

Unveiling the origin of cosmic-ray leptons within a coherent multi-channel propagation scenario

Ottavio Fornieri

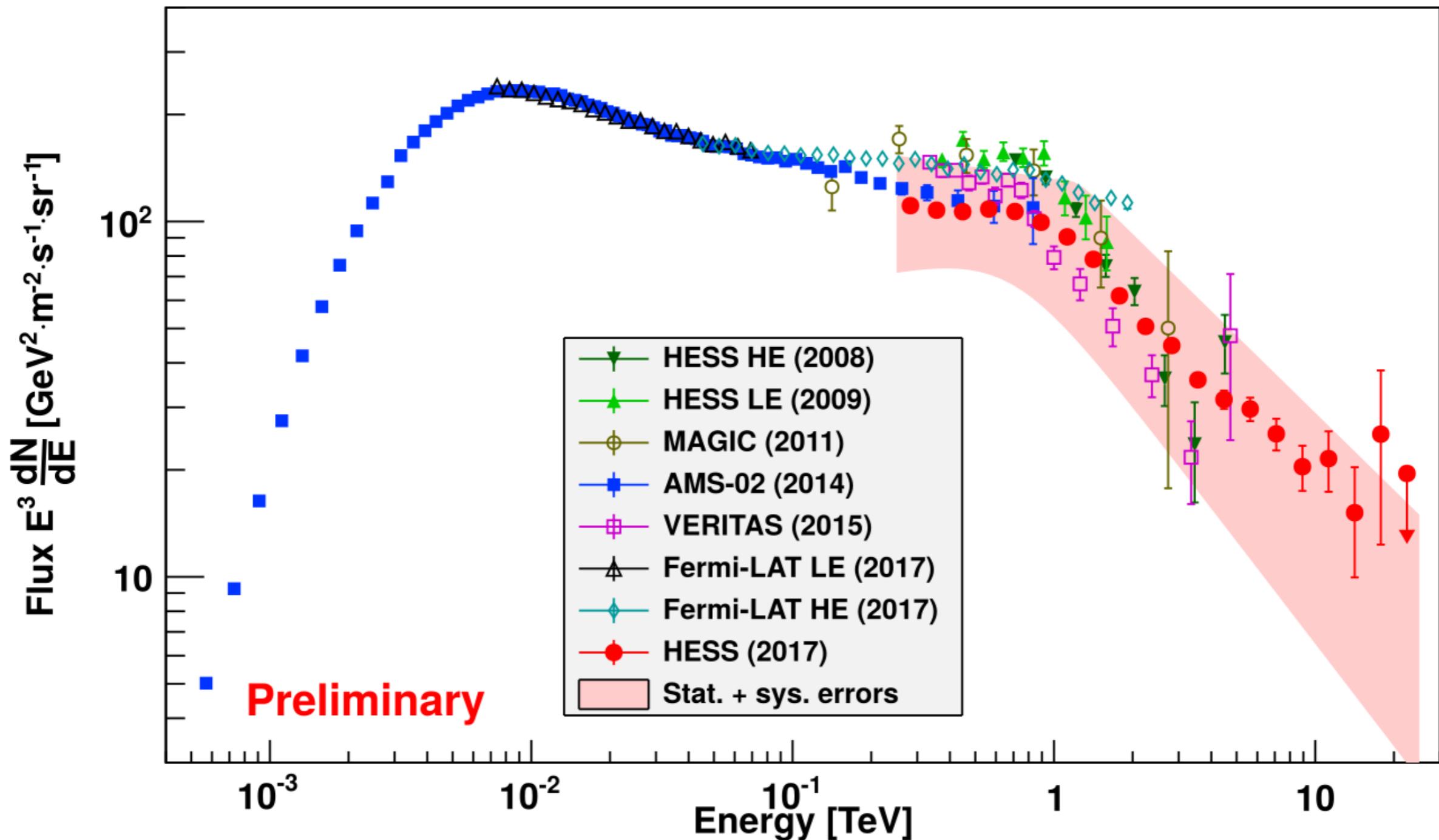
Ph.D. Student @ University of Siena/IFT Madrid

Based on OF, Daniele Gaggero, Dario Grasso, [arXiv:1907.03696](https://arxiv.org/abs/1907.03696)



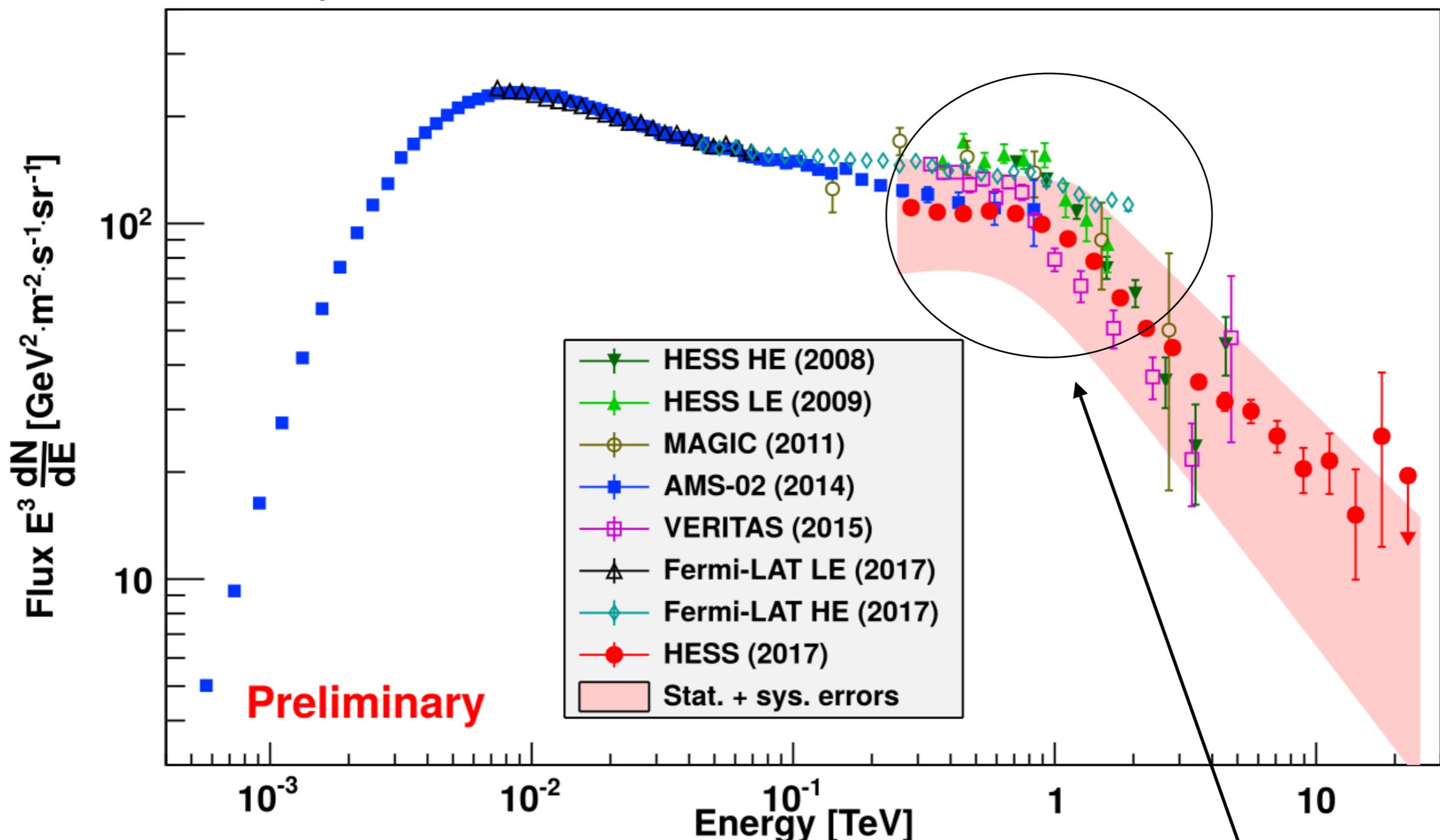
All-lepton Spectrum

D. Kerszberg - ICRC 2017



All-lepton Spectrum

D. Kerszberg - ICRC 2017

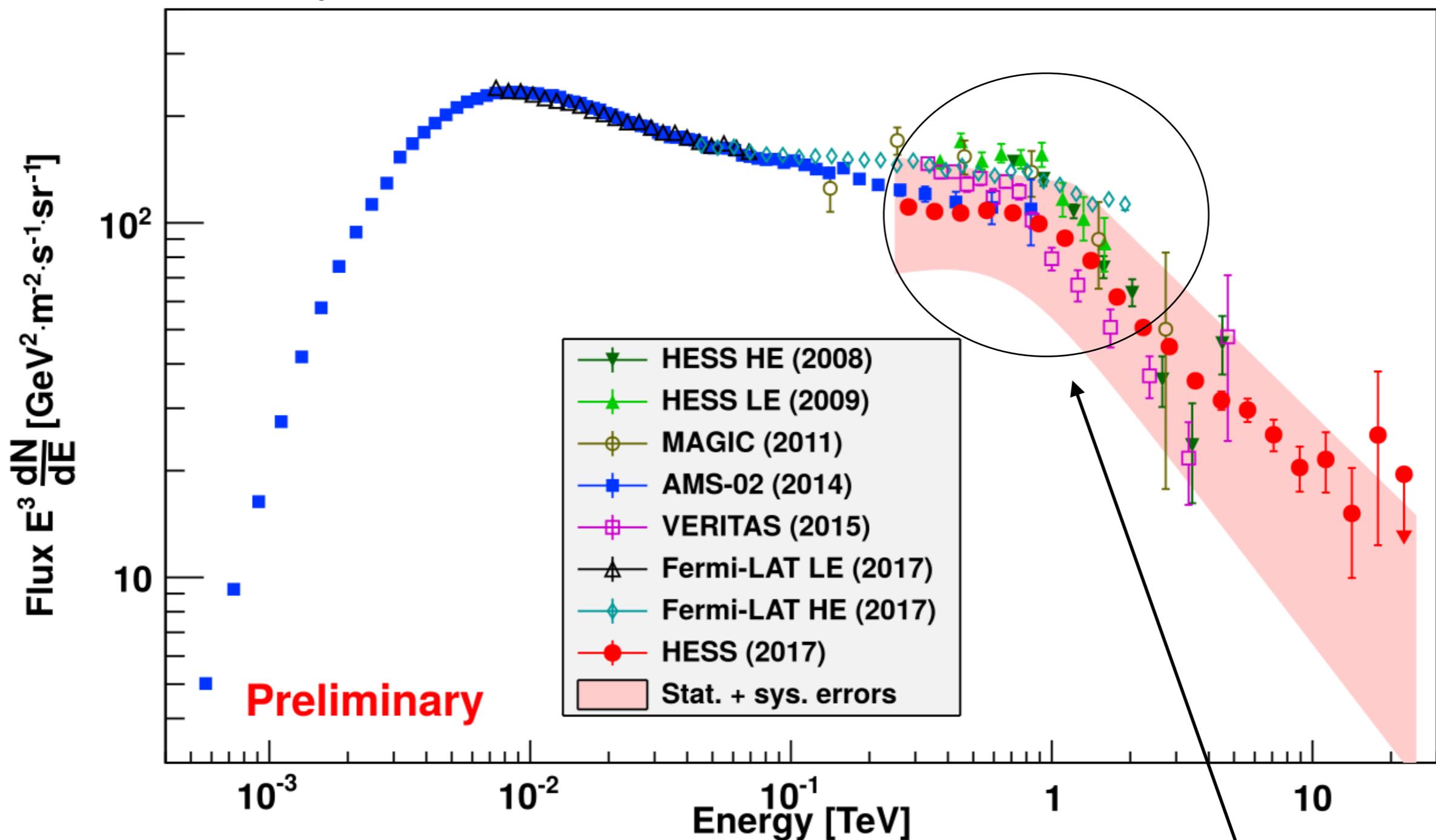


$$\Delta t_{travel} \approx \frac{1}{b_0 E_{obs}} \sim 10^5 \text{ yr}$$

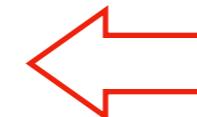
$$\Delta x_{travel} \sim \sqrt{4 D(E) \cdot \Delta t_{travel}} \sim \text{kpc}$$

All-lepton Spectrum

D. Kerszberg - ICRC 2017



Local sources resolved

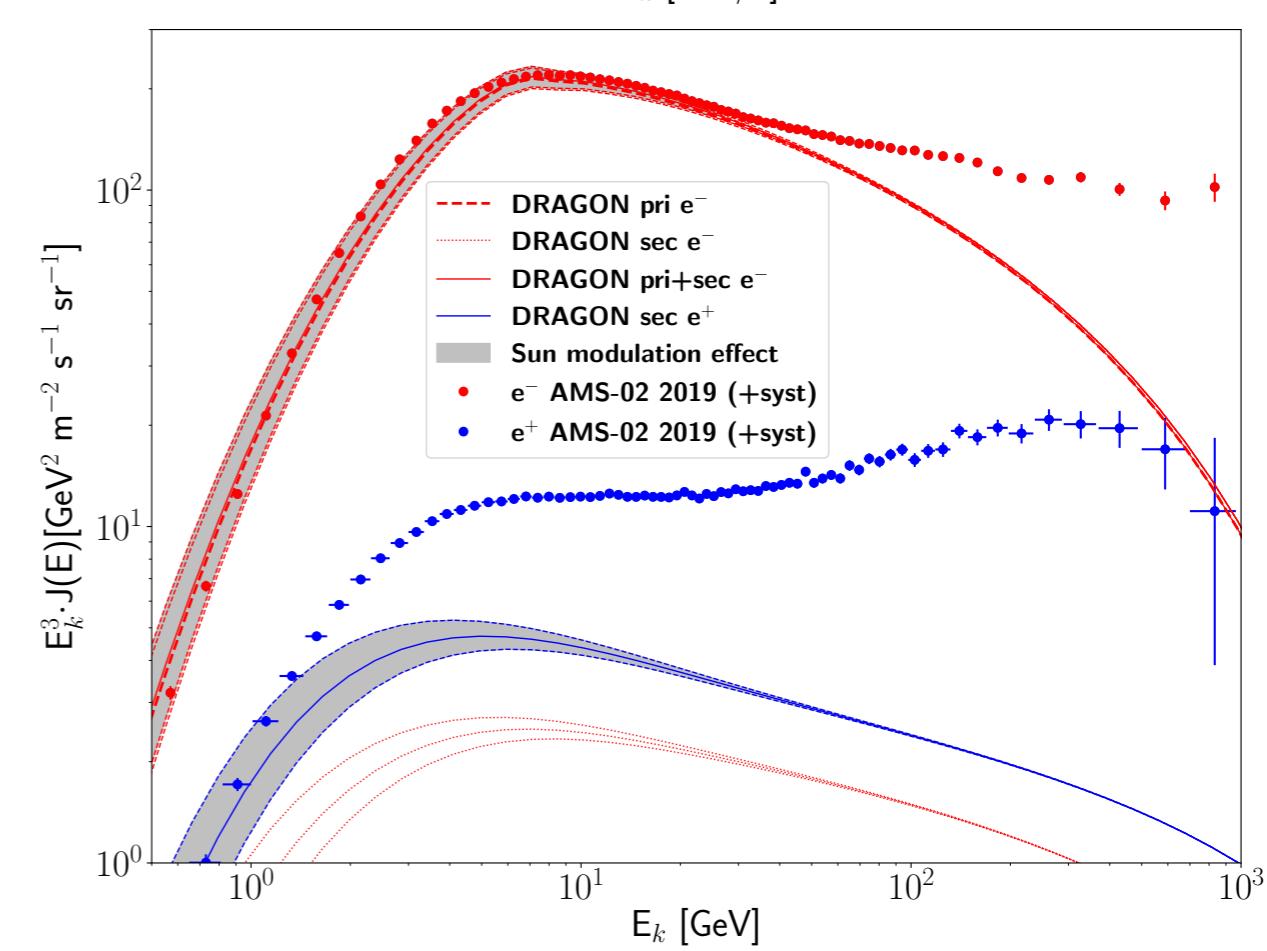
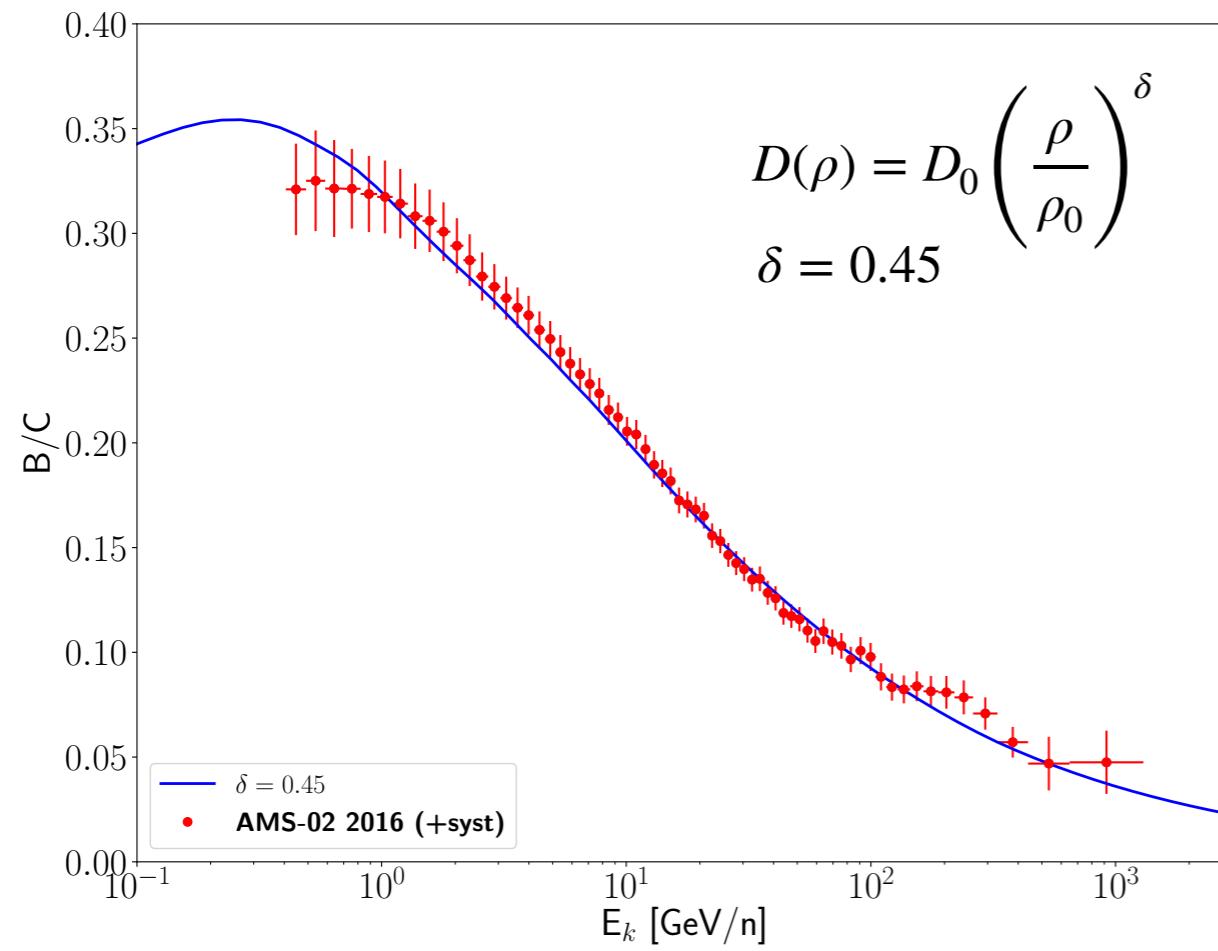
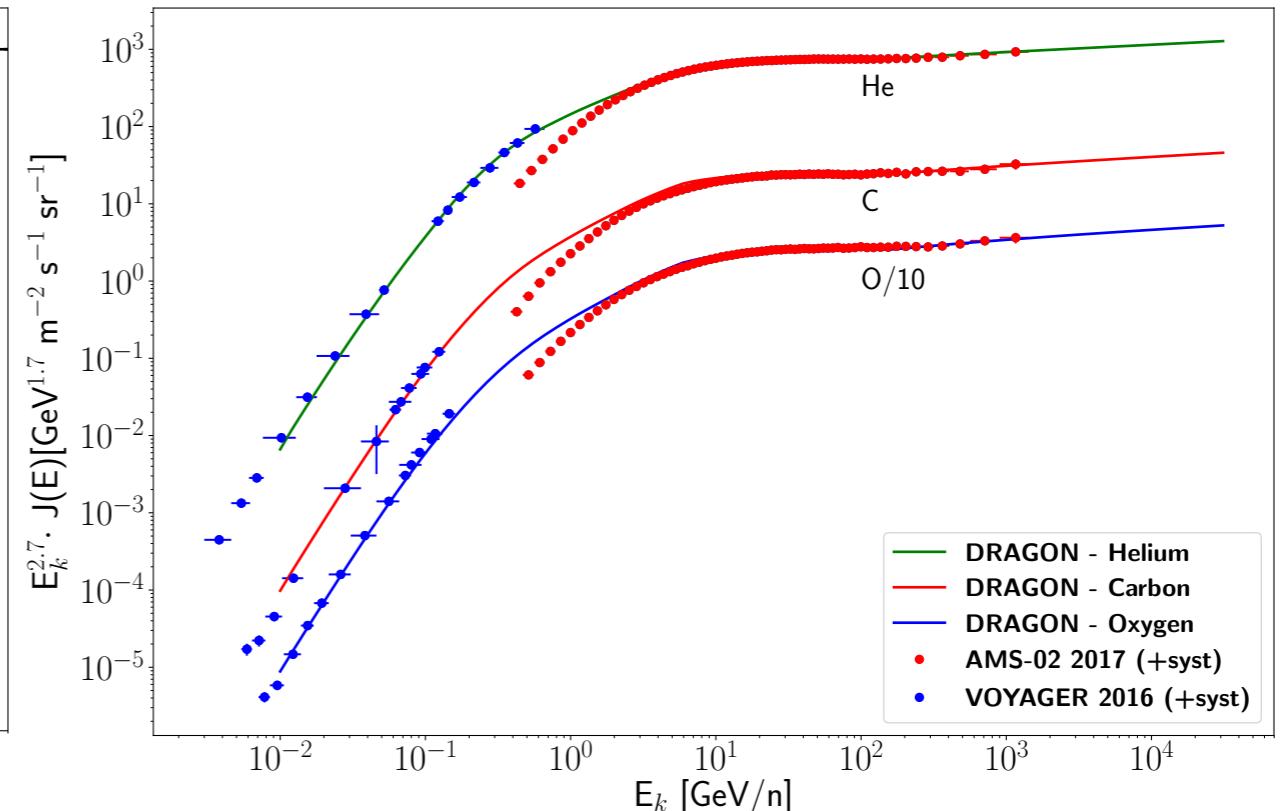
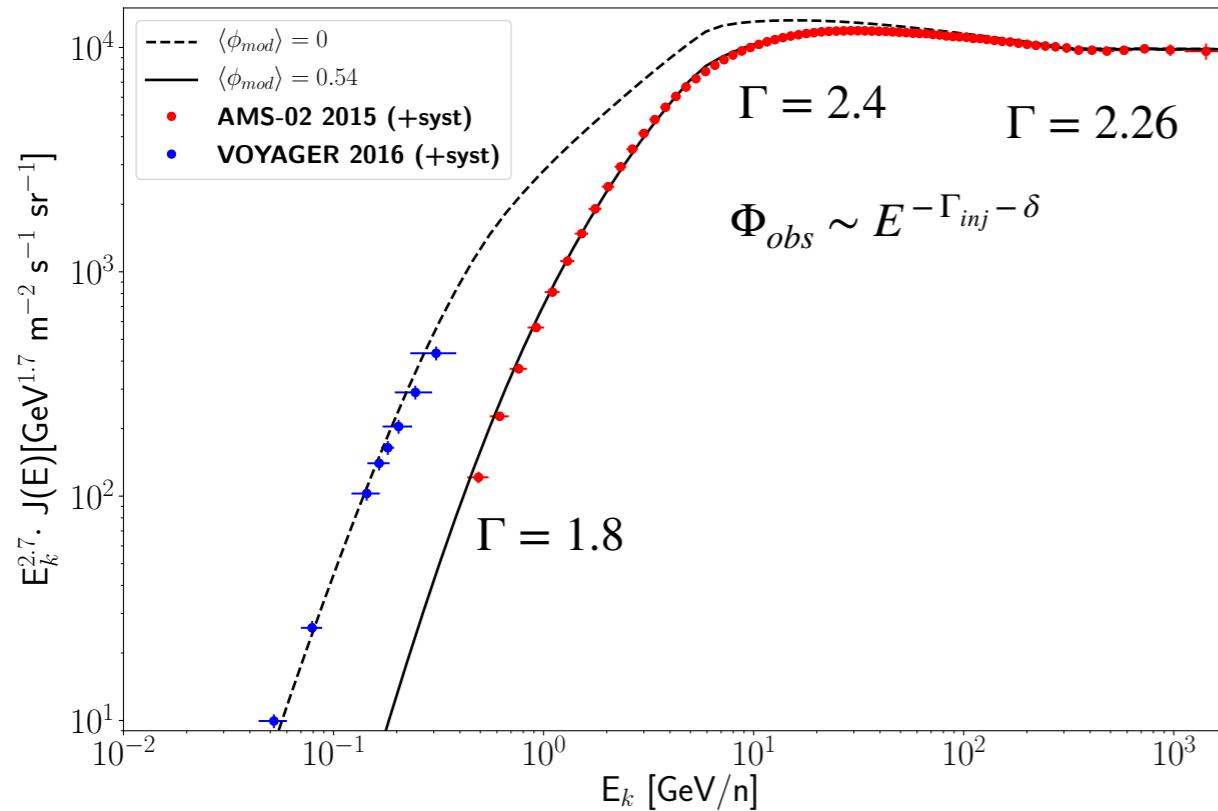


$$\Delta t_{travel} \approx \frac{1}{b_0 E_{obs}} \sim 10^5 \text{ yr}$$

$$\Delta x_{travel} \sim \sqrt{4 D(E) \cdot \Delta t_{travel}} \sim \text{kpc}$$

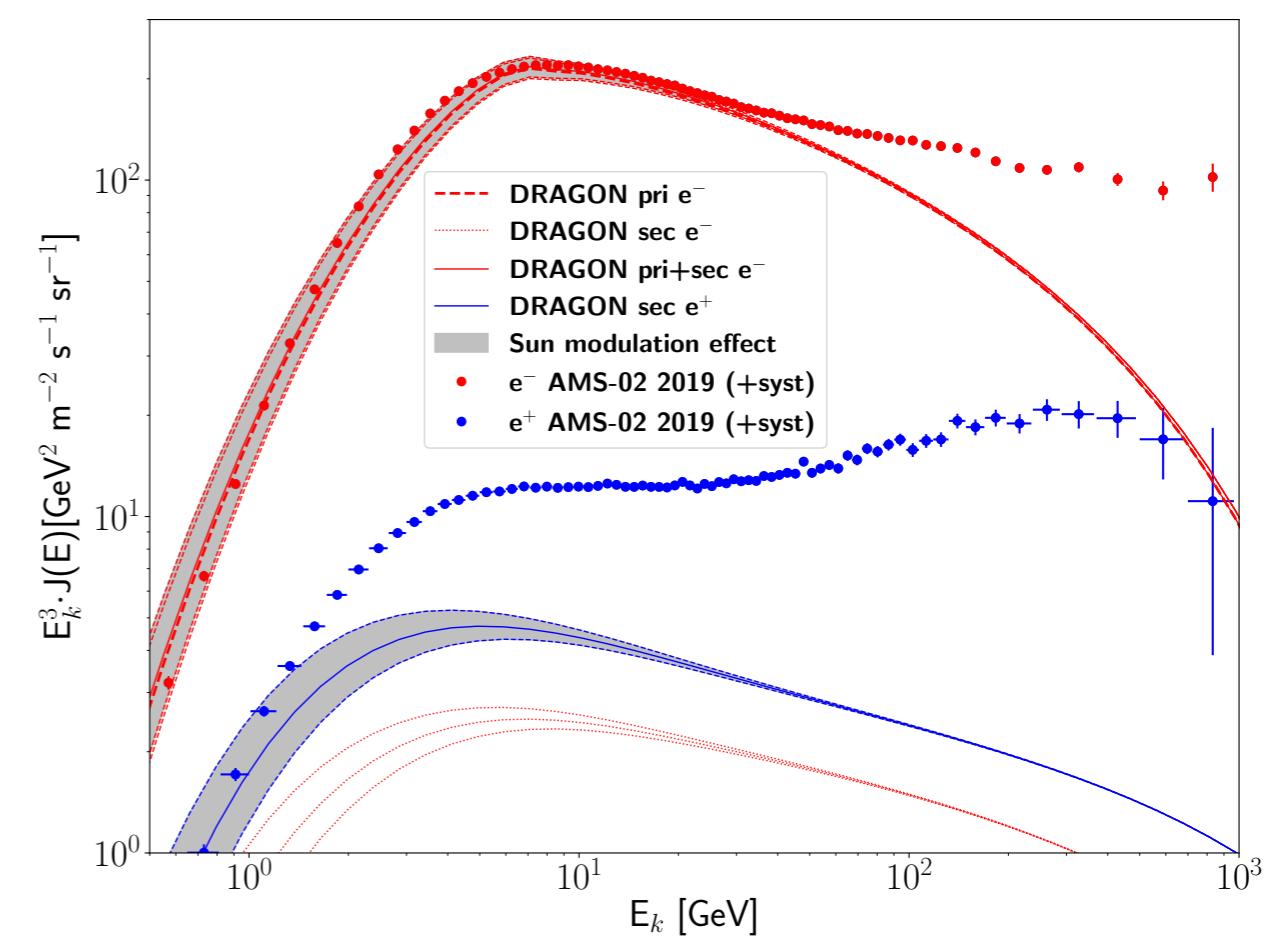
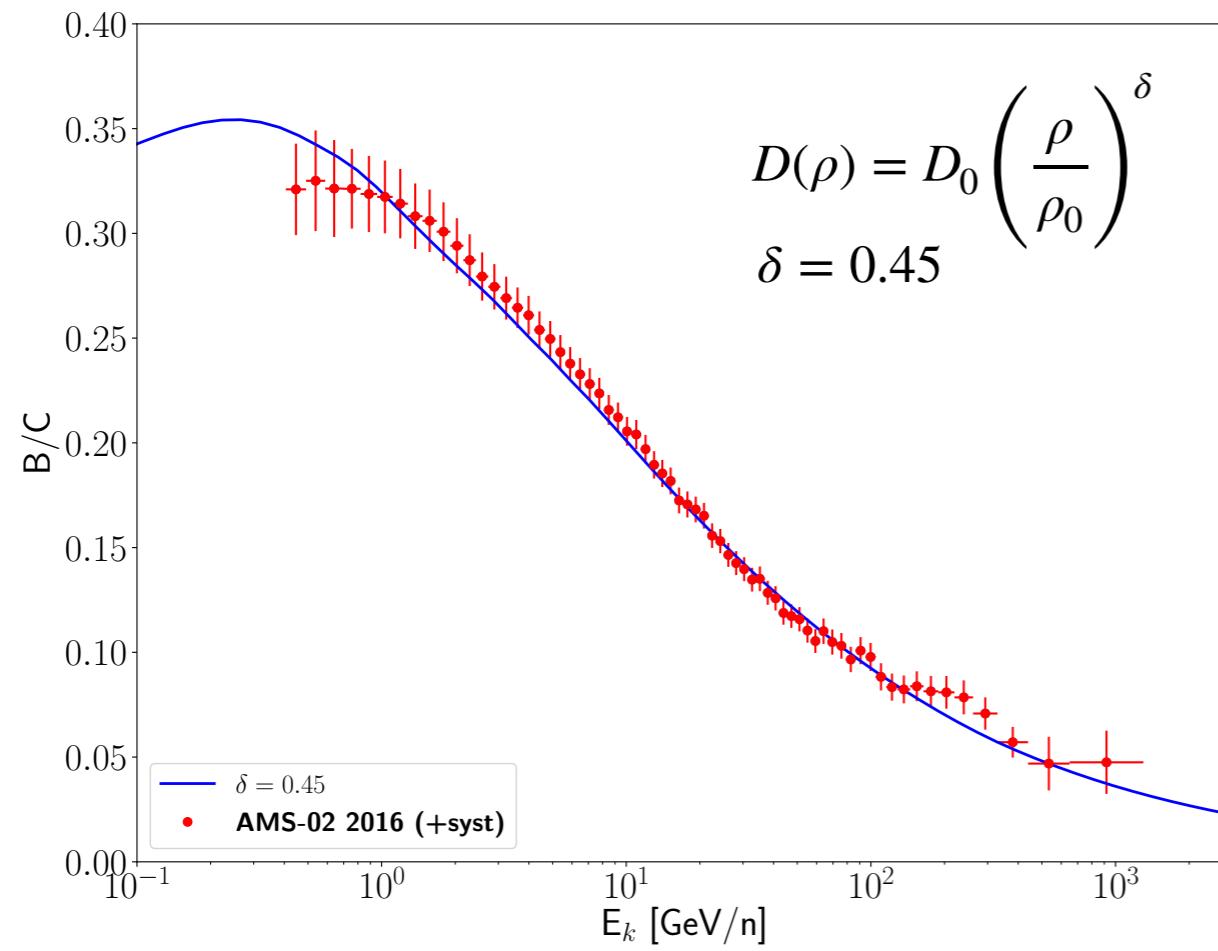
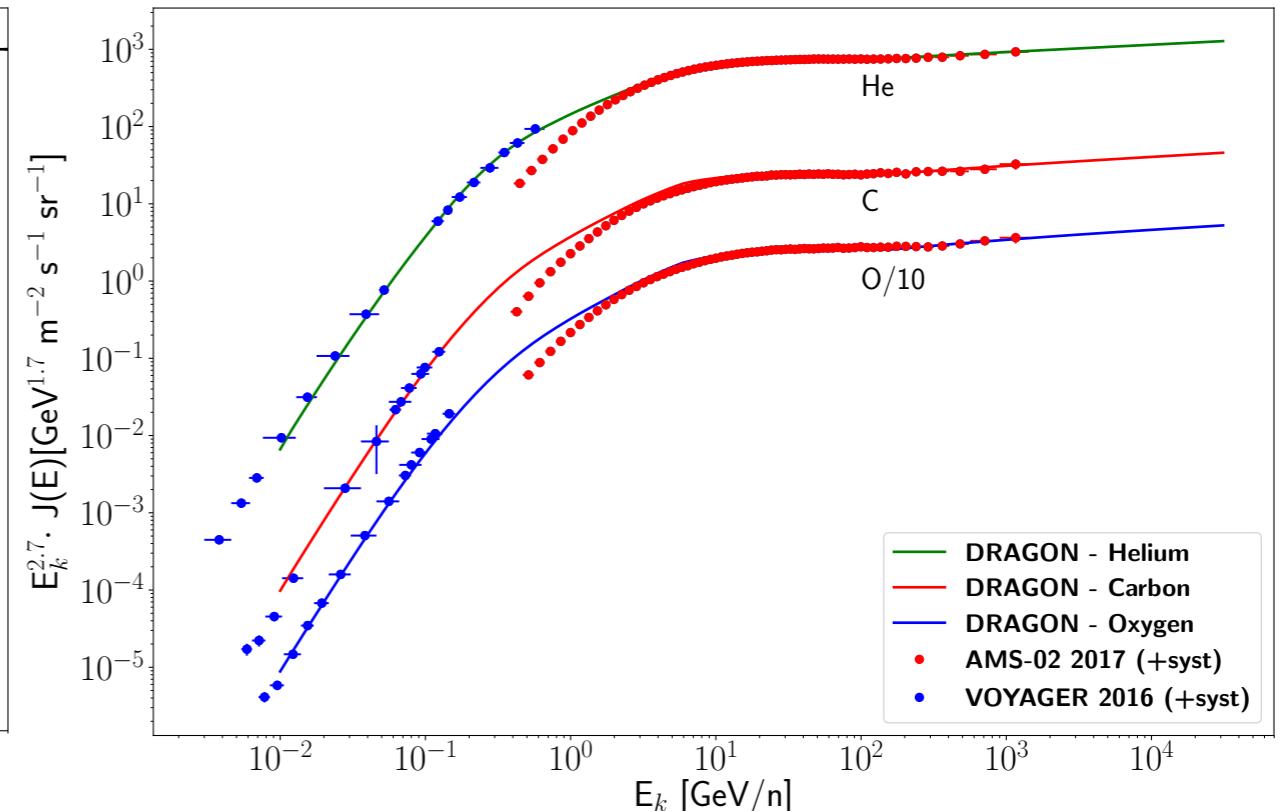
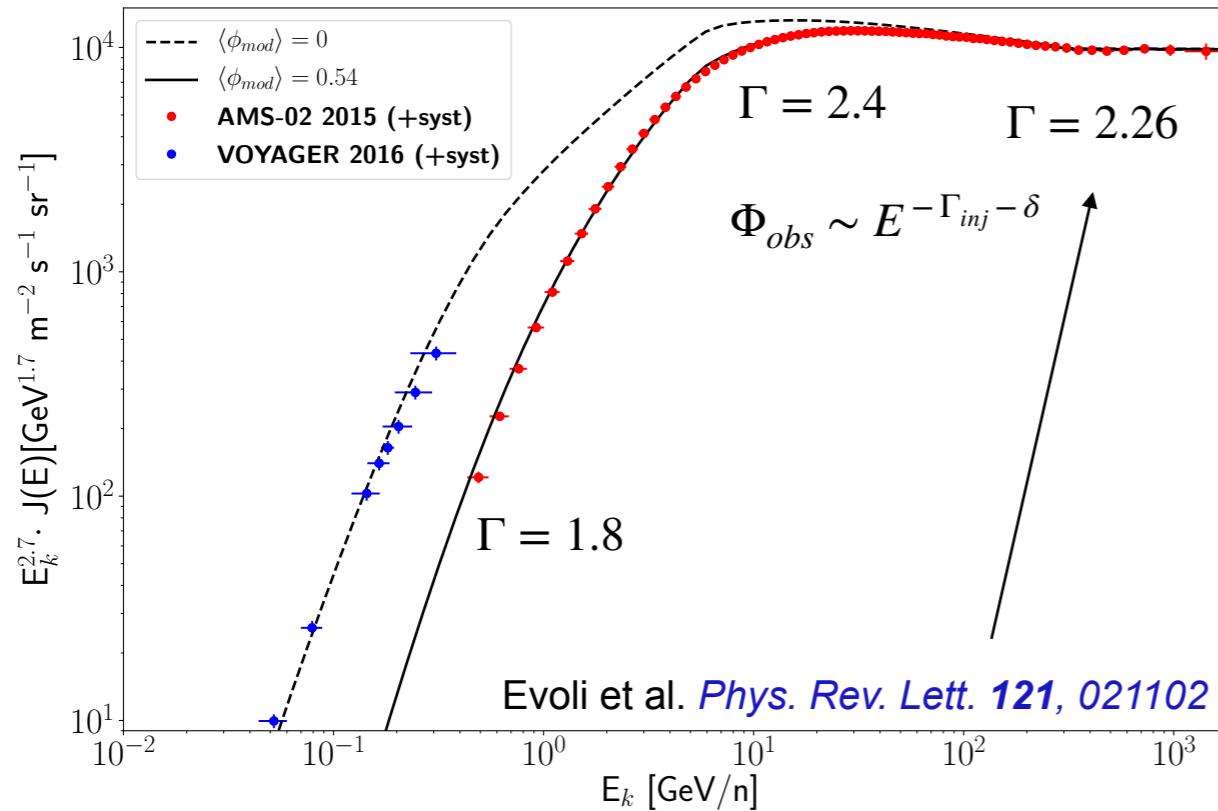
Standard propagation model

DRAGON output: our best fit



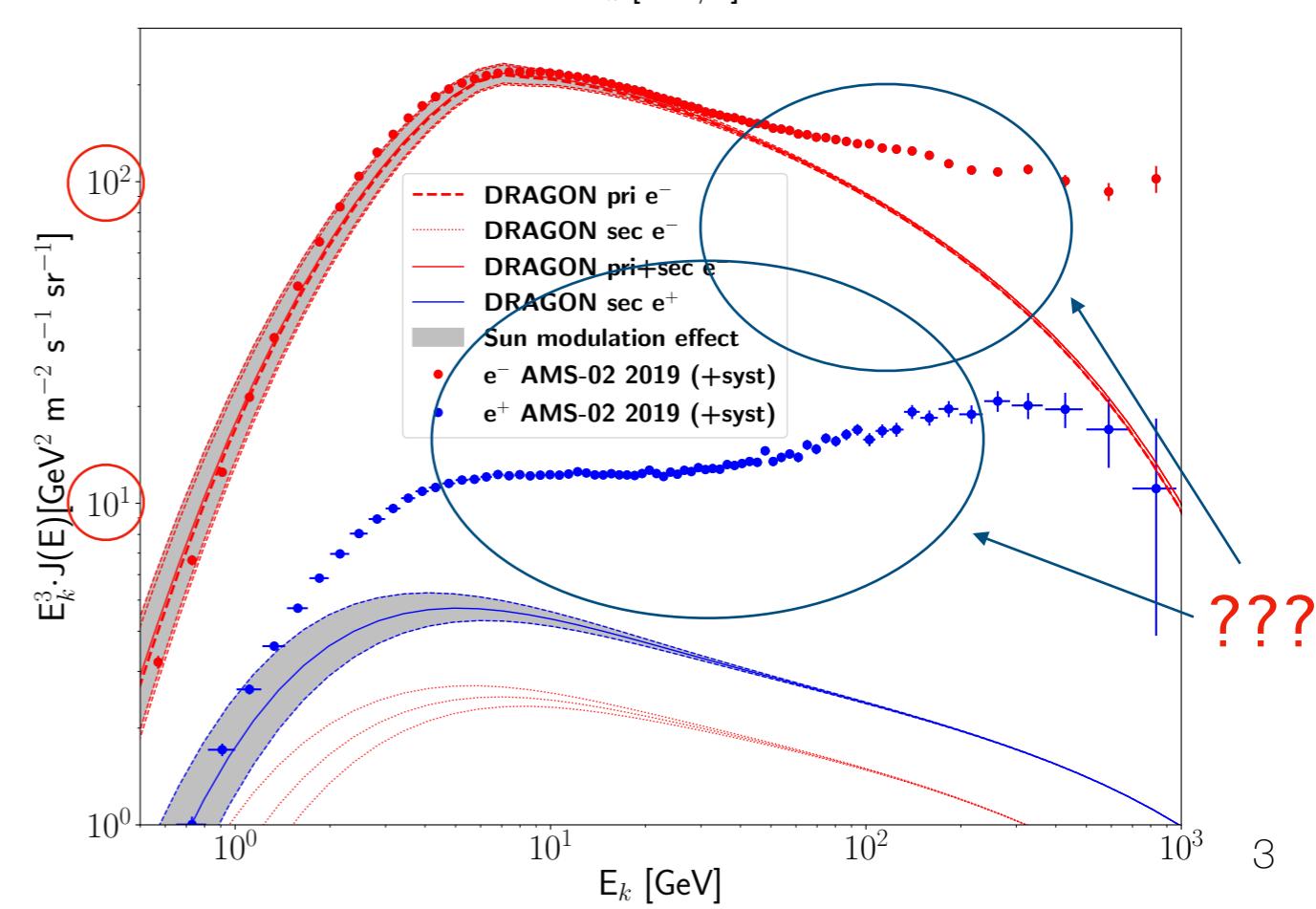
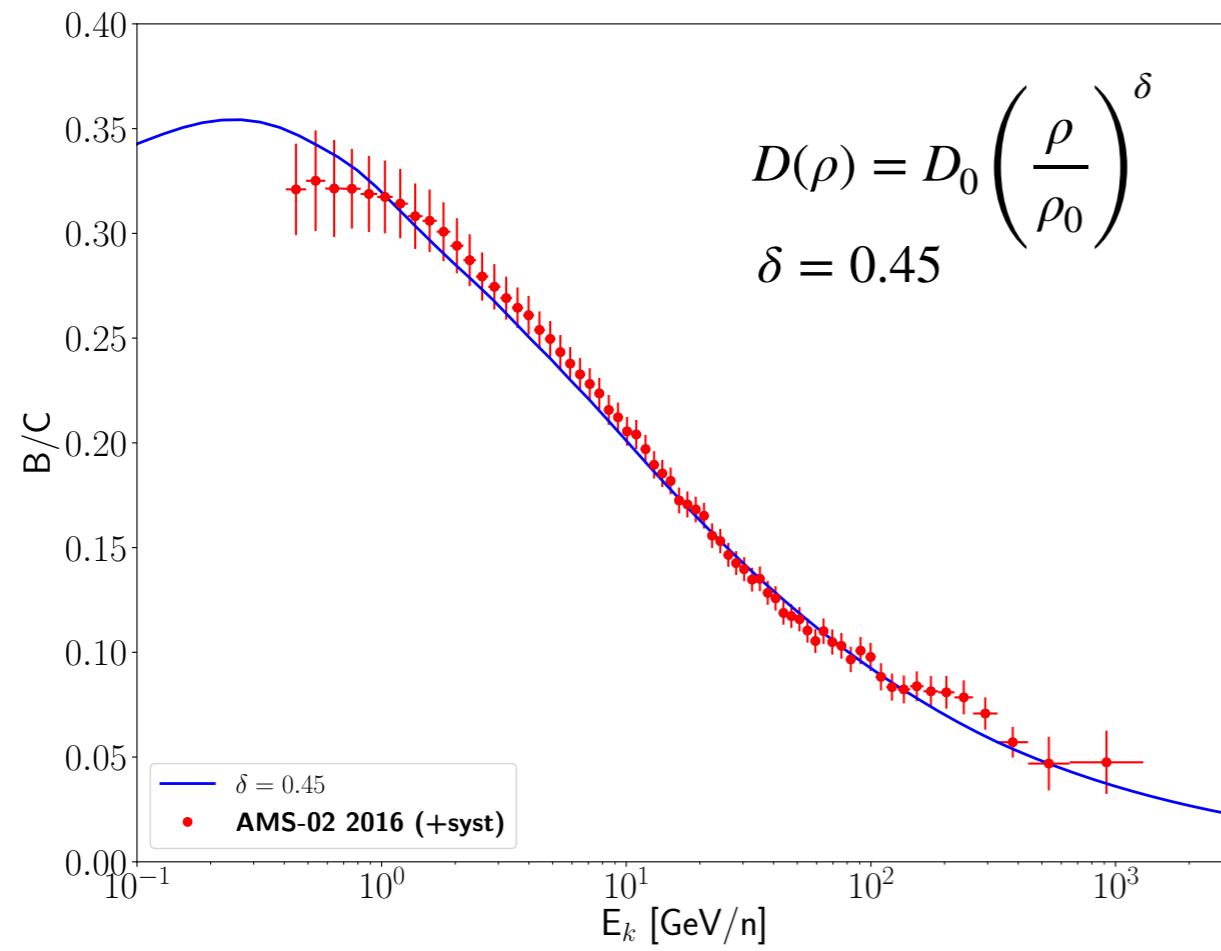
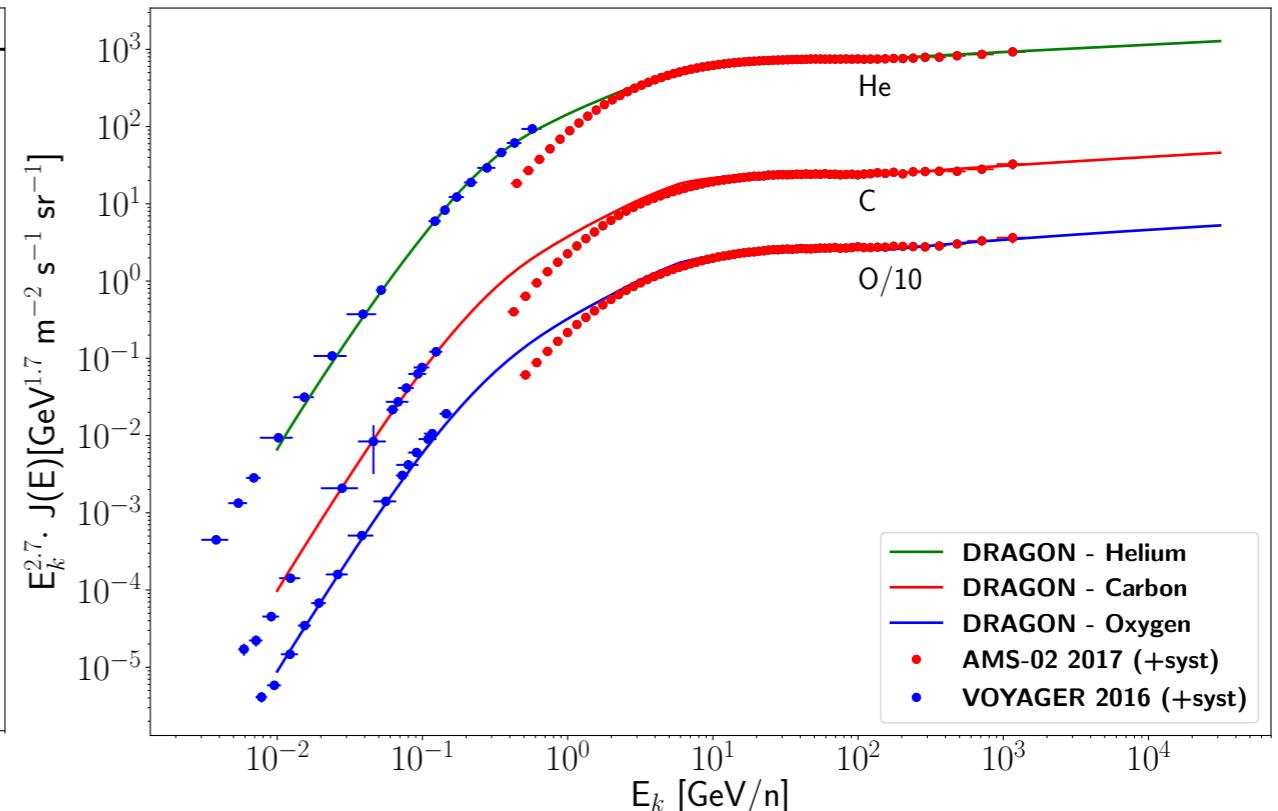
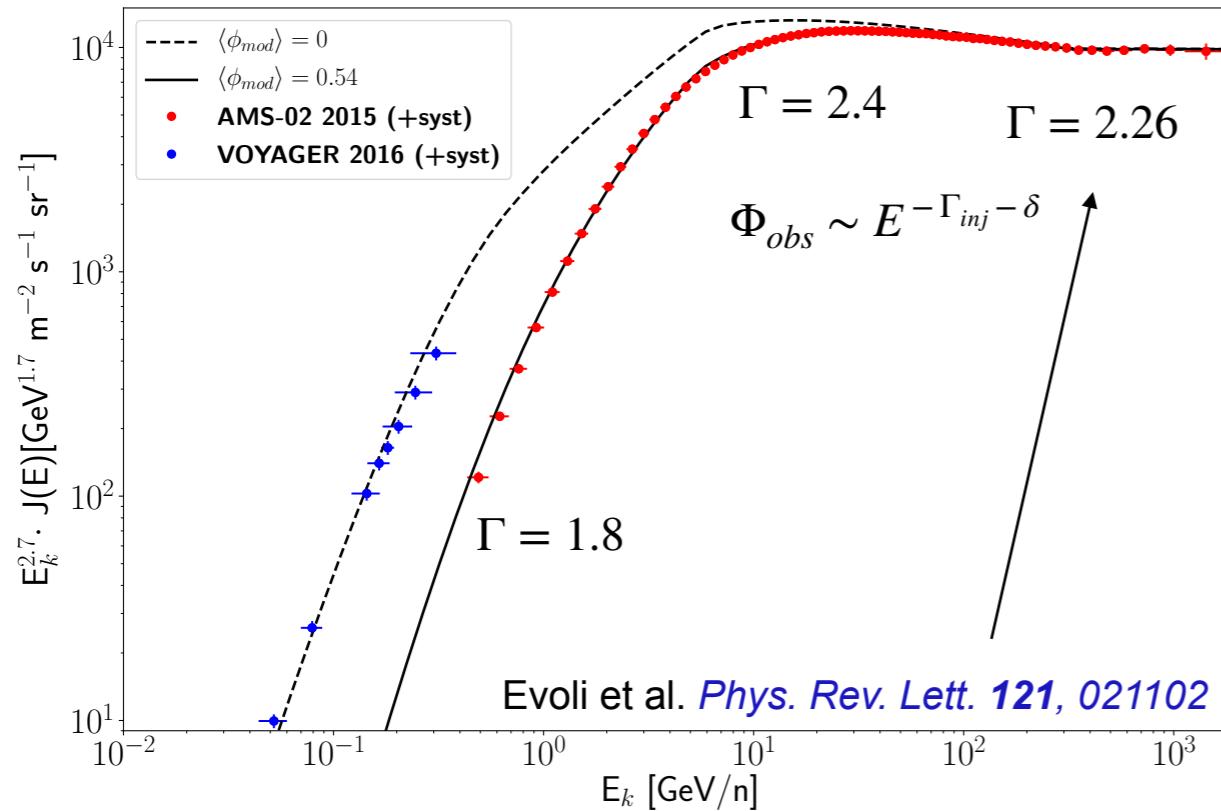
Standard propagation model

DRAGON output: our best fit

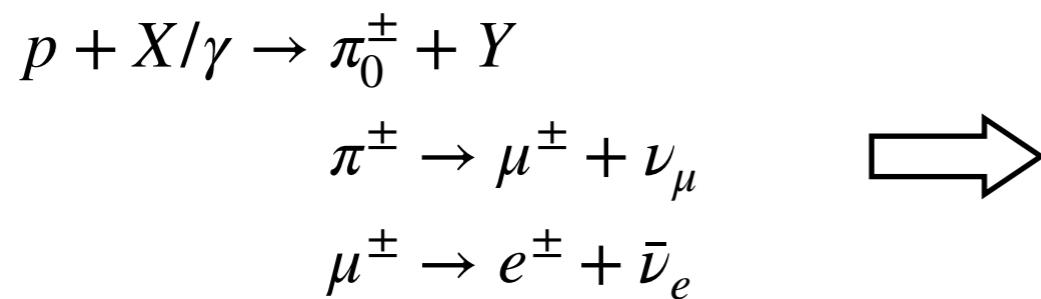


Standard propagation model

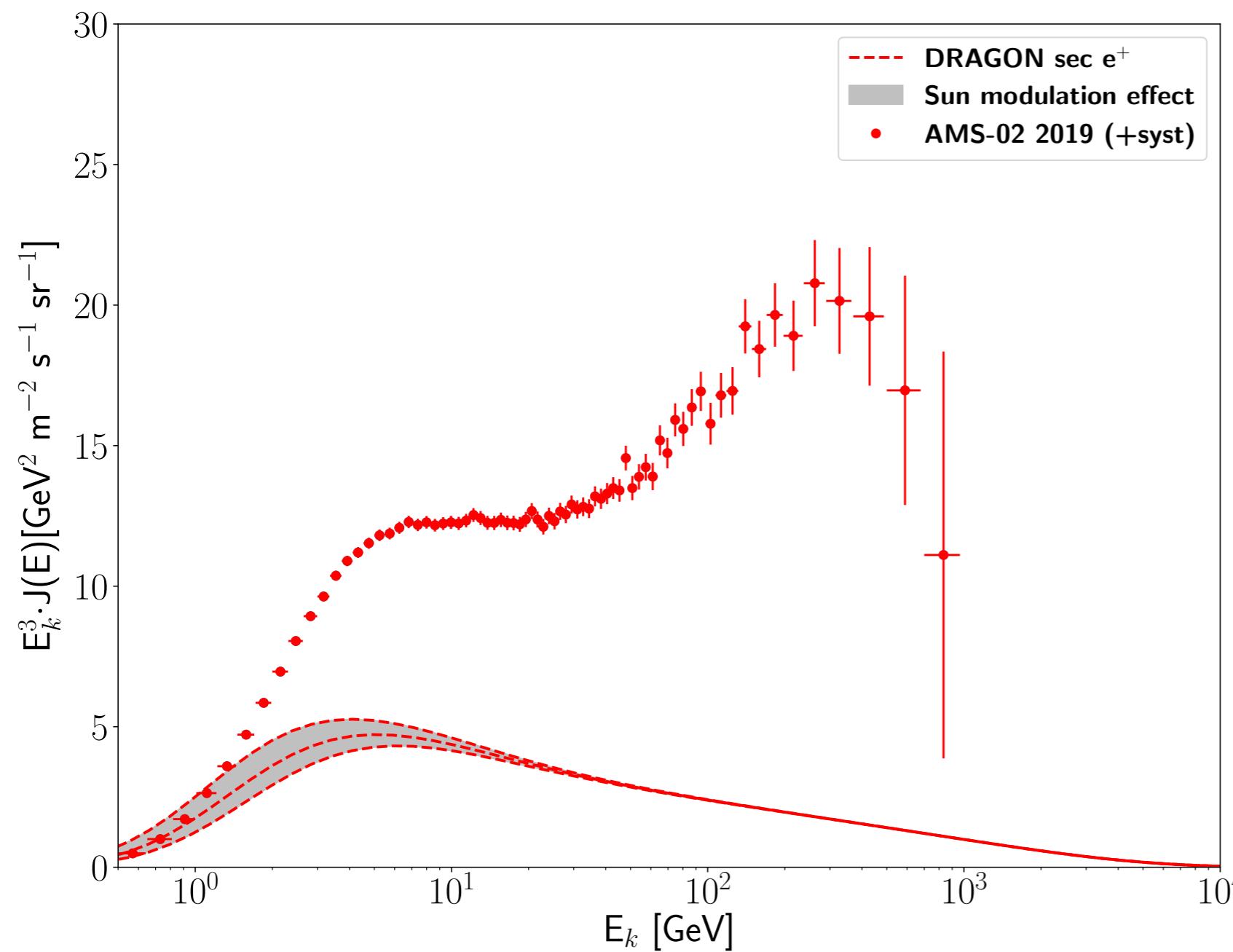
DRAGON output: our best fit



Positron origin



Secondary production ruled by
the protons' and nuclei's flux



- The propagation paradigm has to be changed?
(P.Lipari - *Phys. Rev. D* **99**, 043005)
- Additional source(s) for primary positrons? **(antimatter factories)**

Positron origin

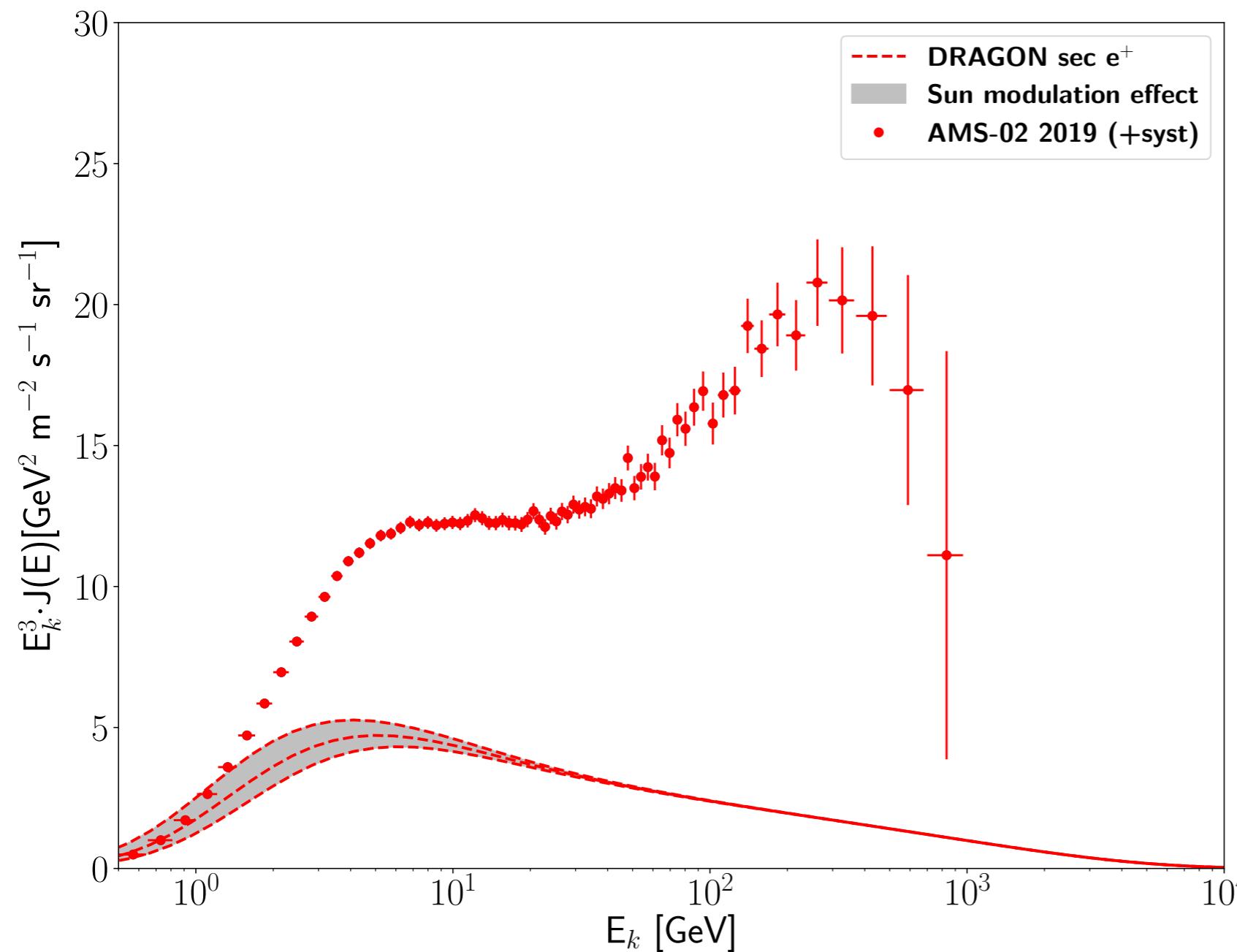
$$p + X/\gamma \rightarrow \pi_0^\pm + Y$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$$

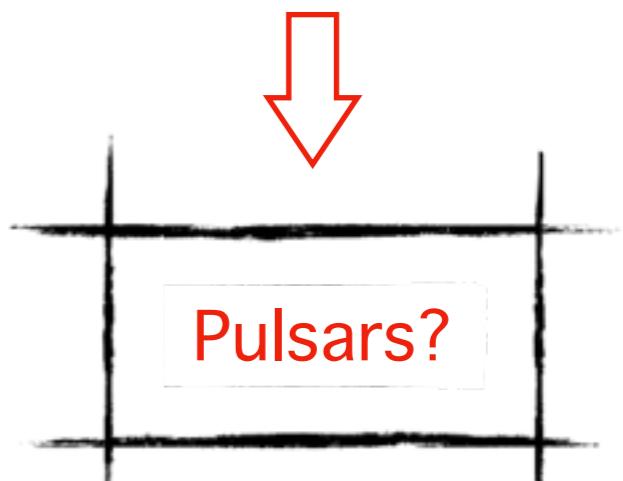
$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_e$$



Secondary production ruled by
the protons' and nuclei's flux



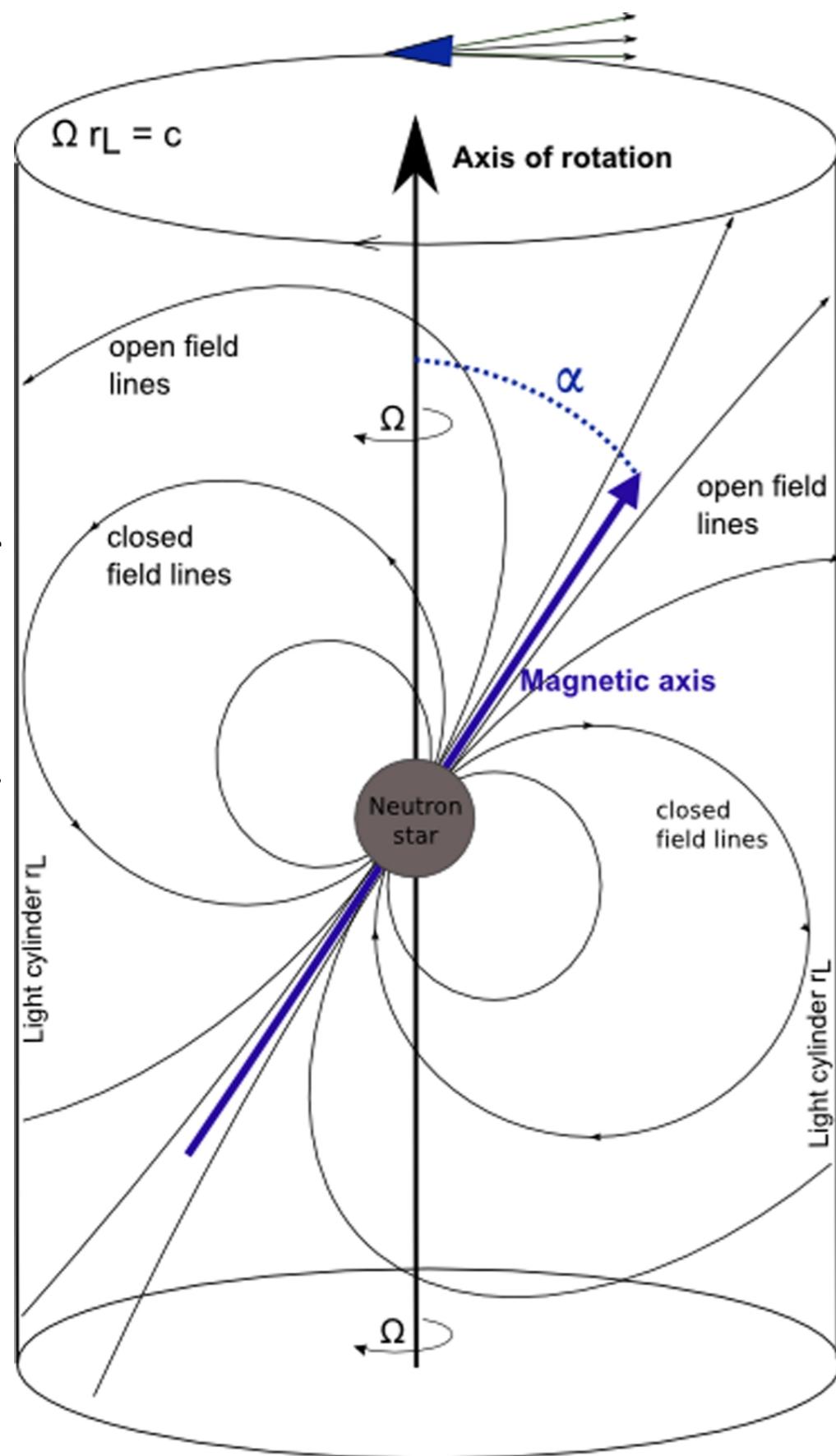
- The propagation paradigm has to be changed?
(P.Lipari - *Phys. Rev. D* **99**, 043005)
- Additional source(s) for primary positrons? **(antimatter factories)**



Rotating neutron stars
with large B-field:

Magnetic-dipole emission?

Observations



Direct

- Rotation period P
- Variation of rotation period $\dot{P} > 0$

Slows down

Derived

- Characteristic age $\tau_{ch} = P / (n - 1)\dot{P}$
- Rate of energy loss $\dot{E}_{rot} = I\Omega\dot{\Omega}$

Model dependent (MD)

- Surface B-field $B_{surf} = 3.2 \cdot 10^{19} \sqrt{PP} [\text{G}]$

Injection in the ISM

(model independent)

$$\dot{\Omega}(t) = -\kappa_0 \Omega^n$$

braking-index

$$\Rightarrow \dot{E}_{rot}(t) = I\Omega\dot{\Omega} \equiv L(t) = \frac{\eta^\pm L_0}{\left(1 + \frac{t}{\tau_0}\right)^{\frac{n+1}{n-1}}}$$

Decaying-luminosity function

Injection in the ISM

(model independent)

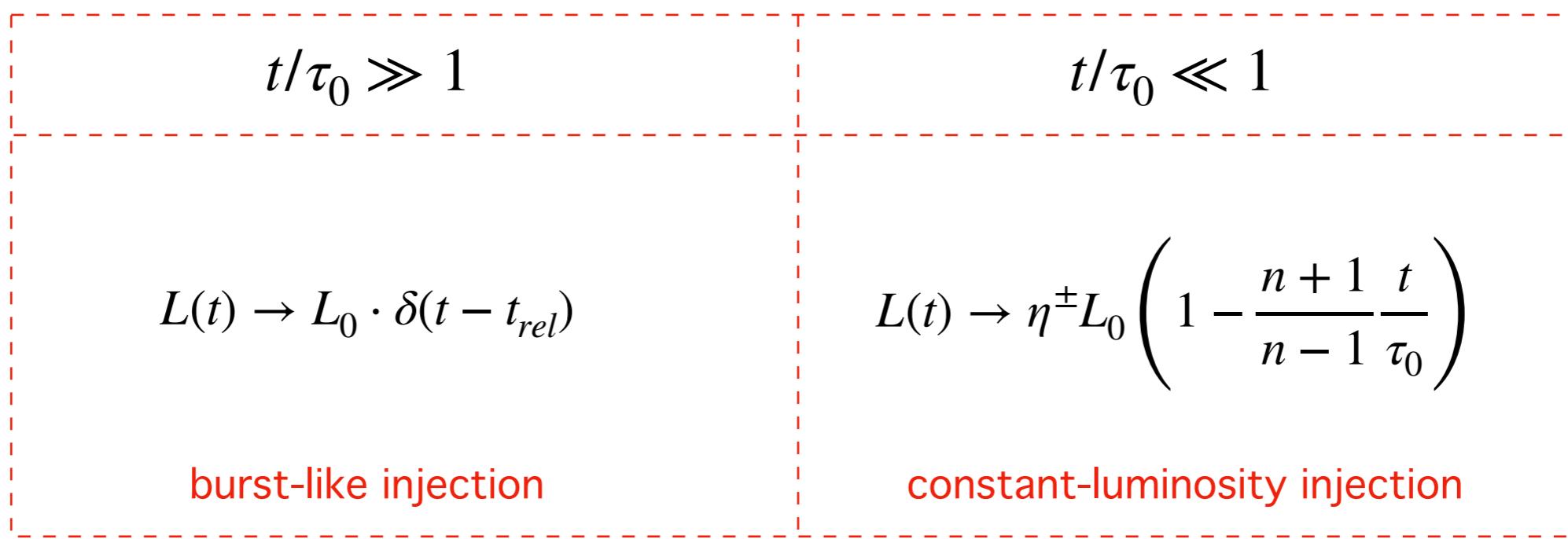
$$\dot{\Omega}(t) = -\kappa_0 \Omega^n$$

braking-index

$$\Rightarrow \dot{E}_{rot}(t) = I\Omega\dot{\Omega} \equiv L(t) = \frac{\eta^\pm L_0}{\left(1 + \frac{t}{\tau_0}\right)^{\frac{n+1}{n-1}}}$$

Decaying-luminosity function

Based on the t/τ_0 ratio



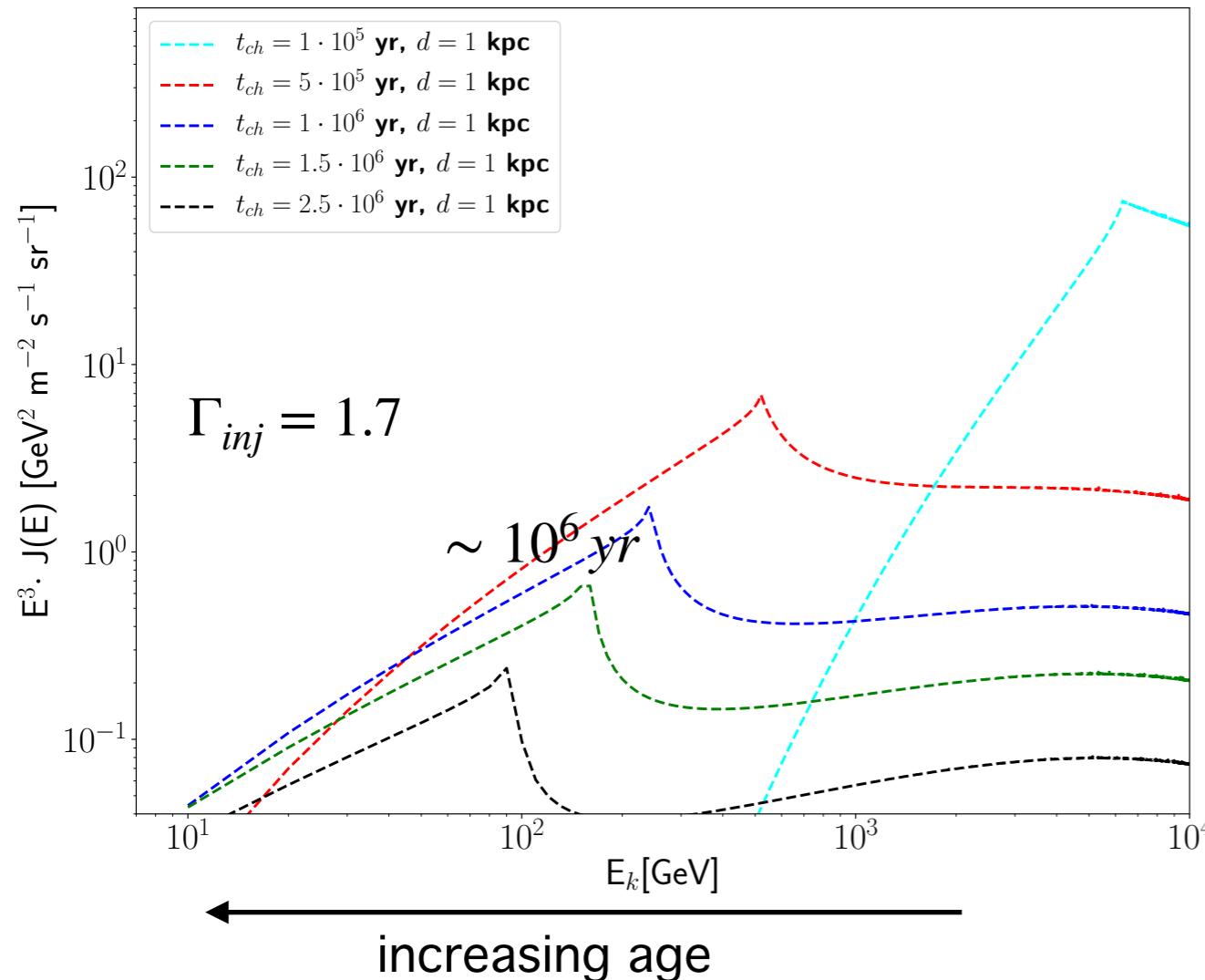
Low-energy e^+ spectrum

Studying the general $L(t)$ solution

$$\frac{\partial f(E, t, r)}{\partial t} = \frac{D(E)}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial f}{\partial r} + \frac{\partial}{\partial E} (b(E)f) + Q$$

$$Q = S(E) \textcolor{red}{L(t)} \delta(r)$$

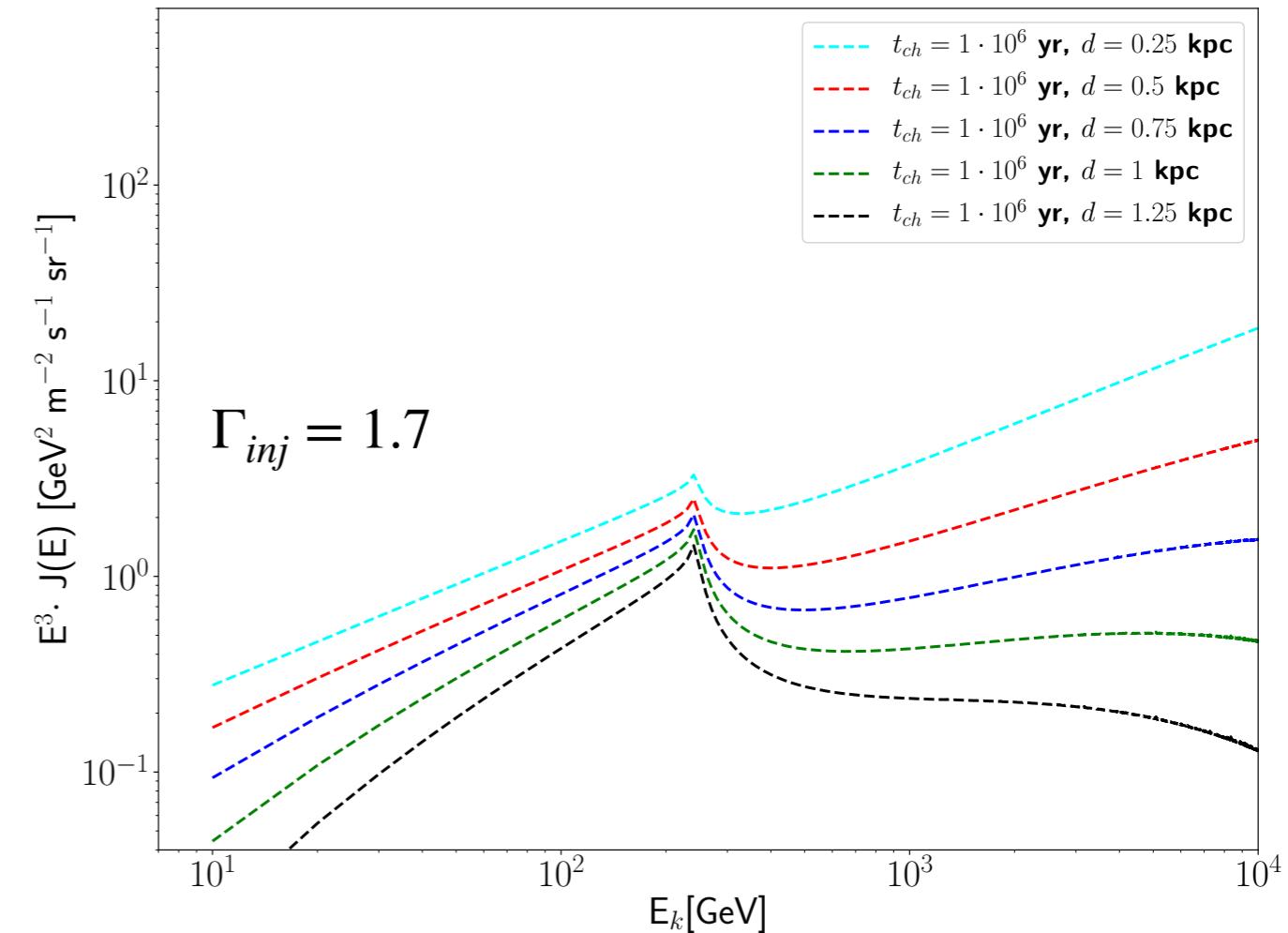
Age



increasing age

$$E_{obs} \approx \frac{1}{b_0 t_{age}}$$

Distance



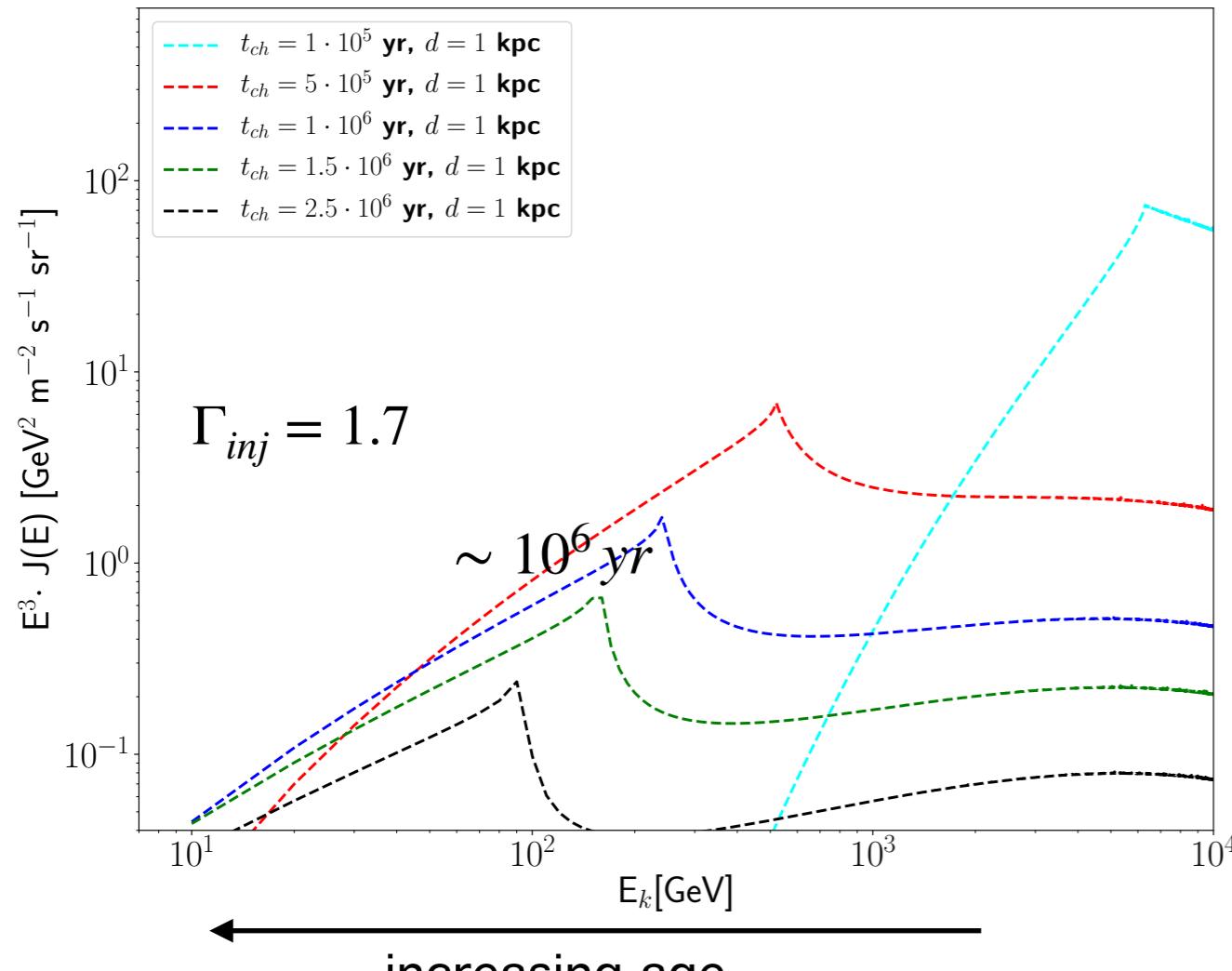
Low-energy e^+ spectrum

Studying the general $L(t)$ solution

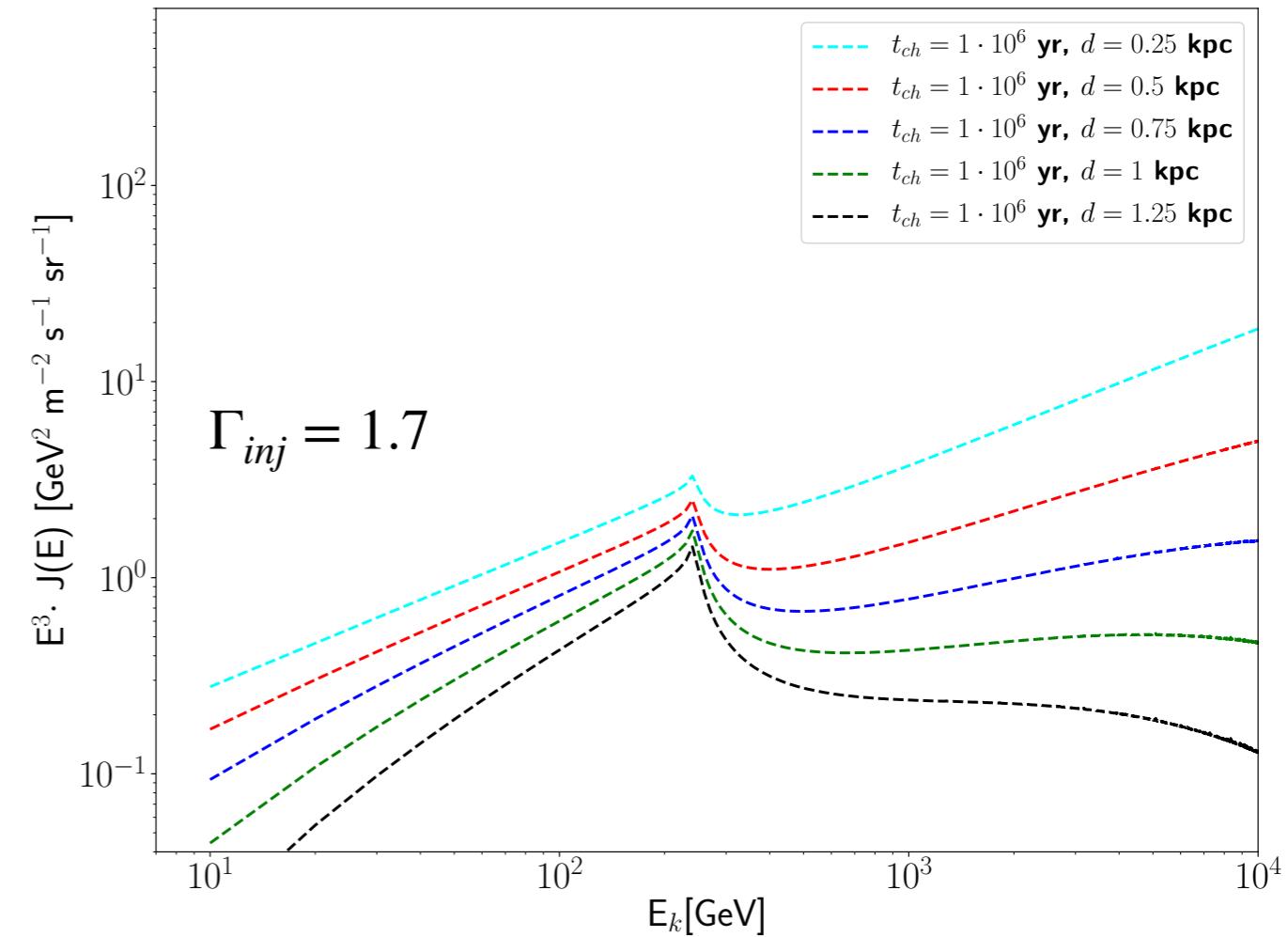
$$\frac{\partial f(E, t, r)}{\partial t} = \frac{D(E)}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial f}{\partial r} + \frac{\partial}{\partial E} (b(E)f) + Q$$

$$Q = S(E) \textcolor{red}{L(t)} \delta(r)$$

Age



Distance



increasing age

$$E_{obs} \approx \frac{1}{b_0 t_{age}}$$

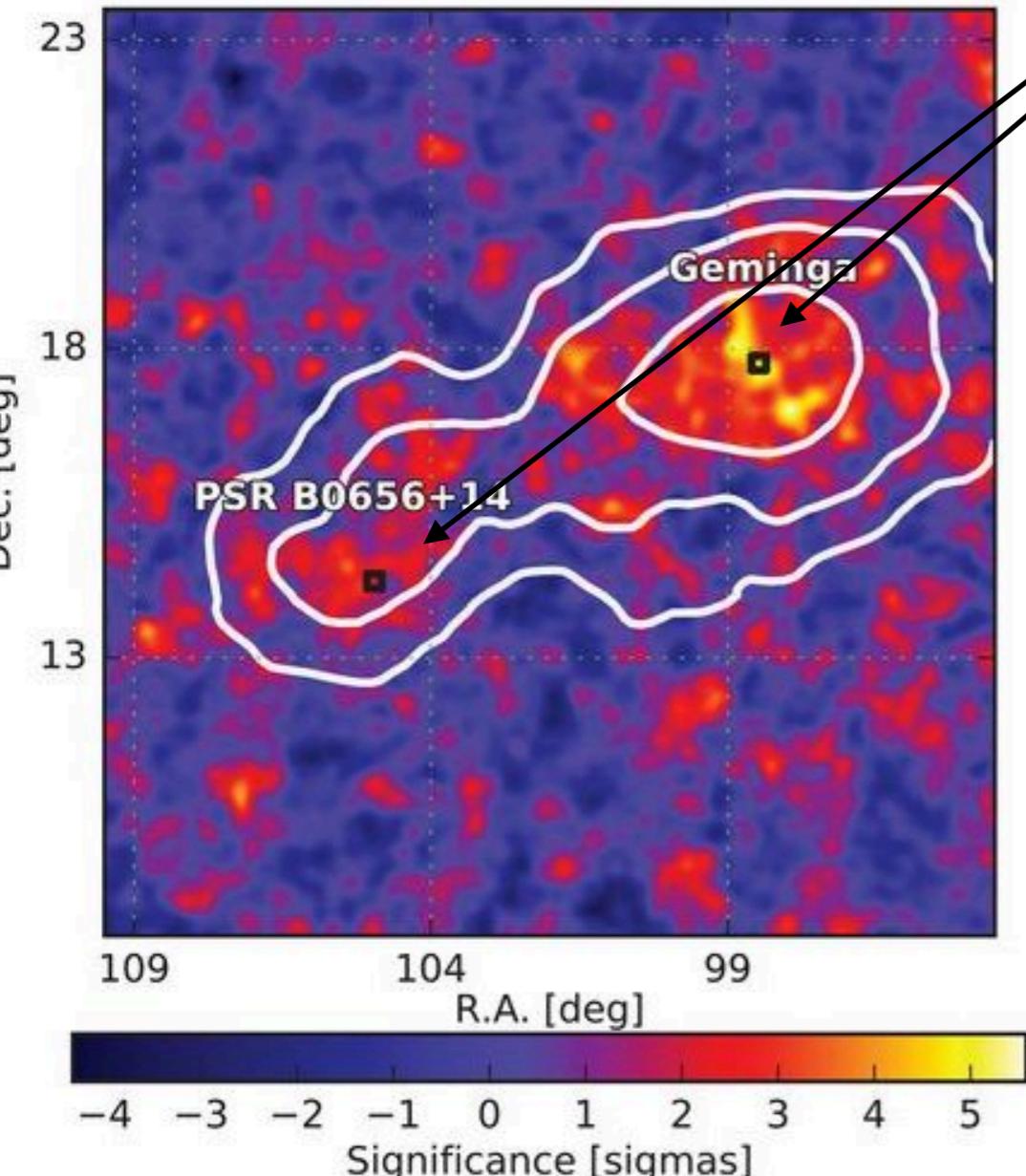
Low-energy spectrum
($E \lesssim 40$ GeV)

convolution of $\mathcal{O}(10^4)$ old ($t_{age} > 10^6$ yr) sources

High-energy e^+ spectrum

Evidence for high-energy e^\pm from Geminga and Monogem

Abeysekara *et al.* Science Vol. 358, Issue 6365



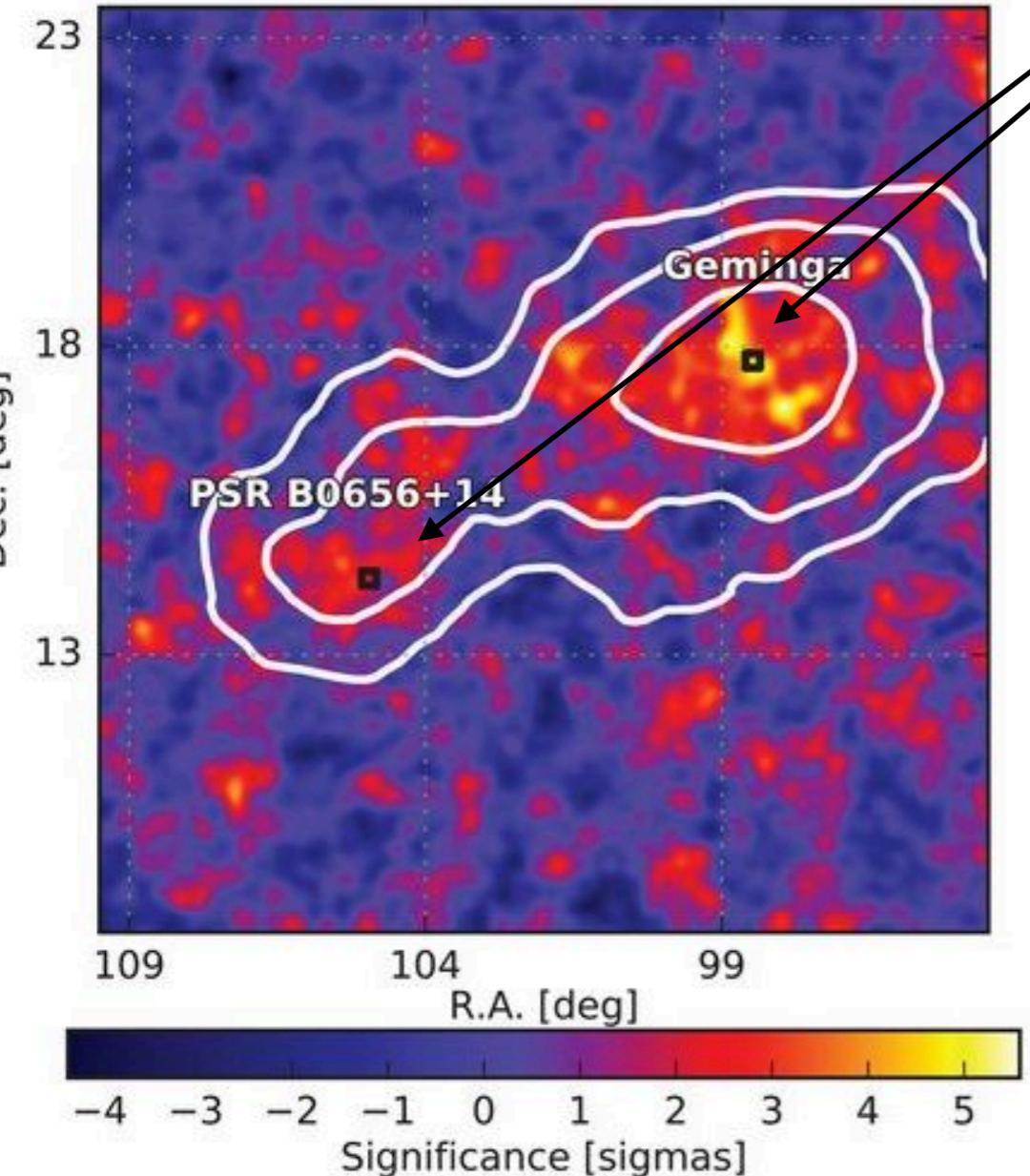
$\sim 20 \text{ TeV } \gamma$ from $\sim 100 \text{ TeV } e^\pm$ (IC)

- Evidence for high confinement region
- Contribution to the local flux under debate
 - (see Di Mauro *et al.* astro-ph/1903.05647)
 - (see Profumo *et al.* astro-ph/1803.09731)
 - (see Johannesson *et al.* astro-ph/1903.05509)
- Theoretical prediction of **broken(?) power-law** injection
 - (see Blasi-Amato astro-ph/1007.4745)
 $\Gamma \in [1,2]$ $E \lesssim 300 \text{ GeV}$
 - $\Gamma > 2$ $E > 300 \text{ GeV}$

High-energy e^+ spectrum

Evidence for high-energy e^\pm from Geminga and Monogem

Abeysekara *et al.* Science Vol. 358, Issue 6365



$\sim 20 \text{ TeV } \gamma$ from $\sim 100 \text{ TeV } e^\pm$ (IC)

- Evidence for high confinement region
- Contribution to the local flux under debate
 - (see Di Mauro *et al.* astro-ph/1903.05647)
 - (see Profumo *et al.* astro-ph/1803.09731)
 - (see Johannesson *et al.* astro-ph/1903.05509)
- Theoretical prediction of **broken(?) power-law** injection
 - (see Blasi-Amato astro-ph/1007.4745)
 $\Gamma \in [1,2]$ $E \lesssim 300 \text{ GeV}$
 $\Gamma > 2$ $E > 300 \text{ GeV}$

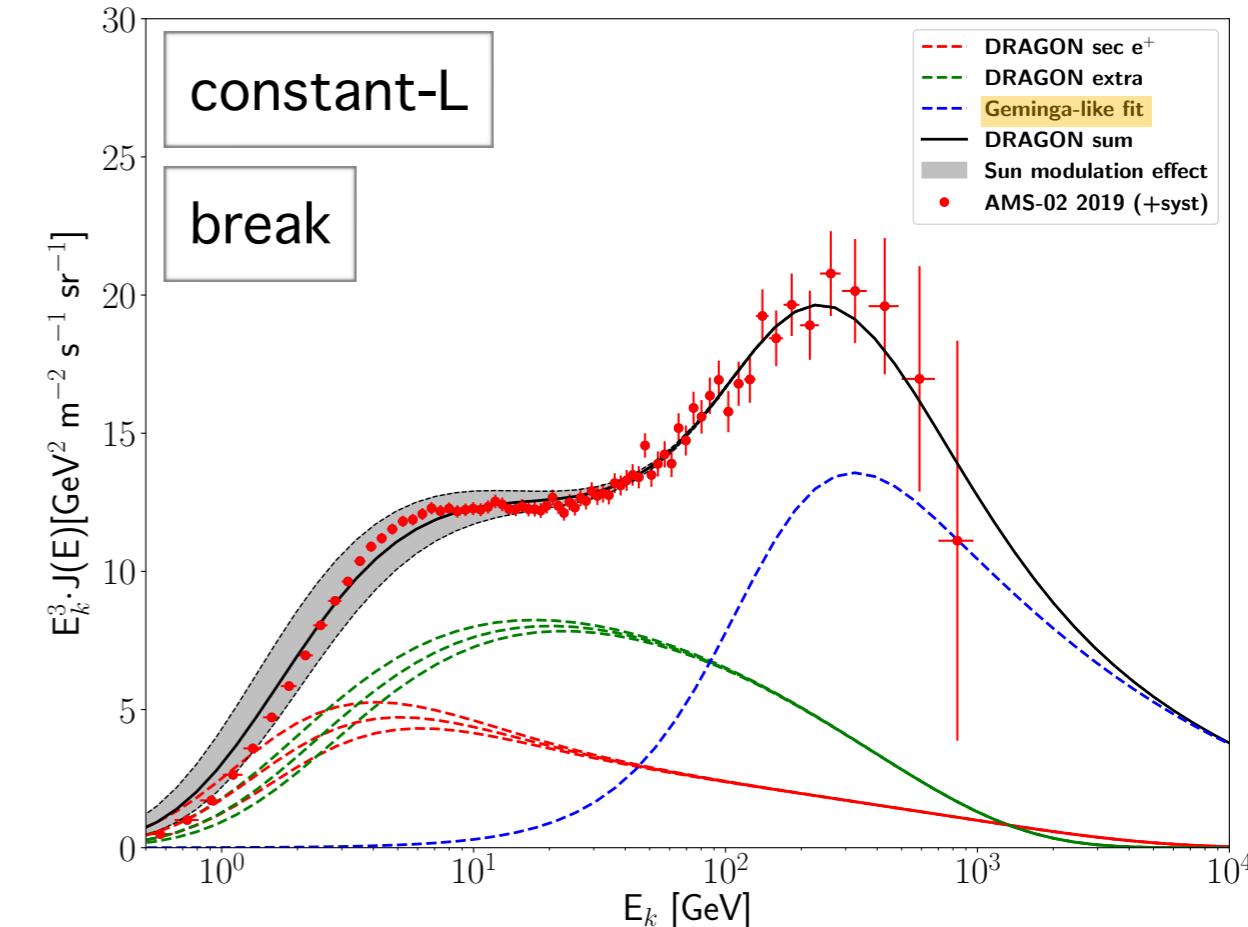
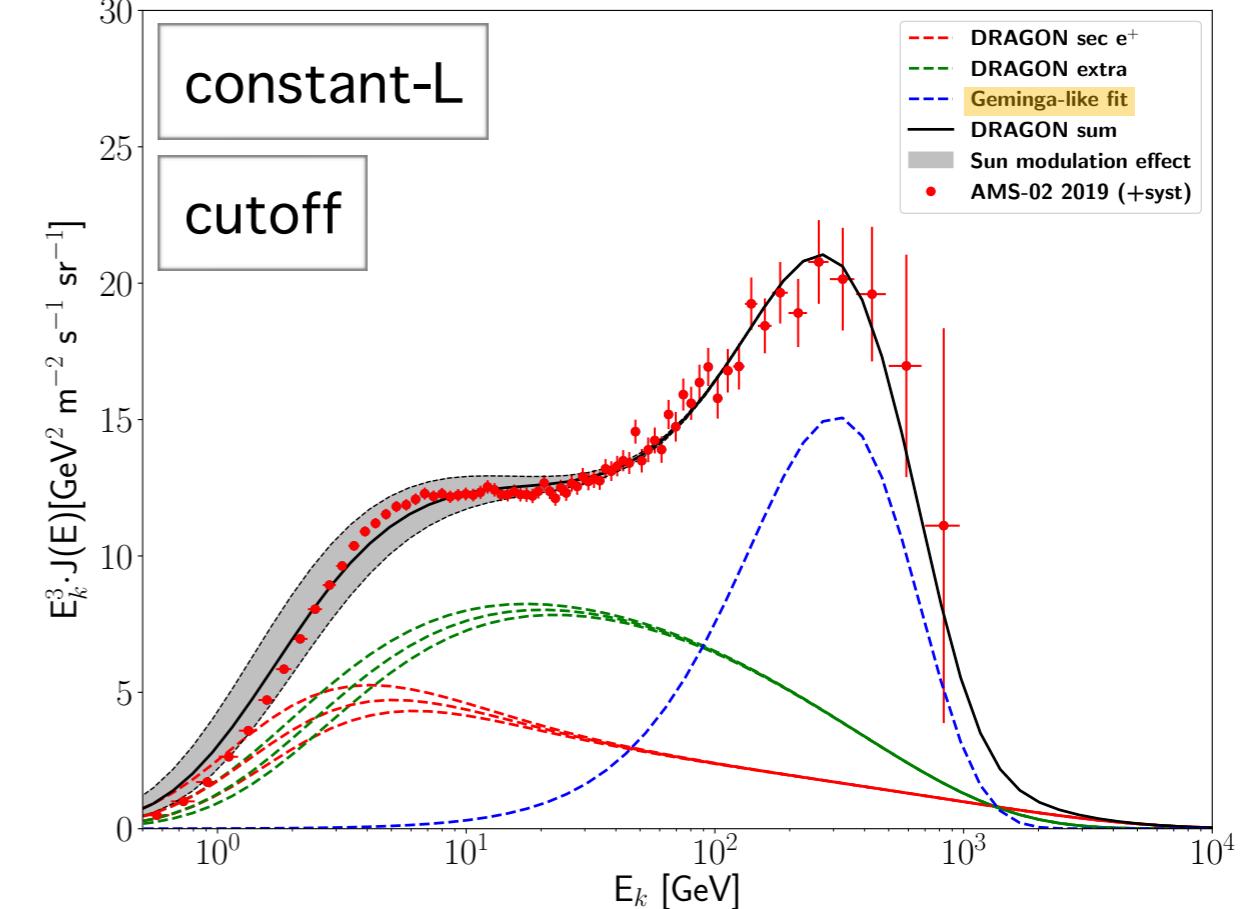
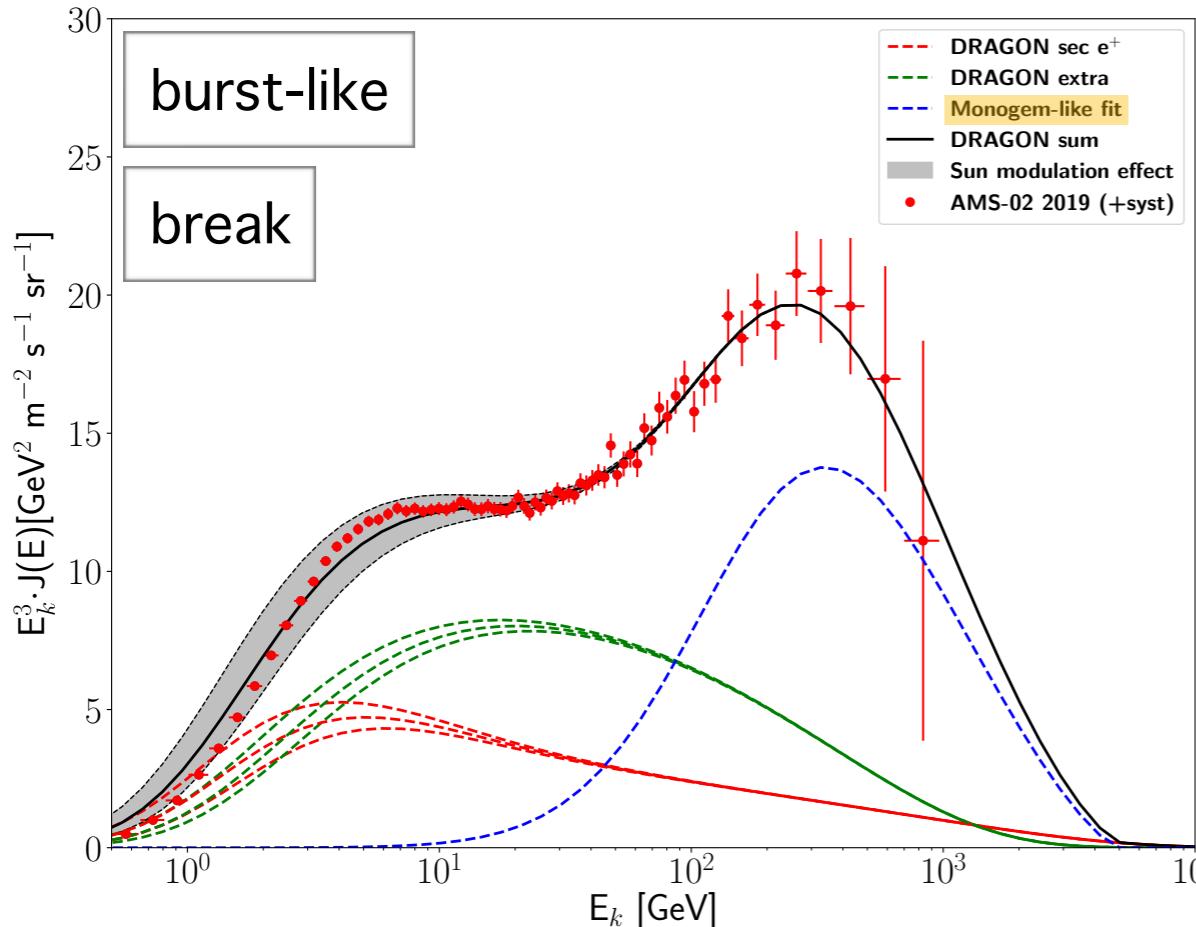
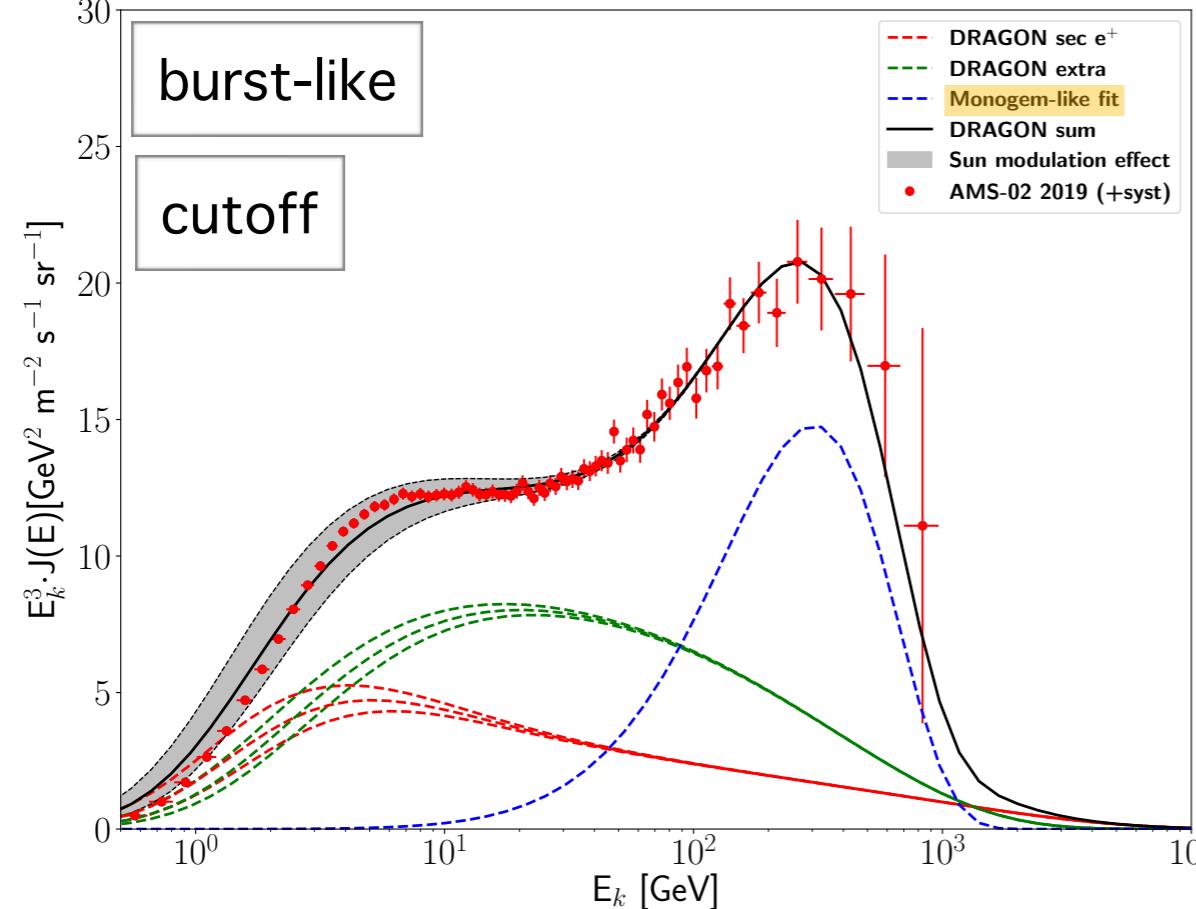
peak energy of the positron flux

High-energy spectrum
($E > 40 \text{ GeV}$)



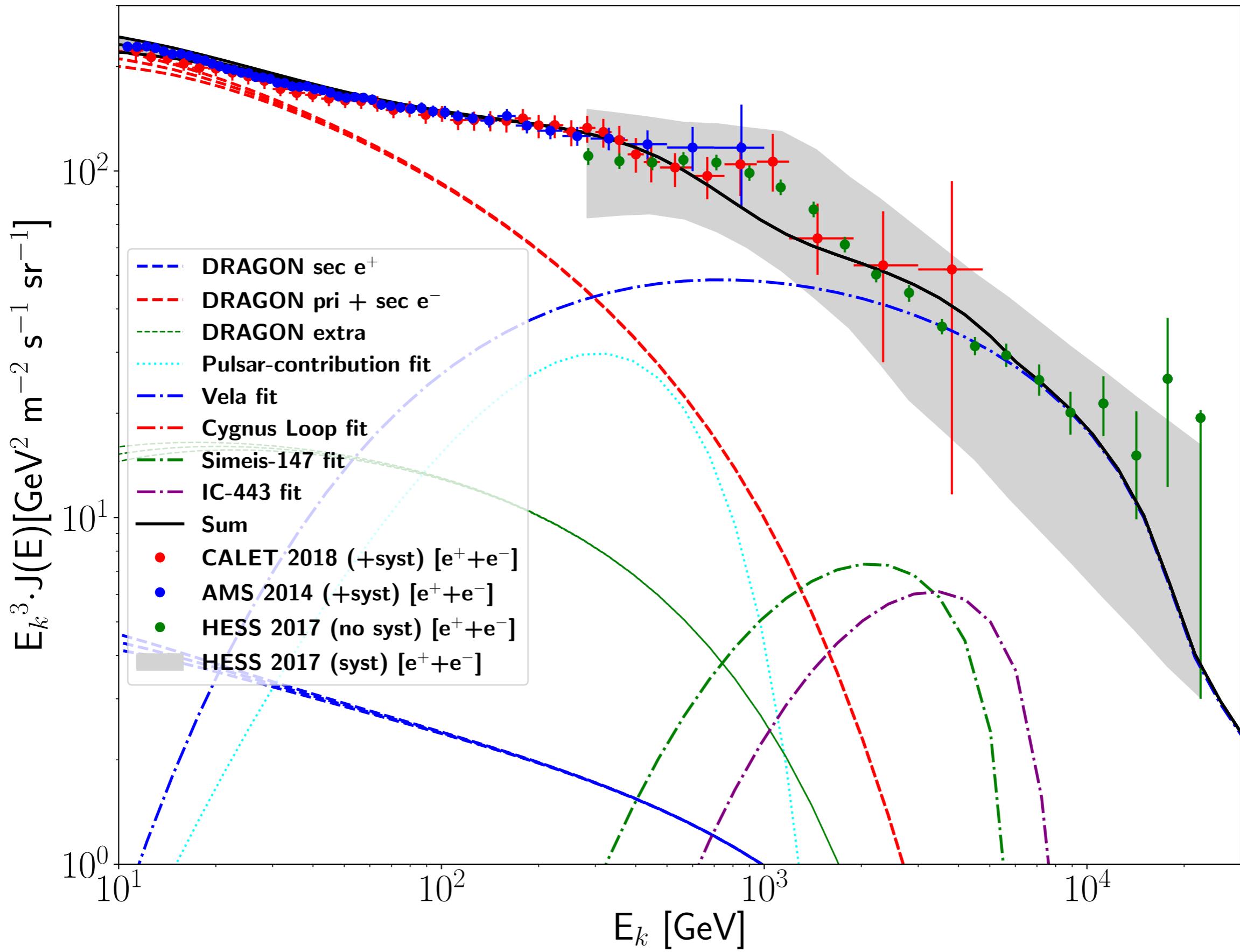
One dominant nearby source with an injection feature (cutoff or break)

Bayesian fit to Positron flux



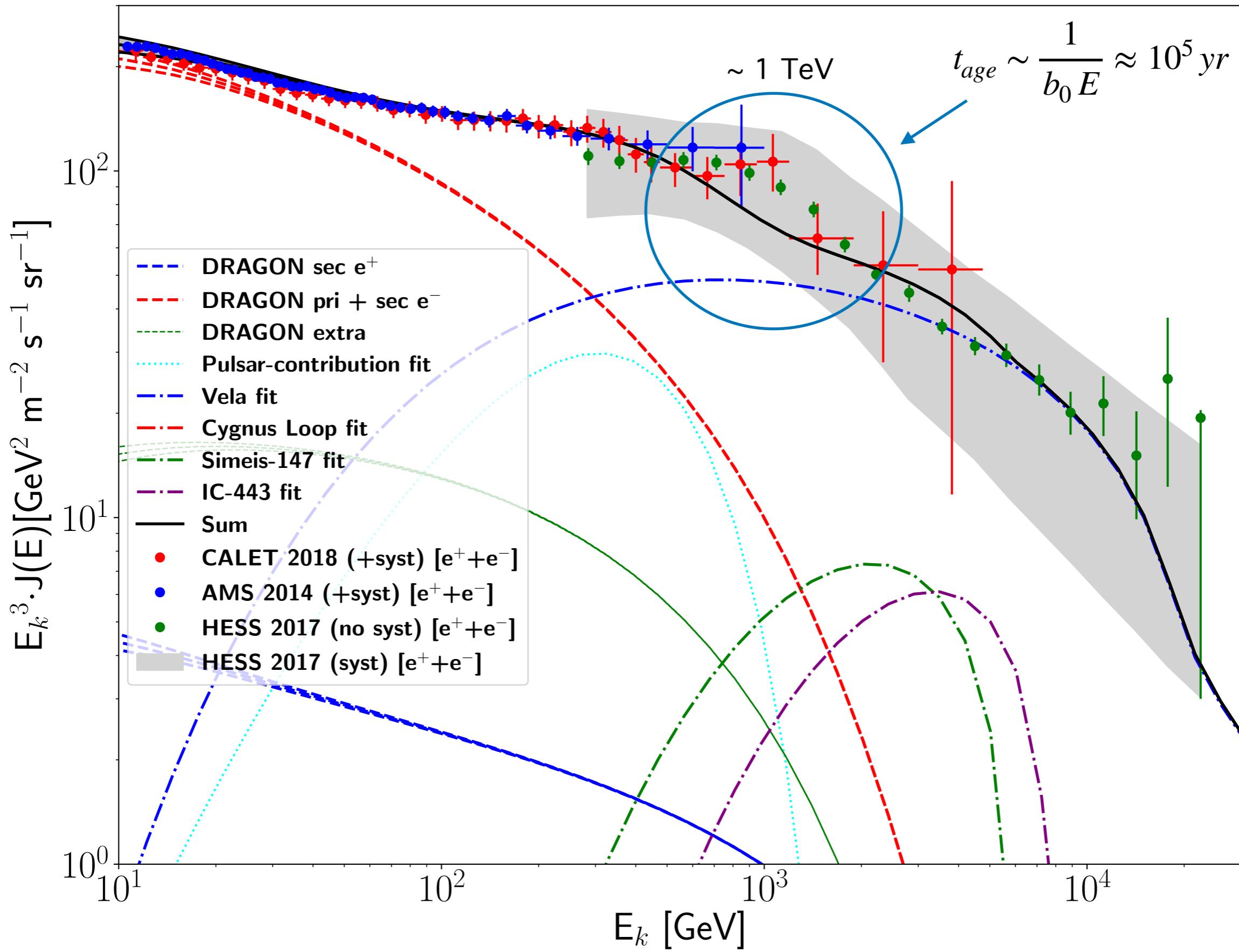
Bayesian fit to $e^+ + e^-$

Observed SNRs



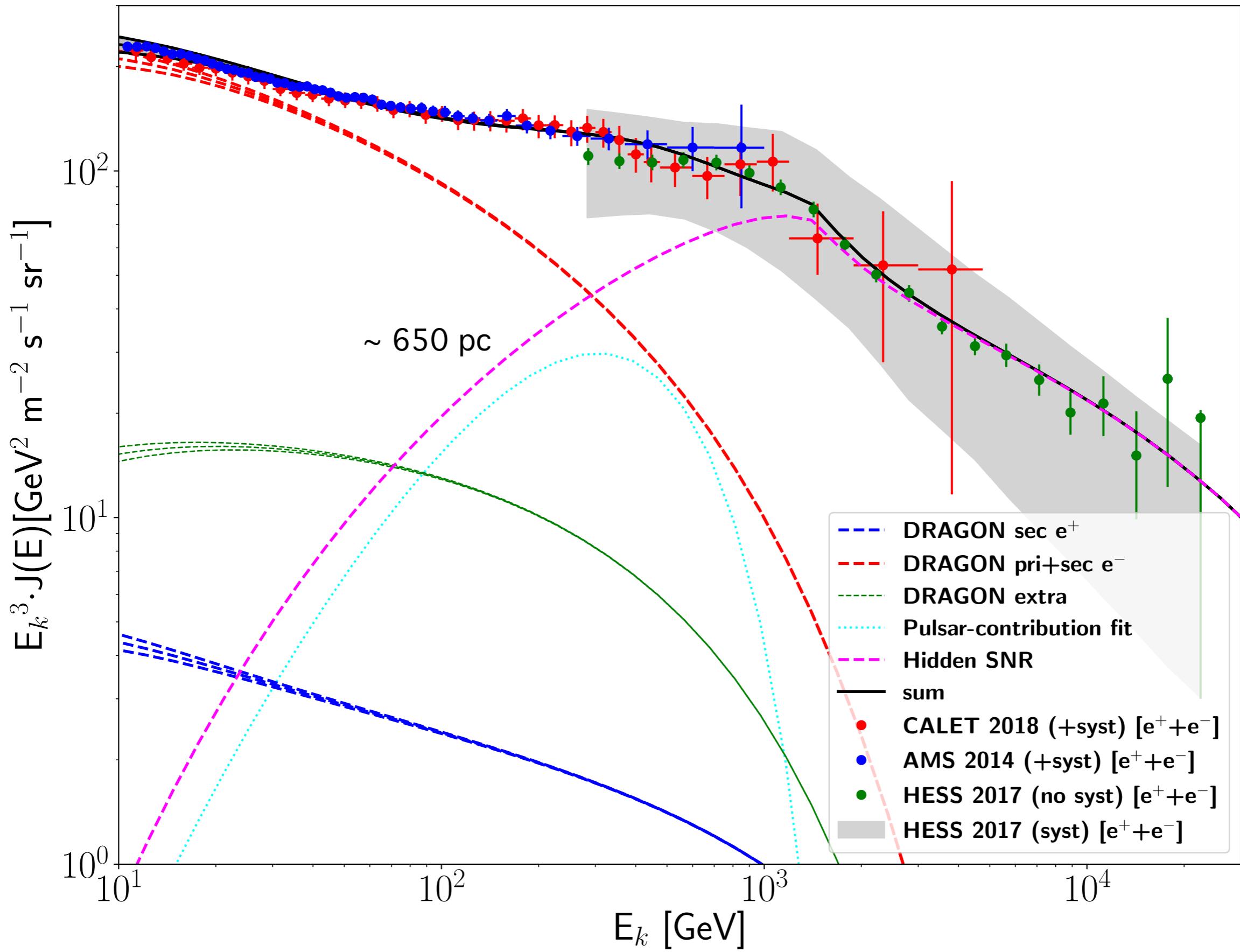
Bayesian fit to $e^+ + e^-$

Observed SNRs



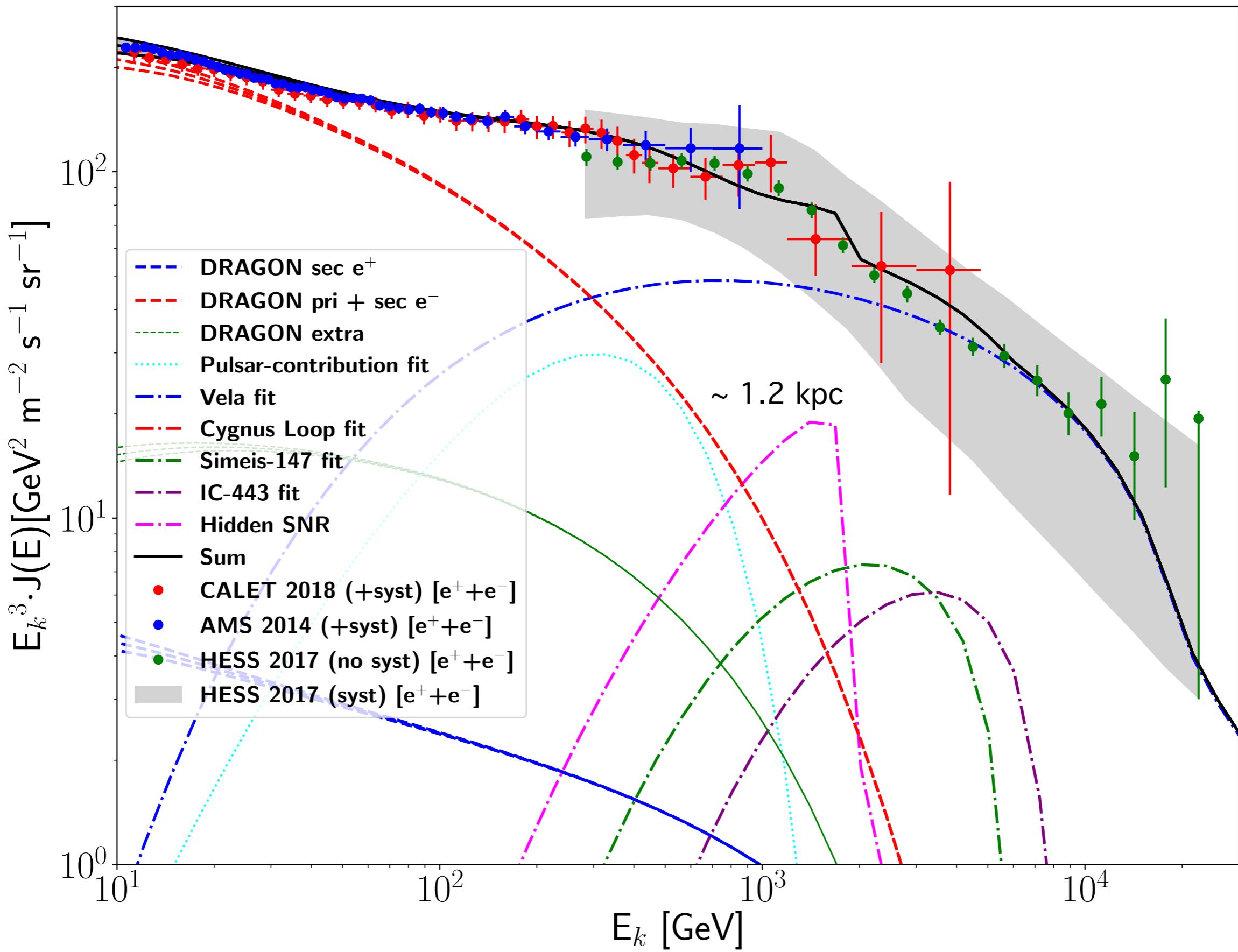
Bayesian fit to $e^+ + e^-$

1 hidden SNR



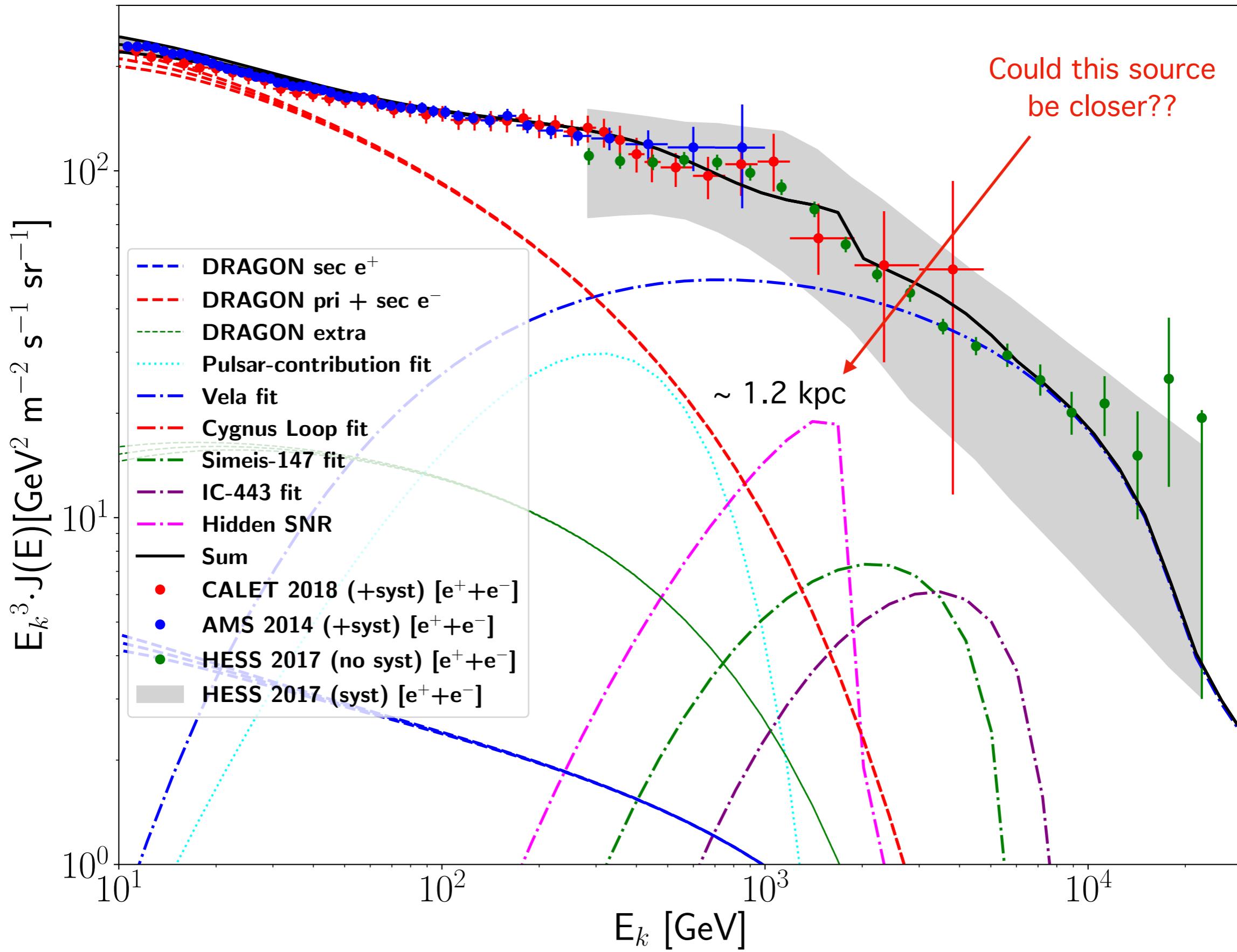
Bayesian fit to $e^+ + e^-$

4 observed + 1 hidden SNR



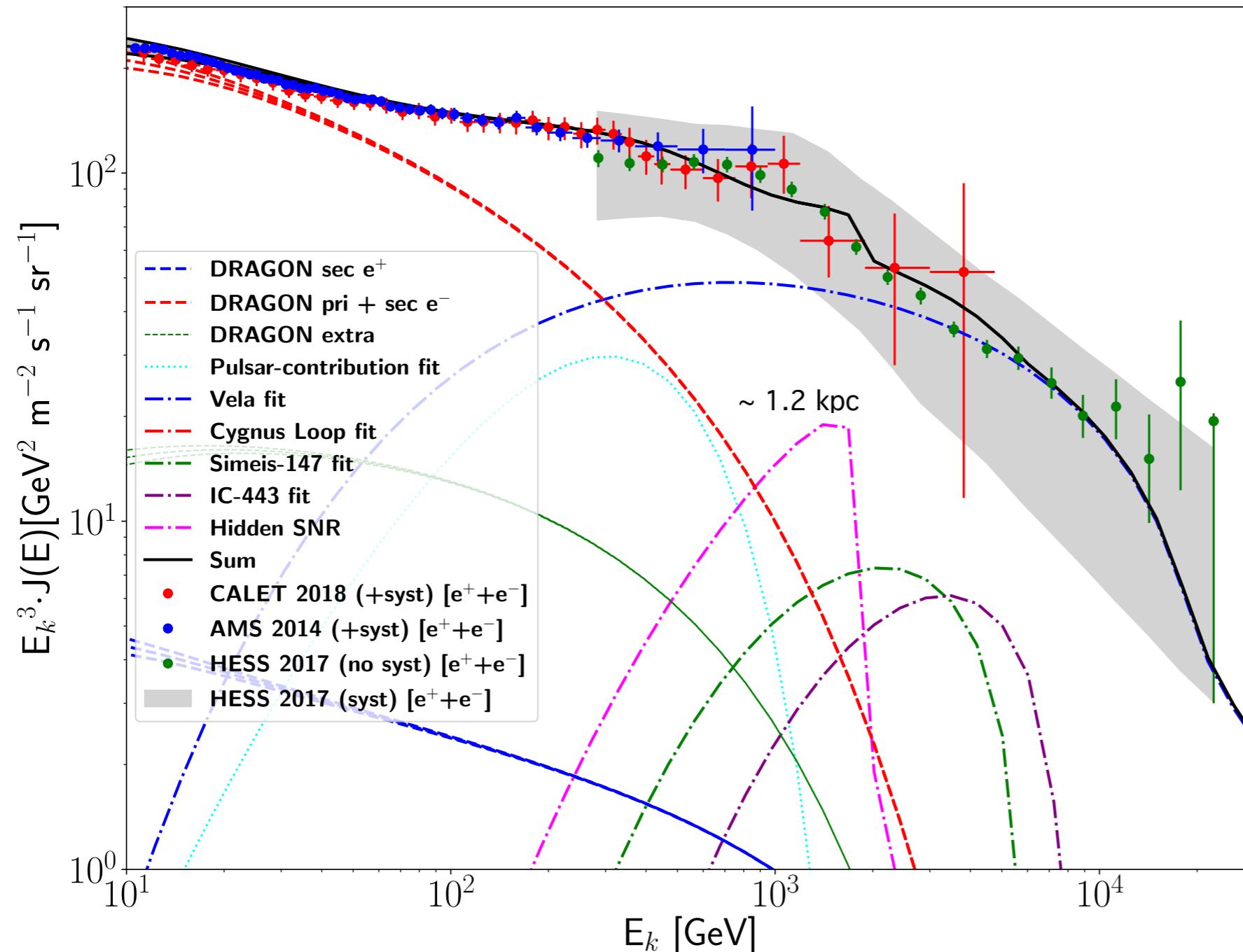
Bayesian fit to $e^+ + e^-$

4 observed + 1 hidden SNR

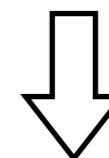


Bayesian fit to $e^+ + e^-$

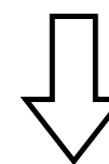
4 observed + 1 hidden SNR



Could this source be closer??



Monogem Ring (~ 300 pc)
(uncertain SNR)



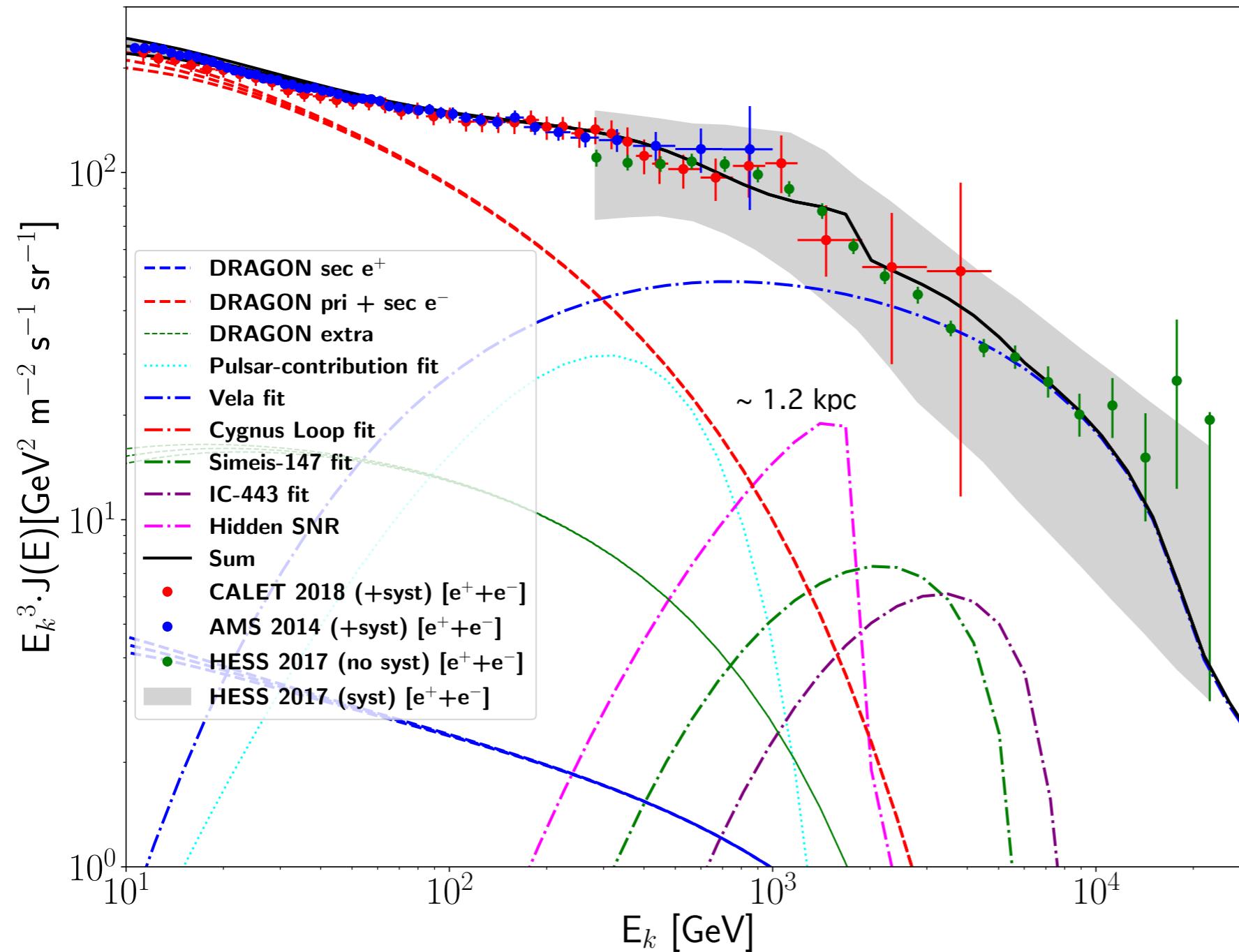
Not according to our
propagation model

$$\left(D_0 = 1.98 \cdot 10^{24} \text{ m}^2/\text{s} @ 1 \text{ GeV} \right)$$

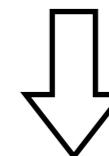
$\delta = 0.45$

Bayesian fit to $e^+ + e^-$

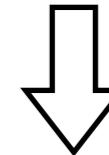
4 observed + 1 hidden SNR



Could this source be closer??



Monogem Ring (~ 300 pc)
(uncertain SNR)



Not according to our
propagation model

$$\left(D_0 = 1.98 \cdot 10^{24} \text{ m}^2/\text{s} @ 1 \text{ GeV} \right)$$

Note: it's possible with different propagation parameters...

(see Recchia-Gabici *Phys. Rev. D* **99**, 103022)

To sum up...

- The standard propagation model presents some **tension in lepton data**
- The invoked pulsar emission mechanisms are not clearly understood and several scenarios are investigated to fit the positron flux
- The observed SNRs do not reproduce the ~ 1 TeV feature in the all-lepton flux
- A shell around the Earth is identified to search for a **hidden source**.

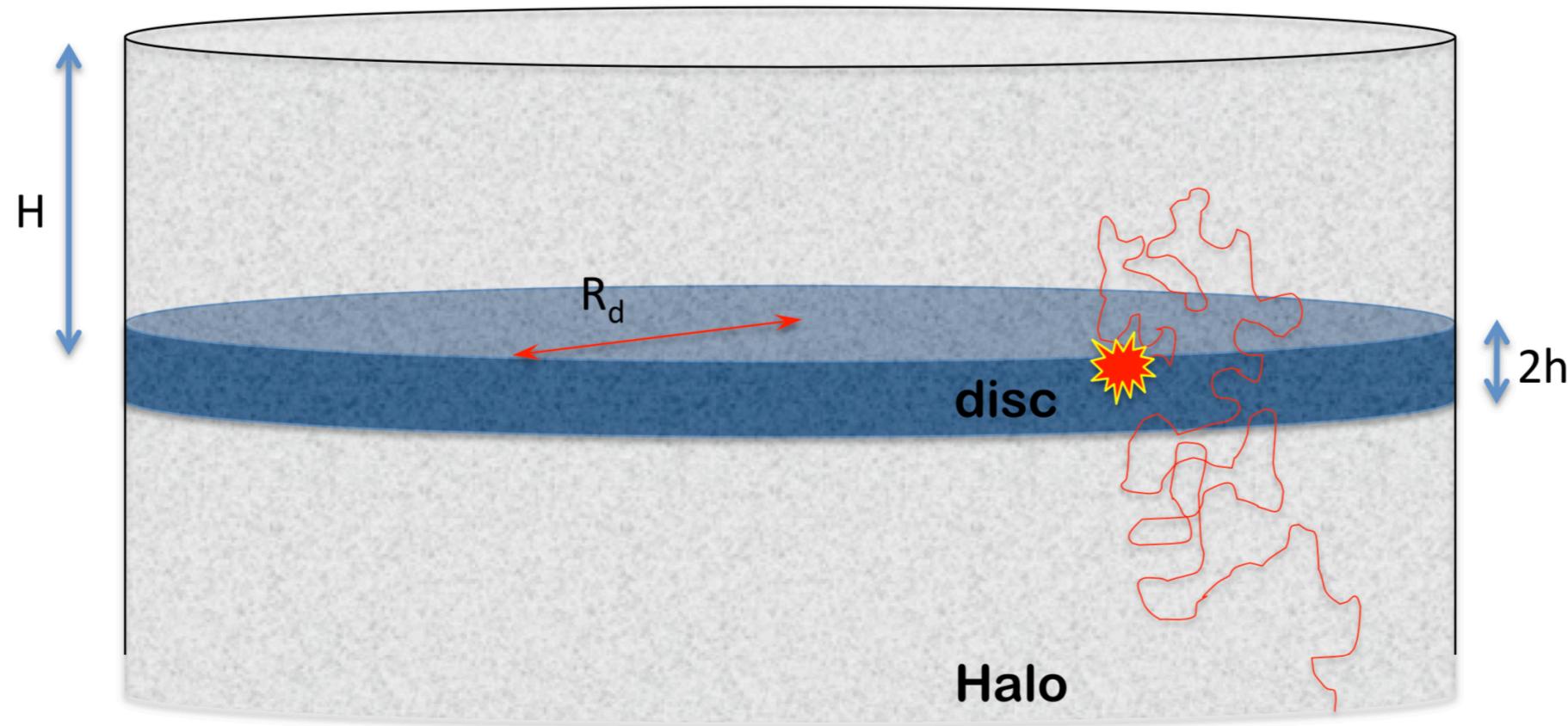
To sum up...

- The standard propagation model presents some **tension in lepton data**
- The invoked pulsar emission mechanisms are not clearly understood and several scenarios are investigated to fit the positron flux
- The observed SNRs do not reproduce the ~ 1 TeV feature in the all-lepton flux
- A shell around the Earth is identified to search for a **hidden source**.

Thanks for listening!

Backup Slides

Standard propagation model

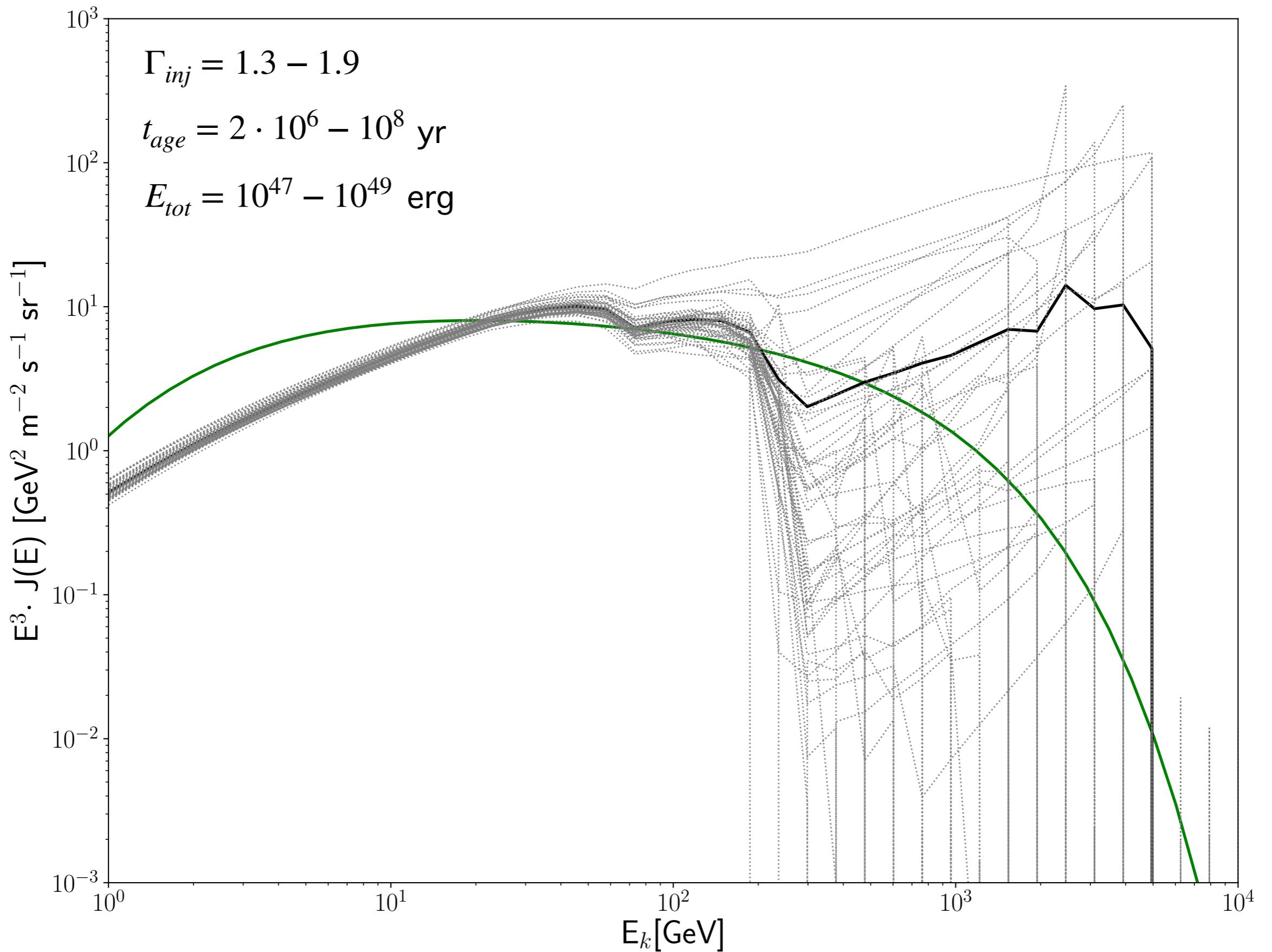


$$\begin{array}{cccccc}
 \text{Diffusion} & \text{Advection} & \text{Re-acceleration} & \text{Losses} & \text{Lorentz} \\
 -\vec{\nabla} \cdot (D \vec{\nabla} N + \vec{v}_w N_i) + \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} \left(\frac{N_i}{p^2} \right) \right] - \frac{\partial}{\partial p} \left[\dot{p} N_i - \frac{p}{3} (\vec{\nabla} \cdot \vec{v}_w) N_i \right] =
 \end{array}$$

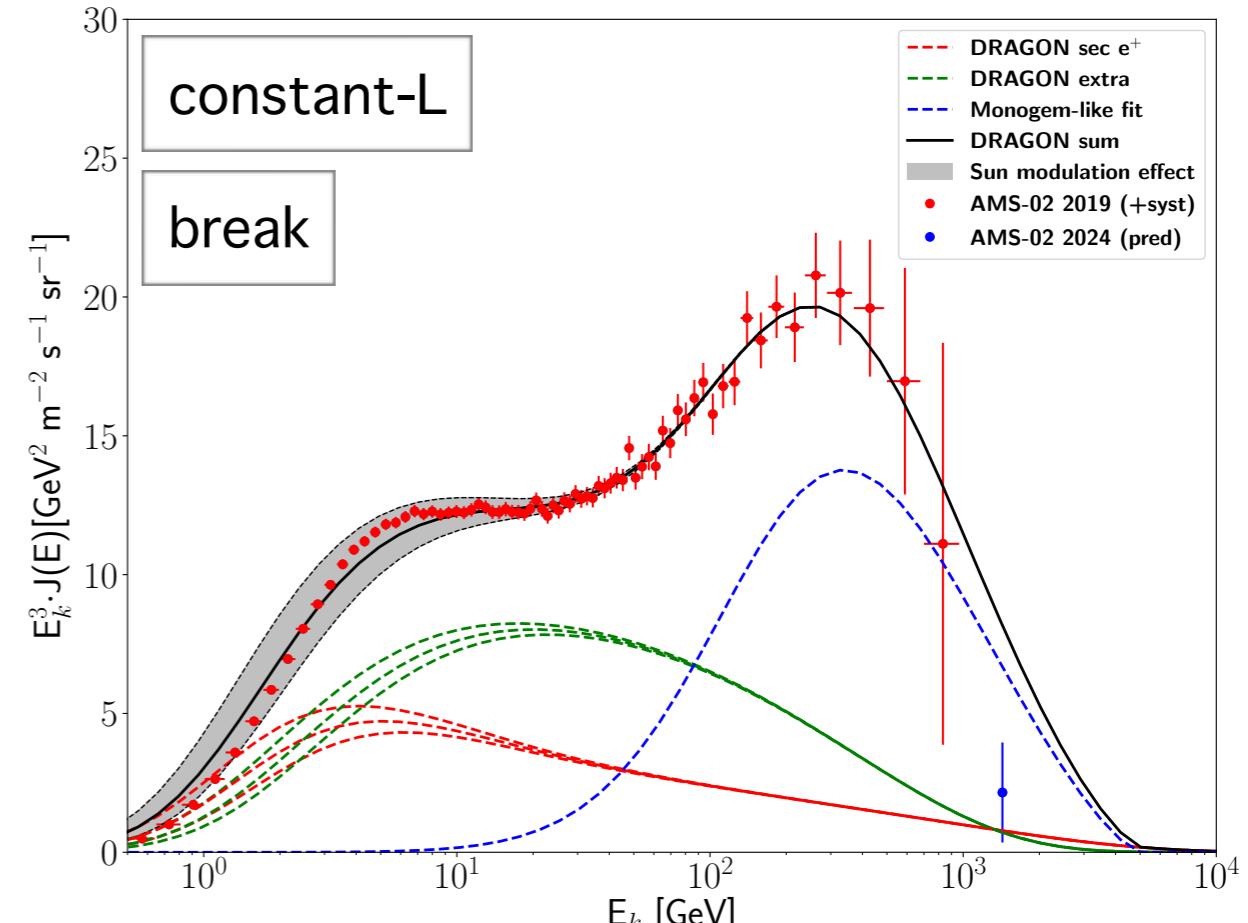
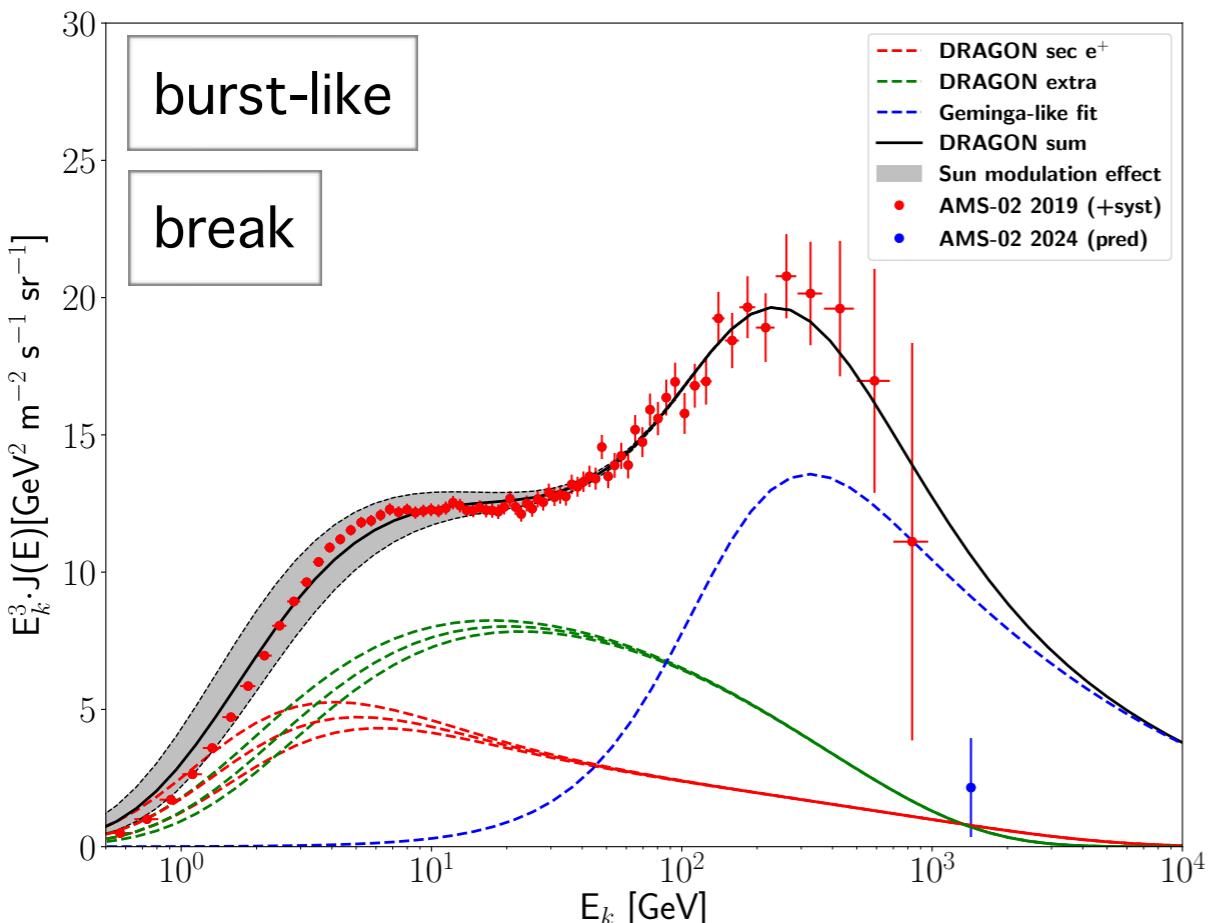
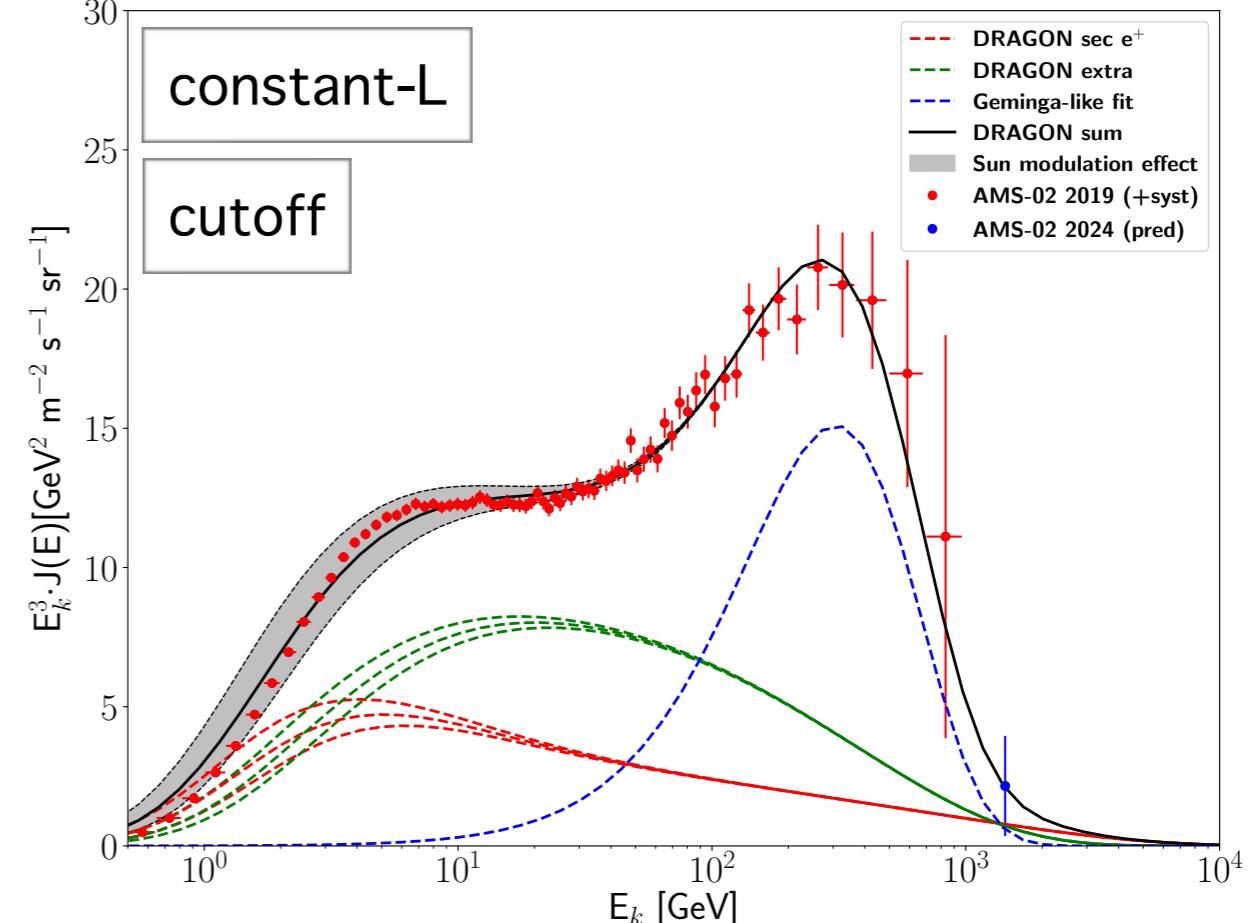
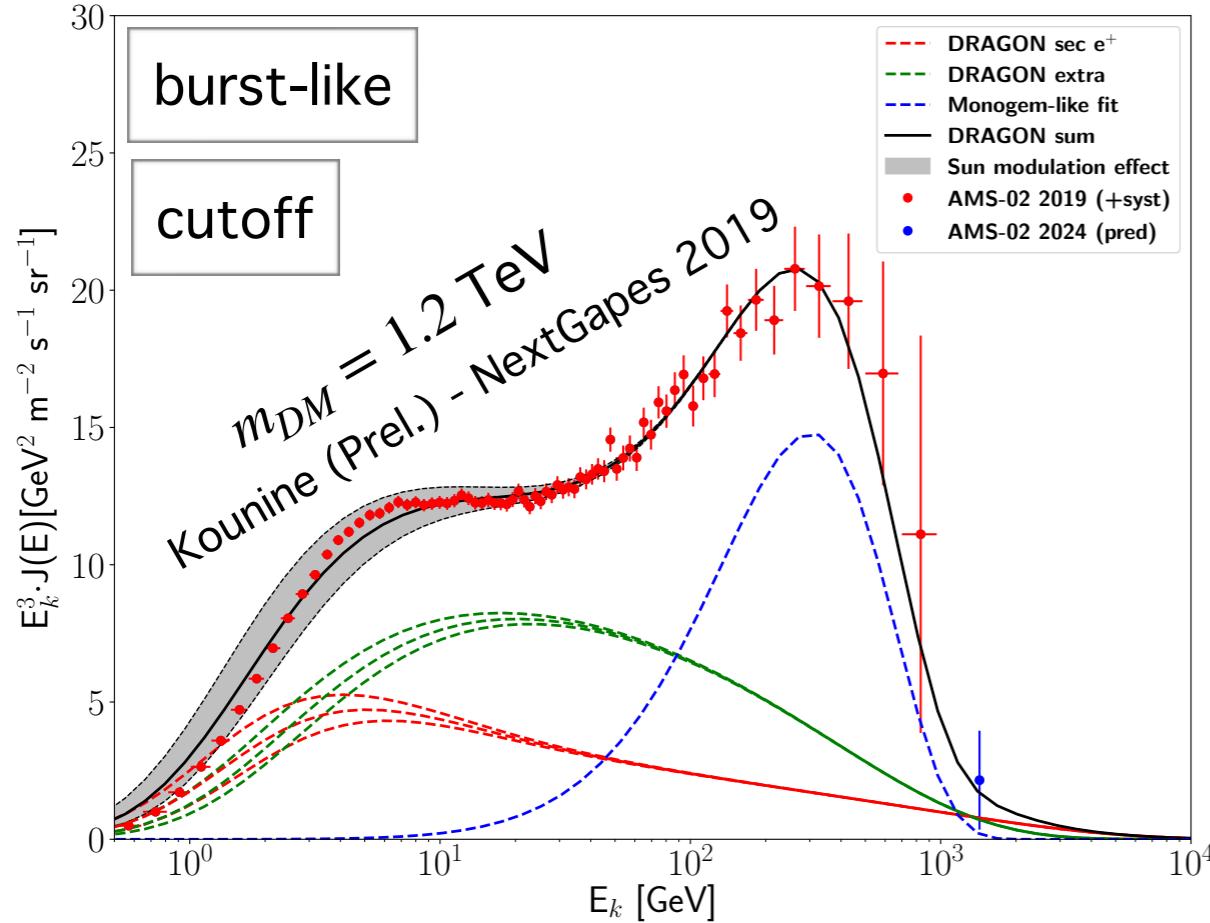
$$Q_{source} + \sum_{i<j} \left(c\beta n_{gas} \sigma_{j \rightarrow i} + \frac{1}{\gamma \tau_{j \rightarrow i}} \right) N_j - \left(c\beta n_{gas} \sigma_i + \frac{1}{\gamma \tau_i} \right) N_i$$

Spallation:
secondary production
Decay:
secondary production

MC-based extra-component



AMS 2024 DM-based prediction



Implications of the MD model

Hypothesis



The bulk of the energy is released by the pulsar via magnetic-dipole emission

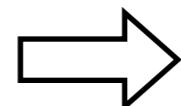
$$\frac{dE_{rot}}{dt} = - \frac{dE_{rad}}{dt} \Rightarrow I\Omega\dot{\Omega} = - \frac{B^2 R^6 \Omega^4}{6c^3} \Rightarrow$$

$$\Rightarrow \dot{\Omega} = -\kappa_{0,MD}\Omega^3$$

$$[\kappa_{0,MD}] \equiv \left[\frac{B^2 R^6}{6Ic^3} \right] = [t]$$

$n = 3$
characteristic of the MD emission.

It is observed $1 < n < 2.4$



$$L(t) = \frac{\eta^\pm L_0}{\left(1 + \frac{t}{\tau_{0,MD}}\right)^2}$$

$$[\tau_{0,MD}] \equiv \left[\frac{3Ic^3}{B^2 R^6 \Omega_0^2} \right] = [t]$$

- For nominal ($n=3$) ATNF pulsars

$$\rightarrow t/\tau_{0,MD} \ll 1 \rightarrow$$

Constant injection

- But
 - $n < 3$ (observed)
 - fit of data (Aharonian & Atoyan 1995)

$$\xrightarrow{?} t/\tau_{0,MD} \gg 1 \rightarrow$$

Burst-like injection

E.m. emission from a system of charges

Energy transfer per unit surface per unit time
(Poynting vector)

$$\vec{S} = c \frac{\vec{H}^2}{4\pi} \hat{n}$$

$$\Rightarrow dI = c \frac{\vec{H}^2}{4\pi} R_0^2 \underbrace{d\Omega}_{\text{infinitesimal surface element}}$$

- First order in $\sim \frac{|\vec{r}'|}{\lambda}$

electric dipole emission

$$dI = \frac{\ddot{d}^2}{4\pi c^3} \sin^2 \theta d\Omega$$

$$\theta = \widehat{\vec{d}} \hat{n}$$

$$\vec{d} = \sum e \vec{r}' \quad \text{electric dipole moment}$$

- Second order in $\sim \frac{|\vec{r}'|}{\lambda}$

magnetic dipole emission

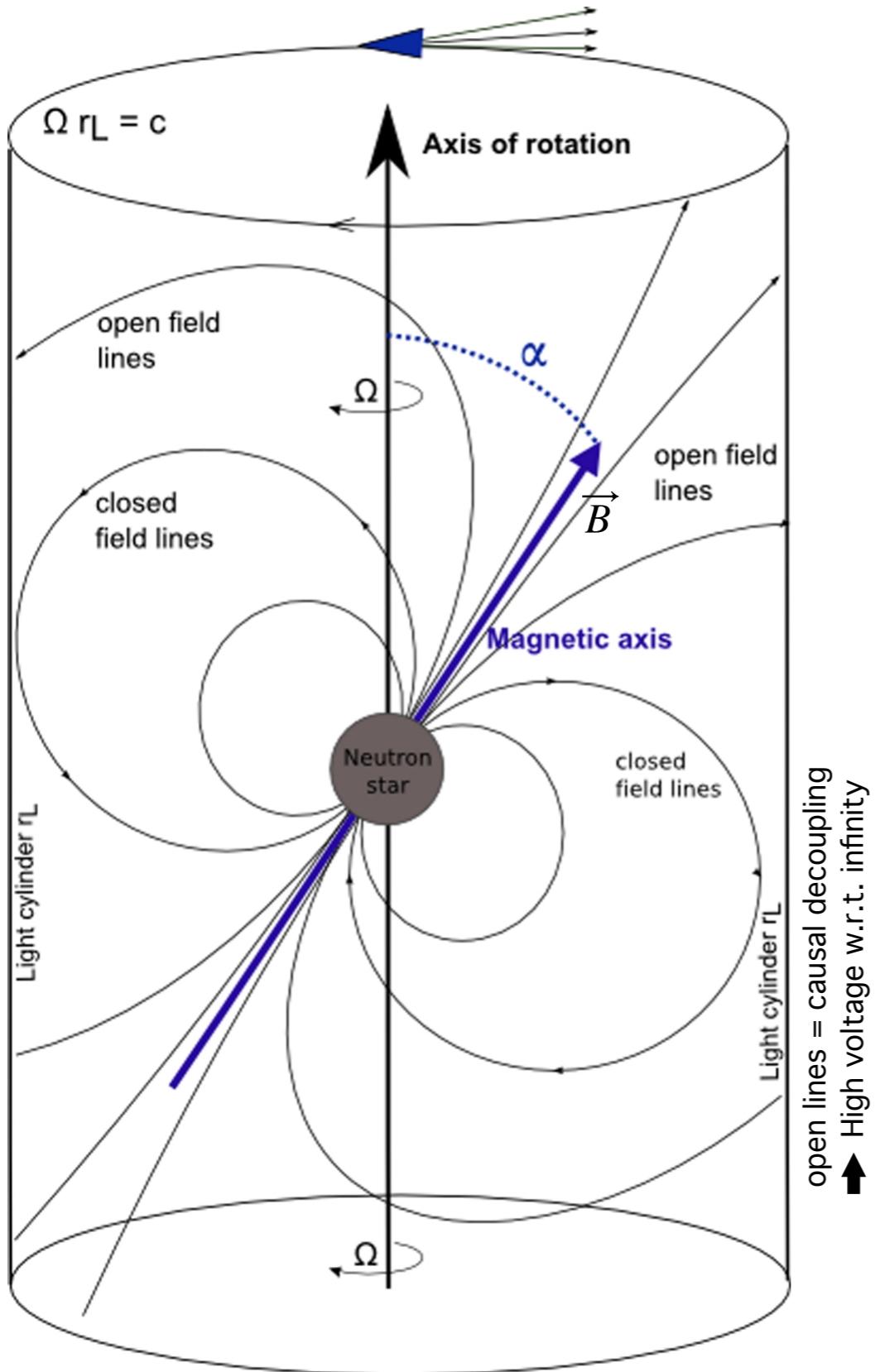
$$dI = \left(\begin{array}{l} \text{electric} \\ \text{quadrupole} \\ \text{term} \end{array} \right) + \frac{\ddot{m}^2}{4\pi c^3} \sin^2 \theta d\Omega$$

$$\theta = \widehat{\vec{m}} \hat{n}$$

$$\vec{m} = \frac{1}{2c} \sum e (\vec{r}' \times \vec{v}) \quad \text{magnetic dipole moment}$$

At first approximation we can assume that pulsars have no electric dipole nor electric quadrupole!

Particle emission from pulsars



- As the star rotates, surface charges (mostly e^-) move in a magnetic field
$$\Rightarrow \vec{E} = \frac{\vec{F}_L}{q} = \vec{v} \times \vec{B}$$
and then get extracted from the pulsar.
- Charges follow the field lines:
 - Along the closed ones there forms a current (synchrotron light is present but not very energetic as \vec{B} is weaker than in the polar cap here)
 - Along the open ones charges escape into outer regions (synchrotron light is intense and can get to the Earth)
→ **This is the observed radio pulse!**
- $e^- + \gamma_B \rightarrow e^- + \gamma_B + \gamma_{sync}$ initiating an e.m. cascade,
→ pair production e^+e^- up to $\sim 10^6$.

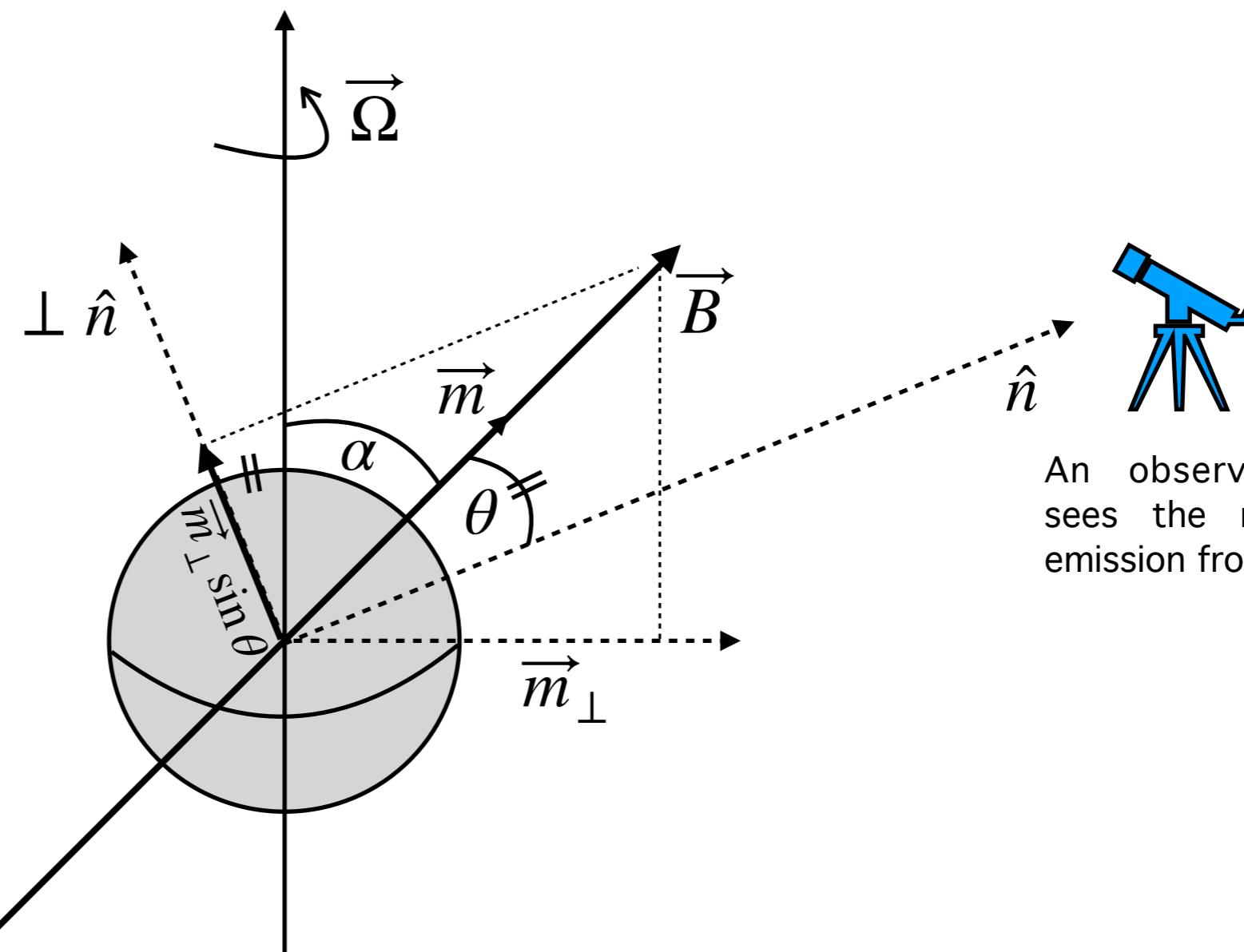
Pulsar magnetic-dipole emission

- For the dipole to emit, we need

$$\vec{\Omega} \nparallel \vec{B} \Rightarrow \alpha \neq 0 \\ \Rightarrow \dot{\vec{m}}_{\perp} \neq 0$$

- For us to see the emission, we need

$$\theta \neq 0$$



An observer here sees the maximum emission from \vec{m}_{\perp} .

This radiation depends on the variation of \vec{m}_{\perp} , which follows the rotation



$$\nu_{m.d.} \sim \frac{1}{P} \quad P=1.3s \text{ (Bell)} \quad \frac{1}{s} \sim \text{Hz}$$

$$E_{\gamma} \sim 4 \cdot 10^{-15} \text{ eV}$$

does not account for Bell observation of $E_{\gamma} \sim 4 \cdot 10^{-7} \text{ eV}$

$\nu_{m.d.}$ is very low energetic and gets absorbed by the surrounding ISM,
 → it's not the observed periodic pulse!