Probing the Interstellar Turbulence through TeV halos

Ruoyu Liu (柳若愚)
Nanjing University

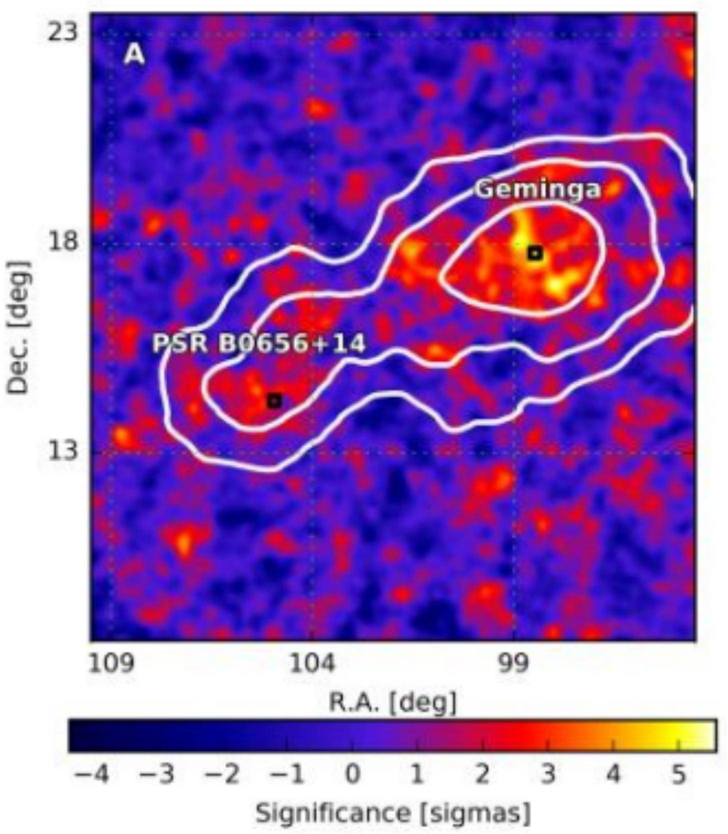
Collaborators: Huirong Yan, Heshou Zhang, Chong Ge, Xiao-Na Sun, Xiang-Yu Wang

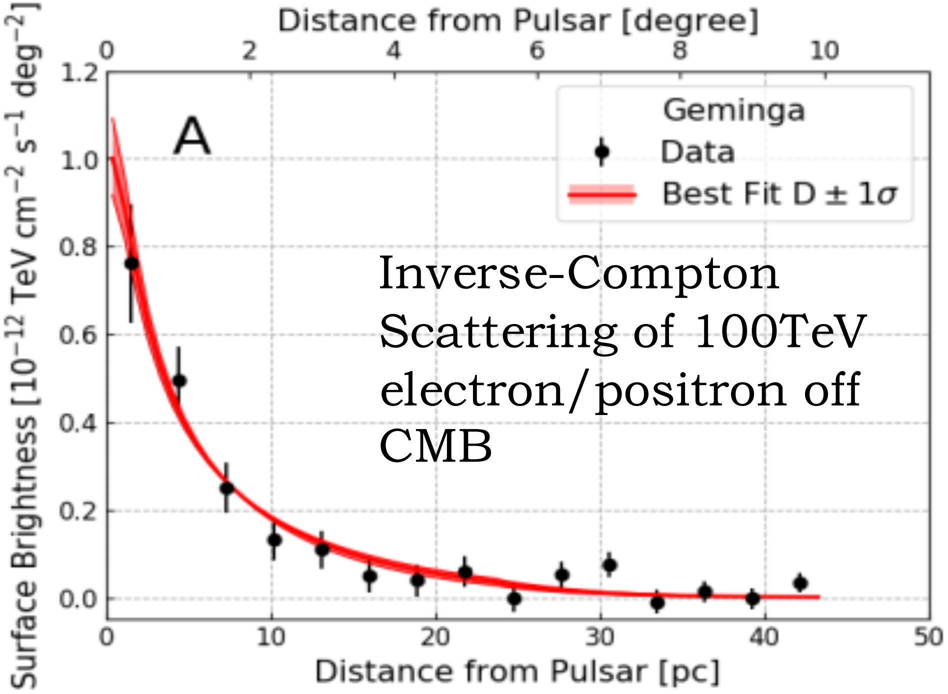
10th High Altitude Air Shower Workshop, 07.01.2020, Nanjing

Outline

- A brief introduction to TeV halo observed by HAWC
- An anisotropic diffusion model for the TeV halo
- Study the interstellar turbulence with TeV halos
- Summary

HAWC's observation on Geminga and Monogem





Inverse-Compton Scattering of 100TeV electron/positron off CMB

HAWC Collaboration 2017, Science, 2017, 358, 911

D_{100} (Diffusion coefficient of 100TeV electrons from joint fit of two PWNe)	[x10^{27} cm^2/sec]	4.5 ± 1.2

See 2018, Fang et al. 2018, Profumo et al. 2018, Tang & Piran 2018

Two orders of magnitude smaller than the typical ISM diffusion coefficient

The generation of a very inefficient diffusion region

Small diffusion coefficient-> saturation of turbulence at small scale (r_g=0.04pc (E_e/100TeV)(B/3μG)$^{-1}$)

① CR self-regulation
Streaming instability

the mechanism of self-generated Alfv́en waves due to the streaming instability **cannot** work to produce such a low diffusion coefficient even in the most optimistic scenario where the energy loss of electrons and the dissipation of the Alfven waves are neglected. The reason is simple as **Geminga is too weak to generate enough high energy electrons at the late age**. **(Fang et al., 2019, MNRAS)**

② strong external turbulence

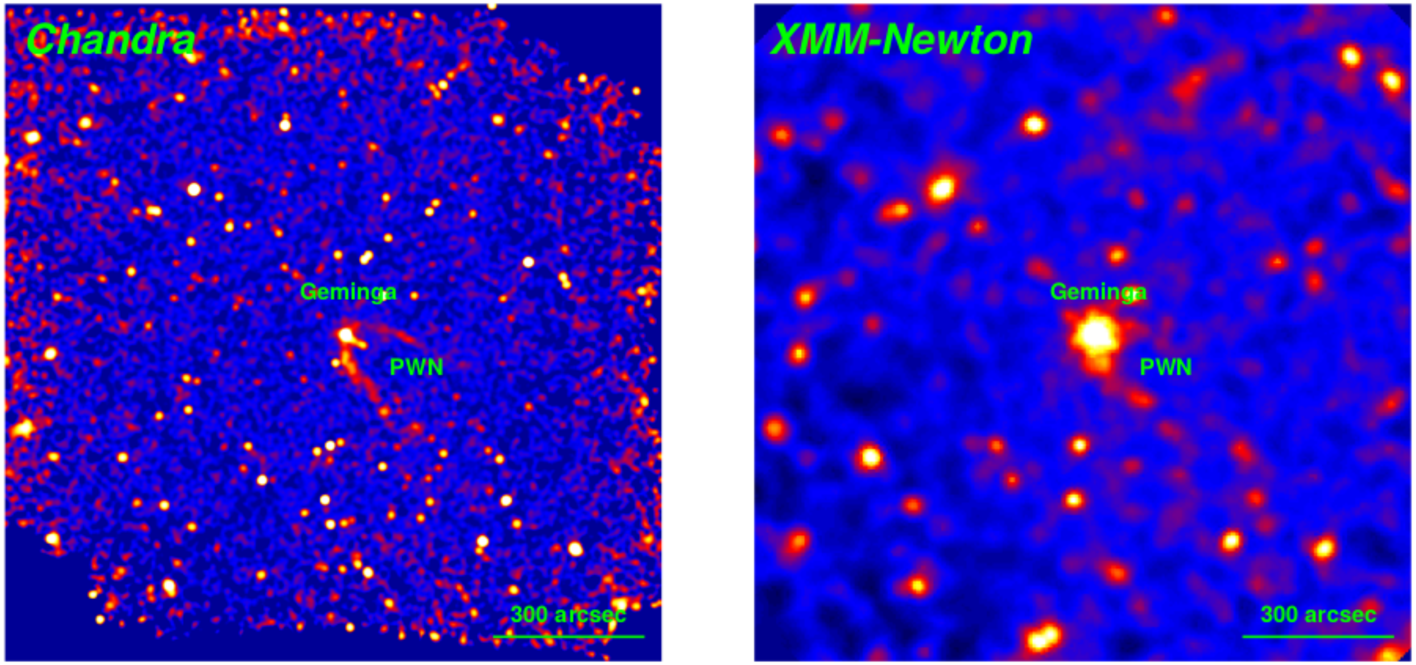
Very chaotic topology & not-too-small B?

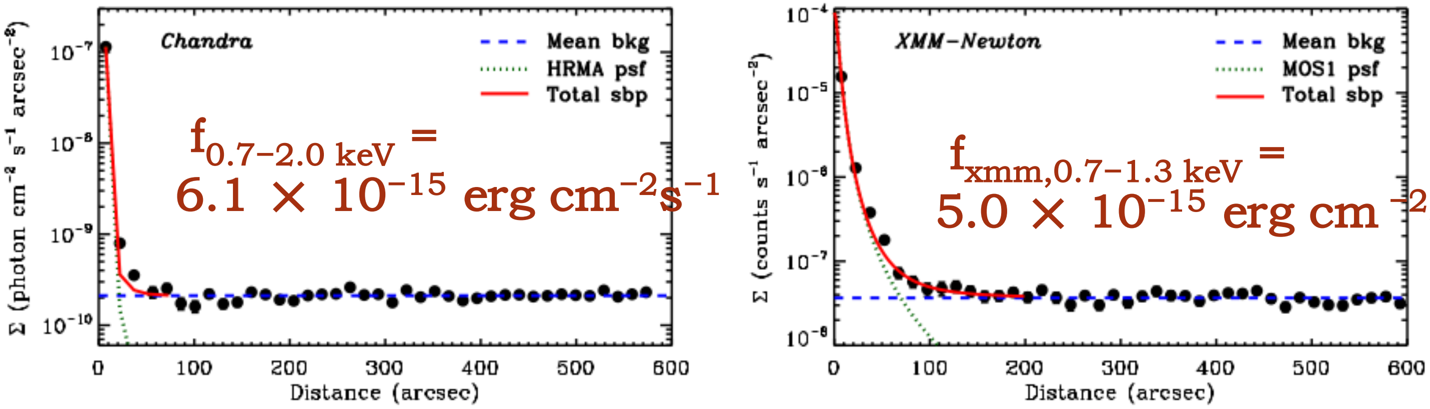
(e.g. L_{inj}~1pc & B=3μG, Lopez-Coto & Giacinti 2018, MNRAS)

X-ray emission

$$\left.\begin{aligned}\epsilon_{\rm IC} &\sim 20(E_e/100{\rm TeV})^2\,{\rm TeV}.\\ \epsilon_{\rm syn} &\sim 0.6(E_e/100{\rm TeV})^2(B/3\mu{\rm G})\,{\rm keV}\end{aligned}\right\} \quad F_{\rm keV}/F_{\rm 10TeV} \simeq B^2/8\pi U_{\rm CMB} \sim 1(B/3\mu{\rm G})^2$$

Test with X-ray observation

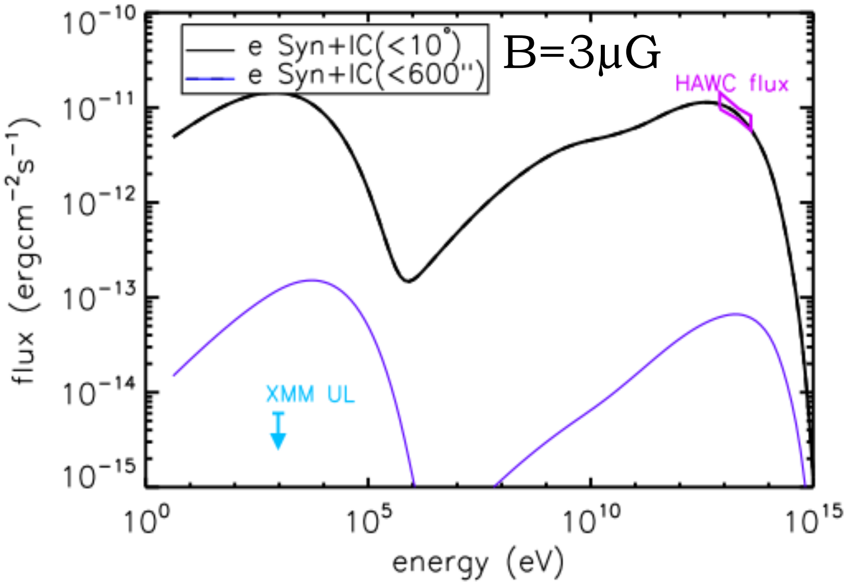


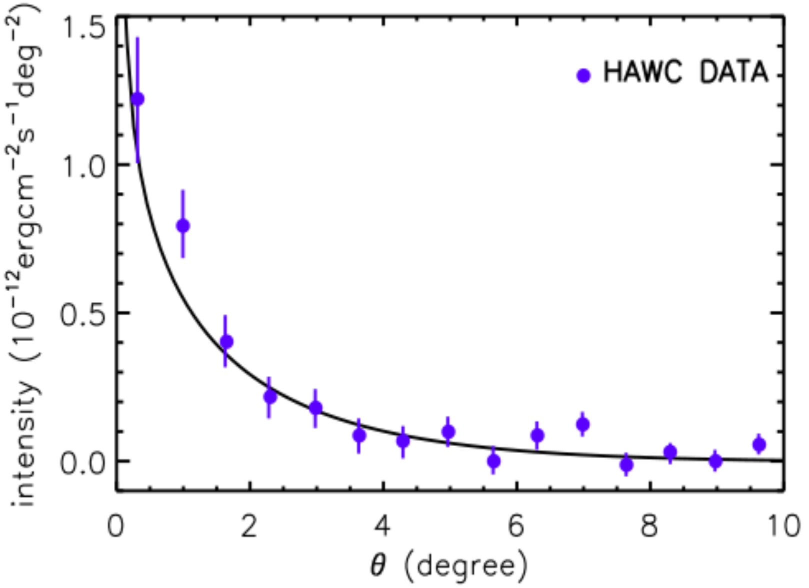


$f_{0.7-2.0\ \mathrm{keV}} = 6.1 \times 10^{-15}$ erg cm^{-2}s^{-1}

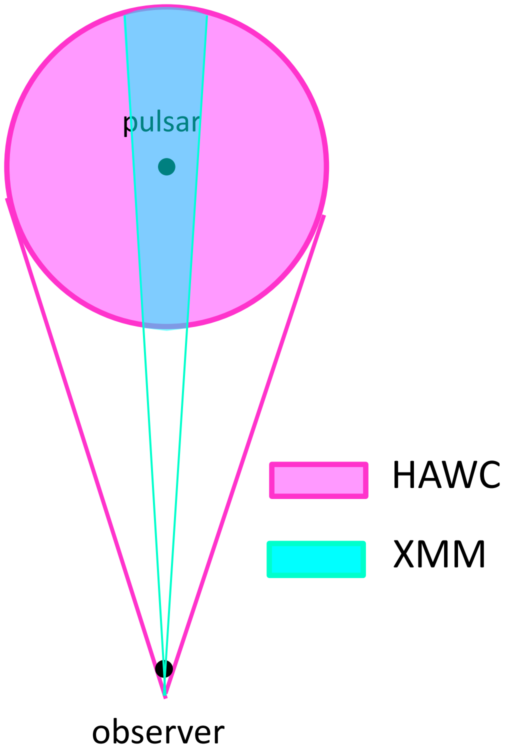
$f_{\mathrm{xmm},0.7-1.3\ \mathrm{keV}} = 5.0 \times 10^{-15}$ erg cm^{-2}s^{-1}

Liu, Ge, Sun & Wang 2019, ApJ





Line of sight integration

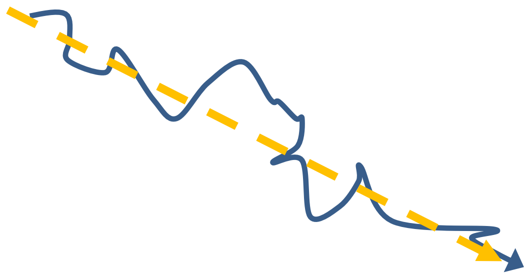


B=3μG → 0.8μG

TeV Observation → small diffusion coefficient → strong & chaotic B field

X-ray Observation → weak B field

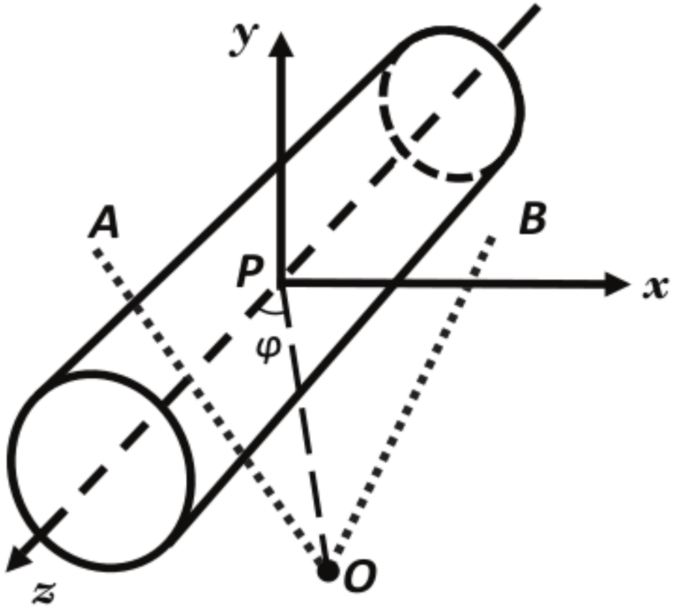
Anisotropic diffusion



ISM turbulence: coherent length 50-100pc, mean B field 3-6μG

sub-Alfvenic ($M_A \sim \Delta B/B < 1$) turbulence, anisotropic

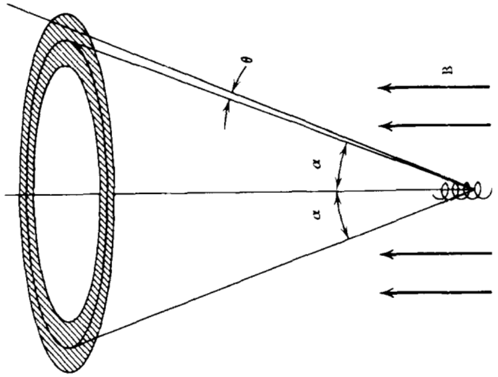
$$D_{zz} = D_{\|} = D_0(E_e/1\mathrm{GeV})^q$$
$$D_{rr} = D_{\perp} = D_{zz} M_A^4$$

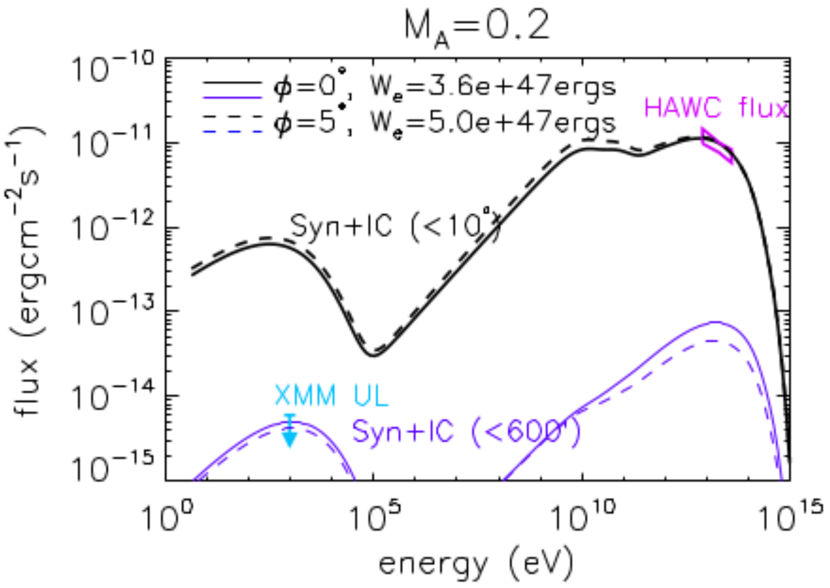


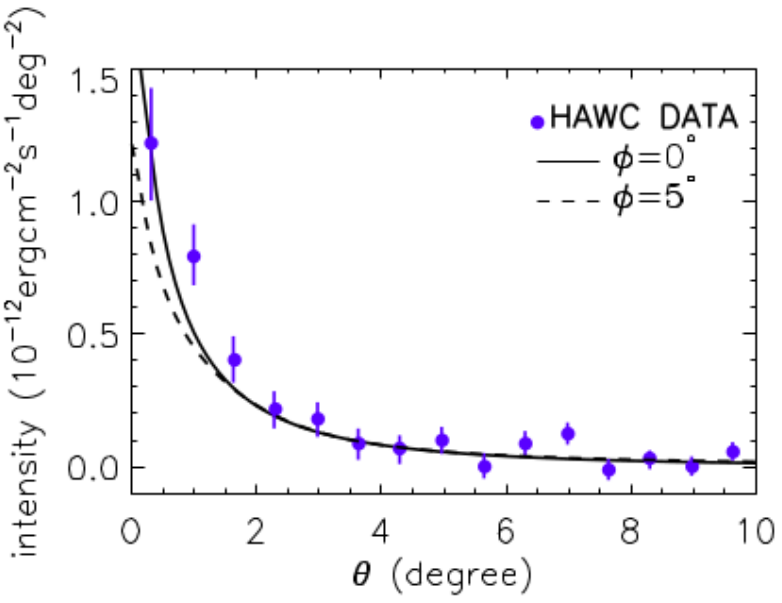
X-ray emission can be reduced significantly if the mean B field is roughly aligned with our line of sight

$$P = \frac{2q^4B^2\gamma^2\beta^2\sin^2\alpha}{3m^2c^3} \qquad \omega_c = \frac{3\gamma^2 qB\sin\alpha}{2mc}$$

Rybicki & Lightman 1979



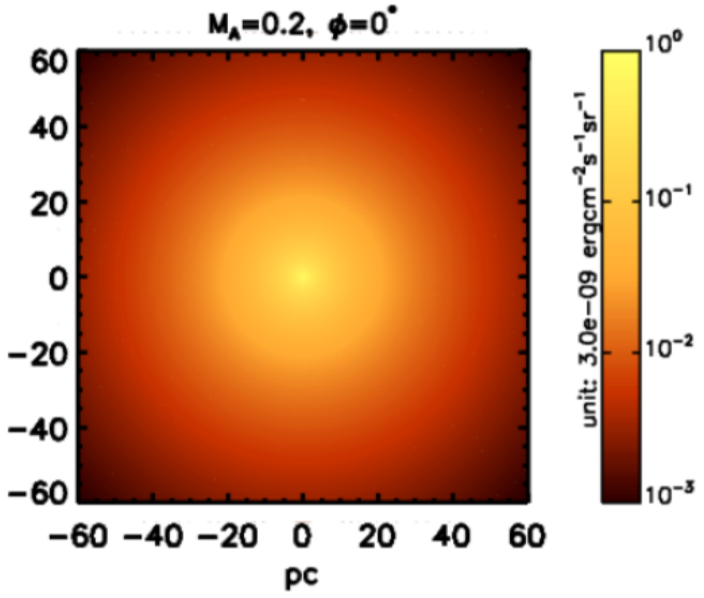




Liu, Yan & Zhang. 2019, PRL

M_A~0.2, φ<5°

Mean B field well aligned with LOS



Mean B field in other TeV halos cannot be always aligned with LOS

M_A may change from place to place in ISM

Some implications

If the anisotropic diffusion model is correct

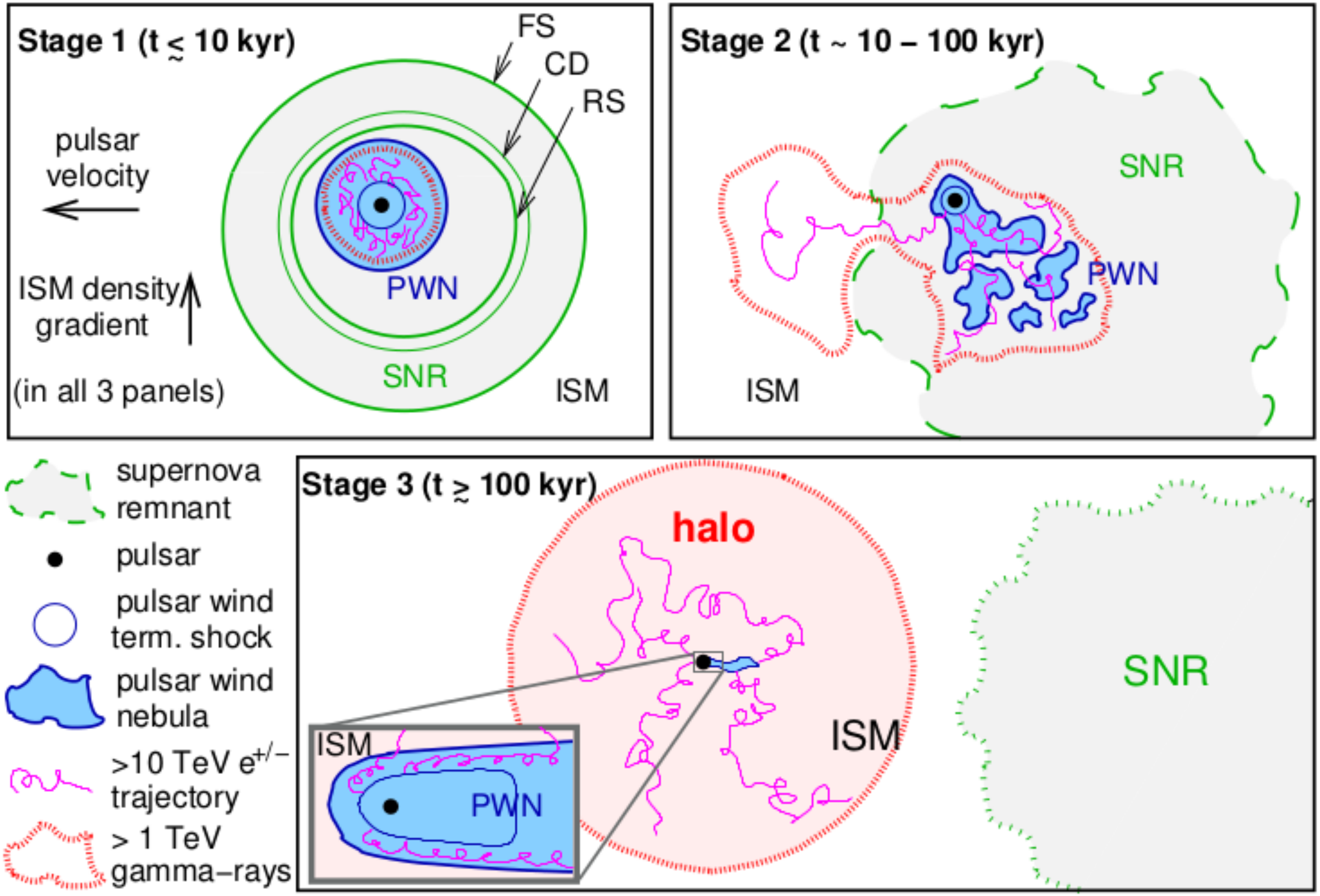
1. Suppose to see TeV halo with other morphologies (selection effect, aligned B field makes the halo more compact -> more detectable)

1. The morphology + multiwavelength spectrum contain the information of the local turbulence

1. Global transport of CR in the Galaxy; local CR spectrum & anisotropy

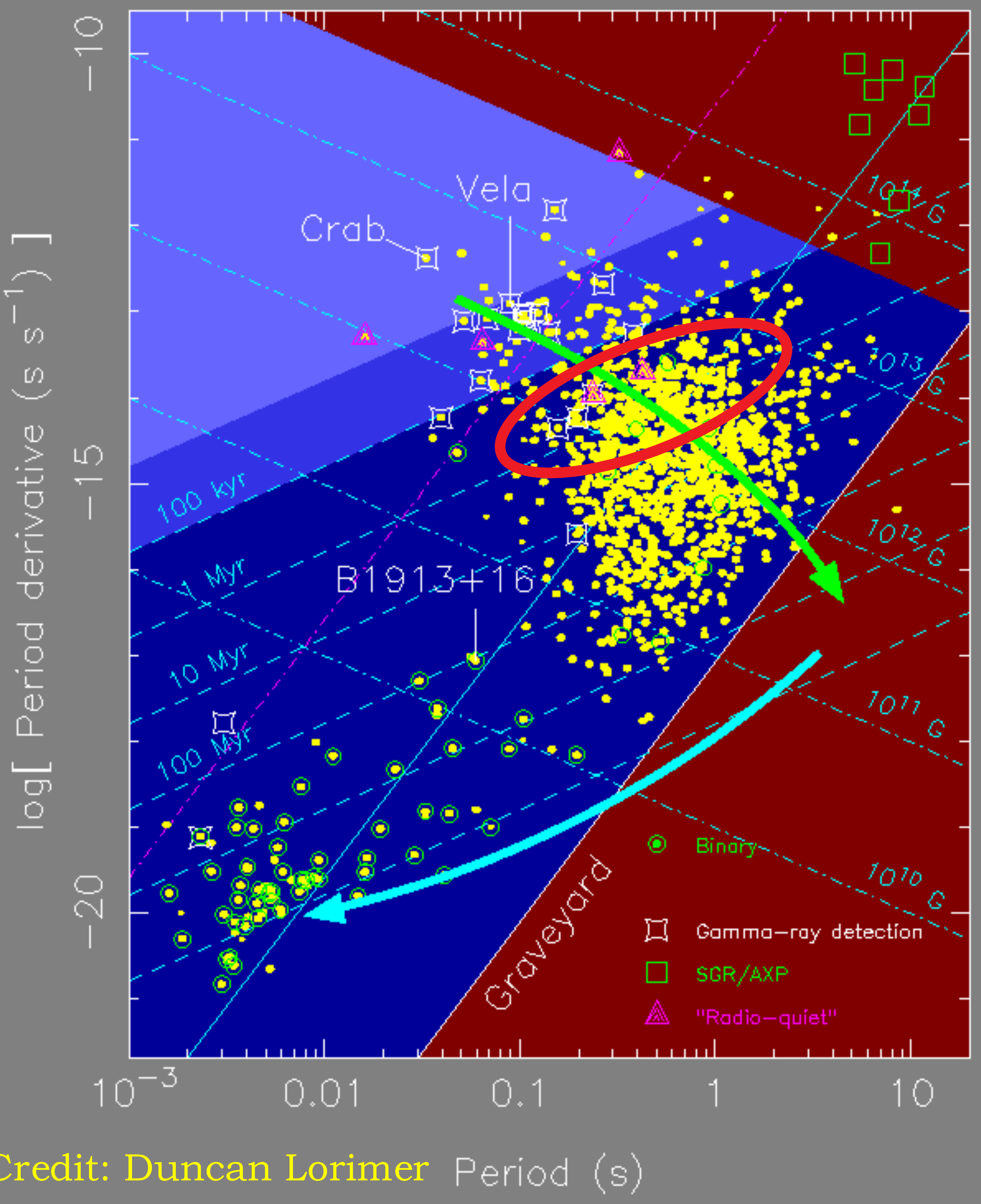
Need to look for more TeV halos…

A general picture for TeV halo



Giacinti et al. 2019

How many potential TeV halos in our Galaxy?



Credit: Duncan Lorimer

Selection Criteria:

T_{age}>100kyr

$F=\eta_{\gamma}L_s/4\pi d^2>F_{lim}$

η_{γ}~0.07% (for Geminga)

Ratio of 100TeV luminosity to spindown luminosity

158 pulsars with expected 100TeV flux above LHAASO's 5yr sensitivity & inside FOV

Why 100TeV?

1. LHAASO sensitivity
2. Good angular resolution (0.15°)
3. Less influence from proper motion

Setup of the calculation

$P=0.1s$, $dP/dt=-10^{-14}s^{-1}$, $I=10^{45}g\ cm^2$,

$P_0=30ms$, $\Omega=-A\Omega^n$, $n=3$, $d=1kpc$

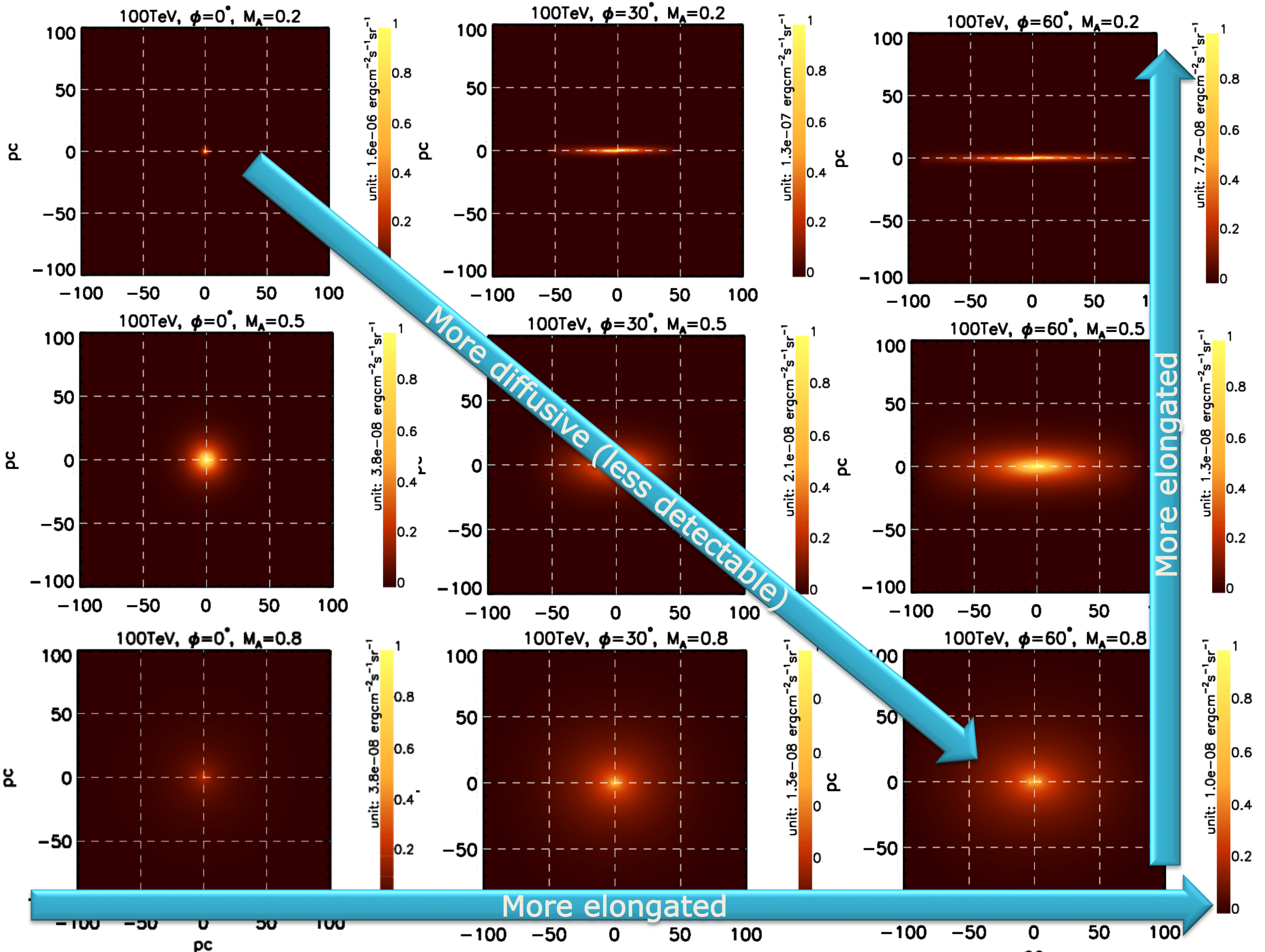
$t_{age}=160kyr$, $L_s=4e35erg/s$

50% convert to electron/positron

accelerated in PL with p=1.6, exp cutoff at 500TeV

$B=5\mu G$, $D_{//}=10^{28}cm^2/s\ (E/1GeV)^{1/3}$

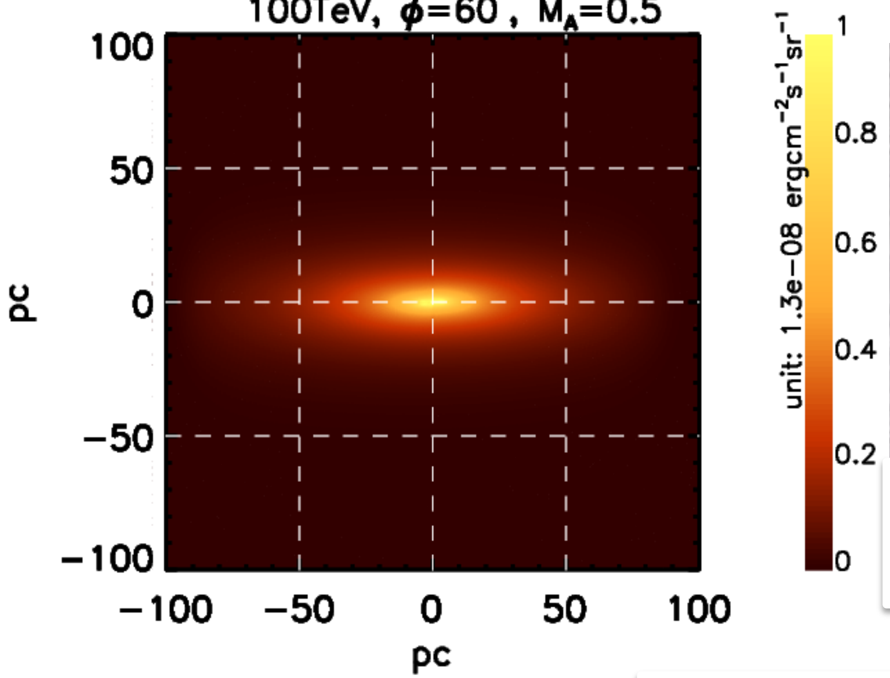
CMB, average IR & VIS density ($0.3eV/cm^3$) in the ISM

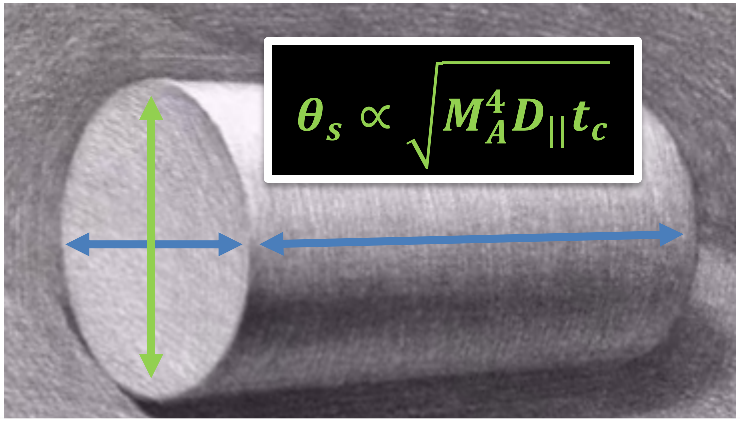


More diffusive (less detectable)

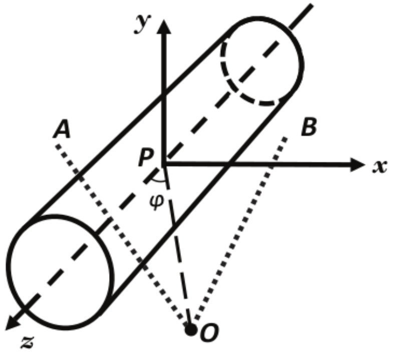
More elongated

More elongated



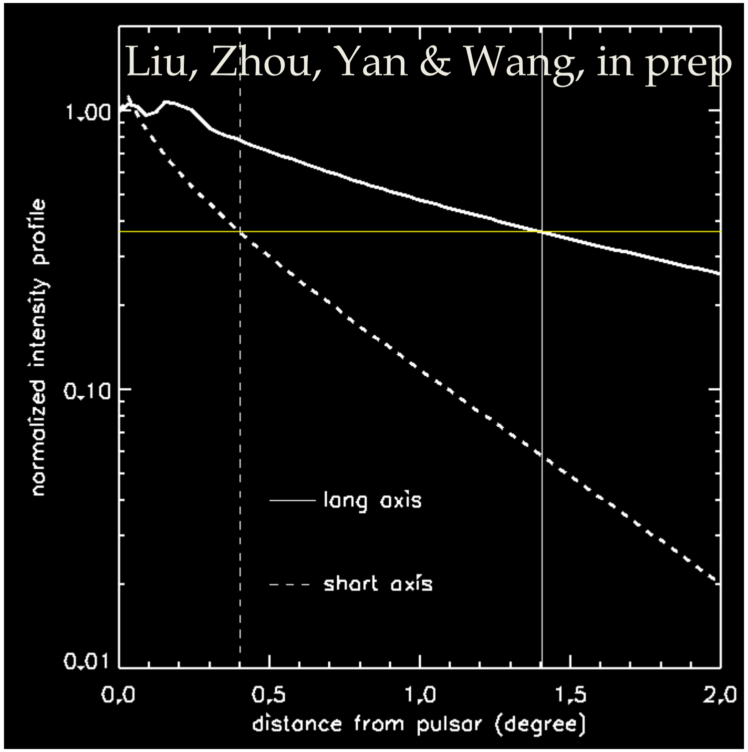


$$\theta_s \propto \sqrt{M_A^4 D_{||} t_c}$$

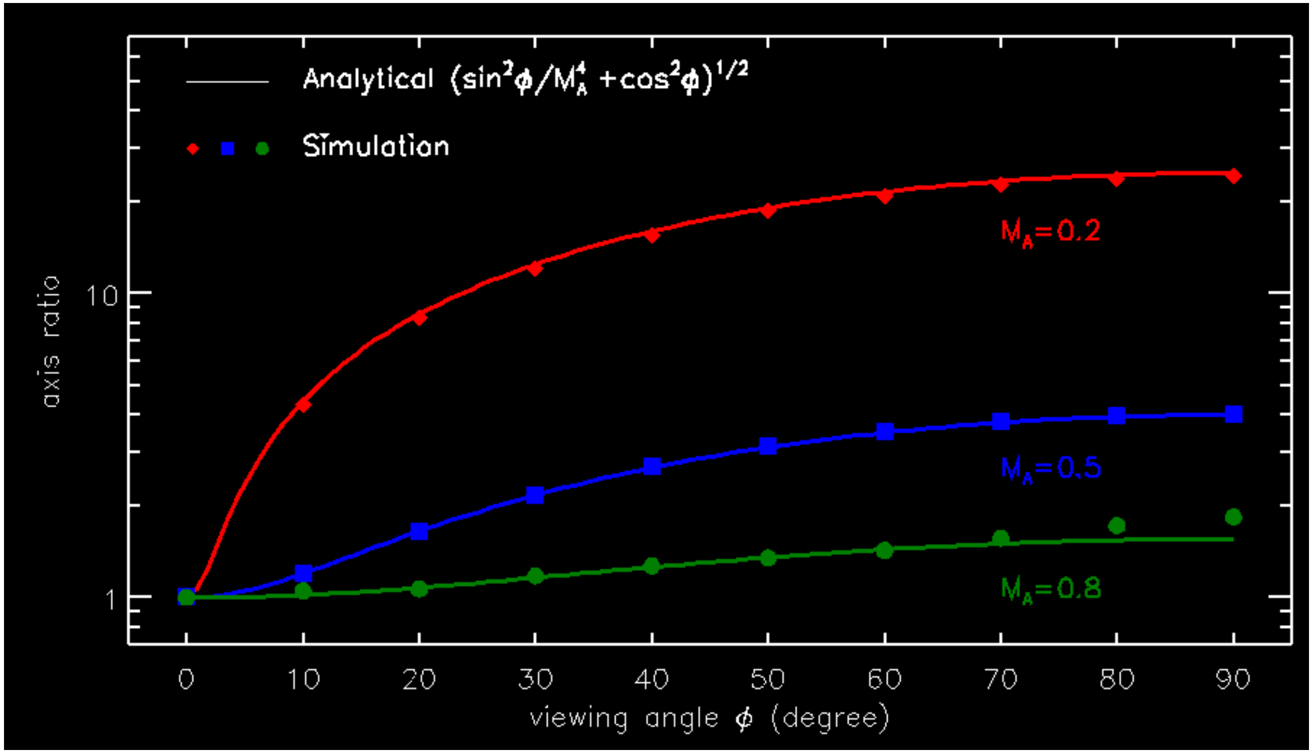


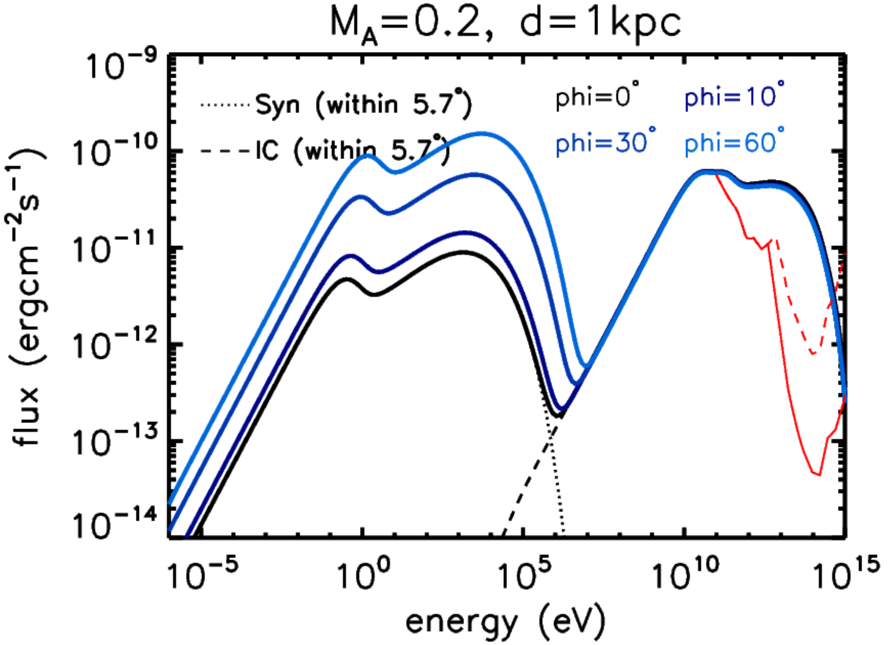
$$\theta_l \propto \sqrt{M_A^4 D_{||} t_c \cos\varphi}\,,\ \sqrt{D_{||} t_c \sin\varphi}$$

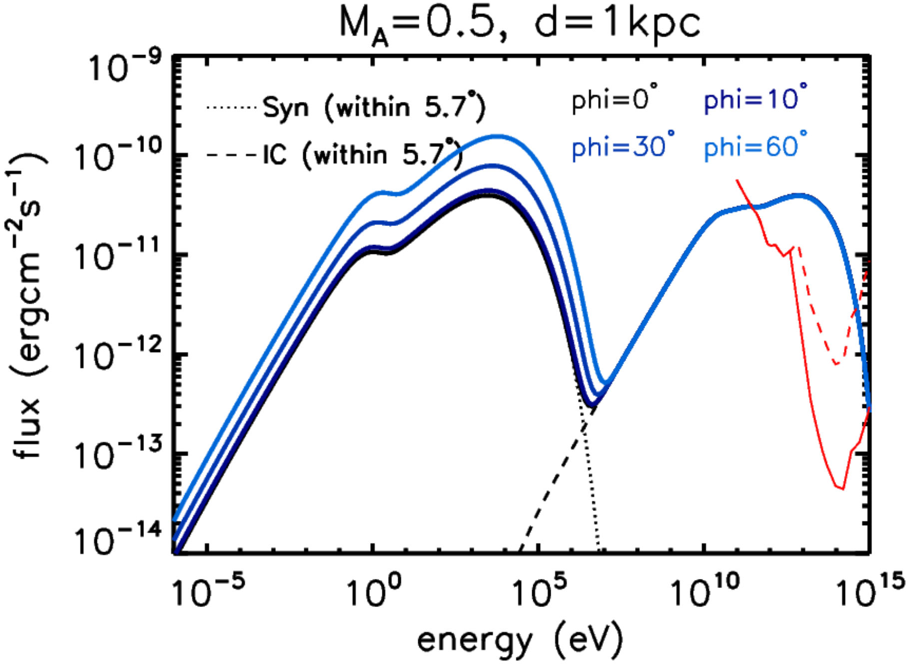
Ratio between long axis to short axis

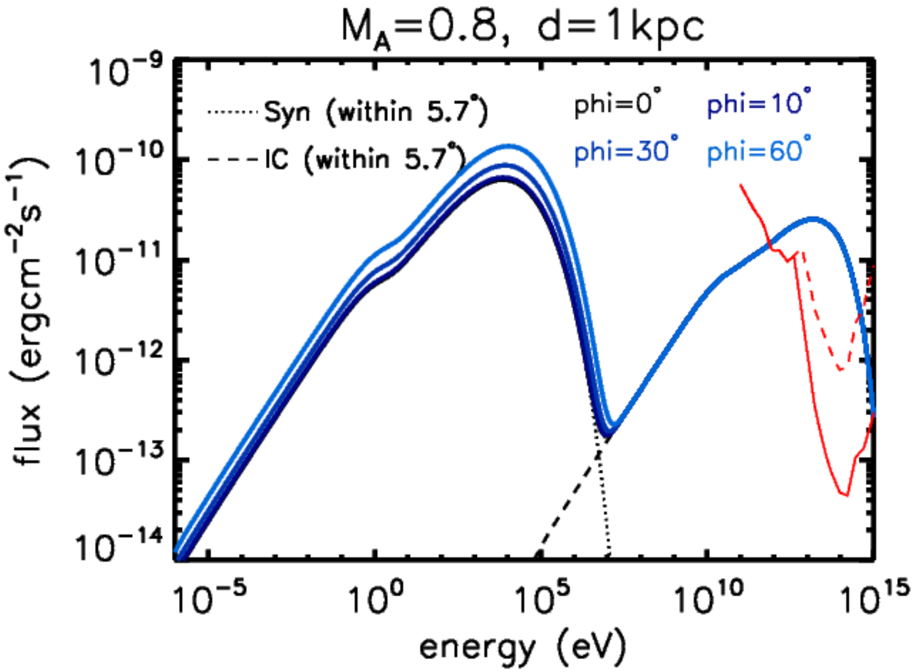


Liu, Zhou, Yan & Wang, in prep




$M_A=0.2$, d=1kpc


$M_A=0.5$, d=1kpc


$M_A=0.8$, d=1kpc

Syn/IC ratio: dependent on M_A and φ

Solid Red: assuming KM2A background free (=point source sensitivity)
Dashed Red: KM2A sensitivity = ps sensitivity x (θ/θ_{PSF})

Summary

- Anisotropic diffusion model can simultaneously explain multi-TeV observation by HAWC and X-ray observation by XMM-Newton/Chandra on Geminga's TeV halo
  — Need further test!

- There are potentially many more TeV halos in our Galaxy and LHAASO is a finding machine for TeV halos

- TeV halos serve as a tool to study the ISM turbulence, which is fundamentally important to understand the transport of CRs in our Galaxy (especially the local cosmic ray fog)

- Unresolved TeV halos may form a foreground at multi-TeV energy (might contaminate the diffuse emission from pp in ISM and weak extended sources, need a careful evaluation)

Thanks for your attention