Modelling the transport of electrons in HESS J1825-137

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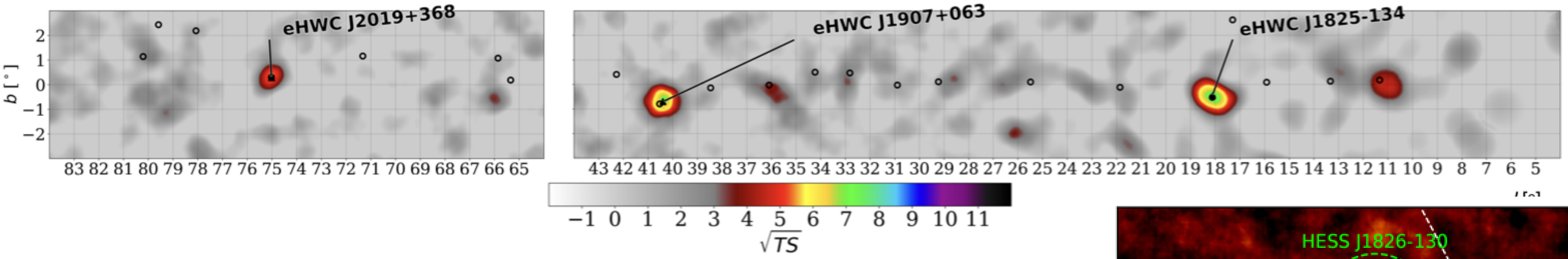
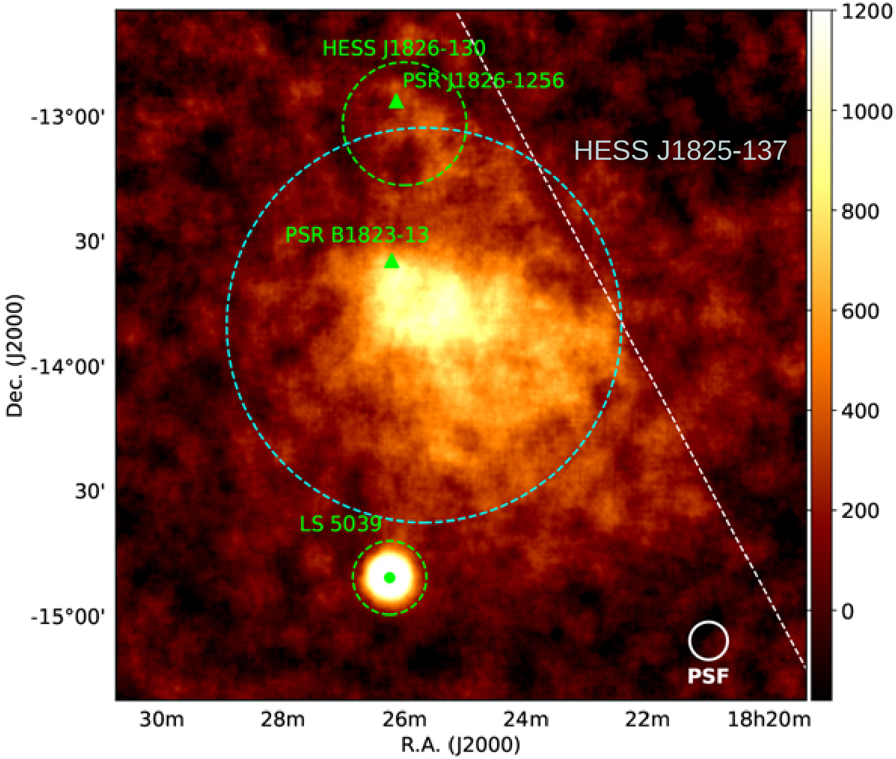
HESS J1825-137

(HAWC Collaboration et al. (2019))



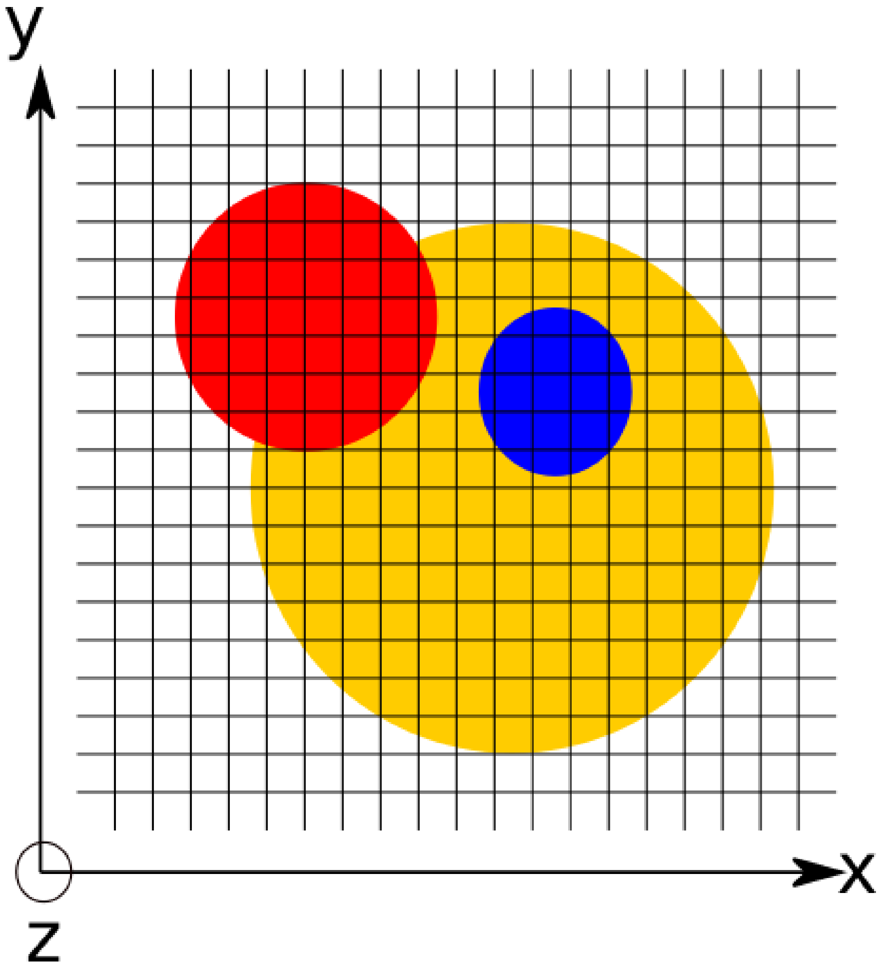
- One of the most luminous TeV gamma-ray pulsar wind nebulae (PWNe)
- HAWC and LHAASO have observed γ-rays > 100TeV towards HESS J1825-137
- Possible TeV Halo towards HESS J1825-137
- Characteristic age of 21.4 kyr (Aharonian et al. 2006)



(H.E.S.S. Collaboration et al., 2019)

Modelling HESS J1825-137 – Brief Overview

- The transport of electrons will be modelled across a 3D Cartesian grid using a finite difference method with powering pulsar, PSR 1826-1334, as the source of electrons
- Each voxel in the 3D grid is allowed to vary in number density and magnetic field, allowing detailed modelling of the interstellar gas
- Assuming simple isotropic diffusion, the final electron energy distribution will be predicted. From this we can gain predictions of the gamma-ray morphology and spectral energy distributions



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Modelling HESS J1825-137 – Brief Overview

- Van Etten & Romani (2011) conducted multizone modelling with a spherical shell approach. They found that that an older age of 40kyr best explained the X-ray and gamma-ray data
- We will model both 21ky and 40kyr

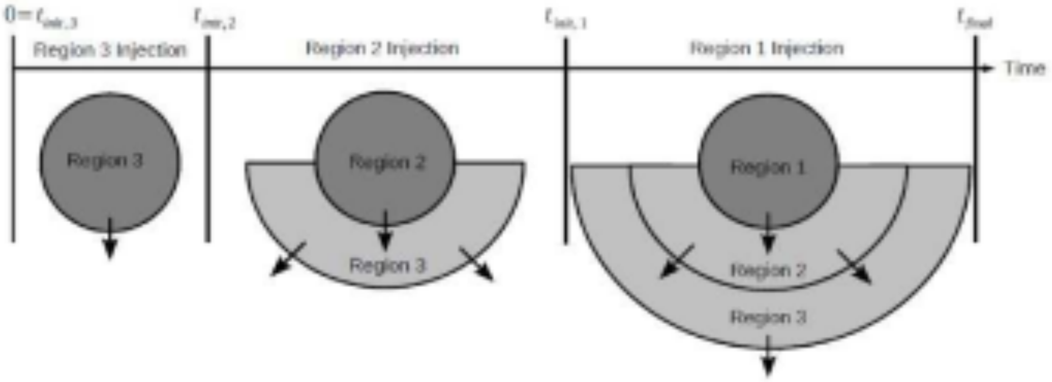

FIG. 5.— Snapshots of the evolution of nebular bubbles over three injection epochs. Dark gray corresponds to injection from the pulsar, light gray denotes the cooling phase, and arrows indicate diffusing particles.

(Van Etten & Romani, 2011)

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Basic Model – Single Zone Modelling

- Takes a region of constant density and magnetic field and injects cosmic rays into the centre of region
- This region is allowed to evolve in time and the spectral energy distribution (SED) can be modelled
- The SED will be compared to Suzaku and H.E.S.S. observations towards HESS J1825-137
- While unable to encapsulate the complexity of the region towards HESS J1825-137, a general insight can be gained before more detailed modelling

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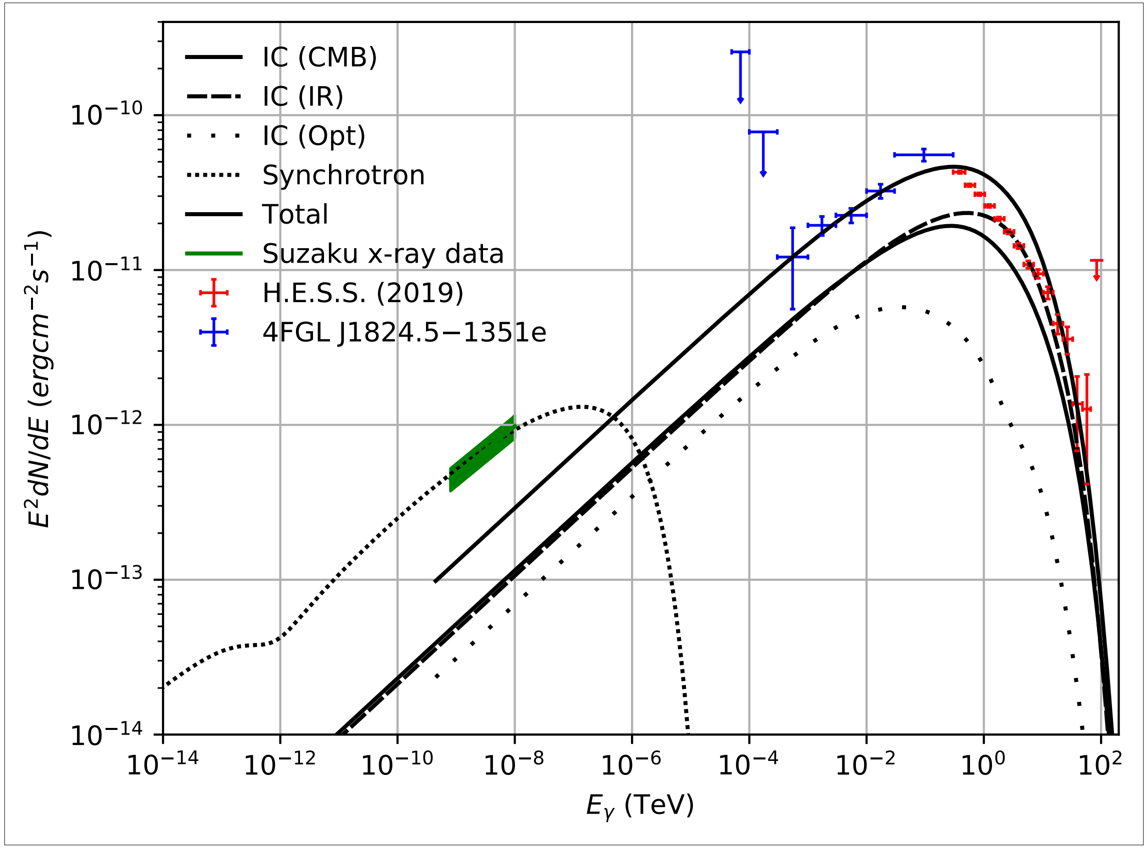
Single Zone Modelling: 21 kyr



$t = 21$ kyr

Parameter	HESS Value	Suzaku Value	units
$\dot{E}$	6×10^{38}	3×10^{35}	$\mathrm{erg\,s^{-1}}$
d	4	4	kpc
r	0.70	0.025	°
n	0.5	0.5	$\mathrm{cm^{-3}}$
B	5	40	µG
D_0	3×10^{29}	3×10^{29}	$\mathrm{cm^2\,s^{-1}}$
χ	0.5	0.5	
Γ	2.3	1.9	
E_c	50	1000	TeV
T_{IR}	60	60	K
U_{IR}	0.7	0.7	$\mathrm{eV\,cm^{-3}}$
T_{opt}	3500	3500	K
U_{opt}	1.9	1.9	$\mathrm{eV\,cm^{-3}}$

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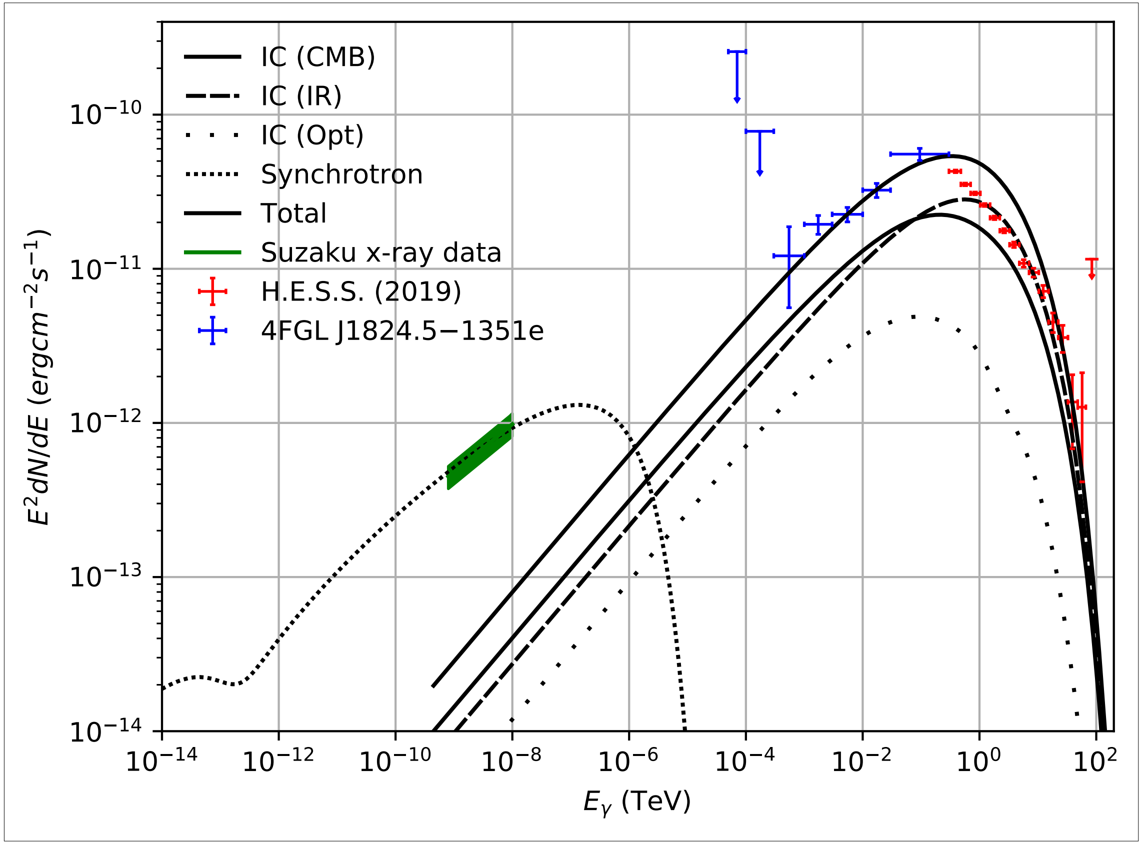
Single Zone Modelling: 40 kyr



$t = 40$ kyr

Parameter	HESS Value	Suzaku Value	units
$\dot{E}$	5.5×10^{37}	3×10^{35}	erg s^{-1}
d	4	4	kpc
r	0.70	0.025	$\circ$
n	0.5	0.5	cm^{-3}
B	5	40	µG
D_0	3×10^{29}	3×10^{29}	cm^2 s^{-1}
χ	0.5	0.5	
Γ	2.1	1.9	
E_c	40	1000	TeV
$T_{\rm IR}$	60	60	K
$U_{\rm IR}$	0.7	0.7	eV cm^{-3}
$T_{\rm opt}$	3500	3500	K
$U_{\rm opt}$	1.9	1.9	eV cm^{-3}

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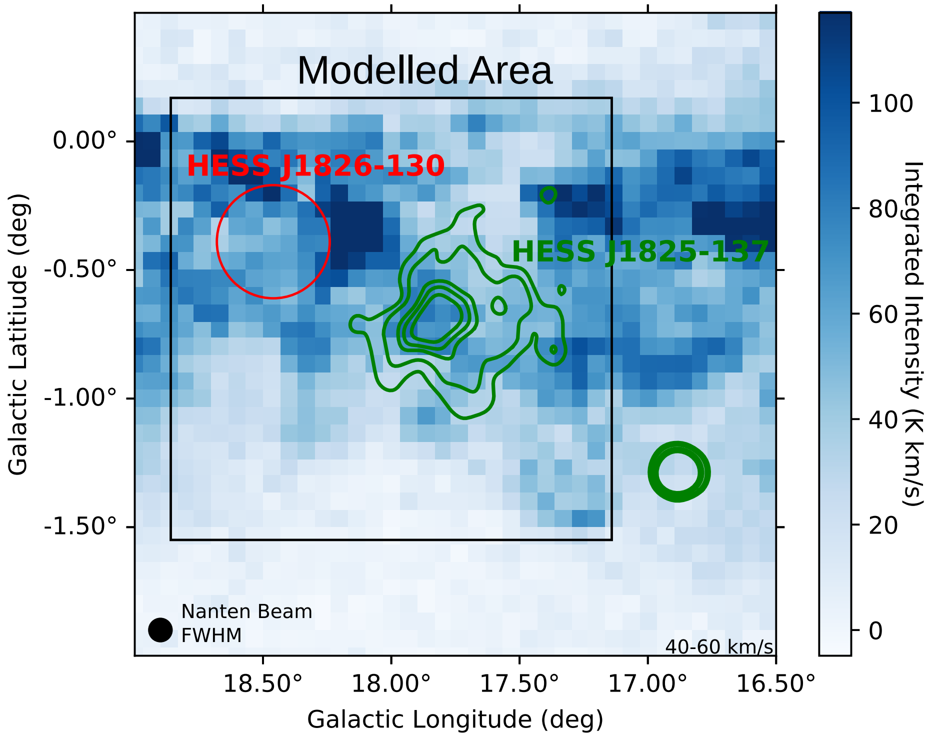
Molecular Gas Towards HESS J1825-137

- 12CO(1-0) gas can be used as a molecular tracer for H_2 gas
- PSR 1826-1336 has pulsar dispersion measurement of 3.9 ± 0.4 kpc
- Nanten 12CO(1-0) in velocity range 40-60km/s (3.5-4.5 kpc as given by Brand & Blitz 1993)
- Progenitor stellar winds would create a void of low density gas.



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Multizone Modelling: Diffusion Equation

- The evolution of the cosmic ray energy distribution (and electrons) can be described by a Flokker-Planck equation (Cesarsky & Voelk 1977):

$$
\begin{aligned}
\frac{\partial n}{\partial t} &= -\nabla(D(\boldsymbol{r},\gamma)\cdot\nabla n) + \frac{\partial}{\partial\gamma}(\dot{\gamma}n) + S(\gamma,\boldsymbol{r},t) \\
&= \left\{\frac{\partial n}{\partial t}\right\}_{\text{diffusion}} + \left\{\frac{\partial n}{\partial t}\right\}_{\text{radiative}} + \left\{\frac{\partial n}{\partial t}\right\}_{\text{source term}}
\end{aligned}
$$

- We are assuming a simple case of isotropic diffusion of cosmic rays.
- Impossible to solve analytically unless under certain circumstances

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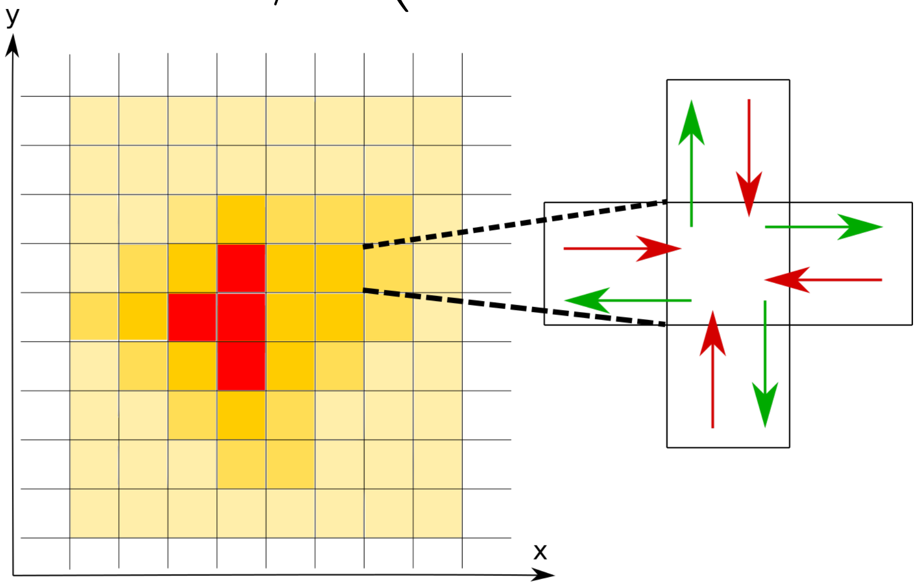
Diffusion Equation – Numerical Approach

$$\left. n \right|_{\substack{\gamma \\ t \\ x,y,z}} = \sum_{\{i=x,y,z\}} \left[\frac{\dot{\gamma}_0}{\dot{\gamma}} \boldsymbol{D} \Big|_{\substack{\gamma_0 \\ t-\Delta t \\ i+\Delta i/2}} \left(\left. n \right|_{\substack{\gamma_0 \\ t-\Delta t \\ i+\Delta i}} - \left. n \right|_{\substack{\gamma_0 \\ t-\Delta t \\ i}} \right) \right.$$

$$\left. + \frac{\dot{\gamma}_0'}{\dot{\gamma}} \boldsymbol{D} \Big|_{\substack{\gamma_0' \\ t-\Delta t \\ i+\Delta i/2}} \left(\left. n \right|_{\substack{\gamma_0' \\ t-\Delta t \\ i-\Delta i}} - \left. n \right|_{\substack{\gamma_0' \\ t-\Delta t \\ i}} \right) \right]$$



Magnetic Field towards HESS J1825-137

- Magnetic Field due to the ISM gas:

$$B_{\rm gas}(n) = \begin{cases} B_0, & n < 300\ {\rm cm}^{-3} \\ B_0\left(\frac{n}{300\ {\rm cm}^{-3}}\right)^{\alpha}, & n > 300\ {\rm cm}^{-3} \end{cases}$$

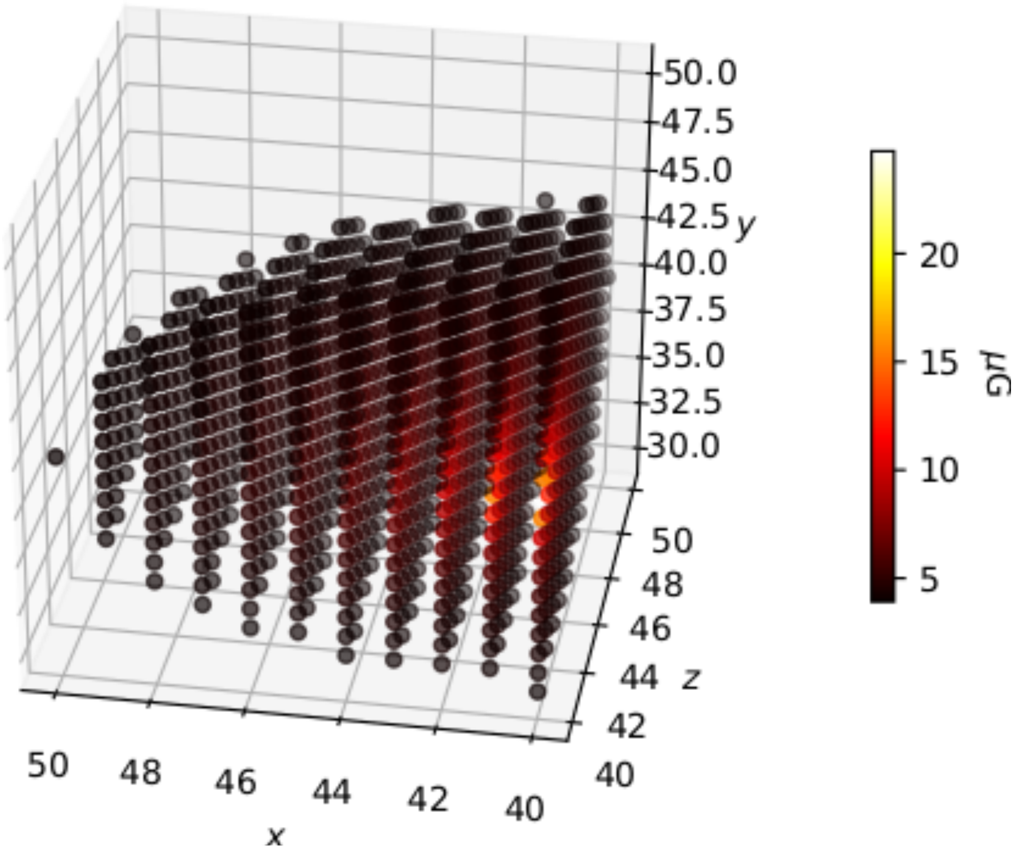
(Crutcher et al. 2010)

- Magnetic Field due to the PWN:

$$B_{\rm PWN}(r) = B_0\left(\frac{r}{r_{\rm ts}}\right)^{-\beta}$$

  - Similar approach to Van Etten & Romani (2011) but they have an extra time dependence.

- $B_{total} = B_{gas} + B_{PWN}$



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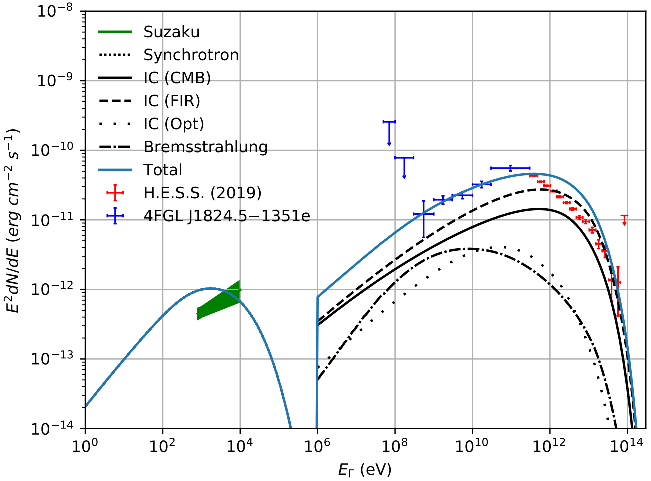
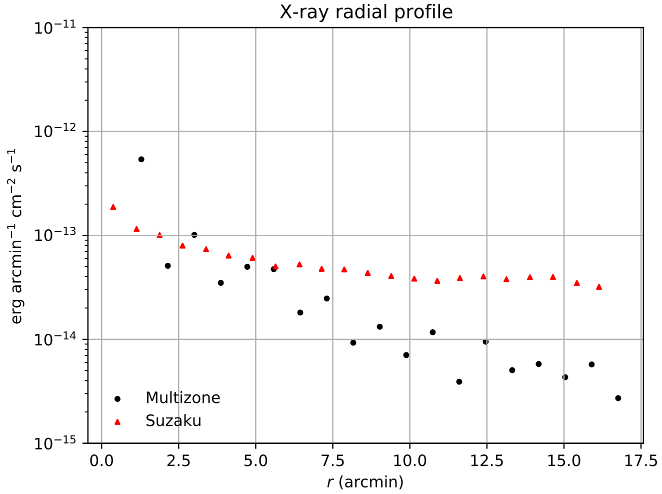
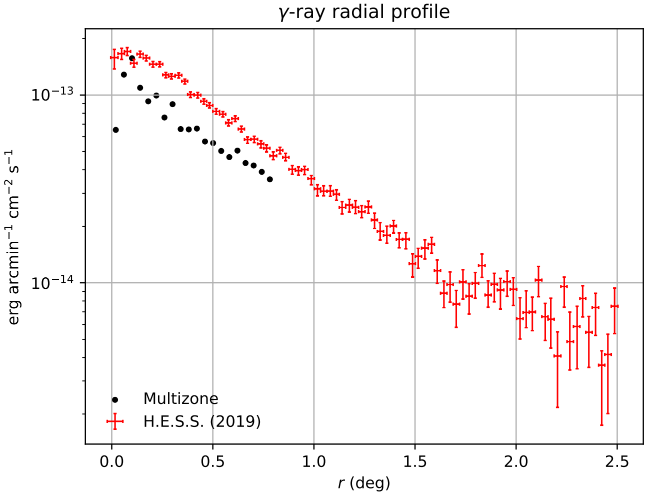
Multizone Modeling: 21 kyr

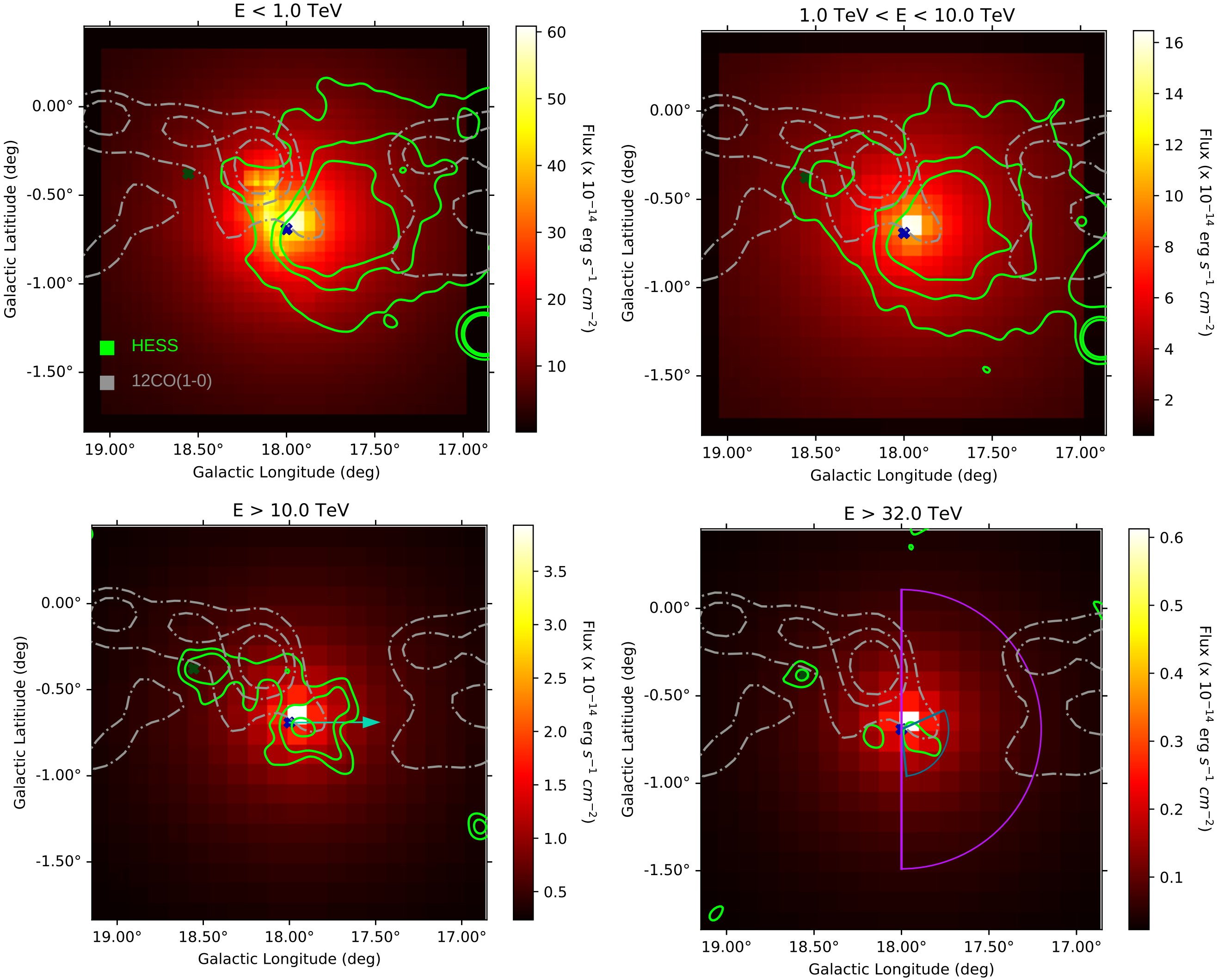




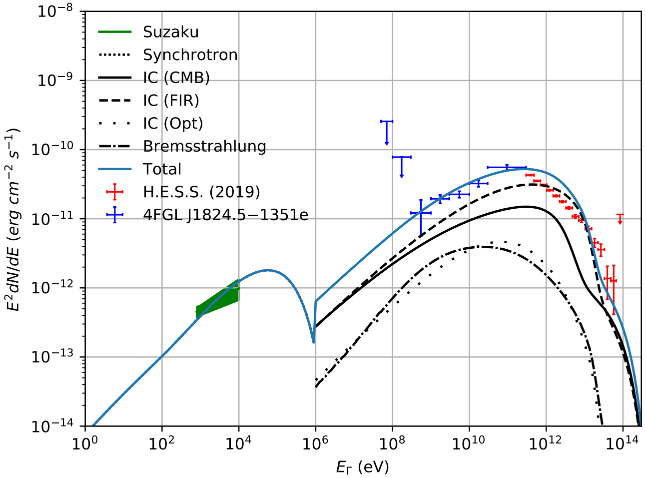


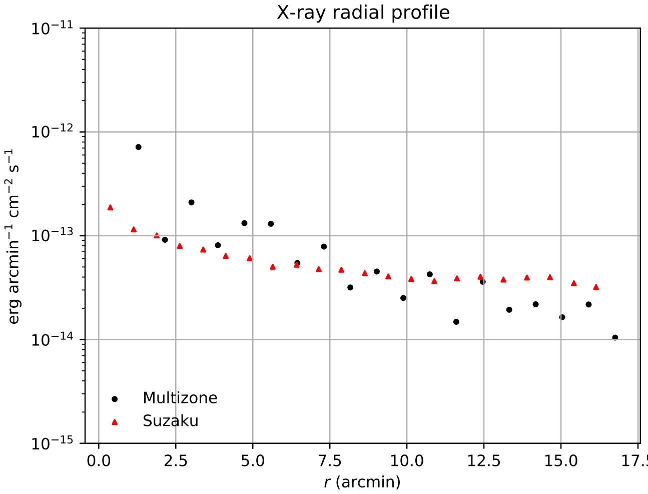
Parameter	Value	Fixed
t	21 kyr	Y
d	4.0 kpc	Y
$\dot{E}(t_{\rm age})$	3.0×10^{37} erg s^{-1}	N
D_0	3.0×10^{27} cm^2 s^{-1}	Y
χ	0.25	N
Γ	2.0	N
E_c	40 TeV	N
B_0	70 μG	N
β	−0.9	N
$r_{\rm ts}$	0.03 pc	Y
n	2	N
ΔX	2 pc	Y

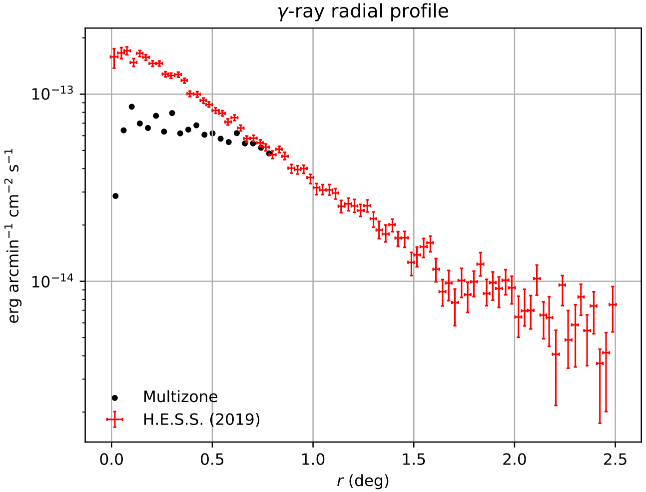
Multizone Modeling: 21 kyr



Multizone Modeling: 40 kyr



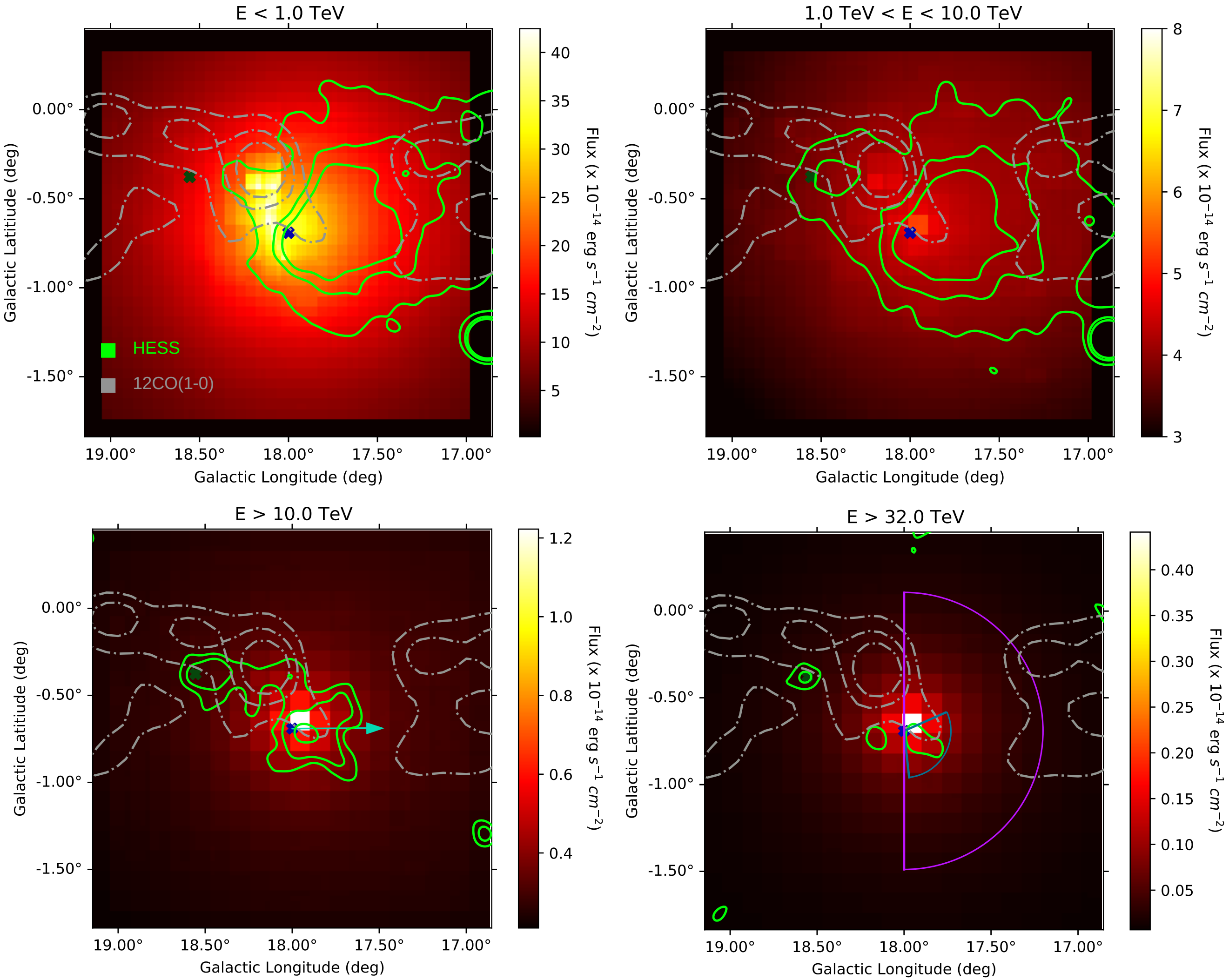




Parameter	Value	Fixed	Van Etten
t	40 kyr	Y	40 kyr
d	4.0 kpc	Y	4 kpc
$\dot{E}(t_{\rm age})$	4.0×10^{35} erg s^{-1}	N	⋆
D_0	3.0×10^{27} cm^2 s^{-1}	Y	⋆
χ	0.1	N	⋆
Γ	1.9	N	2.24
E_c	500 TeV	N	230 TeV
B_0	450 μG	N	400 μG ⋆
β	−0.7	N	-0.69 ⋆
$r_{\rm ts}$	0.03 pc	Y	0.03 pc
n	2	N	2.0
ΔX	2 pc	Y	⋆

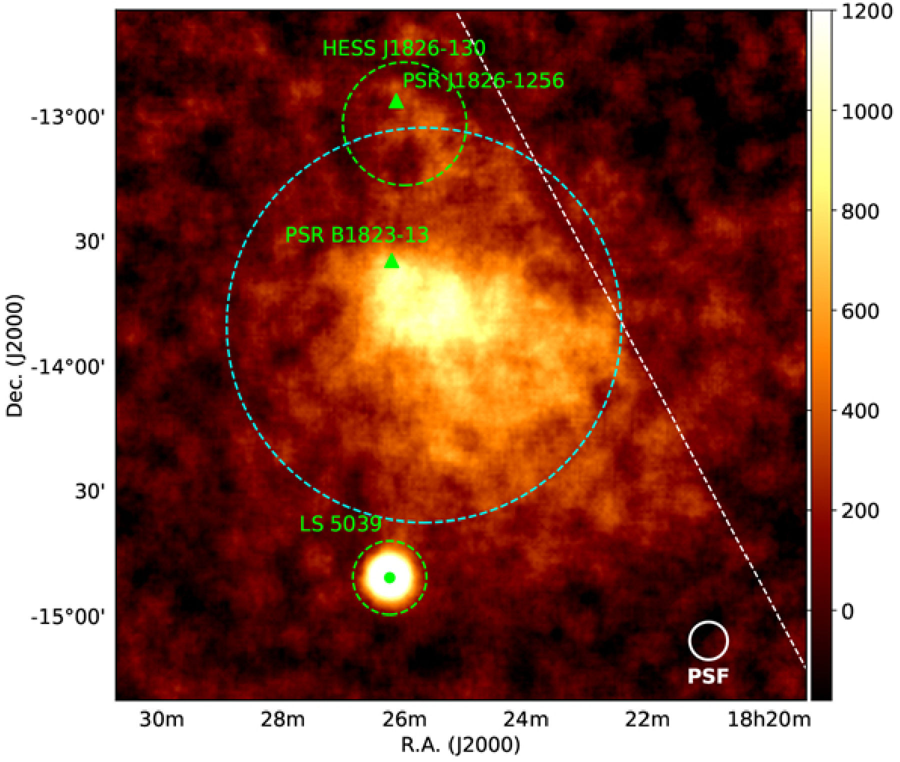
⋆ = treated differently

Multizone Modeling: 40 kyr



Advection?

- Gamma-ray morphology towards HESS J1825-137 is not symmetric
- H.E.S.S. Collaboration et al., 2019 suggested bulk motion of particles towards the south east with velocity 0.01c
- Currently the Multizone model only considers isotropic particle diffusion with asymmetry coming from Bremsstrahlung interactions.



(H.E.S.S. Collaboration et al., 2019)

Advection

- Assume that advection is energy and spatially independent.

$$\left(\frac{\partial n}{\partial t}\right)_{\text{adv}} = -\nabla \cdot (n\boldsymbol{v}_A)$$

$$n\Bigg|\begin{array}{l}\gamma\\ t\\ x,y,z\end{array} = \sum_{\{i=x,y,z\}} v_i \left[\frac{\dot{\gamma}_0}{\dot{\gamma}}\left(n\Bigg|\begin{array}{l}\gamma_0\\ t-\Delta t\\ i+\Delta i\end{array} - n\Bigg|\begin{array}{l}\gamma_0\\ t-\Delta t\\ i\end{array}\right)\right.$$

$$\left. + \frac{\dot{\gamma}_0'}{\dot{\gamma}}\left(n\Bigg|\begin{array}{l}\gamma_0'\\ t-\Delta t\\ i-\Delta i\end{array} - n\Bigg|\begin{array}{l}\gamma_0'\\ t-\Delta t\\ i\end{array}\right)\right]$$

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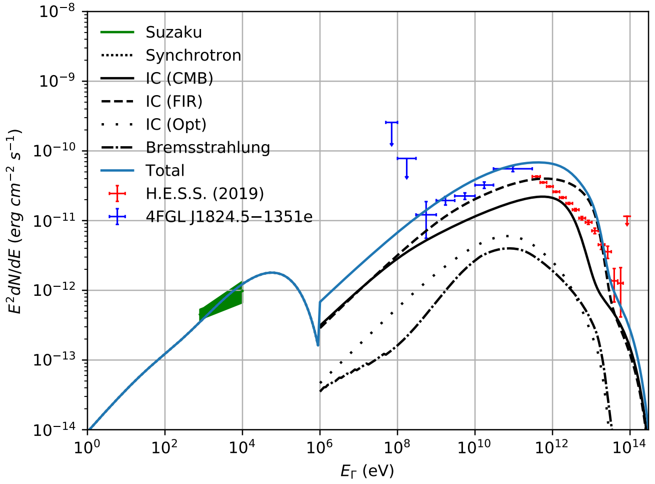
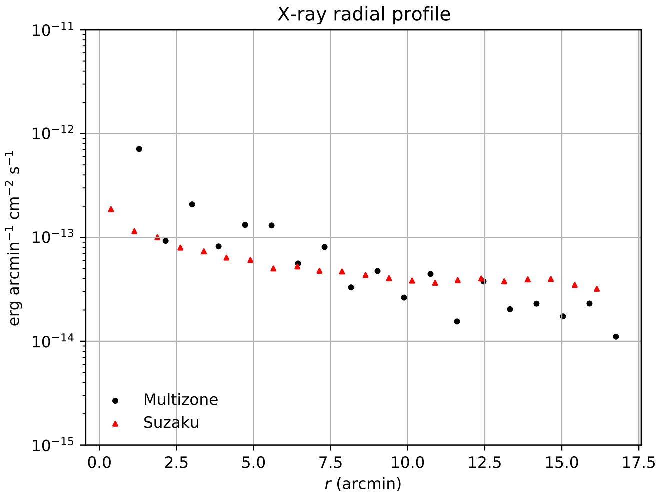
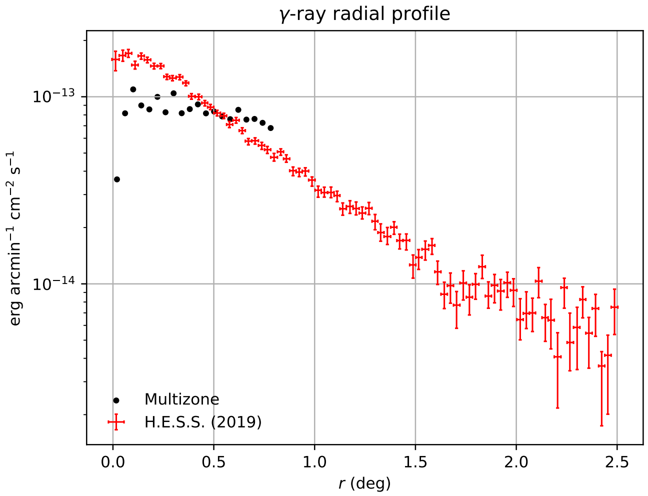
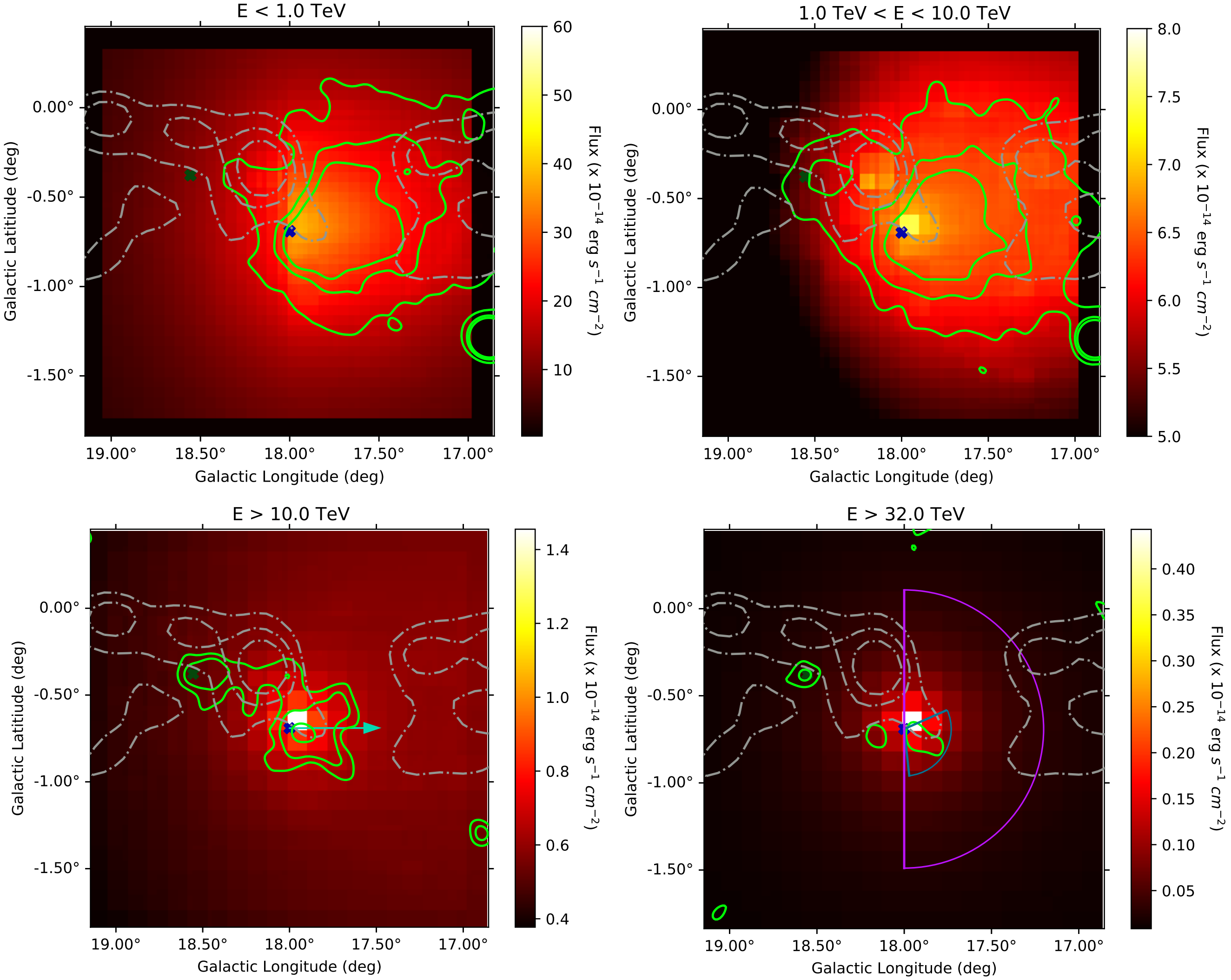
Advection: 40 kyr





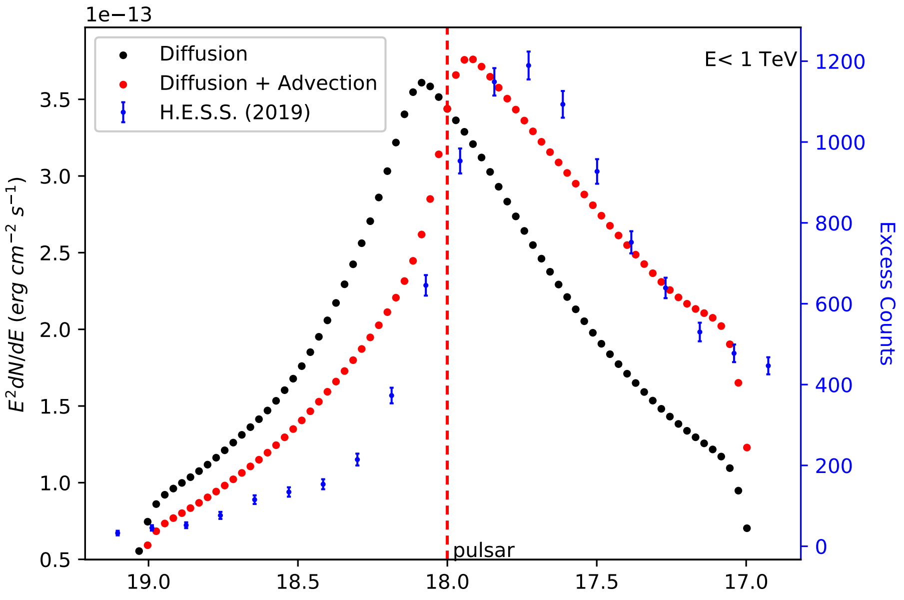


Advection: 40 kyr



What's Next?

- Comparison of model slice profiles to H.E.S.S. observations
- More detailed comparison of the gamma morphology to the model.
- A hadronic component to the PWN?
- Contamination of nearby HESS J1826-130 from HESS J1825-137?
- Spatial dependence on advection
    - Advection is more dominant closer to the PWN
- Model other sources?



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Diffusion and Radiative Cooling – optional slide

- Diffusion Coefficient (Gabici et al. 2007):

$$D(E,B) = \chi D_0 \sqrt{\frac{E/\mathrm{TeV}}{B/3\ \mu\mathrm{G}}} \quad [\mathrm{cm}^2\,\mathrm{s}^{-1}]$$

- $D_0 = 1 \times 10^{29}$ cm^2/s and χ is the diffusion suppression factor.
- Leptonic losses:

$$\dot{\gamma}(\gamma) = b_s\gamma^2 + b_c(3\ln\gamma + 18.8) + 5.3b_b + \sum_{t=i} b^i_{\mathrm{IC}}\gamma^2 F^i_{\mathrm{KN}}(\gamma)$$

$$= \text{synchrotron losses} + \text{Coulomb losses} + \text{Bremsstrahlung losses} + \text{inverse Compton losses}$$

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