Acceleration of High-Energy Particles in the Jets of the Microquasar SS433

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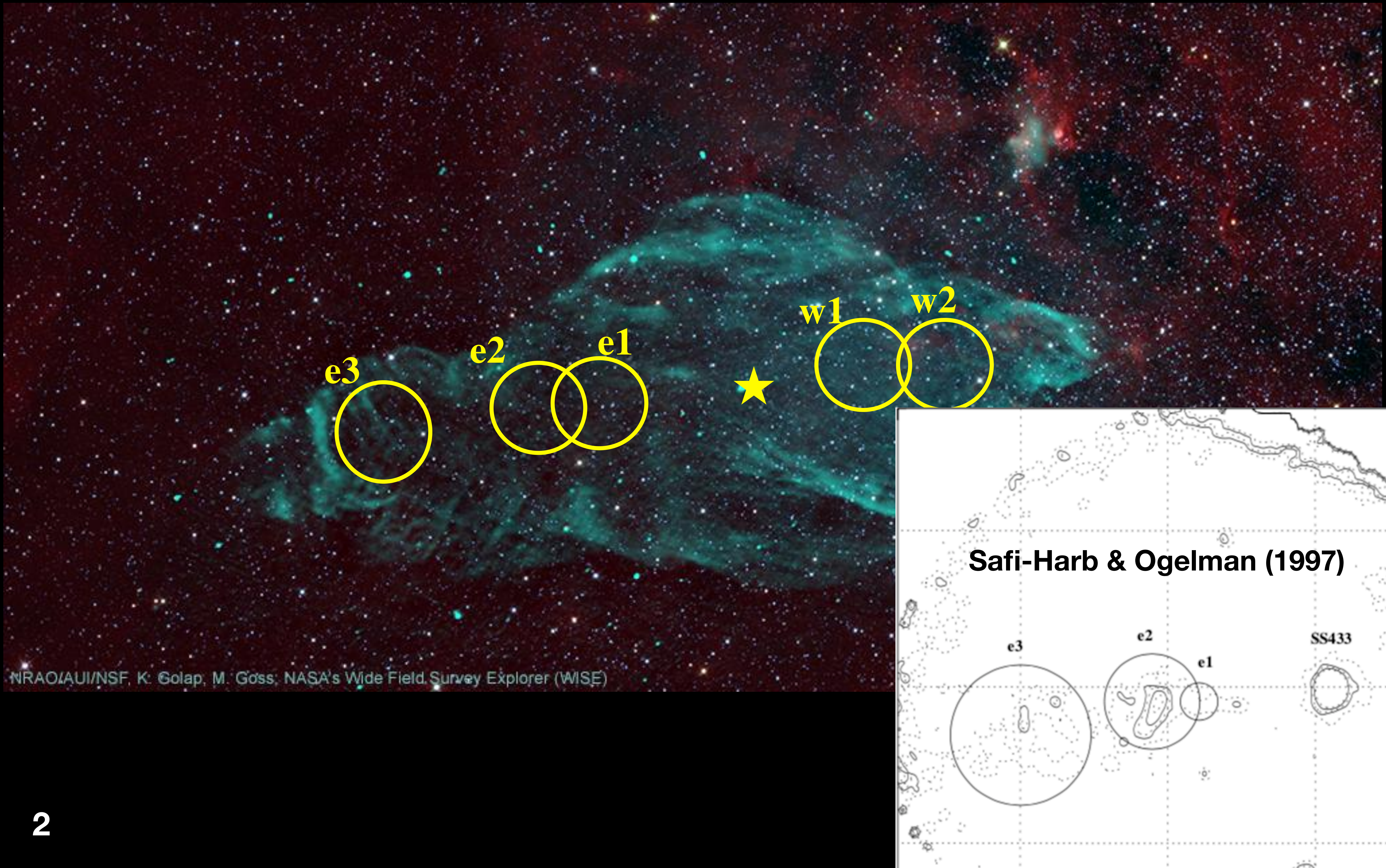
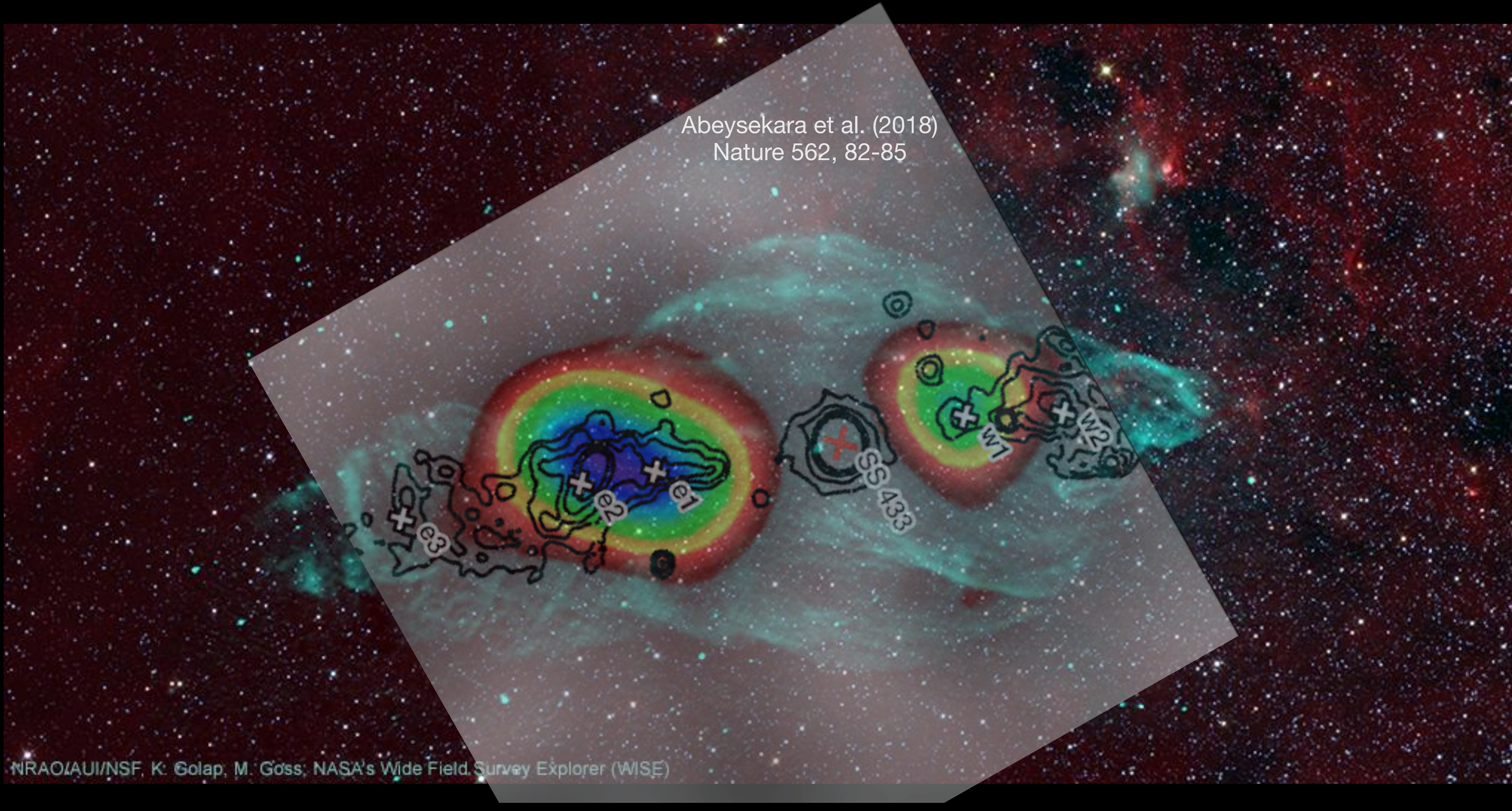
X-ray knots along the Jets

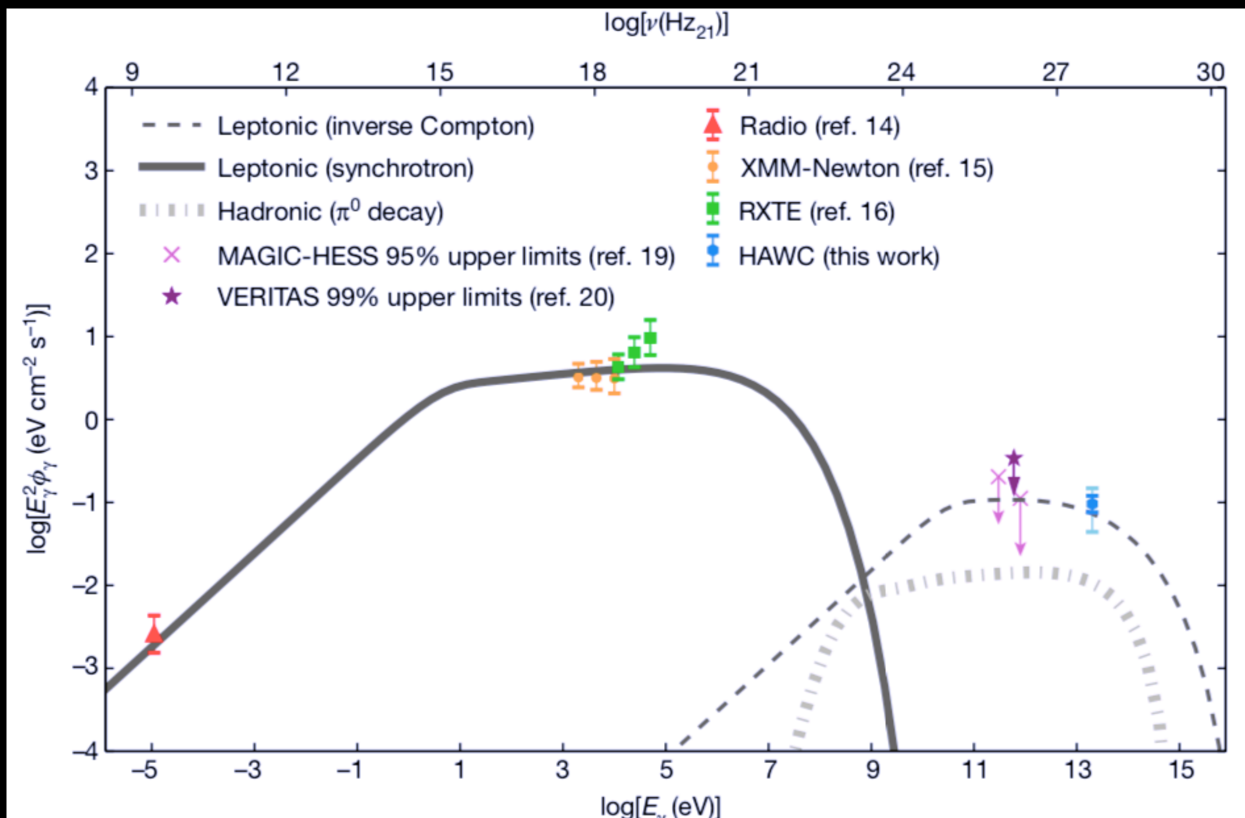


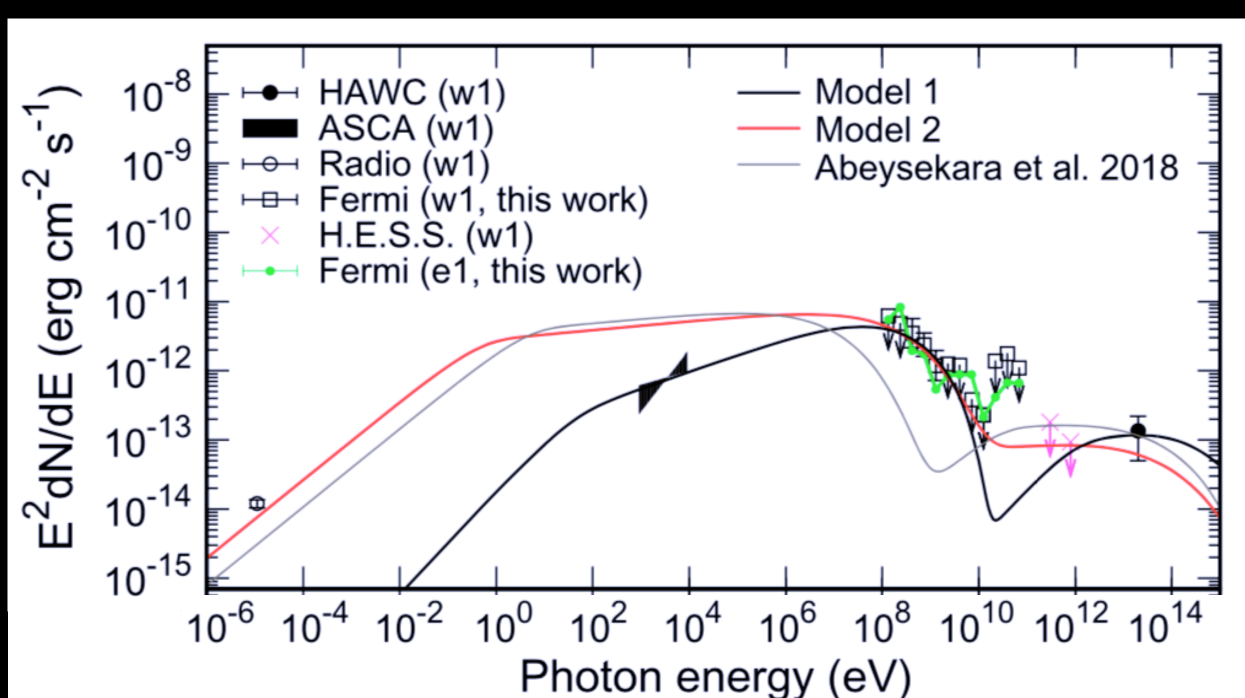
VHE photons from knots



- Knots in the jets of SS433 are plausible sites of particle acceleration

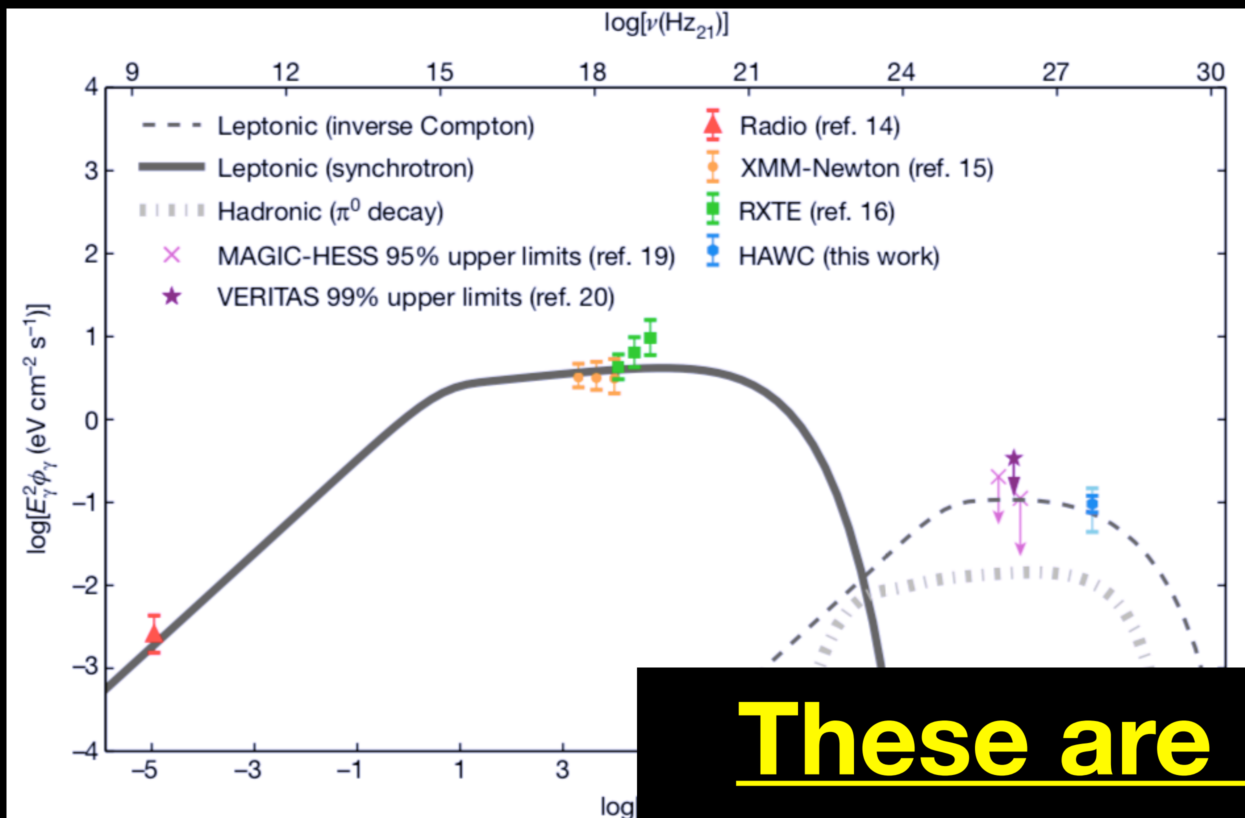
Interpretations ?

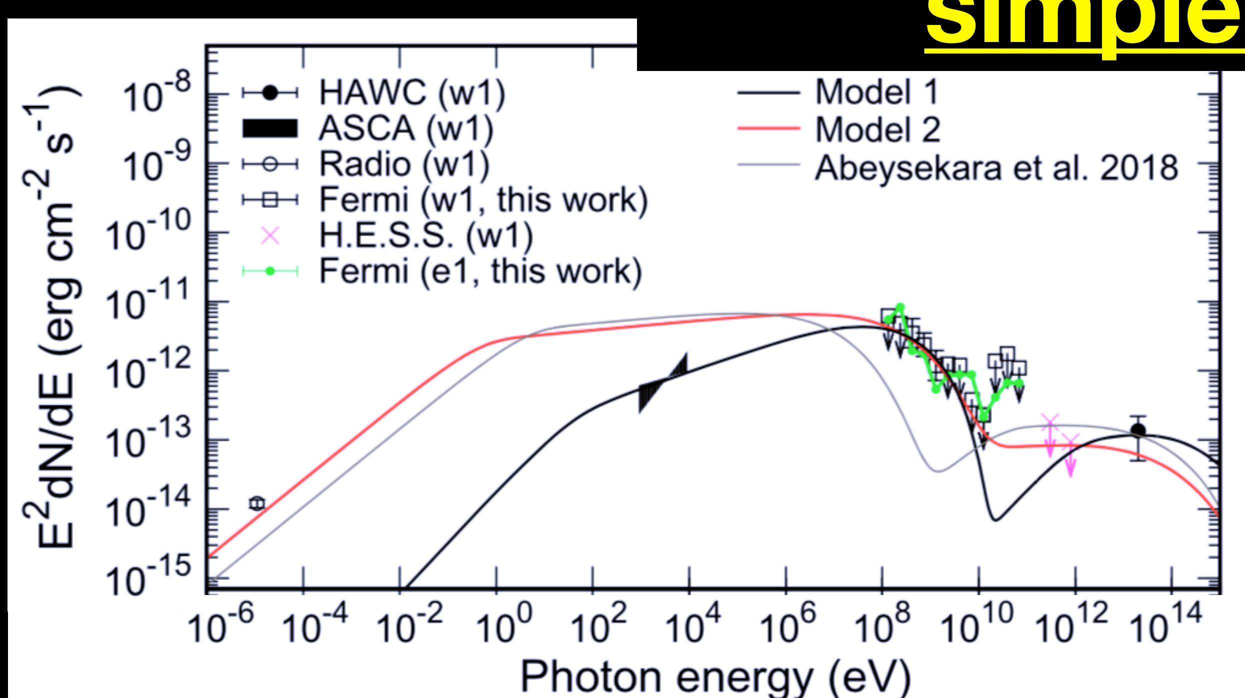




- Abeysekara et al. (2018) :
  - e1 region
  - leptonic model fits broadband SED
- Xing et al. (2019) :
  - w1 region
  - leptonic model does not explain X-ray/radio data

Interpretations ?





- Abeysekara et al. (2018) :
  - e1 region
  - leptonic model fits broadband SED

<u>These are based on very simple models…</u>

- Xing et al. (2019) :
  - w1 region
  - leptonic model <u>does not</u> explain X-ray/radio data

Our Work

- We use a more detailed model of nonthermal emission from microquasar jet, with aim of :
  - see whether leptonic model works
  - quantify acceleration efficiency
  - make predictions for future observations

Model

Particle Production

- Energetics : Total jet power is distributed for proton, relativistic electron (L_e), and magnetic field (L_B).

- Acceleration : parametrized as $t_{\rm acc} = \eta_{\rm acc}\frac{r_L}{c}$
- Maximum energy : defined by cooling or confinement
  - cooling limit $t_{\rm cool} > t_{\rm acc}$
  - confinement limit $R > \sqrt{6Dt_{\rm acc}}$

- Diffusion : scaled to the Bohm limit $D = \eta_g D_{\rm Bohm} = \eta_g \frac{cr_L}{3}$

Particle Cooling

- Cooling due to adiabatic and radiative (synchrotron and inverse Compton) losses.
- We include adiabatic loss :

$$\dot{\gamma}_{\rm ad} = \frac{\gamma}{3}\frac{d\ln\rho}{dt} = -\frac{2}{3}\frac{v_z}{\Gamma R(z)}\frac{\partial R}{\partial z}\gamma$$

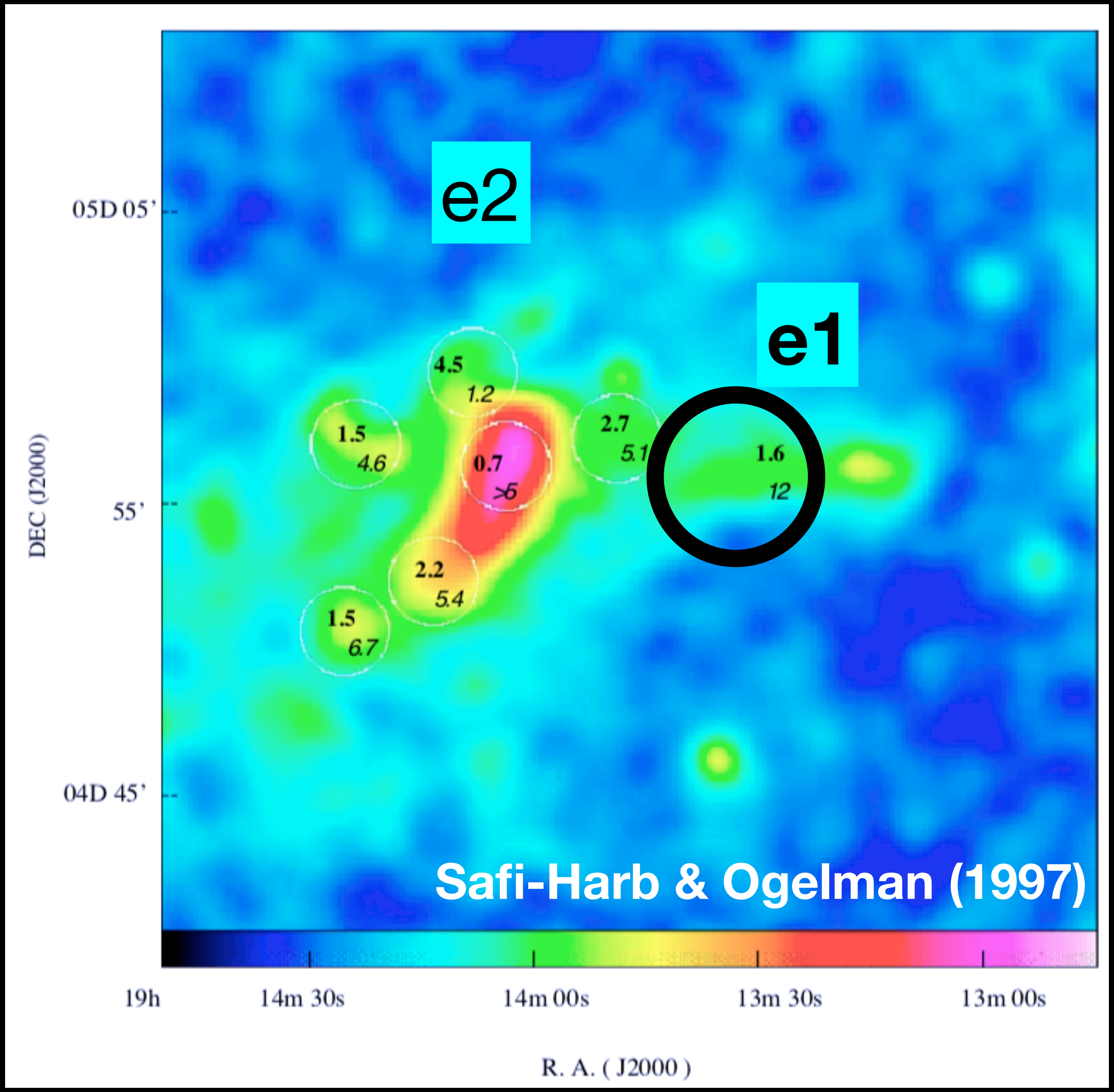
- To evaluate adiabatic loss rate, we parametrize the jet radius as $R(z) = z\alpha_j$ (i.e., conical jets).

Particle Evolution and Emission

- Transport equation describes the evolution of spatial-energy density : $\frac{\partial n(\gamma, z, t)}{\partial t} + v_z \frac{\partial n(\gamma, z, t)}{dz} + \frac{\partial}{\partial \gamma}[\dot{\gamma} n(\gamma, z, t)] = \dot{q}(\gamma)\delta(z - z_0)$
- Electron injection :
  - Static case and specific coordinate in the laboratory frame (z_0)
  - Assume a power-law above energy of 1 GeV : $\dot{q}(\gamma) \propto \gamma^{-p_{\mathrm{inj}}}$
- Integrate to obtain electron spectrum in the knots: $\frac{dN}{d\gamma} = \int_{z_0}^{z_1} n dz$
- Emission from electrons : Synchrotron + Inverse-Compton
  - Dominant photon field is the Galactic diffuse background
  - SSC is neglected

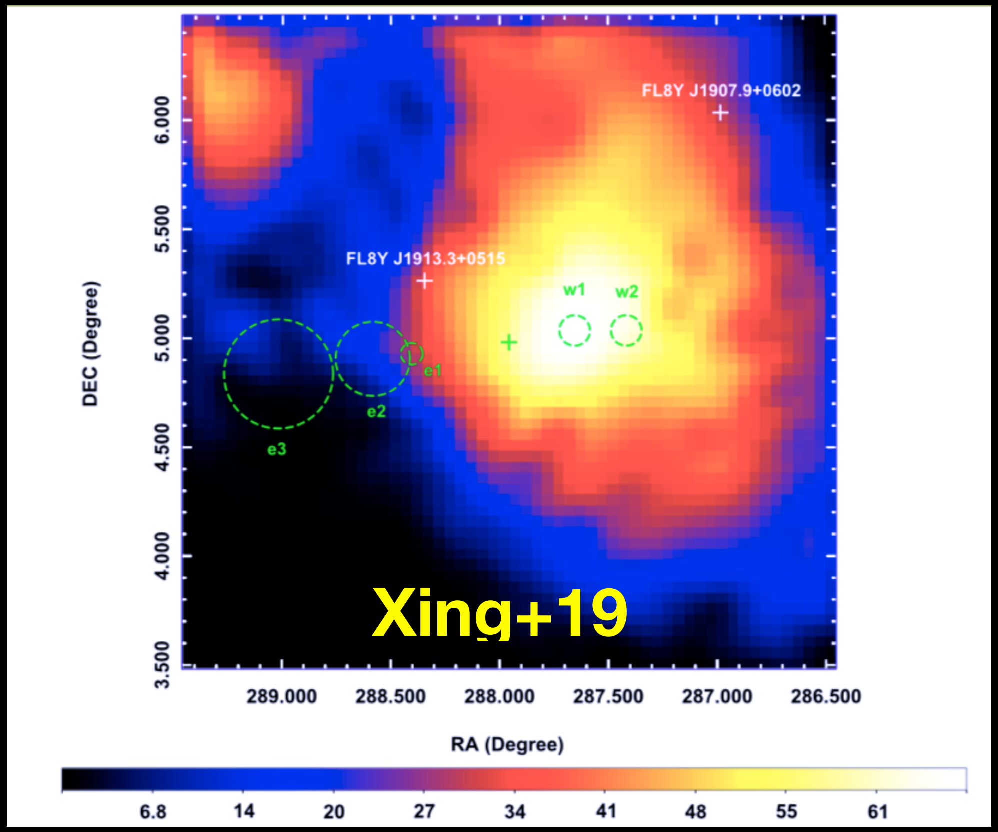
Observed Parameters

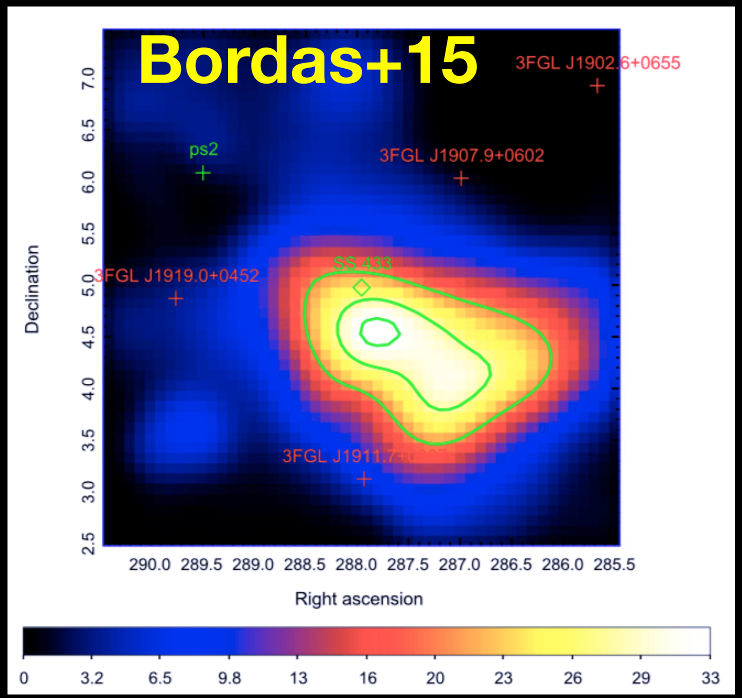
- Jet speed : $v_z = 0.26c$ (though maybe decelerated at knots)
- Jet kinetic energy : $(\Gamma - 1)\dot{M}_{\rm jet}c^2 = 10^{39}$ erg/s, part of which is distributed to the magnetic and electron power
- Define knot region from X-ray data:
  - Radius : ~ 6 pc
  - Location : ~ 30 pc from the binary

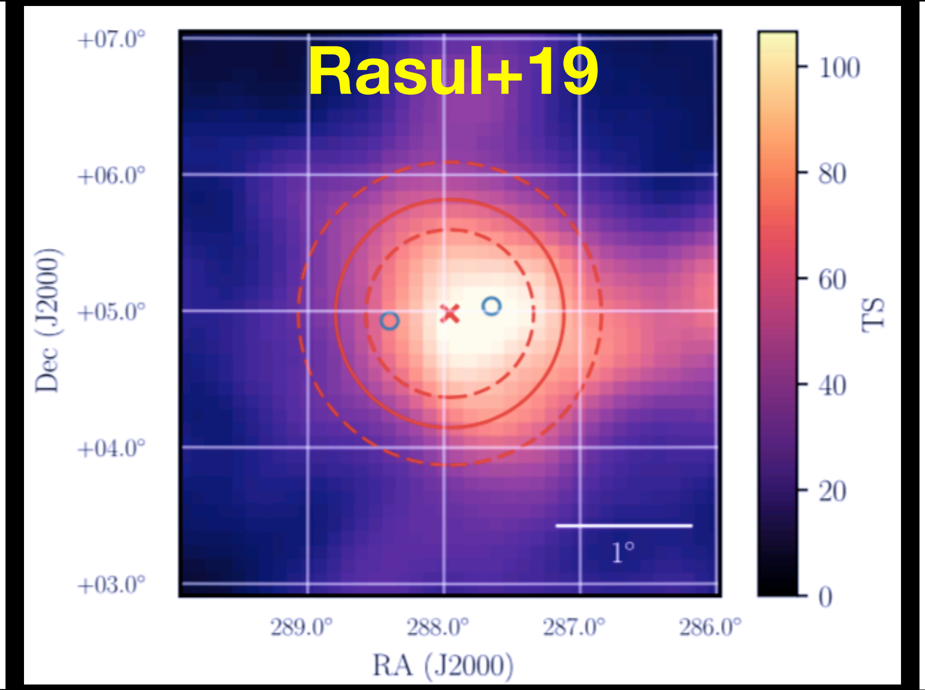


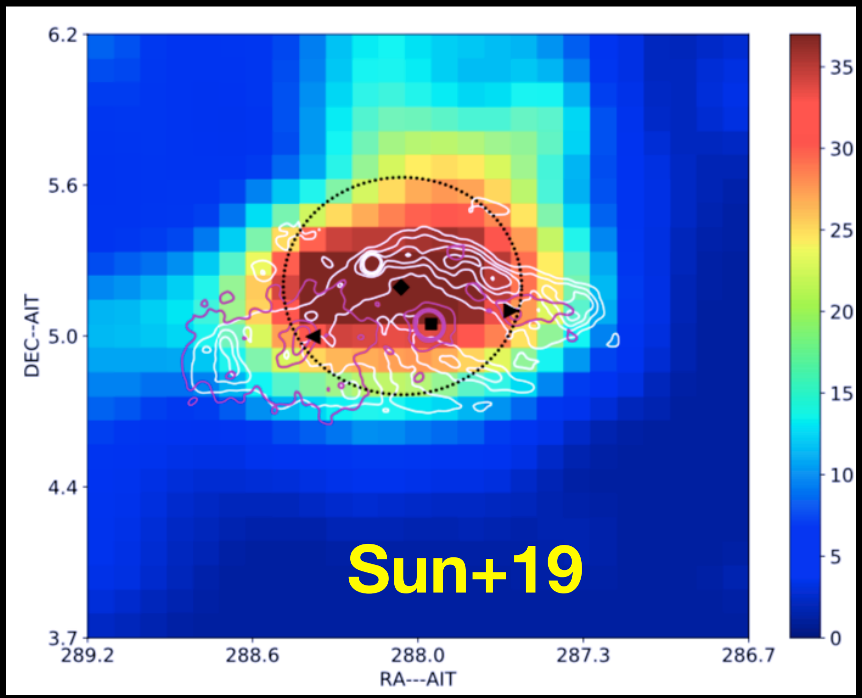
GeV observations

- Various analysis on Fermi data
- Emission region is uncertain
- We treat all GeV data as upper limits on knot emission





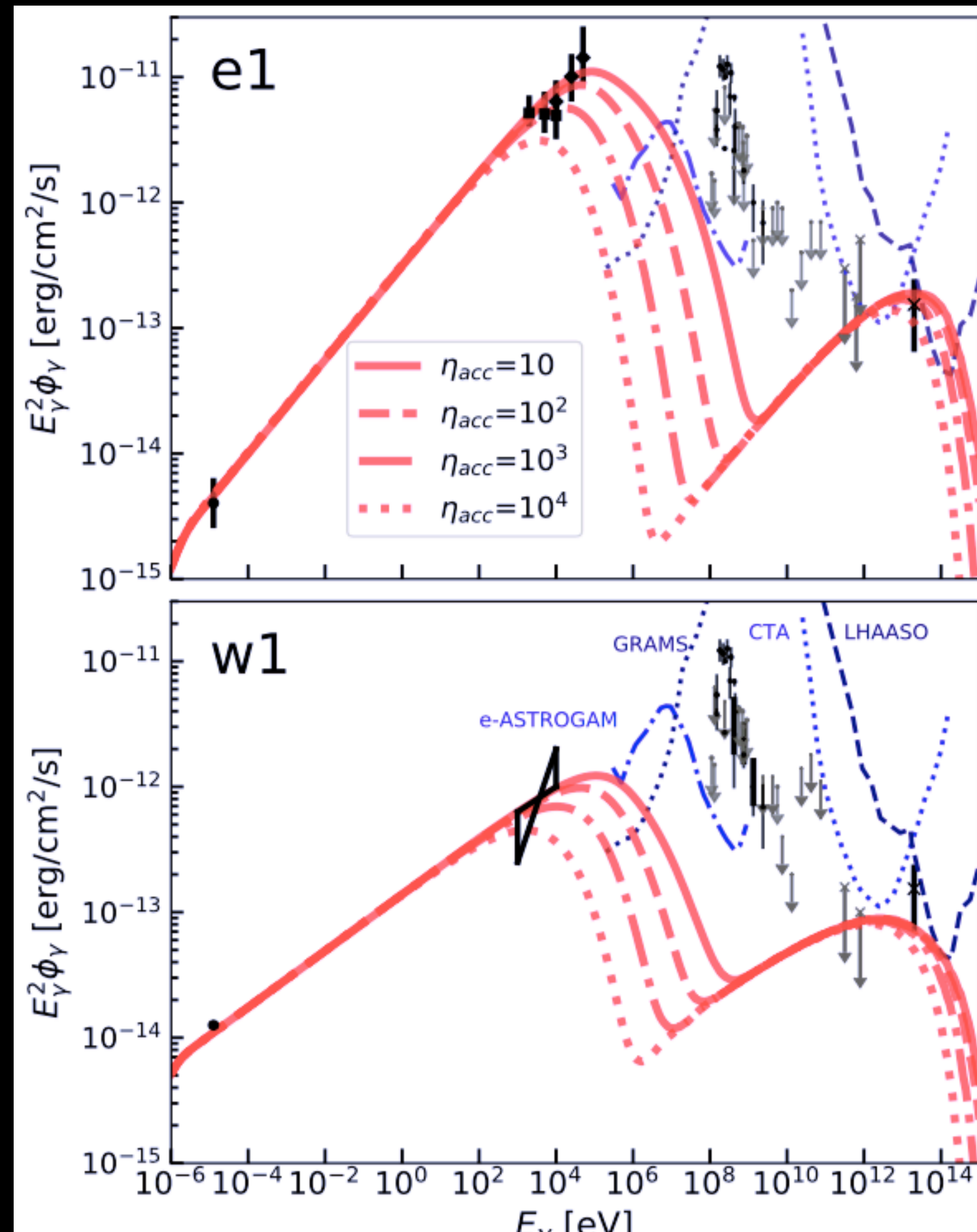




Results

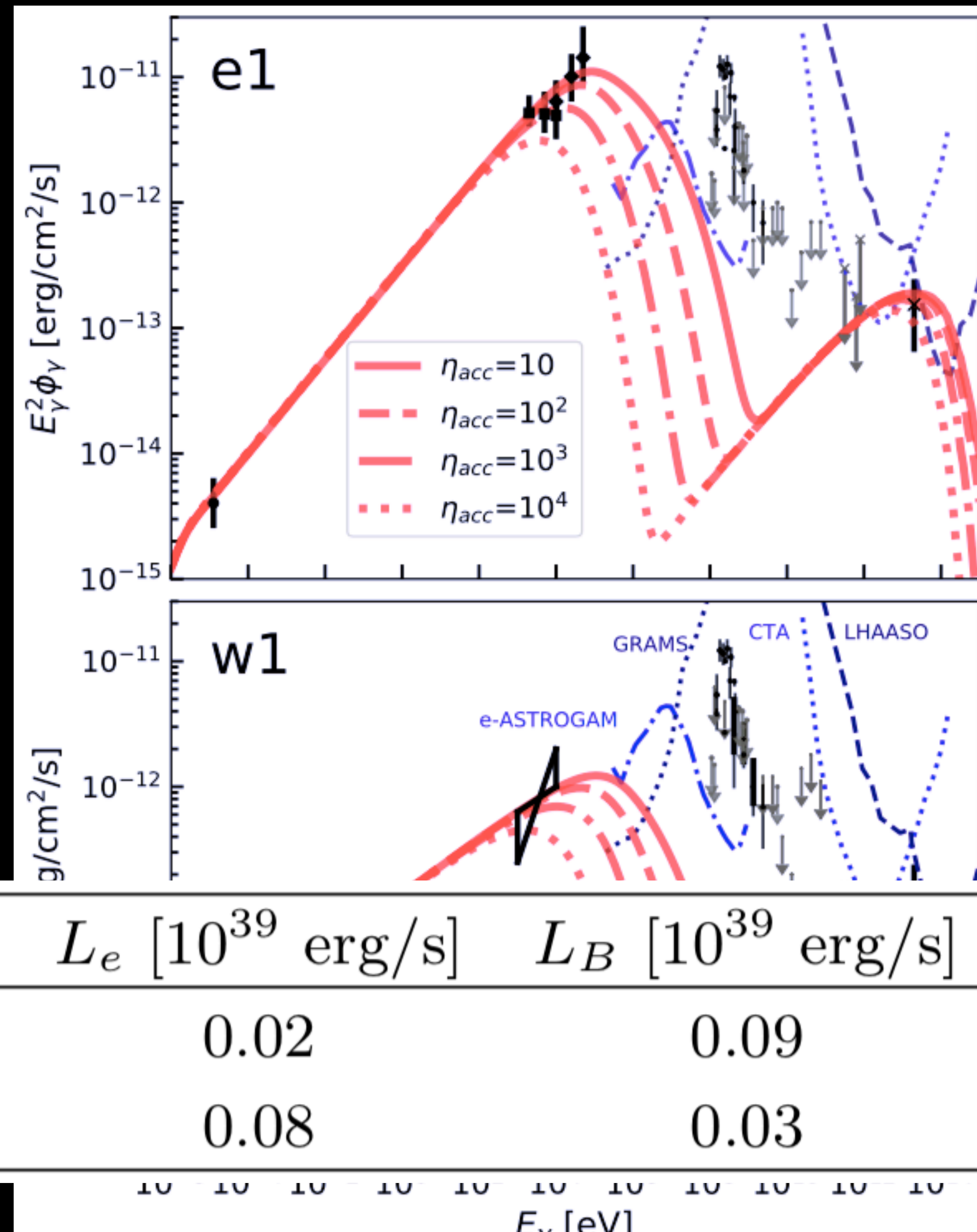
Overall SED

- Overall SED explained with leptonic models for both regions
- Assuming that maximum particle energy is limited by synchrotron loss.



Overall SED

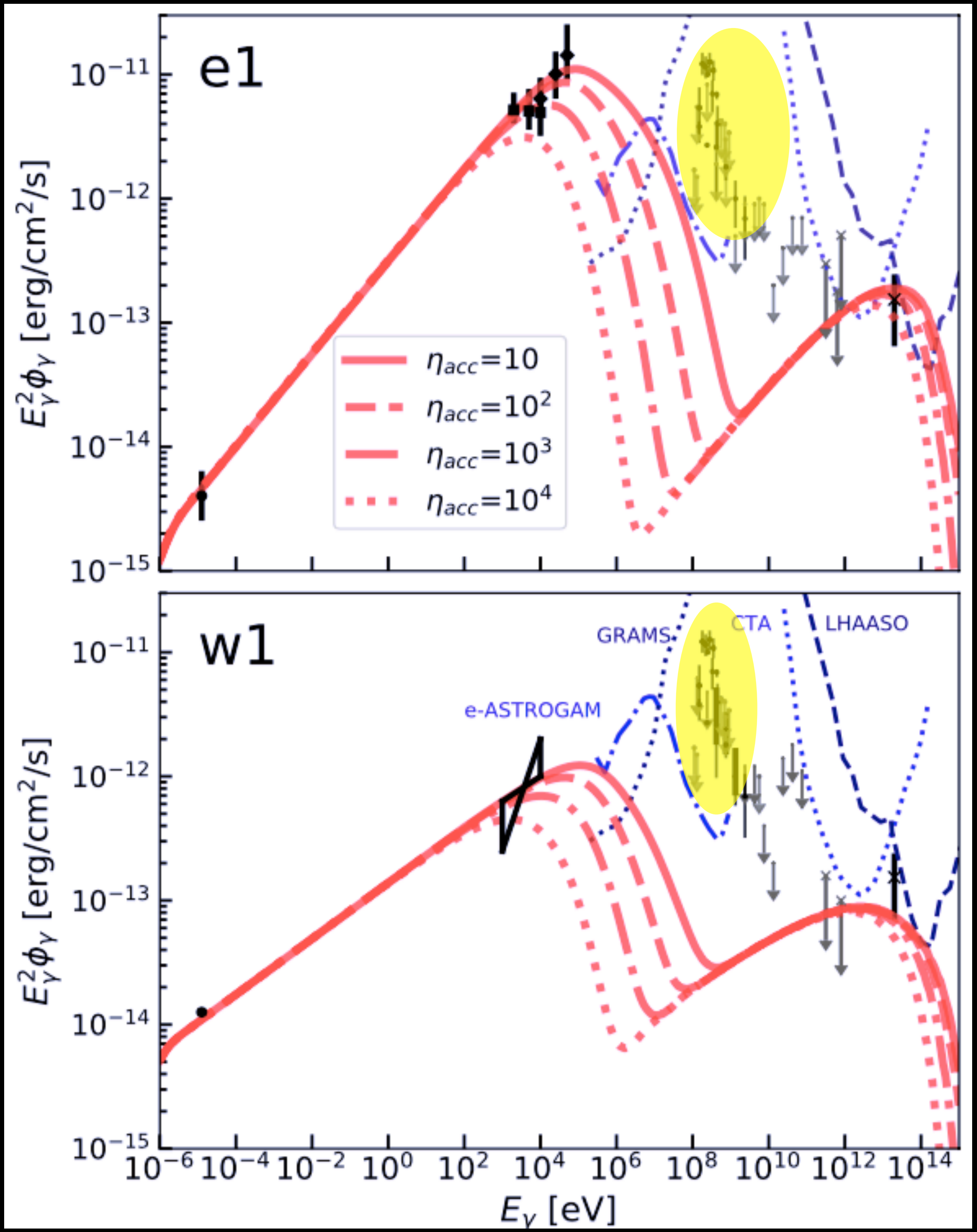
- Overall SED explained with leptonic models for both regions
- Assuming that maximum particle energy is limited by synchrotron loss.
- Derived magnetic fields are 16 μG and 9 μG for e1 and w1



Region	$p_{\rm inj}$	L_e [10^{39} erg/s]	L_B [10^{39} erg/s]
e1	2.25	0.02	0.09
w1	2.55	0.08	0.03

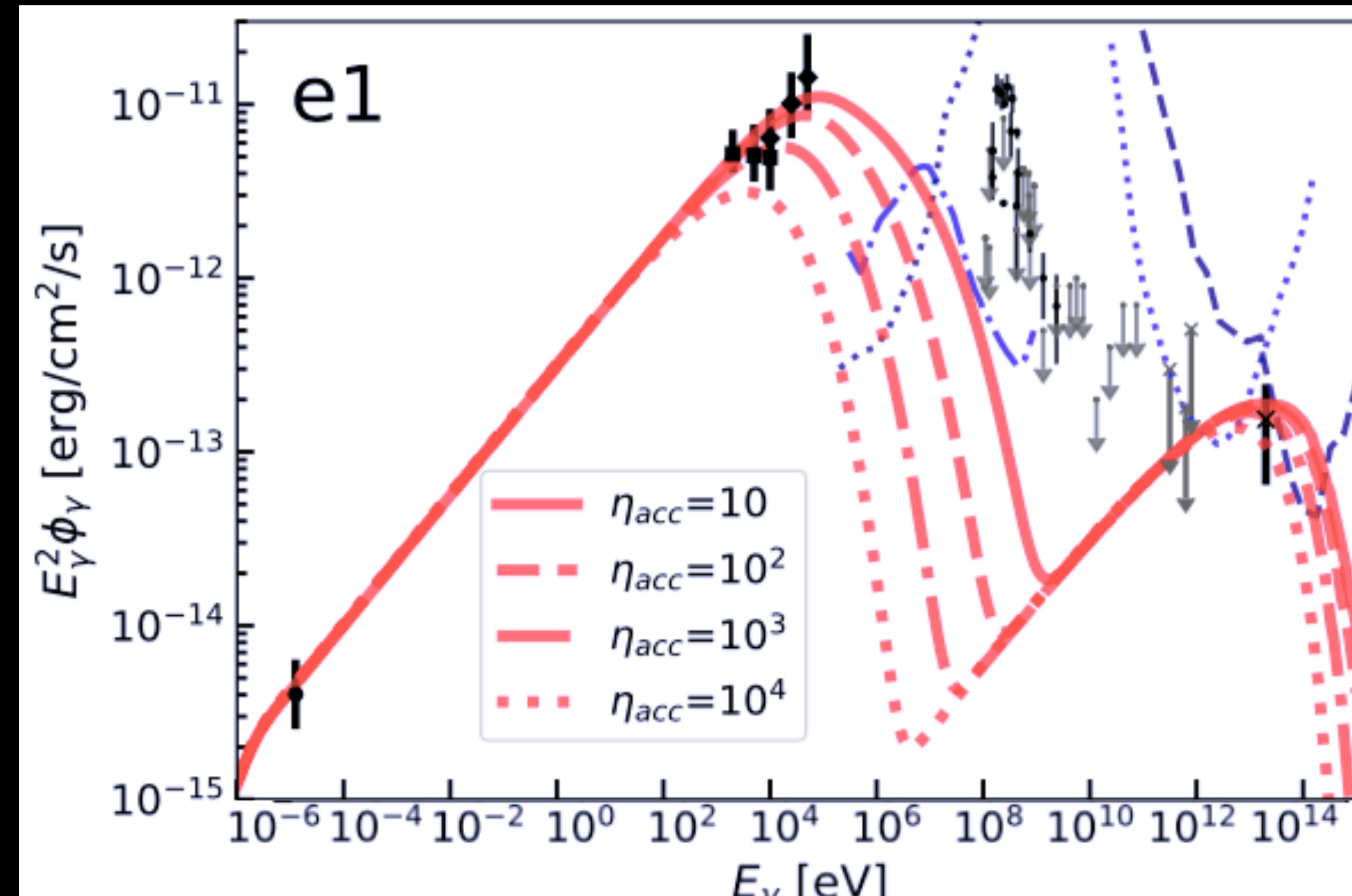
GeV data

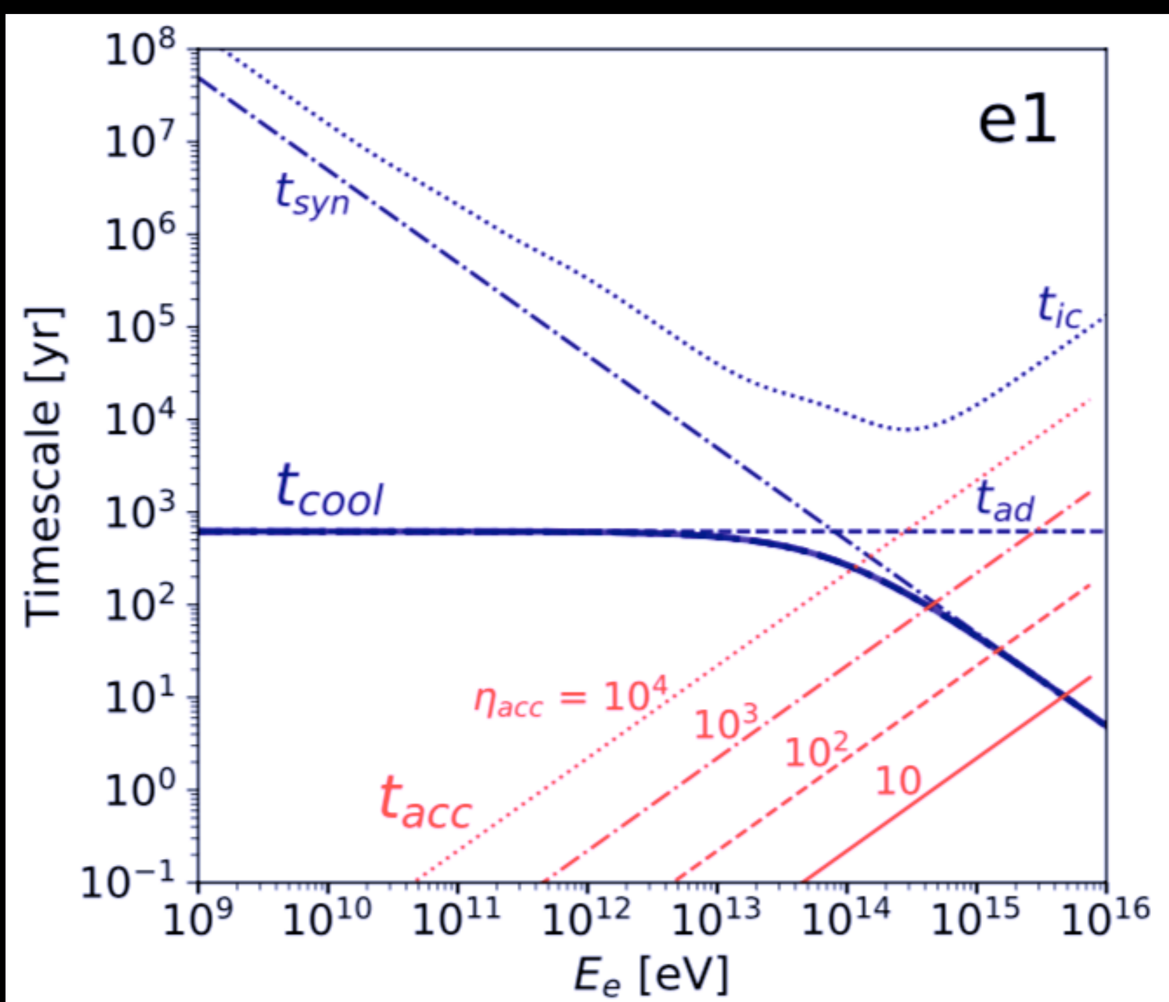
- GeV data remain unexplained within the knot model
- Mostly from other regions? Hadronic emission?

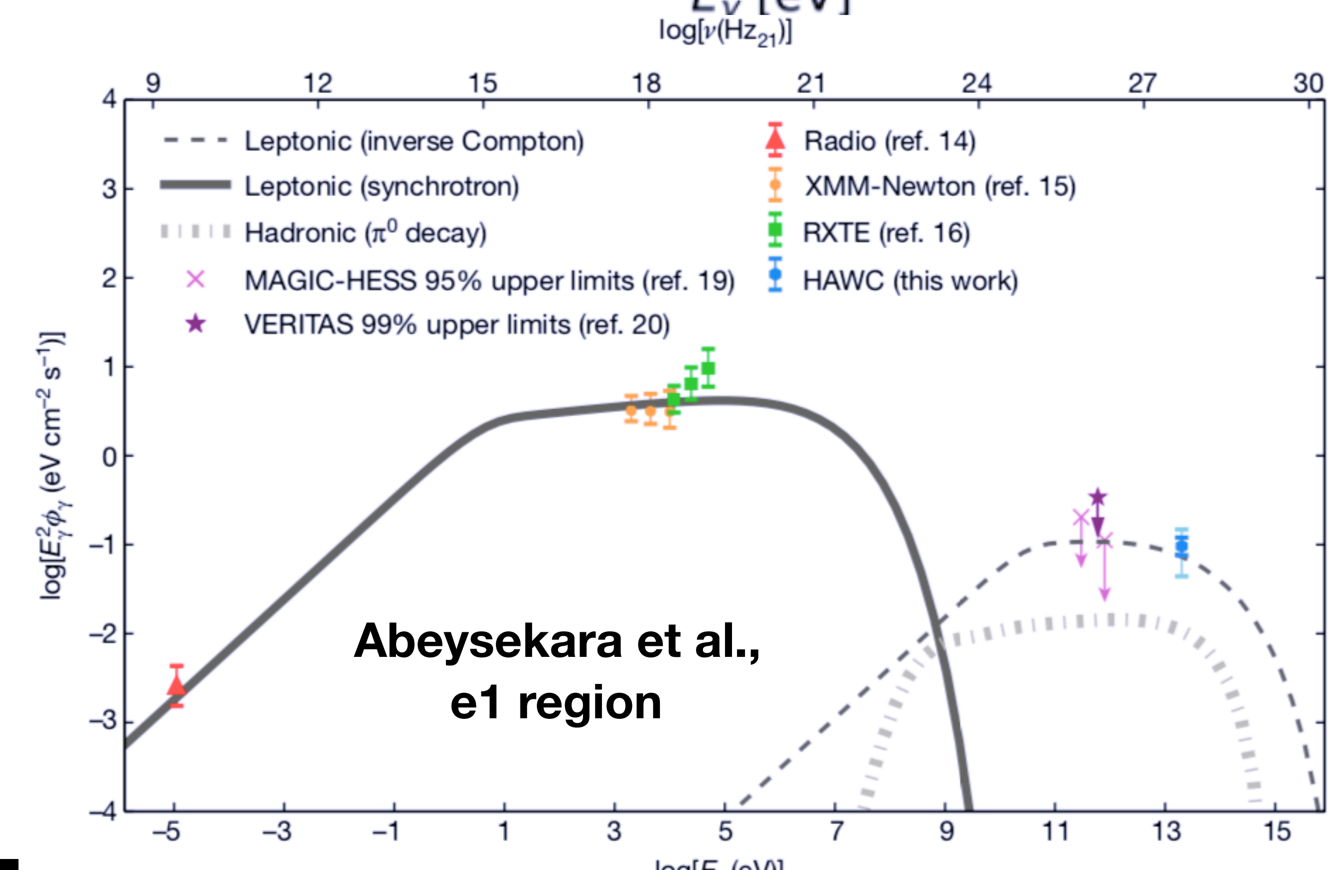


Comparison with other work (e1)

- Very different spectral shape at hard X-ray.
- Adiabatic loss is significant below ~ 100 TeV.

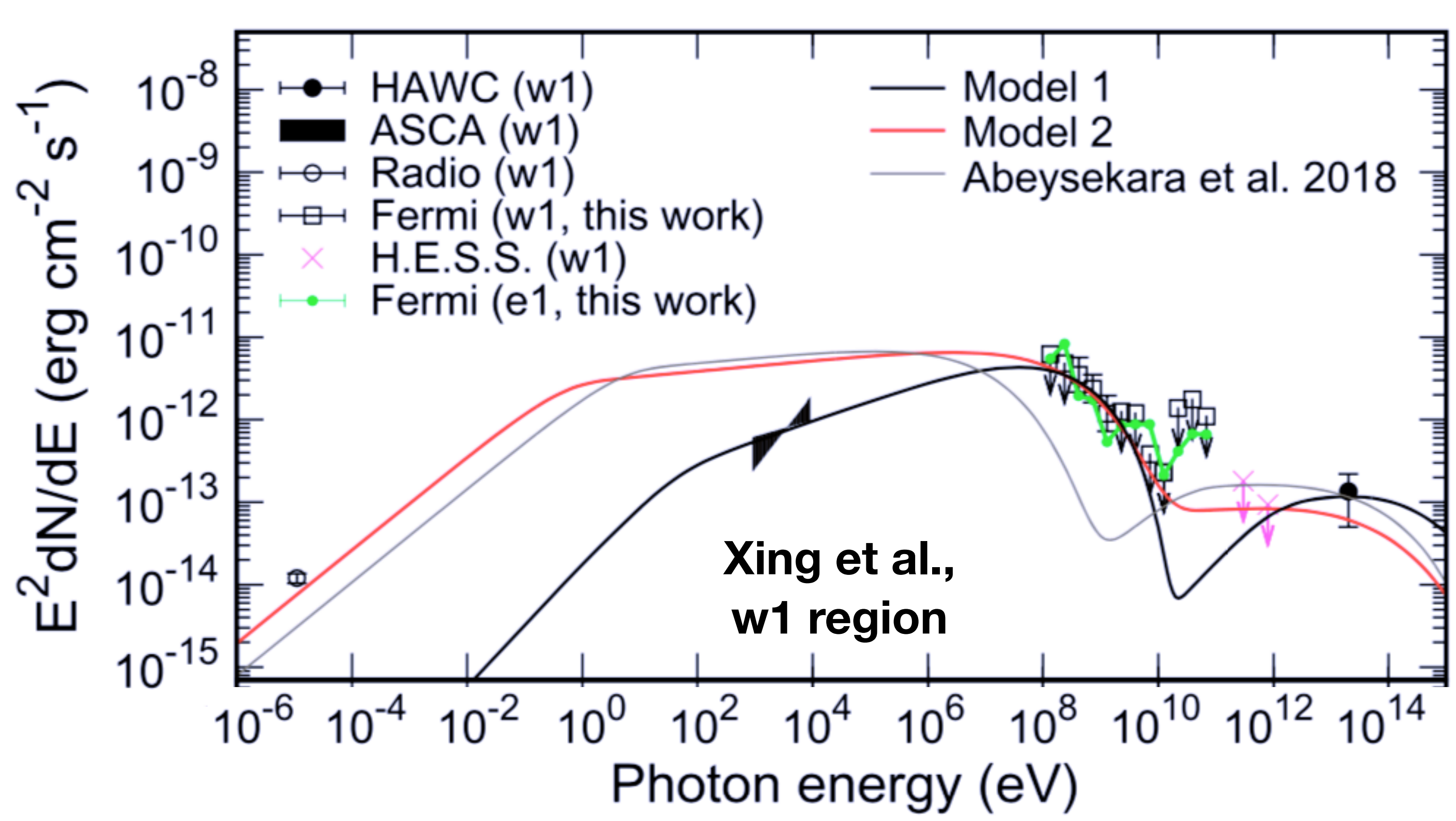


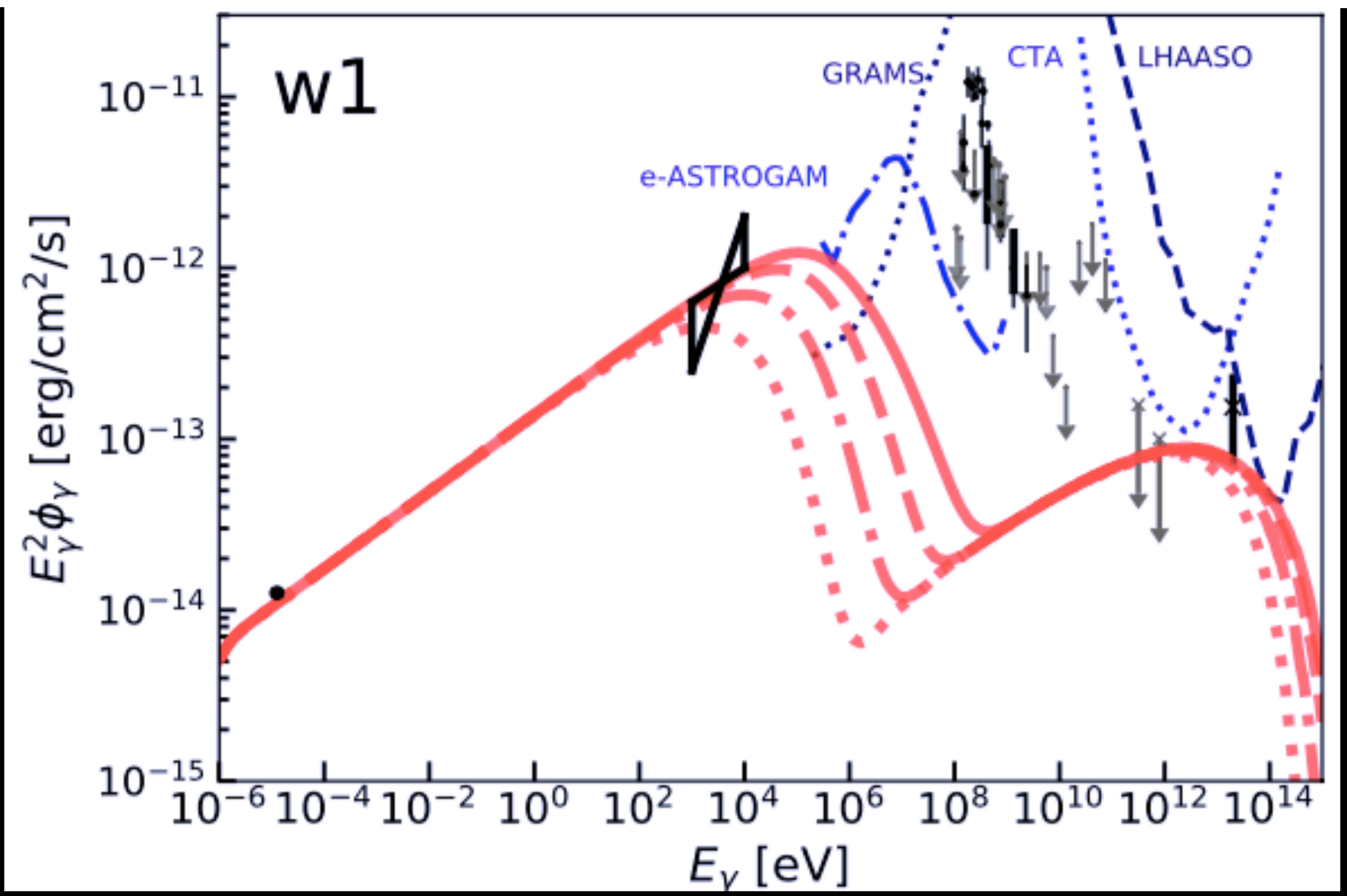




Comparison with other work (w1)

- Radio/X-ray data are explained with our leptonic models
- Electrons are injected with a soft spectral index $p_{\rm inj} = 2.55$ in our case.





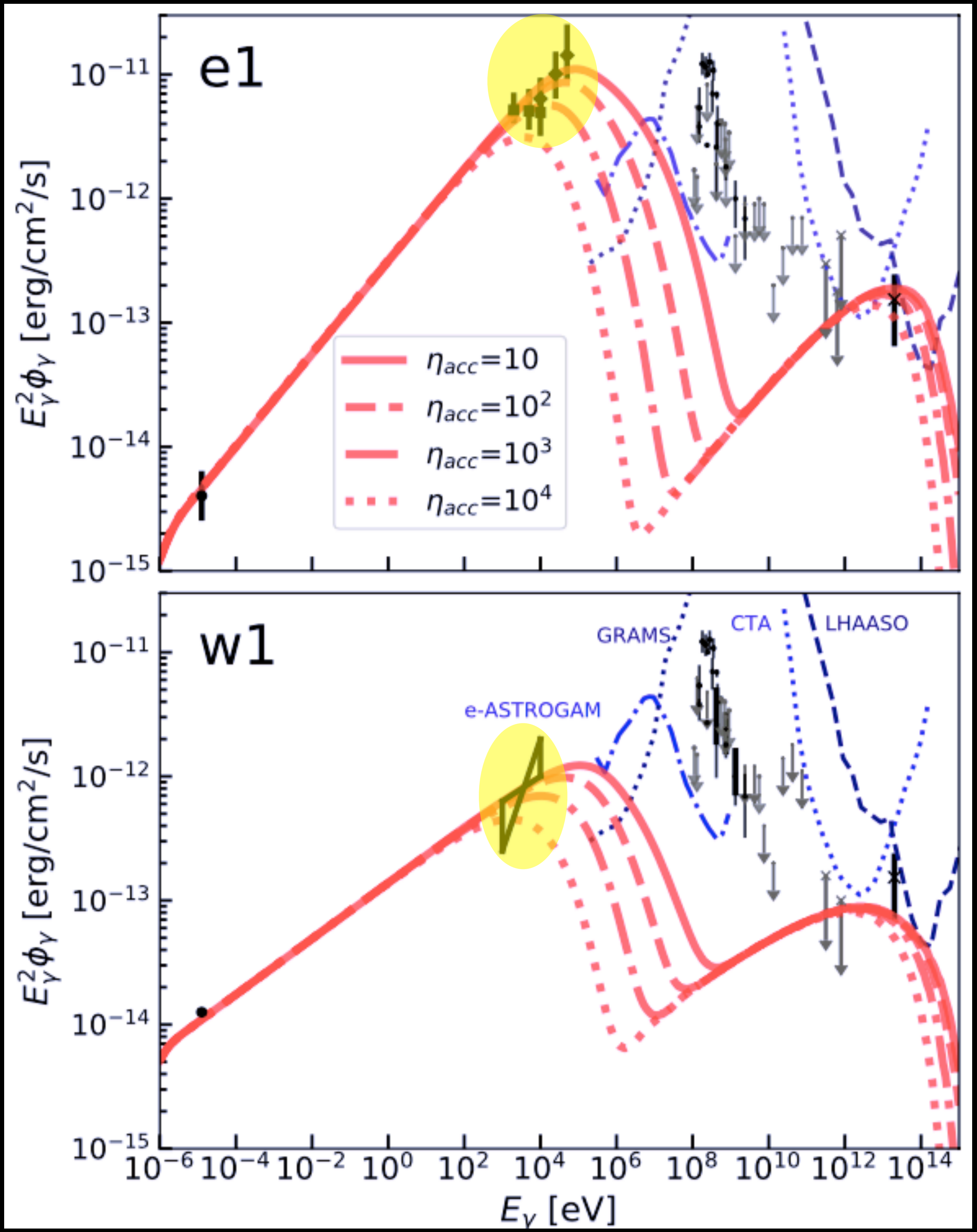
Need for High Acceleration Efficiency

- A high efficiency of $\eta_{\rm acc} \lesssim 10^2$ is needed to explain the X-ray data:

$$E_{\rm e,max}^{\rm syn} = 1.5\ {\rm PeV} \left(\frac{\eta_{\rm acc}}{10^2}\right)^{-1/2} \left(\frac{B}{16\ \mu G}\right)^{-1/2}$$

- This suggests the presence of PeV protons:

$$E_{\rm p,max}^{\rm con} = 6\ {\rm PeV} \left(\frac{\eta_{\rm acc}\eta_g}{10^2}\right)^{-1/2}$$

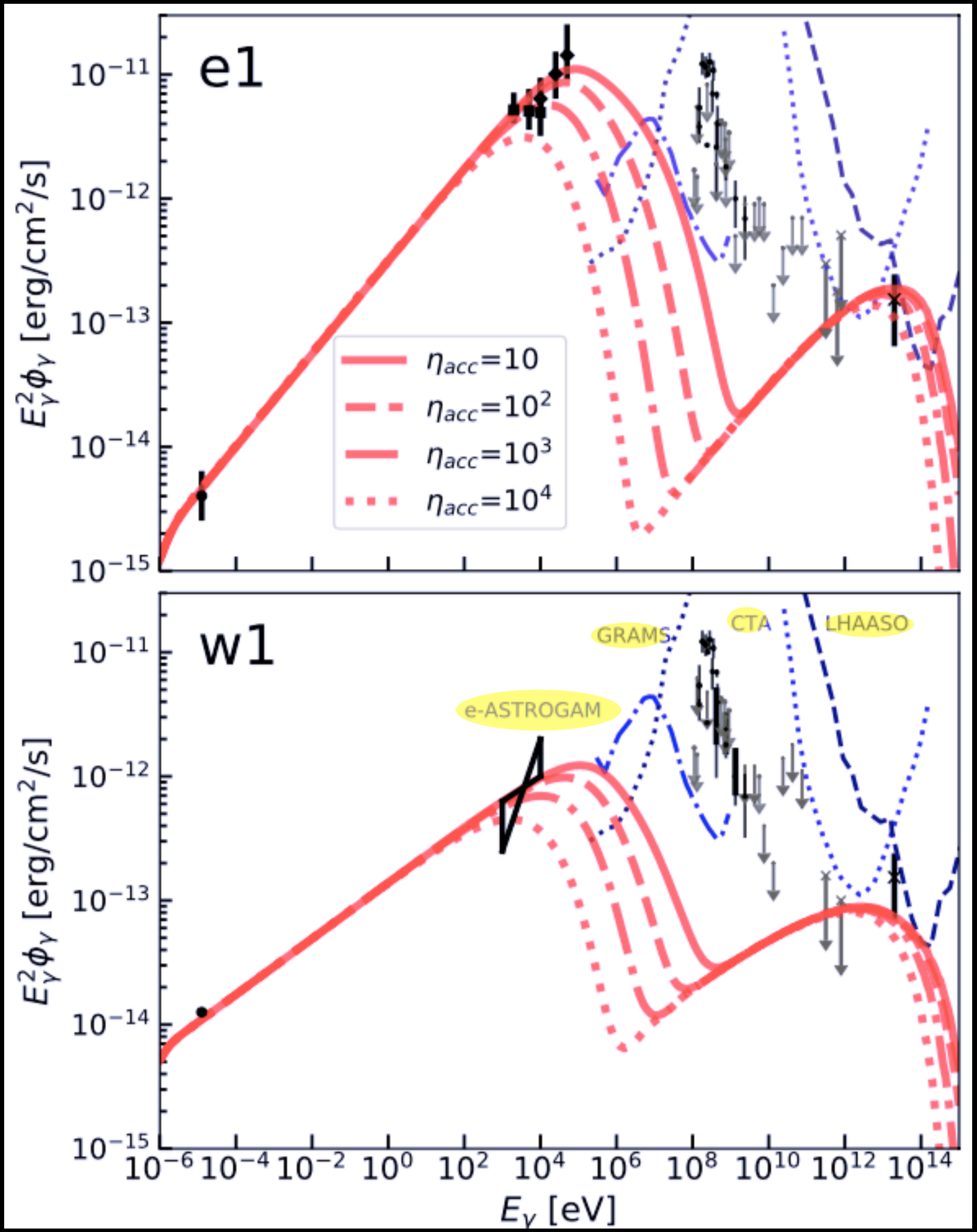


Need for High Acceleration Efficiency

- We require $\eta_{\rm acc} \lesssim 10^2$ to explain the X-ray data
- The diffusive shock acceleration could work, if diffusion should be close to the Bohm limit.
- $\eta_{\rm acc}^{\rm DSA} = \dfrac{200}{\eta_g} \left(\dfrac{\beta_{\rm sh}}{0.26} \right)^{-2}$
- The stochastic acceleration may be inefficient, though not ruled out.
- $\eta_{\rm acc}^{\rm SA} \simeq \dfrac{10^3}{\xi_B} \left(\dfrac{\dot{M}}{10^{-7}\ M_{\odot}/yr} \right)$, where $\xi_B = (\delta B/B)^2$

Future Prospects

- Hard X-ray and MeV gamma-ray observations will detect spectral turnover and cutoff
- Critical test of our models and strong constraints on $\eta_{\rm acc}$
- CTA and LHAASO may also detect VHE emission (though not guaranteed, especially for w1 region)



Summary

Summary

- Overall spectral energy distribution from `e1/w1` can be explained with our simple leptonic models.
- GeV data remain unexplained: from other regions and/or hadronic component?
- Need a very high efficiency of $\eta_{\rm acc} \lesssim 10^2$: could be realized by DSA near Bohm limit?
- Future hard X-ray and MeV gamma-ray observations will critically test our models.