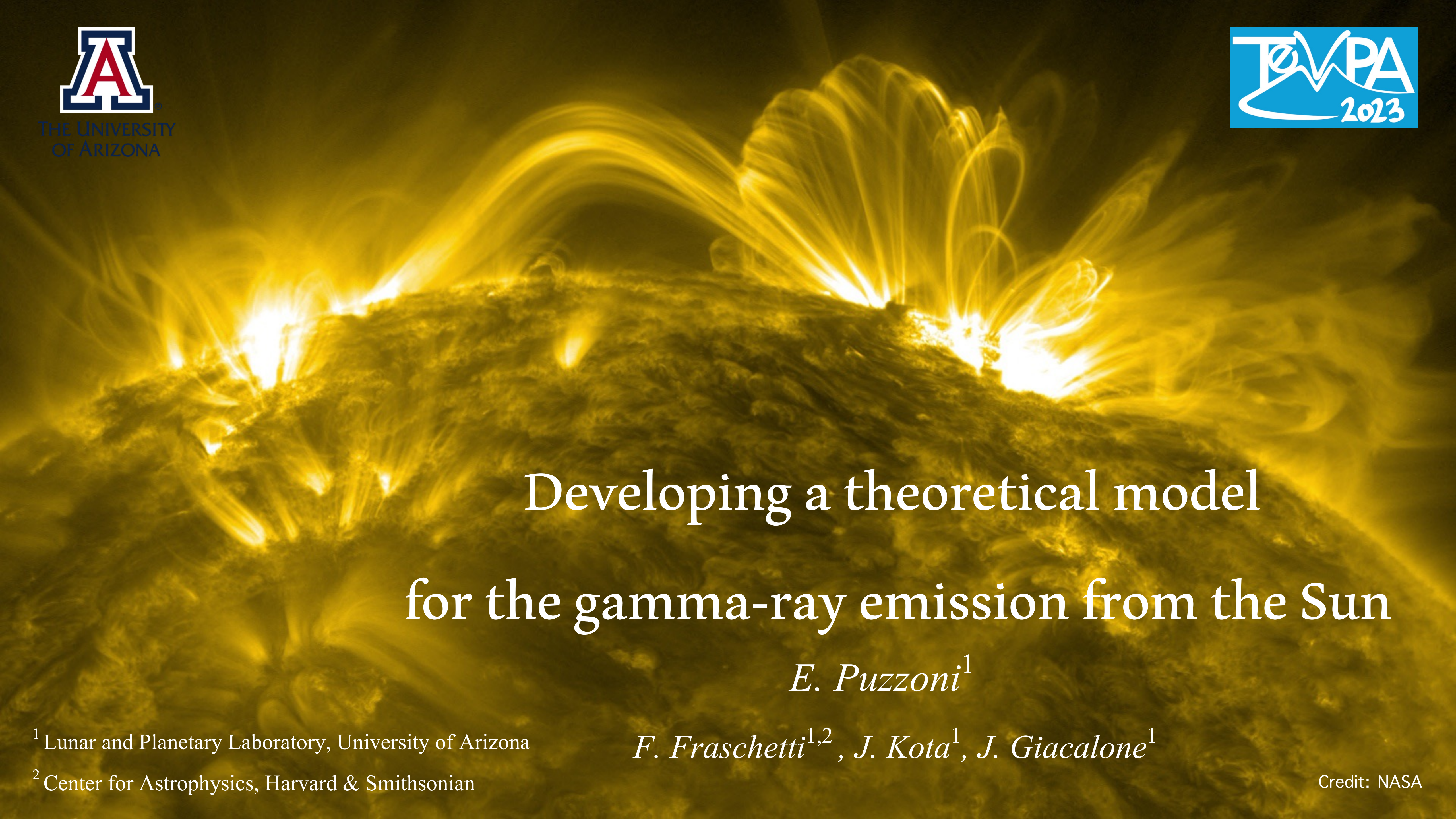


Developing a theoretical model for the gamma-ray emission from the Sun

E. Puzzoni[1]

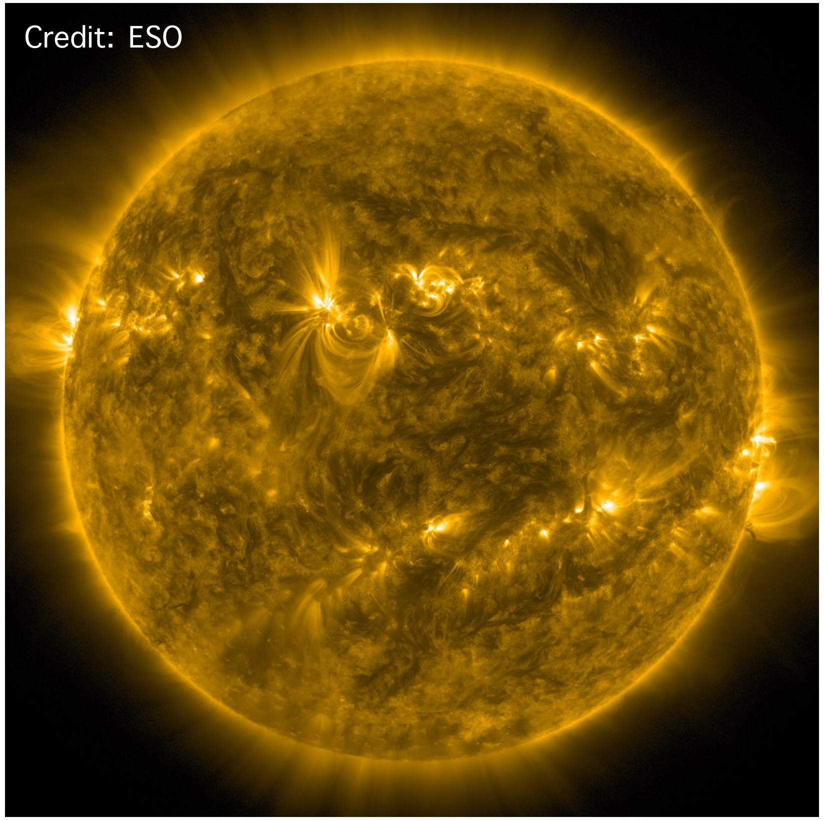
F. Fraschetti[1,2] *, J. Kota*[1]*, J. Giacalone*[1]

[1] Lunar and Planetary Laboratory, University of Arizona

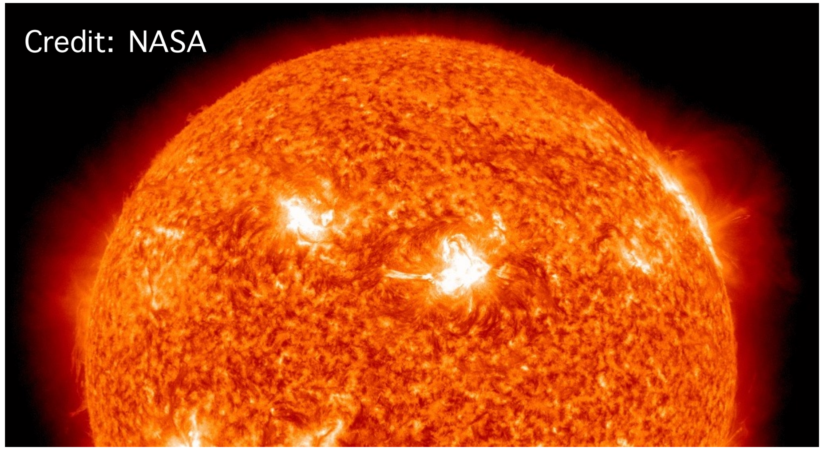
[2] Center for Astrophysics, Harvard & Smithsonian

Credit: NASA

Emission mechanisms

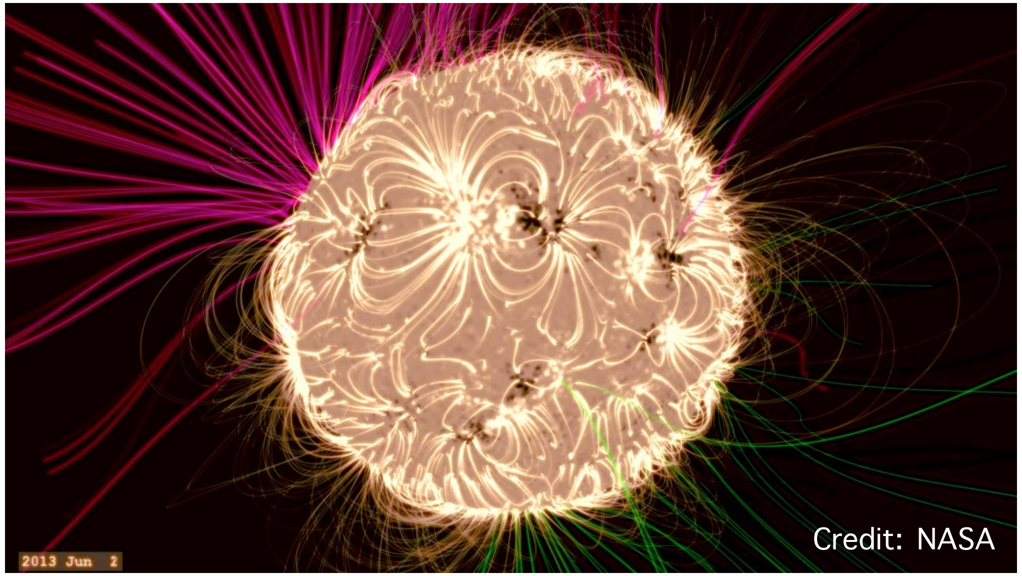


- **Inverse-Compton scattering**: cosmic-ray electrons interacting with solar photons (solar halo)
- **Bombardment by hadronic cosmic rays** (mostly protons) interacting with solar gas (solar disk)
- **Solar flares and coronal mass ejections**



The existing theoretical model

Magnetic fields are crucial!



Seckel, Stanev, and Gaisser model (1991)

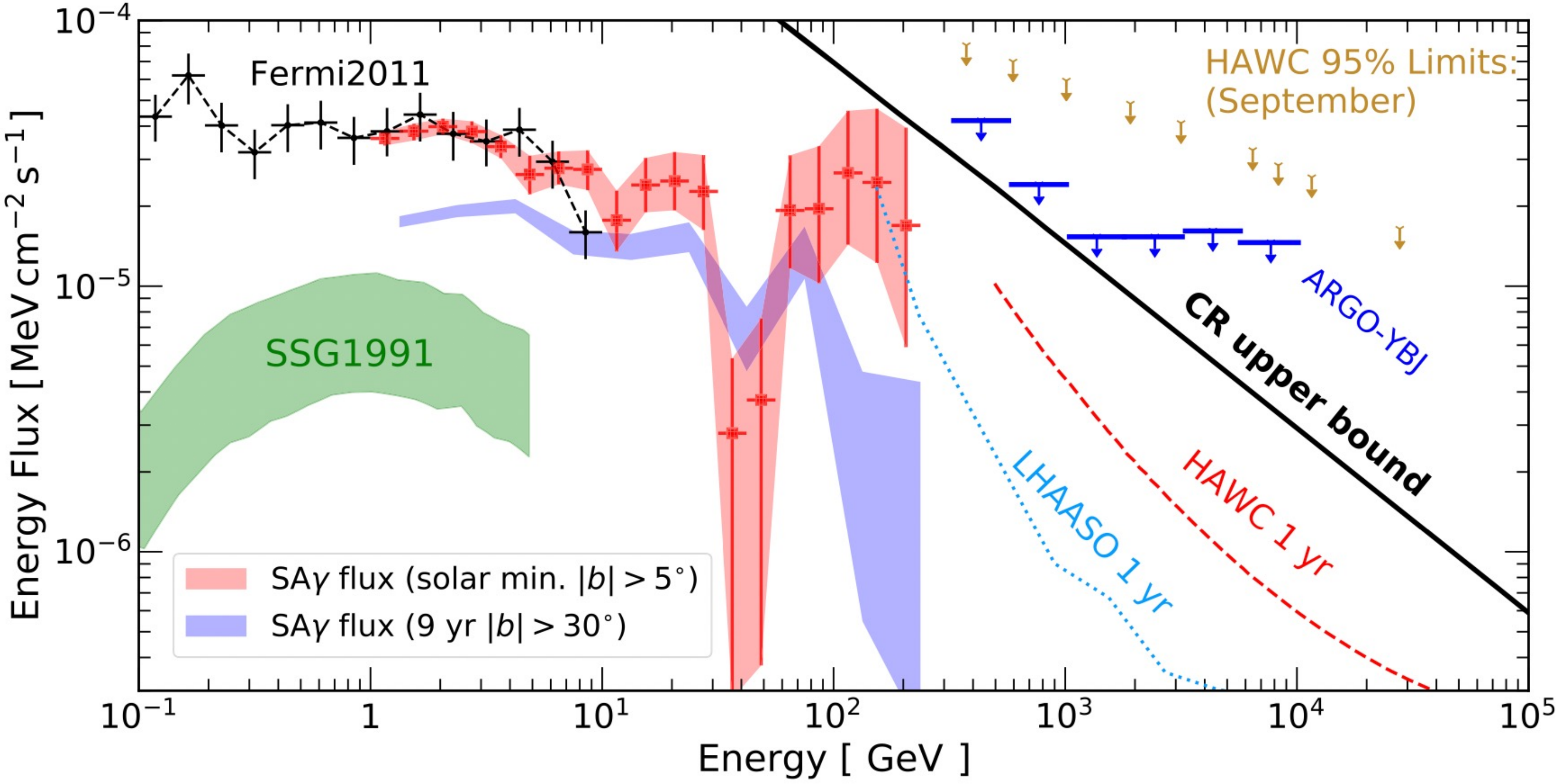
Magnetic flux tubes can reverse incoming protons deep within the solar atmosphere, where they have an appreciable probability of producing outgoing γ-rays.

γ-ray flux is greatly enhanced!

"Current technology is improving to the point that such a flux of GeV γ-rays should be detectable by the EGRET instrument of the Gamma Ray Observatory (GRO)"

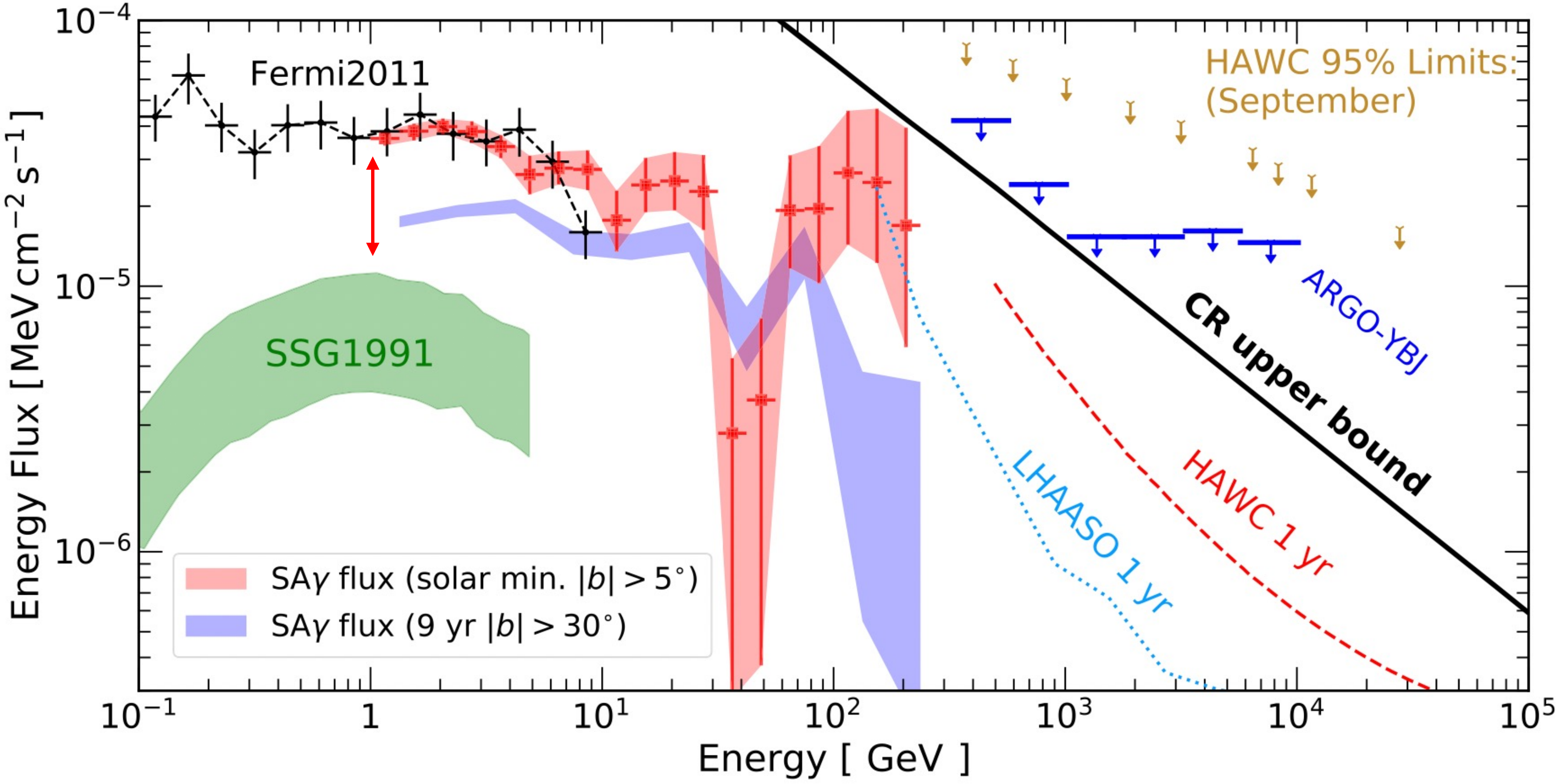
- Fermi Gamma-ray Space Telescope
- High-Altitude Water Cherenkov Gamma-ray Observatory (HAWC)

The observational problem



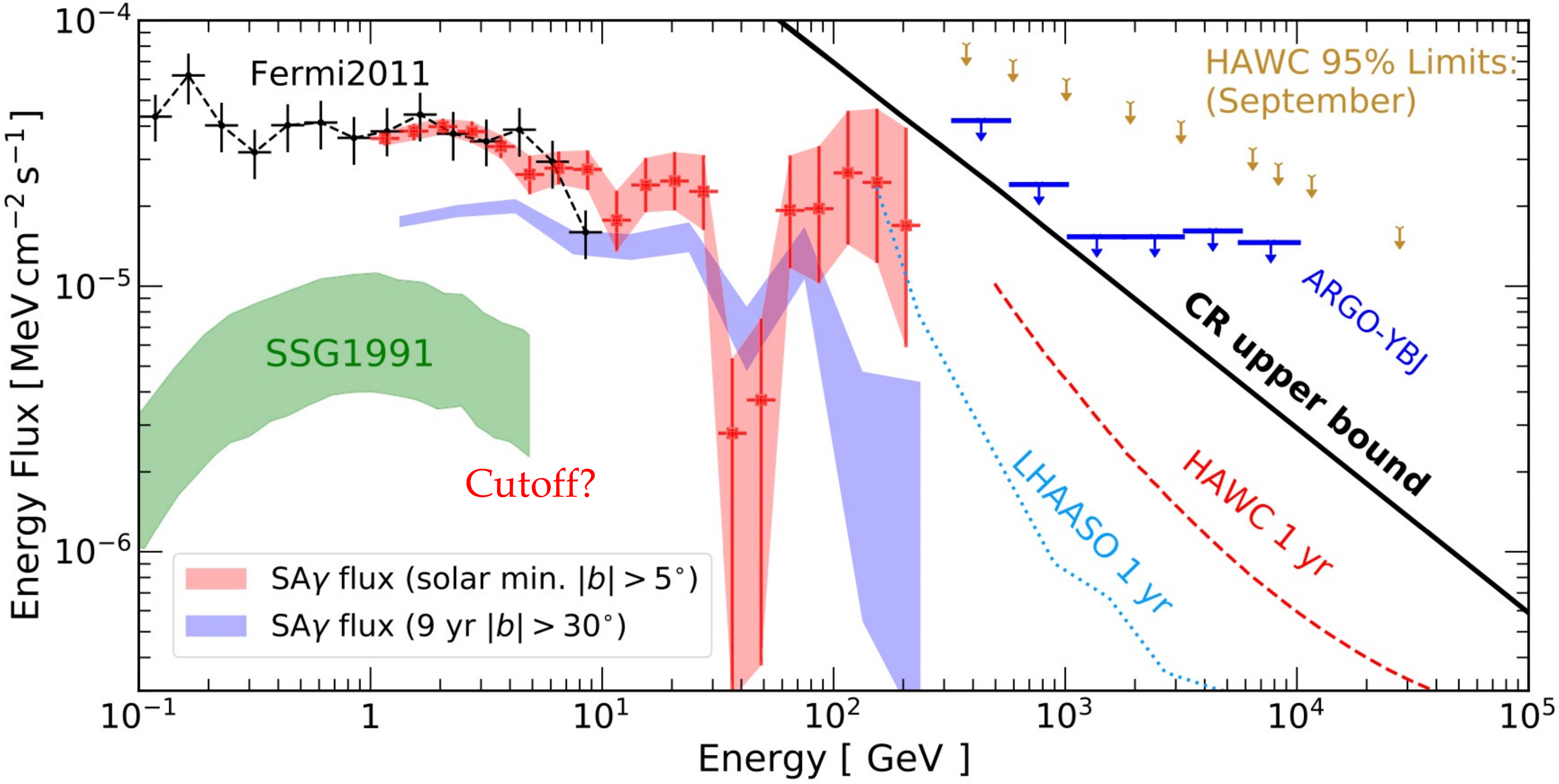
Credits: Tang et al. 2018

The observational problem



Credits: Tang et al. 2018

The observational problem



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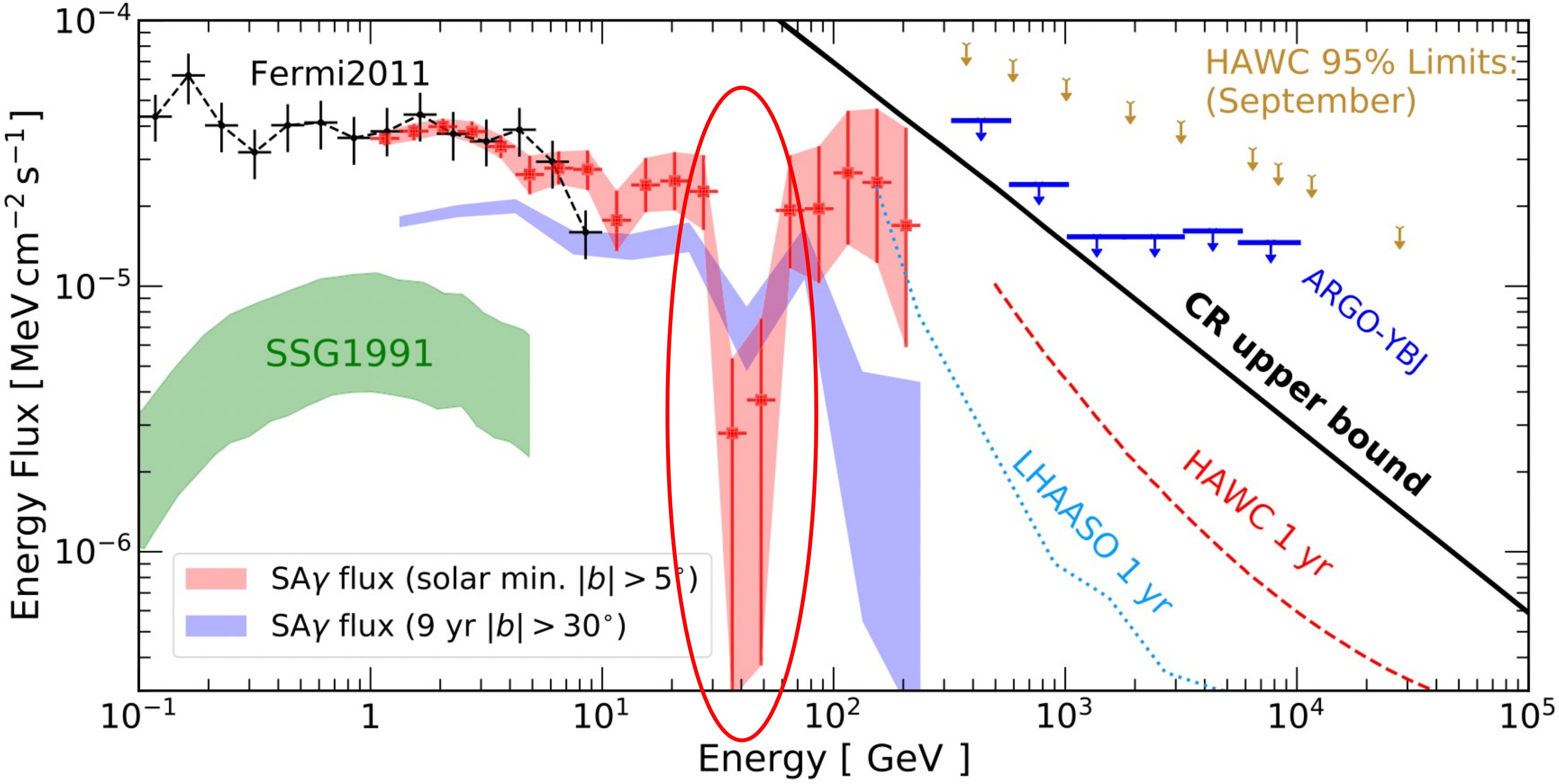

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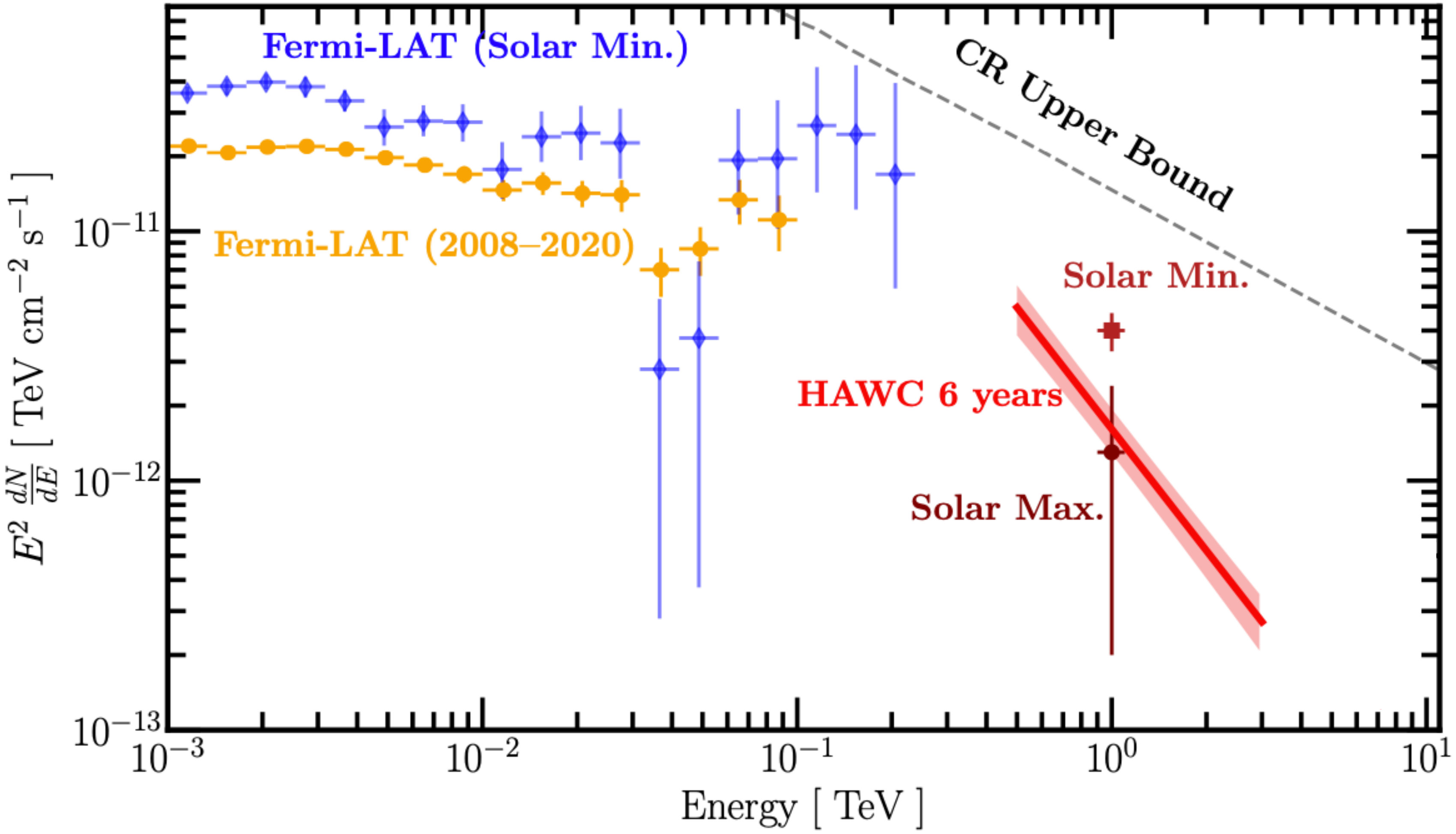
The observational problem



Credits: HAWC Collaboration (2022)

Magnetic field arcade

The equilibrium magnetic field is a potential arcade contained in the xy-plane

$$A(x,y) = B_0 \Lambda_B \cos\left(\frac{x}{\Lambda_B}\right) e^{-\frac{y}{\Lambda_B}}$$

And the magnetic field components are given by

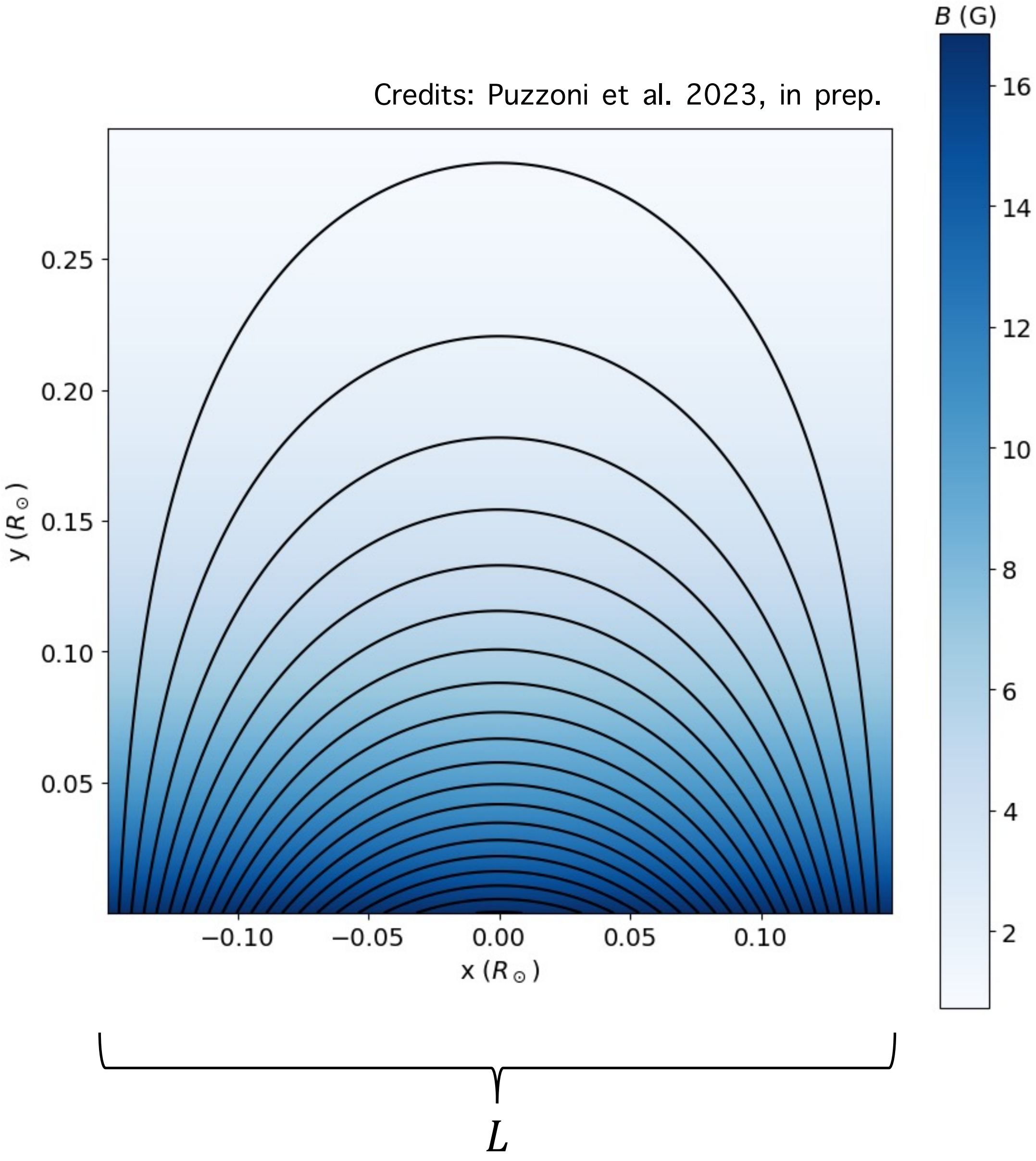
$$B_x(x,y) = -B_0 \cos\left(\frac{x}{\Lambda_B}\right) e^{-\frac{y}{\Lambda_B}}$$

$$B_y(x,y) = B_0 \sin\left(\frac{x}{\Lambda_B}\right) e^{-\frac{y}{\Lambda_B}}$$

$B_0 = 10/e^{-\frac{0.05}{\Lambda_B}}$: magnetic field strength at the base

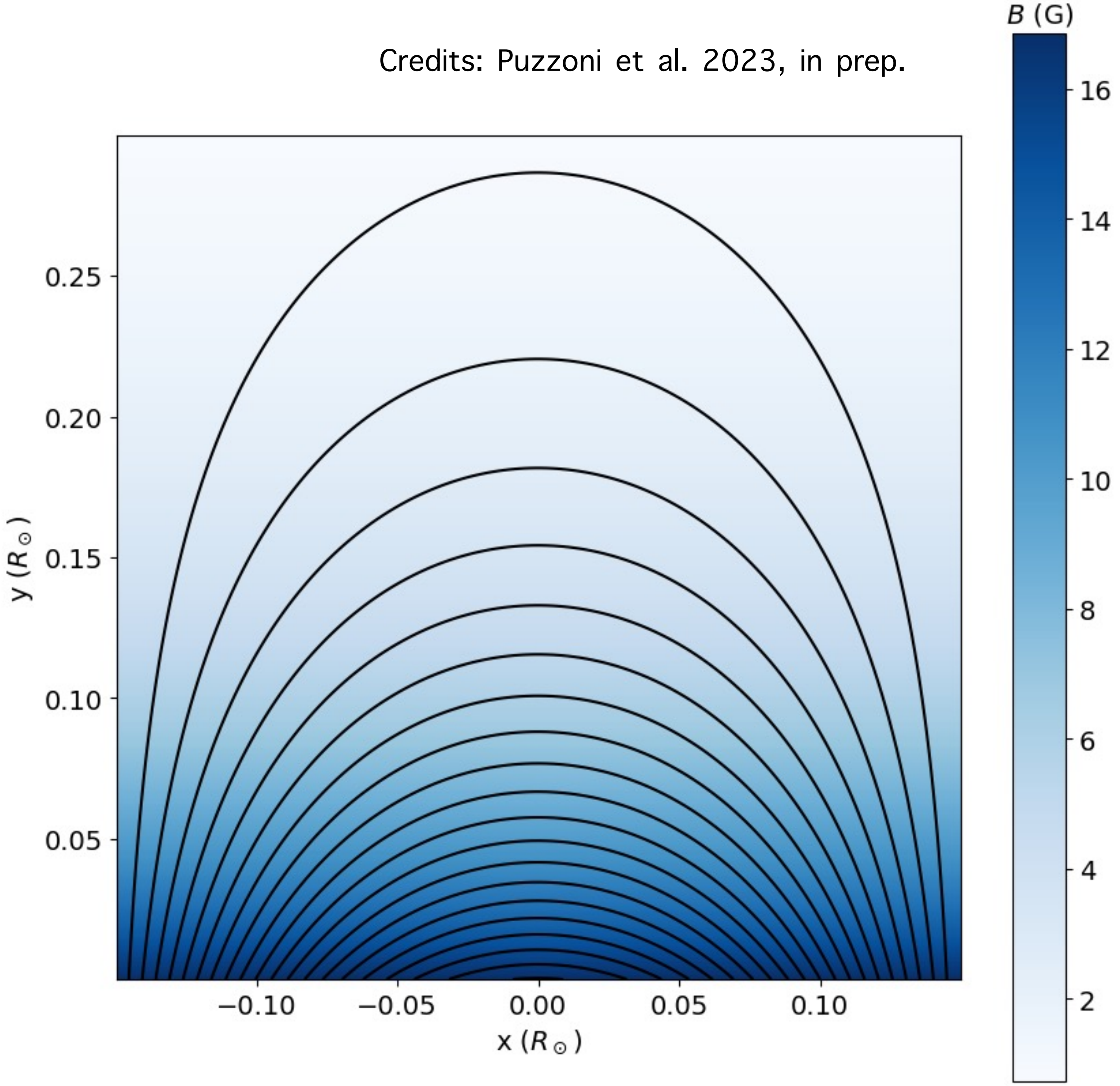
$\Lambda_B = L/\pi$: magnetic scale height

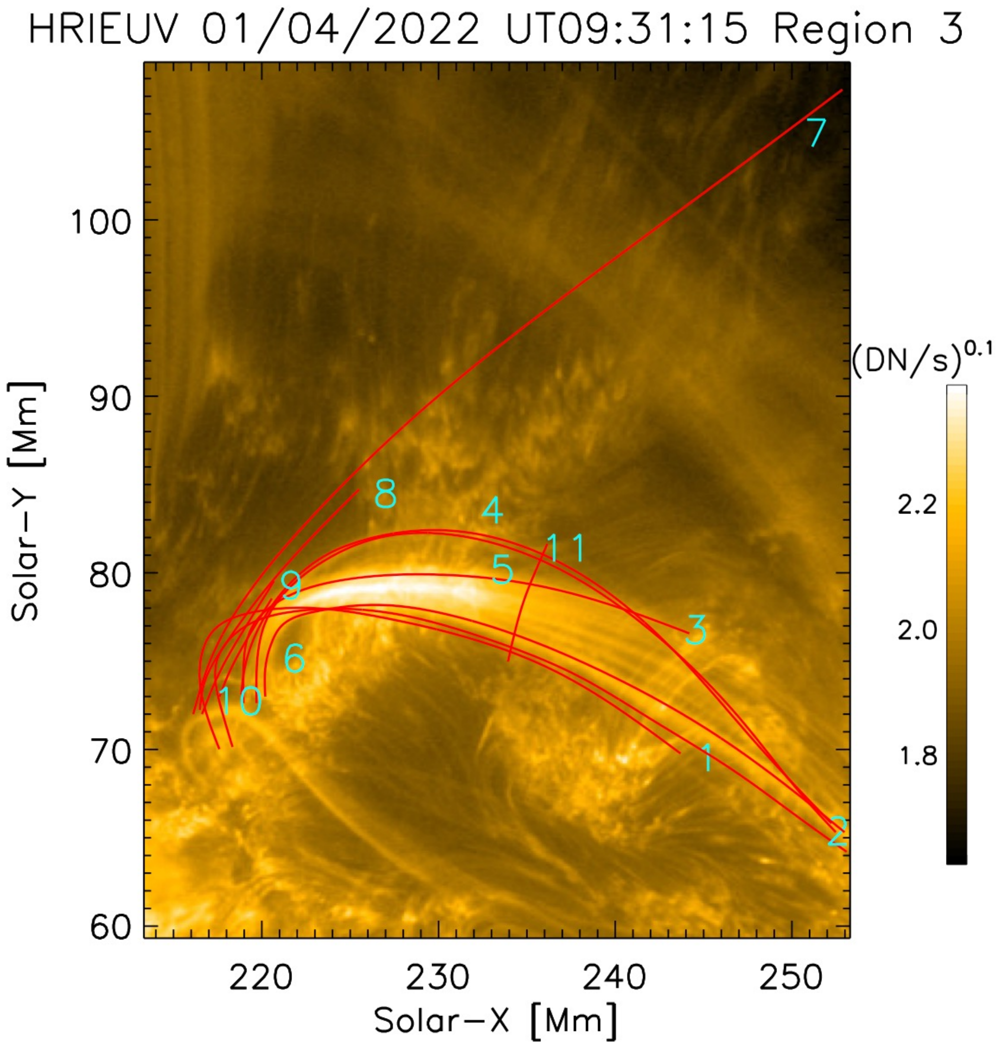
Credits: Oliver et al. 1993, Rial et al. 2013



Credits: Antolin et al. 2023

Credits: Puzzoni et al. 2023, in prep.





From *Solar Orbiter* observations

THEORETICAL MODEL

Turbulent magnetic field

$$\boldsymbol{B}_{tot}(x,y,z) = \boldsymbol{B}(x,y) + \delta\boldsymbol{B}(x,y,z)$$

$$\delta\boldsymbol{B}(x,y,z) = \sum_{n=1}^{N_m} A(k_n)\, \hat{\boldsymbol{\xi}}\, e^{ik_n z'_n + i\beta_n}$$

Credits: Giacalone and Jokipii 1999

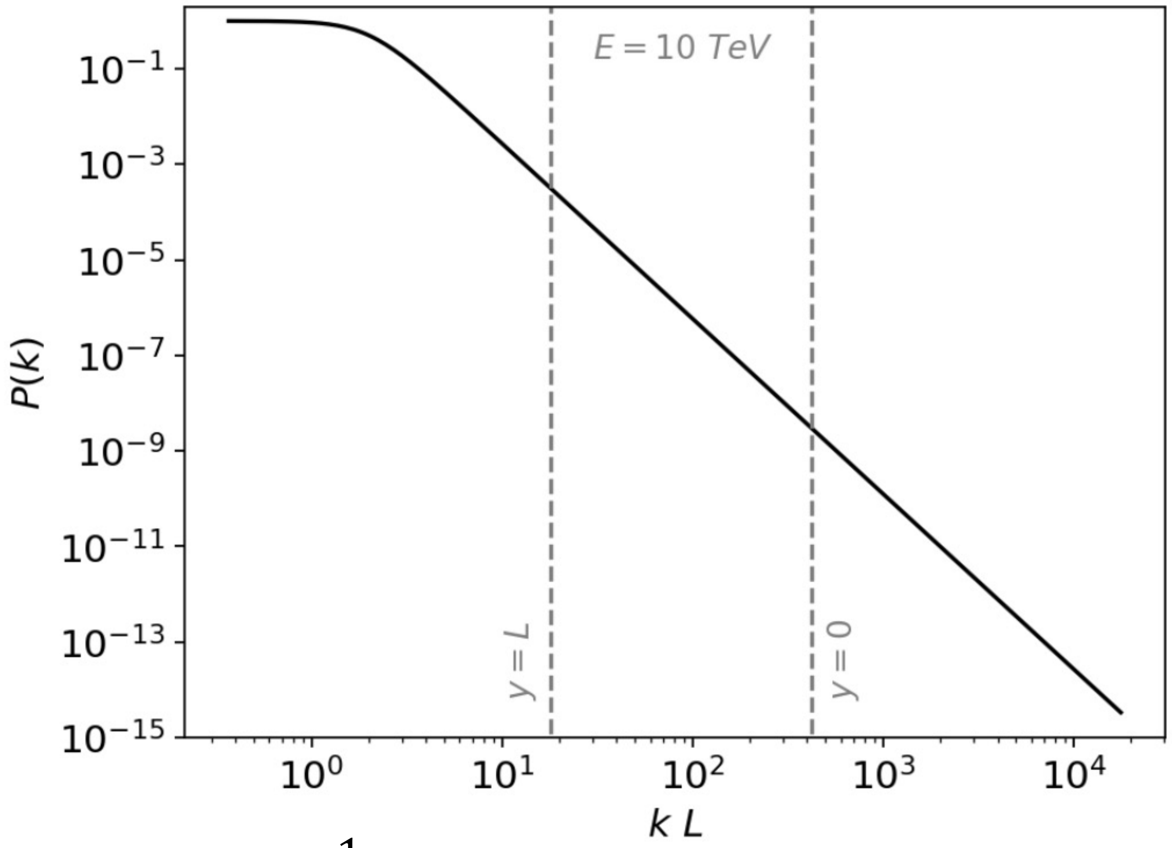
$$L_{MIN} = 10^{-4}\ R_{sun} \qquad L_{MAX} = 5 \times 10^{4} L_{MIN}$$

$$L_c = \frac{L}{2} = 0.15\ R_{sun}$$

$$\gamma = \frac{11}{3}$$

$$\sigma^2 = < \delta\boldsymbol{B}^2(x,y,z) > / \boldsymbol{B}^2(x,y)$$

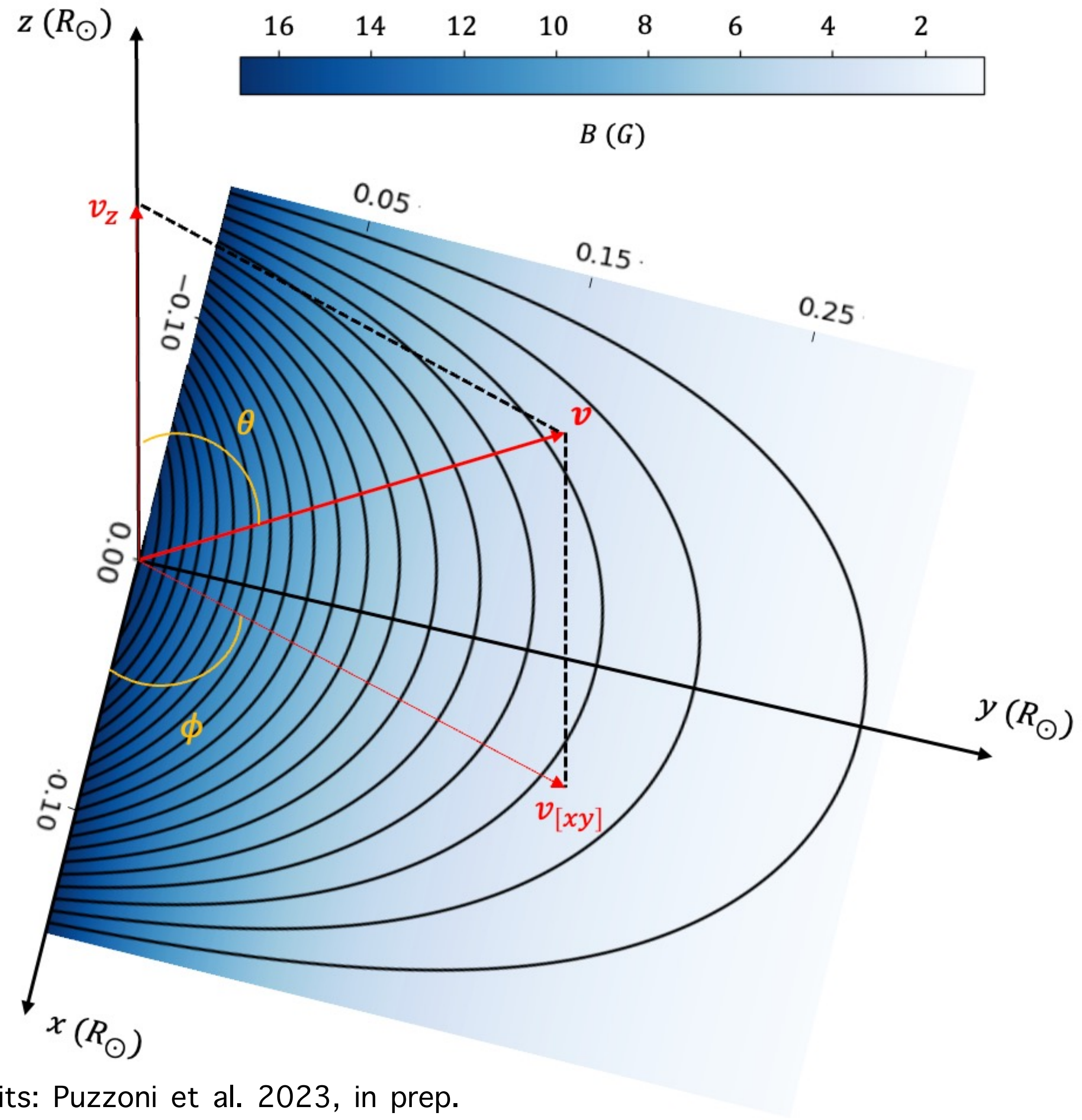
Credits: Puzzoni et al. 2023, in prep.



$$P(k) = \frac{1}{1 + (kL_c)^{\gamma}}$$

THEORETICAL MODEL

Particles initialization



Credits: Puzzoni et al. 2023, in prep.

$$v_x = v_0 \sin\theta \cos\varphi$$

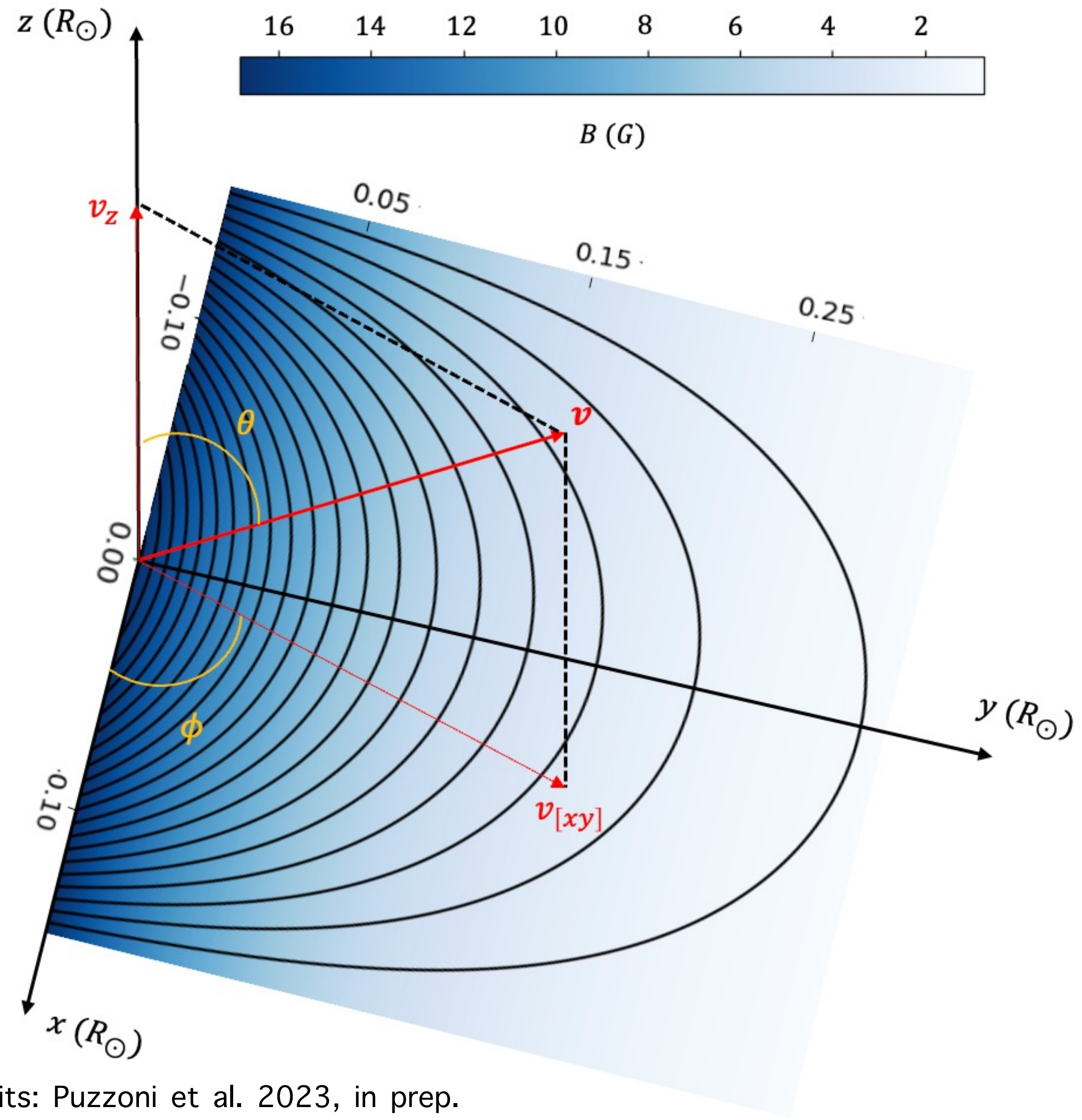
$$v_y = v_0 \sin\theta \sin\varphi$$

$$v_z = v_0 \cos\theta$$

$$\theta = \arccos(1 - 2\mathcal{R}[0,1]) \qquad \varphi = 2\pi\mathcal{R}[0,1]$$

- Different initial energies: 100 GeV – 10 TeV
- $\sigma^2 = 0, 0.01, 0.1, 1$
- Injected in strips at discrete distances from the Sun surface

Particles initialization



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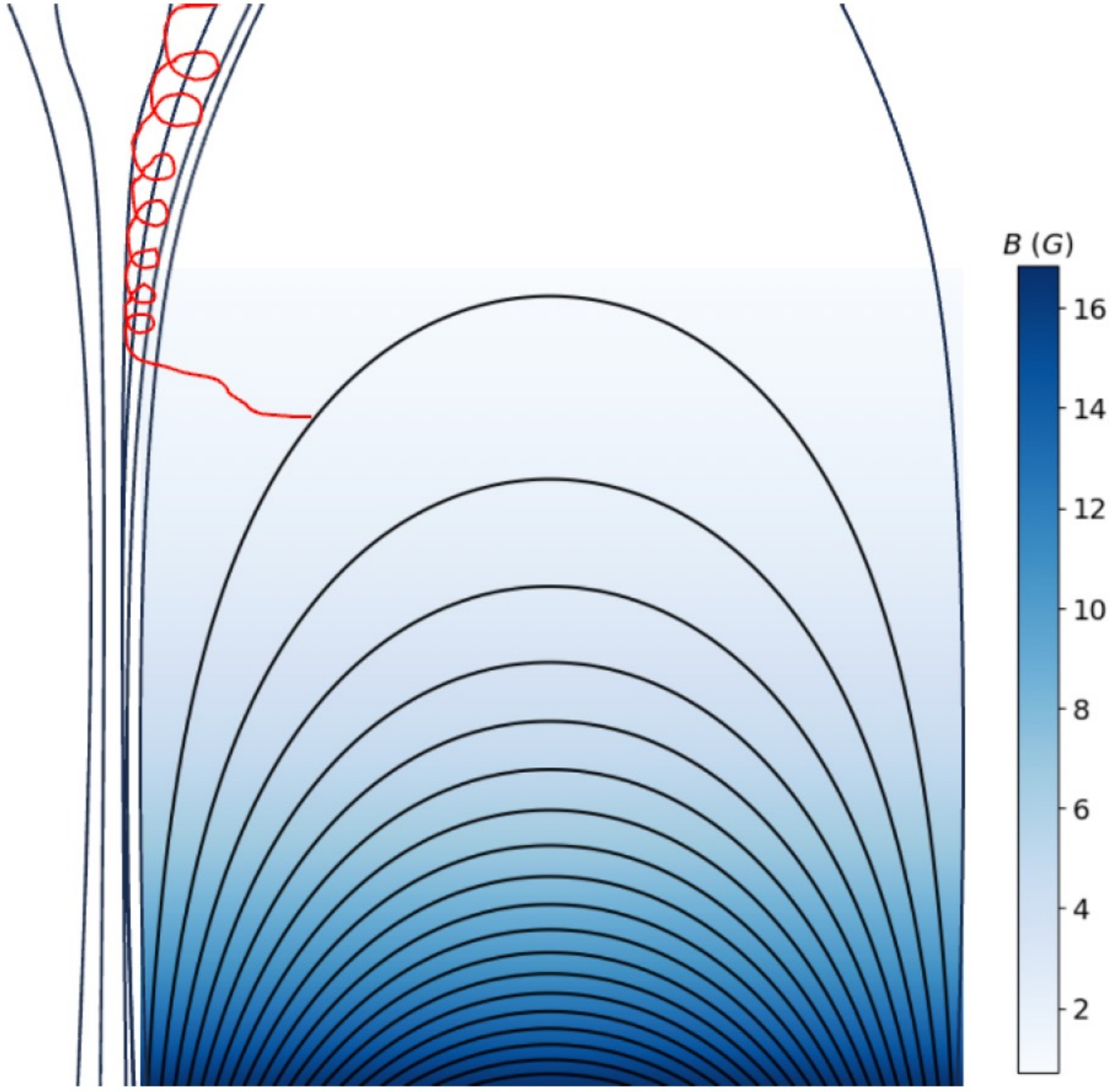


THEORETICAL MODEL

NUMERICAL METHOD

Grid and boundaries

Grid resolution : $\mathbf{1000 \times 1000}$

Particles are considered *escaped* when

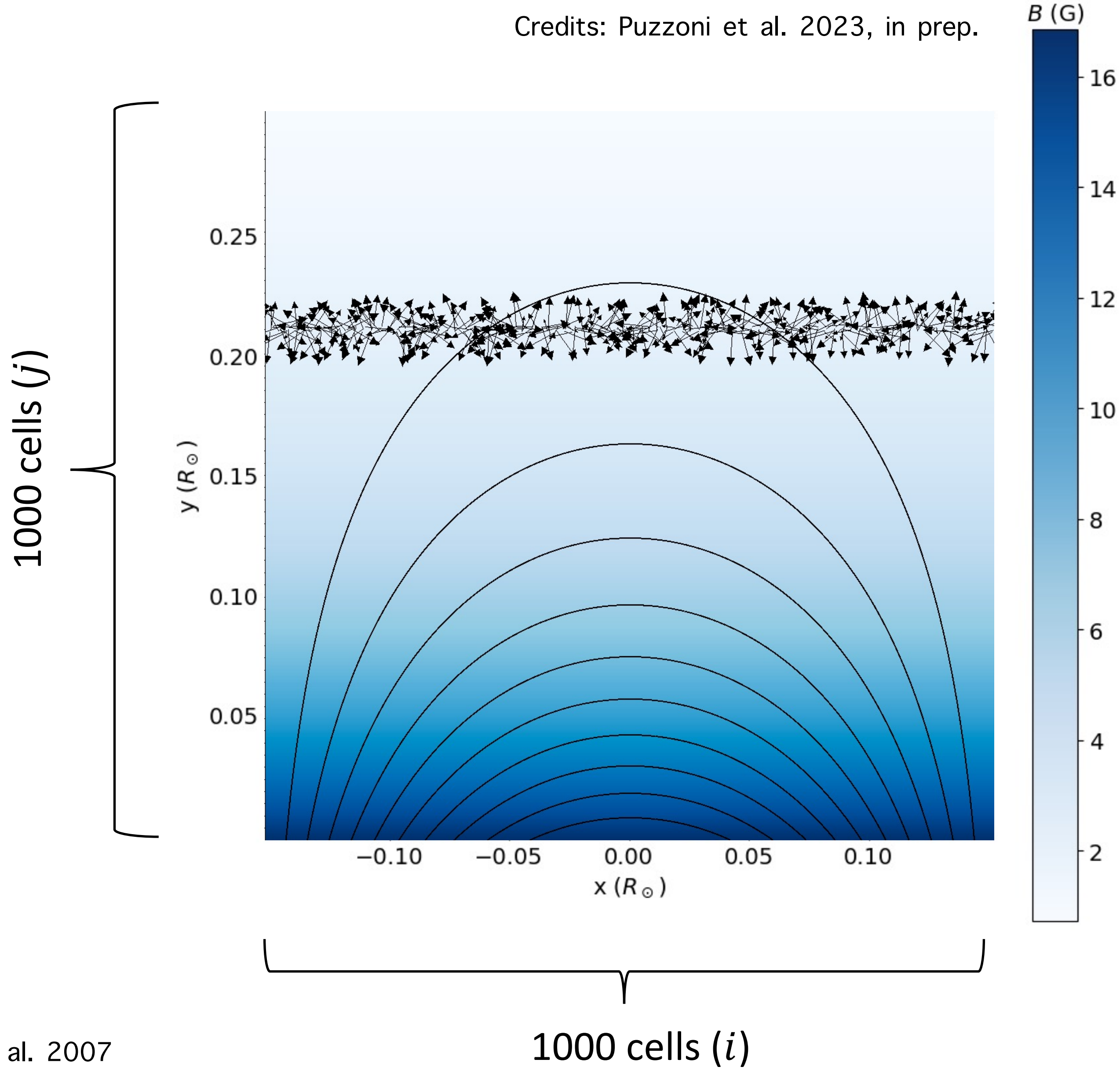
- they leave the computational domain in the $x - y$ plane
- $z > 0.1\, R_{sun}$ or $z < -0.1\, R_{sun}$

1 test-particle proton/cell

(particle mover: Boris integrator in the PLUTO code)

Credits: Mignone et al. 2007

Credits: Puzzoni et al. 2023, in prep.



NUMERICAL METHOD

Grid and boundaries

Grid resolution : **1000 × 1000**

$$\rho = \rho_0 e^{-\frac{y}{\Lambda_B}}$$

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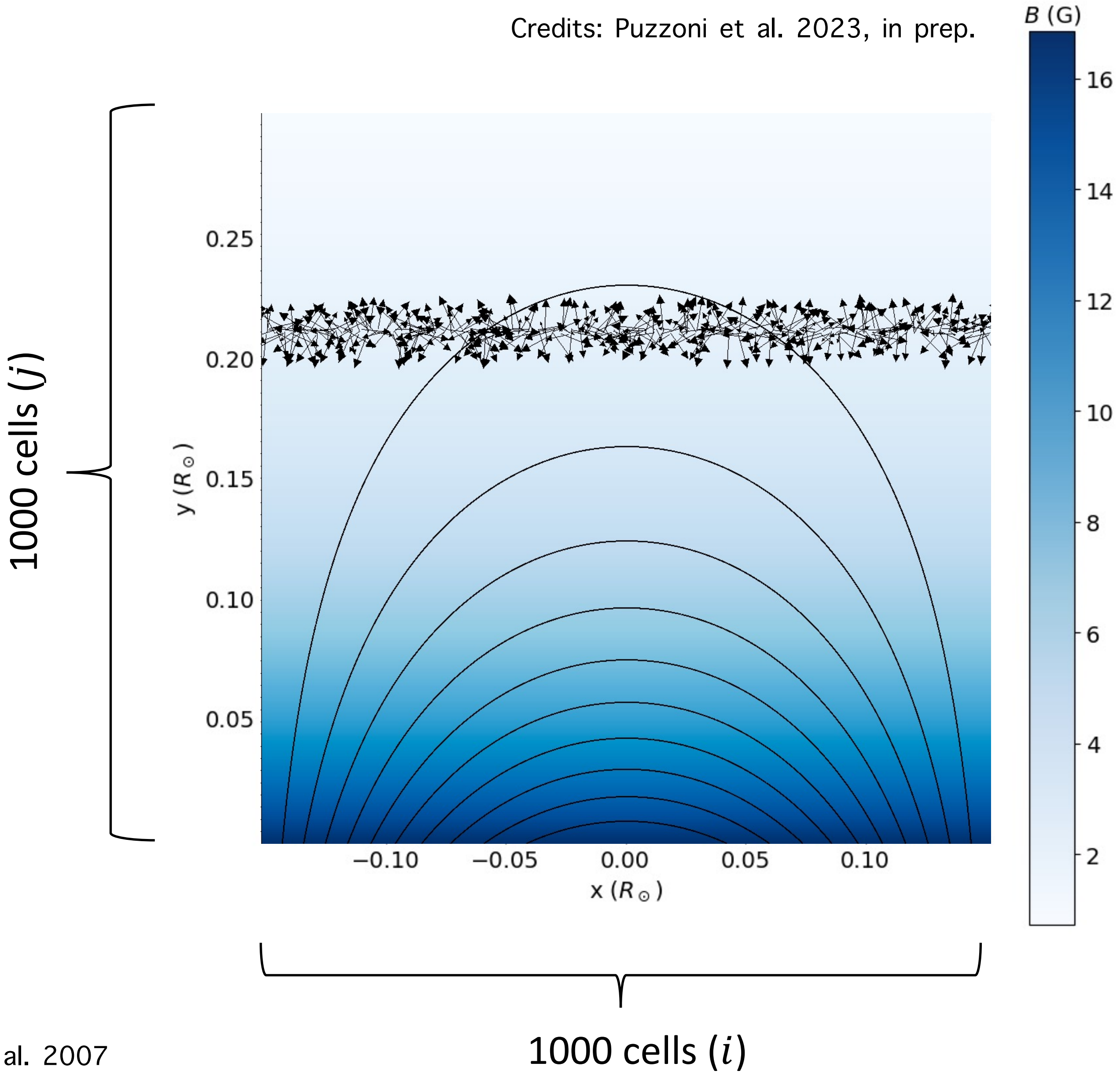
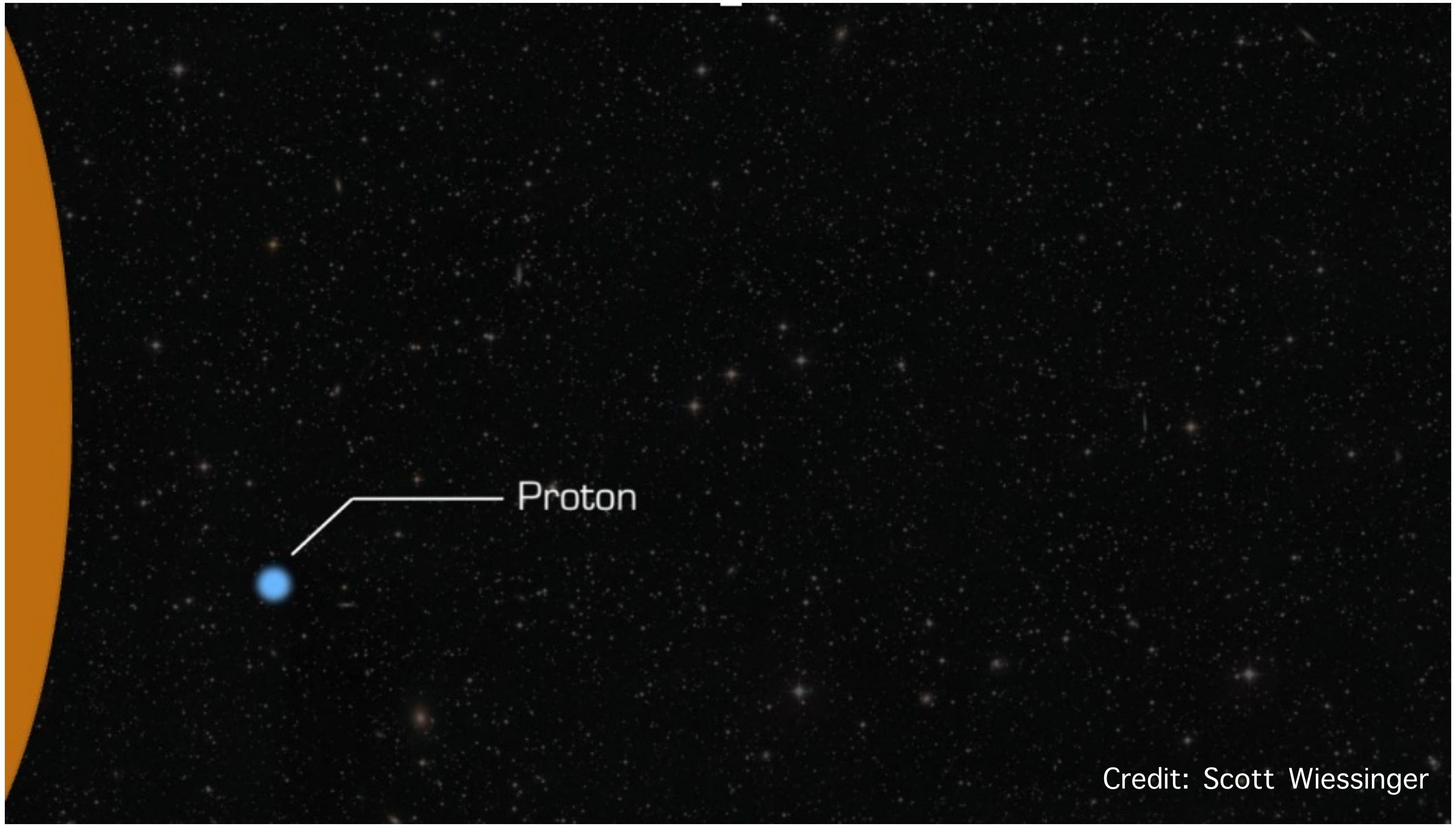


Gamma-rays production



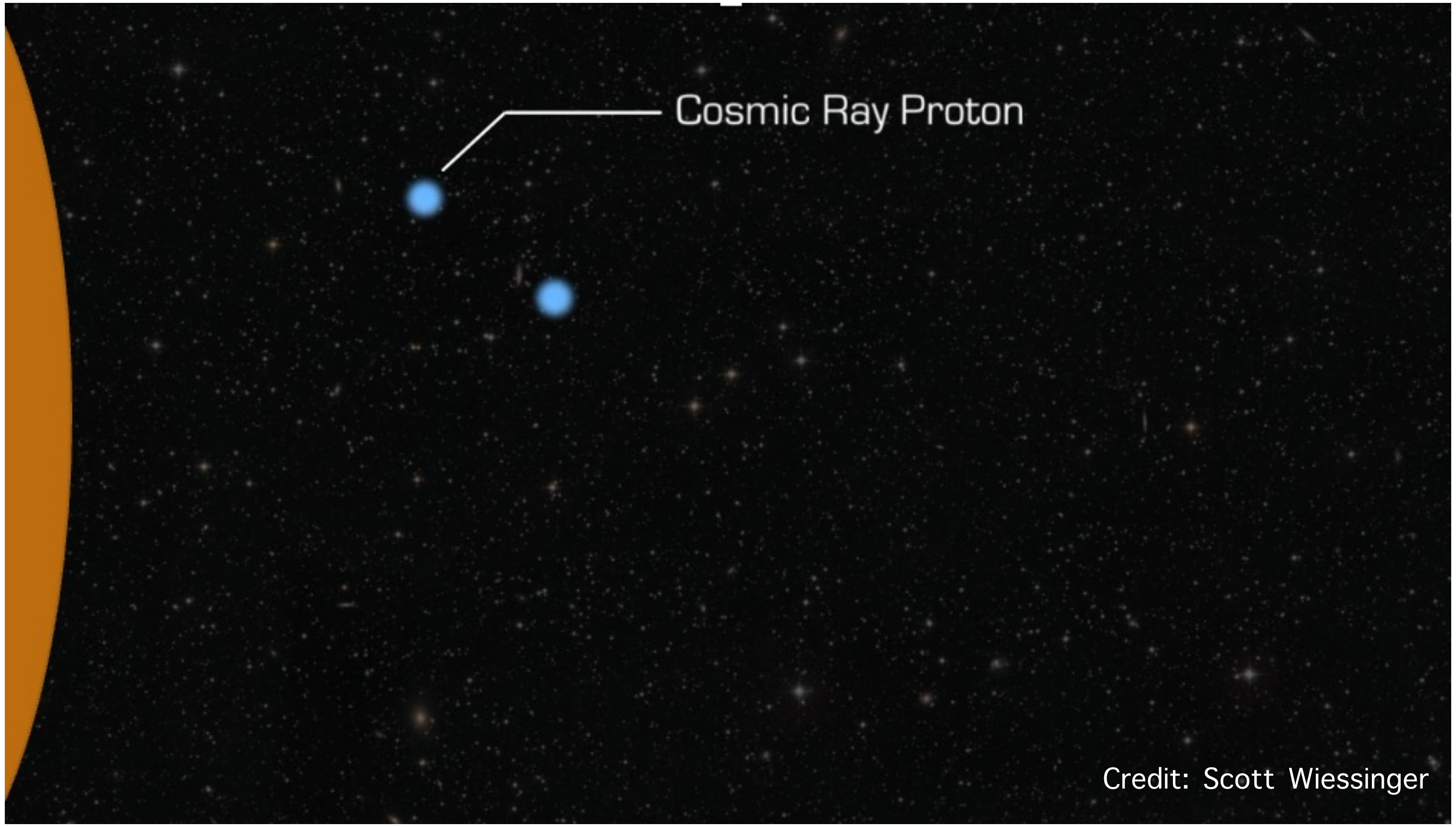
We focus on the protons escaping from the Sun as they can produce gamma-rays that are observed at Earth

↓

Particles filters: particles interacting with $v_y > 0$

$$t_{int}(y) = \frac{1}{n(y)\sigma_c v} < \Delta t$$

Gamma-rays production



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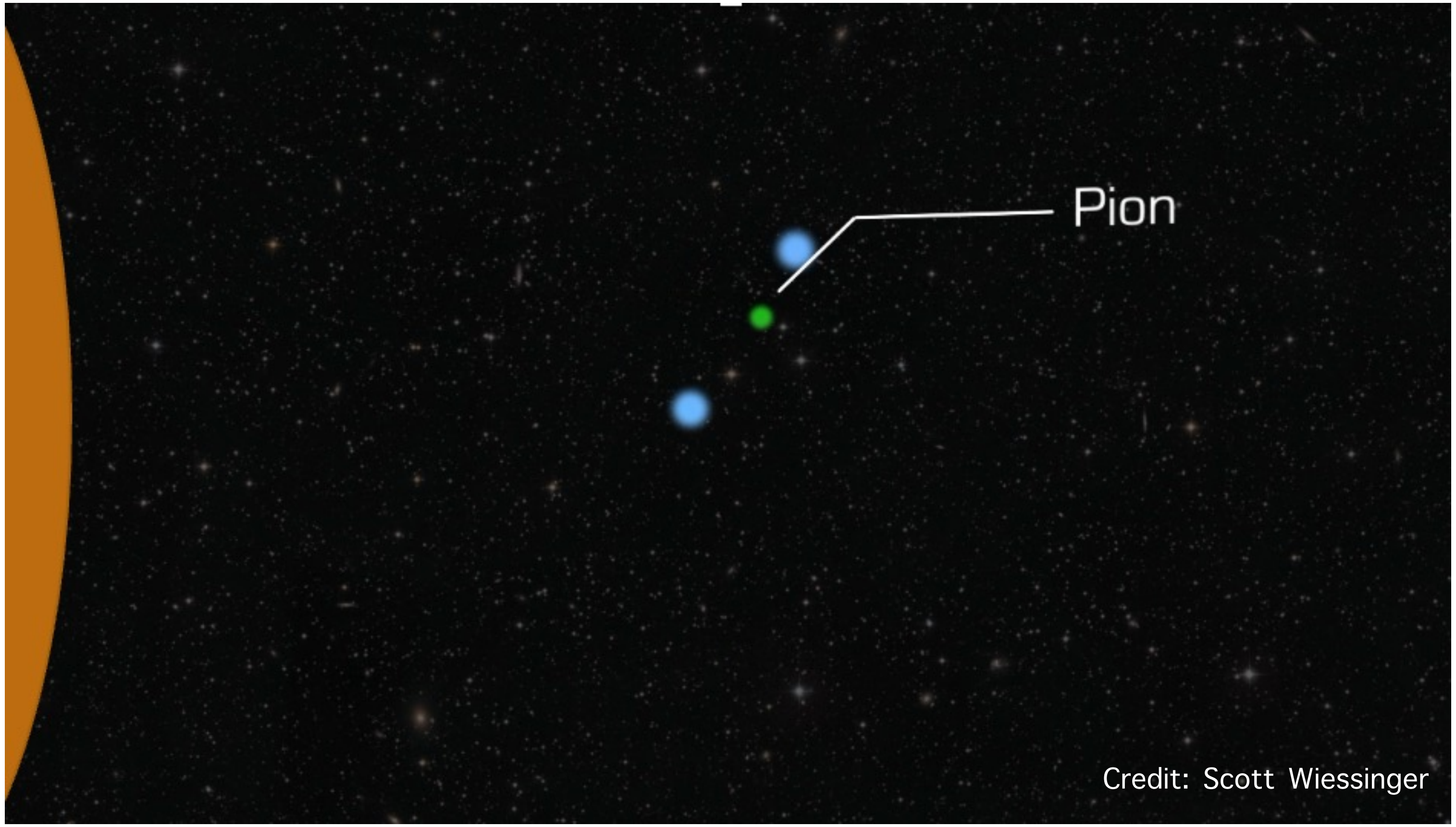

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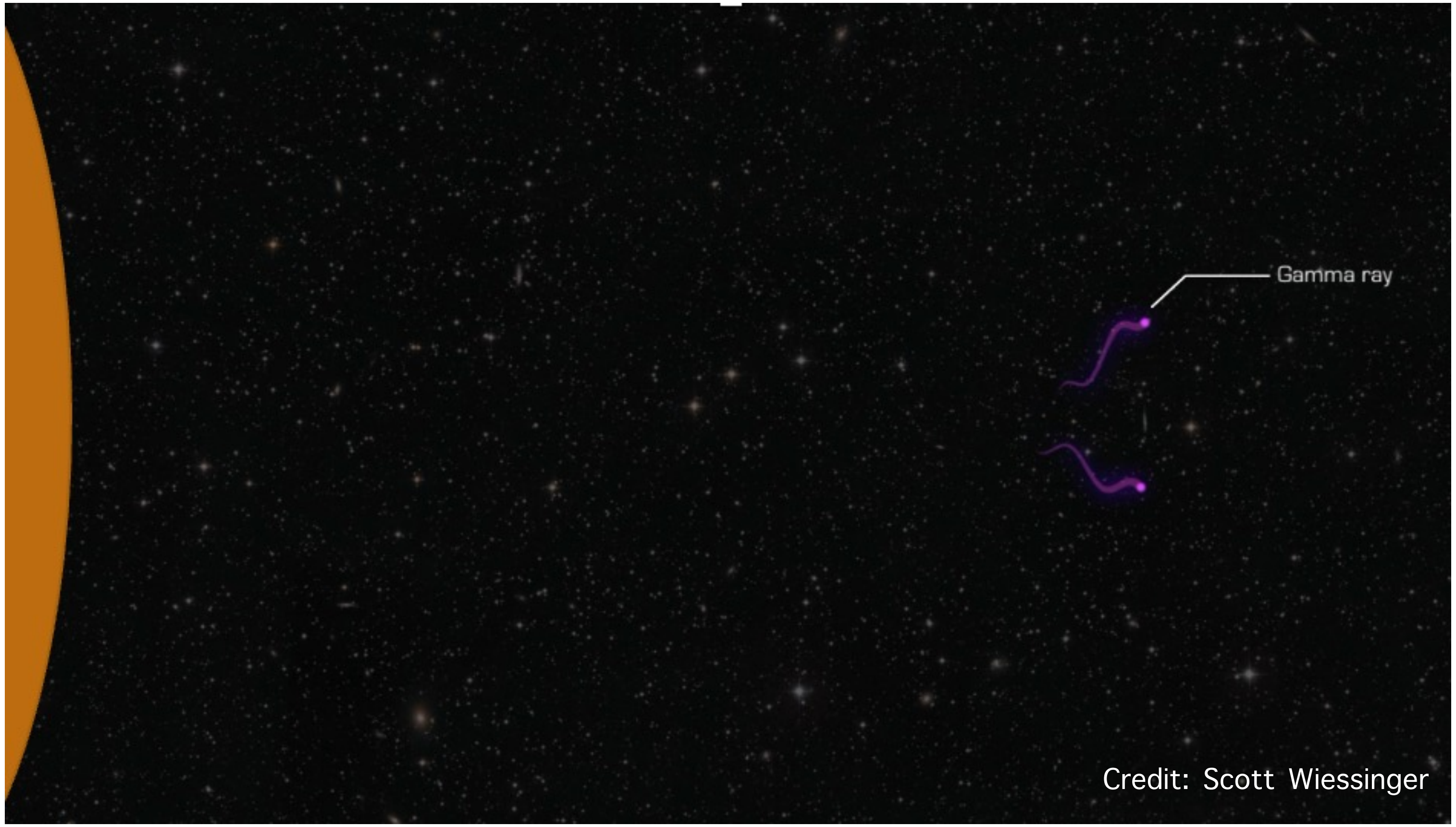

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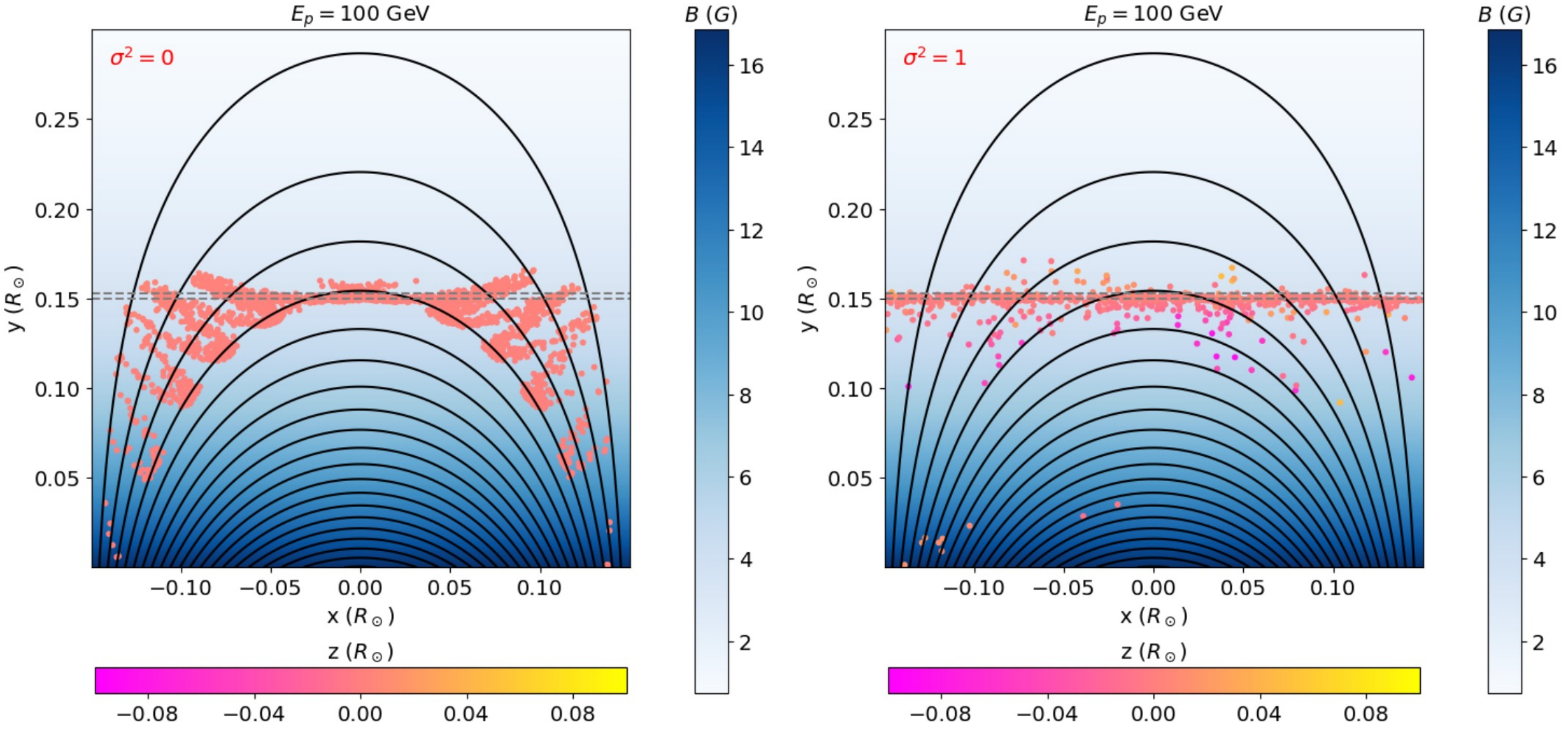
Interaction dependence on turbulence

$$\kappa_{\parallel}(x, y, v) \propto \frac{B^2(x, y)}{\sigma^2},$$

$$\kappa_{\perp}(x, y, v) \propto \frac{\sigma^2}{B^2(x, y)}.$$

$$\lambda_{\parallel} = 3\kappa_{\parallel}/v$$



Credits: Puzzoni et al. 2023, in prep.

Interaction dependence on turbulence

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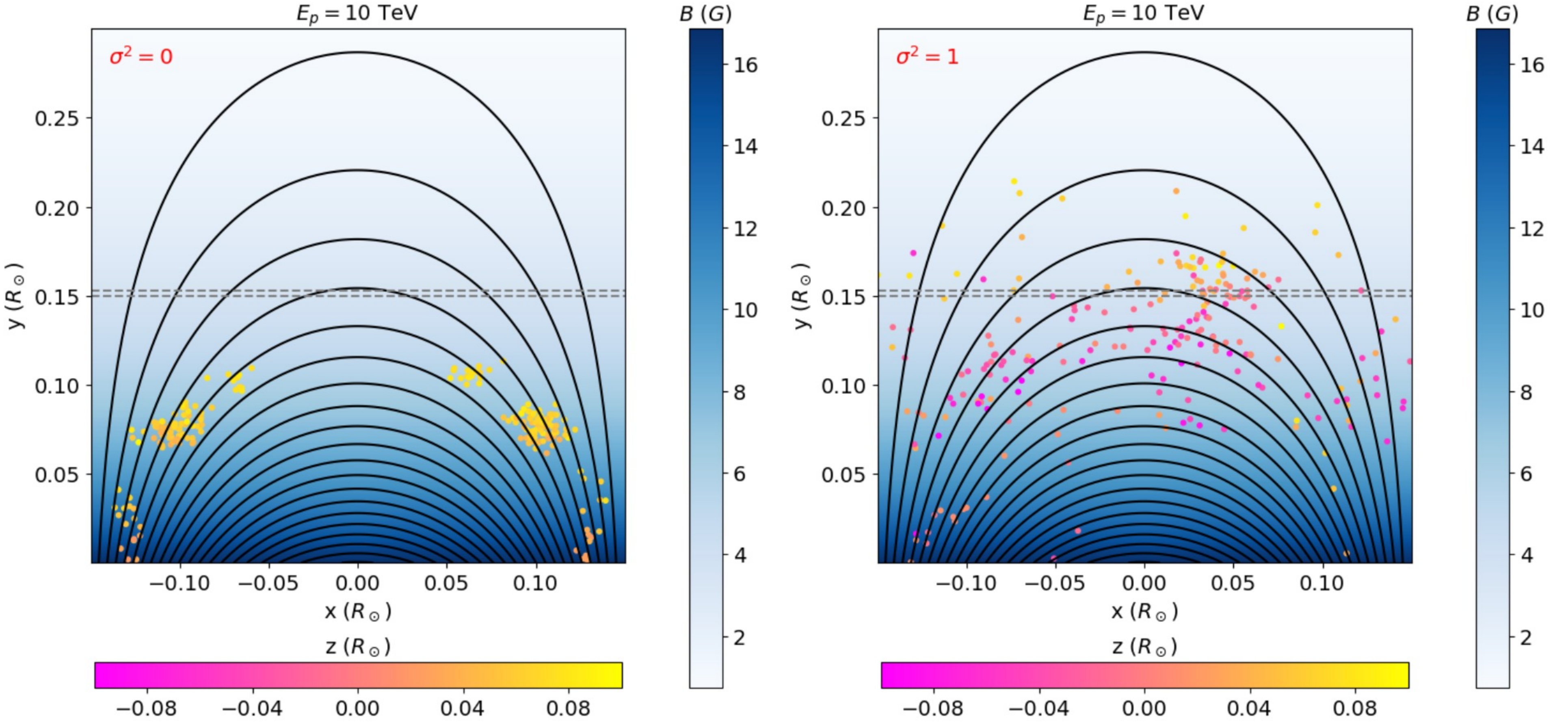
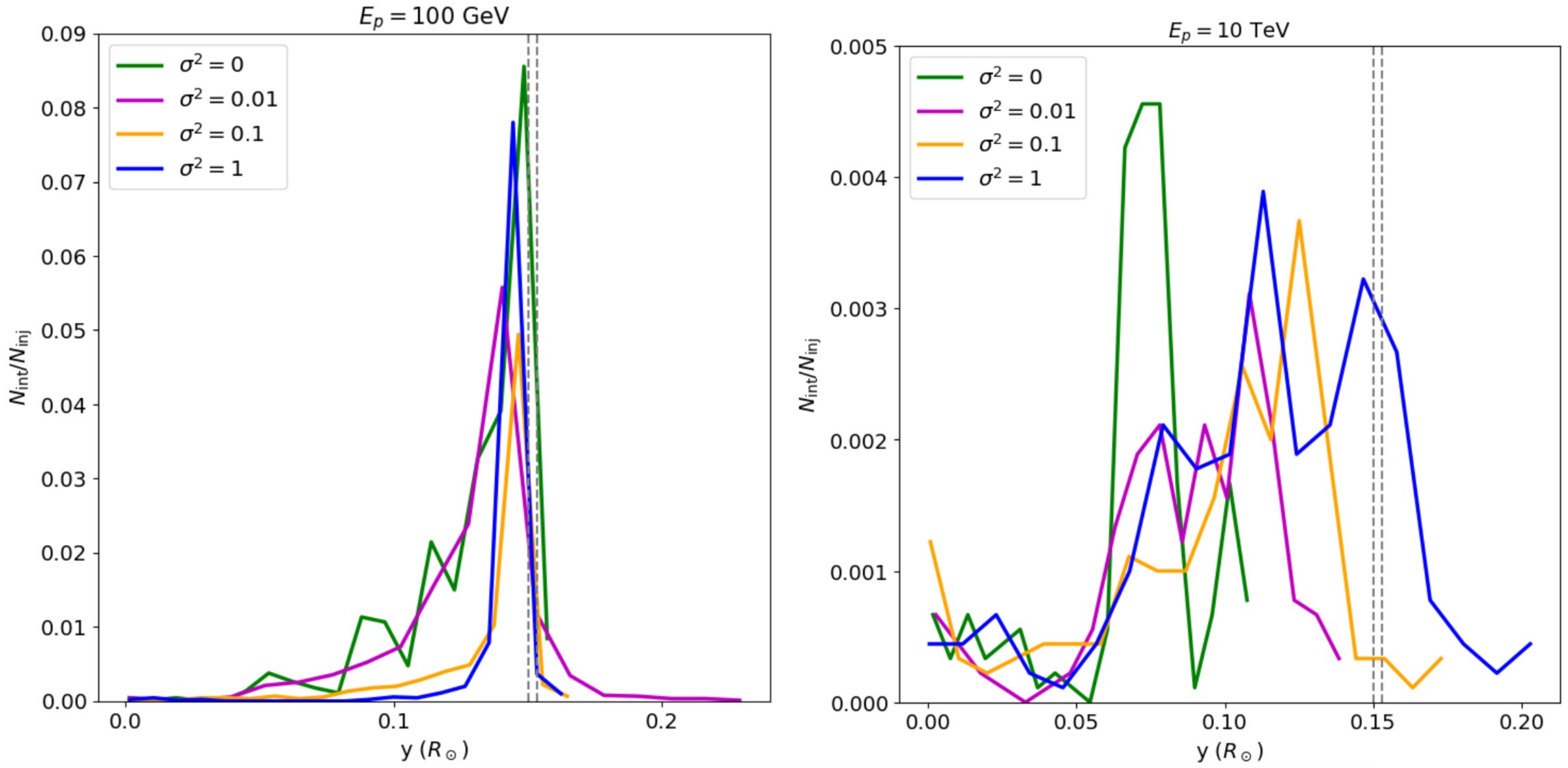


Credits: Puzzoni et al. 2023, in prep.

Interaction dependence on turbulence



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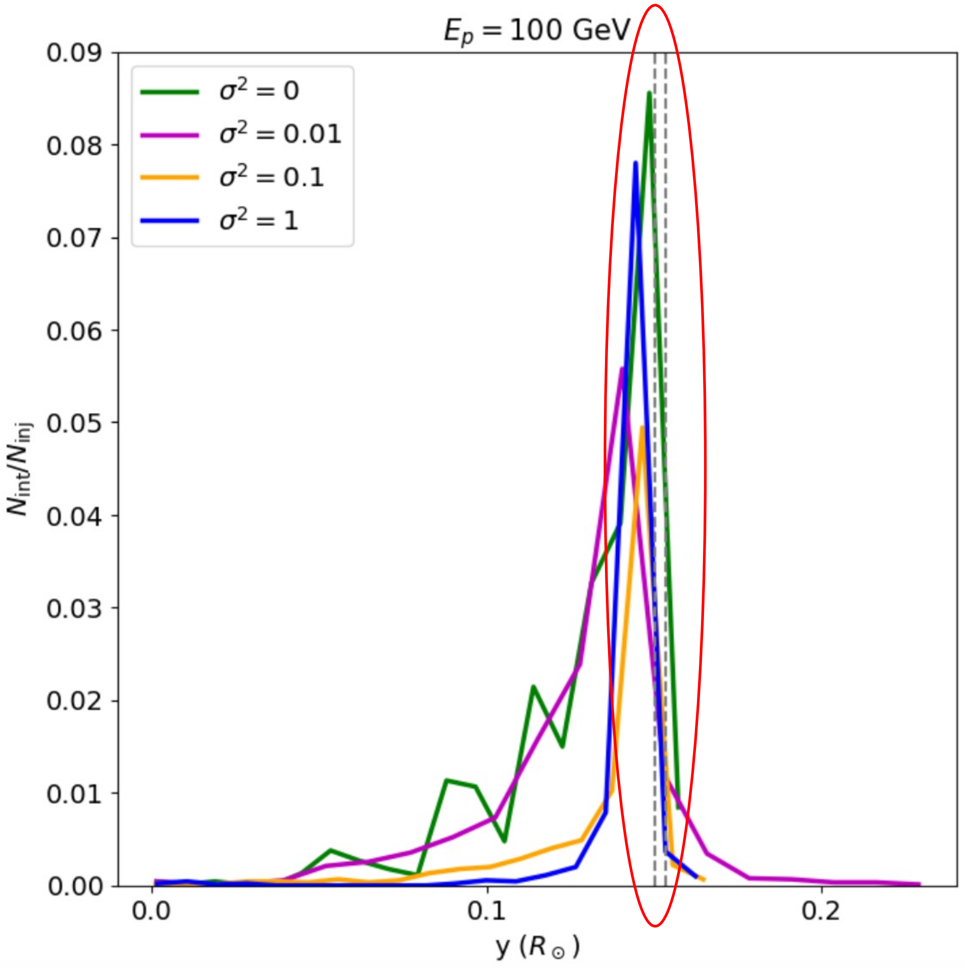
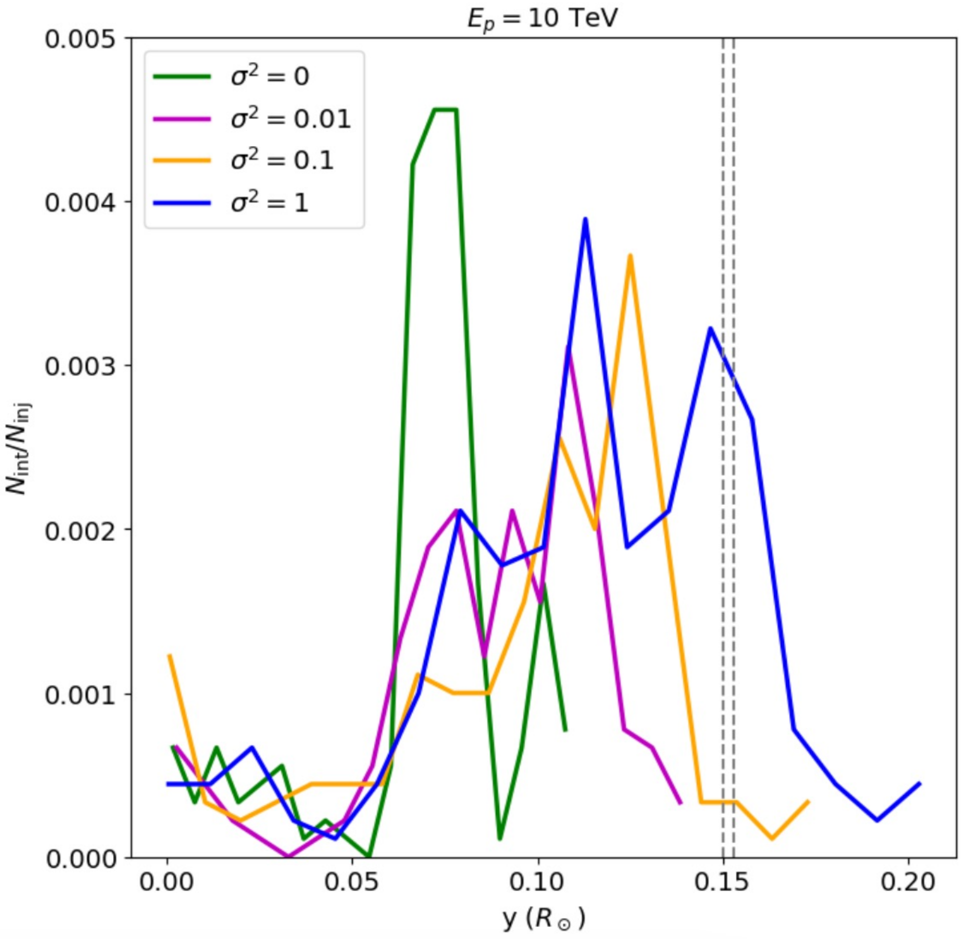
Interaction dependence on turbulence





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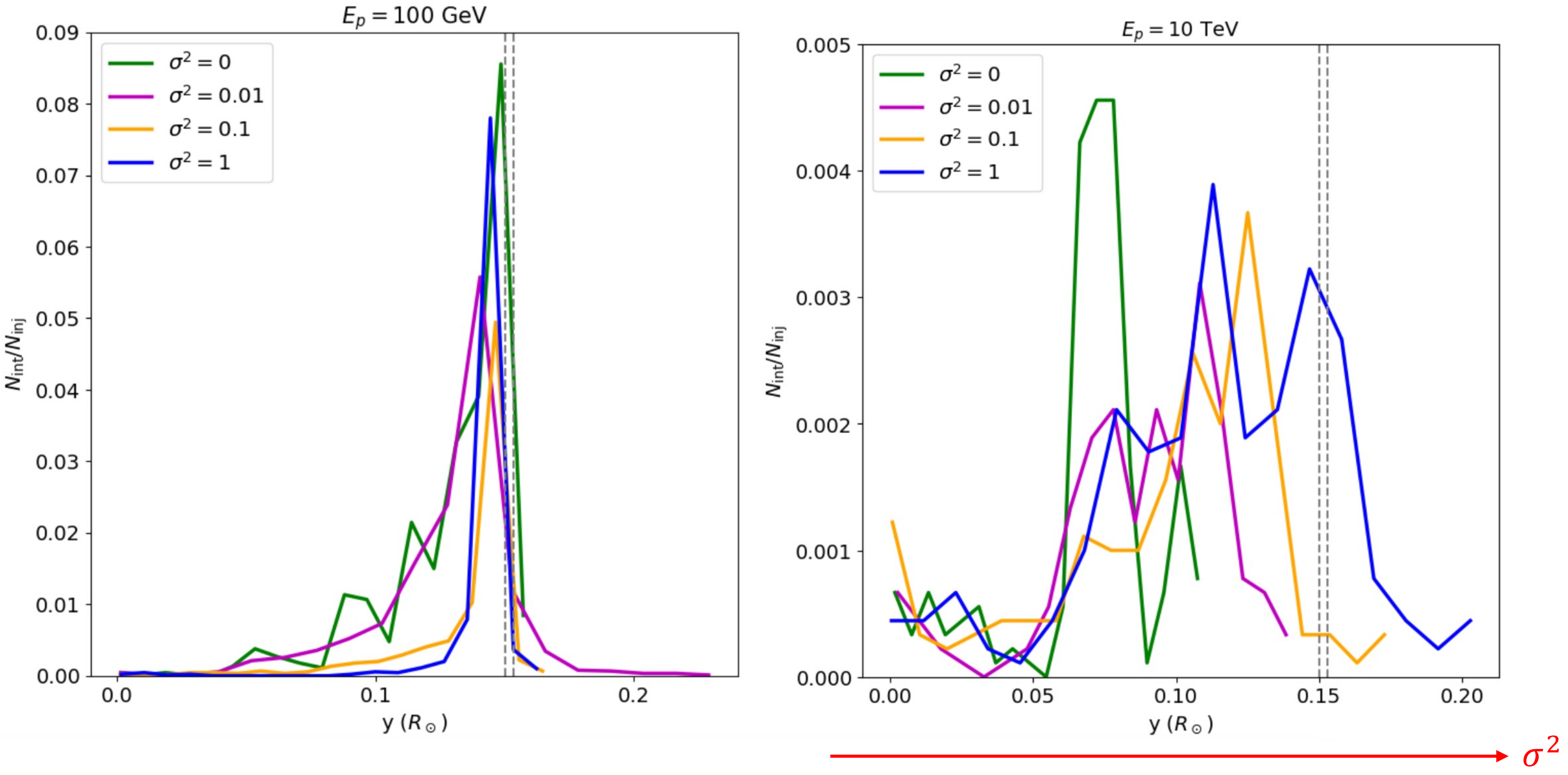
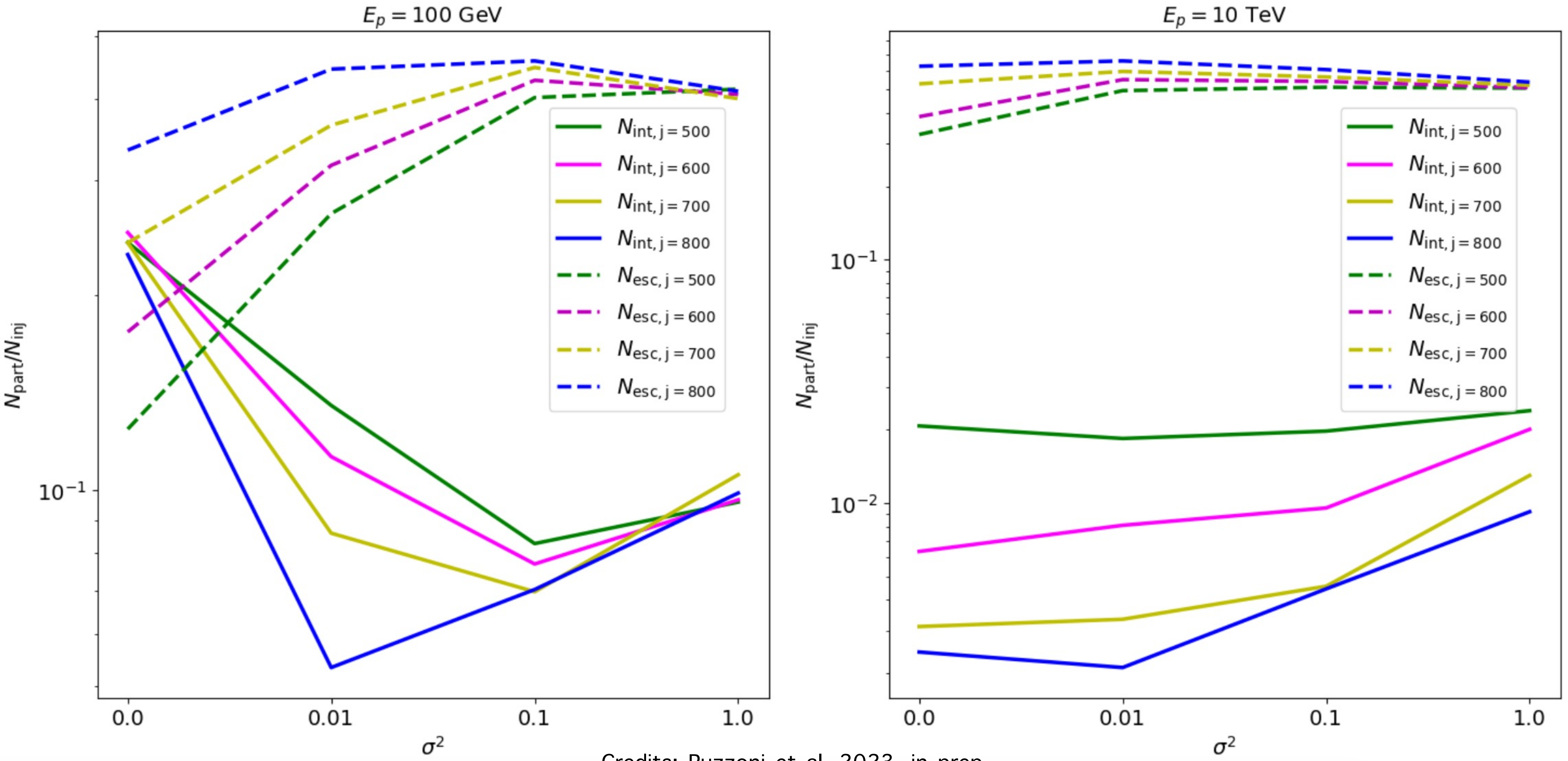
Interaction dependence on turbulence



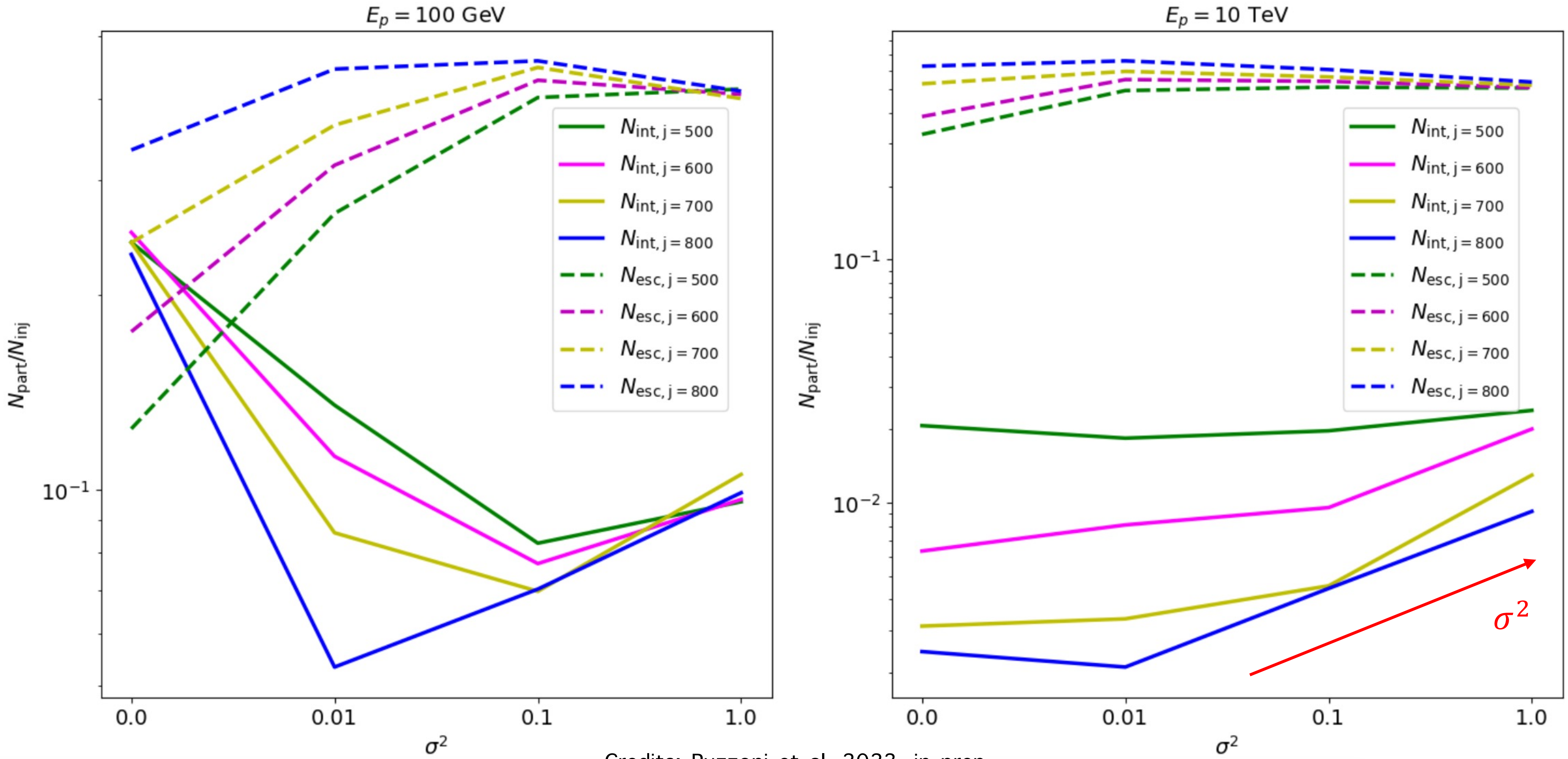
Credits: Puzzoni et al. 2023, in prep.

Interacting vs escaping particles



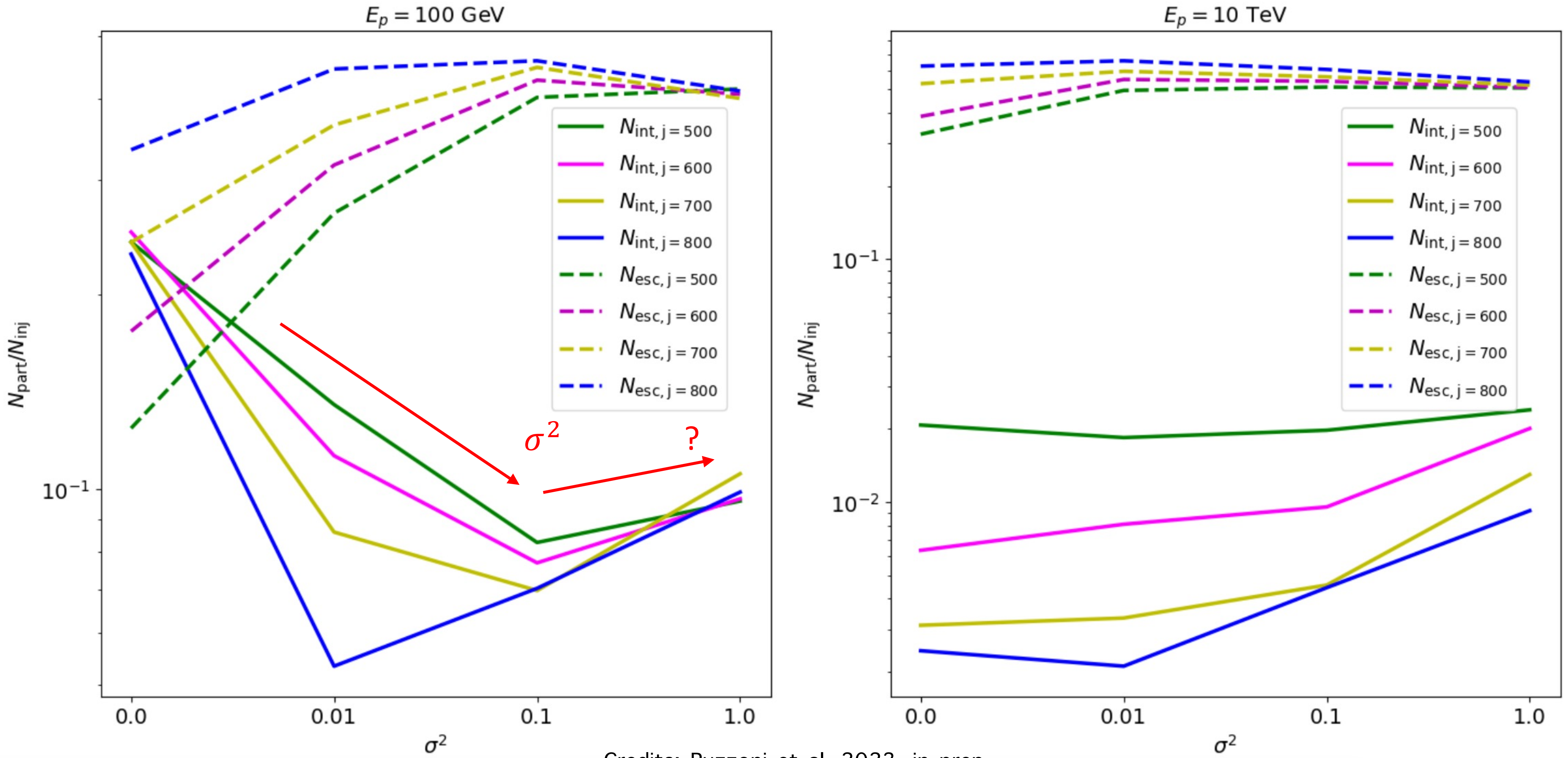
Credits: Puzzoni et al. 2023, in prep.

Interacting vs escaping particles



Credits: Puzzoni et al. 2023, in prep.

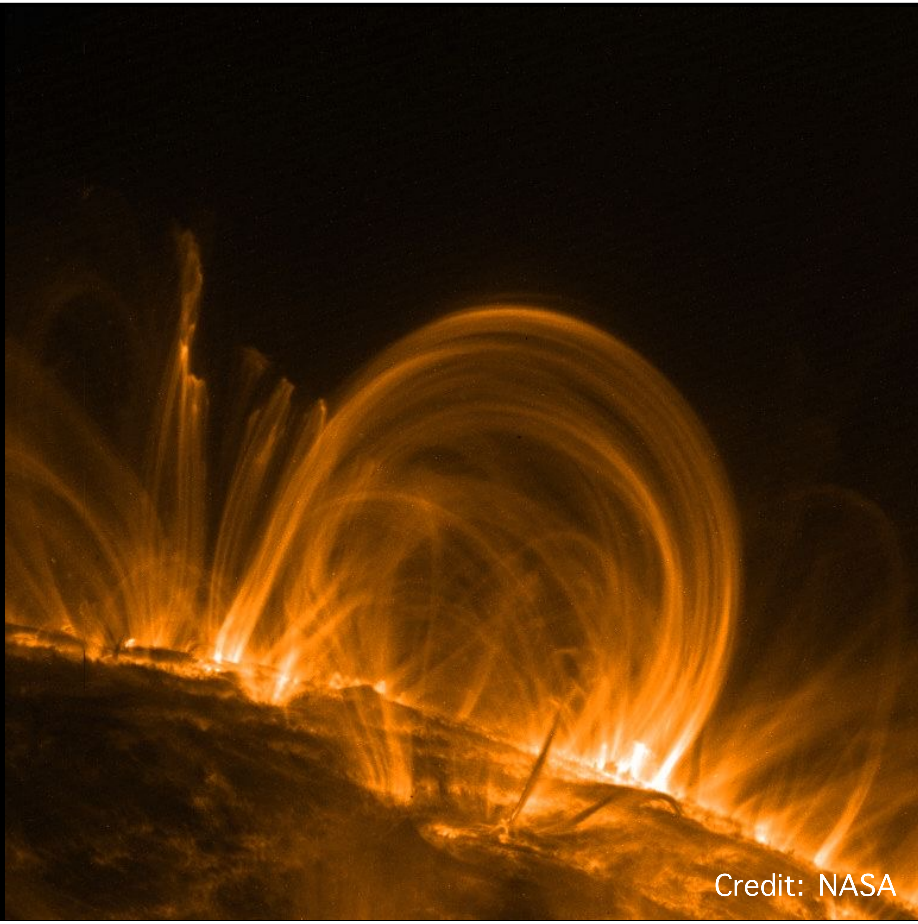
Interacting vs escaping particles

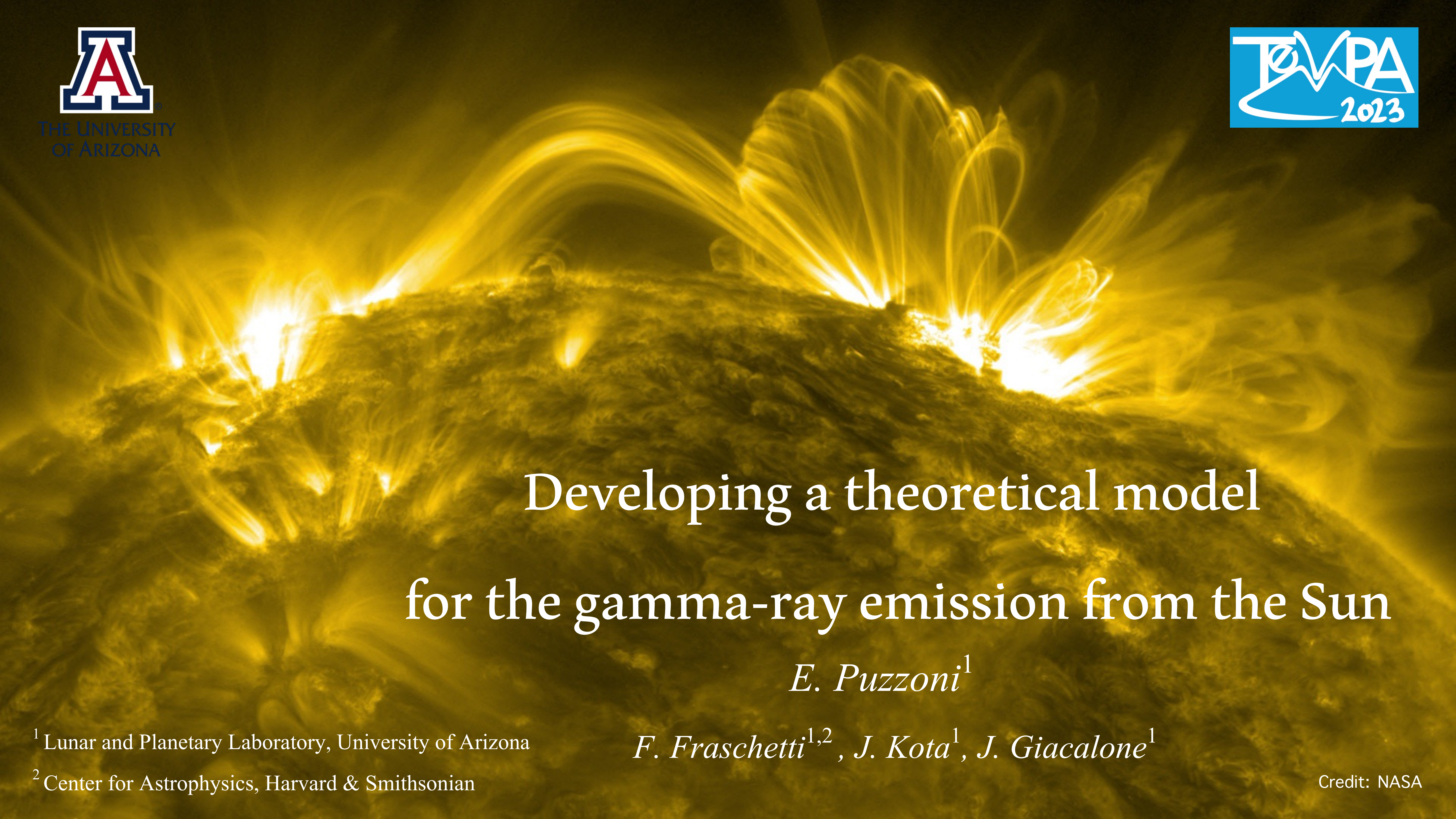


Credits: Puzzoni et al. 2023, in prep.

Conclusions and outlooks

- Turbulence plays a crucial role in trapping GCRs
- Trapping efficiency depends on the particles energy
- Calculation of γ-ray flux
- Explore different parameters (Λ_B)





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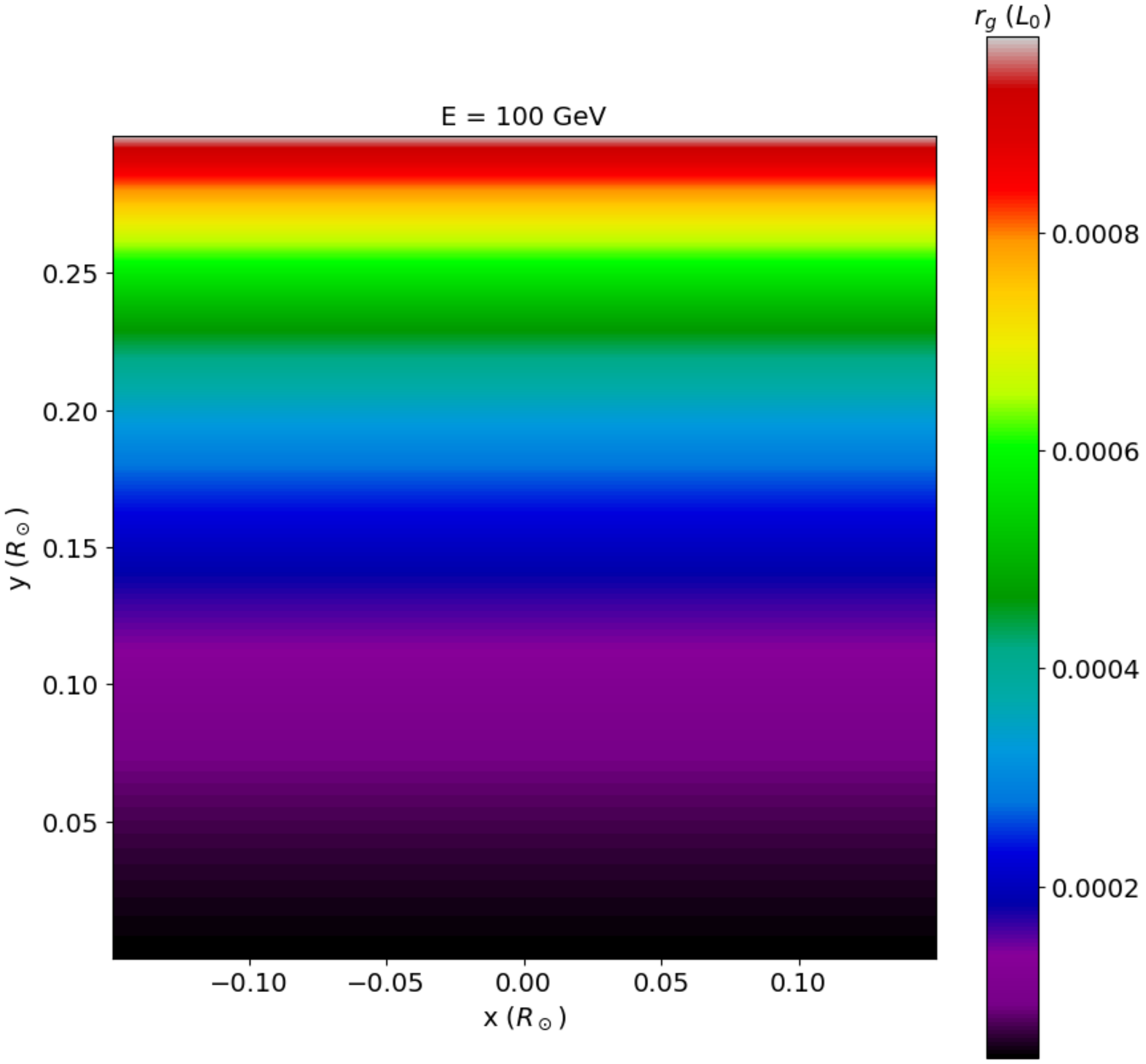
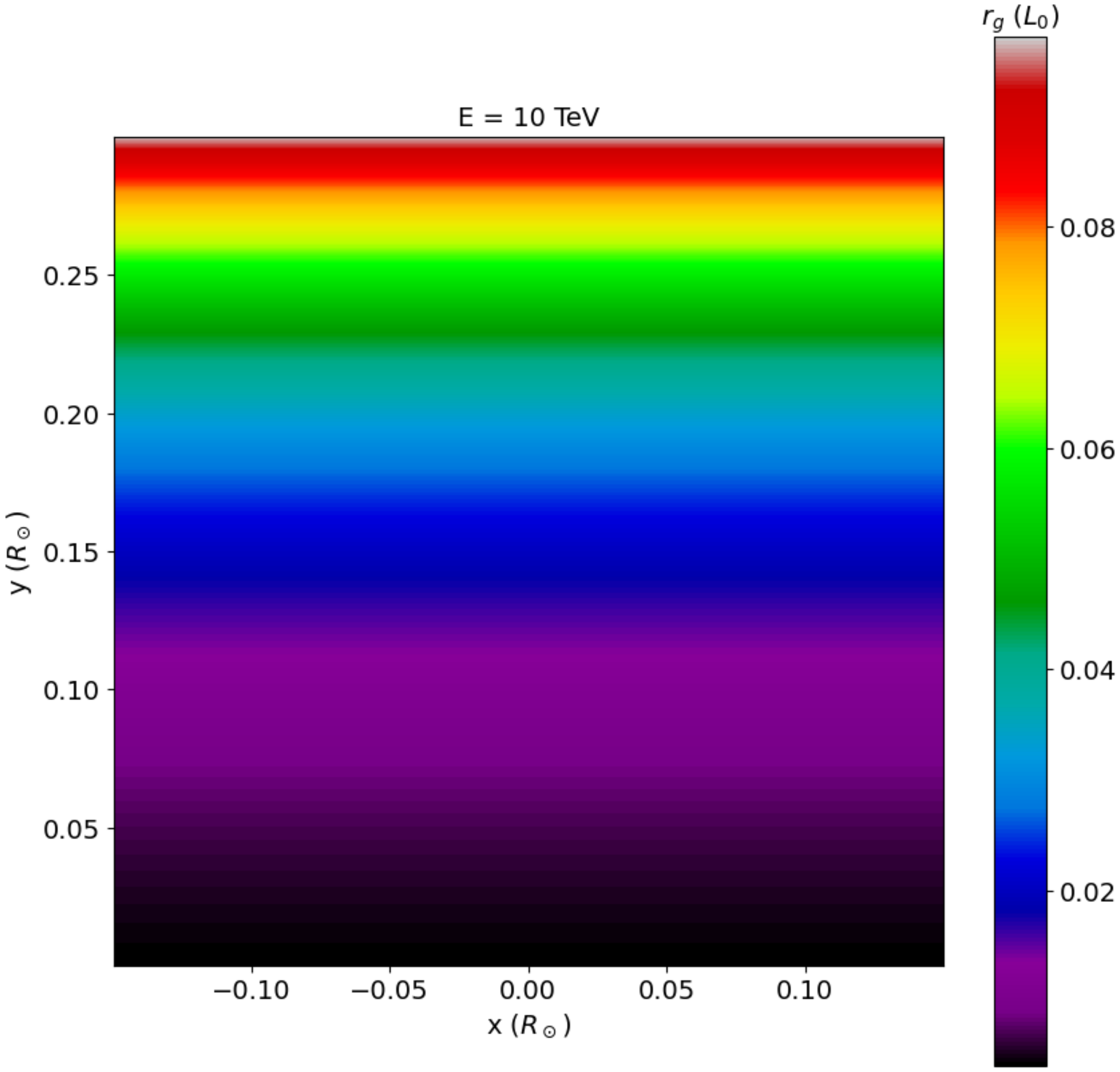
Credit: NASA

GYRORADIUS


E = 100 GeV
r_g (L_0)
0.0008
0.0006
0.0004
0.0002
0.25
0.20
0.15
0.10
0.05
y ($R_\odot$)
−0.10
−0.05
0.00
0.05
0.10
x ($R_\odot$)


E = 10 TeV
r_g (L_0)
0.08
0.06
0.04
0.02
0.25
0.20
0.15
0.10
0.05
y ($R_\odot$)
−0.10
−0.05
0.00
0.05
0.10
x ($R_\odot$)

TURBULENCE EQUATIONS

Credits: Giacalone and Jokipii 1999

$$\delta \boldsymbol{B}(x, y, z) = \sum_{n=1}^{N_m} A(k_n) \hat{\boldsymbol{\xi}}_n \exp\left(i k_n z'_n + i \beta_n\right) , \qquad (3)$$

where

$$\hat{\boldsymbol{\xi}}_n = \cos \alpha_n \hat{\boldsymbol{x}}'_n + i \sin \alpha_n \hat{\boldsymbol{y}}'_n \qquad (4)$$

and

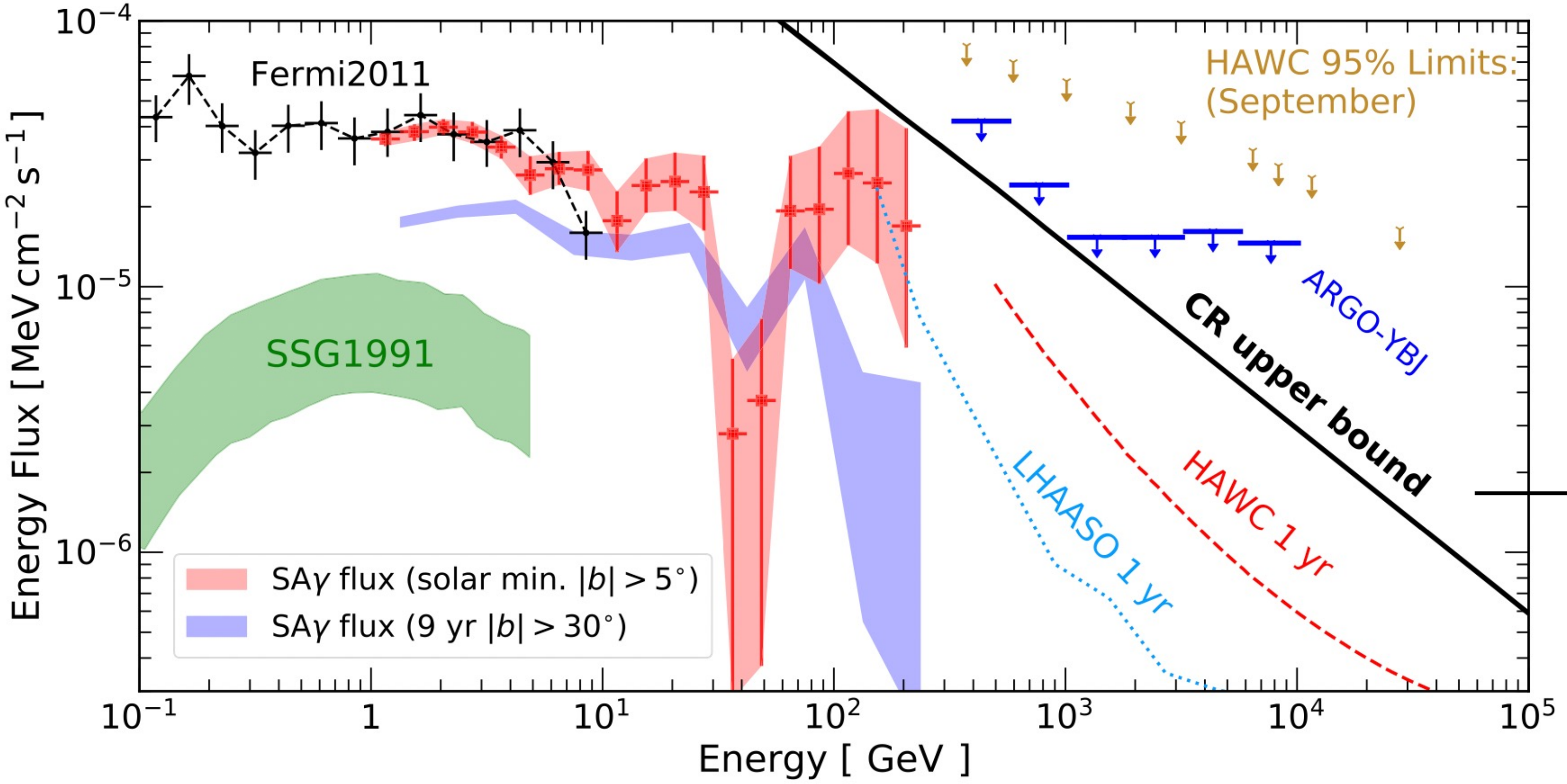
$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos\theta_n \cos\phi_n & \cos\theta_n \sin\phi_n & -\sin\theta_n \\ -\sin\phi_n & \cos\phi_n & 0 \\ \sin\theta_n \cos\phi_n & \sin\theta_n \sin\phi_n & \cos\theta_n \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} . \qquad (5)$$

$$A^2(k_n) = \sigma^2 G(k_n) \left[\sum_{n=1}^{N_m} G(k_n) \right]^{-1} , \qquad (6)$$

where

$$G(k_n) = \frac{\Delta V_n}{1 + (k_n L_c)^{\gamma}} . \qquad (7)$$

FERMI DATA



Credits: Tang et al. 2018

- Fermi 2011
- Fermi solar minimum 2008-2010
- Fermi 9 years 2008-2017

→ Theoretical maximum gamma-ray flux the Sun can produce with cosmic rays

INTERACTION TIME

$$t_{int}(y) = \frac{1}{n(y)\sigma_c(m_p c^2 \gamma) v}$$

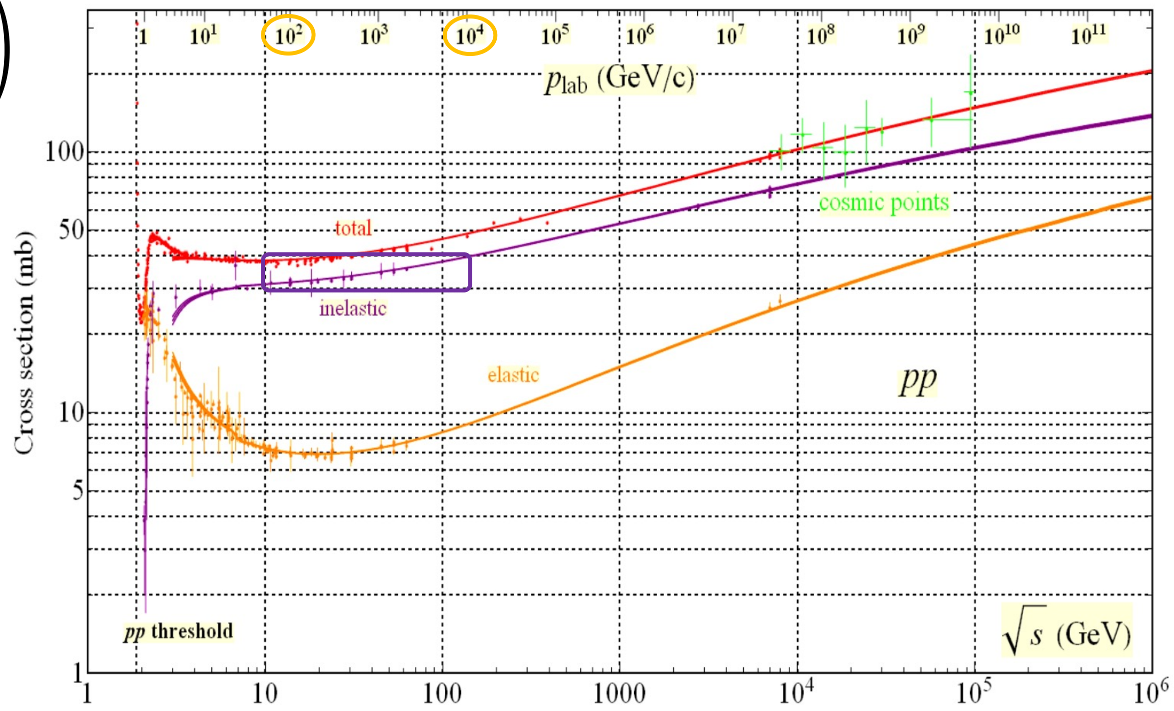
Credits: Kafexhiu et al. 2014

$$\sigma_c = \left[30.7 - 0.96\log\left(\frac{m_p c^2\gamma}{m_p c^2\gamma^{th}}\right) + 0.18\log^2\left(\frac{m_p c^2\gamma}{m_p c^2\gamma^{th}}\right)\right] \times \left[1 - \left(\frac{m_p c^2\gamma^{th}}{m_p c^2\gamma}\right)^{1.9}\right]^3 mb$$

$$v = c$$

$$n(y) = n_0 e^{-\frac{y}{\Lambda_B}}$$

Credits: Tanabashi et al. 2018



Additional filter on particles: $t_{int} < \Delta t$ + ($v_y > 0$)

BACKUP SLIDES

PARTICLES MOTION

$$\begin{cases} \dfrac{d\boldsymbol{x}_p}{dt} = \boldsymbol{v}_p \\ \dfrac{d(\gamma\boldsymbol{v})_p}{dt} = \left(\dfrac{e}{mc}\right)_p \boldsymbol{v}_p \times \boldsymbol{B} \end{cases}$$

MAGNETIC FIELD ARCADE + TURBULENT COMPONENT

DRIFT VELOCITY

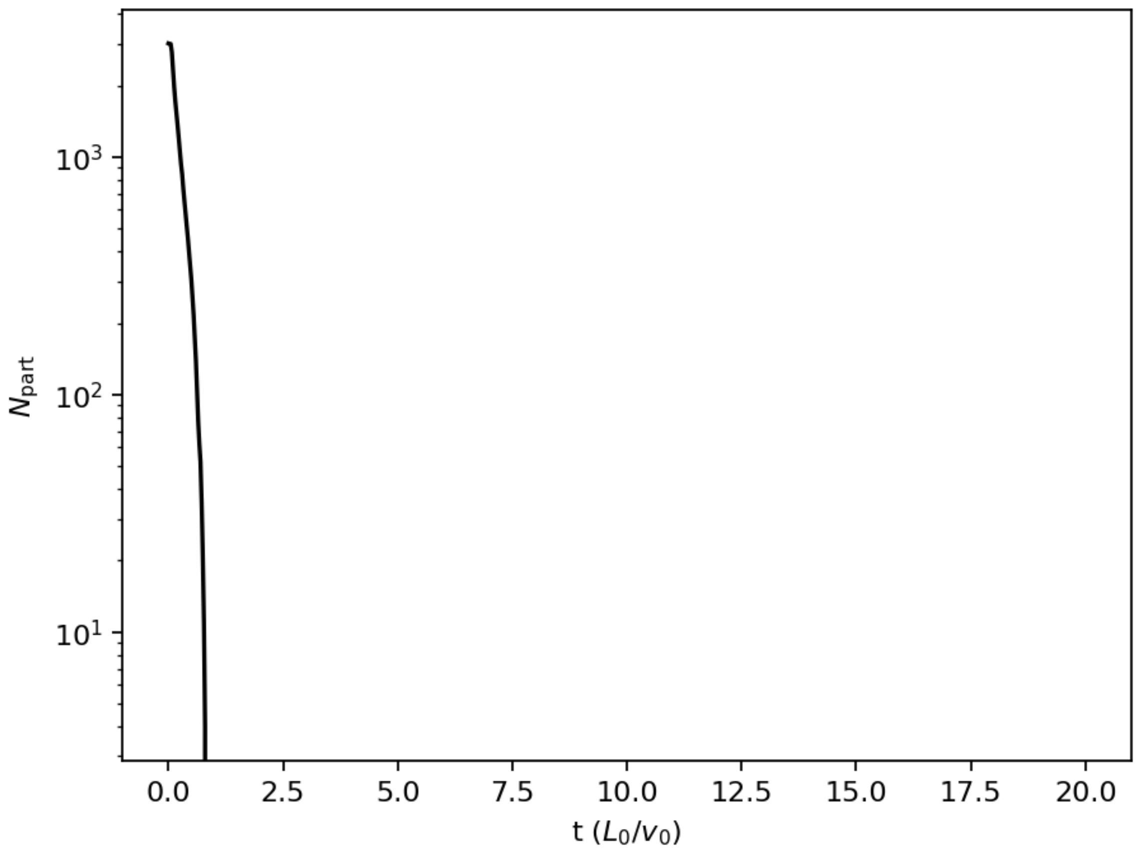
$$\boldsymbol{v}_{CG} = \boldsymbol{v}_G + \boldsymbol{v}_c = -\frac{\gamma m c B_0^2}{2qB^3\Lambda_B}\left(v_\perp^2 + 2v_\parallel^2\right)\cos\left(\frac{x}{\Lambda_B}\right)e^{-\frac{2y}{\Lambda_B}}\,\hat{\boldsymbol{k}}$$

TRAPPING EFFECT

$800 < j < 810$

100 GeV case

NO TURBULENCE



WITH TURBULENCE