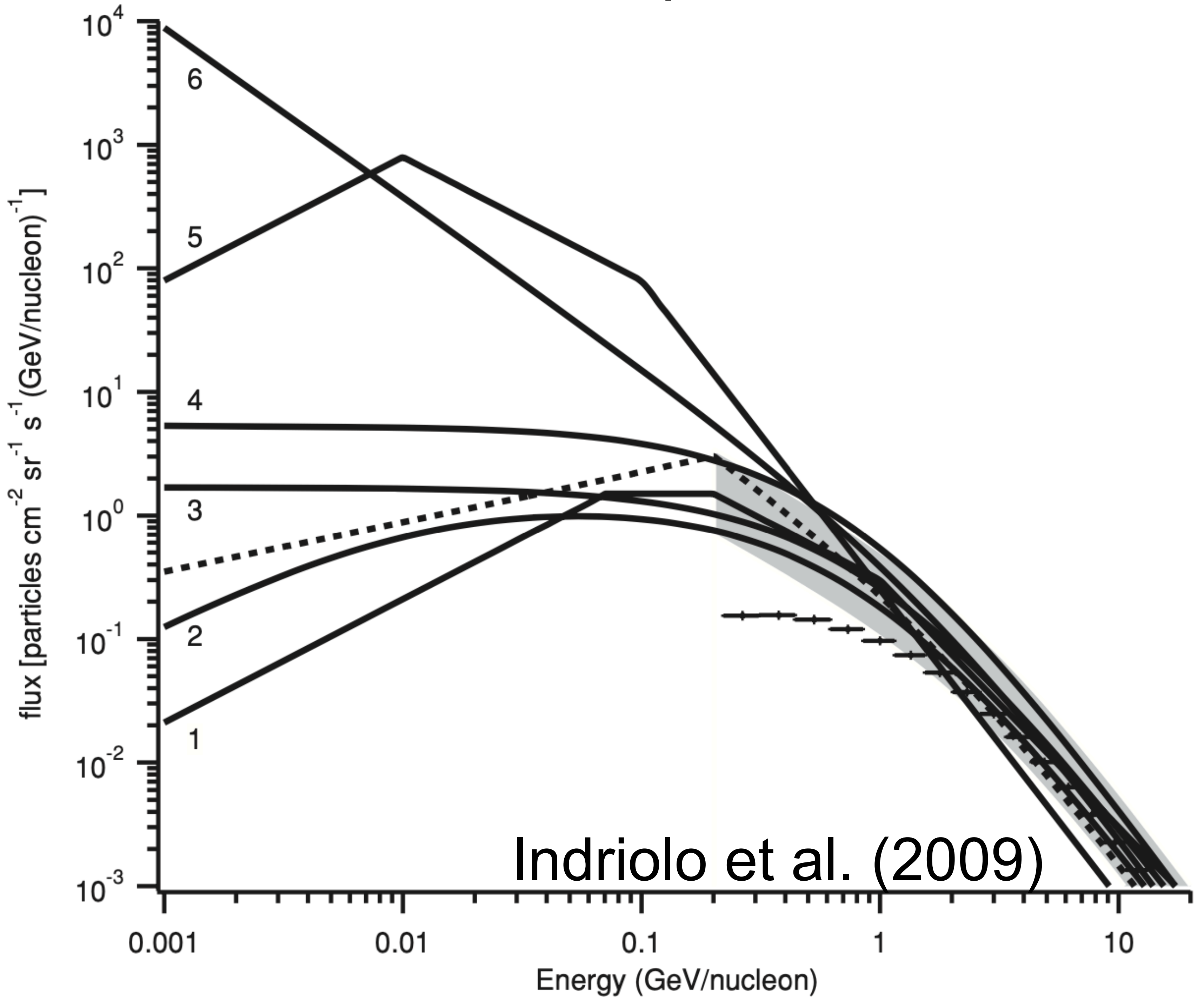
Low-energy Cosmic Rays

CR ionization rate measured in Galactic diffuse molecular clouds: from 10^{-16} s^{-1} to 10^{-14} s^{-1} $\gg$ the one which is calculated for the standard CR flux thought to be produced by DSA in SNRs (10^{-17} s^{-1})

An additional LECR nuclei component in our Galaxy ???



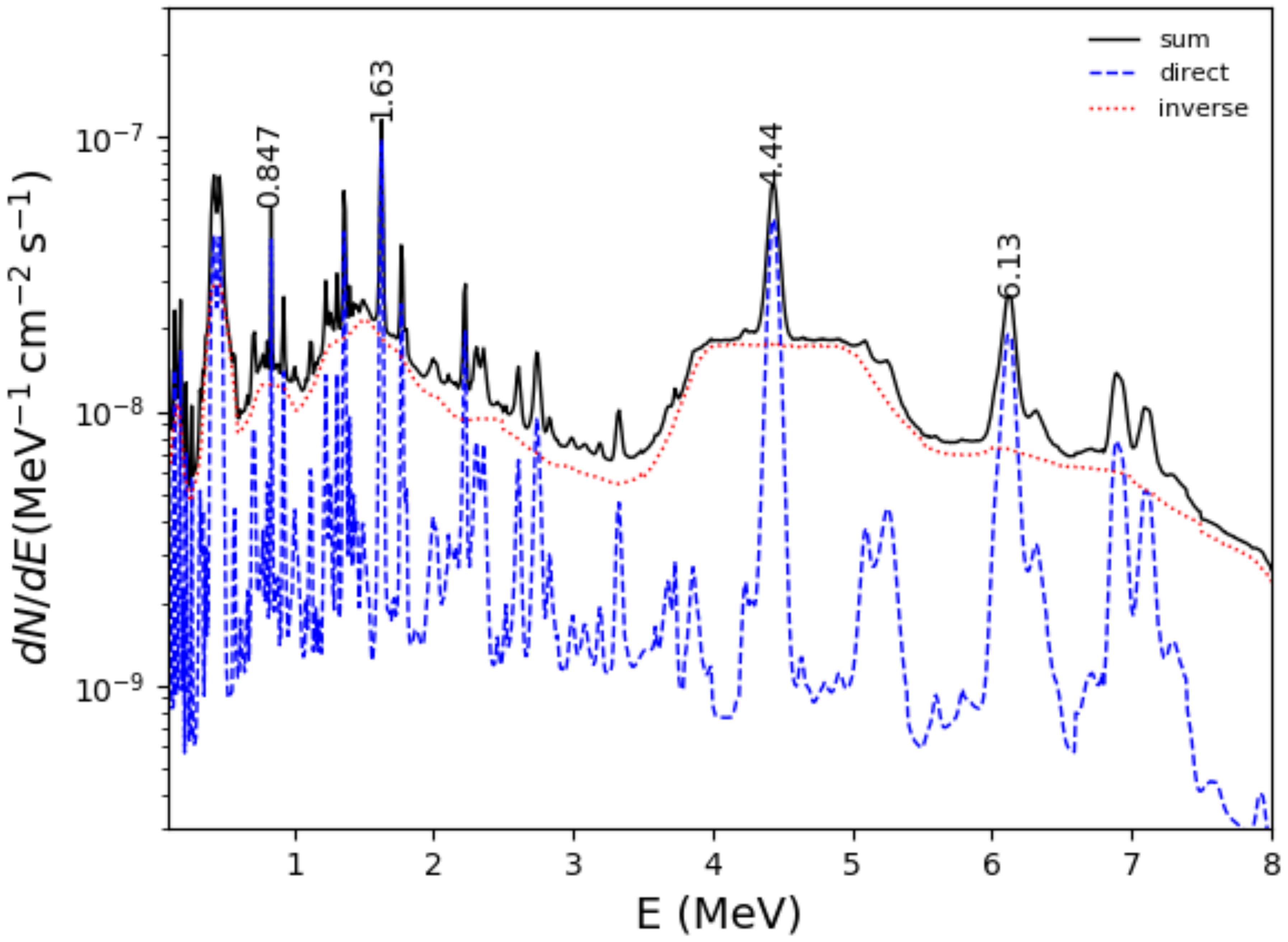
Example CR spectra used in the literature over the past few decades.



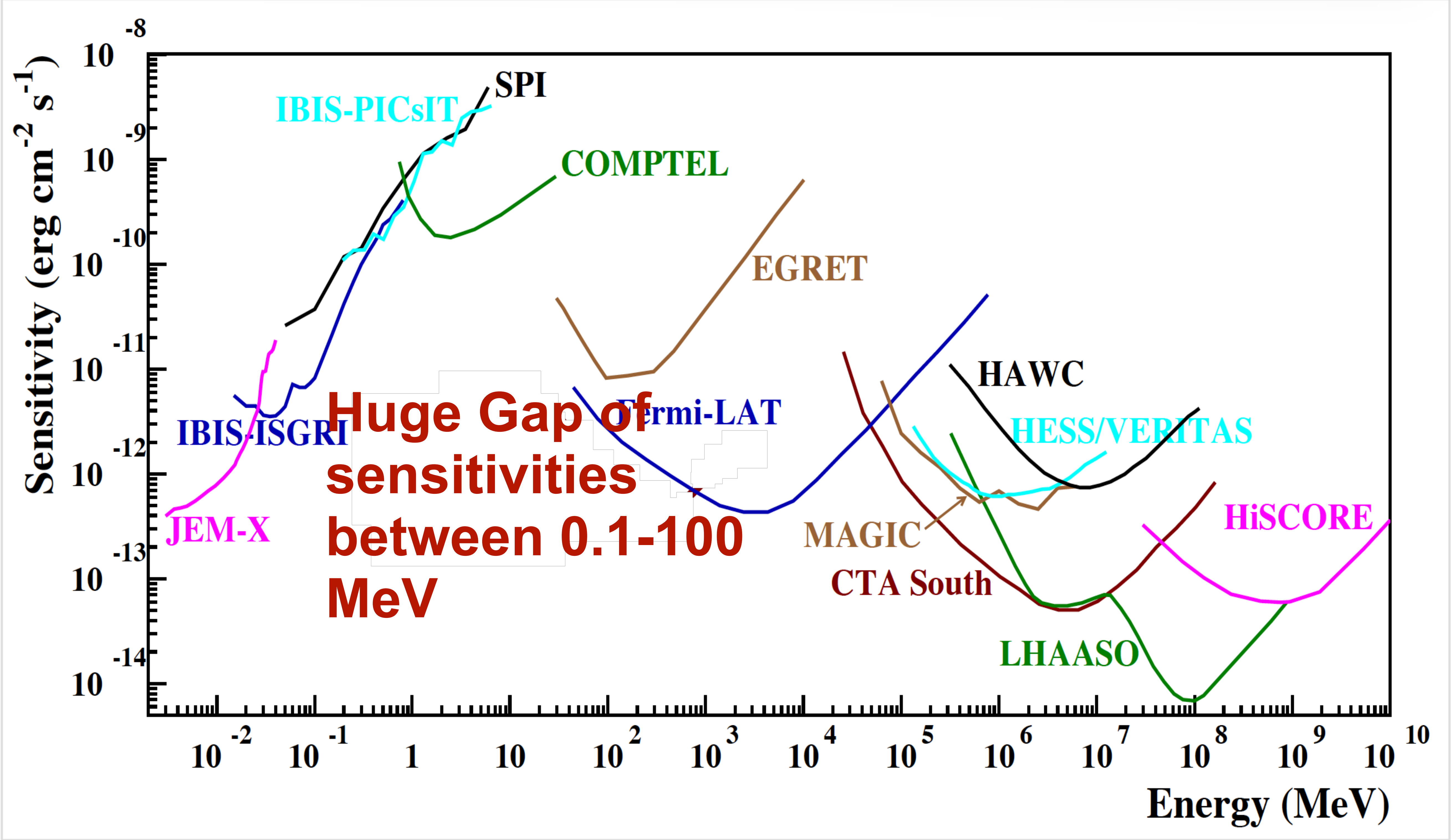
However, neither the nature - electrons or nuclei - nor the spectrum of the LECR component can be deduced from the measurements of ionization rate.

Nuclear de-excitation line emission from LECRs

Nuclear de-excitation line emission:
distinguish nuclei & electrons, provide information of the LECRs and the medium.



12C : 4.44 MeV 16O : 6.13 MeV (**~0.1-10 MeV**)

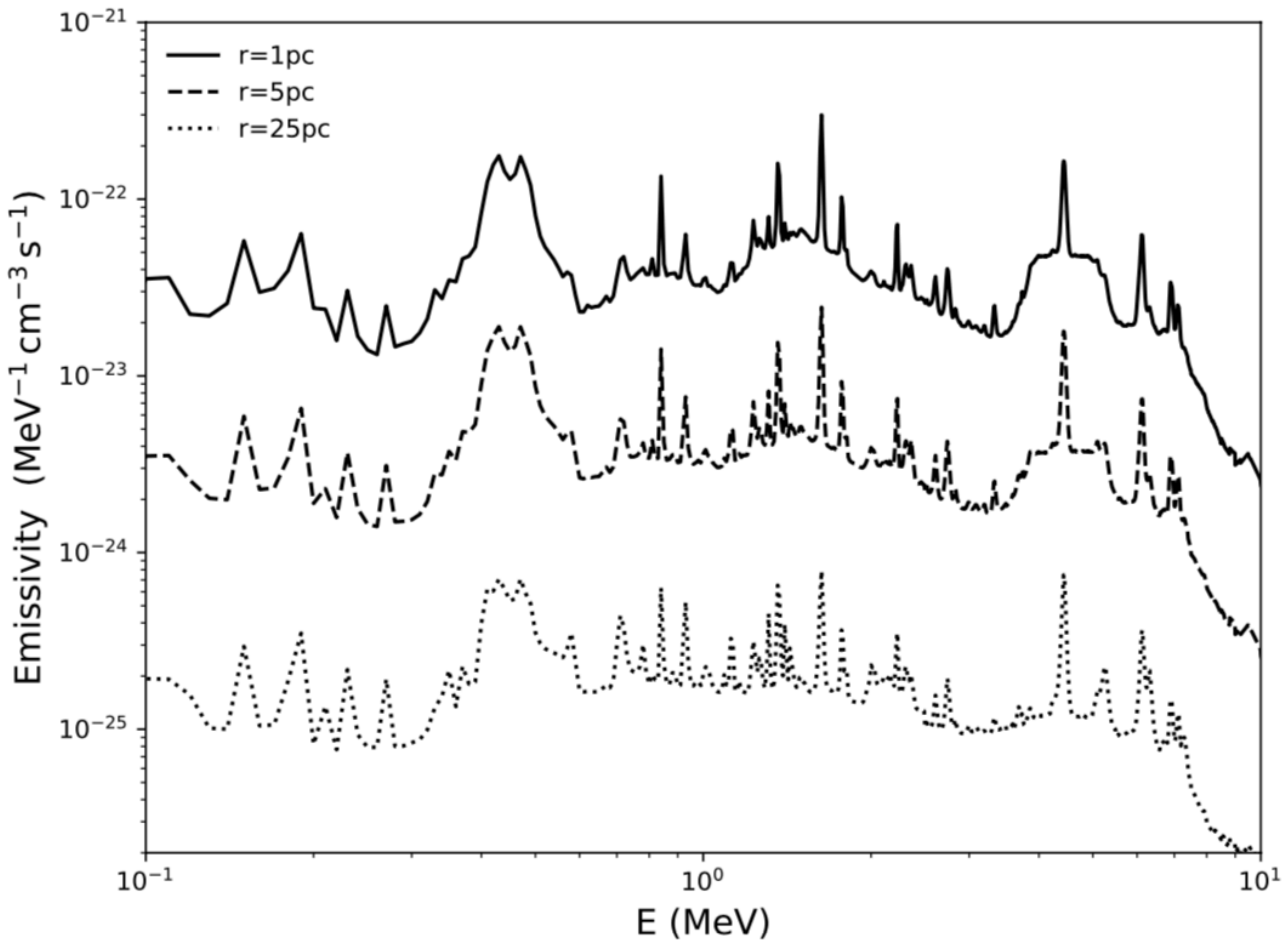


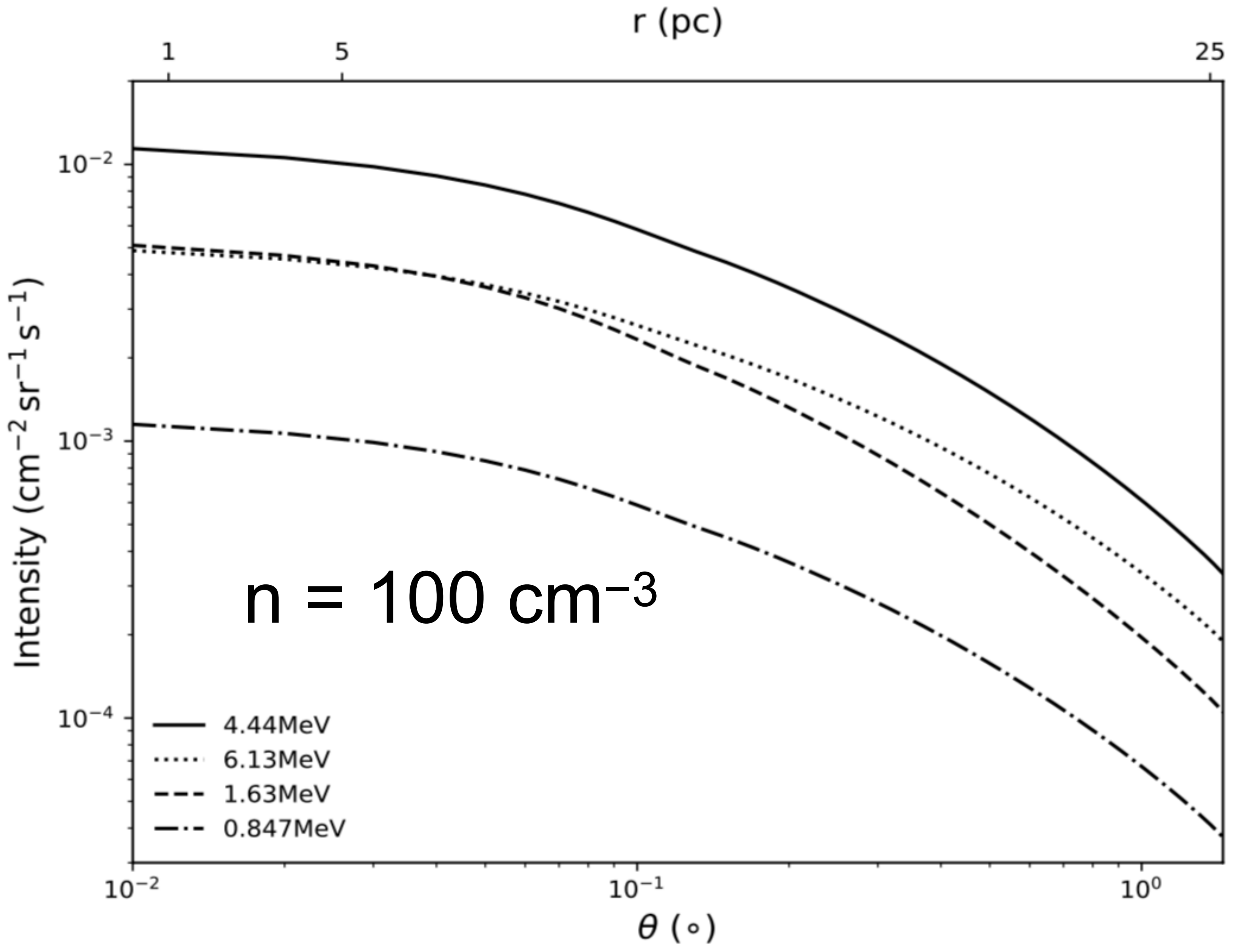
Proposed or ongoing MeV gamma-ray projects in recent years:
MeGaT, MASS, MeVGRO, MeVCube, e-ASTROGAM, AMEGO, COSI, GRAMS, GECCO, HARPO, SMILE…

MeV nuclear line emission from a hypothetic CR source

A point source that continuously injecting CRs , Q=1e38 erg s^{-1}, d=1 kpc, spectra index s=2.0
Elemental Composition: CR (Voyager) + medium (solar)

The line fluxes drop sharply with θ, almost negligible at θ~1.5° (r~25 pc)





Integrated 4.44 MeV line flux

n (cm^{-3})	χ	Flux (photon cm^{-2} s^{-1})
1	1.0	5.49×10^{-9}
1	0.1	3.25×10^{-8}
1	0.01	1.25×10^{-7}
100	1.0	1.25×10^{-7}
100	0.1	3.16×10^{-7}
100	0.01	5.96×10^{-7}

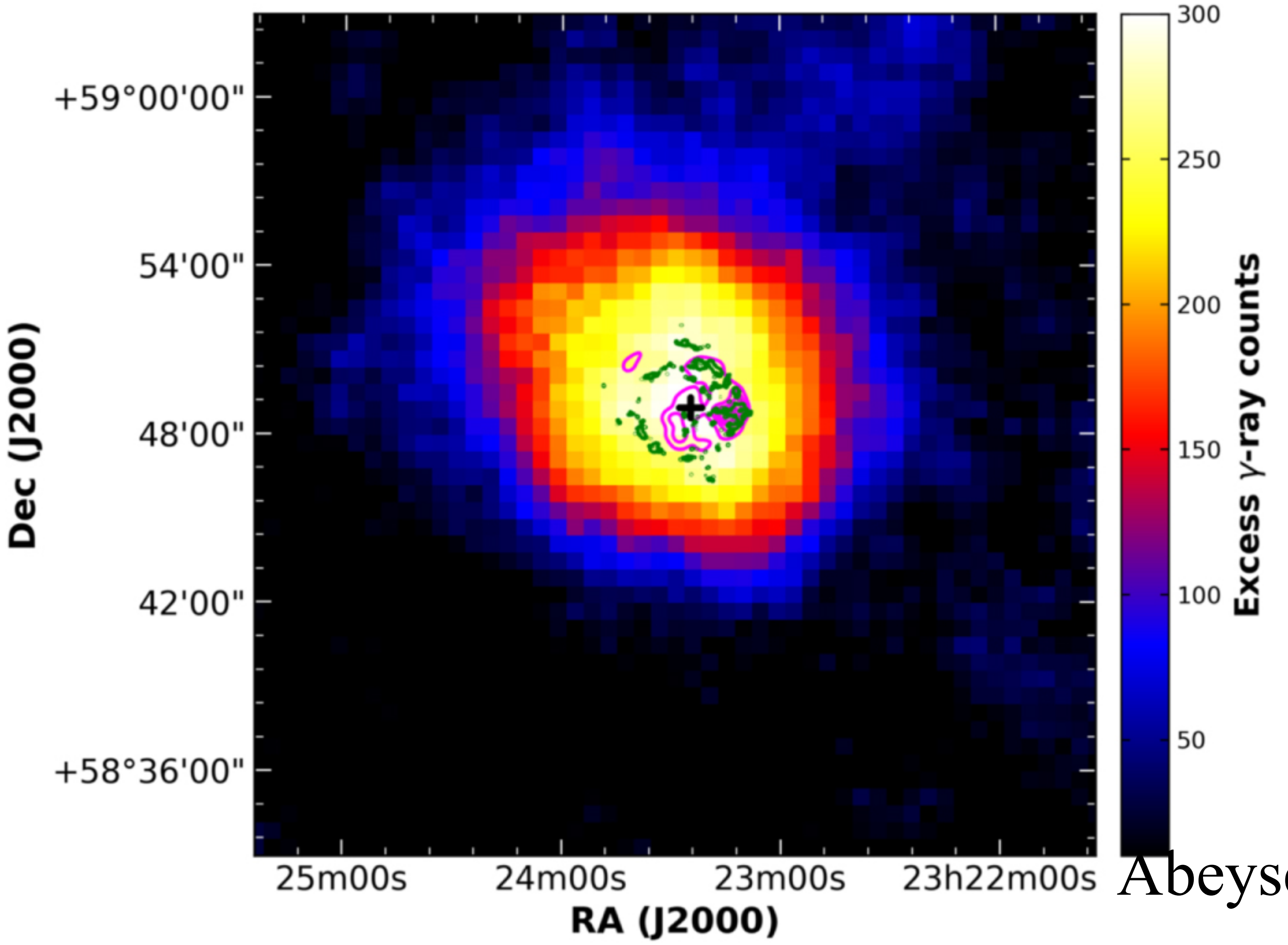
Point-like emission given the angular resolution of next-generation MeV γ-ray detectors.
For the detection, sensitivity requirement: 10^{-6} to10^{-7} ph cm^{-2} s^{-1}

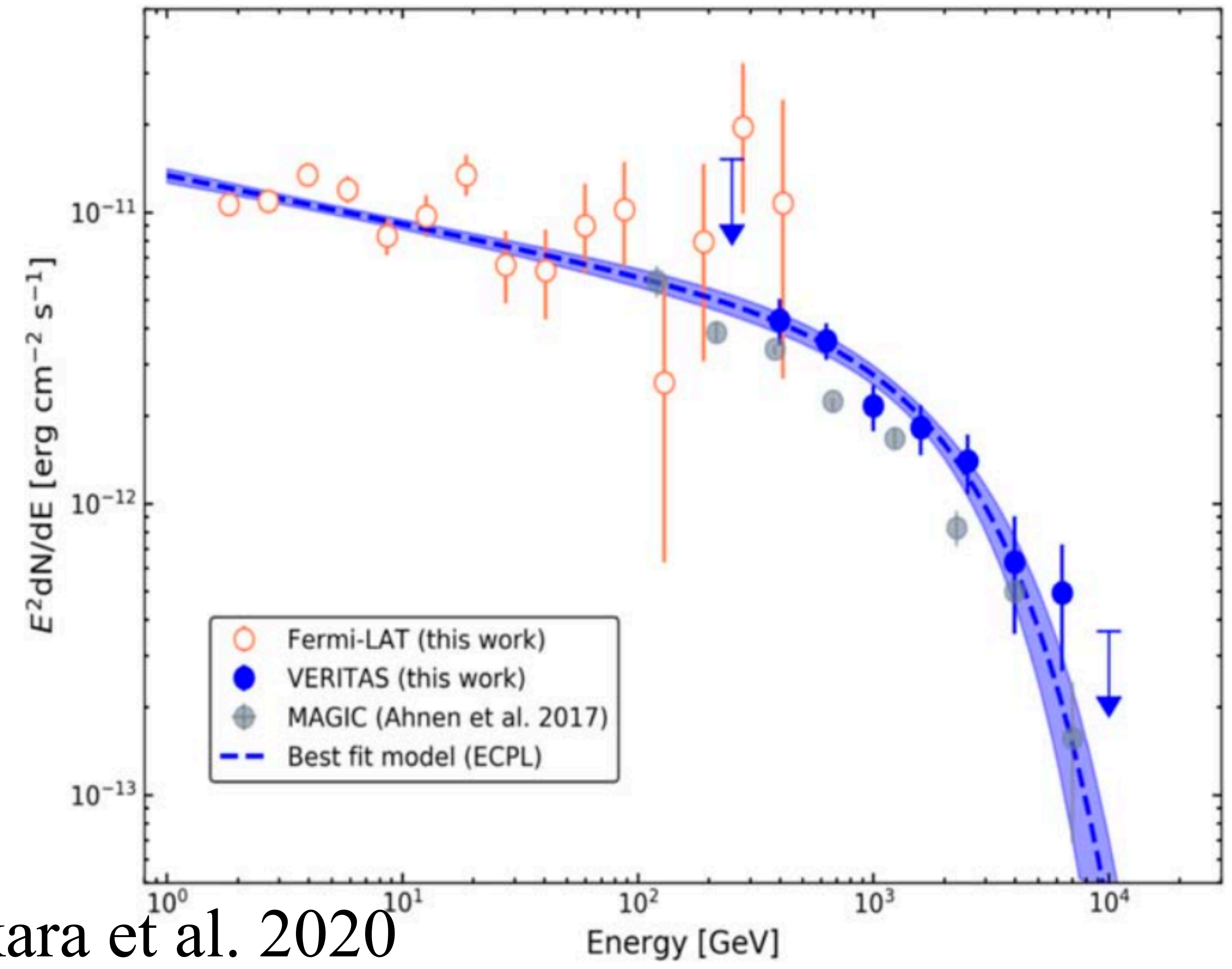
B. Liu, R.-z. Yang and F. Aharonian, 2021, A&A

SNR Cas A

Cassiopeia A: a young remnant of a core-collapse SN exploded ~ 340 yrs ago.
distance: ~3.4 kpc radius: 2.5 pc (2.5')

Chandra X-ray Image of Cas A
Credit: NASA/CXC/SAO





Abeysekara et al. 2020

The origin of these GeV-TeV γ-rays: hadronic, leptonic, hadronic+leptonic ?

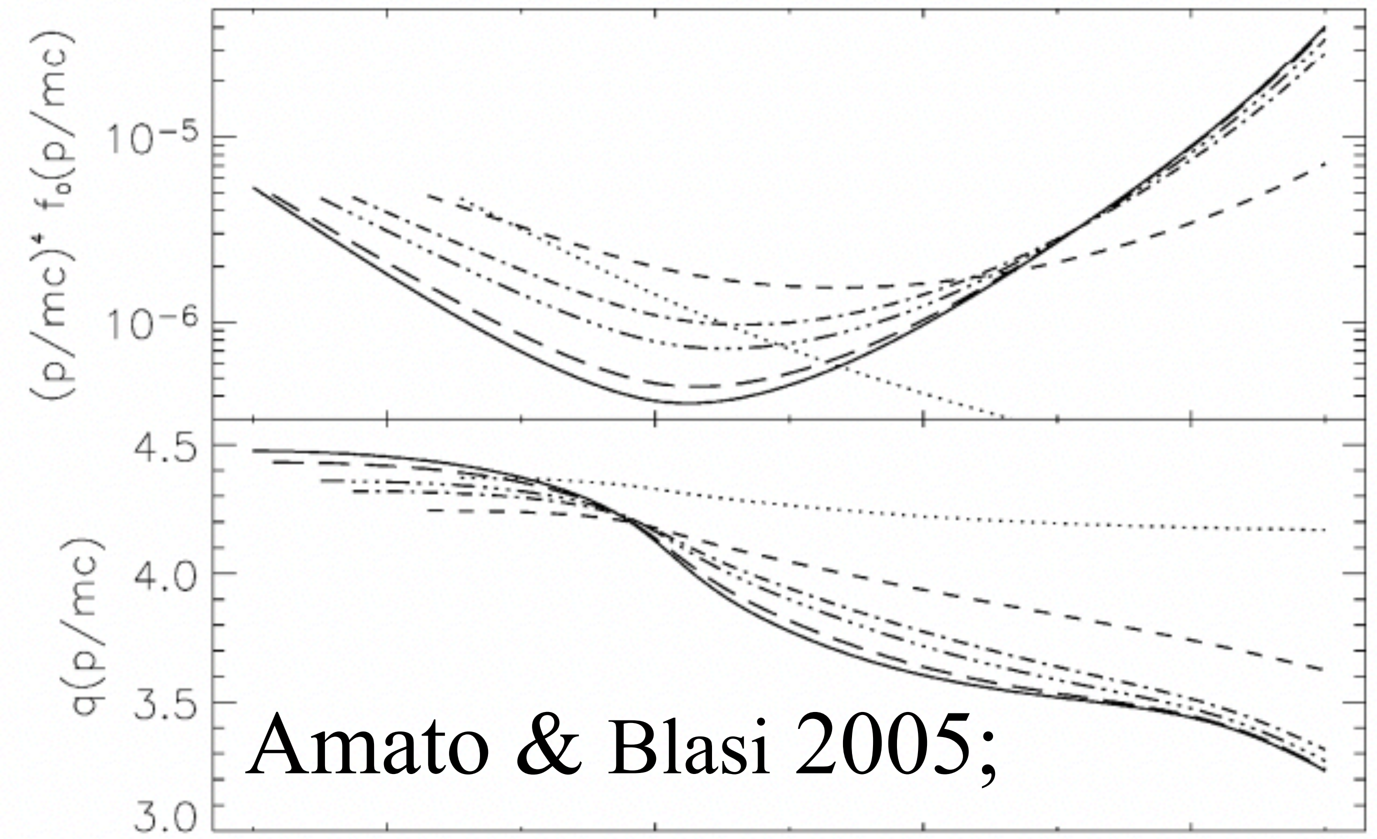
Most studies show that a hadronic components is needed. (e.g. Abdo et al. 2010; Yuan et al. 2013; Zirakashvili et al. 2014; Ahnen et al. 2017; Zhang & Liu 2019; Abeysekara et al. 2020)

The GeV-TeV gamma-rays emission can constrain the fluxes of the high energy nuclei.

New estimation of the nuclear de-excitation line emission from SNR Cas A

Studies of nonlinear shock acceleration predict that the spectra of the accelerated particles show some concavity in momentum space.

The nuclei spectra: ~ p^{-4}, at low energies, flatter than p^{-4} at the highest energies. (e.g., Amato & Blasi 2005; Caprioli et al. 2011).



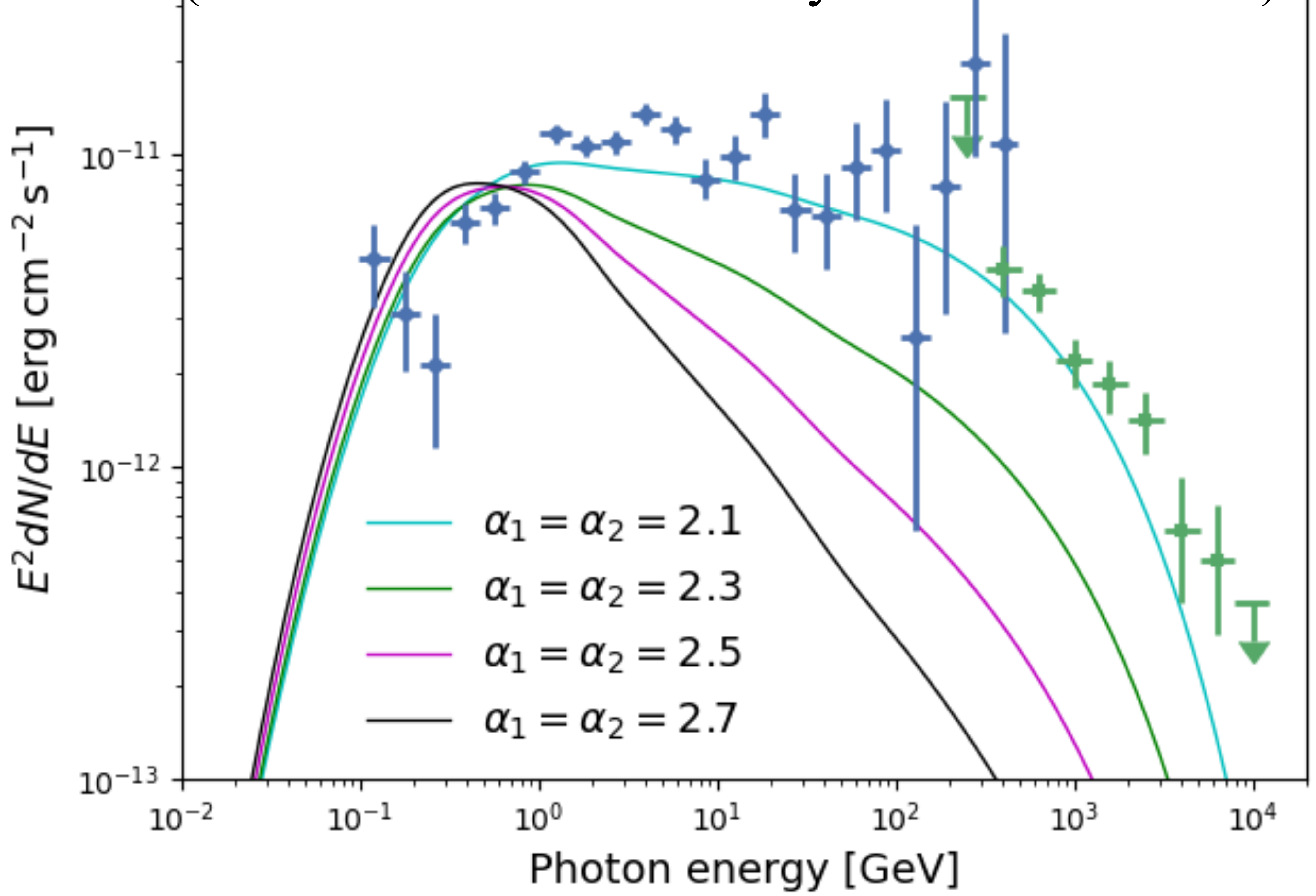
Spectral distribution of protons accelerated by Cas A: (simplified assumption)

$$F(E)=\begin{cases} N_0\left[\frac{p(E)}{p(E_b)}\right]^{-\alpha_1}\exp\left[\frac{-p(E)}{p(E_{cut})}\right], & \text{if } E \geq E_b \\ N_0\left[\frac{p(E)}{p(E_b)}\right]^{-\alpha_2}\exp\left[\frac{-p(E)}{p(E_{cut})}\right], & \text{if } E < E_b \end{cases}.$$

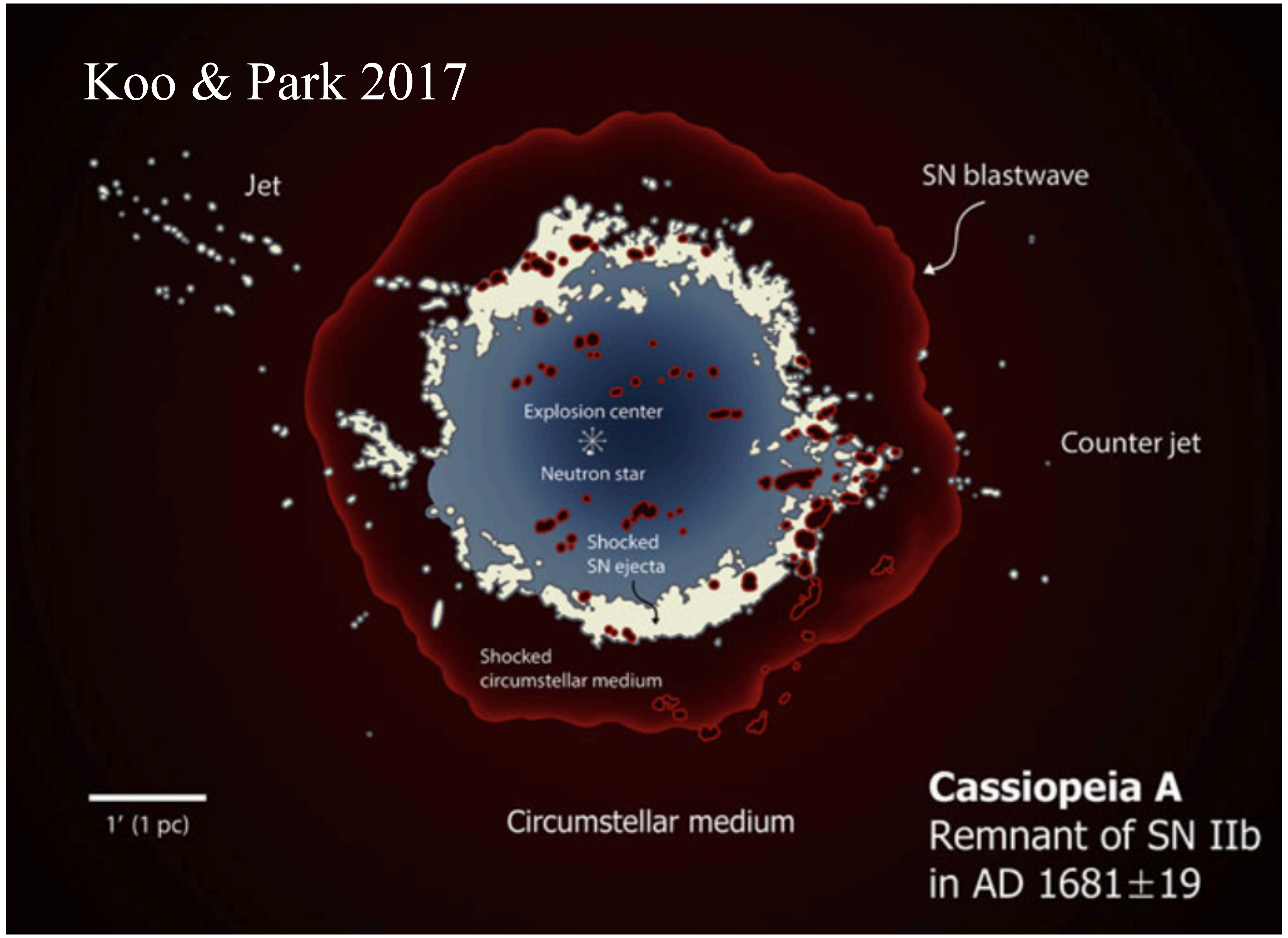
E_{cut}= 10 TeV, E_b=0.2 GeV,

α_1=2.0 — 2.7, α_2=α_1, 3.0, 4.0

(GeV-TeV data from Abeysekara et al. 2020)



New estimation of the nuclear de-excitation line emission from SNR Cas A



Schematic picture of SNR Cas A

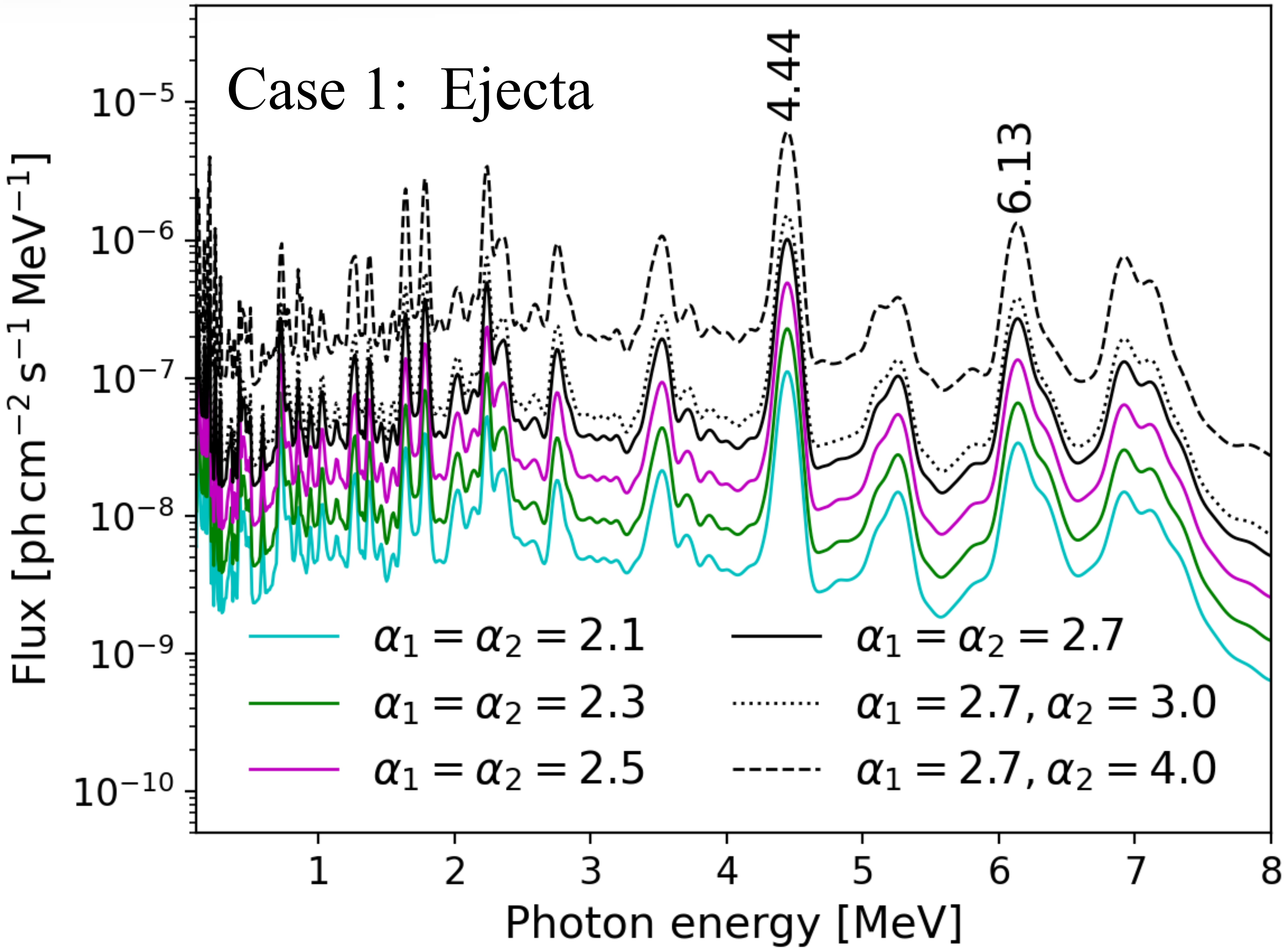
White and *blue colours* represent SN material;

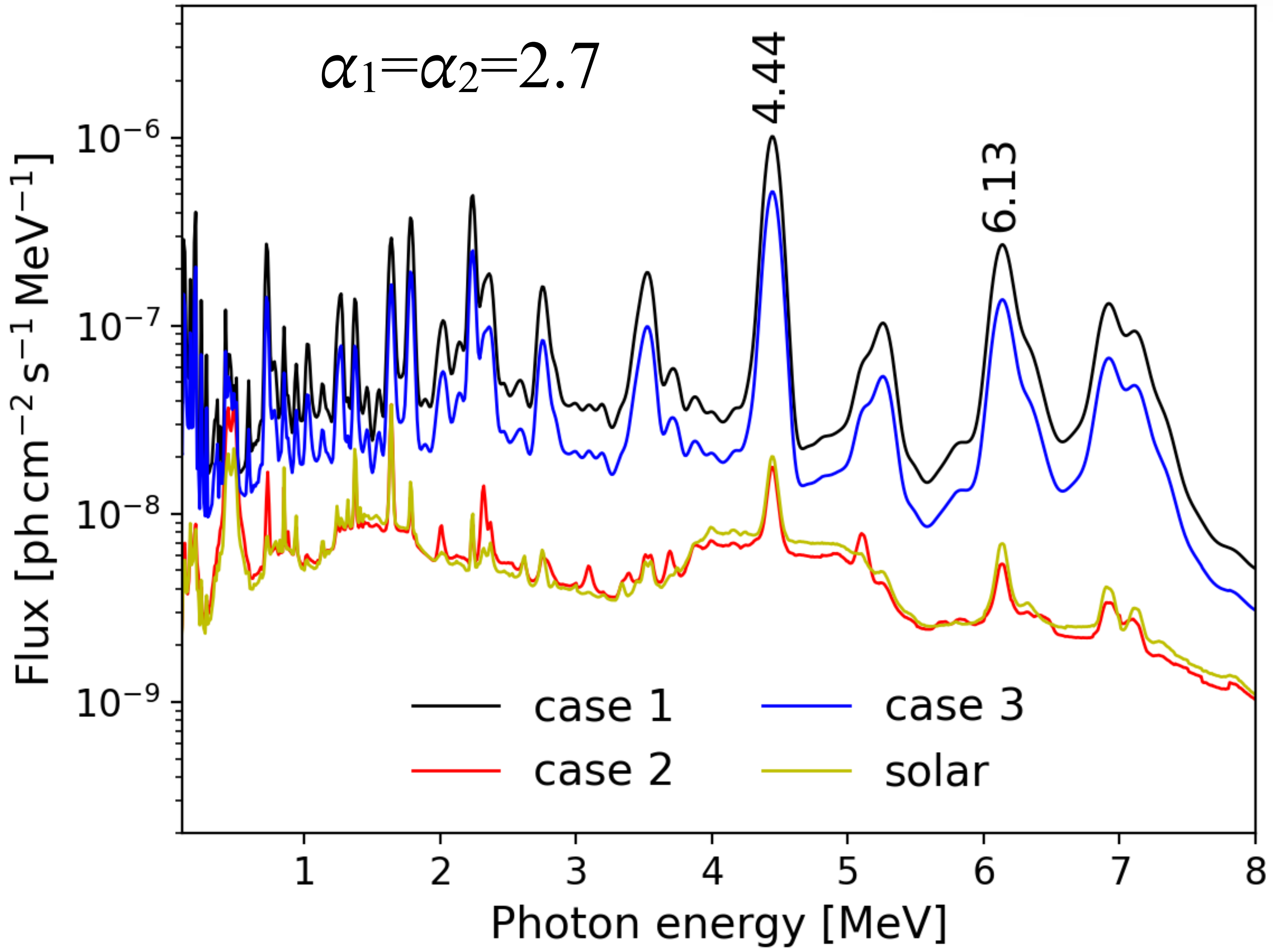
red color represents the CSM

	CR [a] n_{el}/n_H	Solar [b] n_{el}/n_H	CSM [c] $n_{el}/n_\odot$	Ejecta [d] n_{el}/n_O
H	1	1	1	0.01-0.05*
He	8.140×10^{-2}	8.414×10^{-2}	3	0.1-0.5*
C	1.671×10^{-3}	2.455×10^{-4}	1	0.5*
N	2.444×10^{-4}	7.244×10^{-5}	15	0.1*
O	1.570×10^{-3}	5.370×10^{-4}	1	1
Ne	1.507×10^{-4}	1.122×10^{-4}	1	0.02
Mg	2.264×10^{-4}	3.467×10^{-5}	1	0.005
Si	1.898×10^{-4}	3.388×10^{-5}	1	0.05
S	2.087×10^{-5}	1.445×10^{-5}	1	0.05
Ar	4.554×10^{-6}	3.162×10^{-6}	1	0.005
Ca	1.195×10^{-5}	2.042×10^{-6}	1	0.004*
Fe	1.152×10^{-4}	2.884×10^{-5}	1	0.005

[a] Number density ratio relative to H, adopted from the Voyager measurement of local LECR abundance (see Cummings et al. 2016, Table 3).
[b] Number density ratio relative to H, adopted the recommended present-day solar abundance (see Lodders 2010, Table 6).
[c] Number density ratio relative to the solar value, adopted for the CSM of Cas A, mainly referred to Hwang & Laming (2012).
[d] Number density ratio relative to O, mainly adopted from Docenko & Sunyaev (2010).

New estimation of the nuclear de-excitation line emission from SNR Cas A





$$F(E)=\begin{cases} N_0\left[\frac{p(E)}{p(E_\mathrm{b})}\right]^{-\alpha_1}\exp\left[\frac{-p(E)}{p(E_\mathrm{cut})}\right], & \text{if } E \geq E_\mathrm{b} \\ N_0\left[\frac{p(E)}{p(E_\mathrm{b})}\right]^{-\alpha_2}\exp\left[\frac{-p(E)}{p(E_\mathrm{cut})}\right], & \text{if } E < E_\mathrm{b} \end{cases}.$$

α_1=2.0–2.7, α_2=α_1, 3.0, 4.0

Integrated 4.44 MeV and 6.13 MeV line fluxes of various cases

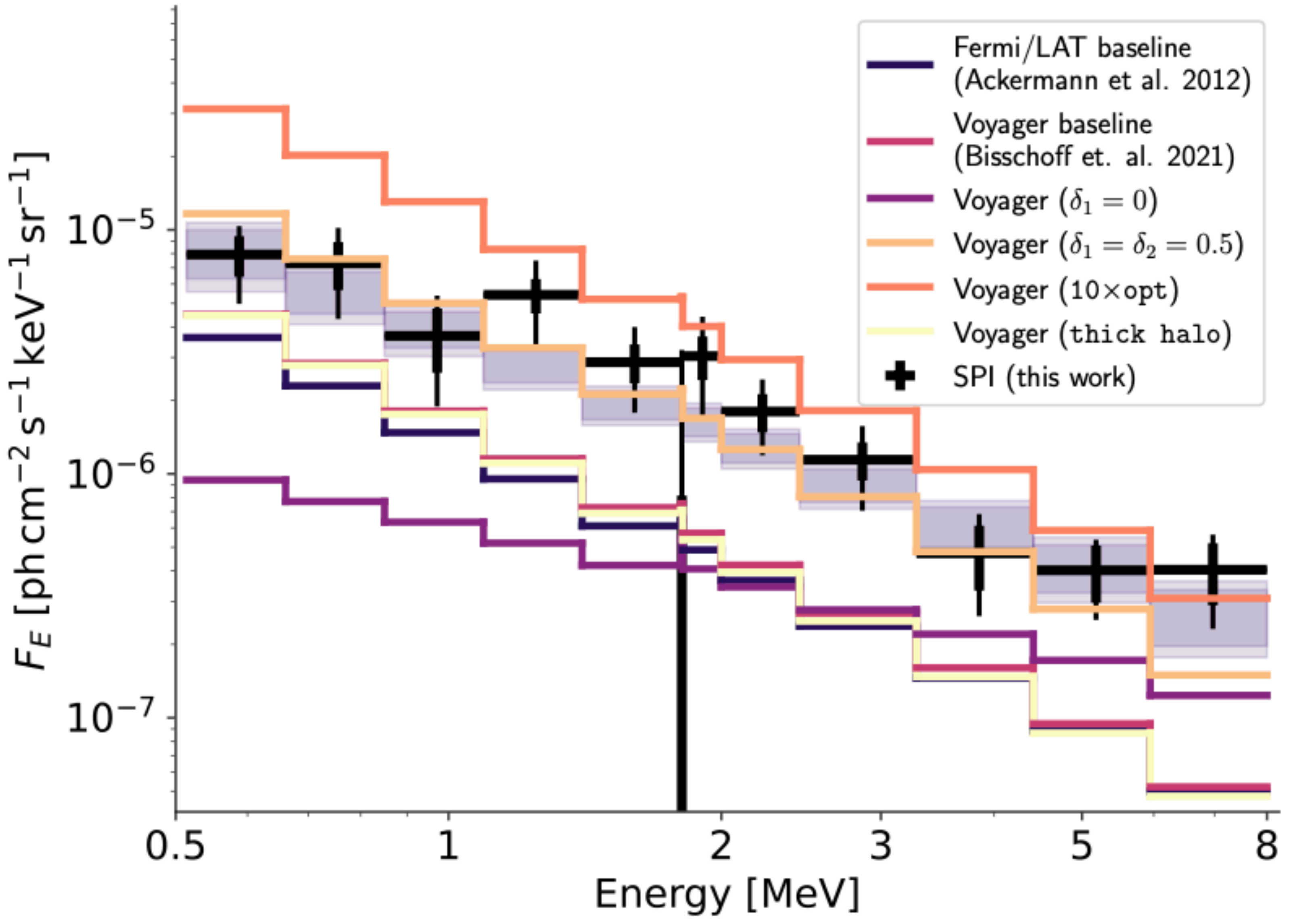
	Medium	4.44 MeV	6.13 MeV
case 1	Ejecta	(0.09–7.71)×10^{-7}	(0.04–2.10)×10^{-7}
case 2	CSM	(0.10–8.84)×10^{-9}	(0.04–2.66)×10^{-9}
case 3	Ejecta+CSM	(0.05–3.93)×10^{-7}	(0.02–1.06)×10^{-7}

B. Liu, R.-z. Yang∗, X.-y. He and F. Aharonian, 2023, MNRAS

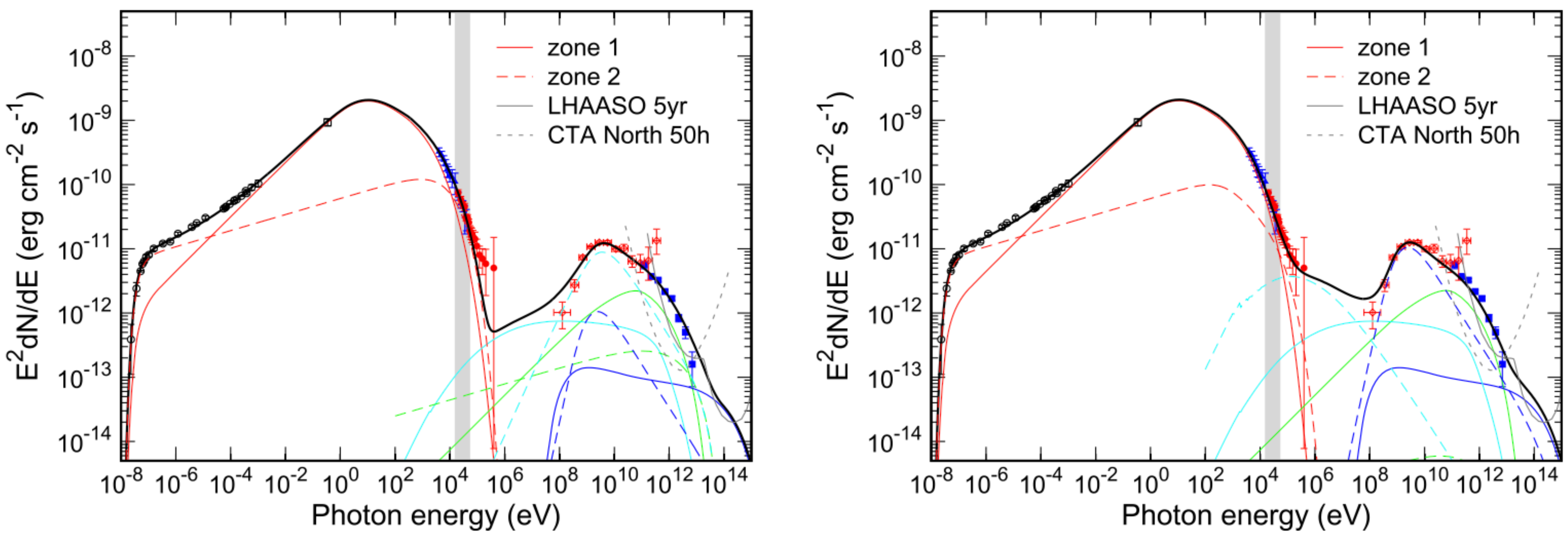
New estimation of the nuclear de-excitation line emission from SNR Cas A

MeV continuum background

- Diffuse Galactic emission: new results from the analysis with the spectrometer SPI aboard INTEGRAL in the range of 0.5–8.0 MeV around the Galactic center (Siegert et al. 2022) .
- MeV continuum emission from Cas A: mainly non-thermal bremsstrahlung from electrons, predicted energy fluxes <~6e^{-12} erg cm^{-2} s^{-1} @ MeV from different scenarios on the origin of the GeV-TeV emission.



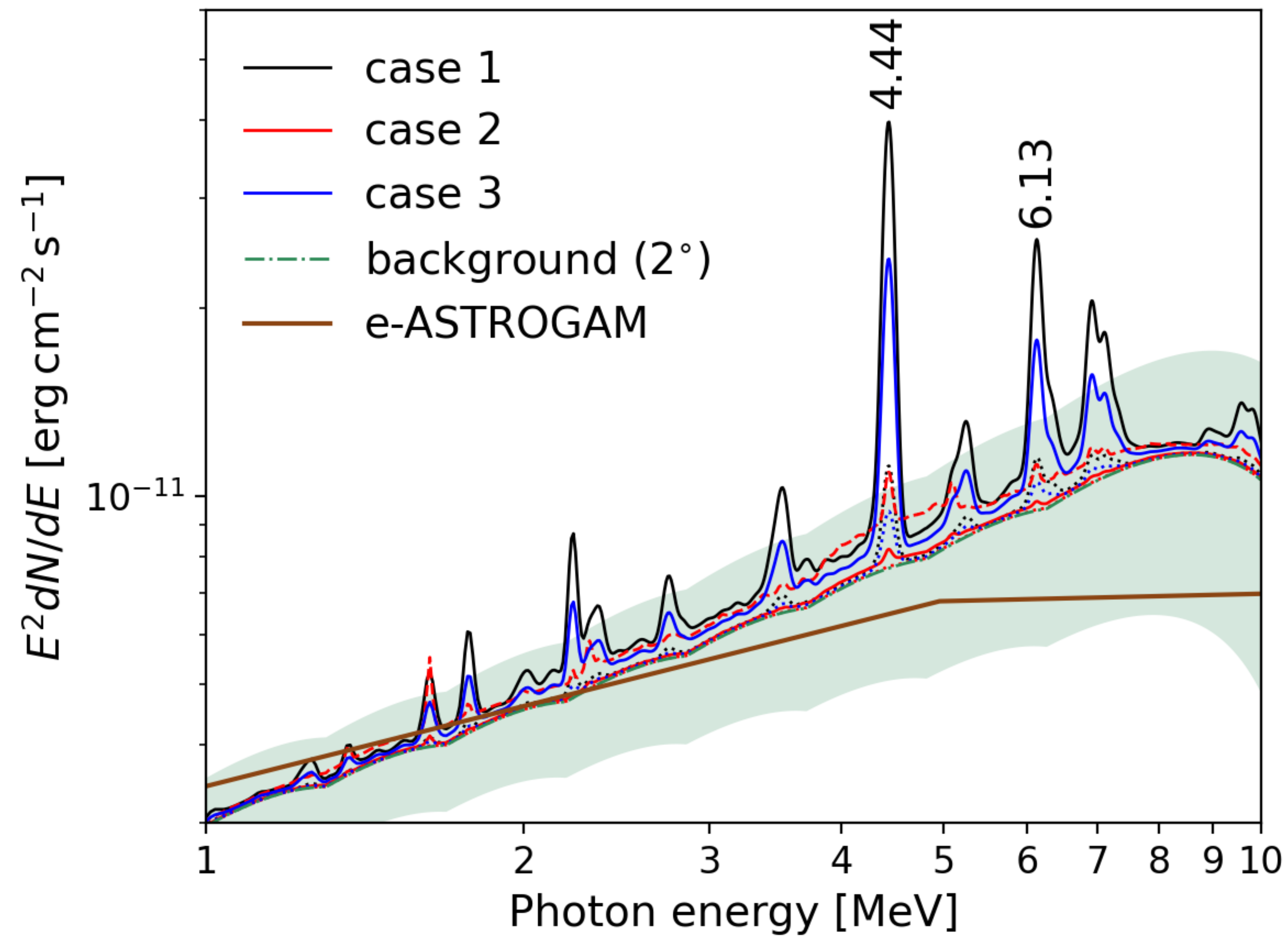
Siegert et al. 2022

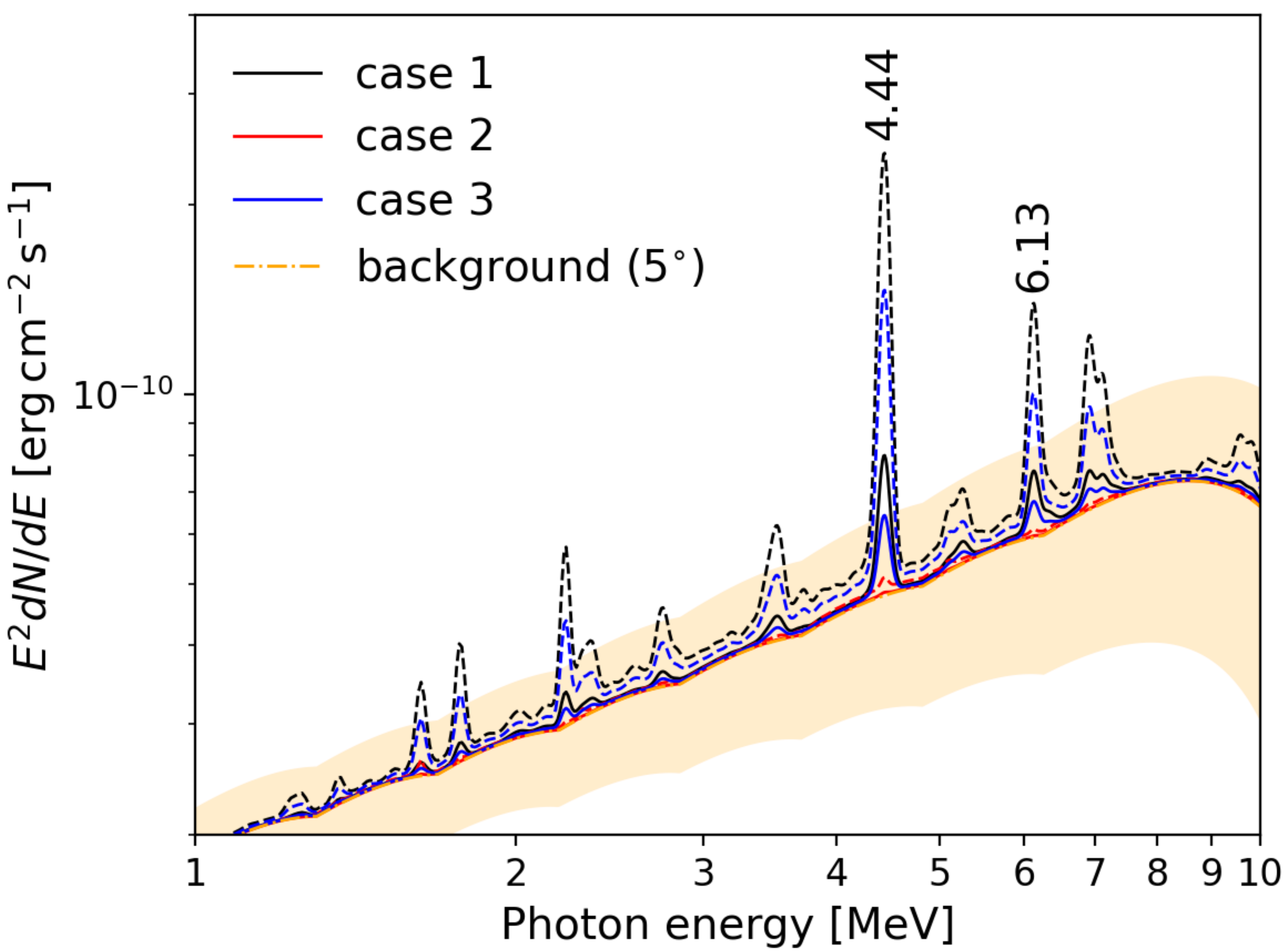


Zhang & Liu 2019

New estimation of the nuclear de-excitation line emission from SNR Cas A

Detectability of the next-generation MeV detectors:
angular resolution



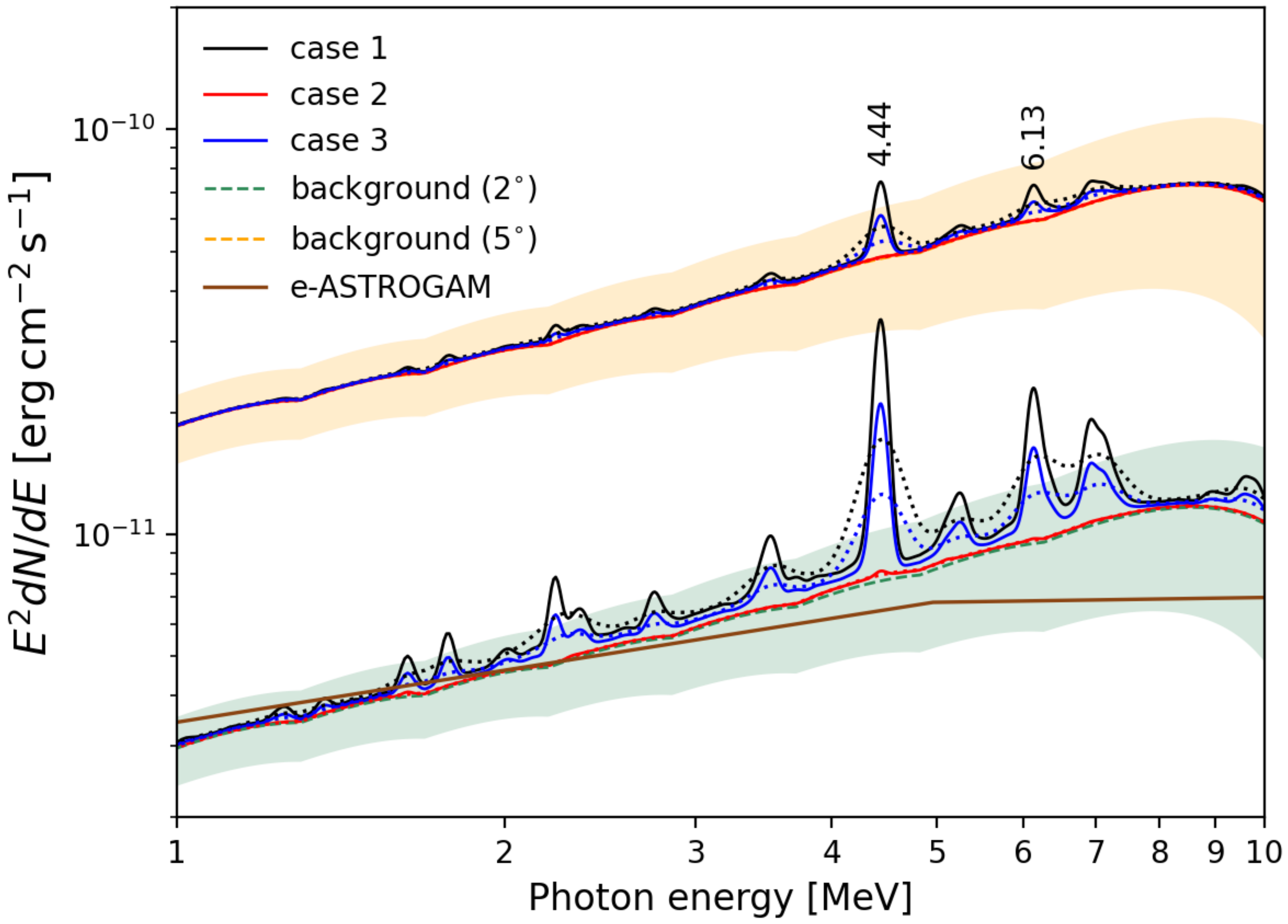


The overall MeV γ-ray emission from Cas A region with extrapolated diffuse background added.

solid lines $\alpha_1 = \alpha_2 = 2.7$, dotted lines : $\alpha_1 = \alpha_2 = 2.1$, dashed lines : $\alpha_1 = 2.7$, $\alpha_2 = 4.0$.

New estimation of the nuclear de-excitation line emission from SNR Cas A

Detectability of the next-generation MeV detectors: energy resolution



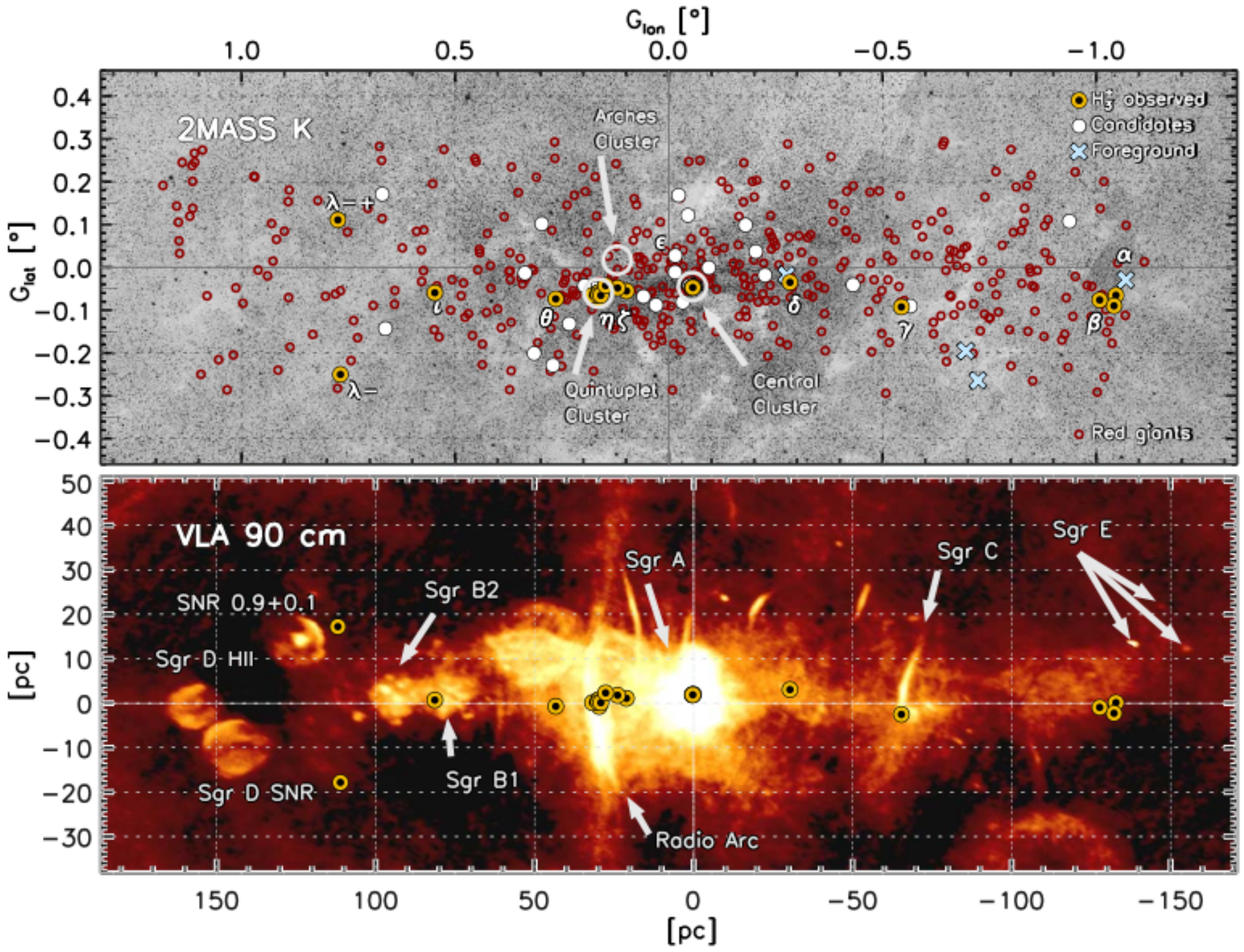
The overall MeV γ-ray emission from Cas A region with extrapolated diffuse background added ($\alpha_1 = \alpha_2 = 2.7$)

solid lines: $\Delta E/E$= 2%

dotted lines: $\Delta E/E$=10%

B. Liu, R.-z. Yang$*$, X.-y. He and F. Aharonian, 2023, MNRAS

Probe the LECRs in the center molecular zone (CMZ)



Oka et al. (2019)

Measured ionization rate in the CMZ :

Oka et al. 2019: ~ 2× 10^{-14} s^{-1}

Indriolo et al. 2015: ~ 10^{-14} s^{-1}

Le Petit et al. 2015 ~ >= 10^{-14} s^{-1}

- Origin of the high ionization rate: LECR proton, electron.. ? Additional component of LECRs may be needed
- Local LECR accelerators: star clusters, star-forming region, MBH, protostellar winds/jets
- PSF of next-generation of MeV telescope (MeGaT) ~2°, the CMZ region can be seen as a point-like source.

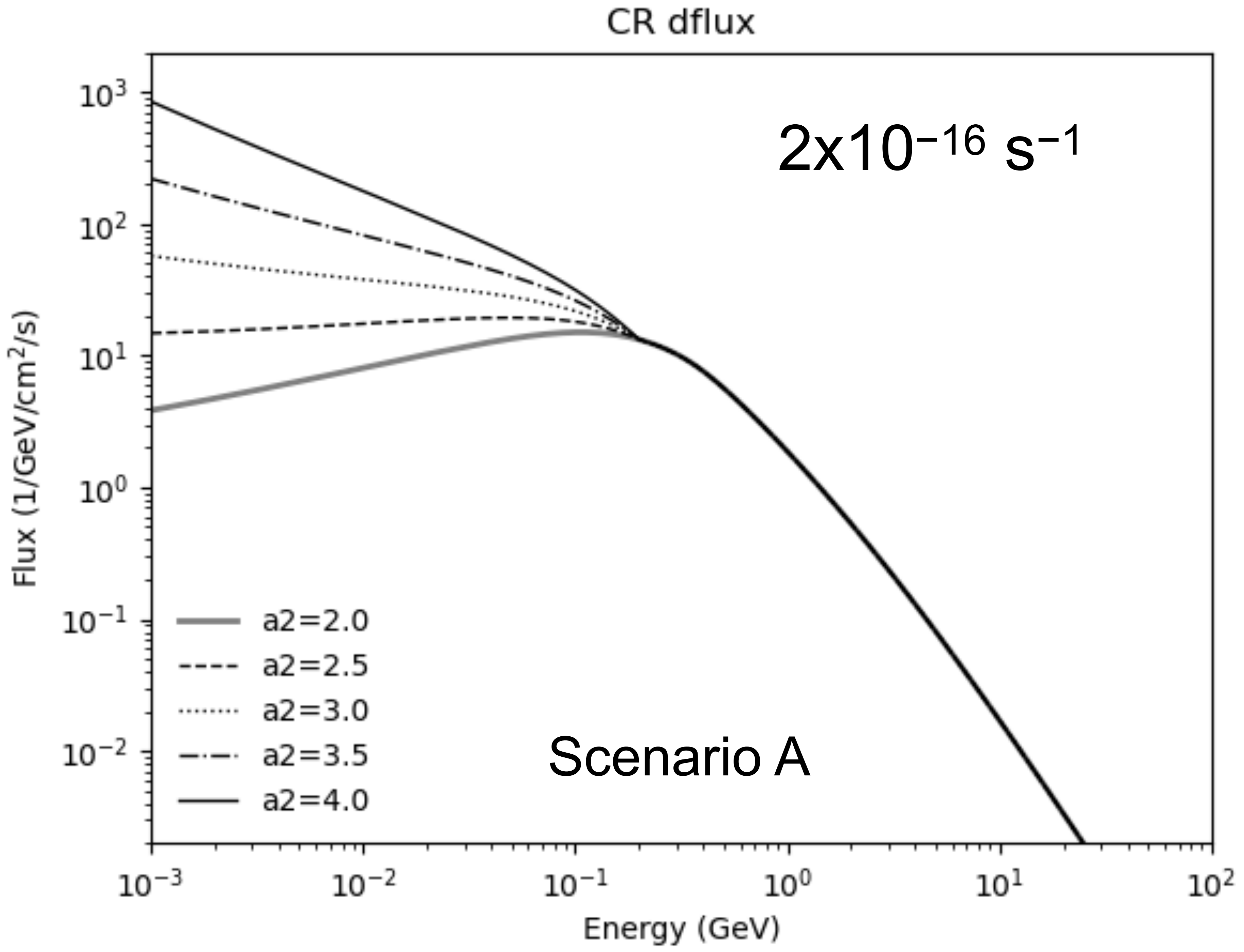
Probe the LECRs in the center molecular zone (CMZ)

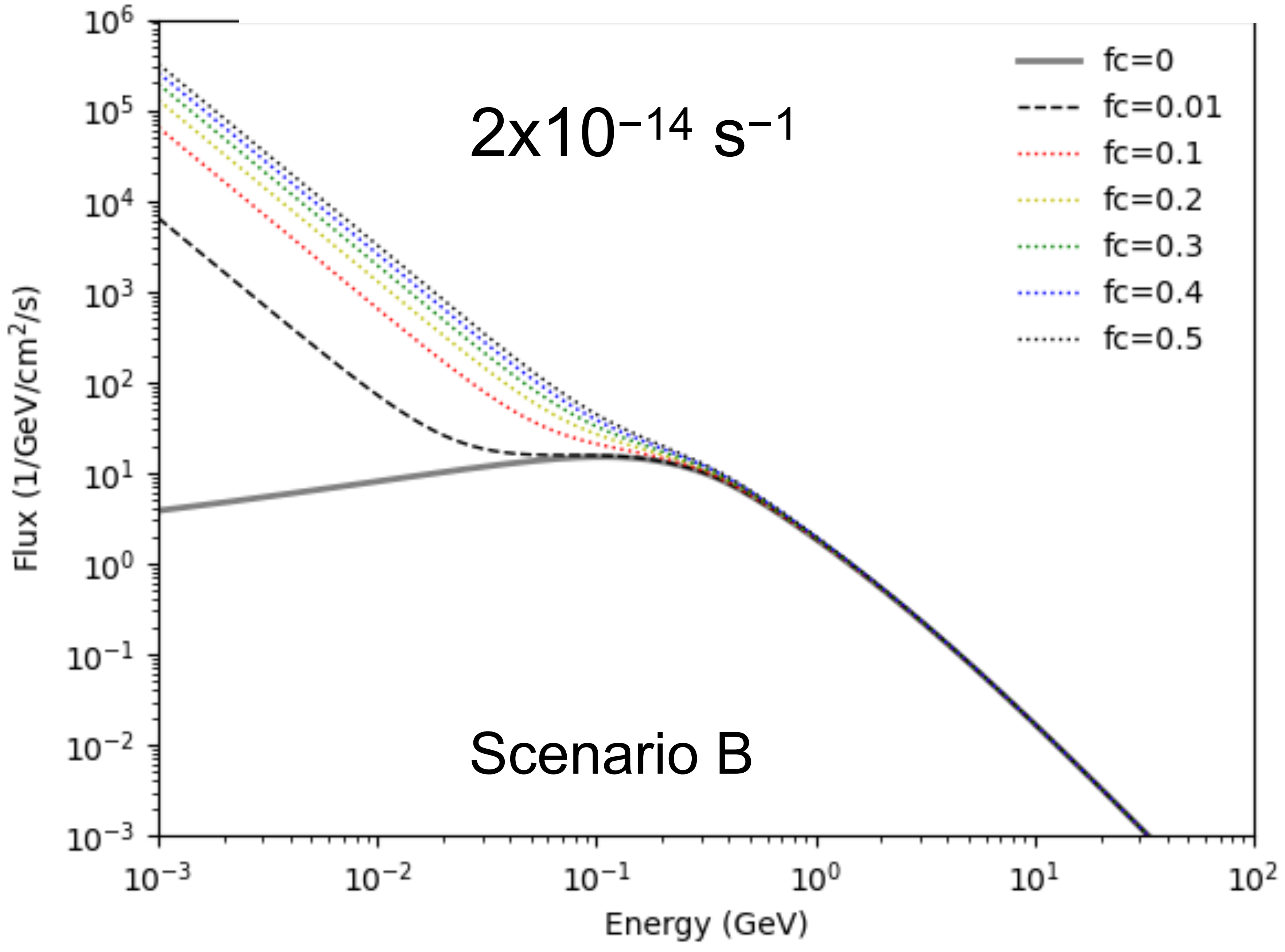
Scenario A: continuous injection $Q_{\rm in}$ (piecewise power-law distribution, $E_{\rm b}$ = 0.2 GeV, α1 = 2.0, and α2 =2.0, 2.5, 3.0, 3.5, and 4.0)

Scenario B: continuous injection $Q_{\rm in}$ (simple power-law distribution, α1 = α2 = 2.0) and a local carrot component $Q_{\rm c}(E)$ (α = 4, $E_{\rm cut}$ =1, 2, 4, and 10 MeV, $f_{\rm c}$ for different enhancements of LECRs)

$$Q_{\rm in}(E) = \begin{cases} Q_0 \left[\frac{p(E)}{p(E_{\rm b})}\right]^{-\alpha_1}, & \text{if } E \geq E_{\rm b} \\ Q_0 \left[\frac{p(E)}{p(E_{\rm b})}\right]^{-\alpha_2}, & \text{if } E < E_{\rm b} \end{cases}.$$

$$Q_{\rm c}(E) = \begin{cases} f_{\rm c} Q_{\rm lb}(E_{\rm b}) \left[\frac{p(E)}{p(E_{\rm b})}\right]^{-\alpha}, & \text{if } E \geq E_{\rm cut} \\ 0, & \text{if } E < E_{\rm cut} \end{cases}.$$

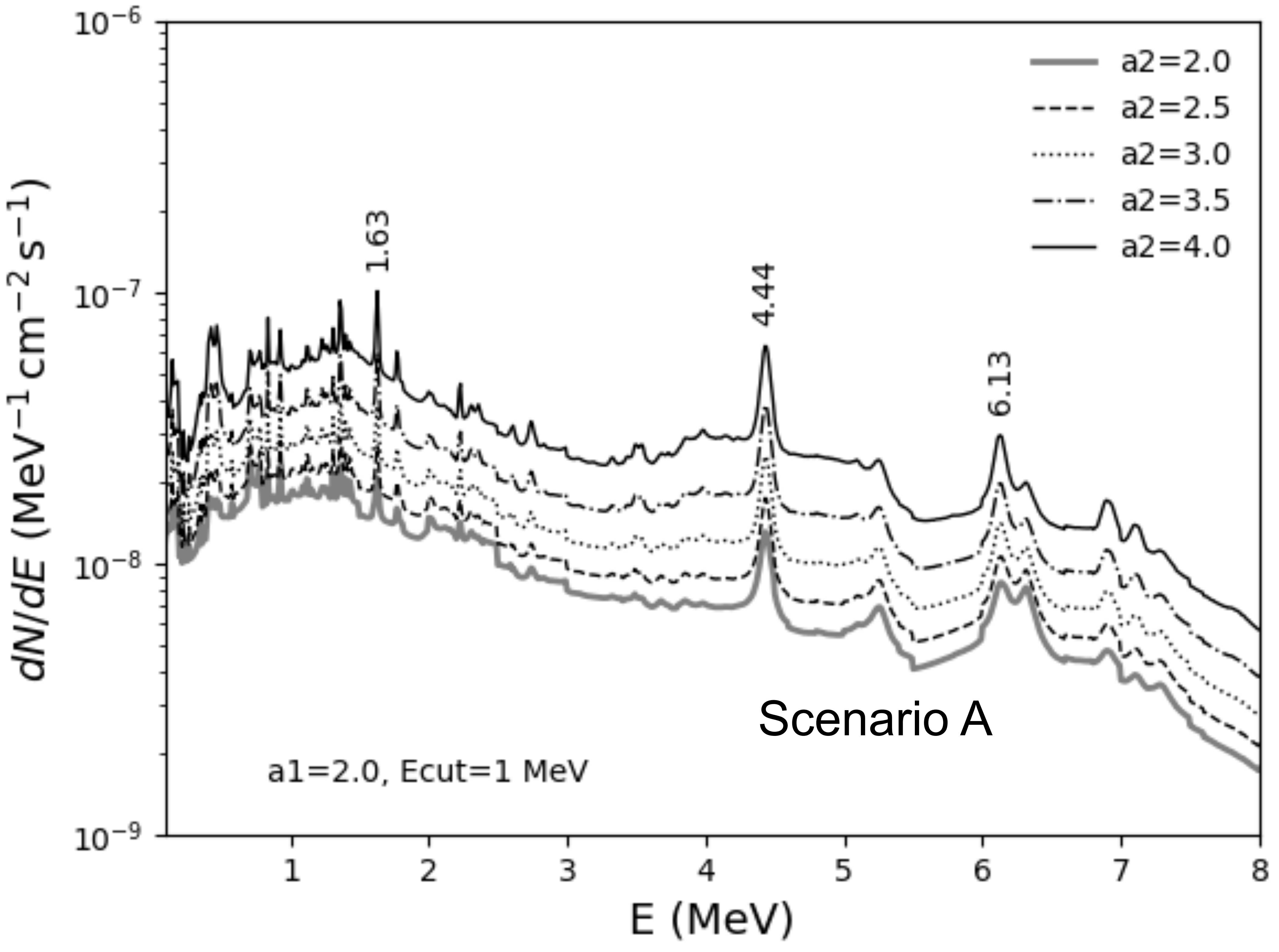


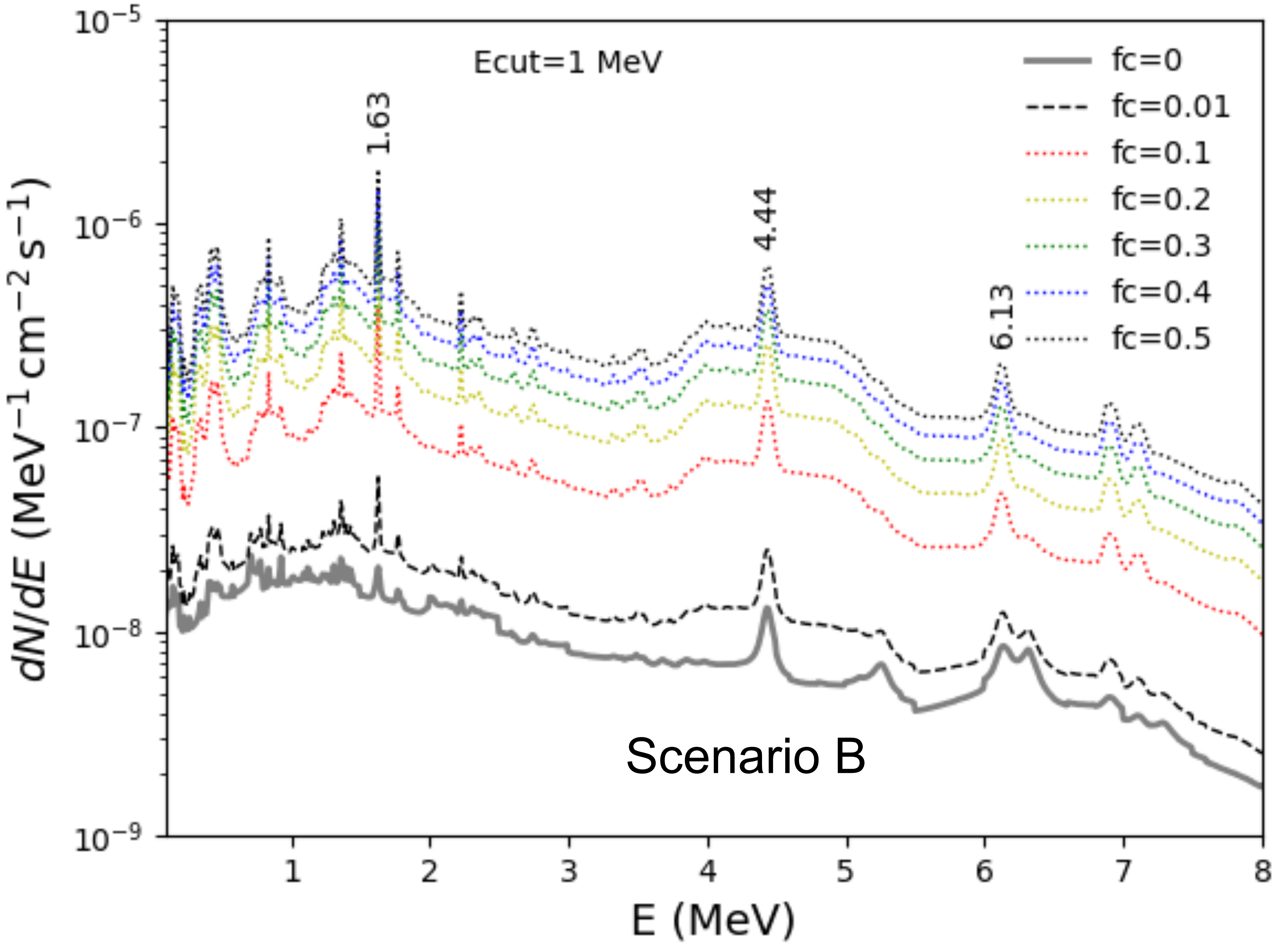


B. Liu & R.-z. Yang (to be submitted)

Probe the LECRs in the center molecular zone (CMZ)

Estimated MeV nuclear de-excitation line emission for different scenarios

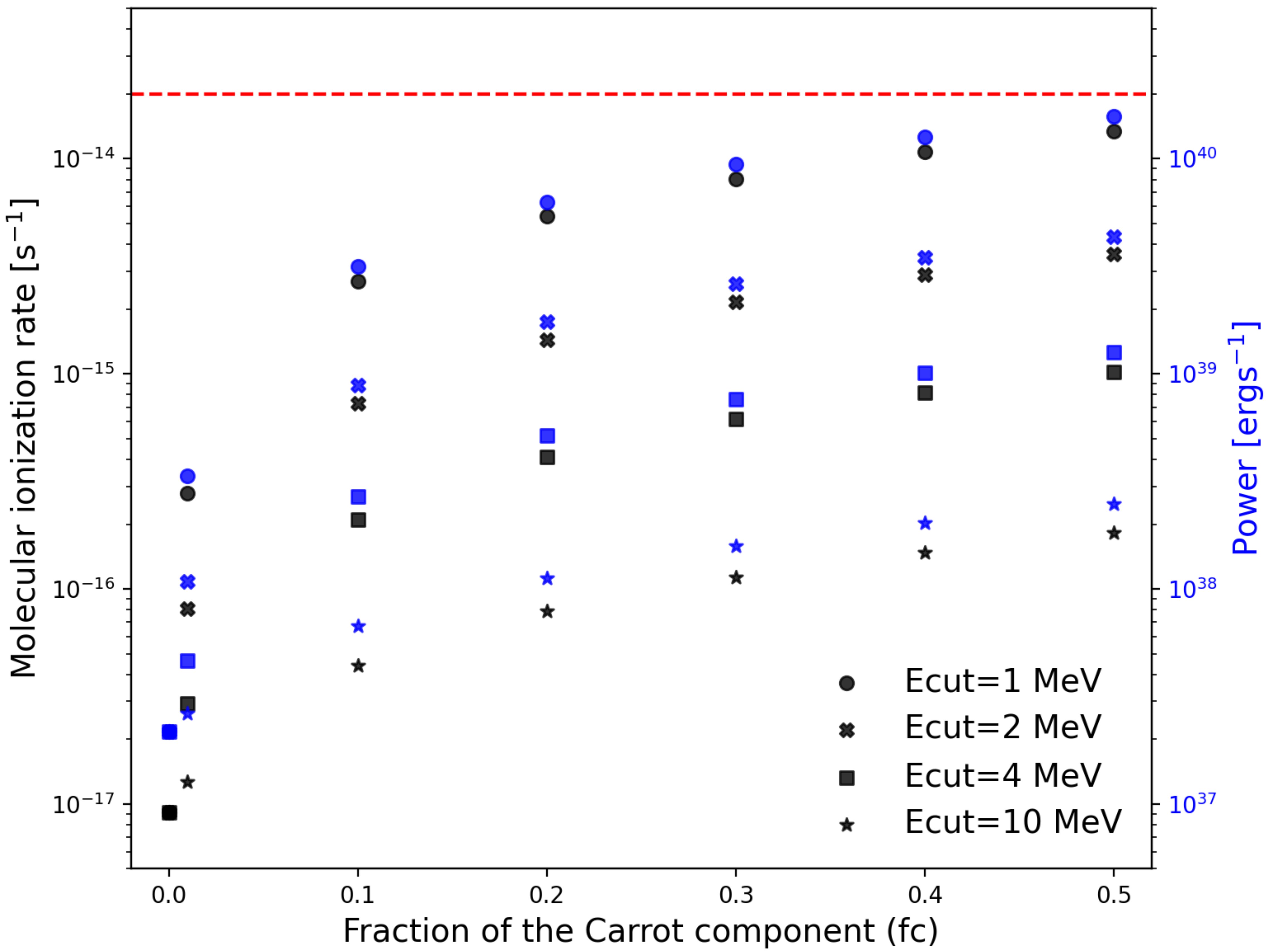


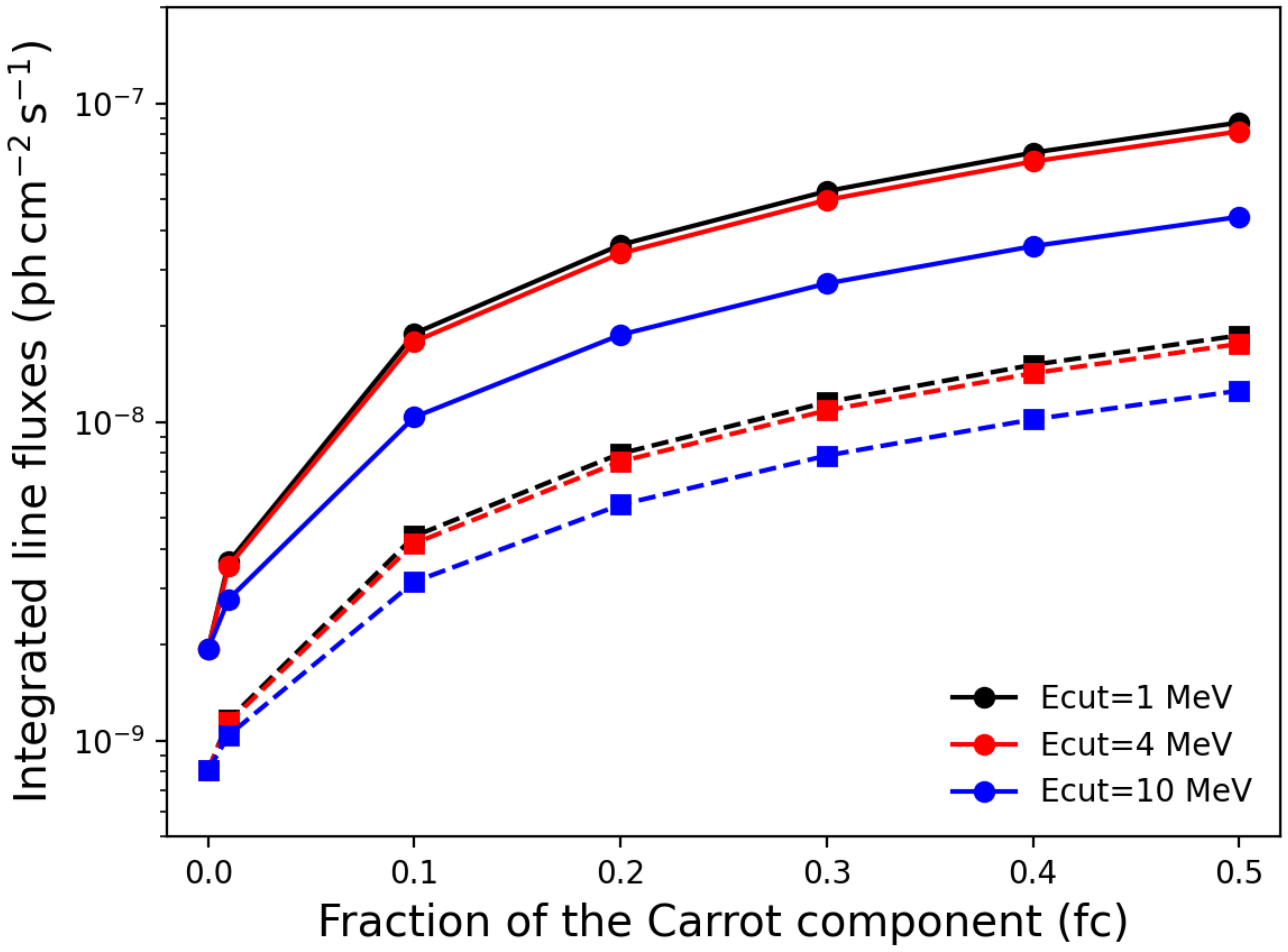


B. Liu & R.-z. Yang (to be submitted)

Probe the LECRs in the center molecular zone (CMZ)

Ionization rate, power and integrated line fluxes for additional LECR component (Carrot)

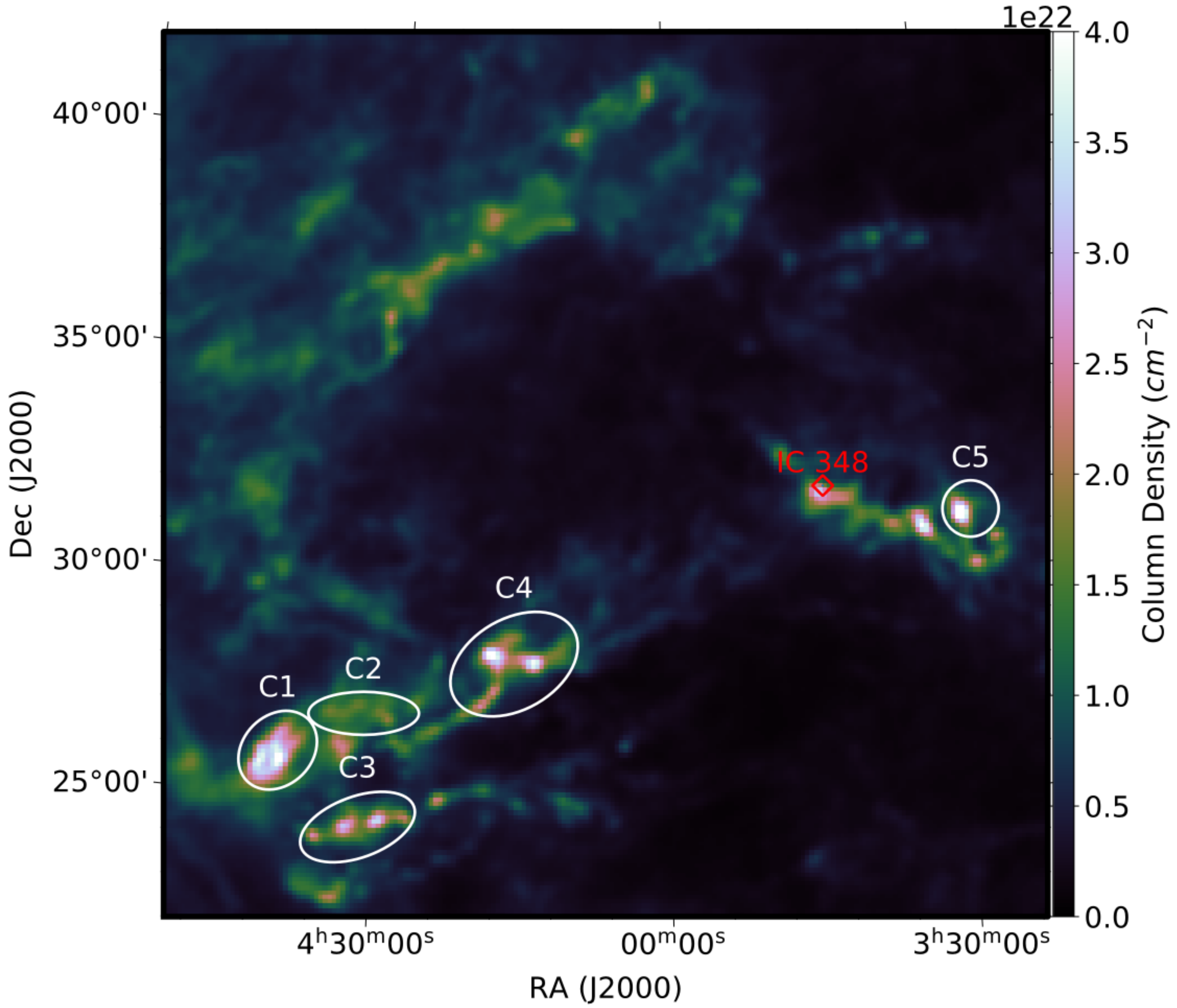




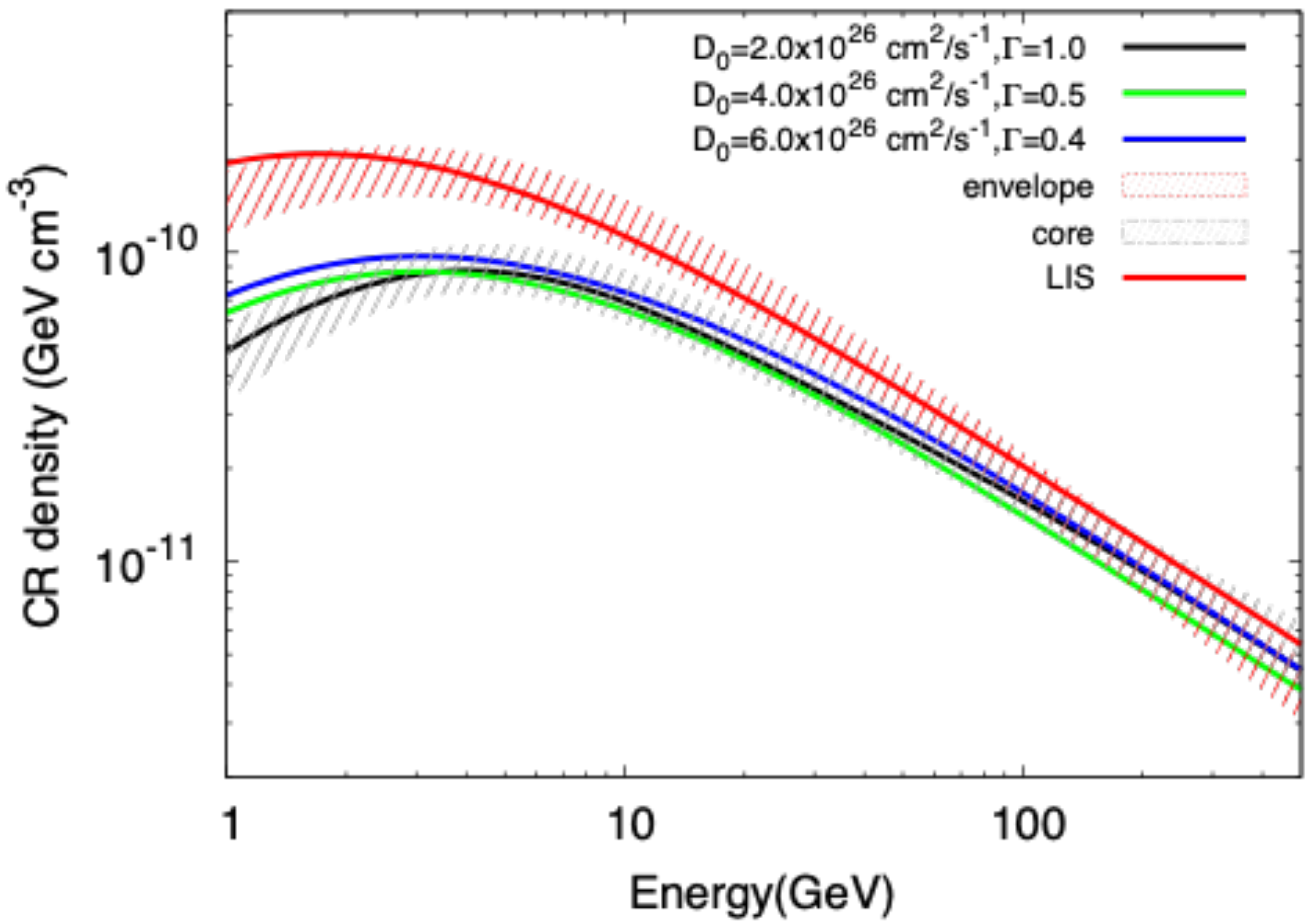
B. Liu & R-z Yang (to be submitted)

Study the propagation of CRs in giant molecular clouds (GMC)

Effective shielding of $\lesssim$10 GeV cosmic rays from dense molecular clumps (Yang et al. 2023, NA)



The total column density (in units of cm^{-2}) distribution of Taurus and Perseus molecular clouds, derived from the Planck dust opacity map.



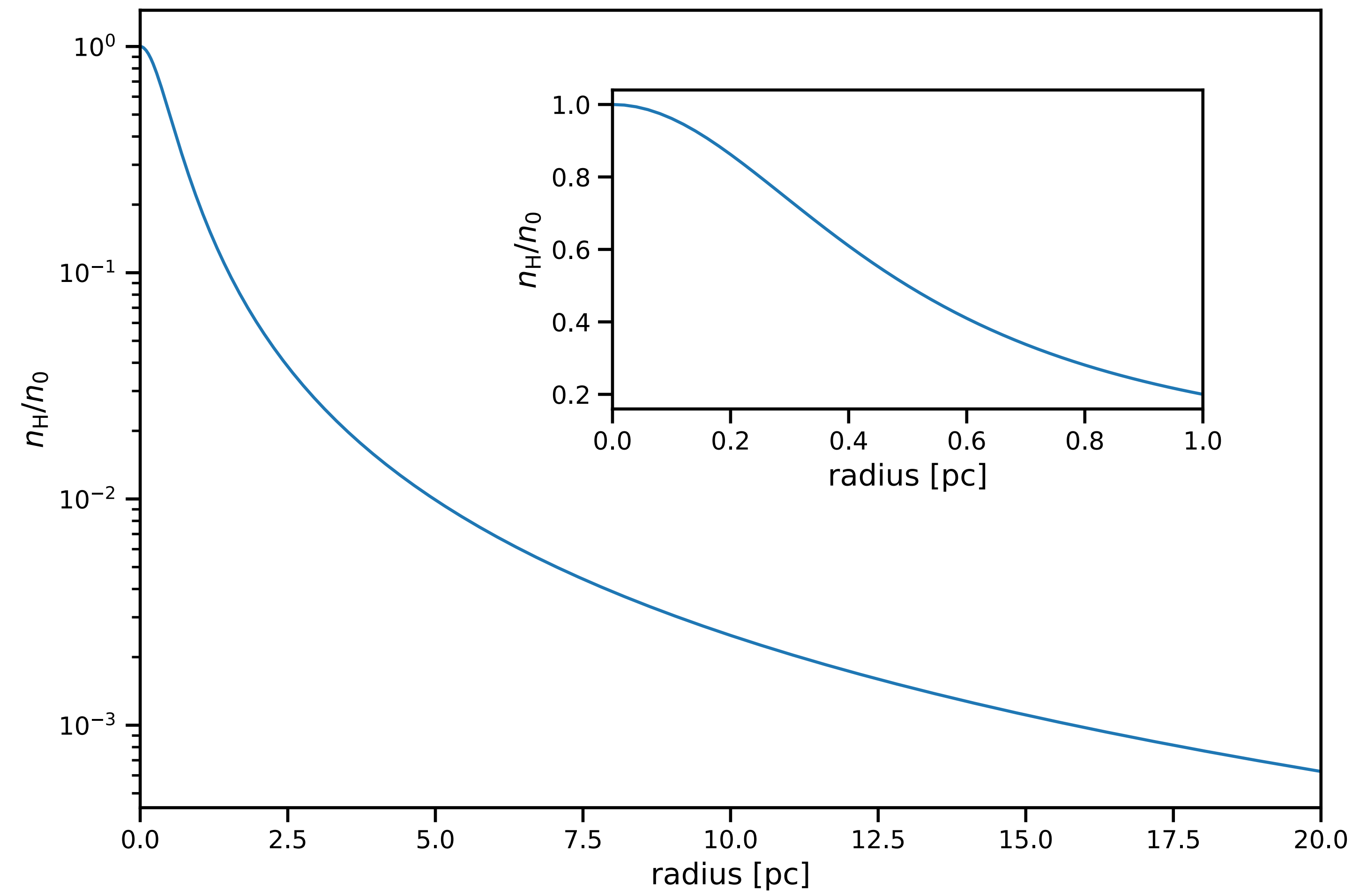
The derived CR energy density distribution.

Much slower diffusion (~10^{26} cm^2/s) of CR protons in dense cores comparing to that in ISM (4e28 cm^2/s).

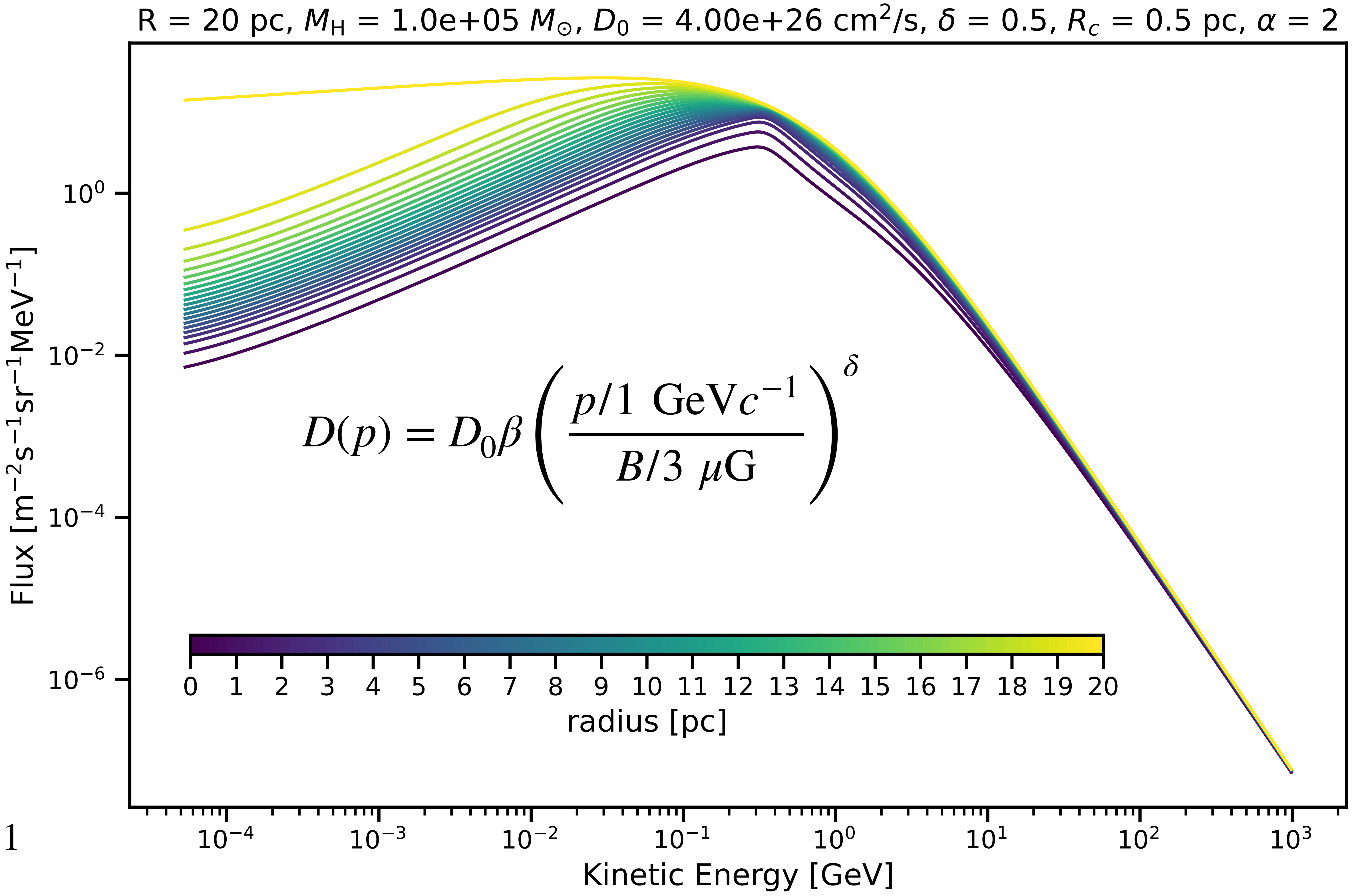
Study the propagation of CRs in giant molecular clouds (GMC)

Assumptions for the calculation of CR spectra in GMC (no inside CR source)

$$n_{\rm H} = n_{\rm HI} + 2n_{\rm H_2} = \frac{n_0}{1 + (r/R_{\rm c})^{\alpha}} \qquad B = 10\left(\frac{n_{\rm H}}{300{\rm cm^{-3}}}\right)^{1/2}\mu{\rm G}$$



$$j_{\rm LIS}(E_{\rm k}) = 2.70\frac{E_{\rm k}^{1.12}}{\beta^2}\left(\frac{E_{\rm k}+0.67}{1.67}\right)^{-3.93} \quad {\rm m^{-2}s^{-1}sr^{-1}MeV^{-1}}$$

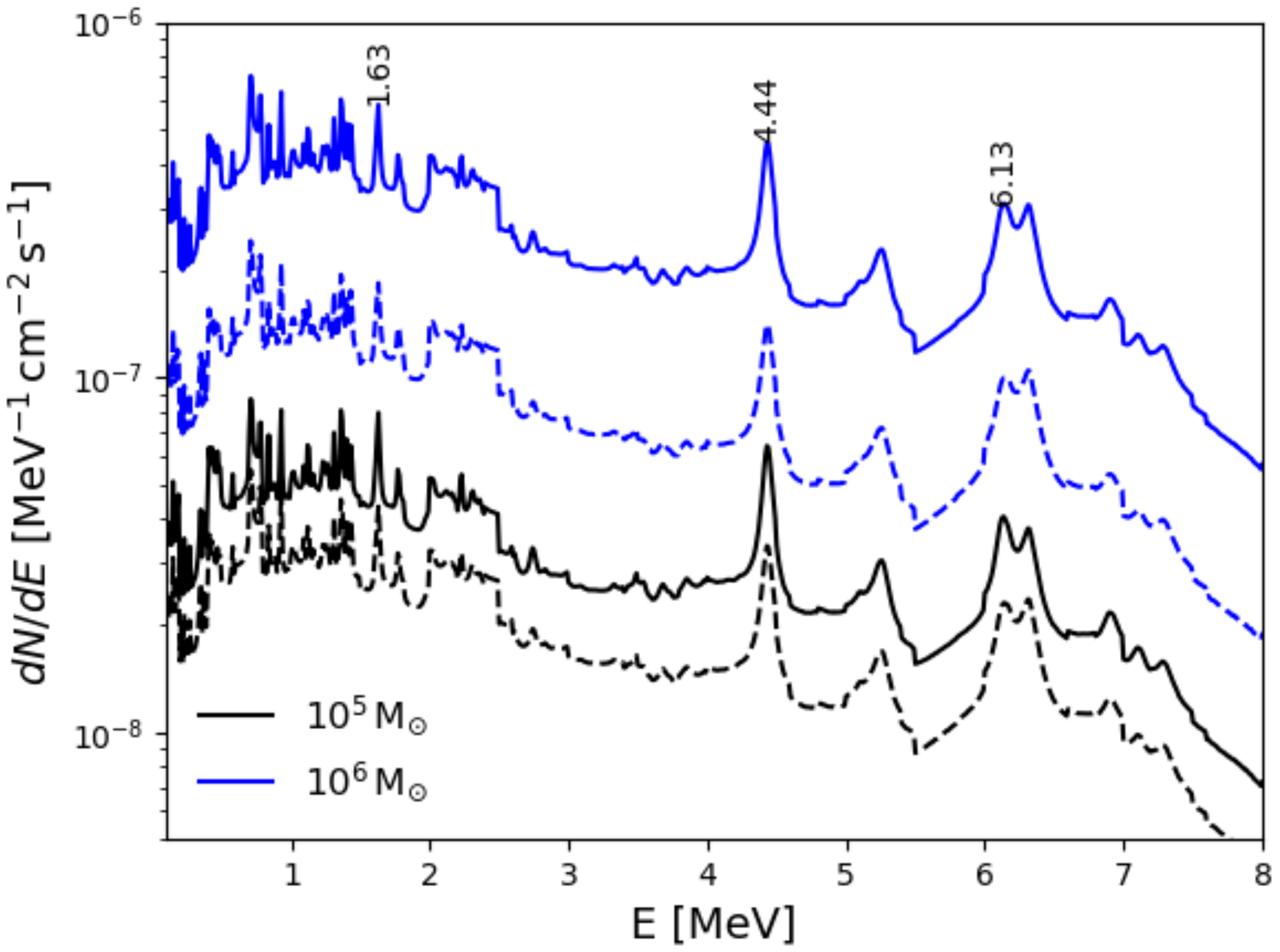


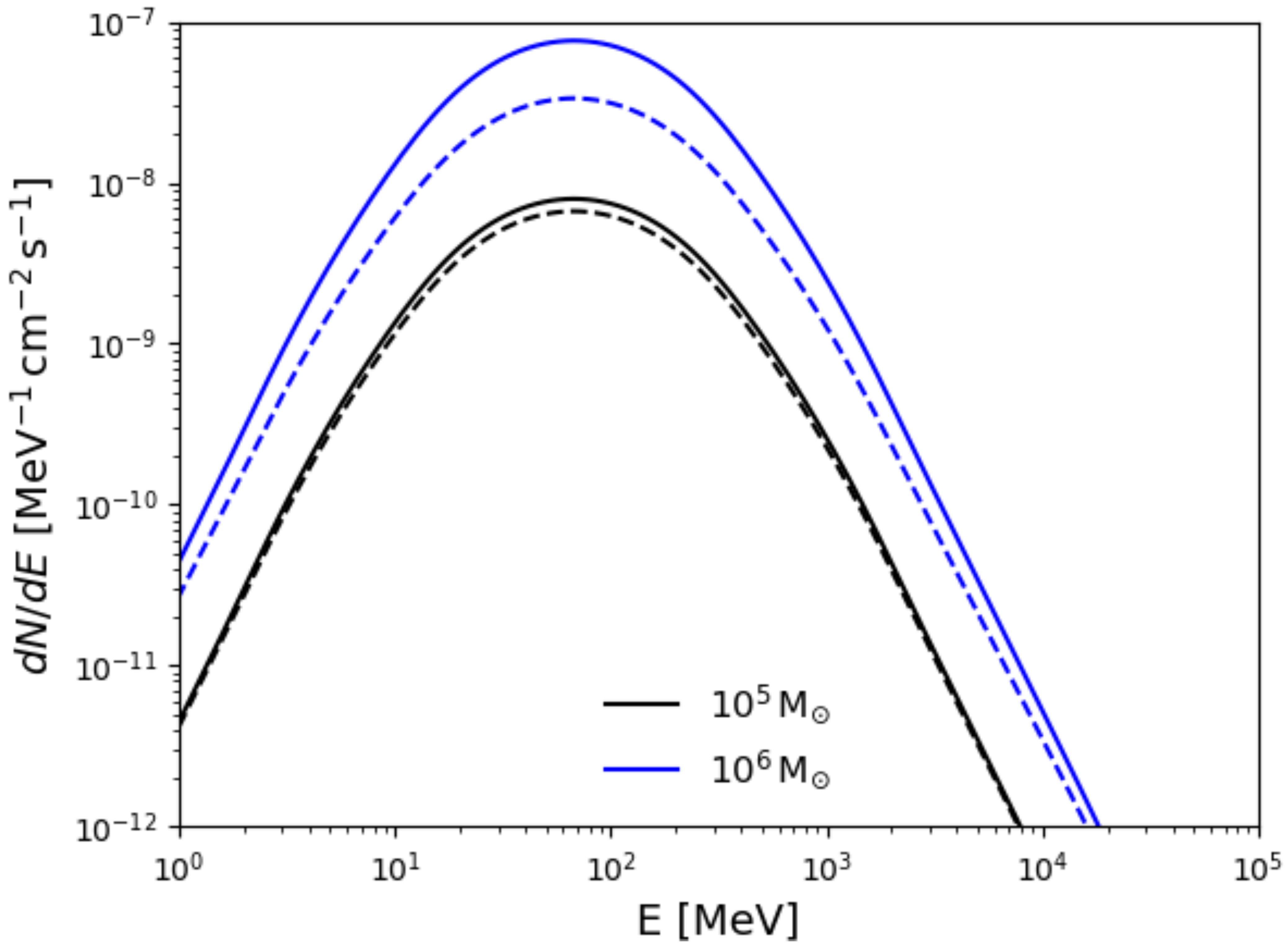
$$D(p) = D_0\beta\left(\frac{p/1\ {\rm GeV}c^{-1}}{B/3\ \mu{\rm G}}\right)^{\delta}$$

Z.-d. Shi, B. Liu & R.-z. Yang (A&A 692,128)

Study the propagation of CRs in giant molecular clouds (GMC)

Calculated MeV nuclear de-excitation line emission and pion-decay continuum emission

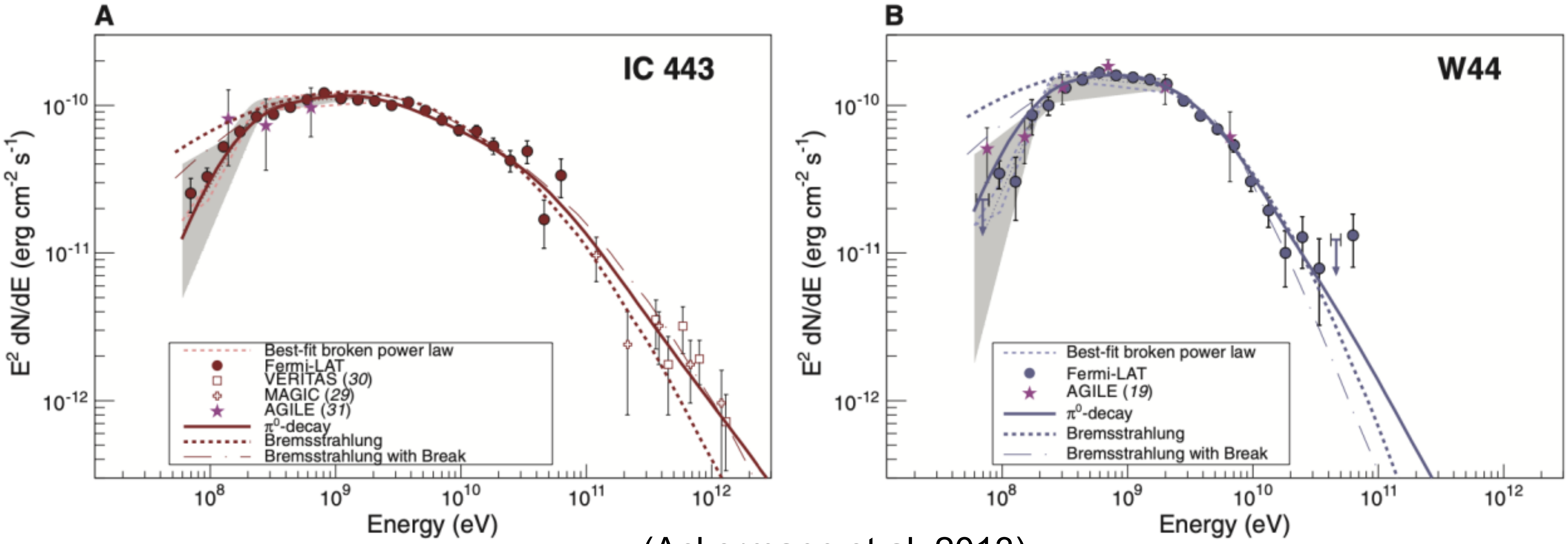




Z.-d. Shi, B. Liu & R.-z. Yang (preliminary results)

Precise measurement of pion-bump structure (in the case of W44)

“pion-bump” as the direct evidence of CR proton acceleration



(Ackermann et al. 2013)

Fermi-LAT observed pion-bump structure from SNRs, but the results are controversial.

Precise measurement of pion-bump structure (in the case of W44)

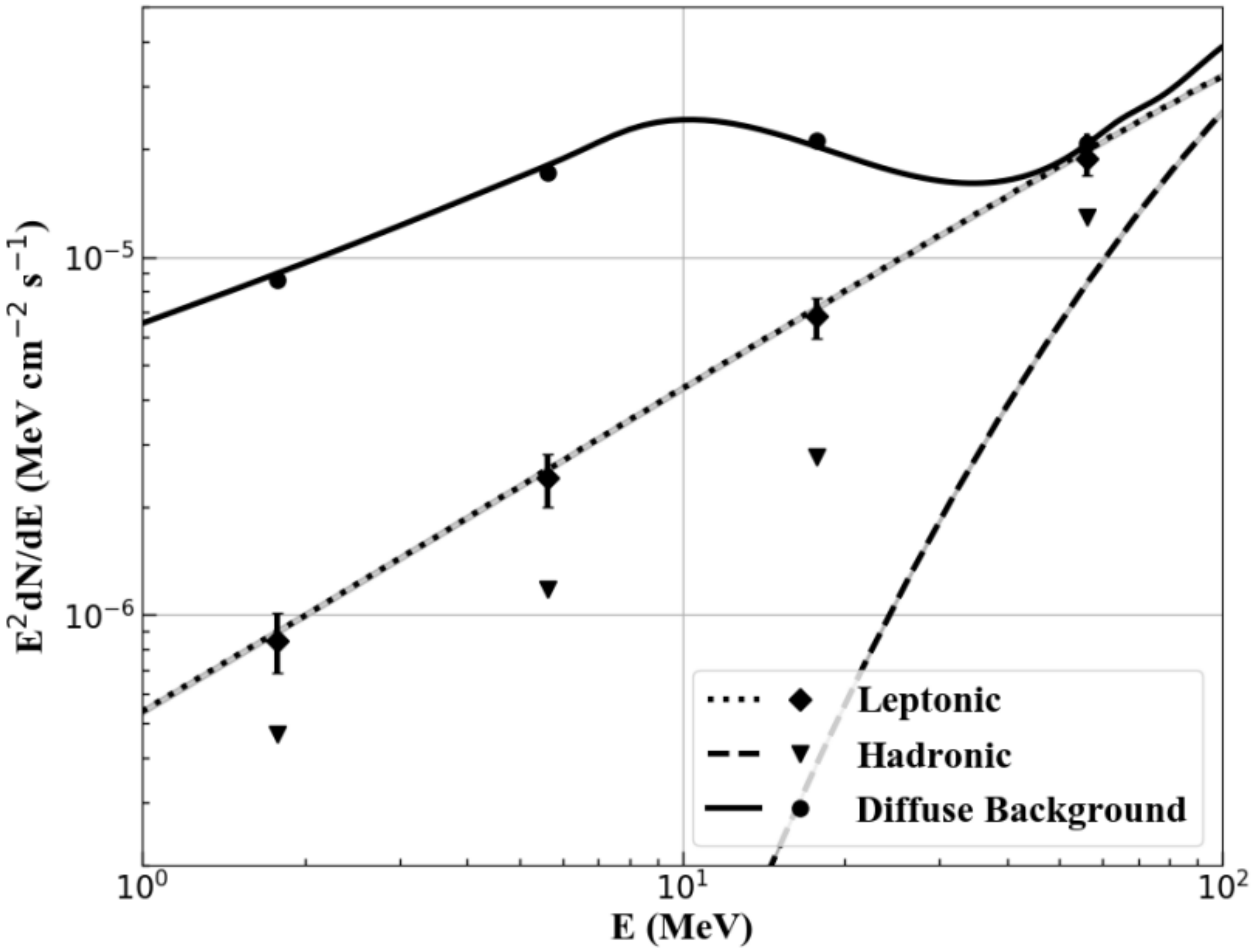
$A_{\rm eff} = 100\ {\rm cm}^2$, Angular resolution : 1°, $T_{\rm obs} = 2$ month

$$N_{\rm counts} = \int_{E_{\rm lower}}^{E_{\rm upper}} F(E) T_{\rm obs} A_{\rm eff}(E) dE$$

$$\sigma = \sqrt{N_{\rm total}} = \sqrt{N_{\rm signal} + N_{\rm bkg}}$$

$$S = \frac{N_{\rm signal}}{\sqrt{N_{\rm signal} + N_{\rm bkg}}}$$

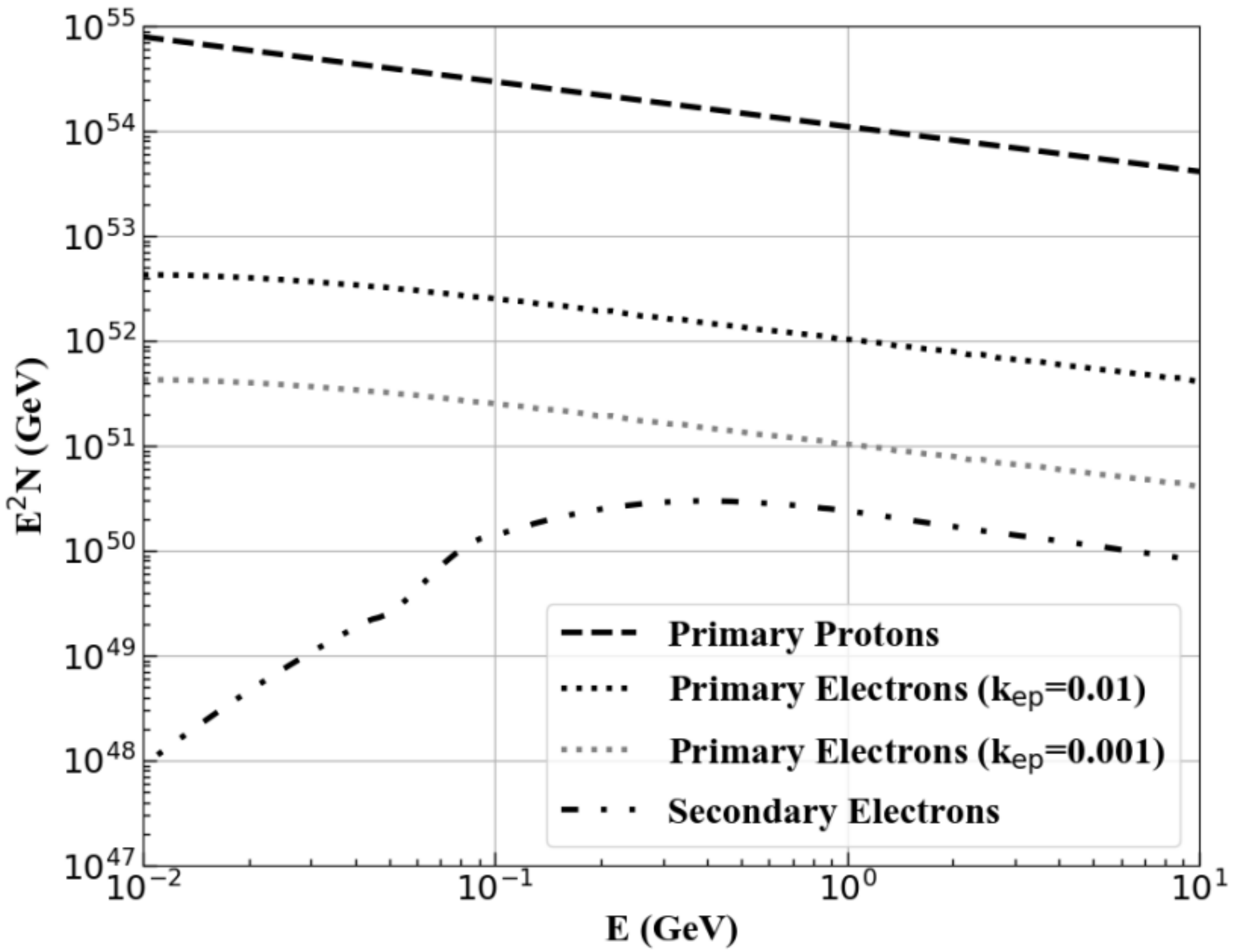
log(E/MeV)	$N_{\rm signal}$	$N_{\rm bkg}$	S (σ)
0.0-0.5	306	3099	5.24
0.5-1.0	274	1954	5.80
1.0-1.5	245	763	7.72
1.5-2.0	213	236	10.05

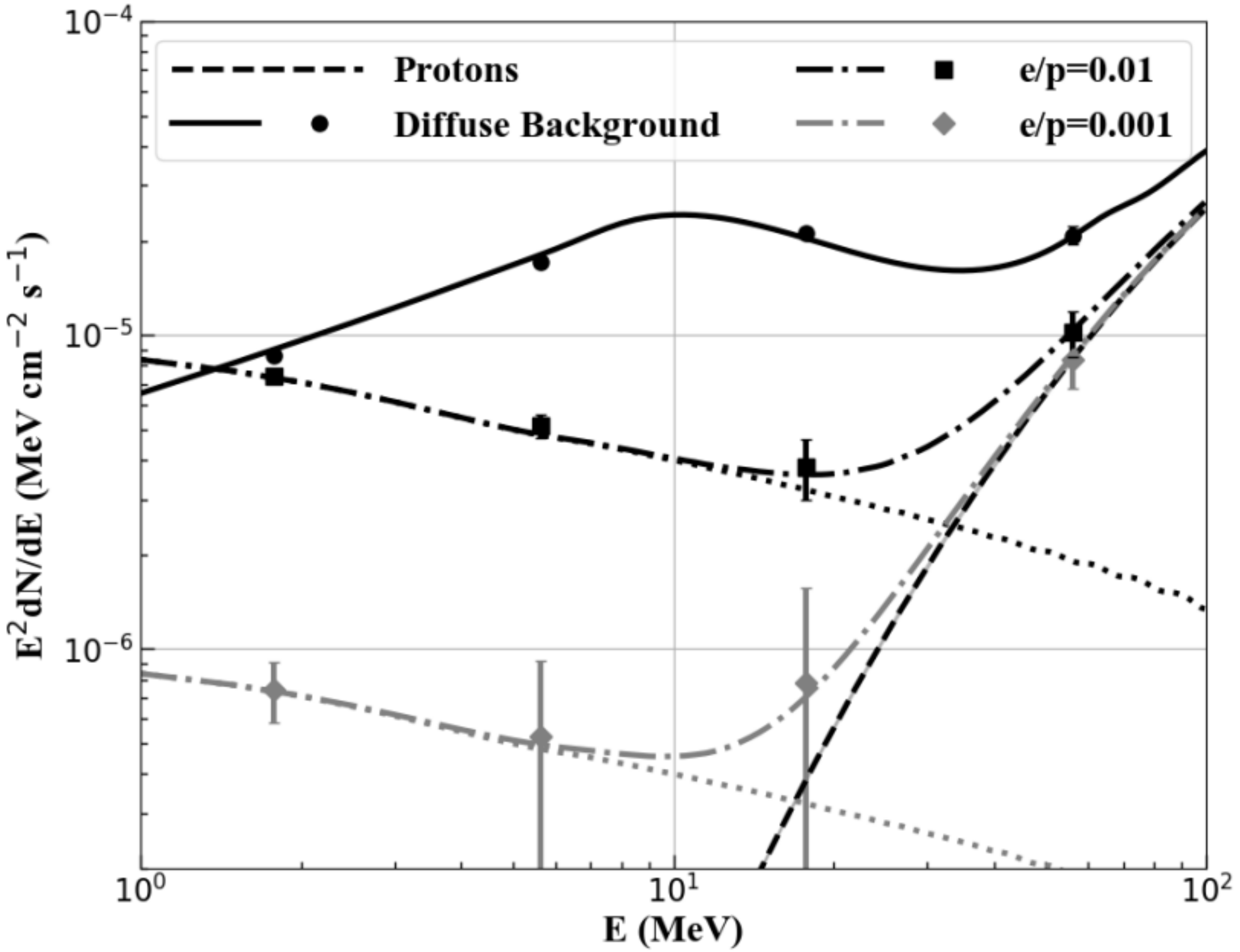


J.-h. Liu, B. Liu & R.-z. Yang, PRD（2024）

Precise measurement of pion-bump structure (in the case of W44)

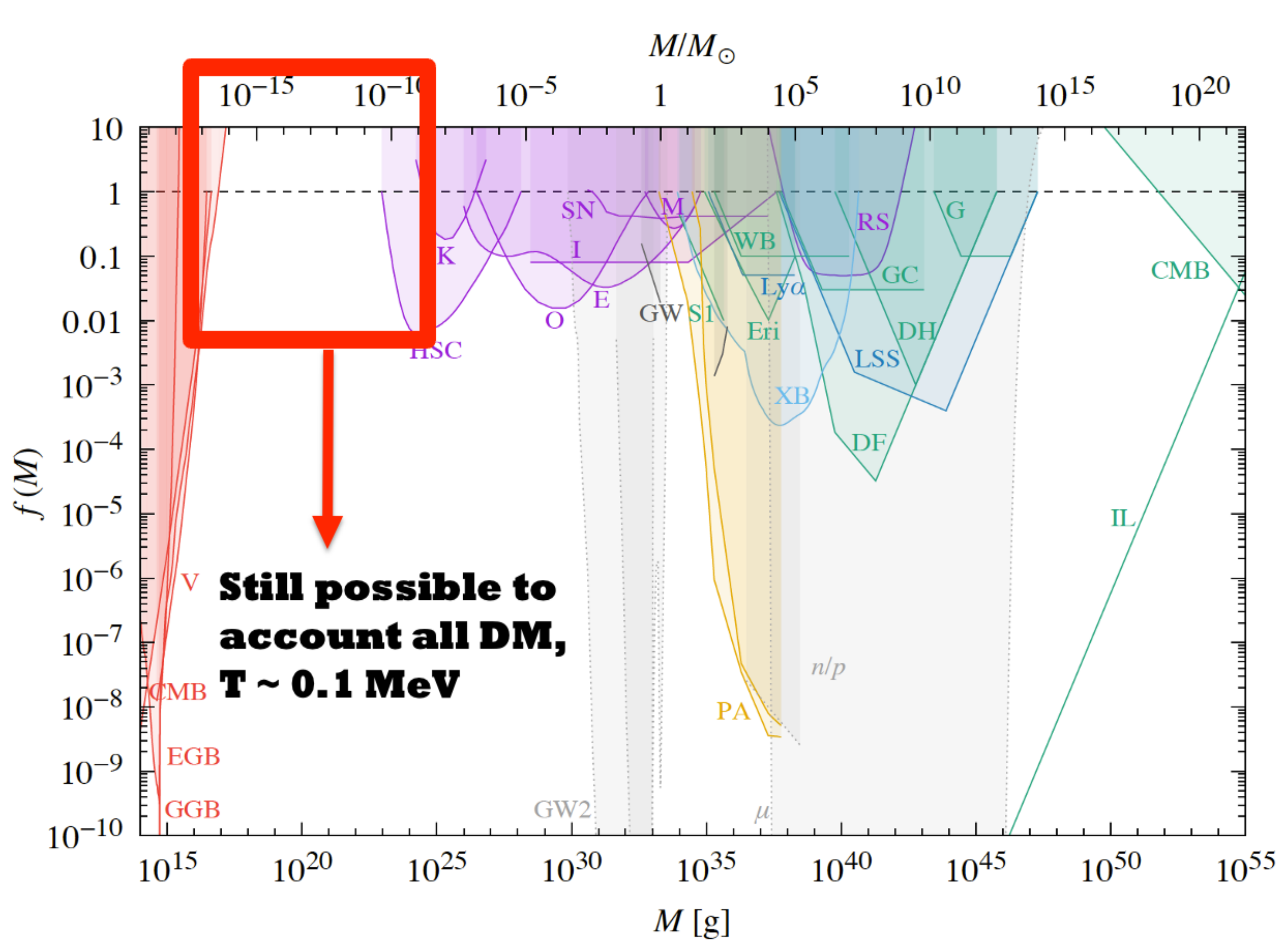
Limit e/p ratio via MeV observation

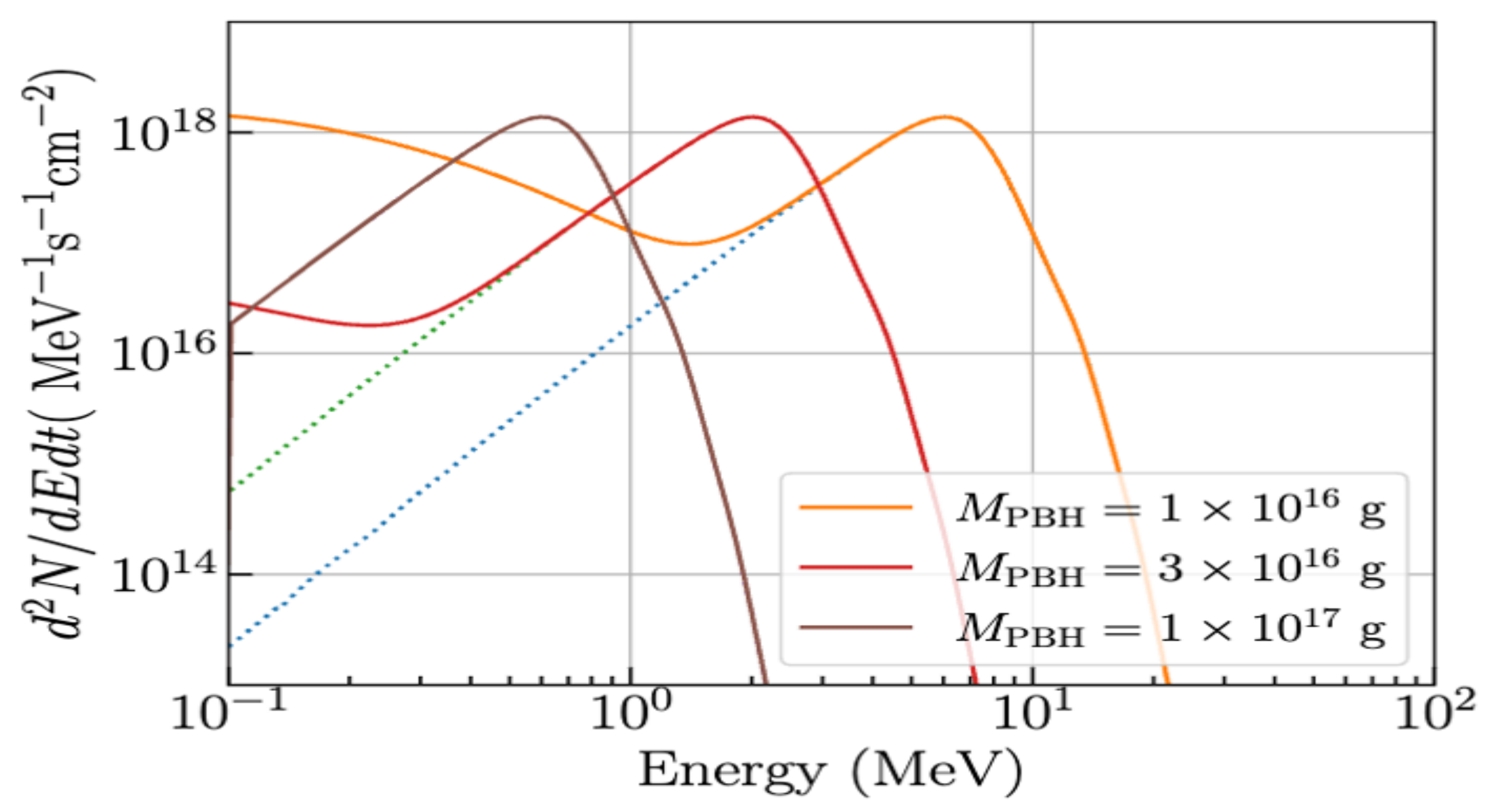


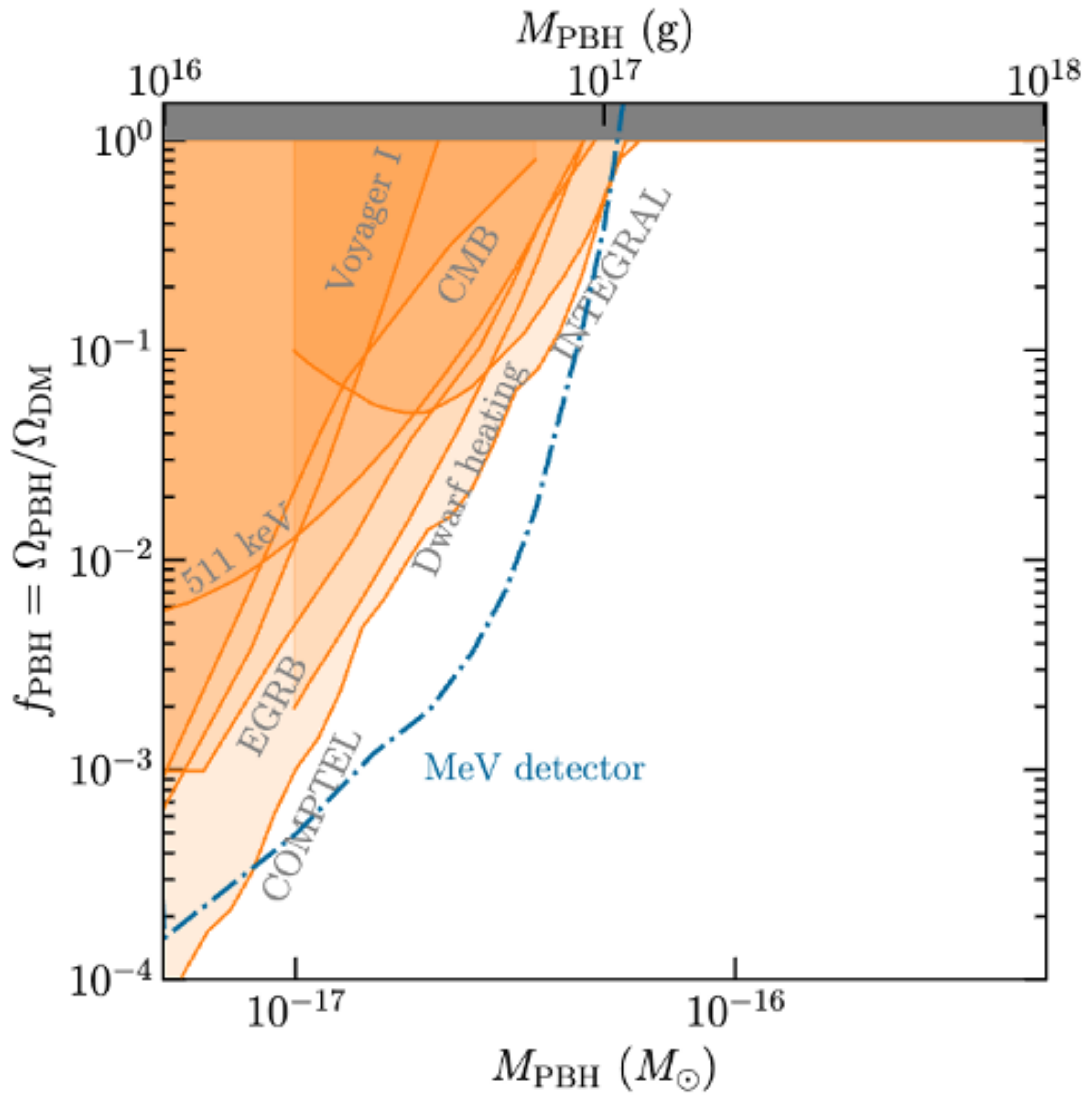


J.-h. Liu, B. Liu & R.-z. Yang, PRD（2024）

Dark Matter (Primoldial black holes)

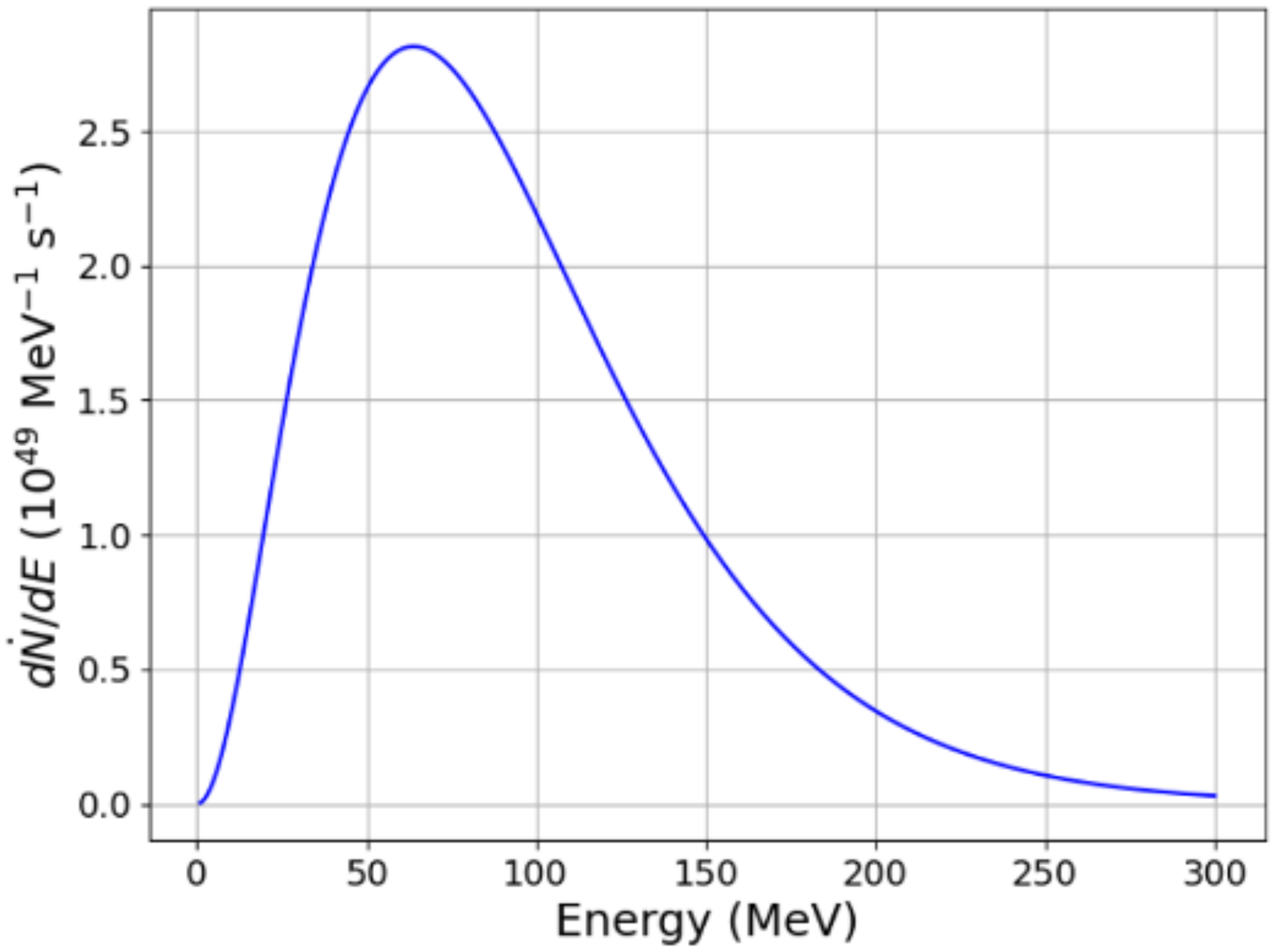




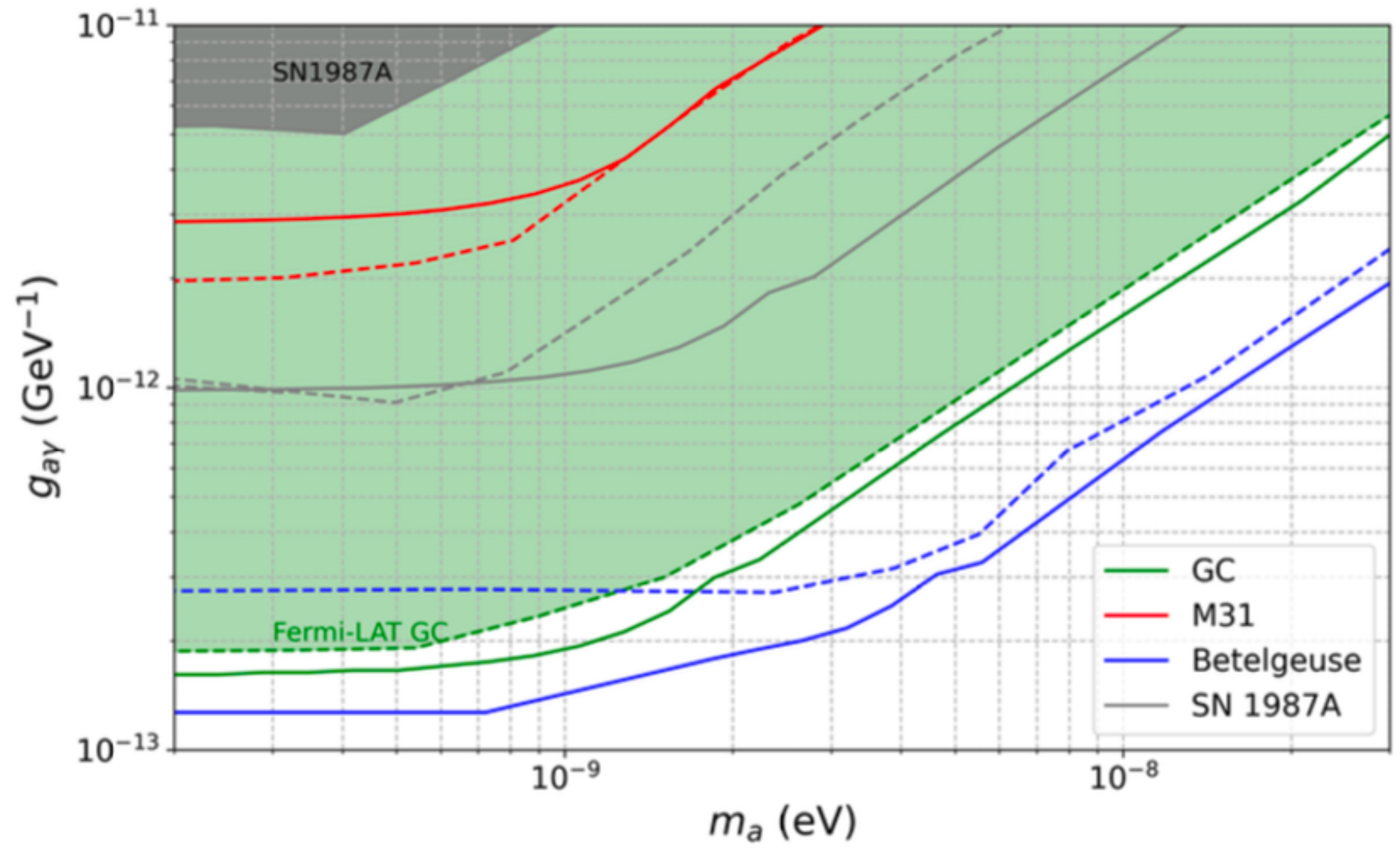


MeVGro Type detectors can set more stringent upper limit
Xie, et.al PRD (2023)

Dark Matter (Axion from SNe)



Intergrated ALP intensity in the first 10s of SNe

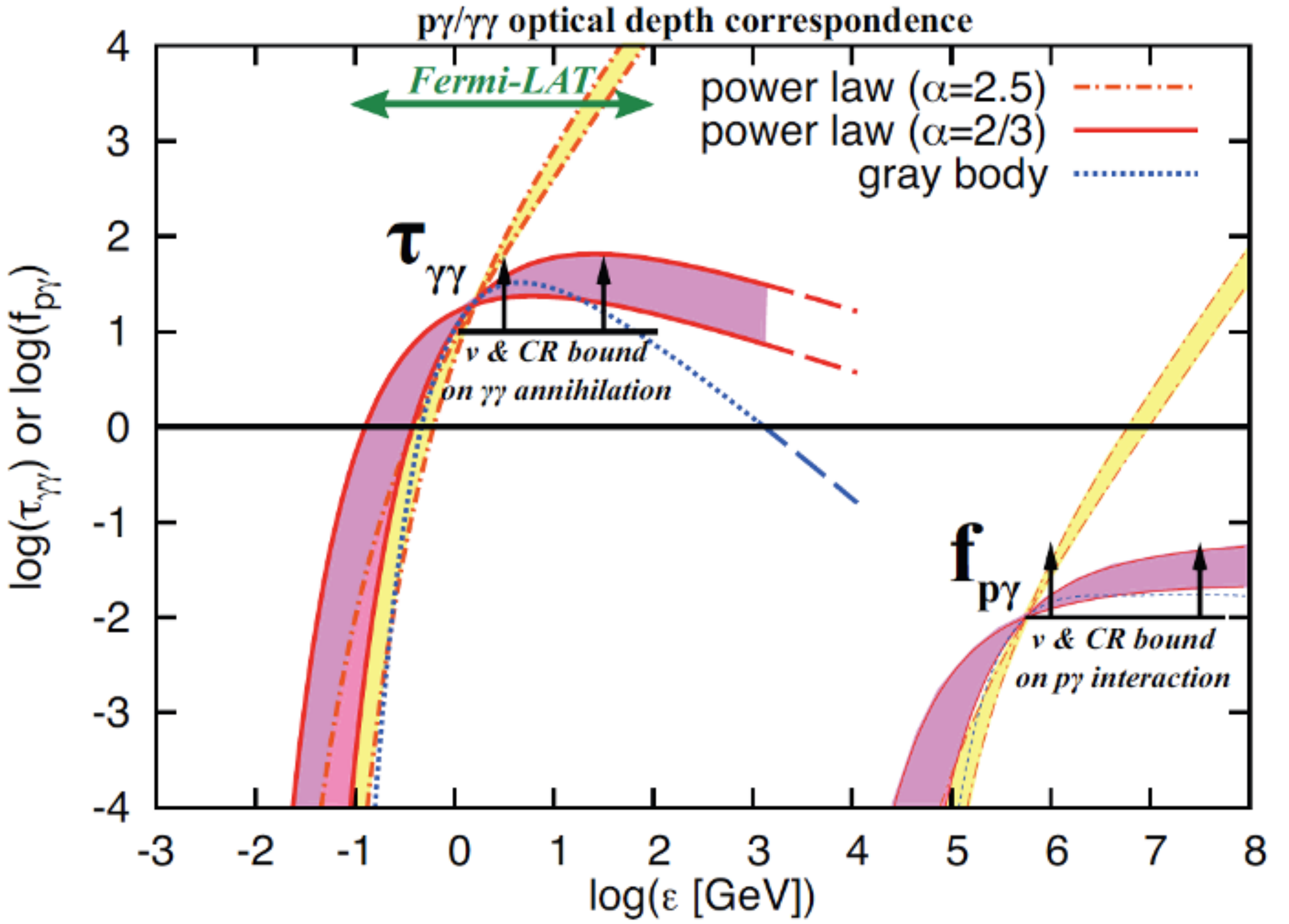


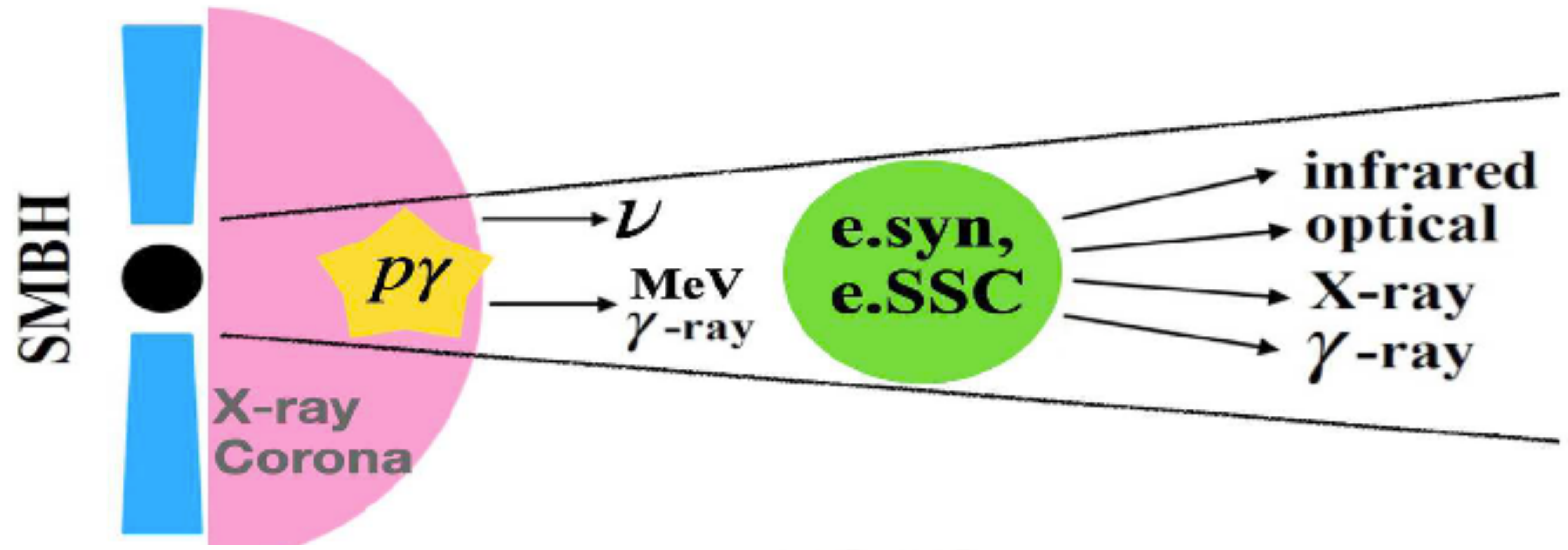
Detectability of future MeV instruments
Xie et.al CPC (2025)

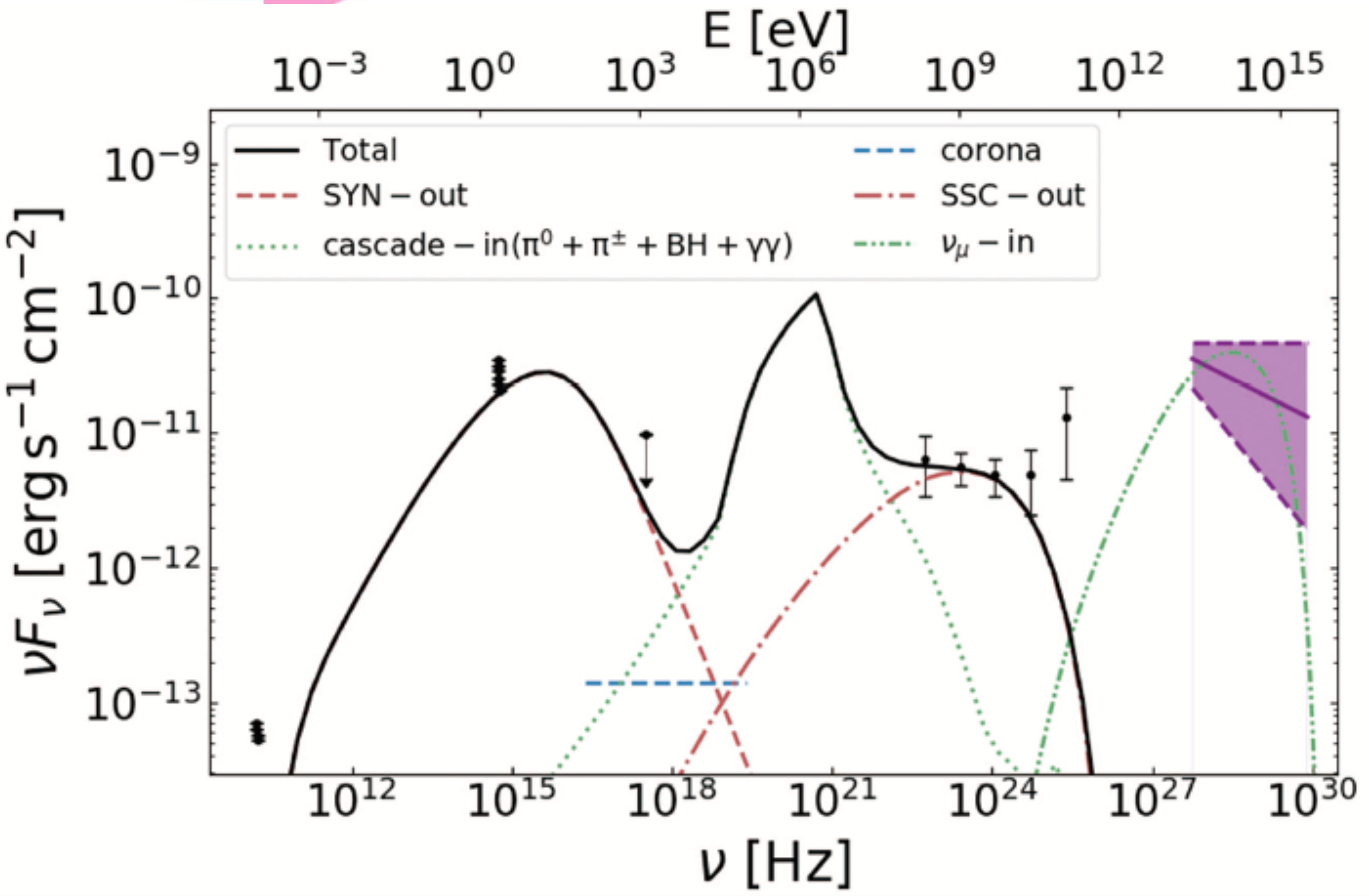
Neutrino sources

- **Neutrinos sources are probably dark in gamma-rays above GeV**
- **The associated electromagnetic cascade will have SEDs peaked at MeV**

Inuoe et.al 2019, Xue et.al 2021, Murase et.al 2015







MeV Gamma-ray Telescope Mission (MeGaT)

TPC+CdZnTe Calarimeter

➢30×30×30cm^3 proton type

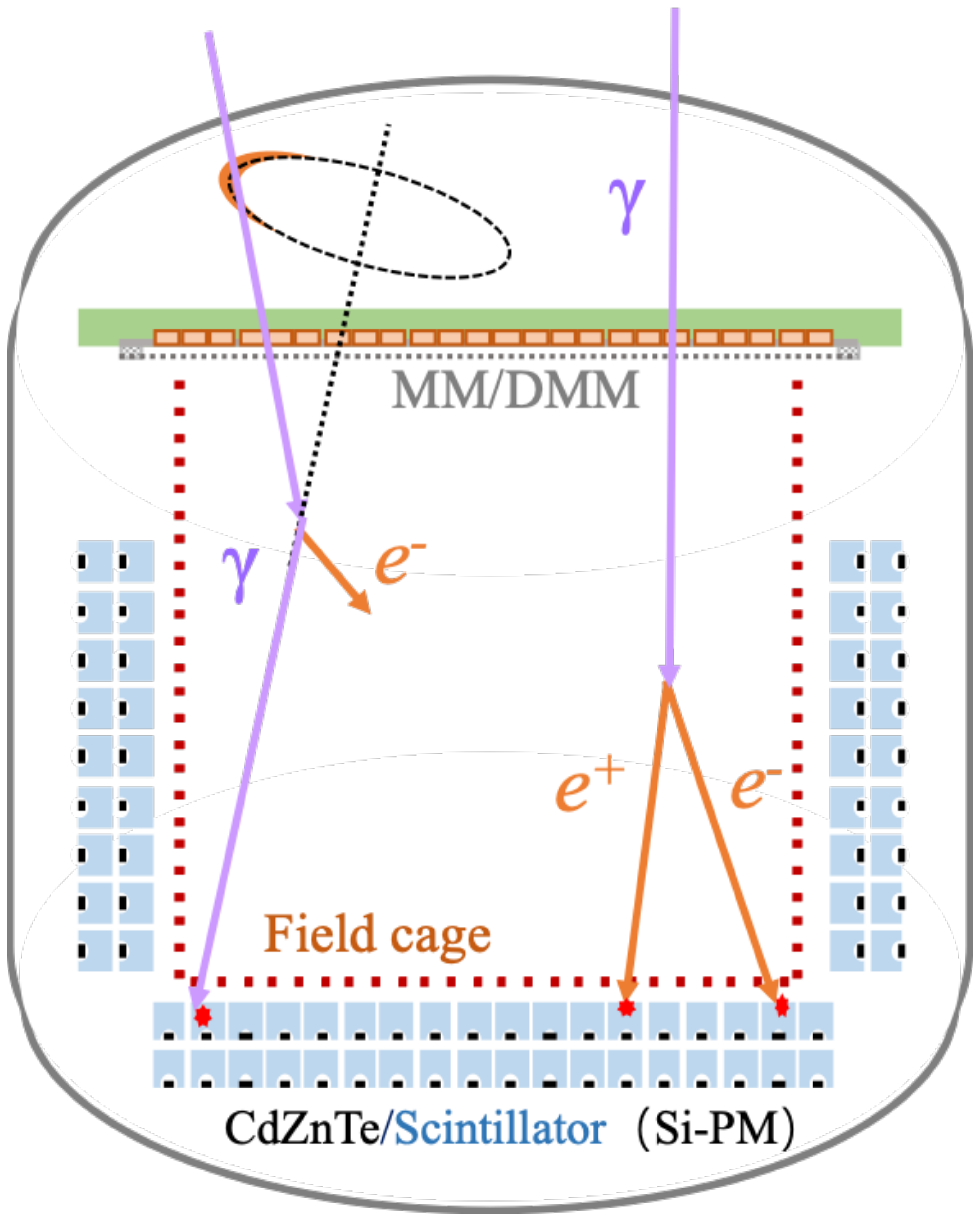
➢100×100× 80 cm^3 ➢3-10 bar

➢energy range: 0.3MeV-100 MeV

➢PSF: 2°@MeV, 0.5°@100 MeV

(Data and figure from Zhi-yong Zhang)

Schematic of MeGaT



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