Sources of Cosmic Ray Antinuclei

focusing on SNRs and PBHs

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Potential sources of antinuclei in cosmic rays

- known astro/particle physics
  - cosmic ray + interstellar medium collisions – *secondaries*
  - acceleration of secondaries in *supernova remnant shockwaves*
- new physics
  - *dark matter* annihilation and decay
  - *primordial black hole* evaporation
- new cosmology
  - antimatter-dominated regions?

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- known astro/particle physics → known?
  - cosmic ray + interstellar medium collisions – *secondaries*
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- new physics
  - *dark matter* annihilation and decay → main motivation
  - *primordial black hole* evaporation → single parameter signal
- new cosmology
  - antimatter-dominated regions? → calculability?

Sources and Signals

Want to calculate antinuclei fluxes observable by our detectors – need:

1. source model
   - source physics
   - cross sections etc. specific to antinuclei
   - source context: spatial distribution etc.
2. propagation model
   - extragalactic?
   - galactic
   - heliospheric
   - geomagnetic

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Secondary cosmic rays – antinuclei physics

Why we are interested in low-energy antinuclei

- baryon asymmetry of the universe $\Rightarrow \bar{p}$ interesting
- baryon number conservation
  - pp-collisions: $\bar{d}$, $^3\overline{\mathrm{He}}$ always produced boosted
  - S/B boost for low-energy antinuclei from DM/PBHs

$$\begin{cases} \underset{1}{p} + \underset{1}{p} \longrightarrow \underset{-1}{\bar{p}} + \underset{3}{X} & \sqrt{s}_{\mathrm{thr}} = 4m_p & E_{\mathrm{thr}} = 6m_p \\ \underset{1}{p} + \underset{1}{p} \longrightarrow \underset{-2}{\bar{d}} + \underset{4}{Y} & \sqrt{s}_{\mathrm{thr}} = 6m_p & E_{\mathrm{thr}} = 16m_p \\ \underset{1}{p} + \underset{1}{p} \longrightarrow \underset{-3}{\overline{\mathrm{He}}^3} + \underset{5}{Z} & \sqrt{s}_{\mathrm{thr}} = 8m_p & E_{\mathrm{thr}} = 30m_p \end{cases}$$

Secondary cosmic rays – flux characteristics

$$\Phi_i \sim Q_i \cdot \tau_i^{\text{residence}}$$

- primaries:
  - $Q \sim E^{-2.x}$ power-law source
  - $\tau \sim E^{-0.3\cdots0.5}$ diffusion losses
- secondaries:

$$Q_{\bar{N}}^{\text{sec}}(T_{\bar{N}}, \vec{r}) \propto \sum_{\text{species } i,j} n_j(\vec{r}) \int_{T_{\text{thr}}} dT_i \, \frac{d\sigma_{ij\to\bar{N}+X}(T_i \to T_{\bar{N}})}{dT_{\bar{N}}} \Phi_i(T_i, \vec{r})$$

  - secondary power law $\propto Q_{\text{prim}}\tau_{\text{prim}}\tau_{\text{sec}}$ softer than primary
  - uncertainties in $\sigma_{ij\to\bar{N}+X}$
  - uncertainties in propagation (power-law τ too simple)

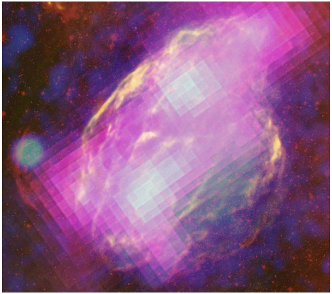
Secondary cosmic rays – uncertainties

- AMS-02 measures $\Phi_{\bar{p}}$ to $\mathcal{O}(10\%)$ accuracy $\Rightarrow$ sensitive probe of NP *if* secondary flux prediction precise
- low-energy $\bar{d}$, $^{3}\overline{\mathrm{He}}$ have negligible background from standard secondaries
- what about additional astrophysical components?
  - are antinuclei safe from the positron excess?

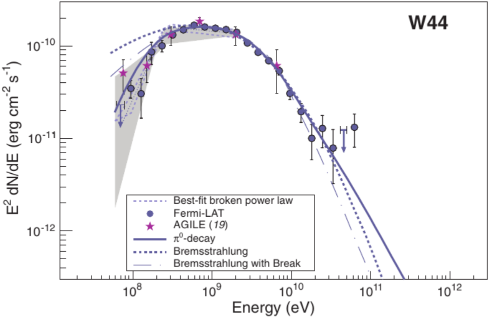
[Herms+’16][Tomassetti,Oliva’17]

Supernova remnants – source physics

- exploding star creates shockwave in surrounding ISM
- first order Fermi acceleration, source of power-law cosmic rays
- kinetic energy of ejecta $\Rightarrow \vec{B}$-turbulence & cosmic rays



NASA



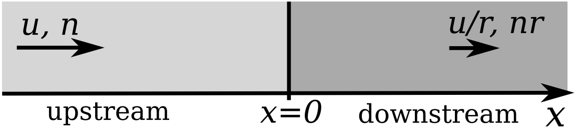
[FermiLAT'13]

Supernova remnants – stationary plane shock model

- diffusion-convection equation for phase space density $f(\vec{r},\vec{p})$

$$\frac{\partial f}{\partial t} = -u\frac{\partial f}{\partial x} + D\frac{\partial^2 f}{\partial x^2} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f}{\partial p} - \Gamma^{\text{inel.}} f + q \equiv 0$$

- geometry:

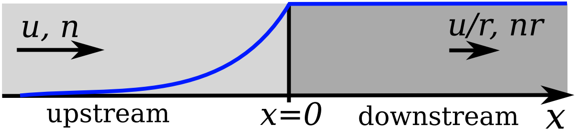


- result

$$f(x=0,p) \propto p^{-\alpha}, \qquad \alpha = \frac{3r}{r-1}$$

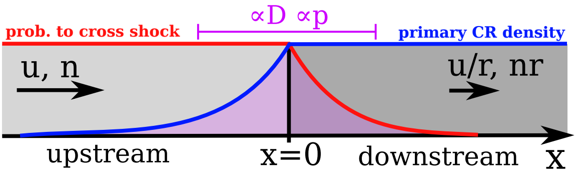
[Drury'83][Reynolds'08]

Supernova remnants – secondaries



- primaries accelerated at shock
  - advected downstream
  - some diffuse into upstream
  - secondary source term $\propto n\Phi_{\text{primary}}$

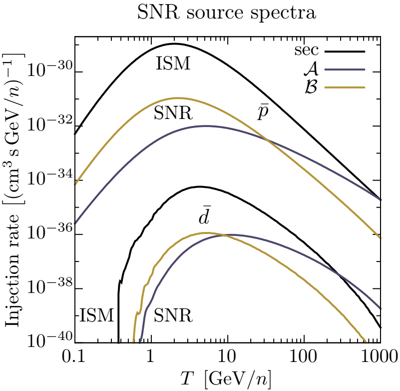
Supernova remnants – secondaries



- primaries accelerated at shock
  - advected downstream
  - some diffuse into upstream
  - secondary source term $\propto n\Phi_{\mathrm{primary}}$
- probability to cross shock
  - secondaries that cross the shock are also accelerated
- accelerated particles escape eg. when the shock dies

e.g.: [Berezhko+'03] [Blasi,Serpico'06] [Kachelriess+'11]

Supernova remnants – source spectra



$$\text{sec} \propto E^{-\alpha-2\delta_{\text{prop}}}, \qquad \mathcal{B} \propto E^{-\alpha-\delta_{\text{prop}}}, \qquad \mathcal{A} \propto E^{-\alpha-\delta_{\text{prop}}+1}$$

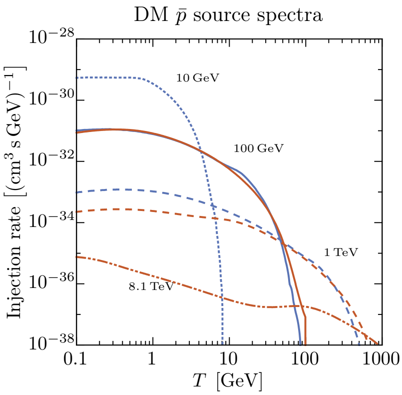
$\Rightarrow$ no relevant contribution to low-energy antinuclei searches

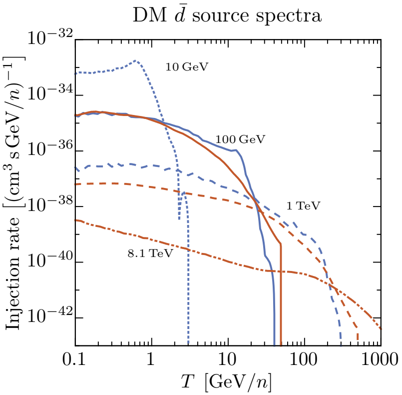
Dark Matter

... see talk by Fiorenza Donato this morning.

- WIMP annihilation or relic particle decay into pair of SM particles
  - *pair* production → enhance S/B by looking at antinuclei
  - produced without boost
- antinuclei yield sensitive to size of "collection area" ∼ diffusive halo

Dark Matter – example source functions





using [IbarraWild'13]

- peaked at low energies
- stands out at high energies from astrophysical $\propto E^2$ power law spectrum

Antinuclei from Primordial Black Hole evaporation

Outline

1. Primordial Black Holes – origins & constraints
2. Hawking evaporation
3. Antinuclei flux
    - calculation
    - role in PBH detection

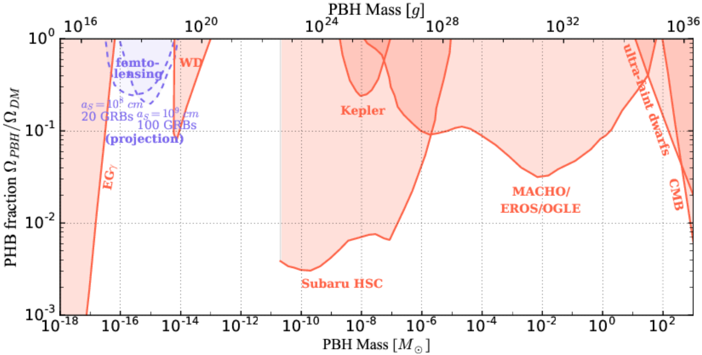
For reviews see e.g.

[Green'1403.1198][Carr'astro-ph/0511743][Carr+'1607.06077][Sasaki+'1801.05235]

Primordial Black Holes – are they dark matter?

Yes, but how much?

- see A. Coogan on Friday

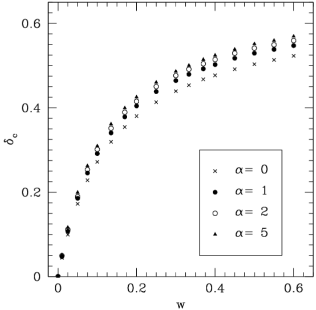


[Katz+'18]

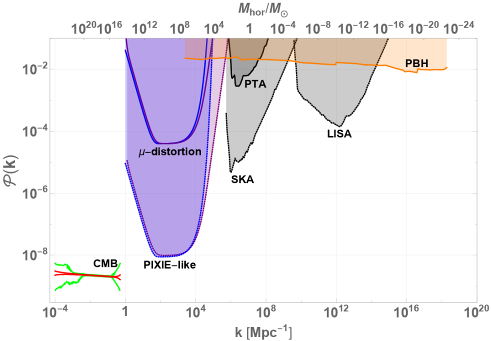
Primordial Black Holes – Formation

Are they new physics?

1. large density fluctuations [Carr'75]
   - formation at horizon entry,
     $M_{\mathrm{PBH}} \sim M_{\mathrm{hor.}} \simeq c^3 t/G \simeq 10^{15}\,(t/10^{23} s)$ g.



[MuscoMiller'13]



[Byrnes+'19]

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3. bubble collisions in phase transitions [Hawking'82]

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$\Rightarrow$ PBHs would be evidence of new particle physics

- $\rho_{\rm PBH} \propto a^{-3}$ while $\rho_{\rm rad} \propto a^{-4}$
  - can probe very rare events in the early universe

Primordial Black Holes – Evaporation

Theory

Black holes evaporate [Hawking'75, Page'76]

$$T = \frac{M_{\rm Pl}^2}{8\pi M_{\rm PBH}} \approx \frac{1.06\,\mathrm{GeV}}{M_{\rm PBH}/10^{13}\,\mathrm{g}}$$

$$\frac{\mathrm{d}^2 N_j}{\mathrm{d}Q\mathrm{d}t} = \frac{\Gamma_j}{2\pi\left(\exp\left(Q/T\right) - (-1)^{2s_j}\right)}$$

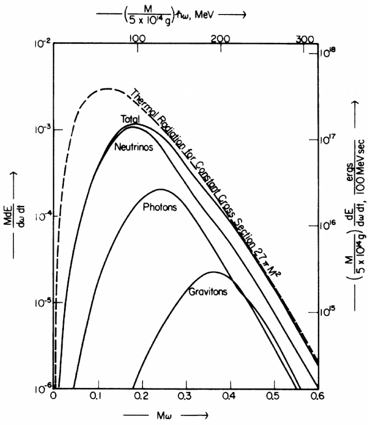


FIG. 1. Power spectra from a black hole

Primordial Black Holes – Evaporation

Mass evolution

Mass loss

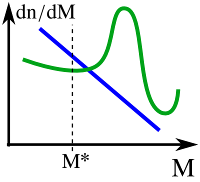
$$\frac{\mathrm{d}M_{\mathrm{PBH}}}{\mathrm{d}t} = -\alpha M_{\mathrm{PBH}}^{-2}$$

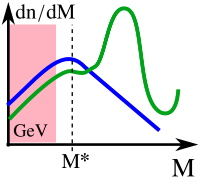
Initial mass of PBHs evaporating today

$$M^*_{\mathrm{PBH}} = (3\alpha t_{\mathrm{univ}})^{1/3} = 5 \times 10^{14}\,\mathrm{g}$$

$\Rightarrow$ temperature $T(M^*_{\mathrm{PBH}}) \approx 21$ MeV

$\Rightarrow$ relevant part of PBH mass function is $\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}M_{\mathrm{PBH}}} \propto M^2_{\mathrm{PBH}}$, determined by evaporation





Primordial Black Holes – Evaporation

Antinuclei

Antinuclei spectrum from a single BH:

$$\frac{\mathrm{d}^2 N_{\bar{N}}(M_{\rm PBH})}{\mathrm{d}E\mathrm{d}t} = \sum_{j=q,g} \int_{Q=E}^{\infty} \alpha_j \frac{\mathrm{d}^2 N_j\,(M_{\rm PBH})}{\mathrm{d}Q\mathrm{d}t}\;\frac{\mathrm{d}g_{\bar{N},j}(Q,E)}{\mathrm{d}E}\,\mathrm{d}Q$$

[MacGibbon,Webber'90]

Antinuclei source term from a PBH population:

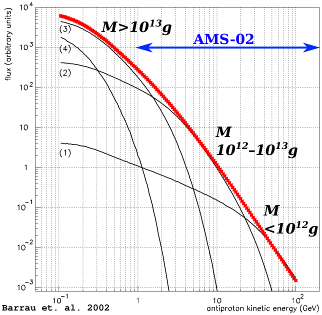
$$Q_{\bar{N}}^{\rm PBH}(\vec{r},E) = \int \mathrm{d}M_{\rm PBH} \frac{\mathrm{d}^2 N_{\bar{N}}(M_{\rm PBH})}{\mathrm{d}E\mathrm{d}t}\,\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}M_{\rm PBH}}\;\frac{\rho_{\rm PBH}\,(\vec{r})}{\overline{M}_{\rm PBH}}$$

alternative: normalise by rate density of PBH explosions

- spectrum: specific superposition of GeV-scale DM spectra
- distribution: like decaying dark matter

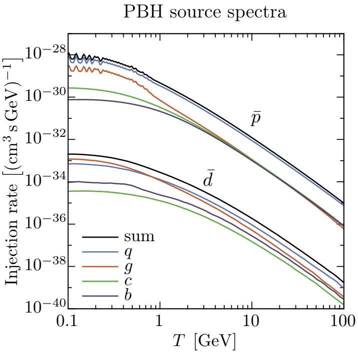
Primordial Black Holes – Antinuclei source spectra

contributions from different $M_{\rm PBH}$

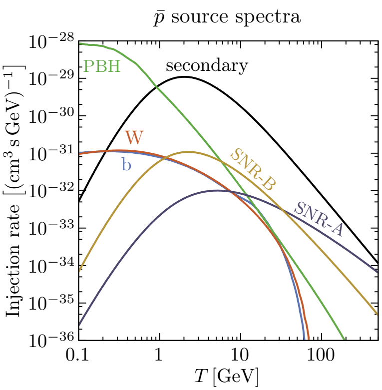


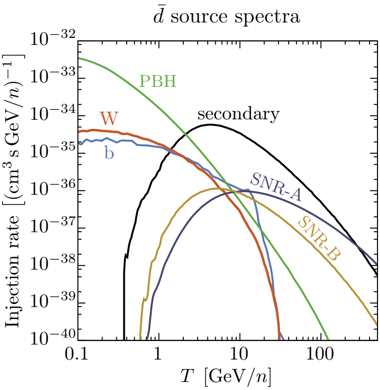
adapted from [Barrau+'astro-ph/0112486]

contributions by primary

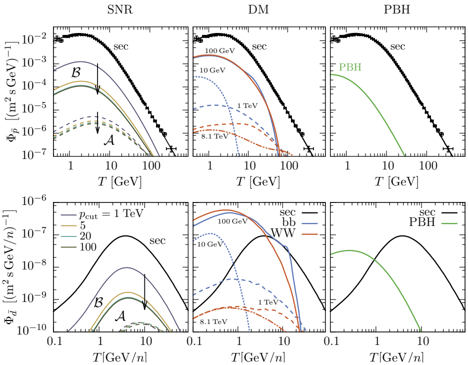


Summary – Sources





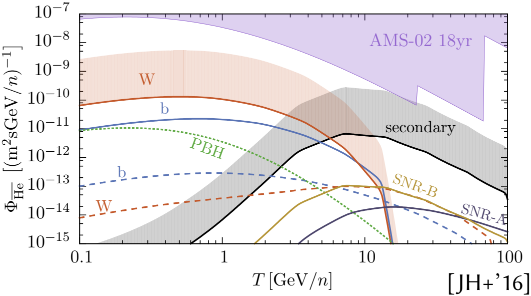
Summary – Antiprotons and antideuterons



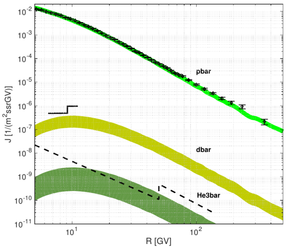
convincing detection of exotics requires

- in $\bar{p}$: knowledge of background
  - $\bar{p}$-excess? [Cuoco+'16] [Reinert,Winkler'17] [Cholis+'19] [Cuoco+'19]
- in $\bar{d}$: exposure

Summary – Antihelium



[JH+'16]



[Blum+'17]

- AMS-02 antihelium flux sensitivity ~ flat in $^3\overline{\mathrm{He}}/\mathrm{He}$ [Kounine'1009.5349]
- $\bar{d}$ more promising for DM/PBH detection

Summary

Sources of light cosmic ray antinuclei

- secondaries
  - guaranteed
  - boosted production → interested in low-energy antinuclei
- SNR accelerated secondaries
  - can modify the high energy secondary flux
- dark matter
  - *low energy antinuclei promising discovery channel!*
- primordial black holes
  - very predictive spectrum
  - interesting benchmark to look at

references: arXiv:1610.00699

Primordial Black Holes

Graybody factors

Hawking radiation relates the emission and absorption rates of black holes. Absorption cross sections were calculated by numerically solving the appropriate wave equations in the black hole spacetime. [Page+'76,Page'76,Page'77]