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INFN BARI
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Cosmic-ray interactions with the Sun

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Introduction

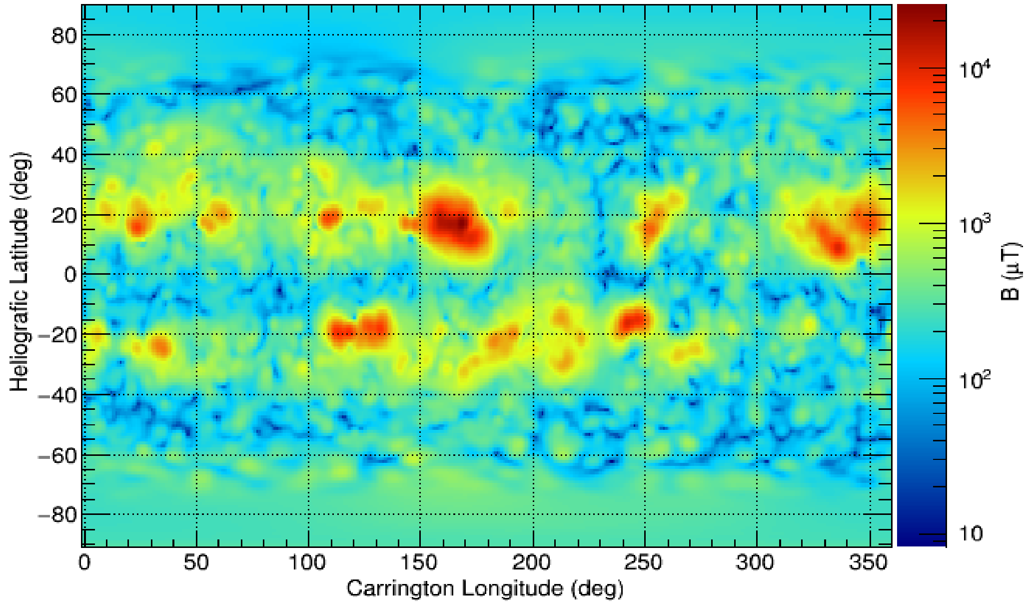
- The Sun is a bright source of high-energy gamma rays
- The solar gamma-ray emission consists of two components:
  - Disk emission
    - Due to cosmic-ray nuclei interacting with the solar surface
    - Localized around the solar disk
    - The strong magnetic field nearby the Sun affects this emission
  - Diffuse emission
    - due to the inverse Compton scatterings of cosmic ray electrons (and positrons) with the solar optical photons
    - Extends up to tens of degrees from the Sun
- The knowledge of solar emission could be used to constrain exotic processes
  - Example: production of standard model particles in the annihilations/decays of dark matter particles captured by the Sun
- This work is focused on the modeling of the disk emission
  - A full simulation with the FLUKA code has been employed to calculate the yields of secondary particles produced by the interactions of cosmic rays with the Sun

Outline

- Simulation set-up
  - Inner magnetic field configuration
  - Interplanetary field configuration
  - Solar composition
  - Radial density, temperature and pressure profiles
- Production yields of secondary particles
- Cosmic-ray spectra at the Sun and secondary spectra at the Earth
- Effect of the inner magnetic field on the secondary spectra
- Conclusion and outlook

Simulation set-up (1)

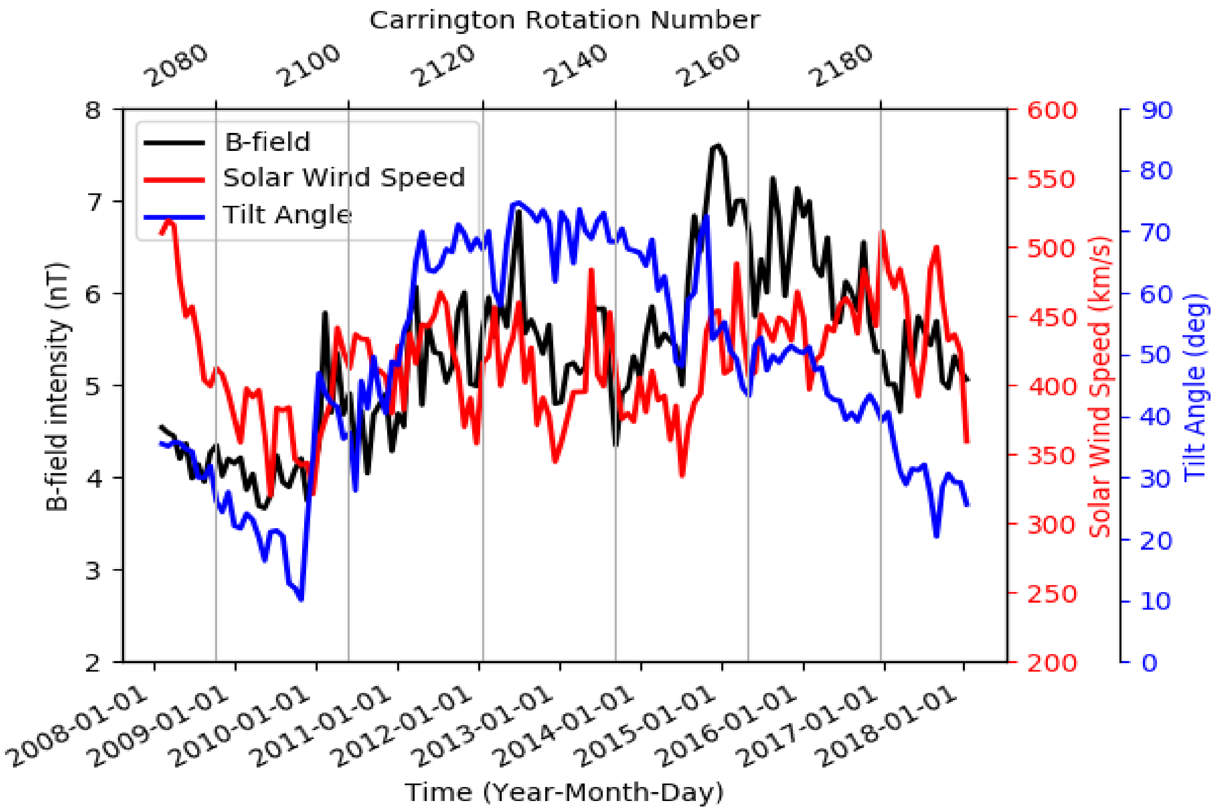
- Inner magnetic field in the region close to the Sun
  - Model of the magnetic field up to a distance of 2.5R⊙ (=Rs, i.e. solar surface region)
  - The potential field source surface (PFSS) model is adopted in which the field is purely radial at the source surface
    - Synoptic magnetic field maps are available as a function of the Carrington longitude and latitude angles for each Carrington Rotation number (CRn) from the Solar Dynamics Observatory Joint Science Operations Center (JSOC) at Stanford
  - An enhanced field configuration has been also implemented, based on the BIFROST MHD model



Magnetic field intensity as a function of the Carrington longitude and latitude angles at R⊙ for the CRn 2111 (2011-06-05 17h to 2011-07-03 00h)

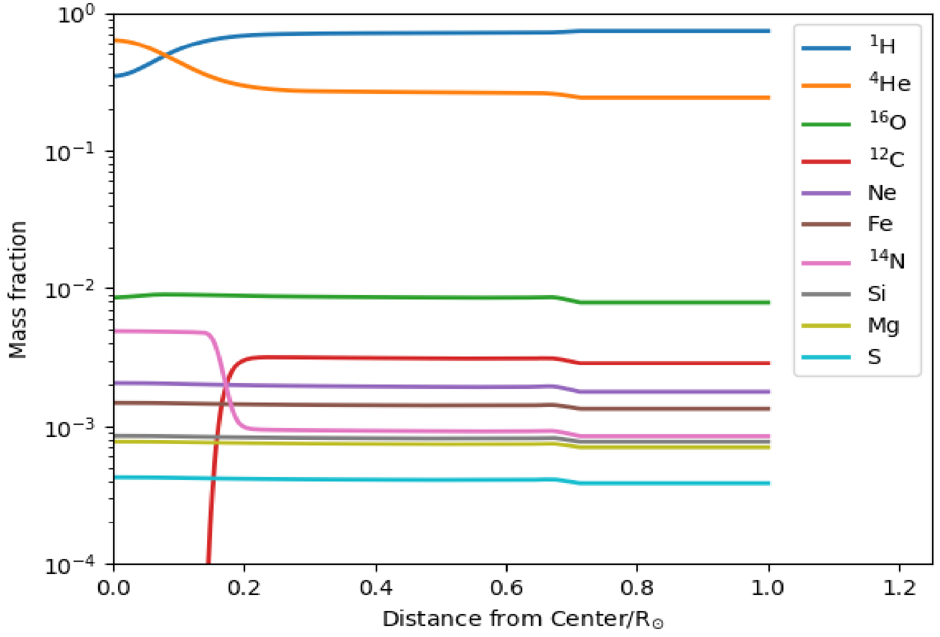
Simulation set-up (2)

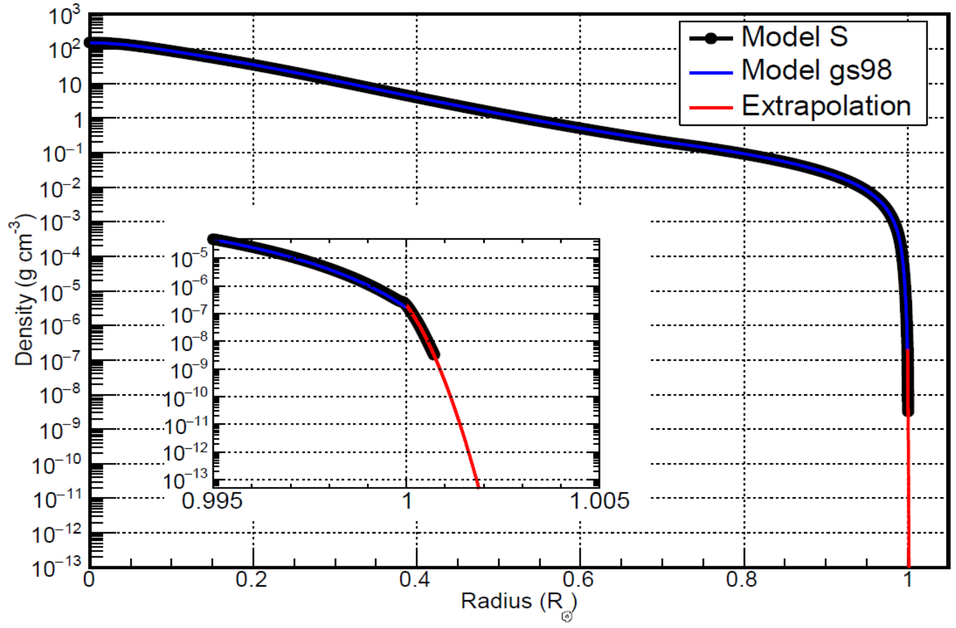
- The Parker model ($r>R_s$) is adopted for the interplanetary magnetic field
  - Intensity of the magnetic field at Earth and solar wind velocity derived from the observations of the ACE satellite
  - The tilt angle of the heliospheric current sheet as a function of time is extracted from the Wilcox Solar Observatory public data



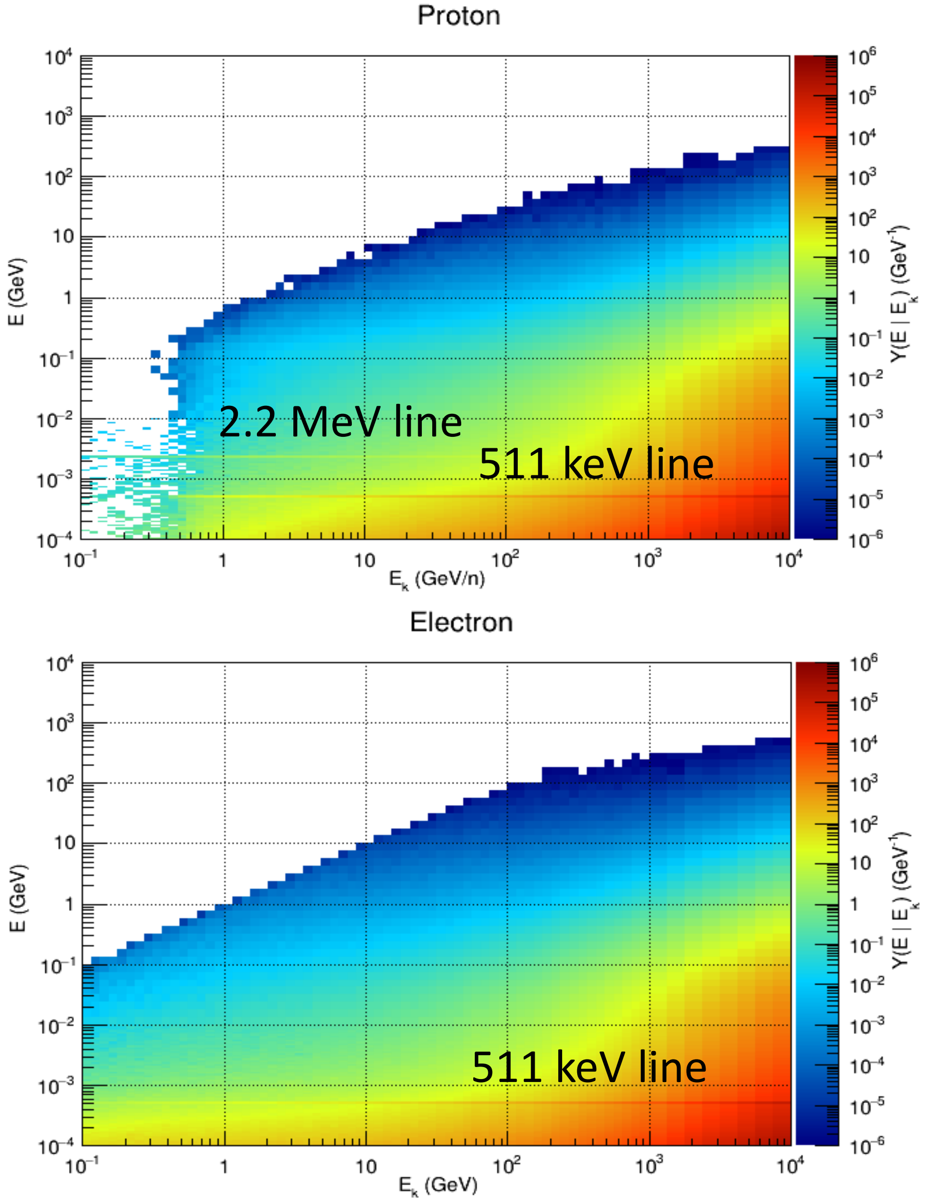
Simulation set-up (3)

- Solar composition
  - Mass composition of the Sun as a function of the radial distance from the center taken from the Standard Solar Models (SSMs) Vinyoles et al. Astrophys. J. 835, 202 (2017) (hereafter Model gs98)
- For the radial density, temperature and pressure profiles we use the model provided by Christensen-Dalsgaard et al. Science 272, 1286 (1996) (hereafter Model S)
  - The model extends up to about 500 km above the solar surface
  - Model gs98 is very similar to the Model S
  - The density model has been extrapolated to higher altitudes up to about 1400 km





Simulation results: gamma-ray yield



- Examples of gamma-ray yields from primary protons, He nuclei and electrons
- Particles generated on a sphere of radius r=Rs(=2.5R⊙), with an isotropic and uniform distribution
- The inner B-field configuration is the PFSS @ CRn 2111

Secondary spectra at the Earth

- Differential intensity of secondary particles at production:

$$I_s(E_s) = \sum_i \int Y_{s,i}(E_s|\, E_k)\; I_i(E_k) dE_k$$

  - s = secondary particle species (gamma rays, neutrinos, …)
  - $I_i(E_k)$ = intensity of the i-th species of cosmic rays (protons, He nuclei, electrons) at the Sun
    - They have been calculated with a dedicated propagation code in the solar system and by using the spectra measured at the Earth by AMS in different epochs as reference

- Flux of secondaries at Earth:

$$\phi_s(E_s) = \frac{\pi\, R_{gen}^2}{R_{Earth}^2} I_s(E_s)\, \mathcal{F}(E_s)$$

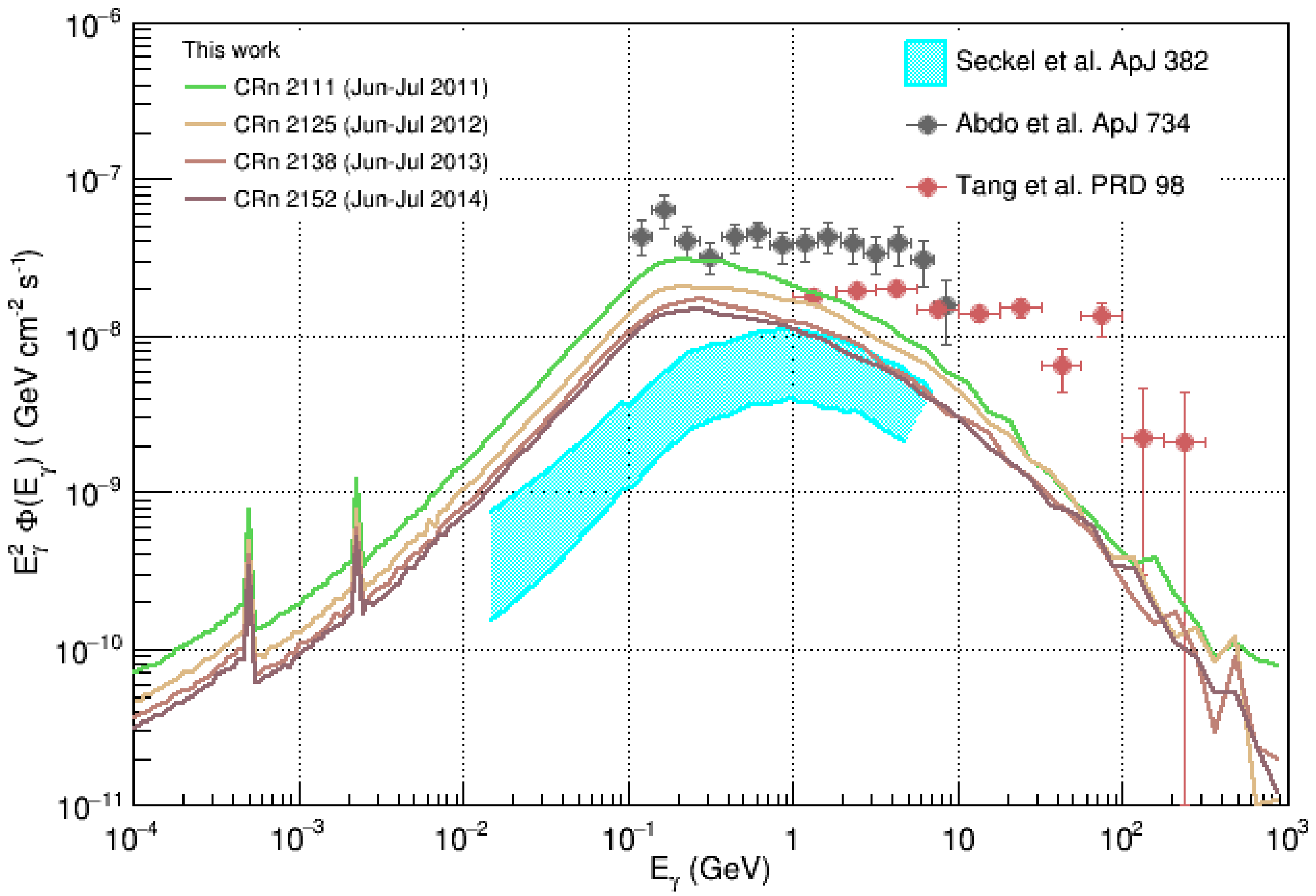
  - $\mathcal{F}(E_s)$ = fraction of secondaries with energy Es which can reach the Earth's orbit from the Sun
    - For gamma rays and neutrinos we assume $\mathcal{F}(E_s) = 1$

- We assume that the Earth's orbit lays on a sphere centered on the Sun with radius r = R_{earth} (i.e. we do not simulate the Earth orbital motion)

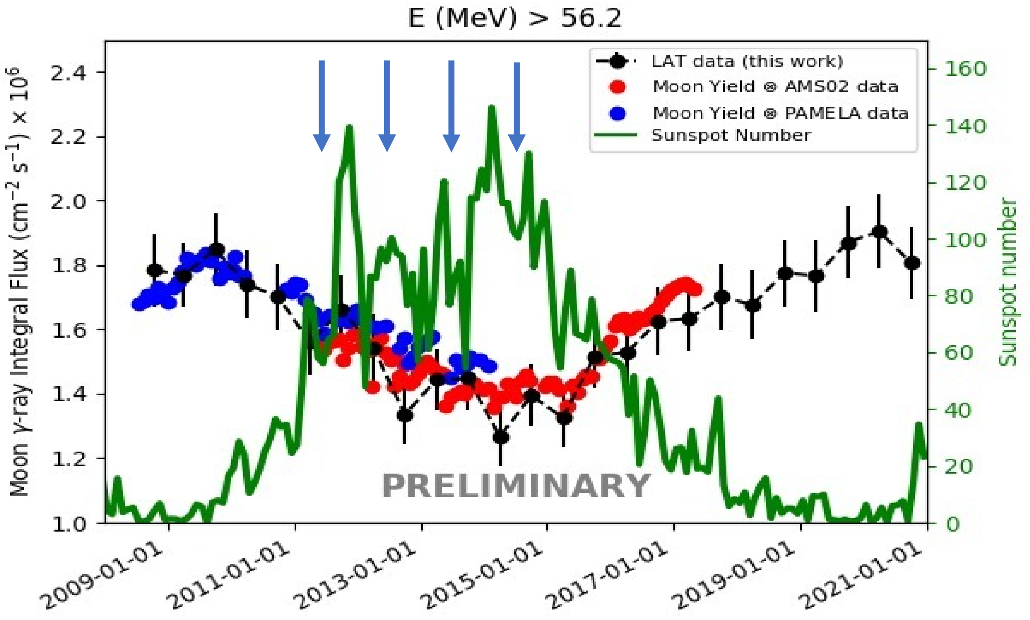
Gamma-ray fluxes at the Earth

CR	$\Phi_\gamma(>100\ \mathrm{MeV})$ $\times10^{-7}\ \mathrm{cm^{-2}\ s^{-1}}$	$\Phi_\gamma(>1\ \mathrm{GeV})$ $\times10^{-8}\ \mathrm{cm^{-2}\ s^{-1}}$	$\Phi_\gamma(>10\ \mathrm{GeV})$ $\times10^{-9}\ \mathrm{cm^{-2}\ s^{-1}}$
2111	2.59 ± 0.02	1.42 ± 0.02	2.61 ± 0.10
2125	1.79 ± 0.01	1.16 ± 0.02	2.19 ± 0.08
2138	1.38 ± 0.01	0.84 ± 0.02	1.66 ± 0.06
2152	1.23 ± 0.01	0.74 ± 0.02	1.51 ± 0.05

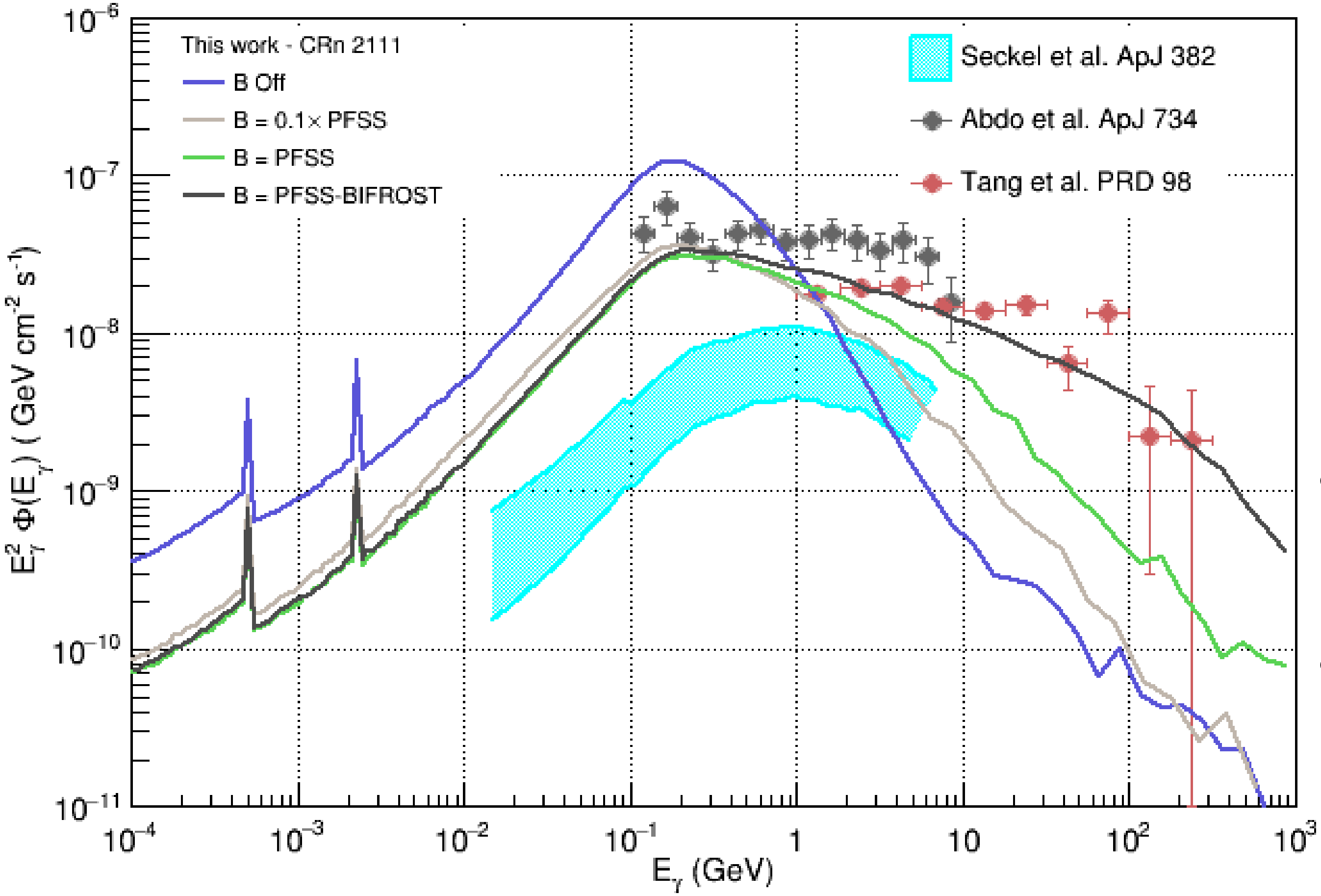
Predicted fluxes for four different Carrington Rotation Numbers



- Fermi-LAT Moon data (see S. De Gaetano+, contribution at this conference)



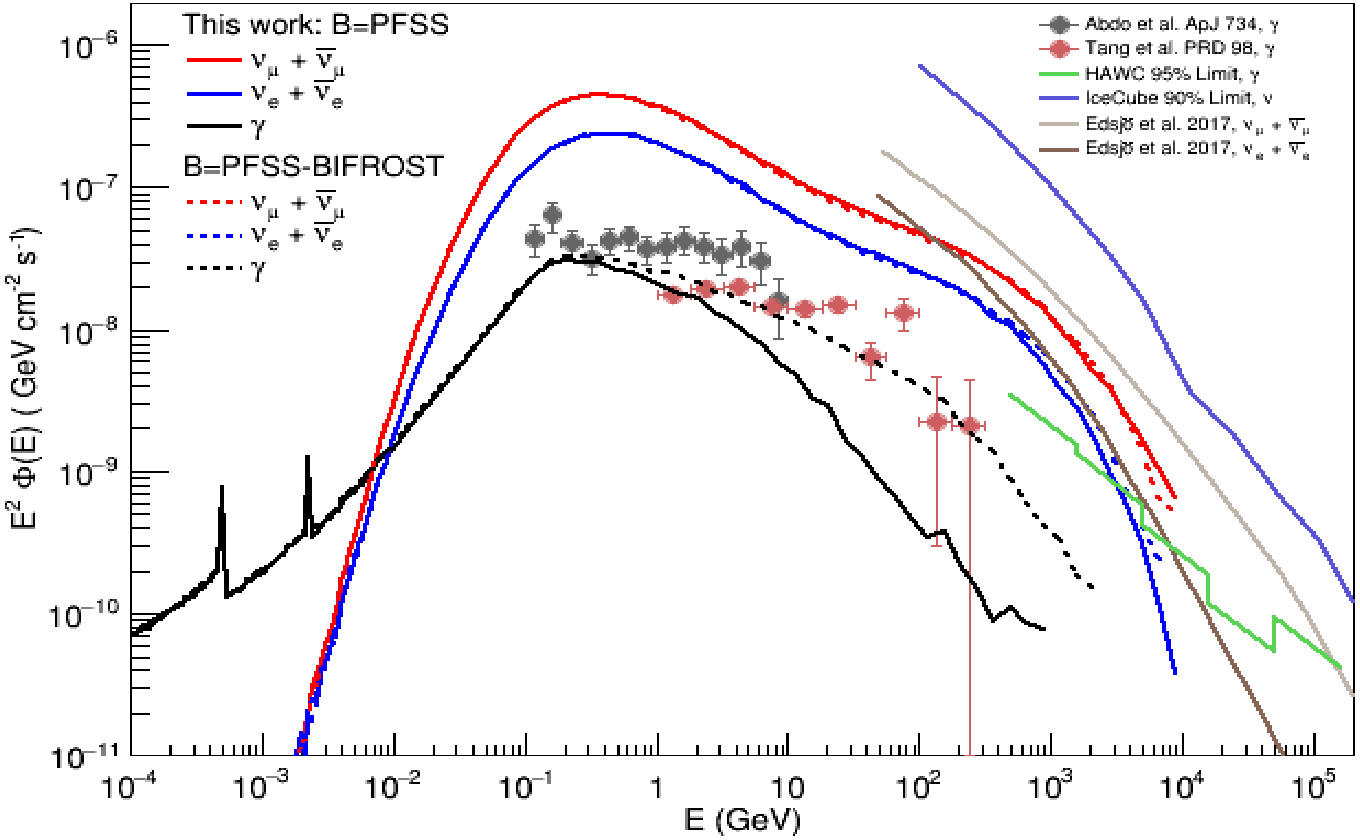
Effect of the inner magnetic field



- We have implemented different magnetic field configurations starting from the PFSS model @CRn 2111:
  - B = 0: null inner magnetic field;
  - 0.1 × PFSS: the original PFSS magnetic field intensity is reduced of a factor 10;
  - enhanced B field configuration near the Sun ($r/R_\odot < 1.01$) following the BIFROST model (A&A 585, A4 (2016) and A&A 531 A154 (2011)): we increase the original PFSS maps near the Sun to follow the BIFROST profile
    - The enhancement factor is about 25 at the solar surface
- The cosmic-ray intensity at the Sun still depends on the interplanetary magnetic field
- The high energy region of the gamma-ray spectrum is strongly affected by the intensity of the inner magnetic field

Gamma-ray and neutrino fluxes at the Earth

- The production of neutrinos is closely related to that of gamma rays in the solar disk
  - We neglect the absorption of neutrinos inside the Sun



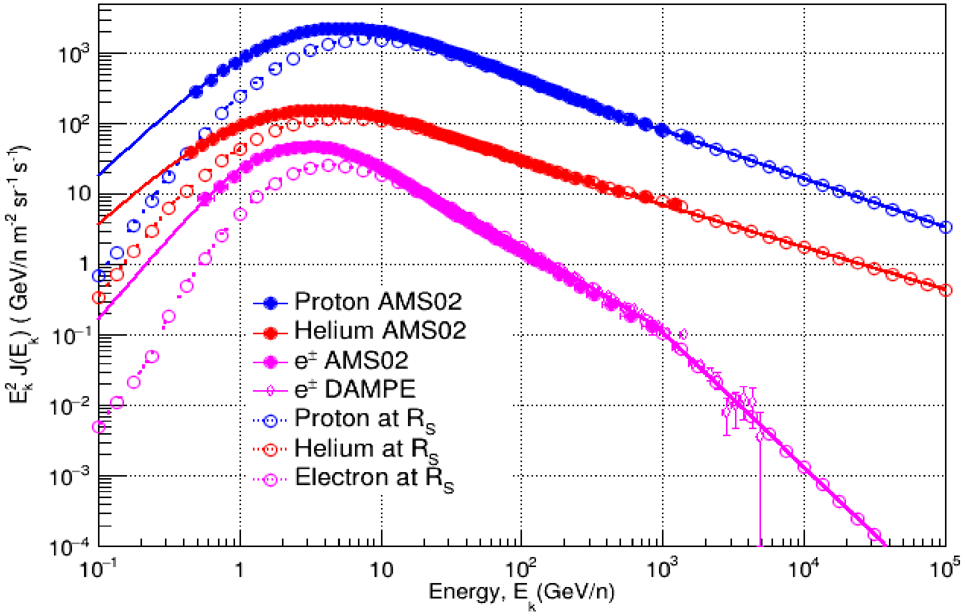
Summary and outlook

- The current measurements of the gamma-ray disk emission with the Fermi-LAT data seems to require an enhanced B-field configuration
- The yields of secondaries are strongly affected by the intensity of the magnetic field, in particular at high energies
  - Any suggestions for the inner magnetic field configuration would be appreciated
- However, the magnetic field should also affect the inverse Compton gamma-ray emission close to the Sun
  - The current IC models assume a straight-line track for the electrons in the optical solar photon field
- To get a complete picture of the solar gamma-ray emission the inverse Compton scattering needs to be calculated in presence of magnetic field
  - Work still in progress
- More details in Phys. Rev. D 101, 083011 (2020) https://arxiv.org/abs/2001.09933

BACKUP

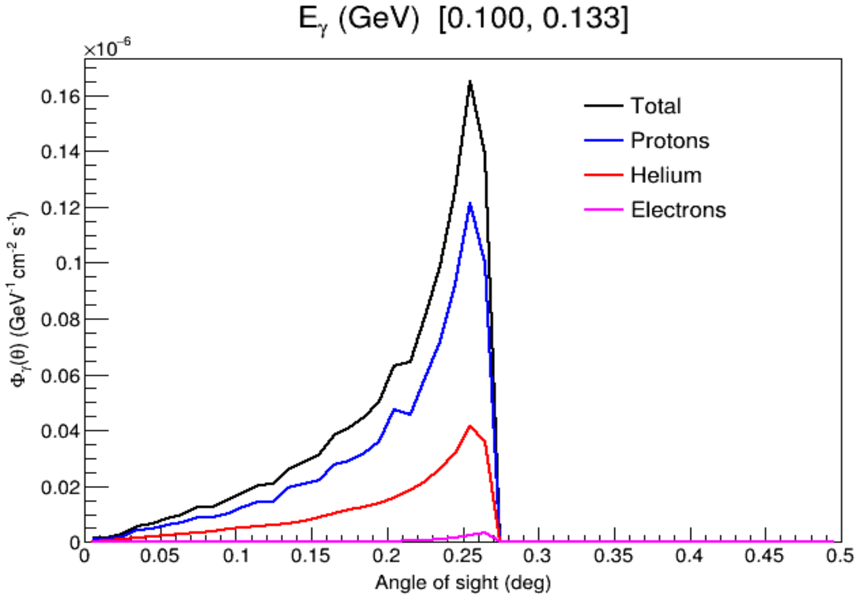
Cosmic rays at the Sun

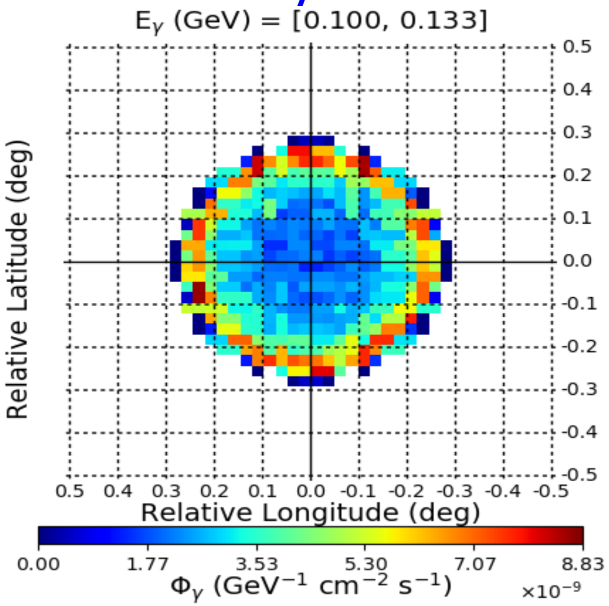
- Cosmic rays impinging on the solar atmosphere are those which can reach the Sun from the interplanetary space
  - 3D transport of cosmic rays in the Solar System simulated with a custom version of the Helioprop code
    - a set of pseudo-particles are injected on the surface of the generation sphere near the Sun and followed backwards in time until they reach a sphere of radius 1 A.U.
- We use the cosmic-ray spectra measured at the Earth by AMS in different epochs as reference

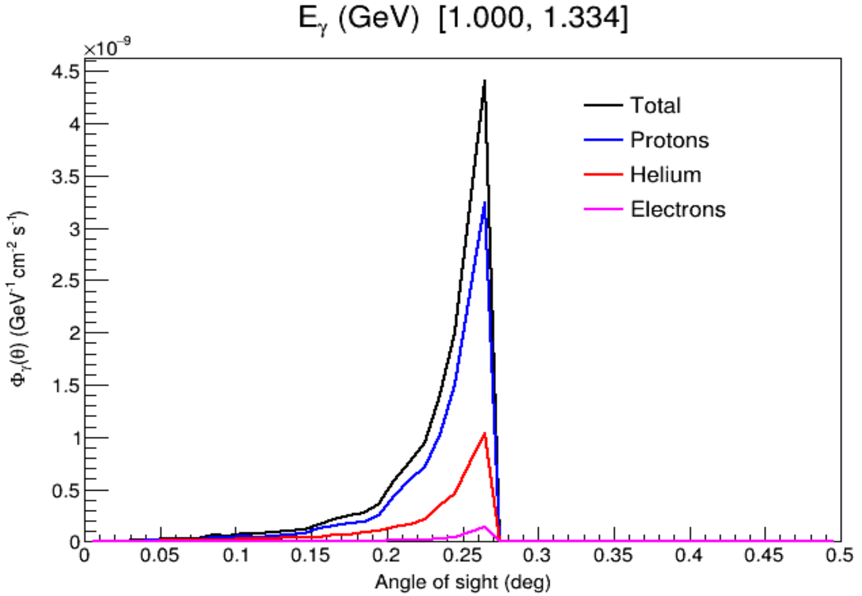


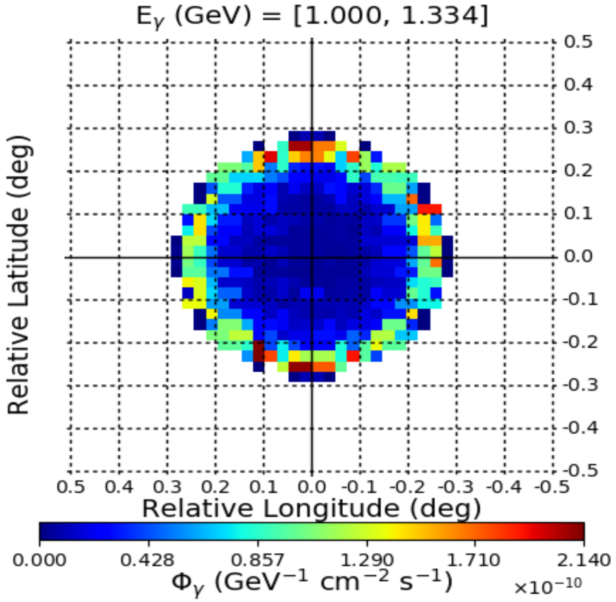
- Proton, helium and electron intensities as function of the kinetic energy
- Full circles correspond to the data measured by AMS-02 at Earth during CRn 2111
- Open circles with dashed lines indicate the intensities near the Sun at Rs= 2.5 R⊙ evaluated with Helioprop

Angular emission of gamma-ray flux



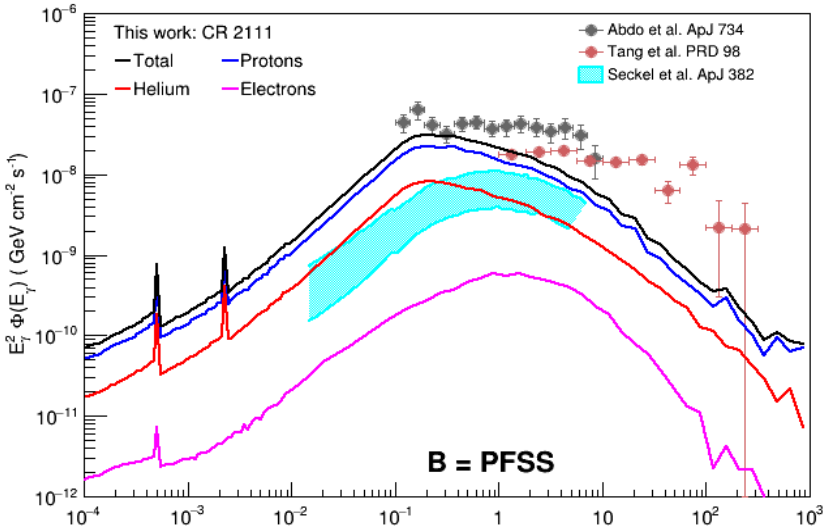




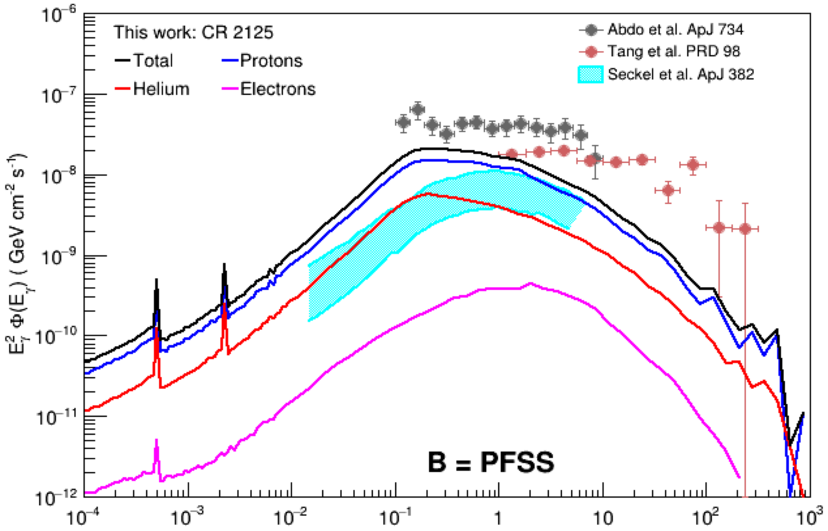


Gamma-ray fluxes at the Earth

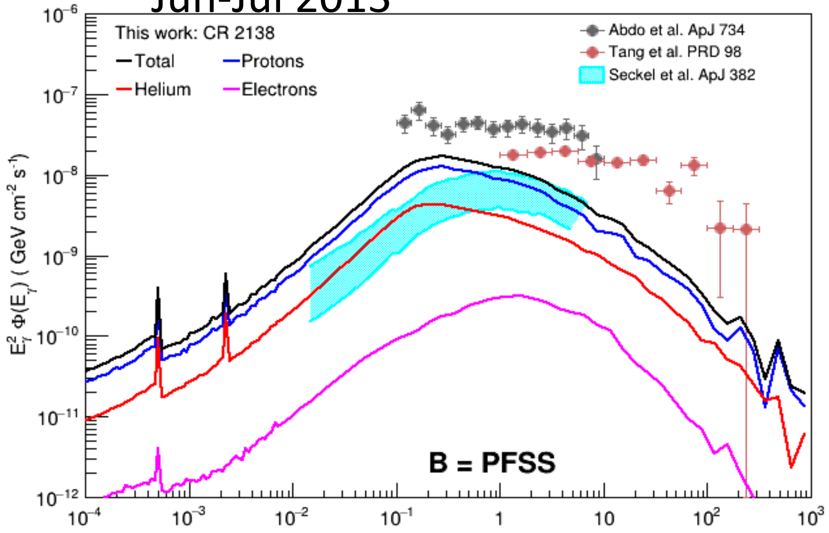
Jun-Jul 2011



Jun-Jul 2012



Jun-Jul 2013



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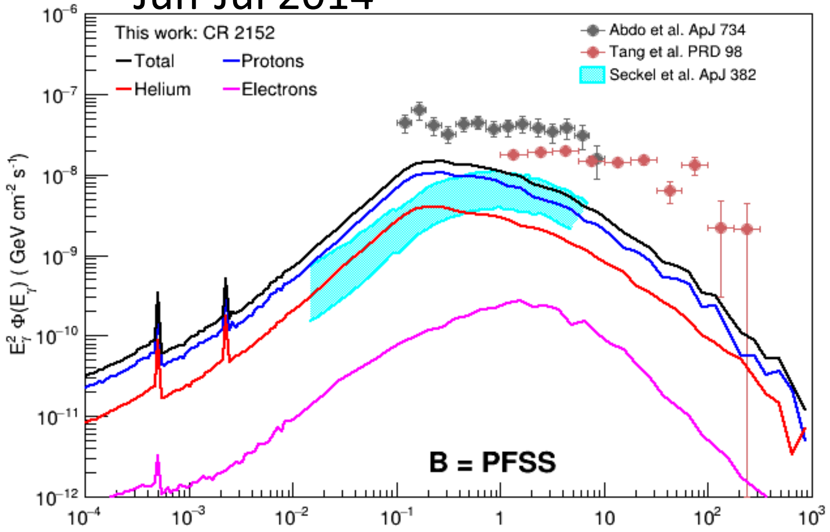

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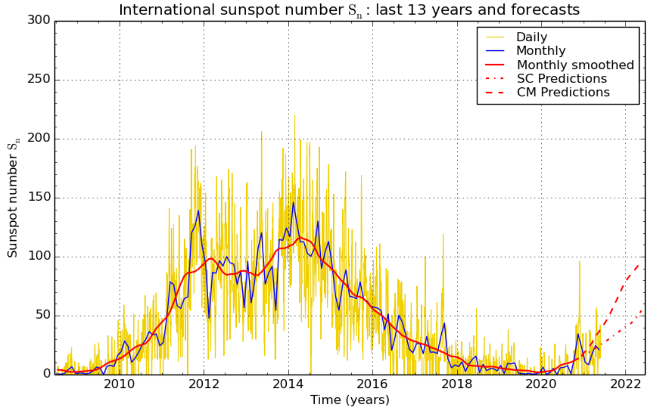

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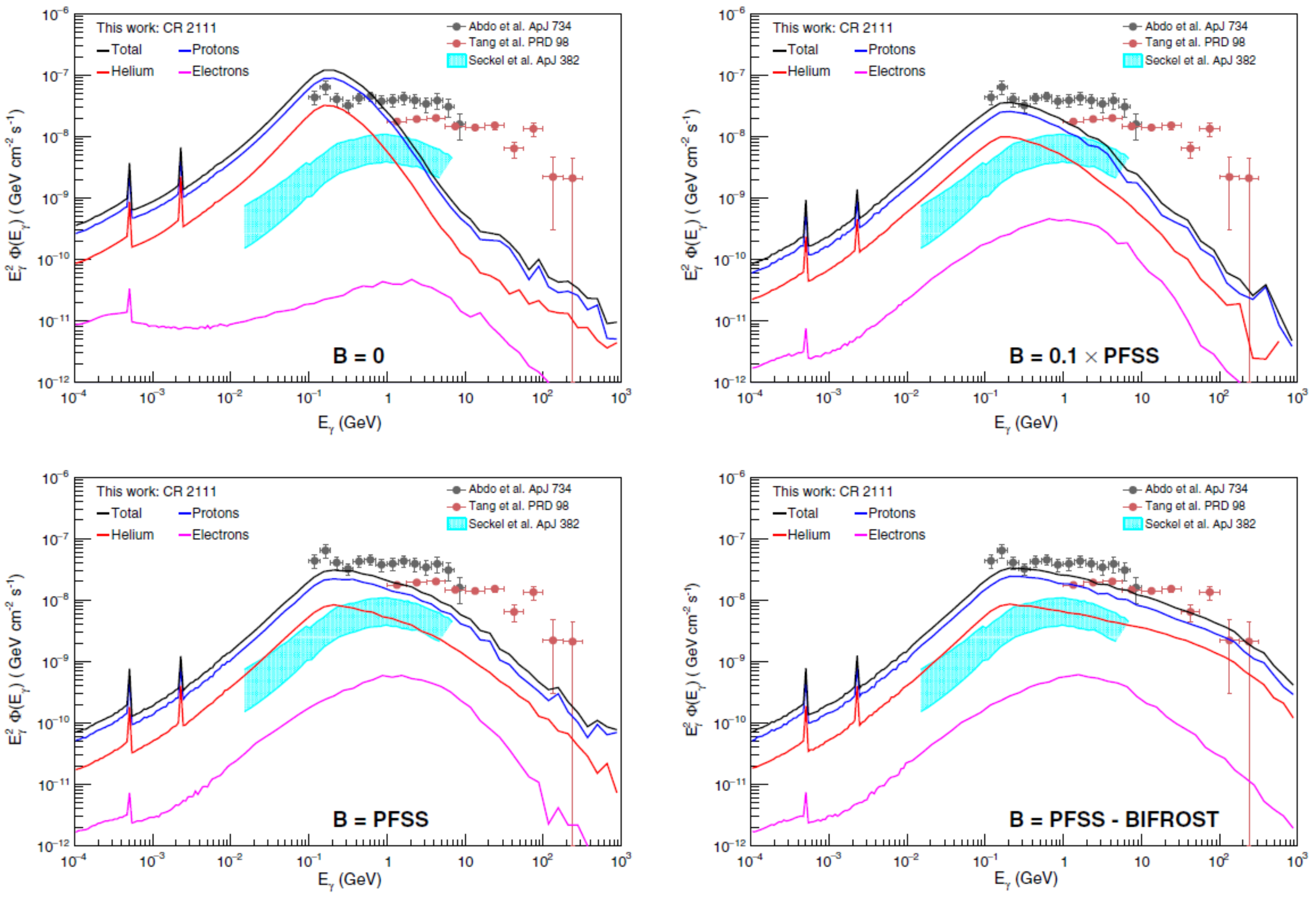

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