Giant cosmic ray halos around M31 and the Milky Way

Stefano Gabici
APC, Paris
stefano.gabici@apc.univ-paris7.fr

www.cnrs.fr

Recchia, Gabici, Aharonian, Niro, ApJ, 914, 135 (2021)

M31 in gamma rays

- Past attempts to detect M31 in gamma rays:
  - **SAS-2** (Fichtel+ 1975)
    - **COS-B** (Pollock+ 1981)
      - **EGRET** (Sreekumar+ 1994, Hartman+ 1999)

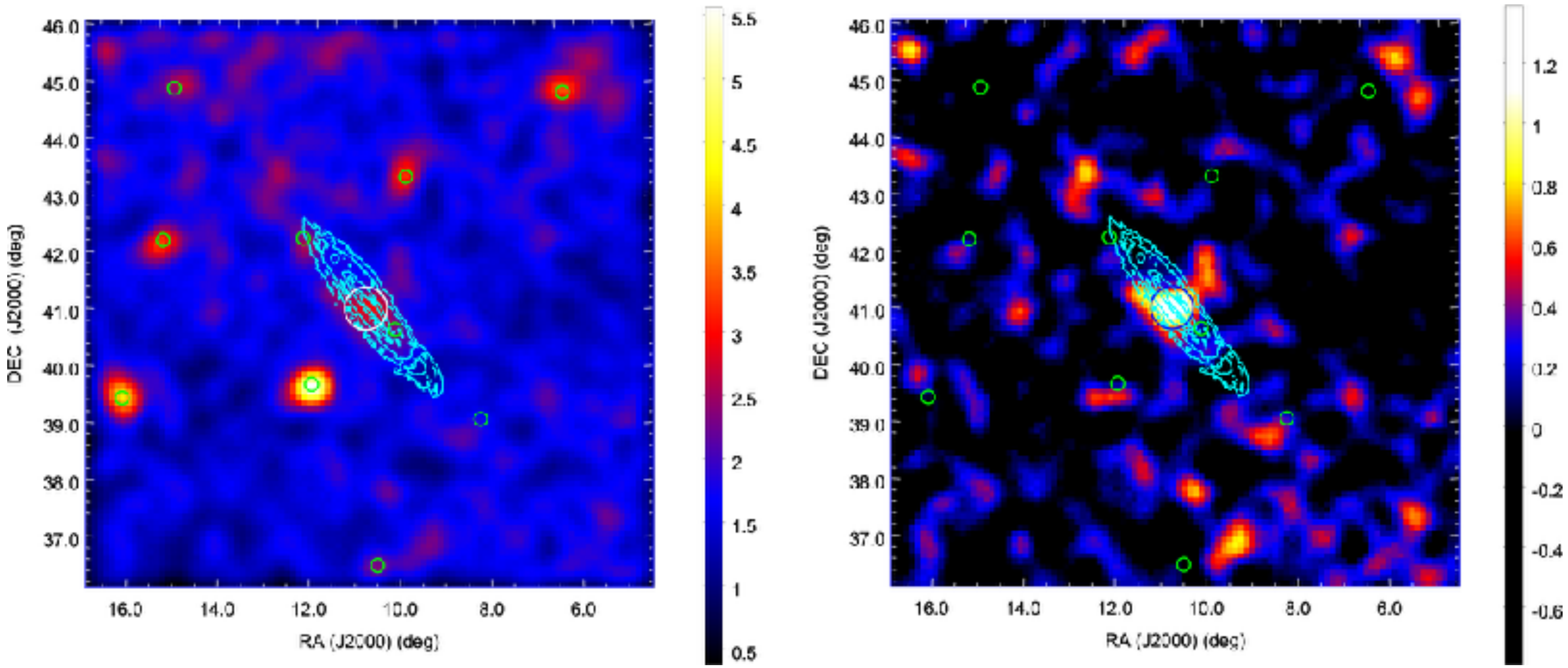
M31 in gamma rays

☑ **Past attempts to detect M31 in gamma rays:**

- **SAS-2** (Fichtel+ 1975)
- **COS-B** (Pollock+ 1981)
- **EGRET** (Sreekumar+ 1994, Hartman+ 1999)

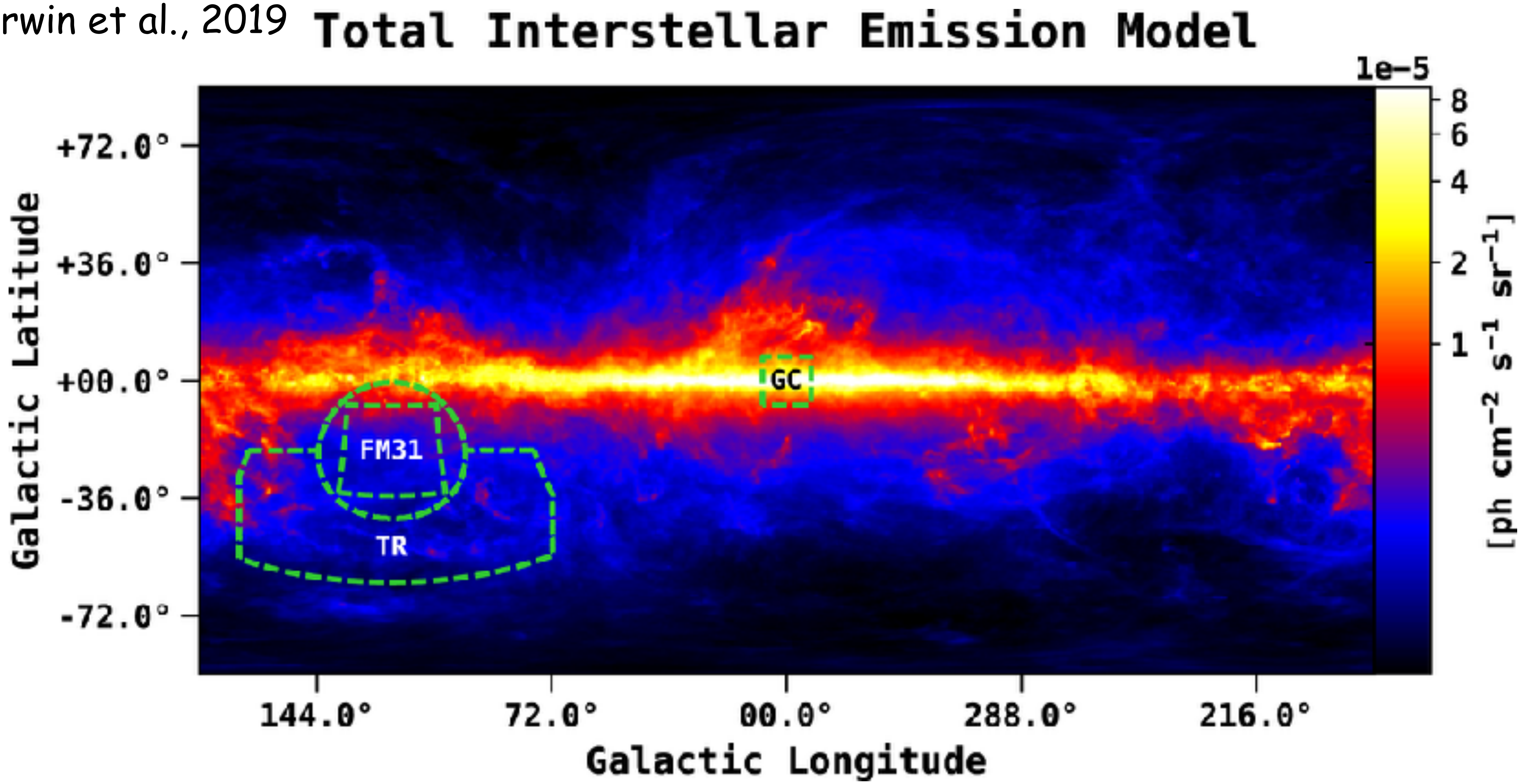
☑ **The Fermi era:**

- **Detection >100 MeV gamma-rays** (Abdo+ 2010; Ögelamn+ 2011)
- **No correlation with disk**, emission from inner 5 kpc (Ackermann+ 2017)
- **Fermi Bubbles-like structure?** (Phsirkov+ 2016)



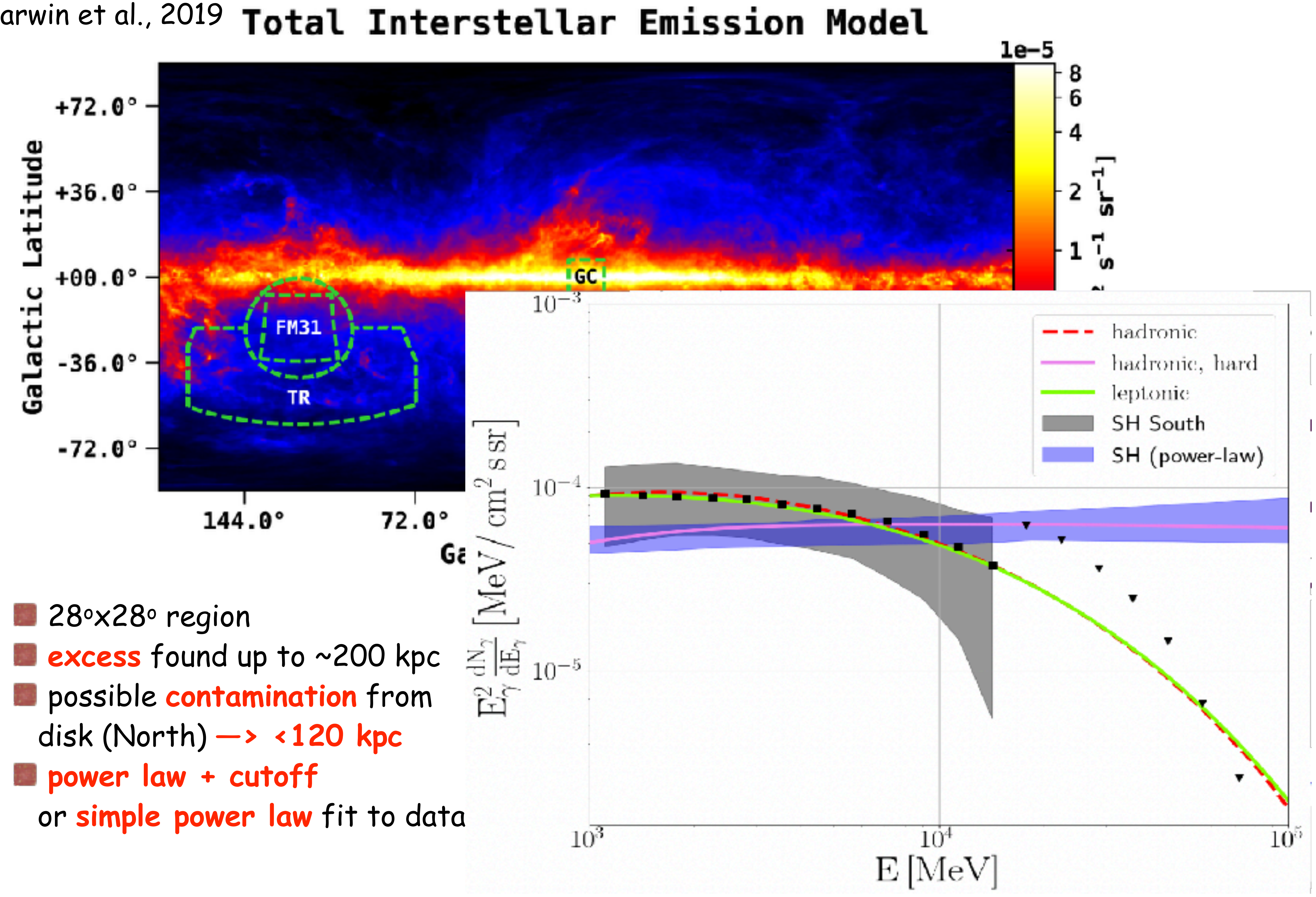
A giant gamma-ray halo around M31

Karwin et al., 2019



A giant gamma-ray halo around M31

Karwin et al., 2019



- 28°x28° region
- excess found up to ~200 kpc
- possible contamination from disk (North) —> <120 kpc
- power law + cutoff or simple power law fit to data

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6 \ \mathrm{TeV}$

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6 \ \mathrm{TeV}$

very fast cooling time in the CMB: $\tau_{ICS} \approx (E_e/\mathrm{TeV})^{-1} \ \mathrm{Myr}$

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6\ \mathrm{TeV}$

very fast cooling time in the CMB: $\tau_{ICS} \approx (E_e/\mathrm{TeV})^{-1}\ \mathrm{Myr}$

Fast cooling regime —> $\boxed{L_e = L_\gamma}$

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6 \ \mathrm{TeV}$

very fast cooling time in the CMB: $\tau_{ICS} \approx (E_e/\mathrm{TeV})^{-1} \ \mathrm{Myr}$

Fast cooling regime —> $\boxed{L_e = L_\gamma}$

Hadronic: proton-proton interactions

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6 \ \mathrm{TeV}$

very fast cooling time in the CMB: $\tau_{ICS} \approx (E_e/\mathrm{TeV})^{-1} \ \ \mathrm{Myr}$

Fast cooling regime → $\boxed{L_e = L_\gamma}$

Hadronic: proton-proton interactions

radiation produced by protons of energy: $E_p \approx 0.01 - 1 \ \mathrm{TeV}$

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6 \ \mathrm{TeV}$

very fast cooling time in the CMB: $\tau_{ICS} \approx (E_e/\mathrm{TeV})^{-1} \ \mathrm{Myr}$

Fast cooling regime —> $\boxed{L_e = L_\gamma}$

Hadronic: proton-proton interactions

radiation produced by protons of energy: $E_p \approx 0.01 - 1 \ \mathrm{TeV}$

for gas densities < 10^{-3} cm^{-3} —> cooling time is longer than Hubble time!

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6 \ \mathrm{TeV}$

very fast cooling time in the CMB: $\tau_{ICS} \approx \left(E_e/\mathrm{TeV}\right)^{-1} \ \mathrm{Myr}$

Fast cooling regime —> $\boxed{L_e = L_\gamma}$

Hadronic: proton-proton interactions

radiation produced by protons of energy: $E_p \approx 0.01 - 1 \ \mathrm{TeV}$

for gas densities < 10^{-3} cm^{-3} —> cooling time is longer than Hubble time!

$$L_p \approx L_\gamma \left(\tau_{res}/\tau_{pp}\right) \approx 2 \times 10^{41} \left(\tau_{res}/\mathrm{Gyr}\right)^{-1} \left(n_{gas}/10^{-3} \mathrm{cm}^{-3}\right)^{-1} \mathrm{erg/s}$$

Hadronic or leptonic?

$$L_\gamma \lesssim 2 \times 10^{39} \mathrm{erg/s}$$

Leptonic: inverse Compton scattering

radiation produced by electrons of energy: $E_e \approx 0.6 - 6 \ \mathrm{TeV}$

very fast cooling time in the CMB: $\tau_{ICS} \approx (E_e/\mathrm{TeV})^{-1} \ \mathrm{Myr}$

Fast cooling regime —> $\boxed{L_e = L_\gamma}$

Hadronic: proton-proton interactions

radiation produced by protons of energy: $E_p \approx 0.01 - 1 \ \mathrm{TeV}$

for gas densities < 10^{-3} cm^{-3} —> cooling time is longer than Hubble time!

$$L_p \approx L_\gamma \left(\tau_{res}/\tau_{pp}\right) \approx \boxed{2 \times 10^{41}} \left(\tau_{res}/\mathrm{Gyr}\right)^{-1} \left(n_{gas}/10^{-3}\mathrm{cm}^{-3}\right)^{-1} \mathrm{erg/s}$$

which is, in both scenarios, similar to the CR output of the Milky Way —> tight, but feasible energy budget

Problems…

Standard picture for CR origin in the MW: CRs are accelerated at sources in the disk, and remain confined for 10s of millions of years in the halo. Is this picture a good description of what we see from Andromeda?

Problems...

Standard picture for CR origin in the MW: CRs are accelerated at sources in the disk, and remain confined for 10s of millions of years in the halo. Is this picture a good description of what we see from Andromeda?

Leptonic: losses are too effective

energy loss time very short —> impossible for electrons to fill a region of size ~100 kpc

Problems...

Standard picture for CR origin in the MW: CRs are accelerated at sources in the disk, and remain confined for 10s of millions of years in the halo. Is this picture a good description of what we see from Andromeda?

Leptonic: losses are too effective

energy loss time very short —> impossible for electrons to fill a region of size ~100 kpc

Hadronic: large spatial gradients

extremely long loss time —> protons are loss free

Problems...

Standard picture for CR origin in the MW: CRs are accelerated at sources in the disk, and remain confined for 10s of millions of years in the halo. Is this picture a good description of what we see from Andromeda?

Leptonic: losses are too effective

energy loss time very short —> impossible for electrons to fill a region of size ~100 kpc

Hadronic: large spatial gradients

extremely long loss time —> protons are loss free

the transport in the halo is due to spatial
diffusion + advection in a galactic wind

Problems…

Standard picture for CR origin in the MW: CRs are accelerated at sources in the disk, and remain confined for 10s of millions of years in the halo. Is this picture a good description of what we see from Andromeda?

Leptonic: losses are too effective

energy loss time very short —> impossible for electrons to fill a region of size ~100 kpc

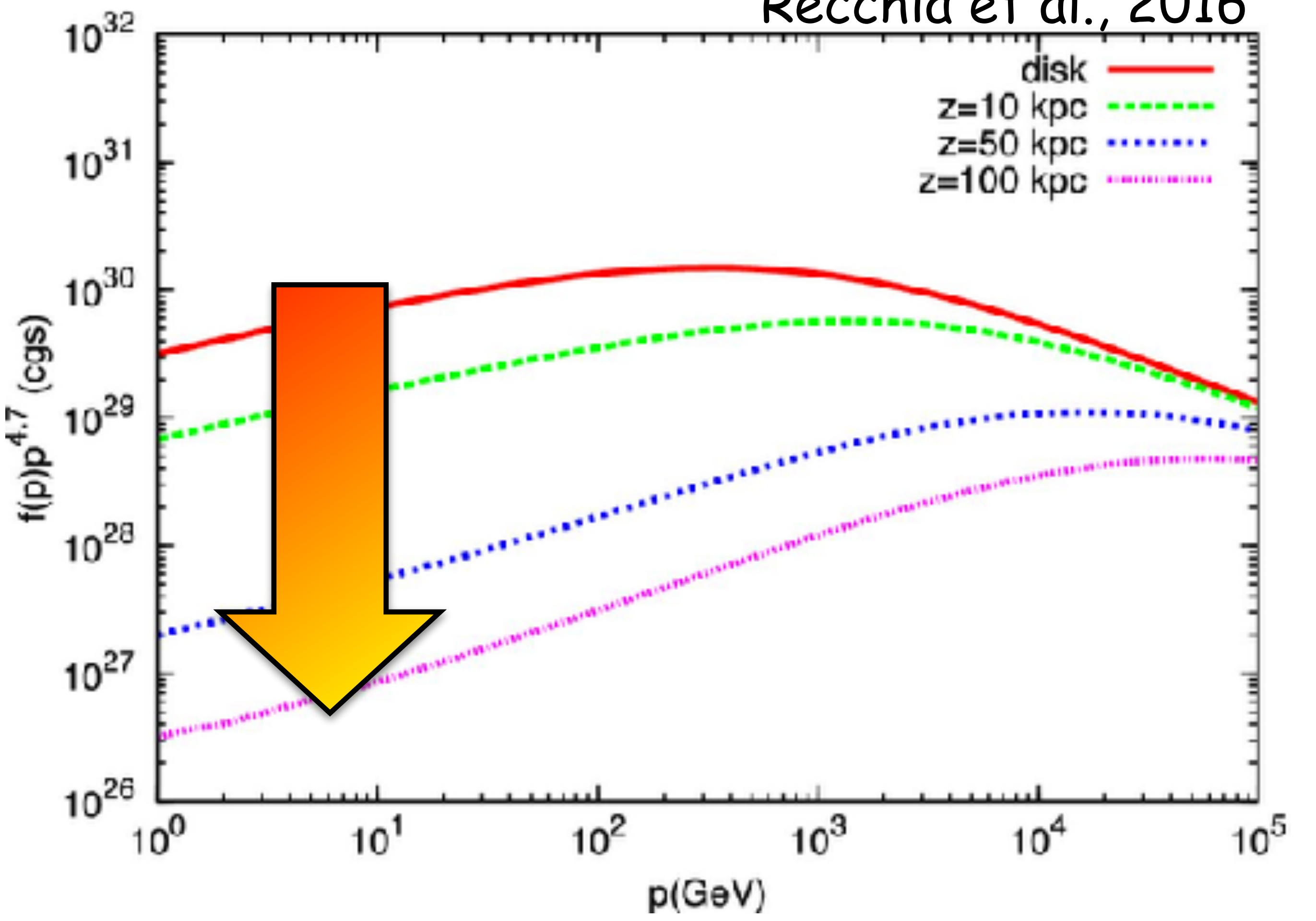
Hadronic: large spatial gradients

extremely long loss time —> protons are loss free

the transport in the halo is due to spatial diffusion + advection in a galactic wind

models predict a drop of CR density with height above the disk

Recchia et al., 2016



Problems…

Standard picture for CR origin in the MW: CRs are accelerated at sources in the disk, and remain confined for 10s of millions of years in the halo. Is this picture a good description of what we see from Andromeda?

Leptonic: losses are too effective

energy loss time very short —> impossible for electrons to fill a region of size ~100 kpc

Hadronic: large spatial gradients

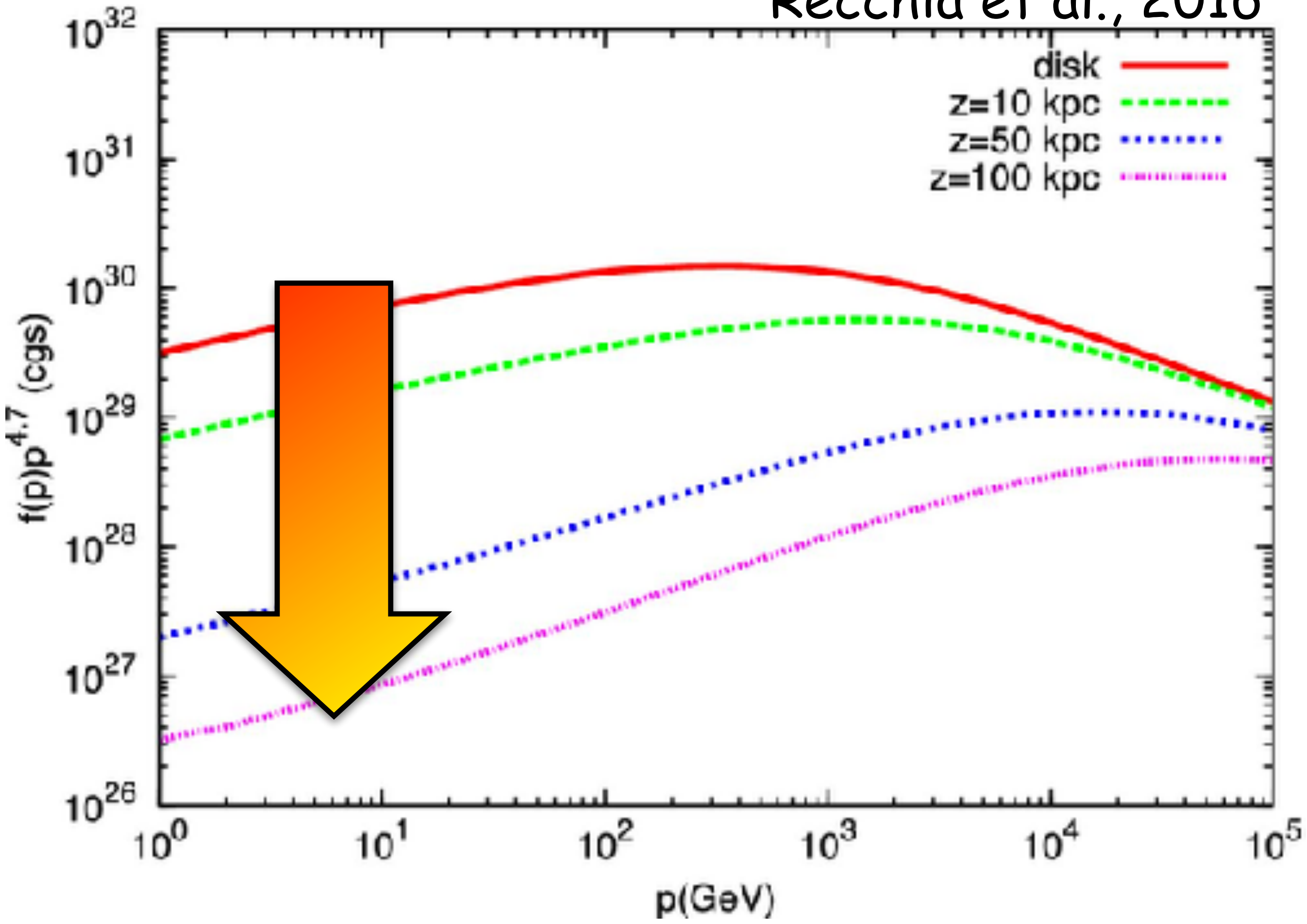
extremely long loss time —> protons are loss free

the transport in the halo is due to spatial diffusion + advection in a galactic wind

models predict a drop of CR density with height above the disk

in this context, explaining the gamma ray halo would require a very large CR density in the disk —> the disk is not as bright as needed

Recchia et al., 2016



Way out #1: in situ acceleration

Accretion shock?

free fall velocity —> $v_{ff} \sim 3 \times 10^2 \left(\frac{M}{10^{12} M_\odot}\right)^{1/2} \left(\frac{R_{sh}}{100\ \mathrm{kpc}}\right)^{1/2} \mathrm{km/s}$

Way out #1: in situ acceleration

Accretion shock?

free fall velocity —> $$v_{ff} \sim 3 \times 10^2 \left(\frac{M}{10^{12} M_\odot} \right)^{1/2} \left(\frac{R_{sh}}{100 \text{ kpc}} \right)^{1/2} \text{km/s}$$

shock luminosity

$$L_{sh} = (4\pi R_{sh}^2) \left(\frac{1}{2} \varrho_{gas}^{out} v_{ff}^3 \right) \sim 3 \times 10^{42} \left(\frac{M}{10^{12} M_\odot} \right)^{3/2} \left(\frac{R_{sh}}{100 \text{ kpc}} \right)^{1/2} \left(\frac{n_{gas}^{out}}{10^{-4} \text{cm}^{-3}} \right) \text{erg/s}$$

Way out #1: in situ acceleration

Accretion shock?

free fall velocity —> $v_{ff} \sim 3 \times 10^2 \left(\frac{M}{10^{12} M_\odot}\right)^{1/2} \left(\frac{R_{sh}}{100 \text{ kpc}}\right)^{1/2} \text{km/s}$

shock luminosity

$$L_{sh} = (4\pi R_{sh}^2) \left(\frac{1}{2} \varrho_{gas}^{out} v_{ff}^3\right) \boxed{\sim 3 \times 10^{42}} \left(\frac{M}{10^{12} M_\odot}\right)^{3/2} \left(\frac{R_{sh}}{100 \text{ kpc}}\right)^{1/2} \left(\frac{n_{gas}^{out}}{10^{-4} \text{cm}^{-3}}\right) \text{erg/s}$$

there is enough energy!

Way out #1: in situ acceleration

Accretion shock?

free fall velocity —> $v_{ff} \sim 3 \times 10^2 \left(\frac{M}{10^{12} M_\odot}\right)^{1/2} \left(\frac{R_{sh}}{100 \text{ kpc}}\right)^{1/2} \text{km/s}$

shock luminosity

$$L_{sh} = (4\pi R_{sh}^2) \left(\frac{1}{2} \varrho_{gas}^{out} v_{ff}^3\right) \sim 3 \times 10^{42} \left(\frac{M}{10^{12} M_\odot}\right)^{3/2} \left(\frac{R_{sh}}{100 \text{ kpc}}\right)^{1/2} \left(\frac{n_{gas}^{out}}{10^{-4} \text{cm}^{-3}}\right) \text{erg/s}$$

there is enough energy!

Termination shock powered by the SMBH activity?

Way out #1: in situ acceleration

Accretion shock?

free fall velocity —> $v_{ff} \sim 3 \times 10^2 \left(\frac{M}{10^{12} M_\odot}\right)^{1/2} \left(\frac{R_{sh}}{100 \text{ kpc}}\right)^{1/2} \text{km/s}$

shock luminosity

$$L_{sh} = (4\pi R_{sh}^2) \left(\frac{1}{2} \varrho_{gas}^{out} v_{ff}^3\right) \boxed{\sim 3 \times 10^{42}} \left(\frac{M}{10^{12} M_\odot}\right)^{3/2} \left(\frac{R_{sh}}{100 \text{ kpc}}\right)^{1/2} \left(\frac{n_{gas}^{out}}{10^{-4} \text{cm}^{-3}}\right) \text{erg/s}$$

there is enough energy!

Termination shock powered by the SMBH activity?

continuous injection of energy L_{BH} at the SMBH —> a dimensional argument leads to:

$$v_{sh} \sim \left(\frac{L_{BH}}{\varrho_{gas}^{out}}\right)^{1/5} t^{-2/5} \approx 3 \times 10^2 \left(\frac{L_{BH}}{10^{43} \text{erg/s}}\right)^{1/5} \left(\frac{n_{gas}^{out}}{10^{-4} \text{cm}^{-3}}\right)^{-1/5} \left(\frac{t}{\text{Gyr}}\right)^{-2/5} \text{km/s}$$

Way out #1: in situ acceleration

Accretion shock?

free fall velocity —> $v_{ff} \sim 3 \times 10^2 \left(\frac{M}{10^{12} M_\odot} \right)^{1/2} \left(\frac{R_{sh}}{100 \text{ kpc}} \right)^{1/2} \text{km/s}$

shock luminosity

$$L_{sh} = (4\pi R_{sh}^2) \left(\frac{1}{2} \varrho_{gas}^{out} v_{ff}^3 \right) \boxed{\sim 3 \times 10^{42}} \left(\frac{M}{10^{12} M_\odot} \right)^{3/2} \left(\frac{R_{sh}}{100 \text{ kpc}} \right)^{1/2} \left(\frac{n_{gas}^{out}}{10^{-4} \text{cm}^{-3}} \right) \text{erg/s}$$

there is enough energy!

Termination shock powered by the SMBH activity?

continuous injection of energy L_{BH} at the SMBH —> a dimensional argument leads to:

$$v_{sh} \sim \left(\frac{L_{BH}}{\varrho_{gas}^{out}} \right)^{1/5} t^{-2/5} \approx 3 \times 10^2 \left(\frac{L_{BH}}{10^{43} \text{erg/s}} \right)^{1/5} \left(\frac{n_{gas}^{out}}{10^{-4} \text{cm}^{-3}} \right)^{-1/5} \left(\frac{t}{\text{Gyr}} \right)^{-2/5} \text{km/s}$$

$$L_{Edd} \approx 10^{46} \left(\frac{M_{SMBH}}{10^8 M_\odot} \right) \text{erg/s}$$

there is enough energy!

Way out #1: in situ acceleration

Maximum energy of accelerated particles

CR acceleration time at a shock —> $\tau_{acc} = a\frac{D}{v_{sh}^2}$ $a \approx 10$

Way out #1: in situ acceleration

Maximum energy of accelerated particles

CR acceleration time at a shock —> $\tau_{acc} = a \frac{D}{v_{sh}^2}$ $a \approx 10$

Leptonic scenario: $\tau_{acc} = \tau_{loss}$

Way out #1: in situ acceleration

Maximum energy of accelerated particles

CR acceleration time at a shock —> $\tau_{acc} = a \frac{D}{v_{sh}^2}$ $a \approx 10$

Leptonic scenario: $\tau_{acc} = \tau_{loss}$

$$E_e^{max} \approx 24 \left(\frac{v_{sh}}{1000 \text{ km/s}} \right)^3 \left(\frac{n_{gas}}{10^{-4} \text{ cm}^{-3}} \right)^{1/4} \text{TeV}$$

OK!

Way out #1: in situ acceleration

Maximum energy of accelerated particles

CR acceleration time at a shock —> $\tau_{acc} = a \frac{D}{v_{sh}^2}$ $a \approx 10$

Leptonic scenario: $\tau_{acc} = \tau_{loss}$

$$E_e^{max} \approx 24 \left(\frac{v_{sh}}{1000 \text{ km/s}} \right)^3 \left(\frac{n_{gas}}{10^{-4} \text{ cm}^{-3}} \right)^{1/4} \text{TeV}$$

OK!

Hadronic scenario: $\tau_{acc} = \tau_{res}$

Way out #1: in situ acceleration

Maximum energy of accelerated particles

CR acceleration time at a shock —> $\tau_{acc} = a\frac{D}{v_{sh}^2}$ $a \approx 10$

Leptonic scenario: $\tau_{acc} = \tau_{loss}$

$$E_e^{max} \approx 24 \left(\frac{v_{sh}}{1000\ \mathrm{km/s}}\right)^3 \left(\frac{n_{gas}}{10^{-4}\ \mathrm{cm}^{-3}}\right)^{1/4} \mathrm{TeV}$$

OK!

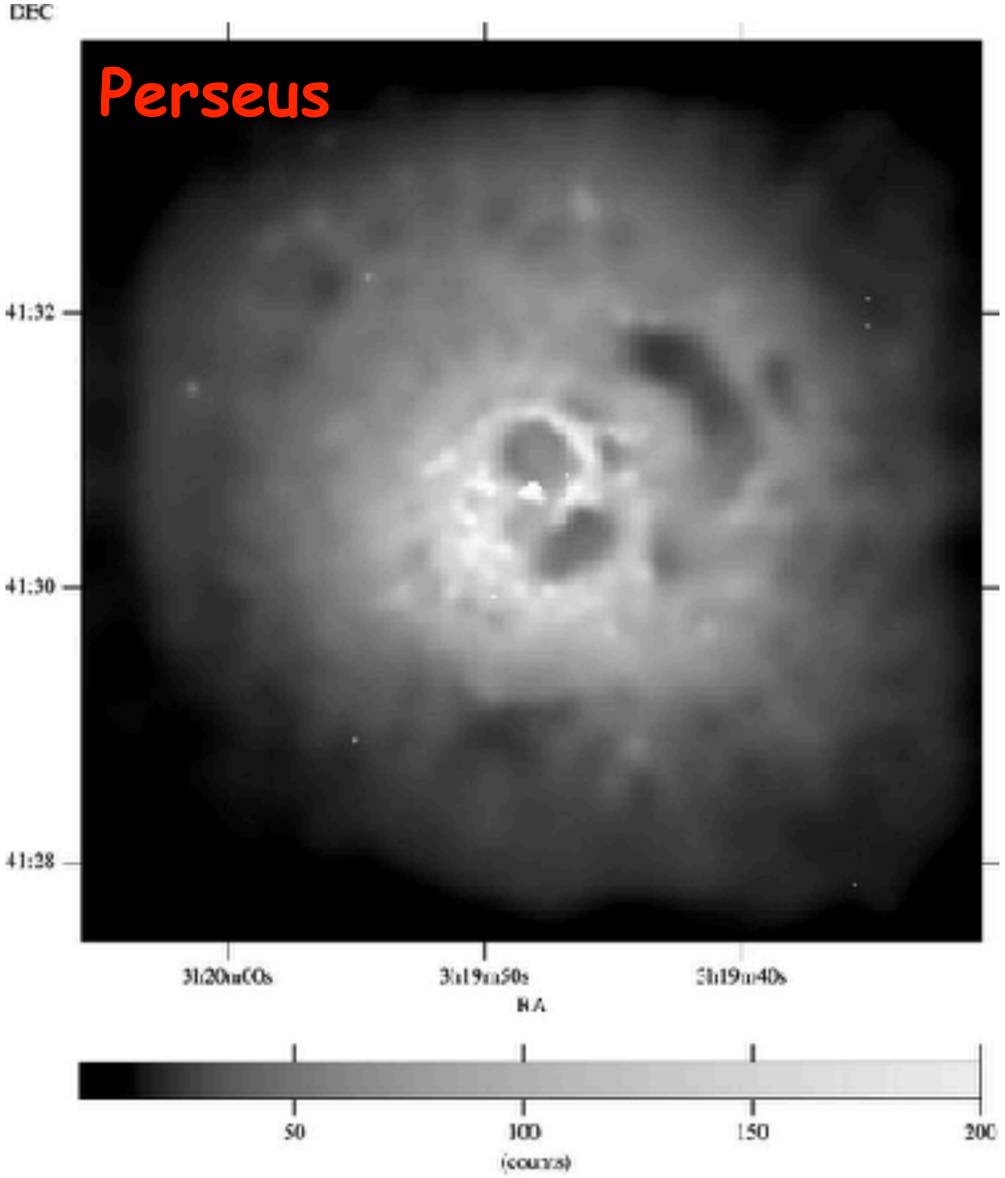
Hadronic scenario: $\tau_{acc} = \tau_{res}$

B-field amplification at shocks:
fraction of shock ram pressure
converted into magnetic pressure

$$E_p^{max} \approx 460 \left(\frac{v_{sh}}{1000\ \mathrm{km/s}}\right)^3 \left(\frac{n_{gas}}{10^{-4}\ \mathrm{cm}^{-3}}\right)^{1/2} \left(\frac{\tau_{res}}{\mathrm{Gyr}}\right) \left(\frac{\xi_B}{0.035}\right)^{1/2} \mathrm{PeV}$$

OK!

Way out #2: buoyant bubbles

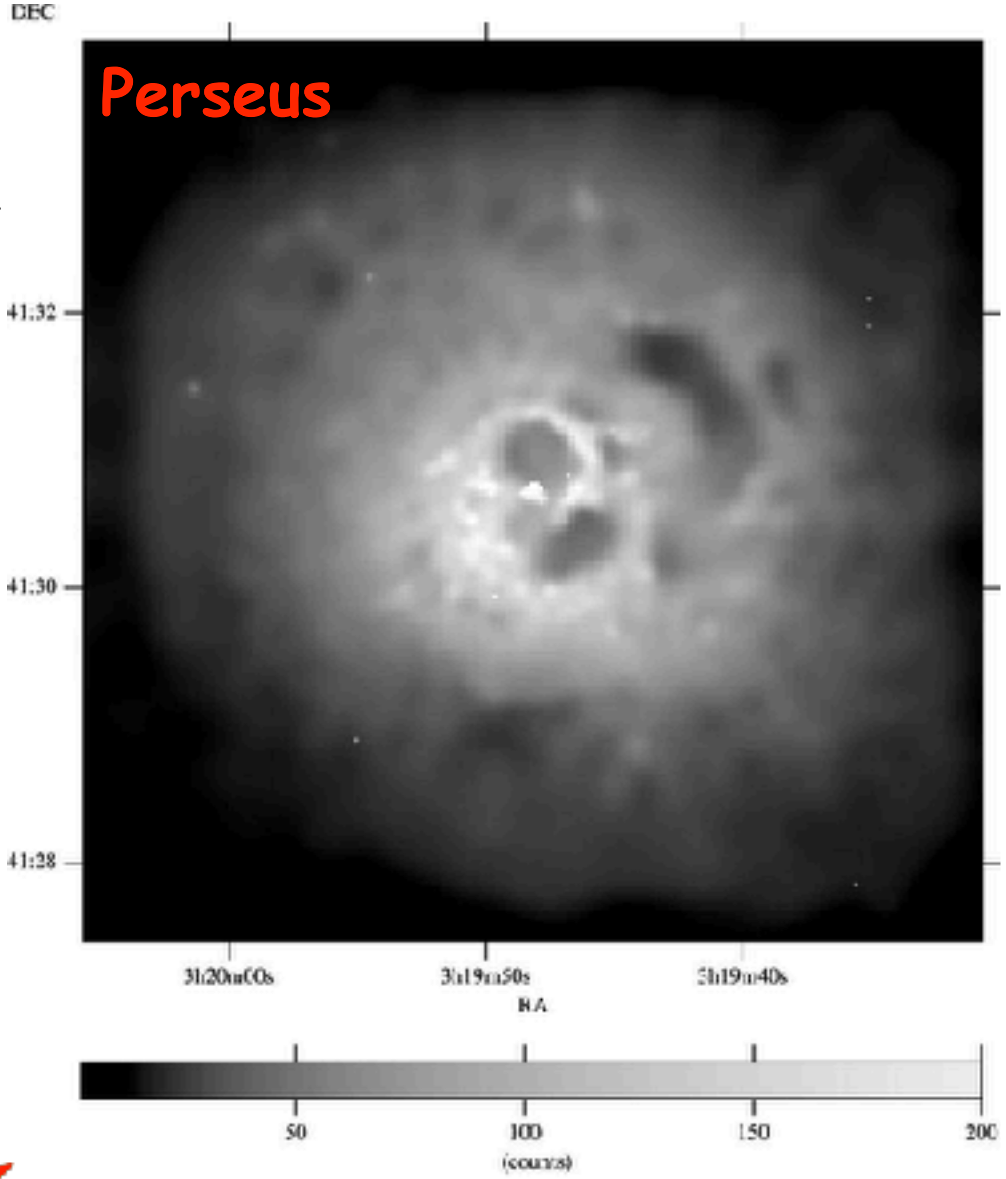


Fabian et al., 2002

☑ **Buoyant bubbles**

- Often present in central regions of galaxy clusters, inflated by AGN activity
- Typical radii of several kpc's
- Rise velocity ~ sound speed ~ 100 km/s
- Lifetime (hydro): $T_b \sim 100$ Myr
- Stabilising effect of B-fields: $T_b \gtrsim 1$ Gyr
- Huge energy reservoir: $W_b \sim 10^{57}$-10^{59} erg

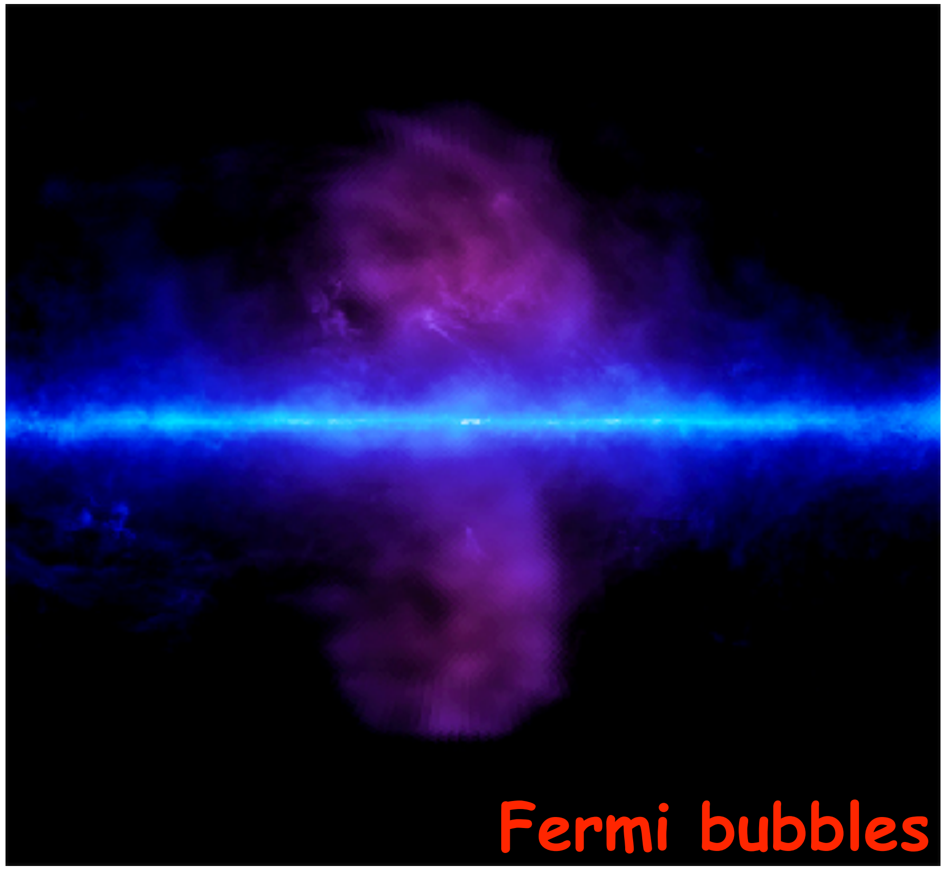
Way out #2: buoyant bubbles



Fabian et al., 2002

☑ **Buoyant bubbles**

- Often present in central regions of galaxy clusters, inflated by AGN activity
- Typical radii of several kpc's
- Rise velocity ~ sound speed ~ 100 km/s
- Lifetime (hydro): $T_b \sim 100$ Myr
- Stabilising effect of B-fields: $T_b \gtrsim 1$ Gyr
- Huge energy reservoir: $W_b \sim 10^{57}$-10^{59} erg



☑ **Fermi bubbles**

- Originated by SMBH or star forming activity
- Radius $\gtrsim 10$ kpc
- Age: few to few tens Myr
- Power ~10^{41}-10^{43} erg/s —> 10^{55}-10^{57} erg
- Are Fermi bubbles the base of a larger structure?

Way out #2: buoyant bubbles

☑ **Proposed scenario**

- CR protons (loss free) transported to the halo inside buoyant bubbles
- in a disruption time they rise up to ~100 kpc
- after disruption CRs are released in the halo
- they spread diffusively in a time T_{diff}
- bubbles are produced at the GC with a frequency ν_b
- $\nu_b > 1/T_{diff}$ —> continuous injection of CR in the halo
- assume $\nu_b = 10^{-8}\mathrm{yr}^{-1}$ and $E_b = 10^{57} E_{b,57}\mathrm{erg}$

Way out #2: buoyant bubbles

☑ **Proposed scenario**

- CR protons (loss free) transported to the halo inside buoyant bubbles
- in a disruption time they rise up to ~100 kpc
- after disruption CRs are released in the halo
- they spread diffusively in a time T_{diff}
- bubbles are produced at the GC with a frequency ν_b
- $\nu_b > 1/T_{diff}$ —> continuous injection of CR in the halo
- assume $\nu_b = 10^{-8} \mathrm{yr}^{-1}$ and $E_b = 10^{57} E_{b,57} \mathrm{erg}$

Way out #2: buoyant bubbles

☑ **Proposed scenario**

- CR protons (loss free) transported to the halo inside buoyant bubbles
- in a disruption time they rise up to ~100 kpc
- after disruption CRs are released in the halo
- they spread diffusively in a time T_{diff}
- bubbles are produced at the GC with a frequency ν_b
- $\nu_b > 1/T_{diff}$ —> continuous injection of CR in the halo
- assume $\nu_b = 10^{-8}\mathrm{yr}^{-1}$ and $E_b = 10^{57} E_{b,57}\mathrm{erg}$

Average CR luminosity in the halo —> $L_{CR} \sim 3 \times 10^{41} \eta E_{b,57} \nu_{b,-8} \mathrm{erg/s}$

Way out #2: buoyant bubbles

☑ **Proposed scenario**

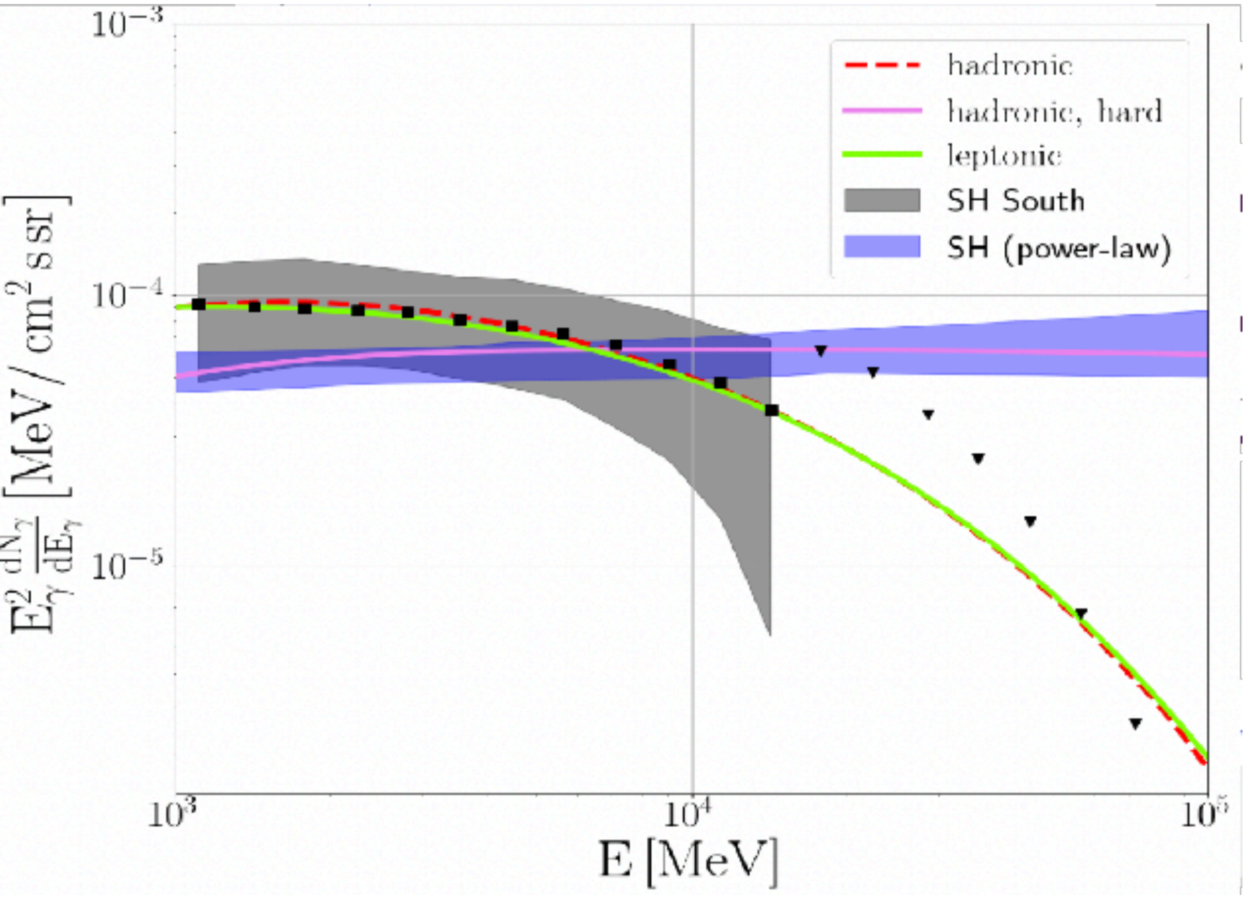
- CR protons (loss free) transported to the halo inside buoyant bubbles
- in a disruption time they rise up to ~100 kpc
- after disruption CRs are released in the halo
- they spread diffusively in a time T_{diff}
- bubbles are produced at the GC with a frequency ν_b
- $\nu_b > 1/T_{diff}$ —> continuous injection of CR in the halo
- assume $\nu_b = 10^{-8} \mathrm{yr}^{-1}$ and $E_b = 10^{57} E_{b,57} \mathrm{erg}$

Average CR luminosity in the halo —> $L_{CR} \sim 3 \times 10^{41} \eta E_{b,57} \nu_{b,-8} \mathrm{erg/s}$

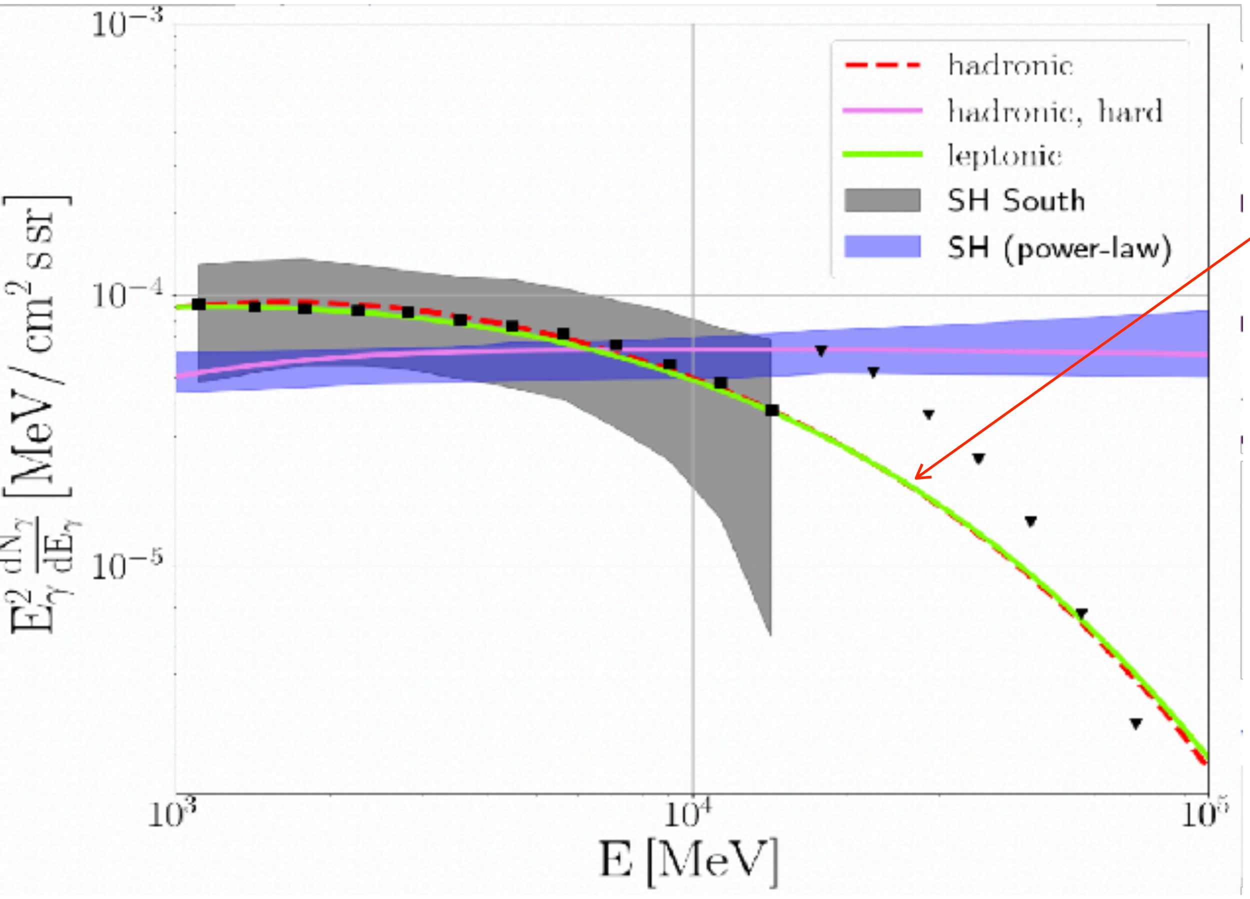
CR acceleration efficiency

$$\eta \sim 0.2 \ E_{b,57}^{-1} \nu_{b,-8}^{-1} \left(n_{gas}/10^{-3} \mathrm{cm}^{-3} \right)^{-1} \left(\tau_{res}/3 \ \mathrm{Gyr} \right)^{-1}$$

Way out #2: buoyant bubbles



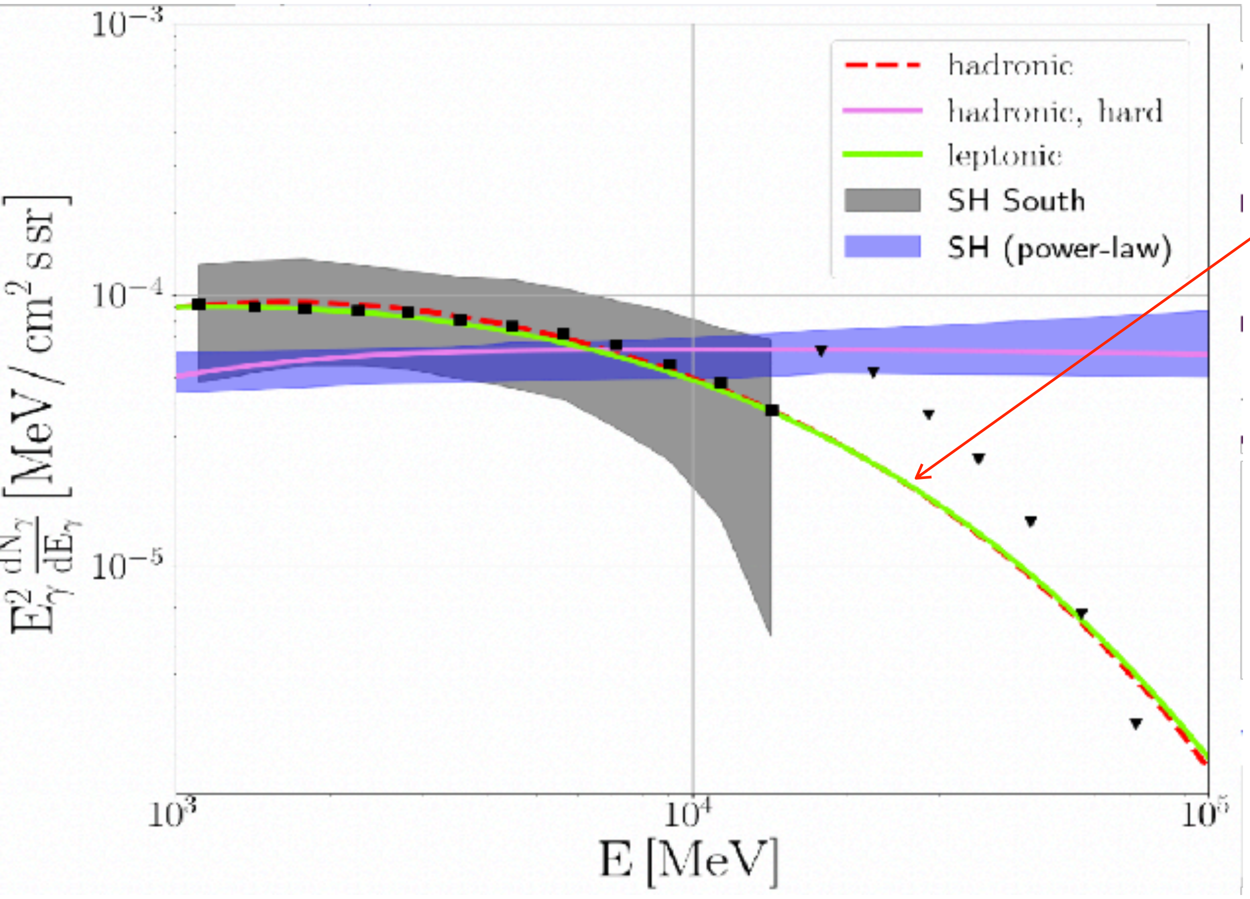
Way out #2: buoyant bubbles



Scenario A —> cutoff @10 GeV

cutoff in the parent CR proton spectrum @100 GeV

Way out #2: buoyant bubbles



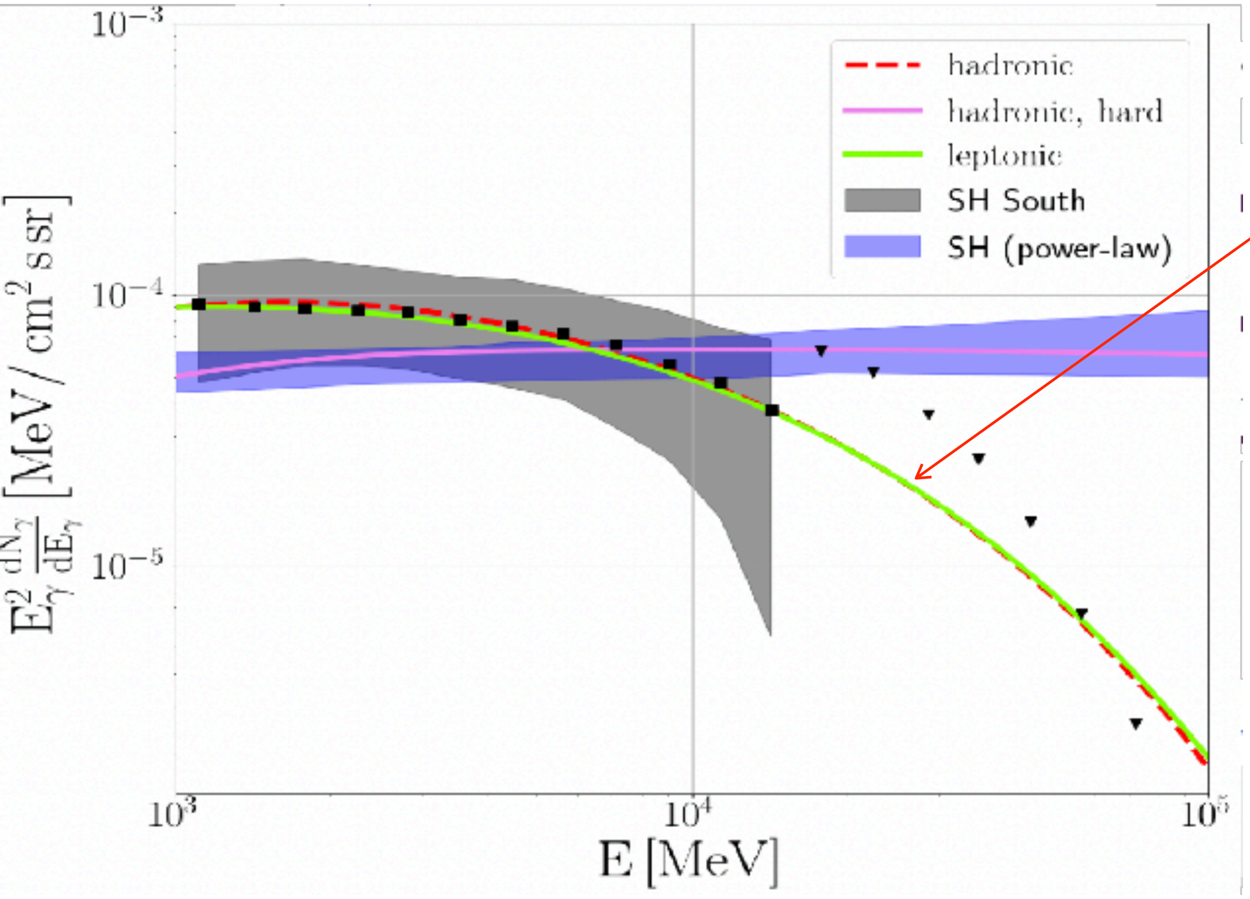
Scenario A —> cutoff @10 GeV

cutoff in the parent CR proton spectrum @100 GeV

D(E) —> energy dependent CR diffusion coefficient

Diffusion time —> $\tau_{diff} \sim \dfrac{R_H^2}{6\ D(E)}$

Way out #2: buoyant bubbles



Scenario A —> cutoff @10 GeV

cutoff in the parent CR proton spectrum @100 GeV

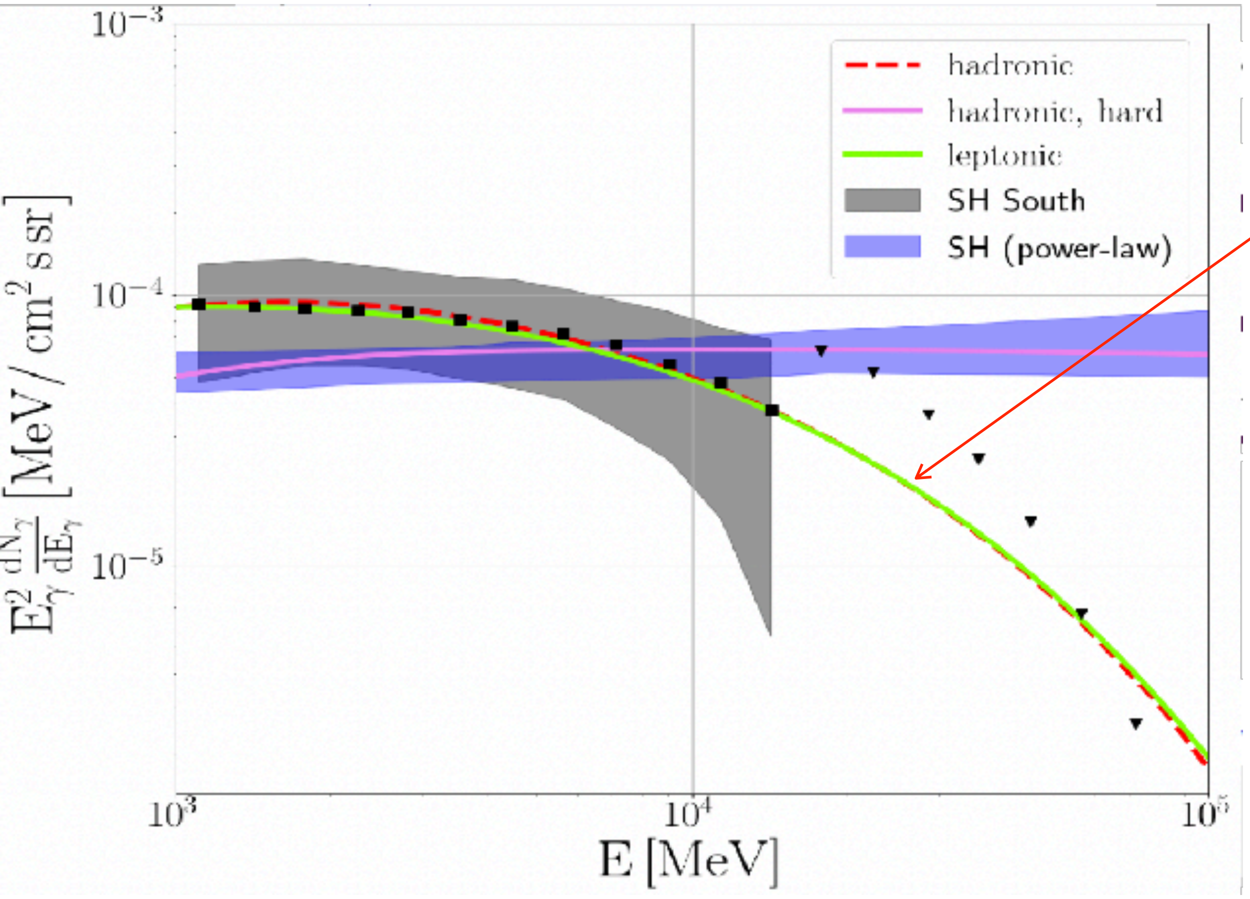
D(E) —> energy dependent CR diffusion coefficient

Diffusion time —> $\tau_{diff} \sim \dfrac{R_H^2}{6\ D(E)}$

$\nu_b > 1/\tau_{diff}$ **—> stationary**

$\nu_b < 1/\tau_{diff}$ **—> intermittent**

Way out #2: buoyant bubbles



Scenario A —> cutoff @10 GeV

cutoff in the parent CR proton spectrum @100 GeV

D(E) —> energy dependent CR diffusion coefficient

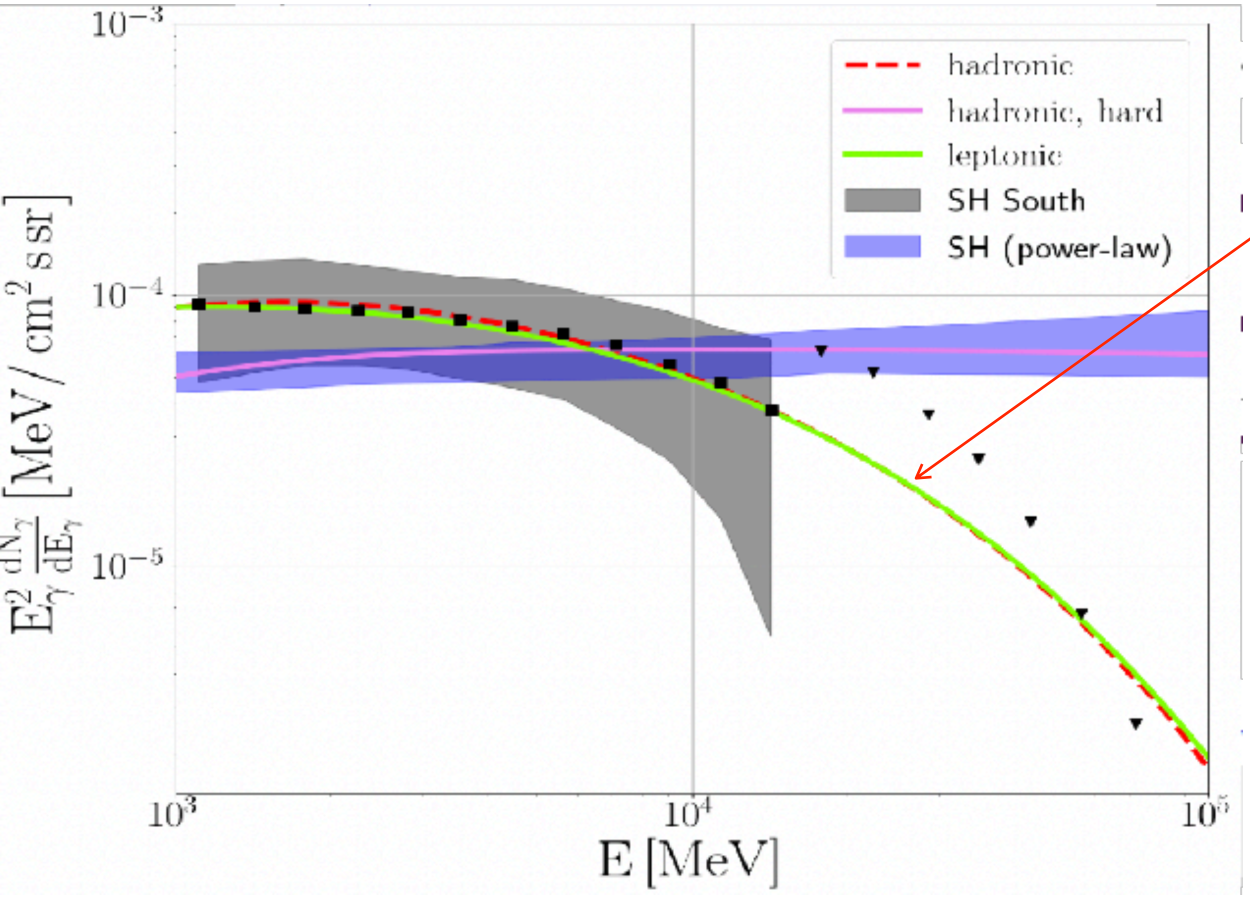
Diffusion time —> $\tau_{diff} \sim \dfrac{R_H^2}{6\ D(E)}$

$\nu_b > 1/\tau_{diff}$ —> **stationary** —> **low E**

$\nu_b < 1/\tau_{diff}$ —> **intermittent** —> **high E**

energy dependent!

Way out #2: buoyant bubbles



Scenario A —> cutoff @10 GeV

cutoff in the parent CR proton spectrum @100 GeV

D(E) —> energy dependent CR diffusion coefficient

Diffusion time —> $\tau_{diff} \sim \dfrac{R_H^2}{6\ D(E)}$

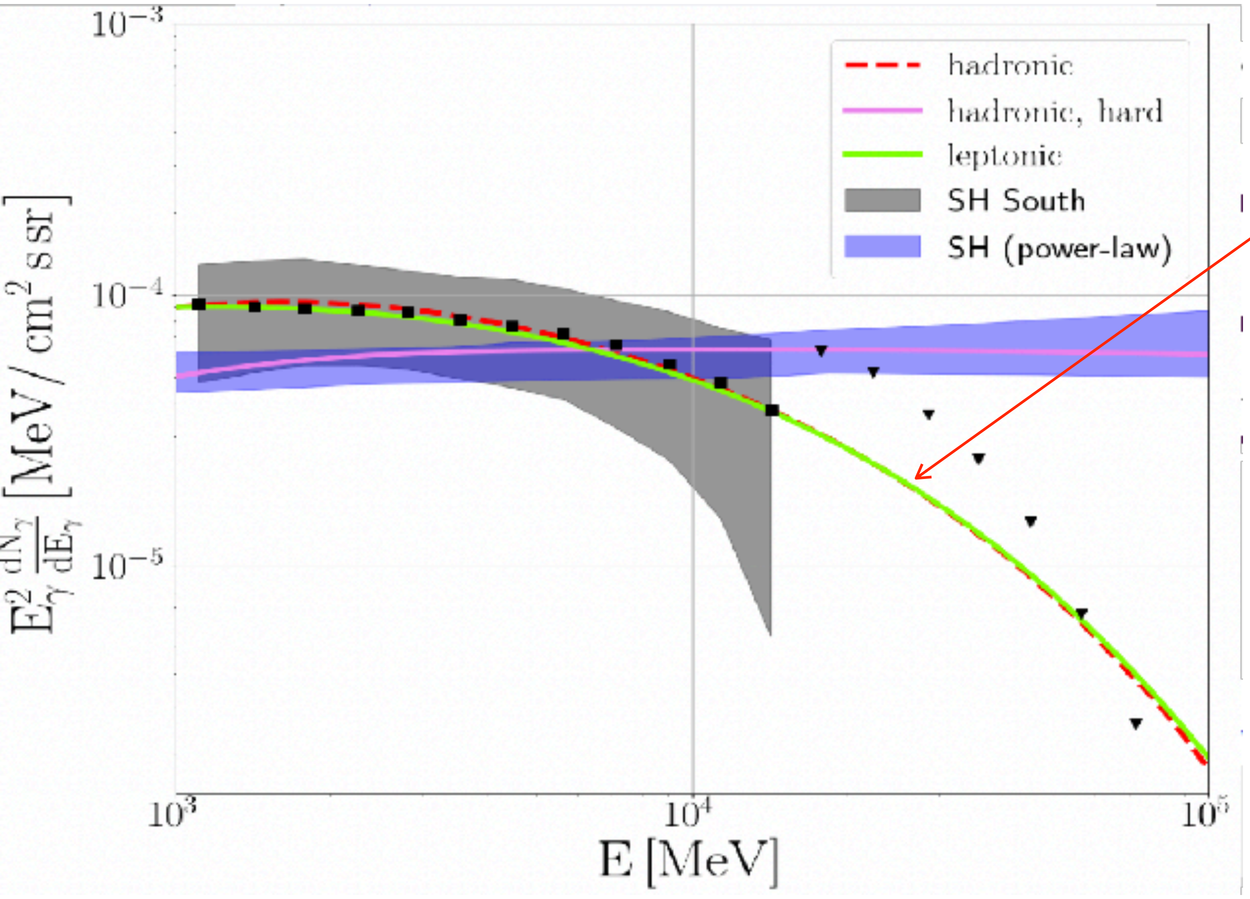
$\nu_b > 1/\tau_{diff}$ —> **stationary** —> **low E**

$\nu_b < 1/\tau_{diff}$ —> **intermittent** —> **high E**

energy dependent!

$$\nu_b \sim 1/\tau_{diff}(100\ \mathrm{GeV}) \Rightarrow D(100\ \mathrm{GeV}) \sim 5 \times 10^{30} \left(\frac{R_H}{100\ \mathrm{kpc}}\right)^2 \nu_{b,-8}\ \mathrm{cm}^2/\mathrm{s}$$

Way out #2: buoyant bubbles



Scenario A —> cutoff @10 GeV

cutoff in the parent CR proton spectrum @100 GeV

D(E) —> energy dependent CR diffusion coefficient

Diffusion time —> $\tau_{diff} \sim \dfrac{R_H^2}{6\ D(E)}$

$\nu_b > 1/\tau_{diff}$ —> stationary —> low E

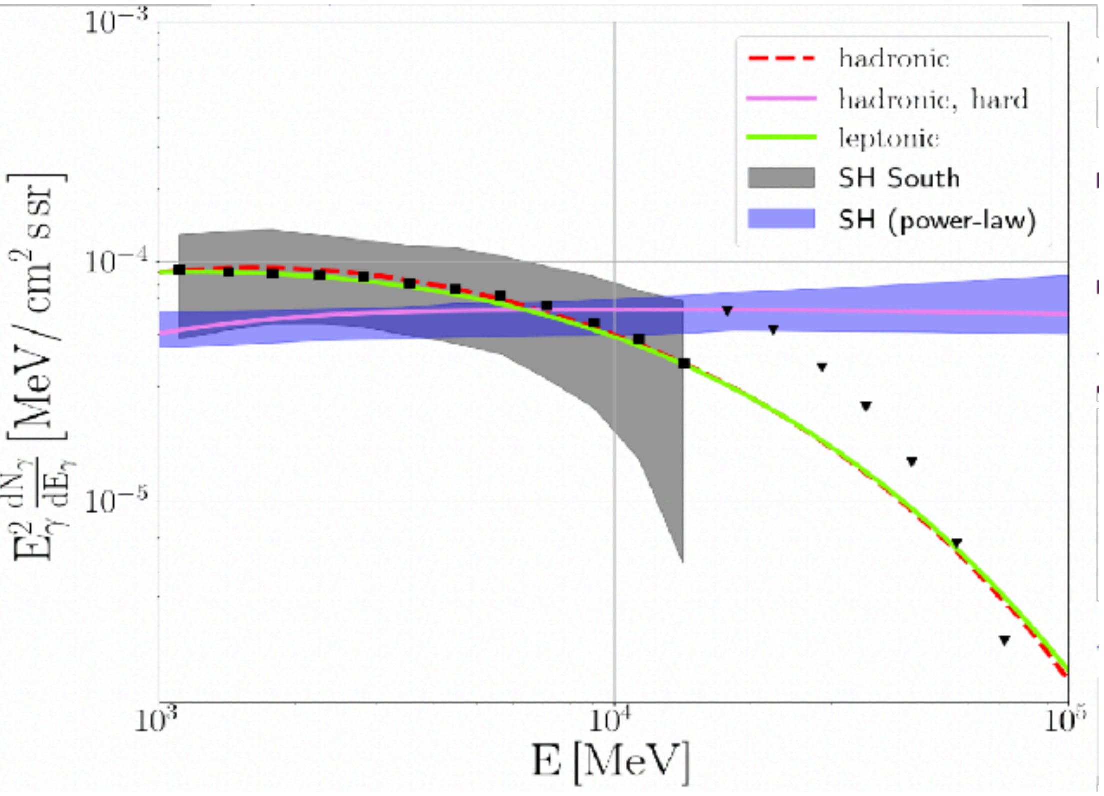
$\nu_b < 1/\tau_{diff}$ —> intermittent —> high E

energy dependent!

$$\nu_b \sim 1/\tau_{diff}(100\ \mathrm{GeV}) \Rightarrow D(100\ \mathrm{GeV}) \sim 5 \times 10^{30} \left(\frac{R_H}{100\ \mathrm{kpc}}\right)^2 \nu_{b,-8}\ \mathrm{cm}^2/\mathrm{s}$$

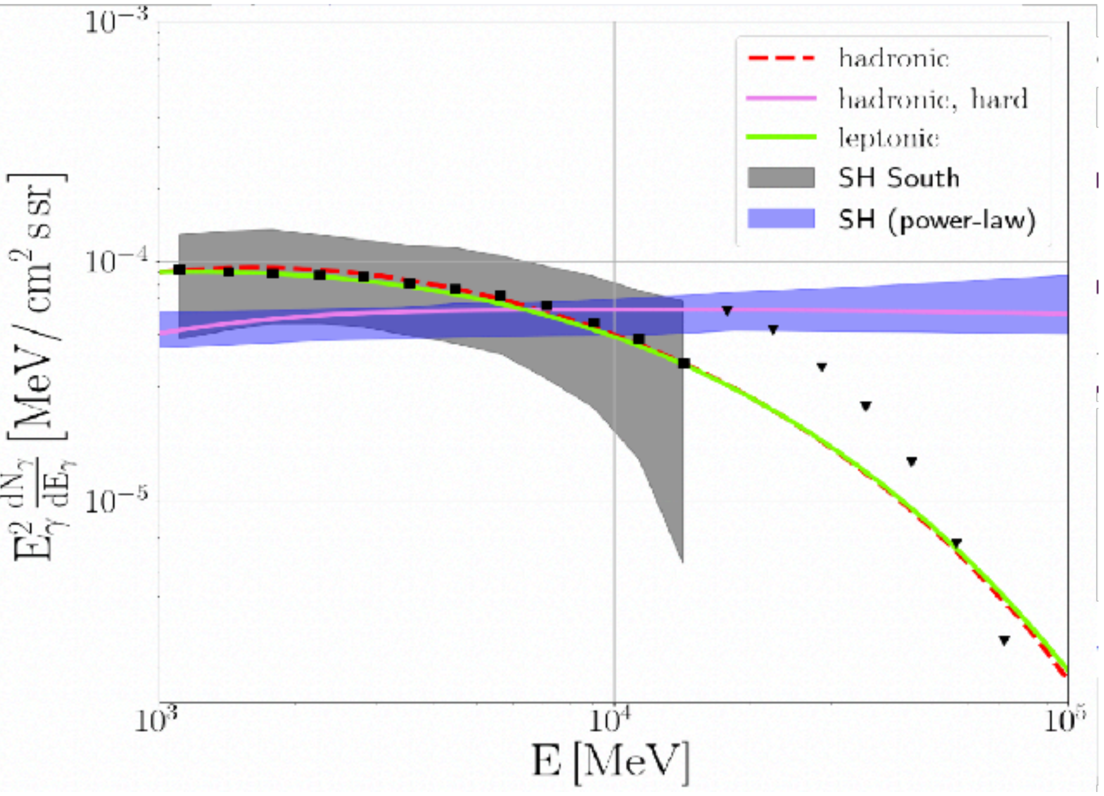
very plausible value

M31 & MW: IceCube neutrinos



Scenario B —> no cutoff

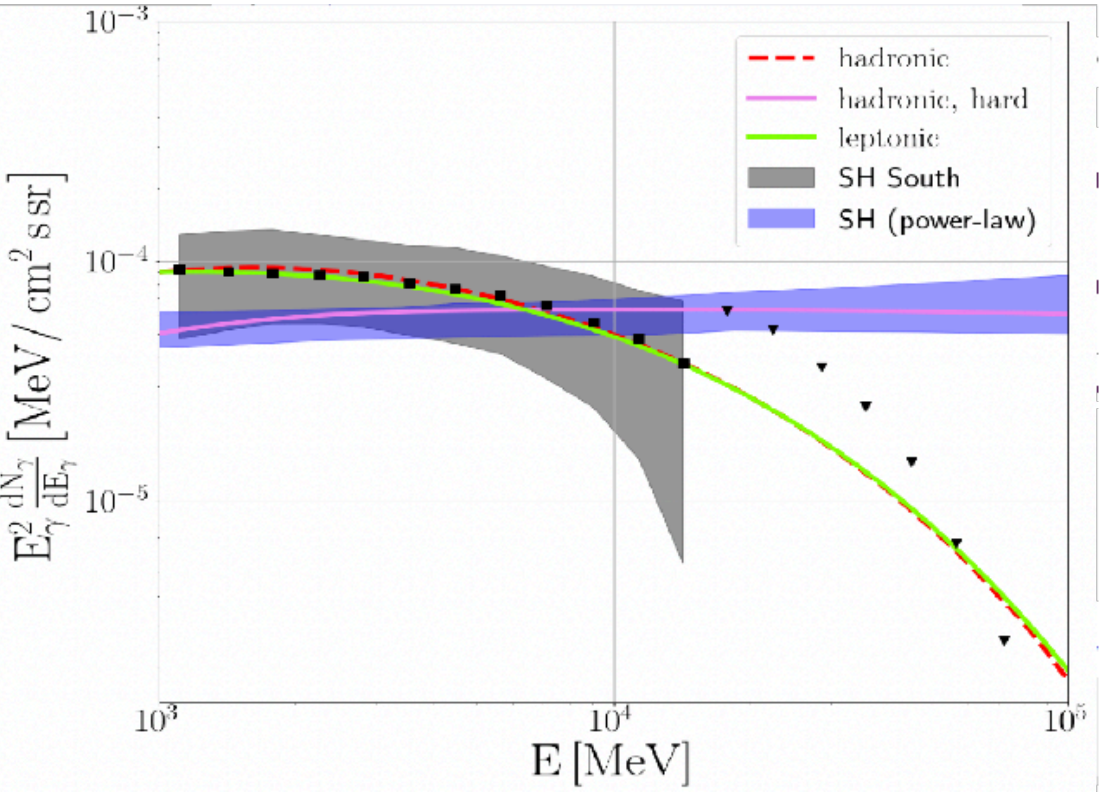
M31 & MW: IceCube neutrinos



Scenario B —> no cutoff

what if giant CR halos are a common feature of galaxies?

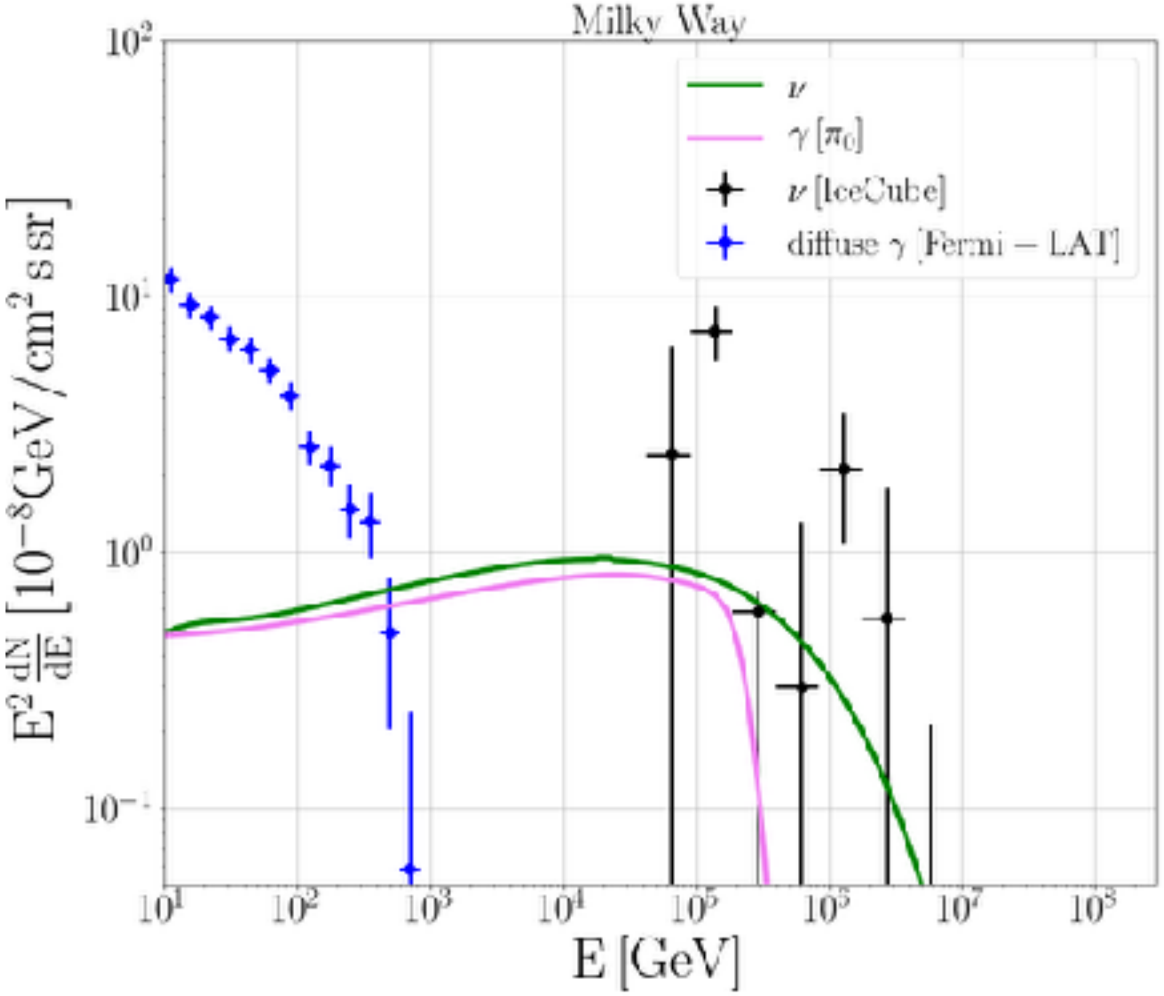
M31 & MW: IceCube neutrinos



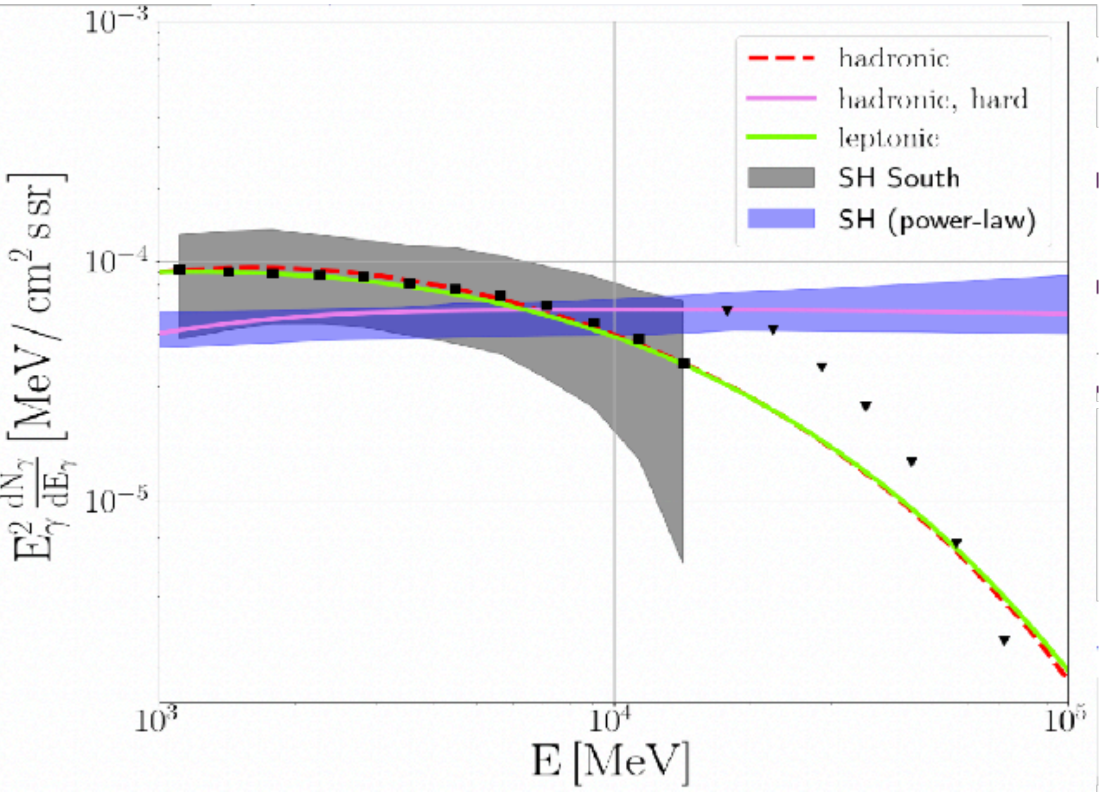
Scenario B —> no cutoff

what if giant CR halos are a common feature of galaxies?

Taylor, SG, Aharonian (2014) proposed that CR p-p interactions in a huge gaseous halo surrounding the Milky Way might explain the isotropic diffuse flux of neutrinos observed by Icecube (black data points and green curve), without violating the limits imposed by the isotropic gamma-ray background (blue data point and pink curve)



M31 & MW: IceCube neutrinos

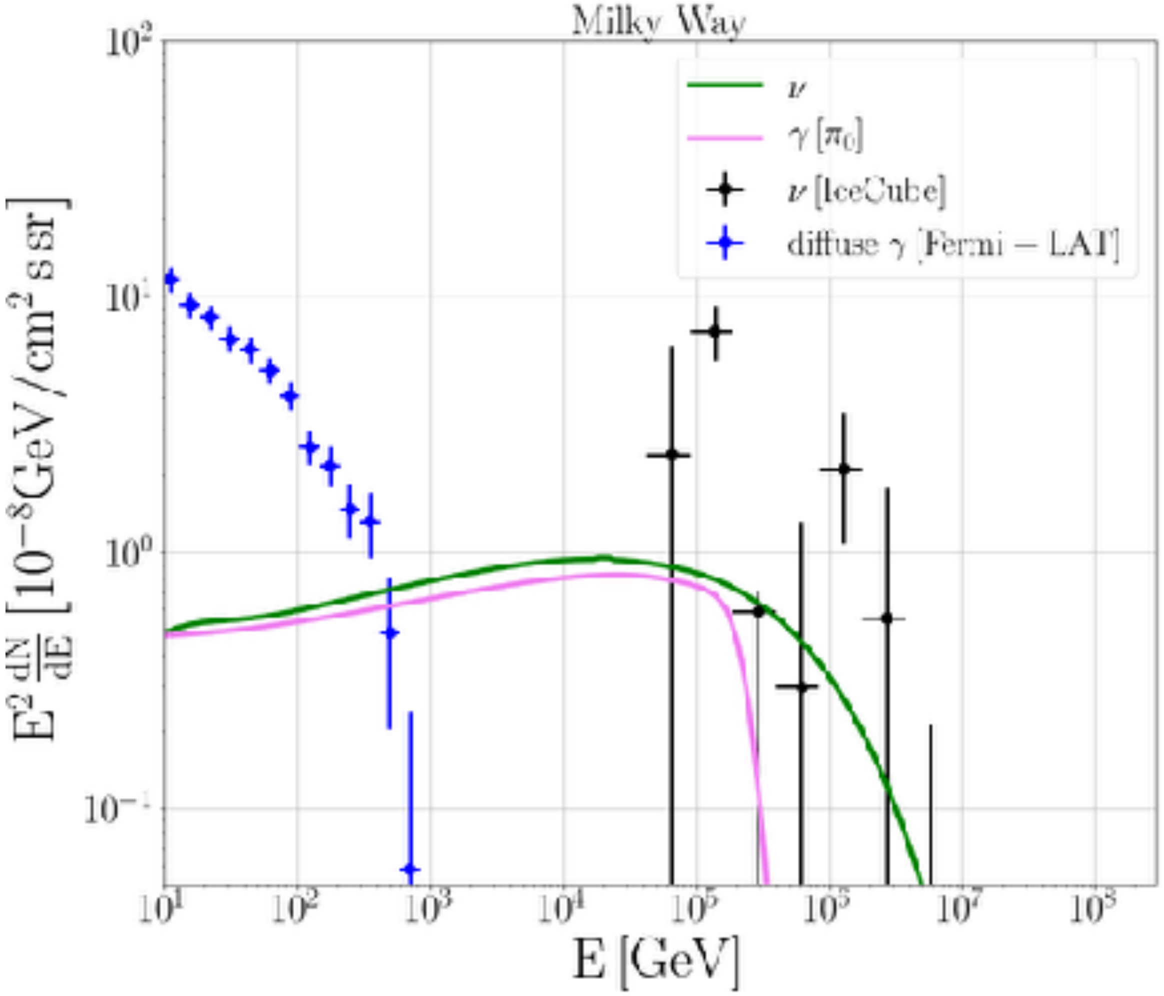


Scenario B —> no cutoff

what if giant CR halos are a common feature of galaxies?

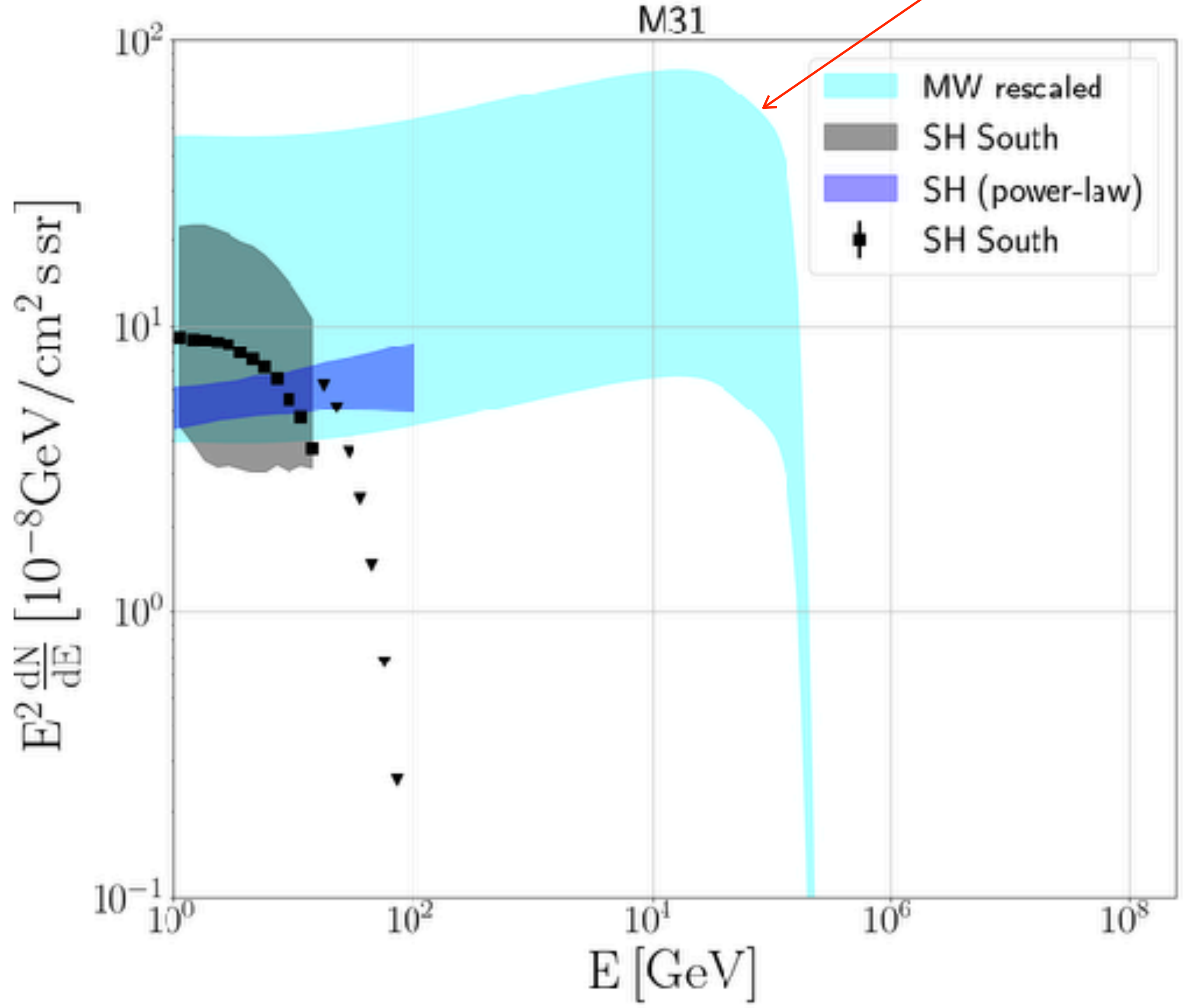
Taylor, SG, Aharonian (2014) proposed that CR p-p interactions in a huge gaseous halo surrounding the Milky Way might explain the isotropic diffuse flux of neutrinos observed by Icecube (black data points and green curve), without violating the limits imposed by the isotropic gamma-ray background (blue data point and pink curve)

Requires a CR proton spectrum extending to the multi-PeV domain



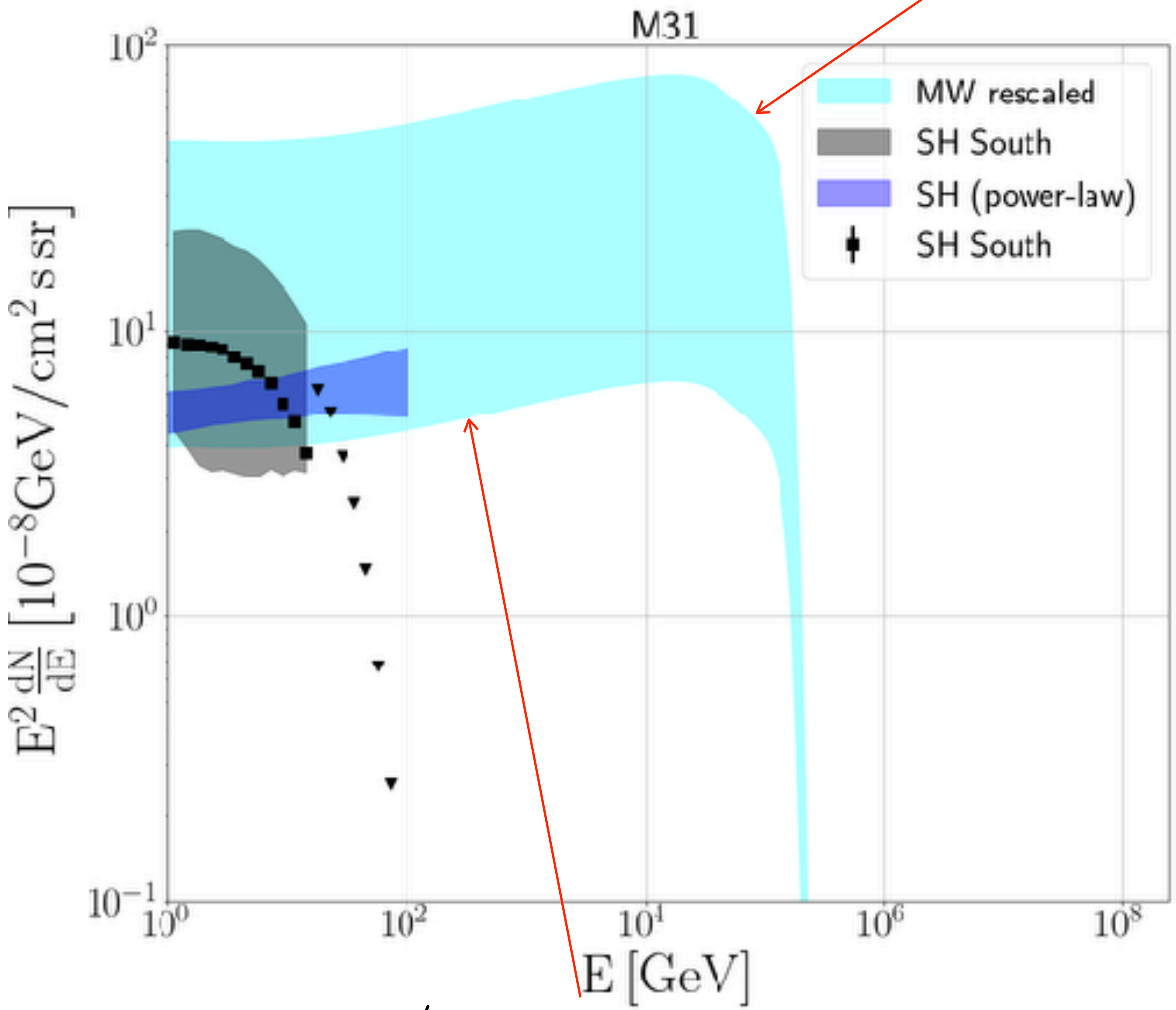
M31 and the MW:are giant halos common?

SMBH activity —> $(M_{SMBH,31}/M_{SMBH,MW}) \sim 33$



M31 and the MW:are giant halos common?

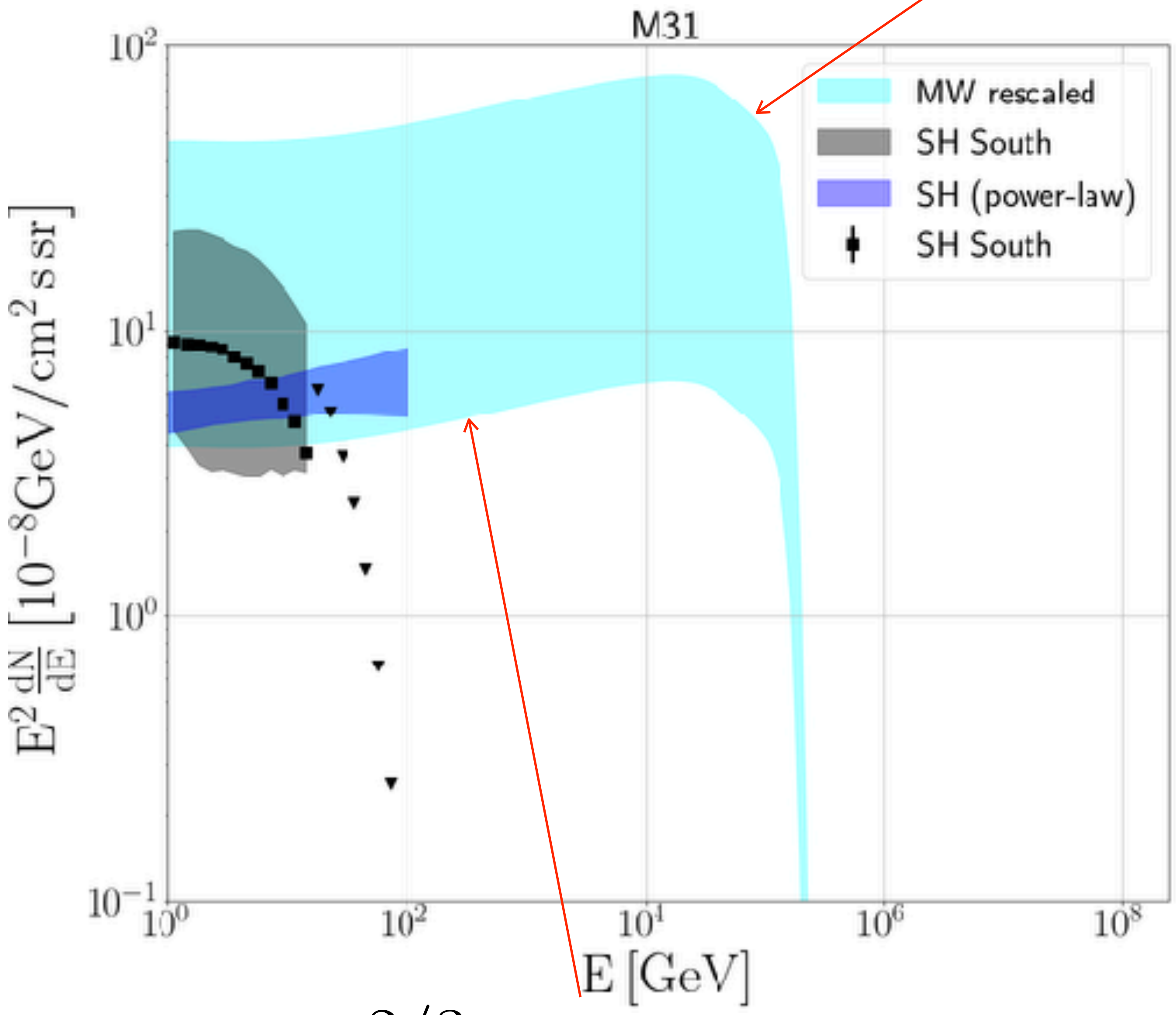
SMBH activity —> $(M_{SMBH,31}/M_{SMBH,MW}) \sim 33$



Accretion shock —> $(M_{31}/M_{MW})^{2/3} \sim 3$

M31 and the MW:are giant halos common?

SMBH activity —> $(M_{SMBH,31}/M_{SMBH,MW}) \sim 33$



Accretion shock —> $(M_{31}/M_{MW})^{2/3} \sim 3$

if giant CR halos are a common feature of galaxies it is possible to explain simultaneously Icecube neutrinos and the diffuse gamma ray emission around M31

Conclusions

☑ **The extended gamma-ray halo detected from M31:**

- can be explained both in terms of leptonic and hadronic processes
  - standard models of CR production in Galactic disks DO NOT WORK
    - first scenario: very large scale (~100 kpc) accretion/termination shock
      - second scenario: CR buoyant bubbles

Conclusions

☑ **The extended gamma-ray halo detected from M31:**

- can be explained both in terms of leptonic and hadronic processes
  - standard models of CR production in Galactic disks DO NOT WORK
    - first scenario: very large scale (~100 kpc) accretion/termination shock
      - second scenario: CR buoyant bubbles

☑ **Similarity with the Milky Way?**

- a giant halo of gas surrounding the MW is known to exist
  - giant halos might be a common feature of spiral galaxies (?)
    - circumgalactic gas —> target for CR p-p interactions
      - the same interactions responsible for the gamma-ray emission from the halo of M31 could take place in the MW halo and produce neutrinos at the level of the isotropic flux observed by IceCube!