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The displaced TeV signal of Terzan 5 and implications for CR transport

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Co-authors + publication details

Teraelectronvolt gamma-ray emission near globular cluster Terzan 5 as a probe of cosmic ray transport

Krumholz, Crocker, Bahramian & Bordas, Nature Astronomy 8, 1284–1293 (2024)

Nomenclature

- “Ter 5” = Terzan 5
- “GC” = Globular Cluster
- “MSP” = millisecond pulsar

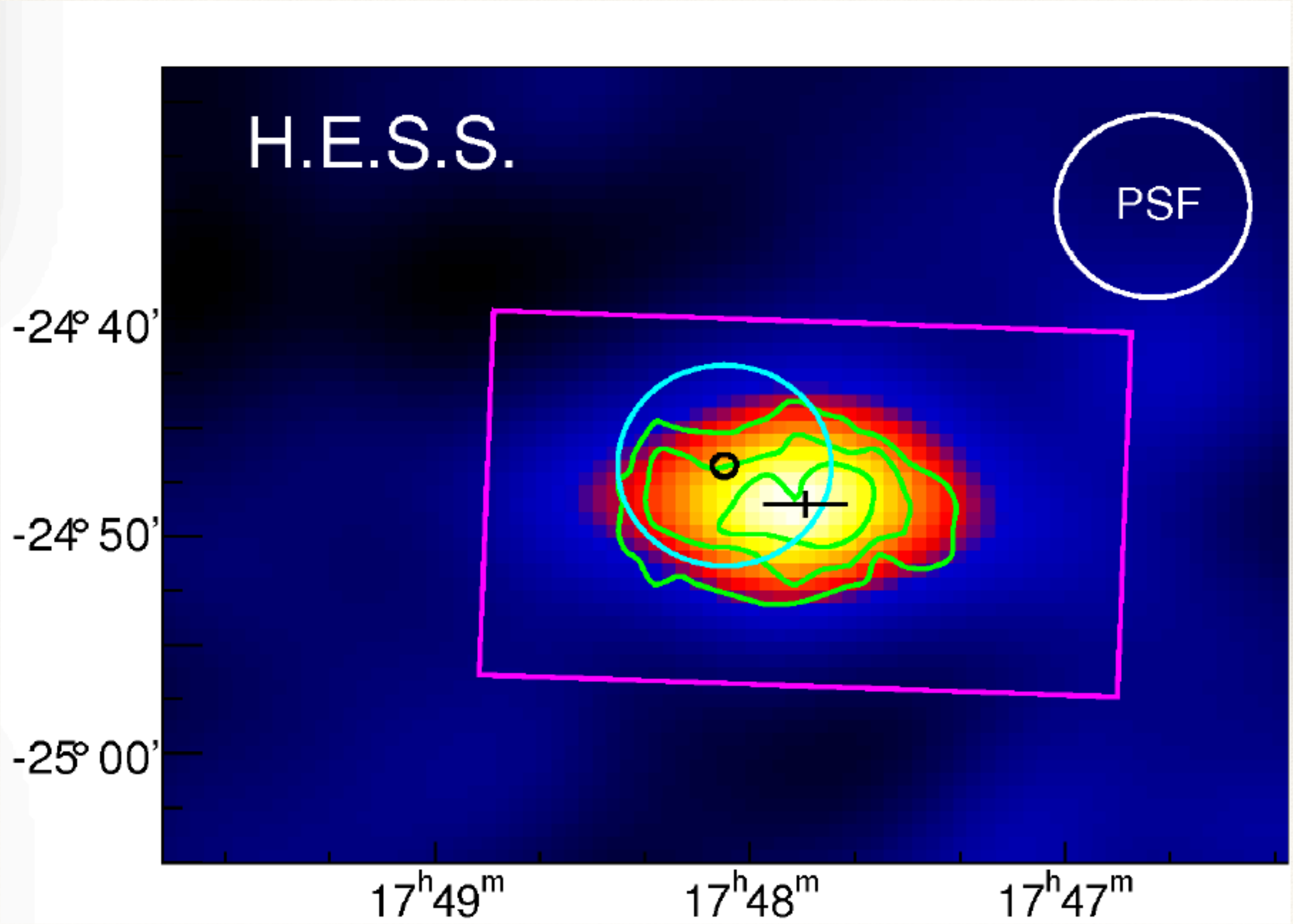
Terzan 5 Globular Cluster

- One of the Milky Way's most massive GCs
- Largest (radio identified) MSP population of any GC
- Brightest gamma-ray (GeV band) GC
- Located in the inner Galaxy, only 200 pc above plane; one of the Galactic bulge GCs

Terzan 5 as high energy source

- About 30 Galactic MSPs detected in ~GeV band with *Fermi* data
- Terzan 5, u*niquely amongst GCs*, detected in the **TeV** band by HESS (Abramowski+2011)
- The Terzan 5 associated TeV source is semi-resolved and extended
- BUT the **centroid** of the extended TeV emission is **displaced** off GC centre (where the MSPs concentrate) by ~8 pc

Terzan 5 @ TeV (Abramowski+2011)



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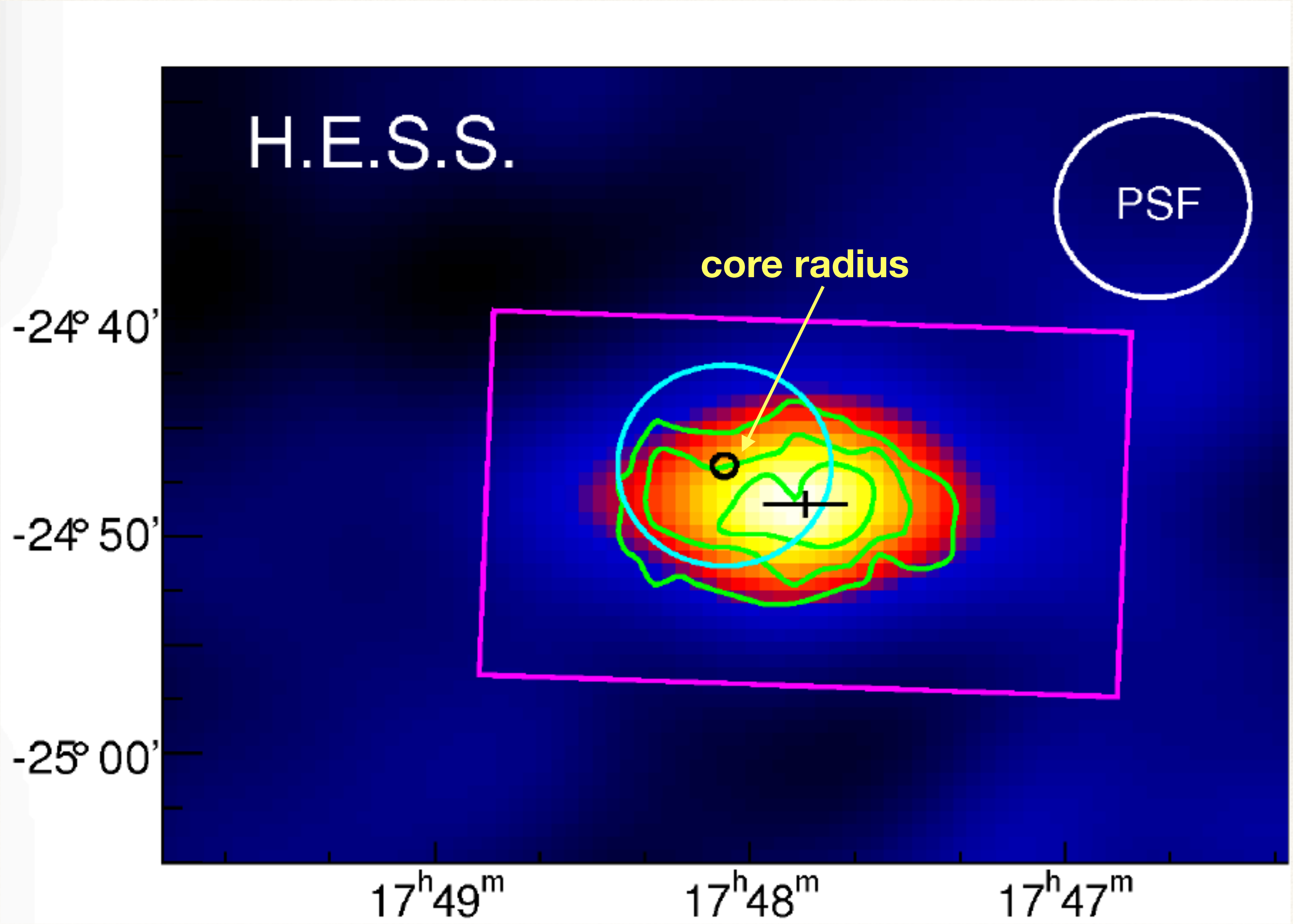

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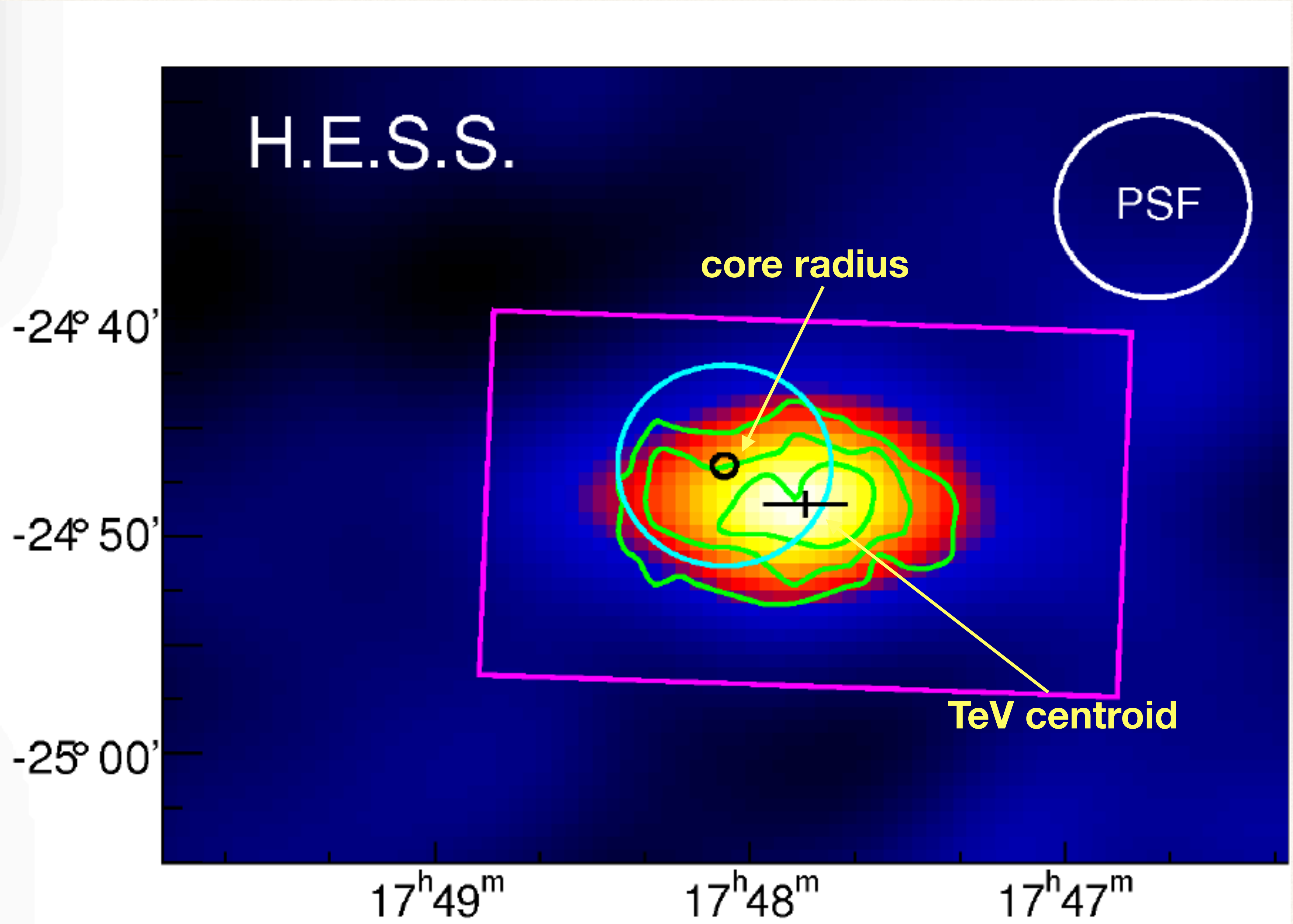

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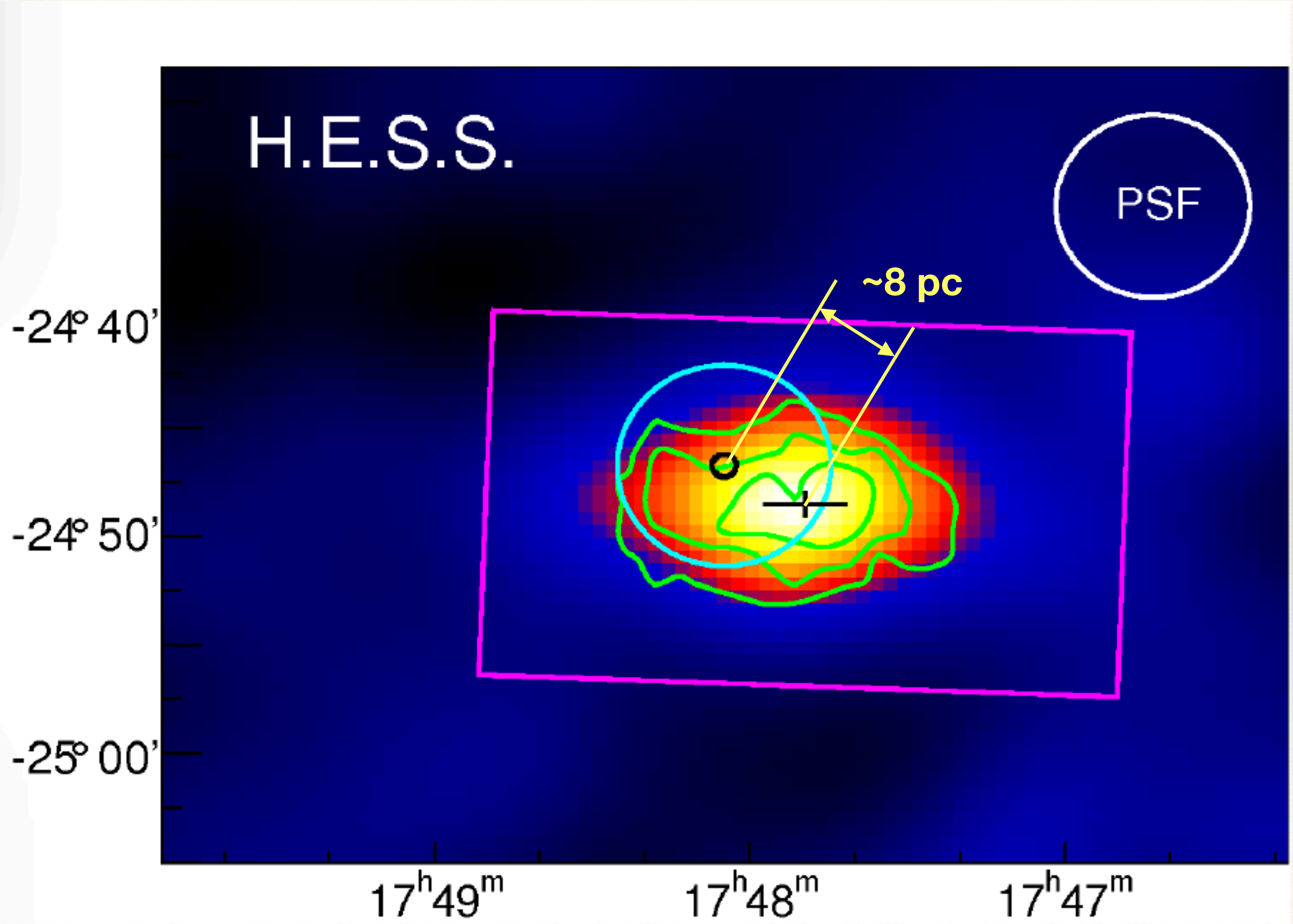
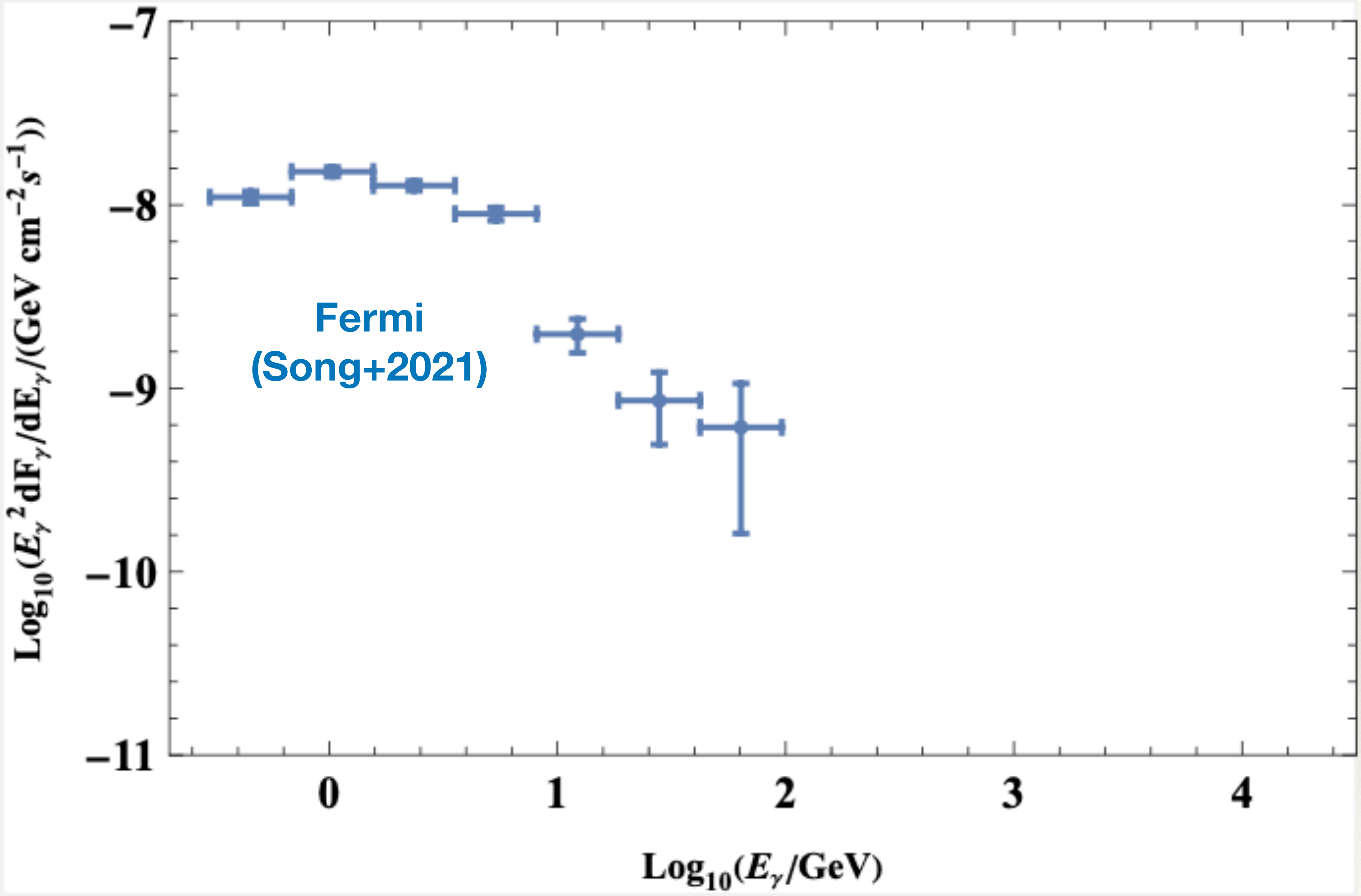


Is the TeV source *really* associated to Ter 5?

- HESS collab. (Abramowski+) 2011 calculate the chance overlap probability as $\sim 10^{-4}$
- The GeV and TeV spectral data points match well

Spectrum Ter 5



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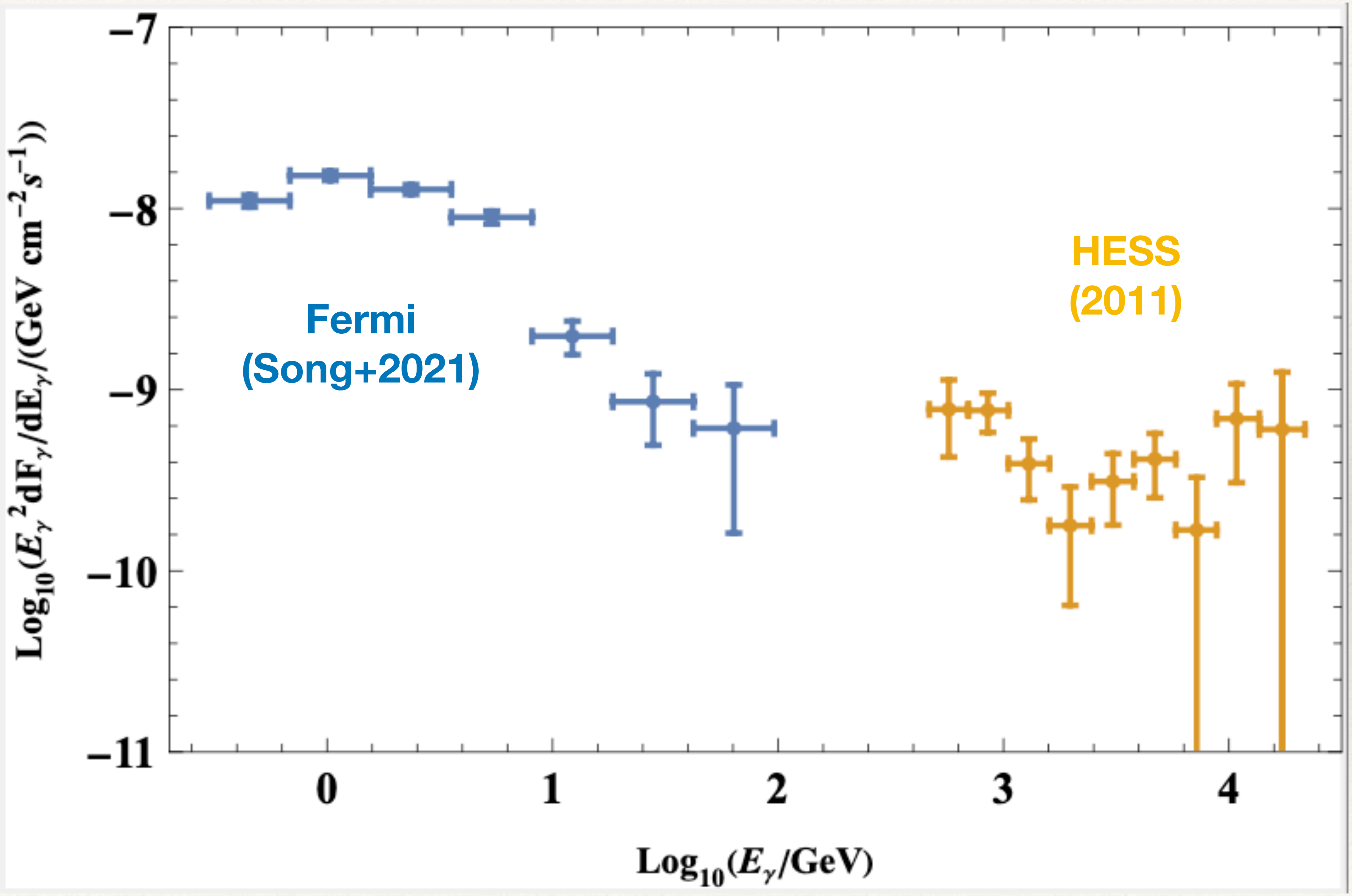
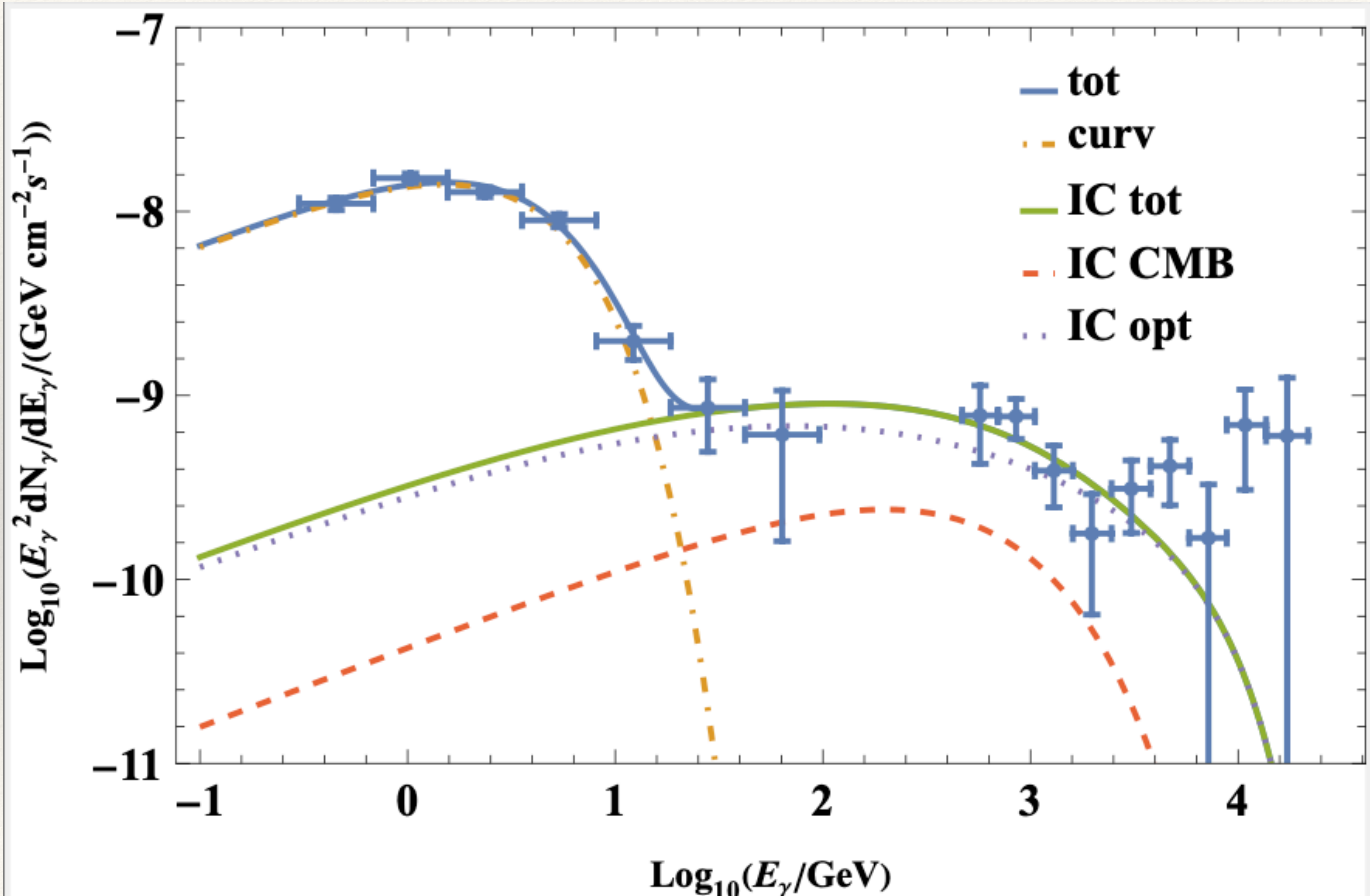


Is the TeV source really associated to Ter 5?

- Abramowski+2011 calculate the chance overlap probability as $\sim 10^{-4}$
- The GeV and TeV spectral data points match well

…*working hypothesis*: the TeV source **is** associated to Ter 5

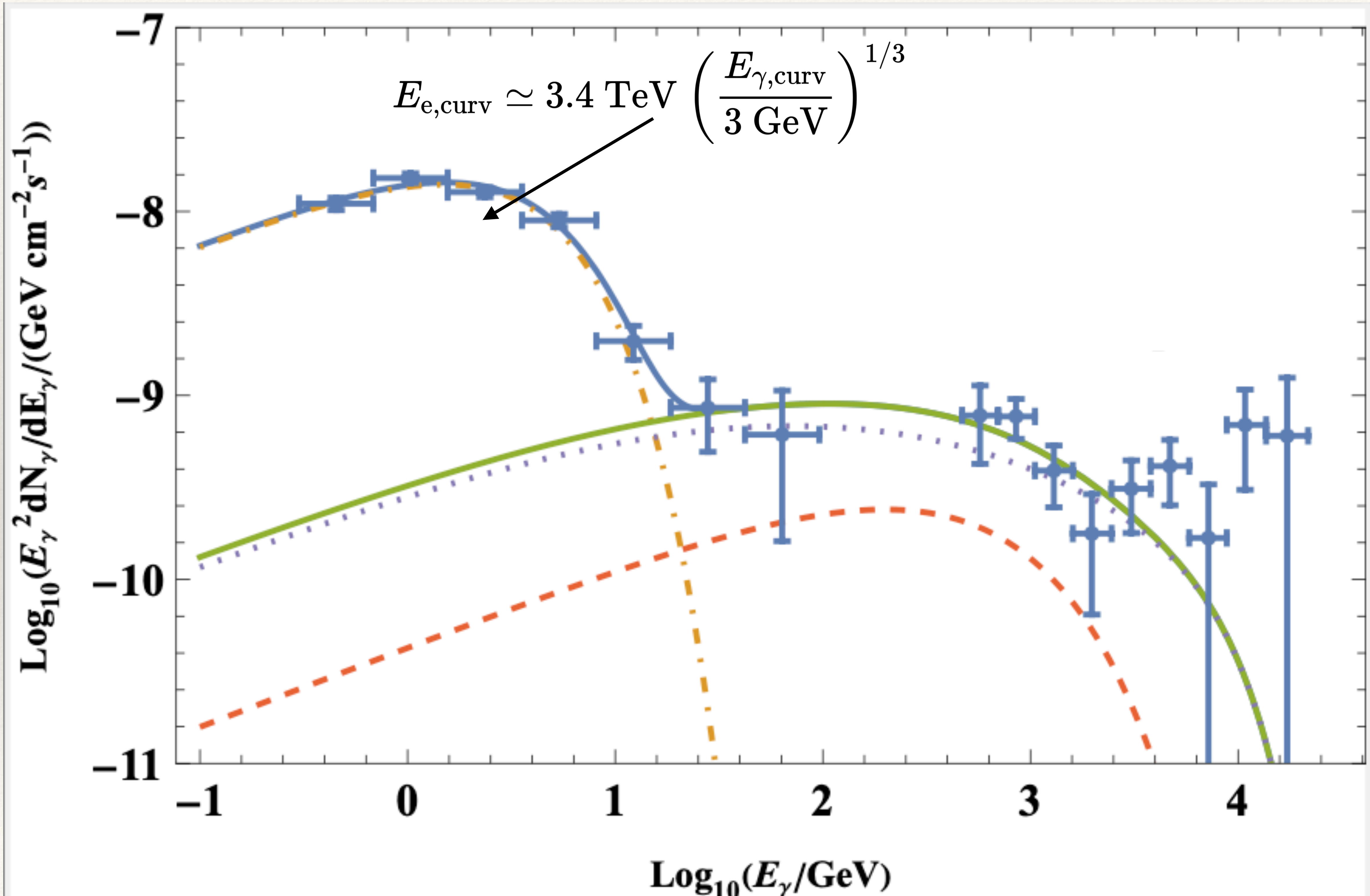
Spectrum well fit as curvature radiation + inverse Compton



First Mystery: why the displacement?

- Lightfield energy density and density of MSP sources should peak in the centre of the GC, so why doesn't the TeV surface brightness peak here?

Second Mystery: how do we get sufficiently energetic electrons?



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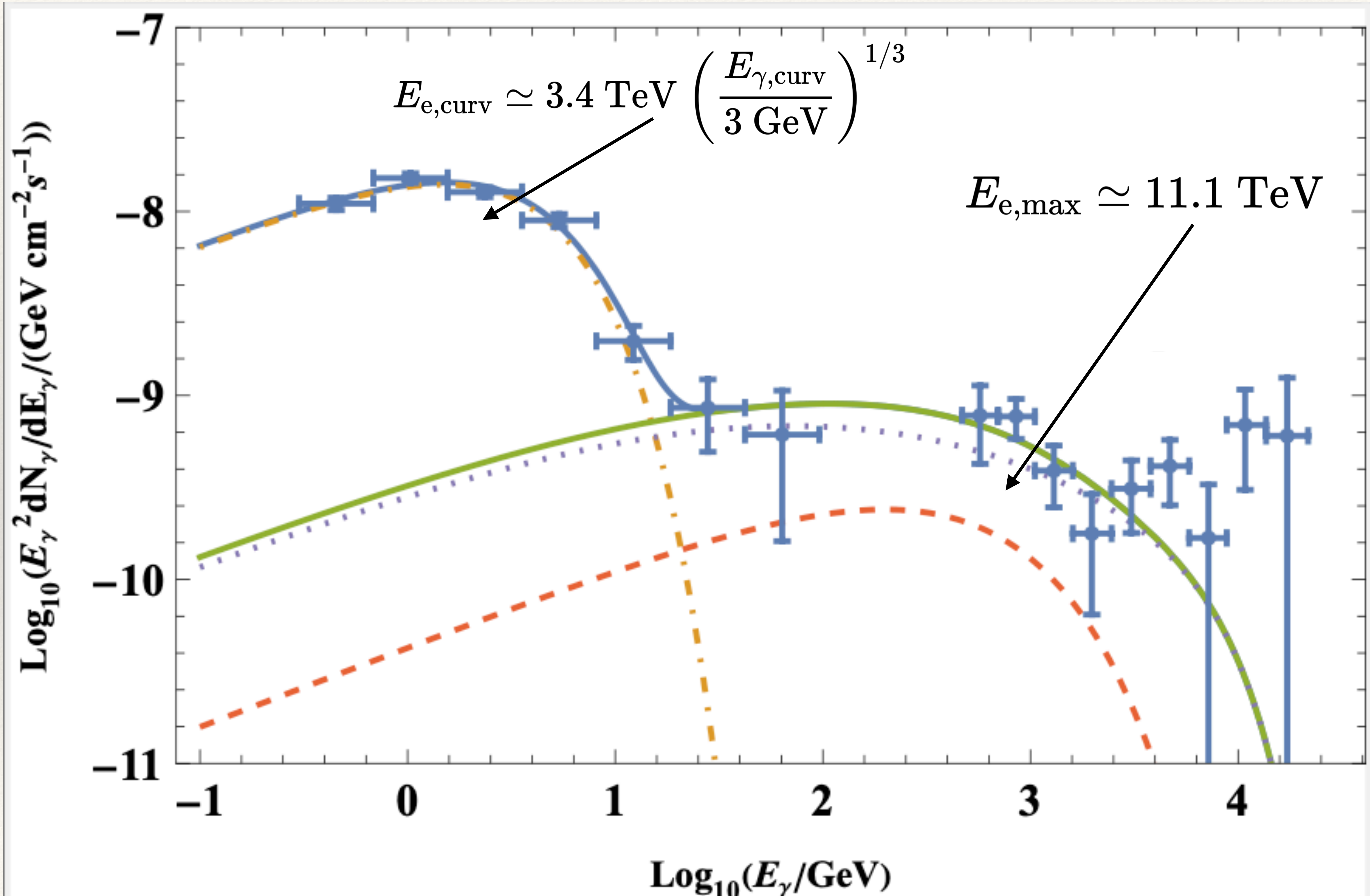

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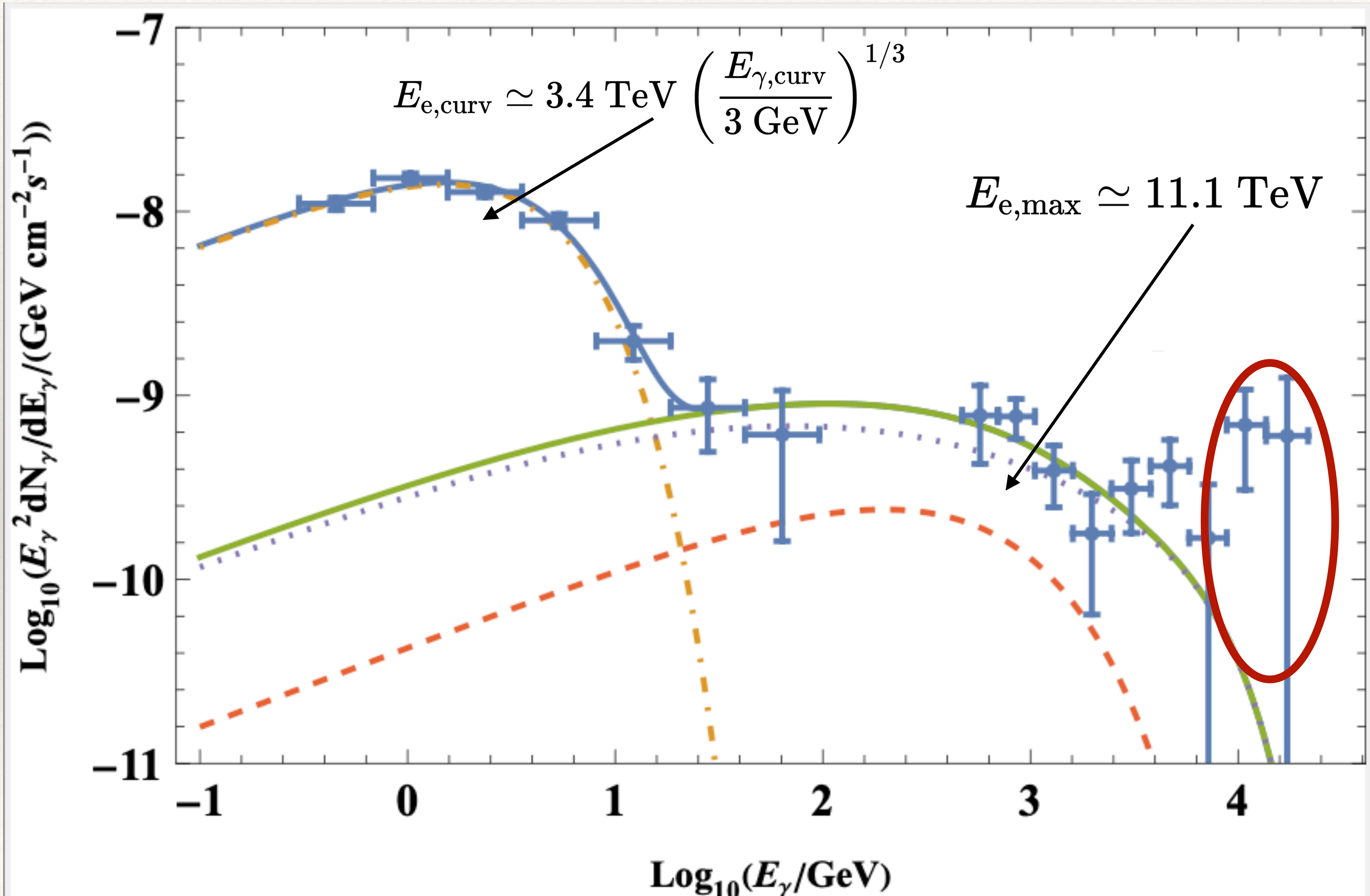

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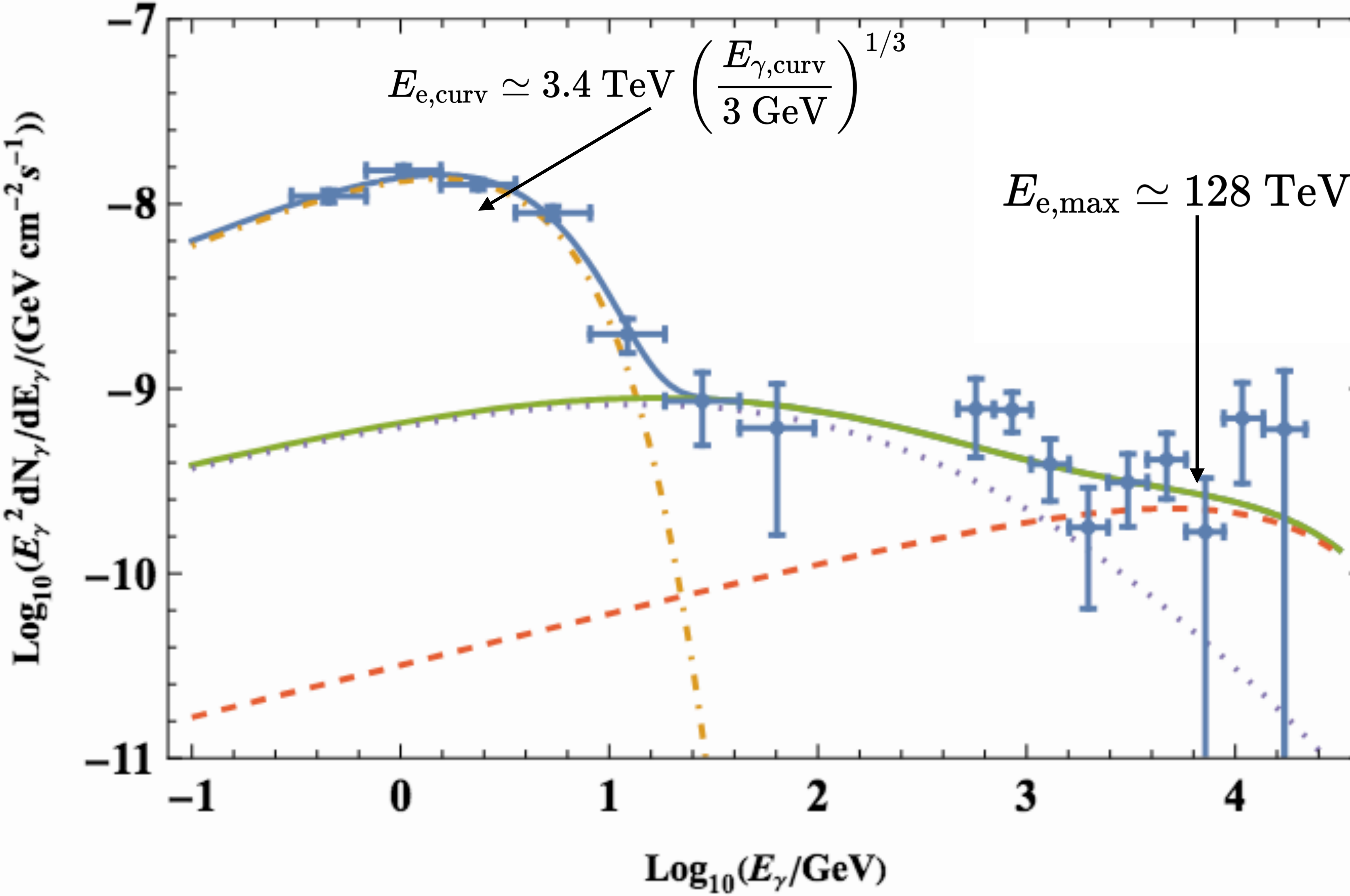


Broad Scenario

- Following Bednarek & Sobczak 2014, Bednarek+ 2016:
- Individual MSP (relativistic pair) winds aggregate into a single, global wind off the GC
- The GC is moving at $\gtrsim$ 100 km/s with respect to the ISM; this motion is both **super-sonic** and **super-Alfvenic**
- ⇛Expect the analogue of a 'giant' bow-shock pulsar wind nebula: a (global) termination shock nested inside a bow shock and a magnetotail

Stand-off distance to contact discontinuity

$$R_{\rm SO} = 0.35\ \mathrm{pc} \left(\frac{\dot{E}_{\rm wind,37}}{\mathrm{n}_{\rm H,-1}} \right)^{1/2} (v_{\rm Ter5,2})^{-1}$$

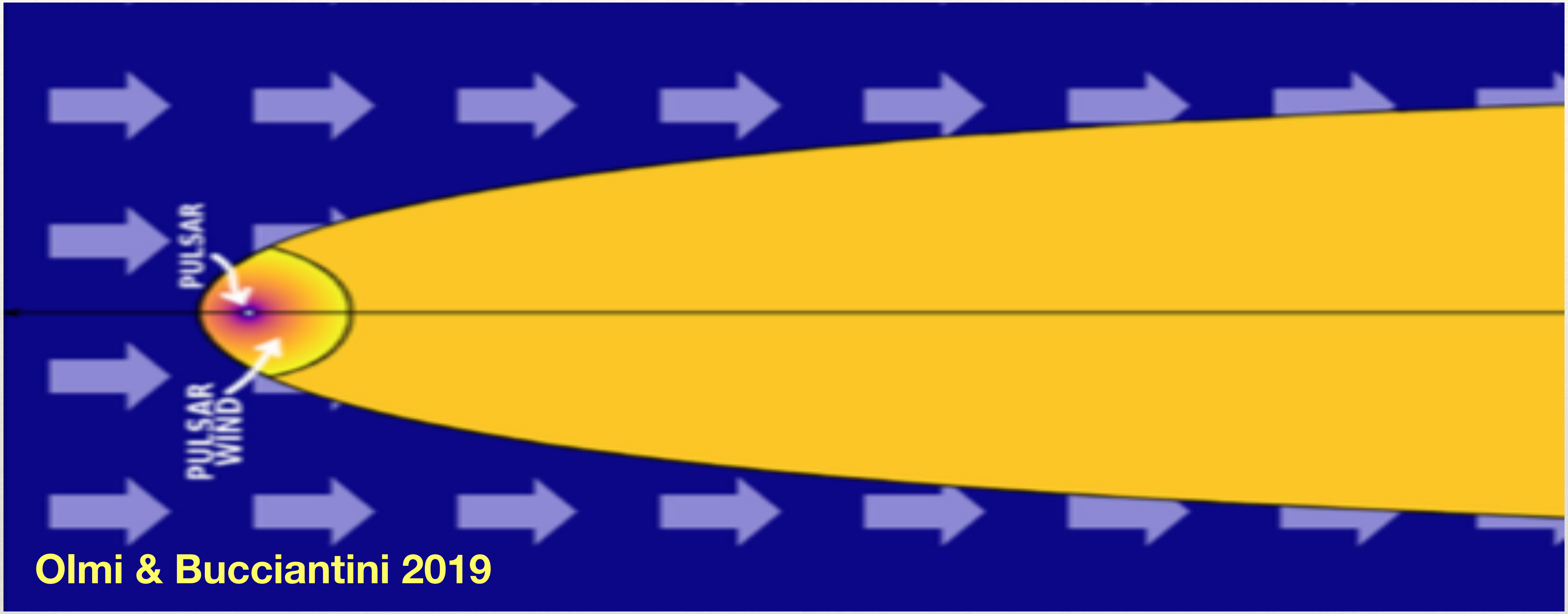
- $R_{SO} \ll R_{offset} \sim 7$ pc
- *Why doesn't the TeV centroid correspond to the acceleration region?*

Our scenario

Why the displacement?

- A cosmic ray transport effect?
- Point: the TeV+ radiation is produced by CR $e^{\pm}$ with energies > 10 TeV, or Lorentz gamma factors > 10^7 ; if $e^{\pm}$ are not moving in our direction, we do not see the radiation they emit
- The GC is moving super-sonically through the disk ISM
- It has a bow shock and a magnetotail in the direction opposite its motion in the local ISM gas rest frame

The Big Mystery: why the displacement?



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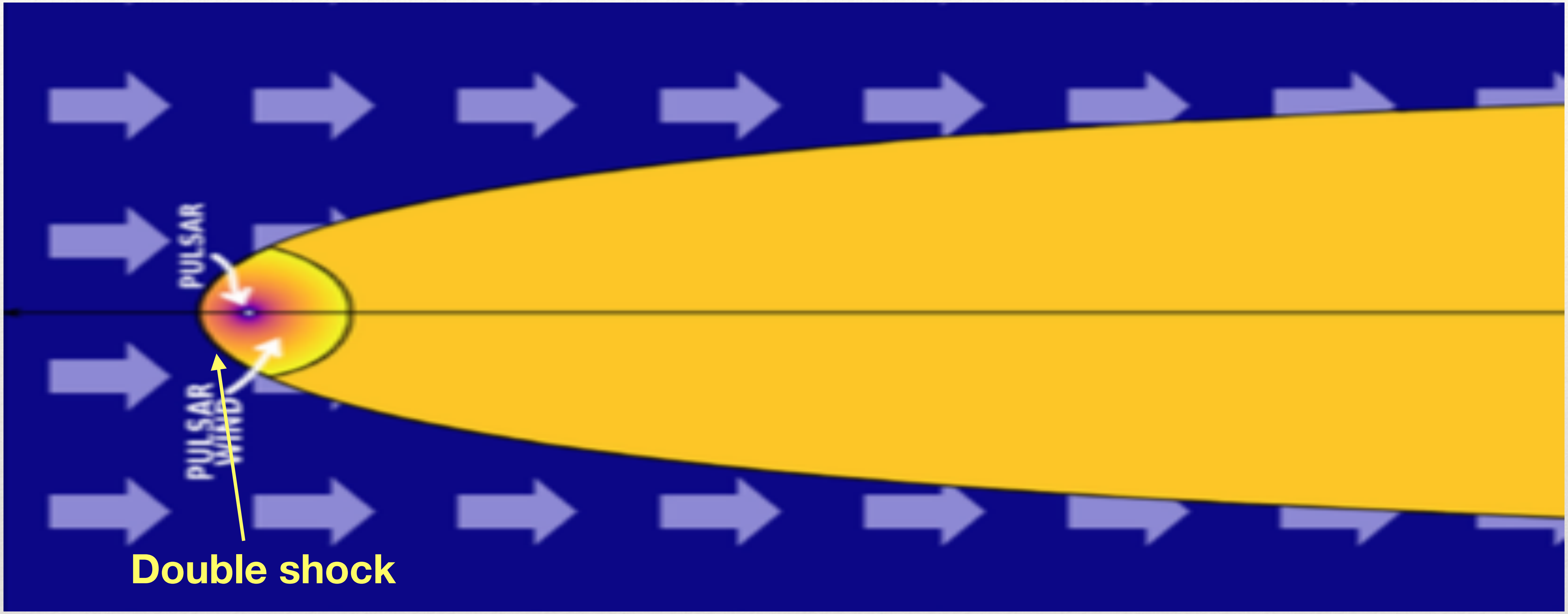

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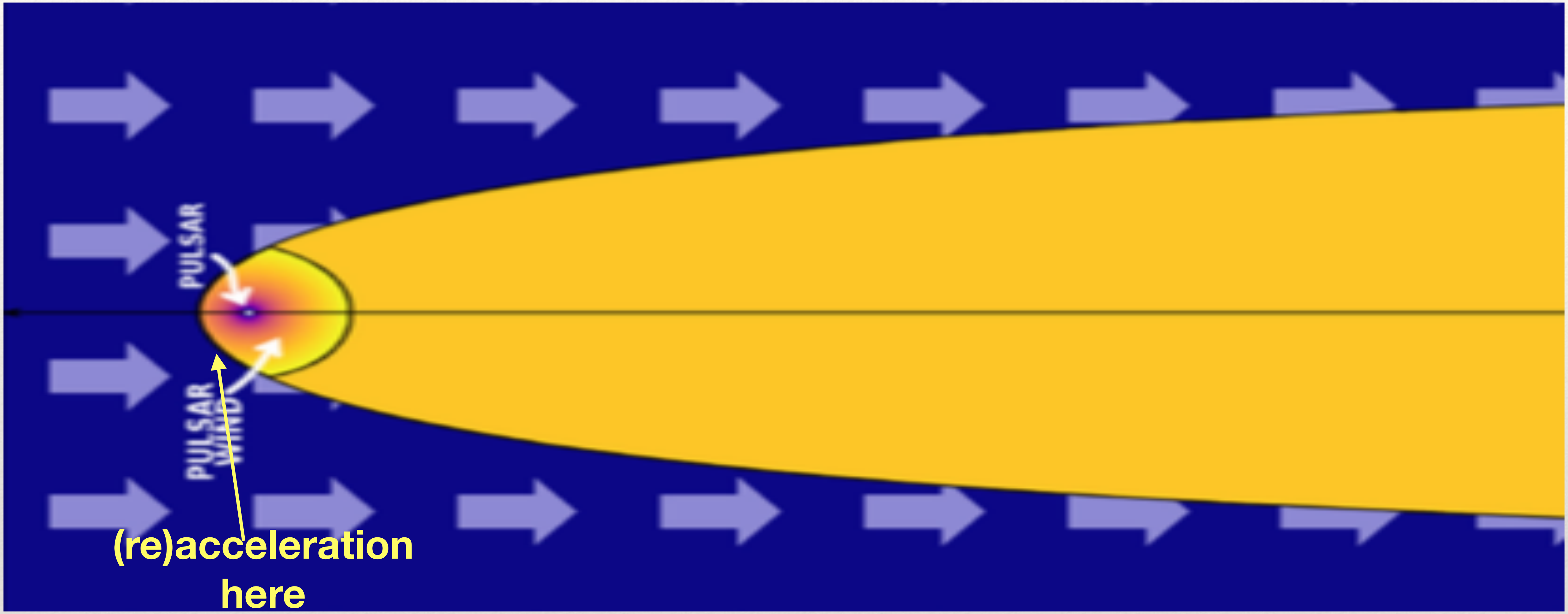

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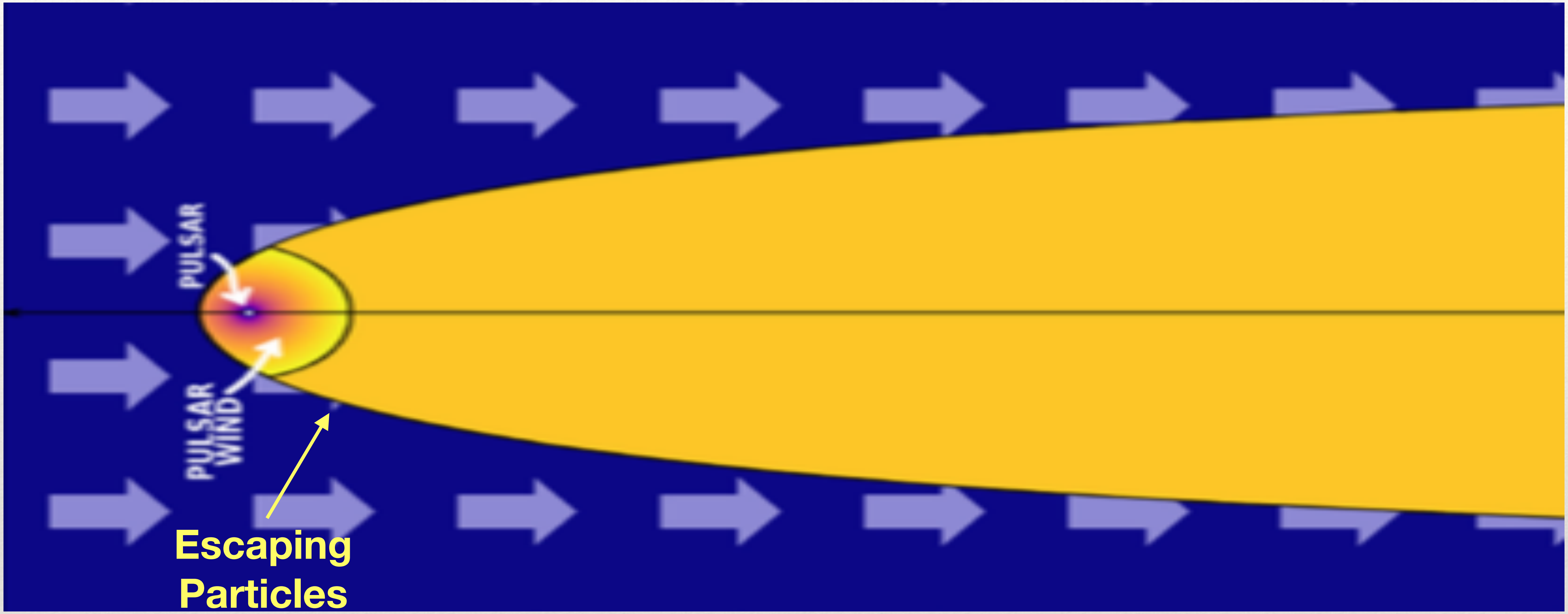

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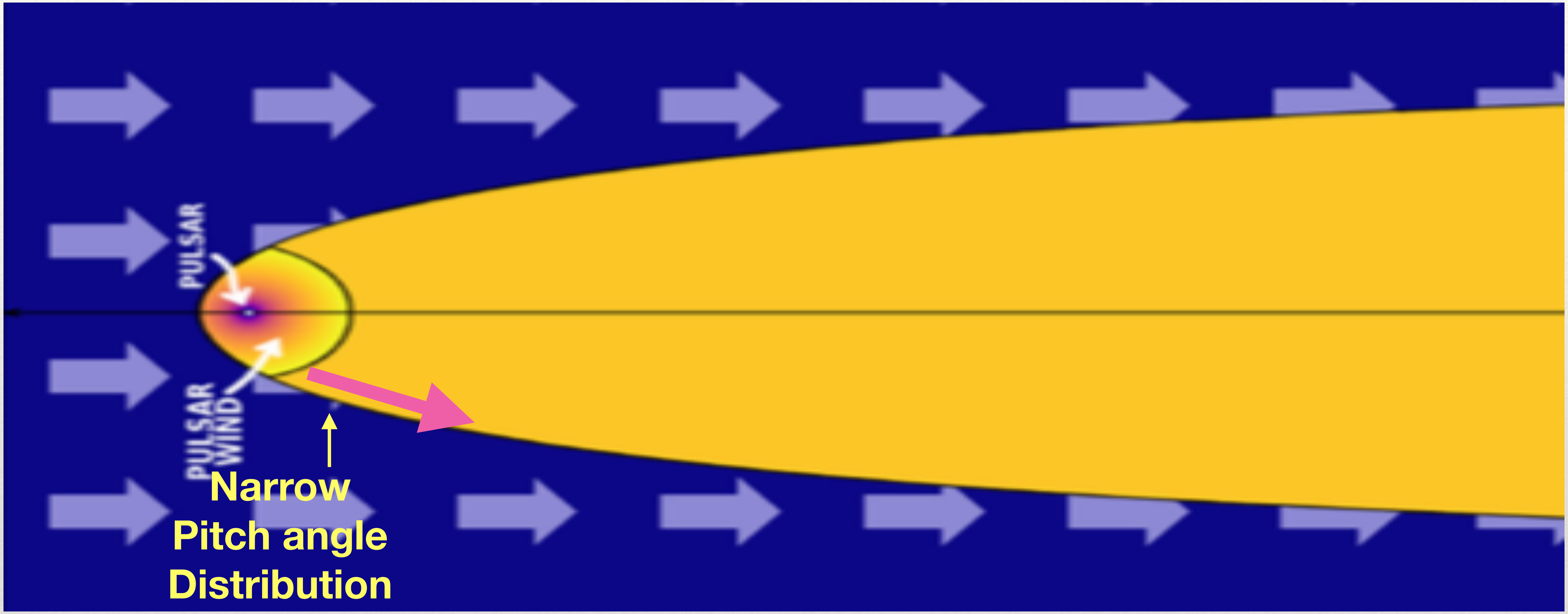

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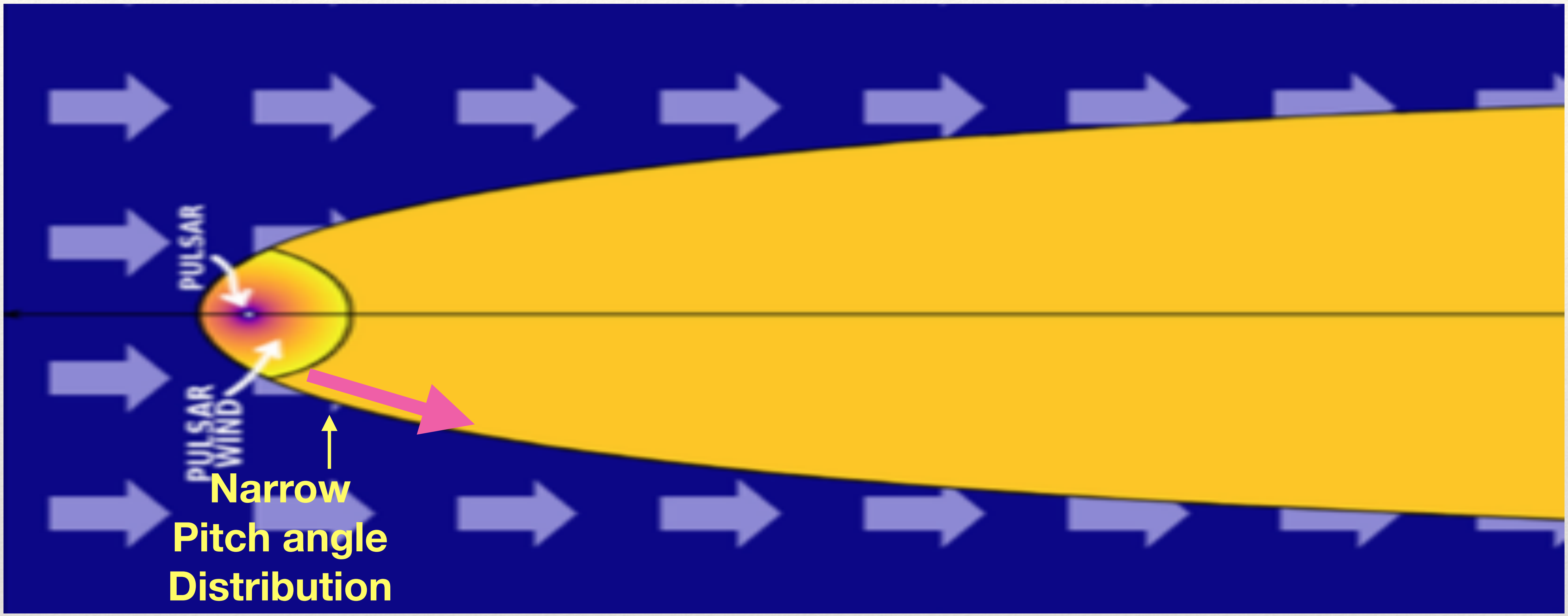
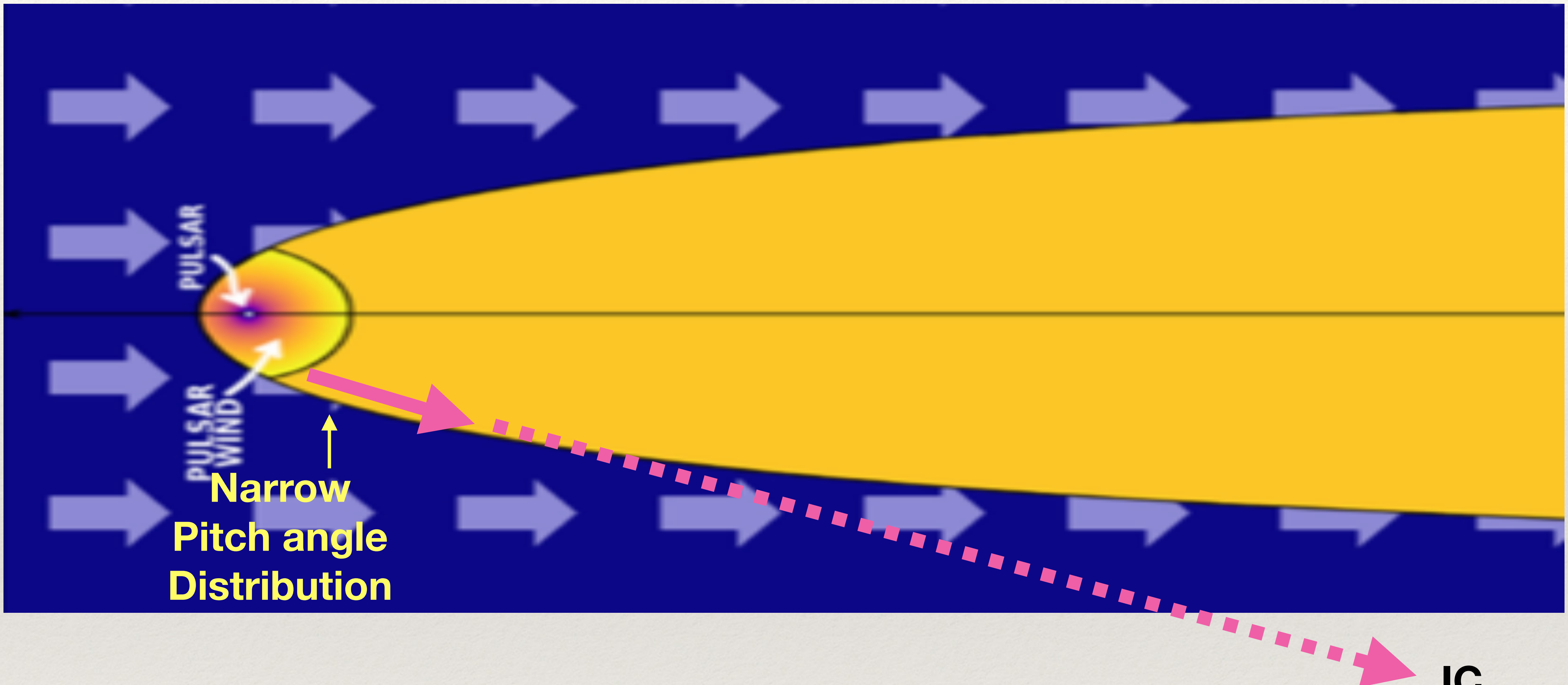


These particles
moving at
speed light

The Big Mystery: why the displacement?



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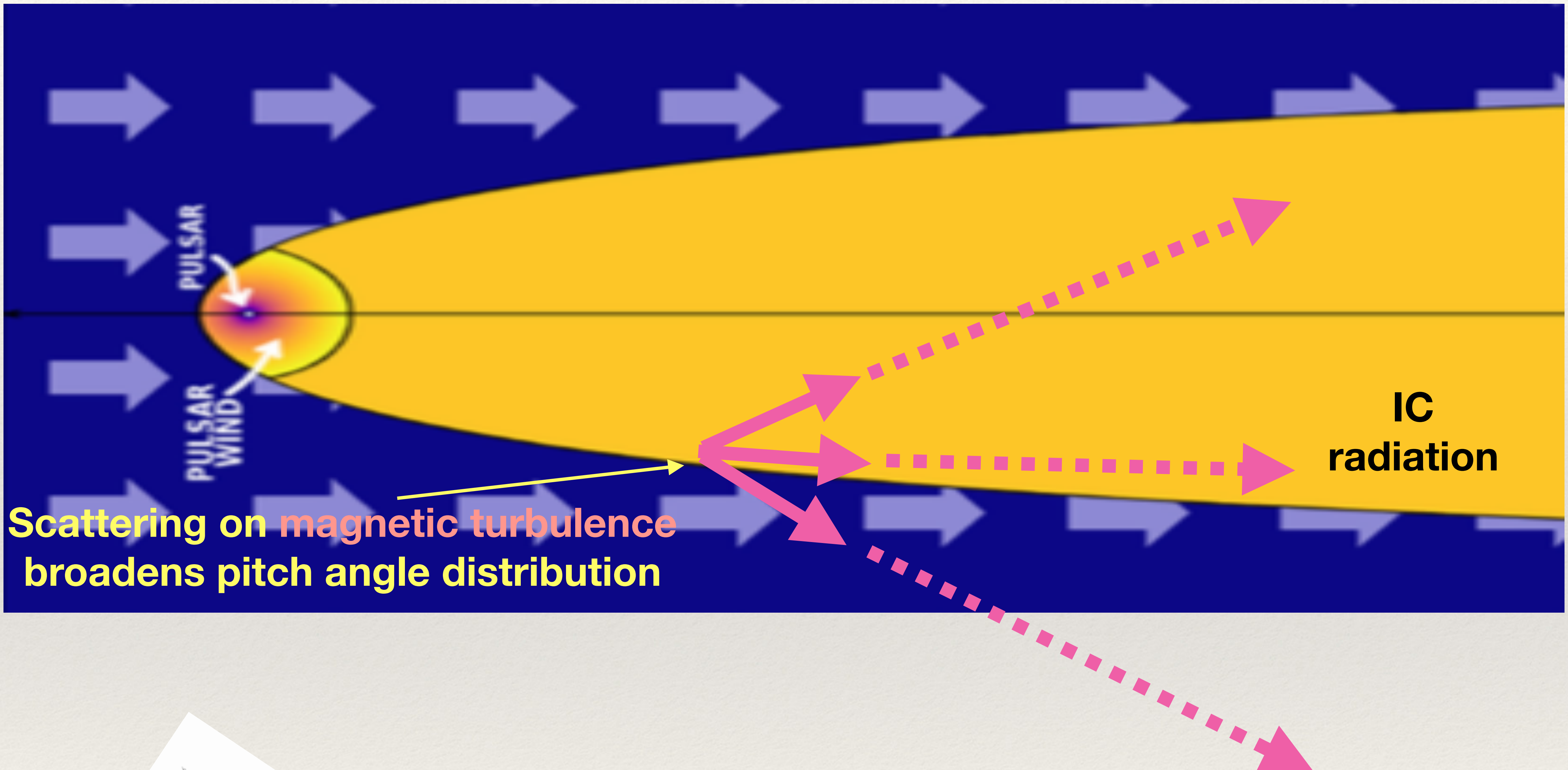

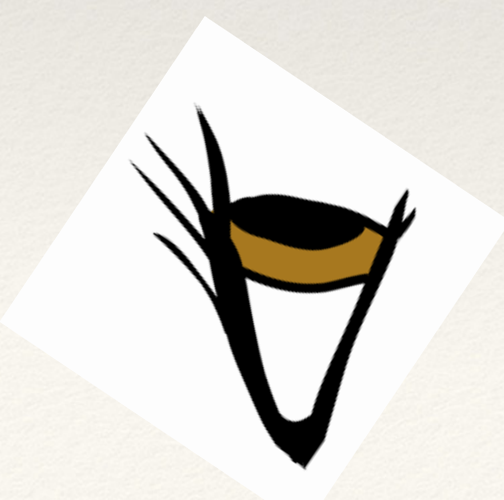

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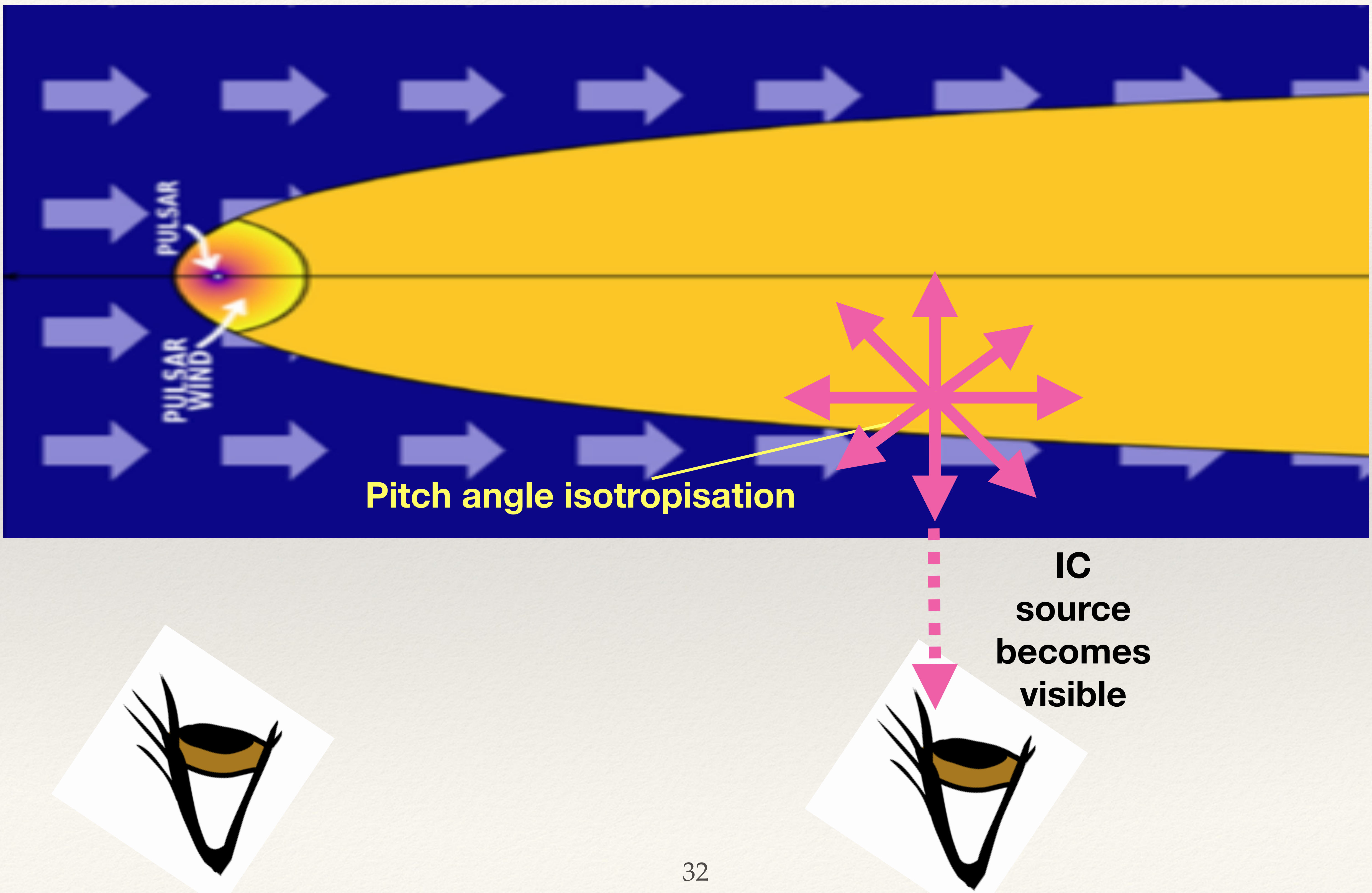


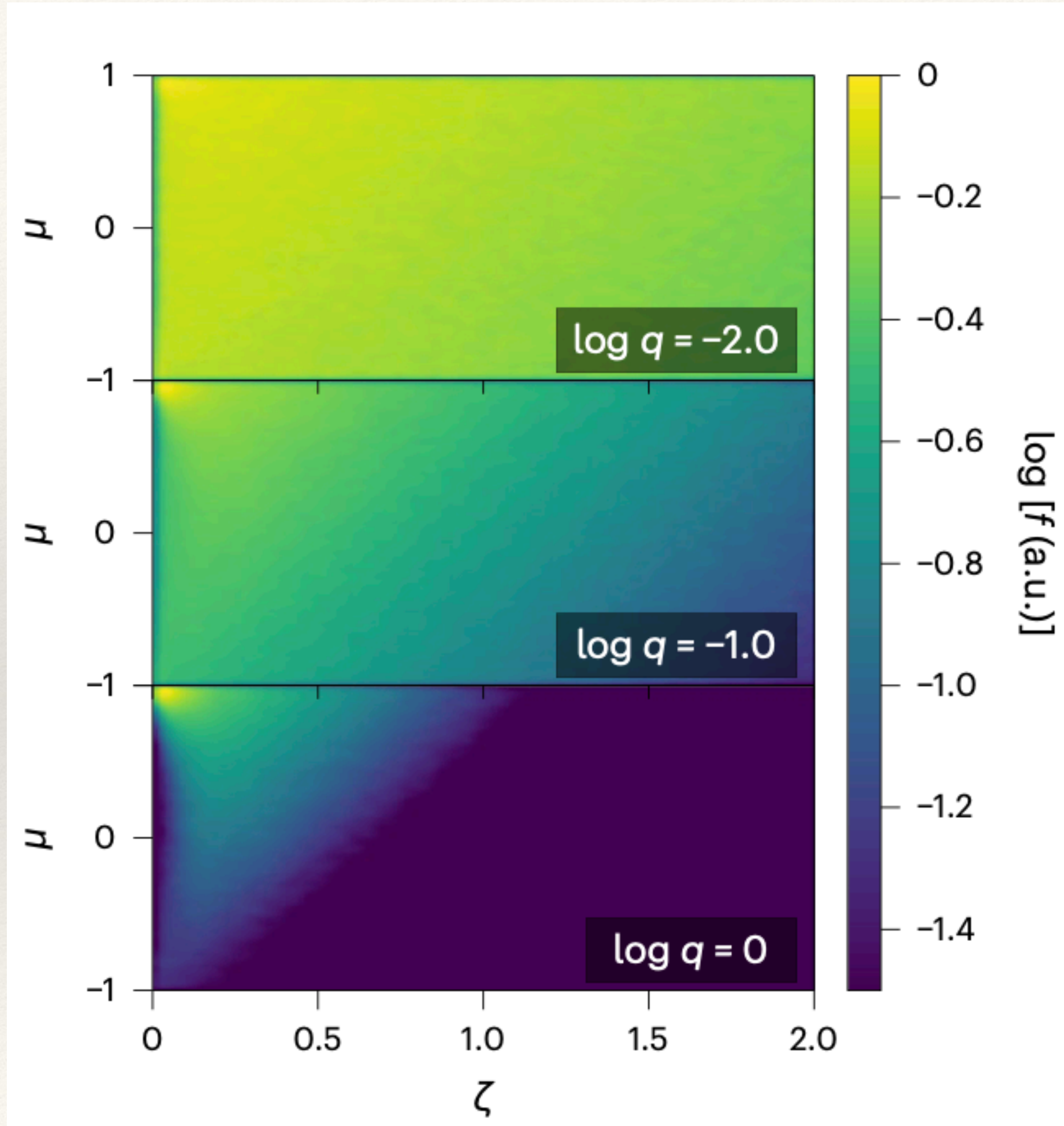
Numerical modelling with CRIPTIC

- Non-dimensionalise the transport equation which includes a pitch angle diffusion term (energy independent for simplicity)
- CRIPTIC (Krumholz+2022) transforms the PDE into an Ito stochastic ODE describing the evolution of sample CR packets
- CRIPTIC propagates the packets over a trajectory in the 3D configuration space = (1D position, magnitude momentum, pitch angle)
- The CR distribution function is found from a kernel density estimate over the ensemble of trajectories

Results with CRIPTIC

$$q = \frac{p}{p_0}$$

***p*₀ : momentum where (synchrotron loss time) = (pitch angle scattering time)**



$$\zeta = (K_\mu / c) z$$

Results with CRIPTIC

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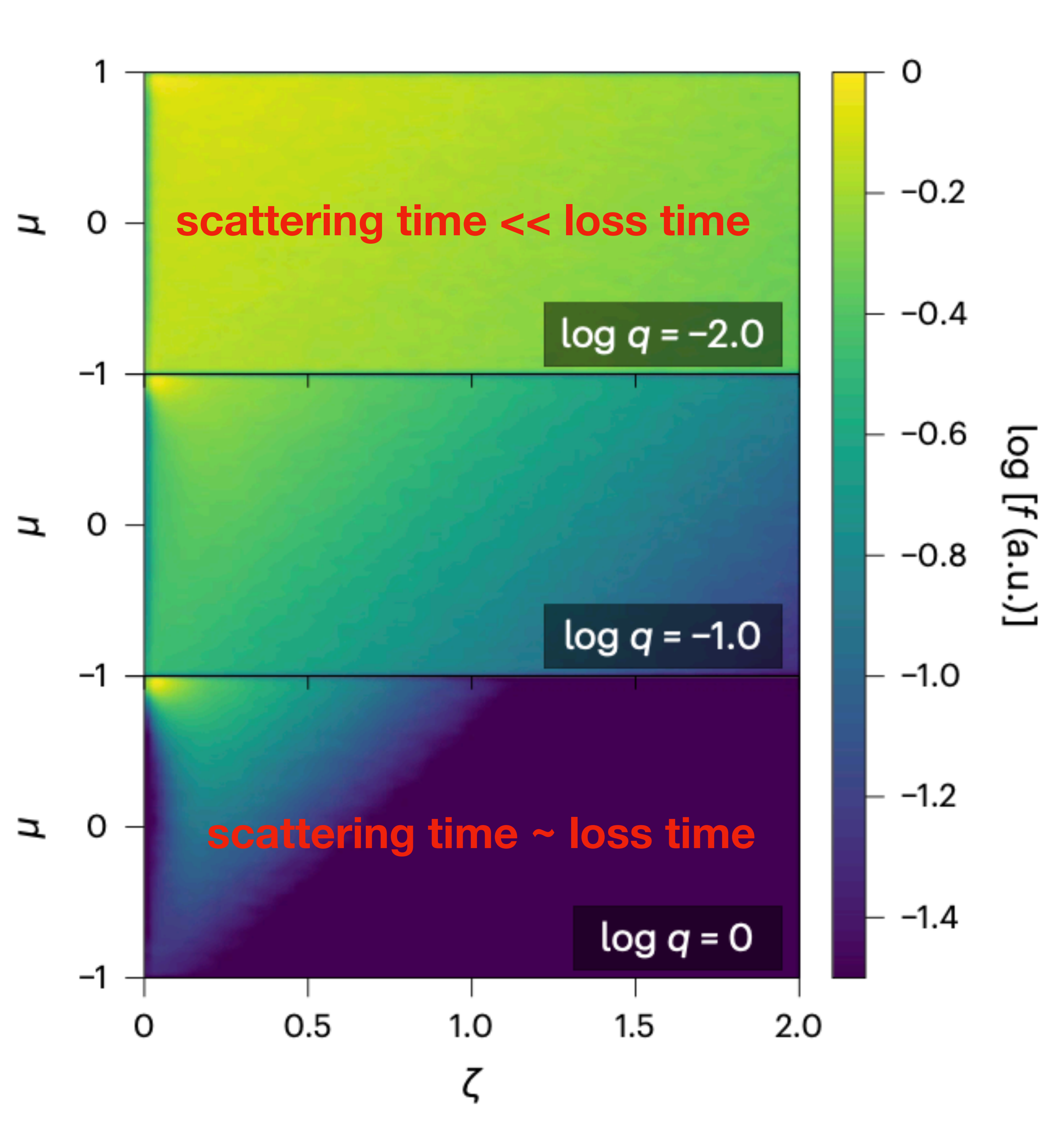

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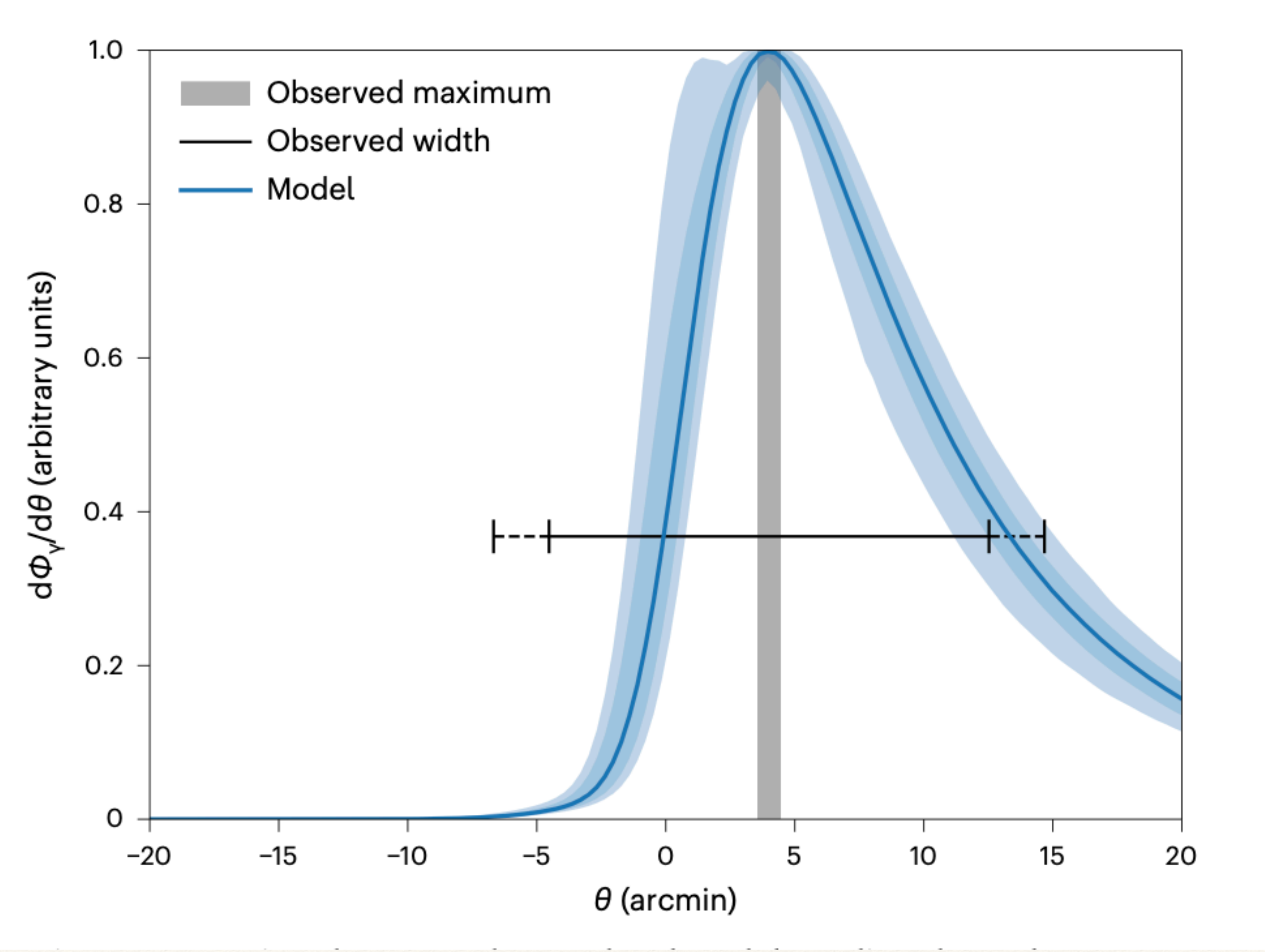

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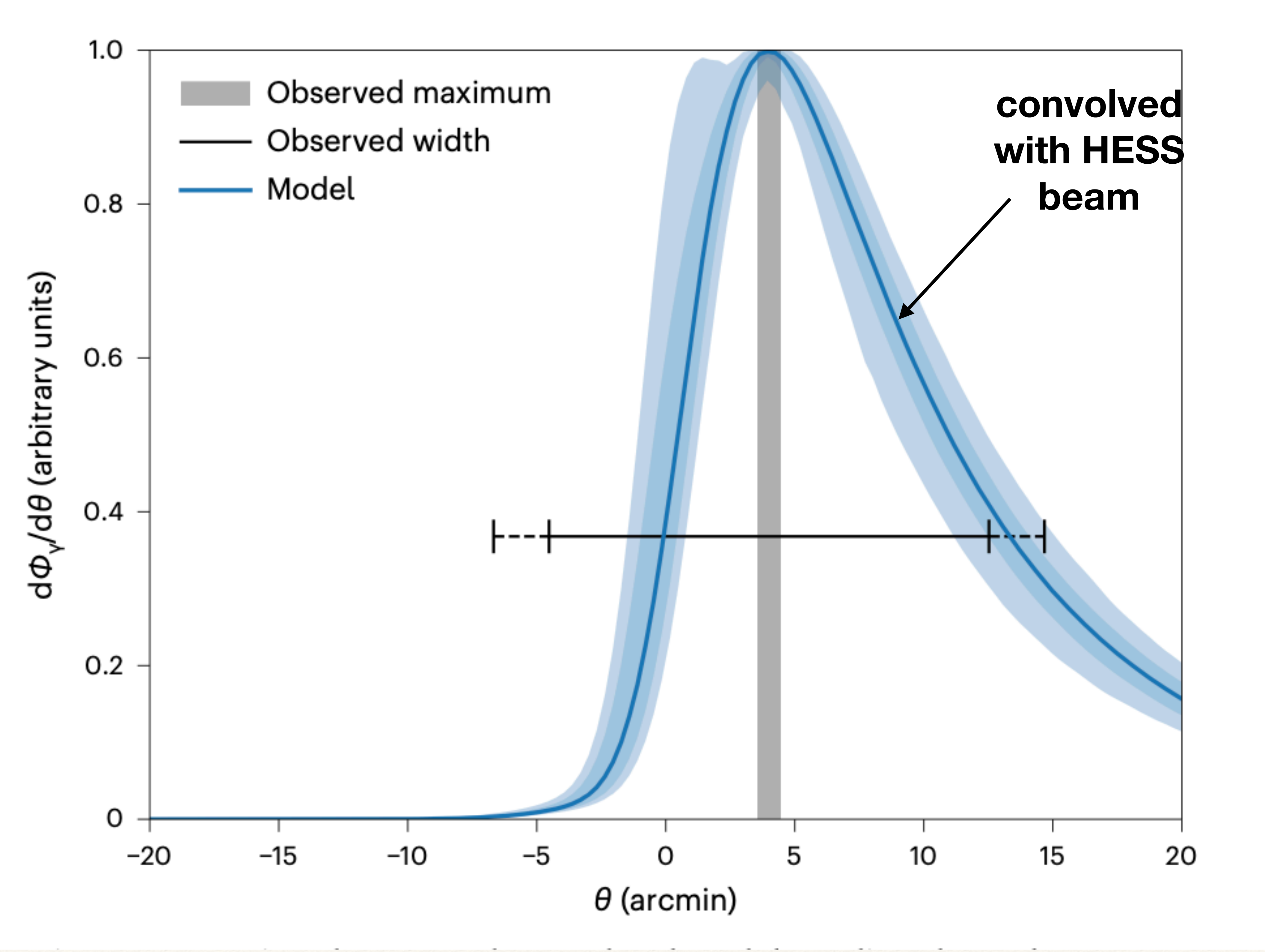
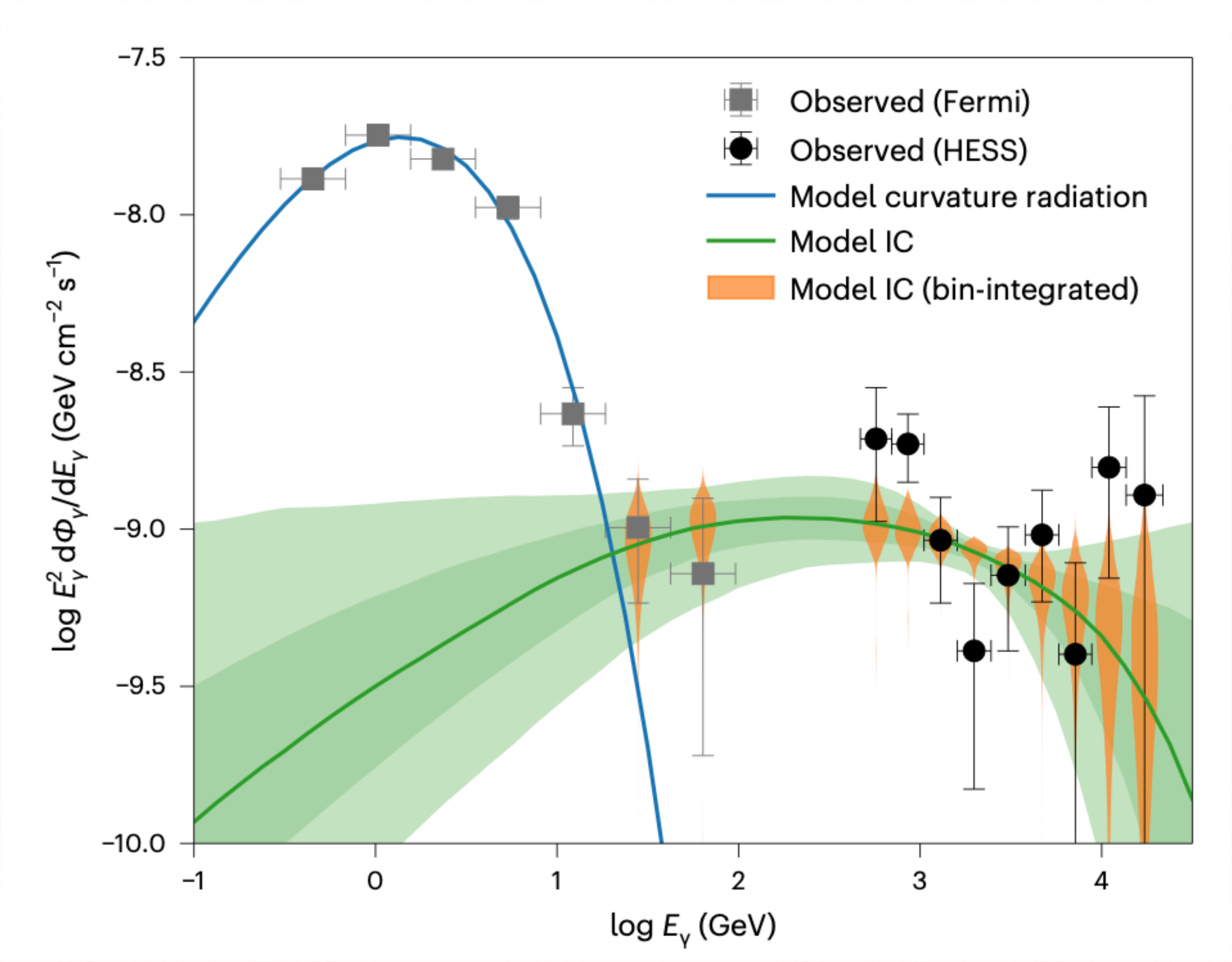


[The width of the profile is also a good match to the HESS observations.]

Results with CRIPTIC



Results with CRIPTIC

- good fits require pitch angle scattering coefficient:

$$K_\mu = 1.1^{+1.5}_{-0.9} \times 10^{-10}\ \mathrm{s}^{-1}$$

…i.e., $t_{pitch} \sim 300$ yr

- Implies spatial diffusion coefficient:

$$K_x = c^2/6K_\mu = 1.4^{+5.5}_{-0.8} \times 10^{30}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$

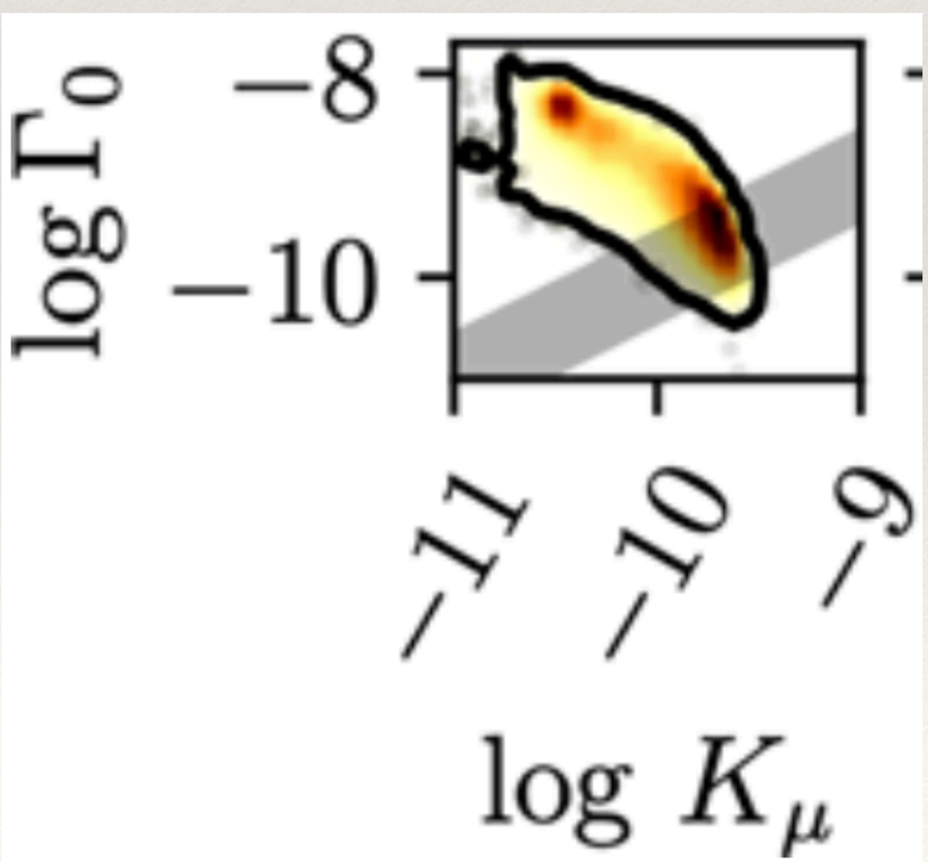
- We can also determine that

$$B = 110^{+80}_{-40}\ \mu\mathrm{G}$$

Results consistent with *self-confinement*

The measured pitch-angle scattering rate is consistent with that expected from Alfven waves driven by (resonant) streaming of ***the CR electrons themselves***:

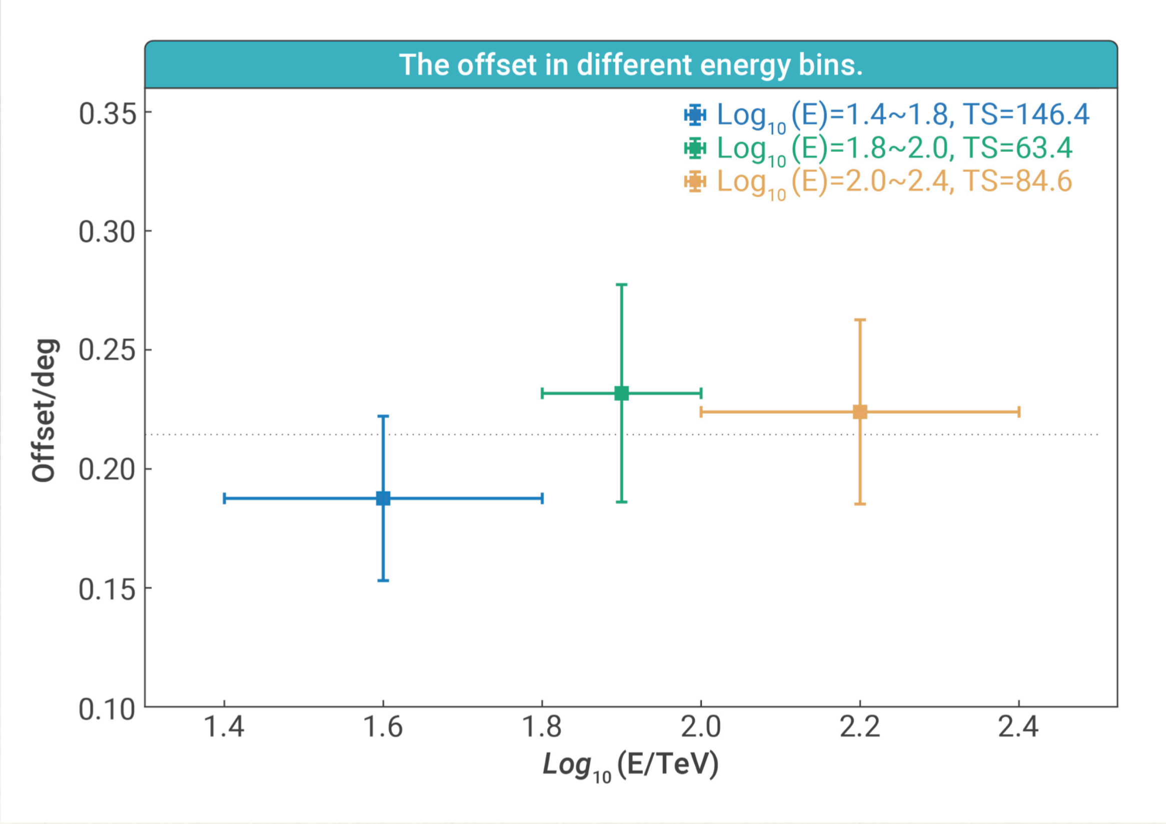
$$K_\mu = 1.1^{+1.5}_{-0.9} \times 10^{-10}\,\mathrm{s}^{-1} \longleftrightarrow \Gamma_0 = 7.2^{+56}_{-6.5} \times 10^{-10}\,\mathrm{s}^{-1}$$



$$\Gamma_{\rm si}(>p) \approx \Omega_{\rm B} \frac{m_{\rm e}}{m_{\rm p}} \frac{n_{\rm CR}(>p)}{n_{\rm H}} \frac{v_{\rm str}(>p)}{v_{\rm A}},$$

1LHAASO J1740+0948u: another example?

- Bow-shock pulsar wind nebula with magnetotail seen in X-ray
- Offset gamma-ray source in direction of tail, ~5 pc from pulsar, spin-down power: ~2e35 erg/s



Cao+2025, arXiv:2502.15447

- Would need a similar pitch angle scattering rate as Ter5, ~1e-10/s, but at higher energies, ~>100 TeV
- Might be possible given reduced cross-section of tail => larger particle density

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Summary

- The displaced TeV source associated to Terzan 5 may reveal pitch-angle isotropisation *in progress*
- This mechanism may operate in other objects

Extra Slides

Transport model

$$\frac{\partial f}{\partial t} = -\mu c \frac{\partial f}{\partial z} + \frac{\partial}{\partial \mu}\left[\left(1-\mu^2\right) K_\mu \frac{\partial f}{\partial \mu}\right] + \frac{m_e c}{t_{c,0}} \frac{1}{p^2} \frac{\partial}{\partial p}\left[p^2\left(1-\mu^2\right)\left(\frac{p}{m_e c}\right)^2 f\right] + \dot{N}\frac{dn}{dp}\delta(z)\Theta(\mu-\mu_0),$$

Transport model

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$$\mu = \cos\theta$$

Transport model

Pitch angle diffusion

$$\frac{\partial f}{\partial t} = -\mu c \frac{\partial f}{\partial z} + \frac{\partial}{\partial \mu}\left[\left(1-\mu^2\right) K_\mu \frac{\partial f}{\partial \mu}\right] + \frac{m_e c}{t_{c,0}} \frac{1}{p^2} \frac{\partial}{\partial p}\left[p^2\left(1-\mu^2\right)\left(\frac{p}{m_e c}\right)^2 f\right] + \dot{N}\frac{dn}{dp}\delta(z)\Theta(\mu-\mu_0),$$

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Continuous momentum loss (synchrotron)

Transport model

Pitch angle diffusion

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$$\mu = \cos\theta$$

Continuous momentum loss

Source term

Energetics?

- $L_{curv} \sim 5 \, . \, 10^{35}$ erg/s
- $L_{IC} \sim 5 \, . \, 10^{34}$ erg/s
- $\dot{E}_{\rm s.d.} \gtrsim 10^{37}$ erg/s …aggregated spin-down power 21 MSPs

Energetics?

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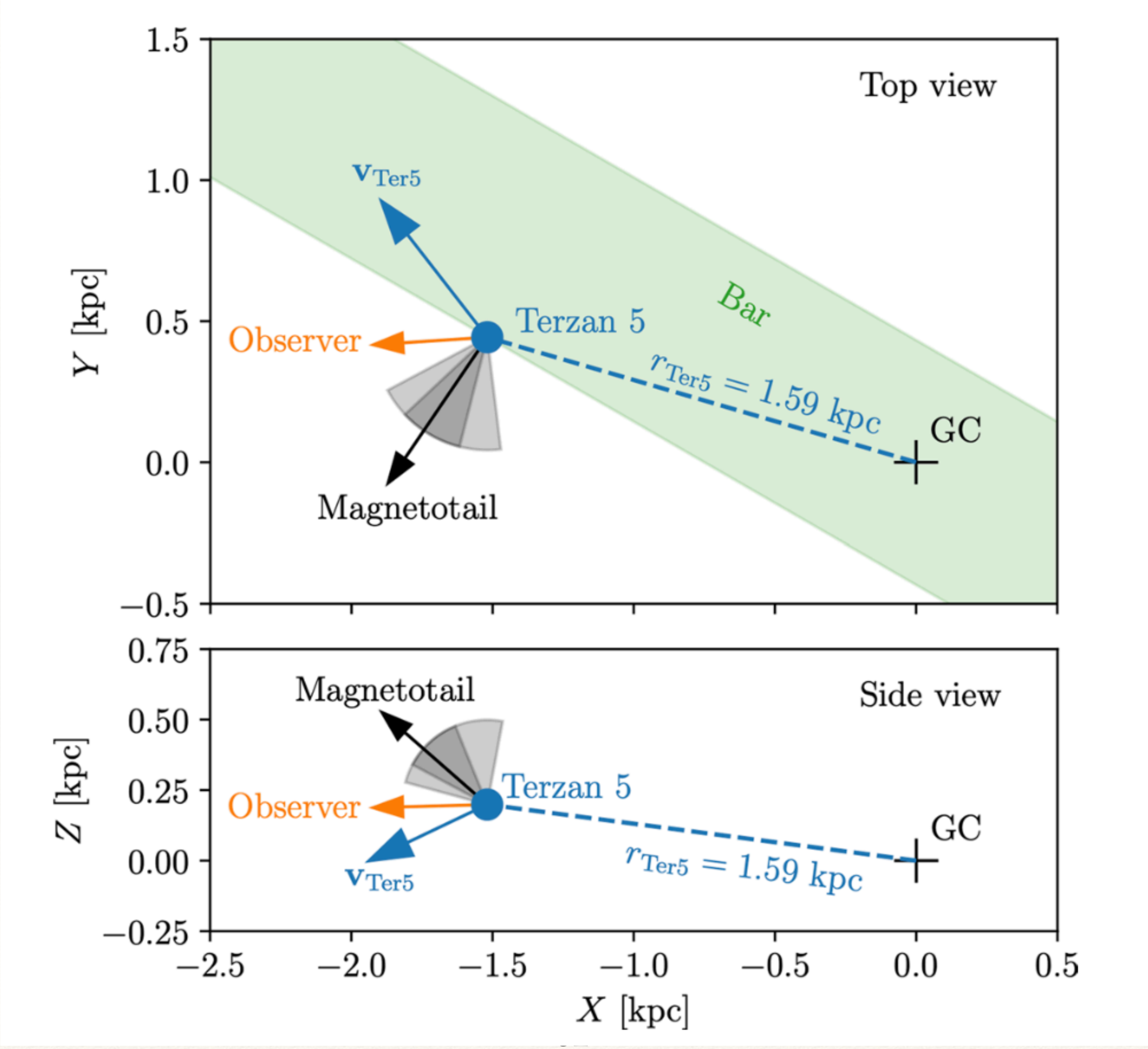
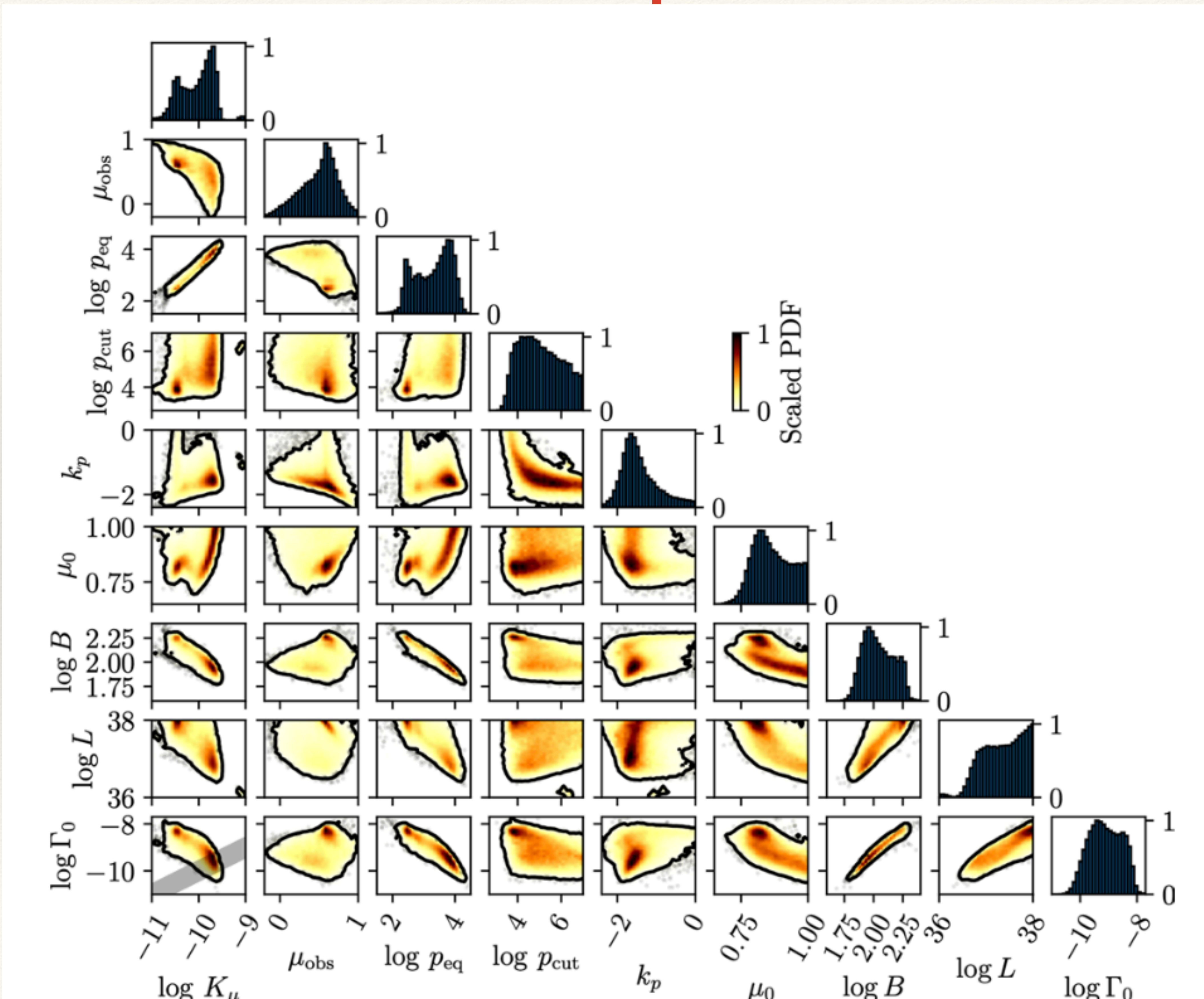
✓

Geometry



Top view
Bar
Terzan 5
Observer
Magnetotail
GC
$\mathbf{v}_{\mathrm{Ter5}}$
$r_{\mathrm{Ter5}} = 1.59$ kpc
Side view
Y [kpc]
Z [kpc]
X [kpc]
1.5
1.0
0.5
0.0
−0.5
0.75
0.50
0.25
0.00
−0.25
−2.5
−2.0
−1.5
−1.0
0.5

Corner plot

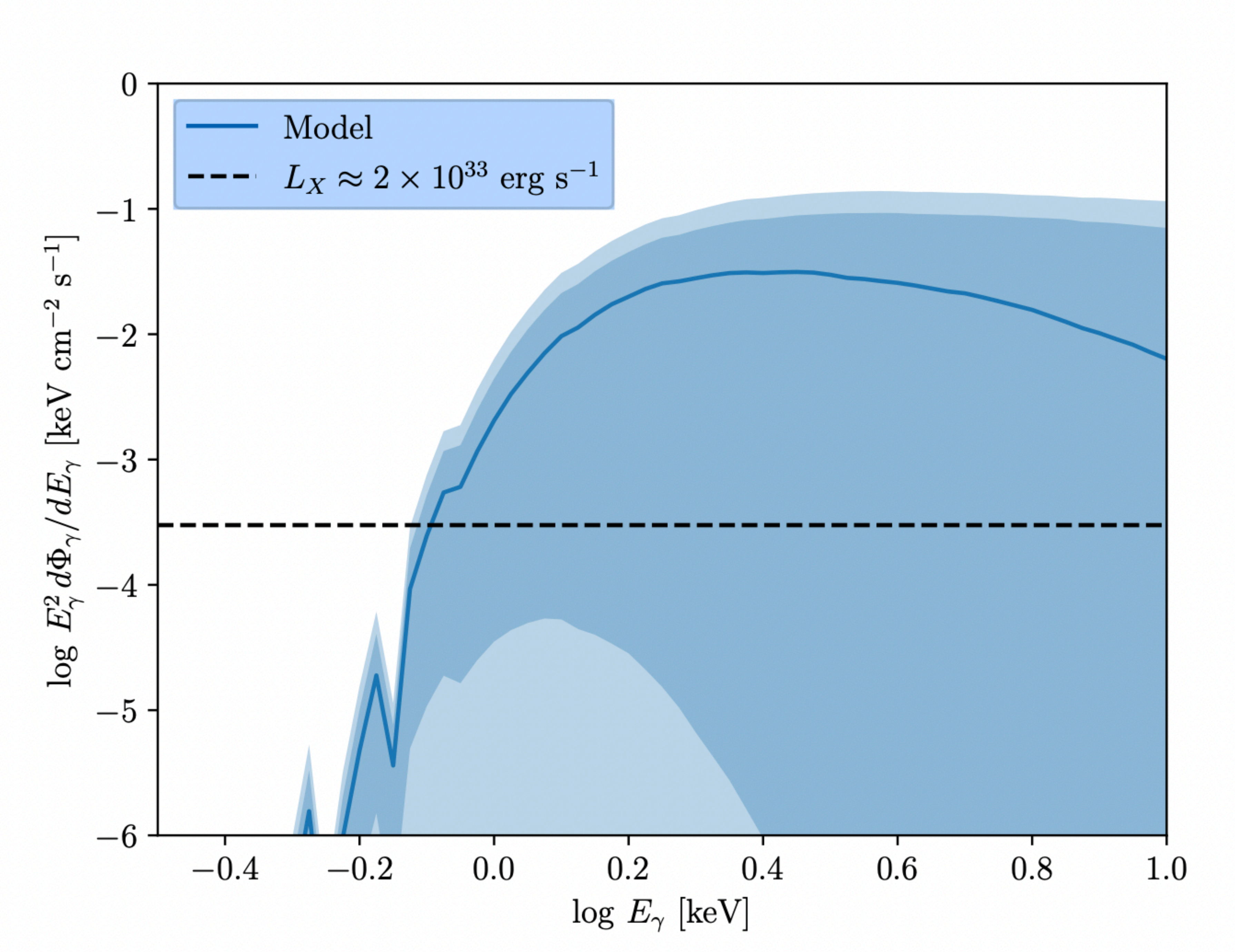


Scaled PDF
μ_{obs}
$\log\ p_{eq}$
$\log\ p_{cut}$
k_p
μ_0
$\log B$
$\log L$
$\log \Gamma_0$
$\log\ K_\mu$

Marginal posteriors for model parameters

Quantity	Unit	Percentiles 2.28	15.89	50	84.13	97.72
$\chi^2_{\rm red}$	-	1.71	1.96	2.14	2.42	2.89
$\log K_\mu$	s^{-1}	−10.66	−10.44	−9.97	−9.70	−9.59
$\log p_{\rm eq}$	GeV/c	2.34	2.60	3.40	3.87	4.14
$\log p_{\rm cut}$	GeV/c	3.62	4.07	5.00	6.21	6.88
k_p	-	−2.11	−1.81	−1.51	−0.95	−0.22
μ_0	-	0.74	0.80	0.86	0.95	0.99
$\mu_{\rm obs}$	-	−0.06	0.24	0.54	0.71	0.88
$\log B$	μG	1.82	1.91	2.03	2.19	2.27
$\log L$	erg s^{-1}	36.59	36.89	37.39	37.83	37.98
$\log \Gamma_0$	s^{-1}	−10.18	−9.71	−9.14	−8.51	−8.20
$\log E_{\rm sy}$	keV	−3.48	−2.93	−1.42	−0.55	−0.11

X-ray synchrotron?



Extended Data Figure 3 | Model-predicted synchrotron spectrum. The blue line shows the median synchrotron spectrum as a function of photon energy E_γ predicted by our best-fitting model, and the shaded blue bands around it show the 68% and 95% confidence intervals. The quantity shown includes the effects of interstellar absorption between Terzan 5 and the Sun, assuming a hydrogen column[28] $N_H = 2 \times 10^{22}$ cm^{-2}; the sharp features visible below 1 keV correspond to absorption edges. The black dashed line is an approximate limit corresponding to $L_X = 4\pi d^2_{\rm Ter5} E^2_\gamma (d\Phi_\gamma/dE_\gamma) = 2 \times 10^{33}$ erg s^{-1}, the X-ray luminosity estimated by ref. [28].

Emission from acceleration region?

$$L_{\rm acc} \approx \frac{E_e}{t_{\rm IC}} \approx \frac{t_{\rm esc}}{t_{\rm IC}} L_{\rm CR}$$

$$t_{\rm IC} = \frac{3 m_e c}{4\gamma\sigma_T a_R T_{\rm CMB}^4}$$

$$t_{\rm esc} \approx \frac{R_{\rm acc}^2}{\eta K_{\rm Bohm}} = \frac{3eBR_{\rm acc}^2}{\eta\gamma m_e c^3}$$

$$R_{\rm acc} = \xi \frac{\gamma_{\rm cut} m_e c^2}{eB} = 1.1 \times 10^{-3} p_{\rm cut} B_2^{-1} \xi \ {\rm pc},$$

$$L_{\rm acc} \approx \frac{4\sigma_T a_R T_{\rm CMB}^4 \gamma_{\rm cut}^2 \xi^2}{eB\eta} L_{\rm CR} = 8.9 \times 10^{-7} p_{\rm cut,5}^2 B_2^{-1} \frac{\xi^2}{\eta} L_{\rm CR}.$$

This implies a γ-ray flux from the accelerator region that is a factor of ~ **100 smaller** than the measured energy-integrated flux of the displaced γ-ray emission observed by HESS in the TeV band

Maximum energy?

- $E_{e,IC}$ ~ 100 TeV (Thomson regime off CMB)
- $$E_{\rm e,max} \sim \frac{70\ \rm TeV}{\eta}\sqrt{f_B\ \dot{E}_{\rm wind,37}\ v_{\rm T5,2}}$$ [Bykov+2017]

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$$v_{\rm T5} \equiv v_{\rm T5,2}\ 100\ \rm km/s$$

$$\dot{E}_{\rm wind} \equiv \dot{E}_{\rm wind,37}\ 10^{37}\ \rm erg/s$$

Maximum energy?

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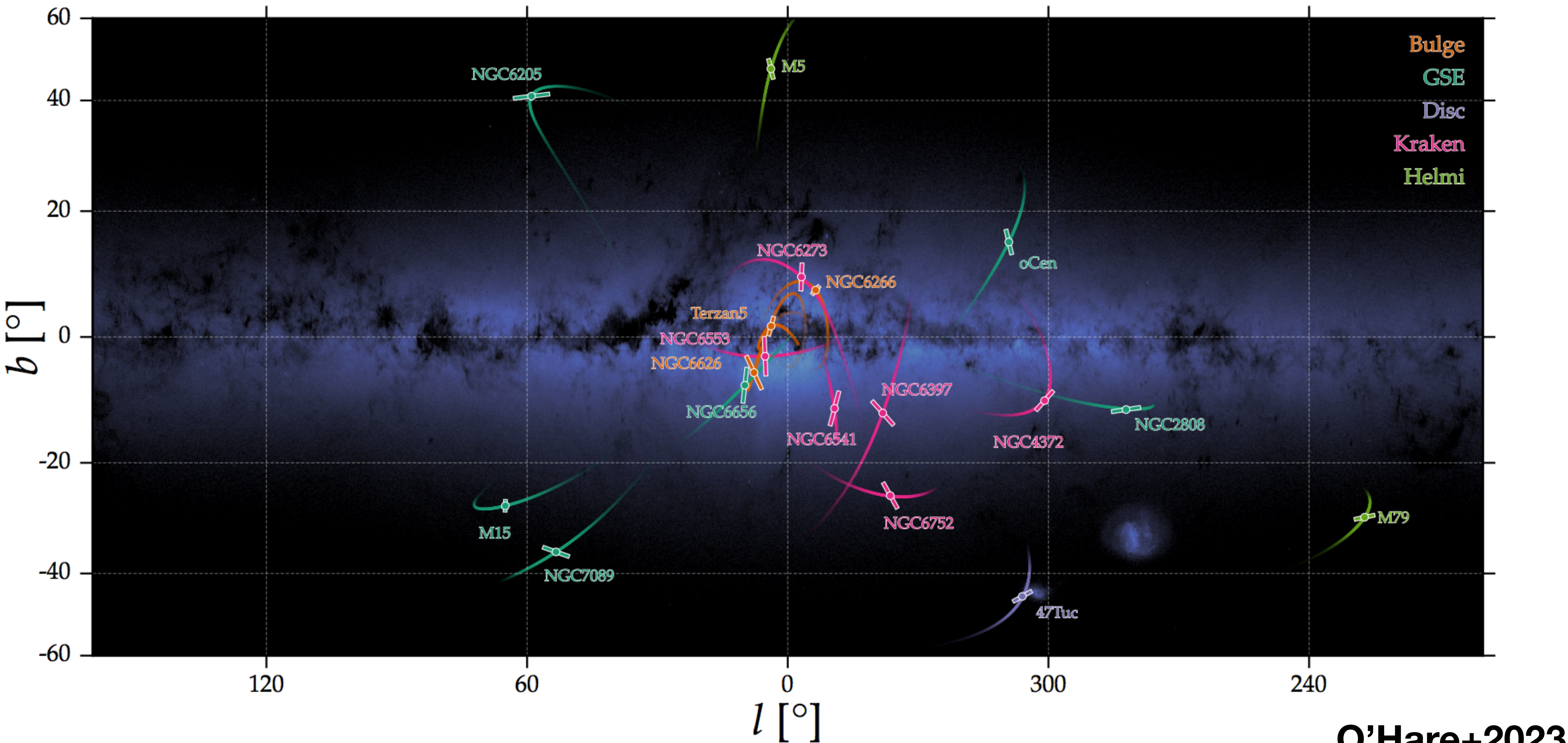
✔

Characteristic magnetic field

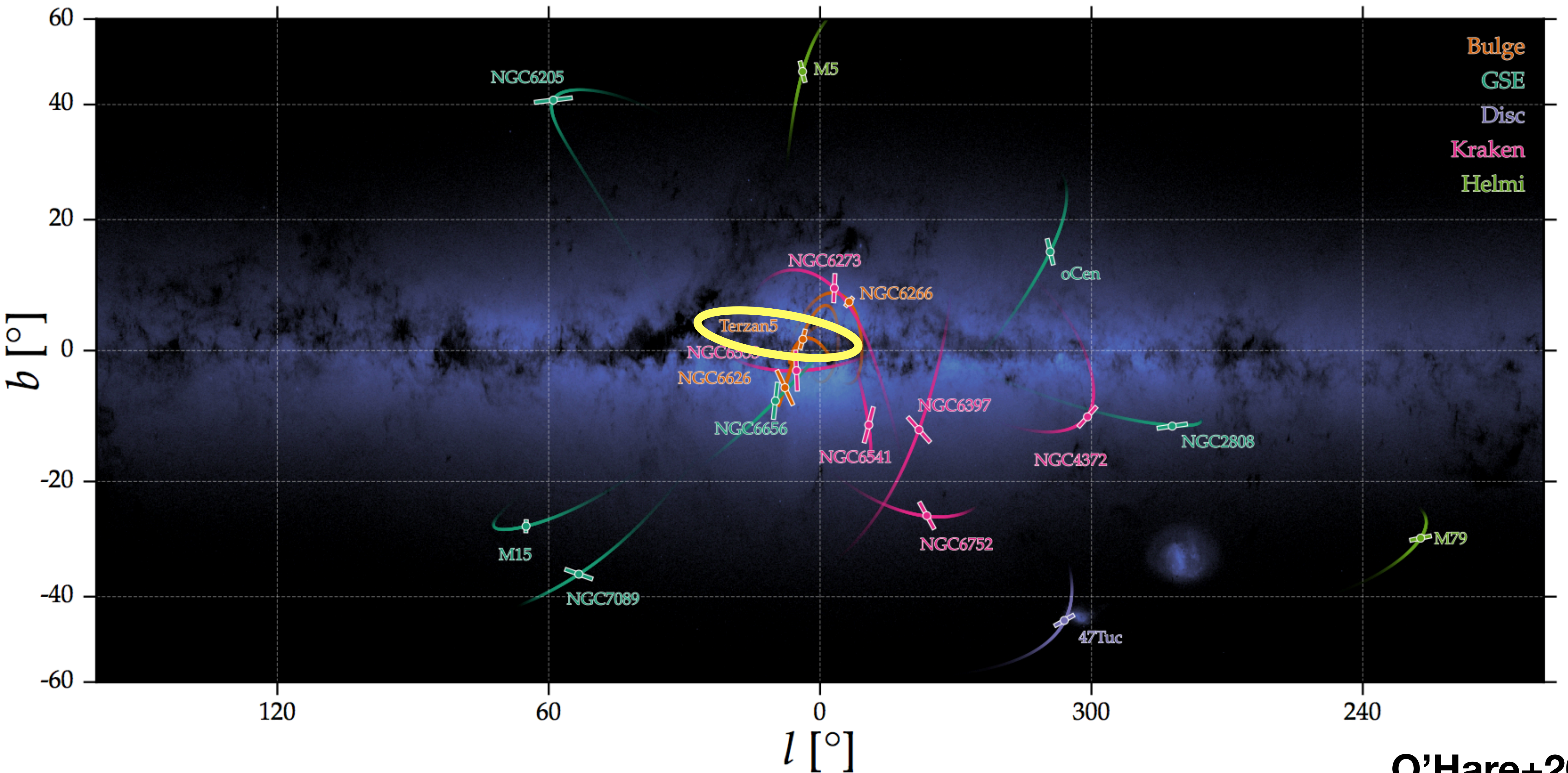
$$B \approx v_c\sqrt{4\pi\mu_H n_H} = 54(v_c/100\,\mathrm{km\,s^{-1}})(n_H/1\,\mathrm{cm^{-3}})^{1/2}\,\mu\mathrm{G}$$

Terzan 5 Globular Cluster



O'Hare+2023

Terzan 5 Globular Cluster



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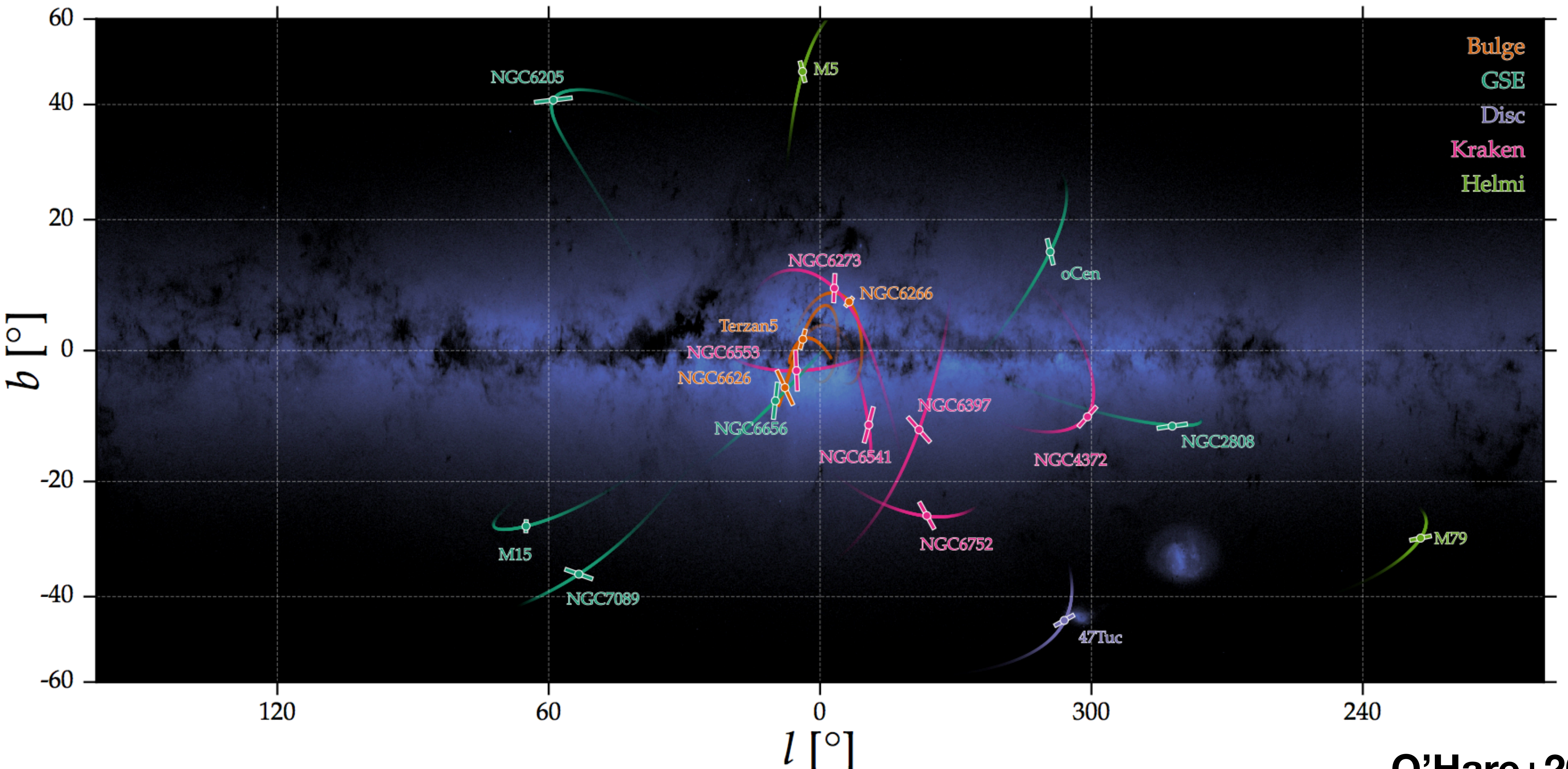

O'Hare+2023