Cosmic ray transport in Starburst galaxies and possible observables
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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
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 ($U_{rad} \approx 10^3 eV cm^{-3}$)

Star cluster

ISM cloud

Hot pressurized medium ($T > 10^6 K, P \approx 10^7 K cm^{-3}$)

Acceleration site
CR transport in SBNi

Star cluster
ISM cloud
Hot pressurized medium ($T > 10^6 K$, $P \approx 10^7 K\, cm^{-3}$)
Acceleration site

Escaping proton

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

\[
Q_p(p) = \frac{R_{SN} \xi_{SN}(p)}{V} \propto \frac{R_{SN}}{V} \left( \frac{p}{mc} \right)^{-\alpha} e^{-p/p_{p,max}}
\]

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

\[ \tau_{loss}(p) = \left\{ \sum_j \left[ \frac{1}{E} \left( \frac{dE}{dt} \right)_j \right] \right\}^{-1} \]

The particle injection is balanced by losses and escape

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

\[ \tau_{adv} = \frac{R}{v_{wind}} \quad \tau_{diff}(p) = \frac{R^2}{D(p)} \]
Are SBNi CR calorimeters?

\[ D(p) = r_L(p)\nu(p)/3\mathcal{F}(k) \]

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

\[ k_0^{-1} = L_0 = 1\ pc \]

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

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

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

Electrons

<table>
<thead>
<tr>
<th>( D_L (\text{Mpc}) )</th>
<th>( B_{SN} (\text{yr}^{-1}) )</th>
<th>( R (\text{pc}) )</th>
<th>( \alpha )</th>
<th>( B (\mu\text{G}) )</th>
<th>( v_{\text{wind}} (\text{km/s}) )</th>
<th>( n_{\text{ISM}} (\text{cm}^{-3}) )</th>
<th>( U_{\text{RAD}} (\text{eV/cm}^3) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>0.05</td>
<td>200</td>
<td>4.25</td>
<td>200</td>
<td>500</td>
<td>125</td>
<td>3400</td>
</tr>
</tbody>
</table>
Are SBNi CR calorimeters?

\begin{table}[h]
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{\$D_L$ (Mpc)} & \textbf{\$\bar{\mathcal{R}}_{\text{SN}}$ (yr$^{-1}$)} & \textbf{\$R$ (pc)} & \textbf{\$\alpha$} & \textbf{\$B$ (\mu G)} & \textbf{\$v_{\text{wind}}$ (km/s)} & \textbf{\$n_{\text{ISM}}$ (cm$^{-3}$)} & \textbf{\$U_{\text{RAD}}$ (eV/cm$^3$)} \\
\hline
3.8 & 0.05 & 200 & 4.25 & 200 & 500 & 125 & 3400 \\
\hline
\end{tabular}
\end{table}
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

![Graphs showing particle distributions and emission rates.](image)
Hard X-rays as hadronic marker
Hard X-rays as hadronic marker
Hard X-rays as hadronic marker

\[ p^4 f(p) [\text{arbitrary units}] \]

\[ p [\text{GeV}] \]

\[ E^2 F(E) [\text{GeV cm}^{-2} \text{s}^{-1}] \]

\[ \text{Energy [GeV]} \]

**Graphs:**
- \( p(A) \)
- \( p(C) \)
- \( \pi^0(A) \)
- \( \pi^0(C) \)
- IC(A)
- IC(C)
- SYN(A)
- SYN(C)
- BREM
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

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

\[ q_{\gamma,N}^\text{SBN} \left( E, \psi \right) = \left( \frac{\psi}{\psi_{\text{M82}}} \right) q_{\gamma,N}^{\text{M82}} \left( E \right) \]

\[ \Phi_{\gamma,N}(E) = \frac{1}{4\pi} \int_0^{4.2} d\zeta \frac{dV_C}{d\zeta} \int_{\psi_{\min}} d \log \psi \Phi_{\text{SFR}}(\psi, z) \left[ 1 + \zeta \right]^2 f_{\gamma,N}(E \left[ 1 + \zeta \right], \psi) \]
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

Back up slides
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:

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

Secondaries-to-primaries ratio:

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

Tertiaries-to-secondaries ratio:

\[ \frac{q_{ter,e}(p)}{q_{sec,e}(p)} \approx \tau_{\gamma\gamma}(pc)(\tilde{\kappa}/\kappa)^{\alpha-3}/2 \]
The case of NGC 253

![Graphs showing energy spectra with various components and observations.](image-url)
SFRD & SFRF

- Madau & Dickinson (2014)
- Gruppioni et al. (2015)
- this work

\[ \text{SFRD} \left[ M_\odot \text{yr}^{-1} \text{Mpc}^{-3} \right] \]

\[ \log \Phi \left[ \text{Mpc}^{-3} \text{dex}^{-1} \right] \]

\[ \log \text{SFR} \left[ M_\odot \text{yr}^{-1} \right] \]
Idea beyond the diffuse flux 1

Calorimetric assumption for SB:
\[ \tau_{\text{loss}} \leq \tau_{\text{adv}} \rightarrow (n\sigma c\xi)^{-1} \leq R/v_{\text{wind}} \]

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

According to Kennicutt relation

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

The SFR is obtained as: \[ \psi = \pi R^2 \Sigma_{\text{SFR}} \]
Idea beyond the diffuse flux 2

Calorimetric assumption for SB is well motivated because

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

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

\[ q_{\gamma,\nu}(E) \propto q_p(E/\kappa) \begin{cases} \text{Const} & \tau_{\text{loss}} \ll \tau_{\text{adv}} \\ \Sigma_{\text{gas}} & \tau_{\text{adv}} \ll \tau_{\text{loss}} \end{cases} \]
P max & injection slope

![Graph showing energy distribution of particles](image-url)
P max estimate

The maximum energy in DSA can be estimated as

\[ D(E_{max}) = 0.1R_{SNR}u_{sh} \]

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

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