GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

# Cosmic ray transport in Starburst galaxies and possible observables

## PoS (ICRC 2019) 382

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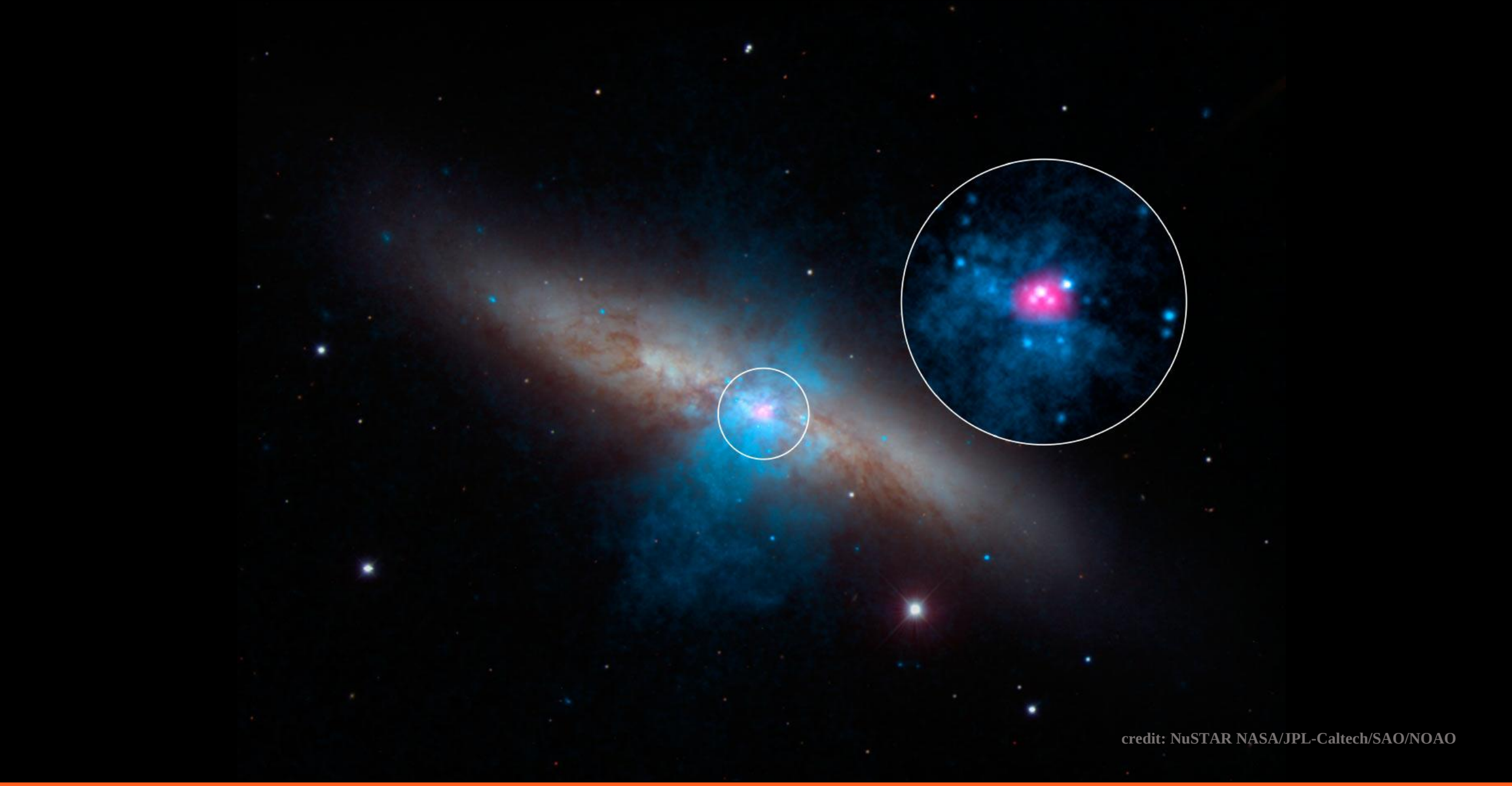
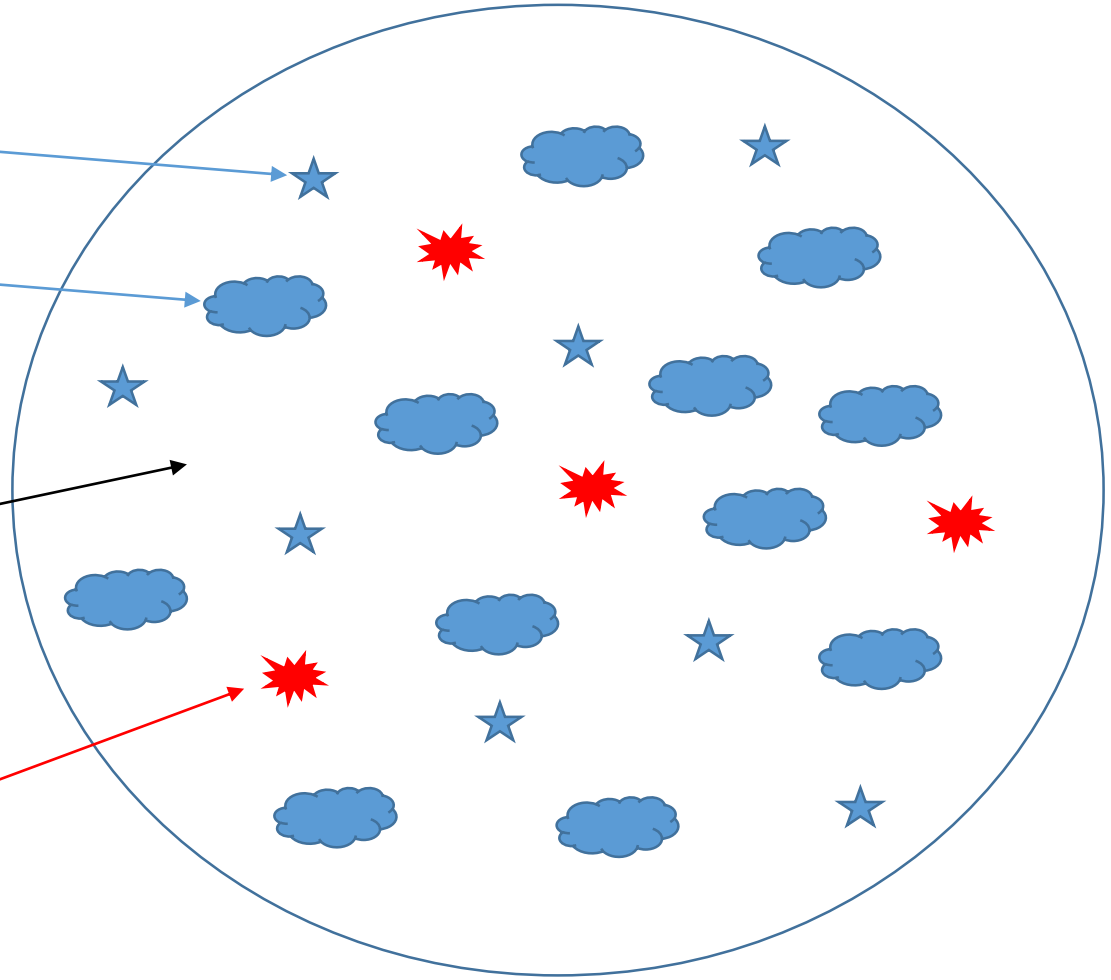
# Outline

- Cosmic ray transport in starburst nuclei (SBNi)
- Are SBNi cosmic ray calorimeters?
- Hard X-rays as hadronic marker
- Starburst contribution to the diffuse neutrino flux

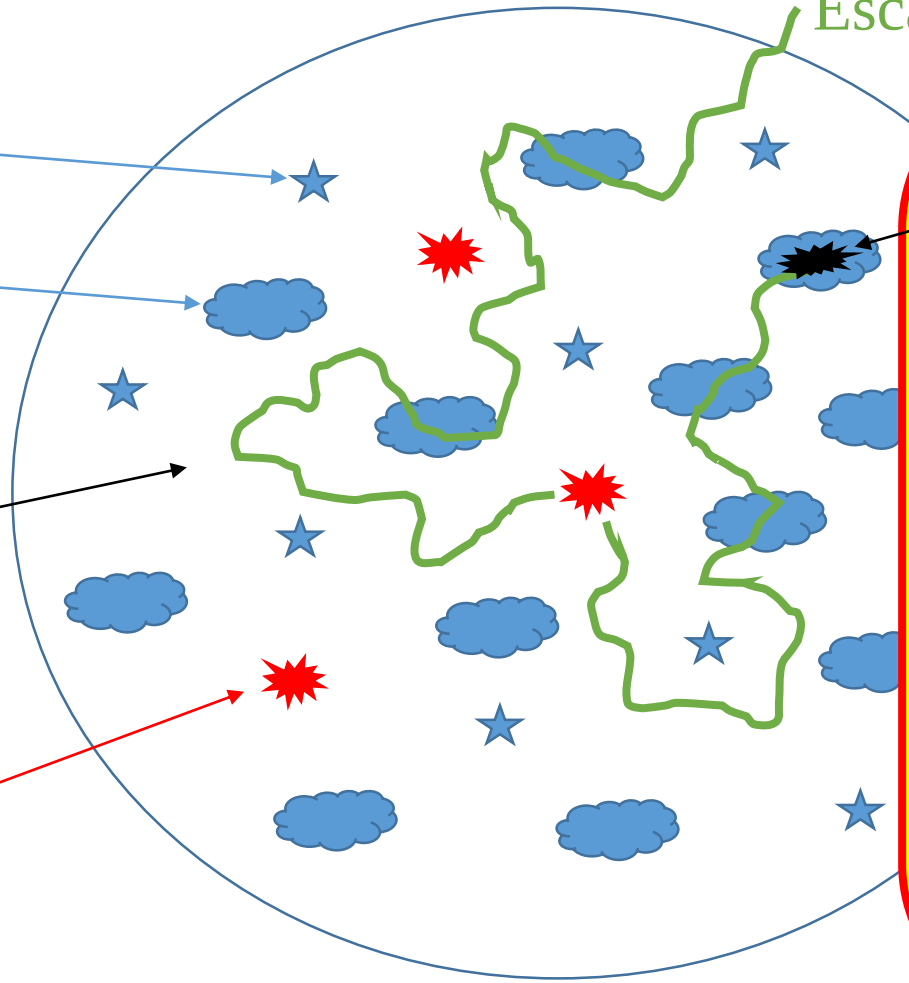

credit: NuSTAR NASA/JPL-Caltech/SAO/NOAO

# CR transport in SBNi




- Star formation and supernovae lead the launch of a powerful wind
- SB medium is expected to be highly turbulent
- Strong magnetic field is inferred (B $\gtrsim 10^2\ \mu G$)
- Intense IR and OPT thermal photon fields ($U_{rad} \approx 10^3 eV cm^{-3}$)

# CR transport in SBNi




pp interaction

$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^-$$

$$\pi^\pm \rightarrow e^\pm + \bar{\nu}_\mu + \nu_\mu + \nu_e(\bar{\nu}_e)$$

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

$$\gamma_{VHE} + \gamma_{BKG} \rightarrow e^+ + e^-$$

# CR transport in SBNi

Particles are injected by supernovae

$$Q_p(p) = \frac{\mathcal{R}_{SN}\aleph_{SN}(p)}{V} \propto \frac{\mathcal{R}_{SN}}{V}\left(\frac{p}{mc}\right)^{-\alpha} e^{-p/p_{p,max}}$$

The particle injection is balanced by losses and escape

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

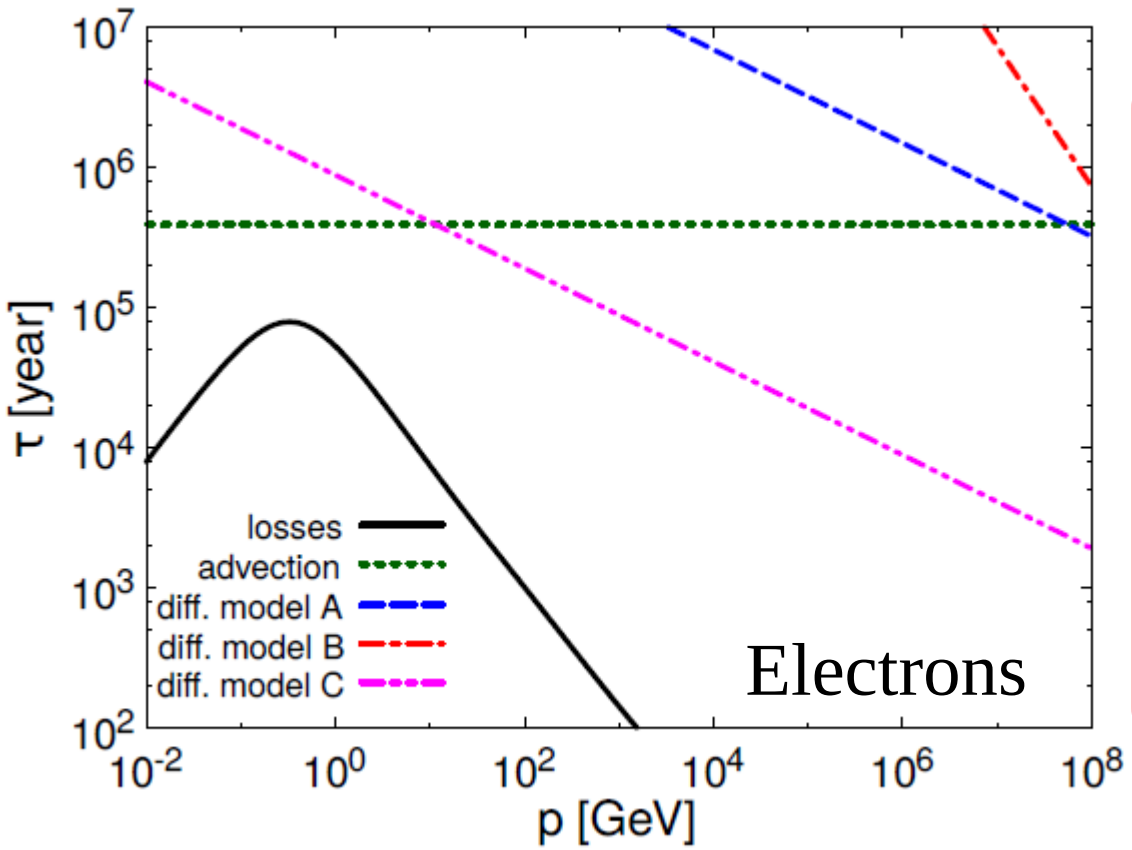
# CR transport in SBNi

$$\tau_{loss}(p) = \left\{\sum_j \left[\frac{1}{E}\left(\frac{dE}{dt}\right)_j\right]\right\}^{-1} \qquad \tau_{adv} = R/v_{wind} \qquad \tau_{diff}(p) = R^2/D(p)$$

The particle injection is balanced by losses and escape

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

# Are SBNi CR calorimeters?




$$D(p) = r_L(p)v(p)/3\mathcal{F}(k)$$

$$\int_{k_0}^{\infty} dk\ \mathcal{F}(k)/k = \eta_B$$

$$k_0^{-1} = L_0 = 1\ pc$$

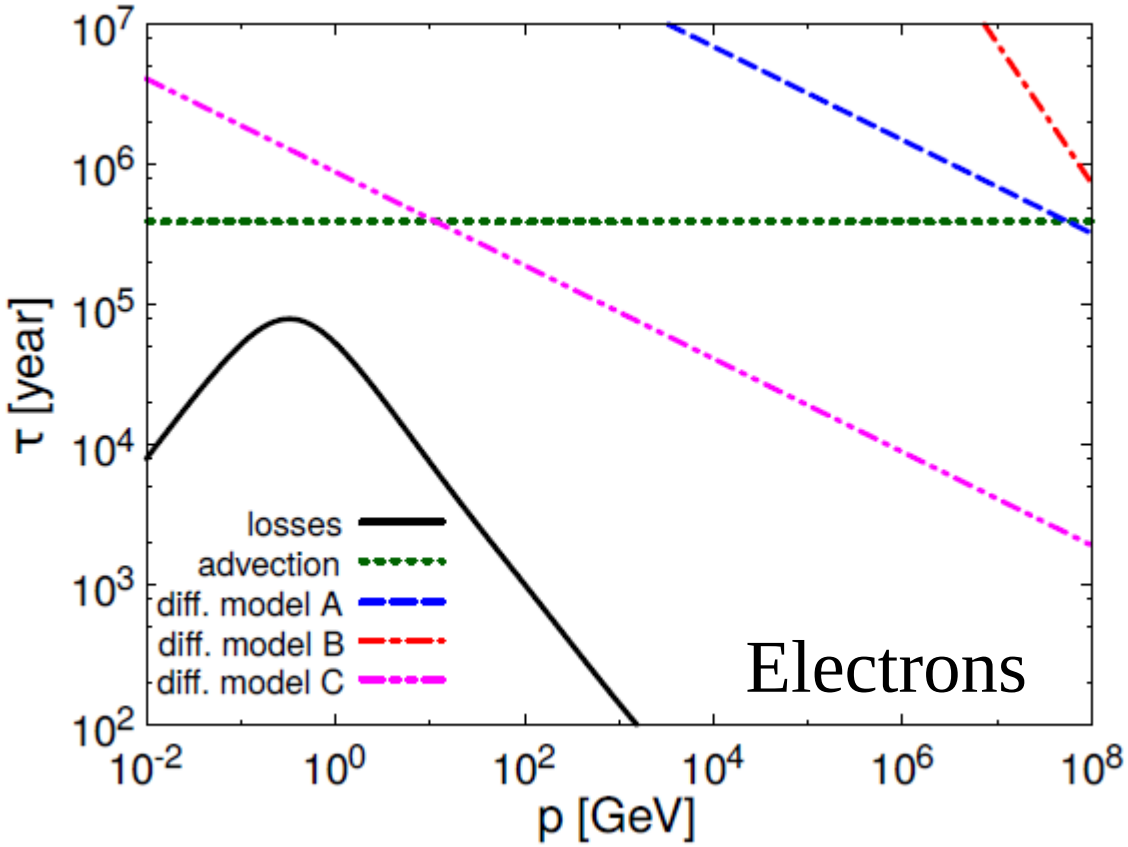
$A)\ \mathcal{F}(k) \propto k^{-2/3}$ - $\eta_B \approx 1$

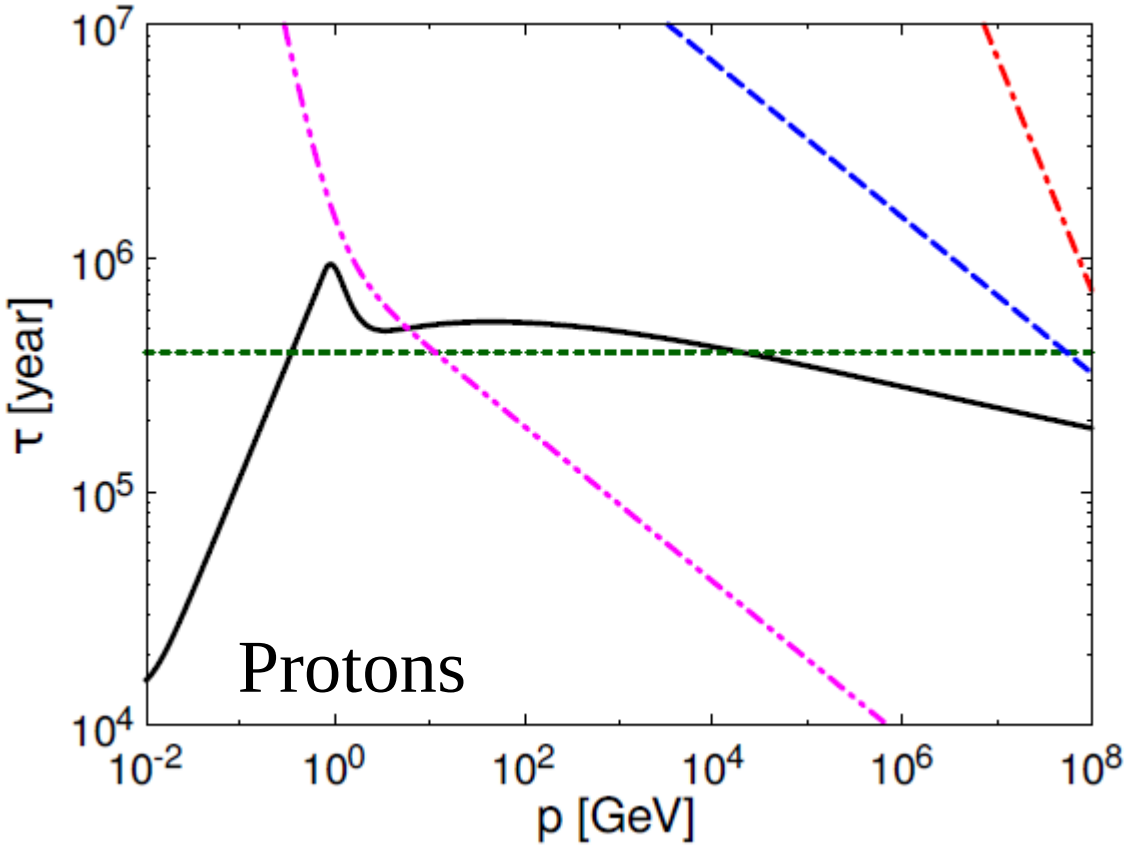
$B)\ \mathcal{F}(k) = 1$

$C)\ \mathcal{F}(k) \propto k^{-2/3}$ - $\eta_B \ll 1$

| $D_L$(Mpc) | $\mathscr{R}_{SN}(yr^{-1})$ | $R(pc)$ | $\alpha$ | $B(\mu G)$ | $v_{wind}(\frac{km}{s})$ | $n_{ISM}(cm^{-3})$ | $U_{RAD}(\frac{eV}{cm^3})$ |
|---|---|---|---|---|---|---|---|
| 3.8 | 0.05 | 200 | 4.25 | 200 | 500 | 125 | 3400 |

# Are SBNi CR calorimeters?

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|---|---|---|---|---|---|---|---|
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# Are SBNi CR calorimeters?

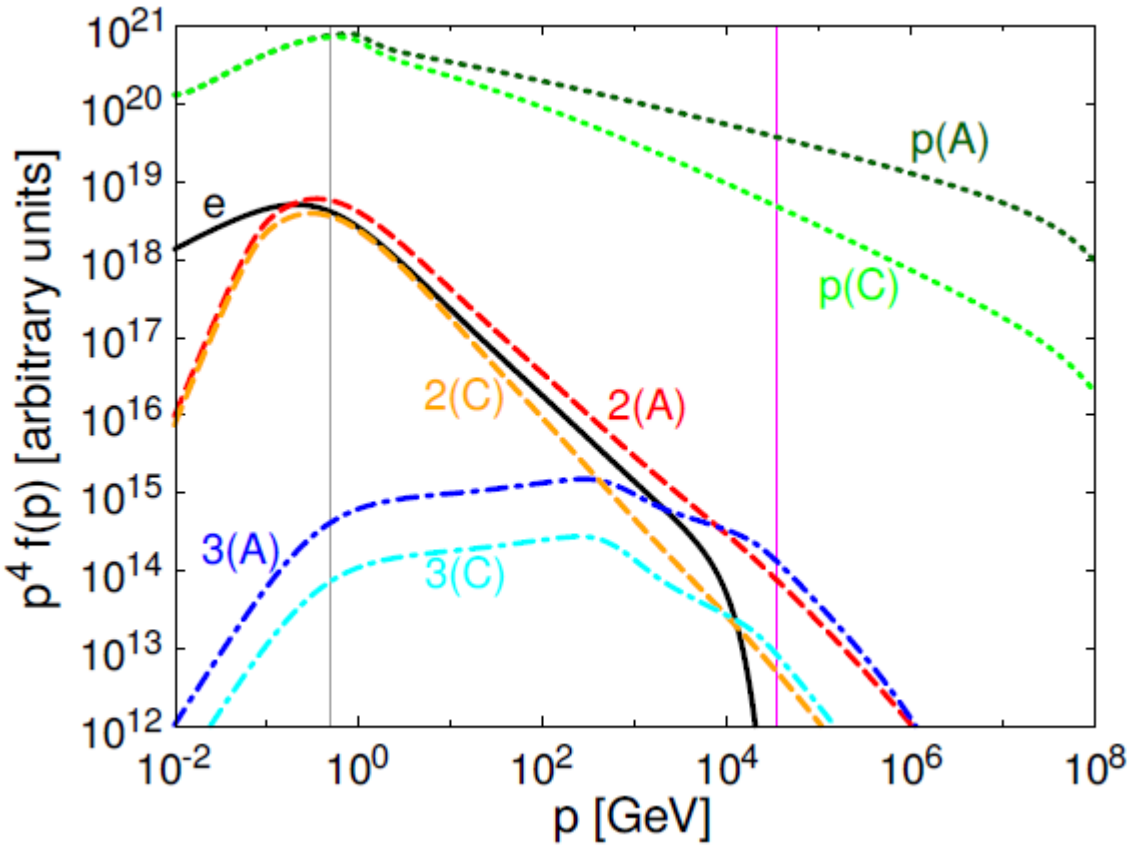
1. Electrons are likely well confined in starburst environment

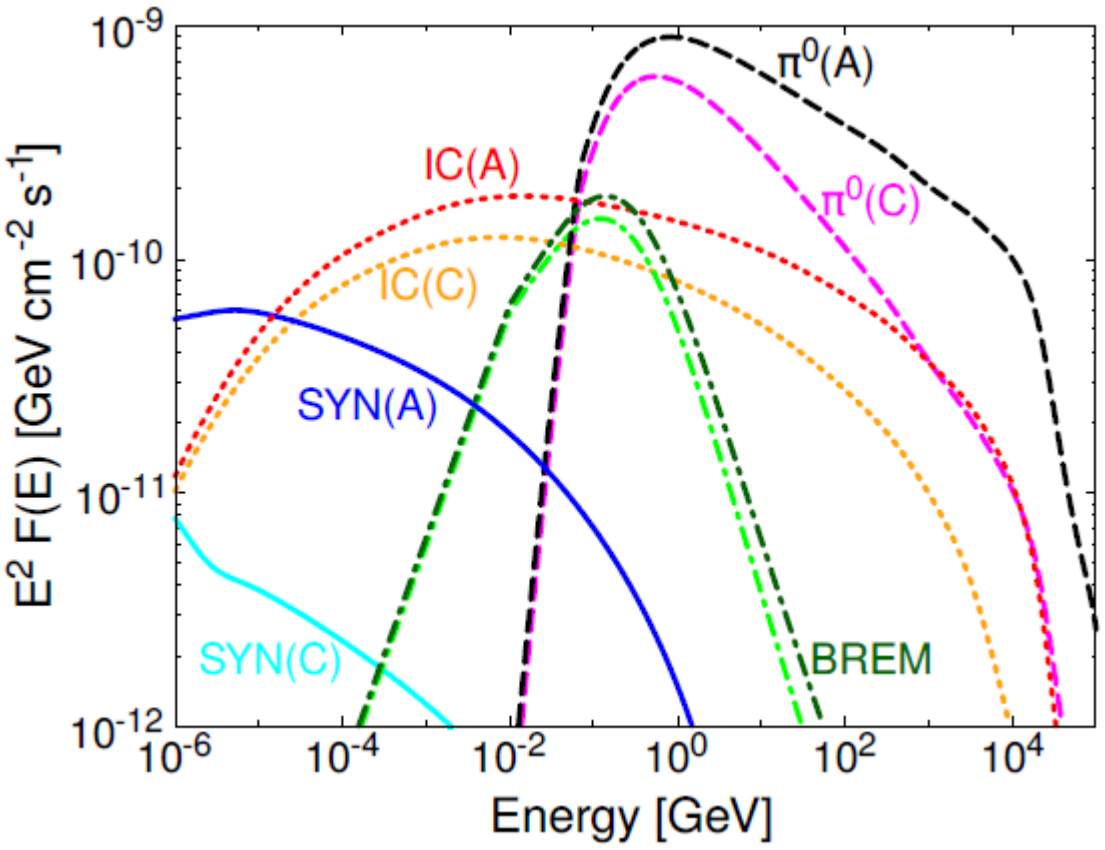
2. Proton calorimetry is not guaranteed but

   - High level of turbulence
   - High ISM density

   suggest that diffusion escape might be negligible and energy losses can compete with the advection

# Hard X-rays as hadronic marker



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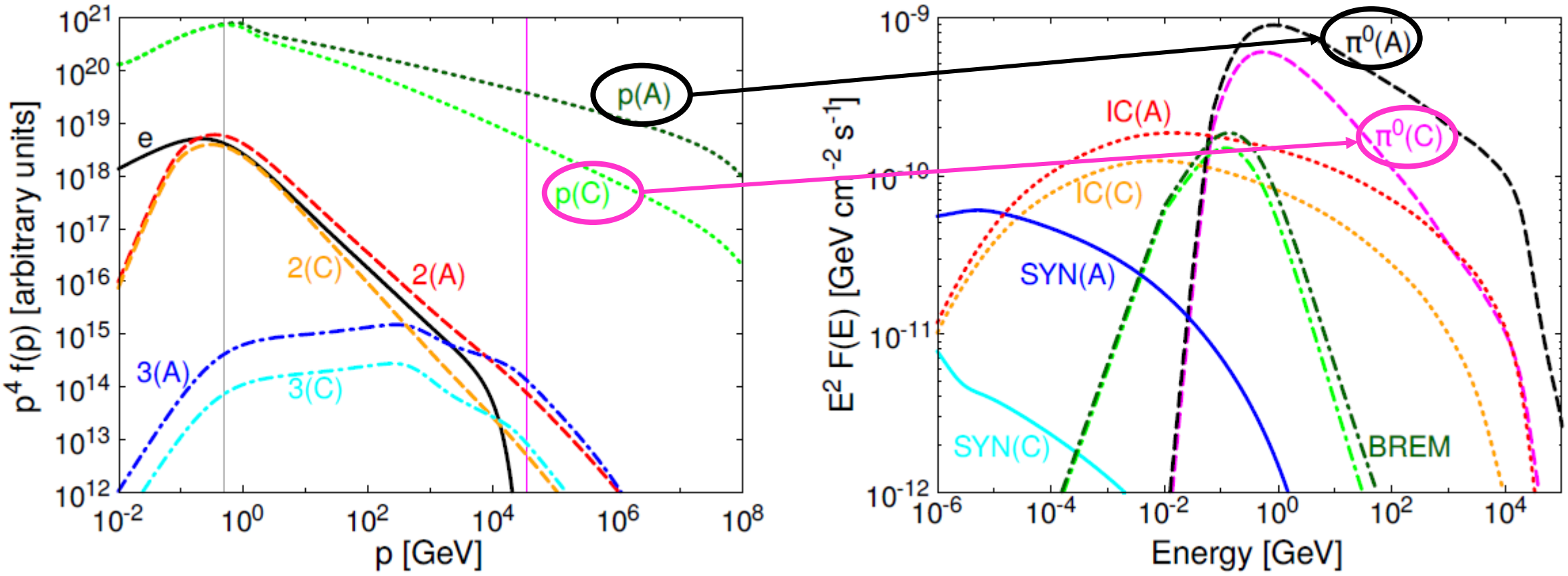
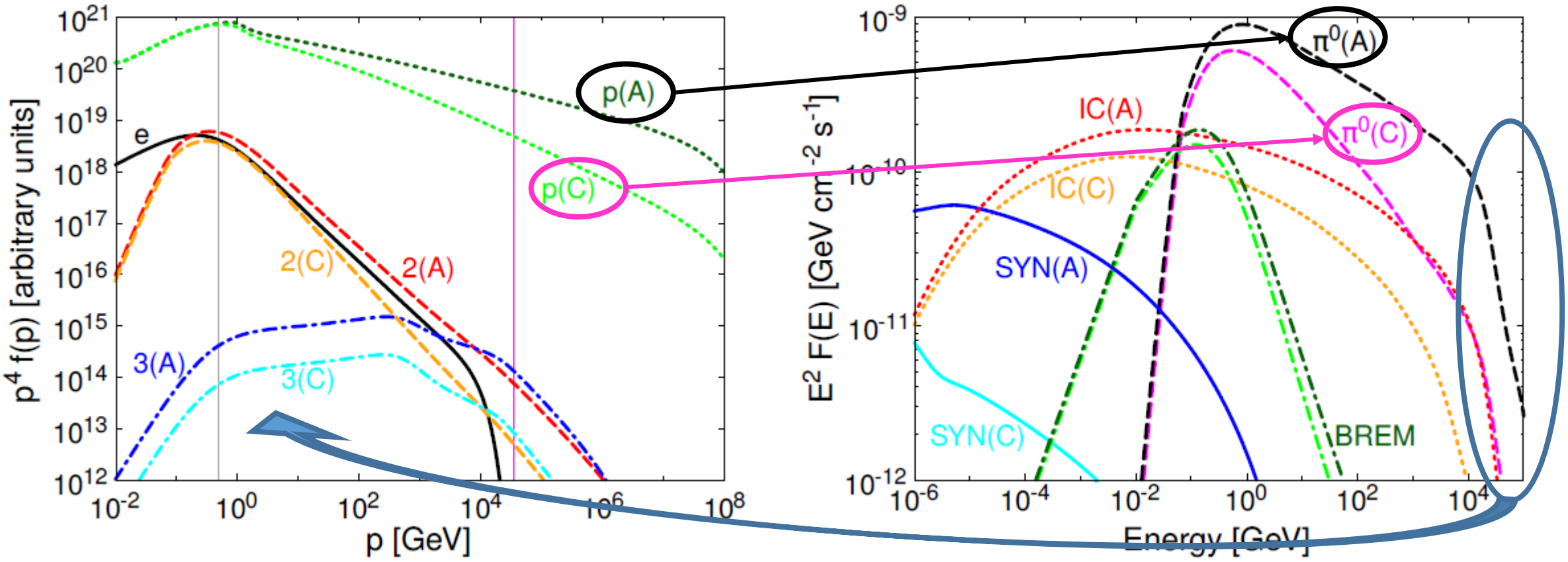


# Hard X-rays as hadronic marker



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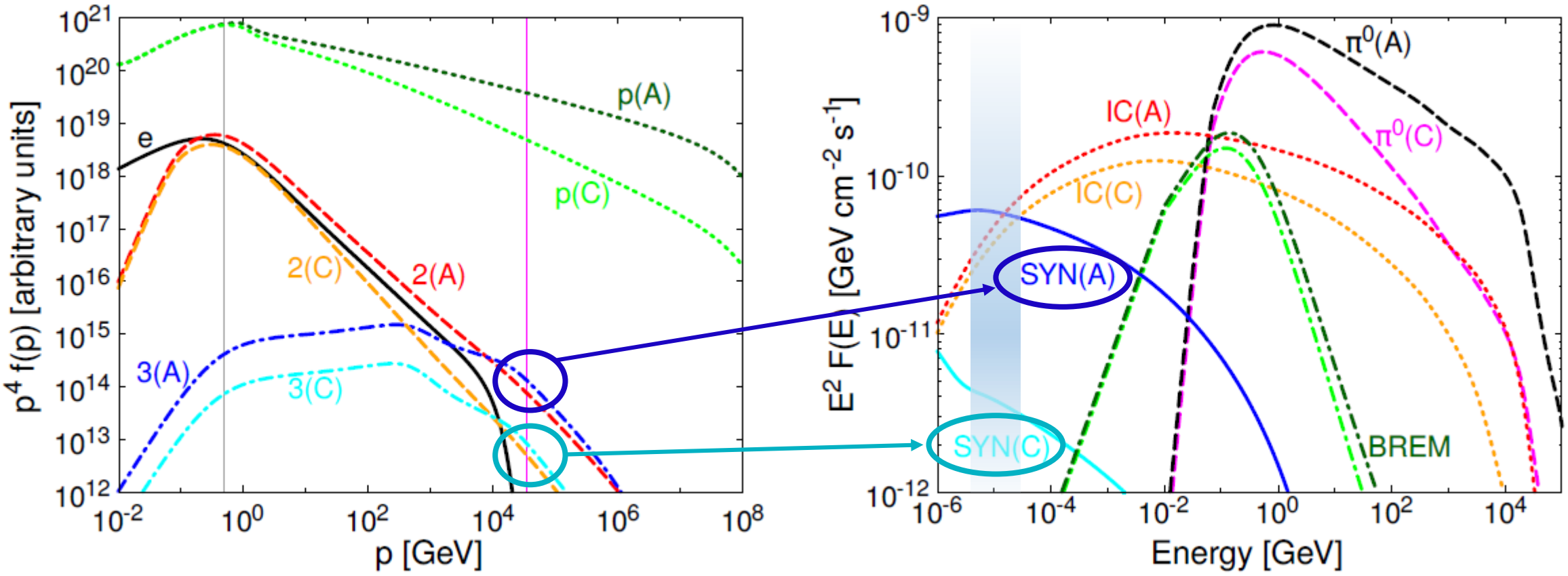


# Take home message 1

The combined observation of

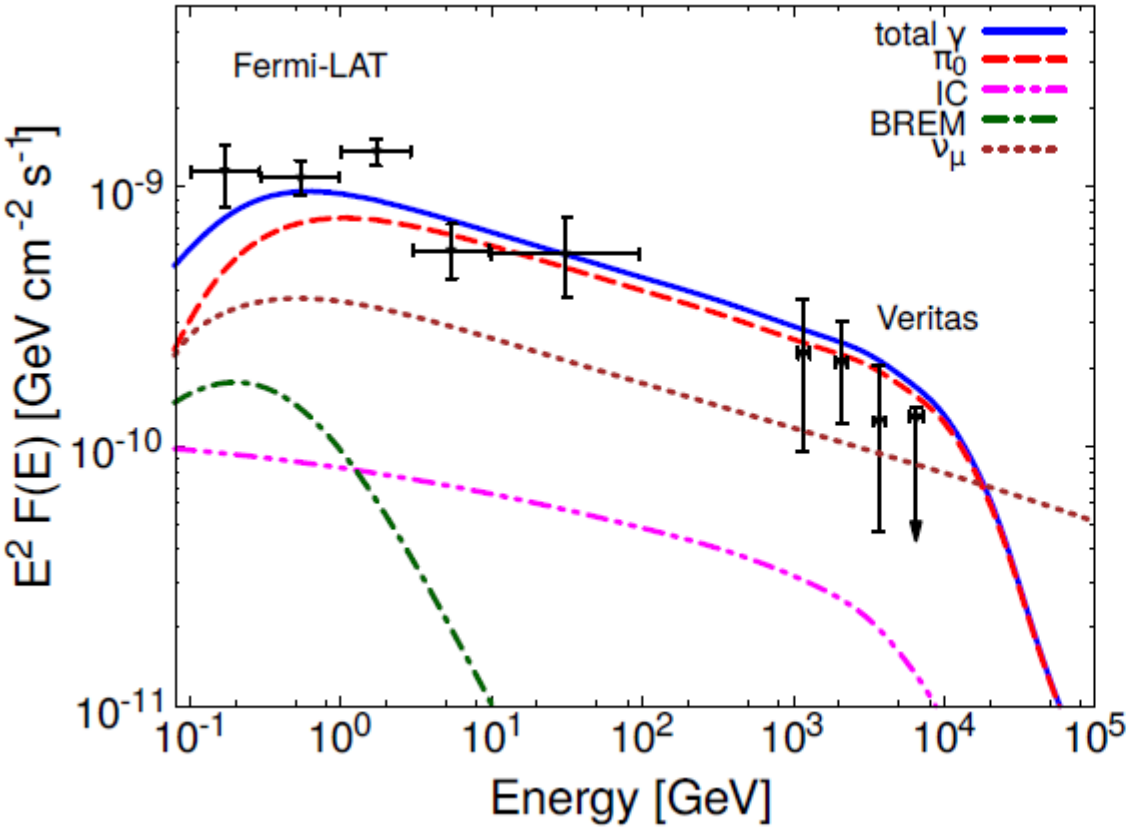
1. Hard gamma-ray spectrum
2. Enhanced and softer hard X-ray flux

would support CR calorimetry

# Starburst contribution in the diffuse neutrino flux

- Starburst are promisingly close to be hadronic calorimeters
- Gamma rays at VHE are partially absorbed and reprocessed in X-rays
- Neutrino flux from a single SBN is currently too faint to be detected but the star formation history of the Universe suggests that starburst galaxies are much more numerous at $1<z<2$

# Starburst contribution to the diffuse neutrino flux

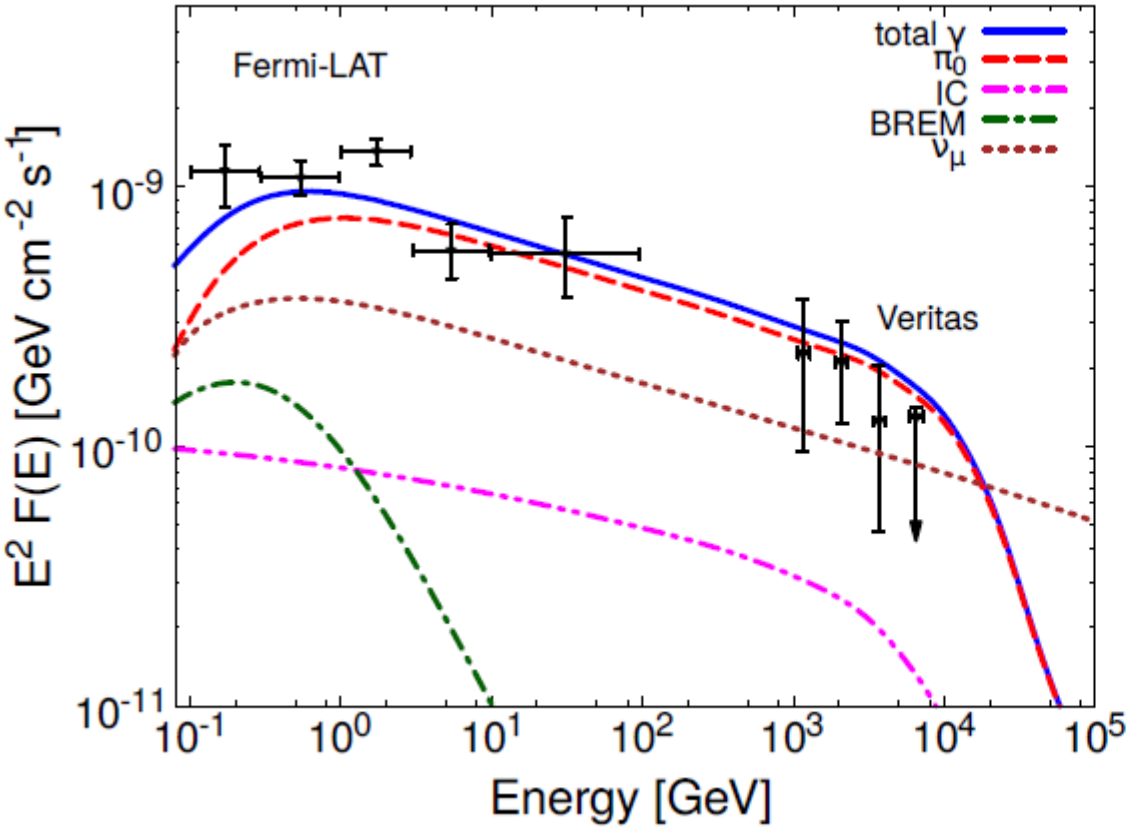


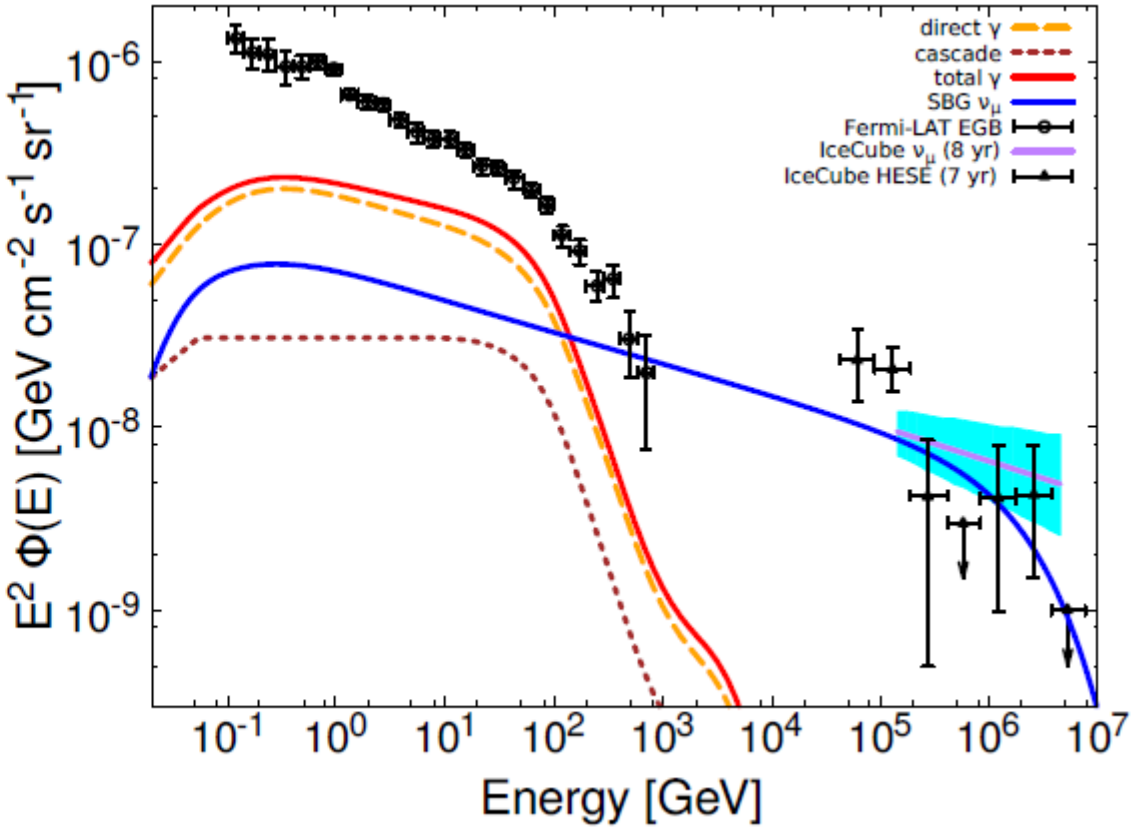

$$\Phi(\psi,z)\,d\log\psi = \tilde{\Phi}\left(\frac{\psi}{\tilde{\psi}}\right)^{1-\tilde{\alpha}} \exp\left[-\frac{1}{2\tilde{\sigma}^2}\log^2\left(1+\frac{\psi}{\tilde{\psi}}\right)\right] d\log\psi$$

$$q_{\gamma,\nu}^{\mathrm{SBN}}(E,\psi) = \left(\frac{\psi}{\psi_{\mathrm{M82}}}\right) q_{\gamma,\nu}^{M82}(E)$$

$$\Phi_{\gamma,\nu}(E) = \frac{1}{4\pi}\int_0^{4.2} dz\,\frac{dV_{\mathrm{C}}}{dz}\int_{\psi_{\mathrm{min}}} d\log\psi\,\Phi_{\mathrm{SFR}}(\psi,z)\,[1+z]^2 f_{\gamma,\nu}(E[1+z],\psi)$$

# Starburst contribution to the diffuse neutrino flux




- Main constraint: Blazar contamination to the > 50 GeV flux
- Internal absorption of gamma rays lower the energy content of the EM cascade

# Take home message 2

- Sensitivity of current neutrino observatories is unlikely to be enough for a direct detection of a nearby SBN

- The high number density of starbursts expected at $1<z<2$ could provide a diffuse flux that can be the leading contribute to current IceCube observations > 200 TeV

# Conclusions

- The environment of starburst nuclei is promising for hadronic confinement
- The combined observation of hard gamma-ray spectra and enhanced hard X-ray flux would strongly support calorimetry
- Good confinement conditions can allow starbursts to explain the diffuse neutrino flux observed by IceCube >200 TeV

# Thanks for your attention!

# References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# Back up slides

# Secondaries & tertiaries 1

Estimate of pp secondaries:

$$q_{sec,e}(p) \approx 2\frac{n\sigma_{pp}c}{\kappa^3} f_p(p/\kappa) = 2\eta\kappa^{\alpha-3} q_p(p)$$

Where $\eta = \tau_{p,life}/(n\sigma_{pp}c)^{-1}$, and $\kappa$ is the inelasticity

Estimate of tertiaries:

$$q_{ter,e}(p) \approx \frac{(R/c)n\sigma_{pp}c\, f_p(pc/\tilde{\kappa})}{\tilde{\kappa}} \frac{\tau_{\gamma\gamma}(pc)c^2}{4\pi p^2 R} = \tau_{\gamma\gamma}(pc)\eta\tilde{\kappa}^{\alpha-3} q_p(p)$$

# Secondaries & tertiaries 2

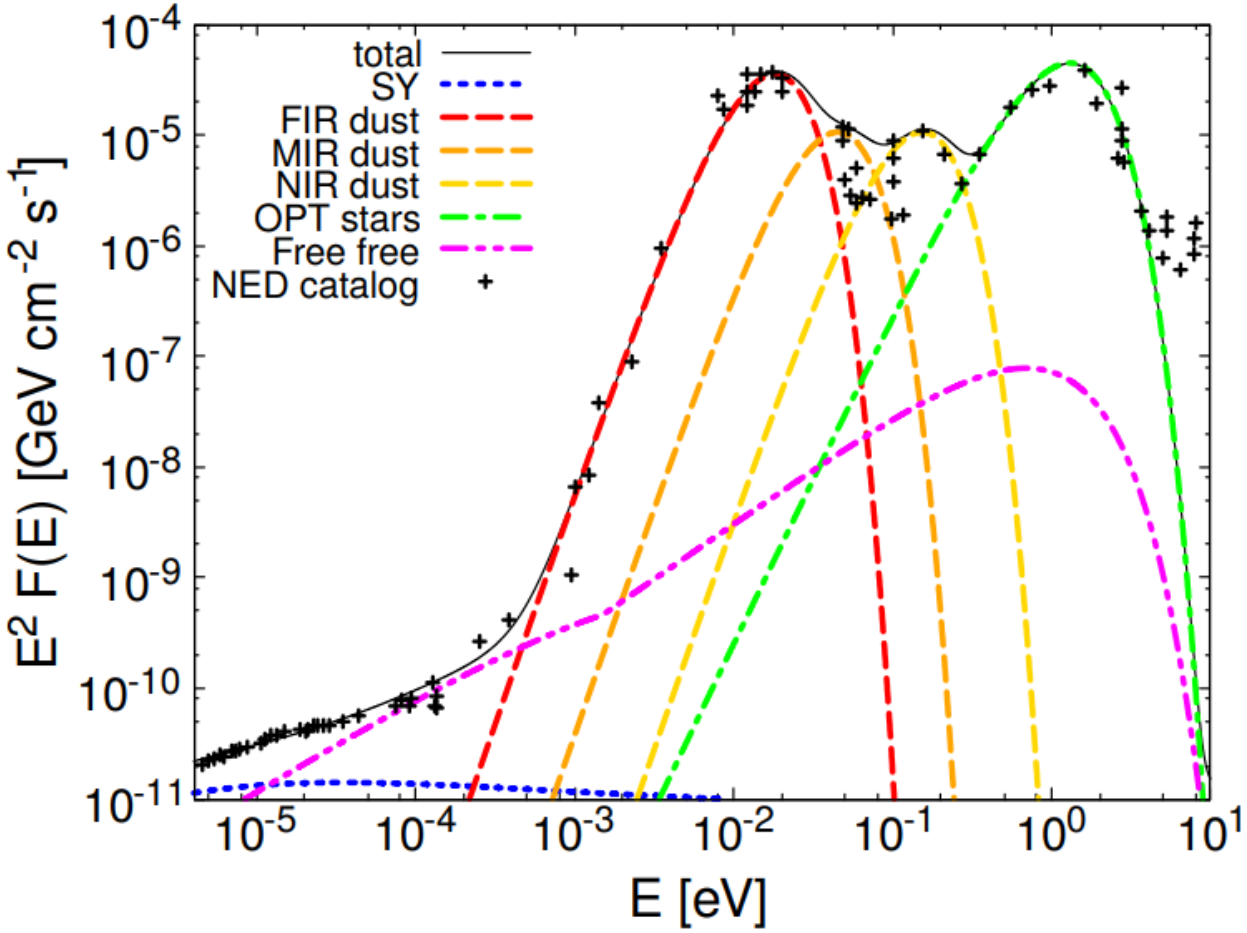
Secondaries-to-primaries ratio:

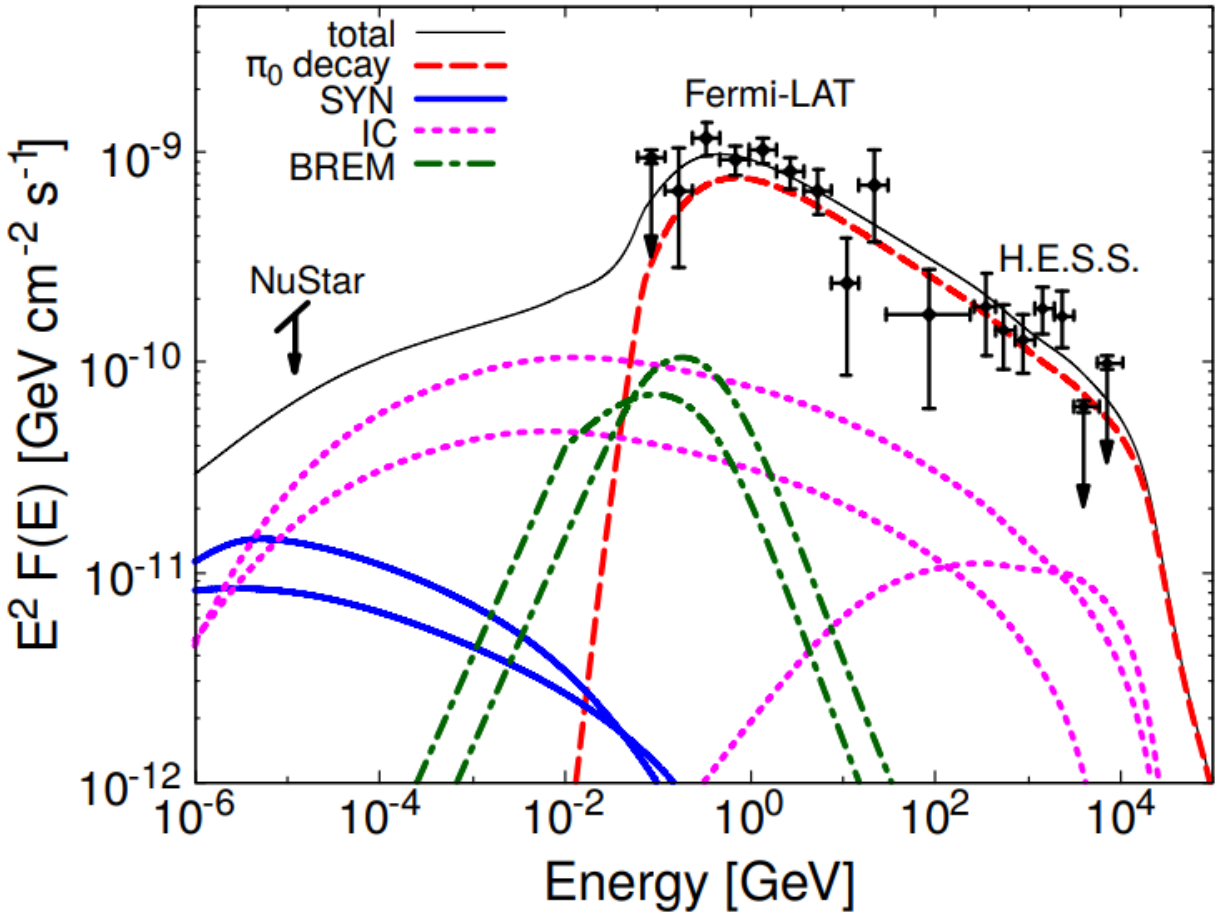
$$q_{sec,e}(p)/q_e(p) \approx 10^2 \eta \kappa^{\alpha-3}$$

Tertiaries-to-secondaries ratio:

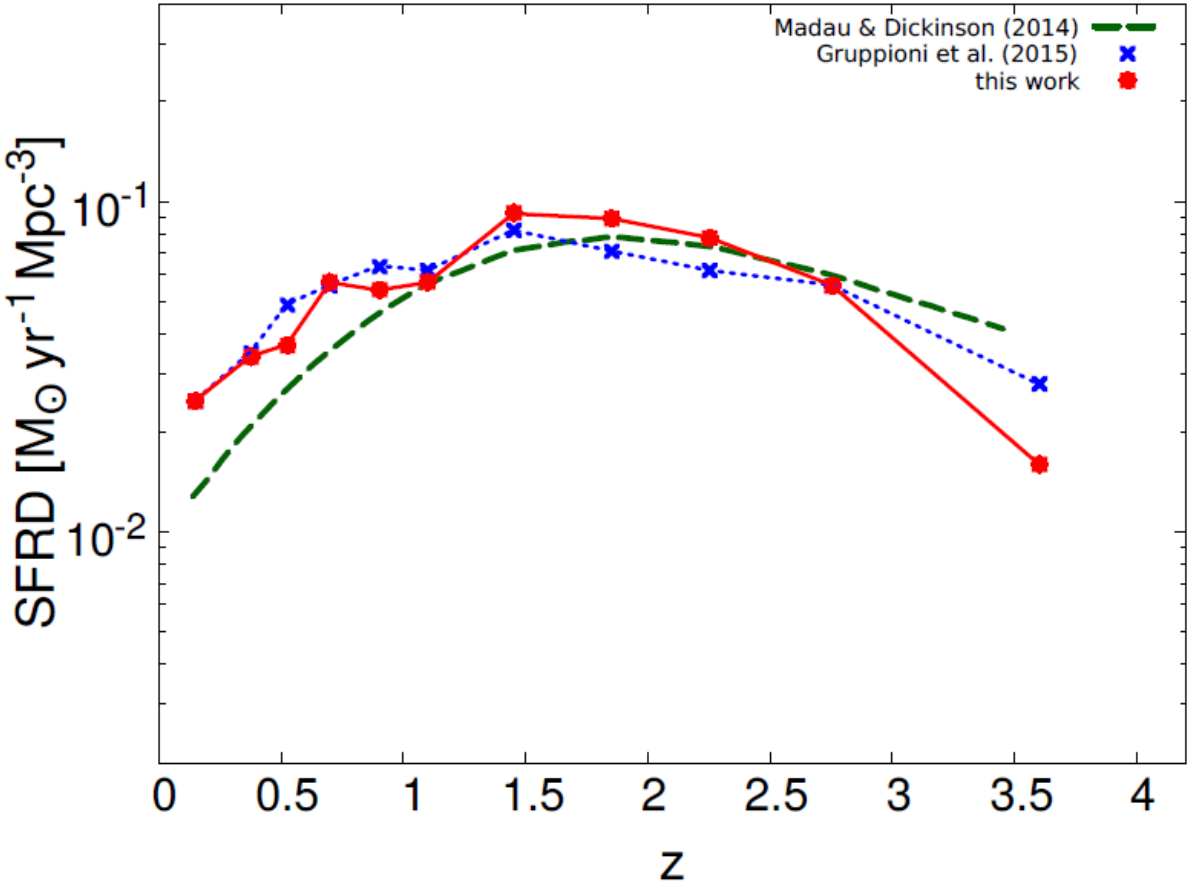
$$q_{ter,e}(p)/q_{sec,e}(p) \approx \tau_{\gamma\gamma}(pc)(\tilde{\kappa}/\kappa)^{\alpha-3}/2$$

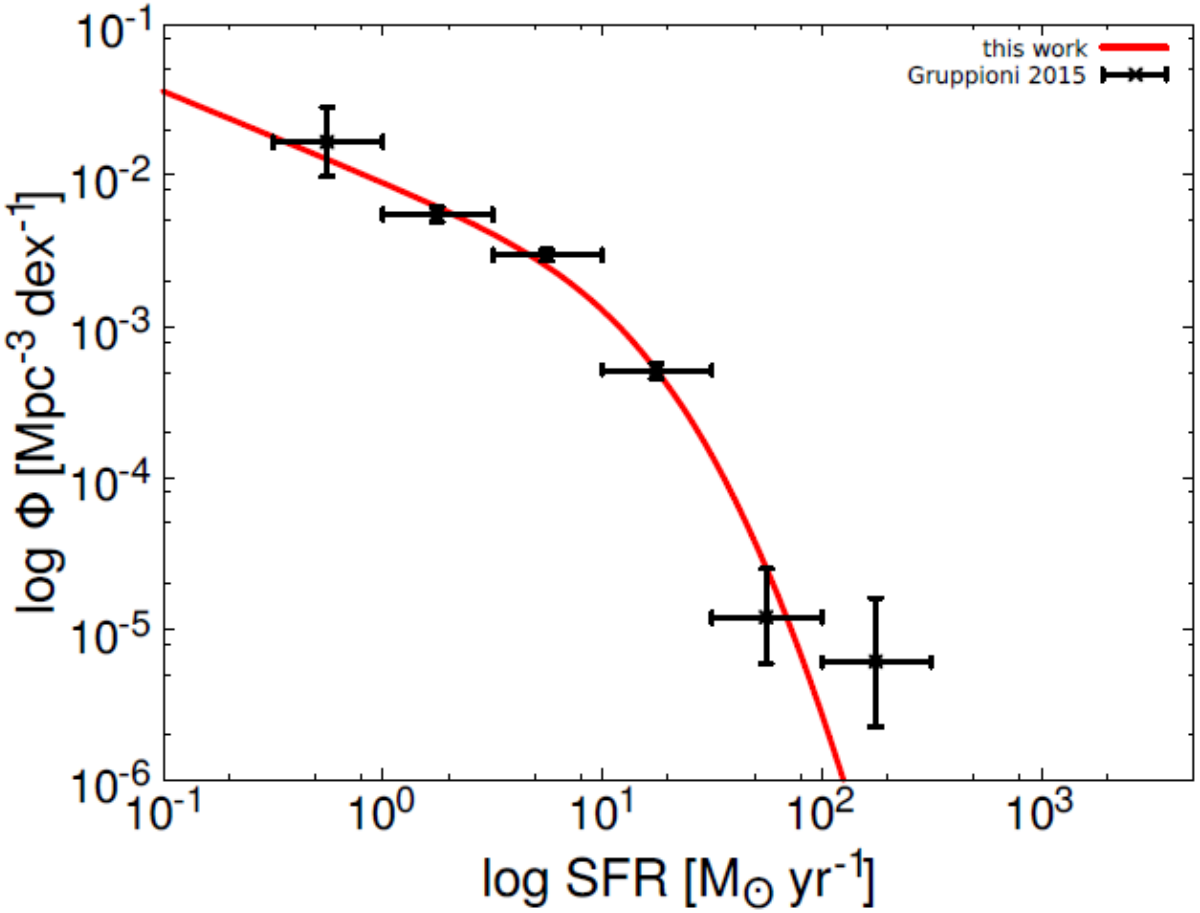
# The case of NGC 253



# SFRD & SFRF


Madau & Dickinson (2014)
Gruppioni et al. (2015)
this work
SFRD [M⊙ yr-1 Mpc-3]
10-1
10-2
0
0.5
1
1.5
2
2.5
3
3.5
4
z


this work
Gruppioni 2015
log Φ [Mpc-3 dex-1]
10-1
10-2
10-3
10-4
10-5
10-6
10-1
100
101
102
103
log SFR [M⊙ yr-1]

# Idea beyond the diffuse flux 1

Calorimetric assumption for SB:

$$\tau_{loss} \leq \tau_{adv} \rightarrow (n\sigma c\xi)^{-1} \leq R/v_{wind}$$

$$\Sigma_{gas} \approx nR \leq v_{wind}(\sigma c\xi)^{-1}$$

According to Kennicutt relation

$$\frac{\Sigma_{SFR}}{M_{\odot} yr^{-1} kpc^{-2}} \approx 2.5\ 10^{-4} \left(\frac{\Sigma_{gas}}{M_{\odot} pc^{-2}}\right)^{1.4}$$

The SFR is obtained as: $\psi = \pi R^2 \Sigma_{SFR}$

# Idea beyond the diffuse flux 2

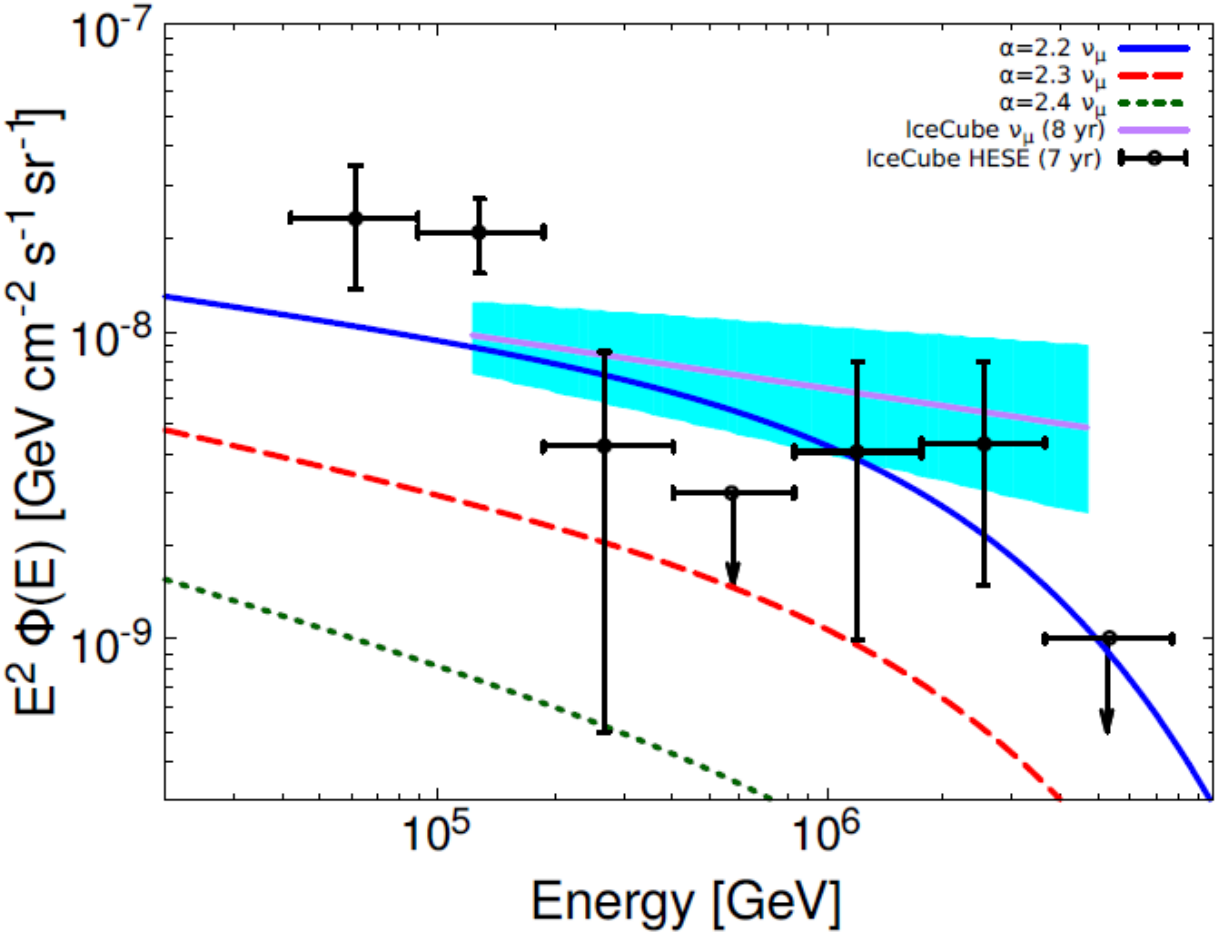
Calorimetric assumption for SB is well motivated because

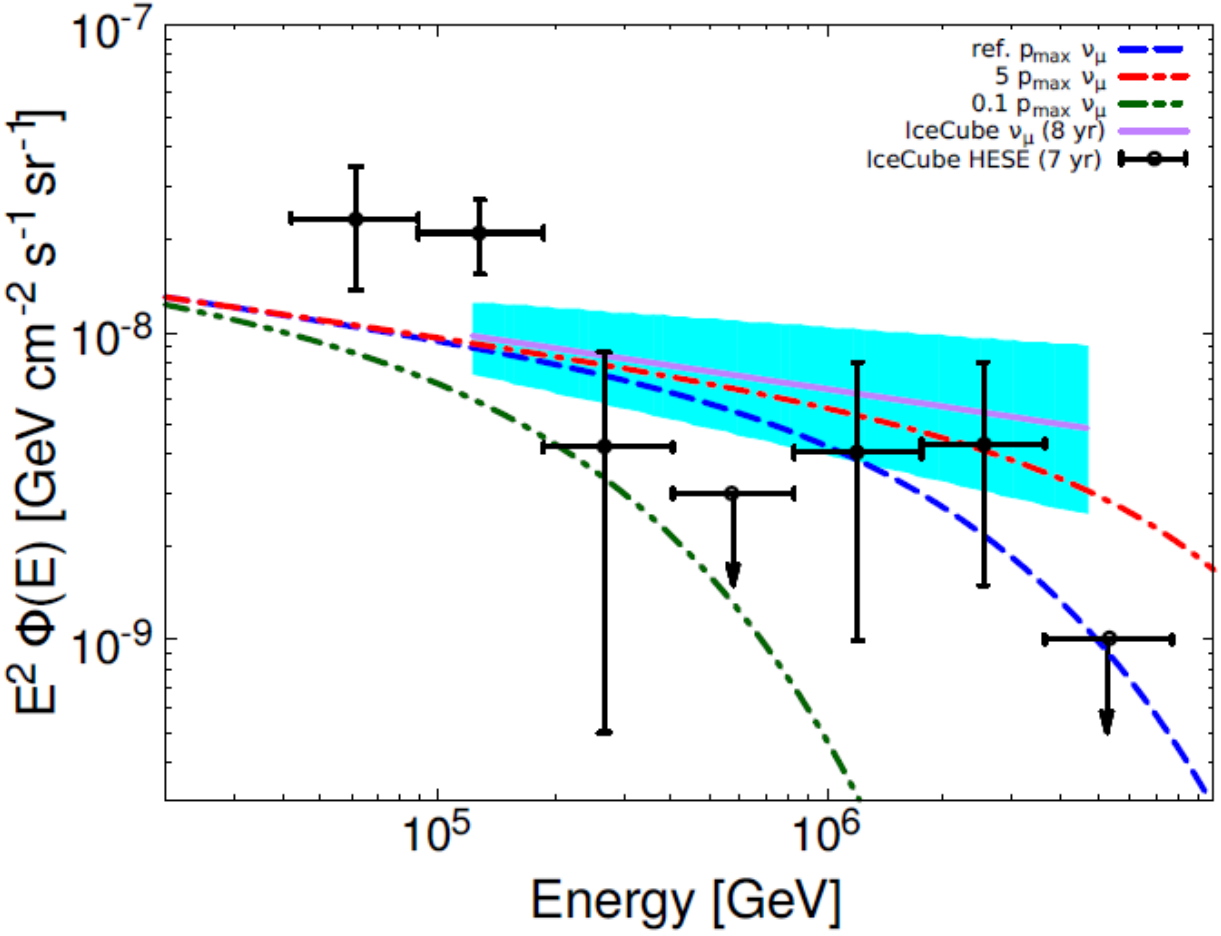
$$q_{\gamma,\nu}(E) \approx \frac{n\sigma c}{\kappa} f_p(E/\kappa) \propto n\sigma c\, q_p(E/\kappa) \begin{cases} \tau_{loss} & \tau_{loss} \ll \tau_{adv} \\ \tau_{adv} & \tau_{adv} \ll \tau_{loss} \end{cases}$$

$$q_{\gamma,\nu}(E) \propto n\sigma c\, q_p(E/\kappa) \begin{cases} (n\sigma c/\kappa)^{-1} & \tau_{loss} \ll \tau_{adv} \\ R/v_{wind} & \tau_{adv} \ll \tau_{loss} \end{cases}$$

$$q_{\gamma,\nu}(E) \propto q_p\,(E/\kappa) \begin{cases} Const. & \tau_{loss} \ll \tau_{adv} \\ \Sigma_{gas} & \tau_{adv} \ll \tau_{loss} \end{cases}$$

# P max & injection slope



# P max estimate

The maximum energy in DSA can be estimated as

$$D(E_{max}) = 0.1 R_{SNR} u_{sh}$$

Where $R_{SNR} = R_3\ 3\ pc$ (see Fenech et al. 2009) and $u_{sh} = u_4\ 10^4 km/s$

Assuming Bohm diffusion at the shock and $B = B_{mG}\ mG$ one can obtain

$$E_{max} = 30\ PeV\ \times R_3 u_4 B_{mG}$$