Interpreting the High-energy Sub-exponentially Cutoff Spectral Shape of the Vela Pulsar

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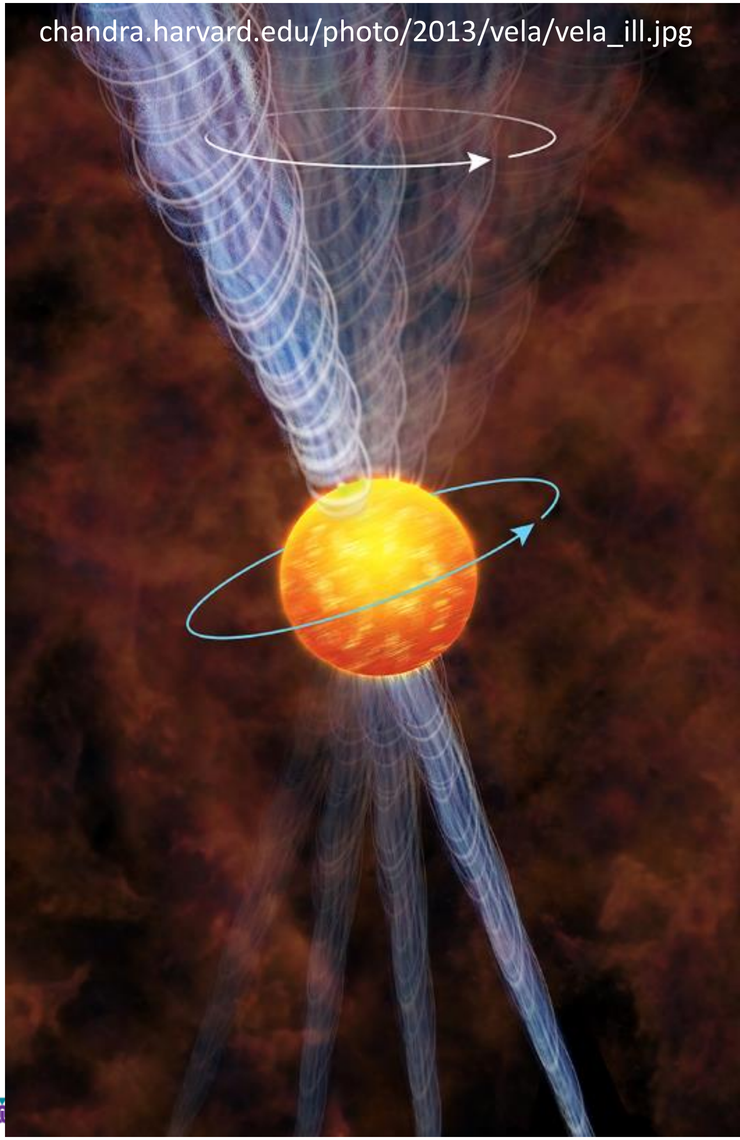
Outline

- Vela Pulsar
- Gamma-ray observations
- Curvature Radiation (CR)
- Synchro-curvature (SC) emission
- Initial parameter study
- Conclusion

https://upload.wikimedia.org/wikipedia/commons/thumb/1/1d/Vela_Pulsar_jet.jpg/300px-Vela_Pulsar_jet.jpg

The Vela Pulsar

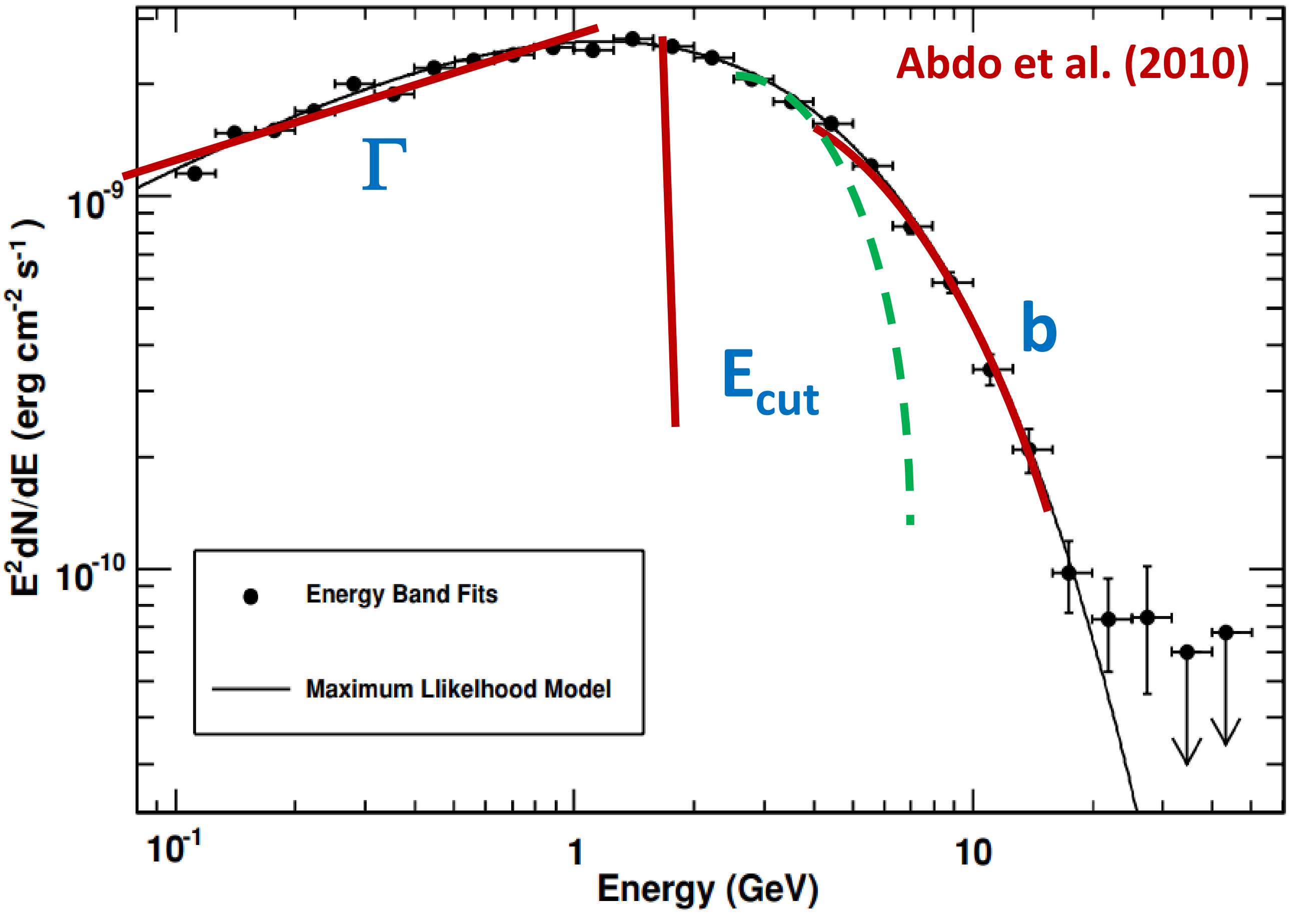
- Brightest persistent (non-flaring) source in GeV gamma-ray sky
- Detected in 1972 by SAS-2 (Thompson et al. 1975)
- Phase-resolved results – COS-B (Grenier et al. 1988) and EGRET (Kanbach et al. 1994; Fierro et al. 1998)
- First source to be studied by *AGILE* (Pellizzoni et al. 2009)
- Calibration source for *Fermi* LAT
- *Fermi* LAT observations ruled out PC models; P3 vs. E_γ



NWU®

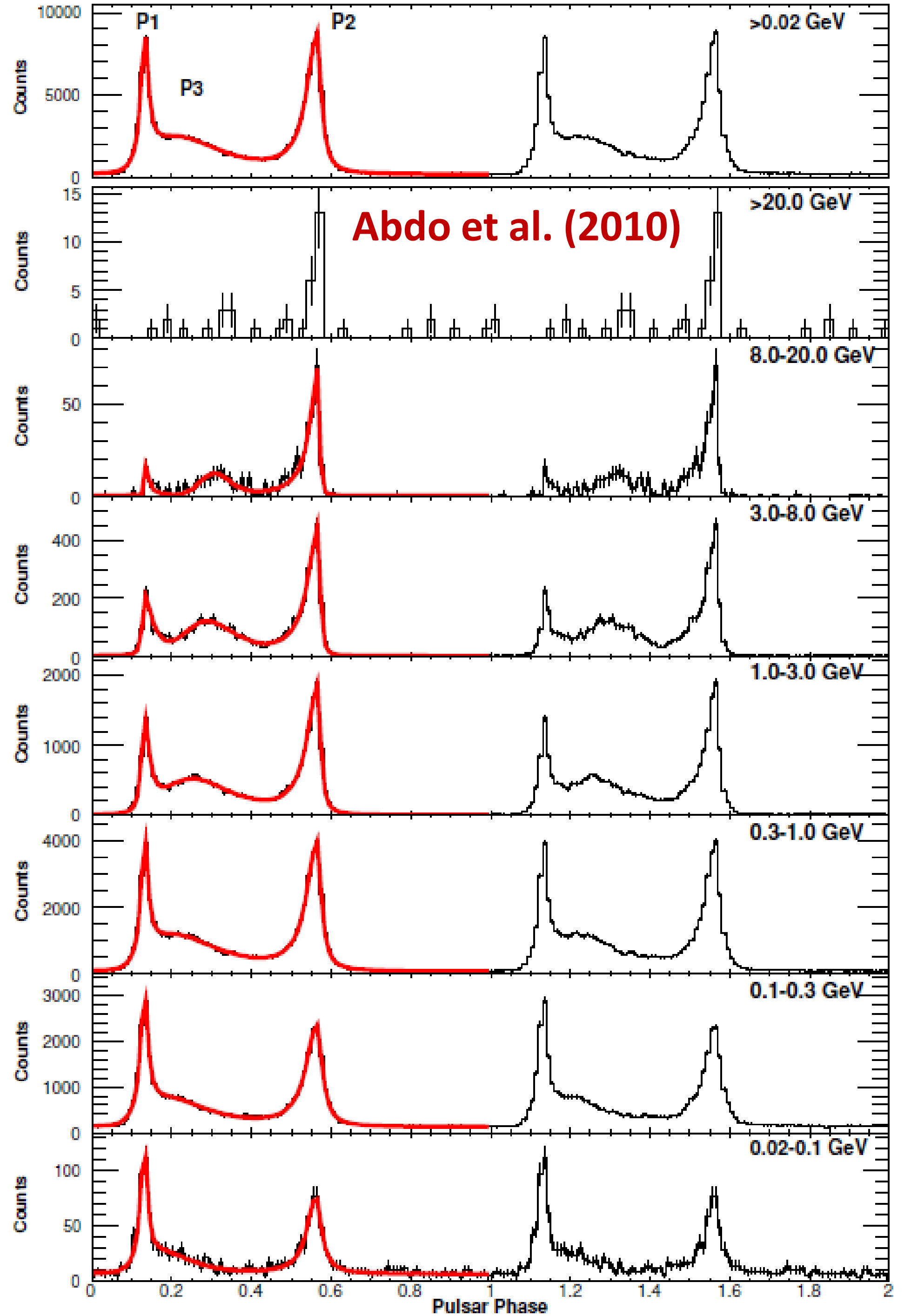
HE Observations of Vela

- Age ~ 11 kyr
- d ~ 0.3 kpc,
- Ė ~ 7e36 erg/s
- Glitching
- Γ ~ 1.4
- E_{cut} ~ 2 GeV,
- b ~ 0.7
- b < 1 inconsistent with magnetic pair attenuation thus favours outer-magnetosphere models

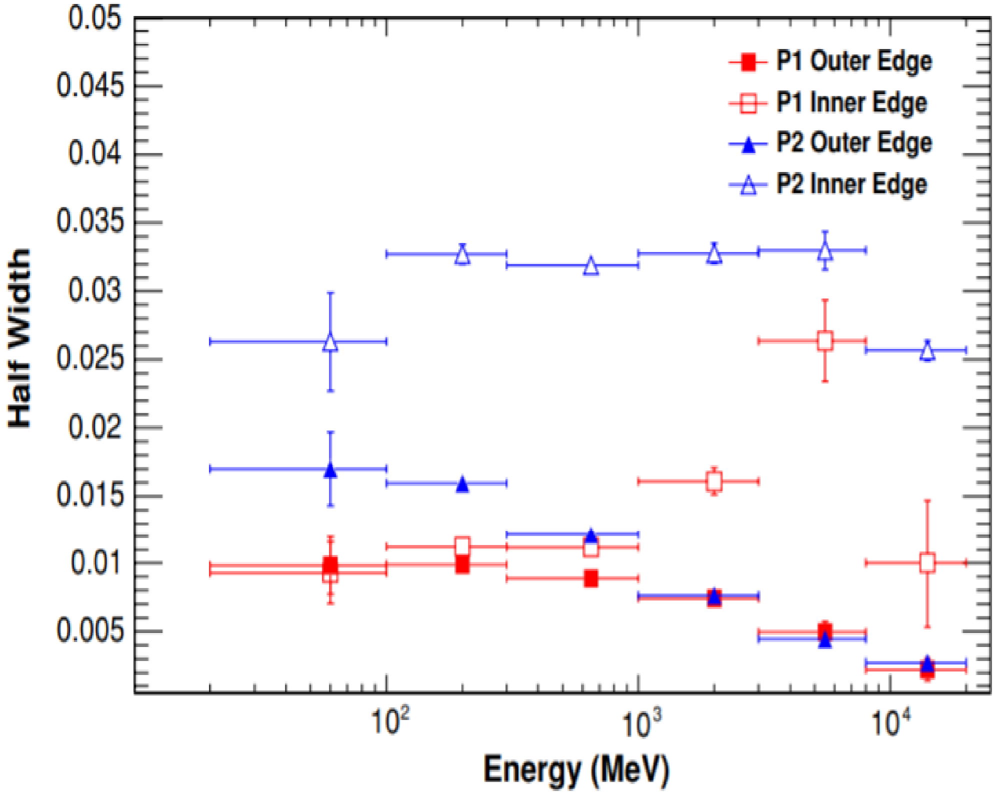


HE Light Curves

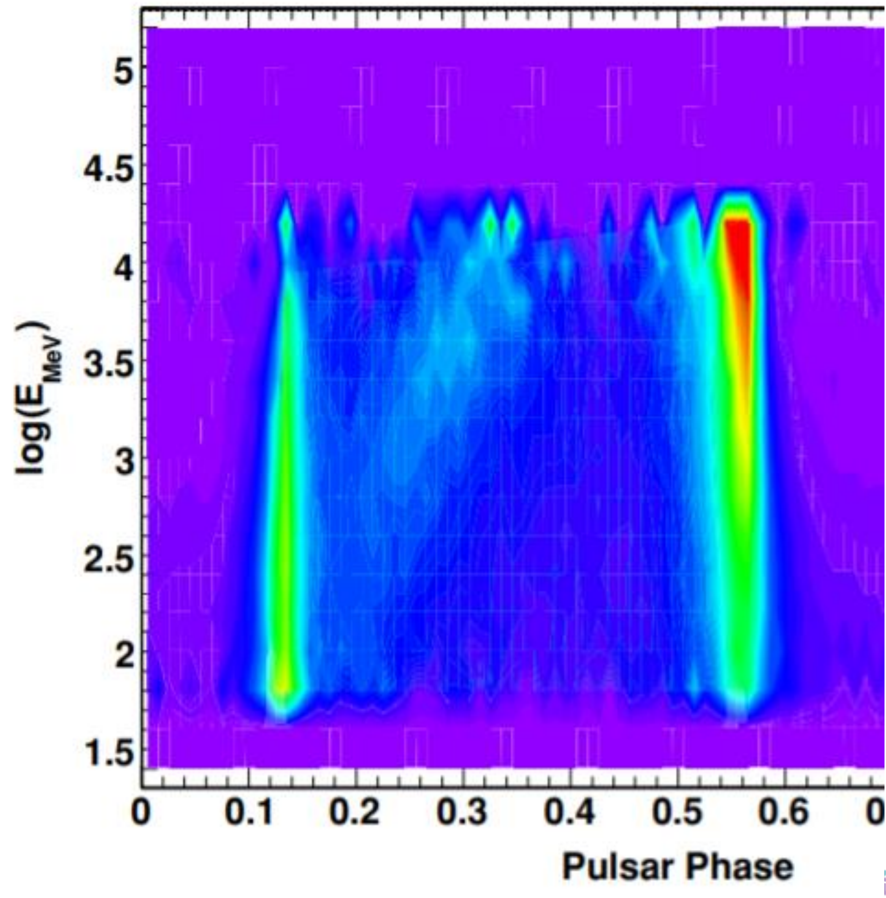
- Vela light curves' energy evolution:
  - P1/P2
  - Φ
  - W
  - Edges
  - Bridge (P3)



HE Light Curves

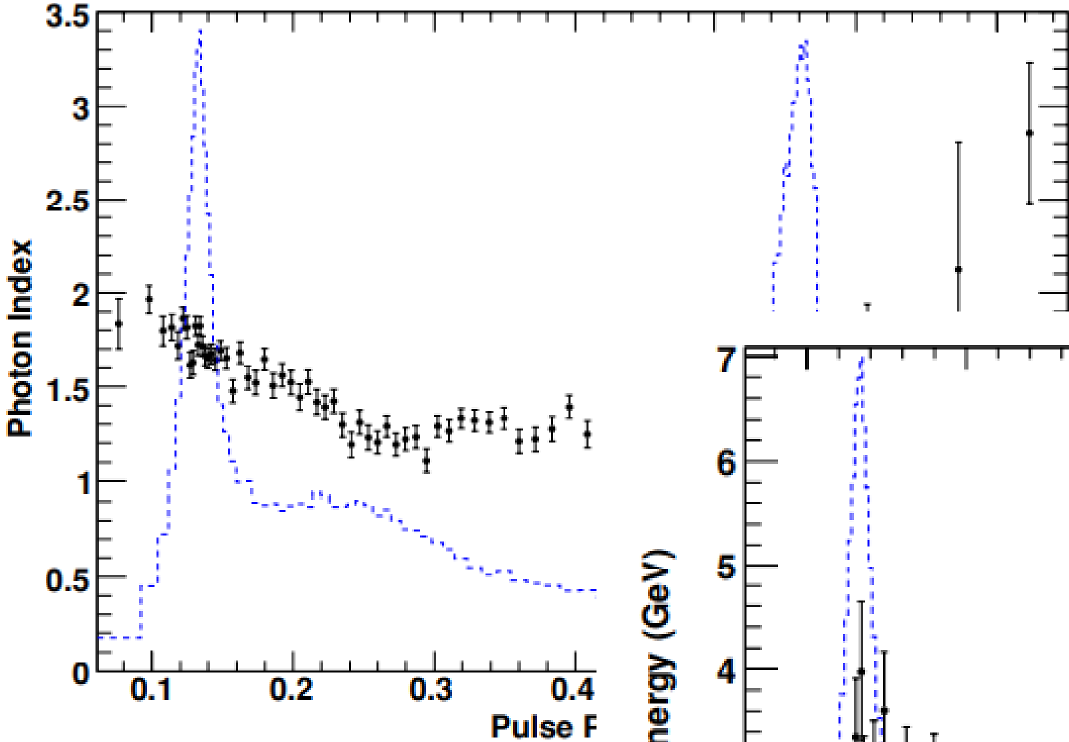


Abdo et al. (2010)



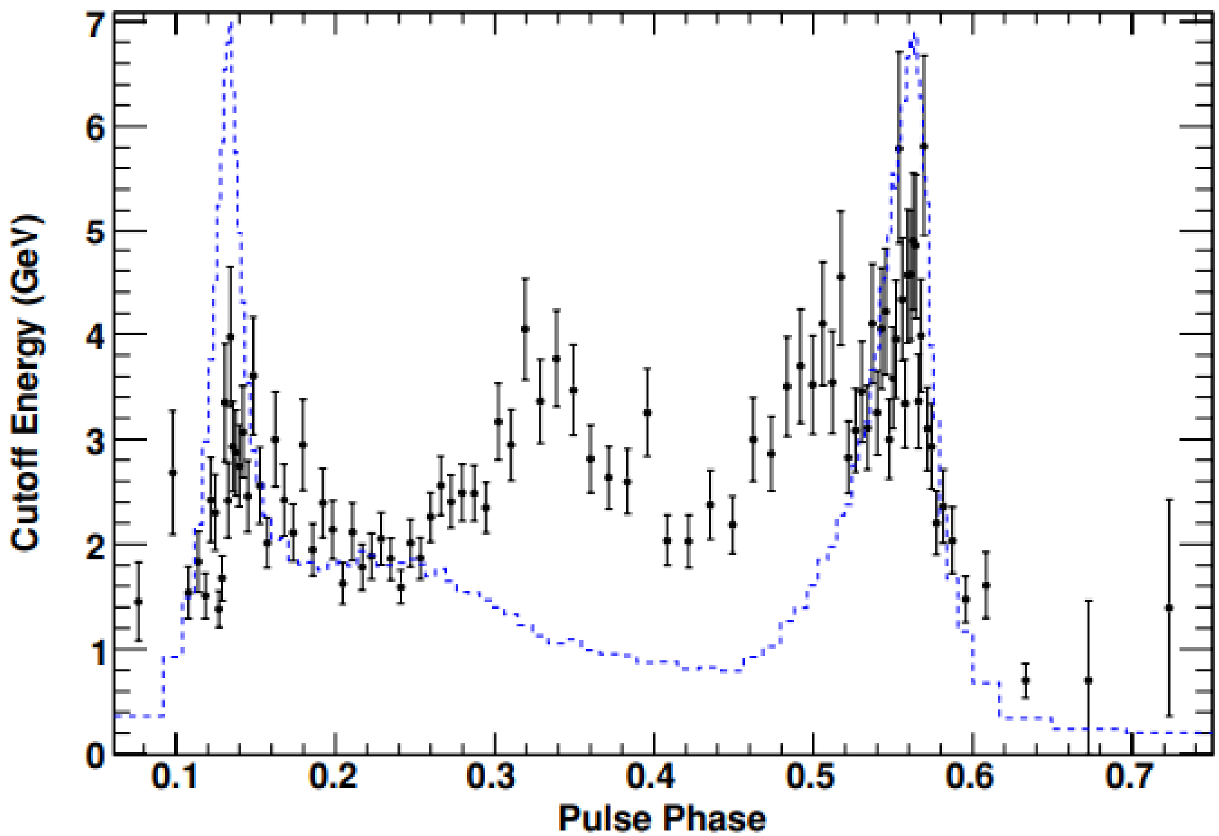
- Vela LC energy evolution: P1/P2, ϕ, W, edges, bridge

HE Phase-resolved HE Spectrum



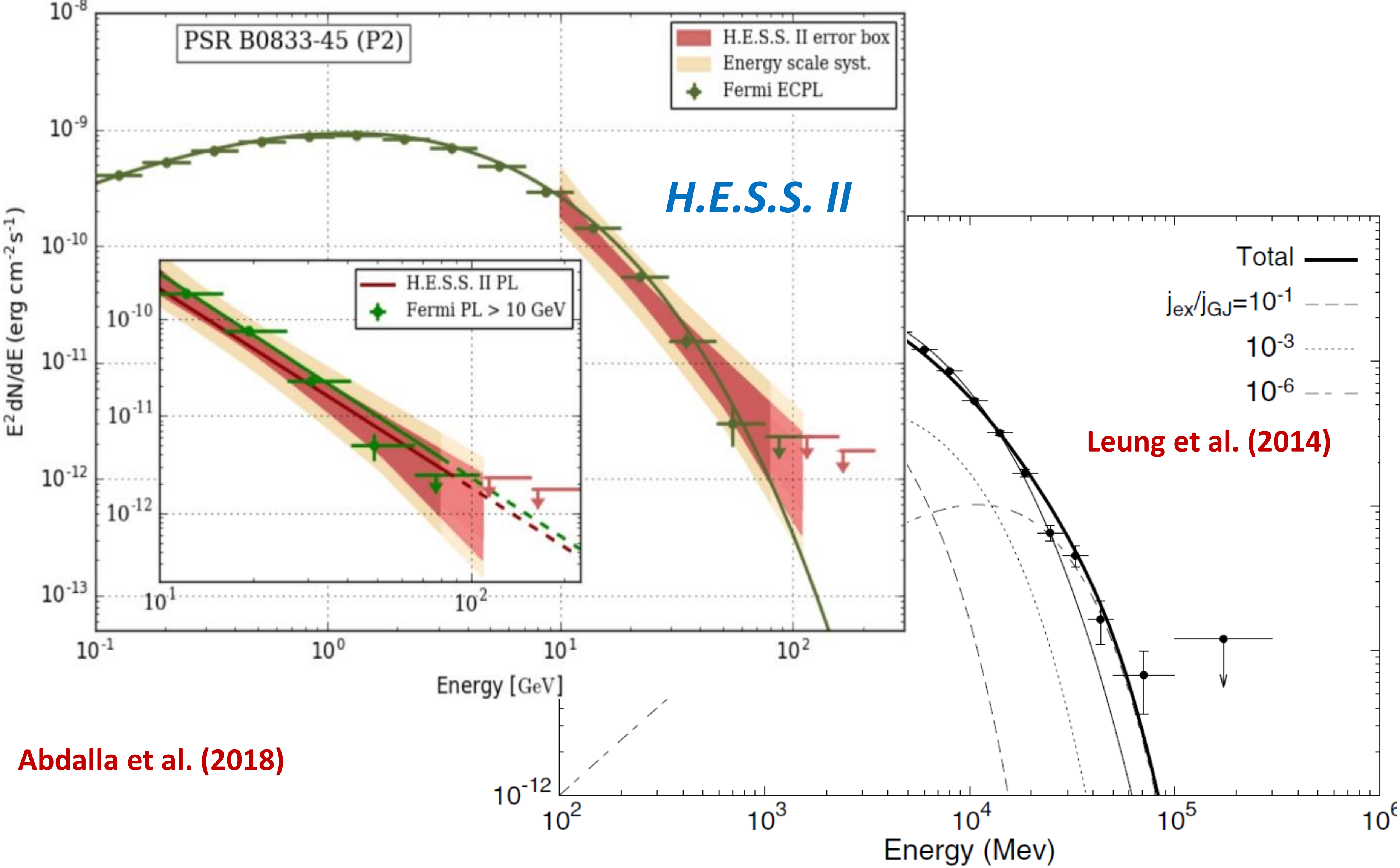
- Variation of Γ with ϕ

- Variation of E_{cut} with ϕ



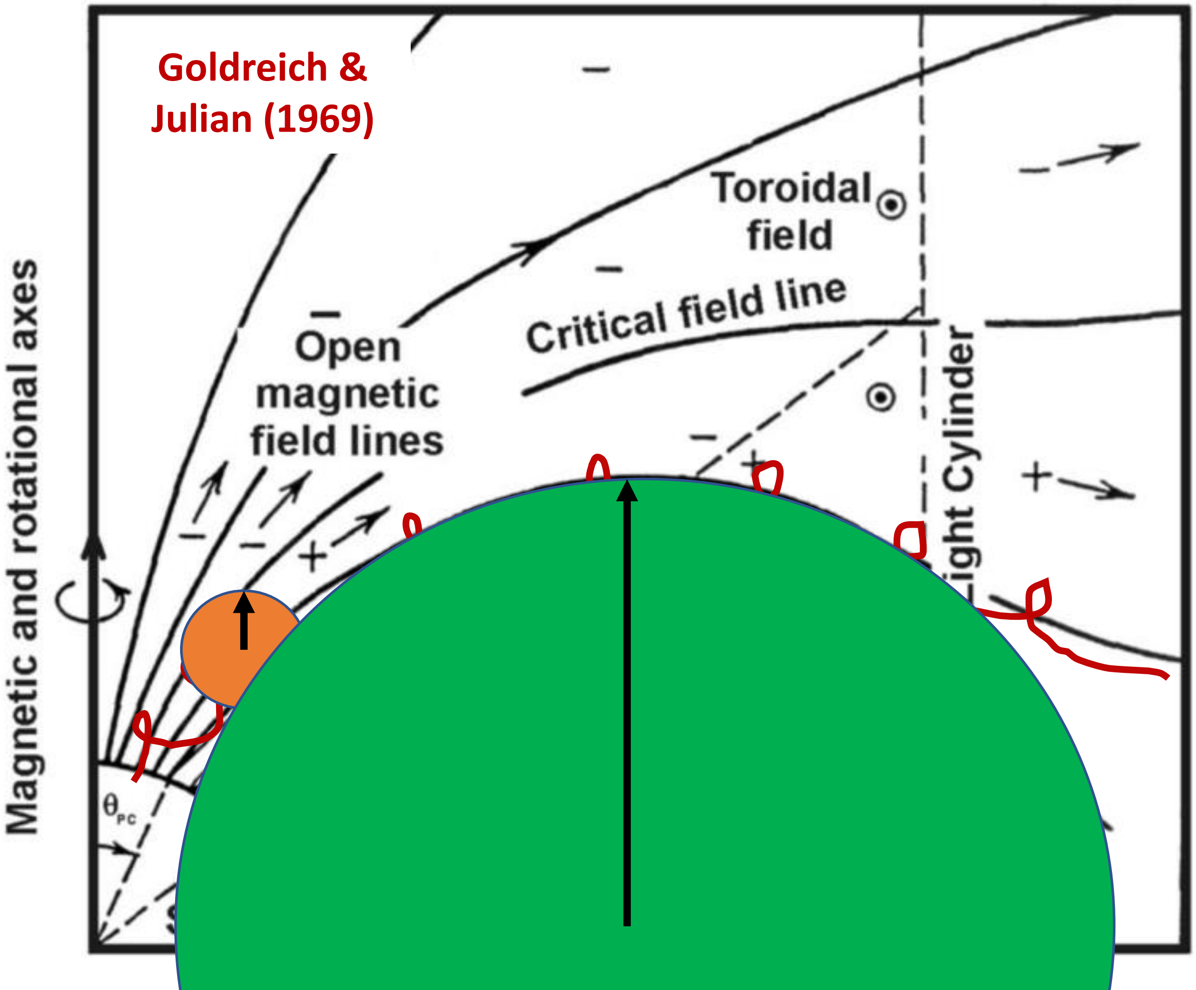
Abdo et al. (2010)

Pulsations up to ~100 GeV



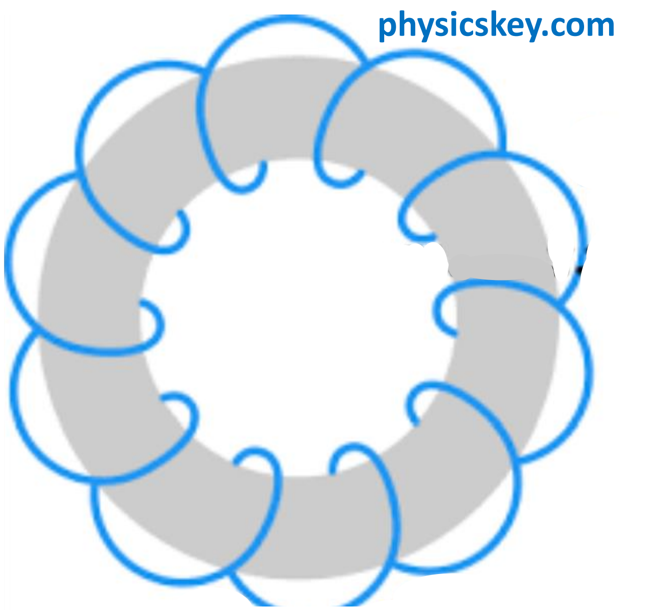
Abdalla et al. (2018)

Two Components of Particle motion



- Perpendicular: SR
- Parallel: CR

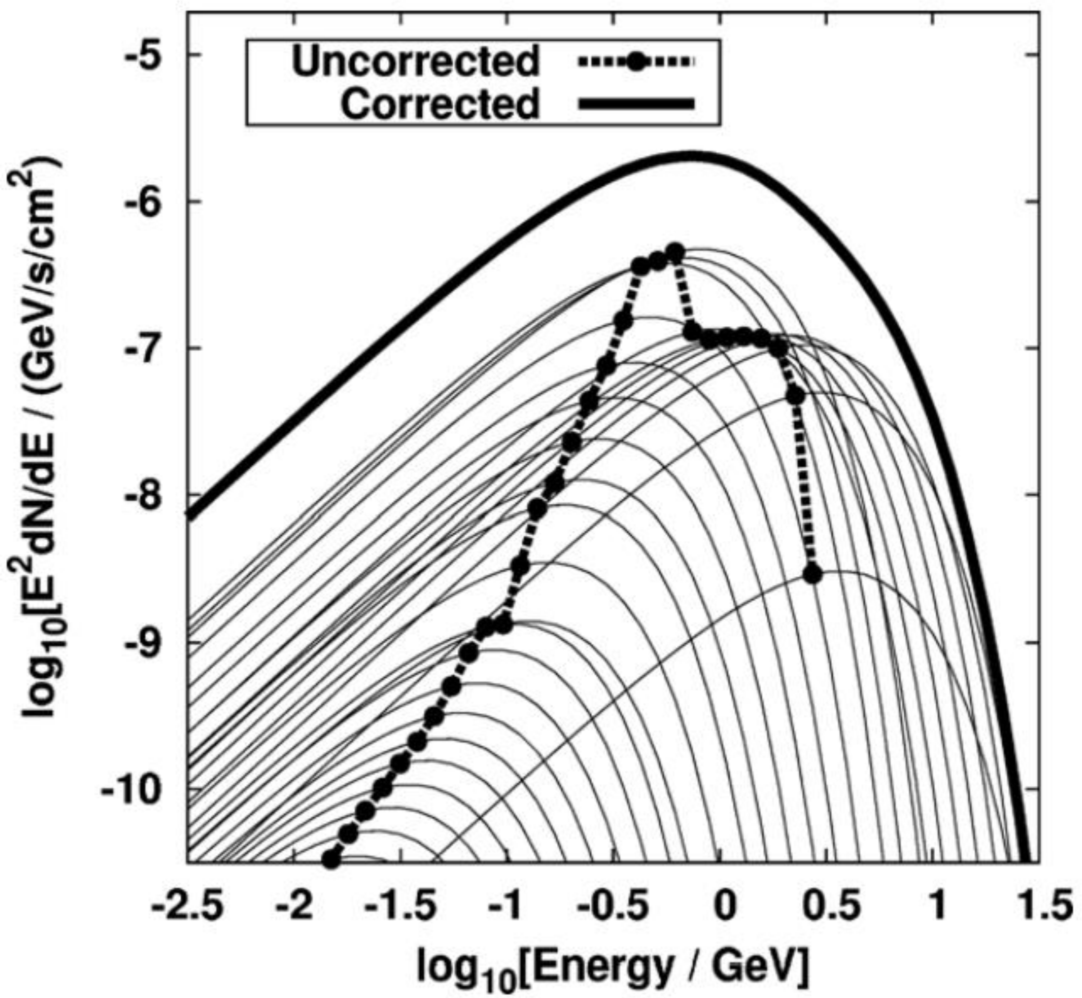
Synchro-curvature (SC)



Cheng & Zhang (1996)

Cumulative Spectra – Sub-exponential HE tail

- Cf. Celik, Johnson (circa 2009)



Venter & de Jager (2010)

Curvature Radiation

Radiation Reaction (CRR):

$$\dot{\gamma} = \dot{\gamma}_{\rm gain} + \dot{\gamma}_{\rm loss} = \frac{1}{m_e c^2}\left[ceE_{\parallel} - \frac{2ce^2\gamma^4}{3\rho_c^2}\right]$$

$$e|E_{||}| \sim \frac{2e^2\gamma_{\rm RR}^4}{3\rho_c^2}$$

Spectral cutoff:

$$E_{\rm CR} = \hbar\omega_{\rm CR} = \frac{3\hbar c\gamma^3}{2\rho_c} = \frac{3\lambda\!\!\!^{-}_C\gamma^3}{2\rho_c}m_e c^2$$

$$E_{\gamma,\,\rm cutoff} \sim 4\,E_{||,4}^{3/4}\,\rho_{c,8}^{1/2} \quad {\rm GeV}$$

Total loss rate:

$$\int \left(\frac{dP}{dE}\right)_{\rm CR} dE = \dot{E}_{\rm CR} = -\frac{2e^2c\gamma^4}{3\rho_c^2}$$

Venter & de Jager (2010)

Curvature Radiation

Radiation Spectrum:

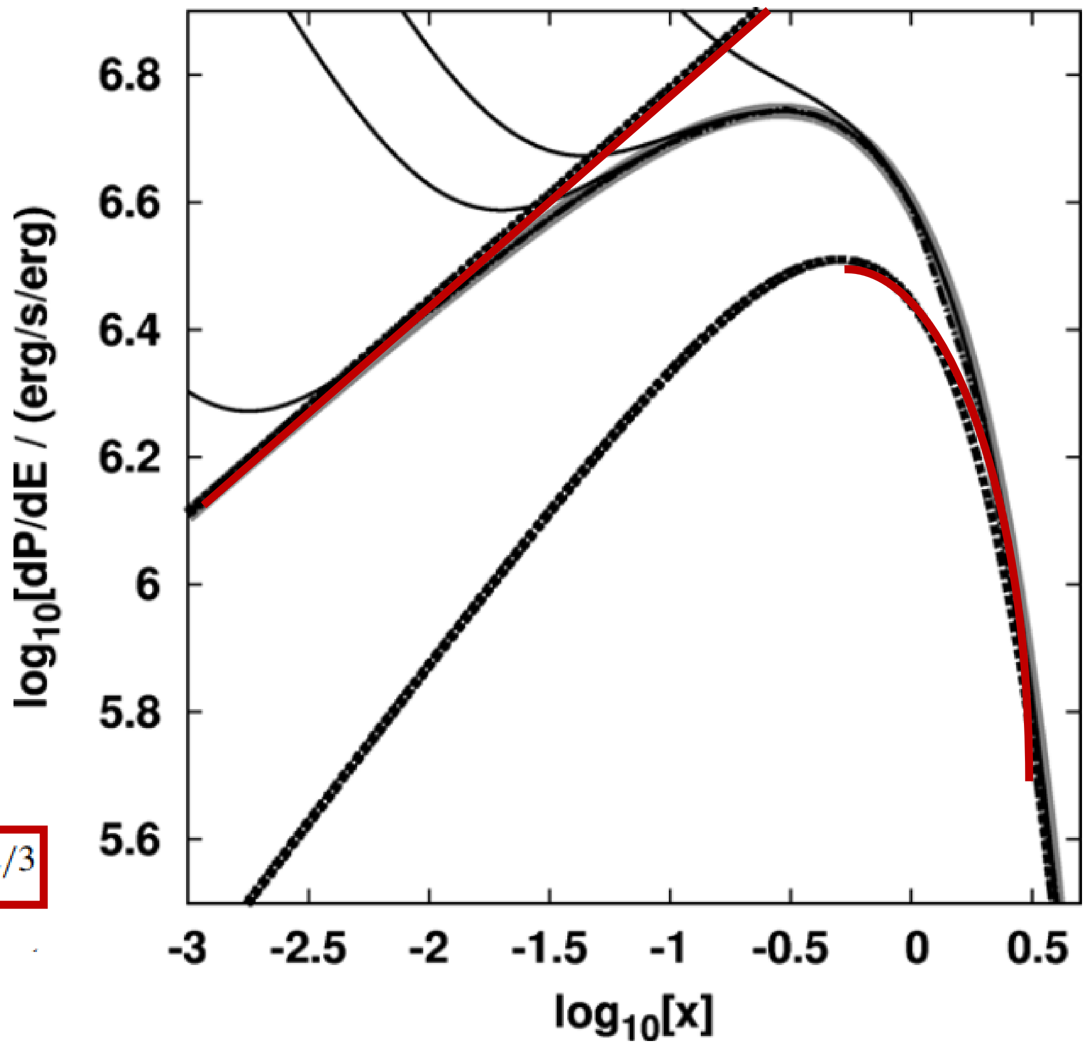
$$\left(\frac{dP}{dE}\right)_{\rm CR} = \frac{\sqrt{3}\alpha_f \gamma c}{2\pi\rho_c}\kappa\left(\frac{E_\gamma}{E_{\rm CR}}\right)$$

$$\kappa(x) \equiv x\int_x^\infty K_{5/3}(x')\,dx'$$

Limits:

$$\left(\frac{dN}{dE}\right)_{\rm low} \approx \frac{0.518\alpha_f}{dA\hbar^{1/3}}\left(\frac{c}{\rho_c}\right)^{2/3} E_\gamma^{-2/3}$$

$$\left(\frac{dN}{dE}\right)_{\rm high} \approx \frac{0.282\alpha_f}{dA}\left(\frac{c}{\gamma\rho_c\hbar}\right)^{1/2} E_\gamma^{-1/2} e^{-E_\gamma/E_{\rm CR}}$$



Venter & de Jager (2010)

Synchro-curvature Radiation

- Encapsulates 2 limits: CR, SR
- "Magnetic brehmsstrahlung"

Vigano et al. (2015)
Cheng & Zhang (1996)
Zhang, Xia & Yang (2000)
Kelner & Aharonian (2012)
Prosekin, Kelner & Aharonian (2013)

Cutoff energy:

$$E_{\rm CR} = \frac{3\hbar c\gamma^3}{2\rho_c} \Rightarrow E_{\rm c}(\Gamma, r_{\rm c}, r_{\rm gyr}, \alpha) = \frac{3}{2}\hbar c Q_2 \Gamma^3$$

$$\xi = \frac{r_{\rm c}}{r_{\rm gyr}} \frac{\sin^2\alpha}{\cos^2\alpha}$$

$$Q_2^2 = \frac{\cos^4\alpha}{r_{\rm c}^2}\left[1 + 3\xi + \xi^2 + \frac{r_{\rm gyr}}{r_{\rm c}}\right]$$

$$g_r = \frac{r_{\rm c}^2}{r_{\rm eff}^2}\frac{[1 + 7(r_{\rm eff}Q_2)^{-2}]}{8(Q_2 r_{\rm eff})^{-1}}$$

Total power:

$$\int \left(\frac{dP}{dE}\right)_{\rm CR} dE = -\frac{2e^2c\gamma^4}{3\rho_c^2} \Rightarrow P_{\rm sc} = \frac{2(Ze)^2\Gamma^4 c}{3r_{\rm c}^2} g_r$$

Synchro-curvature Radiation

- **Encapsulates 2 limits: CR, SR**
- **“Magnetic brehmsstrahlung”**

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Radiation Spectrum:

$$\left(\frac{dP}{dE}\right)_{\rm CR} = \frac{\sqrt{3}\alpha_f \gamma c}{2\pi\rho_c}\kappa\left(\frac{E_\gamma}{E_{\rm CR}}\right)$$

→

$$\frac{\mathrm{d}P_{\rm sc}}{\mathrm{d}E} = \frac{\sqrt{3}(Ze)^2\Gamma y}{4\pi\hbar r_{\rm eff}}[(1+z)F(y) - (1-z)K_{2/3}(y)],$$

where

$$y(E, \Gamma, r_{\rm c}, r_{\rm gyr}, \alpha) \equiv \frac{E}{E_{\rm c}},$$

$$z = (Q_2 r_{\rm eff})^{-2},$$

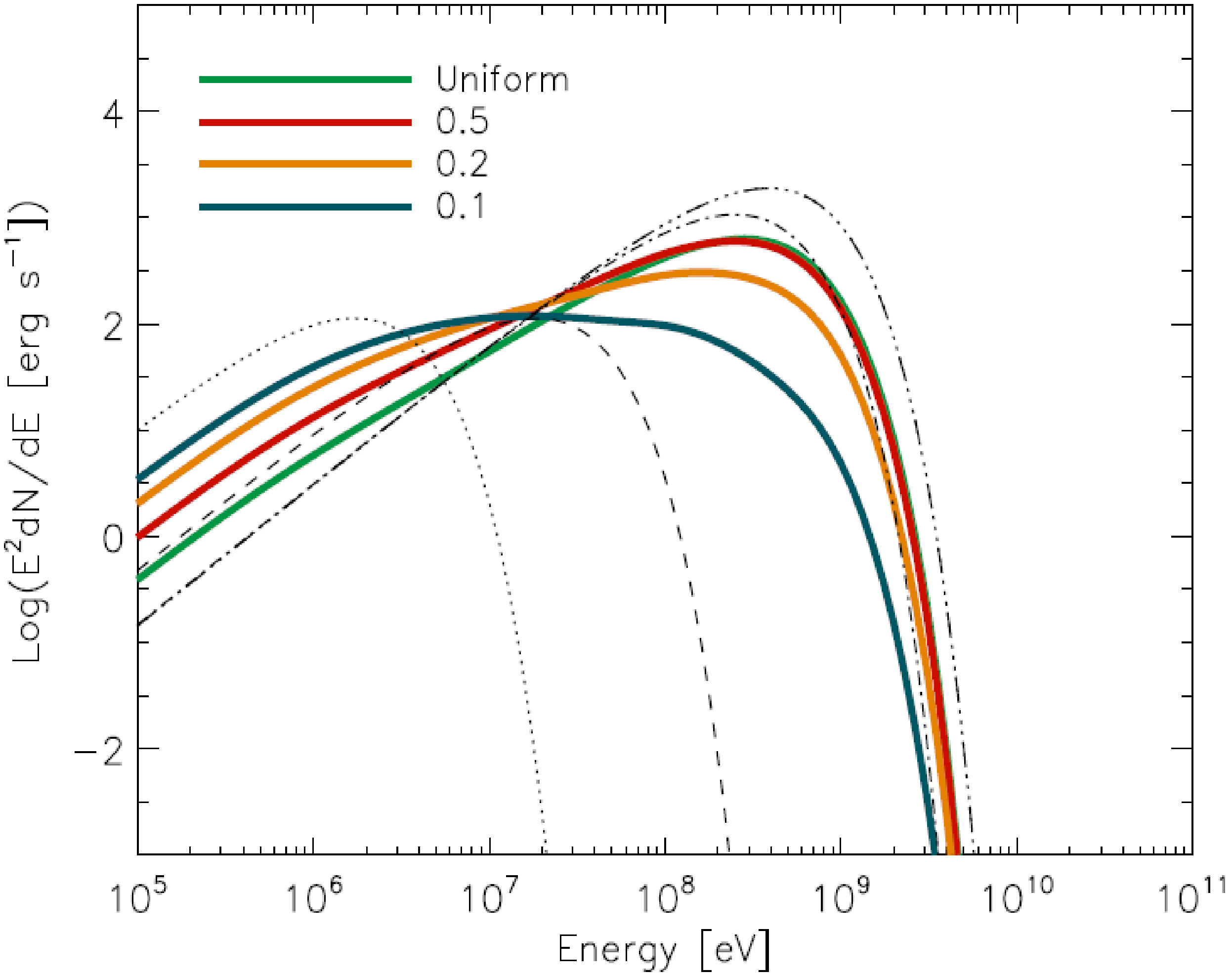
$$F(y) = \int_y^\infty K_{5/3}(y')\, dy',$$

$$r_{\rm eff} = \frac{r_{\rm c}}{\cos^2\alpha}\left(1 + \xi + \frac{r_{\rm gyr}}{r_{\rm c}}\right)^{-1}$$

Synchro-curvature Radiation

Vigano et al. (2015)

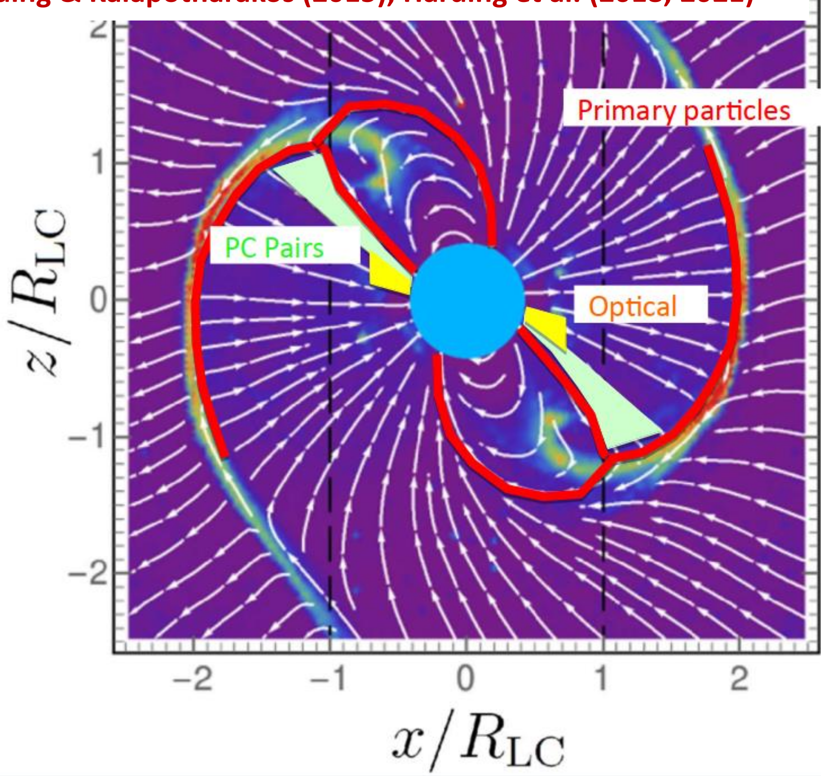
- **Single-particle spectra are modulated by particle dynamics (dN_e/dE, γ) and local *B*-field structure (ρ_c)**



Separatrix / CS Model

- Force-free magnetosphere.
- Primaries (γ_{inj}~ 10^2) from PC; pairs (γ ~ 10^5) from cascade in offset-PC B-field (Harding & Muslimov 2011a,b).
- Primaries accelerated only near separatrix and predominantly in CS (out to $r = 2R_{LC}$) assuming a constant or two-step E-field (reaching γ ~ $10^7 – 10^8$).
- No pair acceleration. Free primary / pair multiplicities. Injection at ϕ_{PC} where $J/J_{GJ} < 0$.
- Empirical radio core / cone model. Resonant cyclotron absorption of radio photons by particles (cf. Lyubarski & Petrova 1998).
- Solve particle dynamics in observer frame.
- SC (CR+SR), ICS, SSC radiation mechanisms.

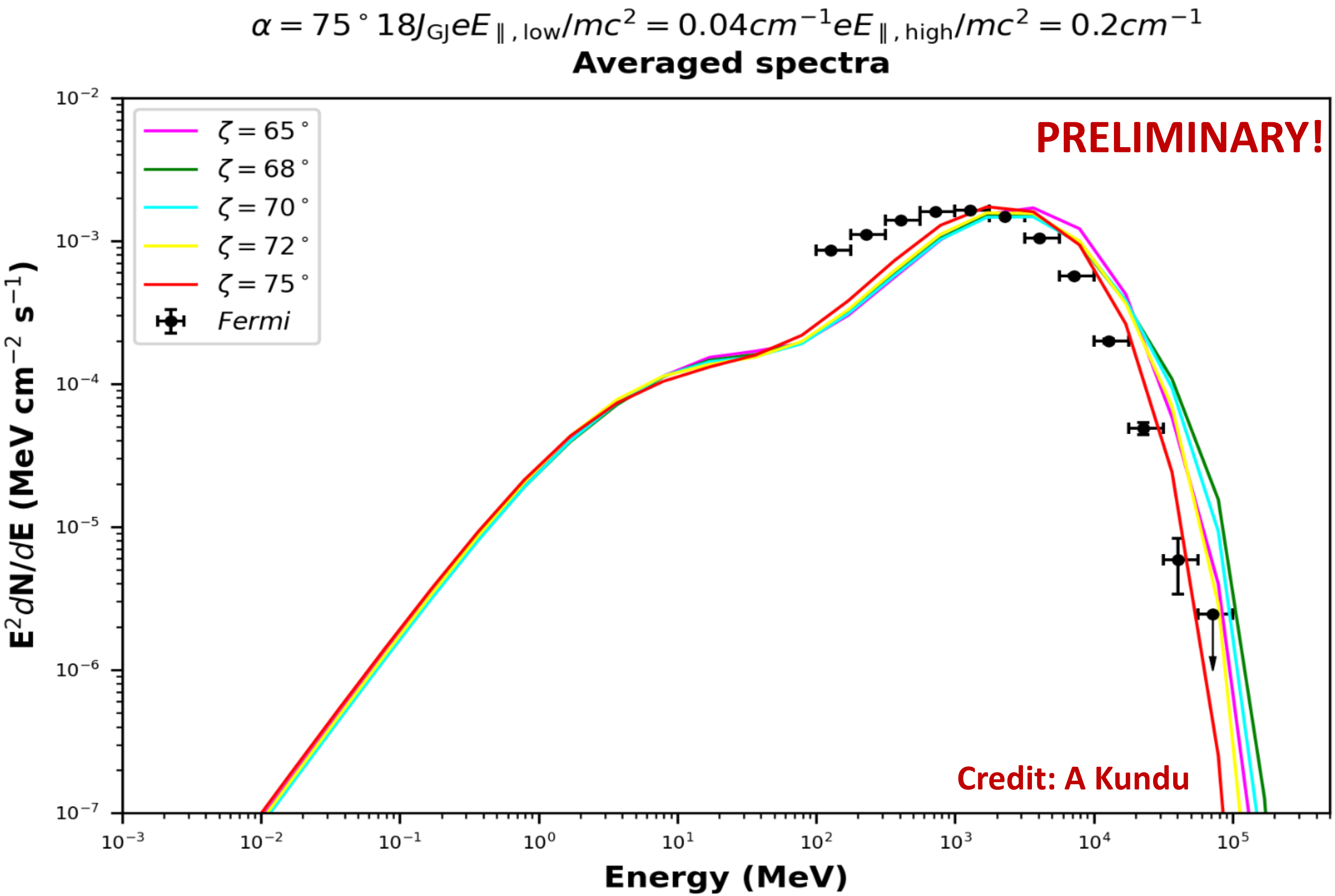
Harding & Kalapotharakos (2015), Harding et al. (2018, 2021)



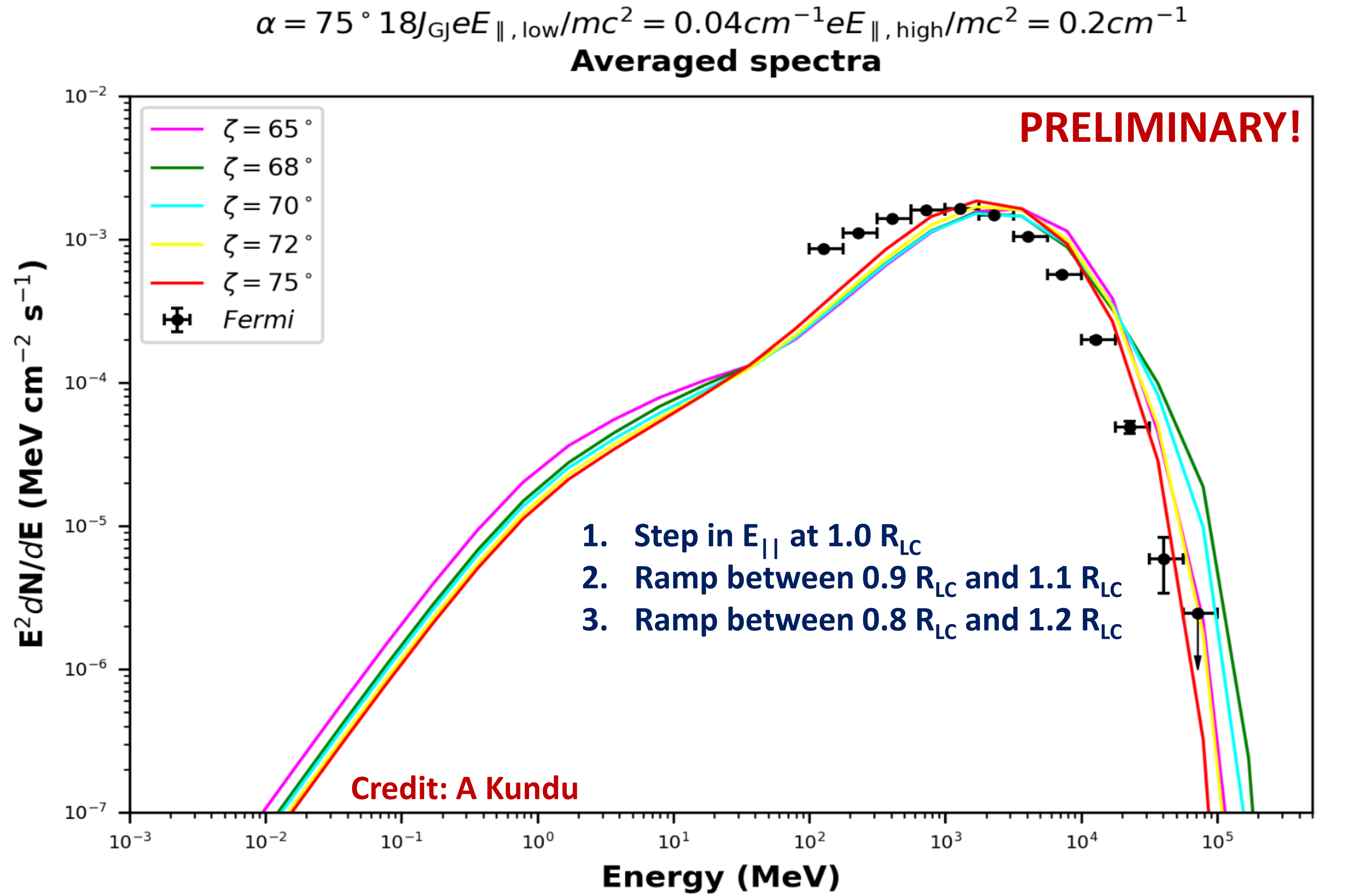
$$\frac{d\gamma}{dt} = \frac{eE_{\|}}{mc} - \frac{2e^4}{3m^3c^5}B^2p_{\perp}^2 - \frac{2e^2\gamma^4}{3\rho_c^2},$$

$$\frac{dp_{\perp}}{dt} = -\frac{3}{2}\frac{c}{r}p_{\perp} - \frac{2e^4}{3m^3c^5}B^2p_{\perp}^3\frac{1}{\gamma}.$$

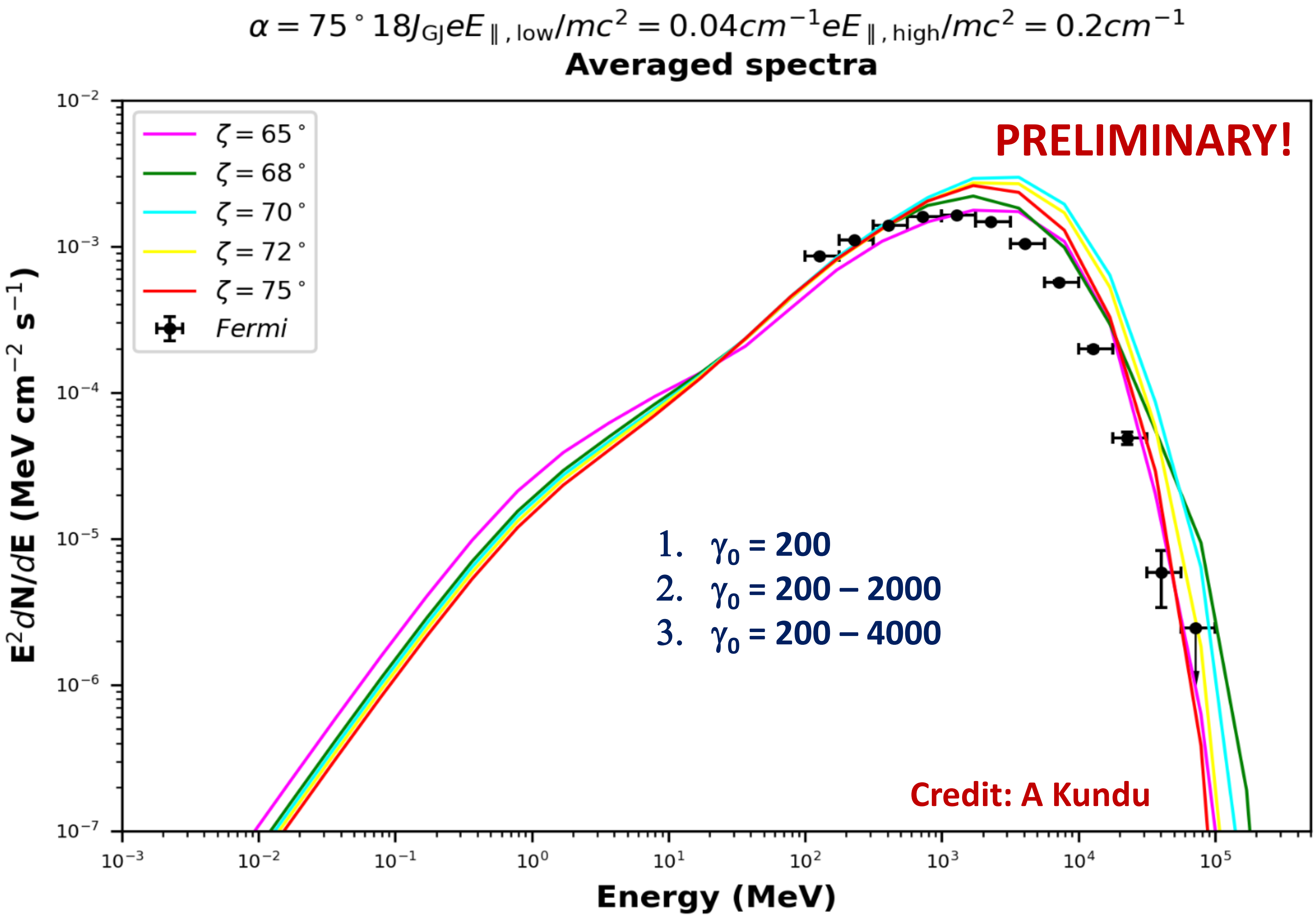
SC: change in ζ



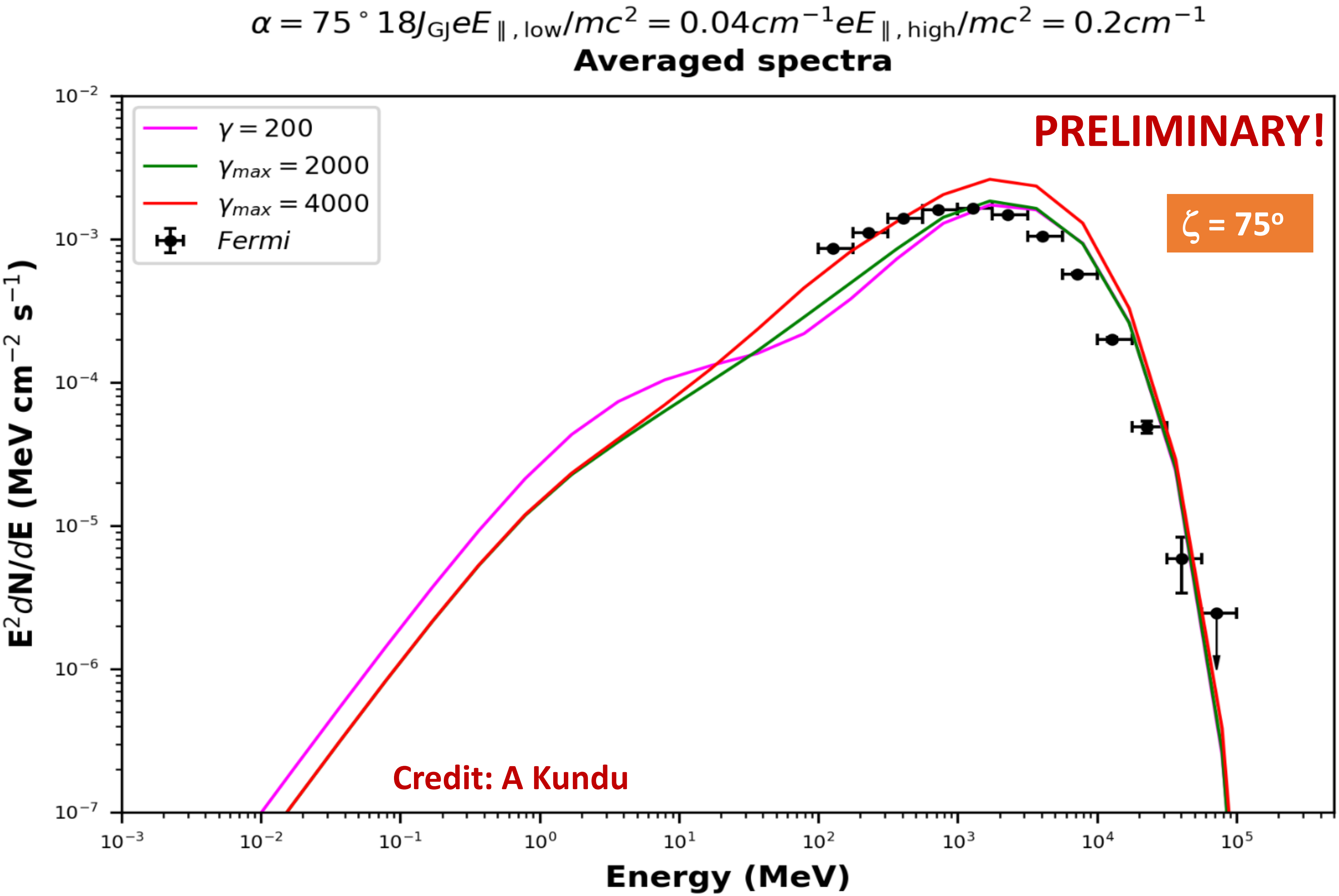
SC: change in $E_{||}(r)$



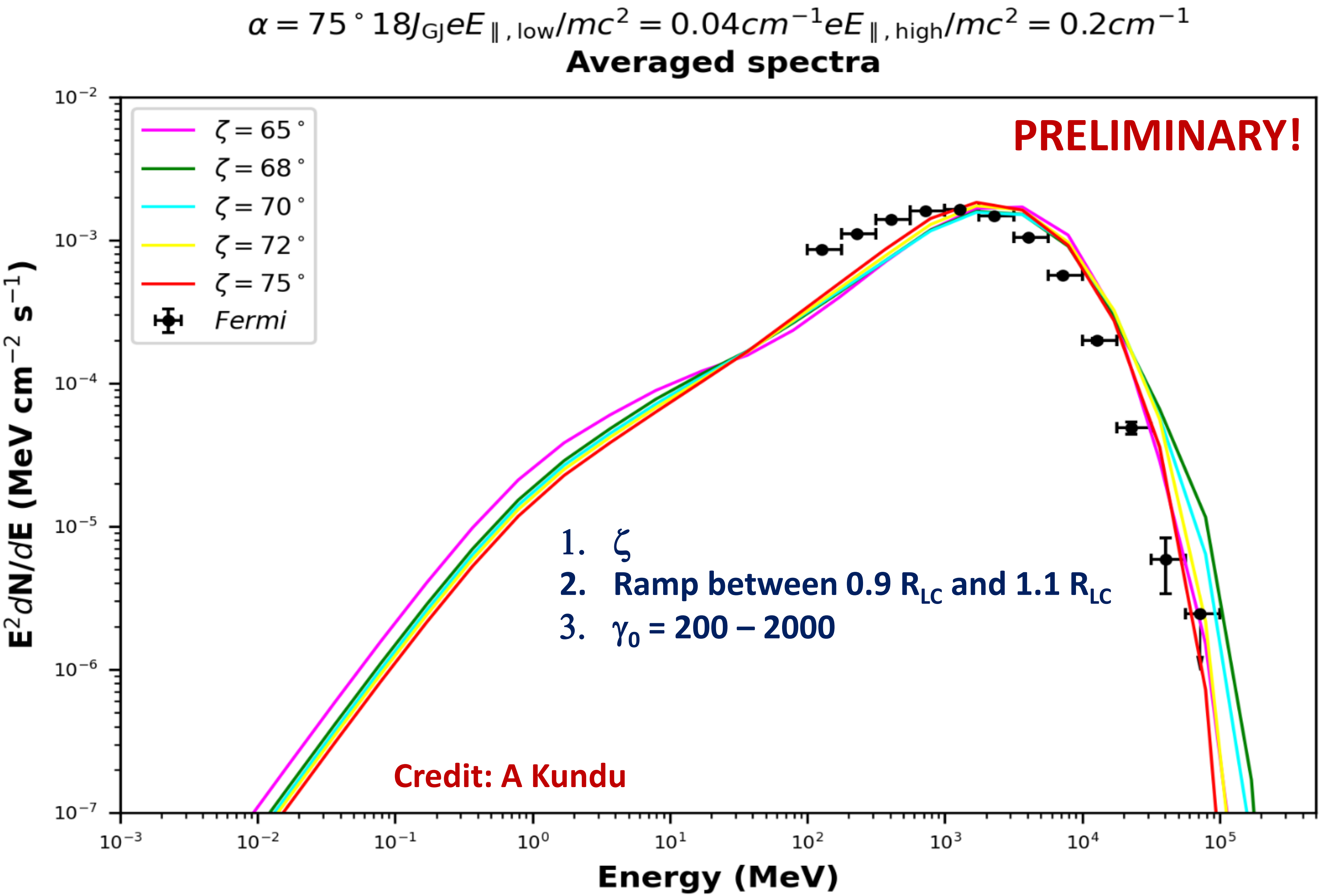
SC: change in $\dot{N}(\phi)$



SC: change in $\dot{N}(\phi)$

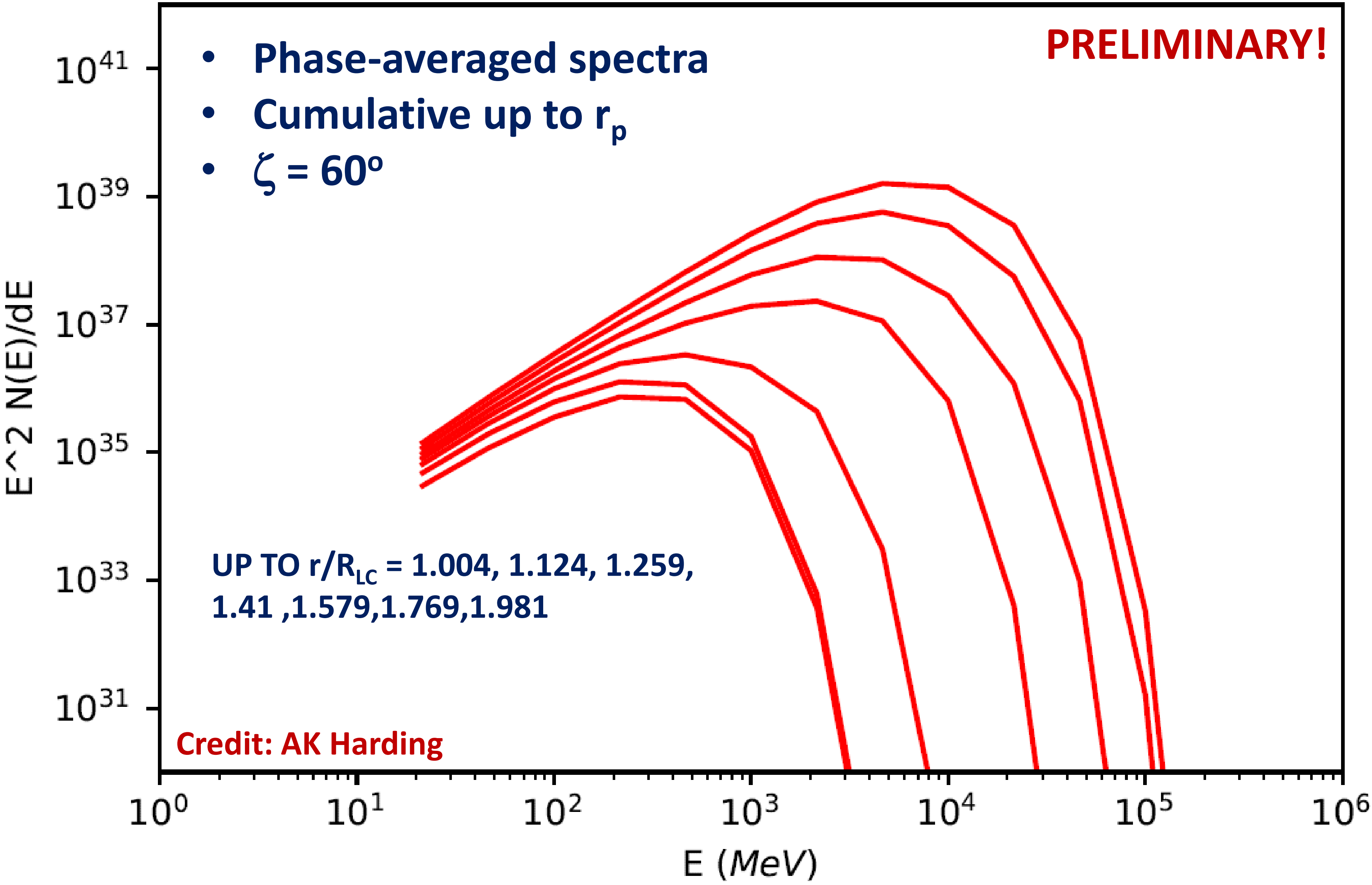


SC: Mix

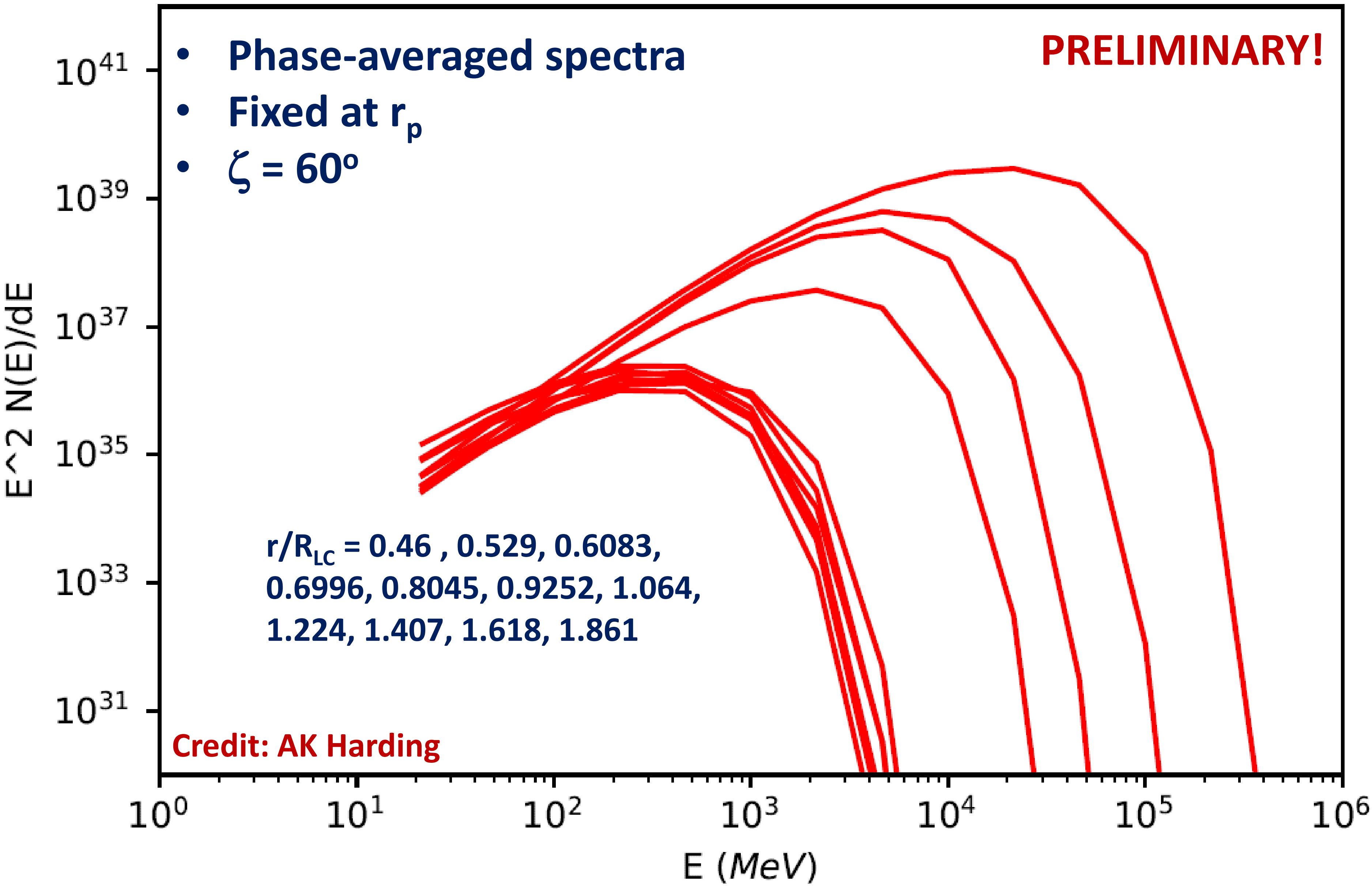


$\alpha = 75^\circ 18 J_{GJ} eE_{\parallel,\mathrm{low}}/mc^2 = 0.04 cm^{-1} eE_{\parallel,\mathrm{high}}/mc^2 = 0.2 cm^{-1}$
Averaged spectra
PRELIMINARY!
$\zeta = 65^\circ$
$\zeta = 68^\circ$
$\zeta = 70^\circ$
$\zeta = 72^\circ$
$\zeta = 75^\circ$
Fermi
1. ζ
2. Ramp between 0.9 R_{LC} and 1.1 R_{LC}
3. γ_0 = 200 – 2000
Credit: A Kundu
$E^2 dN/dE$ (MeV cm^{-2} s^{-1})
Energy (MeV)

Cumulative SC vs. Altitude

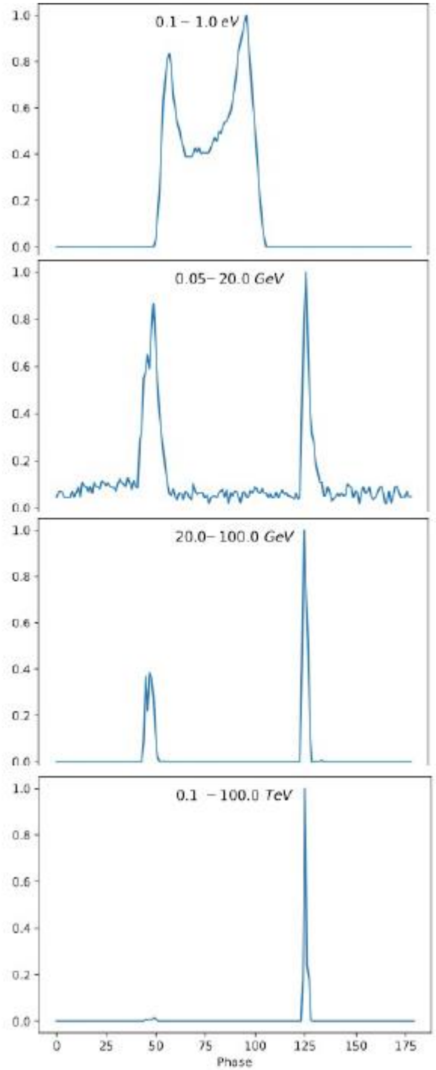


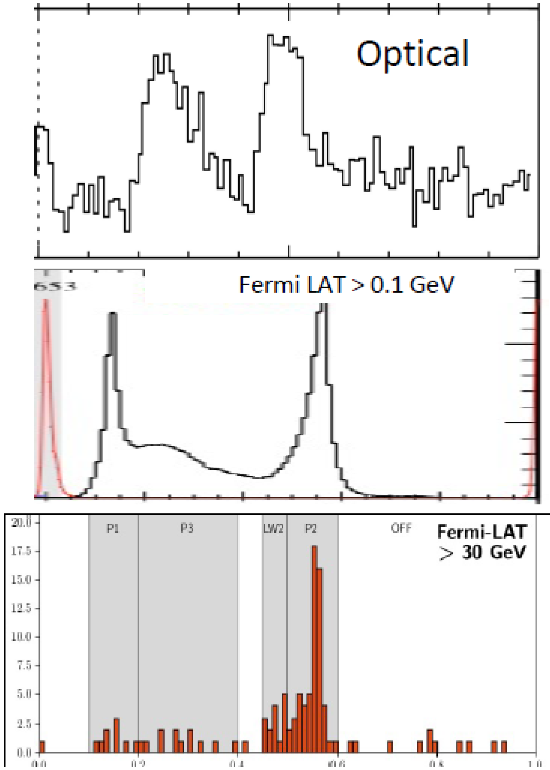
‘Differential’ SC vs. Altitude



P1/P2 vs. E_γ

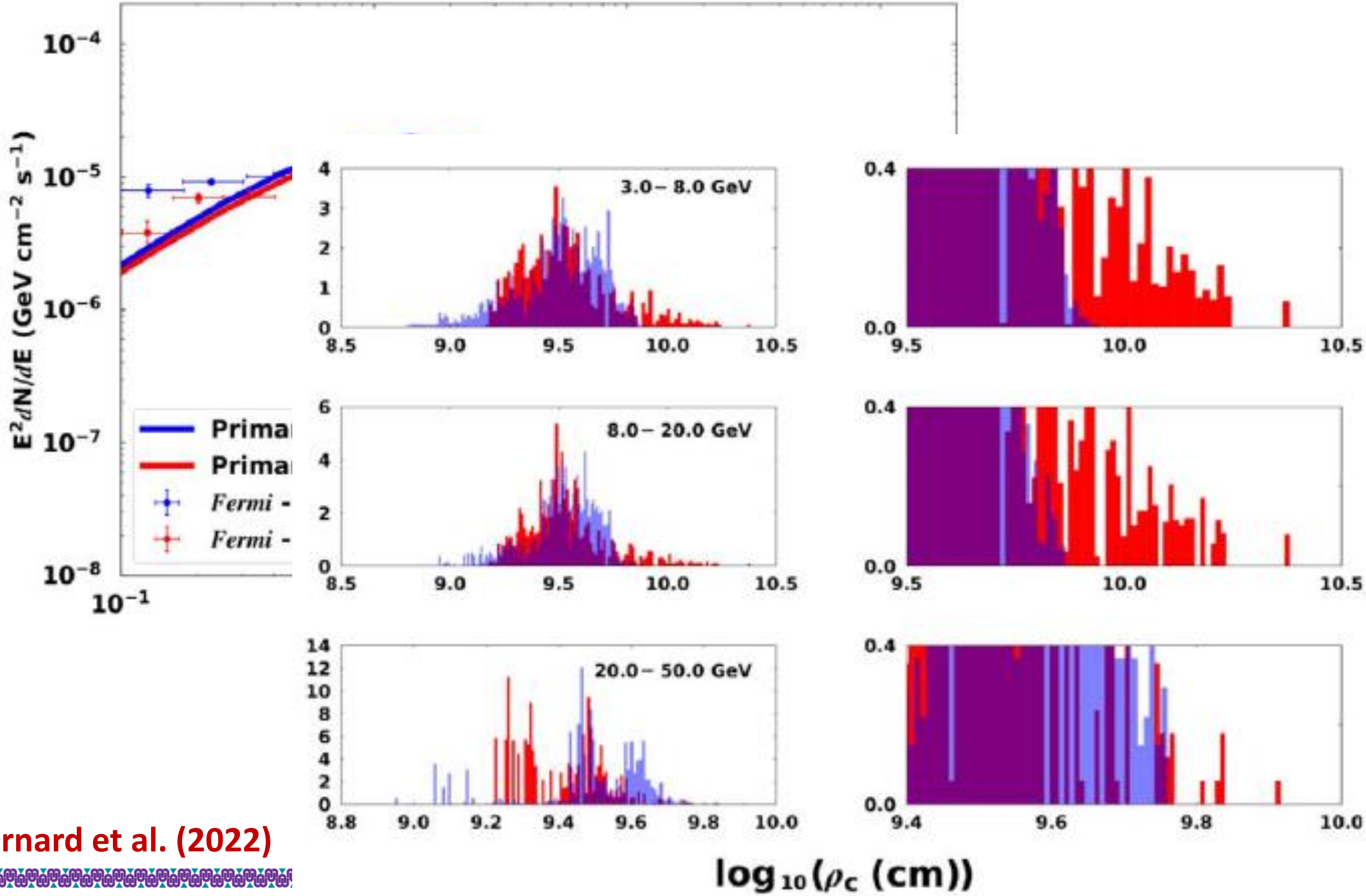
- Reasonable multi-wavelength LC predictions
- P1/P2 vs. E_γ effect: higher-energy photons in P2 – larger ρ_c
- Only P2 in TeV: highest-energy particles responsible
- Narrowing of peaks with energy
- $E_{||}(\phi)$ leading to azimuthally-dependent emissivity improves radio-to-γ lags





Harding et al. (2021)

P1/P2 vs. E_γ



Barnard et al. (2022)

Conclusions

- Vela is a unique source with high-quality, multi-band data
- HE spectrum: sub-exponential tail
- Traditionally: CR
- SC may give a broader spectral (GeV) peak
- SC vs. altitude:
  - Differential and integral; parameter study
  - Build-up of broad(er) spectrum – dominant in CS
  - Compare spectra below / beyond R_{LC}
  - Local $\gamma \sim 10^8$, $\rho_c \sim 10-100\ R_{LC}$ – are the ranges adequate?
- Constraining model parameters via spectral shape?
- Joint fitting of spectra and light curves more constraining

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"For the LORD is the great God, the great King above all gods. In His hand are the depths of the earth, and the mountain peaks belong to Him (Psalm 95:3-4).