Recent Developments in Astroparticle Physics

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A working definition of “astroparticle physics” for this talk

Large and active experimental and theoretical field. This overview will be a bit biased, focussing mainly on searches for dark matter
2013-14 News items

DM indirect γ-ray signals

PeV neutrinos in IceCube

Cosmic ray positron fraction

DM Direct detection limits

CMB B-modes from BICEP-2
News items - chronological

- Precision BBN
- Precision CMB
- Multi-messenger astronomy
Precision CMB - focus on sensitivity to new degrees of freedom (Planck, BICEP2)
CMB sensitivity to light degrees of freedom

Important test of new light (relativistic) degrees of freedom, that affect the energy density during radiation domination

\[ \rho_\nu \propto N_{\text{eff}} T^4 \]

[Planck 2013]
CMB sensitivity to DM annihilation

Sensitivity to residual DM annihilation around recombination

[Madhavacheril et al. 2013]
CMB B-modes

• First observation of lensed B-modes
  – EB correlation from SPTPol
  – BB from PolarBear

[PolarBear 2014]
CMB B-modes

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- First claimed observation of primordial B-modes from BICEP2
CMB B-modes

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• If primordial, the signal appears consistent with gravitational waves generated during inflation with a simple \( V \sim m^2 \phi^2 \) inflaton potential

• Inflation at the GUT energy scale of \( 10^{16} \) GeV!

\[
r = 0.14 \left( \frac{H}{10^{14} \text{ GeV}} \right)^2
\]
Any “measurable” value of \( r \) would point against high scale axion DM due to the constraints on isocurvature perturbations.
Precision BBN
• Recent determinations of the BBN Deuterium abundance from BBN, using absorption in metal-poor high-z Lyman-α systems
  – percent-level consistency of baryon abundance with CMB

[Diagram showing log(D/H) vs. [O/H] with 1σ and 2σ bands and Planck values labeled]
DM in the late universe
Indirect DM detection

• results from the Fermi satellite
Indirect DM detection

Galactic center: highest rate, but many other sources including transients

Satellites: low background, but astrophysical uncertainties

[Kuhlen et al]
Indirect DM detection

- results from the Fermi satellite
  - annihilation constraints now close to the s-wave benchmark from thermal freeze-out
  \[ \Omega_{\text{DM}} h^2 \sim 0.1 \left( \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

From regions around the galactic center

Combined limits from 15 dwarf spheroidal satellites
Indirect DM detection

Identifying astrophysical signatures of DM annihilation...

It’s like searching for a needle...

... in a needlestack

The signatures are photons, cosmic rays, etc, and there are usually many astrophysical backgrounds...
Indirect DM detection

• Hints from the galactic center…?
  – DM annihilation or astrophysics? (e.g. MSPs, transients,…)

• Also, a claim of new 3.57 keV x-ray line in clusters…
  [Bulbul et al, 2014]
• (earlier hints of a 130 GeV line are dissipating)
Indirect DM detection

- AMS-02 verified the anomalous rise in the cosmic ray positron fraction \( \frac{e^+}{(e^++e^-)} \)
  - dark matter annihilation or a local source (e.g. pulsars)?

[AMS-02, 2013]
PeV (astrophysical) neutrinos

• First observation of astrophysical neutrinos

[IceCube ’14]
• First observation of astrophysical neutrinos

37 events (background ~ 10), flavor universal and isotropic in direction

expect to be linked to high-energy cosmic rays...

[IceCube ’14]
Impressive direct detection sensitivity to thermal relic (WIMP) dark matter in the halo with $O$(GeV - TeV) mass, and spin-independent scattering with nuclei.
Candidate events from DAMA, CoGeNT, CRESST, CDMS(Si) not confirmed by LUX, SuperCDMS, CDMSLite
But, thermal relic (WIMP-like) dark matter could be light (sub-GeV). What sensitivity do we have to this low mass region?
Fixed target DM searches - Neutrino Beams

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]

\[ p + p(n) \rightarrow V^* \rightarrow \bar{\chi}\chi \]
\[ \pi^0, \eta \rightarrow V\gamma \rightarrow \bar{\chi}\chi\gamma \]

\[ \chi + e \rightarrow \chi + e \]

\[ \chi + N \rightarrow \chi + N \]

Sensitivity within search currently underway at MiniBooNE (run as a beam dump to reduce neutrino background)

[deNiverville et al '11, Dharmapalan et al '12; Batell, deNiverville et al '14]
Fixed target DM searches - Neutrino Beams

\[
\begin{align*}
\pi^+ &\rightarrow \mu^+ \nu_{\mu} & \mu^+ &\rightarrow e^+ \nu_e \bar{\nu}_{\mu} \\
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\]

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Proposal to use T2K/SuperK (exploiting timing cuts) to explore higher mass range

[CAP talk by C. Nantais]
Other probes of light DM

$A' \rightarrow \text{invisible} \ (m_\chi = 1 \text{ MeV})$

- Monophotons at BaBar, and possibly Belle-II?  [Essig et al ’13]
- Rare decays
- Electron fixed target proposal at JLab  [Izaguirre et al ’13]

[Snowmass NLWCP WG, Essig, Jaros, Wester et al ’13]
In place of conclusions...

• As we’re in Sudbury, can’t over-emphasize the global importance of SNOLAB for observational astroparticle physics, with neutrino and direct detection dark matter searches.
Can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

- LSND - 800 MeV beam, $10^{23}$ POT, detector at 30m
- MiniBooNE - 9 GeV beam, 650 ton detector at 500m
- T2K - 30 GeV beam, off-axis detectors, near (280m), far (Super-K)
- (CHARM, MINOS, NOvA, LBNE,...)
Fixed target DM searches - Neutrino Beams

\[ \mathcal{L} = -\frac{1}{4} V_{\mu\nu}^2 - \frac{\kappa}{2} V_{\mu\nu} F_{\mu\nu} - \frac{1}{2} m_{V}^2 V_{\mu}^2 + |D_{\mu}\chi|^2 - m_{DM}^2 |\chi|^2 + \cdots \]

DM candidate, coupled through $U(1)'$

\[ \mathcal{L}_{\text{int}} = -\kappa e V_\mu J^\mu_{\text{em}} \]

$N_\chi \to N_\chi$, $m_\chi = 10$ MeV, $\alpha' = 0.1$, POT = $2 \times 10^{20}$

[Batell, deNiverville et al '14]