DESY - 19/05/2023

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Giant Cosmic-Ray Halos around M31 and the Milky Way

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Overview

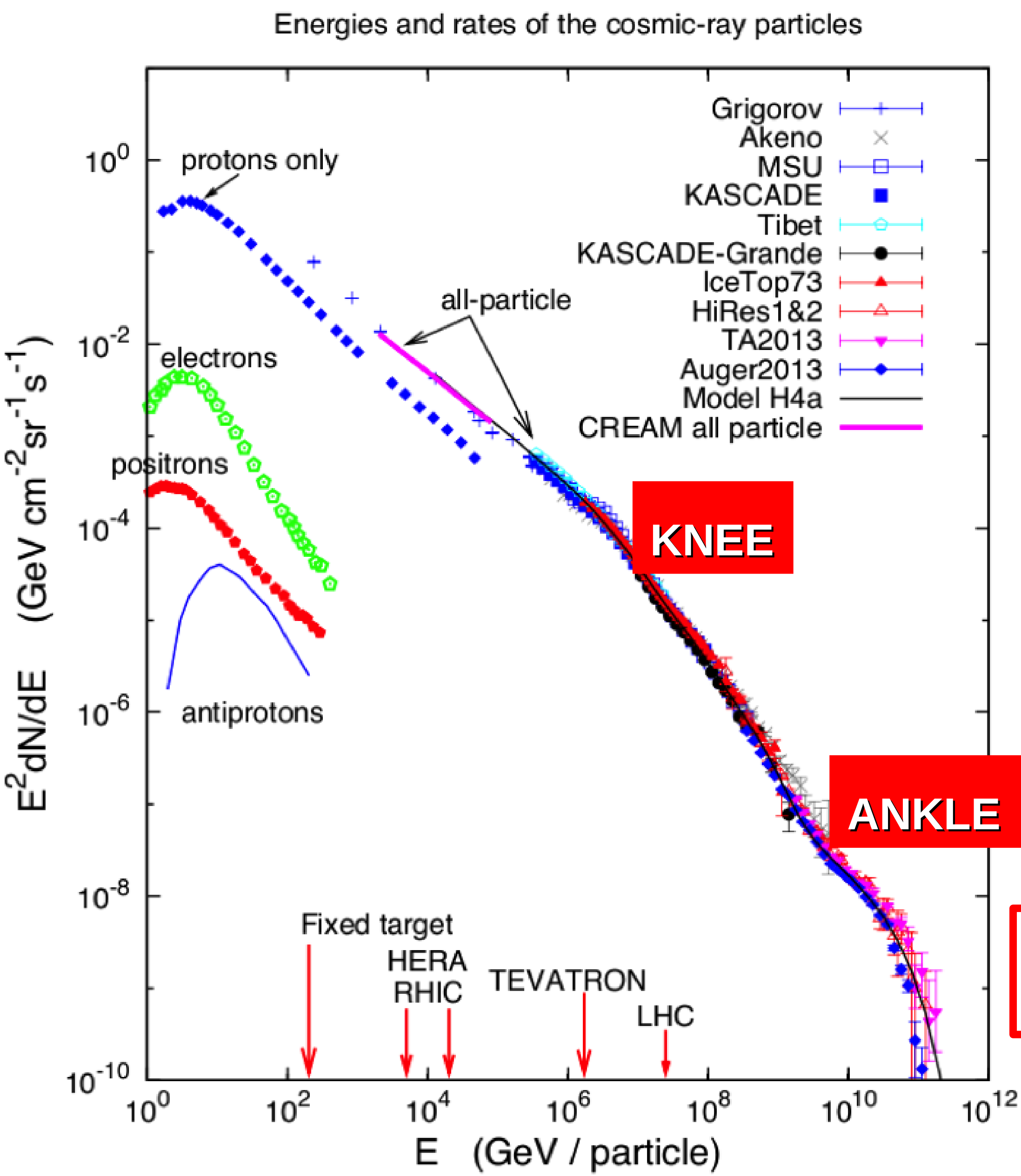
- cosmic rays and gamma-rays - a brief recap
- summary of gamma-ray observations of M31
- **gaseous halos** of Milky Way and M31

- **giant gamma-ray halo of M31**
  - **energetics**
  - possible **cosmic-ray origin**

- M31 and MW: gamma-rays and **neutrinos**

- summary
- perspectives & issues

CRs in a nutshell



observed spectrum

Protons - 87%
He - 12%
Heavier nuclei - 1%

electrons
positrons
antiprotons

$$E_{\mathrm{CR}} \approx E_{\mathrm{TH}} \approx E_{\mathrm{MAG}} \sim 1\mathrm{eV}/\mathrm{cm}^3$$

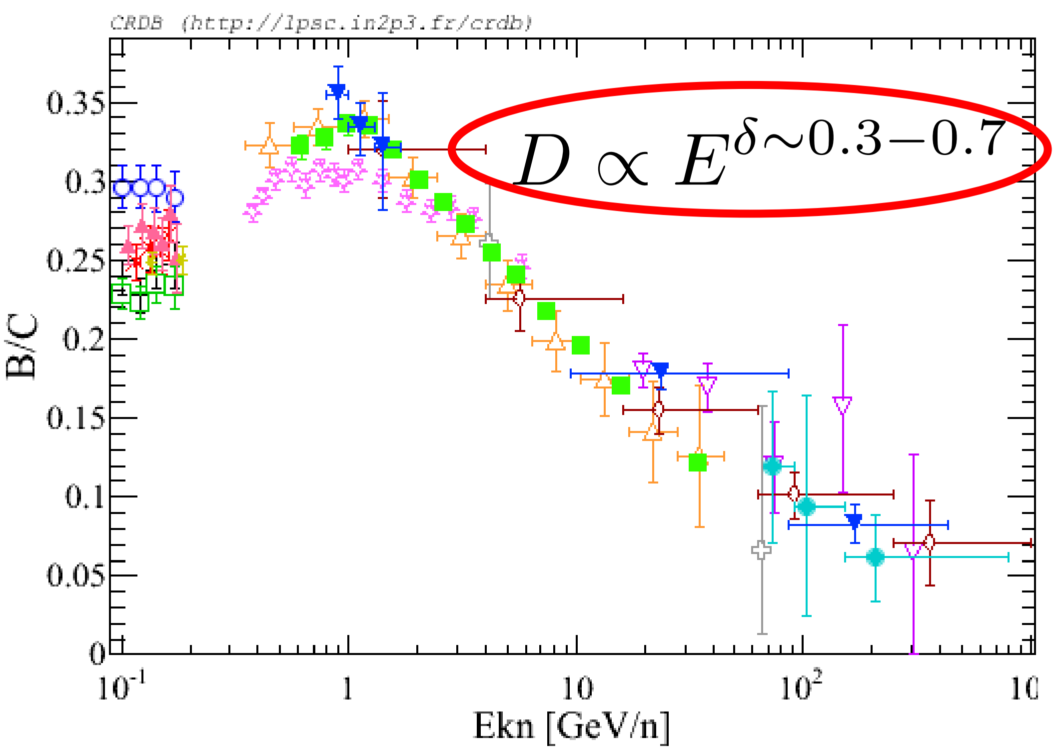
CRs in a nutshell

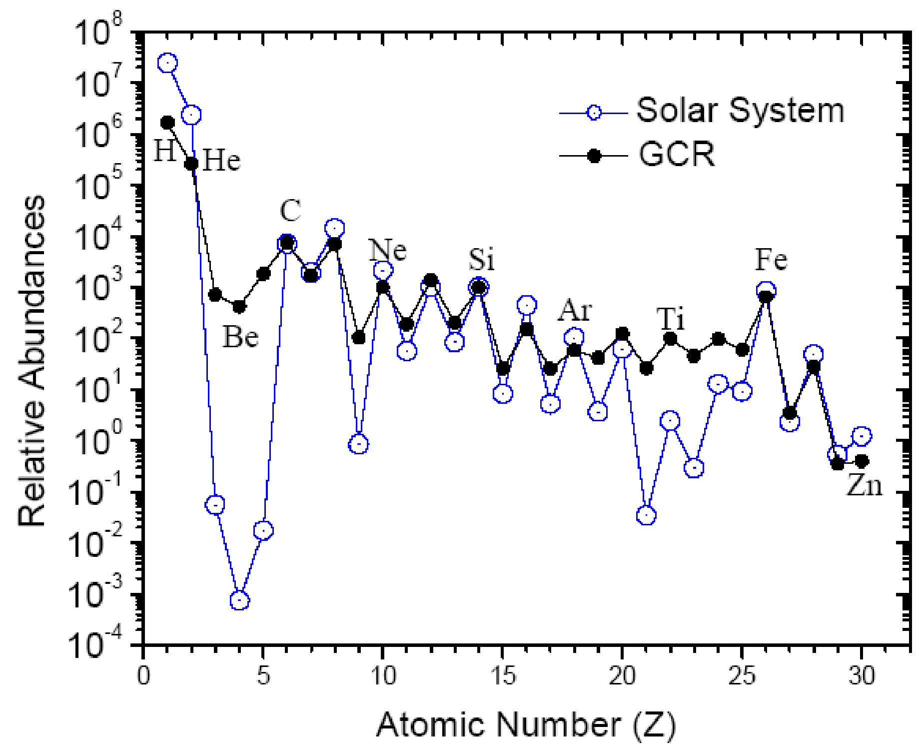
primary CRs - accelerate from ISM
secondary CRs - primaries + ISM (spallation)

secondary/primary --->
info on residence time in disk/Galaxy
unstable nuclei --->

$$\tau_{\rm res} \approx 10^7\,{\rm yr} \gg \tau_{\rm ball}$$

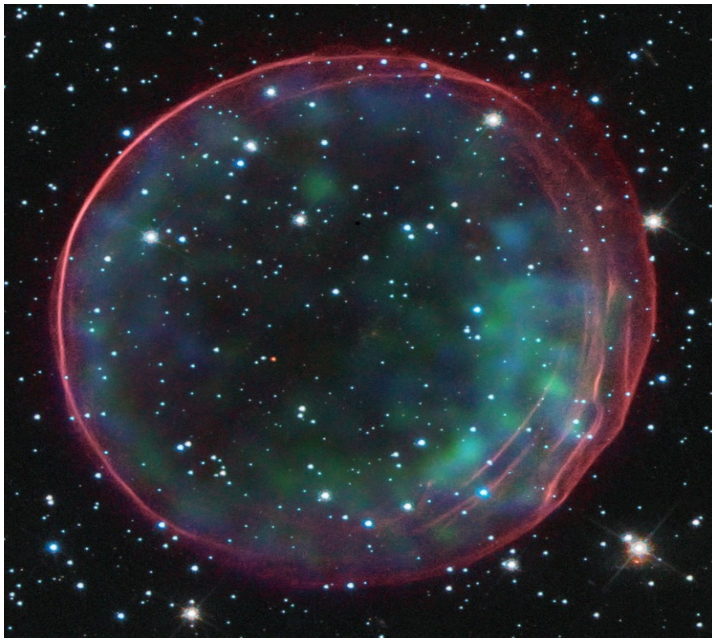
DIFFUSIVE TRANSPORT

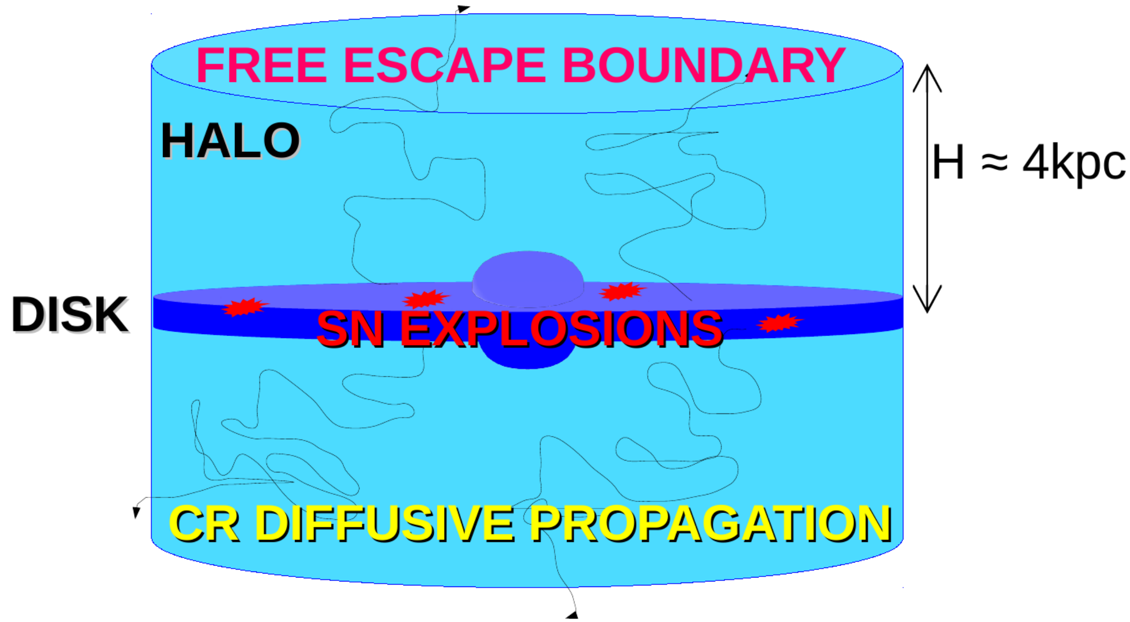




CRs in a nutshell - SNR paradigm

3-10% OF SNe MECHANICAL ENERGY





DIFFUSIVE SHOCK ACCELERATION

- Robust theoretical framework
- Power law spectrum
- Acceleration up to the knee (?)
- Knee: maximum energy for different species

DIFFUSIVE PROPAGATION

- Confinement of CRs in the Galaxy
- secondary/primary CRs
- Small anisotropy
- few kpc halo ?

CRs in a nutshell - source of diffusion

CRs are scattered by "resonant" magnetic inhomogeneities $k \sim 1/R_L$

Pre-existing magnetic turbulence

Streaming CRs can excite plasma (Alfvénic) turbulence

CR gradient → transfer momentum to waves

generate resonant waves $k \sim 1/R_L$

CR current → waves on scales $<< R_L$

grow to $\approx R_L$

non-resonant instability

CRs and radiative outputs

HADRONIC

- proton-proton interactions
- p + ISM
- pions
- π_0 ---> gamma rays
- charged π ---> neutrinos

LEPTONIC

- electrons/positrons
- synchrotron on Galactic B-filed

  radio, X-rays
- Invercse Compton Scattering

  on CMB, ISRF

  gamma-rays

Gamma-ray observations - M31

PAST

- Fermi-LAT - integrated gamma-ray luminosity

  $L_\gamma(> 100\mathrm{MeV}) \approx 6.6 \times 10^{41}\ \mathrm{erg/s}$ Abdo et al. 2010

- concentrated in the **inner ~ 5 kpc region**
- does **not correlate with the gaseous disk**

  Ackermann et al. 2017

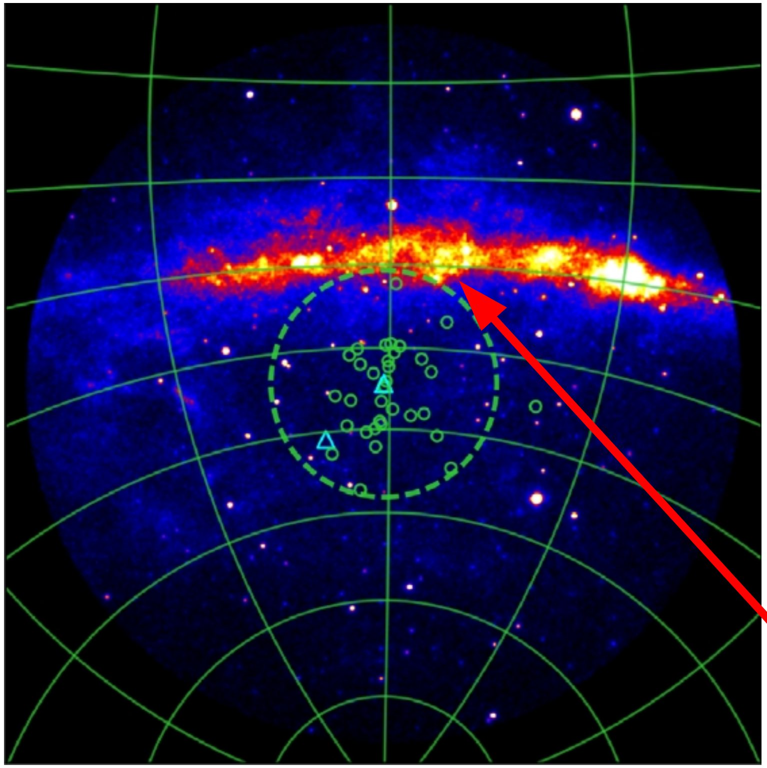
- evidence for ***Fermi Bubbles***-like structure

  Pshirkov et al. 2016

Gamma-ray observations - M31

RECENT ANALYSIS OF *Fermi*-LAT DATA

Karwin et al. 2019



Contamination with MW disk

Photons 1-100 GeV

- 28 deg x 28 deg region
- **200 kpc** projected radius
- excess up to ~ 120-200 kpc

Spherical template

- IG r < 5.5 kpc
- SH 5.5 < r < 120 kpc
- OH 120 < r < 200 kpc

+ **North** and **South** arcs

Gamma-ray observations - M31

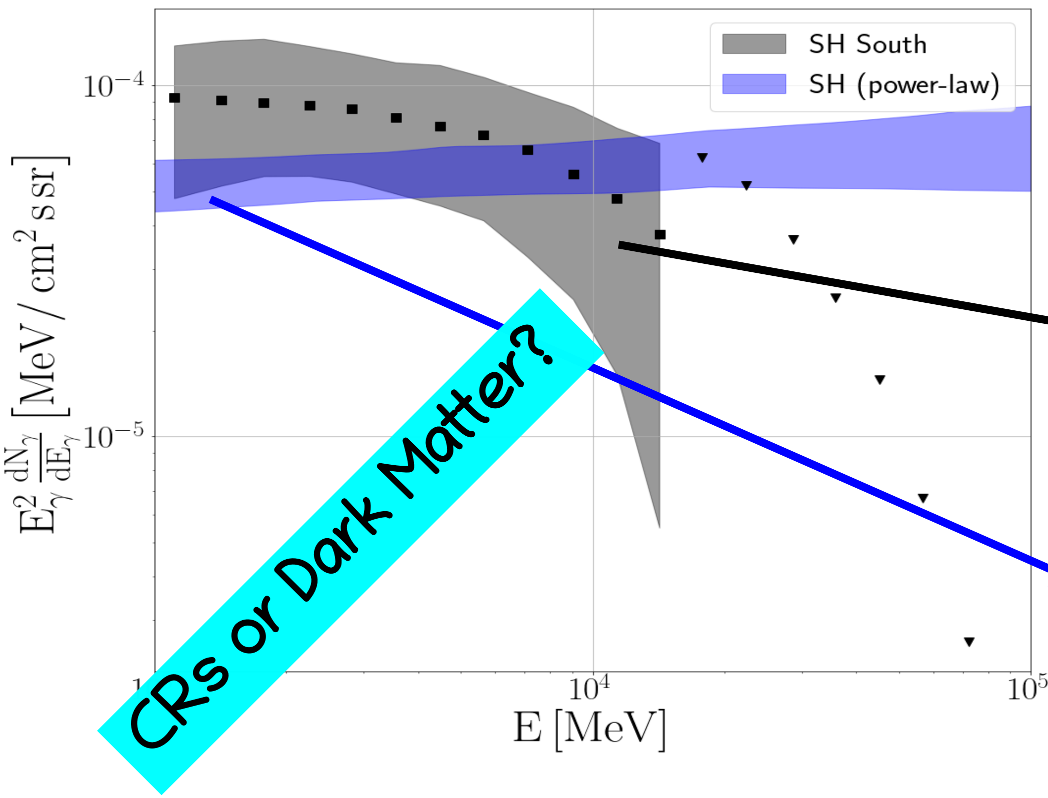
Karwin et al. 2019

Photons 1-100 GeV

SH likely connected with the M31

for OH not clear

$$L_\gamma^{SH} \sim 1.7 - 1.9 \times 10^{39}\,\mathrm{erg/s}$$



The spectrum is unclear...

Power-law + cut off (best fit)

$$\propto E_{\mathrm{GeV}}^{-1.9} \exp(-E_{\mathrm{GeV}}/11.6)$$

Power-law (other analysis)

$$\propto E_{\mathrm{GeV}}^{-2.0}$$

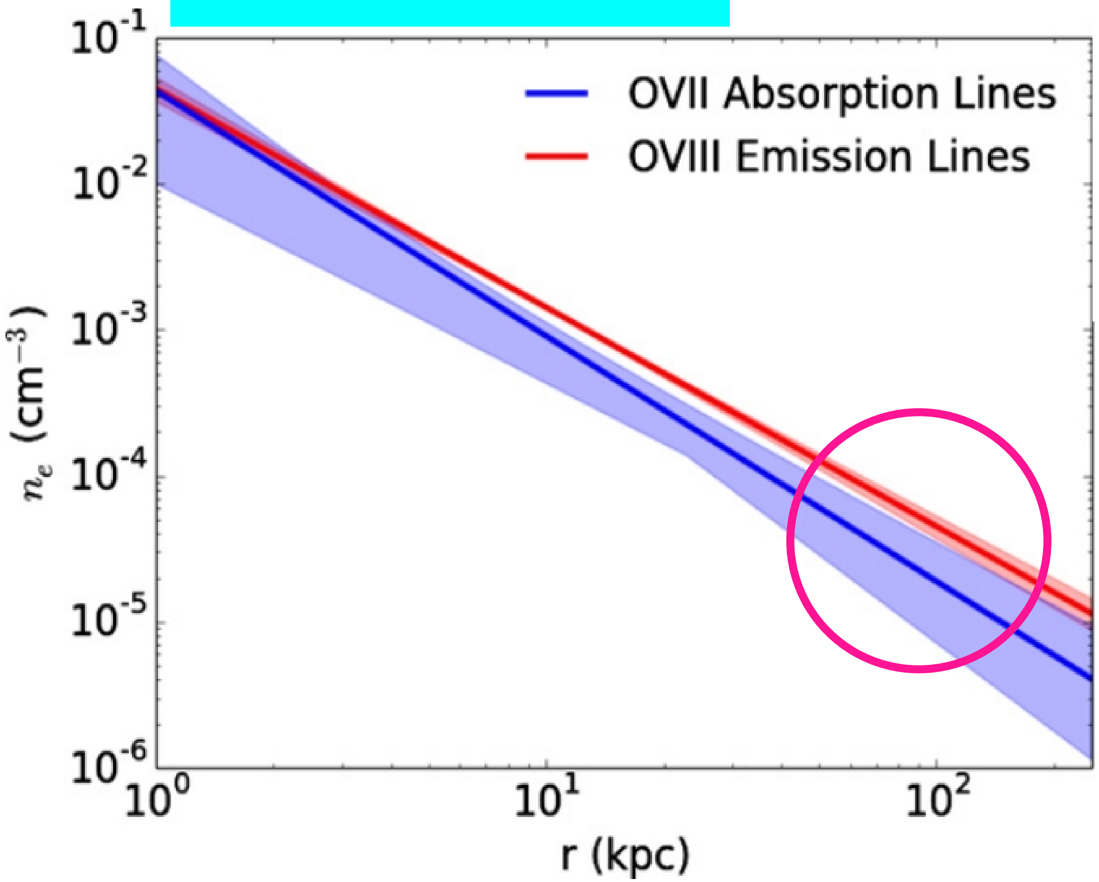
Gaseous Halos MW and M31

- detected extended halo (~ 200 kpc) around the MW
  - OVII, OVII X-ray abs/em lines Miller & Bregman 2013, 2015 Fang et al. 2012 Gupta et al. 2012
  - ram pressure stripping dwarf Gatto et al. 2013
  - cosmological simulations Nuza et al. 2014
- $n \sim 10^{-4}$–10^{-3} cm^{-3}, $T \sim 10^6$, $M \approx 10^{10} - 10^{11} M_\odot$
- hot bridge between MW and M31 Qu et al. 2020
- missing barions, gamma-rays, neutrinos

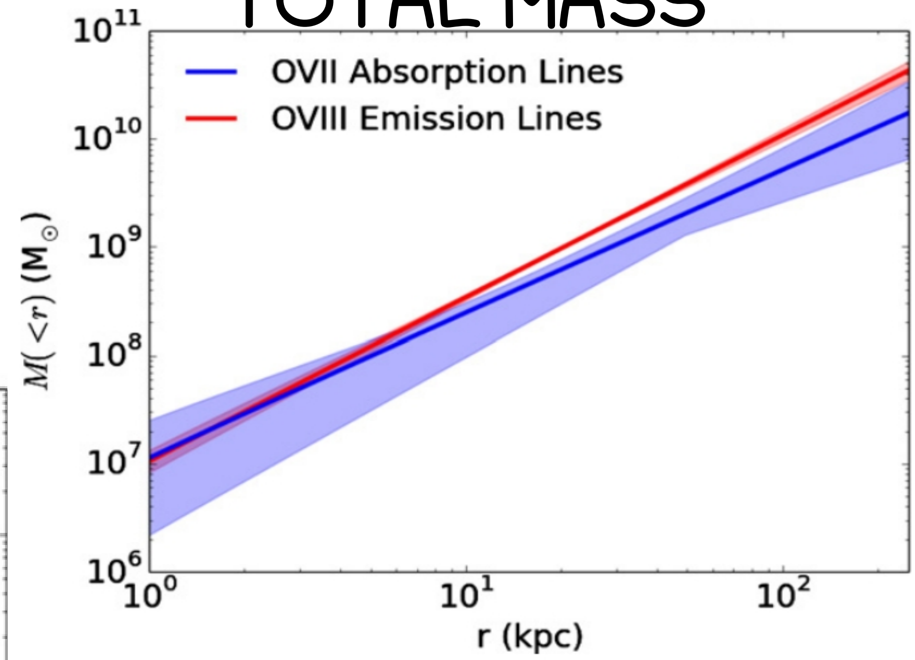
Gaseous Halos MW and M31

Miller & Bregman 2015

GAS DENSITY



TOTAL MASS



SH emission: energetics

$$L_\gamma^{SH} \sim 1.7 - 1.9 \times 10^{39}\,\mathrm{erg/s}$$

Recchia et al. 2019

$$E_e \approx 0.6 - 6\,\mathrm{TeV}$$

Leptonic scenario

$$\tau_{CMB} \sim 1.3 \times 10^6 E_{\mathrm{TeV}}^{-1}\,\mathrm{yr}$$

$$L_e = L_\gamma^{SH}$$

$$L_{CR}^{MW} \sim 10^{41}\,\mathrm{erg/s}$$

$$\omega_{CR}^{MW,disk}(1\,\mathrm{GeV}) \sim 1\,\frac{\mathrm{eV}}{\mathrm{cm}^3}$$

$$\propto E^{-0.7}$$

$$E_p \approx 10 - 1000\,\mathrm{GeV}$$

Hadronic scenario

$$\tau_{pp} \sim 7 \times 10^{10} n_{H,-3}^{-1}\,\mathrm{yr}$$

$$\tau_{res} \approx 10^9 - 10^{10}\,\mathrm{yr}$$

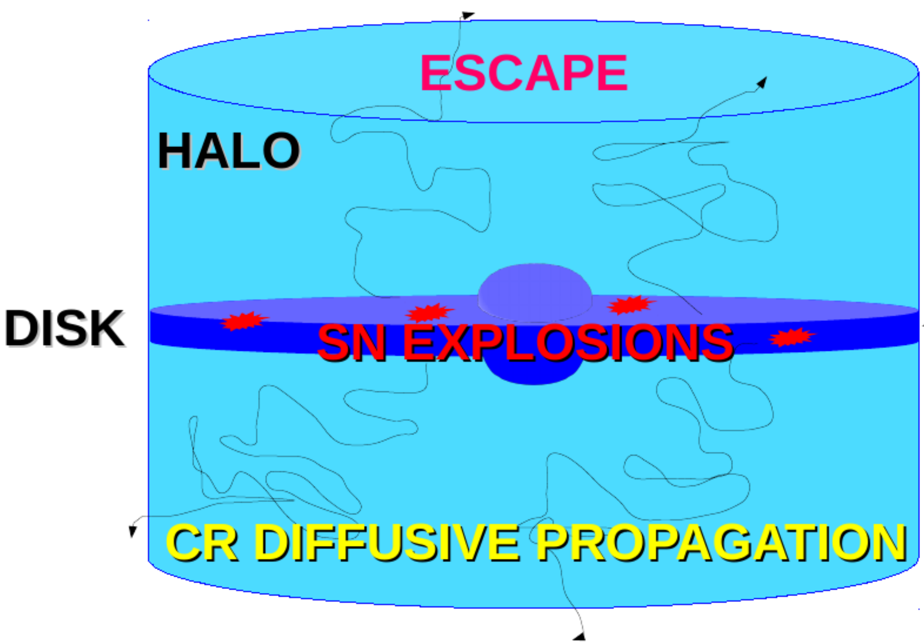
$$n_H \sim 10^{-4} - 10^{-3}\,\mathrm{cm}^{-3}$$

$$L_p \approx 1.8 \times 10^{41}\,\tau_{res,9}^{-1} n_{H,-3}^{-1}\,\mathrm{erg/s}$$

$$\omega_{CR,p} \approx 0.02\,n_{H,-3}^{-1}\,\mathrm{eV/cm}^3$$

Typical CR transport scenarios

- source(s) in the GC or disk
- "direct" diffusion (+ advection ...) toward halo



MAY IT WORK?

NO

Obvious for electrons (losses)

Typical CR transport scenarios

protons

$$\epsilon(r) \propto n_{CR}(r) n_H(r)$$

emissivity — CR density — gas density

Optimistic scenario, moderate drop of CR density

- Constant D and continuous injection $n_{CR}(r) \propto 1/r$
- Gas density drops with r $n_{disk} \sim 1\,\mathrm{cm}^{-3}$
  $n_{SH} \sim 10^{-4} - 10^{-3}\,\mathrm{cm}^{-3}$

$$\frac{\epsilon(r=1)}{\epsilon(r=100)} \approx 10^5 \frac{n_{disk}}{n_{SH,-3}} \qquad \frac{\epsilon(IG)}{\epsilon(SH)} \approx 10^3$$

With D(r), a galactic wind ..., even worse

... or, if we fix the SH emissitivity, the M31 disk should be very bright in gamma rays

Way out 1: in situ acceleration

Acceleration of e- and p at a **shock** located in the SH, R_{SH}~**100 kpc**

Recchia et al. 2019

$$L_p \approx 1.8 \times 10^{41}\, \tau_{res,9}^{-1} n_{H,-3}^{-1}\, \mathrm{erg/s}$$

$$L_\gamma^{SH} \sim 1.7 - 1.9 \times 10^{39}\, \mathrm{erg/s}$$

$$L_{SNR}^{MW} \sim 10^{42}\, \mathrm{erg/s}$$

accretion shock (existence in M31 or MW?)

$$\nu_{ff} \sim 0.3 \times 10^3 M_{12}^{1/2} R_{SH,2}^{-1/2}\, \mathrm{km/s}$$

free fall velocity

$$L_s \approx (4\pi R_{SH,2}^2) \frac{\rho_0 \nu_{ff}^2}{2}$$
$$\approx 3.4 \times 10^{42} M_{12}^{3/2} R_{SH,2}^{1/2} n_{0,-4}\, \mathrm{erg/s}$$

shock luminosity

GALAXY MASS

acceleration efficiency < few %

Way out 1: in situ acceleration

Acceleration of e- and p at a **shock** located in the SH, R_{SH}~**100 kpc**

$$L_p \approx 1.8 \times 10^{41}\, \tau_{res,9}^{-1} n_{H,-3}^{-1}\, \mathrm{erg/s}$$

$$L_\gamma^{SH} \sim 1.7 - 1.9 \times 10^{39}\, \mathrm{erg/s}$$

$$L_{SNR}^{MW} \sim 10^{42}\, \mathrm{erg/s}$$

termination shock powered by the GC activity

$$u_s \approx 0.2 \times 10^3 L_{GC,43}^{1/5} \tau_{GC,9}^{-2/5} n_{0,-4}^{-1/5}\, \mathrm{km/s}$$

shock velocity

$$L_{Edd}\ 1.3 \times 10^{46} \left(\frac{M_{BH}}{10^8\, M_\odot}\right) \mathrm{erg/s}$$

Eddington luminosity

BLACK HOLE MASS

Way out 1: in situ acceleration

CR acceleration $\tau_{acc} \sim aD(E)/u_s^2$ $a \sim 10$

electrons	protons
$E_e \approx 0.6 - 6\,\mathrm{TeV}$	$E_p \approx 10 - 1000\,\mathrm{GeV}$
$\tau_{acc} = \tau_{loss}$	$\tau_{acc} = \tau_{res}$
$E_{max,e} \approx 24\, u_{s,3}^3 n_{0,-4}^{1/4}\,\mathrm{TeV}$	$E_{max,p} \approx 460\, u_{s,3}^3 n_{0,-4}^{1/2}\,\mathrm{PeV}$

Efficiencies < few %

No problem with Emax and efficiency,for both e- and p

Spectral slope depends on the shock Mach number...,
$T \sim 10^6$, $c_s \sim$ **100 km/s, weak shocks?**

Way out 2: buoyant bubbles

Recchia et al. 2019

Buoyant Bubbles

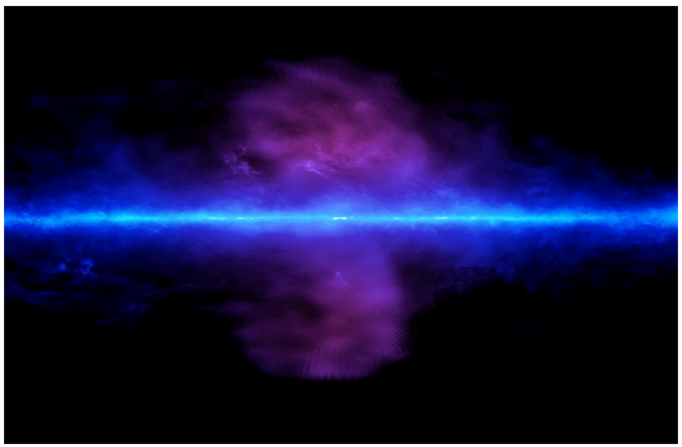
- Often present in central regions of galaxy clusters (**in galaxies?**)
- Radius of few kpc
- Rise velocity ~ sound speed (~ 100 km/s, HIM)
- Lifetime $\tau_b \approx 10^8\,\mathrm{yr}$
- Stabilizing action of a B-field $\tau_b \gtrsim 10^9\,\mathrm{yr}$

$$W_B \approx 10^{57},\ \text{up to}\, 10^{59}\ \mathrm{erg}$$

***Fermi* Bubbles base of a larger structure ?**

***Fermi*-Bubbles similar structure in M31**

Pshirkov et al. 2016



$$r \gtrsim 10\,\mathrm{kpc}$$

star formation/ GC activity

timescale few-few tens Myr

$$10^{41} - 10^{43}\ \mathrm{erg/s}$$

$$W_B \approx 10^{55} - \text{few}\, 10^{57}\ \mathrm{erg}$$

Way out 2: buoyant bubbles

Buoyant Bubbles

- Periodic activity of the M31 GC emits bubbles $\nu_b \approx 1/10^8\,\mathrm{yr}^{-1}$
- Inject CRs with average luminosity $L_p =\sim 3.2 \times 10^{41} \eta E_{B,57} \nu_{B,-8}\,\mathrm{erg/s}$
- Efficiency (compare with required luminosity) takes into account adiabatic energy losses $\eta \approx 0.56 \tau_{res,9}^{-1} n_{H,-3}^{-1} E_{B,57}^{-1} \nu_{B,-8}^{-1}$

- CRs are **transported within a bubble into the SH halo**
- With typical **rise velocity c_s~ 100 km/s** before disruption
- **After disruption** CR diffuse spherically ~ 100 kpc distance

$$\tau_{rise} \approx 10^9\,\mathrm{yr}\frac{R_{\mathrm{SH},2}}{c_{s,2}}$$

$$\tau_{diff} = R_{SH}^2/6\,D \approx 10^9\,\mathrm{yr}\frac{R^2_{\mathrm{SH},2}}{D_{30}}$$

Way out 2: buoyant bubbles

Buoyant Bubbles

- CRs are **transported within a bubble into the SH halo**
- With typical **rise velocity c_s~ 100 km/s** before disruption
- **After disruption** CR diffuse spherically ~ 100 kpc distance

$$\nu_B > 1/\tau_{diff}$$ → **Contribution of several bubbles overlaps - stationarity**

$$\nu_B < 1/\tau_{diff}$$ → **Intermittency**

$$E_c \approx 100\,\mathrm{GeV}$$

Cut-off, observed ?

Constrain on D

$$D(E) < D(E_c) = 5\times 10^{30} R_{SH,2}^2 \nu_{B,-8}\,\mathrm{cm}^2/\mathrm{s}$$

Way out 2: buoyant bubbles

Buoyant Bubbles - CARTOON

- if D flat in energy
- or CRs confined for the lifetime of M31

→ No Ec

Few kpc radius

$R \sim 100\,\mathrm{kpc}$

GC

SH

Bubble disrupt diffusion

GC

... summary so far

The extended gamma-ray emission of M31 can accounted for by

GC activity
(buoyant bubble, termination shock) → Scale with BH mass

Accretion shock → Scale with galaxy mass

- in both scenarios the **CR population in the disk and in the halo are decoupled**
- at high energies (> TeV) CR **density in halo can be > in disk**
  (hard vs steep spectrum)
- this is also important for neutrinos from the MW halo
- energetics, morphology and spectrum can be accounted for

Diffuse Icecube neutrinos from the MW halo

Seminal work by Taylor et al. 2014

$$\frac{N_\nu^{\rm halo}}{N_\nu^{\rm disk}} \approx 0.5 \frac{n^h_{-3}}{n^d_0} \frac{R^h_2}{R^d_1}$$

- relative number of neutrinos from disk and halo with uniform CR population
- **hard** ~ **E**$^{-2}$ CR spectrum in the halo
- **large confinement times**

$$L_\nu = K_\nu \left(1 - e^{-\frac{\tau_{\rm res}}{\tau_{\rm pp}}}\right) L_p$$

neutrino VS proton luminosity

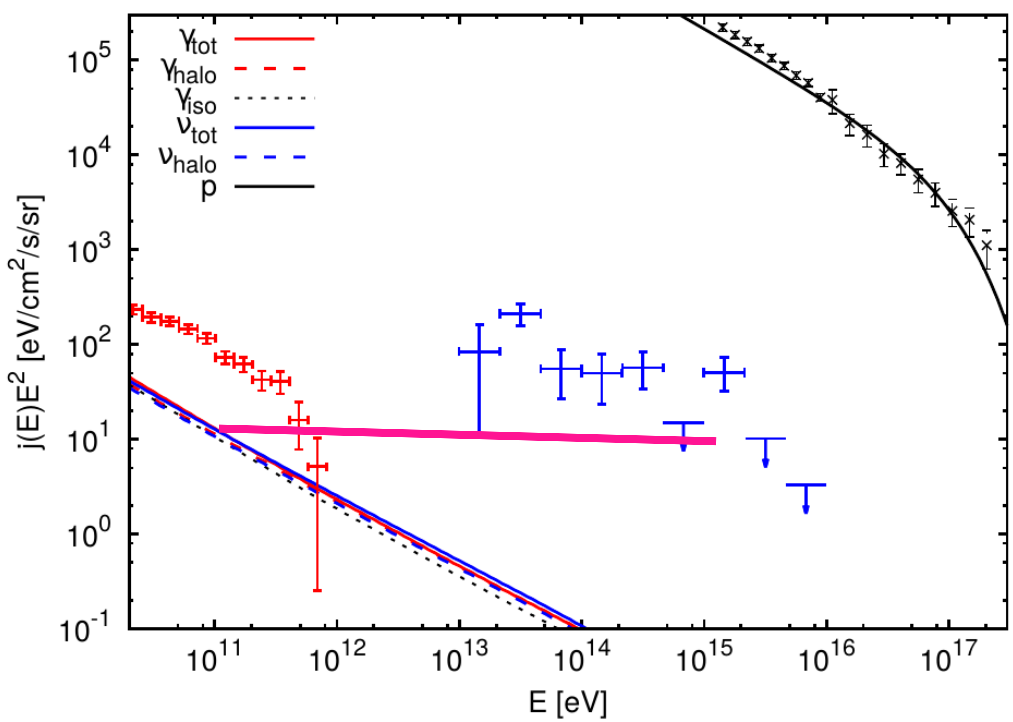
$$\tau_{pp} \sim 7 \times 10^{10} n_{H,-3}^{-1}\,{\rm yr}$$

$$\tau_{res} = 3 \times 10^9\,{\rm yr} \frac{R^2_{\rm SH,2}}{D_{30}} = 3 \times 10^9\,{\rm yr} \frac{R_{\rm SH,2}}{u_{\rm adv,30}}$$

R~ 100 kpc and $t_{pp} < t_{res}$ gives $L_\nu \sim L_p \sim 10^{39}$ **erg/s**
neutrino spectrum reflects source spectrum

Diffuse Icecube neutrinos from the MW halo

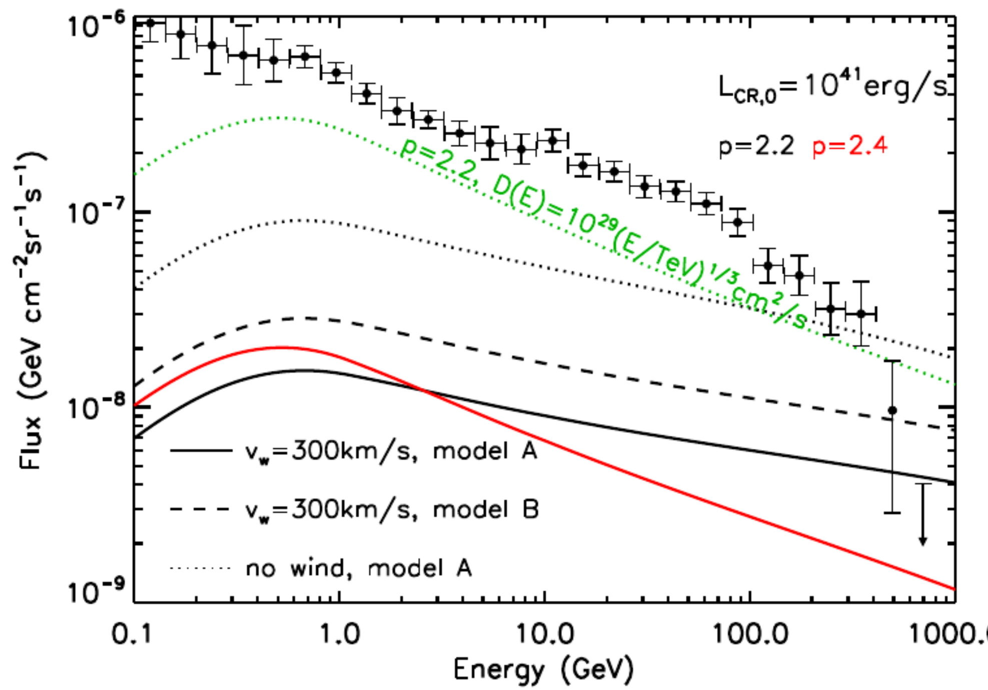
Kalashev & Troitsky 2016



Injection in GC ~ $E^{-2.4}$

D(E) ~ 10^{29} cm^2/s $E^{1/3}$

Liu et al. 2019 (gamma-rays)



Need hard spectrum in halo

Need to "decouple" disk-halo

Self-confinement in MW halo

Blasi & Amato 2019

- current of CRs trying to free-escape from the disk in regions with low-B

- **excitation of Bell instability**
- suppression of diffusion coefficient
- displacement of plama at v_A

- 10^8-10^9 yr in ~ 10 kpc halo

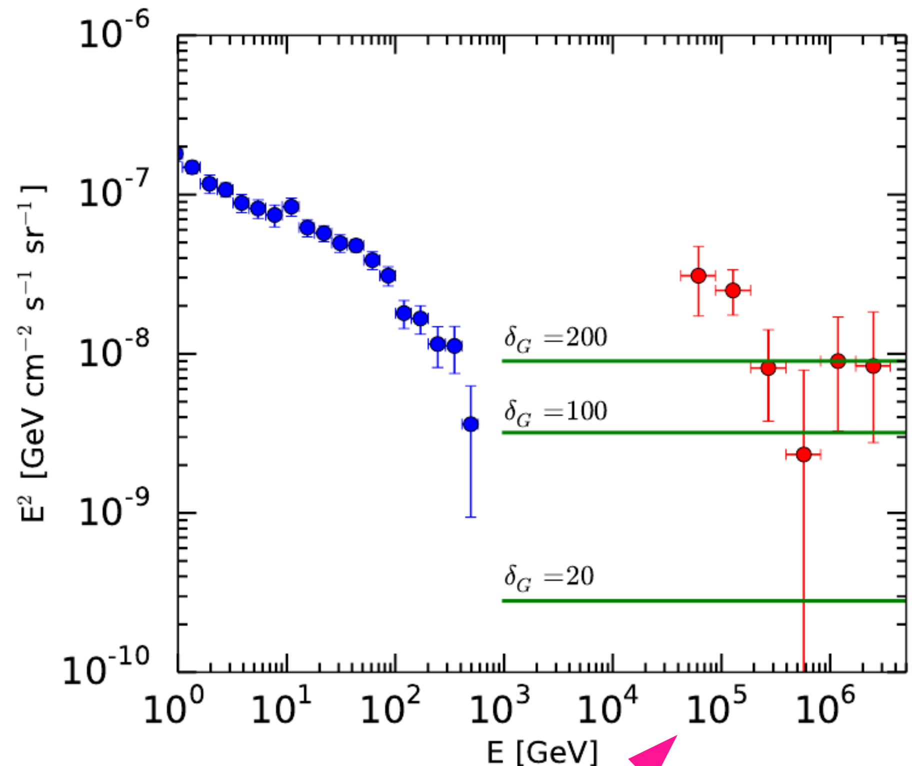
$$\frac{E^2 \phi_{CR}}{c} > \frac{B_0^2}{4\pi}$$

$$\phi_{CR}(E) = \frac{L_{CR}}{2\pi R_d^2} E^{-2}$$

$$B_{\rm sat} \approx 2.2 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1} {\rm G}$$

$$D(E) \approx 1.5 \times 10^{24} E_{\rm GeV} L_{41}^{1/2} R_{10} {\rm cm}^2/{\rm s}$$

$$v_A \approx 5 \times L_{41}^{1/2} R_{10}^{-1} n_{-4}^{-1/2} {\rm km/s}$$



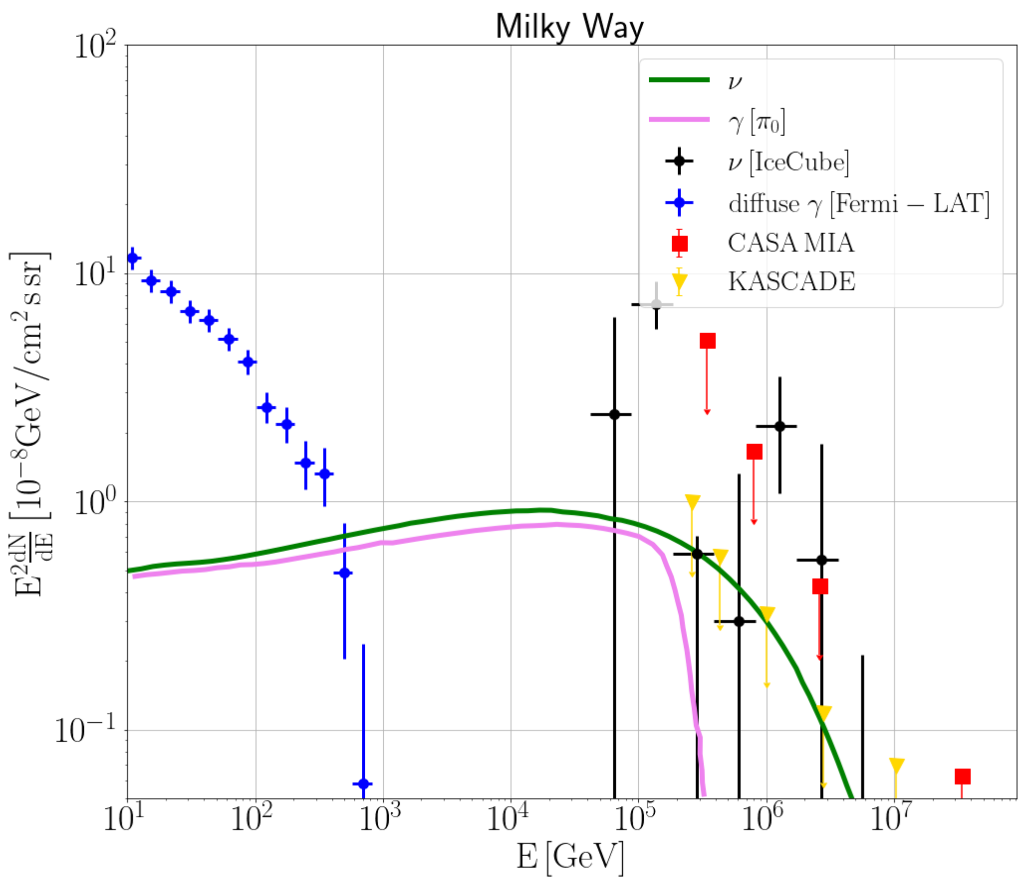
halo~10 kpc
problems with gamma?

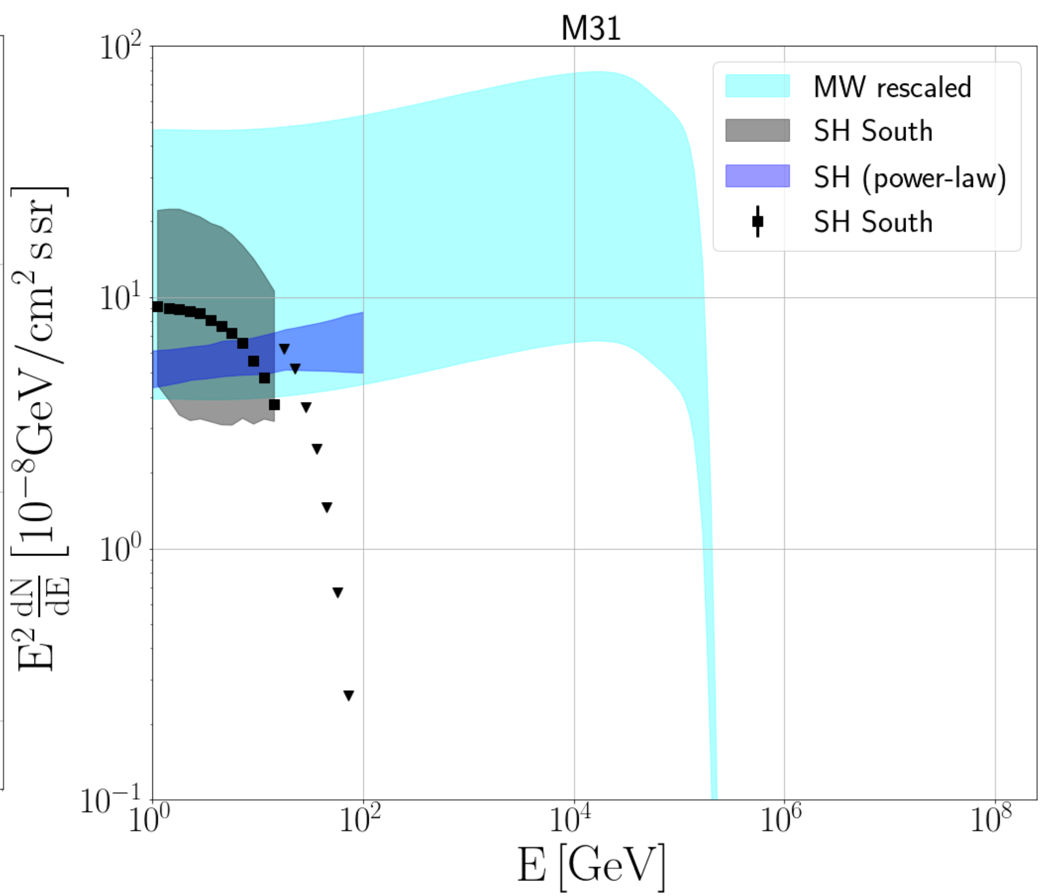
M31 - MW
gamma rays - neutrinos

Recchia et al. 2019

Assume diffuse Icecube neutrino flux are produce in the MW halo
R~100 kpc

Rescale CR density assuming that the emissions in M31 and MW have a similar origin





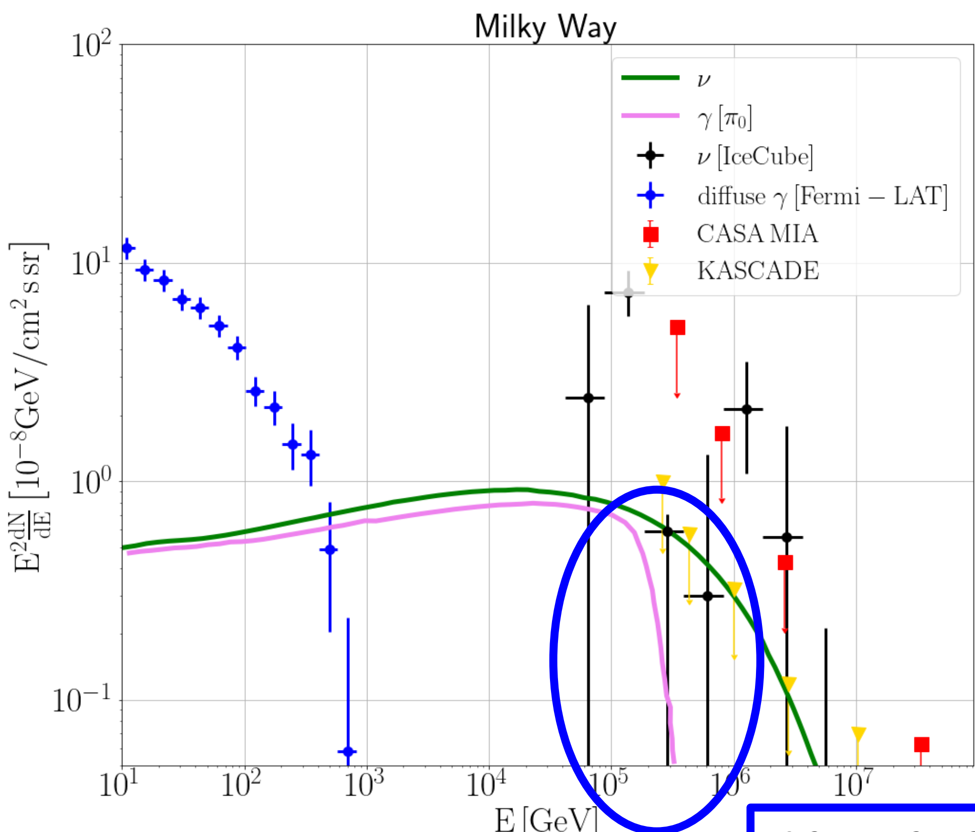
M31 - MW

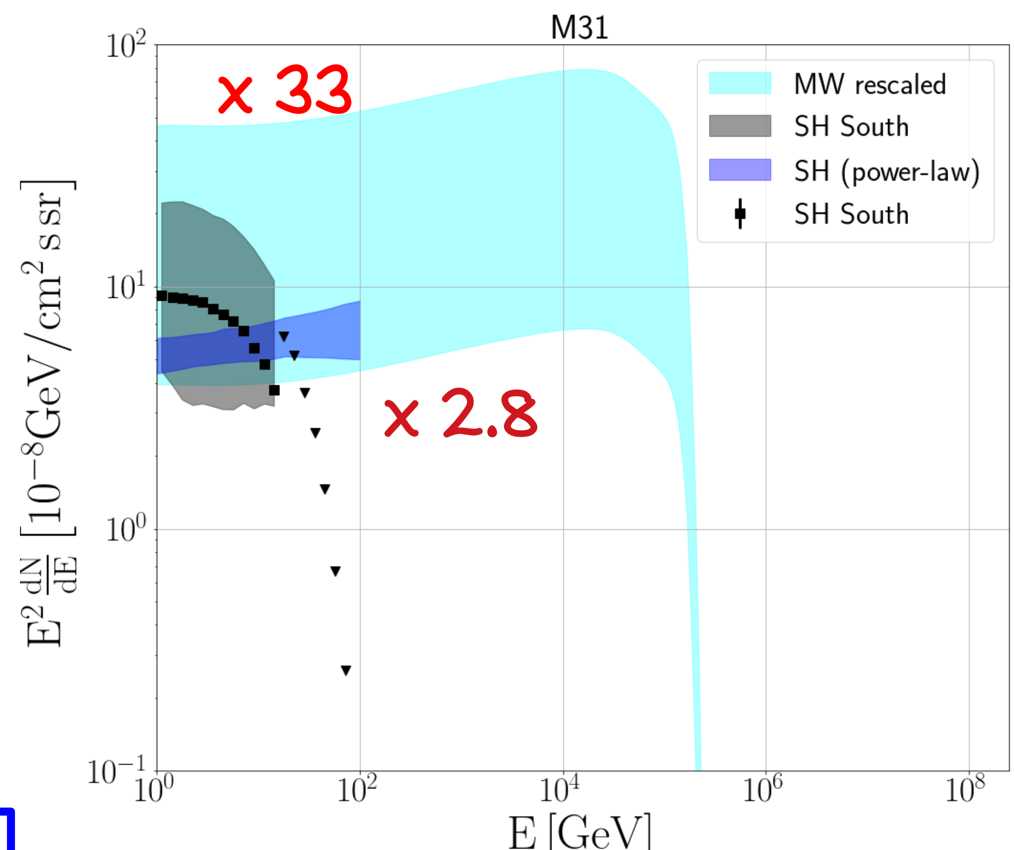
gamma rays - neutrinos

can work if hard gamma-ray spectrum in SH of M31

$(M_{M31}/M_{MW})^{3/2}$ → factor 2.8

$M_{BH,M31}/M_{BH,MW}$ → factor 33



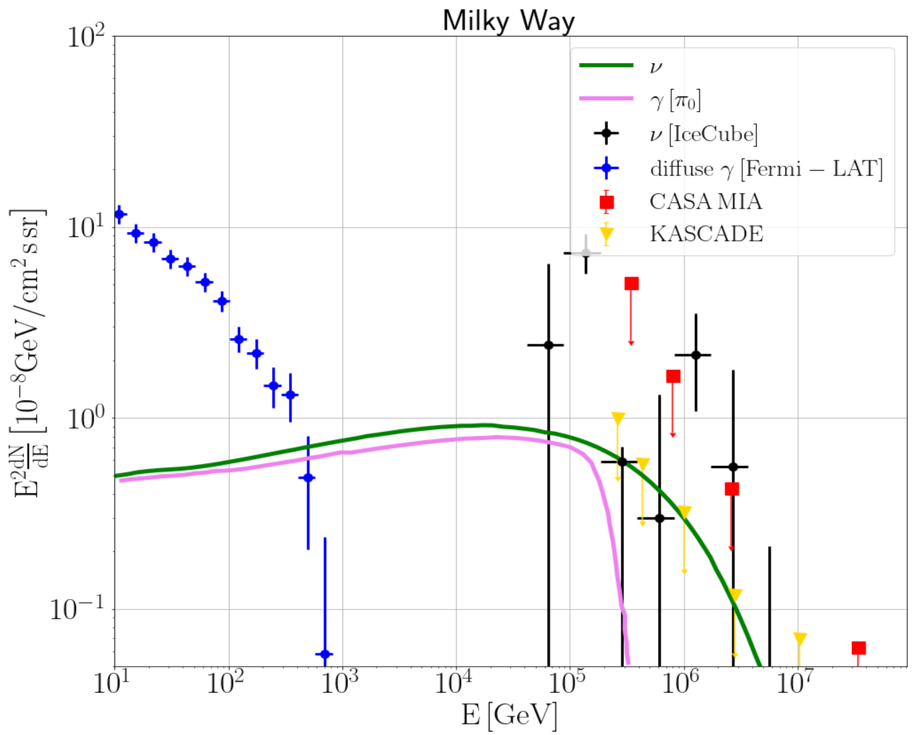


gamma-ray absorption

Vernetto & Lipari (2016)

M31 - MW: multimessanger

- recovery of isotropic diffuse gamma-ray emission **above ~TeV**
  - ~ 10^{-8} GeV/cm^2 s sr
  - up to < PeV



- M31 contribution to Icecube isotropic flux
  - about ~ 5%
  - extended ~ 15°

- contribution from MW-like galaxies within ~ 3 Gpc subdominant
  - flux from M31-like galaxy at d> 10 Mpc below detection limit
  - but **enhanced nuclear/starburst** (NGC 1068)

- **diffuse X-ray** from secondary e- << extragal. diffuse X-ray bck
  - **L^{MW}_x (1-100 keV) ~ 10^{37} erg/s** $R_{H,2}{}^2$
  - flux ~ 6×10^{-14} $R_{H,2}{}^2$ (d/3Mpc)$^{-2}$ erg/cm^2 s
  - θ ~ 2° $R_{H,2}$(d/3Mpc)$^{-1}$
  - **difficult to detect?**

$$E_X^{\rm synch} \approx 2B_{-7}E^2_{e,\rm PeV}\,\rm keV$$

$$E_X^{\rm CMB} \approx 4E^2_{e,\rm GeV}\,\rm keV$$

Take-Home Message

The extended gamma-ray emission of M31 can accounted for by

GC activity
(buoyant bubble, termination shock) → Scale with BH mass

Accretion shock → Scale with galaxy mass

- if spectrum is hard and up to ~PeV
- if similar scenarios hold in the MW

the isotropic Icecube neutrino flux may be naturally explained with a production in the MW halo

Perspectives & Issues

- **showed the feasibility of shock and buoyant bubbles scenarios but details should be addressed for both MW and M31**
  - existence of accretion shock?
  - formation of termination shock?
  - strong shocks? acceleration?

  - buoyant bubbles in MW-like galaxies?
  - larger structure beyond Fermi Bubbles?

- **is the gamma-ray spectrum of M31 hard up to ~PeV or cut-off at ~10-100 GeV?**
  - very important for interpreting Icecube neutrino
  - may be checked by LHAASO?

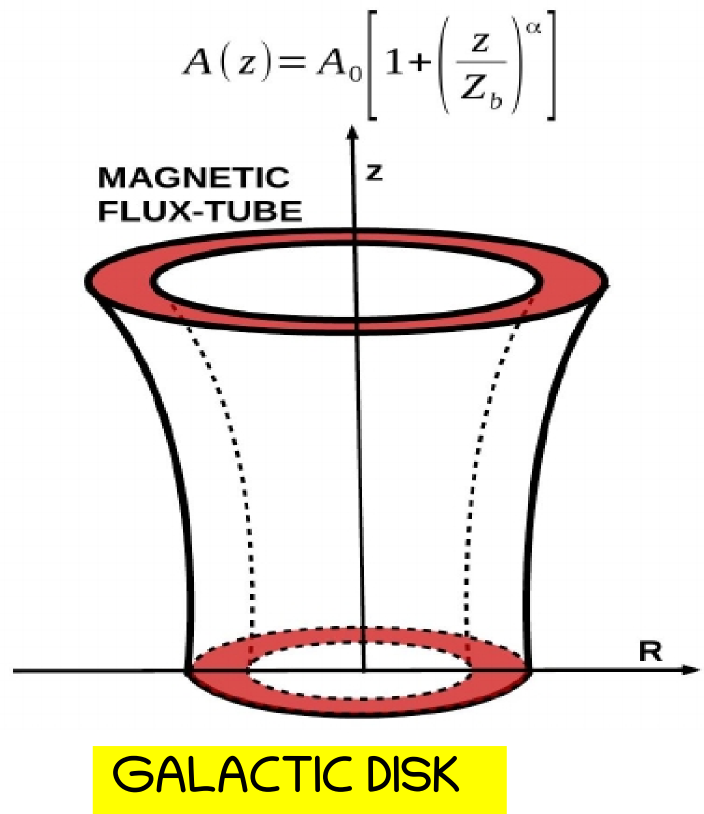
- **source of CR scattering at ~ 100 kpc in galactic halos?**

- check potential gamma-ray signals from LMC
- UHECRs from M31? Zirakashvili et al. 2022


Thank You

Propagation in galactic wind

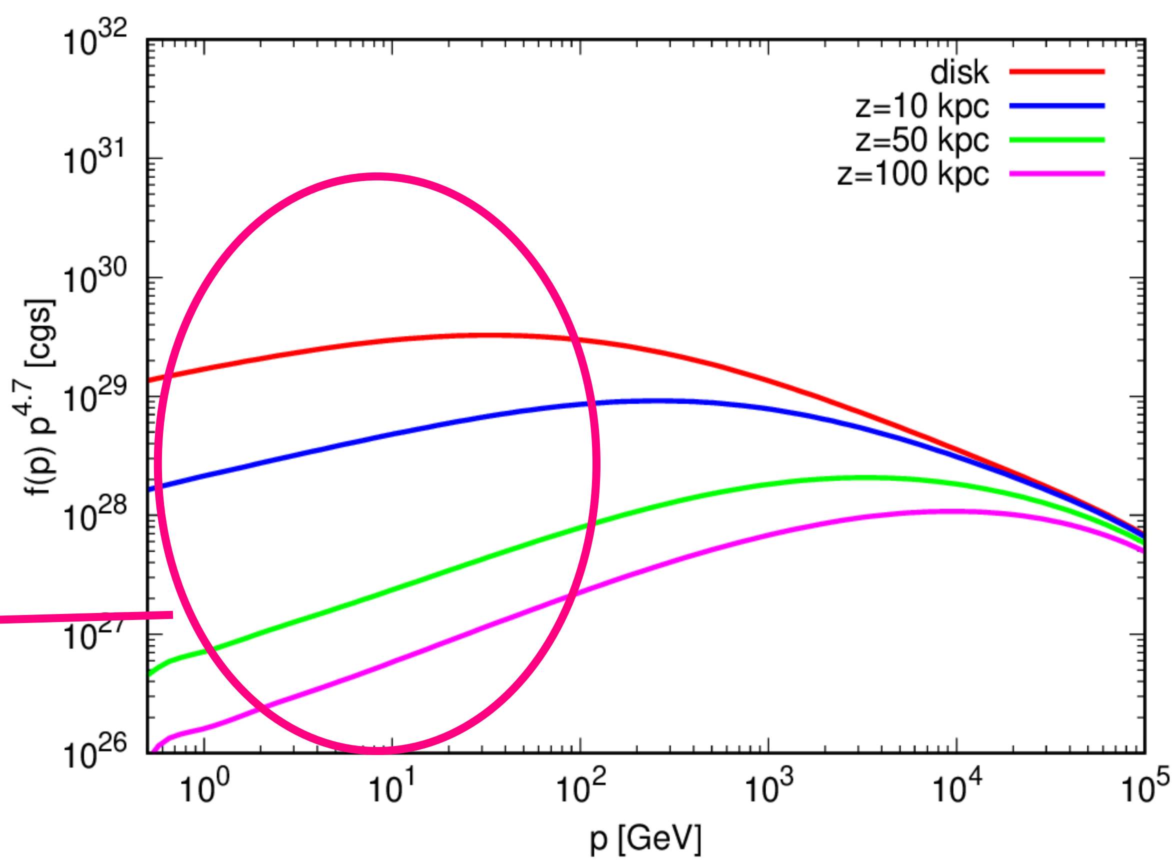
Recchia et al. 2016



$\epsilon(z) \propto n_{CR}(z) n_H(z)$

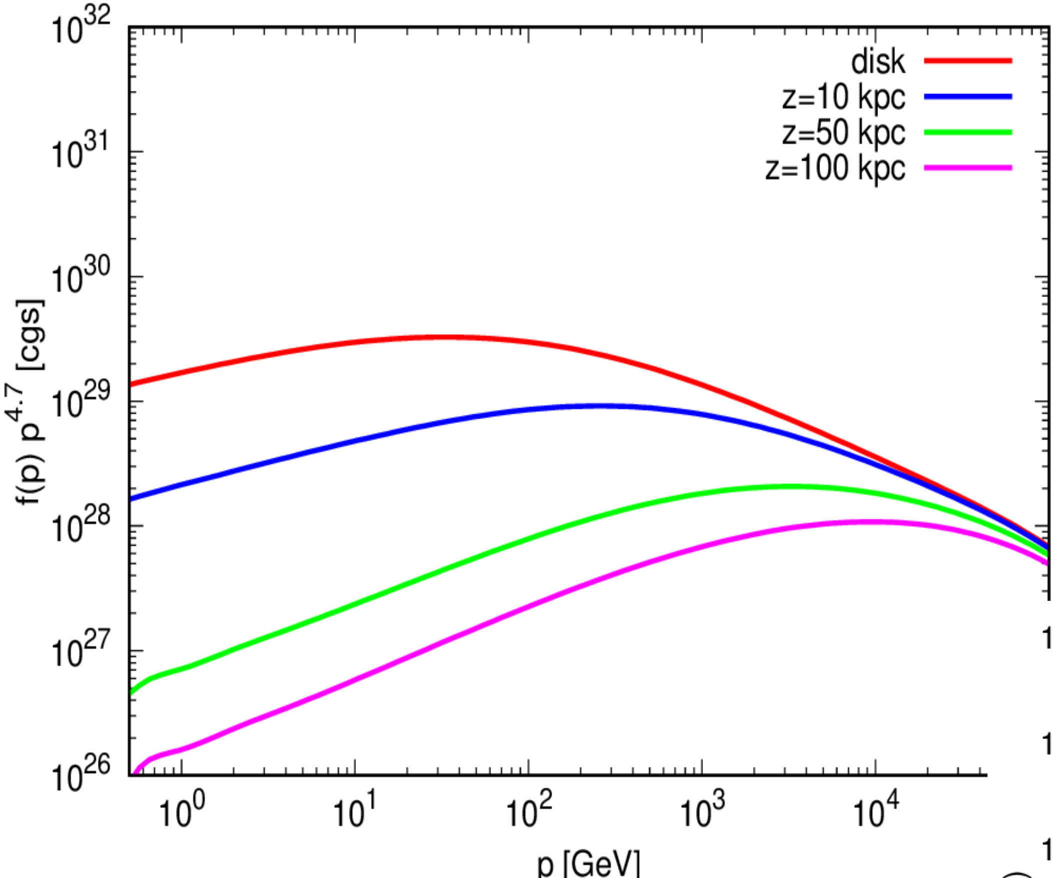
$D(z)$ diffusion coefficient

$u(z)$ galactic wind

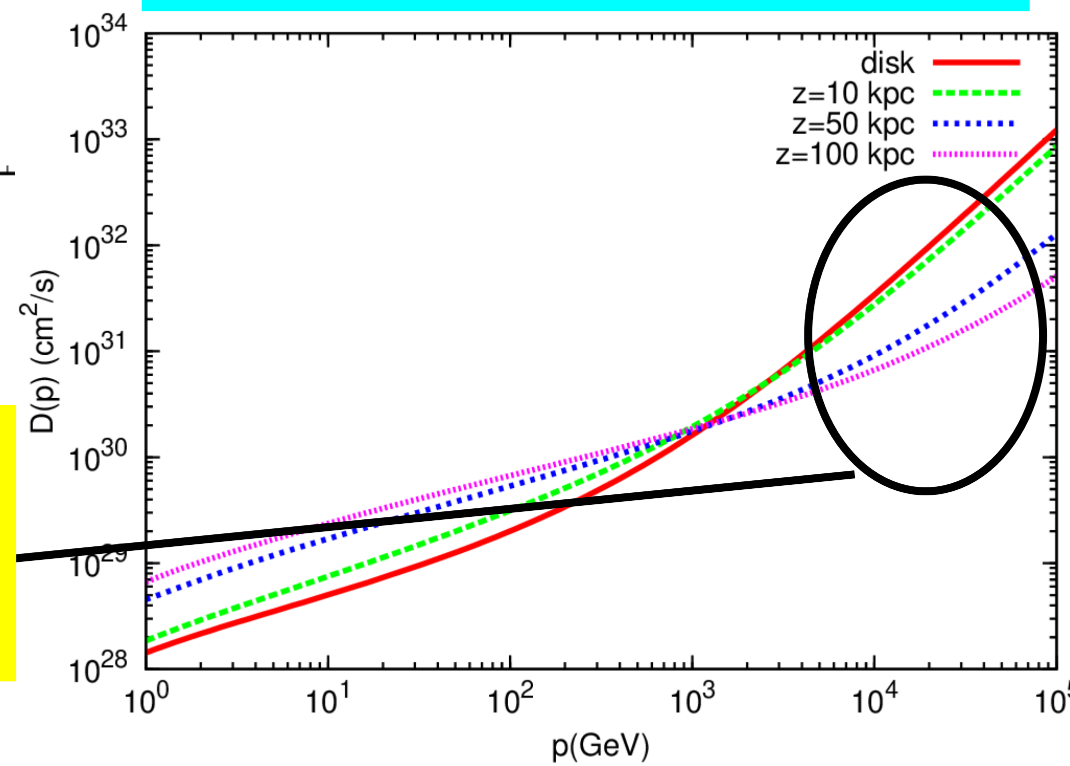


CR density
Strong decrease with z...

Propagation in galactic wind



Self-generated diffusion



effect of non linearity may give

- mild increase below ~ 1 TeV
- even a decrease above TeV