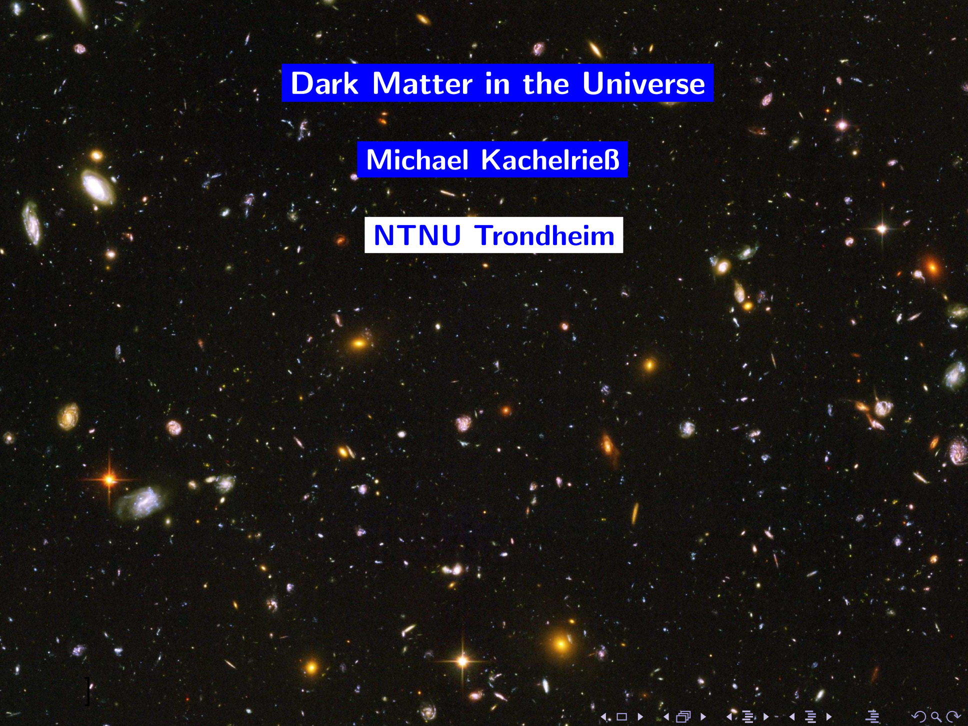
Dark Matter in the Universe

Michael Kachelrieß

NTNU Trondheim



Experimental anomalies:

- WMAP haze: synchrotron radiation from the GC

Experimental anomalies:

- WMAP haze: synchrotron radiation from the GC
- Integral: positron annihilation line from the Galactic bulge

Experimental anomalies:

- WMAP haze: synchrotron radiation from the GC
- Integral: positron annihilation line from the Galactic bulge
- EGRET excess, surplus of diffuse γ-rays

Experimental anomalies:

- WMAP haze: synchrotron radiation from the GC
- Integral: positron annihilation line from the Galactic bulge
- EGRET excess, surplus of diffuse γ-rays
- PAMELA anomaly: positrons, but no anti-protons

Experimental anomalies:

- WMAP haze: synchrotron radiation from the GC
- Integral: positron annihilation line from the Galactic bulge
- EGRET excess, surplus of diffuse γ-rays
- PAMELA anomaly: positrons, but no anti-protons
- ATIC anomaly: positrons, but no anti-protons

Experimental anomalies:

- WMAP haze: synchrotron radiation from the GC
- Integral: positron annihilation line from the Galactic bulge
- EGRET excess, surplus of diffuse γ-rays
- PAMELA anomaly: positrons, but no anti-protons
- ATIC anomaly: positrons, but no anti-protons
- HESS: TeV γ-rays from GC

Experimental anomalies:

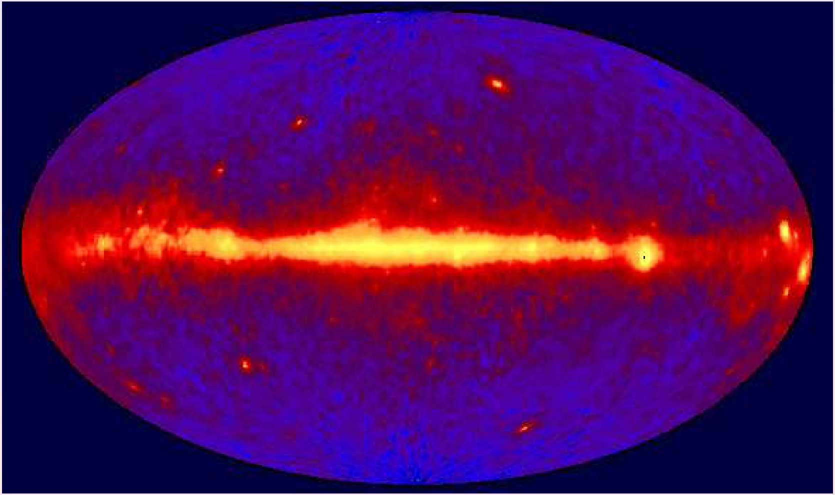
- WMAP haze: synchrotron radiation from the GC
- Integral: positron annihilation line from the Galactic bulge
- EGRET excess, surplus of diffuse γ-rays
- PAMELA anomaly: positrons, but no anti-protons
- ATIC anomaly: positrons, but no anti-protons
- HESS: TeV γ-rays from GC

- DAMA/Libra modulation signal

Earlier indirect detection claims:

[Elsässer, Mannheim '04]

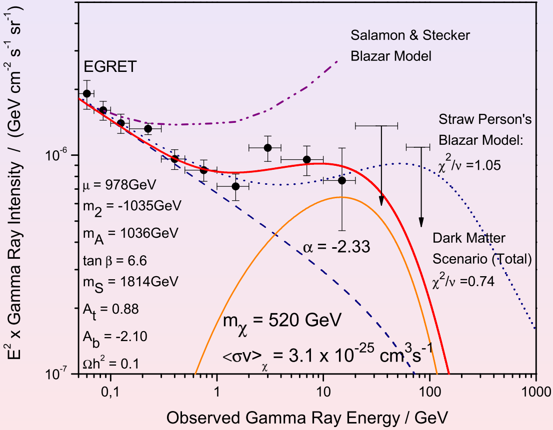
- Signal from
  extragalactic $\chi\chi$ annihilations in the diffuse photon background:



Earlier indirect detection claims:

[Elsässer, Mannheim '04]

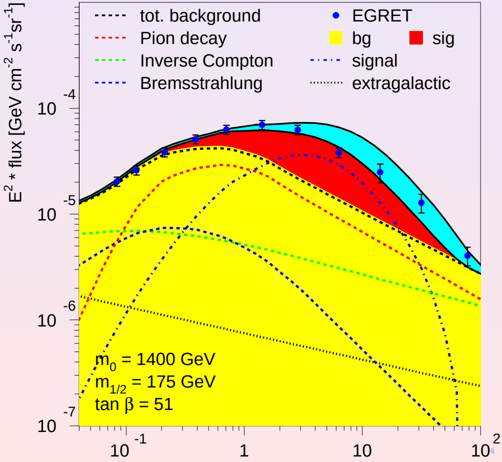
- Signal from extragalactic $\chi\chi$ annihilations in the diffuse photon background:



Earlier indirect detection claims:

[*de Boer et al.* '03–08]

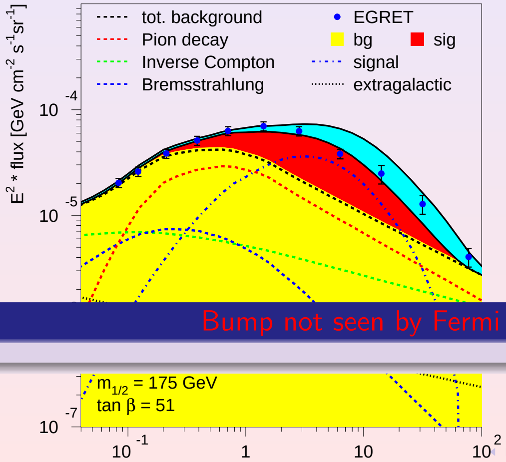
- Signal from Galactic $\chi\chi$ annihilations in the diffuse photon flux:



Earlier indirect detection claims:

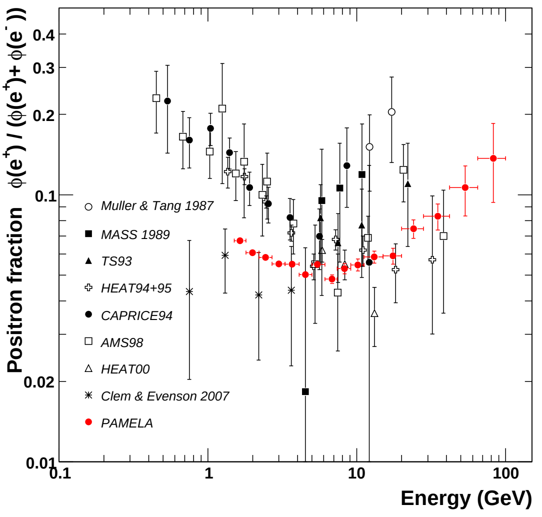
[de Boer et al. '03–08]

- Signal from Galactic $\chi\chi$ annihilations in the diffuse photon flux:

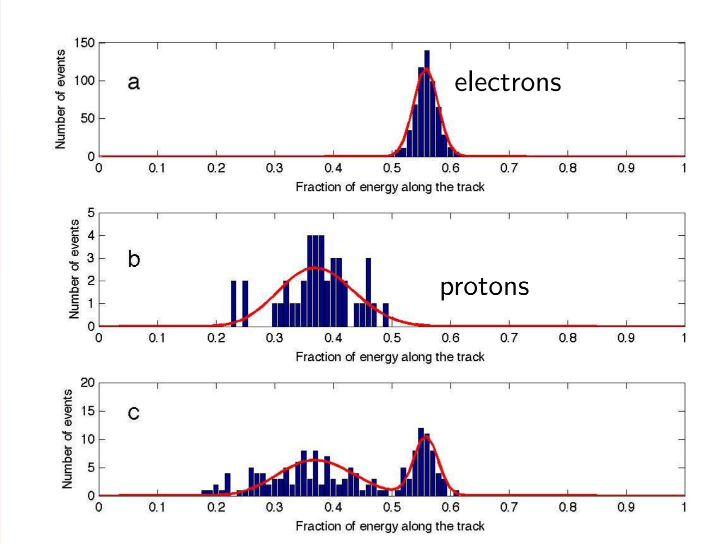


Bump not seen by Fermi

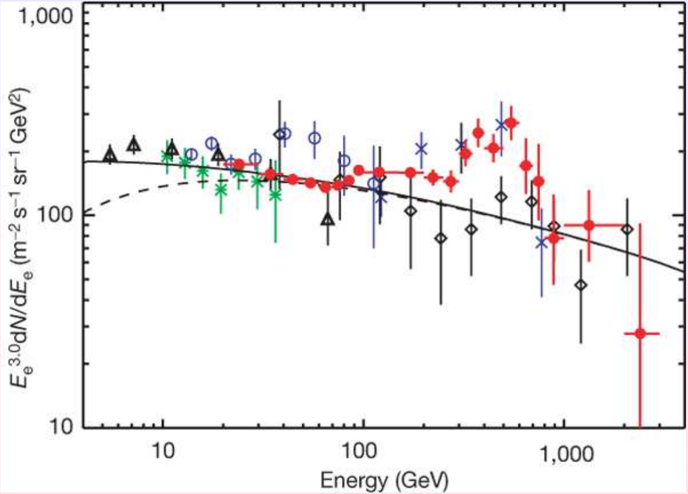
PAMELA anomaly



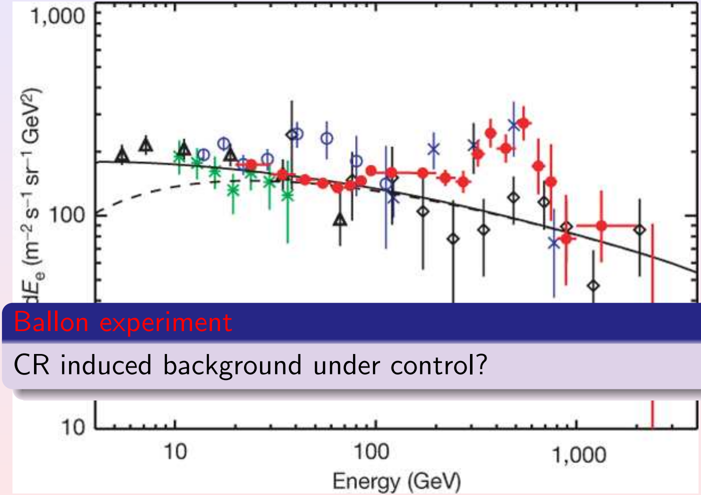
PAMELA anomaly: positron-proton identification via dE/dx, topology



ATIC anomaly



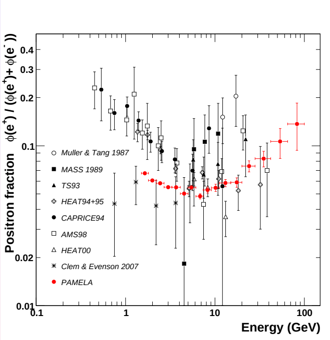
ATIC anomaly

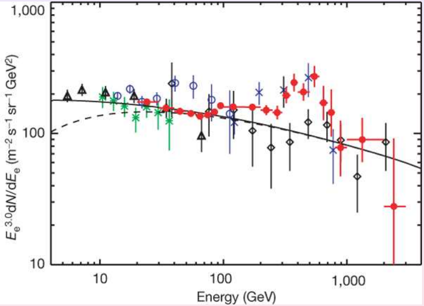


Ballon experiment

CR induced background under control?

PAMELA and ATIC anomaly





Possible explanations for the PAMELA anomaly:

- Dark matter
    - requires large boost factors
        - Sommerfeld enhancement
        - dense, cold clumps

Possible explanations for the PAMELA anomaly:

- Dark matter
  - requires large boost factors
    - Sommerfeld enhancement
    - dense, cold clumps
  - “exclusive” coupling to leptons

Possible explanations for the PAMELA anomaly:

- Dark matter
  - requires large boost factors
    - Sommerfeld enhancement
    - dense, cold clumps
  - “exclusive” coupling to leptons
- Astrophysics: as primaries from
  - pulsars
  - supernova remanants (SNR)

Astrophysical sources for anti-matter: CR secondaries

- standard secenario for Galactic CRs:
  - sources are SNRs:
    kinetic energy output of SNe:
    $10M_\odot$ ejected with $v \sim 5 \times 10^8$ cm/s every 30 yr
    $\Rightarrow L_{\rm SN,kin} \sim 3 \times 10^{42}$ erg/s
  - explains local energy density of CR $\varepsilon_{\rm CR} \sim 1$ eV/cm^3 for a escape time from disc $\tau_{\rm esc} \sim 6 \times 10^6$ yr

Astrophysical sources for anti-matter: CR secondaries

- standard secenario for Galactic CRs:
  - sources are SNRs:
    kinetic energy output of SNe:
    $10M_\odot$ ejected with $v \sim 5 \times 10^8$ cm/s every 30 yr
    $\Rightarrow L_{\rm SN,kin} \sim 3 \times 10^{42}$ erg/s
  - explains local energy density of CR $\varepsilon_{\rm CR} \sim 1$ eV/cm^3 for a escape time from disc $\tau_{\rm esc} \sim 6 \times 10^6$ yr
  - 1.order Fermi shock acceleration $\Rightarrow dN/dE \propto E^{-\gamma}$ with $\gamma = 2.0 - 2.2$
  - diffusion with $D(E) \propto \tau_{\rm esc}(E) \sim E^{-\delta}$ and $\delta \sim 0.6$ explains observed spectrum $E^{-2.6}$

Astrophysical sources for anti-matter: CR secondaries

- standard secenario for Galactic CRs:
  - sources are SNRs:
    kinetic energy output of SNe:
    $10M_\odot$ ejected with $v \sim 5 \times 10^8$ cm/s every 30 yr
    $\Rightarrow L_{\rm SN,kin} \sim 3 \times 10^{42}$ erg/s
  - explains local energy density of CR $\varepsilon_{\rm CR} \sim 1$ eV/cm^3 for a escape time from disc $\tau_{\rm esc} \sim 6 \times 10^6$ yr
  - 1.order Fermi shock acceleration $\Rightarrow dN/dE \propto E^{-\gamma}$ with $\gamma = 2.0 - 2.2$
  - diffusion with $D(E) \propto \tau_{\rm esc}(E) \sim E^{-\delta}$ and $\delta \sim 0.6$ explains observed spectrum $E^{-2.6}$
- electrons, positrons: $\tau_{\rm loss} \ll \tau_{\rm esc}$ and $\tau_{\rm loss} \propto 1/E$

Astrophysical sources for anti-matter: CR secondaries

- standard secenario for Galactic CRs:
  - sources are SNRs:
    kinetic energy output of SNe:
    $10M_\odot$ ejected with $v \sim 5 \times 10^8$ cm/s every 30 yr
    $\Rightarrow L_{\text{SN,kin}} \sim 3 \times 10^{42}$ erg/s
  - explains local energy density of CR $\varepsilon_{\text{CR}} \sim 1$ eV/cm^3 for a escape time from disc $\tau_{\text{esc}} \sim 6 \times 10^6$ yr
  - 1.order Fermi shock acceleration $\Rightarrow dN/dE \propto E^{-\gamma}$ with $\gamma = 2.0 - 2.2$
  - diffusion with $D(E) \propto \tau_{\text{esc}}(E) \sim E^{-\delta}$ and $\delta \sim 0.6$ explains observed spectrum $E^{-2.6}$
- electrons, positrons: $\tau_{\text{loss}} \ll \tau_{\text{esc}}$ and $\tau_{\text{loss}} \propto 1/E$
- electrons $dN_-/dE \propto E^{-\gamma-1}$
- positrons $dN_+/dE \propto E^{-\gamma-\delta-1}$

Astrophysical sources for anti-matter: CR secondaries

- standard secenario for Galactic CRs:
  - sources are SNRs:
    kinetic energy output of SNe:
    $10M_\odot$ ejected with $v \sim 5 \times 10^8$ cm/s every 30 yr
    $\Rightarrow L_{\mathrm{SN,kin}} \sim 3 \times 10^{42}$ erg/s
  - explains local energy density of CR $\varepsilon_{\mathrm{CR}} \sim 1$ eV/cm^3 for a escape time from disc $\tau_{\mathrm{esc}} \sim 6 \times 10^6$ yr
  - 1.order Fermi shock acceleration $\Rightarrow dN/dE \propto E^{-\gamma}$ with $\gamma = 2.0 - 2.2$
  - diffusion with $D(E) \propto \tau_{\mathrm{esc}}(E) \sim E^{-\delta}$ and $\delta \sim 0.6$ explains observed spectrum $E^{-2.6}$
- electrons, positrons: $\tau_{\mathrm{loss}} \ll \tau_{\mathrm{esc}}$ and $\tau_{\mathrm{loss}} \propto 1/E$
- electrons $dN_-/dE \propto E^{-\gamma-1}$
- positrons $dN_+/dE \propto E^{-\gamma-\delta-1}$

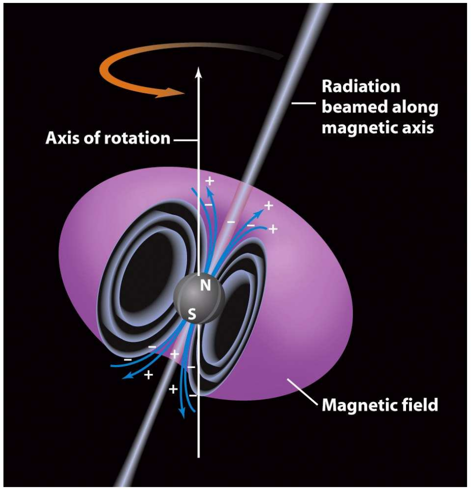
$\Rightarrow$ ratio

$$\frac{n_+}{n_-} \propto E^{-\delta}$$

$\Rightarrow$ secondaries cannot expalain increasing positron fraction

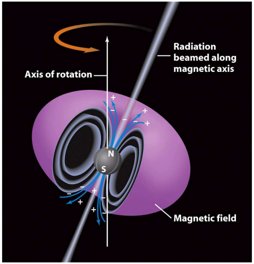
Astrophysical explanations I: Pulsars

- Pulsar: (fast) rotating, stronly magnetized neutron star



Astrophysical explanations I: Pulsars

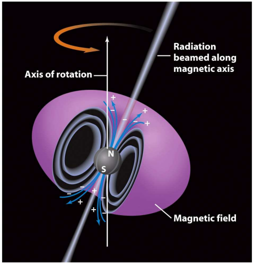
- Pulsar: (fast) rotating, stronly magnetized neutron star



- suggested as source of CRs up-to 10^{20} eV

Astrophysical explanations I: Pulsars

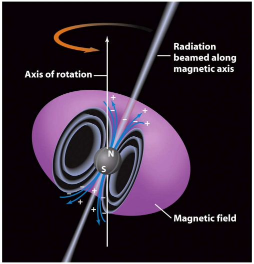
- Pulsar: (fast) rotating, stronly magnetized neutron star



- suggested as source of CRs up-to 10^{20} eV
- produce hard spectrum, $dN/dE \sim E^{-1.5}$

Astrophysical explanations I: Pulsars

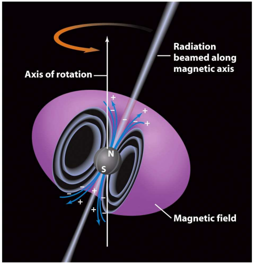
- Pulsar: (fast) rotating, stronly magnetized neutron star



- suggested as source of CRs up-to 10^{20} eV
- produce hard spectrum, $dN/dE \sim E^{-1.5}$
- old pulsars ($\gtrsim 10^5$yr) lost nebula $\Rightarrow$ positrons can escape

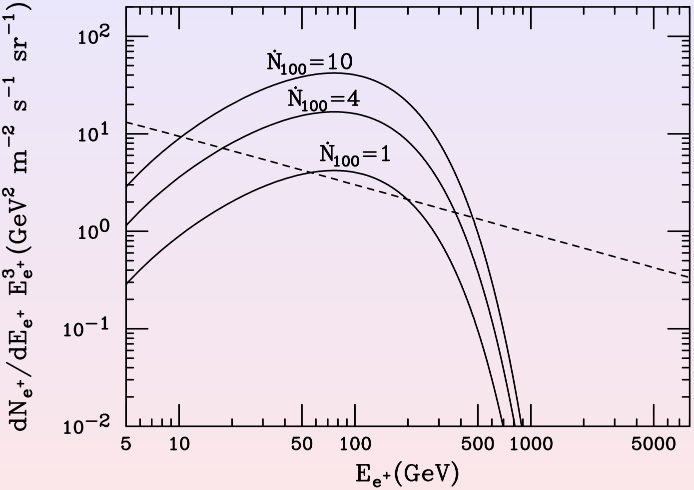
Astrophysical explanations I: Pulsars

- Pulsar: (fast) rotating, stronly magnetized neutron star

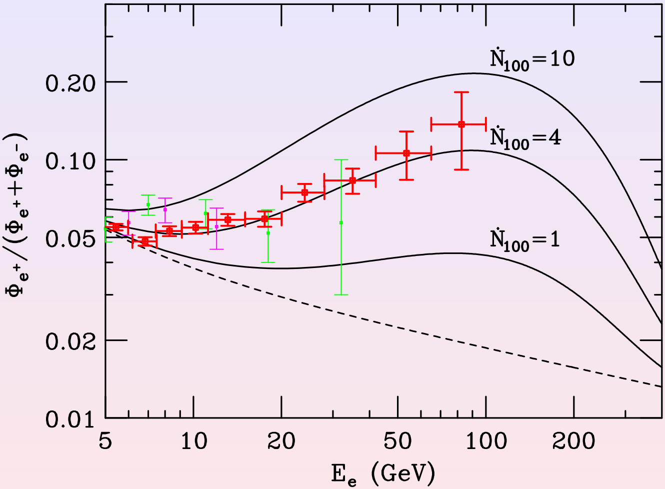


- suggested as source of CRs up-to 10^{20} eV
- produce hard spectrum, $dN/dE \sim E^{-1.5}$
- old pulsars ($\gtrsim 10^5$yr) lost nebula $\Rightarrow$ positrons can escape
- few sources (Geminga, B06556+14) may dominate HE part
- anisotropy or peaks possible

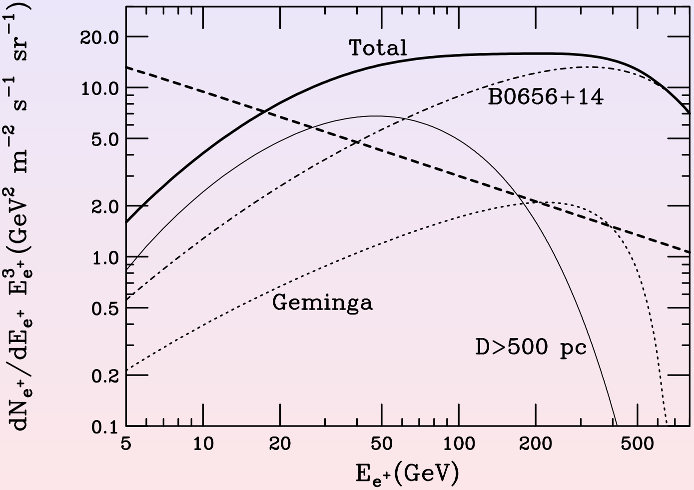
Astrophysical explanations I: Pulsars



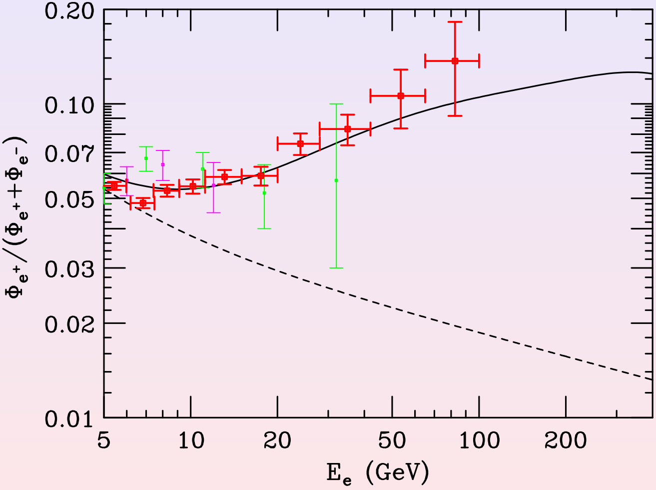
Astrophysical explanations I: Pulsars



Astrophysical explanations: Pulsars - Geminga+B06556+14



Astrophysical explanations: Pulsars - Geminga+B06556+14



Astrophysical explanations: Pulsars

- if Geminga and B06556+14 dominate HE part:

Astrophysical explanations: Pulsars

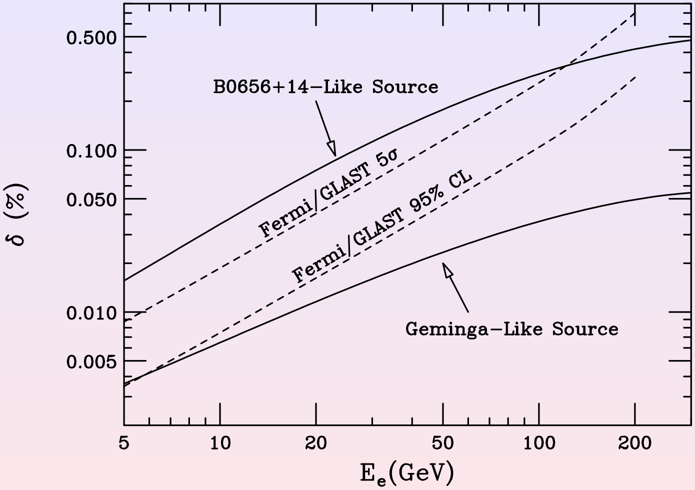
- if Geminga and B06556+14 dominate HE part:
- implies anisotropy
- from Fick's law

$$\mathcal{F}_a(E) = -D_{ab}\nabla_b n(E,x)$$

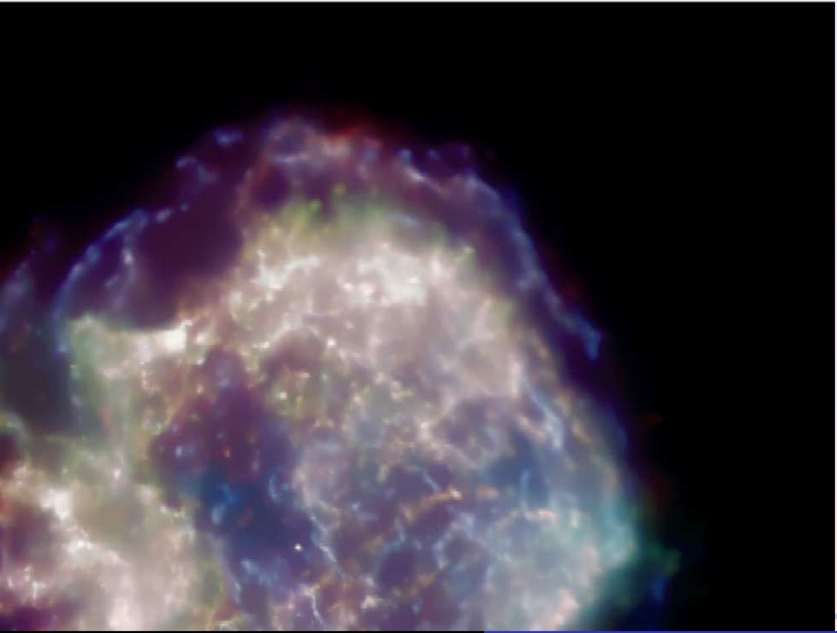
- anisotropy

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = 3D\frac{1}{n}\frac{\partial n}{n\partial z}$$

Astrophysical explanations: Pulsars



Astrophysical explanations: old SNRs



Astrophysical explanations II: SNR

[*P. Blasi '09*]

- $N_{CR}(E) \gg N_e(E)$ for energies $E \gg m_p$ in acceleration region

Astrophysical explanations II: SNR

[P. Blasi '09]

- $N_{CR}(E) \gg N_e(E)$ for energies $E \gg m_p$ in acceleration region
- significant $e^{\pm}$ production even for small τ_{pp} in source

Astrophysical explanations II: SNR

[P. Blasi '09]

- $N_{CR}(E) \gg N_e(E)$ for energies $E \gg m_p$ in acceleration region
- significant $e^{\pm}$ production even for small τ_{pp} in source
- secondary $e^{\pm}$ are accelerated, spectra becomes harder

Astrophysical explanations II: SNR

[*P. Blasi '09*]

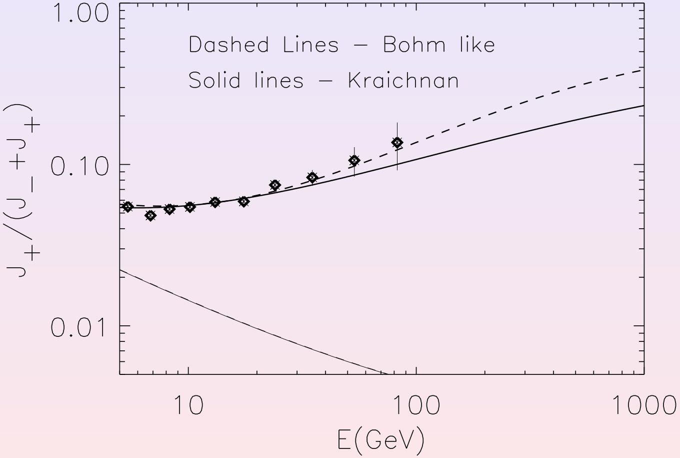
- $N_{CR}(E) \gg N_e(E)$ for energies $E \gg m_p$ in acceleration region
- significant $e^\pm$ production even for small τ_{pp} in source
- secondary $e^\pm$ are accelerated, spectra becomes harder

$\Rightarrow$ several important implications for CR physics

- predicts also increase of $\bar{p}/p$

Astrophysical explanations II: SNR

[*P. Blasi '09*]



Neutralino annihilations

- CDM velocitities $v^2 \sim v_\odot^2 \sim 10^{-6}$

$\Rightarrow$ p-wave annihilations strongly suppressed

Neutralino annihilations

- CDM velocitities $v^2 \sim v_\odot^2 \sim 10^{-6}$

$\Rightarrow$ p-wave annihilations strongly suppressed

- for Majorana particles: s-wave $\sigma \propto m_f^2$

$\Rightarrow$ annihilations into b, t quarks and W, Z, h, H, A

Neutralino annihilations

- CDM velocitities $v^2 \sim v_\odot^2 \sim 10^{-6}$

$\Rightarrow$ p-wave annihilations strongly suppressed

- for Majorana particles: s-wave $\sigma \propto m_f^2$

$\Rightarrow$ annihilations into b, t quarks and W, Z, h, H, A

- typical hadronization spectra with
$\phi_\nu(E)/2 \sim \phi_\gamma(E) \sim 3\phi_e(E) \sim 10\phi_N(E)$

Neutralino annihilations

- CDM velocitities $v^2 \sim v_\odot^2 \sim 10^{-6}$

$\Rightarrow$ p-wave annihilations strongly suppressed

- for Majorana particles: s-wave $\sigma \propto m_f^2$

$\Rightarrow$ annihilations into b, t quarks and W, Z, h, H, A

- typical hadronization spectra with $\phi_\nu(E)/2 \sim \phi_\gamma(E) \sim 3\phi_e(E) \sim 10\phi_N(E)$
- photon signal

$$I_{\rm sm}(E,\psi) = \frac{dN_i}{dE}\,\frac{\langle\sigma v\rangle}{2\,m_X^2}\int_{\rm l.o.s.} ds\,\frac{\rho^2[r(s,\psi)]}{4\pi},$$

Neutralino annihilations

- CDM velocitities $v^2 \sim v_\odot^2 \sim 10^{-6}$

$\Rightarrow$ p-wave annihilations strongly suppressed

- for Majorana particles: s-wave $\sigma \propto m_f^2$

$\Rightarrow$ annihilations into b, t quarks and W, Z, h, H, A

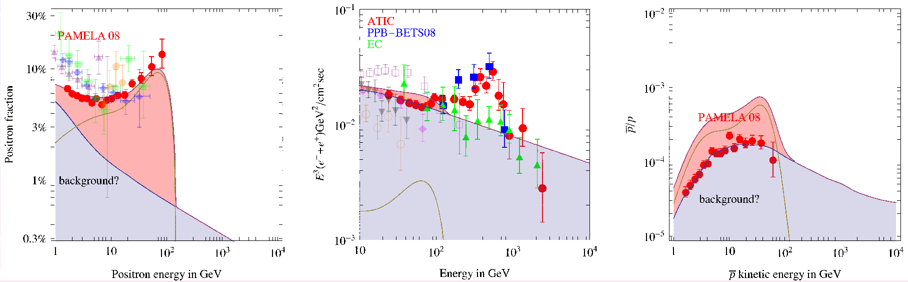
- typical hadronization spectra with $\phi_\nu(E)/2 \sim \phi_\gamma(E) \sim 3\phi_e(E) \sim 10\phi_N(E)$
- photon signal

$$I_{\rm sm}(E,\psi) = \frac{dN_i}{dE}\,\frac{\langle\sigma v\rangle}{2\,m_X^2} \int_{\rm l.o.s.} ds\, \frac{\rho^2[r(s,\psi)]}{4\pi},$$

- main uncertainty: “boost factor” $=$ enhancement compared to $\langle\sigma v\rangle = 3\times 10^{-26}{\rm cm}^3/{\rm s}$ and $\rho = \rho_{\rm sm}$

DM annihilations and PAMELA/ATIC

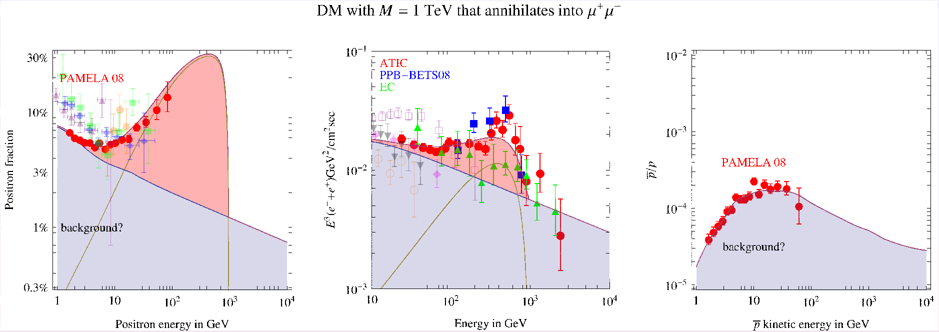
DM with $M = 150$ GeV that annihilates into W^+W^-



standard branching ratios and mass:

- overproduction of anti-protons

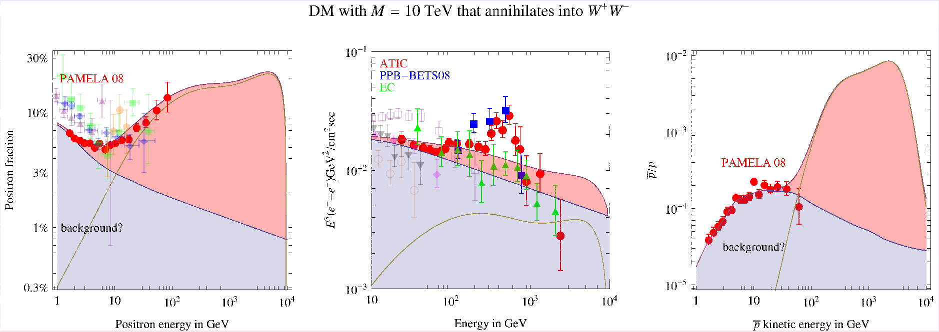
DM annihilations and PAMELA/ATIC



non-standard branching ratios: only leptons

- best-fit to ATIC
- boost factor 1000 needed
- but minimal γ-ray flux from Bremsstrahlung, not seen

DM annihilations and PAMELA/ATIC


DM with $M = 10$ TeV that annihilates into W^+W^-

standard branching ratios:

- hide $\bar{p}$ above $E_{\max}$ of Pamela
- happy with $M = 10$ TeV?

Boost factor

- particle physics:
  - $\langle\sigma v\rangle \propto 1/v$ allowed by unitarity
  - requires s-channel resonances or bound states

Boost factor

- particle physics:
    - $\langle\sigma v\rangle \propto 1/v$ allowed by unitarity
    - requires s-channel resonances or bound states
    - Sommerfeld enhancement in Coulomb limit

$$S_0 = \frac{\pi x}{1-\exp(-\pi x)}, \qquad x = \frac{g^2}{\beta}$$

Boost factor

- particle physics:
  - $\langle\sigma v\rangle \propto 1/v$ allowed by unitarity
  - requires s-channel resonances or bound states
  - Sommerfeld enhancement in Coulomb limit

$$S_0 = \frac{\pi x}{1 - \exp(-\pi x)}\,, \qquad\qquad x = \frac{g^2}{\beta}$$

  - for Coulomb limit, add new light boson

Boost factor

- particle physics:
    - $\langle \sigma v \rangle \propto 1/v$ allowed by unitarity
    - requires s-channel resonances or bound states
    - Sommerfeld enhancement in Coulomb limit

$$S_0 = \frac{\pi x}{1 - \exp(-\pi x)}\,, \qquad x = \frac{g^2}{\beta}$$

    - for Coulomb limit, add new light boson
- astrophysics:
- clumpy substructure of DM halo

Boost factor

- particle physics:
  - $\langle\sigma v\rangle \propto 1/v$ allowed by unitarity
  - requires s-channel resonances or bound states
  - Sommerfeld enhancement in Coulomb limit

$$S_0 = \frac{\pi x}{1 - \exp(-\pi x)}\,, \qquad x = \frac{g^2}{\beta}$$

  - for Coulomb limit, add new light boson
- astrophysics:
- clumpy substructure of DM halo
- Dm in clumps may be colder

⇒ both effects magnify each other

Summary

- Cosmology probes only generic properties of DM:
  abundance, cold, dissipation-less

Summary

- Cosmology probes only generic properties of DM: abundance, cold, dissipation-less
- various candidates with these properties: neutralino, gravitino, axion, axino, SHDM, . . .

Summary

- Cosmology probes only generic properties of DM: abundance, cold, dissipation-less
- various candidates with these properties: neutralino, gravitino, axion, axino, SHDM, ...
- only a combination of accelerator, direct and/or indirect searches can identify the DM particle

Summary

- Cosmology probes only generic properties of DM: abundance, cold, dissipation-less
- various candidates with these properties: neutralino, gravitino, axion, axino, SHDM, . . .
- only a combination of accelerator, direct and/or indirect searches can identify the DM particle
- even in the best-case scenario (SUSY at LHC), confirmation of LSP as DM by (in-) direct searches necessary

- all sorts of data are coming!