TMEX 2025 - Qhy Nhon 2025

MSP TeV emisison in globular clusters

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

Roland Crocker

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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

Why should you care?

- Cosmic rays are (mostly) highly relativistic particles that move at ~speed of light
- But the Galaxy "traps" cosmic rays such that, *at a population level,* they escape the midplane at a (energy-dependent) effective velocity $v_{drift} << c$
- At a certain level of approximation, cosmic ray transport can be phenomenologically described as a random walk (with an energy-dependent mfp), i.e., ***diffusion***
- Why is this?

Why do cosmic rays diffuse?

- One idea: (effective) CR spatial diffusion arises from pitch angle scattering of the CRs on magnetic waves of a similar size as the gyro-radius of the CRs
- Another idea: under certain circumstances (effective drift of the population faster than the Alfven speed + sufficient number density), the CRs themselves will excite Alfven waves on the gyro-radius scale

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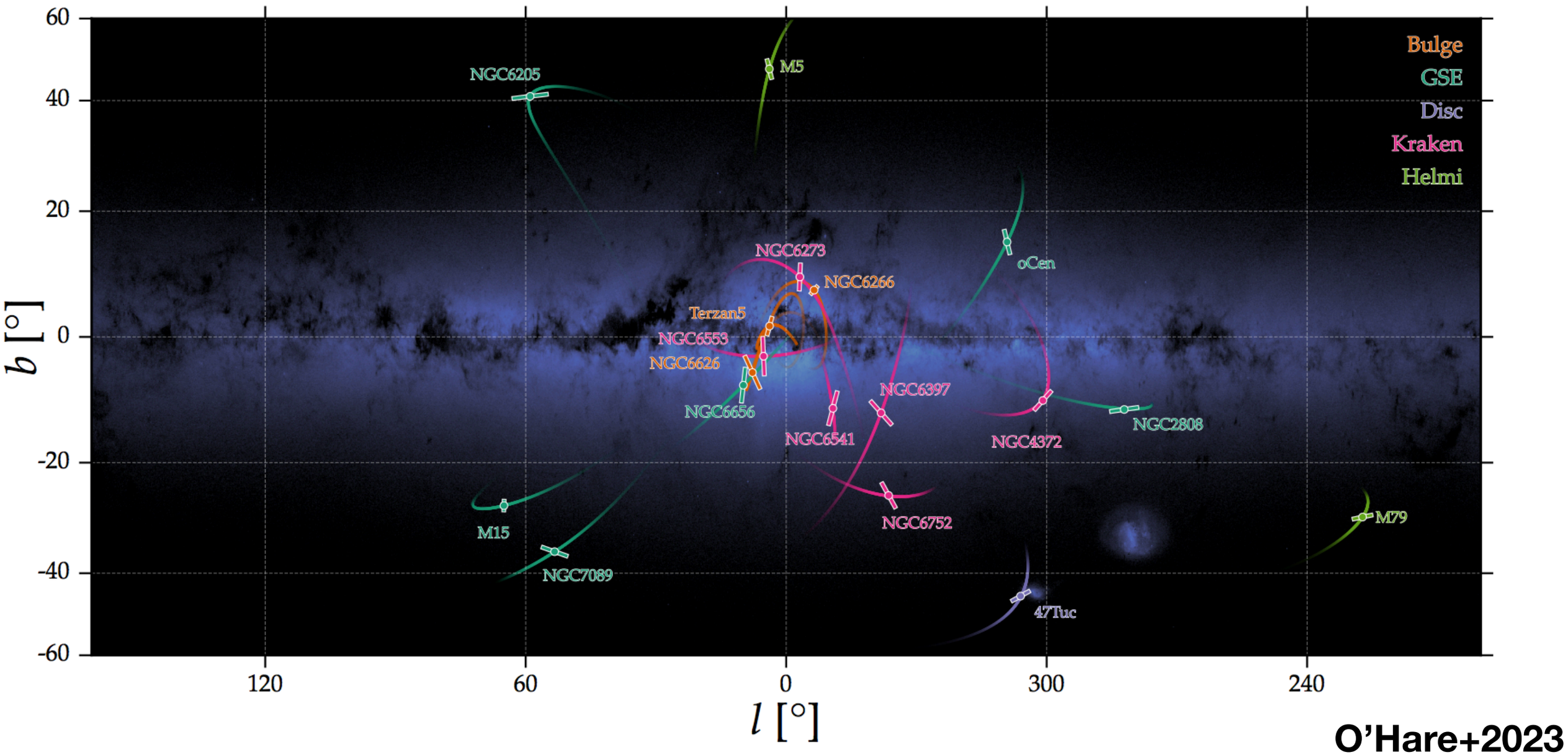
The idea: the high-energy phenomenology of Terzan 5 shows this process in action

Terzan 5 Globular Cluster

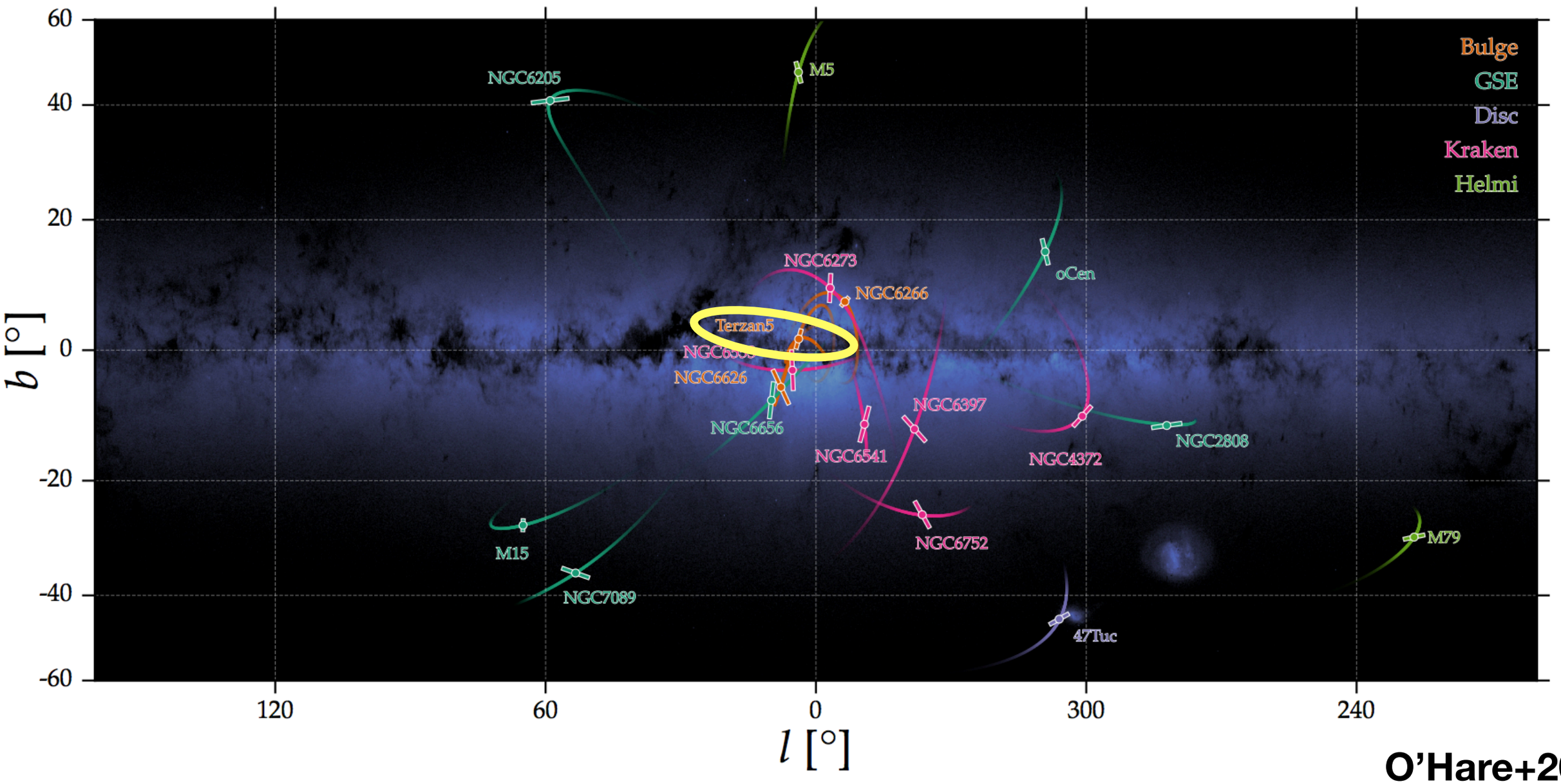
- One of the Milky Way's most massive GCs
- Largest (radio identified) MSP population of any GC
- Brightest gamma-ray (GeV band) GC
- Located in the inner Galaxy, only 200 pc above plane; one of the Galactic bulge GCs

Terzan 5 Globular Cluster



O'Hare+2023

Terzan 5 Globular Cluster



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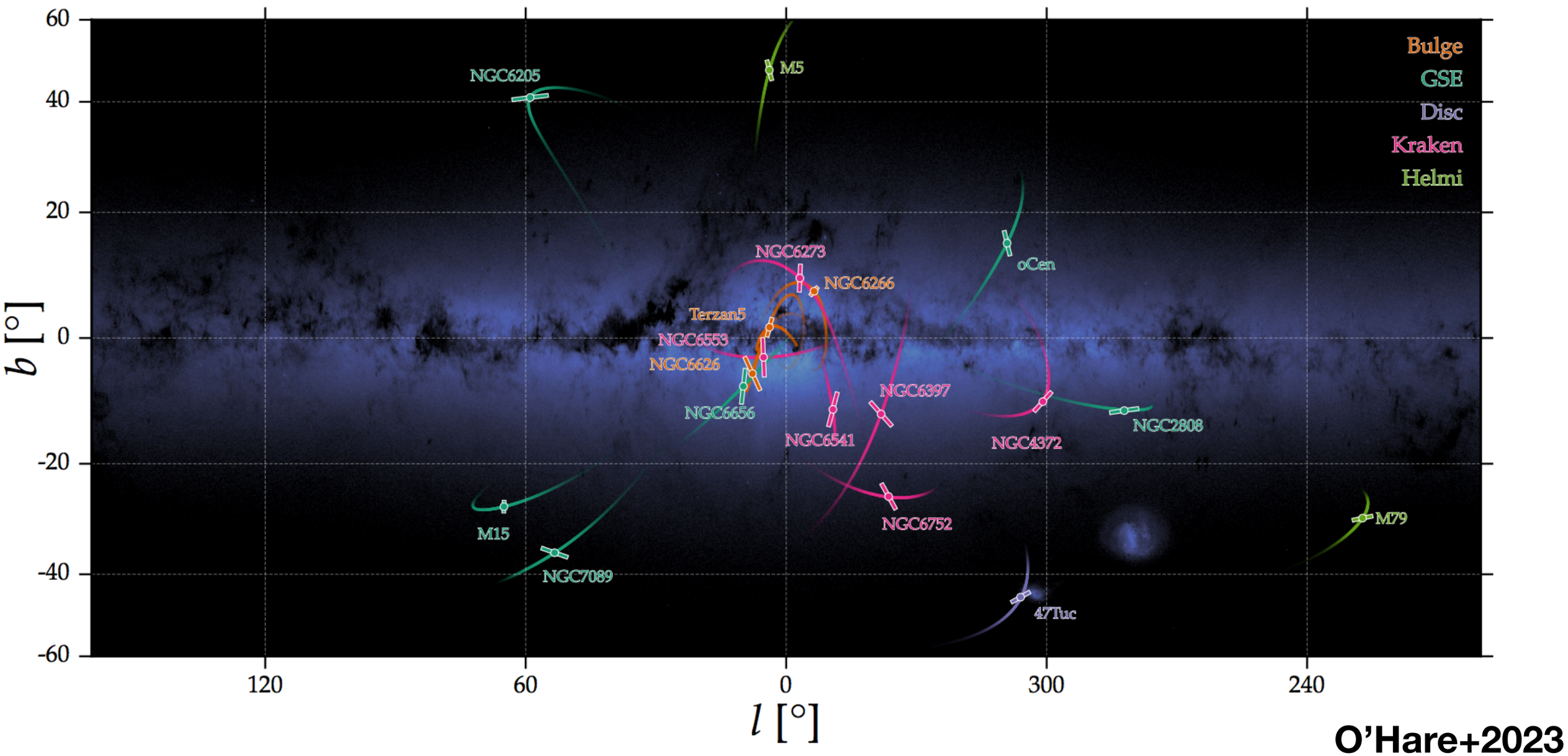

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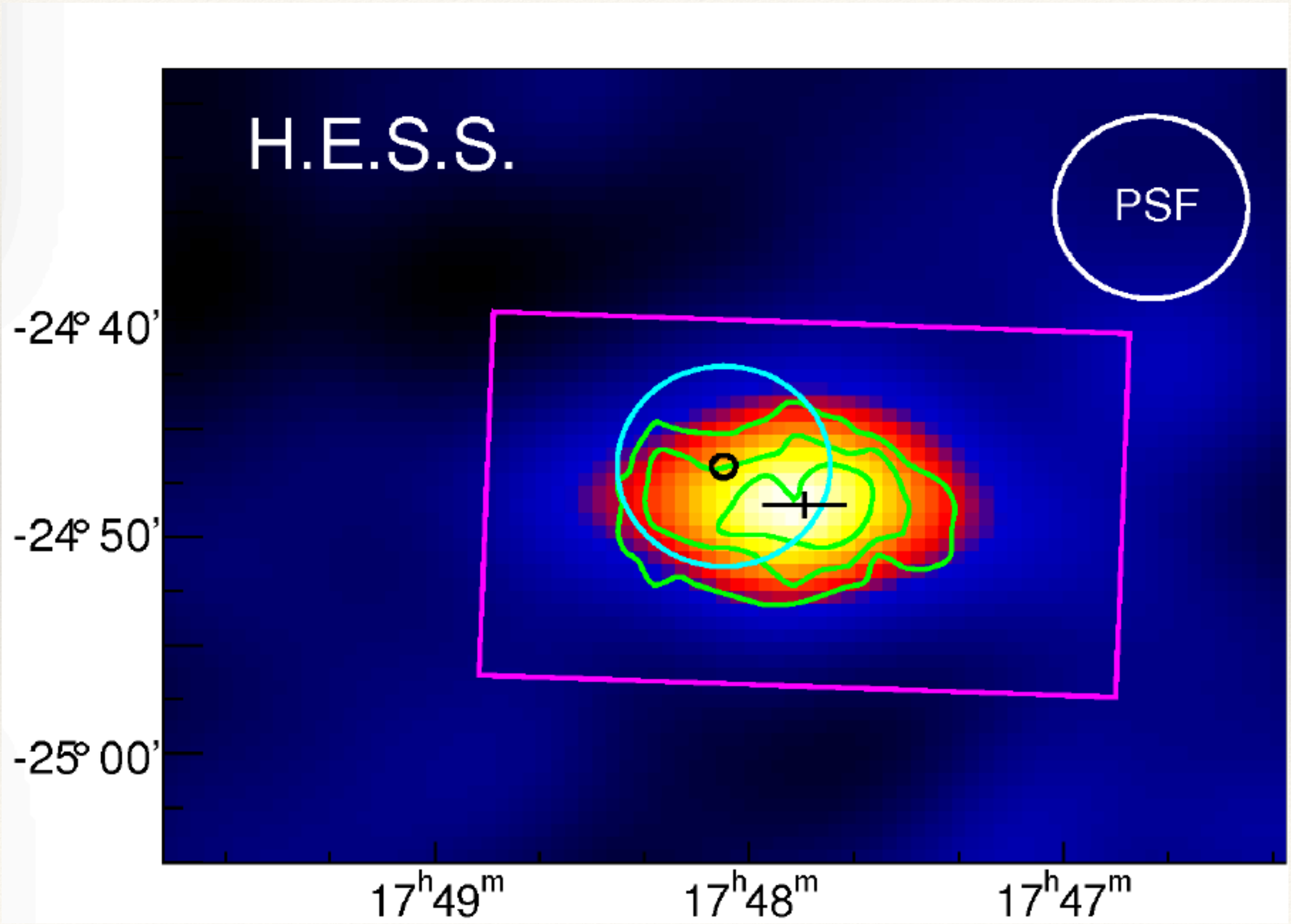
Terzan 5 as high energy source

- 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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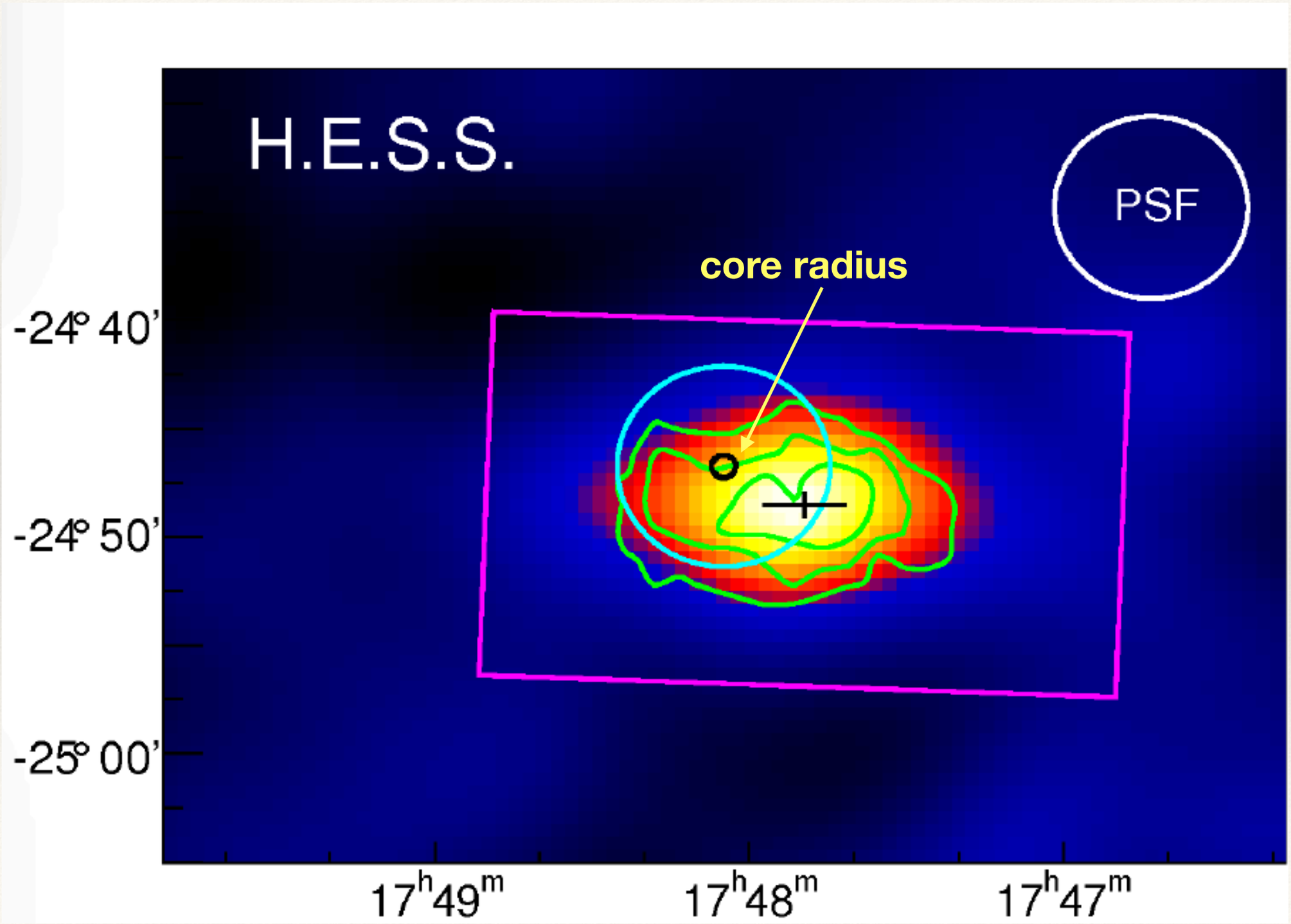

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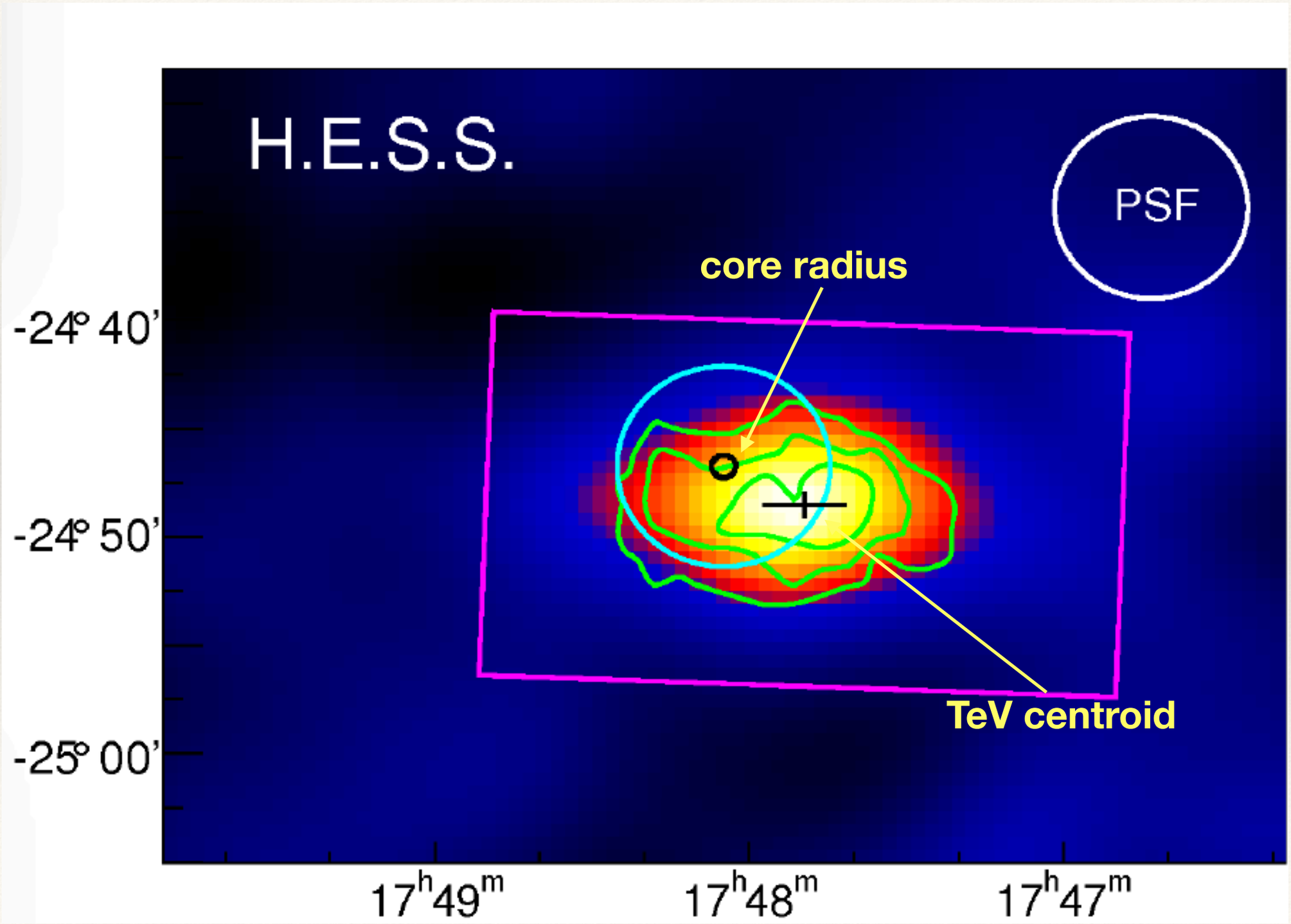

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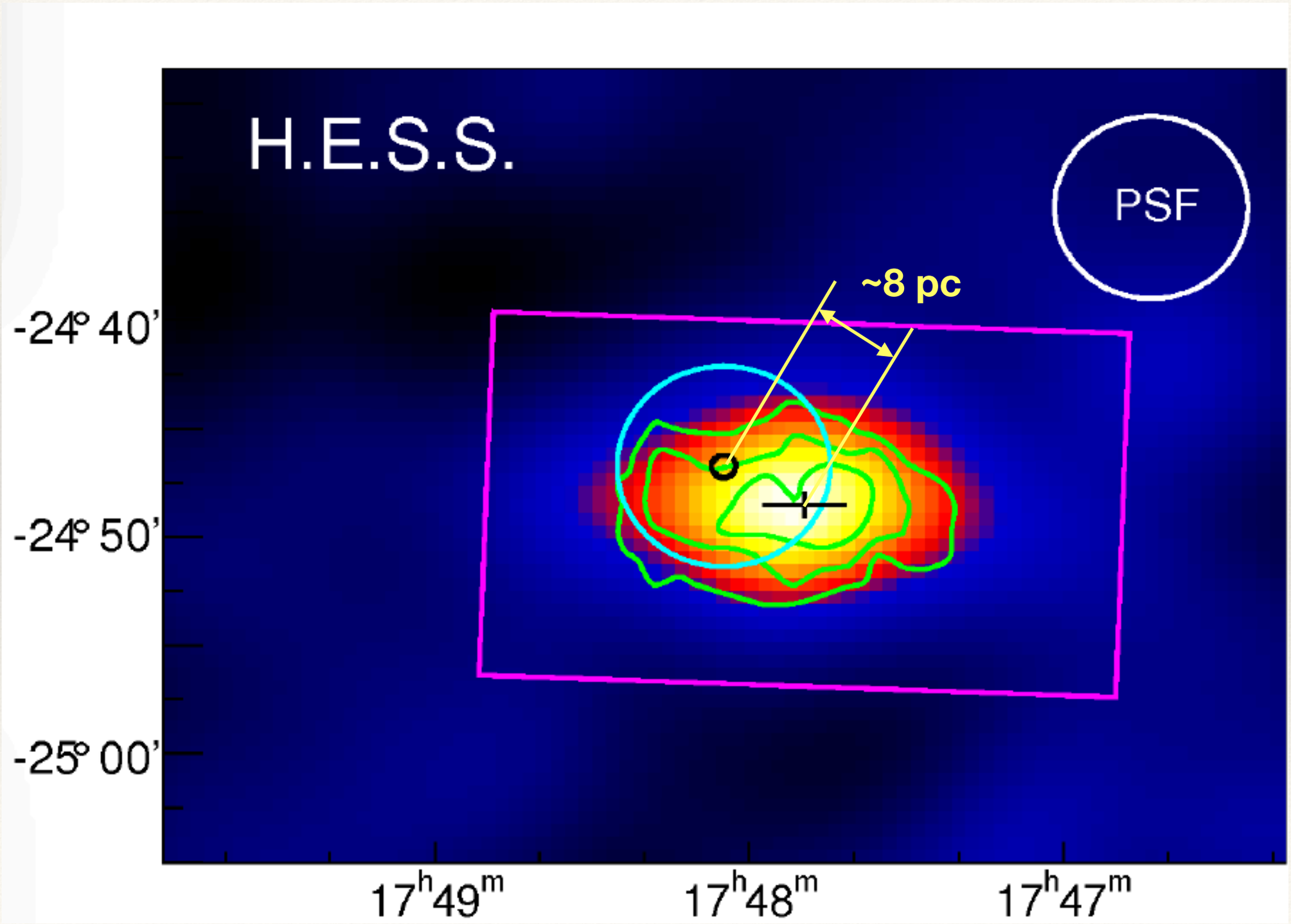
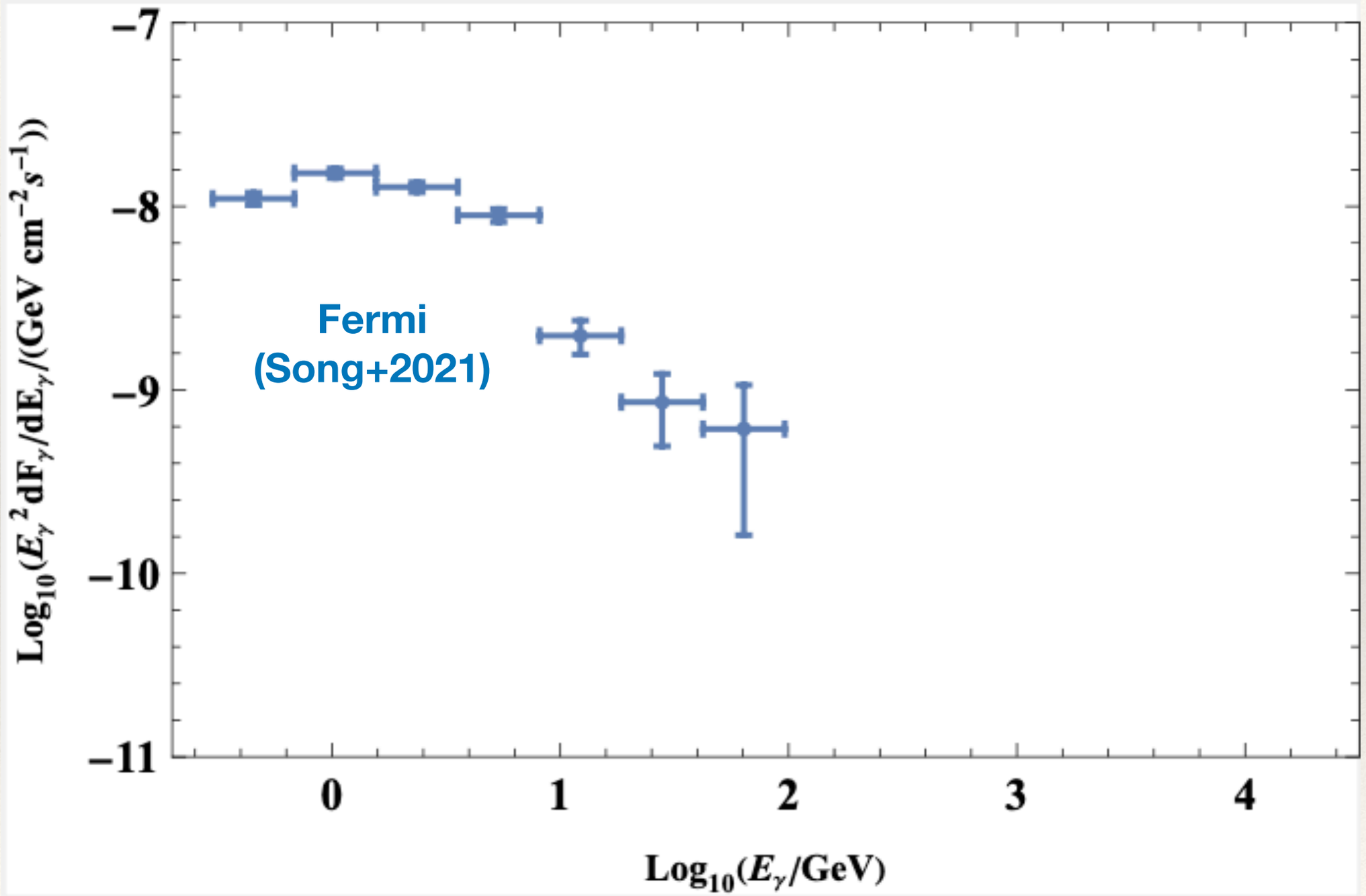


Is the TeV source *really* associated to Ter 5?

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

Spectrum Ter 5



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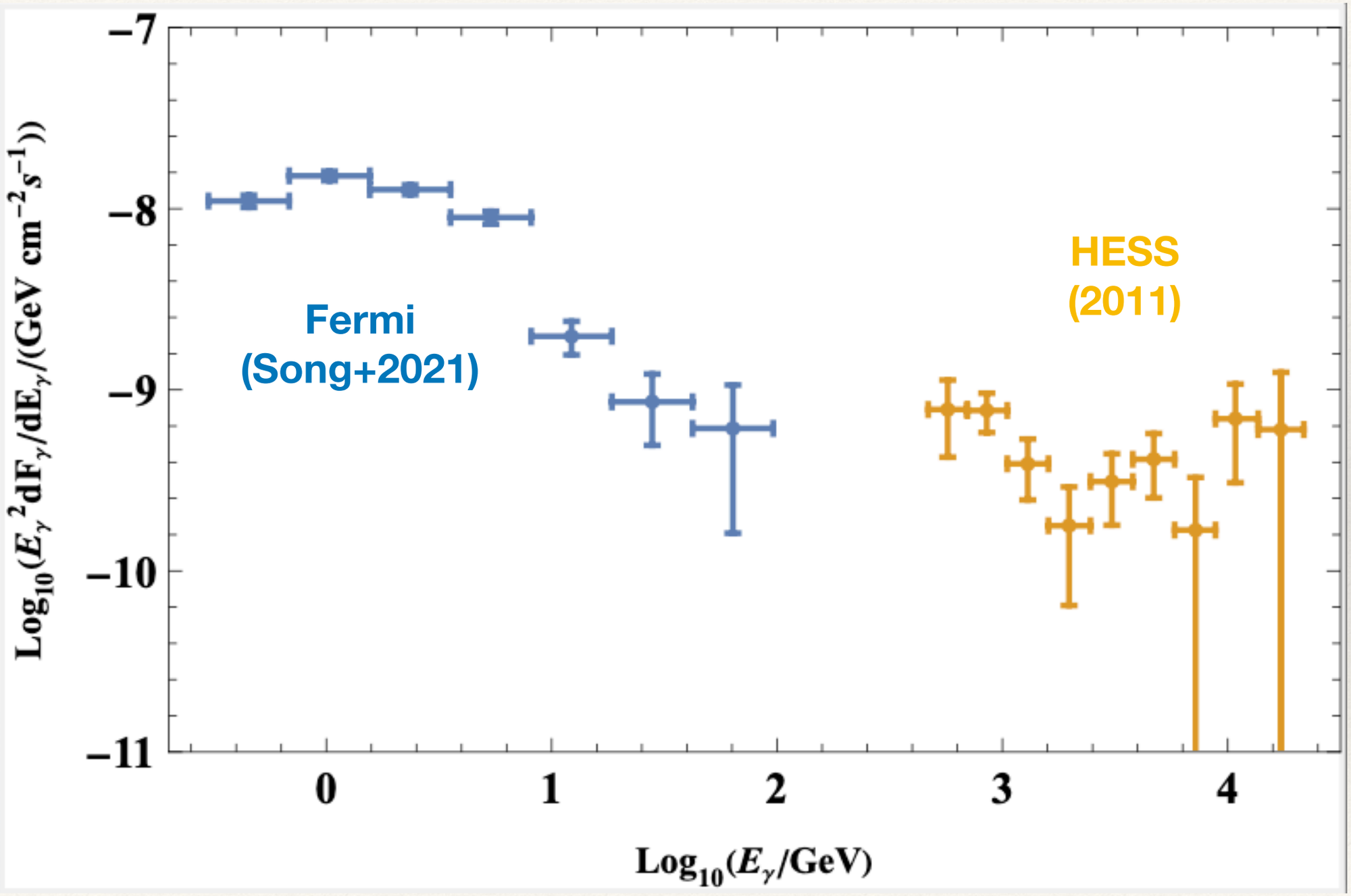
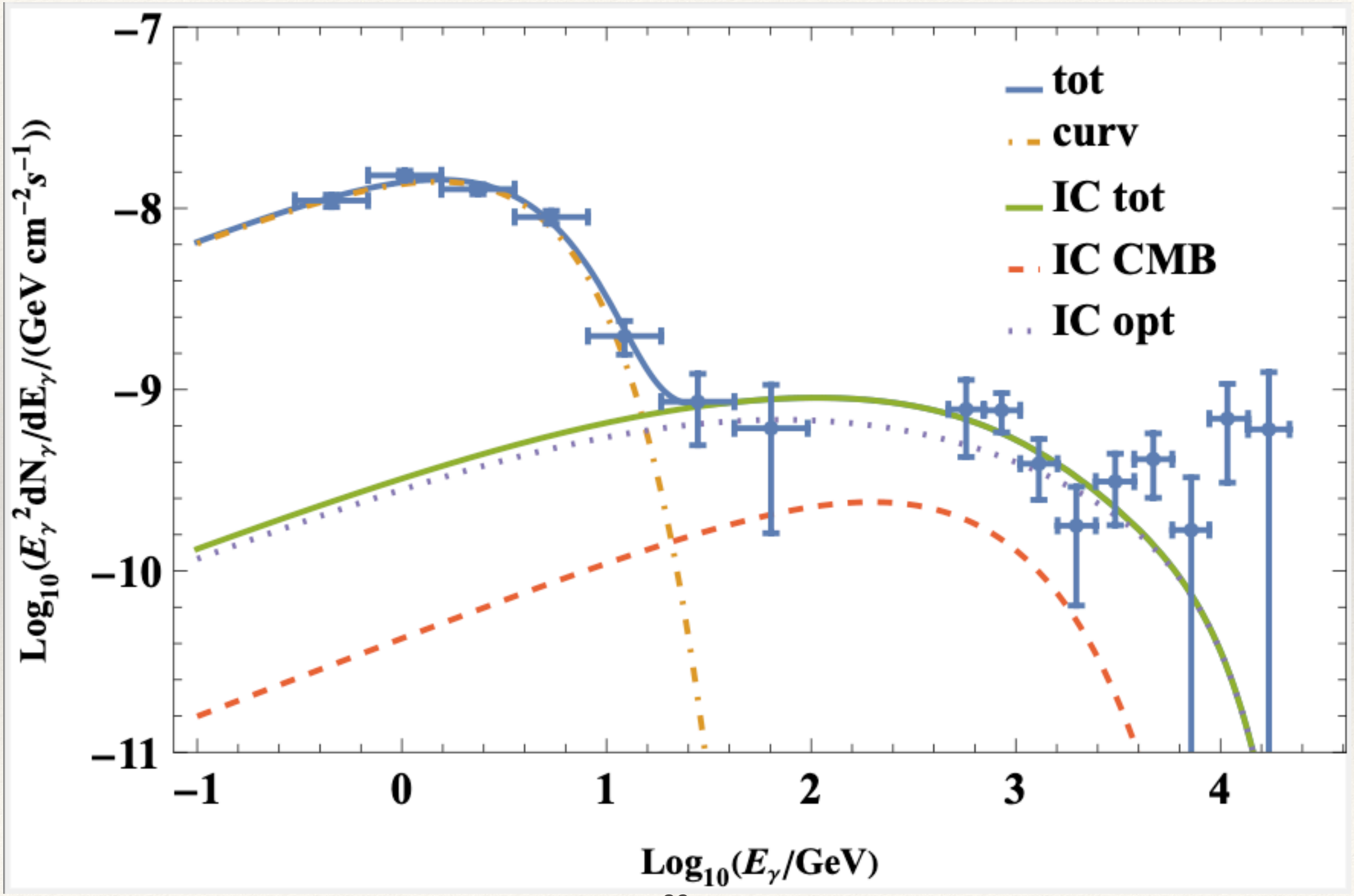


Is the TeV source really associated to Ter 5?

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

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

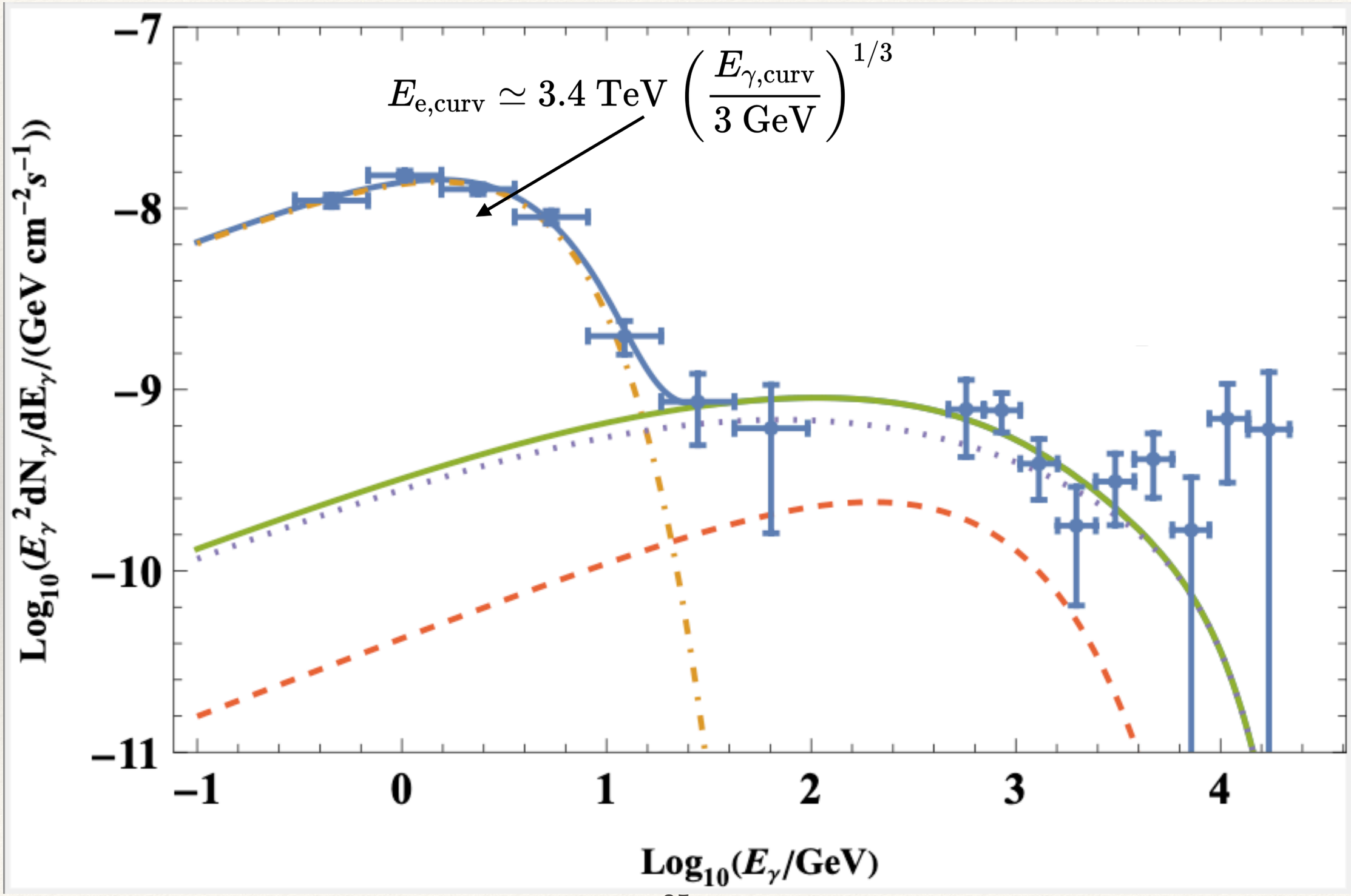
Spectrum well fit as curvature radiation + inverse Compton



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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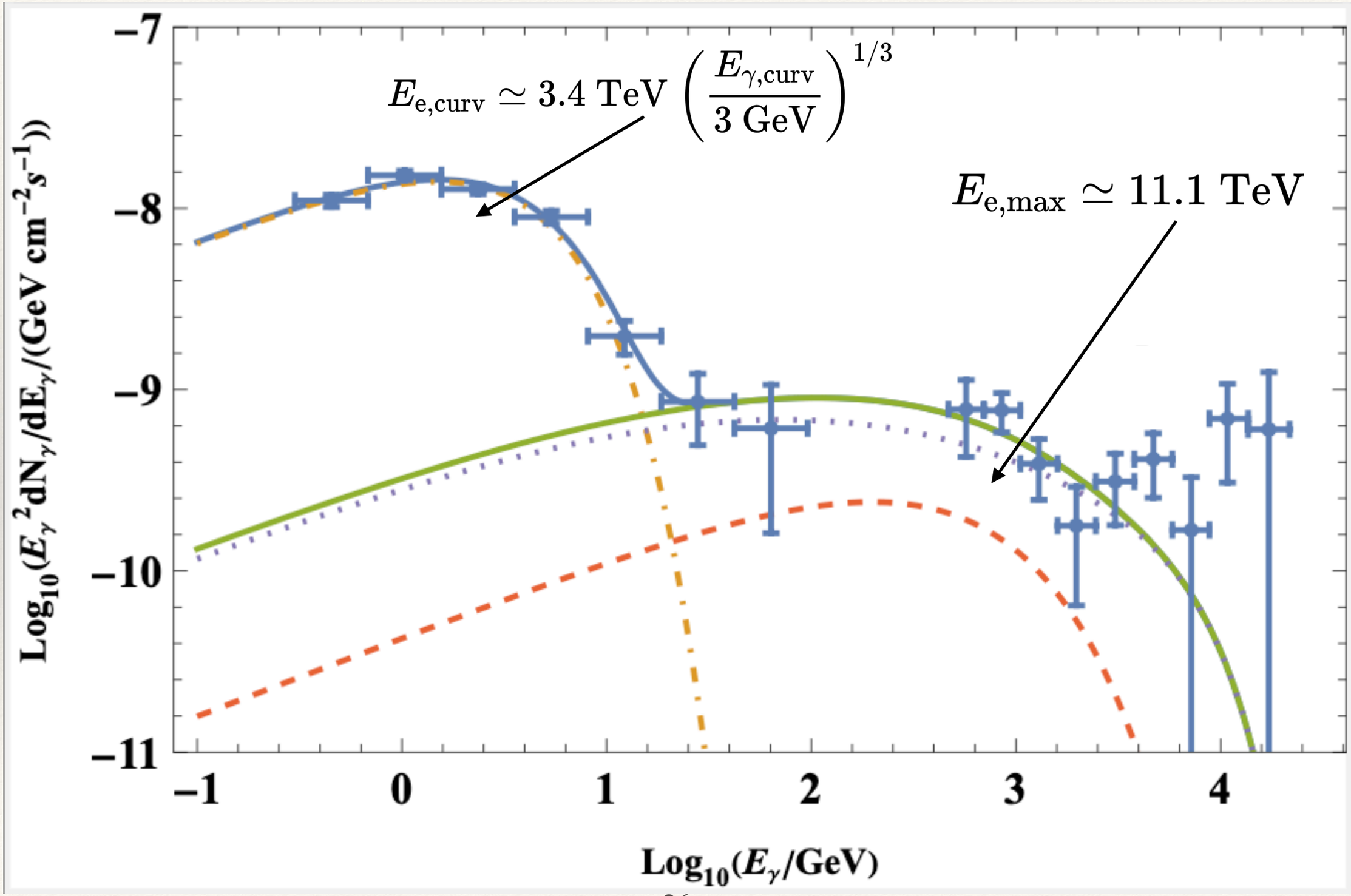

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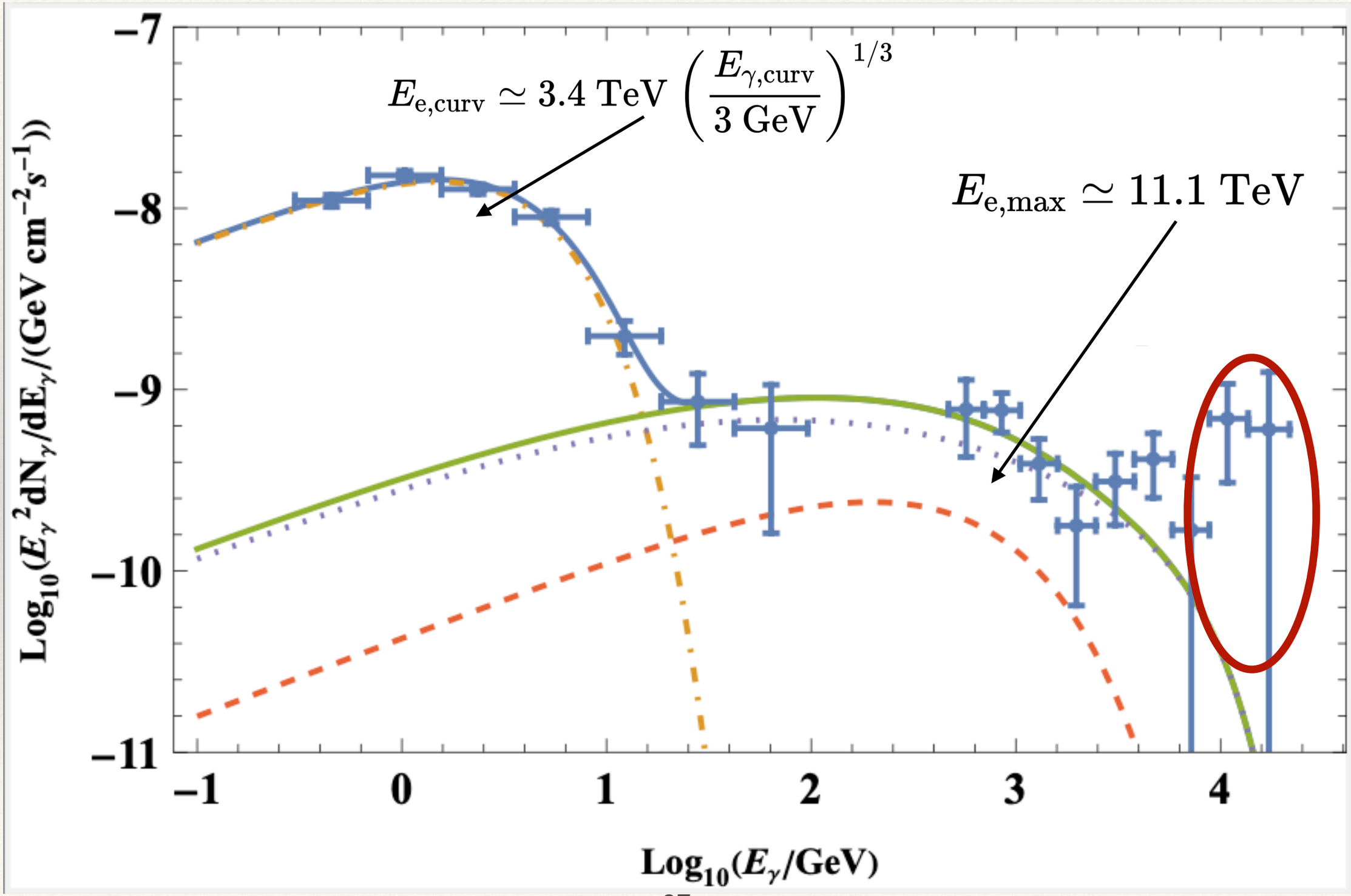

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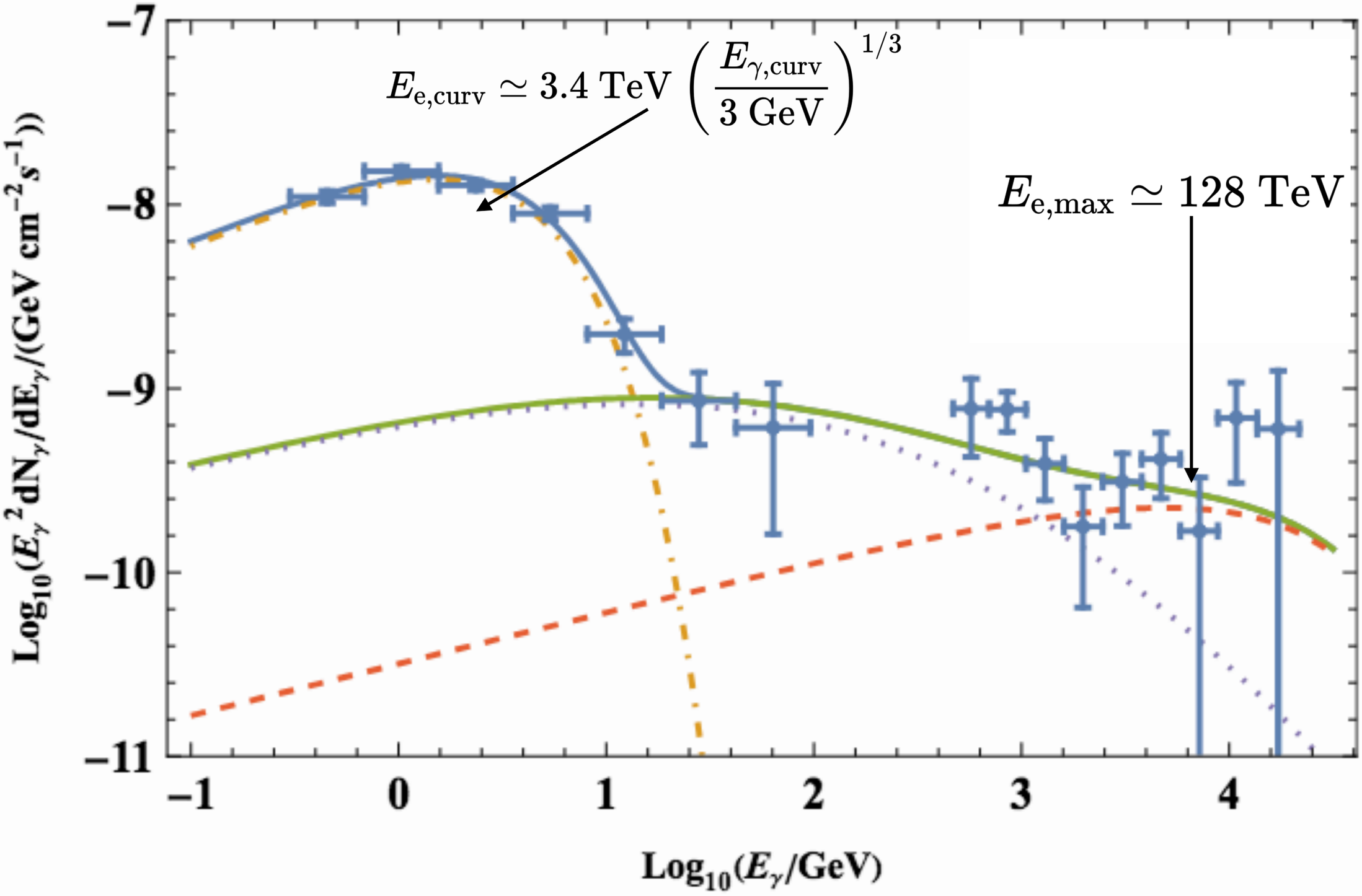

Broad Scenario

- 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 ≳ 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

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

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

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

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Stand-off distance to contact discontinuity

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

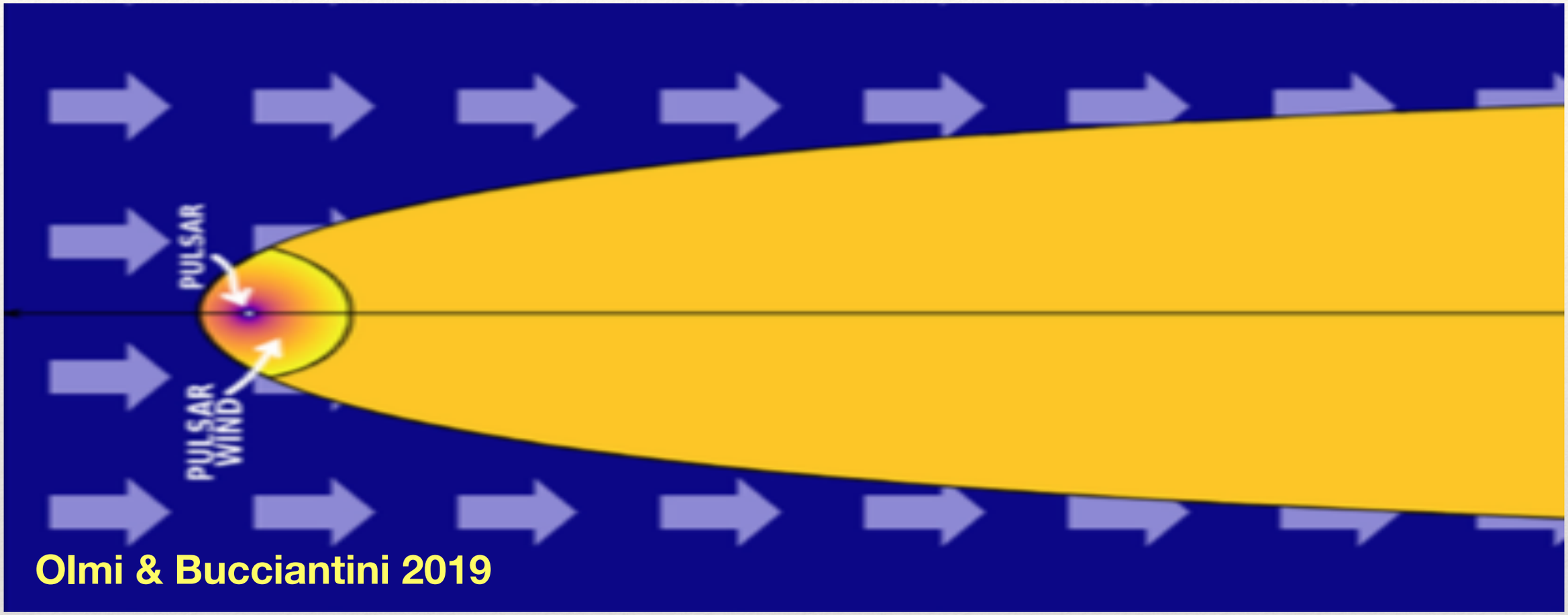
- $R_{SO} \ll R_{offset} \sim 7$ pc
- *Why doesn't the TeV centroid correspond to the acceleration region?*

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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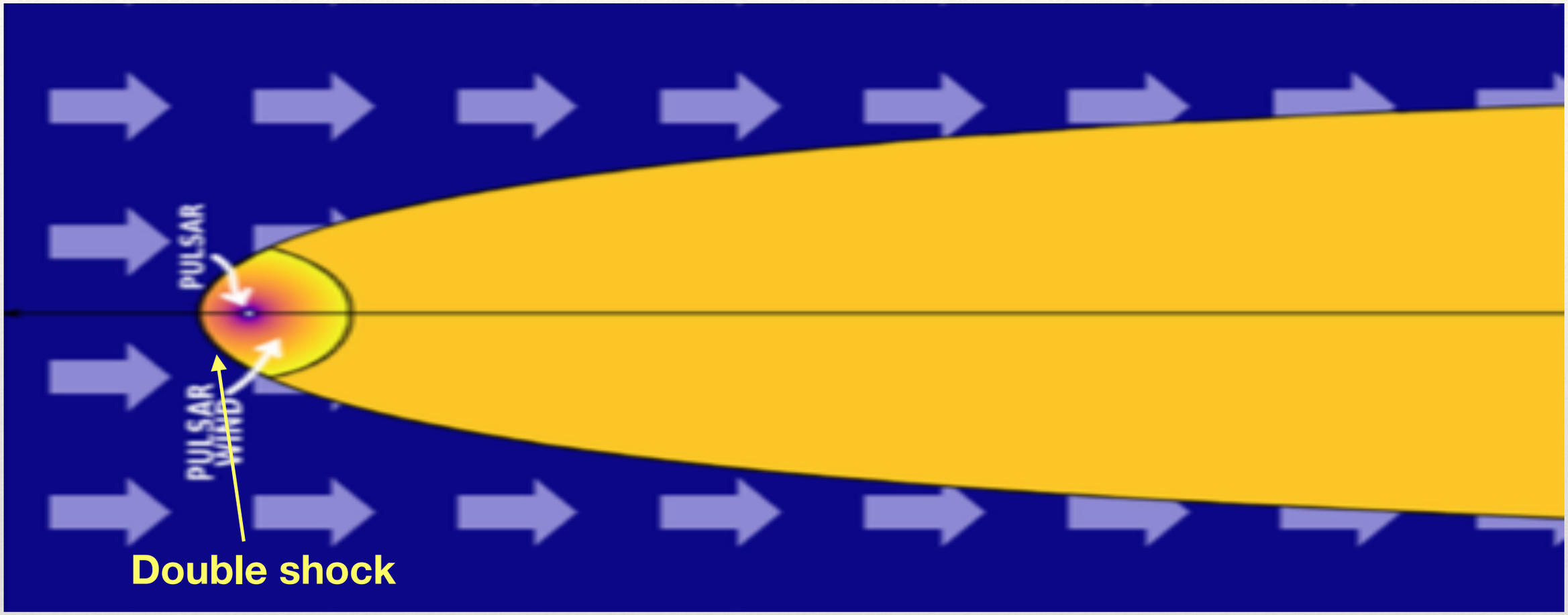

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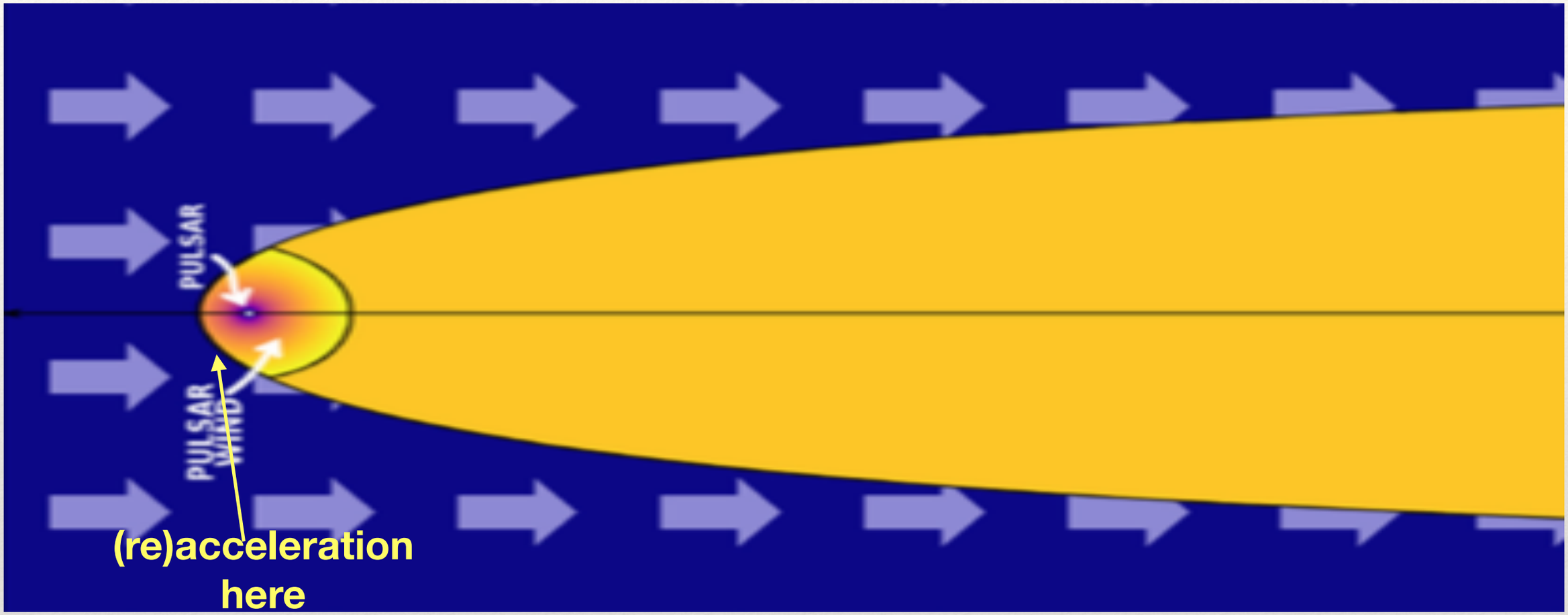

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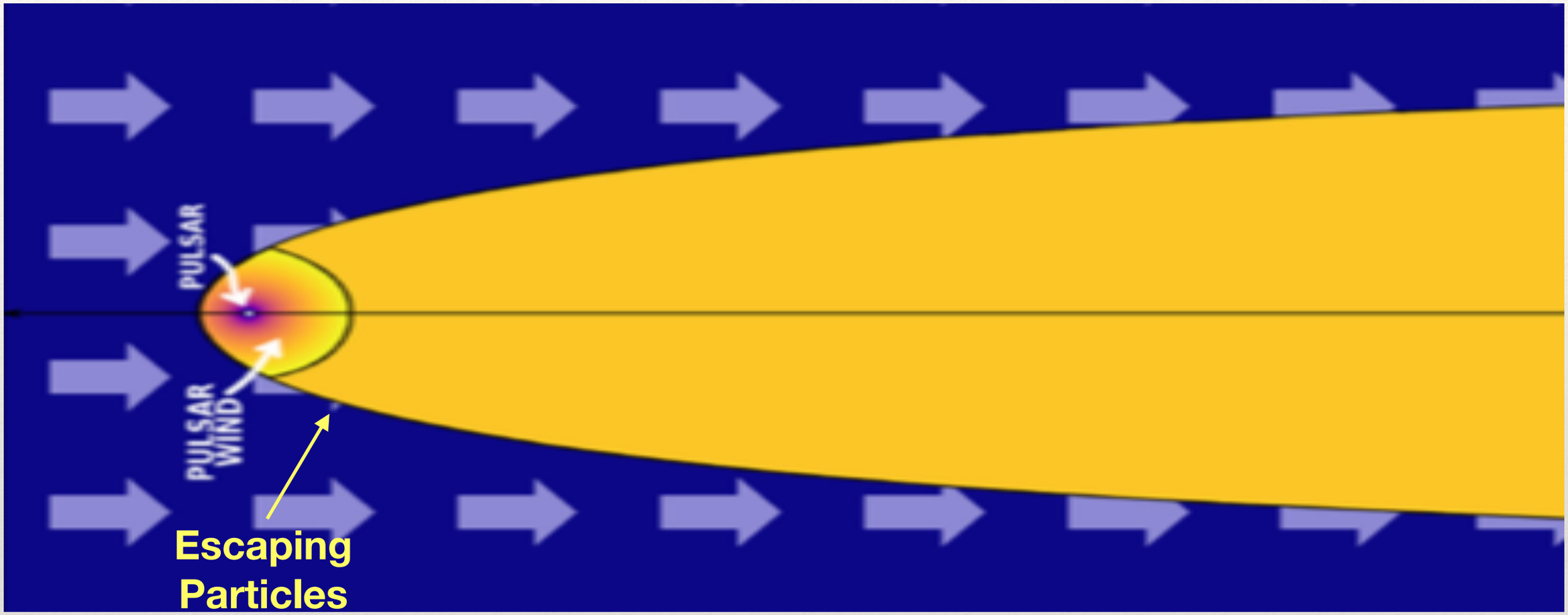

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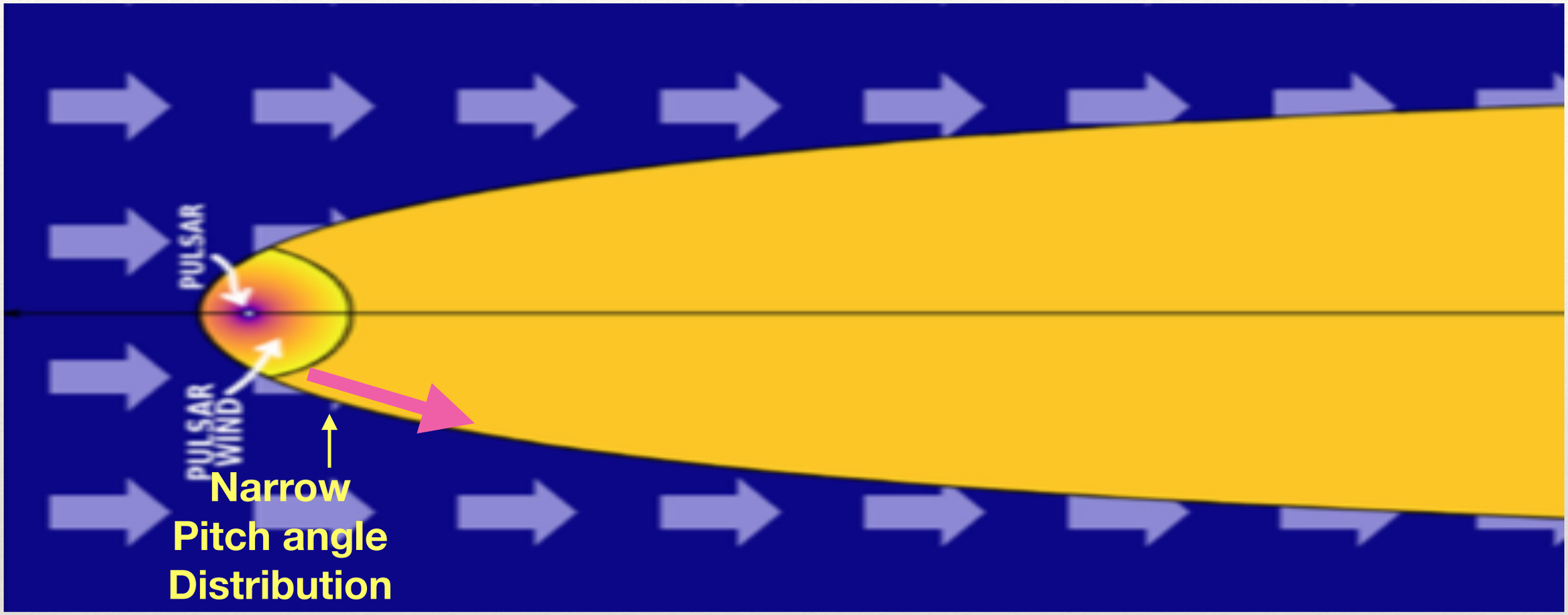

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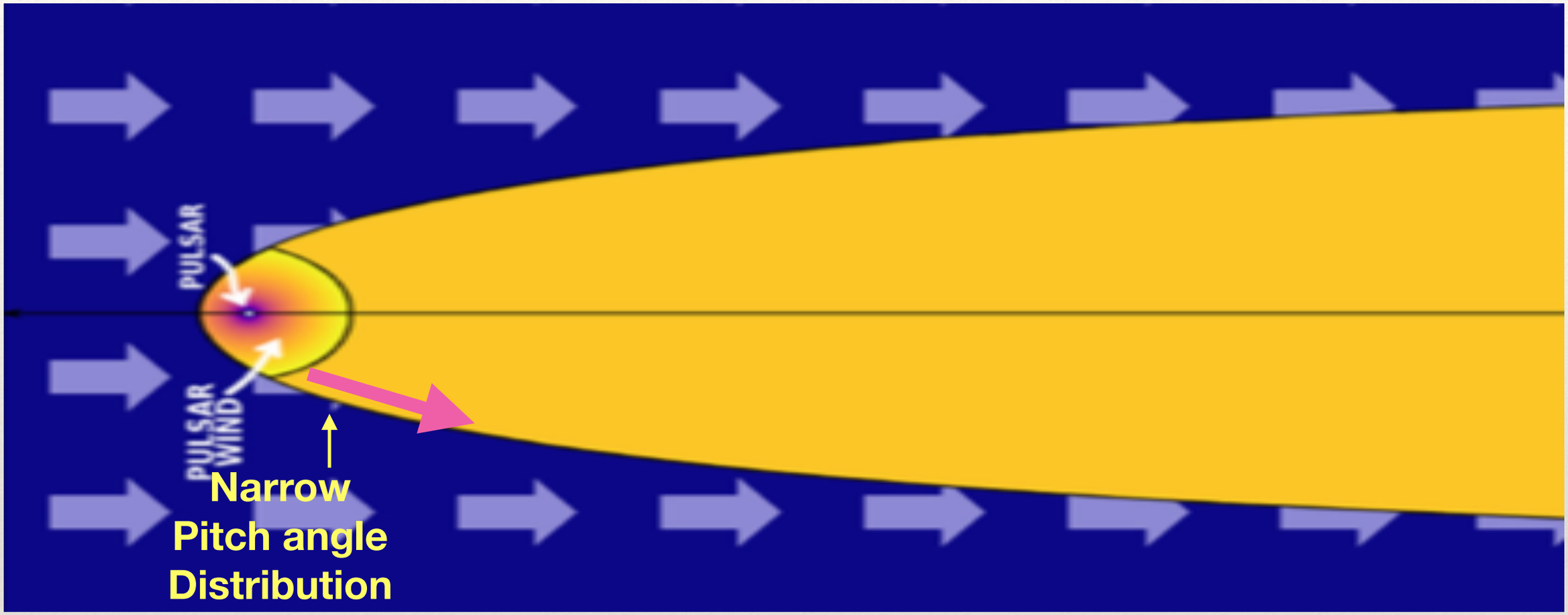

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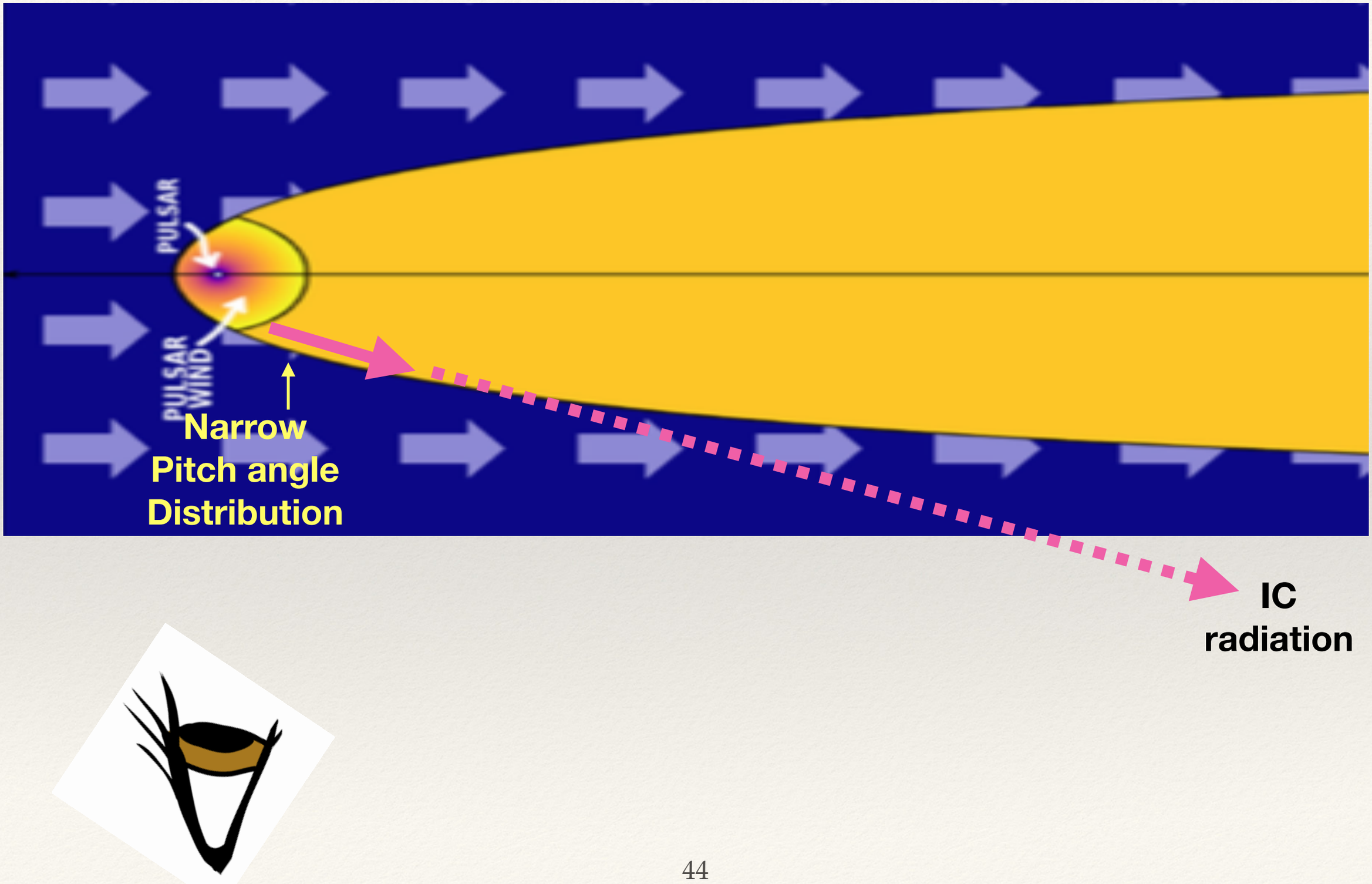

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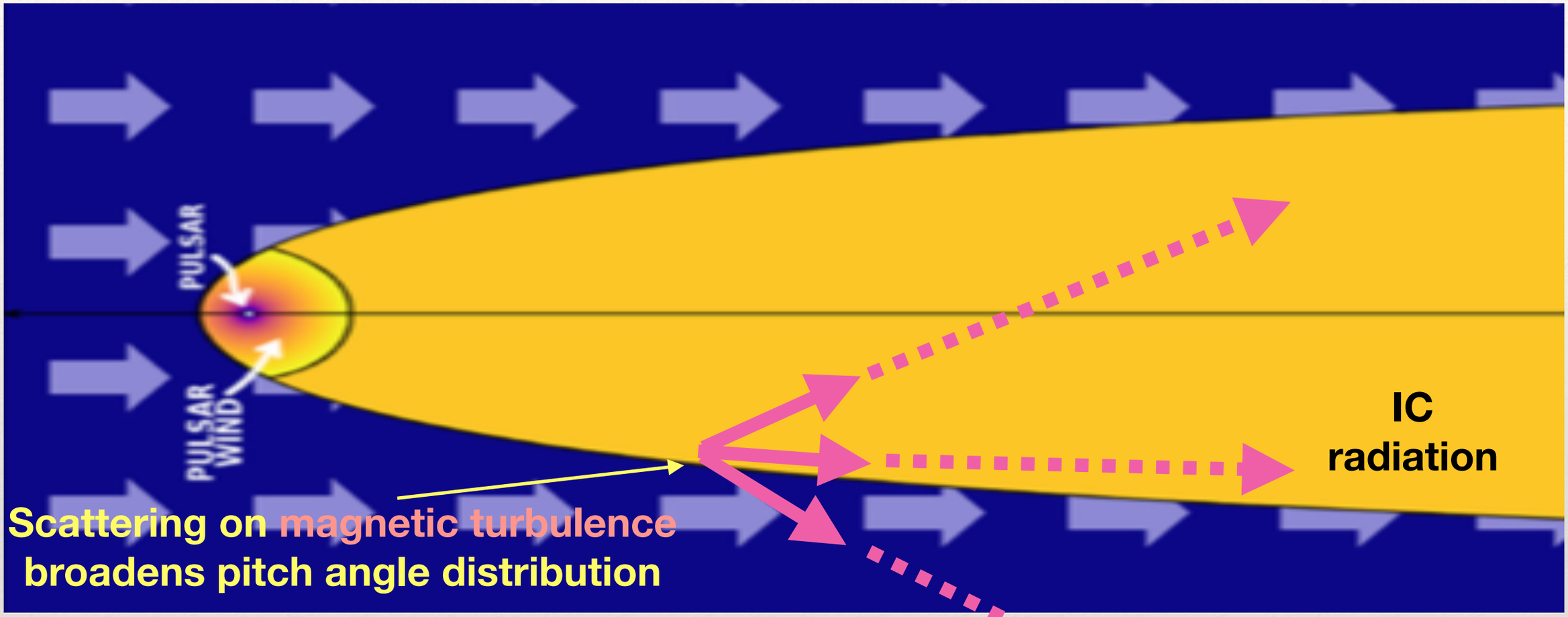

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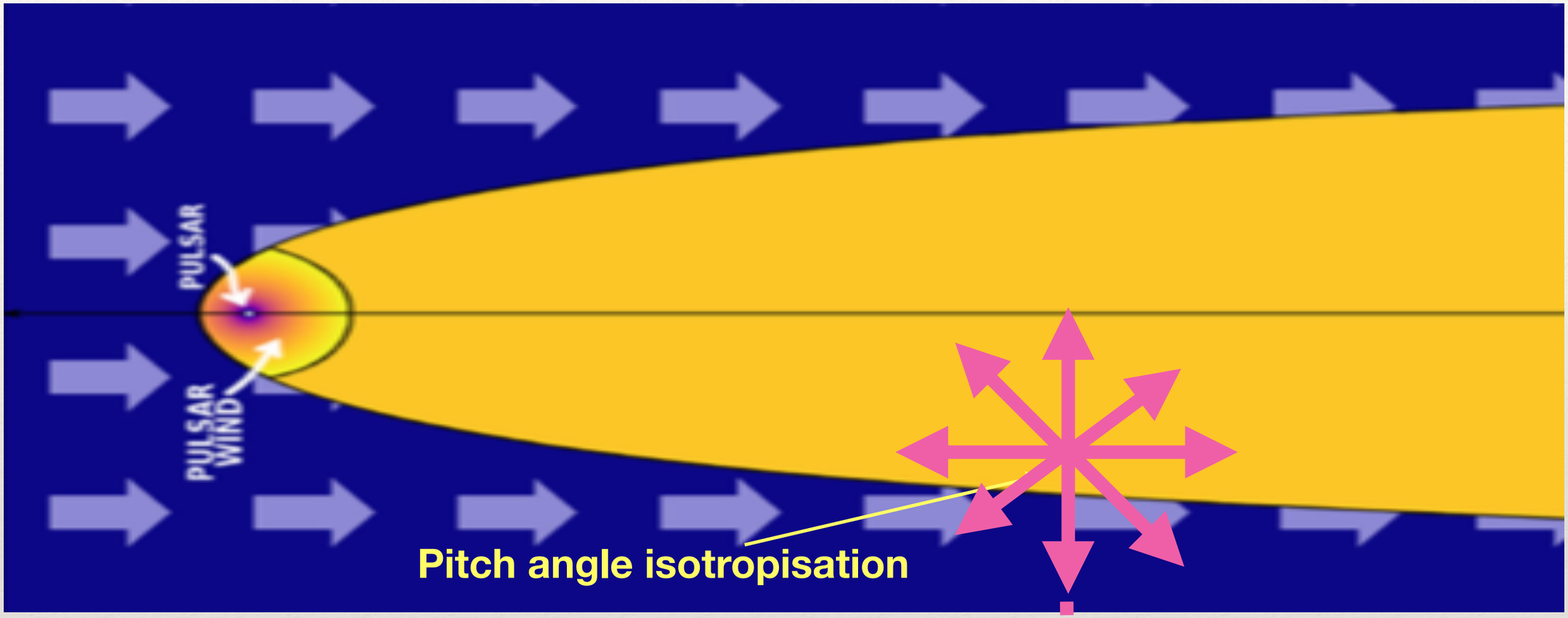

Transport model

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

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Transport model

Pitch angle diffusion

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Continuous momentum loss (synchrotron)

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Continuous momentum loss

Source term

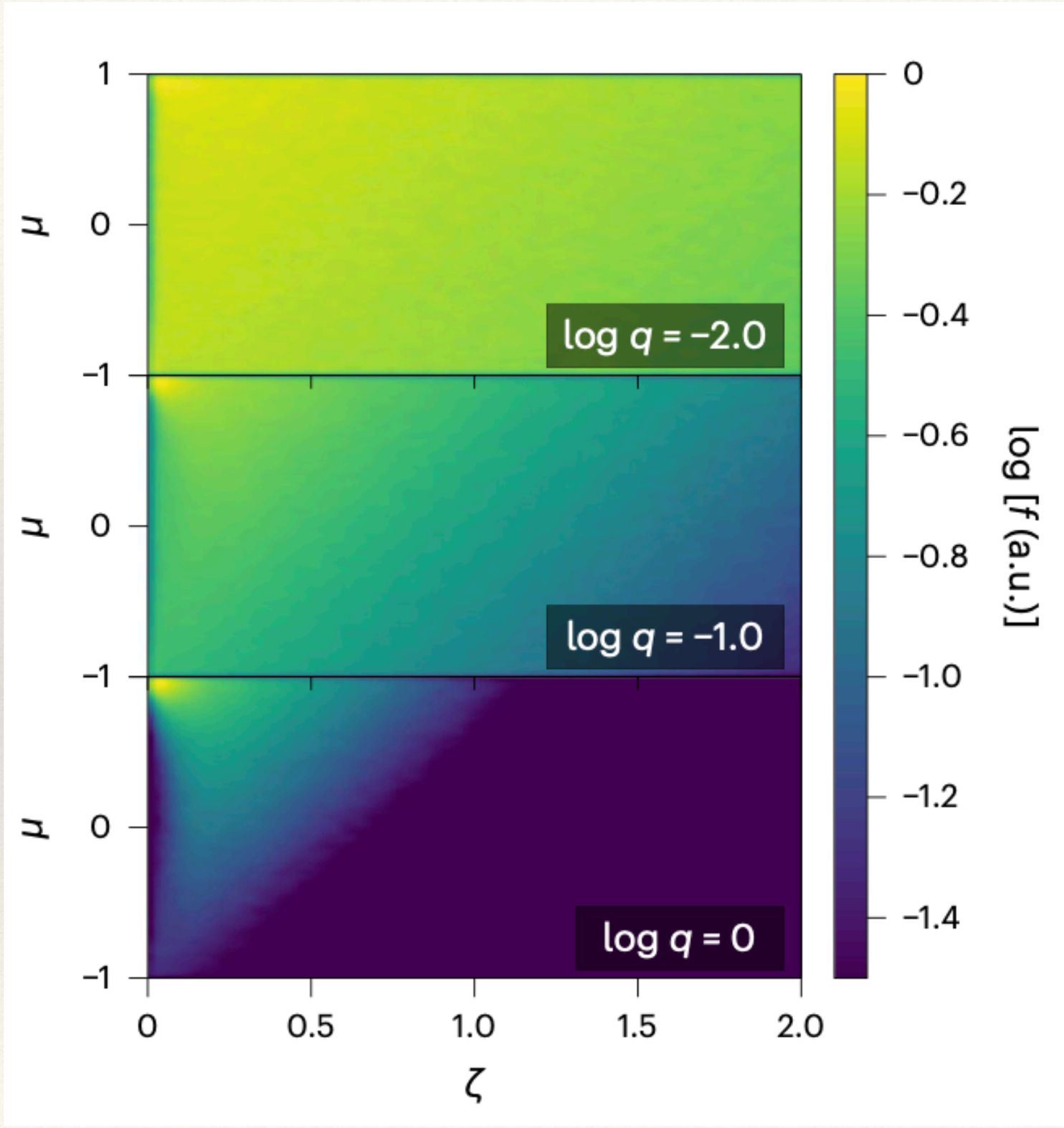
Numerical modelling with CRIPTIC

- Non-dimensionalise the transport equation
- 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)



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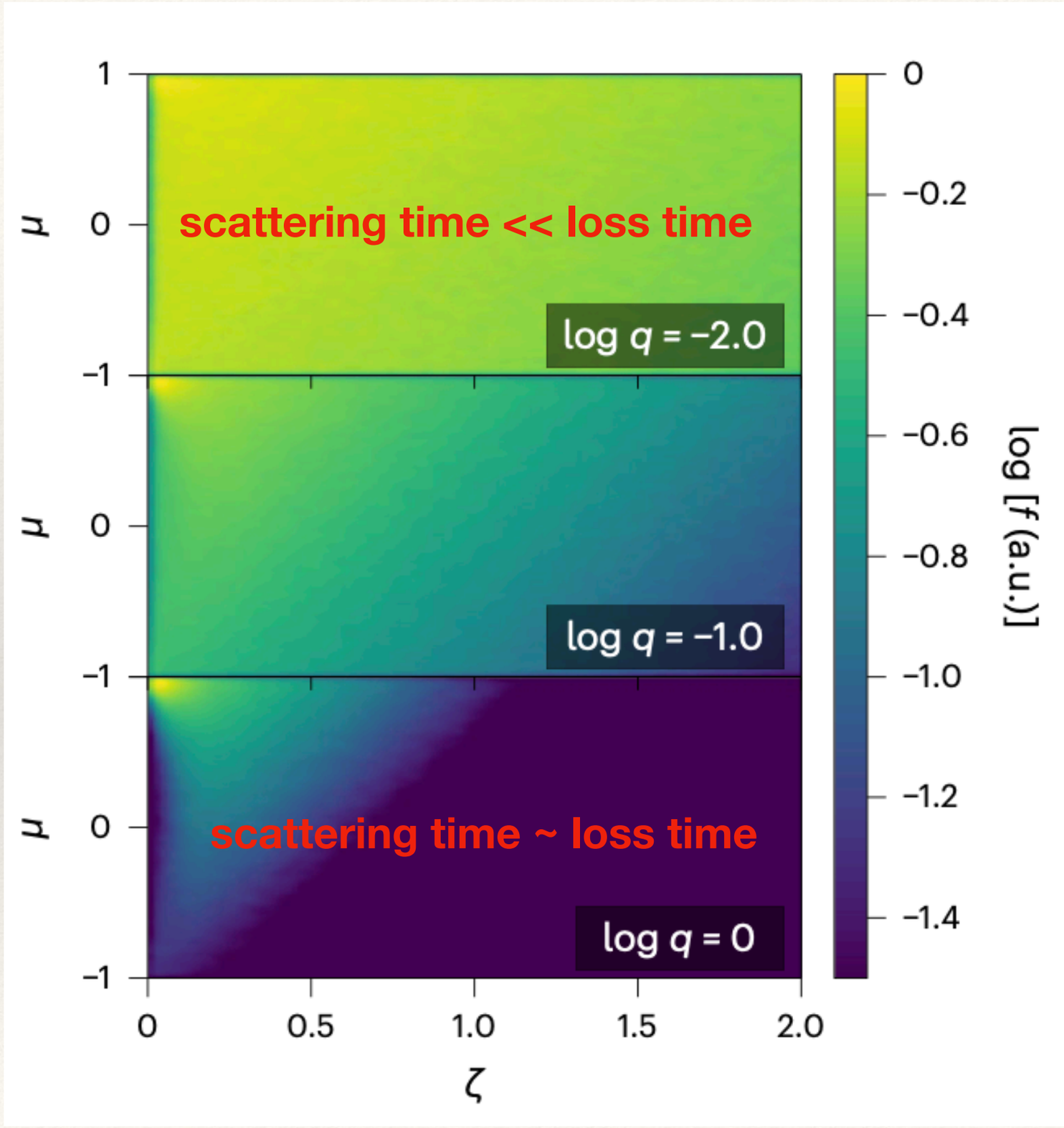

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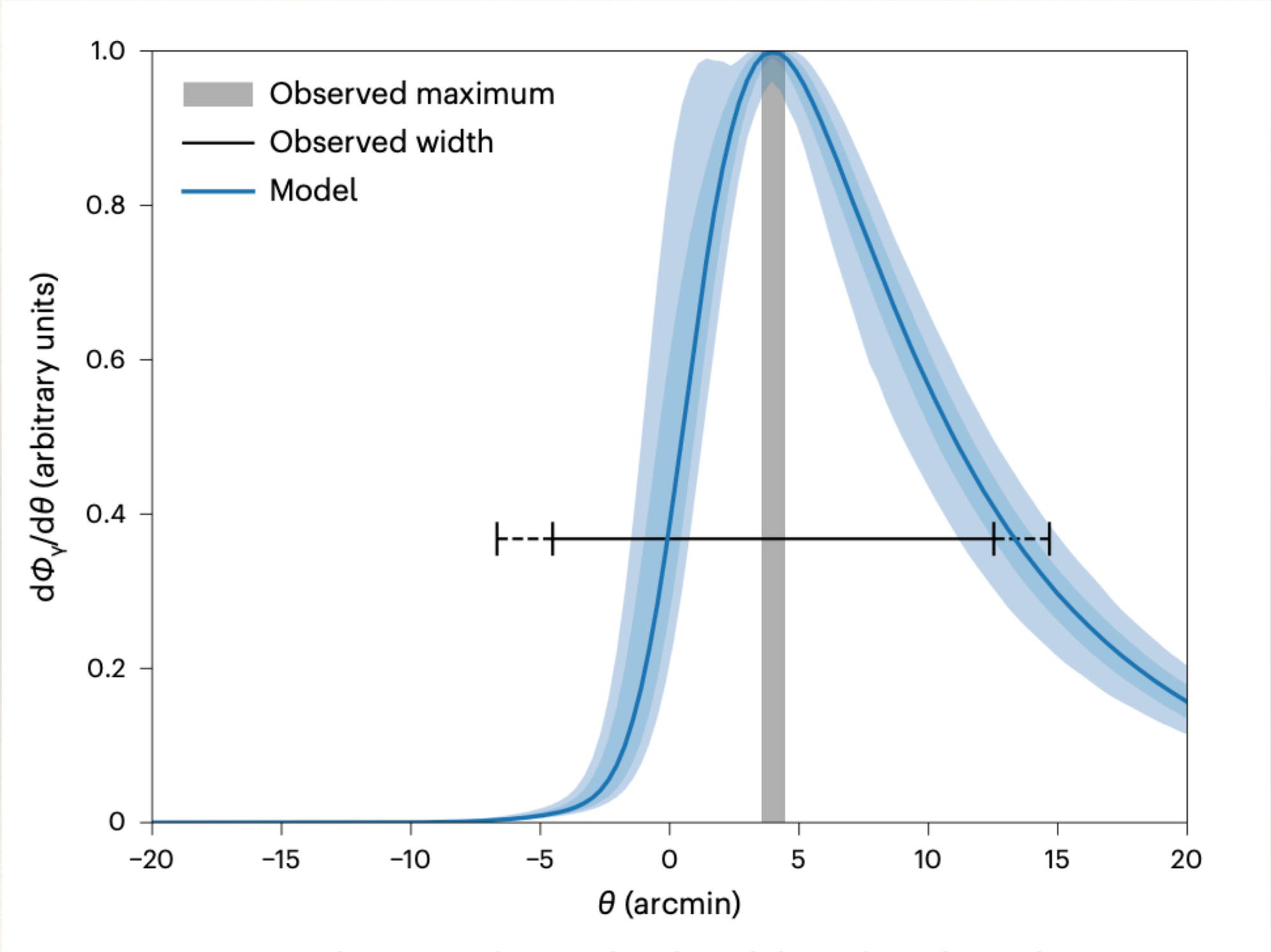

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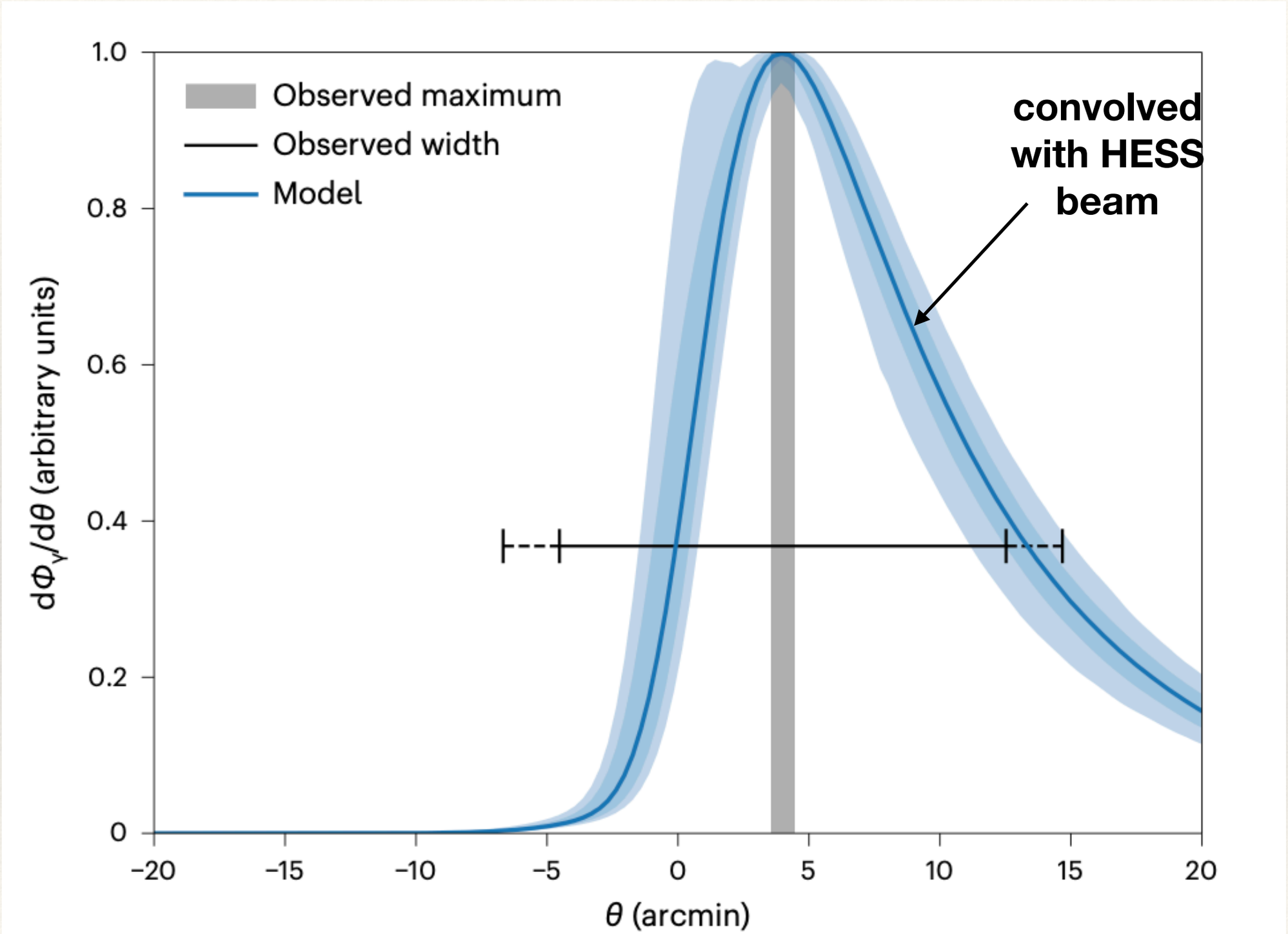
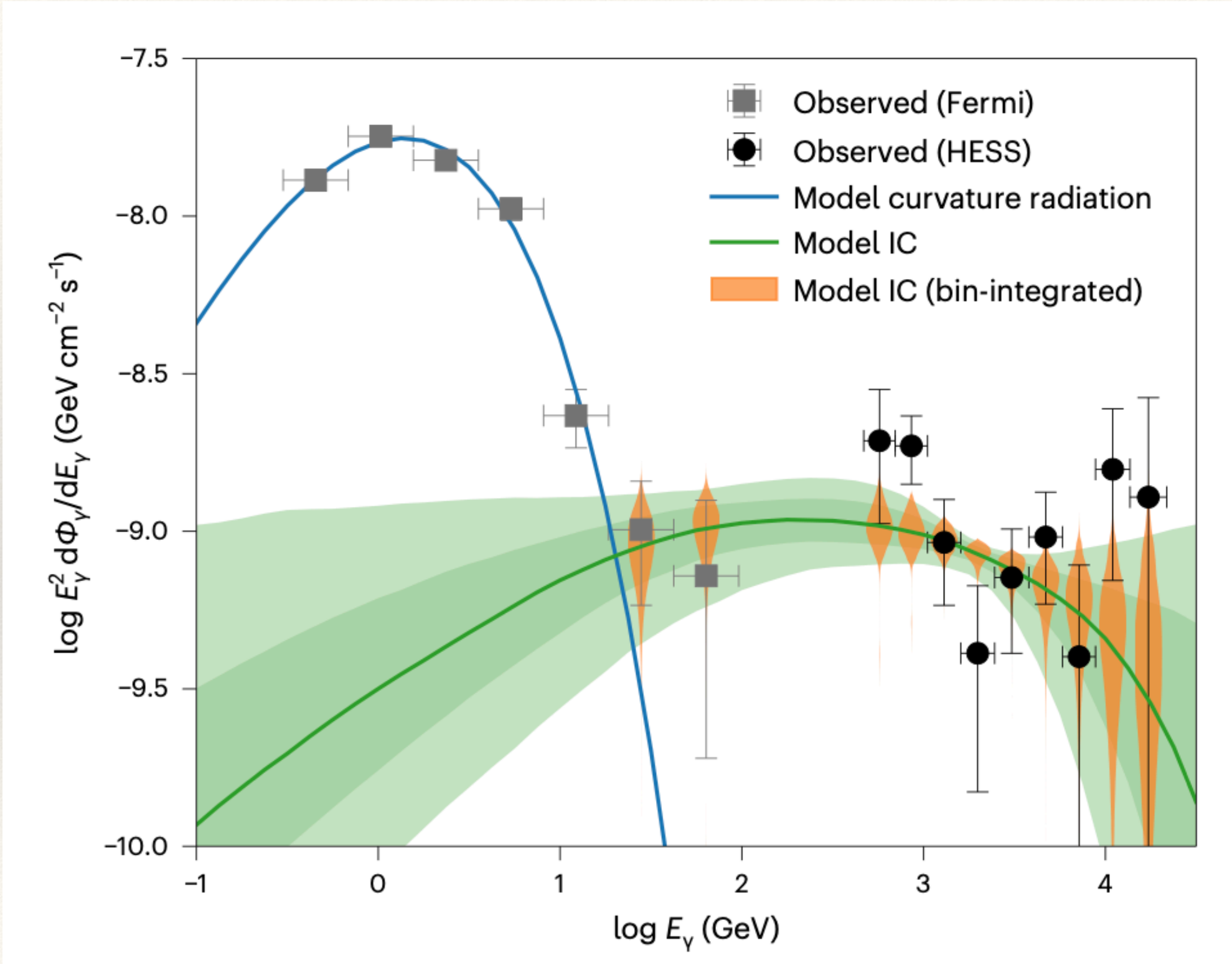


[The width of the profile is also a good match to the HESS observations.]

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:

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

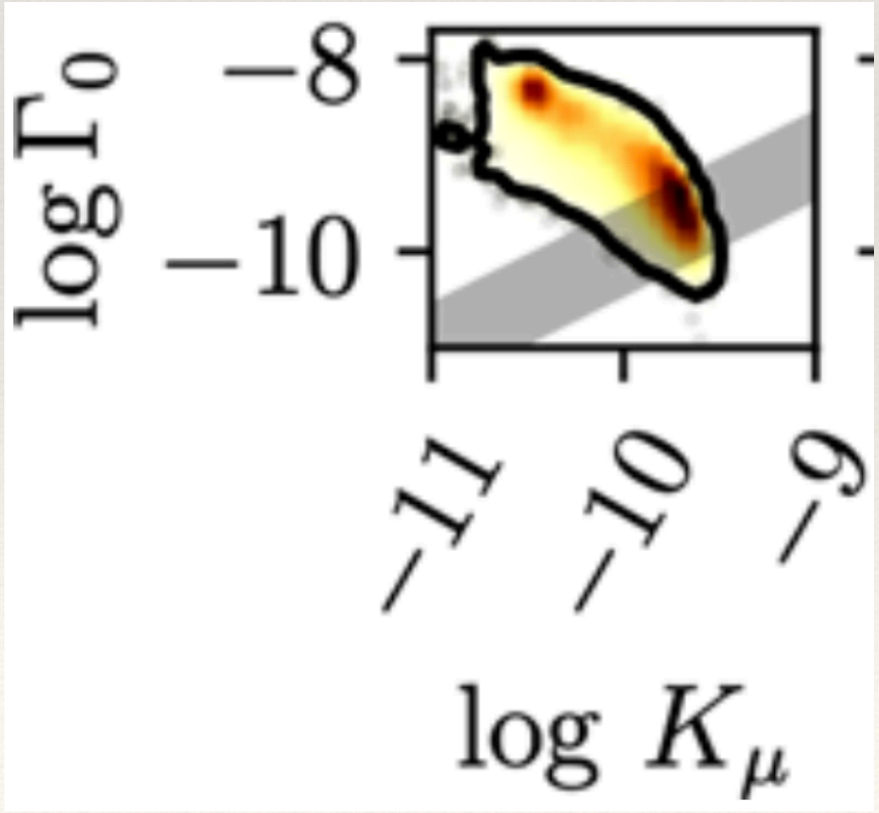
- We can also determine that

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

Results consistent with *self-confinement*

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

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



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

Summary

- The displaced TeV source associated to Terzan 5 may reveal pitch-angle isotropisation *in progress*