Galactic Cosmic-Ray Propagation in the Inner Heliosphere: Improved Force-Field Model

Jung-Tsung Li (OSU)

TeVPA 2022

In collaboration with
John Beacom and Annika Peter

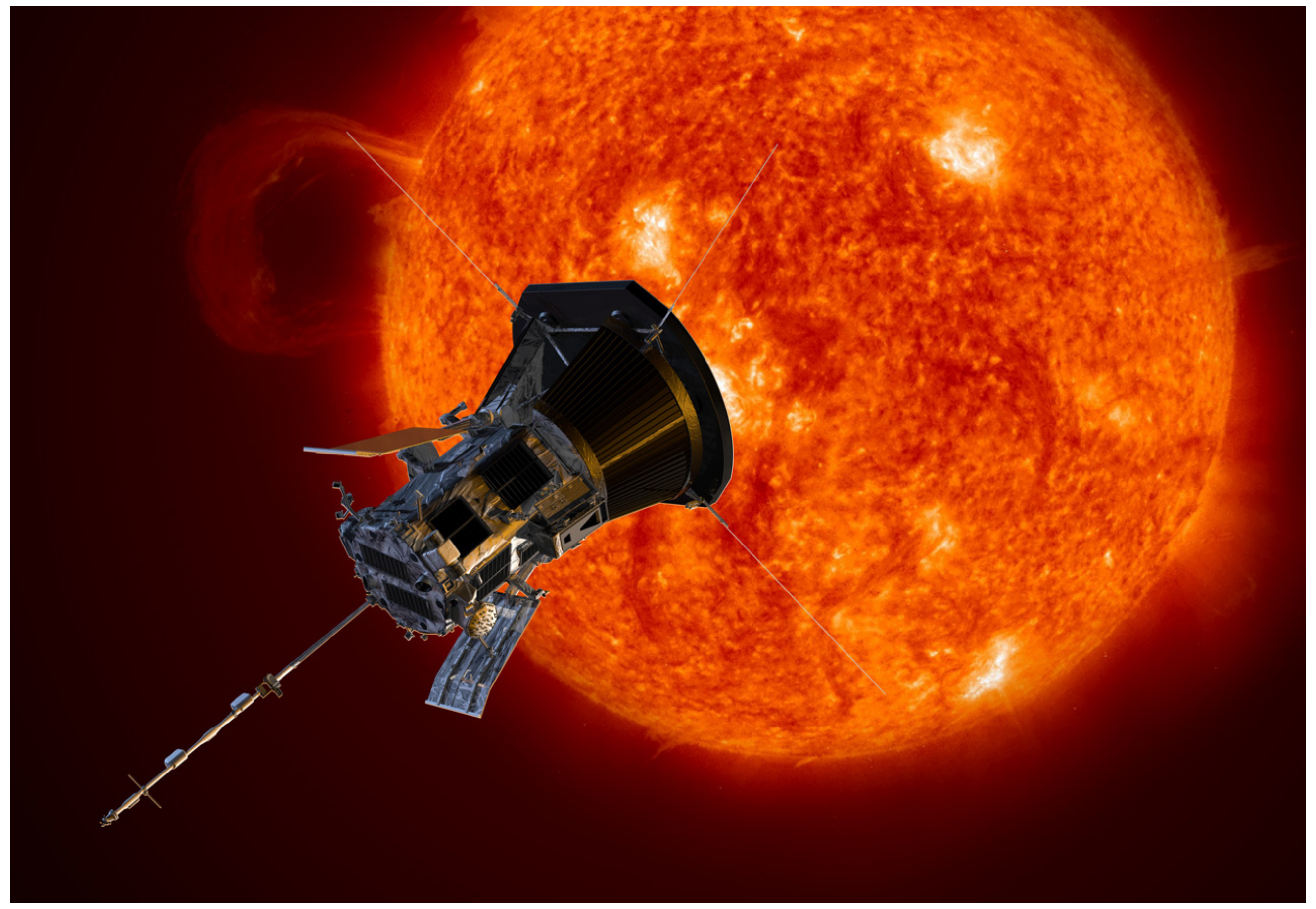
(arXiv: 2206.14815)

ccapp.osu.edu

The Ohio State University

Galactic Cosmic Ray Near The Sun

Parker Solar Probe (PSP)



- PSP reaches 0.05 AU from the Sun
- Radial gradients of anomalous CR
- Will provide energy spectrum of galactic CR

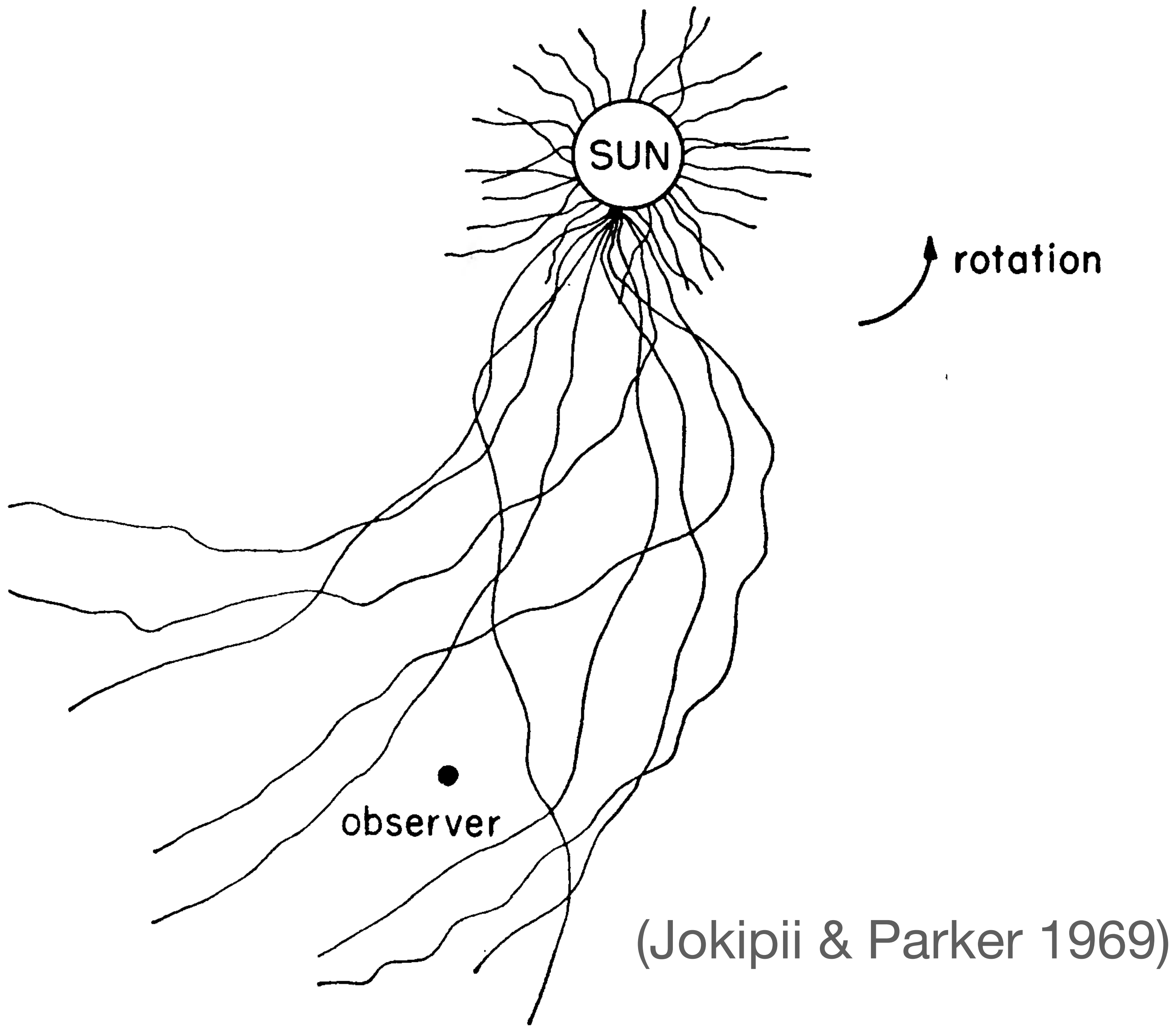
(Fox et al 2016; Rankin et al 2021, 2022)

Fermi Gamma-ray Telescope

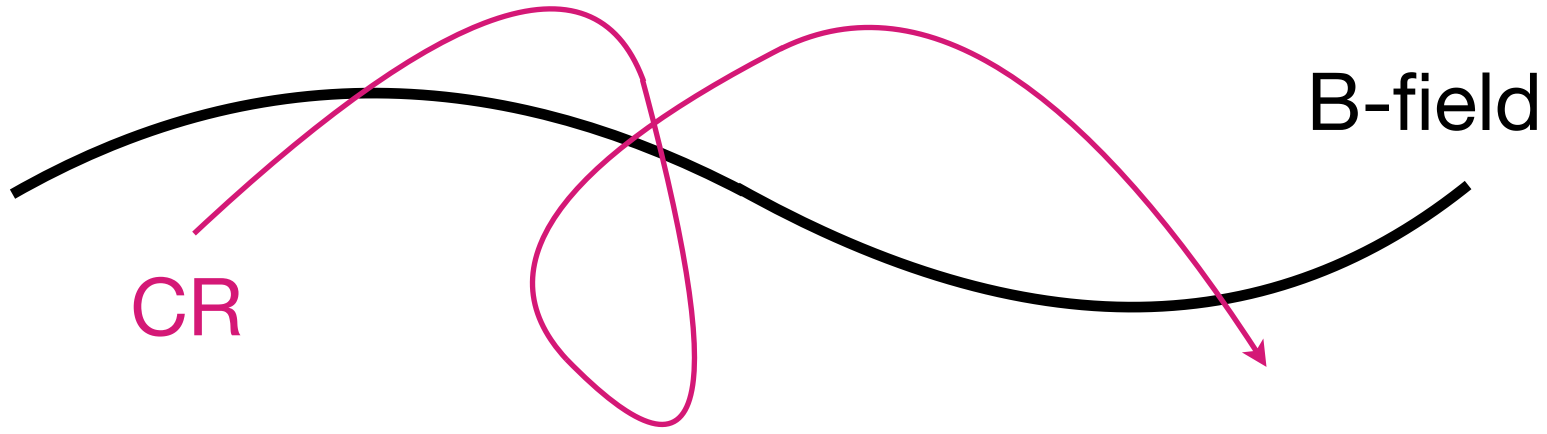
- Gamma-ray emission from the Sun
- Galactic CR interaction with solar photon and atmosphere
- Require understanding of CR intensity near solar surface

(Moskalenko et al 2006; Abdo et al 2011; Ng et al 2016; Linden et al 2022)

Solar Modulation



(Jokipii & Parker 1969)



Modulation process (short version):

- Solar wind carries magnetic turbulence
- Magnetic turbulence interacts with CR
- CR intensity is *reduced* as particles propagates toward the Sun

** Drift effect and charge-sign dependence are not considered in this work

Initial condition:

- Precise cosmic-ray measurements from AMS, PAMELA, etc
- Magnetic turbulence between Earth and Sun is known (from PSP)

Goal:

- Simple model of CR intensity at all heliocentric radii < 1 AU

Force-Field Model

- Full cosmic ray transport equation, in the solar system frame (Parker 1965; Gleeson & Webb 1978)

$$\frac{\partial U_p}{\partial t} + \nabla \cdot \left(C \mathbf{V}_{\rm sw} U_p \right) - \nabla \cdot \left(\kappa \cdot \nabla U_p \right) + v_{\rm D} \cdot \nabla U_p + \frac{1}{3} \frac{\partial}{\partial p} \left(p \mathbf{V}_{\rm sw} \cdot \nabla U_p \right) = 0$$

Rate change | Convection | Diffusion | Drift | Momentum loss

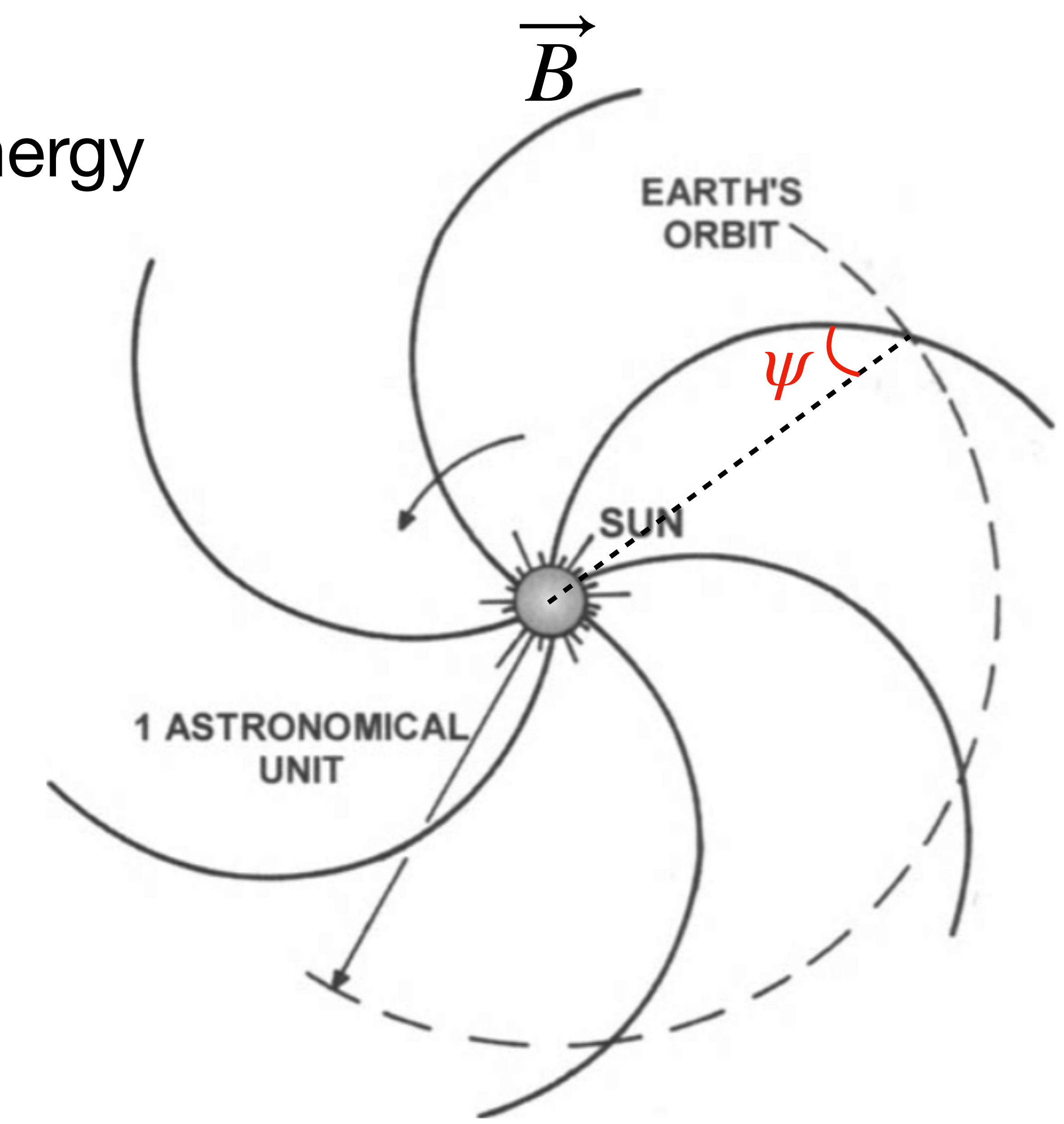
- 1D force-field model: convection flux balances diffusion flux (Gleeson & Axford 1966)

1. Force-field solution $\frac{J_E\left(E, r_1\right)}{E^2 - E_0^2} = \frac{J_E\left(E + \Delta\Phi, r_2\right)}{(E + \Delta\Phi)^2 - E_0^2}$ where $\Delta\Phi$ is modulation potential energy

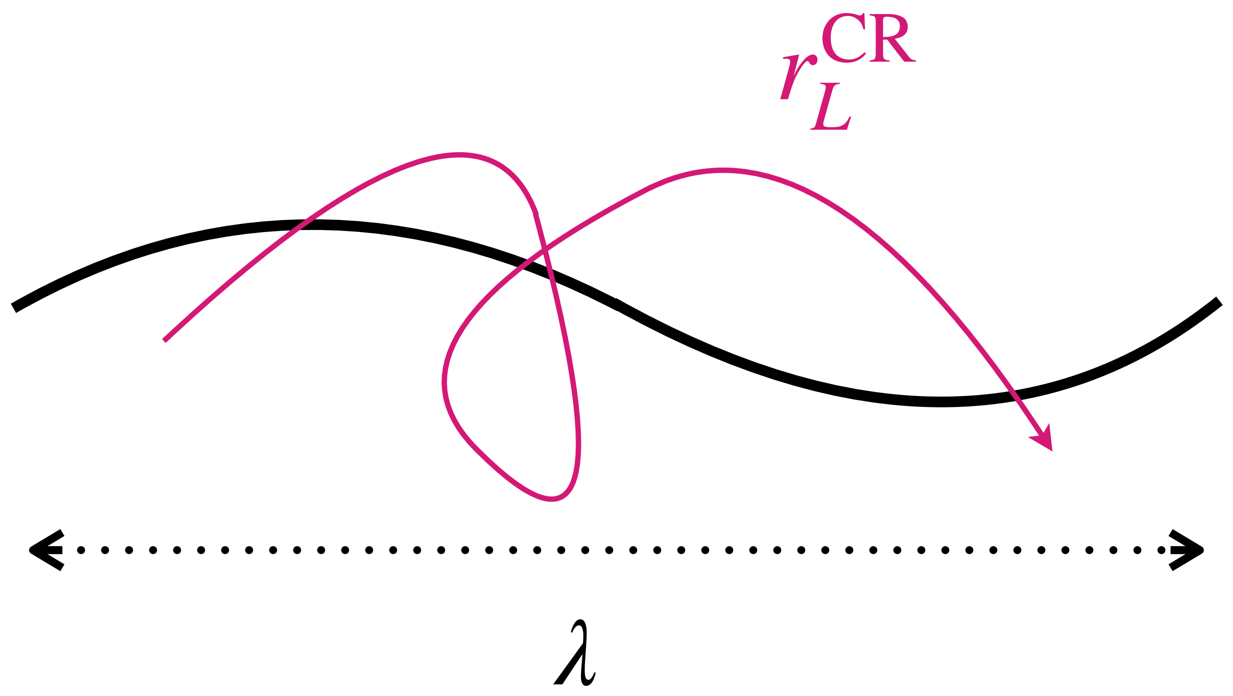
2. Characteristic eqn $\frac{dE}{dr} = \frac{V_{\rm sw}}{3\kappa_{rr}} \frac{\left(E^2 - E_0^2\right)}{E}$

$\kappa_{rr} = \kappa_{\|} \cos^2 \psi + \kappa_{\perp} \sin^2 \psi$ in the plane, with $\kappa_{\|} \gg \kappa_{\perp}$ in the inner heliosphere

$\kappa_{\|}$ is determined from CR resonant interaction with magnetic turbulence



Quasi-linear theory (QLT)



- Quasi-linear theory describes the slow evolution of the particle distribution in a weak turbulent plasma back to a marginally stable state.

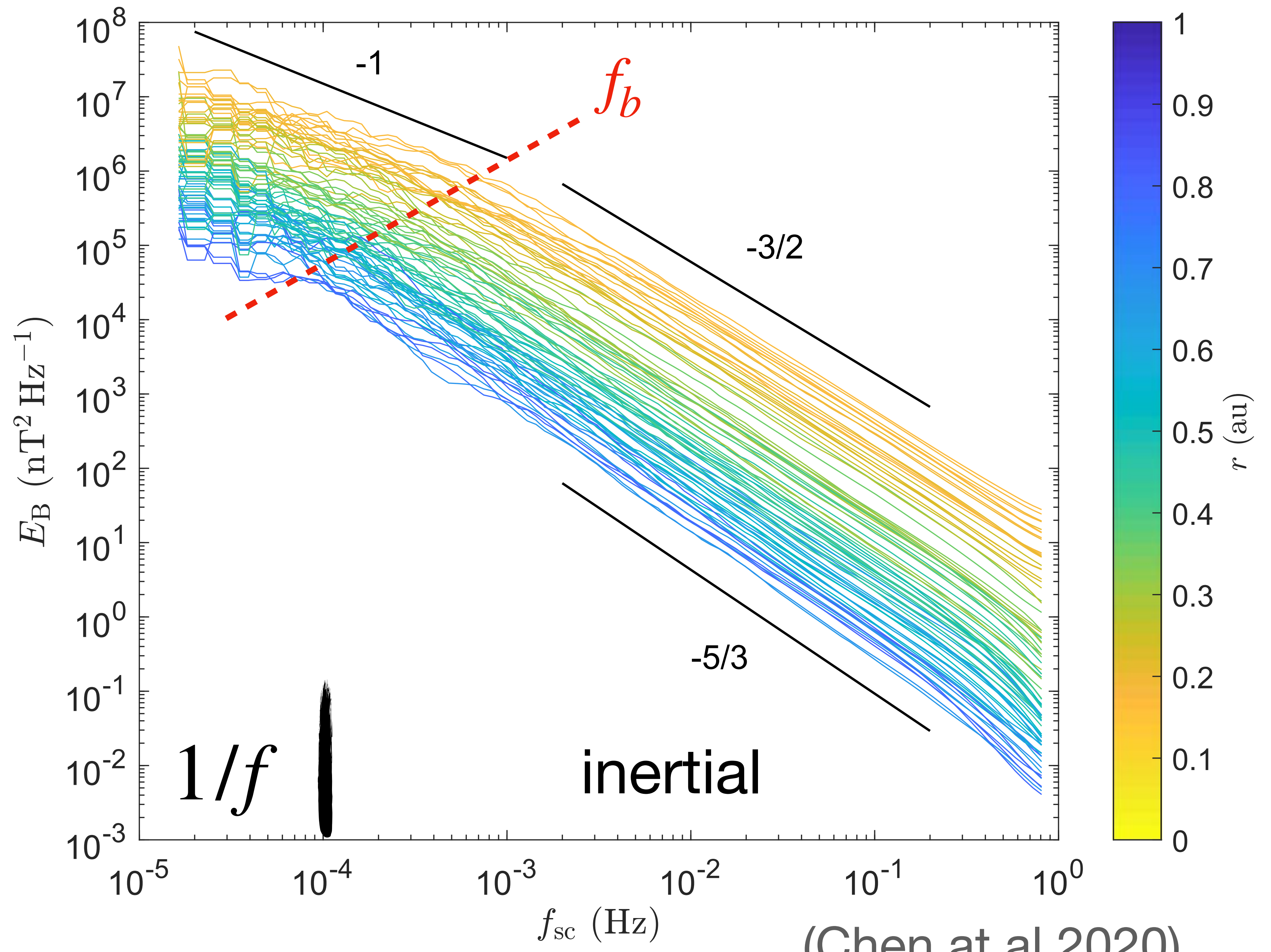
$$\kappa_{\parallel} = \frac{v^2}{4}\int_{\mu_{\min,s}}^{1} \frac{\left(1-\mu^2\right)^2}{D_{\mu\mu}} d\mu \qquad D_{\mu\mu} = \frac{1-\mu^2}{2|\mu|v}\left(\frac{\Omega_{0,s}}{|\langle \mathbf{B} \rangle|}\right)^2 V_{\rm sw}(r)\, E_{{\rm B},xx}\left(f_{\rm res}, r\right)$$

(Jokipii 1966)

μ: cosine of pitch angle

$E_{\rm B}$: magnetic power spectrum

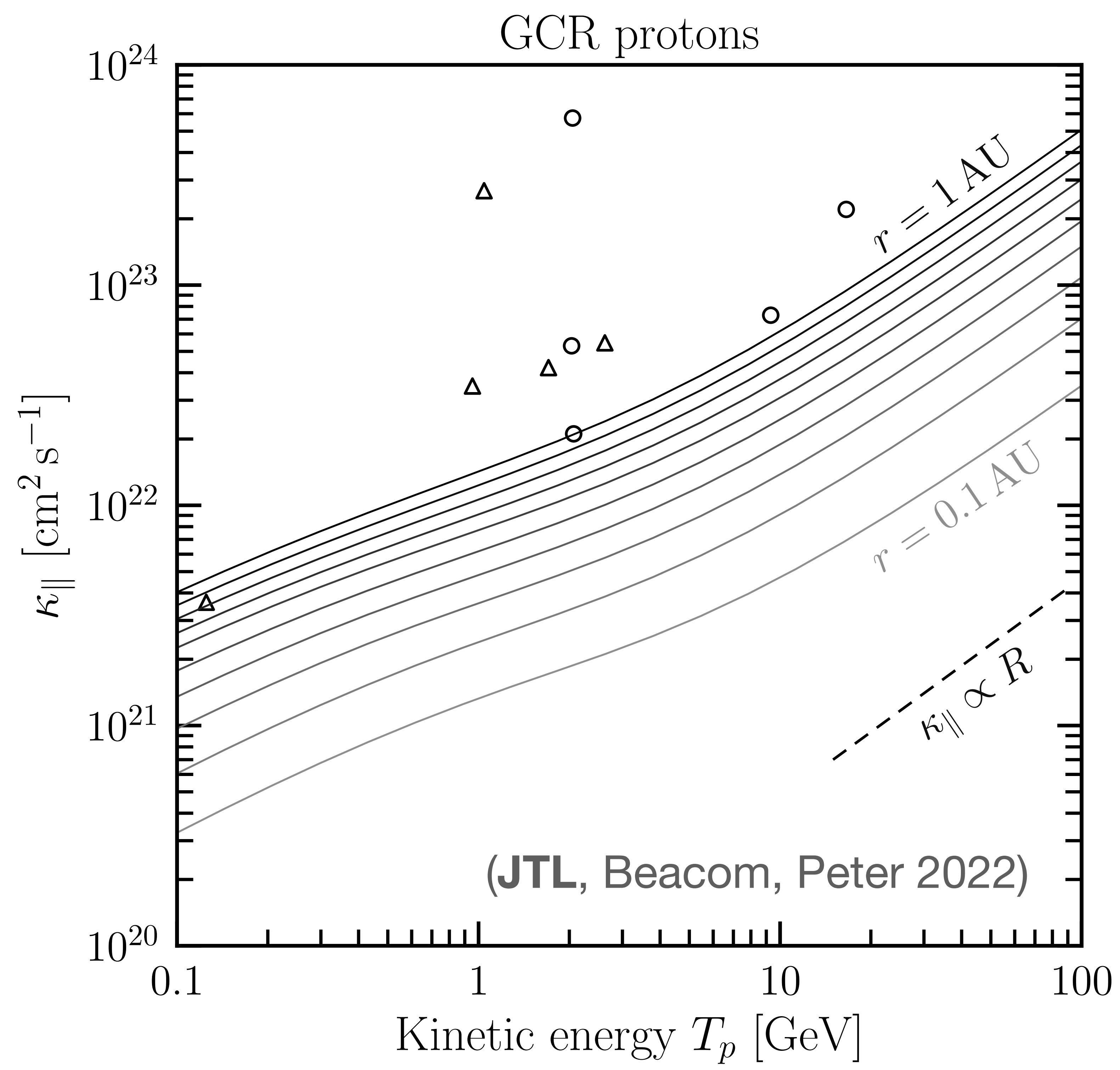
f_b: frequency break

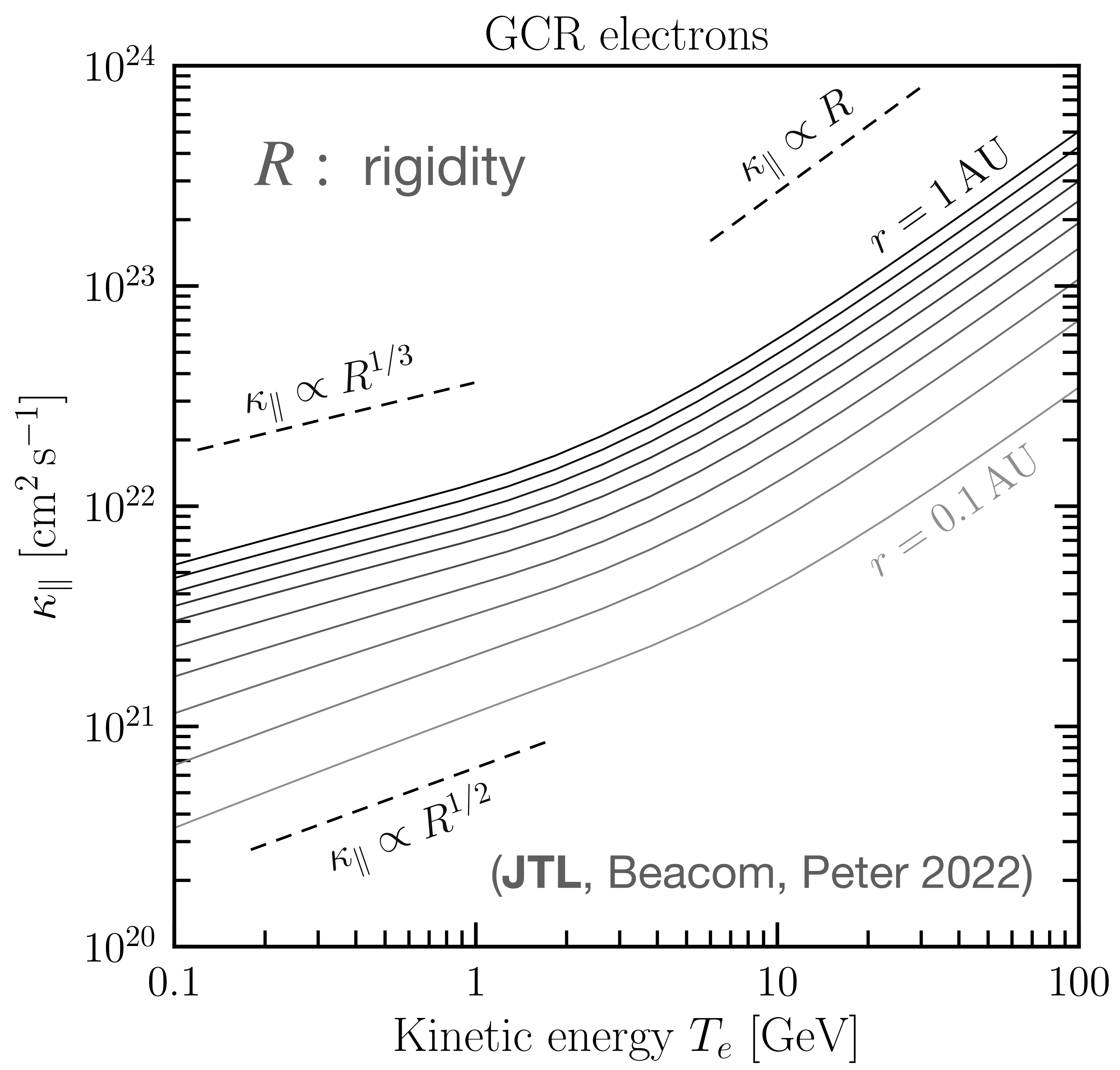


(Chen at al 2020)

- PSP measurement of magnetic power spectrum (Chen et al 2020)
  A. Turbulence evolution down to 0.17 AU
  B. Frequency break f_b which separates 1/f range and inertial range turbulence

Diffusion Coefficient



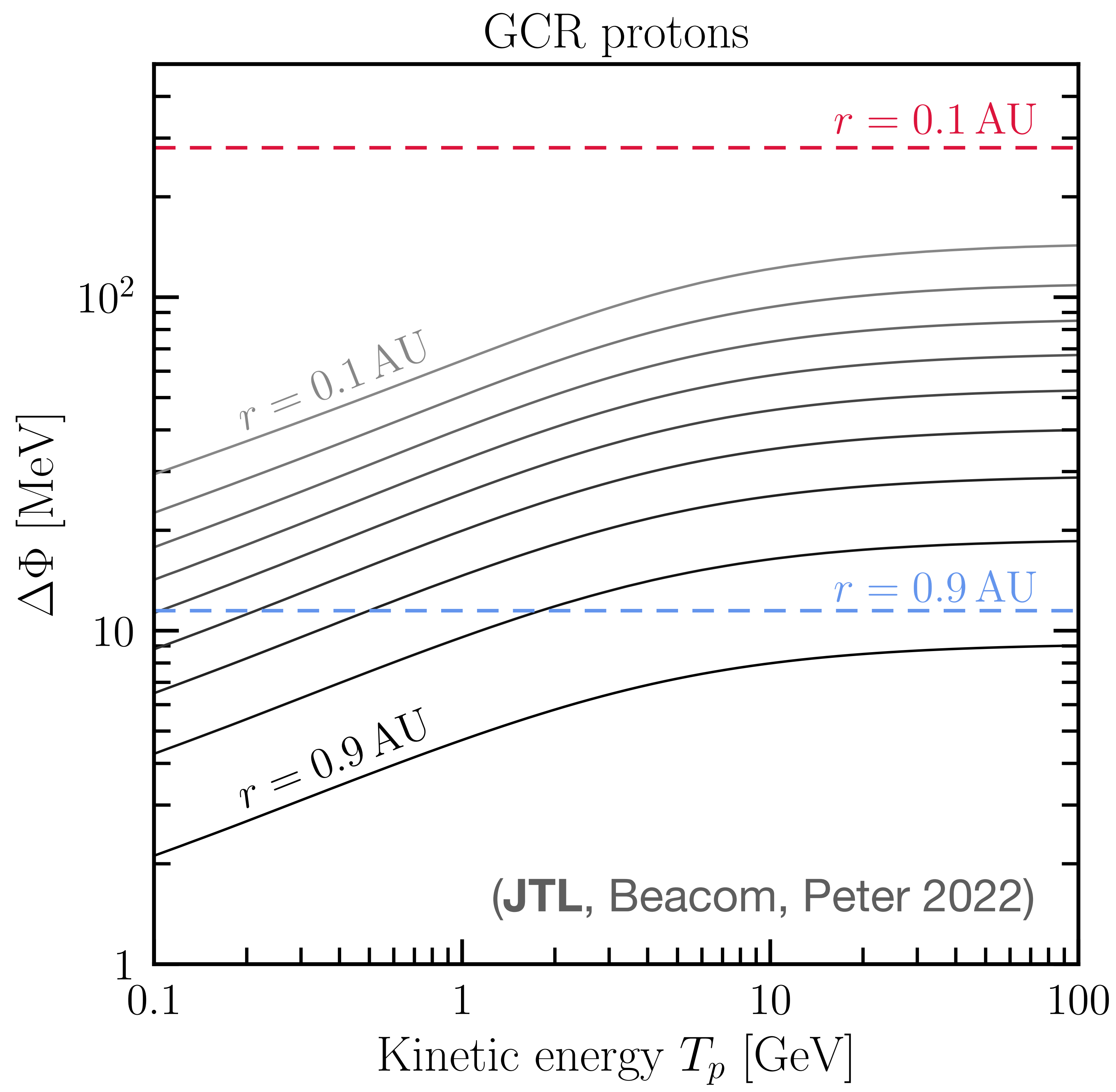


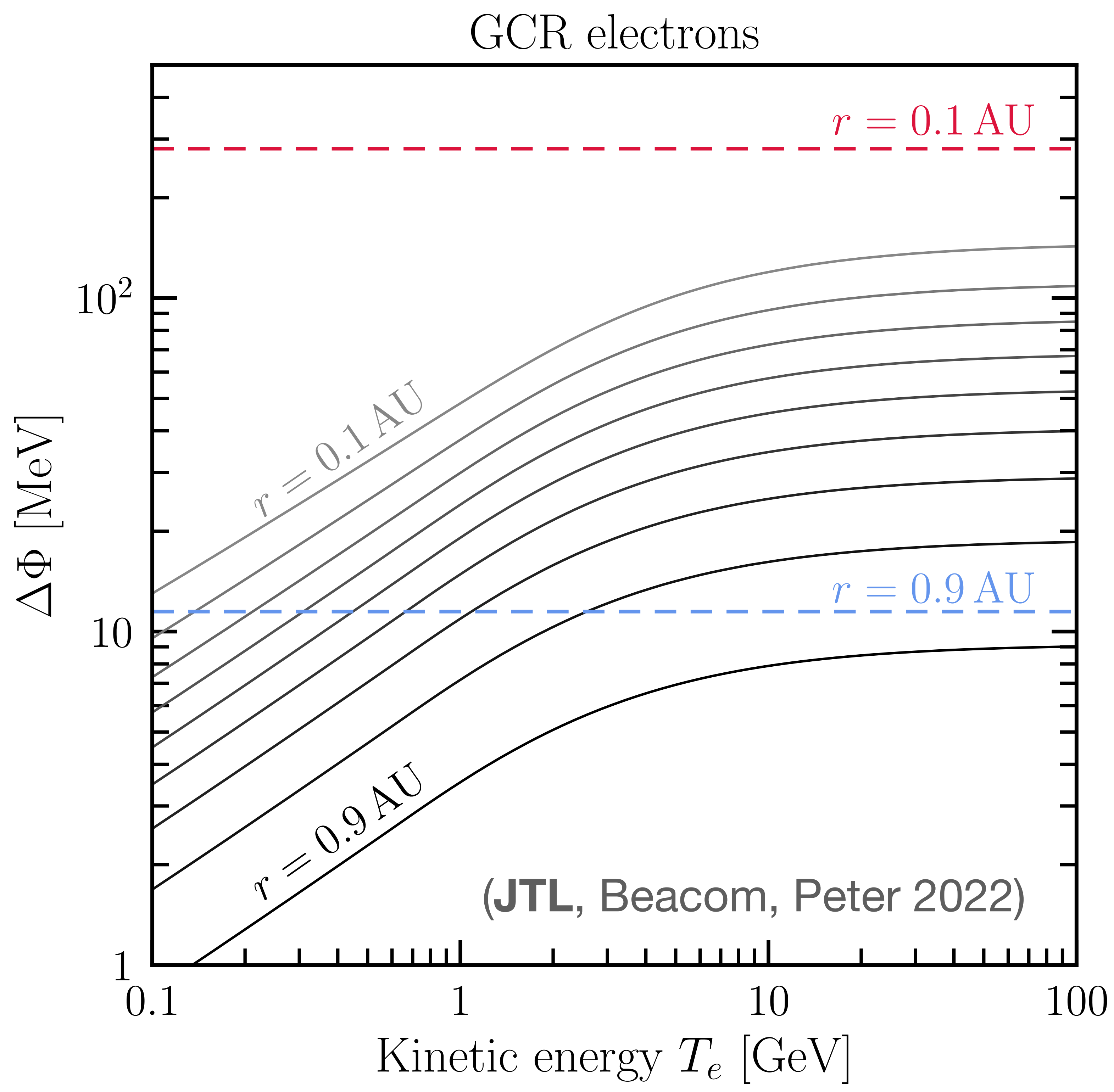
Circle and triangle: measurements of CR proton, from Palmer 1982

Measured mean free path is approximately 2 times
higher than QLT result, known as Palmer consensus

(See also Bieber et al 1996)

Modulation Potential Energy

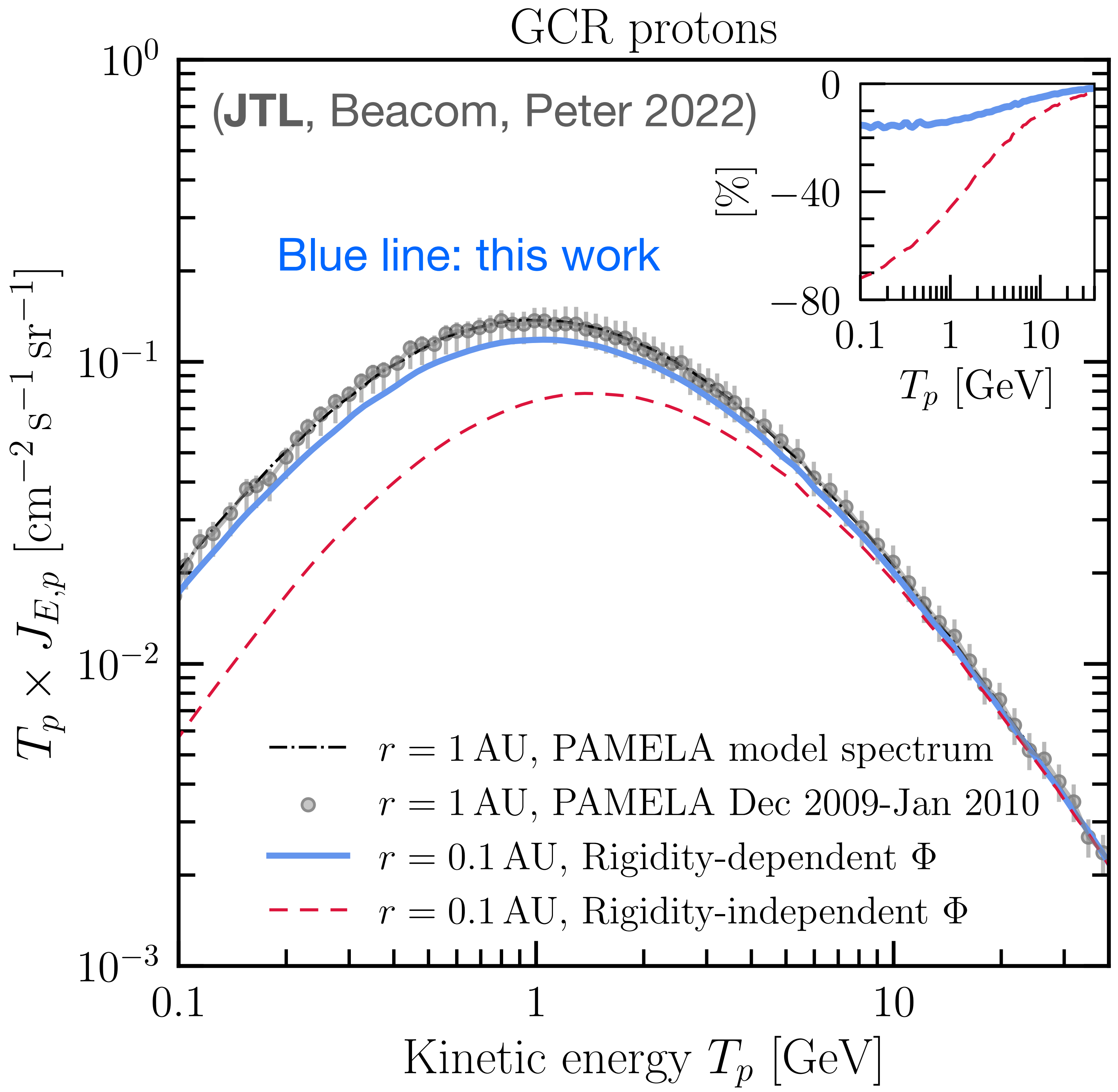


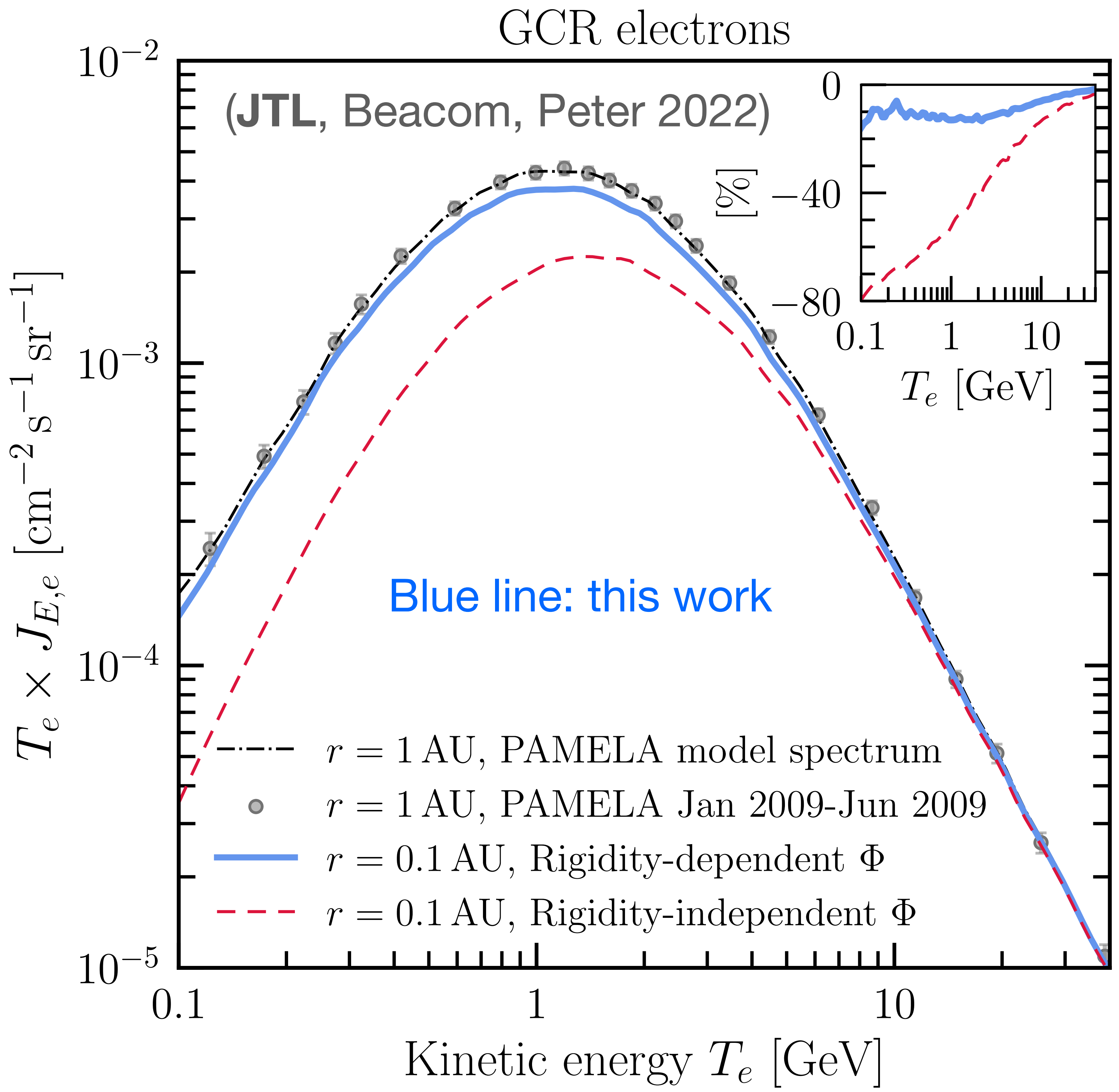


Small modulation potential increase for $E_{\mathrm{kin}} \lesssim 10\ \mathrm{GeV}$

Magnetic spectrum ($1/f$ v.s. inertial) matters

Cosmic-Ray Energy Spectrum

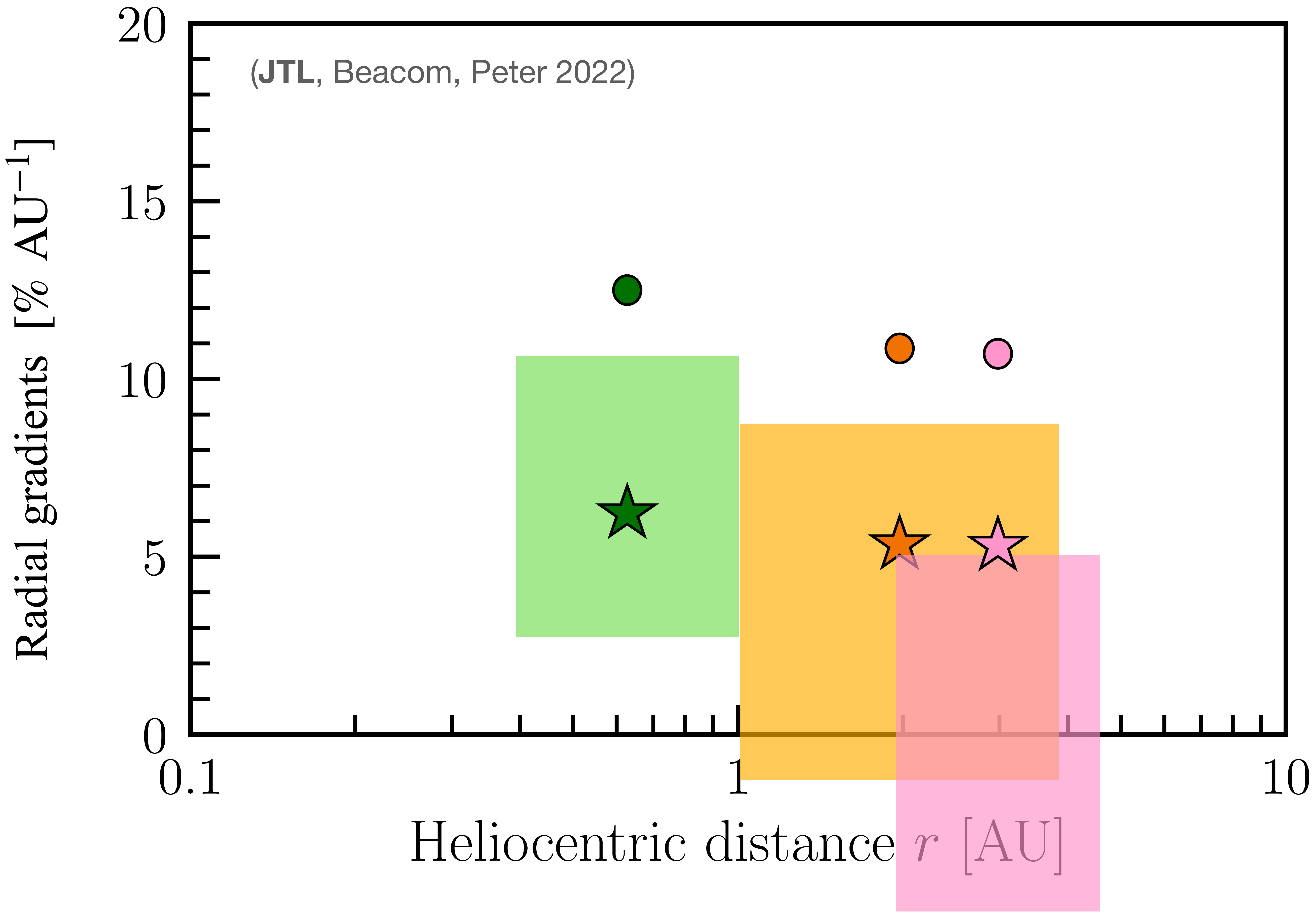




Modulation in the inner heliosphere is modest

$\approx 10~\%$ reduction of intensity from 1 AU to 0.1 AU

Radial Gradient



- Measurements

6.6 ± 4 [%AU^{-1}] (Marquardt & Heber 2019)

3.8 ± 5 [%AU^{-1}] (McDonald et al 1977)

0 ± 5 [%AU^{-1}] (McDonald et al 1977)

- This work

Standard QLT

Standard QLT $\times \frac{1}{2}$

(motivated by Palmer consensus)

Conclusion

- A simple force-field model provides a good result for inner-heliospheric modulation when a realistic magnetic turbulence is incorporated in the diffusion calculation
- Drift velocity and heliospheric current sheets are not incorporated in the force-field model.
  - Require a comparison between force-field solution and a full numerical results of Parker's transport equation
- Main takeaway: solar modulation is modest from 1 AU to 0.1 AU
- Application in the study of solar gamma-ray