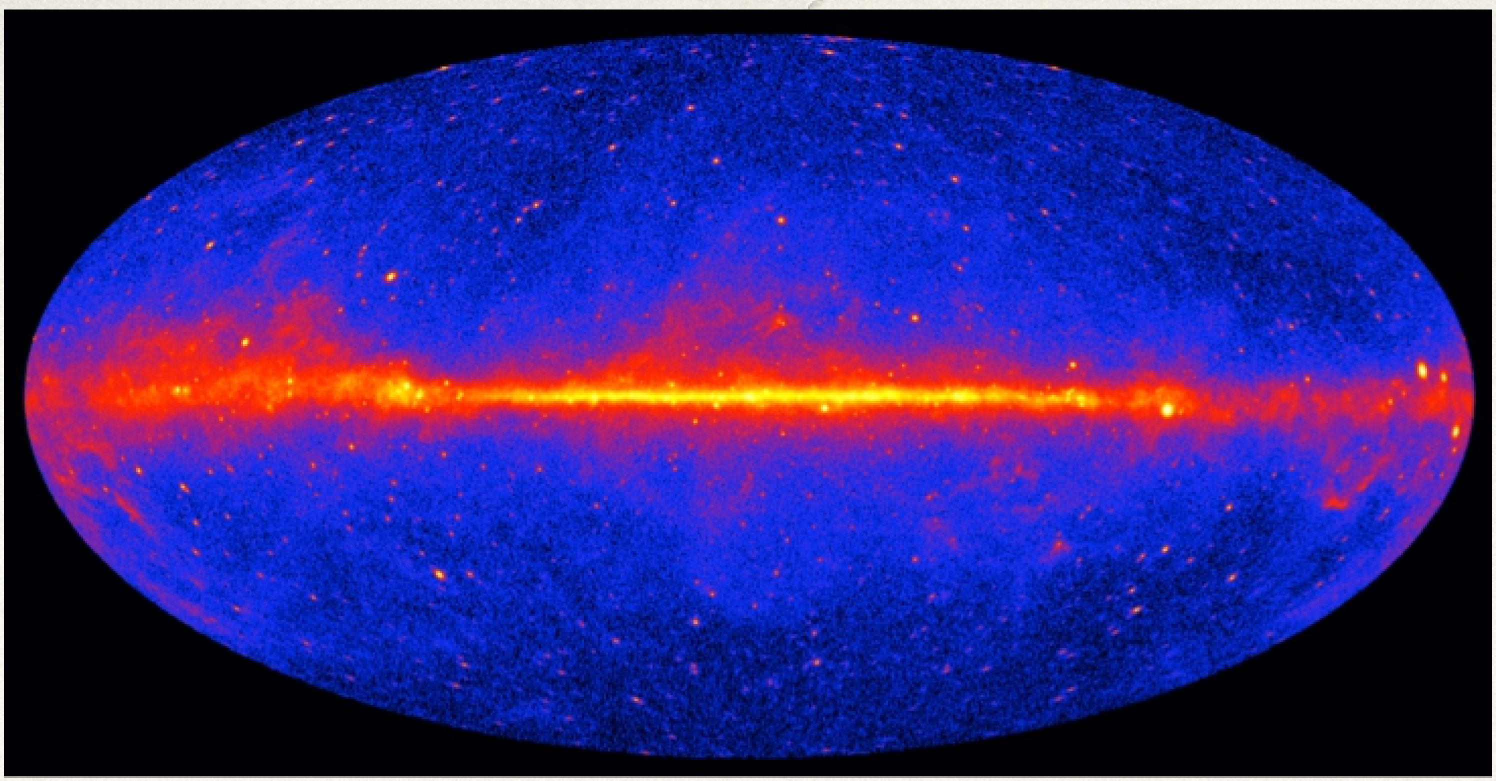


Prediction for neutrino and γ-ray flux from the Galactic plane and star-forming galaxies

Giovanni Morlino,

INAF/Osservatorio Astrofisico di Arcetri, Firenze, ITALY

Neutrini, fotoni e onde gravitazionali:
nuove prospettive per l'astrofisica delle alte energie

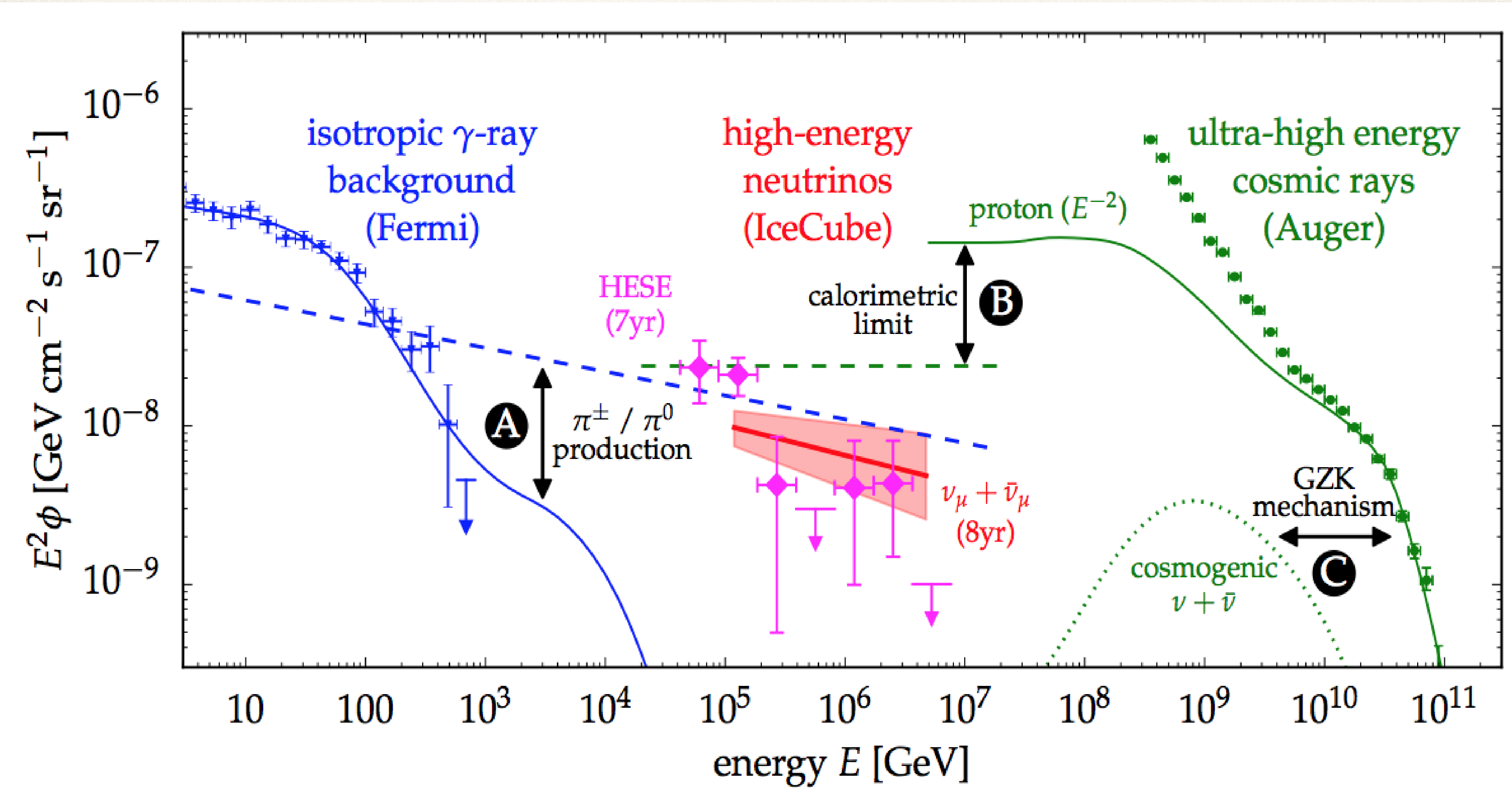
26-28 Nov, 2019 – Catania, ITALY

Summary

- **Milky way**
  - Anisotropy studies
  - γ-rays and ν form CR propagation models
  - Contribution from unresolved sources

- **Contribution from Star-burst galaxies**
  - CR propagation and confinement in SBNi
  - Multiwavelength modeling of individual SBNi
  - Integrated contribution over the cosmic history
  - Reacceleration at the termination shock

Astrophysical neutrino flux



(Curtesy of M. Ahalers, arXiv:1811.07633)

Astrophysical neutrino flux

Basic lessons to bring home

1. Gamma-rays from cascades saturates the EGB

$$p + p \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\gamma \longrightarrow \textbf{e.m. cascade} \\ \pi^\pm \rightarrow \nu_e \;\; 2\nu_\mu \end{cases}$$

➡ Maybe gammas are absorbed inside the sources (or not produced...)

2. Diffuse neutrino flux is close to the calorimetric limit of UHECRs confined in their sources (at energies below the ankle).

➡ Neutrinos sources may be the same producing UHECRs

ν contribution from the Milky Way

Data based approach

- Angular distribution: anisotropy/correlation studies
- Spectral distribution: single power law vs. multiple components

Model based approach

- ν flux prediction from CR production/propagation theory
  - Contribution from sources
  - Diffuse emission
    - ★ disk
    - ★ bulge
    - ★ halo

disk, bulge → anisotropic

halo → isotropic

Estimates of Galactic contribution to ν flux

Summary of some results

IceCube collaboration, Aartsen et al. Science 342 (2013)	Not significant
IceCube collaboration, Aartsen et al. PRL 113 (2014)	Not significant
IceCube collaboration, Aartsen et al. ICRC (2017)	Not significant
Troitsky, JETP Lett. (2015)	Not significant
Chianese, Miele, Morisi & Vitagliano (2016)	Not significant
Neronov and Semikoz. (2016)	**Pure isotropic distribution excluded at 3σ**
Albert et al. (2017)	Not significant
IceCube collaboration, Aartsen et al. ICRC (2017)	**< 14% (@ 90% C.L.; 7 yr data)**
Padovani et al. MNRAS 457 (2016)	<~ 7% (single source id. SNRs)
Palladino and F. Vissani, ApJ 826 (2016)	<~20-30% (@E < 100-300 TeV) (sout-north differnet slopes)
Ahlers, Y. Bai, V. Barger and R. Lu PRD 93 (2016)	4-8% (E > 50 TeV) (prediction from CR propagation models)

Anisotropy of ν flux

[Denton, Marfatia & Weiler (2017)]

From a likelihood analysis of 50 events > 60 TeV:

$$\mathcal{L}_i(f_{\rm gal}) = \left[\mathcal{L}_{{\rm gal|astro},i}(f_{\rm gal}) + \mathcal{L}_{{\rm exgal|astro},i}(f_{\rm gal})\right] \mathcal{L}_{{\rm astro},i} + \frac{1}{4\pi}\mathcal{L}_{{\rm bkg},i}\,.$$

Galactic (halo+bulge+disk) — **Extra-galactic (iso)** — **Background (iso)**

Best fit values:

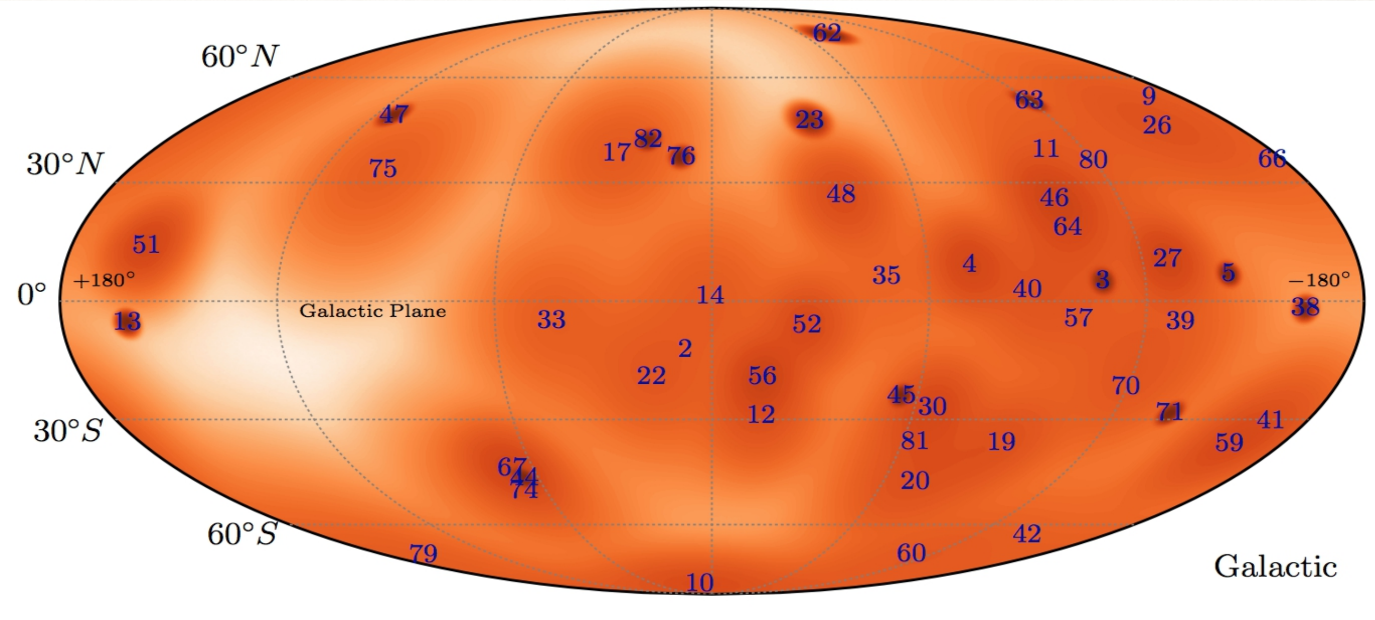
$f_{\rm gal} = 1.3\%$

$f_{\rm exgal} = 90.6\%$

$f_{\rm bkg} = 8.1\%$

CL	$f_{\rm gal}$
1σ	< 0.057
90%	< 0.095
2σ	< 0.12
3σ	< 0.2
4σ	< 0.28
5σ	< 0.38

Arrival direction of 50 events with *E* > 60 TeV



Basic Halo model

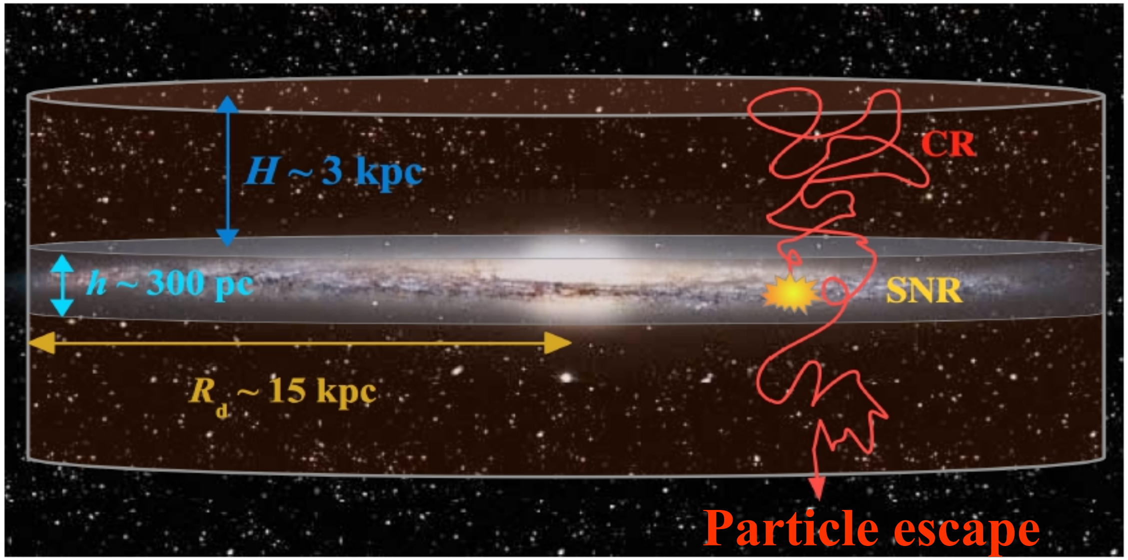
In the basic picture of CR propagation model:

- CRs diffuse in a magnetic halo larger than the Galactic disc
- The CR distribution vanish at $z = H$ (H~3-4 kpc from diffuse synchrotron emission)
- The diffusion coefficient $D(E)$ is assumed constant everywhere in the halo

$$\tau_{esc}(E) = \frac{H^2}{2D(E)}$$

$$D(E) \propto E^{-1/3}$$

Suggesting Kolmogorov turbulence



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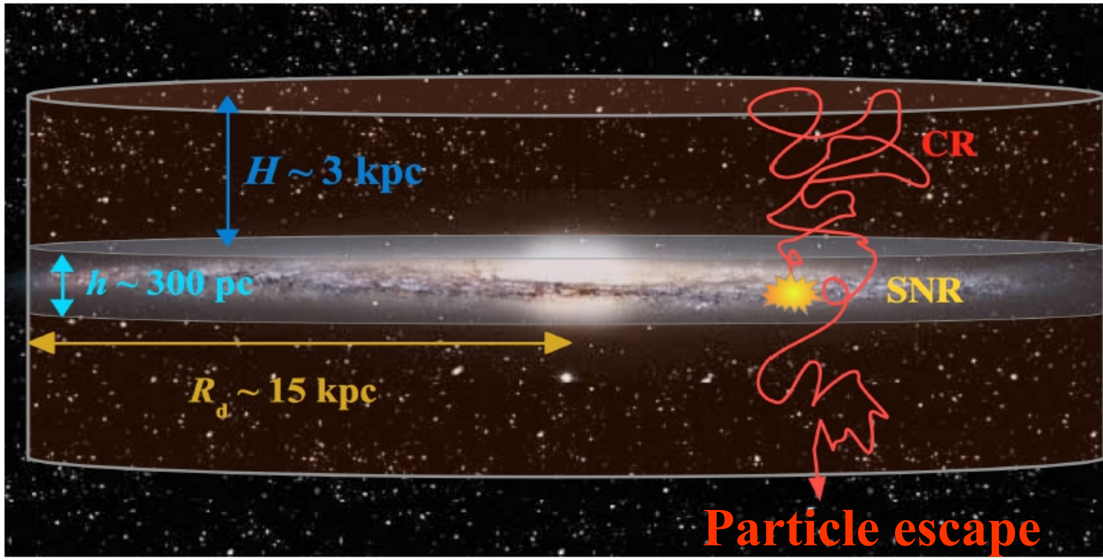


This picture is unsatisfactory for at least two reasons:

- Which is the physical meaning of H ?
- What generates the diffusion?

Some observed anomalies suggest a more complex propagation model

Galactic γ-ray background from CR propagation models

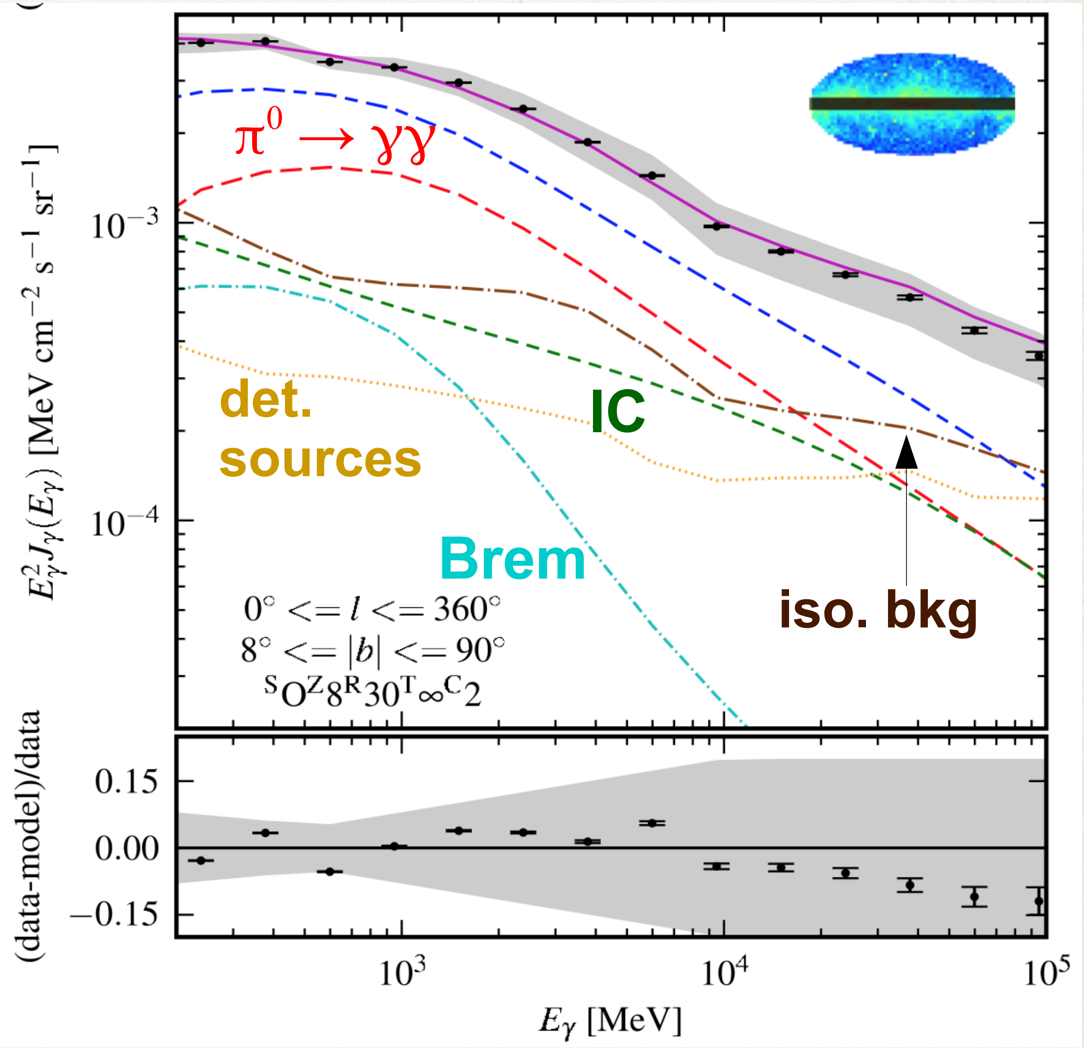
[Ackerman et al. ApJ 750, 3 (2012)]

Modeling of γ-ray flux from CR propagation model using GALPROP

Model based on
- spatially uniform CR diffusion
- constant halo size

Constant CR slope in the Galaxy

Outer region



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Modeling of γ-ray flux from CR propagation model using GALPROP

Model based on
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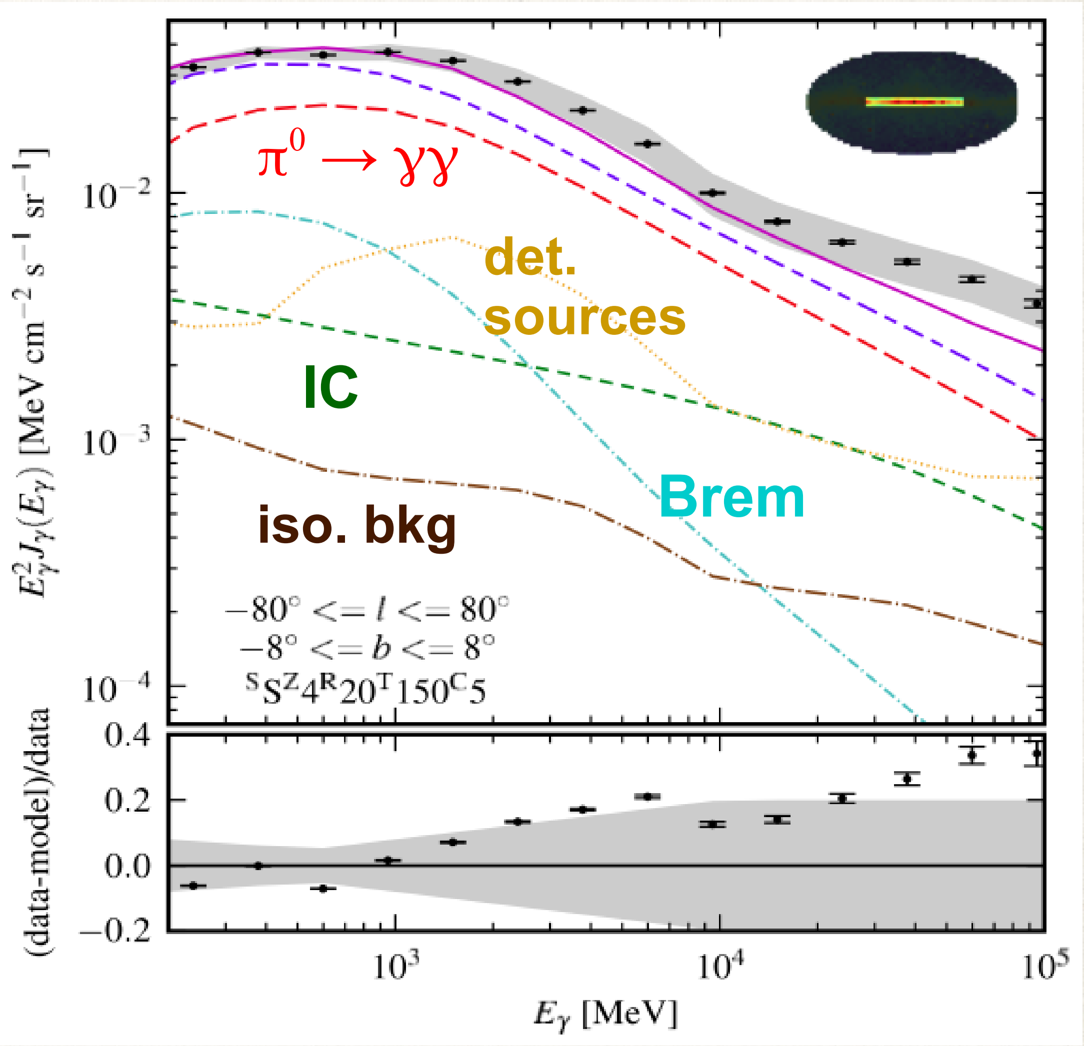
Constant CR slope in the Galaxy

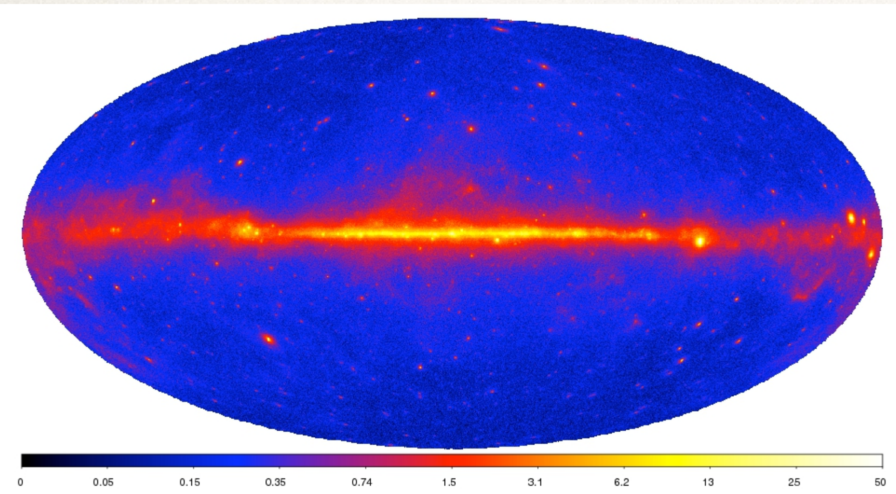
Deficit of γ-ray flux @ $E >$ few GeV in the inner disk region

Inner disk region



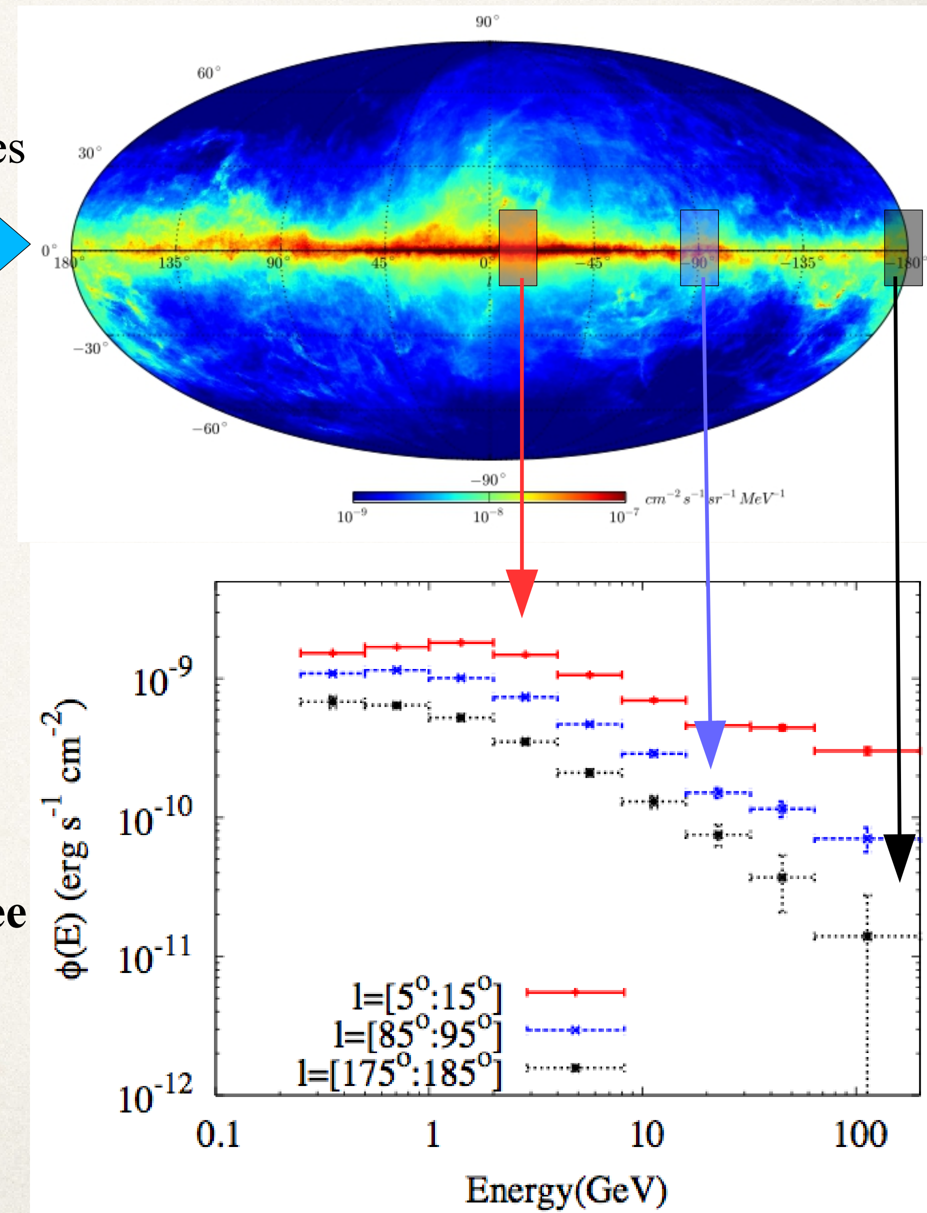
Using the diffuse Galactic γ-ray emission

FermiLAT all sky map



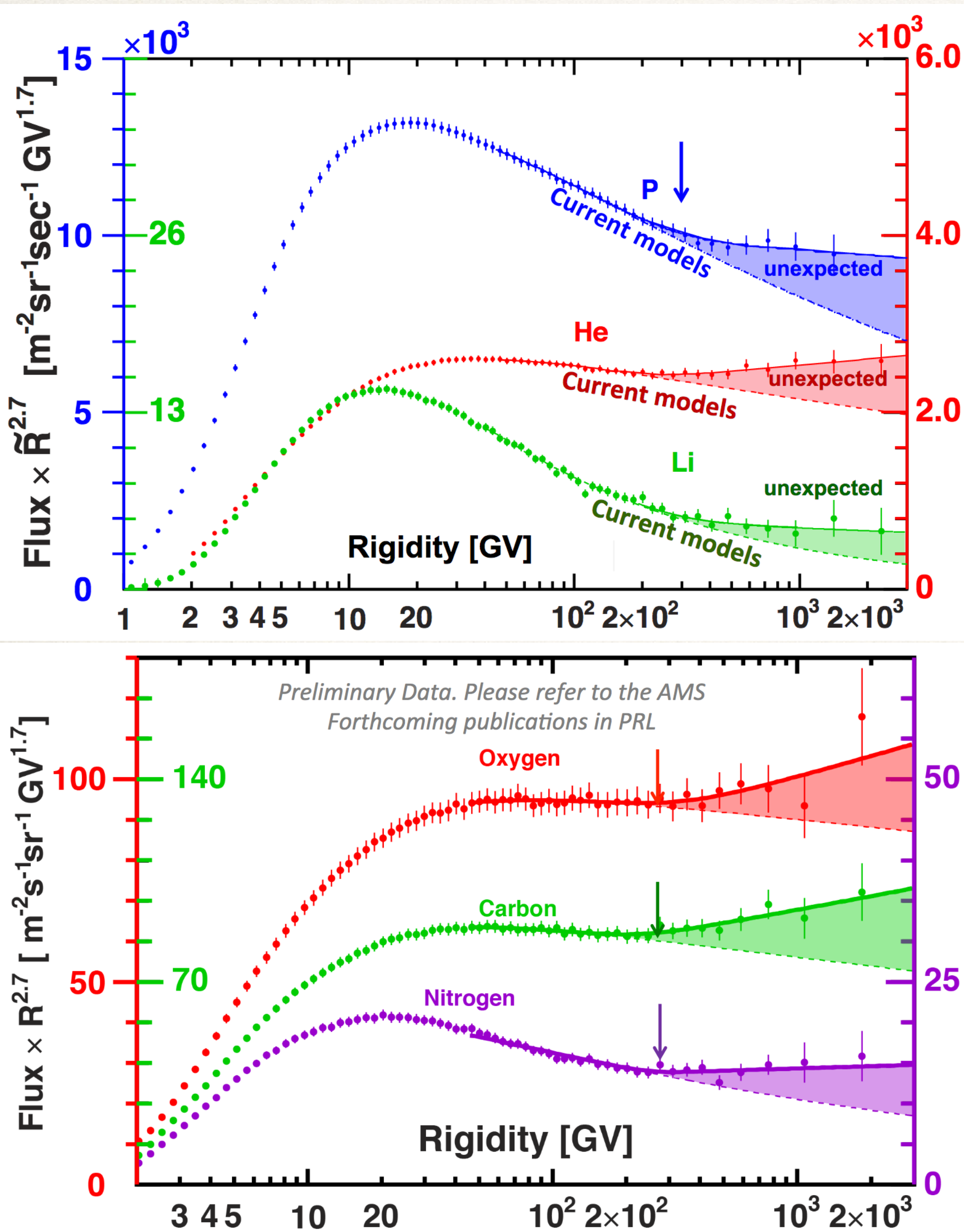
Subtracting known sources

FermiLAT diffuse emission



Diffuse Galactic γ-ray flux for three different angular sectors extracted from the Fermi-LAT data
[Yang-Aharonian-Evoli(2016)]

1st anomaly: spectral hardening



Recent measurements by PAMELA and AMS-02 revealed the existance of a fine structure:

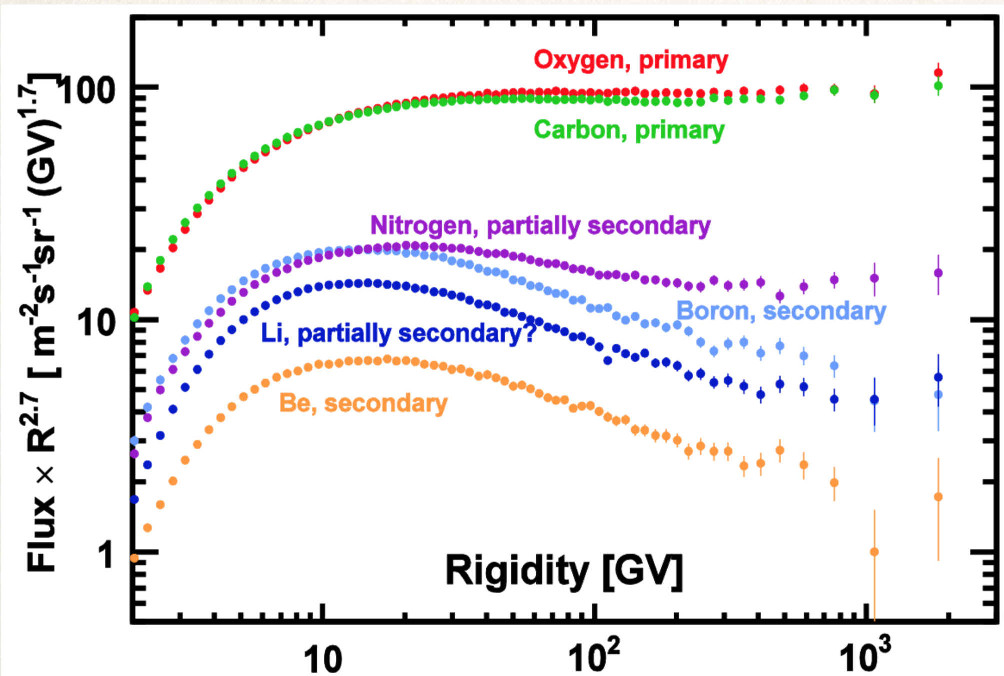
At rigidity of ~300 GV all spectra show a spectral hardening

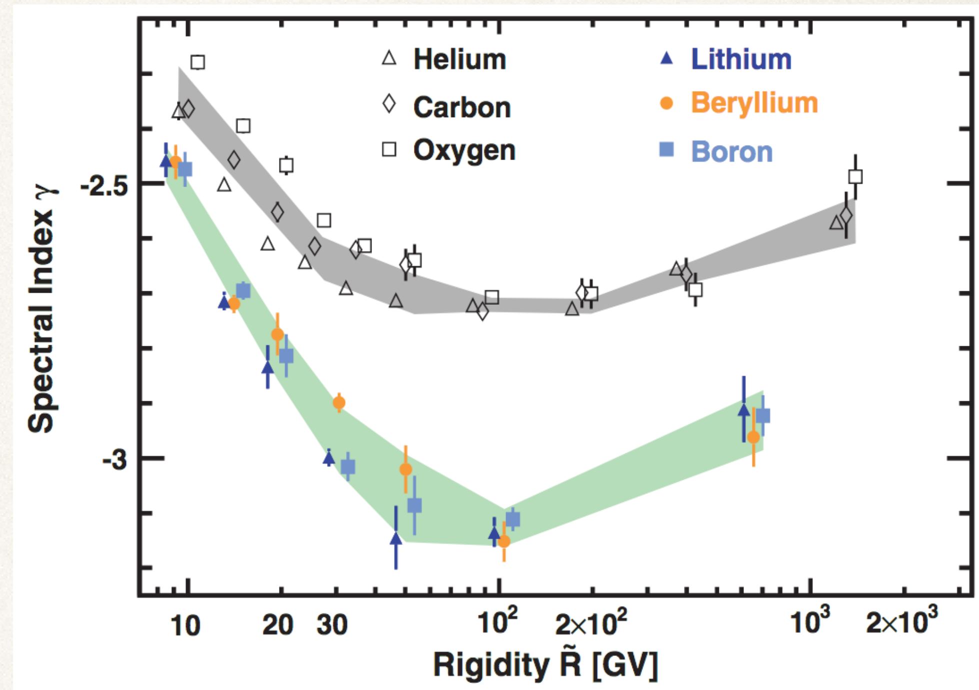
NO MORE A SIMPLE POWER-LAW

$$f_0(p) = \frac{Q_{SN}(p)}{2\pi R^2_{disc}} \frac{H}{D(p)} \propto E^{-\gamma-\delta}$$

Either the injected spectrum or the diffusion present a break at ~300 GV

Spectral hardening for secondary CRs





[AMS collaboration, PRL 120,021101, 2019]

$$f_{sec}(p) = f_{pri} \times \tau_{esc} \propto p^{-\gamma-2\delta}$$

The spectral hardening of secondary species is larger than primaries

⇒ supports the origin of break due to propagation rather than primary acceleration

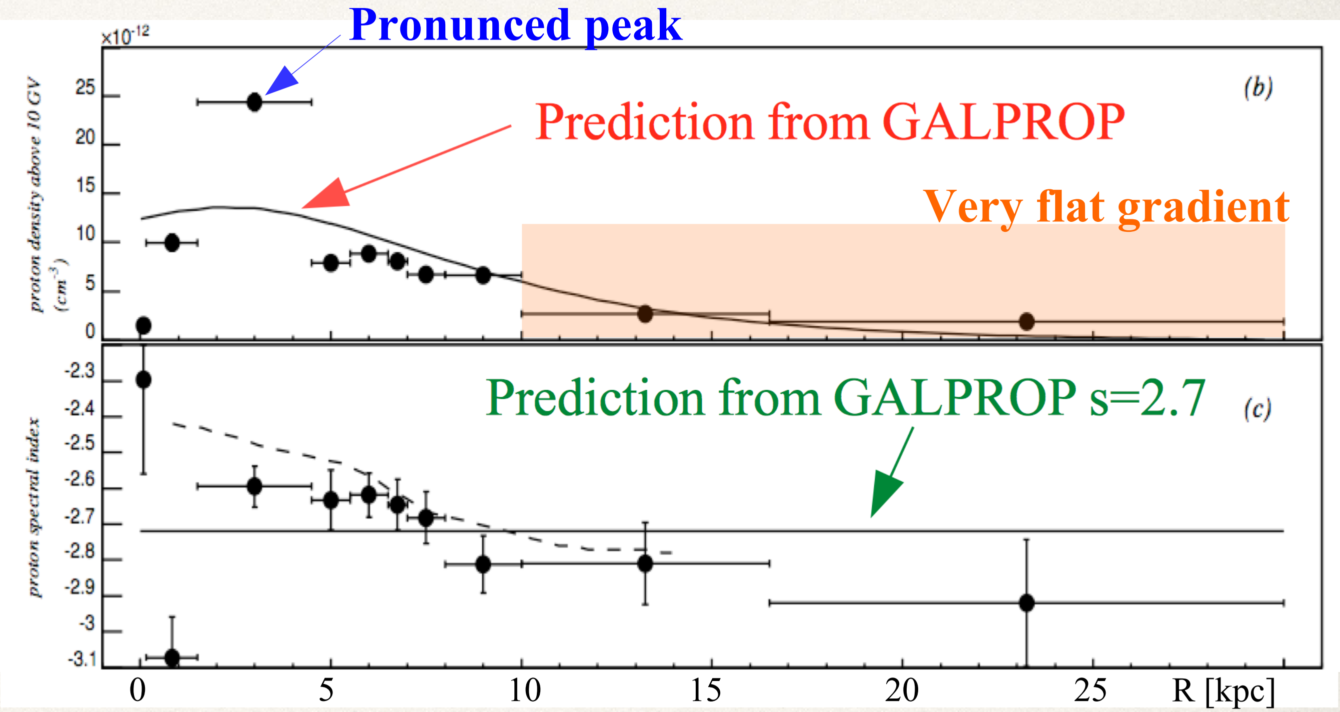
2^{nd} snomaly: the cosmic ray distribution in the Galactic plane

Recent results from the Fermi-LAT collaboration on the CR distribution in the Galactic plane [Acero et al. arXiv:1602.07246]

- In the outer region ($R > 8$ kpc) the CR density at ~20 GeV is flat
(i.e. decreases much slower than the source distribution)

- In the inner region the CR density has a peak at ~ 3 kpc

- The slope @ 20 GeV is not constant



This scenario is difficult to accommodate in a standard diffusion model where the diffusion is uniform in the Galalxy

Possible solutions

In the context of the standard halo model several solution have been proposed:

- Extended halo, $H > 4$ kpc
  (Dogiel, Uryson, 1988; Strong et al.,1988; Bloemen, 1993, Ackerman et al., 2011)

  ⇒ predices a flat spectrum (but not flat enough)

  ⇒ cannot explain the denity bump in the inner Galaxy
- Flatter distribution of SNR in the outer Galaxy
  (Ackerman et al., 2011)
- Enhancement of CO/H_2 density ratio (X_{CO}) in the outer Galaxy (Strong et al., 2004)
- Injection dependence on the ISM temperature

  (Erlykin et al., 2015)
- Advection effects due to the Galactic wind

  (Bloemen, 1993; Breitschwerdt, Dogiel, Voelk, 2002)

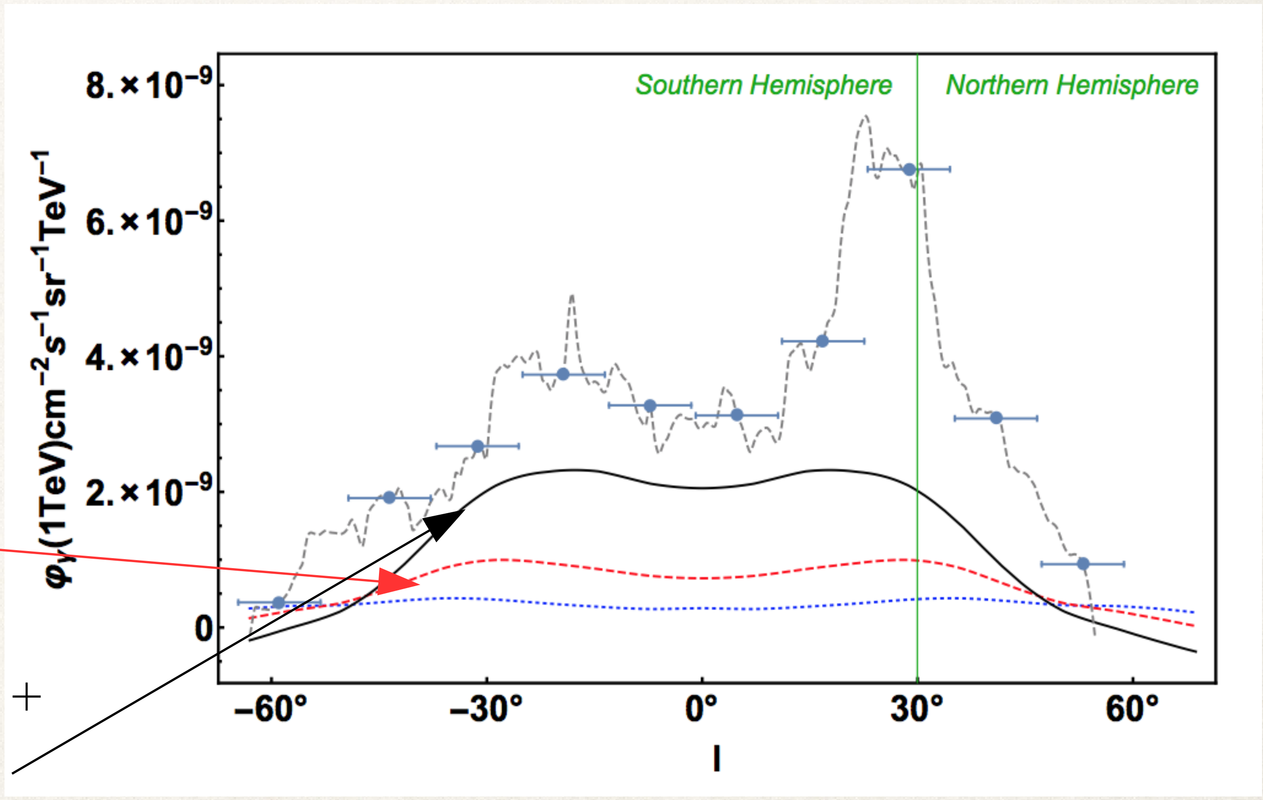
None of these ideas can simoultaneously account for all signatures

- flatness R > 8 kpc,
- peak at R~3-4 kpc,
- variation in the slope

Galacic γ-ray emission > 1 TeV

High energy gamma-ray observatories (MILAGRO, HESS, ARGO-YBJ) all show some excess at $E >$ TeV in the central disk region

HESS total emission E > 1 TeV b < 2°



CR density ∝ SNR distribution
+ constant slope

CR density ∝ SNR distribution +
hardening in the inner galaxy

[Pagliaroli & Villante (2018)]

Model for Galactic γ-ray background

[Gaggero, Grasso, Marinelli et al. ApJL 815 (2015)]

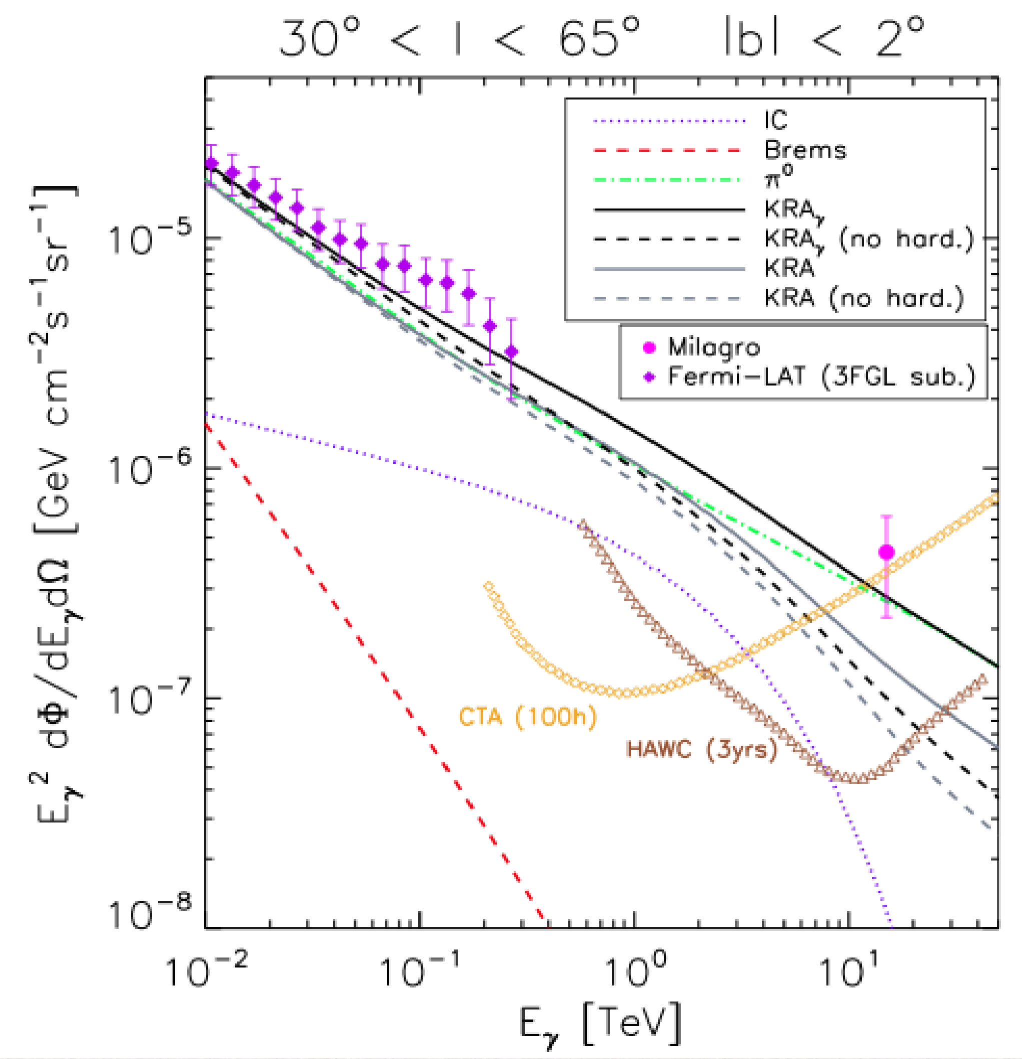
Motivated by GeV Fermi-LAT excess and Milagro data, Gaggero et al. (21015) suggested a diffusion dependence on Galactocentric distance

$$D(E) \propto E^{\delta}$$

$$N(E) \propto \frac{Q_{inj}}{D(E)} \propto E^{-\gamma-\delta}$$

$$\delta = 0.035\,\frac{R}{kpc} + 0.21 \Rightarrow \begin{cases} N(E, R_{Sol}) \propto E^{-2.7} \\ N(E, 1\,kpc) \propto E^{-2.45} \end{cases}$$

Diffuse g-ray flux from the central disk



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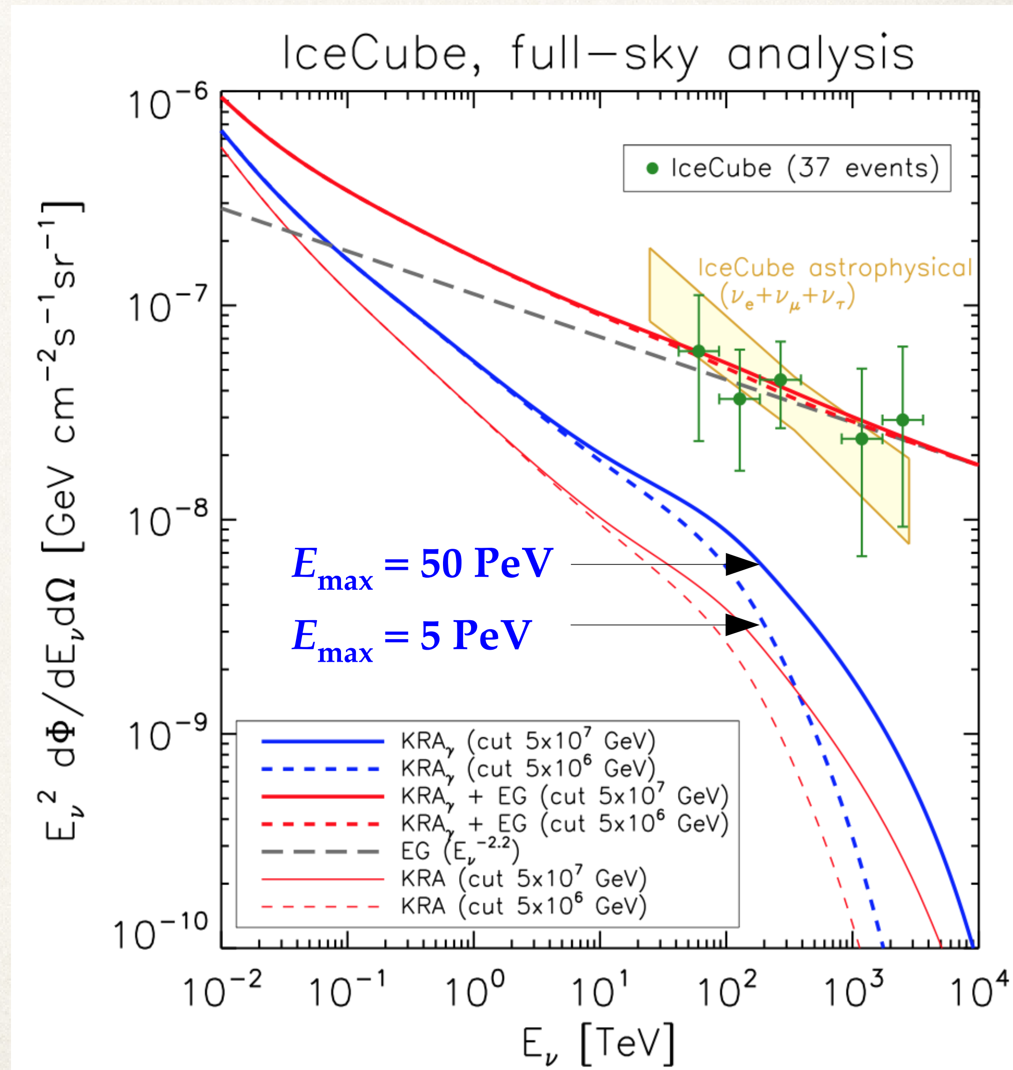
The most optimistic version of this model (E_{max} = 50 PeV) can account for ~20% of ν flux @ 100 TeV

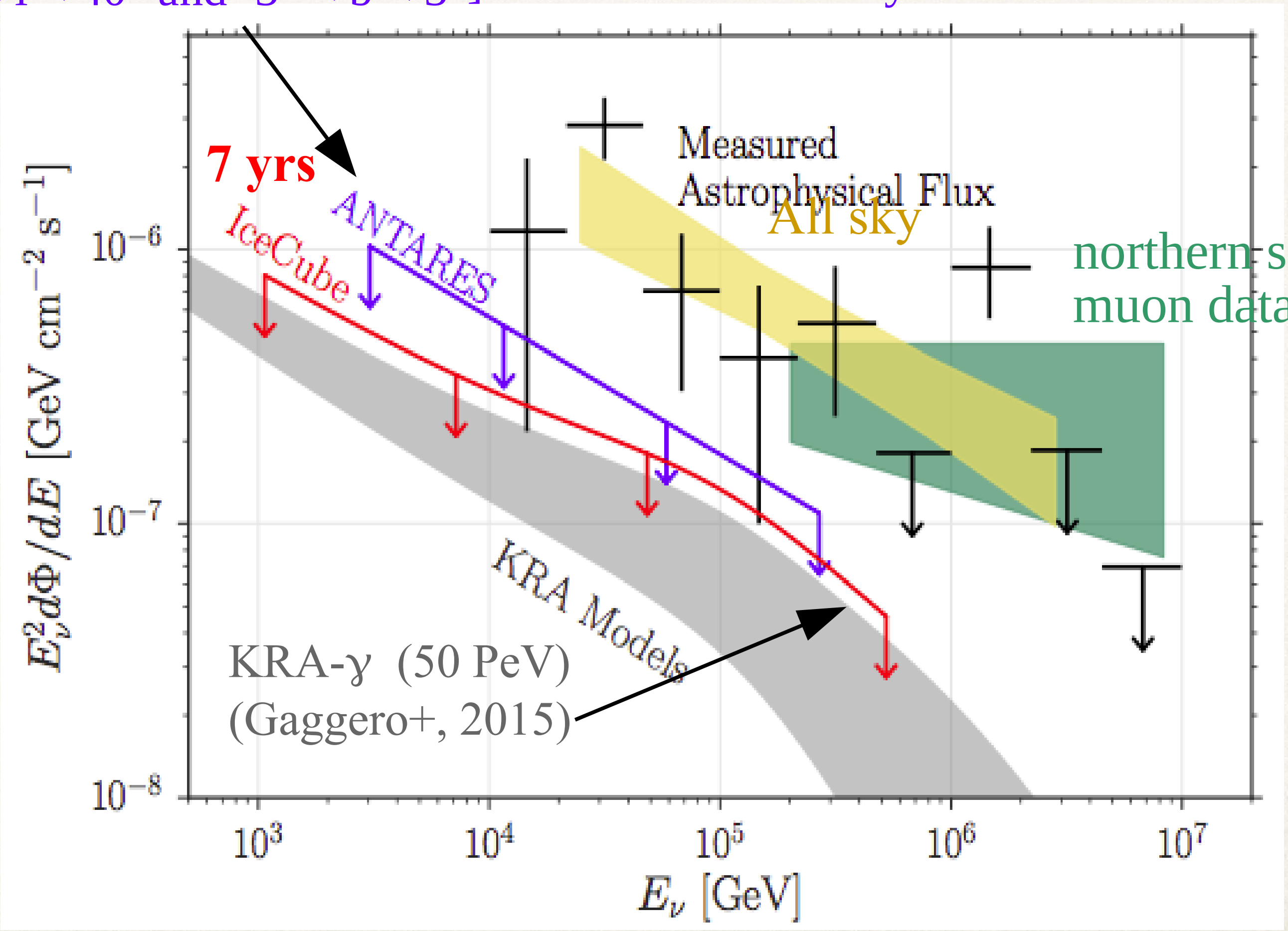


Anisotropy of ν flux

[Aartsen et al. IceCube coll. (2017)]

Final result from combined analysis:
Galactic disk contribution on 7 yrs IceCube data < 14% (@ 90% C.L.)

Antares GC [-40° < l < 40° and -3° < b < 3°] rescaled to whole sky

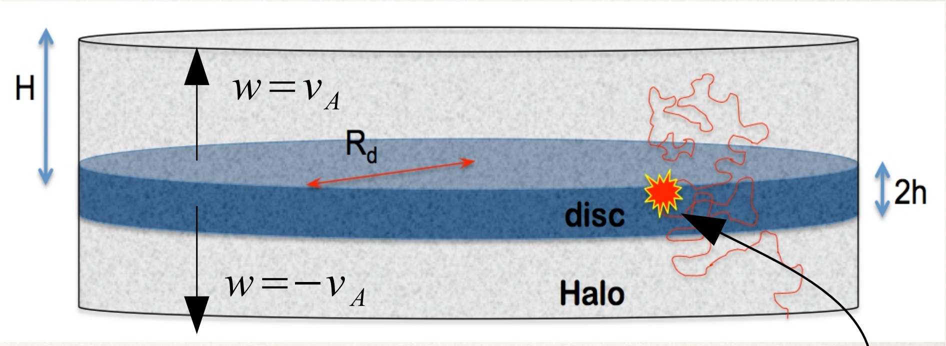


Possible role of self-generated turbulence

(Recchia, Blasi, GM, MNRAS 462, 2016)

- CR escaping from the Galactic plane produce magnetic turbulence through resonant streaming instability

$$\Gamma_{\rm cr} = \frac{16\pi^2}{3}\frac{v_A}{\mathcal{F}(k)B_0^2}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{p=eB_0/kc}$$



- Turbulence scatter CRs (mainly) along large scale mag. field lines with Bohm-like diffusion coefficent

$$D(z,p) = \frac{r_L(p)v(p)}{3}\left[\frac{1}{\mathcal{F}(k)}\right]_{k=1/r_L}$$

Spectrum injected at the disk

$$Q_0(p,R) \propto N_{SNR}(R)\, p^{-\gamma}$$

- CRs are also advected by the global motion of the waves at the Alfvén speed

Propagated spectrum in the disk

$$f_{disk}(p) \propto p^7 \left(\frac{Q_0(p,R)}{B_0(R)}\right)^s ; \qquad s=1\div3$$

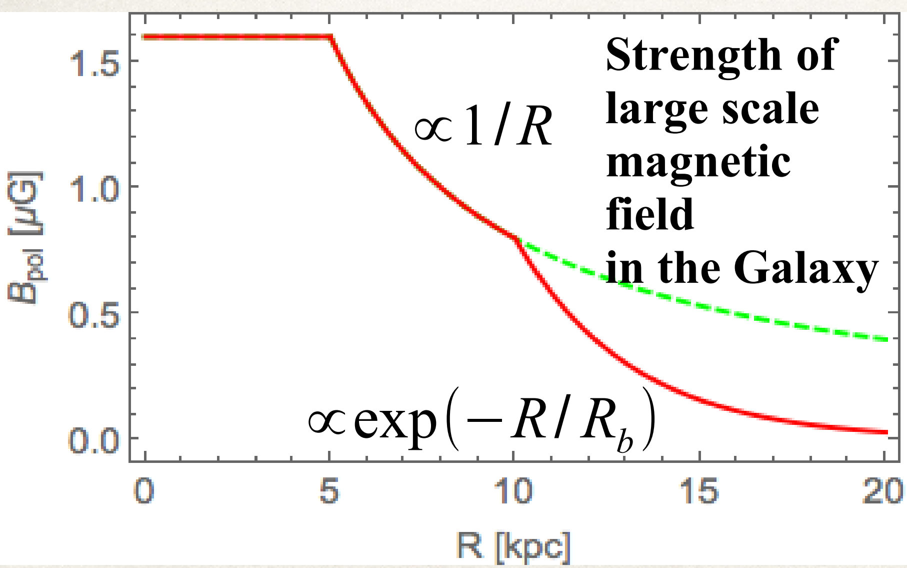
Self-generated turbulence and the gradient problem

(Recchia, Blasi, GM, MNRAS 462, 2016)

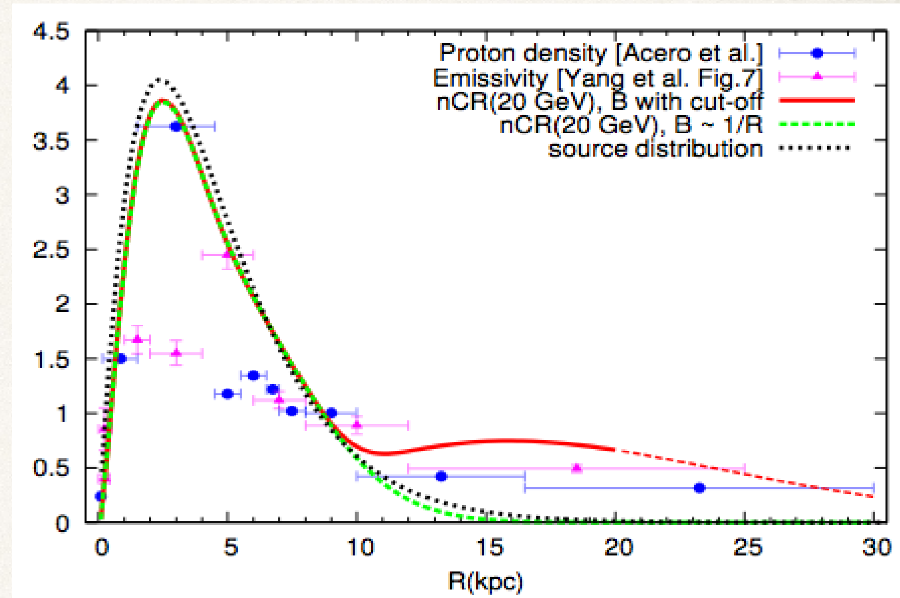
Self-generated turbulence could explain the gradient and the spectral index changes because it is more effective where *B* is smaller

- less effective in the inner Galaxy
- more effective in the outer Galaxy

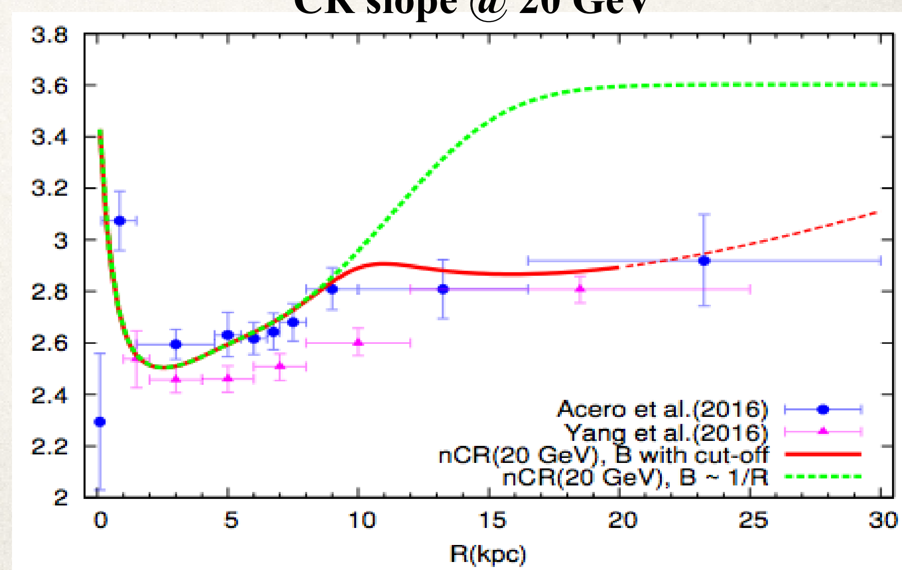
But cannot explain the Milagro data



CR spectrum density @ 20 GeV



CR slope @ 20 GeV



Caveat: unresolved sources

Galactic unresolved sources in the TeV band may modify the conclusion on neutrino flux prediction.

- Hadronic (e.g. SNR) ⇒ no significant modification of ν flux
- Leptonic (IC; e.g. PWNe) ⇒ significant ν flux reduction

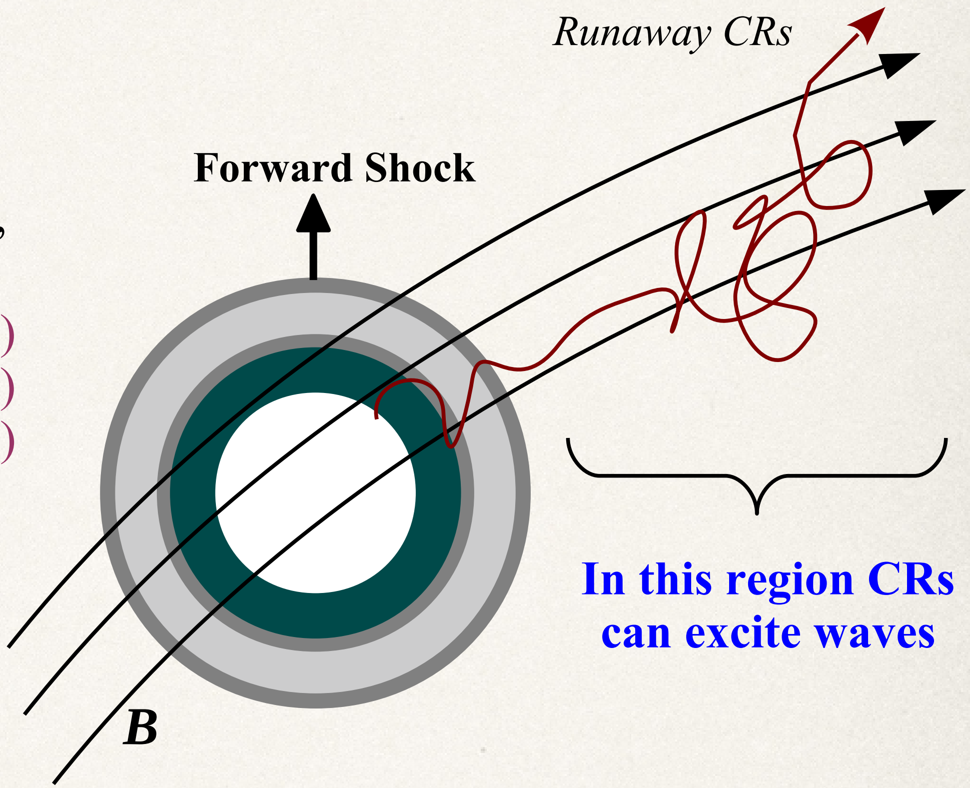
Effect of self-amplification near the CR sources

During the process of escaping, CR can excite magnetic turbulence (via streaming instability) that keep the CR close to the SNR for a long time, up to ~10^5 yr

Malkom et al. (2013)
Nava et al. (2015)
D'Angelo et al. (2017)

During this time CR spend in the vicinity of sources they can produce diffuse emission via

$$\pi^0 \rightarrow \gamma\ \gamma$$



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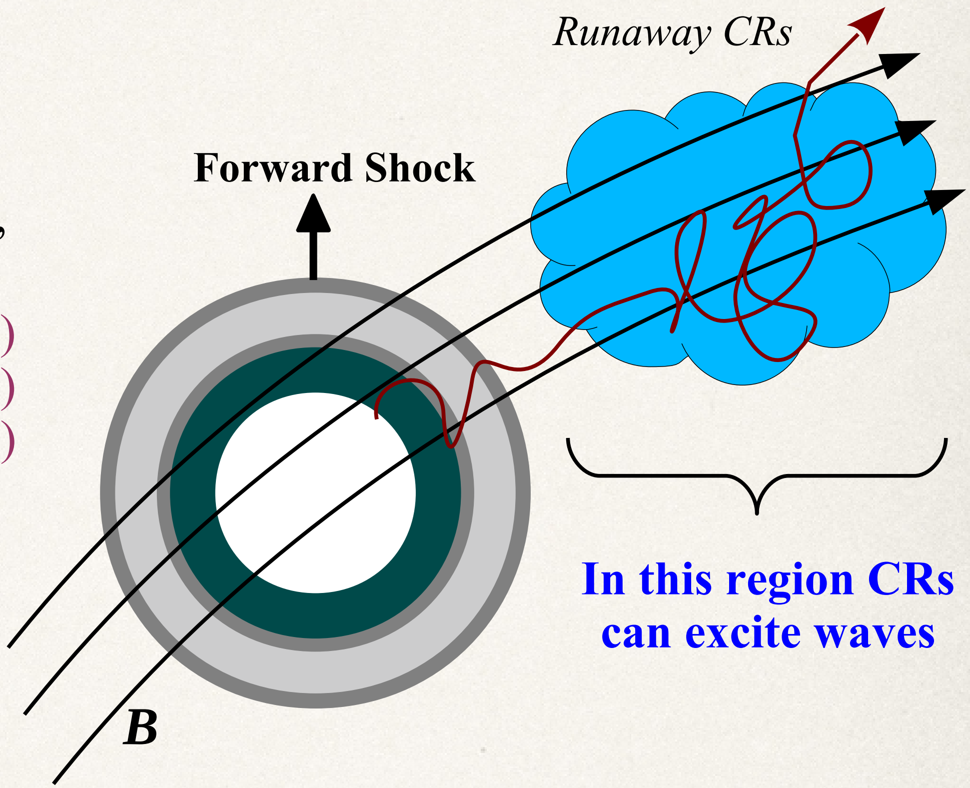

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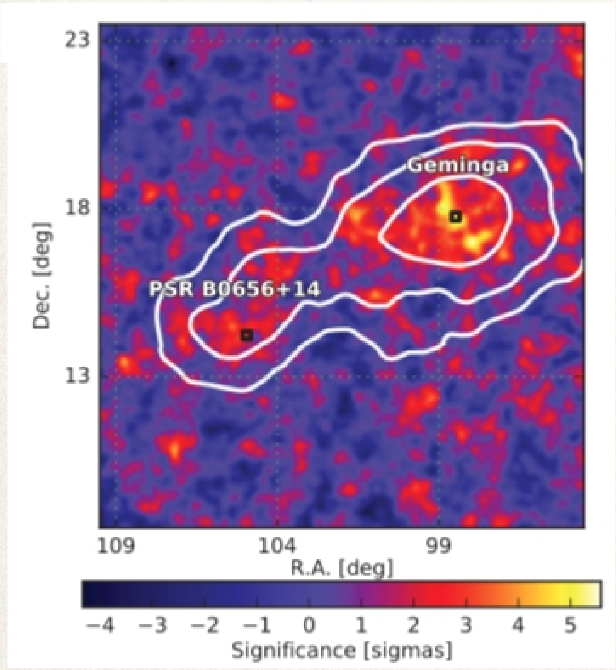
$$\pi^0 \rightarrow \gamma\ \gamma$$

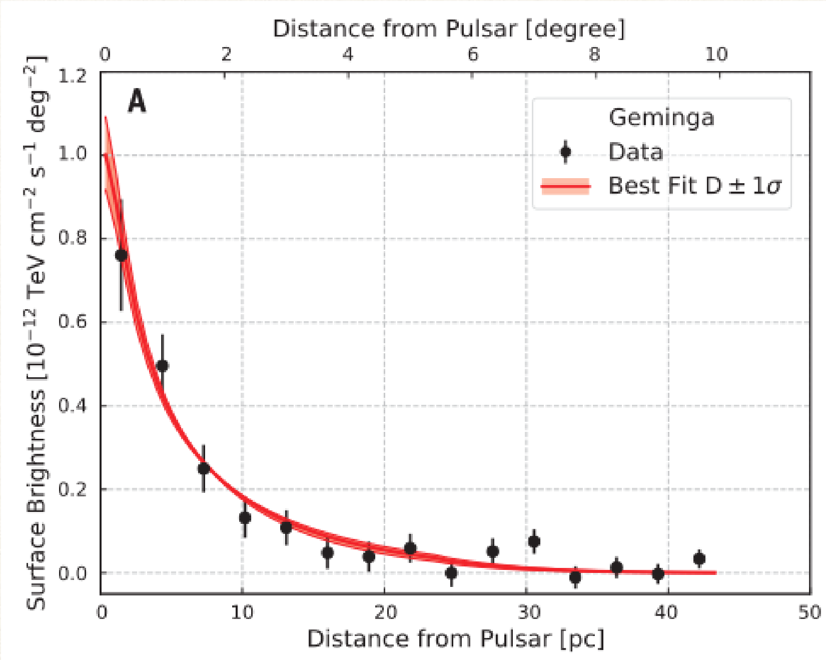
If a molecular cloud is close enough the enhanced γ-ray emission will be seen for long time

CTA will probably discover tens of SNR-MC associations

Contribution from PWNe (TeV halos)

New insight from TeV halos around PWN point towards very small *D* around the sources at 1-20 TeV [Abeysekara et al. HAWK coll., 2017]





$$D(100\,TeV) \simeq 3\times 10^{27}\, cm^2\, s^{-1} \simeq 10^{-3} \times D_{Gal}(100\,TeV)$$ up to 10-20 pc

where $D_{Gal}(p) = 3\times 10^{28}\, E_{GeV}^{1/3}$

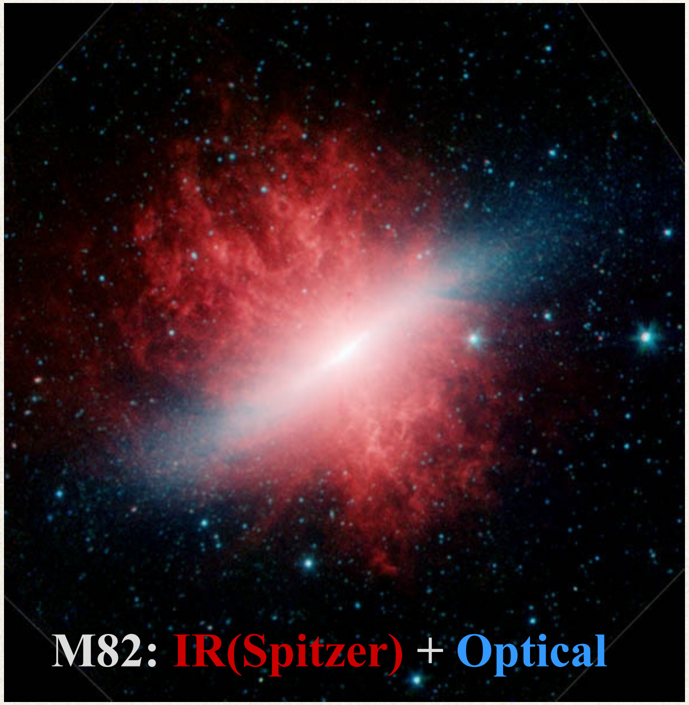
If a relevant fraction of PWNe has TeV halos, they could dominate the TeV gamma-ray Galactic emission.

γ-rays and νs from starburst nuclei

Starburst galaxies are usually associatet to events of galaxy merger

- High star formation rate (10-100 times the Milky Way)
  → large SN rate → high CR production
- High level of turbulence → efficient CR confinement
- Large gas density → **efficient γ and ν production**
- Aboundant (10^4 – 10^5 Gpc^{-3})

The observed γ-ray spectrum is usually hard: $\phi_\gamma \propto E^{-2.2} \div E^{-2.3}$.

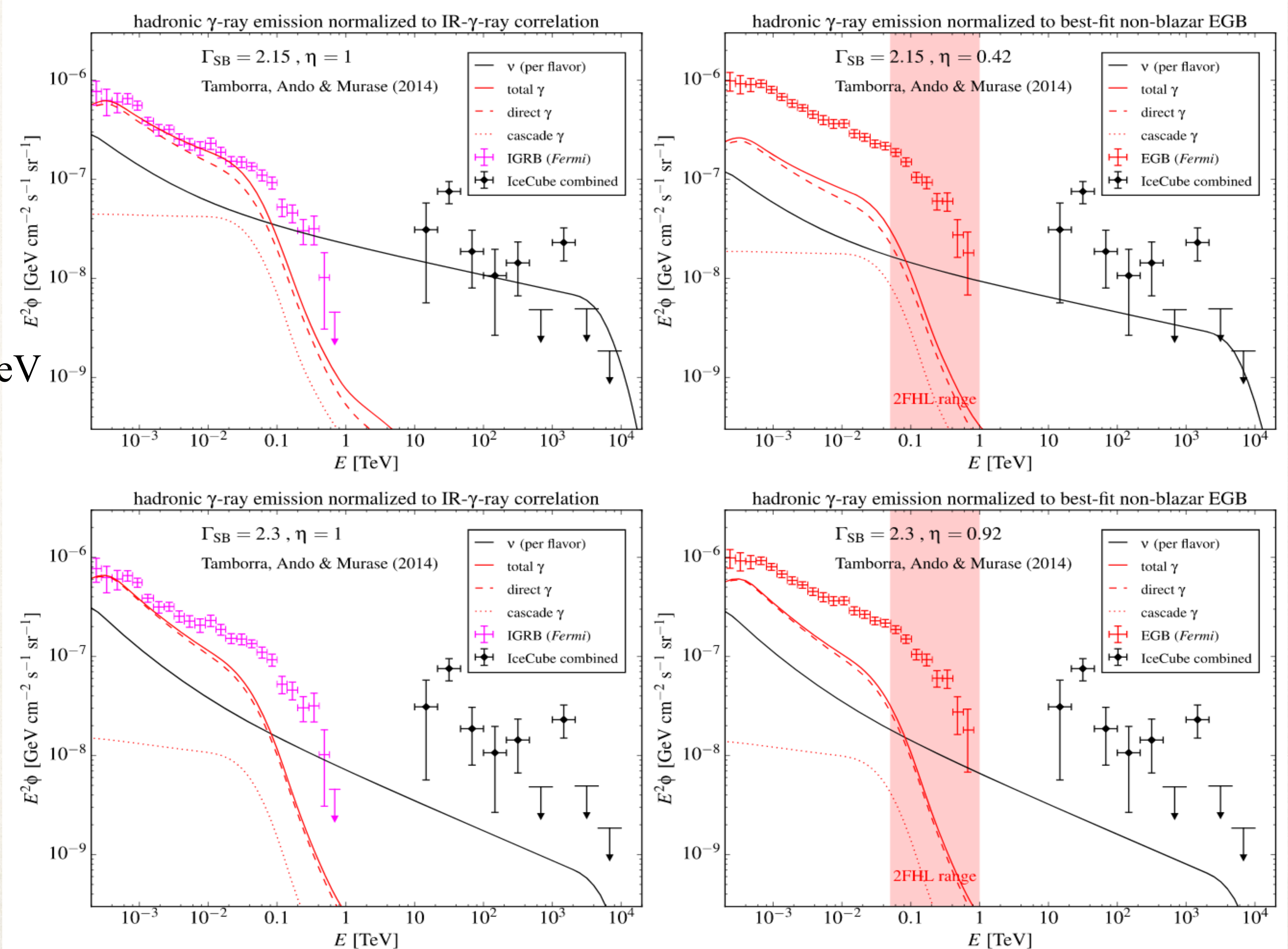


Constraints from EGB

(Bechtol et al. ApJ 836, 47 (2017))

Assuming
Γ_{SB}= 2.2
The maximal contribution of SBG is

- 30% @ 100 TeV
- 60% @ 1 PeV



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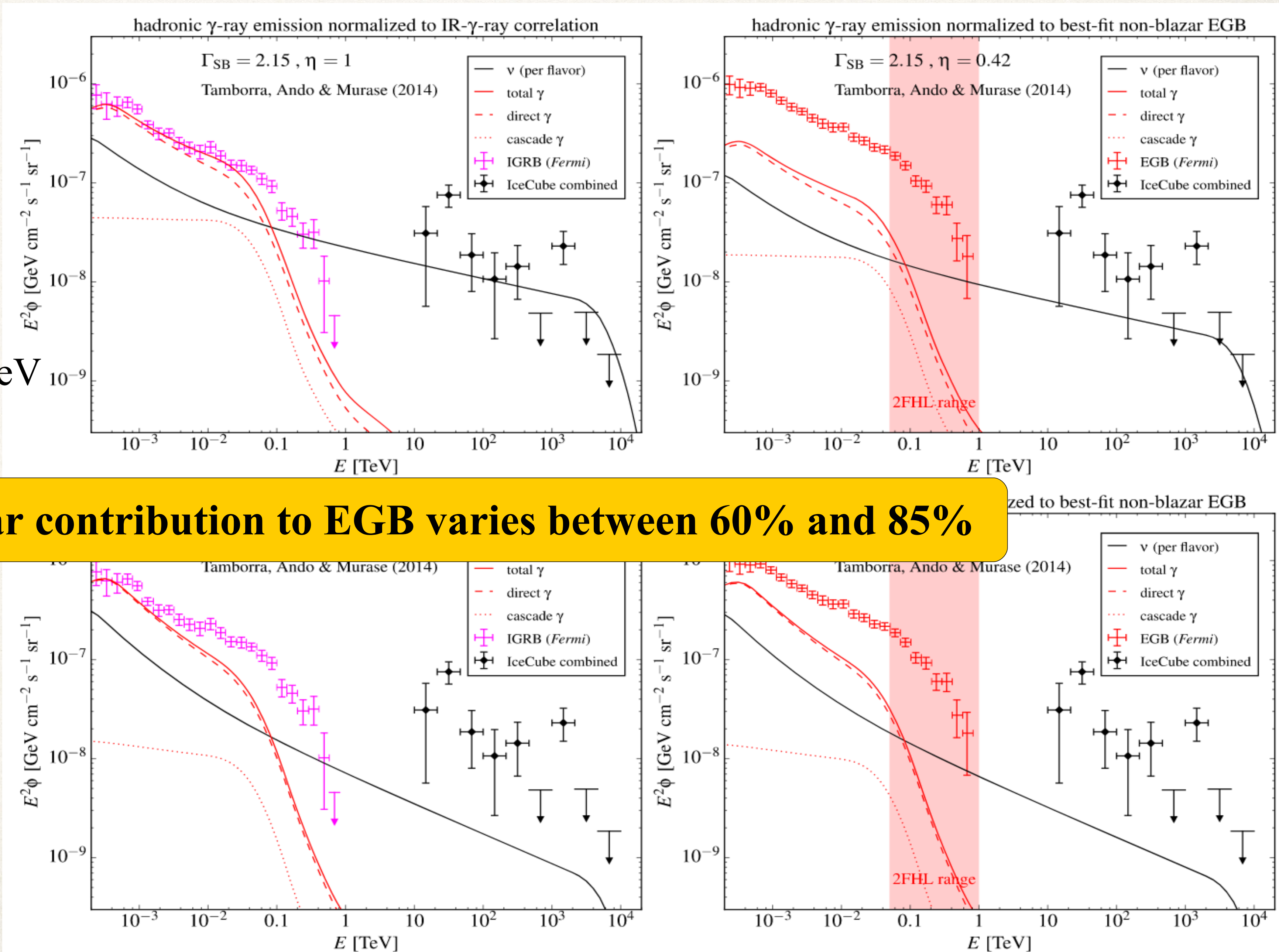

Blazar contribution to EGB varies between 60% and 85%

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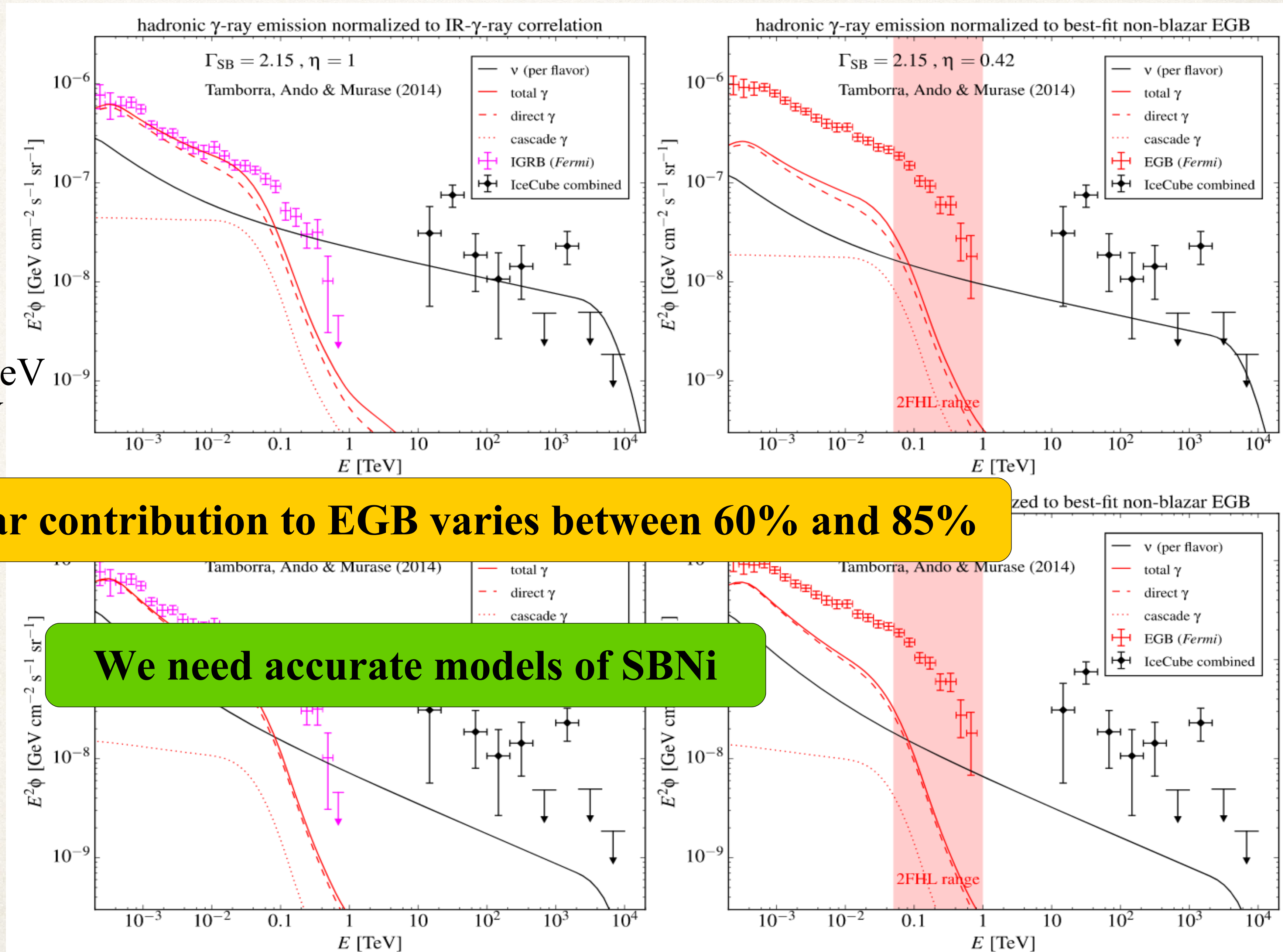


Blazar contribution to EGB varies between 60% and 85%

We need accurate models of SBNi

γ-rays and νs from starburst nuclei

We adopt the leaky-box model

$$\frac{f(p)}{\tau_{loss}}+\frac{f(p)}{\tau_{adv}}+\frac{f(p)}{\tau_{diff}}=Q_{inj}(p)$$

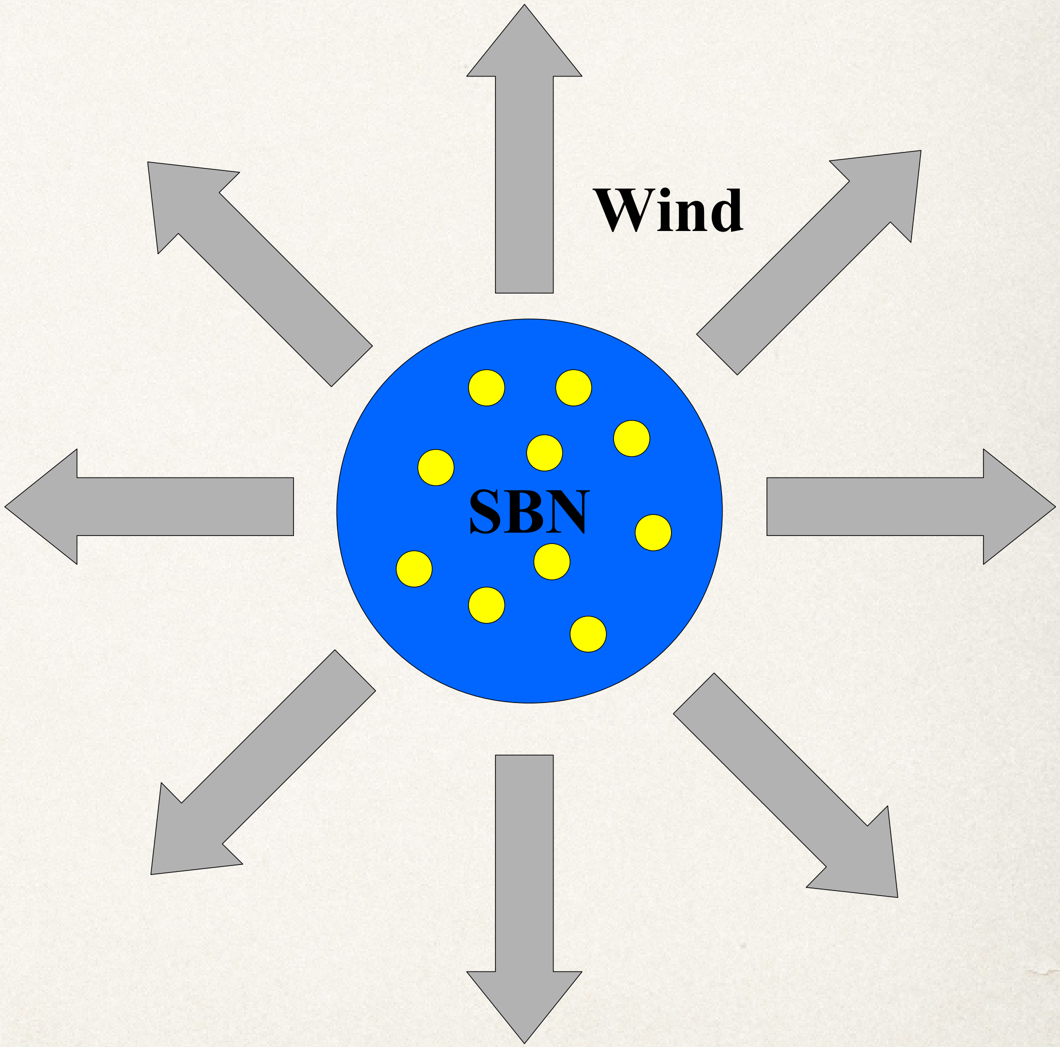
Injection

$$Q(p) = N(p) R_{SN} \; V^{-1};$$
$$N_p(p) \propto p^{-\alpha} e^{-p/p_{max}}$$
$$N_e(p) \propto k_{ep}\, p^{-\alpha} e^{-(p/p_{e,max})^2}$$

Losses

$$\frac{1}{\tau_{loss}}=\sum_i \left(-\frac{1}{E}\frac{dE}{dt}\right)_1$$

$p \rightarrow$ ionization, p-p collisions, Coulomb
$e \rightarrow$ ionization, sync., IC, brem.



CR propagation and confinement inside a SBN

(Peretti, Blasi, Aharonian, GM 2019)

Diffusion

$$D(p)=\frac{r_L(p)v(p)}{3\,k_{res}W(k_{res})}$$

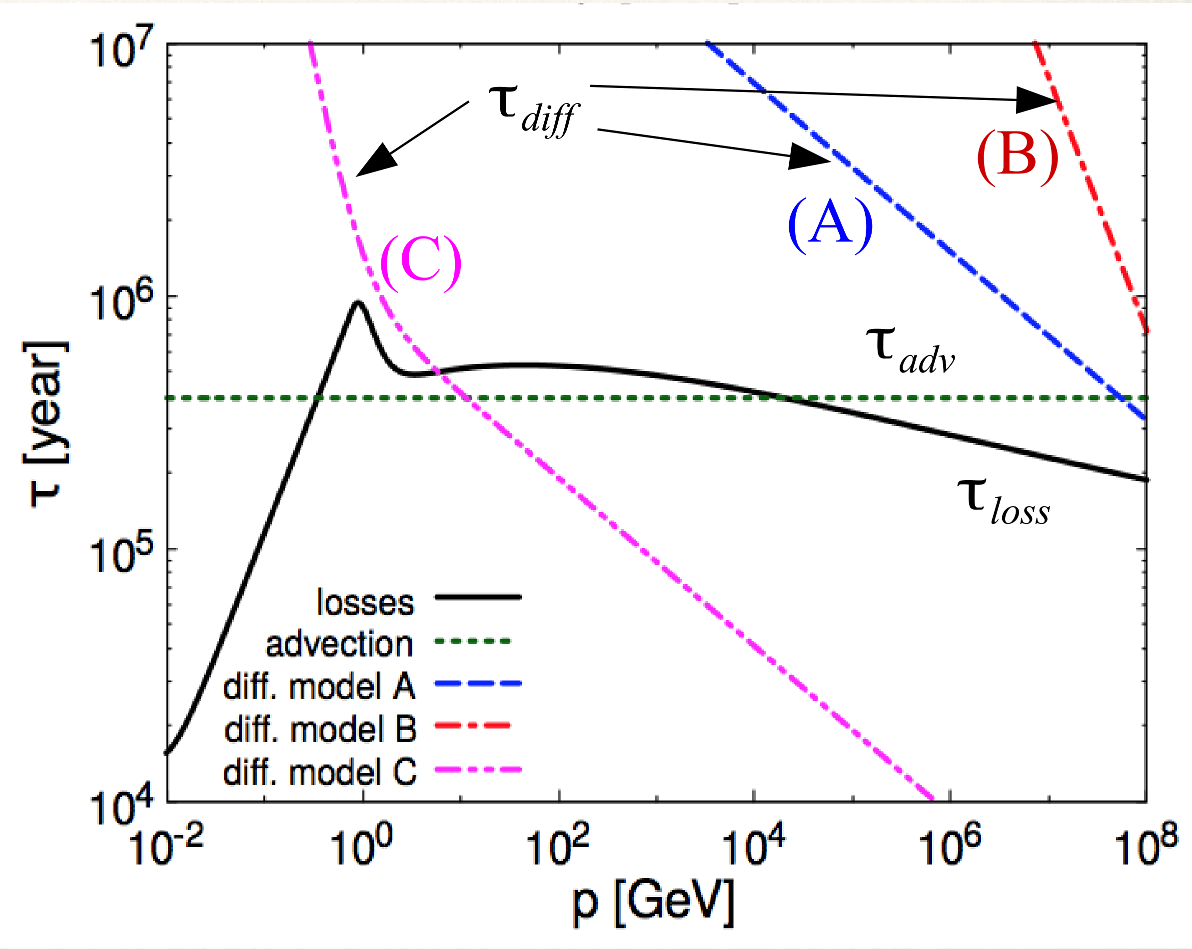
Turbulence

$$W(k)=W_0(k\,L_0)^{-d}$$

A) Kolmogorov:
$d = 5/3;\ L_0 = 1$ pc

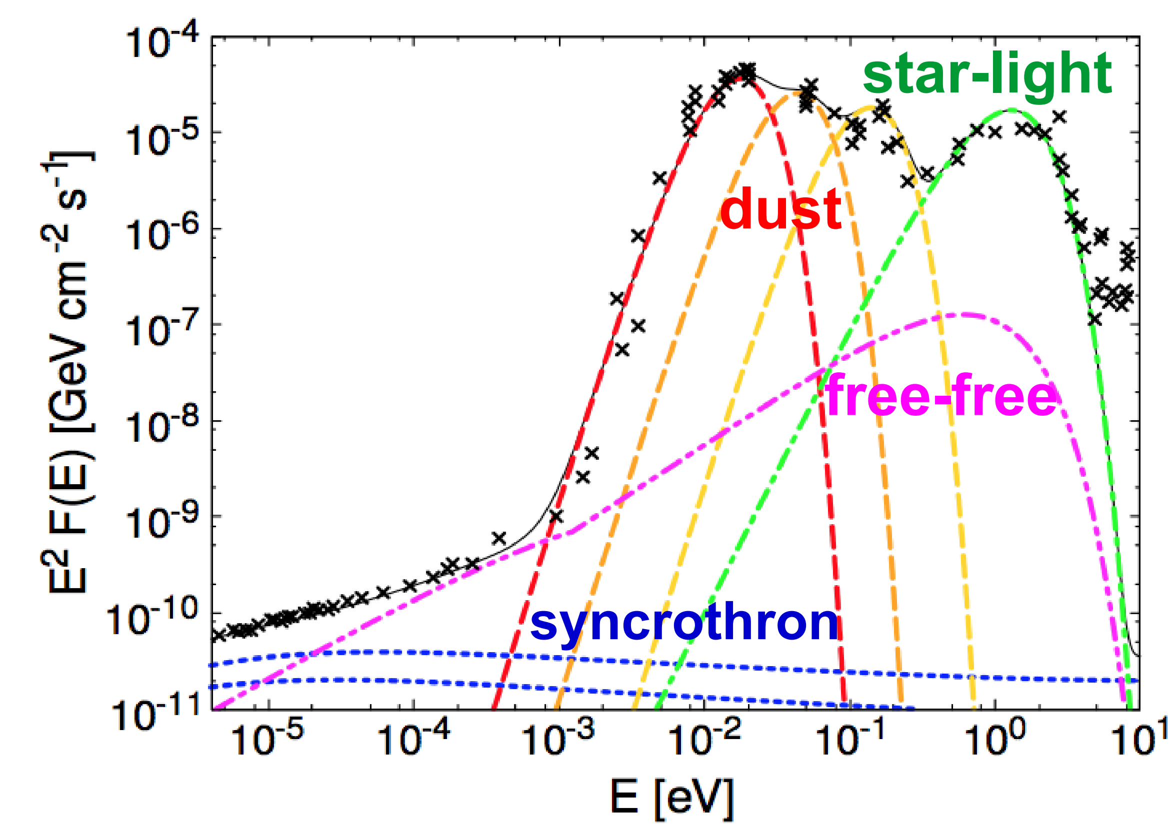
B) Bohm
$d = 0;$

C) Milky Way-like
d = 5/3; $L_0 = 100$ pc



Application to individual starburst galaxies: M82

Fixing the photon background



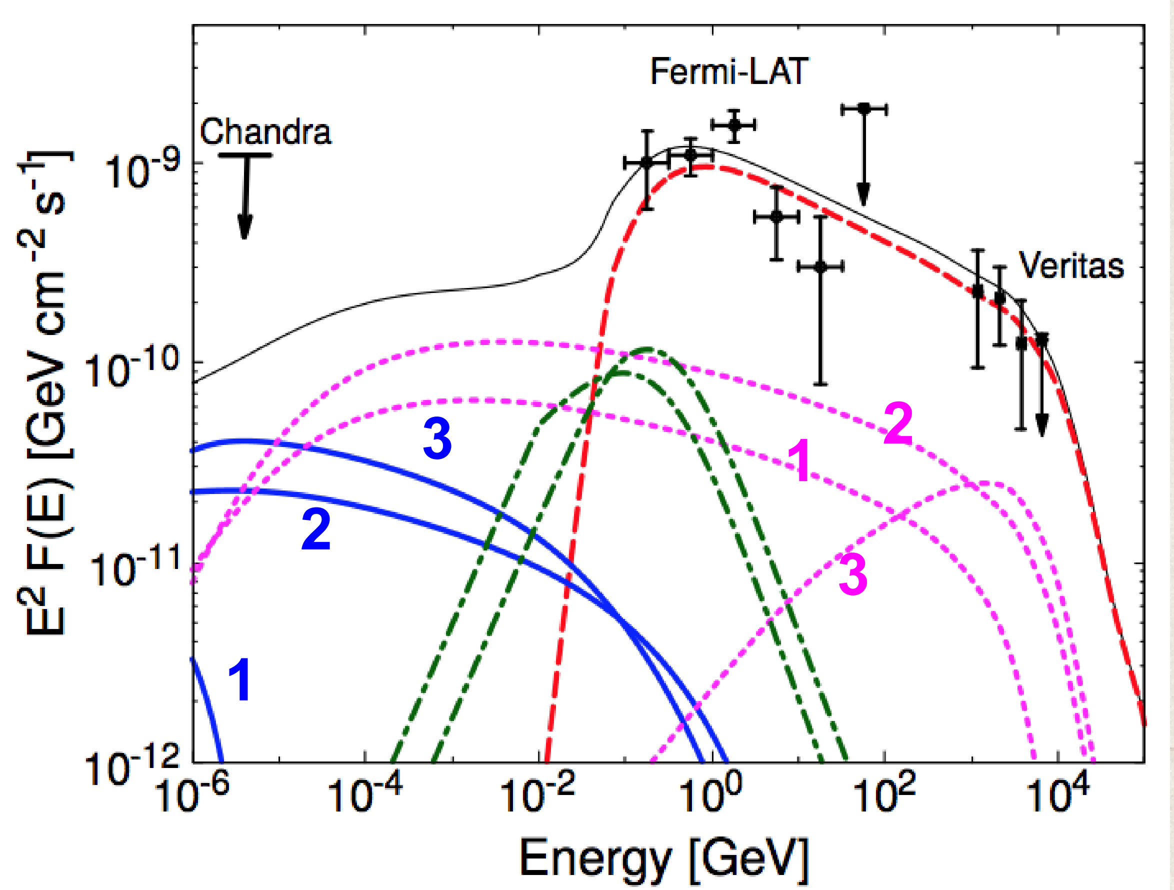
Parameters	NGC253	M82
U^{FIR}_{eV/cm^3} $[\frac{kT}{meV}]$	3480 [3.5]	1618 [3.0]
U^{MIR}_{eV/cm^3} $[\frac{kT}{meV}]$	1044 [8.75]	1132 [7.5]
U^{NIR}_{eV/cm^3} $[\frac{kT}{meV}]$	1044 [29.75]	809 [24.0]
U^{OPT}_{eV/cm^3} $[\frac{kT}{meV}]$	5220 [332.5]	970 [330.0]

Application to individual starburst galaxies: M82

Parameters	NGC253	M82
D_L (Mpc) [z]	3.8 [8.8 10^{-4}]	3.9 [9 10^{-4}]
$\mathcal{R}_{SN}$ (yr^{-1})	0.03	0.05
R (pc)	150	220
α	4.3	4.25
B (μG)	200	225
M_{mol} ($10^8 M_\odot$)	0.63	1.94
n_{ISM} (cm^{-3})	180	175
n_{ion} (cm^{-3})	27	22.75
v_{wind} (km/s)	300	600
T_{plasma} (K)	8000	7000

1 → primaries
2 → secondaries $\pi^\pm \to \mu^\pm \to e^\pm$
3 → tertiaries $\gamma\gamma \to e^+e^-$

$\pi^0 \to \gamma\gamma$
IC
Brem
Sync



Application to individual starburst galaxies: NGC 253

Parameters	NGC253	M82
D_L (Mpc) [z]	3.8 [8.8 10^{-4}]	3.9 [9 10^{-4}]
$\mathcal{R}_{SN}$ (yr^{-1})	0.03	0.05
R (pc)	150	220
α	4.3	4.25
B (μG)	200	225
M_{mol} ($10^8 M_\odot$)	0.63	1.94
n_{ISM} (cm^{-3})	180	175
n_{ion} (cm^{-3})	27	22.75
v_{wind} (km/s)	300	600
T_{plasma} (K)	8000	7000

$\pi^0 \rightarrow \gamma\gamma$
IC
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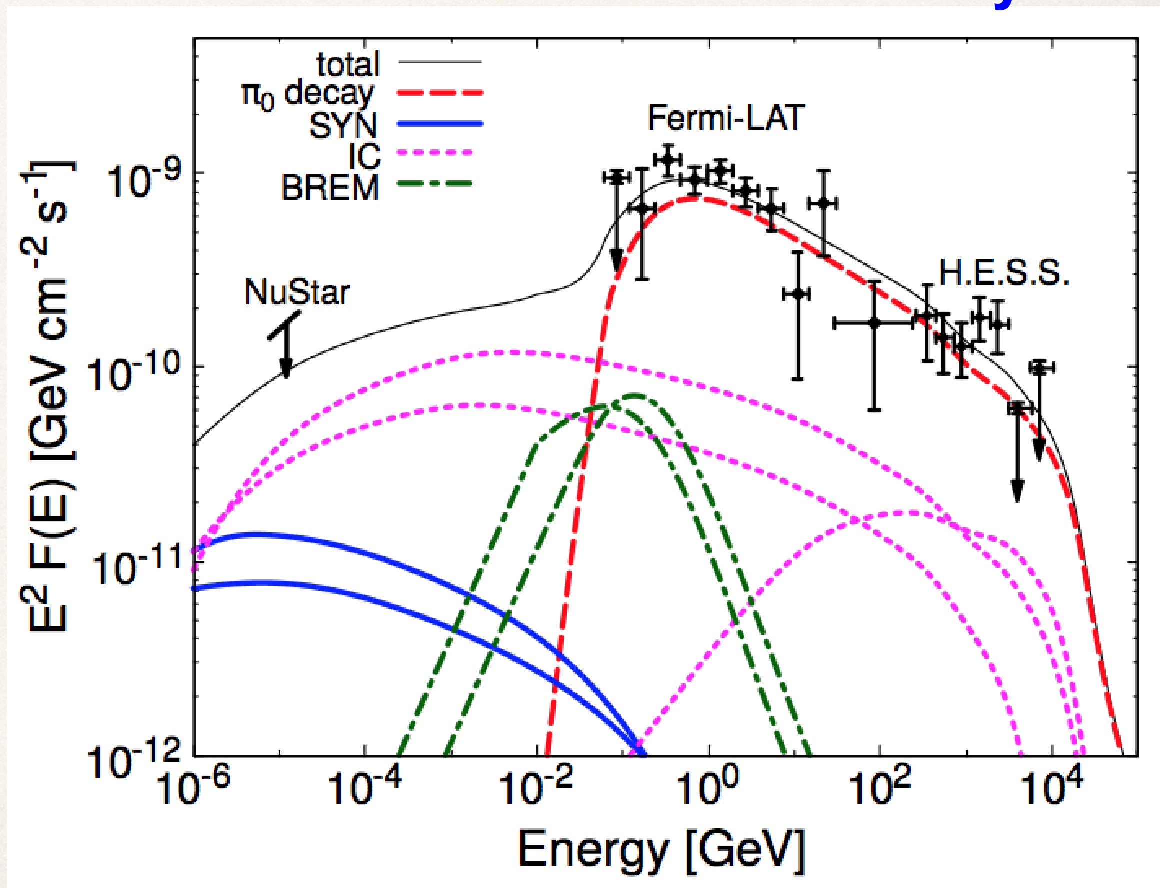

SBNi contribution to the diffuse fluxes

Determining the calorimetric condition

(Peretti, Blasi, Aharonian, GM 2019)

Definition of starburst galaxies as efficient neutrinos factories
→ requires efficient CR confinement

$$\tau_{loss} < \tau_{esc} \approx \tau_{adv}$$

$$\begin{cases} \tau_{loss} \approx \dfrac{1}{n_{ISM}\, c\, \sigma_{pp}\, \eta} \\ \tau_{adv} \approx R/v_{wind} \end{cases}$$

Surface gas density

$$\Sigma_{gas} = n_{ISM}\, m_p\, R$$

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Using the Kennicutt (1998) relation

$$\frac{\Sigma^*_{\rm SFR}}{M_\odot {\rm yr}^{-1} {\rm kpc}^{-2}} = (2.5 \pm 0.7) \times 10^{-4} \left[\frac{\Sigma^*_{\rm gas}}{1\ M_\odot {\rm pc}^{-2}}\right]^{1.4 \pm 0.15}$$

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$$\psi^* = \Sigma^*_{\rm SFR} \pi R^2 \approx 0.9^{+2.2}_{-0.7} \left[\frac{R}{0.25\ {\rm kpc}}\right]^2 {\rm M_\odot yr^{-1}}.$$

Efficient calorimeter if $\psi > \psi^*$

Counting the SBNi

(Peretti, Blasi, Aharonian, GM 2019)

Gamma and neutrino spectra

$$q_{\gamma,\nu}(E) \propto \begin{cases} q(p) & \tau_{\rm loss} \ll \tau_{\rm adv} \\ [n_{\rm ISM}\sigma_{pp}c]q_p(p)R/v_{\rm wind} & \tau_{\rm loss} \gg \tau_{\rm adv} \end{cases}.$$

Calorimetric limit

Gamma and neutrino flux from a single SBN

$$f^{\rm SBN}_{\gamma,\nu}(E,\psi) = \left(\frac{\psi}{\psi_{\rm M82}}\right) f^{M82}_{\gamma,\nu}(E),$$

for $\psi > \psi^*$

Determining the SFRF from a fit to IR+UV data [Gruppioni et al.(2015)]

$$\Phi(\psi)\, d\log\psi = \tilde{\Phi}\left(\frac{\psi}{\tilde{\psi}}\right)^{1-\tilde{\alpha}} \exp\left[-\frac{1}{2\tilde{\sigma}^2}\log^2\left(1+\frac{\psi}{\tilde{\psi}}\right)\right] d\log\psi,$$

Gamma-ray and neutrino flux integrated over the cosmological history

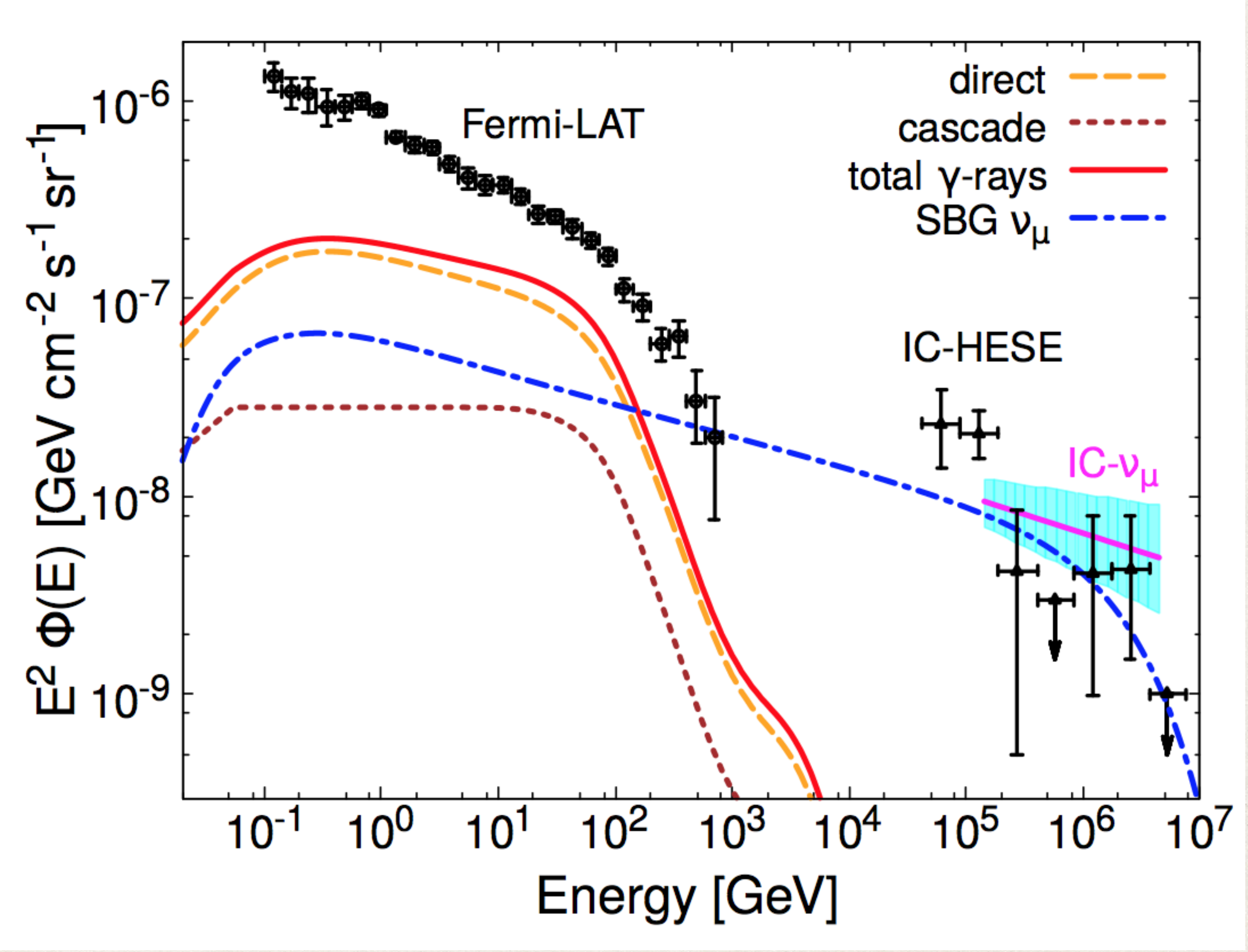
$$\Phi_{\gamma,\nu}(E) = \frac{1}{4\pi}\int d\Omega \int_0^{4.2} dz\, \frac{dV_C(z)}{dz\, d\Omega} \times \int_{\psi^*} d\log\psi\; \Phi_{\rm SFR}(\psi,z)\,[1+z]^2 f_{\gamma,\nu}(E[1+z],\psi).$$

SBNi contribtion to the diffuse fluxes

(Peretti, Blasi, Aharonian, GM, Cristofari arXiv:1911.06163)

Values tuned from M82

parameter	value
$p_{p,\max}$	10^2 PeV
α	4.2
R	0.25 kpc
D_L	3.9 Mpc
ξ_{CR}	0.1
$\mathcal{R}_{SN}$	0.06 yr^{-1}
B	200 μG
n_{ISM}	100 cm^{-3}
v_{wind}	700 km/s
U_{rad}	2500 eV/cm^3



Changing the maximum energy and slope

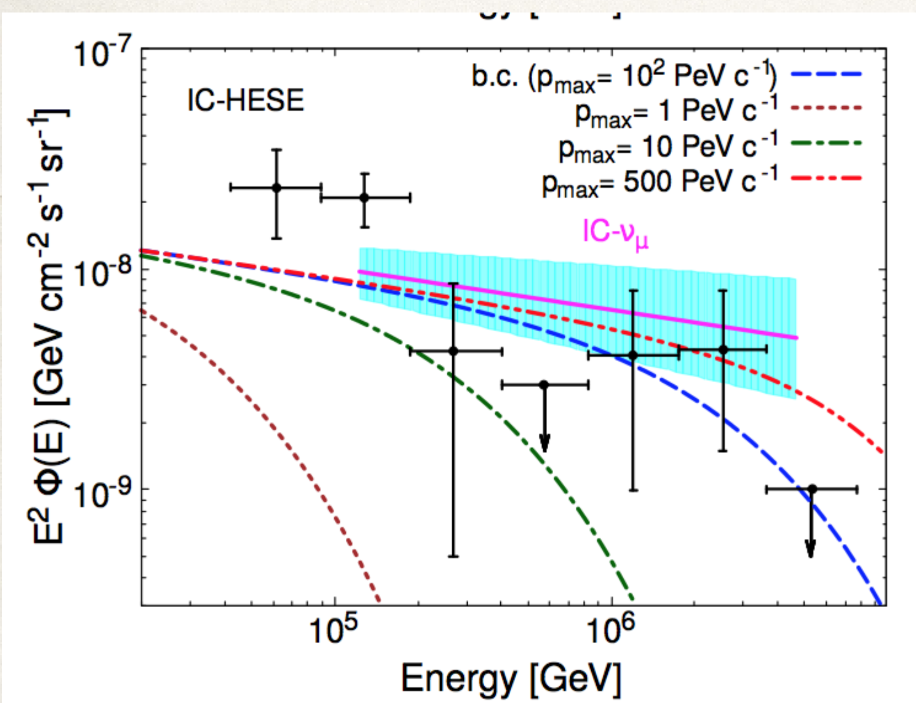
(Peretti, Blasi, Aharonian, GM, Cristofari   arXiv:1911.06163)

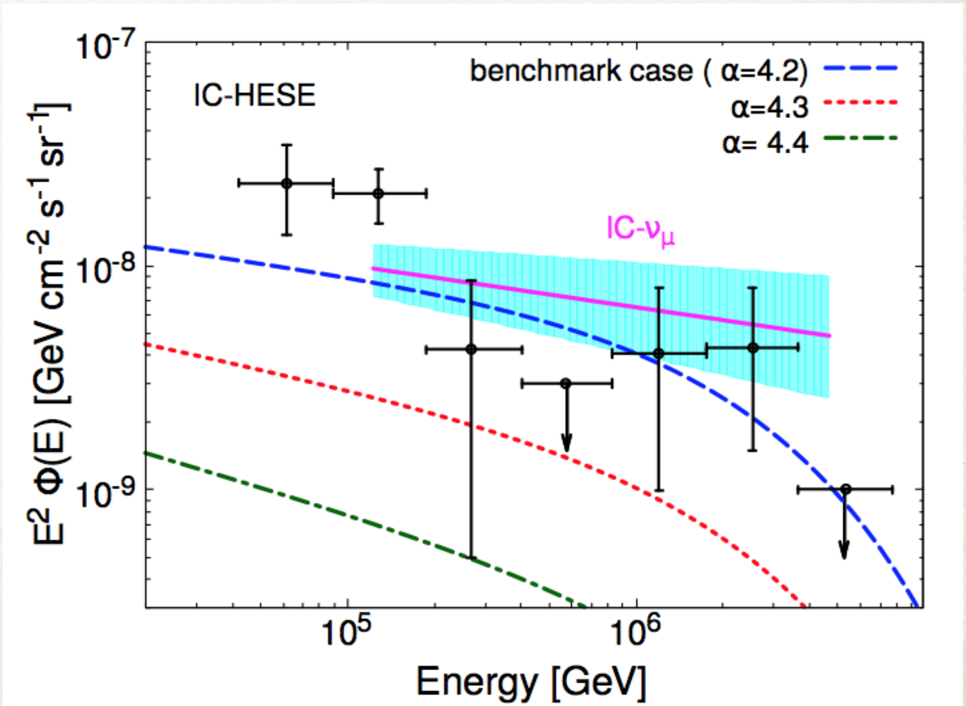
Maximum energy > 50 PeV are required.
How can be produced?

If the sources are SNR the physics should be similar to Milky Way SNR.

Possible role of turbulence?

Required hard slope ~2.2





Contribtion to EGB from normal galaxies

(Peretti, Blasi, Aharonian, GM, Cristofari   arXiv:1911.06163)

What about normal galaxies?

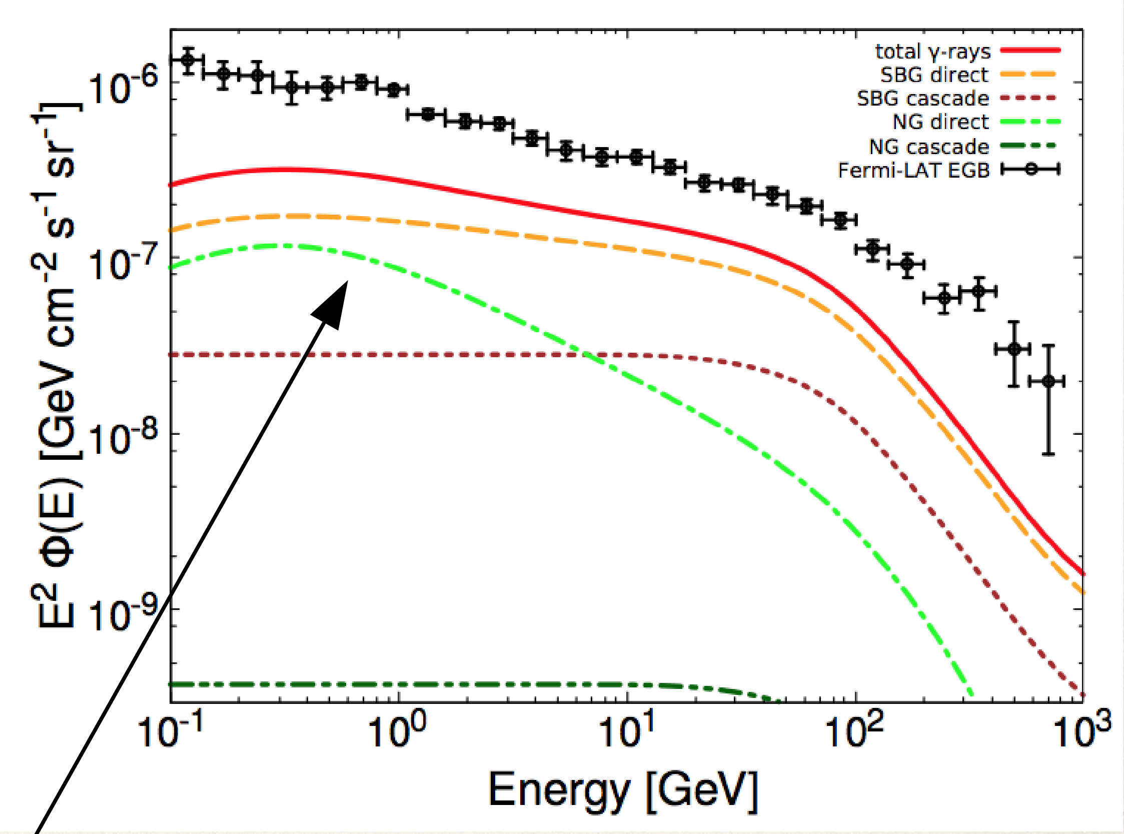
They aren't calorimeters

→ steeper slope $N(E) \sim E^{-2.7}$

Assuming that galaxies with

$$\psi < \tilde{\psi} \approx 1 \left(\frac{R}{250\ pc}\right)^2 \frac{M_{Sol}}{yr}$$

are all like the Milky Way



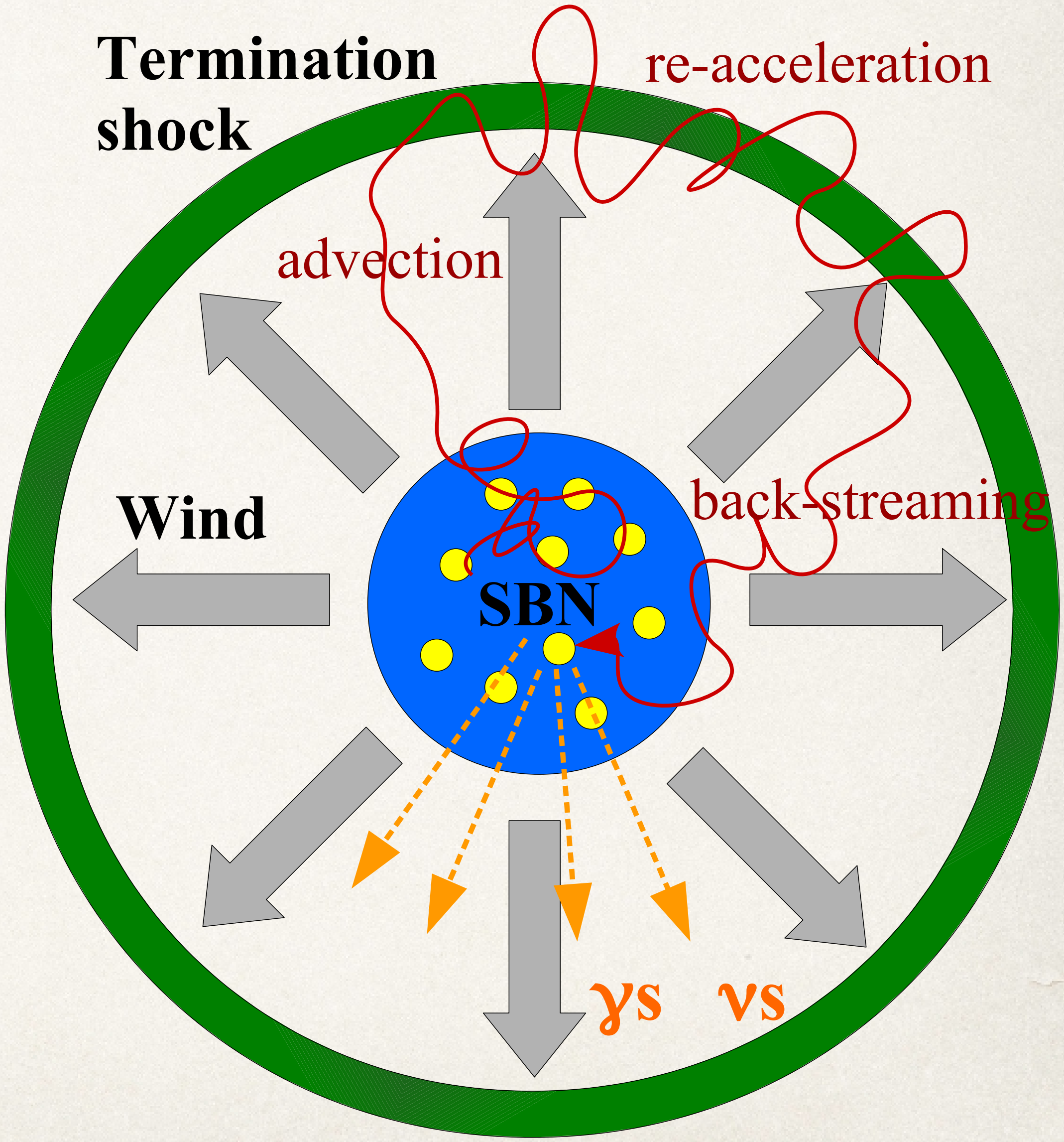
- Contribution to diffuse ν flux is negligible
- Contribution to diffuse γ-ray flux is negligible

Contribution to γ-rays and νs from the termination shock

(Peretti, GM, Blasi, *in preparation*)

- Particles advected away from the SBN can be reaccelerated by the wind termination shock
- Only highest energy partiles can counter stream back to the nucleus
- Hadronic interactions inside the nucleus will produce only high energy neutrinos

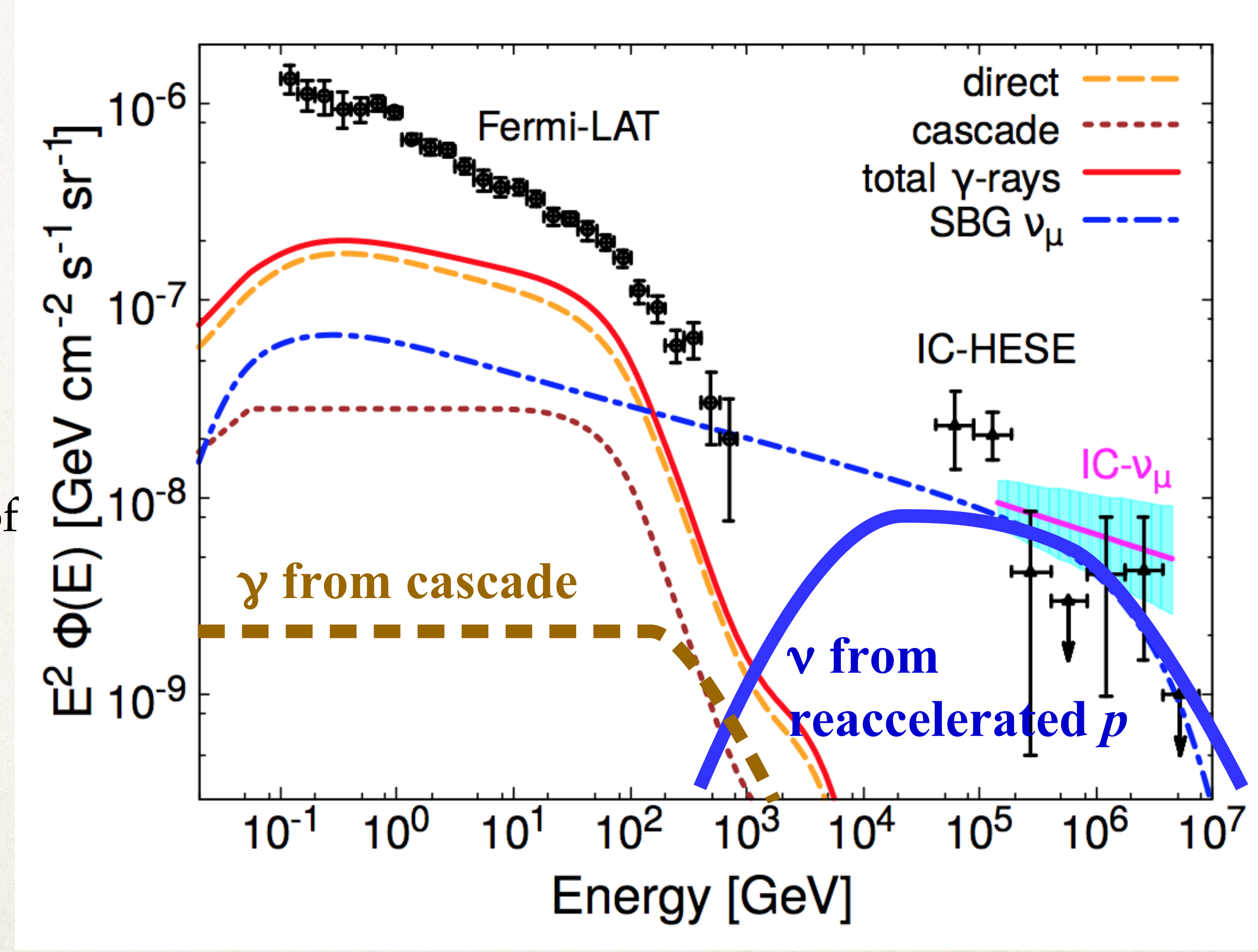
Low energy γ-rays will not be produced!!!



Contribution to γ-rays and νs from the termination shock

(Peretti, GM, Blasi, *in preparation*)

- Reaccelerated CR can explain the highest neutrino flux
- Expected spectrum $\sim E^{-2} - E^{-2.2}$
- γ-rays @ 50 TeV absent
- Negligible contribution of γ from e.m cascade



Conclusions

Contribution to astrophysical neutrino flux

- **Galactic disk** may contribute $< 20\%$
  - Possible contribution from Galactic large scale halo?
- **AGNs** may contribute $< 30\%$ for 10 TeV $< E <$ 2 PeV (lack of correlation)
  [Aartsen et al. (IceCube), Astrophys. J. 835, 45 (2017)]
  - Contribution from non resolved Blazars?
    Requires rapid positive evolution $(1+z)^5$ [Neronov & Semikoz (2018)]
- **Starburst galaxies** may explain the majority of neutrino flux > 200 TeV
  - Marginally compatible with the EGB
  - Still unclear if E_{max} ~ 100 PeV may be obtained

↓

Reacceleration of CR from SB-wind termination shock may resolve both issues.