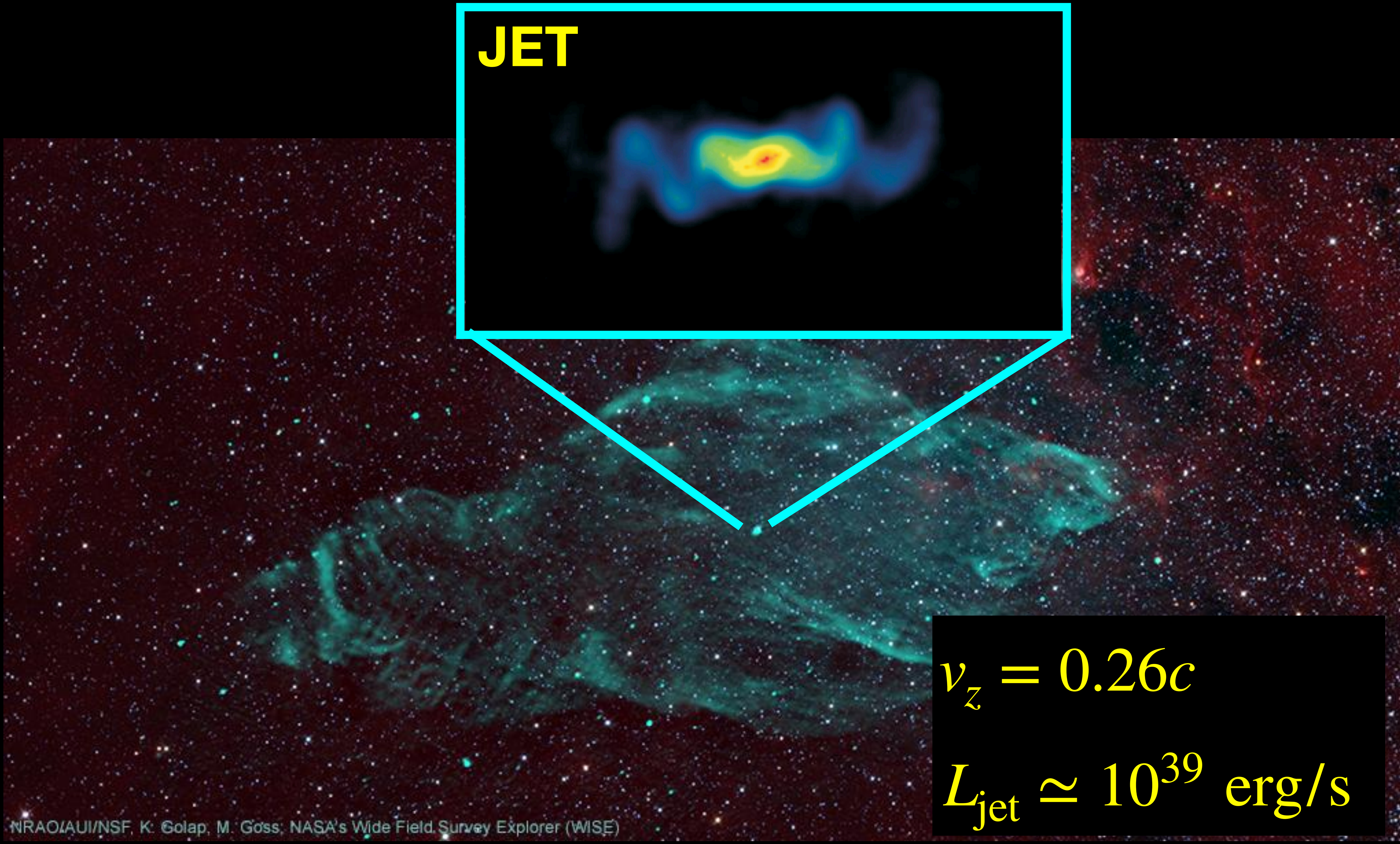
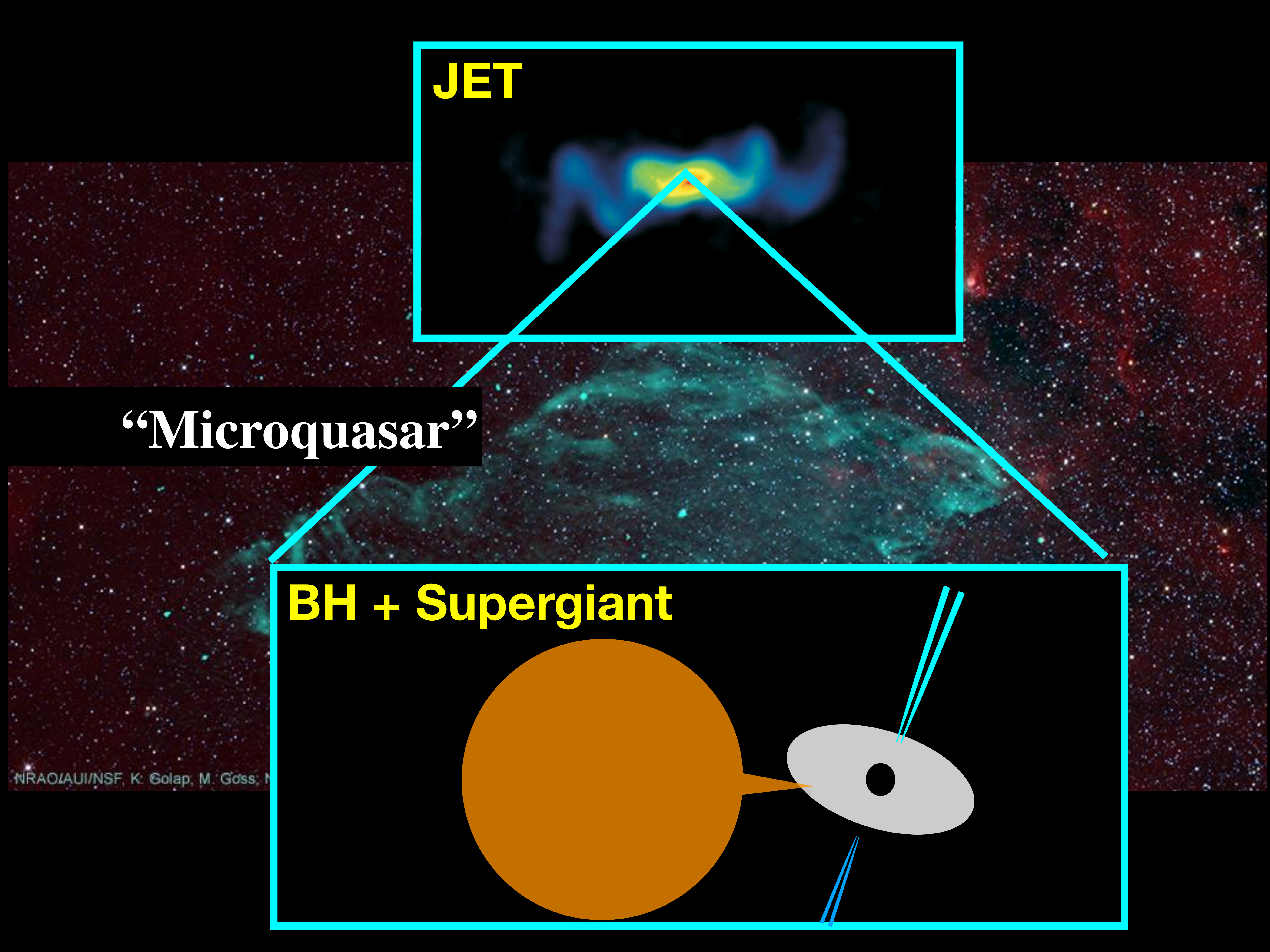
# Probing Particle Acceleration in the Jets of the Microquasar SS433 with MeV gamma rays

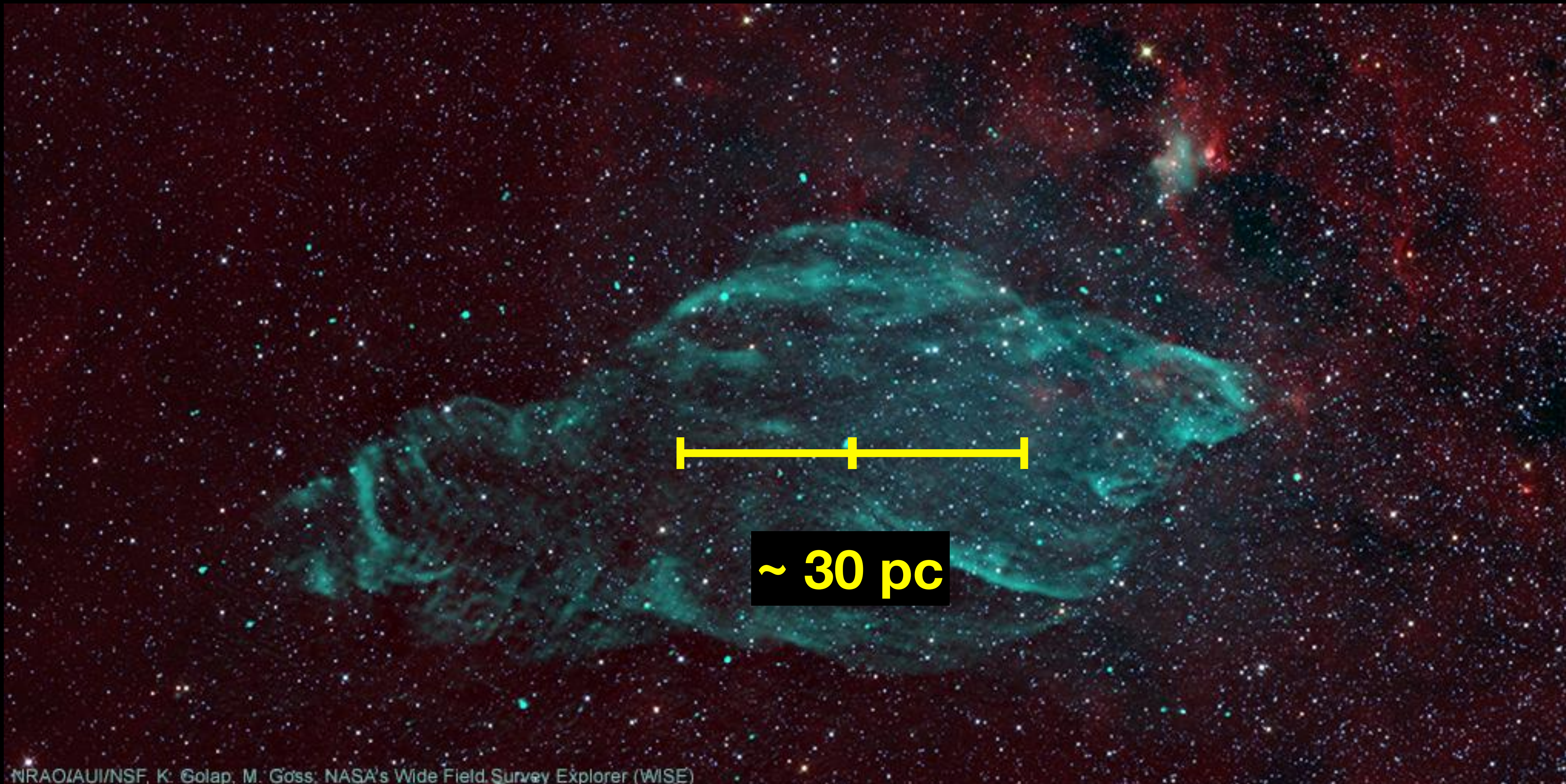

Takahiro Sudoh (Univ. of Tokyo)

with/ Dmitry Khangulyan, Yoshiyuki Inoue

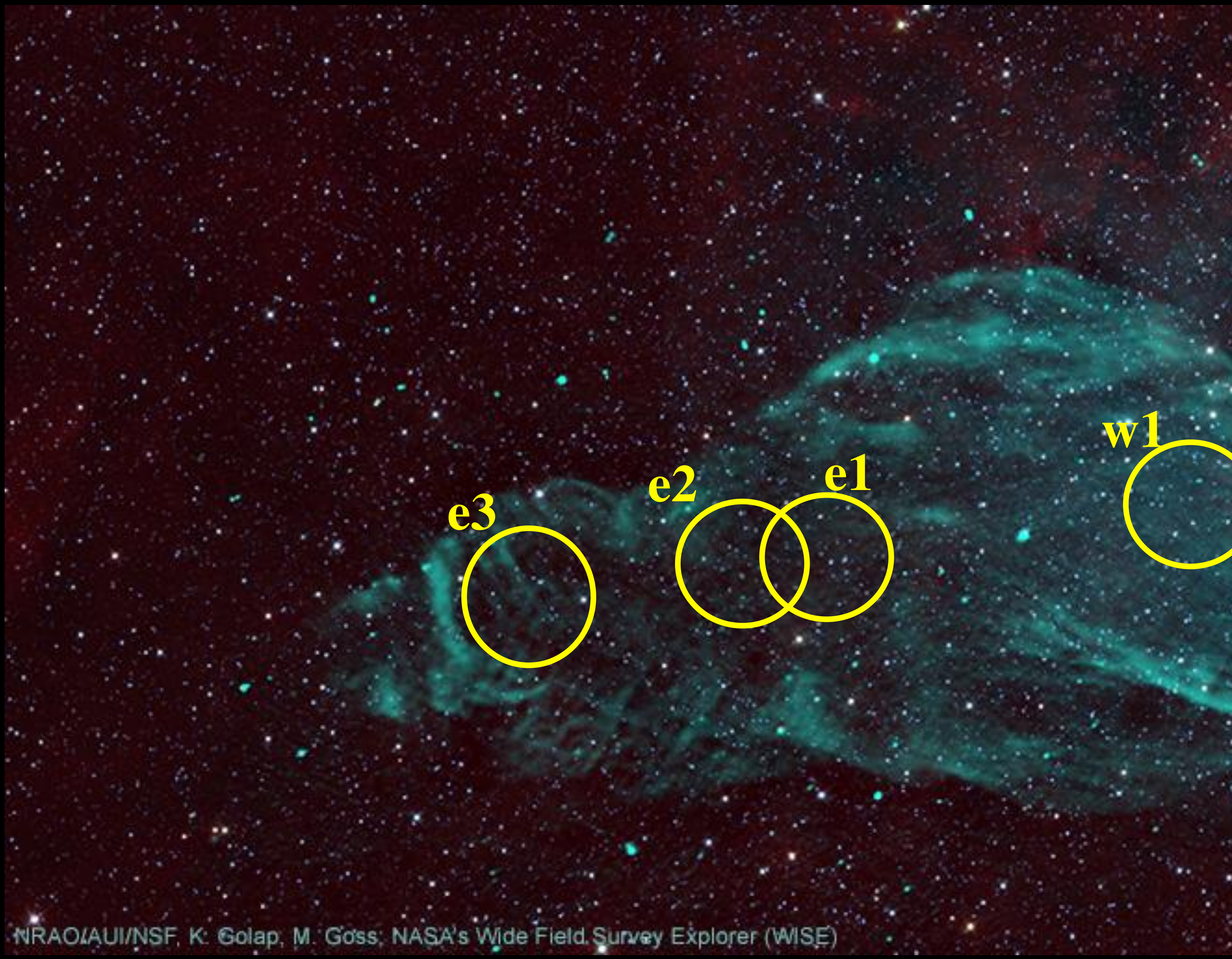

NRAO/AUI/NSF, K. Golap, M. Goss; NASA's Wide Field Survey Explorer (WISE)

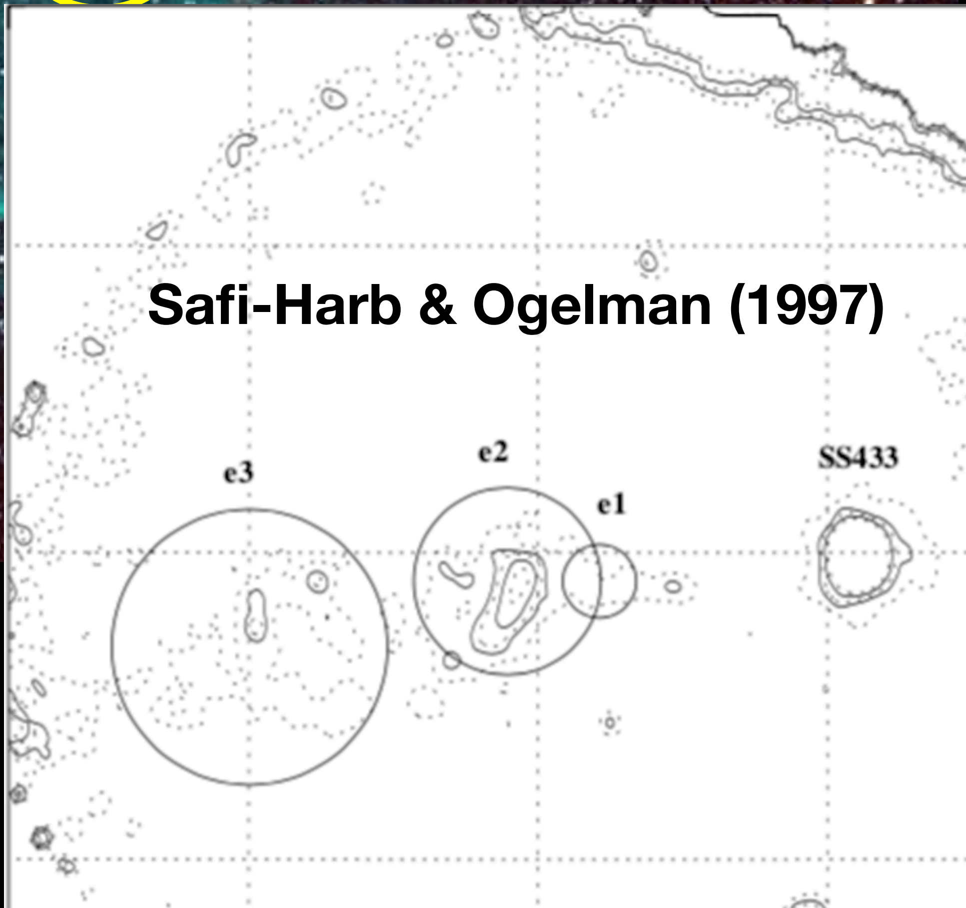

JET
$v_z = 0.26c$
$L_{\rm jet} \simeq 10^{39}$ erg/s
NRAO/AUI/NSF, K. Golap, M. Goss; NASA's Wide Field Survey Explorer (WISE)


JET
“Microquasar”
BH + Supergiant
NRAO/AUI/NSF, K. Golap, M. Goss; N

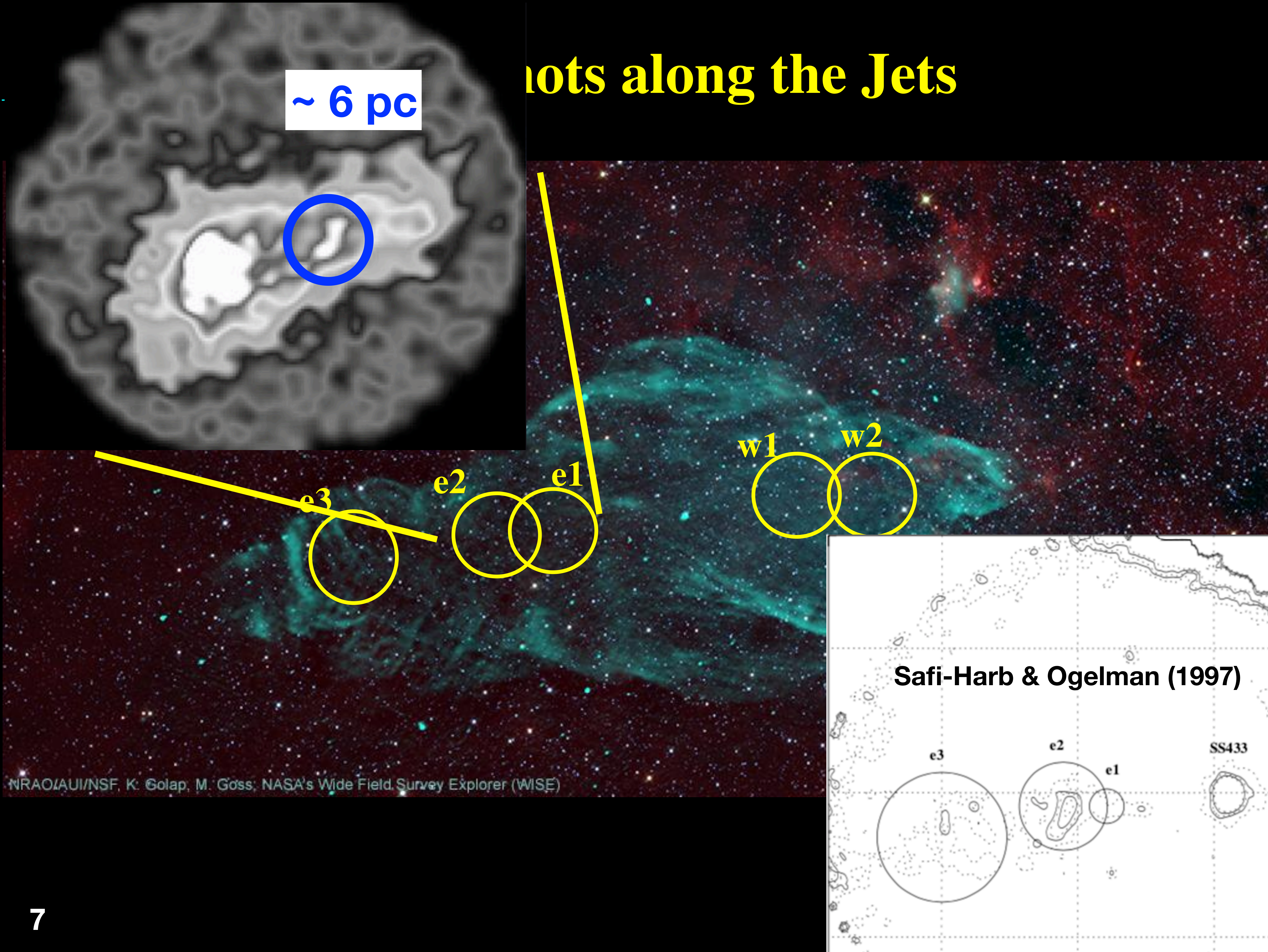

~ 30 pc
NRAO/AUI/NSF, K. Golap, M. Goss; NASA's Wide Field Survey Explorer (WISE)

# X-ray knots along the Jets

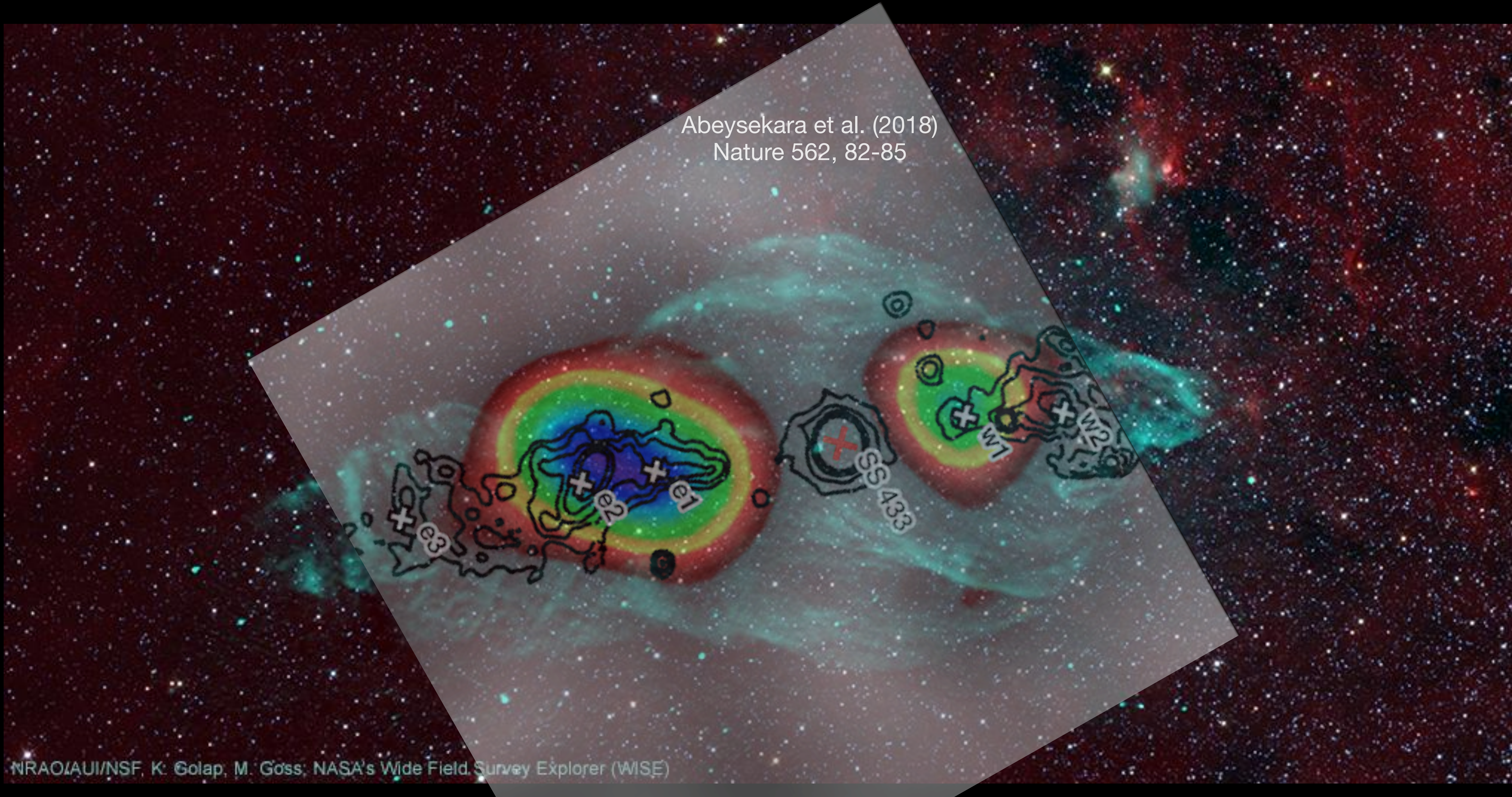


# ots along the Jets

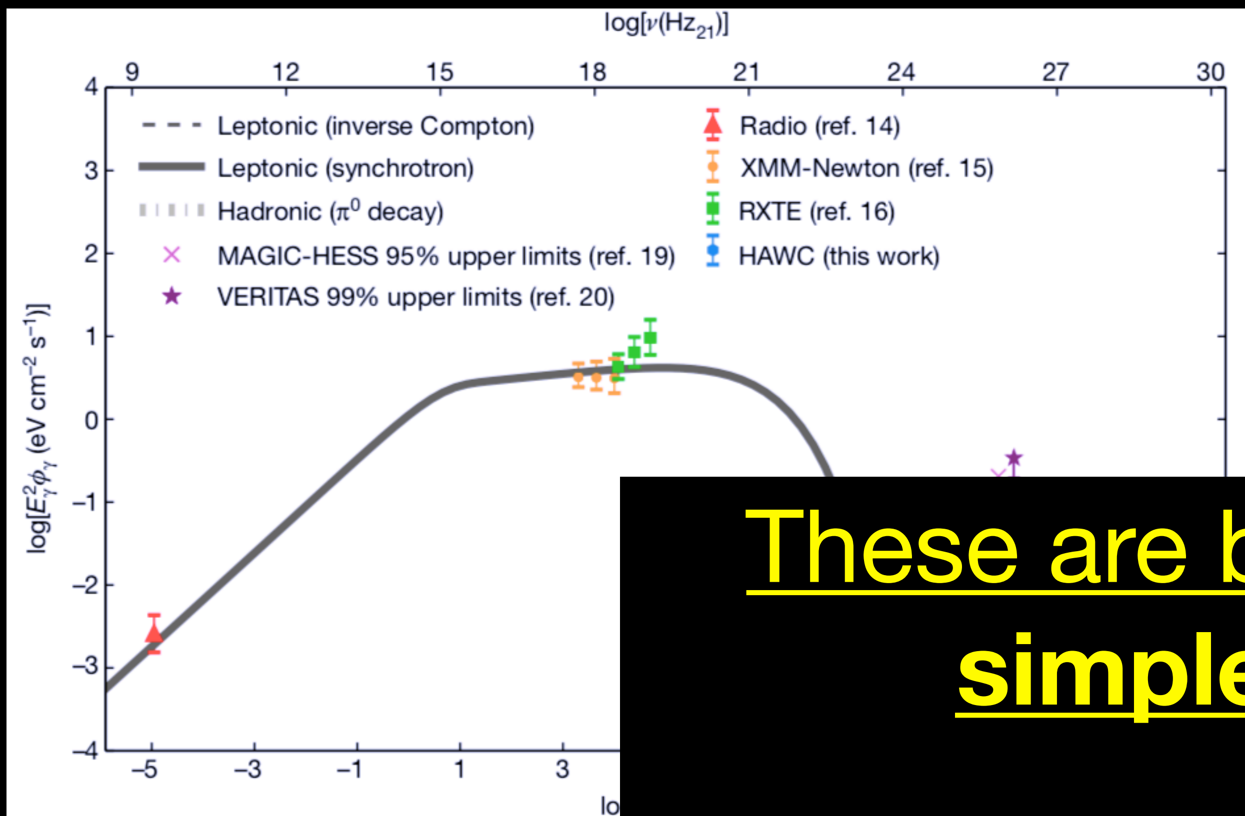


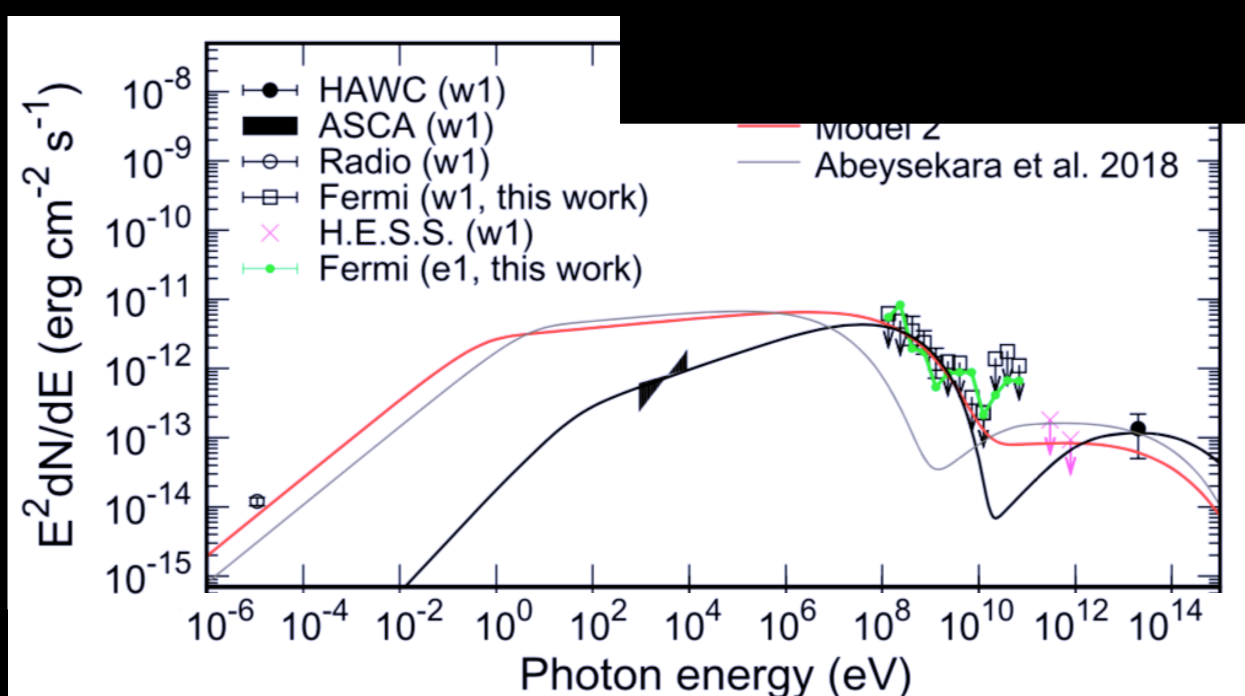
# VHE photons from knots




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

# Interpretations ?



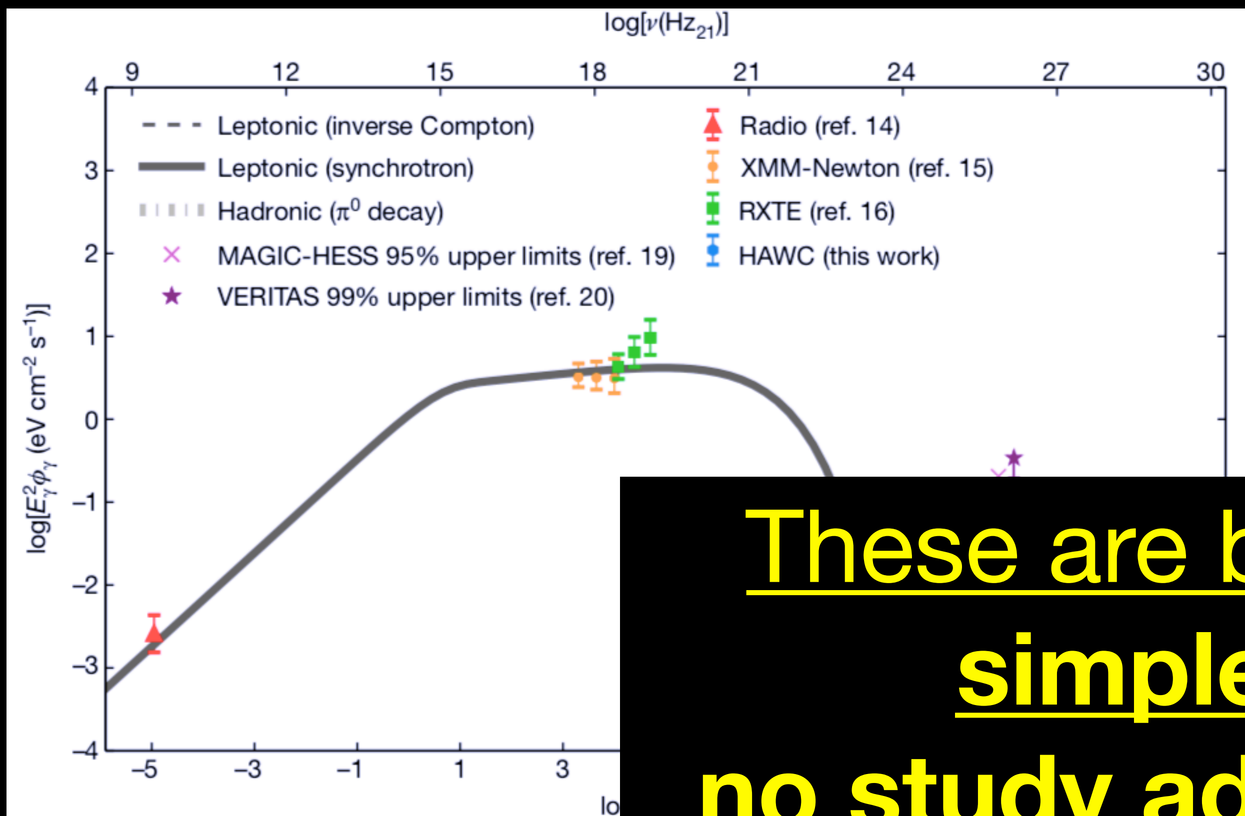



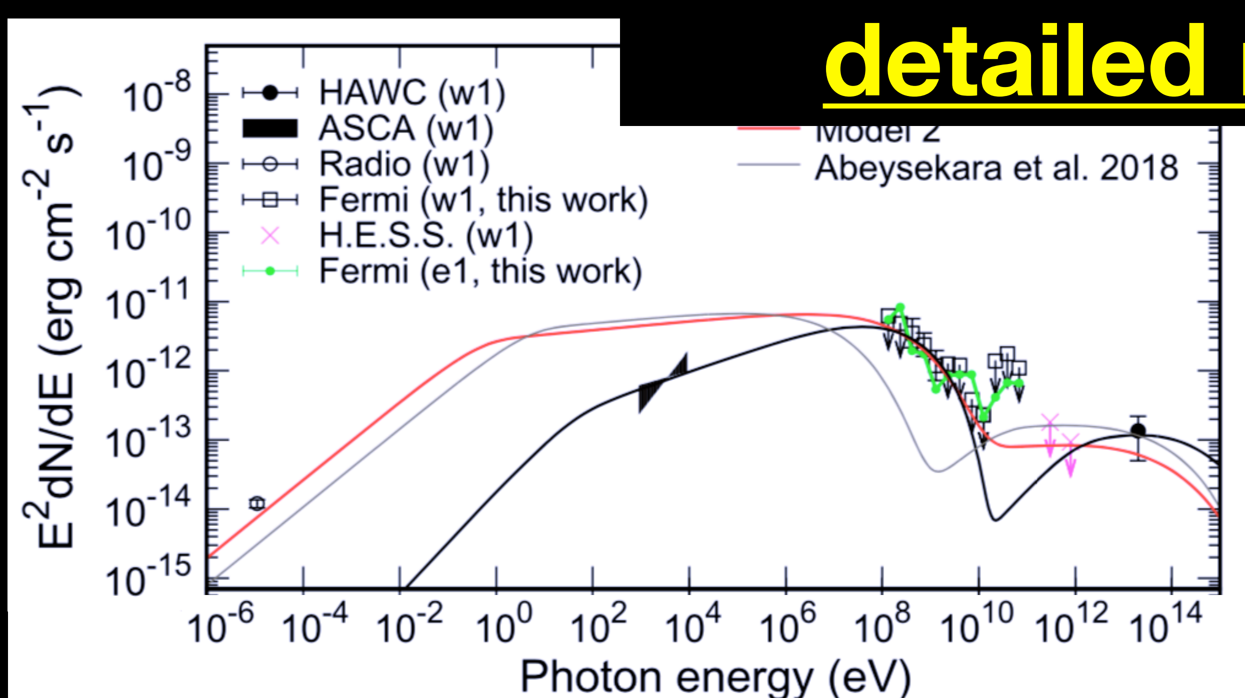

- Abeysekara et al. (2018) :
  - e1 region
  - [redacted]

These are based on **very simple** models;

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

# Interpretations ?




These are based on **very simple** models;

**no study addresses more detailed models yet.**

- Abeysekara et al. (2018) :
  - e1 region
  - el fits
  - ED
- Xing et al. (2019) :
  - w1 region
  - leptonic model does not 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

# Our Work

- We use a more detailed model of nonthermal emission from microquasar jet, with aim of :
  - see whether leptonic model works
    → **It works**
  - quantify acceleration efficiency
    → **Very high (nearly Bohm limit)**
  - make predictions for future observations
    → **Hard X-ray / MeV gamma-ray is the key**

# Model

# Particle Production

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

- Acceleration : parametrized as $t_{\rm acc} = \eta_{\rm acc}\dfrac{r_L}{c}$
- 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 $D = \eta_g D_{\rm Bohm} = \eta_g \dfrac{cr_L}{3}$

## Particle Cooling

- Cooling due to adiabatic and radiative (synchrotron and inverse Compton) losses.
- We include adiabatic loss : $\dot{\gamma}_{\mathrm{ad}} = \frac{\gamma}{3}\frac{d\ln\rho}{dt} = -\frac{2}{3}\frac{v_z}{\Gamma R(z)}\frac{\partial R}{\partial z}\gamma$
- 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 Eq. describes evolution of spatial-energy density :

$$\frac{\partial n(\gamma, z, t)}{\partial t} + v_z \frac{\partial n(\gamma, z, t)}{dz} + \frac{\partial}{\partial \gamma}[\dot{\gamma} n(\gamma, z, t)] = \dot{q}(\gamma)\delta(z - z_0)$$

- Steady injection above energy of 1 GeV : $\dot{q}(\gamma) \propto \gamma^{-p_{\mathrm{inj}}}$

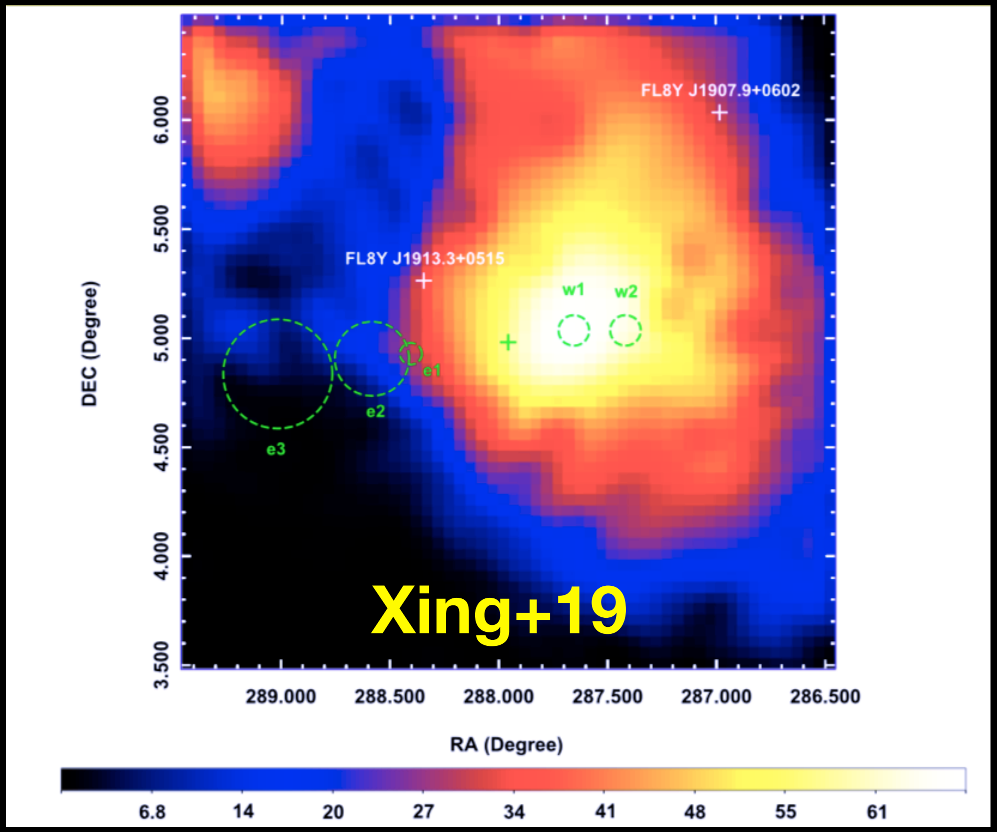
- Integrate to obtain electron spectrum in the knots:

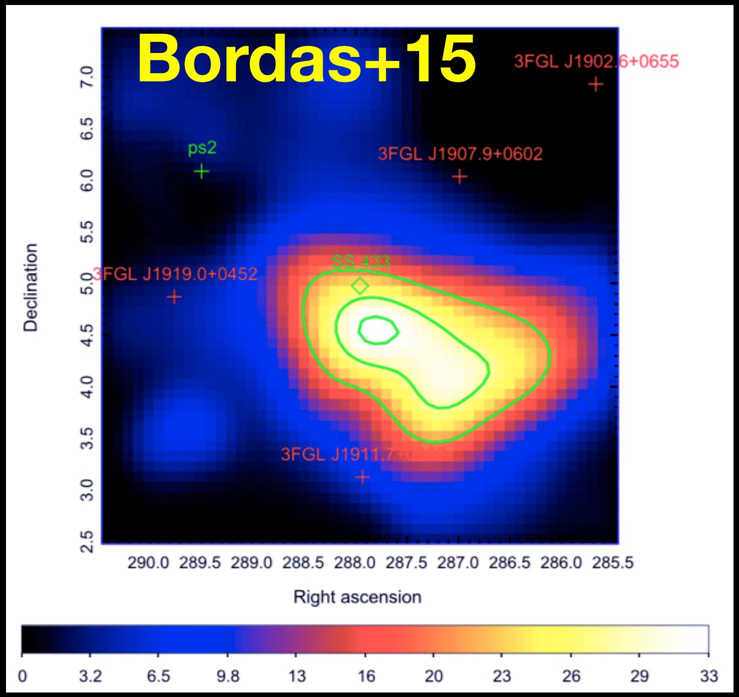
$$\frac{dN}{d\gamma} = \int_{z_0}^{z_1} n dz$$

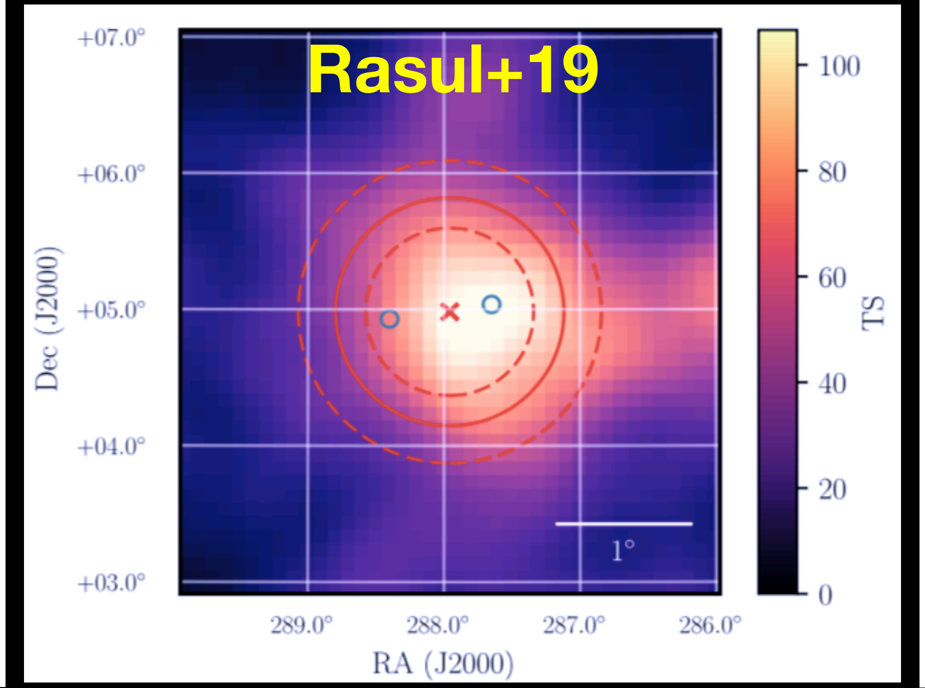
- Emission from electrons : Synchrotron + Inverse-Compton

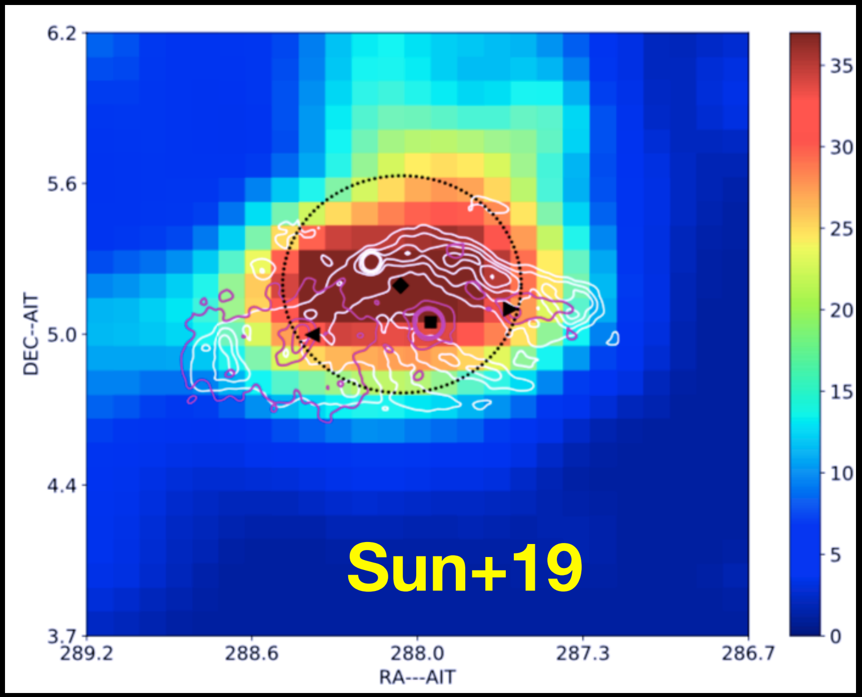
# Comment on GeV observations

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



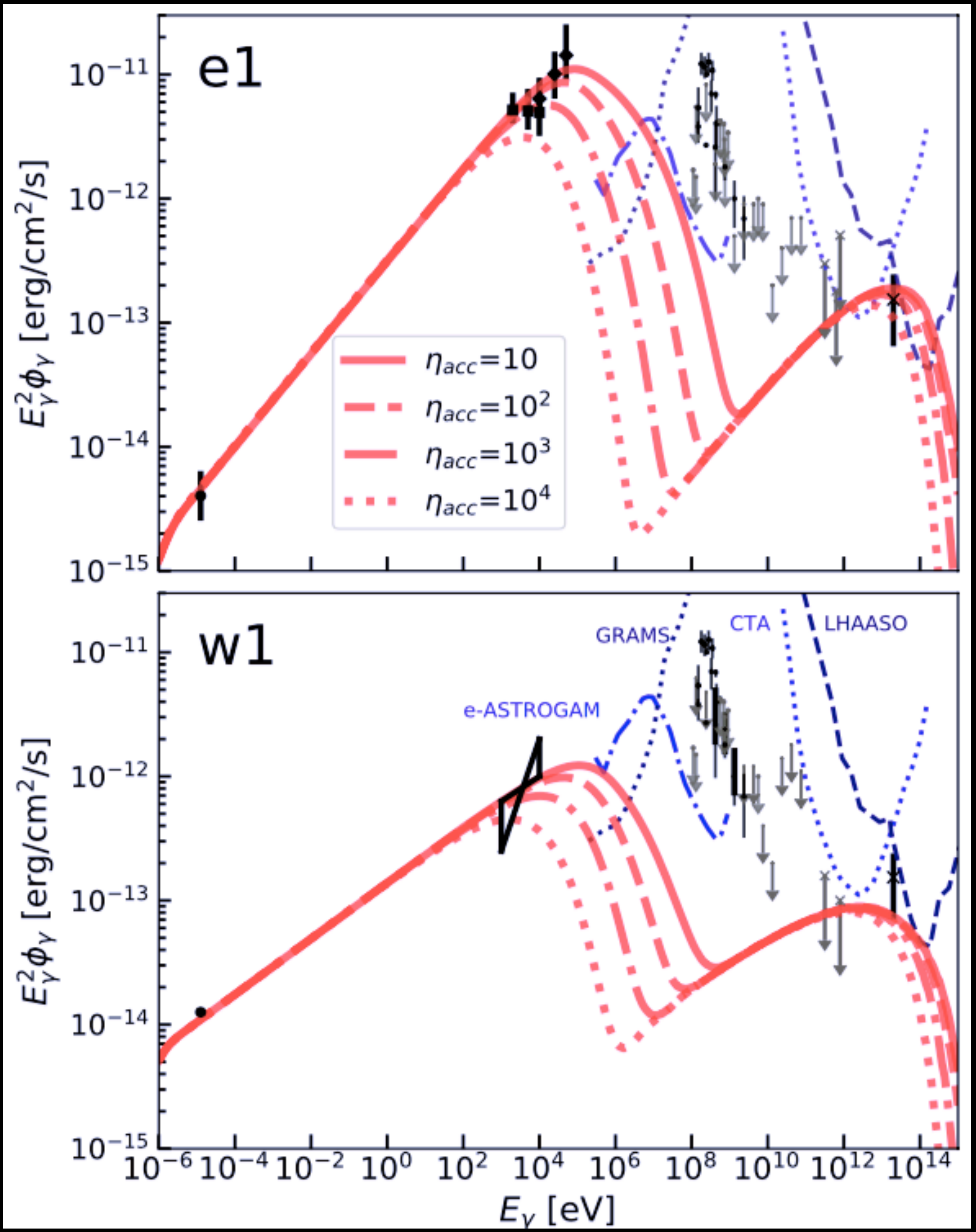



# Results

# Overall SED

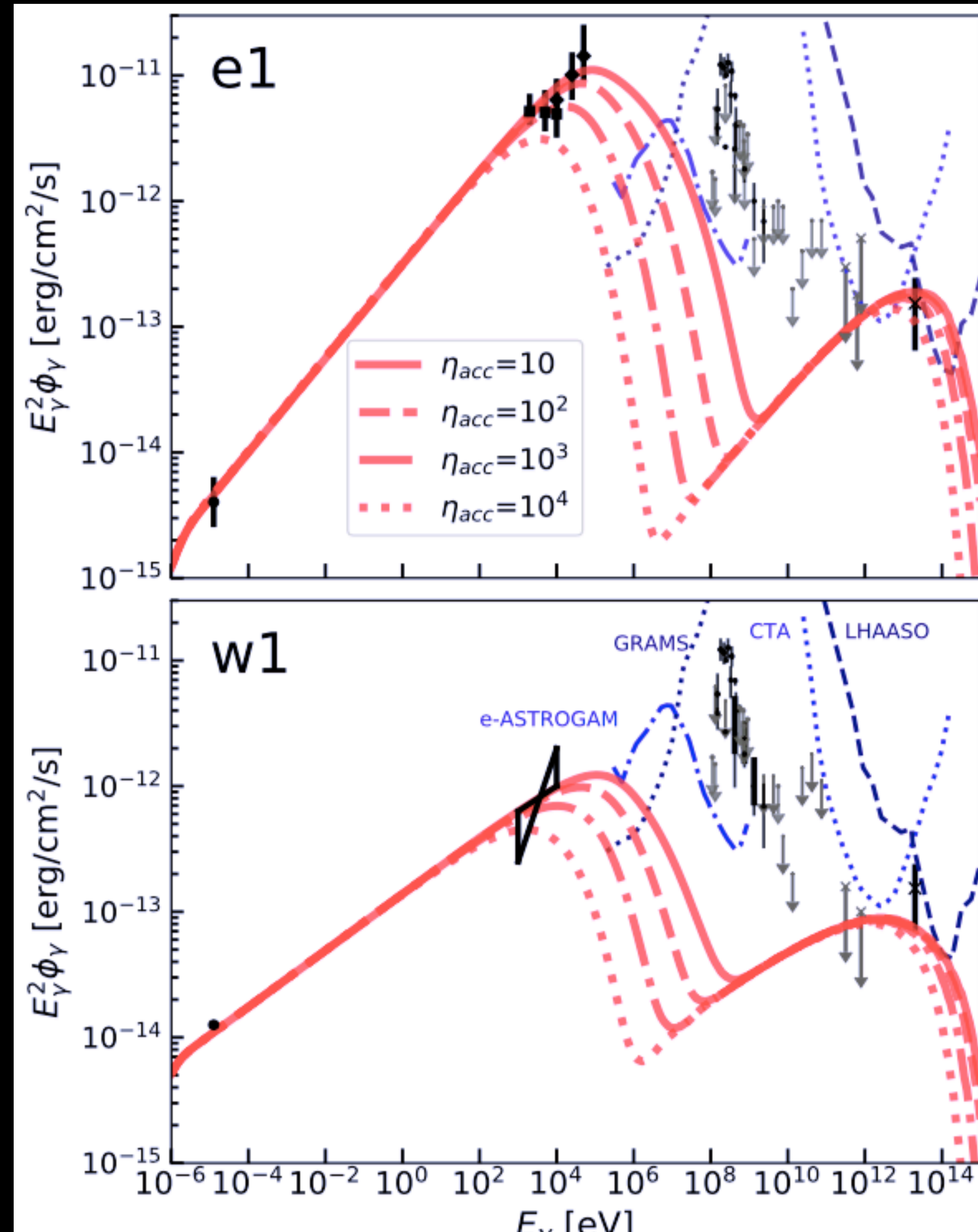
- Overall SED explained with leptonic models for both regions
- Assuming that maximum particle energy is limited by synchrotron loss.



# Overall SED

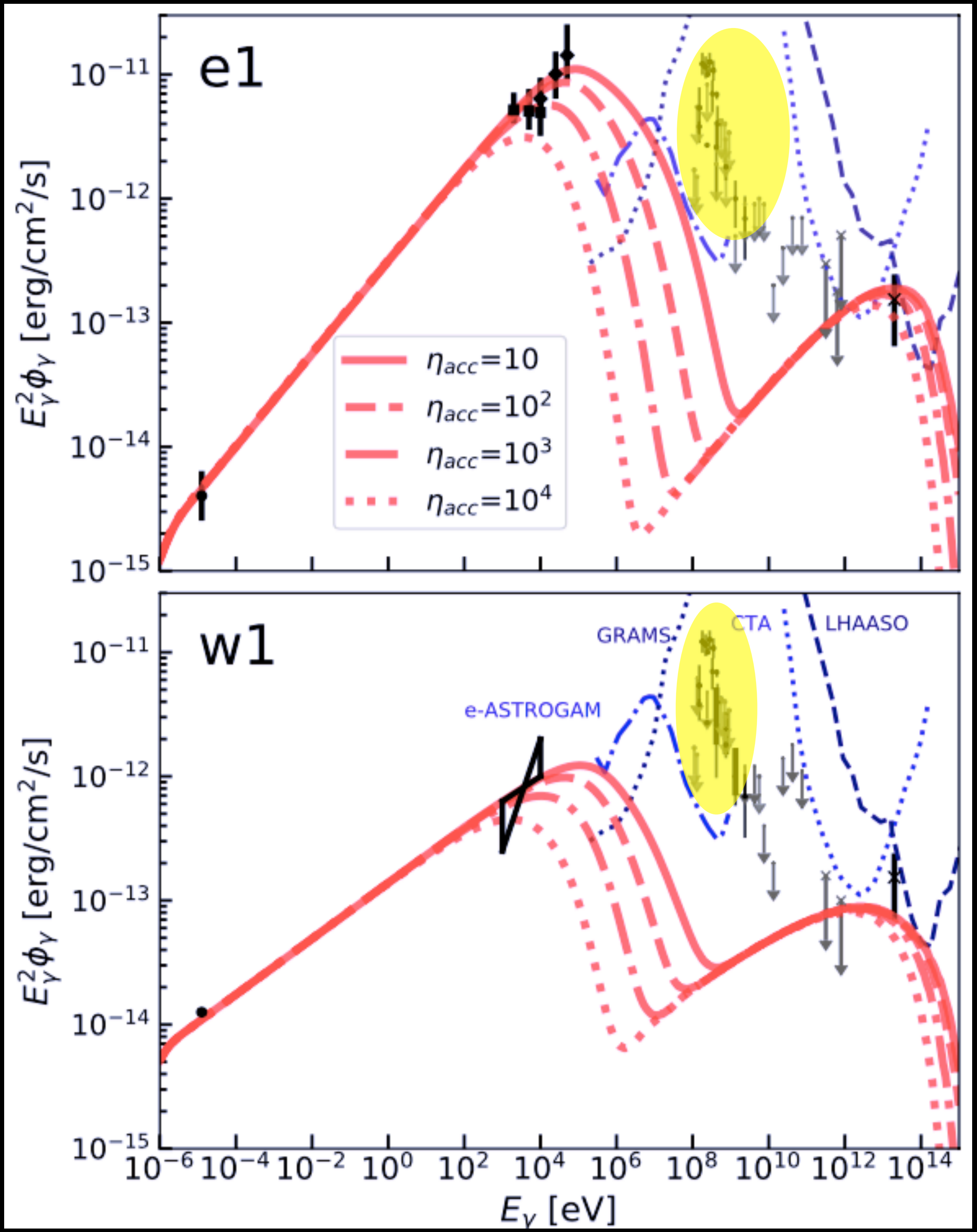
- Overall SED explained with leptonic models for both regions
- Assuming that maximum particle energy is limited by synchrotron loss.
- Derived magnetic fields are 16 $\mu$G and 9 $\mu$G for e1 and w1

| 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 |



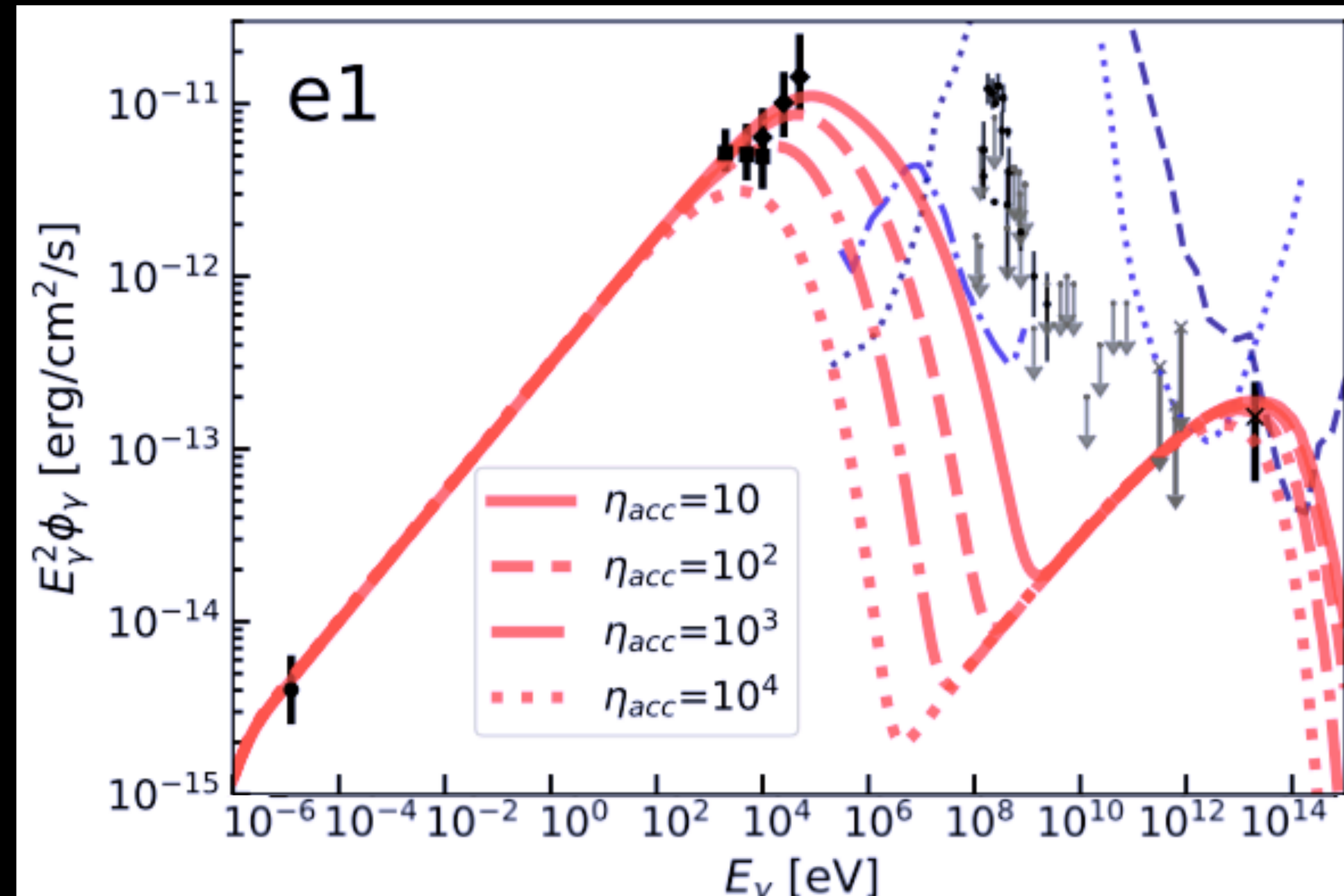
# GeV data

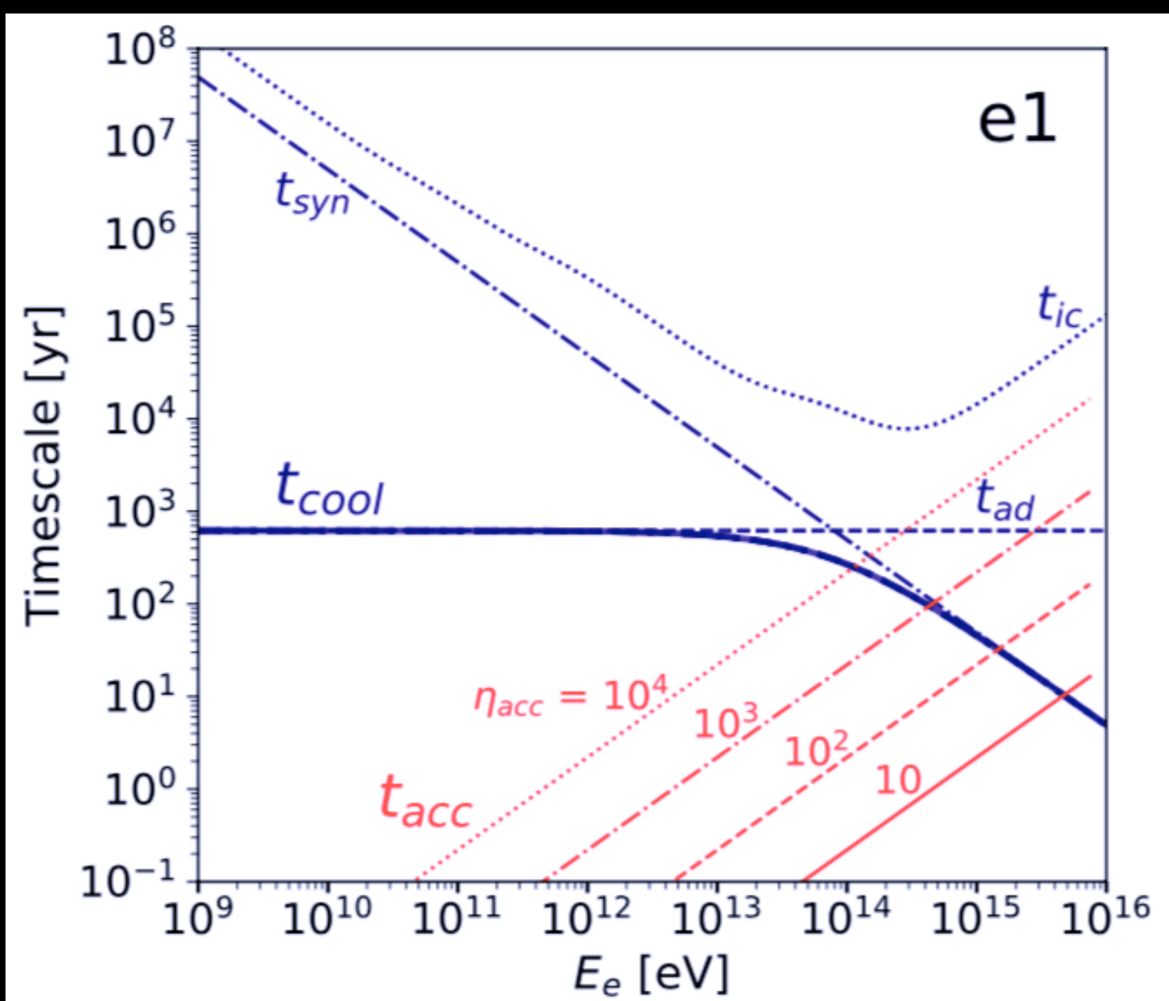
- GeV data remain unexplained within the knot model
- Mostly from other regions? Hadronic emission?

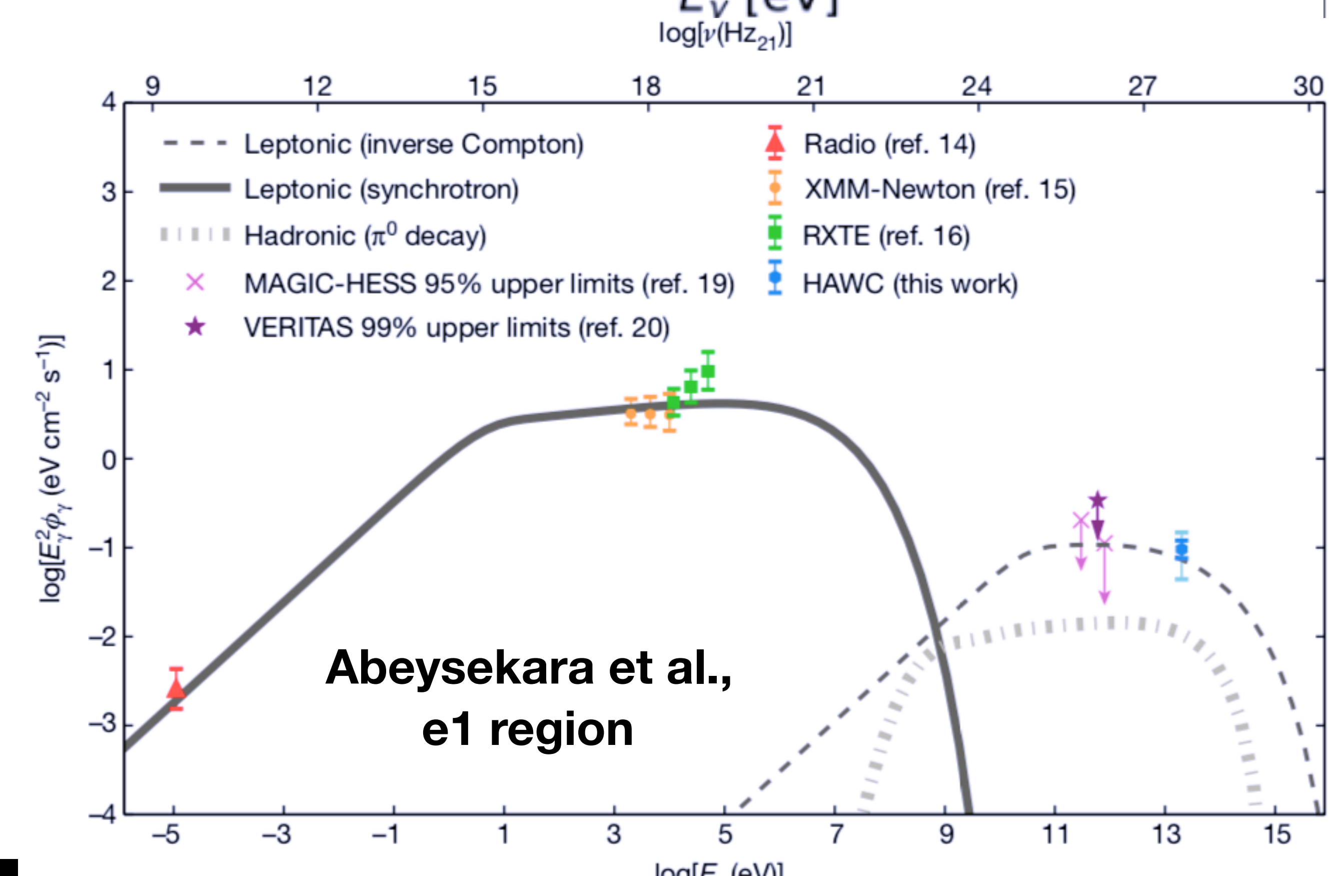


# Comparison with other work (e1)

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

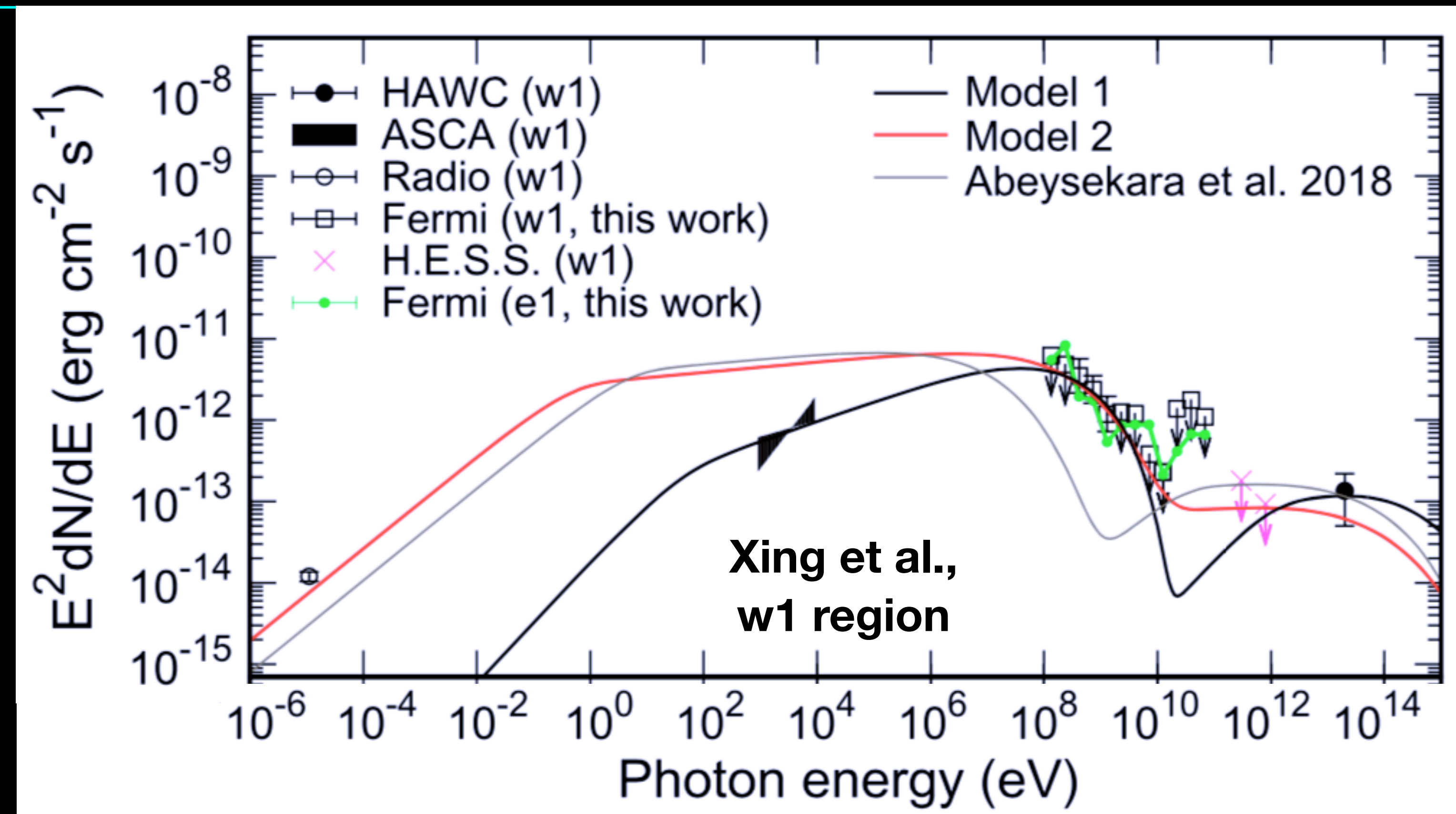


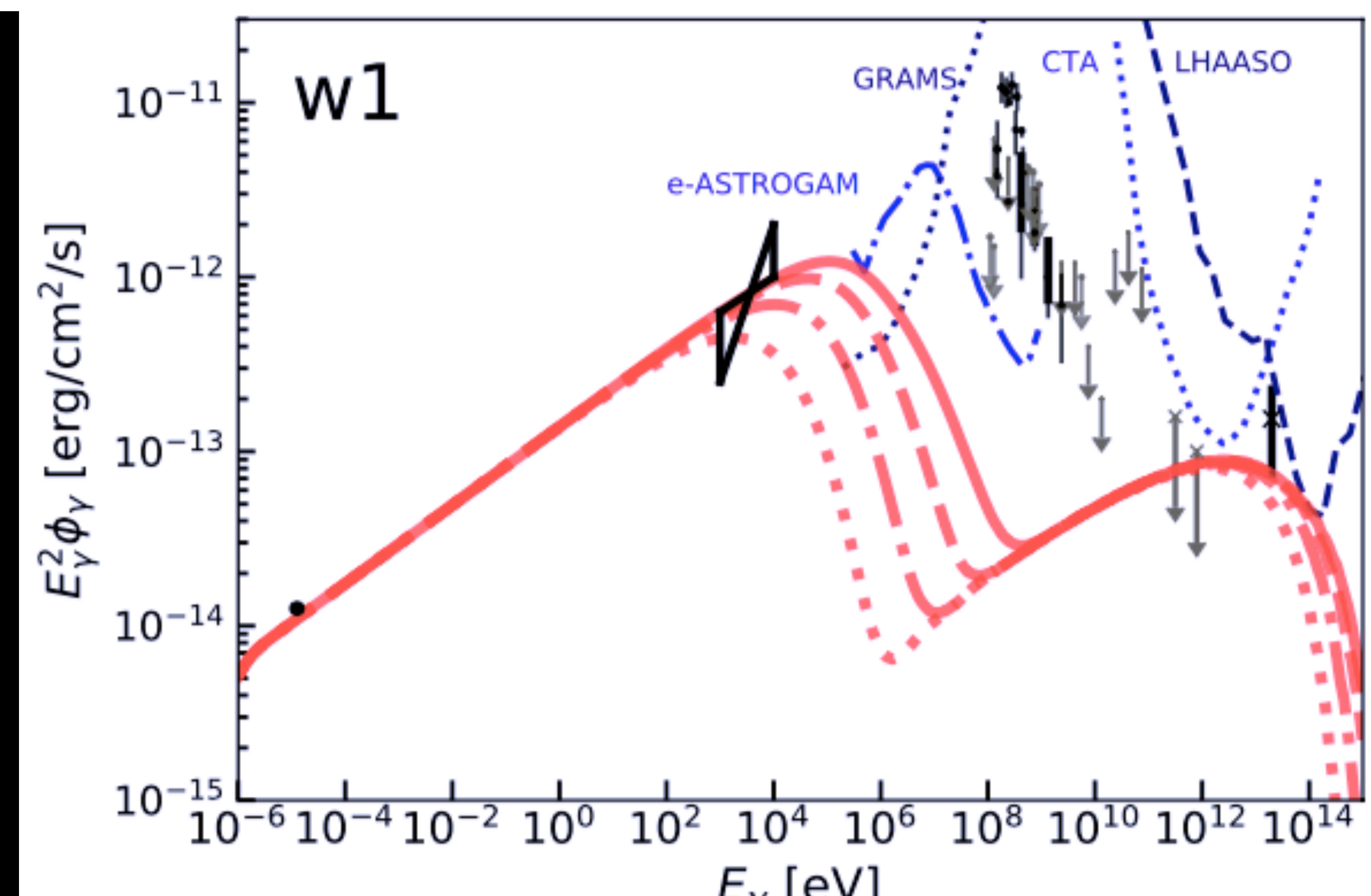



# Comparison with other work (w1)

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



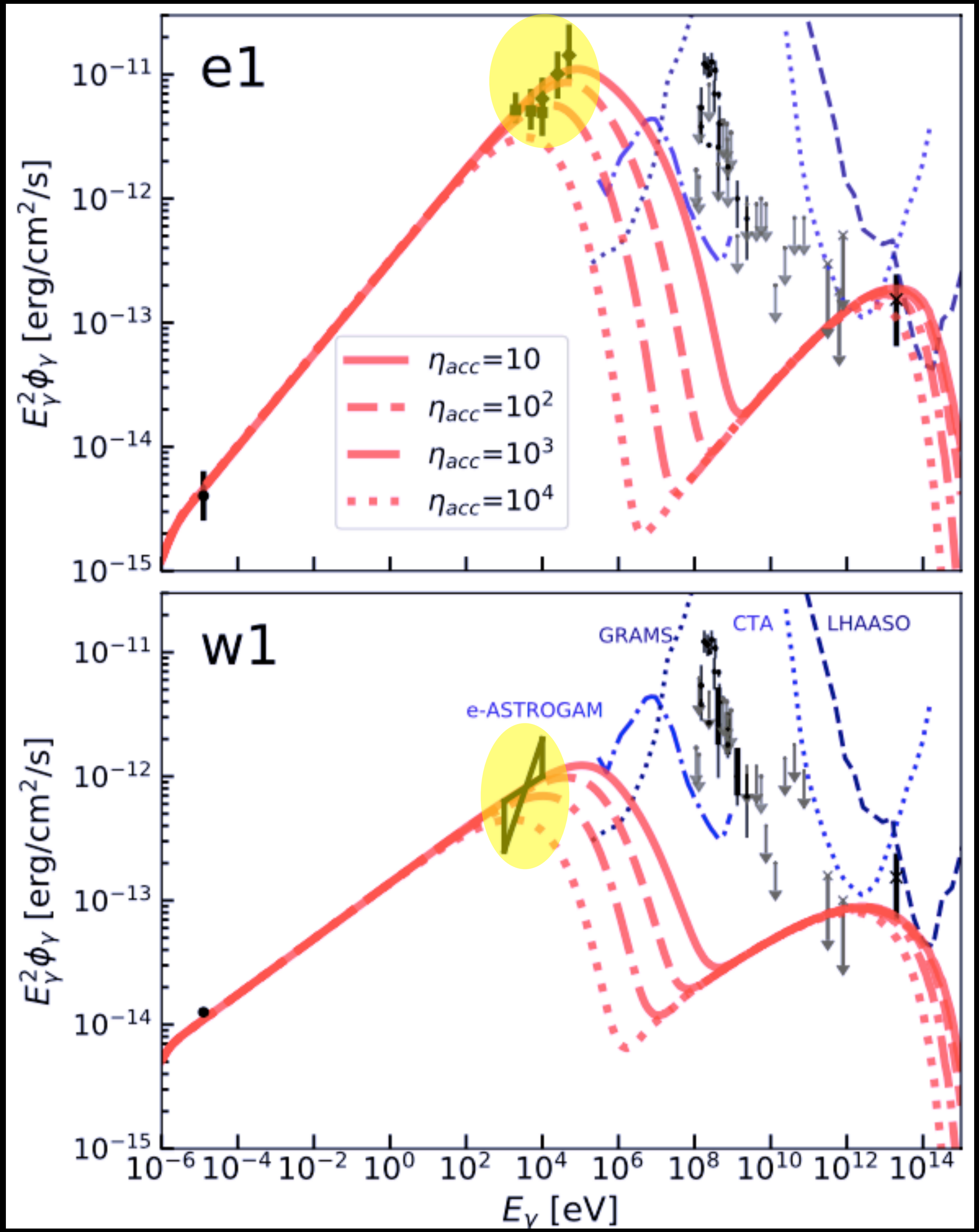
# Need for High Acceleration Efficiency

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

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

- This suggests the presence of PeV protons:

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

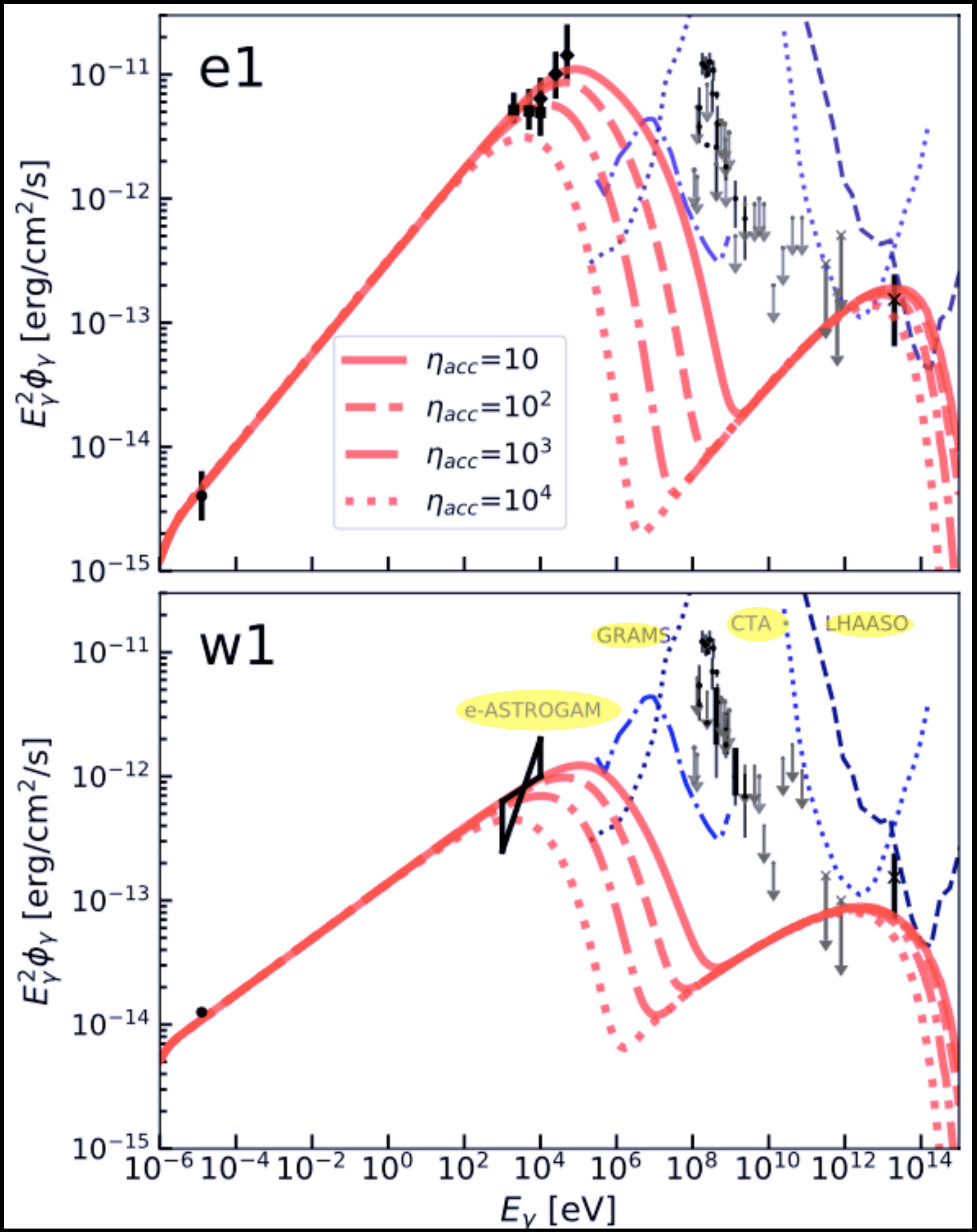


# Need for High Acceleration Efficiency

- Our model require $\eta_{\rm acc} \lesssim 10^2$ to explain the X-ray data
- In the framework of the diffusive shock acceleration, this hints at the Bohm limit: $\eta_g \sim 1$
- $$\eta_{\rm acc}^{\rm DSA} = \frac{200}{\eta_g}\left(\frac{\beta_{\rm sh}}{0.26}\right)^{-2}$$
- Such a fast acceleration is also observed in some supernova remnants: $\eta_g \sim 1$ (e.g., Uchiyama et al. 2007)
- However, jets from BL Lacs appear to have much lower efficiency of particle acceleration: $\eta_g \sim 10^4$ (e.g., Inoue&Tanaka 2016)

# Future Prospects

- Hard X-ray and MeV gamma-ray observations will detect spectral turnover and cutoff
- Critical test of our models and constraints on $\eta_{\mathrm{acc}}$
- CTA and LHAASO may also detect VHE emission.



# Summary

# Nonthermal Particles SS433 Jets

- Spectral energy distribution from knots can be explained with leptonic models.
- GeV data remain unexplained: from other regions and/or hadronic component?
- Need a very high efficiency of $\eta_{\rm acc} \lesssim 10^2$ $\cdots$ hint at diffusive shock acceleration near the Bohm limit?
- Future hard X-ray and MeV gamma-ray observations will critically test our models.

$\rightarrow$ Critical probe of particle acceleration in astrophysical jets